The Impact of Physical Effort and Cybersickness on Environmental Learning and Navigation: A Comparison of Desktop and Treadmill Interfaces

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Abstract

In the present study, participants learned the locations of 12 landmarks by following a guided route either in a desktop virtual environment or on an omnidirectional treadmill paired with a virtual reality headset. Spatial learning and wayfinding efficiency were later assessed across both interface conditions. Additionally, the ratio of physical to cognitive costs for navigating to goals was manipulated across trials. Results indicated that although the two groups did not differ in spatial learning, participants navigating on treadmills selected more efficient routes than those in the desktop group in trials involving high physical cost. Higher levels of self-report cybersickness were associated with reduced spatial learning and wayfinding efficiency, independent of interface condition. These findings validate the use of omnidirectional treadmills for investigating the tradeoff between cognitive and physical effort in navigation. At the same time, reducing cybersickness is essential to ensure the effective use of this technology.

Keywords: large-scale navigation; omnidirectional treadmill; cybersickness; guided-route spatial learning; tradeoff between the cognitive and physical effort

Introduction

In our daily lives, we constantly navigate to different places and make decisions about which routes to take to reach our destination when alternative routes are available. To study human navigation ability and route selection, spatial cognition researchers often use desktop virtual environments (Bohbot et al., 2011; Boone, Gone & Hegarty, 2018; Boone, Maghen & Hegarty, 2019; Brunyé et al., 2017; Marchette, Bakker & Shelton, 2011), ambulatory immersive virtual environments (Chrastil & Warren, 2013, 2015; He, Boone & Hegarty, 2023; Varshney et al., 2024), and real environments (Clemenson et al., 2020; Kozhevnikov et al., 2006; Labate, Pazzaglia & Hegarty, 2013). Each method has advantages and limitations. Desktop virtual environments allow for tight experimental control but often lack ecological validity due to small displays with limited field of view and restricted access to body-based cues to locomotion. In contrast, real environments offer high ecological validity but lack experimental control over factors such as weather, the presence of landmarks, and the ability to manipulate visual cues. Ambulatory immersive virtual environments combine some benefits of both approaches but are limited by the size of available lab space.

Comparison of Spatial Learning and Wayfinding Efficiency across Interfaces

Recent advancements in methodology for studying navigation include the use of omnidirectional treadmills paired with immersive virtual reality. These systems address the space constraints of ambulatory virtual environments and enable researchers to study navigation in large-scale, experimentally controlled environments. However, due to the novelty of treadmill technologies, basic research is needed to evaluate their effectiveness compared to other methods.

Hejtmanek and colleagues (2020) conducted a direct comparison of spatial learning and wayfinding efficiency within the same environment using three different interfaces: a desktop display with a mouse and keyboard, an omnidirectional treadmill, and the real-world environment. They found that performance in the real-world environment was better than both the desktop and omnidirectional treadmill interfaces, while performance between these two interfaces did not differ from each other. However, their study focused on free exploration as the method of environmental learning, which can introduce variability in how participants acquire knowledge of the environment. In a similar study that involved free exploration to learn about the environment, Huffman and Ekstrom (2019) also found no differences in configural knowledge acquisition (spatial learning) of the environment when they compared interfaces that involved walking and turning on the treadmill versus

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walking and turning using a joystick. However, they did not examine subsequent wayfinding efficiency, an important indicator of effective navigation.

Despite these contributions, no study has directly compared both spatial learning and wayfinding efficiency in desktop and treadmill interfaces when the learning experience is controlled through a guided route. Such a comparison using a guided route has only been made between the desktop interface and the real-world environment (Van der Ham et al., 2015). Addressing this knowledge gap is important because learning from a guided route provides a controlled way to study later route selection, such as the preference to take the familiar route that people learned or inferring novel shortcuts, when they are available. As a result, the present study compares spatial learning and wayfinding efficiency between a desktop virtual environment displayed through a monitor with mouse and keyboard, and an omnidirectional treadmill with a head-mounted display in a guided route paradigm.

