

Efficiently Navigating Virtual Environments with Simulated Reference Frames and Body-Based Sensory Information

by

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Abstract

Despite recent advancements in technology, there remain a number of major challenges in Virtual Reality (VR) such as spatial disorientation and motion sickness. People tend to get sick or get lost when they navigate a virtual environment for a while. This dissertation presents two experiments investigating two phenomena that significantly contribute to human spatial updating in VR locomotion.

In the first study, we designed and evaluated two Simulated Reference Frames, i.e., Simulated Cave and Simulated Room, using a mixed-method repeated-measures experiment. Results showed that the Simulated Room can improve participants performance and reduce their perceived motion sickness.

In the second study, we implemented four locomotion interfaces providing translational body-based sensory information at different levels, in order to investigate at which level the information might be enough for sufficient VR locomotion. Results showed that leaning combined with real rotation can help participants perform as good as when they are physically walking.

Keywords: navigational search, reference frame, spatial orientation, spatial updating, virtual reality, motion sickness, task load, locomotion interfaces, body-based sensory information, leaning-based locomotion interfaces

Dedication

This humble work is dedicated to my mother and teachers, who taught me to observe, explore, and understand this world; to my sister and best friends, who have always been with me every step of the way. Thank you for all the love, guidance, and support that you have given me.

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Executive Summary

Virtual Reality (VR) technology is increasingly used in spatial cognition research, as it offers high experimental control in naturalistic multi-modal environments, which is hard to achieve in real-world settings. Although recent technological advances offer a high level of photo-realism, locomotion in VR is still restricted because people might not perceive their self-motion as they would in the real world. This might be related to the inability to use embodied spatial orientation processes, which support spatial awareness and automatic and obligatory spatial updating of our mental representation of surrounds while moving through an environment (real or virtual).

This dissertation includes two studies, with divergent motivations, research questions, and variables of interest. However, they shared the experiment design, i.e., mixed method, repeated measures, navigational search paradigm.

In this first study (Chapter 2), we proposed using visually overlaid rectangular boxes, simulating reference frames in VR, to provide users with an unobtrusive spatial orientation cue that could be added to any landmark-free virtual environment. The mixed-method study investigated how different variations of the visually simulated reference frames might support people in a challenging navigational search task. Performance results showed that the existence of a simulated reference frame yields significant effects on participants' completion time and travel distance in the task. Though a simulated CAVE translating with the navigator (one of the simulated reference frames) did not provide significant benefits, the simulated room (another simulated reference frame depicting a rest frame) significantly boosted user performance in the task as well as improved participants' preference in the post-experiment evaluation. Results suggest that adding a visually simulated reference frame to VR applications might be a cost-effective solution to the spatial disorientation problem in VR.

In the second study (Chapter 3), to fill the gap in the literature about the benefit of the translational component, we investigated how different levels of translational body-based information might influence the performance of participants in a navigational search task in an HMD-based virtual environment. There were four levels of translational body-based information: none (participants using the trackpad of the HTC Vive wand controller to visually translate), upper-body leaning (participants sitting on a Swopper chair, leaning their upper-body to control their visual translation), whole-body leaning (participants stand-

ing on a platform called NaviBoard, leaning their whole body or stepping to navigate the virtual environment), and full translational information (participants physically walking). Results showed that translational body-based sensory information had significant effects on various measures including task performance, task load, and simulator sickness. While participants performed significantly worse when they used a joystick-based interface (HTC Vive wand controller) with no translational body-based information, compared to the other conditions, there was no significant difference between the leaning-based interfaces and actual walking. Deeper data analysis may be needed for more concrete conclusions. However, current results suggest that translational body-based information from a leaning-based interface might suffice for a cost-effective alternative to actual walking in spatial cognition research and applications in VR.

Chapter 1

Introduction

Alex is walking on a hallway to her class with a cup of coffee on her hand. A door suddenly opens right behind her, she keeps walking and turns her head to check whether everything is okay. One of her colleagues, Denise, walks out from that door. Alex turns her whole body around to say hi to Denise, however, she keeps walking backward as she is running late. After the greeting, Alex turns around and continues walking in the original direction, as she rushes to class. She does not forget to stop by a recycle bin to throw the empty cup before going directly to the classroom.

By telling this story, we want to take an example of how people actually locomote in the real world and explain how differently we navigate in VR. In this example, Alex uses multiple sources of online sensory information, e.g., visual, auditory, kinesthetic, vestibular, and offline spatial knowledge of the classroom location and the recycle bin position. There are several common behaviors in the real world that are not often transferred into VR, illustrating the shortcoming of current VR technology. For example, from our experimental observation, VR users tend to keep their heading direction aligned with their moving direction when translating with a controller or joystick, which is different from Alex in the above example when she keeps walking forward while turning her head backward to process another event. Another example is that, even when Alex is talking to Denise (task #1) and stepping backward (task #2), she is still aware of her relative position in the hallway (task #3). Moreover, this spatial knowledge is continuously updated during her motion. It happens so naturally that Alex might not even be able to explain how she can do that, thanks to the simultaneous contribution of various modalities. In stark contrast, VR users might get lost even when they are intentionally focusing on updating their spatial knowledge.

This poses a challenge for researchers to investigate which factors and how they might affect humans when locomoting in VR. In this thesis, we tackle the challenge from two different approaches. In each direction, we extended previous studies by adding novel conditions/levels to the variables of interest, in order to fill the gap in the literature as well as to contribute novel knowledge regarding those independent variables. Particularly, as

reference frames have been showed to play an important role in human spatial updating and we were also interested in investigating how the rectangular reference frame provided by CAVE-like environments might affect users' performance, we visualized reference frames in VR as overlaid rectangular boxes and evaluate their effects using the navigational search task. This approach helps us to avoid potential confounds of having to compare different display types, e.g., CAVE versus HMD. While previous studies showed benefits of reference frames, our study provides experimental evidence that adding very simple *simulated reference frame* to the virtual environment can help improve user performance significantly. Similarly, body-based sensory information has been showed to allow people to efficiently navigate virtual environments. However, the translational component of it seem to be of different importance. In this study, we aim to investigate the *translational body-based sensory information*, which tends to be associated with physical walking. Interestingly, our results suggest that partial translational information might suffice for people to efficiently navigate in VR.

This is a cumulative thesis which consists of two studies investigating similar problems using the same experiment paradigm, however, employing different independent variables. Individual studies are reported as different papers, the first study has been published as a conference paper in the *Proceedings of IEEE Virtual Reality 2018* and the second one is being prepared for submission at the time that this thesis is being written. Therefore, the introduction and motivation of each study is discussed in the relevant chapters below. In the following chapters, we will present the two studies (Chapter 2 and 3), then summarize their contributions, limitations, and future works (Chapter 4).

- **Chapter 2 - Simulated Reference Frame: A Cost-Effective Solution to Improve Spatial Orientation in VR:** This chapter describes the proposed simulated reference frames, i.e., *Simulated CAVE* and *Simulated Room*. The effect of these simulated reference frames were evaluated using a mixed-method experiment.
- **Chapter 3 - Do We Need Actual Walking inVR? Combining Physical Rotation with Leaning Might Suffice for Efficient Virtual Locomotion:** This chapter investigates the role of the translational body-based sensory information in VR locomotion interfaces, especially when only partial information is available. A mixed-method experiment was conducted to understand which level of translational information people might efficiently navigate a virtual environment.
- **Chapter 4 - Conclusions and Future Works:** This chapter summarizes the contributions and limitations of presented studies and point out the possible future directions for these approaches.

