Accepted at IEEE VR 2026

Can Treadmill Walking Replicate Natural Walking? Optimizing Speed, Platform Tilt, and Training Duration on a Cyberith Virtualizer Elite 2

Sodabe Bandali*
Vanderbilt University, USA

Soumyajit Chakraborty†
Vanderbilt University, USA

Andrew S. McAvan‡
Vanderbilt University, USA

Timothy P. McNamara§
Vanderbilt University, USA

Bobby Bodenheimer¶
Vanderbilt University, USA

ABSTRACT

Locomotion is central to human navigation and spatial learning, with natural walking offering the most effective movement in immersive virtual environments (IVEs) due to its rich proprioceptive and vestibular feedback. However, space constraints often limit natural walking in IVEs, prompting the use of omnidirectional treadmills. The Cyberith Virtualizer Elite 2 enables users to walk in place by sliding their feet on a low-friction, tiltable platform while secured in a harness. It allows control over both tilt angle and walking speed, offering researchers flexibility in adjusting sensorimotor cues. In this study, we examined how tilt angle, speed, and training duration affect distance perception and cybersickness. In Experiment 1, we tested three tilt angles (0°, ∼8.5°, ∼17°) and three speeds (0.8×, 1.0×, 1.2× treadmill speed) during blind walking. A slower speed (0.8×) aligned best with natural walking and minimized cybersickness; users preferred the ∼8.5° tilt. Additional analysis identified ∼0.7× speed with ∼8.5° tilt as preferred. In Experiment 2, we varied training durations (3, 6, or 9 minutes) and found that, with the preferred setup, treadmill distance judgments were comparable to natural walking. At least 6 minutes of training was sufficient for adaptation. These findings offer practical guidance for configuring treadmill locomotion in virtual reality research.

Index Terms: Omnidirectional Treadmill, Distance Estimation, Cybersickness, Natural Walking, Treadmill Walking.

1 INTRODUCTION

Locomotion is fundamental to human navigation, enabling people to move through and interact with their surrounding environment [11, 13, 45, 74]. Active movement supports spatial updating and the acquisition of spatial knowledge [11, 13]. In virtual reality (VR), preserving this natural experience is important for spatial orientation and immersion. Natural walking is often considered the most effective locomotion method because it preserves proprioceptive and vestibular cues critical for accurate spatial judgments [14, 17, 65]; however, it is frequently constrained by limited physical space.

To support locomotion in large immersive virtual environments (IVEs) within constrained physical spaces, researchers have developed alternatives such as steering, teleportation, and redirected walking [2, 20, 56, 58, 72]. These techniques differ in how well they preserve sensorimotor cues, which can influence spatial learning. For example, steering provides continuous motion and optic flow that can aid spatial updating, whereas teleportation disrupts sensorimotor continuity and can impair spatial learning [15, 16, 26, 55]. Redirected walking more closely resembles natural walking and supports spatial learning [39], but it typically requires at least a 6 m × 6 m area [23, 40], which can be impractical for smaller laboratories.

Omnidirectional treadmills offer another approach by enabling continuous locomotion in a small physical footprint while allowing exploration of large IVEs [56]. Devices such as the *Virtuix Omni* [32], *Infinadeck* [57], *Cyberwalk* [67], and *Cyberith Virtualizer Elite 2* [10, 27] make such exploration feasible. In this work, we use the Cyberith Virtualizer Elite 2, where users slide their feet on a low-friction base platform while secured in a harness. On the Virtualizer, users do not translate through physical space. Rather, stepping motions produce foot sliding. Virtual walking speed was therefore determined by a configurable gain between foot sliding velocity and virtual displacement. The base platform can also be adjusted to provide a comfortable platform for the user to slide their feet on. We want to determine an optimal values for the gain and tilt that matches user's perceptual mappings for natural walking. We therefore adopted a blind-walking calibration procedure following Rieser et al. [60], since blind walking provides a direct behavioral measure of internally calibrated locomotion that is independent of visual feedback. These methods have been previously used in VR [49], but here they were used to identify the gain and tilt mapping such that distances reproduced under Virtualizer locomotion matched those during real-world blind walking.

Thus, despite the device's configurability and its increasing use in VR research, we still lack clear guidance on which combinations of tilt and walking-speed gain best preserve natural-walking-like distance judgments while limiting cybersickness. Prior work suggests both parameters matter, but their individual and combined contributions are difficult to disentangle because most studies treat them as fixed settings. For example, Chakraborty et al. [10] compared distance estimation [17, 34] and path integration [11, 33, 38] between treadmill and natural walking using the Virtualizer, but used only the steepest adult-recommended tilt by the manufacturer. While the steep tilt facilitated sliding, it also reduced self-movement control, increasing cybersickness and overwalking. Similarly, Lohman and Turchet [44] reported that walking at natural speed on the same treadmill can substantially increase cybersickness, suggesting that virtual speed reduction may be necessary [69]. Together, these findings motivate a systematic evaluation of base-platform tilt and treadmill walking speed as experimental factors rather than fixed defaults.

Training duration is another unresolved factor. Perceptual-motor recalibration to treadmill-based locomotion in IVEs develops over time [48, 50], and familiarization can improve spatial accuracy [35]. However, longer exposure may also increase cybersickness, and most treadmill studies use ∼3–10 minutes of training. Thus, it remains unclear how much training is needed to reach natural-walking-like performance—especially under a treadmill configuration optimized for both performance and comfort.

---

*e-mail: sodabe.bandali@vanderbilt.edu
†e-mail: soumyajit.chakraborty@vanderbilt.edu
‡e-mail: andrew.mcavan@vanderbilt.edu
§e-mail: t.mcnamara@vanderbilt.edu
¶e-mail: bobby.bodenheimer@vanderbilt.edu

To address these gaps, we systematically examined how base-platform tilt angle, walking-speed gain, and training duration affect distance perception and cybersickness on the Cyberith Virtualizer Elite 2, relative to natural over-ground walking. In Experiment 1, we varied base-platform tilt (0°, ∼8.5°, ∼17°) and walking-speed gain (0.8×, 1.0×, 1.2×) during a blind-walking distance estimation task [10, 17, 35]. Slower virtual walking (0.8×) more closely matched natural walking performance and reduced cybersickness, while tilt had limited effects—though participants preferred ∼8.5° for better control and reduced strain. Further analysis suggested that ∼0.7× speed gain with ∼8.5° tilt best matched natural walking. In Experiment 2, we used these preferred parameters and varied training duration (3, 6, and 9 minutes) to test how training time modulates performance and cybersickness once the treadmill settings are optimized. With the preferred setup, treadmill-based distance judgments were comparable to natural walking across training durations, and exploratory analysis suggested that ≥ 6 minutes of training is sufficient for users to adapt and achieve natural-walking-like performance. Collectively, these results provide practical guidance for configuring treadmill locomotion in VR research.

2 RELATED WORK

A wide range of efforts has aimed to replicate natural walking using treadmills [4, 19] or alternative locomotion devices [25, 61, 71]. Although some systems have achieved promising results, they often suffer from high costs and maintenance challenges [50, 67], while others are limited by their inability to support full-body motion, particularly due to their linear design [64, 65]. In contrast, omnidirectional treadmills offer both translational and rotational body-based cues [7, 8, 12, 52], whereas linear treadmills primarily support translational movement only [64, 65]. Past research suggests that access to both types of cues is critical for developing accurate spatial knowledge [59, 64, 65]. However, the effectiveness of omnidirectional treadmills remains debated. For instance, Semaan et al. [66] reported substantial differences between treadmill and natural walking based on “several kinematic, kinetic, and electromyographic measures,” suggesting that the sensorimotor fidelity of these systems may be limited. More recently, Homami et al. [29] reported that although sliding with the Cyberith Virtualizer Elite 2 reduced effort compared to walking-in-place, both techniques were still less effective than natural walking.

In VR, egocentric distances to objects are often underestimated when using head-mounted displays (HMDs) [6, 9, 17, 30, 34], particularly in action space (2–30 m) [18], which was the range used in our distance estimation task. Blind walking is widely used to perform distance estimation tasks in IVEs and in real world as it reliably captures egocentric distance judgments via motoric output in the real world [6, 36, 46], reflecting a strong perceived-to-acted distance coupling. However, treadmill walking disrupts this coupling. For instance, Kang et al. [31] and Chakraborty et al. [10] reported that participants overwalked distances using the Virtuix Omni and the Cyberith Virtualizer Elite 2 omnidirectional treadmills compared to natural walking in both real and virtual settings. These findings highlight the need for a calibration phase [47, 50], which we included in our study.

Although our current study focused solely on blind walking for distance estimation, prior research has employed other tasks involving a significant number of turns while exploring in IVEs using various omnidirectional treadmills. For instance, using triangle completion tasks on the first-generation Cyberith Virtualizer, Harootonian et al. [28] reported that (i) participants underestimated distances and made larger angular errors during blind treadmill walking, and (ii) distance errors increased with walking distance. In a path integration study on the Virtuix Omni, Dorado et al. [21, 22] found that treadmill walking enabled more accurate path integration than motion-controller steering. However, other studies have shown that walking on the Virtuix Omni leads to poorer performance compared to natural walking [51], steering [73], and linear treadmill walking [3]. These mixed findings indicate no clear consensus on whether omnidirectional treadmill walking can reliably replicate the performance of natural walking.

These mixed findings indicate no clear guidance on whether omnidirectional treadmill locomotion can reliably replicate the performance of natural walking. Importantly, prior studies have also varied in their device settings and protocols. For example, Chakraborty et al. [10] compared treadmill and natural walking for distance estimation and path integration tasks [11, 17, 33, 34, 38], but only tested the steepest tilt setting, which helped users slide their feet easily but led to less control over movement, increased cybersickness, and distance overshooting. Likewise, Lohman and Turchet [44] showed that walking at natural speeds increased discomfort, suggesting that reducing virtual speed could help. Training duration is another source of variability: while short familiarization periods (3–10 minutes) are common [35, 48, 50] longer training may improve accuracy but also raise cybersickness risks.

3 EXPERIMENT 1

This study aimed to identify which (i) tilt angle of the Cyberith Virtualizer Elite 2's base platform and (ii) virtually controlled walking speed allowed participants to (a) estimate distances comparable to natural walking and (b) experience minimal cybersickness. Participants performed a blind-walking task [17] to estimate the location of a virtual traffic cone after walking either naturally in a hallway or on the treadmill. We tested three tilt angles (0°, ∼8.5°, ∼17°), and three treadmill walking speeds (0.8×, 1.0×, and 1.2× normal treadmill walking speed). Tilt angle was treated as a between-subject variable, and walking speed as a within-subject variable. Each tilt group completed the distance estimation task under all three treadmill speed conditions, as well as under the natural walking condition in a hallway for baseline comparison. To minimize practice effects, the order of locomotion methods and walking speeds within each tilt group was counterbalanced. Participants experienced the natural walking condition either before or after all treadmill trials. Treadmill walking speeds were fully counterbalanced across participants (see Figure S2 in the supplementary material for an example execution sequence). Following Lohman and Turchet [44], who reported increased cybersickness at natural walking speed on the device, we tested whether reduced speeds could alleviate cybersickness and improve control. Cybersickness was assessed using the Simulator Sickness Questionnaire (SSQ) [37], administered before and after each navigation phase. Our methodology was adapted from Chakraborty et al. [10], who used a similar blind-walking task to compare treadmill and natural walking.

3.1 Hypotheses

Previous studies [10, 44] have shown that higher tilt angles of the base platform of the Cyberith Virtualizer Elite 2 omnidirectional treadmill can induce severe cybersickness among participants and their spatial judgments can be misled, leading to overwalking. Similarly, walking with normal speed could make people more cybersick on this device [44]. So, based on these findings, we hypothesized that: **H1.1:** Higher tilt angles and walking speeds increase cybersickness due to less control on self-motion as well as physical strain; **H1.2:** Lower tilt angles and walking speeds improve distance perception due to better control on self-motion leading to acquiring better natural proprioceptive cues; and **H1.3:** Lower tilt angles and walking speeds reduce cybersickness by reducing sensory mismatch and increasing control on self-motion.