A Tradeoff between Cognitive and Physical Effort

An important research question raised in navigating large-scale environments is how motivational factors, such as the tradeoff between cognitive and physical effort, influence route selection. When navigating to a goal, a critical decision involves choosing the optimal route. Choosing inefficient familiar routes conserves cognitive resources but costs physical effort. Computing novel shortcuts expends cognitive resources but saves physical effort (Hegarty et al., 2023; Krichmar & He, 2023; Lancia et al., 2023). The use of an omnidirectional treadmill provides a unique opportunity to study how people balance this tradeoff between cognitive and physical effort during navigation. It requires more effort to walk on a treadmill than to navigate by mouse and keyboard in a desktop environment. While previous studies did not find differences in configural knowledge acquisition of the environment between treadmill interfaces and desktop interfaces using mouse and keyboard or joystick (Hejtmanek et al., 2020; Huffman & Ekstrom, 2019), it is possible that differences between interfaces might occur when measuring wayfinding efficiency after learning from a guided route. When individuals walk on treadmills, the physical effort and fatigue associated with walking might motivate them to use cognitive effort to compute efficient routes (shortcuts) more compared to navigating in a desktop virtual environment.

Cybersickness induced by Treadmills

One prominent issue with the use of omnidirectional treadmills is the difficulties of synchronizing a person's movements with the optic flow provided by the head-mounted display. Any mismatch between visual cues and bodily sensations can result in cybersickness (Caserman et al., 2021). Previous studies using omnidirectional treadmills with head-mounted displays have reported varying levels of cybersickness among participants (Chakraborty et al., 2024; Doner et al., 2023; Hejtmanek et al., 2020; Starrett et al., 2019). Cybersickness might divert participants' attention away from learning the environment, increase cognitive load due to the need to monitor physical discomfort, and ultimately impair spatial learning of the environment's layout. Previous studies have shown that increased levels of cybersickness result in slower response times on both visuospatial and psychomotor tasks (Kourtesis, Papadopoulou & Roussos, 2024; Mittelstaedt, Wacker & Stelling, 2018). Cybersickness is also associated with worse performance on a verbal working memory task (the listening span task) and small-scale spatial ability measures, including mental rotation and the water level task (Dahlman et al., 2009; Levine & Stern, 2002). However, no study has directly examined the effects of cybersickness on spatial learning and wayfinding efficiency. Addressing this question is important for validating the use of omnidirectional treadmills to study navigation. Given the negative impact of cybersickness on other cognitive performance, cybersickness could negatively impact spatial learning and wayfinding efficiency.

Goals of the Present Study

The present study aims to answer three key questions: 1) How do learning and navigation differ between the desktop and the omnidirectional treadmill interface in terms of configural knowledge acquisition of the environment and wayfinding efficiency? 2) How does the tradeoff between cognitive and physical effort affect wayfinding efficiency? 3) How does cybersickness influence configural knowledge acquisition of the environment and wayfinding efficiency?

To address these questions, we adapted Marchette et al.'s (2011) Dual Solution Paradigm (DSP). In this paradigm, participants learned the layout of an environment and the locations of 12 landmarks by walking an inefficient fixed route five times. Subsequently, they were tasked with navigating to different learned landmarks (wayfinding). Participants could either follow the previously learned route or infer novel shortcuts based on their experience, making the DSP an effective task for measuring route selection.

Participants were randomly assigned to learn and navigate using one of two interfaces: a desktop interface or an omnidirectional treadmill with a head-mounted display. Their configural knowledge acquisition and wayfinding efficiency were then compared. This design allowed us to examine the tradeoff between cognitive and physical effort: navigation on the desktop interface using a mouse and keyboard imposed relatively low physical costs, whereas walking on the omnidirectional treadmill imposed much higher physical costs. We also varied the physical demands of trials by altering the ratio of the length of the learned routes to the length of available shortcuts to the goal across trials. Higher values in cost ratio represents higher physical costs required for navigation. Additionally, we examined the relationship between spatial learning, wayfinding efficiency and cybersickness ratings.