Chapter 2

Simulated Reference Frame: A Cost-Effective Solution to Improve Spatial Orientation in VR

Abstract Virtual Reality (VR) technology is increasingly used in spatial cognition research, as it offers high experimental control in naturalistic multi-modal environments, which is hard to achieve in real-world settings. Although recent technological advances offer a high level of photo-realism, locomotion in VR is still restricted because people might not perceive their self-motion as they would in the real world. This might be related to the inability to use embodied spatial orientation processes, which support automatic and obligatory updating of our spatial awareness. Previous research has identified the roles reference frames play in retaining spatial orientation. Here, we propose using visually overlaid rectangular boxes, simulating reference frames in VR, to provide users with a better insight into spatial direction in landmark-free virtual environments. The current mixed-method study investigated how different variations of the visually simulated reference frames might support people in a challenging navigational search task. Performance results showed that the existence of a simulated reference frame yields significant effects on participants' completion time and travel distance in the task. Though a simulated CAVE translating with the navigator (one of the simulated reference frames) did not provide significant benefits, the simulated room (another simulated reference frame depicting a rest frame) significantly boosted user performance in the task as well as improved participants' preference in the post-experiment evaluation. Results suggest that adding a visually simulated reference frame to VR applications might be a cost-effective solution to the spatial disorientation problem in VR.

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2.1 Introduction

Virtual Reality (VR) has been increasingly adopted in both scientific research and the entertainment/game industry in recent years. Current VR technology offers not only naturalistic stimuli in a fully immersive and interactive experience, but also physically impossible locomotion modes such as teleporting and flying. In other words, people can easily translate in the simulated world, with little or even no effort.

However, locomotion remains a challenge in VR, as people might not be able to efficiently perceive their self-motion. For instance, when traveling in immersive virtual environments people have been shown to take substantially longer time with keeping track of where they are compared to the real world [75]. Also, people learning a route by exploring a virtual building made more errors when being asked to then walk the same route in a physical building [49]. Various sources of disorientation, such as left-right confusion [51] or the inability to update visually-simulated rotation [1, 28] can substantially affect the effectiveness of virtual locomotion. In general, spatial disorientation happens when the immediate position and orientation cannot be correctly determined, which prevents the human brain from updating the current spatial awareness with recent self-motion [28, 56].

Spatial updating helps people to keep track of their position and orientation when they move through an environment, especially when reliable landmarks are missing [28, 56]. Inconsistencies might occur in such situations when the visual cues suggest that you are translating/rotating, whereas the vestibular system signals the opposite, which commonly happens with simulated movements, especially when stationary. In VR, the spatial updating process is affected by various visuomotor cues [28, 56, 72], and the conflicts between these cues can produce not only disorientation but also motion sickness [23, 35, 48].

Visually-induced motion sickness or simulator sickness is associated with dizziness, nausea, or fatigue of users while being immersed in the virtual world. The latency between physical movement and visual stimuli is one of the factors causing such symptoms [12]. Though recent advances in technology have decreased this latency to a level low enough that people can hardly perceive it, simulator sickness can still occur when there are inconsistencies between the signals across sensory modalities [48]. This sensory conflict is the most widely accepted explanation of such symptoms [19]. Nevertheless, the chance that a person might get motion sickness also depends on other biological aspects such as gender, age, and prior knowledge [35]. While the tendency to get sick therefore varies from person to person [30], the severity of sickness decreases generally with better synchronization between visual and vestibular cues [35, 66].

Cognitive Reference Frames

Reference frames have long been studied in spatial cognition research, and have been shown to significantly affect spatial updating and spatial orientation [29, 38, 21]. A reference frame

defines a set of parameters used to represent the immediate spatial knowledge which enables a person to maintain and update their awareness of position and direction when traveling through an environment. Different reference frames are specified by different sets of parameters, like the x and y of the Cartesian coordinate system or the r and θ of the polar system. These parameters define which kinds of frames are to be used. An egocentric frame is centered on the navigator, whereas an allocentric frame is centered at an external point in the environment [29]. Figure 2.1 illustrates these two different reference frames in physics.

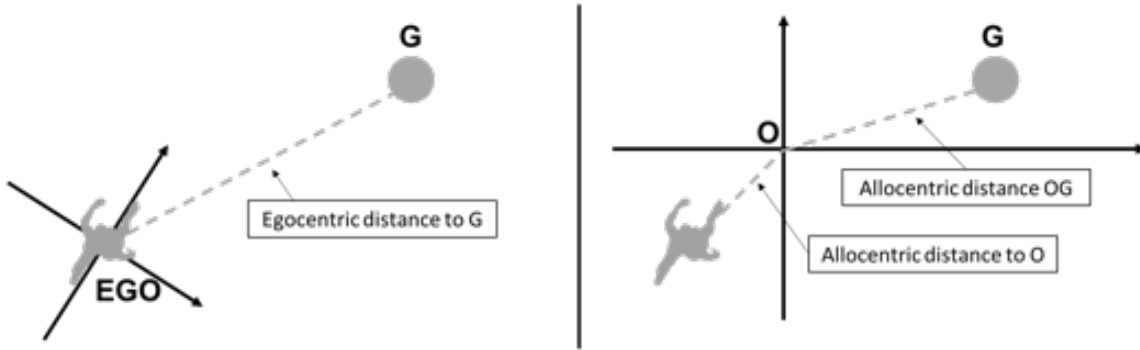


Figure 2.1: Egocentric (left) and allocentric (right) reference frame

Though previous study has investigated the role of cognitive reference frames in spatial cognition and spatial orientation [29, 21], there has been little or even no effort on visualizing/simulating this cognitive concept to assist VR users in maintaining spatial orientation. In the real world, these frames are typically embedded in objects or landmarks, such as a building, a table, our shadow, or even our body components. In this study, we investigate if adding a simulated reference frame to VR could serve as a cost-effective visual cue to facilitate the human spatial orientation process.

Recent studies showed that one’s orientation in a rectangular environment can lead to sensorimotor facilitation or interference when asked to imagine a different environment [54]. However, there is still little knowledge of how the presence of a rectangular reference frame actually affects the way people retain their spatial orientation and act on it in a non-trivial spatial orientation task. This unclear relationship exists in a CAVE, where people are frequently aware of the edges forming the display. This question leads to the need for precise and careful exploration of the effects of the rectangular reference frame for all kinds of VR displays. Towards that goal, we designed a study to investigate the spatial behaviors of participants when doing a navigational search task in virtual environment with or without the presence of an additional simulated reference frame.

Simulating reference frames in immersive VR

Simulated CAVE: Although one could consider using an actual CAVE for the study, we decided to instead simulate the rectangular frame of a CAVE using a head-mounted display (HMD) to avoid possible confounds, i.e., visibility of edges and corners of a CAVE, display resolution, distortion, and brightness, which could affect the performance of the participants [68, 55]. We call this reference frame “simulated CAVE”, because the rectangular frame mimics an actual setup of a six-side CAVE.