3.2 Participants

We conducted an a priori power analysis in *G*Power* to estimate the required sample size. We used a repeated-measures ANOVA


(a) (b) (c)

Figure 1: The images illustrate key task phases: (a) Learning phase—participants walked on the treadmill at their normal speed toward purple traffic posts viewed one at a time, which disappeared upon arrival. (b) Treadmill-based distance estimation—participants viewed a virtual traffic cone, pressed a controller button, and performed blind walking task on the treadmill to estimate the cone's location. (c) Natural walking distance estimation—participants completed the same blind walking task as in (b) using natural walking.

(within–between interaction F-test) assuming Cohen's $f = 0.25$, $\alpha = 0.05$, power = 0.95, three groups (tilt angles), and 12 repeated measurements (4 walking conditions: three speeds plus natural walking × 3 actual distances: 4 m, 5.5 m, and 7 m). The analysis indicated a minimum sample size of 24 participants, consistent with prior work [10,44,51]. Based on this estimate and prior studies, we recruited 39 participants. We excluded data from three participants (2 male, 1 female) due to HMD or treadmill technical issues, leaving 36 participants (19 female, 17 male) aged 19–58 years (M = 28.4 years, SD = 12.5 years). Participants were evenly assigned to the three tilt groups (12 per group): 0° tilt (7 female, 5 male), ∼8.5° tilt (3 female, 9 male), and ∼17° tilt (9 female, 3 male). The study was approved by the Vanderbilt University Institutional Review Board (IRB# 221064), and all participants provided informed consent and received 12 USD compensation.

3.3 Equipment and Design

3.3.1 Hardware and Software

The VR system used in this study included an HTC Vive Focus 3 head-mounted display (HMD) with a resolution of 2448 × 2448 pixels per eye and a 90 Hz refresh rate. It weighs 785 g and has horizontal and vertical field-of-views of 116° and 96°, respectively. The HMD is equipped with a 120 Hz eye tracking module, which added an extra 54 g of weight to the HMD, resulting in a total weight of 839 g. All software was developed using the Unity Game Engine (version 2021.3.27f1).

The Cyberith Virtualizer Elite 2 is an omnidirectional treadmill that supports natural sliding on a base platform that can tilt to five angles (0°, ∼4.25°, ∼8.5°, ∼12.75°, ∼17°; Tilt 0–4). Manufacturer guidelines recommend lower tilts (1–2) for children and higher tilts (3–4) for adults. We tested three tilts: 0° (Tilt 0), ∼8.5° (Tilt 2), and ∼17° (Tilt 4). We excluded Tilt 1 (∼4.25°) because it is intended for children, and excluded Tilt 3 (∼12.75°) to (i) include only one adult-recommended high-tilt setting and (ii) align with Chakraborty et al. [10], who used Tilt 4. A rotating waist ring senses walking direction in the IVE, and low-friction shoe covers (Medium/Large) enable smooth sliding. Users initiate locomotion by leaning forward against the ring while sliding backward on the tilted surface; sliding is possible at Tilt 0 but becomes easier as tilt increases. As with other omnidirectional treadmills, users can move faster or slower by changing their physical sliding pace, and the system can also modulate effective walking speed by adjusting the translation gain between physical sliding and virtual motion (e.g., 0.8× slower or 1.2× faster while maintaining the same physical pace; see [48,49]). In our study, participants walked at their natural sliding pace while we varied this speed gain to identify a setting that yields body-based translational and rotational cues most consistent with over-ground walking. Walking speed Gain was controlled in Unity via the manufacturer package using a 'speed multiplier' variable (default = 1.2, i.e., 1.2× of the participant's natural sliding speed on the device); we evaluated 0.8, 1.0, and 1.2 of this variable, corresponding to 0.8×, 1.0×, and 1.2× of each participant's natural sliding speed on the device. For additional device details, see Hager et al. [27].

3.3.2 Virtual Environments

This experiment used two virtual environments: (i) a training environment to familiarize participants with the treadmill walking (Figure 1(a)), and (ii) a test environment where participants performed the distance estimation tasks using both treadmill and natural walking (Figure 1(b) and (c)). Both environments used a Voronoi grassy ground texture. The only objects present were the task-related targets (i.e., traffic posts in the training environment or a traffic cone in the test environment). We rendered the default Unity skybox and enabled object shadows in both environments.

In the training environment, 12 traffic posts appeared sequentially, one at a time. Participants walked toward each post until collision; inter-post distances ranged from 3.84 m to 12.58 m. The task lasted ∼3 minutes and helped participants adapt to treadmill walking while calibrating walking effort on the device to visual distance, consistent with prior locomotion recalibration studies [1,50]. Training used a veridical 1.0× mapping of each participant's normal sliding speed (i.e., no virtual speed manipulation), establishing a baseline relationship between their natural gait/effort and visually specified distance. In the subsequent blind-walking distance estimation trials, we varied the walking speed gain relative to the 1.0× baseline; because optic flow was unavailable, participants had no visual motion feedback to reveal these changes and continued walking at their natural pace. This design allowed us to test whether reducing or increasing walking speed gain on this device yields distance estimates that better match natural overground walking.

In the test environment, participants judged the egocentric distance to a virtual traffic cone placed at one of five distances: 4 m, 4.75 m, 5.5 m, 6.25 m, or 7 m. We rendered a horizontal guideline on the ground that indicated the participant's starting location for each trial.

3.4 Procedure

After providing informed consent, participants completed the Simulator Sickness Questionnaire (SSQ) to obtain a baseline measurement. They then created room-scale boundaries: when standing on the Virtualizer, participants used the controller to draw a 2 m × 2 m boundary corresponding to the treadmill area. For natural walking, the experimenter assisted them in outlining the physical hallway (13 m ± 2 m long and 2.5 m ± 0.5 m wide) as the walking area.

During the distance estimation task, participants first viewed a virtual traffic cone at a specific distance. They then pressed a button to black out the HMD screen and walked—either on the treadmill or naturally—to the estimated location. For natural walking, the experimenter walked alongside the participants to ensure safety. Upon reaching the estimated location, the participant pressed the button again to initiate the return phase, during which the experimenter guided them back to the starting point. The distance walked before initiating the return phase was recorded using a tape measure. In the treadmill walking condition, there was no return phase; the button press marked the end of the trial, recorded the walked distance, and started the next trial. Figure S1 in the supplementary material shows a pictorial overview of the blind walking process.

Participants completed 13 trials for each walking condition (i.e., a natural walking condition, and three treadmill walking conditions with different walking speeds under a tilt group). The first two were demonstration trials at 4.75 m and 6.25 m. The remaining 11 included 9 data trials (three each at 4 m, 5.5 m, and 7 m) and 2 dummy trials (one each at 4.75 m and 6.25 m). Trials were presented in a pseudo-randomized order such that (i) no two trials of the same distance occurred consecutively, and (ii) no dummy trial appeared at the end. Dummy trials were excluded from analysis and were included only to minimize learning effects. In total, participants performed 52 trials (13 trials × 4 walking conditions) in the study.

After completing each walking condition, participants filled out the SSQ again and were offered a short break. They were allowed to take as much time as they wanted during the break, which typically lasted 3-5 minutes. Before starting another walking condition, participants filled out the SSQ once again to record their current self-reported cybersickness before experiencing the condition. At the end of all four walking conditions, the experimenter thanked the participants for their participation and provided them compensation. Figure S2 in the supplementary material shows the overall distance estimation procedure.

3.5 Results and Discussion

We assessed participants' performance using two primary outcome measures: (i) Proportional Distance Error (PDE) to evaluate their distance perception and (ii) differences between their Post- and Pre-exposure cybersickness scores (i.e., Post−Pre-exposure scores) calculated from the SSQ questionnaires to measure their cybersickness between walking conditions. For PDE, we computed each participant's mean across trials and screened for outliers, defined as mean PDE values beyond ±3 SD from the sample mean; no outliers were identified, so all data were retained. We did not screen SSQ for outliers because its scores fall within a fixed, well-defined range (i.e., 0 - 348.27 for the Total SSQ scores, for example) [37]. We tested normality (Shapiro–Wilk) and homogeneity of variance (Levene's) on our data before performing further statistical analyses. When assumptions were violated, we applied the aligned rank transformation (ART) to the data [75]. Finally, we ran analysis of variance (ANOVA) tests on the transformed or untransformed data using R. For the transformed data, we report the descriptive statistics of the untransformed data for ease of understanding. Although we report all statistical results in the main text, we provide tables of these results in the supplemental material to aid interpretation.

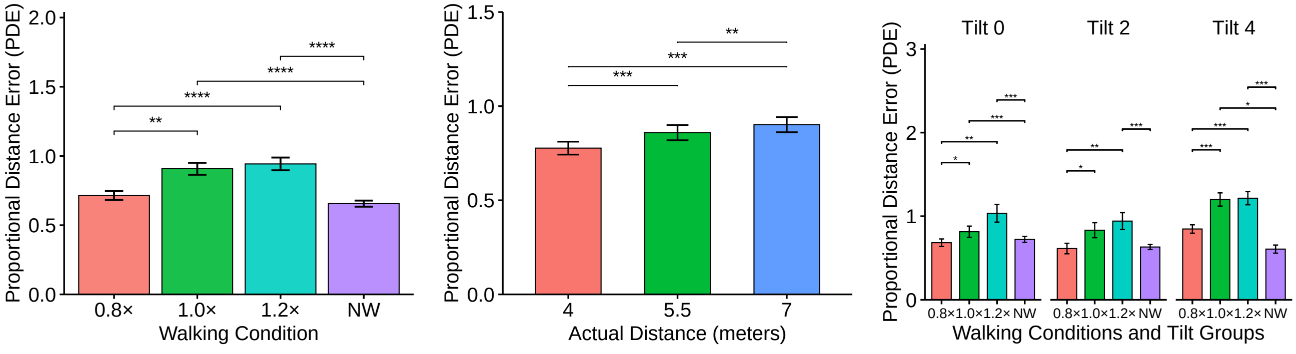
3.5.1 Proportional Distance Error

Proportional Distance Error (PDE) was computed as the ratio of the estimated (walked) distance to the actual target distance from the starting point. A ratio of 1.0 indicates perfect estimation, while ratios above or below 1.0 signify over or underestimation of perceived distances. Shapiro-Wilk test showed that the data was not normal (W = 0.9, $p < 0.001$), and Levene's test showed that the data was homogeneous ($p = 0.133$). Therefore, we transformed the data using ART and ran a 3 (Tilt Groups: 0° (Tilt 0), ∼8.5° (Tilt 2), and ∼17° (Tilt 4)) × 4 (Walking Conditions: Treadmill walking with 3 speeds (0.8×, 1.0×, and 1.2×) and natural walking) × 3 (Actual Distances: 4 m, 5.5 m, and 7 m) × 2 (Walking Conditions Order: Natural Walking First or Treadmill Walking First) mixed-design ANOVA on the mean PDE across trials of the transformed data.