Based on previous research, we did not expect a difference in configural knowledge acquisition between the treadmill and desktop conditions. However, we hypothesized that participants in the treadmill condition would navigate more efficiently than the desktop condition due to savings of physical effort. We also hypothesized a main effect of cost ratio of trials and an interaction between the cost ratio and interface conditions, such that participants navigating on the treadmill would be more likely to choose efficient routes in trials with high physical costs (where the familiar learned route is significantly longer than potential shortcuts) compared to those in desktop condition. Furthermore, we hypothesized that higher levels of cybersickness would be associated with poorer learning and less wayfinding efficiency, independent of the conditions.

Method

Participants

Forty participants (Mean age of 19 years old) were recruited from University of California, Santa Barbara's subject pool and received course credit. They were randomly assigned to learn and navigate a virtual maze (55m x 55m; see **Figure 1A**) either on a desktop (6 males, 13 females) or on an omnidirectional treadmill using a wireless Varjo Aero head-mounted display (8 males, 13 females).

Materials and Apparatus

Dual Solution Paradigm: Participants first learned a guided route through a virtual maze and the locations of 12 landmarks (adapted from Marchette et al., 2011; see **Figure 1)**. They were later asked to navigate from one landmark to another landmark (goal) using any route they preferred. There were 24 wayfinding trials in total, with the ratio of physical cost to cognitive cost varying across trials. Participants were given 60 seconds to complete each trial. If they exceeded the time limit, the trial automatically ended and was recorded as a failure. This environment was created and rendered through the Unity program, with the walking speed set to 3 meters per second and approximately matched for both conditions.

Onsite pointing task: This task was designed to measure participants' configural knowledge (spatial learning) of the environment. Participants were positioned in front of one of the learned landmarks in the maze. For the desktop condition, participants were instructed to move their cursor to where they believed the target was located. For the treadmill condition, participants were instructed to turn to face the direction where they thought the target landmark was located and pressed the controller to confirm their choice. There were 24 trials, which had the same starting landmarks and goal landmarks as the 24 wayfinding trials (Figure **2B**).

Cybersickness in Virtual Reality Questionnaires (CSQ-VR): This scale measures level of cybersickness in virtual environments (Kourtesis et al., 2023). The scale consists of six items that assess three types of symptoms: nausea, vestibular issues (e.g., feelings of postural instability and disorientation), and oculomotor discomfort (e.g., visually induced fatigue and discomfort). Each item is rated on a 7-point scale, ranging from 1 (no symptoms) to 7 (extreme symptoms). An example item is: "Do you experience nausea (e.g., stomach pain, acid reflux, or tension to vomit)?" Higher scores indicate greater levels of cybersickness.

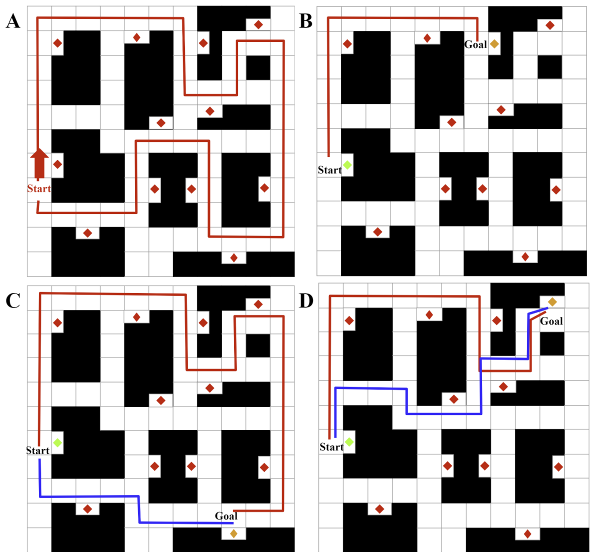

Figure 1: **A.** Bird's-eye view of the environment. The red line indicates the learned route, which traverses through the maze with 12 landmarks, indicated by the red diamond. Each grid square is 5 meters. **B.** Catch trial: The learned route is the shortest. Four catch trials served as checks on if participants learned the route well. **C.** High-cost trial: Example of a trial in which the shortcut (indicated by the blue line) is much shorter than the learned route, resulting in high physical cost when taking the learned route to conserve the cognitive effort. **D.** Low-cost trial: Example of a trial in which the shortcut is similar in length to the learned route, resulting in low physical costs when taking the learned route to conserve the cognitive effort.