Simulated Room: To investigate what aspects of a simulated reference frames really matter for spatial cognition, we designed another simulated reference frame that provides only allocentric cues, i.e., whose position and orientation are independent of the observer. This concept has long been studied and referred to as rest frames [47]. Previous research has also shown that rest frames can help reduce motion sickness and increase the sense of presence in VR [11].

To sum up, we propose using a simple overlaid wireframe of a rectangular box as a frame of reference for participants for VR locomotion. While the simulated CAVE (whose wireframes made users feel like they were at the center of a CAVE) always followed participants, but does not rotate with them, the simulated room was stationary regardless of participants’ movement and rotation, just like when moving in an actual room. Both simulated reference frames are tied to the ground, which reflects the planar nature of the physical world, where people mostly locomote on 2D surfaces. In this study, we aim to investigate if and to what degree simply adding a visual representation of a fictitious rectangular box to virtual scenes might improve users’ spatial orientation. We hypothesize as follows:

- H1:** Both kinds of reference frames improve participants’ performance in a navigational task compared to the no reference frame control condition (e.g. shorten completion time, travel distance, and reduce revisits), because environmental geometry can be used as an orientation cue [22] and both egocentric and allocentric reference frames are known to enhance spatial orientation [28].
- H2:** The simulated room is the most preferred condition, while the simulated CAVE might disturb participants when they are doing the task, as a stable room has higher ecological validity than a box moving with the observer. In other words, we predict that the CAVE-like moving reference frame yields lower preference and usability ratings.
- H3:** Both the simulated CAVE and room can help reduce motion sickness, because both frames provide participants with additional orientation and self-motion cues.



Figure 2.2: Left: Participant wearing an HMD (HTC VIVE) and sitting on the NaviChair locomotion interface. Middle: Visual stimuli of the virtual environment designed to eliminate all visual landmarks. Right: By approaching the box from its front side (the side denoted by a red banner), participants can make the box automatically open to see whether there is a ball inside, and collect the ball by touching it with the controller.

2.2 Stimuli and Apparatus

2.2.1 Virtual Environment

Participants wore a head-mounted display (HMD) displaying a virtual environment consisting of a large grass-textured ground and 16 identical wooden boxes placed on 16 pedestals, as depicted in Figure 2.2. Each of these boxes was randomly positioned and rotated for each trial to avoid learning effects. Boxes were always positioned within a circular area of 5 meter diameter.

Eight of these 16 boxes contained green balls as target objects and participants had to search for and collect all these eight balls to complete a trial. To eliminate potential “cheating” strategies, ball targets were guaranteed to be only visible when the user approached the box from the side with the red board. Environmental fog was added to cancel other visual cues that could guide or re-orient participants.

A HTC Vive HMD was used to binocularly present the virtual environment. The HTC VIVE provides a per-eye resolution of 1080 x 1200 pixels and a binocular Field-Of-View (FOV) of 110° diagonally. Stimuli were generated in real time at 90 Hz using Unity3D. There was no noticeable latency of rendering/tracking during the experiment. The head tracking embedded in the HMD was enabled. When they saw a ball inside a box, participant could simply touch the ball with the wireless hand controller to “collect” it (see Figure 2.2).

To reduce any effect of noise in the real world that could be used as spatialized auditory cues for orientation in the virtual world, noise canceling headphones were used. In addition, a notification sound was played via the headphones whenever a ball was collected successfully.

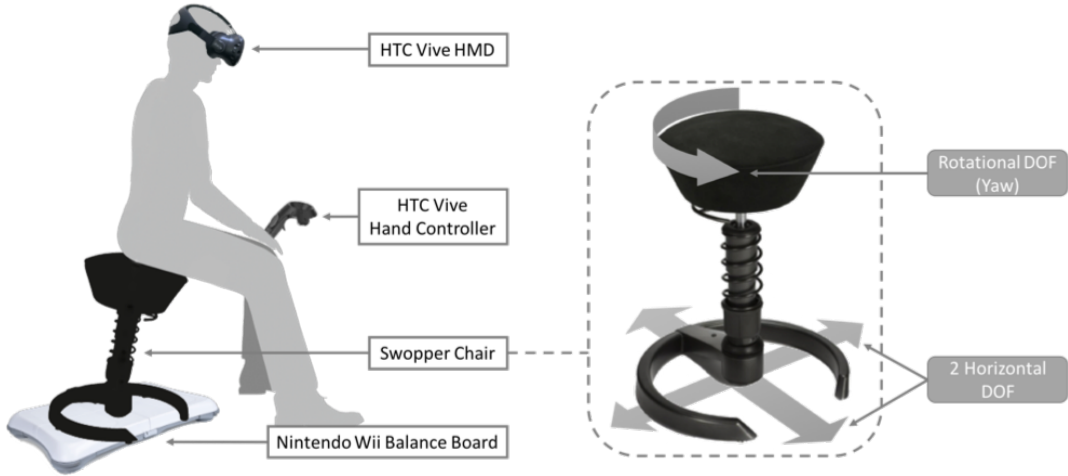


Figure 2.3: Left: Sketch of the setup including HMD, interaction and NaviChair locomotion interface. Right: NaviChair’s DOFs

2.2.2 Locomotion Interfaces

In order to effectively compare our simulated reference frames, we consider several locomotion interfaces that have been proposed previously. Walking is probably one of the most common modes of transportation for humans. It enables people to remain oriented in their immediate environment with little cognitive effort even with closed eyes [56, 46]. Thus, walking is a desirable locomotion mode in VR. However, allowing for actual walking requires tracked free-space walking areas which can be costly, especially when virtual environments are larger than normal room scale. A variety of alternative solutions have been proposed, including walking-in-place and redirected walking. While many of these approaches are promising, they require significant technical, financial, and safety efforts to be implemented, and often become unaffordable or unfeasible for a wider adoption on the market. In this study, we used a leaning-based interface called NaviChair [27, 3] and Joystick as a standard locomotion interface.

NaviChair: This locomotion interface uses the human upper body as a joystick for navigational control in VR [27, 3, 4]. The idea of using embodied interaction to control VR locomotion has appeared repeatedly in various forms. Recent research has shown that locomotion interfaces that allow physical rotation alone (without physical translation/walking) can achieve comparable performance to actual walking in a similar navigational search task [52]. As illustrated in Figure 2.3, the NaviChair interface consists of a commercially available Swopper stool placed on top of a Wii Balance Board to measure user’s weight shifts. In the actual design, a foam slab and a circular wooden plate were placed between the WiiBoard surface and the stool to stabilize the chair as illustrated in Figure 2.2 (left). The NaviChair offered three degrees of freedom (DOFs): Participants controlled simulated yaw

rotations in VR by simply physically rotating with the NaviChair. Translations (left-right and front-back) were controlled by participants’ leaning or otherwise shifting their weight in the desired translation direction, which was tracked by the Wii Balance Board underneath the Swopper stool. That is, the Wii Balance Board measured changes in the location of the center of pressure, which were linearly mapped to translation speed in the virtual scene.

Joystick: In this navigation interface, a wireless Logitech Freedom 2.4 joystick was used. Participants tilted the joystick to translate (in two dimensions) and rotated it to rotate their virtual body in the scene.