The analysis revealed a significant main effect of Walking Conditions on PDEs, $F(3, 89) = 14.58$, $p < 0.001$, $\eta_p^2 = 0.33$. Post hoc Wilcoxon tests with Holm corrections showed that participants under-walked significantly at 0.8× treadmill speed ($M = 0.71$, $SD = 0.33$, $SE = 0.03$) compared to both 1.0× ($M = 0.95$, $SD = 0.50$, $SE = 0.05$, V = -3.40, $p_{adj} = 0.003$, $r = 0.34$) and 1.2× speeds ($M = 1.06$, $SD = 0.58$, $SE = 0.06$, V = -4.66, $p_{adj} < 0.001$, $r = 0.44$). No significant difference was found between the PDEs at 1.0× and 1.2× speeds (V = -1.26, $p_{adj} = 0.423$, $r = 0.13$). Similarly, PDEs at 0.8× treadmill speed did not differ significantly from natural walking ($M = 0.66$, $SD = 0.23$, $SE = 0.02$, $V = 1.03$, $p_{adj} = 0.423$, $r = 0.11$). In contrast, both 1.0× ($V = 4.43$, $p_{adj} < 0.001$, $r = 0.43$) and 1.2× ($V = 5.69$, $p_{adj} < 0.001$, $r = 0.52$) speeds led to significantly more walking compared to natural walking. These findings are illustrated in Figure 2(a). There was no significant main effect of Tilt Groups on PDEs, $F(2, 29) = 1.73$, $p = 0.194$, $\eta_p^2 = 0.11$, nor of Walking Condition Order, $F(1, 29) = 0.60$, $p = 0.44$, $\eta_p^2 = 0.02$. However, a significant main effect of Actual Distance emerged, $F(2, 59) = 28.09$, $p < 0.001$, $\eta_p^2 = 0.49$. Post hoc Wilcoxon tests with Holm corrections revealed that participants under-walked significantly at 4 m ($M = 0.78$, $SD = 0.41$, $SE = 0.03$) compared to 5.5 m ($M = 0.86$, $SD = 0.49$, $SE = 0.04$; V = -4.74, $p_{adj} < 0.001$, $r = 0.53$) and 7 m ($M = 0.90$, $SD = 0.48$, $SE = 0.04$; V = -7.23, $p_{adj} < 0.001$, $r = 0.69$), regardless of walking condition. They also under-walked significantly at 5.5 m than at 7 m (V = -2.49, $p_{adj} = 0.016$, $r = 0.31$), as shown in Figure 2(b).

The main effect of Walking Conditions on PDEs was qualified by a significant interaction with Tilt Groups, $F(6, 89) = 2.29$, $p = 0.042$, $\eta_p^2 = 0.13$. Post hoc Wilcoxon tests with Holm corrections revealed that in the Tilt 0 group (0°), participants under-walked significantly more at 0.8× speed ($M = 0.68$, $SD = 0.27$, $SE = 0.04$) than at 1.0× ($M = 0.81$, $SD = 0.40$, $SE = 0.06$, V = -2.17, $p_{adj} = 0.033$, $r = 0.40$) and 1.2× ($M = 1.04$, $SD = 0.63$, $SE = 0.10$, V = -3.33, $p_{adj} = 0.001$, $r = 0.61$) speeds. Compared to natural walking ($M = 0.72$, $SD = 0.21$, $SE = 0.03$), 0.8× speed did not differ significantly (V = -1.24, $p_{adj} = 0.863$, $r = 0.13$), but both 1.0× and 1.2× speeds resulted in significant over-walking (V = 4.43 and 5.69, respectively, both $p_{adj} < 0.001$, $r = 0.56$ and $r = 0.72$). In the Tilt 2 group (∼8.5°), participants again under-walked significantly more at 0.8× ($M = 0.61$, $SD = 0.37$, $SE = 0.06$) than at 1.0× ($M = 0.83$, $SD = 0.53$, $SE = 0.08$, V = -2.38, $p_{adj} = 0.021$, $r = 0.43$) and 1.2× ($M = 0.94$, $SD = 0.60$, $SE = 0.10$, V = -3.02, $p_{adj} = 0.004$, $r = 0.55$) speeds. No significant differences were found between the PDEs with natural walking ($M = 0.63$, $SD = 0.18$, $SE = 0.03$) and at 0.8× (V = - 1.10, $p_{adj} = 0.271$, $r = 0.22$) or 1.0× (V = - 1.57, $p_{adj} = 0.117$, $r = 0.31$) speeds. However, at 1.2× speed, participants over-walked significantly compared to natural walking ($V = 4.43$, $p_{adj} < 0.001$, $r = 0.56$). In the Tilt 4 group (∼17°), participants again under-walked significantly at 0.8× ($M = 0.84$, $SD = 0.30$, $SE = 0.05$) compared to 1.0× ($M = 1.20$, $SD = 0.47$, $SE = 0.07$, V = -3.82, $p_{adj} < 0.001$, $r = 0.70$) and 1.2× ($M = 1.22$, $SD = 0.47$, $SE = 0.07$, V = -4.09, $p_{adj} < 0.001$, $r = 0.75$) speeds. Again, PDEs at 0.8× speed was not significantly different from natural walking ($M = 0.60$, $SD = 0.26$, $SE = 0.04$, $V = 1.03$, $p_{adj} = 0.228$, $r = 0.19$). 1.0× speed ($V = 2.47$, $p_{adj} = 0.0039$, $r = 0.25$) and 1.2× ($V = 5.69$, $p_{adj} < 0.001$, $r = 0.72$) speeds resulted in significant over-walking relative to natural walking. These findings are illustrated in Figure 2(c).

The main effect of Actual Distances on PDEs was qualified by



(a) (b) (c)

Figure 2: **Experiment 1** results. Figure (a) shows the effects of Walking Conditions (0.8×, 1.0×, 1.2× normal treadmill walking speeds and natural walking (NW)) on distance errors. Treadmill walking at 0.8× speed yielded estimates closest to natural walking. Figure (b) shows the effects of Actual Distances (4 m, 5.5 m, 7 m), with participants generally underestimating distances across conditions. Figure (c) illustrates the interaction between Walking Conditions and Tilt Groups (Tilt 0 = 0°, Tilt 2 = ∼8.5°, Tilt 4 = ∼17°), showing that 0.8× speed produced distance estimates most comparable to natural walking across all tilts. In all plots, the vertical error bars represent standard errors of the means; horizontal bars marked with *, **, and *** indicate $p < 0.05$, $p < 0.01$, and $p < 0.001$.

significant interactions with both Walking Conditions, $F(6, 179)$ = 3.85, p = 0.001, η_p^2 = 0.11, and Tilt Groups, $F(4, 59)$ = 3.76, p = 0.009, η_p^2 = 0.17. However, post hoc Wilcoxon tests with Holm corrections revealed no significant pairwise differences across Walking Conditions or Tilt Groups ($ps > 0.053$). Additionally, we observed a significant three-way interaction between Walking Conditions, Actual Distances, and Tilt Groups, $F(12, 179)$ = 2.35, p = 0.007, η_p^2 = 0.14, as well as a four-way interaction including Walking Condition Orders, $F(12, 179)$ = 2.12, p = 0.020, η_p^2 = 0.12. Nonetheless, post hoc tests for both interactions did not yield any significant differences between conditions ($ps > 0.562$ and $ps > 0.570$, respectively).

These findings suggest that the order of experiencing the natural or treadmill walking locomotion methods, and the tilt angles of the base platform had minimal effect on people's distance perception. Their overall underestimation of distances decreased with increasing actual distances. However, across all tilt angles, walking at a reduced speed of 0.8× the normal treadmill speed resulted in distance perception closely matching natural walking. In contrast, walking at a faster speed (1.2×) led participants to significantly over-walk compared to natural walking estimates. At normal speed (1.0×), participants also over-walked at both the lowest (Tilt 0 or 0°) and highest (Tilt 4 or ∼17°) tilt angles, but not at a medium tilt (Tilt 2 or ∼8.5°), where judgments were comparable to natural walking. This suggests that Tilt 2 enables distance judgment estimates comparable to natural walking when walking speed is maintained at or below normal treadmill walking speed.

3.5.2 Cybersickness

Participants completed the Simulator Sickness Questionnaire (SSQ) before and after each Walking Condition. The SSQ comprises Nausea, Oculomotor, Disorientation, and Total scores[1]. We computed the change in cybersickness symptoms as the difference between post- and pre-exposure scores for each Walking Condition. Shapiro-Wilk tests indicated non-normality across all score differences—Nausea (W = 0.585, $p < 0.0001$), Oculomotor (W = 0.7551, $p < 0.0001$), Disorientation (W = 0.744, $p < 0.0001$), and Total SSQ (W = 0.709, $p < 0.001$)—while Levene's tests confirmed homogeneity of variances—Nausea (p = 0.294), Oculomotor (p = 0.304), Disorientation (p = 0.772), and Total SSQ (p = 0.449). Therefore, we applied ART to the difference scores and conducted a 3 (Tilt Groups: 0°, ∼8.5°, ∼17°) × 4 (Walking Conditions: 0.8×, 1.0×, 1.2× treadmill speeds, and natural walking) mixed-design ANOVA on the transformed data.

We found no significant main effect of Walking Conditions on Nausea ($F(3, 54)$ = 1.71, p = 0.17, η_p^2 = 0.09), Oculomotor ($F(3, 54)$ = 0.28, p = 0.84, η_p^2 = 0.02), Disorientation ($F(3, 54)$ = 1.15, p = 0.34, η_p^2 = 0.06), or Total SSQ score differences ($F(3, 54)$ = 0.44, p = 0.72, η_p^2 = 0.02). Similarly, there were no significant main effects of Tilt Groups on Nausea ($F(2, 18)$ = 0.51, p = 0.61, η_p^2 = 0.05), Oculomotor ($F(2, 18)$ = 0.18, p = 0.83, η_p^2 = 0.02), Disorientation ($F(2, 18)$ = 0.81, p = 0.46, η_p^2 = 0.08), or Total SSQ score differences ($F(2, 18)$ = 0.27, p = 0.77, η_p^2 = 0.03) (see Table S4 and Table S5 in the supplementary material for descriptive statistics of the main effects of Walking Conditions and Tilt Groups on the cybersickness scores). Finally, we observed no significant interaction effects between Walking Conditions and Tilt Groups for any of the SSQ metrics: Nausea ($F(6, 54)$ = 1.92, p = 0.09, η_p^2 = 0.18), Oculomotor ($F(6, 54)$ = 1.51, p = 0.19, η_p^2 = 0.14), Disorientation ($F(6, 54)$ = 1.63, p = 0.15, η_p^2 = 0.25), or Total SSQ score differences ($F(6, 54)$ = 1.78, p = 0.12, η_p^2 = 0.17).

Because frequentist statistics cannot confirm the null hypothesis when results are non-significant, we conducted Bayesian ANOVAs [62] for the models described above. See Section 8 in the Supplementary Materials for more details. Across all models, evidence favored the null hypothesis (BF_{01} range: 4–65), indicating moderate to strong support for the absence of Walking Conditions or Tilt Groups effects on cybersickness.

3.5.3 Post Hoc Regression Analysis

Across all platform tilts (Tilt 0, 2, and 4), distance estimates were closest to natural overground judgments at a treadmill walking speed of 0.8× participants' normal sliding speed. Because we tested only three speed gains, the true best-matching value might lie between them. We therefore fit a linear regression predicting mean PDE from walking-speed gain, pooling across tilts; tilt was

---

[1] Total SSQ score is computed as $3.74 \times (9.54 \times N + 7.58 \times O + 13.92 \times D)$, where N, O, and D refer to the Nausea, Oculomotor, and Disorientation sub-scales, respectively [37].

excluded because it did not significantly affect distance judgments or cybersickness. The analysis was statistically significant ($F(1, 322) = 28.25$, $p < 0.01$, $R^2 = 0.078$, $\beta = 0.874$, 95% CI [0.55, 1.20]), indicating a reliable linear trend. However, the model explained little variance overall, but we expected this given the noisiness of the distance error data. We overlaid the mean PDE from the natural walking condition (0.66) onto the regression line and estimated the corresponding treadmill speed using the formula: Estimated speed = ($meanPDE_{NW}$ - $Intercept$) / $Slope$, substituting values: $(0.66-0.036)/0.874 = 0.71$. Our purpose with the model was interpolation rather than broad prediction: it provided an estimate that ∼0.7× treadmill walking speed would best replicate natural walking in terms of distance estimation performance. This finding is illustrated in Figure 3.

3.5.4 Discussion

In this experiment, we examined how variations in treadmill walking speed and base platform tilt angle influenced participants' distance judgment accuracy and cybersickness, compared to their natural walking performance. Our findings indicate that neither tilt nor treadmill speed induced severe cybersickness, not supporting our hypotheses **H1.1** and **H1.3**. This result contradicts prior findings by Lohman and Turchet and Chakraborty et al. [10, 44], who reported increased cybersickness at normal treadmill speed (1.0×). One possible explanation is that our distance estimation task involved walking in a straight line, minimizing turning. In contrast, prior studies often employed triangle completion tasks requiring frequent turns, which can increase cybersickness. Notably, Chakraborty et al. [10] found significantly higher cybersickness in triangle completion than in distance estimation tasks ($p = 0.02$), supporting the idea that turning increases discomfort.