Virtual Reality Systems: The Omnidirectional treadmill, Cyberith Virtualizer 2 has a round-shaped platform that allows participants to turn and walk in any direction. Sensors on the center of the platform track participants' movements, and the top of the platform has a ring and harness to support participants' weight and allow them to turn their bodies. The treadmill supports a full 360-degree range of motion. It also includes a configuration file to adjust treadmill speed and motion smoothness. The speed parameter was set to 1, and motion smoothness was set to 20 (Hager, Cakmak & Jagers, 2019). The treadmill was interfaced with a Varjo Aero headset, which has a Dual OLED 3.5-inch diagonal display (1,440 × 1,600 pixels per eye), a 90-Hz refresh rate, and a 110° field of view. In addition, participants were given one HTC VIVE handheld controllers to interact with the environment. For the desktop condition, the environment was displayed on a Samsung 49-inch curved monitor.

Procedure

The experiment began by familiarizing participants with the interface (keyboard controls or omnidirectional treadmill), followed by a learning phase in which participants were guided along a fixed path five times to learn the environment (**Figure 2A**). Then, participants completed an onsite pointing task to assess their configural knowledge of the maze (**Figure 2B**). They then completed the wayfinding trials. On each trial, they were placed at one of 12 learned landmarks and tasked with navigating to one of the other landmarks (goal) by taking any route they preferred. At the end of the study, participants completed the CSQ-VR to rate their cybersickness levels during different stages of the task.

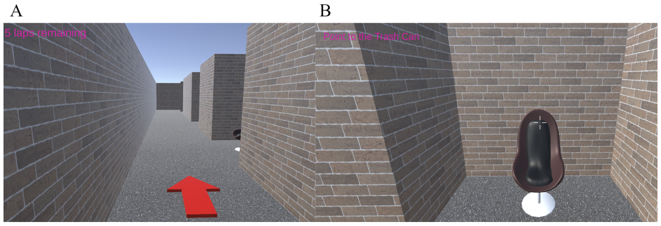

Figure 2: **A.** First person views of the environment during the learning phase. The red arrow provided directions to participants along the route. **B.** An example trial of the pointing task. Participants were put in front of the chair. They need to turn and align the cursor to where they think the trashcan (target) is.

Outcome Measures

The outcome measures included: 1) ***Pointing Error***. We measured configural knowledge of the environment via angular error on the pointing task, with higher error indicating poorer learning of the environment. 2) ***Wayfinding Efficiency***. We measured wayfinding efficiency using the saved distance, that is, distance participants saved by taking a route shorter than the familiar learned route ($(D_{learned} - D_{traveled}) / D_{learned}$)[1]. Positive values indicated a more efficient path than the learned route (greater savings), while negative values indicated a less efficient path than the learned route (lower savings). 3) ***Cybersickness Score*** was reported for learning, pointing, and wayfinding phases, on a scale from 1 (low cybersickness) to 7 (high cybersickness).

Results

Differences of Spatial Learning and Wayfinding Efficiency between Interfaces.

Four participants in the treadmill condition dropped out during the learning phase due to cybersickness. Additionally, eight participants in the treadmill condition dropped out during the wayfinding trials. No participant in desktop condition dropped out of the study during the learning phase. We excluded participants who completed less than half (12) of the wayfinding trials, which left 13 participants in the treadmill condition and 19 in the desktop condition in the analysis of wayfinding efficiency.

Linear mixed-effects models revealed no significant difference between the two groups on either pointing error ($\beta = 0.09$, 95% *CI* [-0.25, 0.44], *SE* = 0.17, *t* = 0.54, *p* = .59; marginal $R^2 = .002$, conditional $R^2 = .41$) or wayfinding efficiency, measured by saved distance ($\beta = -0.06$, 95% *CI* [-0.32, 0.20], *SE* = 0.13, *t* = -0.47, *p* = .64; marginal $R^2 = .001$, conditional $R^2 = .44$), see **Figure 3A** and **3B**. Bayes factors[2] provided anecdotal support for the null hypothesis in pointing error (*BF* = 0.92) and strong support for the null hypothesis in wayfinding efficiency (*BF* = 0.08). More evidence is needed to draw a definitive conclusion about configural knowledge acquisition between groups.