2.2.3 Experiment Task: Navigational Search

In order to evaluate how well people can maintain spatial orientation for the different reference frame condition, we used a navigational search task in which participants are placed in an environment consisting of 16 boxes, and tasked to find eight target objects hidden in these 16 boxes [36, 60]. Initially, participants are located outside of the target area. They had time to plan their path to optimally visit all boxes. We also told them to complete the task in the most effective way which might require them to do the task not only as quickly as possible, but also in a strategic way to avoid errors and to minimize distances traveled. Whenever they were ready, participants pressed the trigger on the controller in their hand to start a trial.

During each trial, participants used the provided locomotion interfaces to navigate through the virtual world. Only when they came close enough to a box and looked at its front side (indicated by a red banner, see Figure 2.2), that side disappeared and showed a target ball, if it existed. Participants were asked to collect all balls by touching them with the controller, which made them disappear. Any touched ball was never shown again, even if its box was revisited so that participants were unable to use it as a navigational cue.

Figure 2.4 shows exemplar trajectory plots for three typical trials from different participants using the NaviChair. The red arrows illustrate the boxes’ location and direction. Whereas the position of a box is exactly at the origin of an arrow, its front direction is indicated by the direction of the arrow. While most participants used either a spiral search or seemingly random search pattern, a few people tried to arrange all the targets by rows in their minds and then systematically scanned through all the targets in zig-zag trajectories.

The number of balls that had already been collected was displayed at the bottom of the screen, so that participants could focus on their search. A trial was ended when either all eight balls had been collected or the allowed period of 3 minutes had expired.

Though the task might not seem to be harder than a normal video game, it actually requires quite high cognitive load, as the task itself requires fast translation, combined with rotation in a very limited time. Moreover, the environment was designed to not provide additional orientation cues such as landmarks or directional lights. Participants had to build up the spatial awareness based on the boxes locations, and maintain it during the task. Most

participants could find the first three balls easily, however, as the ratio of balls to boxes decreases over the task, especially those who did not maintain good spatial orientation and memory found it increasingly difficult.

2.2.4 Simulated Reference Frame

As a studied phenomenon, simulated reference frames were designed following previous theories which consider the center of reference as the most important attribute of a reference

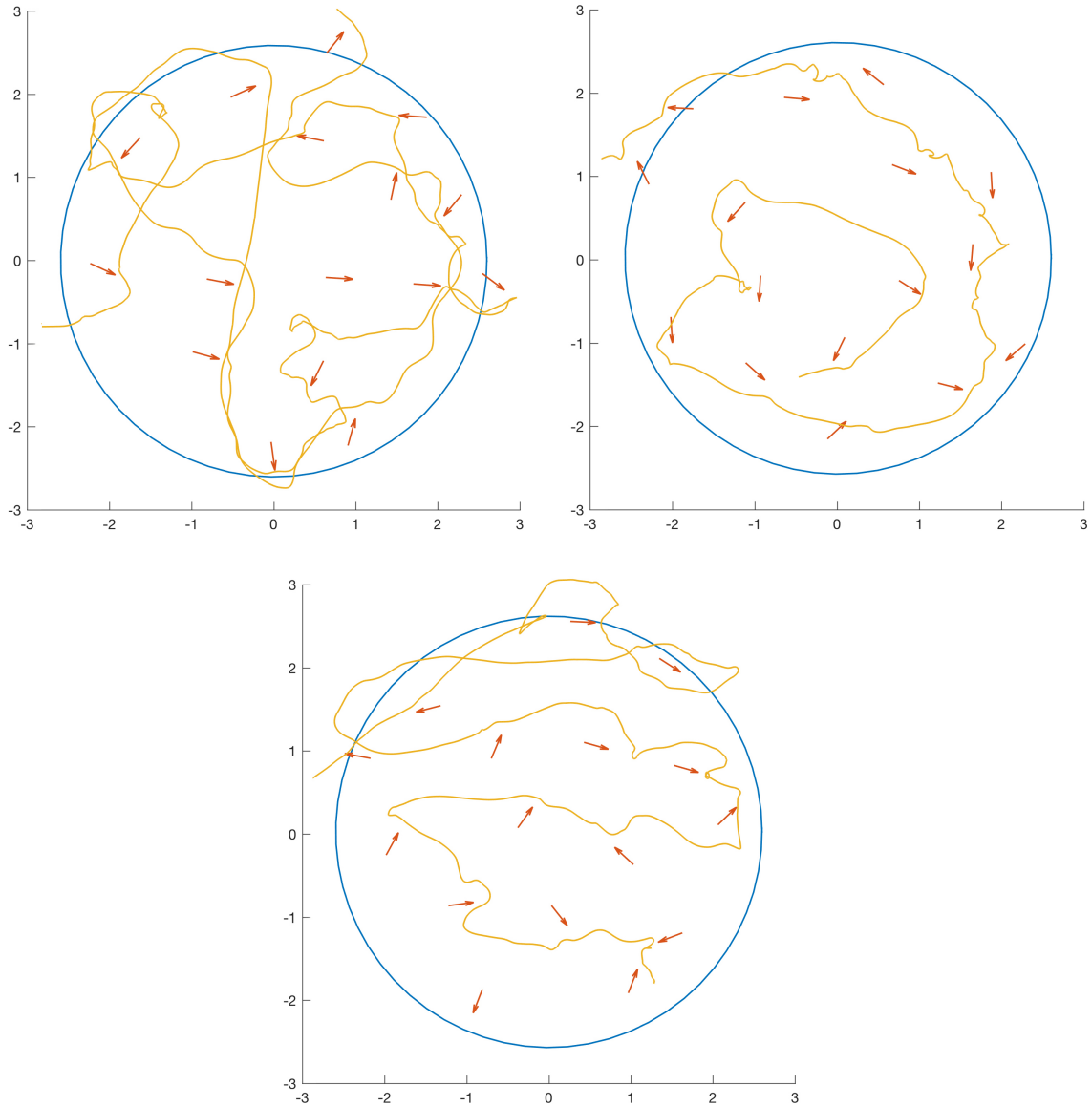


Figure 2.4: Three examples of trajectory plots per trial. Top-Left: (Seemingly) random search without strategy (PT #9, trial #1). Top-Right: Spiral search (PT #5, trial #3). Bottom: Zig-zag search (PT #13, trial #3)

frame [29, 38]. As depicted in Figure 2.5, we compared two variations of reference frames and a baseline condition of no reference frame:

No reference frame: This is a normal condition like any other VR game or simulation. Participants were expected to do the task in a landmark-free environment, so that they had to maintain their spatial orientation without any additional visual cue. The environment was designed to avoid both intrinsic and extrinsic reference frames. This condition, therefore, was ideal to be used as the baseline for assessing the other conditions that included a simulated frame of reference.

Simulated CAVE: A 3D rectangular box of 3 x 4 x 2 meters centered around the user was added to investigate if it might help participants to remain oriented during the task (Figure 2.5). Note that the only visible components of the box were its edges, and the edges did not significantly hide any part of the virtual scene. We deliberately used a rectangular box as we expected that the difference between shorter and longer edges would enhance participants’ spatial orientation (e.g., they could easier distinguish different sides of the frame). In this condition, the frame translated with participants, and they were always positioned at the center of the frame. However, the orientation of the frame stays constant; participants thus feel like they were using an actual six-sided CAVE, which is a classic virtual environment setup that (unintentionally) provides users orientation cues with its edges and corners.