Across all tilt groups, walking at 0.8× of participants' normal treadmill speed yielded distance judgments closely aligned with natural walking. In contrast, higher speeds (1.0× and 1.2×) at the lowest tilt (Tilt 0 or 0°), the steepest tilt (Tilt 4 or ∼17°), and 1.2× speed at the medium tilt (Tilt 2 or ∼8.5°) led to overwalking compared to natural walking, consistent with prior evidence that locomotion speed influences vection and distance perception in VR [53, 70]. At Tilt 2, judgments were comparable to natural walking at both 0.8× and 1.0× speeds. Informal feedback suggested Tilt 2 felt more natural and less physically demanding than Tilt 0, likely due to reduced effort to overcome friction, whereas Tilt 4 was often described as more physically demanding, consistent with research linking steeper inclines to increased muscular effort in VR [10, 24, 54]. Although tilt had no significant main effect, these condition-specific patterns and subjective reports support **H1.2**.

Consistent with prior studies [6, 10, 31, 36], participants generally underestimated distances during natural walking. The average underestimation rate in our study was ∼66%, slightly lower than Kelly's meta-analytic estimate of ∼73.48% across HMDs [34], closely matching Chakraborty et al.'s ∼67% with a similar HMD [10], and marginally better than Buck et al.'s ∼60% using an older HTC VIVE Pro model [5]. Differences in eye height, HMD weight, and field of view likely contribute to this variability [17, 34]. Prior research has shown that omnidirectional treadmills often lead to overwalking—e.g., ∼22% on the Cyberith Virtualizer Elite 2 [10], and ∼56% on the Virtuix Omni [31]—likely due to challenges in controlling balance and speed [64]. We observed similar trends: significant overwalking (≥20%) occurred at higher tilt (Tilt 4) and faster speeds (1.0×, 1.2×). In contrast, walking at 0.8× speed produced ∼29% underestimation—closely matching the ∼34% underestimation observed during natural walking. A regression analysis further estimated that a treadmill speed of ∼0.7× most closely replicates natural walking on the Cyberith Virtualizer Elite 2. Together, these findings suggest that slower speeds and moderate tilt angles can support more naturalistic distance estimation on VR treadmills.

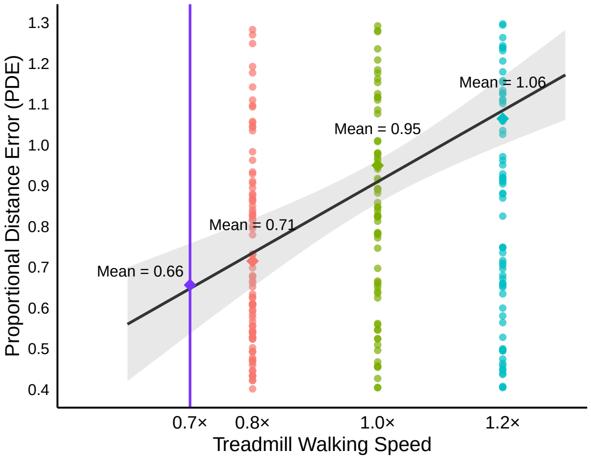


Figure 3: Linear regression of distance errors as a function of treadmill walking speeds (0.8×, 1.0×, 1.2× normal speed). The regression line (black) was fit to treadmill speeds only, with the shaded region indicating the 95% confidence interval. A vertical purple line marks the natural walking condition, plotted at 0.7× treadmill speed, suggesting this speed best approximates natural walking distance perception in IVEs.

Finally, although not directly addressed in the present study, participants' adaptation and familiarity with the treadmill may also influence performance. It is possible that extended training with such devices could reduce errors in distance estimation or improve other spatial tasks, which we have explored in the next study.

4 EXPERIMENT 2

Several prior studies show that users can recalibrate distance judgments during natural walking after training on an omnidirectional treadmill [1, 47, 48, 50]. Building on this work, Experiment 2 examined how training duration on the Cyberith Virtualizer Elite 2 (3, 6, or 9 minutes) affects the extent to which treadmill walking-based distance judgments resemble those made during natural walking, using distance perception and cybersickness as outcomes. Participants were assigned to one between-subject Training Duration group: short (3 min), moderate (6 min), or extended (9 min). Each participant completed a distance estimation task under both treadmill and natural walking conditions (within-subject Walking Condition), with condition order counterbalanced within each duration group. Unlike Experiment 1, treadmill parameters were fixed for all participants based on the preferred settings from Experiment 1: walking speed = 0.7× normal sliding speed and base tilt = Tilt 2 (∼8.5°). Hardware, software, virtual environments, and procedures matched Experiment 1 except that (i) treadmill walking speed and base-platform tilt were held constant between training and distance estimation tasks and (ii) training duration varied by group, i.e., training was time-based: participants repeatedly collided with posts until a timer expired (3/6/9 min), rather than completing a fixed number of 12 collisions as in Experiment 1. Similar to Experiment 1, we computed PDEs of the distance estimation tasks for both walking conditions and administered the SSQ before and after each condition, using Post–Pre scores to quantify cybersickness.

4.1 Hypotheses

Most previous studies typically provided 3–10 minutes of treadmill training before engaging participants in experimental tasks [10, 68].

Also, several prior studies have shown that participants can recalibrate their distance judgments during natural walking after brief training on an omnidirectional treadmill [1,47,48,50]. Building on this literature, we proposed two hypotheses: **H2.1:** Higher training duration on the treadmill will lead to distance judgment performance comparable to that of natural walking; and **H2.2:** Higher training duration on the treadmill will lead to greater cybersickness due to prolonged exposure to continuous movement in the IVE.

4.2 Participants

An a priori power analysis was conducted using G*Power to determine the required sample size. We performed a repeated measures ANOVA with a within-between interaction F-test, assuming a medium effect size ($f = 0.25$), $\alpha = 0.05$, power = 0.95, number of groups = 3 (Training Durations), and number of measurements = 6 (2 Walking Conditions × 3 Actual Distances: 4 m, 5.5 m, 7 m). The analysis indicated a minimum sample size of 36 participants, consistent with prior studies [10,44,51]. Based on this estimate and previous work, we recruited 40 participants. Data from four participants (2 male, 2 female) were excluded due to technical issues with the HMD or treadmill, resulting in a final sample of 36 participants (22 females, 14 males), aged 19–35 years ($M = 24$ years, $SD = 10$ years). Participants were evenly distributed across Training Duration groups (3, 6, or 9 minutes), with 12 participants per group: 8 females and 4 males in the 3-minute condition, 5 females and 7 males in the 6-minute condition, and 8 females and 4 males in the 9-minute condition. The study was approved by our institution's IRB. All participants provided informed consent and received 12 USD for participation.

4.3 Results and Discussion

Measures and data analysis for the current experiment were the same as in Experiment 1. Before conducting quantitative analyses, we screened the PDE data for outliers in the similar way mentioned in section 3.5. No outliers were identified for PDE, and all data were retained for analysis. Following Experiment 1, we report results in text and provide tables in the supplemental material.

4.3.1 Proportional Distance Error

Shapiro-Wilk test showed that the data were not normal ($W = 0.985$, $p = 0.023$), but Levene's test showed that the data were homogeneous ($p = 0.953$). So, we transformed the data using ART and ran a 3 (Training Durations: 3 min, 6 min, and 9 min) × 2 (Walking Conditions: Treadmill walking and natural walking) × 3 (Actual Distances: 4 m, 5.5 m, and 7 m) × 2 (Walking Conditions Order: Natural Walking First or Treadmill Walking conditions First) mixed-design ANOVA on the mean PDE of the transformed data.

We found a significant main effect of Training Durations on PDEs, $F(2, 180) = 11.84$, $p < 0.001$, $\eta_p^2 = 0.12$. Post hoc Wilcoxon tests with Holm corrections showed that participants under-walked significantly when they were trained on the treadmill for 9 mins ($M = 0.615$, $SD = 0.194$, $SE = 0.023$) compared to both 3 mins ($M = 0.78$, $SD = 0.27$, $SE = 0.032$, $V = 4.87$, $p_{adj} < 0.001$, $r = 0.34$), and 6 mins ($M = 0.71$, $SD = 0.24$, $SE = 0.03$, $V = 2.50$, $p_{adj} = 0.026$, $r = 0.18$). Participants also under-walked significantly when they got a training of 6 mins compared to 3 mins ($V = 2.36$, $p_{adj} = 0.026$, $r = 0.17$). These results are visualized in Figure 4(a). We also found a significant main effect of Walking Conditions, $F(1, 180) = 11.10$, $p = 0.001$, $\eta_p^2 = 0.06$. Participants under-walked significantly more during natural walking ($M = 0.644$, $SD = 0.12$, $SE = 0.02$) than treadmill walking ($M = 0.76$, $SD = 0.25$, $SE = 0.04$). Finally, we also found a significant main effect of Actual Distances, $F(2, 180) = 6.27$, $p = 0.002$, $\eta_p^2 = 0.07$. Post hoc Wilcoxon tests with Holm corrections showed that participants under-walked significantly more at 4 m ($M = 0.64$, $SD = 0.20$, $SE = 0.02$) compared to 7 m ($M = 0.76$, $SD = 0.28$, $SE = 0.03$, $V = -3.53$, $p_{adj} = 0.002$, $r = -0.25$). There were no significant difference between the distance errors at 4 m and at 5.5 m ($M = 0.70$, $SD = 0.23$, $SE = 0.02$, $V = -2.04$, $p_{adj} = 0.130$, $r = -0.15$), and at 5.5 m compared to 7 m ($V = -1.49$, $p_{adj} = 0.14$, $r = -0.11$). These results are visualized in Figure 4(c). We did not find a significant main effect of Walking Condition orders, $F(1, 180) = 1.76$, $p = 0.186$, $\eta_p^2 = 0.01$.

The main effects of Training Durations and Walking Conditions were qualified by a significant interaction between these two variables on mean PDEs, $F(2, 180) = 3.42$, $p = 0.035$, $\eta_p^2 = 0.04$. However, Post hoc Wilcoxon tests with Holm corrections found no statistically significant differences between natural and treadmill walking at any of the training durations: at 3 minutes, treadmill walking: $M = 0.87$, $SD = 0.30$, $SE = 0.51$; natural walking: $M = 0.68$, $SD = 0.20$, $SE = 0.03$; $V = -1.86$, $p_{adj} = 0.10$, $r = 0.137$; at 6 minutes, treadmill walking: $M = 0.75$, $SD = 0.32$, $SE = 0.05$; natural walking: $M = 0.67$, $SD = 0.13$, $SE = 0.02$; $V = 1.65$, $p_{adj} = 0.15$, $r = 0.12$; and at 9 minutes, treadmill walking: $M = 0.65$, $SD = 0.23$, $SE = 0.03$; natural walking: $M = 0.57$, $SD = 0.14$, $SE = 0.02$; $V = 0.88$, $p_{adj} = 0.38$, $r = 0.06$.

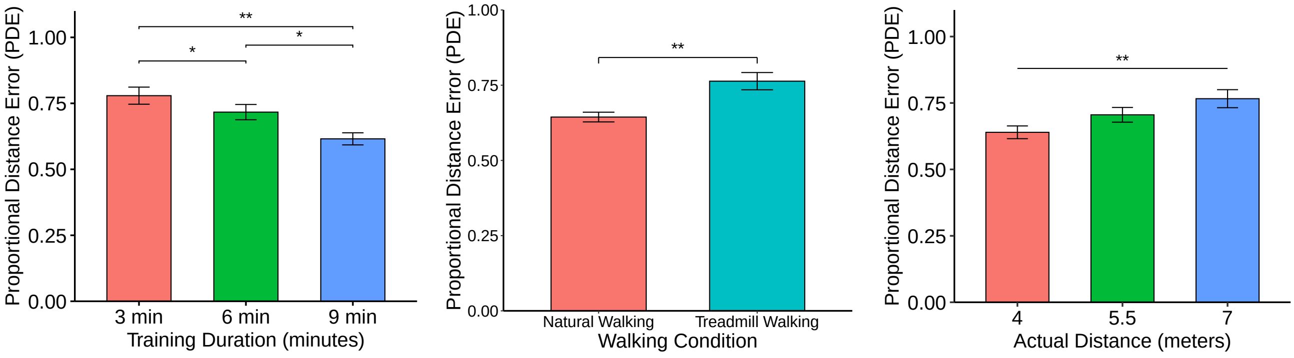
The main effect of Walking Condition was qualified by a significant interaction with Walking Condition Order, $F(1, 180) = 8.76$, $p = 0.003$, $\eta_p^2 = 0.05$. Post hoc Wilcoxon tests with Holm correction revealed that for participants who experienced treadmill walking first, walked significantly more during treadmill walking ($M = 0.83$, $SD = 0.31$, $SE = 0.04$) than during natural walking ($M = 0.62$, $SD = 0.15$, $SE = 0.02$, $V = 4.20$, $p_{adj} < 0.001$, $r = 0.55$). However, for participants who experienced natural walking first, the difference in distance estimation errors between treadmill walking ($M = 0.69$, $SD = 0.26$, $SE = 0.03$) and natural walking ($M = 0.67$, $SD = 0.18$, $SE = 0.02$, $V = 0.82$, $p_{adj} = 0.41$, $r = 0.03$) was not statistically significant.