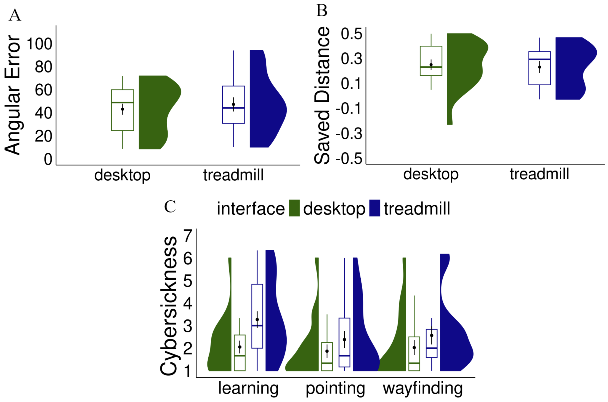

Figure 3: Differences between two interfaces. While the results of pointing error and wayfinding efficiency reported in the main body of text were trial-level analyses, the visualization of outcome variables in the figures were averaged for each participant. **A.** pointing (angular) error. **B.** wayfinding efficiency (saved distance). **C.** cybersickness ratings during different phases.

The Tradeoff between Cognitive and Physical Effort.

Next, we examined whether there was a main effect of cost ratio of trials and an interaction between cost ratio and interface condition on saved distance. The **cost ratio** of each trial was computed as the ratio of the length of the learned route to the goal to the length of the shortest path to the goal (shortcut). As the cost ratio of the trial increased, greater physical effort was expended by taking the learned route (low cognitive cost) relative to the shortcut. Linear mixed-effects models excluding catch trials[3] revealed a significant main

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[1] $D_{learned}$ refers to the distance of the learned route. $D_{traveled}$ refers to participants' traveled distance.

[2] All Bayes factors (BF) were computed using weakly informative prior distribution.

[3] Participants took the learned route (which was also the shortest route) on 43% of catch trials in the desktop condition and 37% of trials in the treadmill condition.

effect of cost ratio ($\beta = 0.42$, 95% *CI* [0.26, 0.58], $SE = 0.08$, $t = 5.21$, $p < .001$), suggesting that as the cost ratio increased (indicating higher physical cost for taking the learned route), participants were more likely to save distance by taking routes that were shorter than the learned route. Additionally, we found a significant interaction between cost ratio and condition ($\beta = 0.17$, 95% *CI* [0.05, 0.29], $SE = 0.06$, $t = 2.83$, $p = .005$; marginal $R^2 = .24$, conditional $R^2 = .51$, see **Figure 4**), and this interaction remained significant ($\beta = 0.17$, 95% *CI* [0.05, 0.28], $SE = 0.06$, $t = 2.80$, $p = .005$) after controlling for participants' knowledge of the environment, as measured by pointing error ($\beta = -0.31$, 95% *CI* [-0.42, -0.20], $SE = 0.06$, $t = -5.47$, $p < .001$; marginal $R^2 = .34$, conditional $R^2 = .51$). This result supported our hypothesis that the treadmill group was more likely to save distance from taking a route shorter than the learned route compared to the desktop group when the cost ratio of the trial was high.

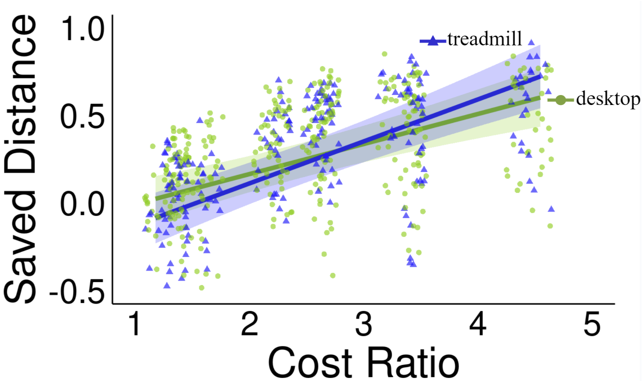

Figure 4. The relationship between the cost ratio of each trial and the distance saved by taking a route shorter than the learned route, separated by interface condition (treadmill: blue; desktop: green). The lines represent model-predicted values from a mixed-effects model, with steeper slopes indicating a stronger effect of cost ratio on distance saved. Observed trial-level data points are overlaid (treadmill: triangles; desktop: circles), illustrating the distribution of performance across interface conditions.