It is important to mention that the simulated CAVE reference frame does not behave exactly like an actual CAVE in the real world. In a CAVE, user can move his or her own head to adjust their relative point-of-view to the frame. However, in the simulated CAVE, the frame is always center-aligned with user’s point-of-view. This characteristic emphasized the egocentric reference cues in the simulated CAVE.

Simulated Room: A 3D rectangular box of 5 x 6.6 x 2 meters, which fully covered the area of target objects, was added in this condition (Figure 2.5). The most important difference compared to the Simulated CAVE was its stationary behavior. That is, neither the position nor orientation of the simulated room reference frame changed with participants’ movement, thus mimicking the cues provided by an actual room or rest frame [47]. The simulated room in this condition can be considered as an additional object in the scene, albeit one that has a clearer intrinsic reference frame than the randomly scattered target objects. Another difference is that the size of simulated room is bigger than a simulated CAVE, as we want it to fully cover the whole area of the navigational search task, a circular area of 5 meter diameter. However, the 3:4 ratio of the simulated CAVE was maintained, and the area of simulated room is hence 5 x 6.6 meters.

The height of both simulated frames is relatively shorter than actual CAVE or room in the real world. We made this choice to fit the HMD’s FOV so that the frames are always visible to observers, no matter in which direction they are looking. The ultimate goal is

that user can easily refer to the frames to maintain spatial orientation with less or even no cognitive load, like how we do in the real world.

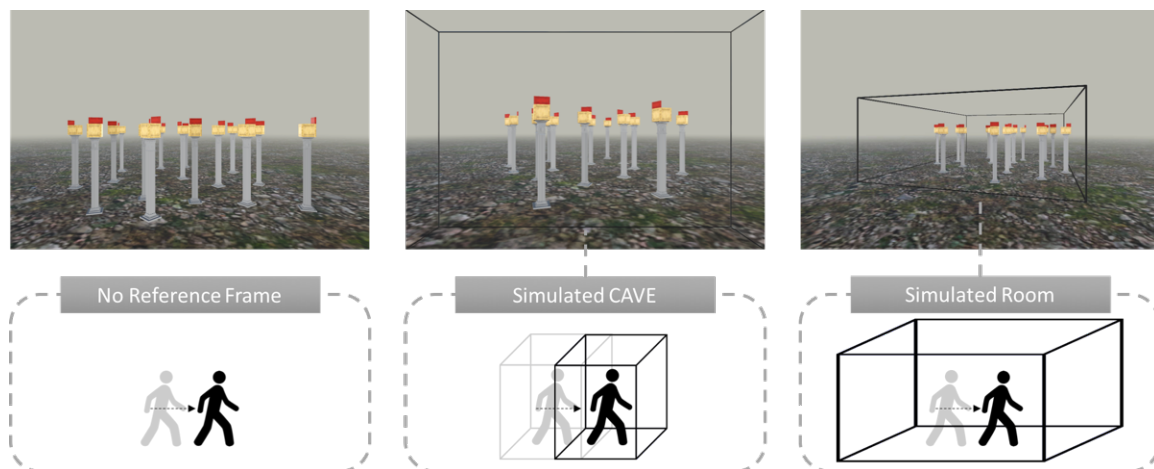


Figure 2.5: Three variations of reference frames. Left: No reference frame. Middle: Simulated CAVE. Right: Simulated Room.

2.3 Experiments

Participants began the study by reading and signing an informed consent form. Then they read printed instructions explaining the task as well as the use of the equipment. Each participant completed a single practice trial in the training section to get familiar with the interface and then one trial for each condition. Order of conditions were balanced across participants to account for potential order effects. Each trial lasted three minutes on average.

After each trial, participants were asked to fill out a questionnaire on a computer. They rated the previously experienced condition using visual analog ratings with a scale ranging from 0 to 100, on aspects such as ease of use, learnability, comfort, usability, controllability, enjoyment, motion sickness, and preference (different from other ratings, preference was rated using a Likert scale from 0 to 10). This evaluation section was also a chance for the participants to take a break between different conditions, which helped to prevent motion sickness. Breaks lasted from one to ten minutes up to participants, we only started next trials when participants were ready. After the last trial, participants also completed a short exit survey in addition to their previous evaluation and were thanked for their participation.

On average, the study took 30 minutes to complete. The studies had approval of the SFU Research Ethics Board (#2012c0022) and all participants signed an informed consent form prior to participating.

2.3.1 Experiment 1: Pilot Study

We ran a pilot study to evaluate the experiment design in general so that we could adjust the main experiment if needed. Pilot testers (PT) were treated exactly the same as participants in the main study.

Participants

Nine volunteers (4 female, 5 male), aged 12-39 years old ($M = 24.33$, $SD = 6.39$), took part in the pilot experiment. While three of them were graduate students who had significant experience with VR, the other six were undergrad students and naive to VR.

Experiment Design

A 2 x 3 repeated-measures experiment was conducted. The independent variables were locomotion interface (2 levels: NaviChair and joystick) and simulated reference frame (3 levels: no reference frame, simulated CAVE, and simulated room). Every participant was supposed to take part in all six conditions, in balanced order. Qualitative data was collected by debriefing and analyzed to investigate potential factors causing motion sickness.

Results

A large portion of participants (4 out of 9) got motion sick and could not finish all six conditions. Thus, only part of their performance data was usable. To investigate, we asked participants several questions. When being asked *"Is there anything annoying or too difficult in this experiment?"*, some participants reported motion sickness as an issue but did not identify the cause (PT #2, 6, 7). Others mentioned difficulties in using locomotion interfaces (PT #1, 8, 9). In their feedback on locomotion interfaces, most participants preferred NaviChair (PT #4: *"The NaviChair was easier to use because it is more intuitive/natural"*. PT #6: *"The NaviChair helped my body feel the motion in real time and I would prefer to use that in a long term scenario"*.). Three participants even identified the joystick locomotion interface as the cause of their motion sickness (PT #5: *"Joystick made feel sick when I was rotating it to one side and move my head to another"*.).

In conclusion, different individuals provided different ideas on how the experiment could be improved, however, the general theme showed that locomotion interfaces and in particular the joystick might have contributed to the issue of motion sickness in this experiment. On the other hand, when comparing between the two interfaces, most participants preferred the NaviChair even though the joystick was more standard and known. This might be related to upper-body leaning being able to facilitate self-motion perception in VR [32, 31].

2.3.2 Experiment 2: Main Study

Based on the pilot study results, we reduced the number of experimental trials from six to three and removed the joystick condition as it seemed like it might be more prone to motion sickness.

Participants

Twenty-one volunteers (13 female, 8 male), aged 18-41 years old ($M = 22.06, SD = 5.01$), took part in the main experiment. Most of them were undergrad students and naive to VR. Twelve participants reported playing computer games weekly, or even daily. The other nine participants did not play computer games at all.

Experiment Design

Based on the pilot study results, the main study was reduced to a one-way repeated-measures design, where the only independent variable was the simulated reference frames (3 levels: no reference frame, simulated CAVE, and simulated room, as before). The reason to drop the joystick condition was to firstly shorten the overall length of the experiment and secondly to prevent motion sickness and increase the chance that participants can complete all conditions. Therefore, even though there were only three conditions in the main study, we decided not to increase the number of trials per condition. Each participant was supposed to complete three trials relevant to three conditions of simulated reference frames, in balanced order.