These findings suggest that a treadmill speed of 0.7× and platform tilt Tilt 2 ($\sim 8.5^\circ$) produces distance judgments that more closely match natural walking, although both conditions showed overall underestimation of distances. While longer training with this setup increased distance underestimation, treadmill and natural-walking estimates remained comparable across training durations, indicating that these parameters yield natural-walking-like performance largely independent of prior training time. When differences did emerge, participants tended to underestimate distances less using treadmill walking than natural walking. This is notable because natural blind walking is typically associated with distance underestimation [17]; our results suggest that appropriately tuned treadmill parameters can support recalibration to the virtual locomotion mapping in the IVE and improve distance-judgment accuracy.

4.3.2 Cybersickness

Shapiro–Wilk tests revealed non-normal distributions for all cybersickness score differences: Nausea ($W = 0.932$, $p = 0.00095$), Oculomotor ($W = 0.889$, $p < 0.001$), Disorientation ($W = 0.872$, $p < 0.001$), and Total SSQ Score ($W = 0.901$, $p < 0.001$). However, Levene's tests indicated homogeneity of variances for all score differences: Nausea ($p = 0.779$), Oculomotor ($p = 0.758$), Disorientation ($p = 0.389$), and Total SSQ ($p = 0.729$). Therefore, we applied ART transformations to the data and conducted a 3 (Training Durations: 3, 6, 9 minutes) × 2 (Walking Conditions: treadmill and natural walking) mixed ANOVA on the transformed Nausea, Oculomotor, Disorientation, and Total SSQ differences.

We found a significant main effect of Walking Conditions on Nausea differences, $F(1, 32) = 4.95$, $p = 0.033$, $\eta_p^2 = 0.133$, with participants reporting greater nausea during treadmill walking ($M = 6.96$, $SD = 14.5$, $SE = 2.39$) than natural walking ($M = 2.45$, $SD = 11.2$, $SE = 1.89$). However, Walking Conditions had no significant effect on Oculomotor ($F(1, 32) = 0.04$, $p = 0.84$, $\eta_p^2 = 0.001$), Disorientation ($F(1, 32) = 0.06$, $p = 0.81$, $\eta_p^2 = 0.001$),



(a) (b) (c)

Figure 4: **Experiment 2** results. Figure (a) shows the effect of Training Durations (3, 6, 9 minutes) on distance errors, with longer training leading to greater underestimation. Figure (b) illustrates the effects of Walking Conditions—Treadmill Walking at 0.7× normal speed with ∼8.5° tilt (Tilt 2) vs. Natural Walking—revealing significantly greater underestimation during natural walking. Figure (c) represents distance errors across Actual Distances (4 m, 5.5 m, 7 m), showing consistent underestimation regardless of locomotion type. In all plots, the vertical error bars indicate standard errors of the means; horizontal bars marked with *, **, and *** denote $p < 0.05$, $p < 0.01$, and $p < 0.001$.

or Total SSQ score differences ($F(1, 32) = 0.01$, $p = 0.90$, $\eta_p^2 = 0.04$). Similarly, Training Durations had no significant effect on Nausea ($F(2, 32) = 0.75$, $p = 0.48$, $\eta_p^2 = 0.04$), Oculomotor ($F(2, 32) = 0.34$, $p = 0.71$, $\eta_p^2 = 0.02$), Disorientation ($F(2, 32) = 0.17$, $p = 0.84$, $\eta_p^2 = 0.01$), or Total SSQ score differences ($F(2, 32) = 0.14$, $p = 0.87$, $\eta_p^2 = 0.01$) (see Table S9 and Table S10 in the supplementary material for descriptive statistics of the main effects of Training Durations and Walking Conditions on the cybersickness scores). No significant interactions were found between Walking Conditions and Training Durations for Nausea ($F(2, 32) = 0.06$, $p = 0.94$, $\eta_p^2 = 0.004$), Oculomotor ($F(2, 32) = 2.32$, $p = 0.11$, $\eta_p^2 = 0.13$), Disorientation ($F(2, 32) = 0.17$, $p = 0.85$, $\eta_p^2 = 0.01$), or Total SSQ score differences ($F(2, 32) = 0.77$, $p = 0.47$, $\eta_p^2 = 0.05$). Overall, these findings suggest that although participants reported greater nausea during treadmill walking than natural walking, the preferred treadmill configuration (i.e., 0.7× normal walking speed, and ∼8.5° base platform tilt or Tilt 2) did not lead to increased cybersickness over time in the present task, as longer training durations did not lead to significantly higher Total SSQ scores.

4.3.3 Discussion

In this experiment, we examined how treadmill training duration affects distance judgments relative to natural walking. Participants completed 3, 6, or 9 minutes of training before performing the distance estimation task under both treadmill and natural walking conditions. All participants used the preferred treadmill configuration from Experiment 1 (0.7× normal sliding speed; Tilt 2, ∼8.5°), chosen to minimize differences between treadmill and natural walking. Within each training-duration group, treadmill and natural walking did not differ significantly. However, longer training led to greater distance underestimation, contrary to **H2.1**. A plausible explanation is fatigue: treadmill walking may become more effortful with longer exposure, and participants also reported higher nausea during treadmill walking than during natural walking. This accumulating discomfort may degrade spatial judgments over time. Despite this trend, the mean error differences between walking conditions were small and decreased with training (M_{diff}: 3 min = 0.19; 6 min = 0.08; 9 min = 0.08), suggesting that 6 minutes of training may be sufficient for users to achieve treadmill-based distance estimation comparable to natural walking with this setup.

Interestingly, participants did not report severe cybersickness at the preferred treadmill speed and platform tilt, regardless of training duration. This aligns with Mousas et al. [51], who found no SSQ differences between natural walking and walking on the Virtuix Omni. Although encouraging for the Virtualizer, this pattern does not support **H2.2**, which predicted greater cybersickness after 9 minutes of training. In contrast, participants consistently reported higher nausea during treadmill walking than during natural walking, independent of training duration, consistent with prior work [10, 31, 44]. While the treadmill's sliding may provide useful body-based translational and rotational cues [63–65], it may also reduce perceived control, contributing to nausea. Notably, even with these preferred settings, longer training appeared to worsen spatial judgments; thus, applications should avoid prolonged familiarization and instead use brief training—around 6 minutes may suffice—before the main task.

Similar to Experiment 1 and prior research [6, 10, 31, 36], participants in this study also underestimated distances. With the treadmill set to the preferred speed (0.7×) and tilt (∼8.5°), the underestimation was ∼76.3%. During natural walking, underestimation was ∼64.4%, aligning with our previous findings in Experiment 1 (∼66%) and other studies [5, 10, 34]. In contrast to Chakraborty et al., who observed ∼22% overestimation with a 1.0× treadmill speed and ∼17° tilt (Tilt 4), our findings suggest that slower treadmill speeds yield distance judgments closer to those observed during natural walking.

5 GENERAL DISCUSSION

Across two experiments, we investigated how treadmill walking speed, base platform tilt, and training duration influence distance perception and cybersickness when using the Cyberith Virtualizer Elite 2 omnidirectional treadmill in IVEs. Our findings provide clear, practical guidelines for configuring this device to support naturalistic walking. Specifically, Experiment 1 showed that reducing treadmill walking speed to 0.8× the participants' normal walking speed minimized cybersickness and produced distance judgments comparable to natural walking. Further analysis identified a speed of ∼0.7× and a moderate platform tilt of ∼8.5° (Tilt 2) as the preferred configuration for the treadmill. Experiment 2 validated this setup by showing that training duration had no significant effect on performance. With this setup, participants' distance judgments during treadmill walking were comparable to natural walking. Further analysis suggested that at least 6 minutes of training is sufficient for users to adapt to the treadmill locomotion. Together, these findings provide valuable guidance for researchers seeking to replicate natural locomotion under spatial constraints using the current omnidirectional treadmill.

Previous studies using omnidirectional treadmills typically relied on manufacturer-defined or fixed parameter settings, focusing on whether treadmill walking improved or impaired performance relative to other locomotion methods [10, 21, 22, 28, 31, 44, 51, 66]. For instance, Semaan et al. [66] reported substantial differences between treadmill and natural walking based on "several kinematic, kinetic, and electromyographic measures," raising concerns about the sensorimotor fidelity of such systems. Similarly, Ruddle and Lessels [64] noted that while omnidirectional treadmills provide proprioceptive cues for translation and rotation, the vestibular feedback involved in rotational balance differs from natural walking. Despite these insights, few studies have systematically manipulated the configurable parameters of omnidirectional treadmills to determine optimal settings for simulating natural walking. In our studies, we addressed this gap by exploring how adjustments to base platform tilt and walking speed on the Cyberith Virtualizer Elite 2 impact spatial perception. Our findings offer practical guidelines for optimizing configurations of this treadmill to better approximate natural walking on this device.

Prior studies have compared treadmill walking with popular virtual locomotion methods such as steering, teleportation, and walk-in-place [21,22,31,51]. In contrast, our work focused on optimizing treadmill walking to achieve spatial knowledge acquisition comparable to natural walking, while minimizing cybersickness. Our studies build upon work by Chakraborty et al. [10], who similarly investigated treadmill and natural walking but did not explore parameter optimization. While a potential limitation of our approach is the lack of direct comparison with other locomotion techniques, as done in earlier studies, our findings provide baseline optimized values for treadmill parameters that closely simulate natural walking. These values offer a solid foundation for future research to compare optimized treadmill walking with other virtual locomotion methods directly.

In Experiment 2, we used the preferred treadmill configuration: a walking speed of 0.7× and a platform tilt of ∼8.5°. The average PDE was ∼0.76 across training duration groups. However, based on the regression model from Experiment 1, this setup was expected to yield a lower PDE of ∼0.66. The observed value was more consistent with the prediction for a slightly faster speed (0.8×) in Experiment 1. Despite this, the treadmill PDE in Experiment 2 was not significantly different from that of natural walking (overall $M = 0.64$) within each training group, indicating that the prediction was still reasonably accurate. One explanation for the discrepancy is that the Experiment 1 model included data from all tilt levels, whereas Experiment 2 used only Tilt 2. Notably, a model trained solely on Tilt 2 data from Experiment 1 predicts a faster preferred speed (closer to 0.9×).

These findings highlight that distance estimation is highly sensitive to treadmill calibration. This fact was observed in the real world by Reiser et al. [60] for distance estimation, and studied for linear treadmills by Mohler et al. [48, 50] in VR. Our results generalize these results to omnidirectional treadills and emphasize that developers should carefully consider how programmable parameters such as speed and tilt interact to influence spatial perception.

Thus, beyond offering optimized parameters for the Cyberith Virtualizer Elite 2, our findings carry broader implications for the design of omnidirectional treadmills. The principles identified here are likely generalizable to other omnidirectional treadmills such as the *Virtuix Omni*, *Kat Walk*, or *Infinadeck*. These devices also rely on sliding or stepping mechanisms that can benefit from careful parameter tuning, such as walking speed manipulation. Our findings, therefore, offer broader guidance for designing naturalistic virtual locomotion systems that support accurate spatial updating, minimize cybersickness, and better replicate natural walking.