Influences of Cybersickness on Spatial Learning and Navigation Efficiency.

We first compared cybersickness ratings across different phases between two groups. All participants were able to rate their cybersickness during the learning phase. Independent samples *t*-tests revealed that the treadmill group reported significantly more cybersickness during the learning phase than the desktop group, $t\ (38) = -2.60$, $p = .01$, $d = 0.98$. Excluding those who dropped out of the study during the learning phase reduced the group differences in cybersickness, and provided anecdotal support for the alternative hypothesis, $t\ (34) = -1.9$, $p = .06$, $BF = 1.46$. No significant differences in cybersickness between groups were observed and anecdotal support for the null hypothesis was found during the pointing phase ($t\ (34) = -1.10$, $p = .30$, $BF = 0.45$) and the wayfinding phase ($t\ (32) = -1.10$, $p = .30$, $BF = 0.61$), see **Figure 3C**. Then, we examined the relationship between pointing error, saved distance, and cybersickness across all participants[4] (see **Table 1**). Cybersickness reported in the learning phase was associated with greater pointing error and less distance saved, suggesting that cybersickness impairs configural knowledge acquisition, and consequently results in less efficient wayfinding, as predicted.

Variable	1	2	3	4	5
1. pointing error	-				
2. saved distance	**-.71***** **[-.85, -.49]**	-			
3. cybersickness (learning)	.35* [.02, .61]	-.40* [-.66, -.07]	-		
4. cybersickness (pointing)	.34* [.01, .60]	-.36* [-.63, -.01]	**.89***** **[.79, .94]**	-	
5. cybersickness (wayfinding)	.33 [-.01, .60]	-.35 [-.63, .01]	**.94***** **[.87, .97]**	**.85***** **[.72, .92]**	-

Table 1. Correlation table of pointing error, saved distance, and cybersickness. Note: pairwise correlation was used given variables had different numbers of observations. Pointing error, learning cybersickness, and pointing cybersickness: N = 36. Saved distance: N = 32. wayfinding cybersickness: N = 34. Values in square brackets indicate 95% confidence intervals (CI) for each correlation. Correlations in bold were still significant after Holm correction for multiple comparisons. *Indicates p < .05. ** indicates p < .01. *** indicates p <.001.

Discussion

We examined whether learning and navigating using different interfaces resulted in different spatial learning and wayfinding efficiency. We also examined whether walking on a treadmill led to more efficient route selection in trials with high physical cost, compared to navigating using the desktop interface, and whether cybersickness was associated with impaired spatial learning and wayfinding efficiency. Among participants who completed the learning phase without dropping out due to cybersickness, no significant differences in environmental knowledge acquisition or wayfinding efficiency were found between the two interface conditions. However, Bayes factors indicated that more evidence is needed to draw a conclusive interpretation.

We hypothesized that the cost ratio of the wayfinding trials would affect the treadmill group more than the desktop group because the required physical effort navigating in these trials is greater in the treadmill group. Although the cognitive effort of computing a shortcut itself is not affected by the interface, we reasoned that the motivation to expend that cognitive effort would be greater when there is more physical effort to

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[4] We observed the association between cybersickness, pointing error and wayfinding efficiency even after controlling for the effects of condition.

be saved. As predicted, participants were generally motivated to conserve physical effort by selecting more efficient routes when the physical cost of taking the learned route was high (high-cost ratio). Moreover, there was an interaction between the cost ratio and the interface conditions. Specifically, as the physical cost for taking the learned route increases, the treadmill group was more likely to take efficient routes compared to the desktop group. This is consistent with the interpretation that physical demands involved in walking on the treadmill motivate participants to invest cognitive effort in inferring alternative shorter routes when the learned route is long, while the relatively effortless navigation using a mouse and keyboard in the desktop condition produced less motivation to conserve physical effort.