Though there were still 28% (6 out of 21) participants who could not finish all three conditions because of motion sickness, this was significantly less than the pilot study. To increase power without having to run more participants, we included the performance data of the two pilot testers (#4, 8) who started with the NaviChair and completed all trials in this locomotion condition without getting motion sick. In other words, their performance had not been affected by the subsequent joystick condition at all, and the experimental procedures in the pilot and main experiment were otherwise identical. Eventually, data from 17 participants were used for analysis.

Results: Objective Behavior (Performance)

Data of multiple dependent variables for user performance are summarized in Figure 2.6 and were analyzed using repeated-measures ANOVAs and LSD post-hoc tests in SPSS Statistics.

Simulated room helped participants reduce their completion time (Figure 2.6A). An ANOVA revealed a significant effect of reference frame on completion time, $F(2, 32) = 3.582, p = 0.039, \mu_p^2 = 0.183$. LSD's pairwise comparisons showed that simulated room helped participants to complete the task significantly faster ($M = 94.17, SD = 35.37$), compared to the simulated CAVE ($M = 119.76, SD = 39.51$), $p = 0.031$, and no reference

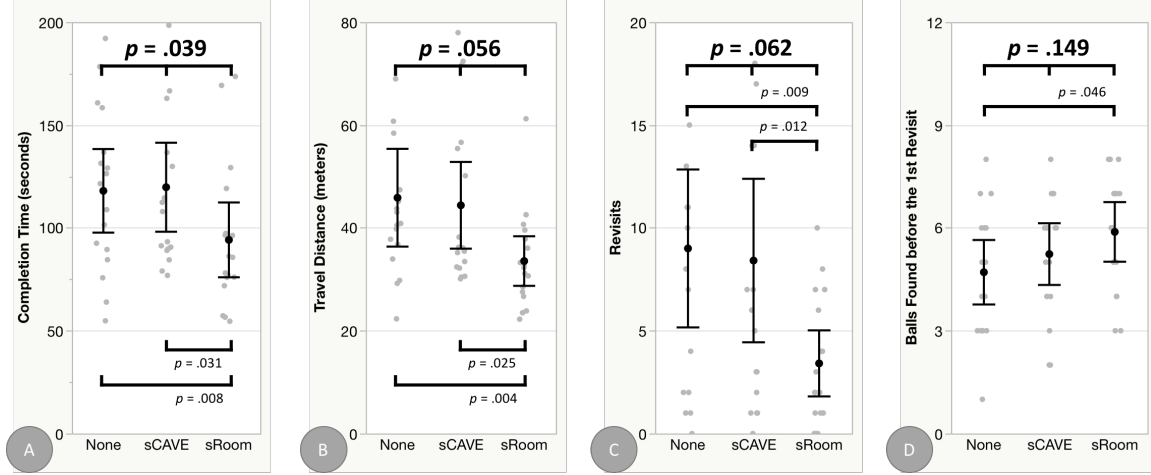


Figure 2.6: Mean data of different dependent measures for performance. Error bars indicate confidence intervals ($CI = 0.95$), gray dots indicate individual participants' data

frame condition ($M = 118.01, SD = 39.51$), $p = 0.008$. No significant difference was found between the presence and the absence of a simulated CAVE, $p = 0.893$. This result partially supports our hypothesis **H1** that simulated reference frames can help user improve their performance, although only the rest frame of the simulated room (but not the simulated CAVE) provided a significant reduction in task completion time.

Simulated room helped participants reduce their travel distance in the virtual world (Figure 2.6B). Mauchly's test was significant, $\chi^2(2) = 9.638, p = 0.008$. The assumption of sphericity, therefore, was violated. The Greenhouse-Geisser correction was used to analyze the travel distance. It showed that using reference frames resulted in a marginal effect on travel distance, $F(1.357, 21.709) = 3.721, p = 0.056, \mu_p^2 = 0.189$. LSD post-hoc tests revealed that participants significantly traveled shorter in the condition of simulated room ($M = 33.55, SD = 2.27$) as compared to no reference frame ($M = 45.87, SD = 4.48$), $p = 0.004$ and the simulated CAVE ($M = 44.39, SD = 3.98$), $p = 0.025$. No significant difference was found between the presence and the absence of the simulated CAVE, $p = 0.820$. To some extent, this result also supports our hypothesis **H1**.

Participants revisited fewer boxes when using simulated room (Figure 2.6C). As Mauchly's test showed that the assumption of sphericity was violated, $\chi^2(2) = 11.523, p = 0.003$, the Greenhouse-Geisser correction was used. Analysis showed that the presence of a reference frame marginally affected the number of box revisits, $F(1.302, 20.831) = 3.617, p = 0.062, \mu_p^2 = 0.184$. LSD post-hoc tests also pointed out that participants made smaller numbers of revisits with the support of a simulated room ($M = 3.41, SD = 0.76$) compared to the baseline condition of no reference frame ($M = 9.00, SD = 1.81$), $p = 0.009$ and the other reference frame, simulated CAVE ($M = 8.41, SD = 1.88$), $p = 0.012$. No significant difference was found between the rest pair of conditions, $p = 0.847$. Similar to previous con-

clusions, this result also shows that only the simulated room could improve performance, while the counterpart (simulated CAVE) yielded no significant benefits.

Simulated room helped increase the numbers of targets found before the first revisit (Figure 2.6D). Though an ANOVA revealed no significant difference between the three conditions in terms of the number of targets found before the first revisit, $F(2, 32) = 2.019, p = 0.149, \mu_p^2 = 0.112$, LSD pairwise comparisons showed that participants found more balls before their first revisit in the simulated room condition ($M = 5.88, SD = 0.41$) relative to the condition of no reference frame ($M = 4.71, SD = 0.44$), $p = 0.046$. Simulated CAVE ($M = 4.94, SD = 2.10$) did not differ from the other conditions, $p's > 0.287$. This suggests that it took longer for participants in the simulated room to make the first error, than in other conditions. The result hence partially supports hypothesis **H1**.

No order effect was revealed. Though we counter-balanced the order of conditions to eliminate systematic effects of order on condition, the limited number of participants and the high drop-out rate might affect the balancing. For this reason, we conducted several ANOVAs to analyze if there were any overall order effects. Analyses revealed no significant effect of the order of trials on completion time, $F(2, 32) = 2.424, p = 0.105$; travel distance, $F(2, 32) = 2.835, p = 0.074$; revisits, $F(2, 32) = 1.495, p = 0.239$; or the number of balls found before the first revisit, $F(2, 32) = 1.795, p = 0.182$.