In summary, while prior studies have questioned whether treadmill walking can match the performance of natural walking, our two studies challenge this view. By systematically optimizing key parameters of an omnidirectional treadmill—walking speed, base platform tilt, and training duration—we found that participants could adapt effectively, resulting in distance judgments comparable to natural walking while experiencing minimal to no cybersickness. These findings offer valuable guidance for future researchers aiming to achieve naturalistic locomotion using a Cyberith Virtualizer Elite 2 omnidirectional treadmill in IVEs.

6 LIMITATIONS AND FUTURE WORK

One limitation of our study is the minimal rotational movement by participants, as the blind-walking task required them to walk straight toward targets. Prior work with greater rotational demands on omnidirectional treadmills has reported higher cybersickness [10, 21, 22, 31, 44], which may also affect spatial judgments. Future work should therefore test whether users remain minimally cybersick during rotation-heavy tasks (e.g., *path integration* [11, 33, 38]) under the preferred configuration identified here (i.e., ∼0.7× speed and ∼8.5° platform tilt; Tilt 2). Another limitation is that these preferred settings are specific to the Cyberith Virtualizer Elite 2. Because many commodity-level omnidirectional treadmills lack a tilt-able base, the optimal tilt may not transfer across devices. However, translation gain is adjustable on most systems, so future work should test whether a similar gain (e.g., ∼0.7× of a user's natural device-specific sliding/walking speed) can produce distance-judgment performance comparable to natural over-ground walking on other treadmills. We also did not evaluate Tilt 1 (∼4.25°) or Tilt 3 (∼12.75°), and Experiment 1 tested only three speed gains on the Virtualizer; broader sampling of speeds and tilts is needed. Finally, we did not display a self-avatar during treadmill training. Prior work suggests that a self-avatar can improve spatial perception in IVEs [41, 42]; examining this factor in our setting could be interesting for future work.

7 CONCLUSION

Across two studies, we investigated the preferred walking speed, base platform tilt, and training duration for effective adaptation to the Cyberith Virtualizer Elite 2 omnidirectional treadmill in distance estimation tasks. In Experiment 1, we found that virtually reducing treadmill walking speed to 0.8× the normal pace—regardless of tilt—reduced cybersickness and yielded distance judgments comparable to natural walking. Further analysis suggested that a speed of ∼0.7× combined with an ∼8.5° platform tilt (Tilt 2) would best match natural walking distance judgments. With the preferred treadmill setup, Experiment 2 found that participants' distance judgments during treadmill walking were comparable to natural walking, regardless of training duration. Exploratory analysis further indicated that at least 6 minutes of training suffices for users to adapt to the treadmill locomotion method. These findings provide practical guidelines for configuring the Virtualizer treadmill in future research aiming for achieving comparable natural walking performance.

ACKNOWLEDGMENTS

This work was supported by the National Science Foundation (grants 1763966 and 2217889) and a Vanderbilt Sesquicentennial Award. We used *ChatGPT* and *Grammarly* for clarity editing.

REFERENCES

[1] H. Adams, G. Narasimham, J. Rieser, S. Creem-Regehr, J. Stefanucci, and B. Bodenheimer. Locomotive recalibration and prism adaptation of children and teens in immersive virtual environments. *IEEE Trans. on Vis. and Comp. Graphics*, 24(4):1408–1417, 2018. doi: 10.1109/TVCG.2018.2794072 3, 6, 7

[2] M. Al Zayer, P. MacNeilage, and E. Folmer. Virtual locomotion: a survey. *IEEE transactions on visualization and computer graphics*, 26(6):2315–2334, 2018. 1

[3] A. Bashir, T. De Regt, and C. Jones. Comparing a friction-based unidirectional treadmill and a slip-style omnidirectional treadmill on first-time hmd-vr user task performance, cybersickness, postural sway, posture angle, ease of use, enjoyment, and effort. *International Journal of Human-Computer Studies*, 179:103101, 2023. doi: 10.1016/j.ijhcs.2023.103101 2

[4] F. P. Brooks Jr. Walkthrough—a dynamic graphics system for simulating virtual buildings. In *Proceedings of the 1986 workshop on Interactive 3D graphics*, pp. 9–21, 1987. 2

[5] L. Buck, R. Paris, and B. Bodenheimer. Distance compression in the htc vive pro: A quick revisitation of resolution. *Frontiers in Virtual Reality*, 2:728667, 2021. 6, 8

[6] L. E. Buck, M. K. Young, and B. Bodenheimer. A comparison of distance estimation in hmd-based virtual environments with different hmd-based conditions. *ACM Transactions on Applied Perception (TAP)*, 15(3):1–15, 2018. 2, 6, 8, 14

[7] T. Cakmak and H. Hager. Cyberith virtualizer: A locomotion device for virtual reality. In *ACM SIGGRAPH 2014 Emerging Technologies*, pp. 1–1, 2014. doi: 10.1145/2614066.2614106 2

[8] D. Calandra, M. Billi, F. Lamberti, A. Sanna, R. Borchiellini, et al. Arm swinging vs treadmill: A comparison between two techniques for locomotion in virtual reality. In *Eurographics (short papers)*, pp. 53–56, 2018. 2

[9] S. Chakraborty, H. Finney, H. Gagnon, S. Creem-Regehr, J. Stefanucci, and B. Bodenheimer. Inter-pupillary distance mismatch does not affect distance perception in action space. In *ACM Symposium on Applied Perception 2024*, pp. 1–9, 2024. 2

[10] S. Chakraborty, A. Kane, H. C. Gagnon, T. P. McNamara, and B. Bodenheimer. Comparative effectiveness of an omnidirectional treadmill versus natural walking for navigating in virtual environments. In *Proc. of ACM Symp. on Applied Perception (SAP '24)*, pp. 1–13. ACM, Dublin, Ireland, 2024. doi: 10.1145/3675231.3675243 1, 2, 3, 6, 7, 8, 9

[11] S. S. Chance, F. Gaunet, A. C. Beall, and J. M. Loomis. Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration. *Presence: Teleops. & Virt. Env.*, 7(2):168–178, 1998. 1, 2, 9

[12] H. Cherni, S. Nicolas, and N. Métayer. Using virtual reality treadmill as a locomotion technique in a navigation task: Impact on user experience–case of the katwalk. *International Journal of Virtual Reality*, 21(1):1–14, 2021. 2

[13] E. R. Chrastil and W. H. Warren. Active and passive contributions to spatial learning. *Psychonomic Bulletin & Rev.*, 19(1):1–23, 2012. 1

[14] E. R. Chrastil and W. H. Warren. Active and passive spatial learning in human navigation: acquisition of survey knowledge. *J. of exp. psych.: learning, memory, and cognition*, 39(5):1520, 2013. 1

[15] C. G. Christou and P. Aristidou. Steering versus teleport locomotion for head mounted displays. In *AVR*, 2017. 1

[16] N. Coomer, S. Bullard, W. Clinton, and B. Williams-Sanders. Evaluating the effects of four vr locomotion methods: joystick, arm-cycling, point-tugging, and teleporting. In *Proceedings of the 15th ACM symposium on applied perception*, pp. 1–8, 2018. 1

[17] S. H. Creem-Regehr, J. K. Stefanucci, and B. Bodenheimer. Perceiving distance in virtual reality: theoretical insights from contemporary technologies. *Philosophical Transactions of the Royal Society B*, 378(1869):20210456, 2023. 1, 2, 6, 7

[18] J. E. Cutting and P. M. Vishton. Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In *Perception of space and motion*, pp. 69–117. Elsevier, 1995. 2

[19] R. P. Darken, T. Allard, and L. B. Achille. Spatial orientation and wayfinding in large-scale virtual spaces: An introduction. *Presence*, 7(2):101–107, 1998. 2

[20] M. Di Luca, H. Seifi, S. Egan, and M. Gonzalez-Franco. Locomotion vault: the extra mile in analyzing vr locomotion techniques. In *Proceedings of the 2021 CHI conference on human factors in computing systems*, pp. 1–10, 2021. 1

[21] J. Dorado, P. Figueroa, J.-R. Chardonnet, F. Merienne, and T. Hernández. Homing by triangle completion in consumer-oriented virtual reality environments. In *2019 IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 1652–1657. IEEE, 2019. 2, 9

[22] J. Dorado, P. Figueroa, J.-R. Chardonnet, F. Merienne, and T. Hernández. Perceived space and spatial performance during path-integration tasks in consumer-oriented virtual reality environments. In *2019 IEEE Conf. on Virtual Reality and 3D User Interfaces (VR)*, pp. 896–897. IEEE, 2019. 2, 9

[23] L. Fan, H. Li, and M. Shi. Redirected walking for exploring immersive virtual spaces with hmd: a comprehensive review and recent advances. *IEEE Transactions on Visualization and Computer Graphics*, 2022. 1

[24] L. Feinstein, D. Garcia, and D. A. Bowman. The impact of treadmill tilt on locomotion and spatial perception in vr. In *Proceedings of the ACM Symposium on Applied Perception (SAP)*, 2022. 6

[25] S. C. Grant and L. E. Magee. Navigation in a virtual environment using a walking interface. 2000. 2

[26] M. J. Habgood, D. Moore, D. Wilson, and S. Alapont. Rapid, continuous movement between nodes as an accessible virtual reality locomotion technique. In *2018 IEEE conference on virtual reality and 3D user interfaces (VR)*, pp. 371–378. IEEE, 2018. 1

[27] H. Hager, T. Cakmak, and J. Jägerskj. Cyberith virtualizer elite 2–second generation vr locomotion device based on a 2 dof motion platform, 2019. 1, 3

[28] S. K. Harootonian, R. C. Wilson, L. Hejtmánek, E. M. Ziskin, and A. D. Ekstrom. Path integration in large-scale space and with novel geometries: Comparing vector addition and encoding-error models. *PLoS computational biology*, 16(5):e1007489, 2020. 2, 9

[29] H. Homami, A. Quigley, and M. D. Barrera Machuca. Omnidirectional vr treadmills walking techniques: Comparing walking-in-place and sliding vs natural walking. In *2025 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 634–644. IEEE, 2025. doi: 10.1109/VR59515.2025.00086 2

[30] V. Interrante, B. Ries, and L. Anderson. The effect of visual enhancement on the perception of egocentric travel in immersive virtual environments. In *IEEE Virtual Reality Conference (VR 2006)*, pp. 27–34. IEEE, 2006.