Previous research has shown that configural knowledge of an environment directly predicts navigation efficiency, with more knowledge associated with more efficient wayfinding (He et al., 2023; Varshney et al., 2024). To account for this, we also controlled participants' spatial learning (measured by pointing error) when analyzing the tradeoff between cognitive and physical effort, and the interaction effect remained. This result suggested that regardless of knowledge, participants implicitly factored in the cognitive and physical costs of each route when selecting their routes.

Evaluating the symptoms of cybersickness, we found that participants in the treadmill group reported more severe symptoms during the learning phase than those in the desktop group, primarily due to participants who dropped out during the learning phase. The two groups reported similar levels of cybersickness during the pointing and wayfinding phases (but note that some of those in the treadmill condition had dropped out by these phases). Cybersickness ratings during the learning phase were associated with both configural knowledge acquisition of the environment and wayfinding efficiency. More severe symptoms were associated with less learning and less navigation efficiency, regardless of interface conditions, which aligns with our interpretation that cybersickness might distract participants from focusing on environment features and impair learning. These results expand on the findings of Dahlman et al. (2009) and Levine and Stern (2002), which demonstrated the negative impact of cybersickness on small-scale spatial abilities, by showing its effects on large-scale spatial learning and navigation. The negative impact of cybersickness on spatial learning and navigation efficiency highlights the need for future studies using omnidirectional treadmills with head-mounted displays to prioritize minimizing cybersickness to ensure data quality. Lohman and Turchet (2022) have shown that reducing walking speed and improving motion smoothness can alleviate symptoms of cybersickness. Although we chose the recommended treadmill parameters (Hager et al., 2019) to alleviate cybersickness, several participants still reported cybersickness and dropped out. We need to explore more ways to reduce treadmill-induced cybersickness.

Limitations and Future Directions

One limitation of this study was the high dropout rate due to cybersickness, with 8 out of 21 participants in the treadmill condition (approximately 40%) excluded from wayfinding analyses. This data loss significantly reduced the usable sample size for comparisons and may have reduced the observed effects of the tradeoff between the cognitive and physical effort in the study, given cybersickness and performance measures are associated. Additionally, the current study lacked a direct measure of cognitive load and therefore cannot provide sufficient evidence regarding whether cybersickness affects performance through increased mental load or distraction. Addressing cybersickness remains critical for future research using treadmills to study spatial learning and navigation, and future studies would benefit from including direct measures of cognitive load.

To mitigate cybersickness, in addition to reducing walking speed and enhancing motion smoothness, future studies could also reduce the duration of treadmill use. For example, participants could learn the environment using the desktop interface and use the treadmill only during the wayfinding phase, which reduce the treadmill use by approximately half. Our results provide anecdotal support that learning the environment on a desktop did not differ from learning on a treadmill to acquire configural knowledge of the environment before transitioning to treadmill-based navigation. This approach may offer a practical strategy for reducing cybersickness while still enabling the study of the tradeoff between cognitive and physical effort during navigation.

Interestingly, participants did not take the learned route in every catch trial, indicating that they may not have been familiar enough with the route to know that it was the shortest path. To address this, additional learning laps can be added into the learning phase in future studies to better familiarize participants with the learned route. This adjustment may result in a larger effect of the tradeoff when physical cost varies across trials.

Conclusion

This study advances our understanding of how navigation interfaces influence spatial learning and wayfinding efficiency. While no significant differences were observed in spatial learning between desktop and treadmill interfaces, the use of treadmill, which requires physical walking, provided valuable insights into the tradeoff between cognitive and physical effort. Participants navigating on the treadmill were more likely to conserve physical efforts as the physical cost of the trials increased. These findings highlight the potential of omnidirectional treadmills for studying navigation, particularly in understanding the influences of motivational factors in route selection. However, the issue of cybersickness remains a challenge. Future research should focus on mitigating cybersickness to maximize the effectiveness of treadmill technologies in studying large-scale spatial navigation.

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