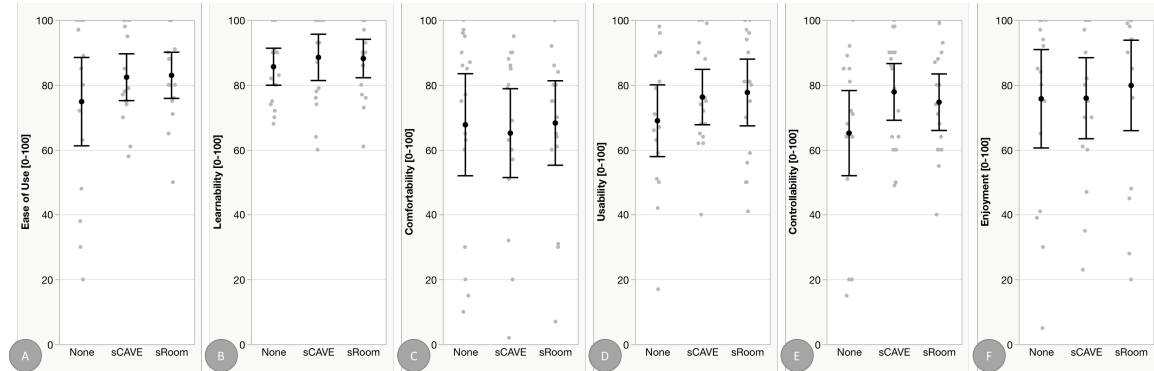


Figure 2.7: Mean data of different dependent measures for user evaluation. Error bars indicate confidence intervals ($CI = 0.95$)

Results: Subjective Evaluation

Data for the different subjective measures are summarized in Figure 2.7 and analyzed using repeated-measures ANOVAs and LSD post-hoc tests. Analyses was done using SPSS Statistics. In general, user evaluations showed that the interface was easy to use ($M = 80.04, SD = 19.05$), highly learnable ($M = 87.39, SD = 12.05$), comfortable ($M = 67.02, SD = 27.09$), usable ($M = 74.28, SD = 19.48$), controllable ($M = 72.53, SD = 20.56$), and enjoyable ($M = 77.14, SD = 26.59$). Yet, there were no significant effects of simulated reference

frame on any of the subjective measures apart from the preference rating and simulator sickness discussed below.

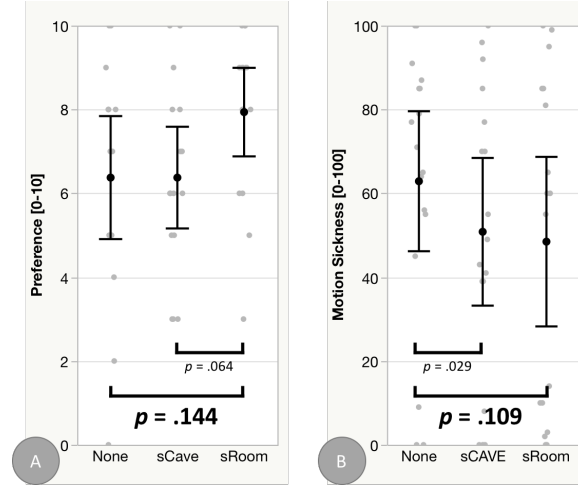


Figure 2.8: Mean data of user preference and self-reported motion sickness. Error bars indicate confidence intervals ($CI = 0.95$)

Simulated room was slightly more preferred. As denoted in Figure 2.8A, most participants rated the simulated room condition as their highest preference ($M = 7.94, SD = 0.50$). Though preference was collected as Likert data, previous studies has shown its feasibility to be analyzed as parametric statistics, even with small sample sizes, unequal variances, and non-normal distribution [9, 44]. An ANOVA revealed that reference frame had no significant effect on user preference, $F(2, 30) = 2.071, p = 0.144, \mu_p^2 = 0.121$. LSD post-hoc tests showed that the simulated room achieved marginally higher preference ($M = 7.94, SD = 0.50$) compared to the simulated CAVE ($M = 6.38, SD = 0.57$), $p = 0.064$, and the condition of no reference frame ($M = 6.38, SD = 0.69$), $p = 0.095$. To some extent, this trend partially supports our hypothesis **H2** that the simulated room is the most preferred condition, even though the simulated CAVE did not yield lower preference than the baseline condition.

Simulated CAVE helped reduce the level of visually-induced motion sickness. In this study we were only interested in overall motion sickness. Thus, we used only a single question rather than the SQS [24] to assess participants' simulator sickness. A single question can be sufficient, if the components of visually-induced motion sickness are not of interest [25]. Though Figure 2.8B suggests that the presence of both the simulated CAVE and simulated room decreased the amount of motion sickness, an ANOVA revealed no significant effect of reference frame on motion sickness, $F(2, 32) = 2.382, p = 0.109, \mu_p^2 = 0.130$. LSD post-hoc tests showed that simulated CAVE ($M = 50.82, SD = 8.31$) significantly reduced the level of motion sickness, compared to no reference frame ($M = 62.88, SD = 7.88$), $p =$

.029. This result partially supported our hypothesis **H3** that the proposed visual cue could reduce users' motion sickness.

A separate ANOVA was run to investigate potential effect of order on reported motion sickness. Yet, there was no significant result, $F(2, 32) = 0.751, p = 0.480$. The high rates of reported motion sickness can be explained by the fact that the navigational search task was designed to be fast and challenging, which required participants to pay close attention to their spatial orientation; while simultaneously building up the spatial awareness of visited boxes; optimizing their path; and traveling fast and effectively. Yet, many participants initially underestimated the task difficulty, and traveled (seemingly) randomly from box to box at high speed. Motion sickness started before they actually recognized the symptoms and slowed down.

2.4 Discussion

Though previous work has shown that the egocentric reference frame is dominant in spatial updating [38], our simulated CAVE, which adds an egocentric frame of reference (at least for translation, but not for rotation), did not show any significant difference compared with the baseline condition of no added reference frame. However, an allocentric frame of reference, mimicking a simulated room acting as a rest frame [47], seemed to be helpful in the navigational search task. Analyses revealed significant benefits in a variety of behavioral measures. In terms of user performance, our hypothesis **H1**, which predicted both kinds of reference frame would improve performance, was partially supported. In fact, only the allocentric frame (simulated room) improved user performance. In terms of usability, hypothesis **H2**, which predicted that the simulated room would be preferred, was partially confirmed, as the differences were not significant. Regarding motion sickness, hypothesis **H3** which predicted that adding reference frames can reduce user motion sickness, was also partially supported, as only simulated CAVE significantly reduced sickness, compared to the baseline condition. These mixed results suggest the potential of a simulated reference frame in enhancing VR locomotion, but also require further study with larger participant numbers for more firm conclusions.

What makes the difference between Simulated CAVE and Simulated Room?

Although both kinds of reference frames brought a visual cue into the virtual environment to help participants remain oriented, the synchronization between the simulated CAVE and participants' translation might not have improved participants' sense of position. That is, with the simulated room, participants could always easily identify the relative position between themselves, the boxes, and the room so that they could recognize not only how much they rotated, but also where they were in the virtual environment. The simulated room's behavior is after all a more natural cue due to our experience with rooms in the real world, whereas the simulated CAVE, which translates (but does not rotate) with the user,

can seem strange, unless users were very familiar with CAVEs (which they were not). The simulated CAVE hence might require more cognitive load for the spatial updating process than the simulated room. Moreover, the simulated CAVE’s movement might also be a distracting factor, although further research would be needed to investigate this explicitly. Another potential explanation for this observation is that the effect was not visible due to the limited number of participants and trials per condition.

Though frame size could be a factor contributing to the difference, with a rectangular wireframe, there is no additional visible detail except a change in edge length as long as the frame is still visible. More importantly, for a frame that moves with participants, the difference between 3x4m and 5x6.6m might not be that obvious.