[31] J. H. Kang, N. Yadav, S. Ramadoss, and J. Yeon. Reliability of distance estimation in virtual reality space: A quantitative approach for construction management. *Computers in Human Behavior*, 145:107773, 2023. doi: 10.1016/j.chb.2023.107773 2, 6, 8, 9

[32] A. Karime, J. D. Hol, and F. C. T. van der Helm. Effects of the virtuix omni on gait and kinematics during virtual reality walking. *Applied Ergonomics*, 96:103482, 2021. doi: 10.1016/j.apergo.2021.103482 1

[33] J. Kelly, T. McNamara, B. Bodenheimer, T. Carr, and J. Rieser. The shape of human navigation: How environmental geometry is used in maintenance of spatial orientation. *Cognition*, 109:281–6, 11 2008. doi: 10.1016/j.cognition.2008.09.001 1, 2, 9

[34] J. W. Kelly. Distance perception in virtual reality: A meta-analysis of the effect of head-mounted display characteristics. *IEEE Trans. on Vis. and Comp. graphics*, 29(12):4978–4989, 2022. 1, 2, 6, 8

[35] J. W. Kelly, L. A. Cherep, and Z. D. Siegel. Blind walking in virtual environments: Effects of visual information and proprioceptive feedback. *Experimental Brain Research*, 237(8):2107–2120, 2019. doi: 10.1007/s00221-019-05557-7 1, 2

[36] J. W. Kelly, T. A. Doty, M. Ambourn, and L. A. Cherep. Distance perception in the oculus quest and oculus quest 2. *Frontiers in Virtual Reality*, 3:850471, 2022. doi: 10.3389/frvir.2022.850471 2, 6, 8

[37] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993. 2, 4, 5

[38] R. L. Klatzky, J. M. Loomis, and R. G. Golledge. Encoding spatial representations through nonvisually guided locomotion: Tests of human path integration. *Psychology of Learning and Motivation*, 37:41–84, 1997. doi: 10.1016/S0079-7421(08)60499-5 1, 2, 9

[39] E. Langbehn, P. Lubos, and F. Steinicke. Evaluation of locomotion techniques for room-scale vr: Joystick, teleportation, and redirected walking. In *Proceedings of the Virtual Reality International Conference-Laval Virtual*, pp. 1–9, 2018. 1

[40] Y.-J. Li, F. Steinicke, and M. Wang. A comprehensive review of redirected walking techniques: Taxonomy, methods, and future directions. *Journal of Computer Science and Technology*, 37(3):561–583, 2022. 1

[41] Q. Lin, J. Rieser, and B. Bodenheimer. Affordance judgments in hmd-based virtual environments: Stepping over a pole and stepping off a ledge. *ACM Transactions on Applied Perception*, 12(2):6:1–6:21, Apr. 2015. doi: 10.1145/2720020 9

[42] Q. Lin, J. J. Rieser, and B. Bodenheimer. Stepping off a ledge in an hmd-based immersive virtual environment. In *Proceedings of the ACM Symposium on Applied Perception*, SAP '13, pp. 107–110. ACM, New York, NY, USA, 2013. doi: 10.1145/2492494.2492511 9

[43] C. C. Liu and M. Aitkin. Bayes factors: Prior sensitivity and model generalizability. *Journal of Mathematical Psychology*, 52(6):362–375, 2008. 14

[44] J. Lohman and L. Turchet. Evaluating cybersickness of walking on an omnidirectional treadmill in virtual reality. *IEEE Transactions on Human-Machine Systems*, 52(4):613–623, 2022. doi: 10.1109/THMS.2022.3148324 1, 2, 3, 6, 7, 8, 9

[45] J. M. Loomis, R. L. Klatzky, R. G. Golledge, and J. W. Philbeck. Human navigation by path integration. In *Wayfinding behavior: Cognitive mapping and other spatial processes*, pp. 125–151. Johns Hopkins University Press, 1999. 1

[46] J. M. Loomis and J. W. Philbeck. Measuring spatial perception with spatial updating and action. In *Embodiment, ego-space, and action*, pp. 17–60. Psychology Press, 2008. 2

[47] B. J. Mohler, S. H. Creem-Regehr, and W. B. Thompson. The influence of feedback on egocentric distance judgments in real and virtual environments. In *Proceedings of the 3rd symposium on Applied perception in graphics and visualization*, pp. 9–14, 2006. 2, 6, 7

[48] B. J. Mohler, W. B. Thompson, and S. H. Creem-Regehr. Perceptual-motor recalibration on a virtual reality treadmill. *Journal of Vision*, 4(8):9–9, 2004. doi: 10.1167/4.8.9 1, 2, 3, 6, 7, 9

[49] B. J. Mohler, W. B. Thompson, S. H. Creem-Regehr, H. L. Pick, and W. H. Warren. Visual flow influences gait transition speed and preferred walking speed. *Experimental Brain Research*, 181(2):221–228, 2007. 1, 3

[50] B. J. Mohler, W. B. Thompson, S. H. Creem-Regehr, P. Willemsen, H. L. Pick, Jr, and J. J. Rieser. Calibration of locomotion resulting from visual motion in a treadmill-based virtual environment. *ACM Trans. on Applied Perception (TAP)*, 4(1):4–es, 2007. 1, 2, 3, 6, 7, 9

[51] C. Mousas, D. Kao, A. Koilias, and B. Rekabdar. Evaluating virtual reality locomotion interfaces on collision avoidance task with a virtual character. *The Visual Computer*, 37(9):2823–2839, 2021. 2, 3, 7, 8, 9

[52] M. Nabiyouni, A. Saktheeswaran, D. A. Bowman, and A. Karanth. Comparing the performance of natural, semi-natural, and non-natural locomotion techniques in virtual reality. In *2015 IEEE symposium on 3D user interfaces (3DUI)*, pp. 3–10. IEEE, 2015. 2

[53] S. Nichols, D. Evans, and D. Haun. Effect of locomotion speed, direction and flux on vection and distance perception in virtual environments. In *Proceedings of the IEEE Virtual Reality Conference*, pp. 65–72, 2000. 6

[54] N. C. Nilsson, R. Nordahl, and S. Serafin. Locomotion in virtual reality: the role of stride frequency and walking speed in cybersickness. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems*, pp. 1–12, 2018. 6

[55] R. Paris, J. Klag, P. Rajan, L. Buck, T. P. McNamara, and B. Bodenheimer. How video game locomotion methods affect navigation in virtual environments. In *ACM Symposium on Applied Perception 2019*, pp. 1–7, 2019. 1

[56] T. C. Peck, H. Fuchs, and M. C. Whitton. Evaluation of reorientation techniques for walking in large virtual environments. In *IEEE Transactions on Visualization and Computer Graphics*, vol. 18, pp. 617–624, 2011. doi: 10.1109/TVCG.2012.61 1

[57] J. Plouzeau, D. Picard, and A. Mebarki. A comparison of an omnidirectional treadmill and natural walking for virtual locomotion. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 558–567. IEEE, 2022. doi: 10.1109/VR51125.2022.00064 1

[58] S. Razzaque, Z. Kohn, and M. C. Whitton. Redirected walking. In *Proceedings of Eurographics*, vol. 9, pp. 105–106, 2005. 1

[59] B. E. Riecke, B. Bodenheimer, T. P. McNamara, B. Williams, P. Peng, and D. Feuereissen. Do we need to walk for effective virtual reality navigation? physical rotations alone may suffice. In *International Conference on Spatial Cognition*, pp. 234–247. Springer, 2010. 2

[60] J. J. Rieser, H. L. Pick, D. A. Ashmead, and A. E. Garing. The calibration of human locomotion and models of perceptual-motor organization. *J. Exp. Psych: Hum. Perc. Perf.*, 21:480–497, 1995. 1, 9

[61] G. P. Roston and T. Peurach. A whole body kinesthetic display device for virtual reality applications. In *Proceedings of International Conference on Robotics and Automation*, vol. 4, pp. 3006–3011. IEEE, 1997. 2

[62] J. N. Rouder, R. D. Morey, P. L. Speckman, and J. M. Province. Default bayes factors for anova designs. *Journal of Mathematical Psychology*, 56(5):356–374, 2012. doi: 10.1016/j.jmp.2012.08.001 5, 14

[63] R. A. Ruddle. The effect of translational and rotational body-based information on navigation. In *Human Walking in Virtual Environments*, pp. 99–112. Springer, 2013. 8

[64] R. A. Ruddle and S. Lessels. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 16(1):1–18, 2009. 2, 6, 8, 9

[65] R. A. Ruddle, E. Volkova, and H. H. Bülthoff. Walking improves your cognitive map in environments that are large-scale and large in extent. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 18(2):1–20, 2011. 1, 2, 8

[66] M. B. Semaan, L. Wallard, V. Ruiz, C. Gillet, S. Leteneur, and E. Simoneau-Buessinger. Is treadmill walking biomechanically comparable to overground walking? a systematic review. *Gait & posture*, 92:249–257, 2022. 2, 9

[67] J. L. Souman, P. R. Giordano, M. Schwaiger, I. Frissen, T. Thümmel, H. Ulbrich, A. D. Luca, H. H. Bülthoff, and M. O. Ernst. Cyberwalk: Enabling unconstrained omnidirectional walking through virtual environments. *ACM Transactions on Applied Perception (TAP)*, 8(4):1–22, 2011. 1, 2

[68] K. M. Stanney, C. M. Fidopiastis, and L. Foster. Motion sickness in virtual reality: Causes, measurement, and mitigation. *Human Factors*, 62(8):1253–1275, 2020. doi: 10.1177/0018720819896280 6

[69] F. Steinicke and G. Bruder. Effects of walking speed on distance estimation and path integration in virtual environments. *IEEE Trans. on Vis. and Computer Graphics*, 8(4):311–322, 2002. 1

[70] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Quantifying the illusion of self-motion in virtual reality. *ACM Transactions on Applied Perception (TAP)*, 7(4):1–27, 2010. 6

[71] D. Swapp, J. Williams, and A. Steed. The implementation of a novel walking interface within an immersive display. In *2010 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 71–74. IEEE, 2010. 2

[72] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks. Walking ¿ walking-in-place ¿ flying, in virtual environments. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques*, pp. 359–364. ACM, 1999. doi: 10.1145/311535.311589 1

[73] L. E. Warren and D. A. Bowman. User experience with semi-natural locomotion techniques in virtual reality: the case of the virtuix omni. In *Proceedings of the 5th symposium on spatial user interaction*, pp. 163–163, 2017. 2

[74] W. H. Warren. Self-motion: Visual perception and locomotion. In W. Epstein and S. Rogers, eds., *Perception of space and motion*, pp. 263–325. Academic Press, 1995. 1

[75] J. O. Wobbrock, L. Findlater, D. Gergle, and J. J. Higgins. The aligned rank transform for nonparametric factorial analyses using only anova procedures. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 143–146. ACM, 2011. 4

Supplementary Materials to Can Treadmill Walking Replicate Natural Walking? Optimizing Speed, Platform Tilt, and Training Duration on a Cyberith Virtualizer Elite 2

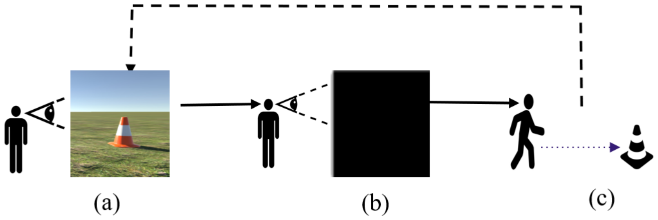


Figure S1: Illustration of the blind-walking procedure used in the distance estimation task: (a) Participants viewed the initial position of a virtual traffic cone. (b) After pressing a button on the controller, the HMD turned black. (c) Participants then walked naturally or on the treadmill to the estimated location of the cone, with the HMD remaining blacked out throughout the walk. In the treadmill condition, participants pressed the button again upon reaching their estimated location to record the data and initiate the next trial. In the natural walking condition, the experimenter measured the walked distance of the participant using a tape measure and then guided them back to the starting position while the HMD remained black. After returning to the starting location, participants pressed the same button on the controller to start the next trial.

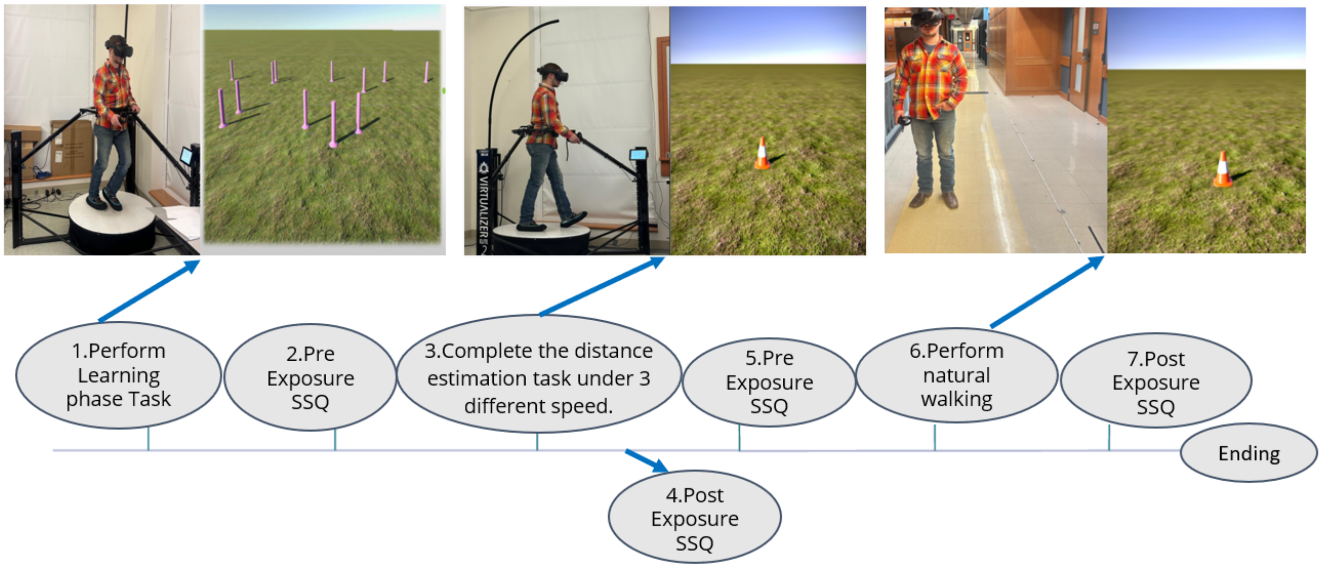


Figure S2: This figure illustrates a possible sequence for a participant in Experiment 1 who completed the treadmill walking phase before the natural walking phase. After receiving instructions on wearing the specialized low-friction shoe covers and stepping onto the treadmill, the participant began with a learning phase to acclimate to treadmill walking, followed by a pre-exposure simulator sickness questionnaire (SSQ). The participant then completed a distance estimation task at one of three treadmill speeds (0.8×, 1.0×, or 1.2×), after which a post-exposure SSQ was administered. This cycle was repeated for each of the three speeds. Pre- and post-exposure SSQs were collected before and after each distance estimation task to assess changes in cybersickness. Upon completing all treadmill trials, the participant performed the distance estimation task under natural walking conditions, again completing SSQs before and after the task. A similar procedure is also followed for Experiment 2. However, instead of experiencing three different speeds for the treadmill walking, participants experienced only one speed, i.e., 0.7× times the normal treadmill walking speed. A similar procedure was followed in Experiment 2, except participants experienced only a single treadmill speed—0.7× their normal walking speed—instead of three varying speeds.

Table S1: Descriptive statistics for pre-exposure, post-exposure, and their difference scores (Post – Pre) on the Simulator Sickness Questionnaire (SSQ) are shown for each Walking Condition in Experiment 1. The table reports Mean (M), Standard Deviation (SD), and Standard Error (SE) for Nausea, Oculomotor, Disorientation, and Total SSQ scores.

Walking Condition	**Condition**	**Nausea (M (SD, SE))**	**Oculomotor (M (SD, SE))**	**Disorientation (M (SD, SE))**	**Total SSQ (M (SD, SE))**
0.8× Treadmill Walking	Pre-Exposure	6.81 (14.82, 3.23)	13.36 (27.74, 6.05)	15.25 (35.46, 7.74)	13.36 (28.74, 6.27)
	Post-Exposure	6.36 (17.42, 3.80)	14.80 (33.34, 7.28)	19.89 (45.65, 9.96)	15.14 (35.05, 7.65)
	Difference	-0.45 (5.62, 1.23)	1.44 (10.34, 2.26)	4.64 (16.67, 3.64)	1.78 (9.87, 2.15)
1.0× Treadmill Walking	Pre-Exposure	5.00 (13.02, 2.84)	11.19 (26.43, 5.77)	15.91 (37.68, 8.22)	11.75 (28.07, 6.13)
	Post-Exposure	7.27 (19.06, 4.16)	13.72 (34.04, 7.43)	21.21 (54.91, 11.98)	15.32 (38.41, 8.38)
	Difference	2.27 (8.48, 1.85)	2.53 (9.69, 2.11)	5.30 (17.87, 3.90)	3.56 (11.50, 2.51)
1.2× Treadmill Walking	Pre-Exposure	1.82 (3.84, 0.84)	7.22 (10.85, 2.37)	11.27 (21.84, 4.77)	7.30 (10.48, 2.29)
	Post-Exposure	5.91 (12.97, 2.83)	11.55 (21.25, 4.64)	16.57 (33.70, 7.35)	12.47 (23.99, 5.23)
	Difference	4.09 (11.90, 2.60)	4.33 (15.64, 3.41)	5.30 (35.07, 7.65)	5.16 (21.04, 4.59)
Natural Walking	Pre-Exposure	5.45 (18.98, 4.14)	10.11 (27.26, 5.95)	17.90 (43.61, 9.52)	11.93 (32.16, 7.02)
	Post-Exposure	2.27 (4.16, 0.91)	6.86 (10.14, 2.21)	10.61 (15.19, 3.31)	7.12 (9.67, 2.11)
	Difference	-3.18 (17.15, 3.74)	-3.25 (20.42, 4.46)	-7.29 (35.39, 7.72)	-4.81 (25.92, 5.66)

Table S2: Descriptive statistics for pre-exposure, post-exposure, and their difference scores (Post – Pre) on the Simulator Sickness Questionnaire (SSQ) are shown for each Tilt Group in Experiment 1. The table reports Mean (M), Standard Deviation (SD), and Standard Error (SE) for Nausea, Oculomotor, Disorientation, and Total SSQ scores.

Tilt Group	**Condition**	**Nausea (M (SD, SE))**	**Oculomotor (M (SD, SE))**	**Disorientation (M (SD, SE))**	**Total SSQ (M (SD, SE))**
Tilt 0 (0°)	Pre-Exposure	6.16 (17.43, 2.52)	12.48 (29.06, 4.20)	18.56 (43.10, 6.22)	13.56 (32.29, 4.66)
	Post-Exposure	7.15 (17.98, 2.60)	14.37 (32.24, 4.65)	20.01 (48.55, 7.01)	15.27 (35.57, 5.13)
	Difference	0.99 (14.89, 2.15)	1.90 (18.20, 2.63)	1.45 (33.76, 4.87)	1.71 (22.86, 3.30)
Tilt 2 (∼8.5°)	Pre-Exposure	1.70 (3.72, 0.70)	4.06 (6.01, 1.14)	6.96 (14.92, 2.82)	4.54 (6.22, 1.18)
	Post-Exposure	1.70 (3.72, 0.70)	4.33 (6.66, 1.26)	8.45 (13.84, 2.61)	5.08 (5.95, 1.13)
	Difference	0.00 (0.00, 0.00)	0.27 (3.85, 0.73)	1.49 (9.54, 1.80)	0.53 (4.16, 0.79)
Tilt 4 (∼17°)	Pre-Exposure	7.15 (8.46, 2.99)	20.84 (24.23, 8.57)	22.62 (27.78, 9.82)	19.17 (22.48, 7.95)
	Post-Exposure	8.35 (12.94, 4.57)	21.79 (25.44, 9.00)	29.58 (39.68, 14.03)	21.97 (27.59, 9.75)
	Difference	1.19 (11.89, 4.20)	0.95 (16.43, 5.81)	6.96 (33.28, 11.76)	2.81 (20.75, 7.34)

Table S3: Descriptive statistics for pre-exposure, post-exposure, and their difference scores (Post – Pre) on the Simulator Sickness Questionnaire (SSQ) are shown for each Training Duration group in Experiment 2. The table reports Mean (M), Standard Deviation (SD), and Standard Error (SE) for Nausea, Oculomotor, Disorientation, and Total SSQ scores.

Training Duration group	**Condition**	**Nausea (M (SD, SE))**	**Oculomotor (M (SD, SE))**	**Disorientation (M (SD, SE))**	**Total SSQ (M (SD, SE))**
3 minutes	Pre-Exposure	3.18 (8.75, 1.79)	3.79 (7.41, 1.51)	7.54 (13.60, 2.78)	5.14 (8.88, 1.81)
	Post-Exposure	9.94 (16.99, 3.47)	12.63 (15.91, 3.25)	17.40 (26.68, 5.45)	14.80 (19.50, 3.98)
	Difference	6.76 (9.94, 2.03)	8.84 (14.60, 2.98)	9.86 (21.12, 4.31)	9.66 (14.83, 3.03)
6 minutes	Pre-Exposure	8.74 (11.22, 2.29)	6.63 (8.46, 1.73)	11.60 (20.39, 4.16)	9.82 (12.02, 2.45)
	Post-Exposure	13.12 (12.52, 2.56)	12.63 (11.54, 2.36)	14.50 (17.65, 3.60)	15.27 (12.47, 2.55)
	Difference	4.37 (15.40, 3.14)	6.00 (14.31, 2.92)	2.90 (21.32, 4.35)	5.45 (16.58, 3.38)
9 minutes	Pre-Exposure	13.91 (24.03, 4.91)	19.27 (34.70, 7.08)	16.24 (30.63, 6.25)	19.32 (33.01, 6.74)
	Post-Exposure	17.09 (24.20, 4.94)	25.27 (44.41, 9.06)	27.26 (45.43, 9.27)	26.49 (41.53, 8.48)
	Difference	3.18 (13.69, 2.79)	6.00 (17.02, 3.47)	11.02 (29.88, 6.10)	7.17 (19.26, 3.93)

Table S4: Descriptive statistics for pre-exposure, post-exposure, and their difference scores (Post – Pre) on the Simulator Sickness Questionnaire (SSQ) are shown for each Walking Condition in Experiment 2. The table reports Mean (M), Standard Deviation (SD), and Standard Error (SE) for Nausea, Oculomotor, Disorientation, and Total SSQ scores.

Walking Condition	**Cybersickness**	**Nausea (M (SD, SE))**	**Oculomotor (M (SD, SE))**	**Disorientation (M (SD, SE))**	**Total SSQ (M (SD, SE))**
Tredmill Walking	Pre-Exposure	11.66 (20.79, 3.47)	15.79 (29.29, 4.88)	15.47 (27.99, 4.67)	16.52 (28.12, 4.69)
	Post-Exposure	13.51 (20.57, 3.43)	21.06 (38.31, 6.39)	20.88 (38.88, 6.48)	21.30 (35.75, 5.96)
	Difference	1.86 (12.66, 2.11)	5.26 (18.73, 3.12)	5.41 (28.87, 4.81)	4.78 (19.70, 3.28)
Natural Walking	Pre-Exposure	5.56 (10.04, 1.67)	4.00 (6.14, 1.02)	8.12 (15.02, 2.50)	6.34 (9.50, 1.58)
	Post-Exposure	13.25 (16.49, 2.75)	12.63 (10.87, 1.81)	18.56 (24.00, 4.00)	16.41 (15.97, 2.66)
	Difference	7.68 (13.06, 2.18)	8.63 (10.59, 1.76)	10.44 (18.93, 3.16)	10.08 (13.13, 2.19)

8 EXPLORATORY BAYESIAN ANALYSIS FOR CYBERSICKNESS IN EXPERIMENT 1

Frequentist statistics allow us to reject the null hypothesis in favor of the alternative when significant effects are found. However, a non-significant result does not provide evidence for the null hypothesis. To evaluate whether no effect exists for Walking Conditions and Tilt Groups on SSQ score differences, we conducted Bayesian ANOVAs following Rouder et al. [62] (For ease of interpretation, the same analysis was not conducted separately for Nausea, Oculomotor, and Disorientation score differences). In this analysis, Bayes Factors (BF_{01}) provide an odds ratio indicating support for the null over the alternative hypothesis. A BF_{01} of 1 implies equal support for both hypotheses (50%), whereas values greater than 3, 10, or 30 suggest 'somewhat,' 'moderate,' or 'strong' evidence in favor of the null hypothesis. Given the sensitivity of Bayes Factors to prior odds [43], we set prior odds to 1, ensuring no bias toward either hypothesis [6].

Bayesian ANOVA revealed BF_{01} = 65.4 (± 1.08%) when comparing the full model including Walking Conditions, Tilt Groups, and their interaction to the null model (random intercepts only), indicating very strong evidence in favor of the null hypothesis. The additive model (Walking Conditions + Tilt Groups) also showed strong support for the null, with BF_{01} = 18.3 (± 1.56%). Main effects models showed BF_{01} = 3.79 (± 0.49%) for Walking Conditions and BF_{01} = 4.94 (± 0.73%) for Tilt Groups, both indicating moderate evidence for the absence of an effect. Overall, these findings suggest that neither Walking Conditions nor platform tilts influenced cybersickness in Experiment 1, and provide quantitative support for the null hypothesis across all tested models.