Do participants need to become familiar with a simulated CAVE before they can take advantage of it? In several measures, such as travel distance, revisit, ease of use, and motion sickness, the simulated CAVE yielded results that lie between the two other conditions. In addition, previous research has also shown the equal contribution of the two kinds of frames, egocentric and allocentric, in spatial updating tasks [29]. In some situations, the egocentric frame was even dominant [38]. In this experiment, participants even rated simulated CAVE to be the least motion sick condition. For these reasons, we believe that if participants could get more familiar with this reference frame, they might be able to use it more efficiently. In the current study, we merely asked participants to do a single trial per condition because we wanted to reduce the potential for motion sickness. But this also poses a limitation for this study. Due to this design decision, we have not only a limited number of participants, but also only a small number of trials per condition, which reduced our power to detect potential effects. Some participants whose first condition was the simulated CAVE reported that they did not notice the frame because they did not feel they needed it. Based on the exit interviews, participants might have taken advantage of the reference frame more efficiently after experiencing the no reference frame condition, as they reported to be much more aware of the difficulties in maintaining spatial orientation without any reference frame.

2.5 Conclusion & Future Work

The ultimate goal of this work is to empower spatial orientation in virtual environments that is as effective as in the real world. One of the explanations for disorientation in VR is the lack of automatic and obligatory spatial updating. Previous research has suggested that physical motion cues are necessary to address this problem. Yet, previous work found that physical motions might not be sufficient to prevent disorientation [64]. Also, reference frames have been identified to support the spatial updating process [29, 21]. Based on these insights, our work thus investigated a reference frame within a spatial cognition study and visualized such frames as overlaid rectangular boxes in the virtual environment. This study

extends previous results by testing the effect of the simulated reference frames on spatial orientation in VR.

While previous studies showed clear benefits of reference frames in a spatial updating task, the current study provides first evidence that simply adding very basic visually simulated reference frames to the virtual scenes can significantly enhance user performance. That is, adding visually simulated reference frames consisting of only a simple wireframe rectangular box was sufficient to help VR users complete a navigational task in shorter times, with less revisits, and with shorter trajectories. Moreover, the presence of these frames did not yield any significant negative effect on the usability, user comfort, simulator sickness, or enjoyment during the VR experience. Our results provide fundamental knowledge for VR spatial researchers and VR-content designers on how to assist users in maintaining spatial orientation by adding visually simulated reference frames to their virtual scenes.

As previous research has suggested that locomotion modes can substantially affect navigational performance [10], it would have been useful to compare different locomotion interfaces. In the pilot study, we tried to investigate this cross effect by comparing the joystick to a leaning-based interface, but had to abort that experiment design due to excessive motion sickness, which was most likely due to participants' fast movements and accelerations.

For the next steps, we would investigate if different locomotion interfaces might modulate the benefit of simulated reference frames, e.g., with an actual walking condition. The potential to compare with such a condition motivated our design with a circular area of 5 meter diameter for the navigational search task. However, limitations through cables and rapid participant movements make this challenging. Here, we focused on the nature of reference frames, i.e., egocentric versus allocentric frames. It would be interesting to consider different aspect of a simulated reference frame, such as shape (rectangular, spherical, cylindrical) and size. Though the sizes of simulated frames in this study were slightly different, we believe any difference was fairly inconspicuous. In future studies, we plan to investigate these aspects more carefully. Investigating the conditions under which spatial orientation is improved will not only deepen our understanding of human spatial cognition, but can also guide the design of more effective VR simulations. Applying a simulated reference frame to other locomotion interfaces and/or other locomotion modes, such as flying or teleporting, is another planned step toward that goal.

Chapter 3

Do We Need Actual Walking in VR? Combining Physical Rotation with Leaning Might Suffice for Efficient Virtual Locomotion

Abstract Walking has always been considered as the gold standard for navigation in Virtual Reality research. Though full rotation is no longer a technical challenge, physical translation is still restricted through limited tracked areas. From a scientific perspective and while rotational information has been shown to be important, the benefit of the translational component is still unclear with mixed results in previous work. To address this gap, we conducted a mixed-method experiment to compare four levels of translational information: none (using the trackpad of the HTC Vive controller to virtually translate), upper-body leaning (sitting on a Swopper chair, leaning the upper-body to locomote), whole-body leaning (standing on a platform called NaviBoard, leaning the whole body or stepping one foot off the center to navigate), and full translational information (physically walking). Results showed that translational information had significant effects on various measures including task performance, task load, and simulator sickness. While participants performed significantly worse when they used a controller with no embodied translational cues, there was no significant difference between the leaning-based interfaces and walking. These results suggested that translational body-based information from a leaning-based interface might provide enough motion cues for efficient locomotion in VR.

Reprinted, with permission, from T. Nguyen-Vo, B. E. Riecke, W. Stuerzlinger, D.-M. Pham, and E. Kruijff, "Do We Need Actual Walking in VR? Combining Physical Rotation with Leaning Might Suffice for Efficient Virtual Locomotion," a manuscript submitted for publication.

3.1 Introduction

Locomotion is critical to many activities in our daily life. This also transfers into Virtual Reality (VR), where most applications similarly involve navigation, either active or passive, with several modes, e.g., walking, driving, swimming, or flying [6]. However, the majority of applications merely support abstract locomotion interfaces through traditional input devices (e.g., game pad, joystick, keyboard, or mouse) or more advanced techniques dedicated to VR (e.g., point-and-click teleportation and gaze-directed steering). The advantages of these locomotion interfaces are that they are affordable, compact and easy to set up. However, the simulation of self-motion offered by these locomotion interfaces are often unconvincing and frequently contribute to disorientation, unease, and motion sickness [6]. Though various alternative locomotion interfaces have been proposed [5, 37, 65], these issues remain as major challenges in VR locomotion which hinder efficient navigation in VR and thus the potential for VR in applications and research.

Most challenges in VR locomotion originate from the differences between VR and the real world, i.e., visual display and interaction. A major VR challenge is *movement fidelity*, which refers to the naturalism of the simulated movement, mostly associated with *body-based sensory information* [71]. Movement fidelity is only partially a technical constraint, as it involves complex interactions between various sensory sources. Also, body-based sensory information has a strong impact on human spatial orientation in VR [71].

3.1.1 Body-based Sensory Information

Sensory information associated with self-movement can be divided into three categories: external (vision, audition, somatosensory), internal (vestibular, kinesthetic), and efferent (efference copy, attention). However, in most cases several sensory sources simultaneously contribute to our spatial knowledge, and thus experimenters cannot examine them separately [71]. For that reason, the term "*body-based sensory information*" has been widely used in spatial cognition research, referring to the amalgam of vestibular, kinesthetic, and efferent information.

For body-based sensory information, the rotational and translational components seem to be of different importance for spatial orientation for the following reasons: The rotational component is considered to be much more important, because previous studies showed that spatial orientation performance could be improved by adding physical rotational cues [2, 34], while there was no significant benefit from adding translational cues [46, 56].

When we locomote through an environment, our ability to update our self position and orientation with little cognitive load is described as automatic spatial updating in cognitive science [46]. In VR, when an abundance of naturalistic landmarks are provided, physical motion cues seems not to matter much to participants' spatial updating [53, 50]. Yet, if such visual landmarks are missing and people cannot automatically re-orient, body-

based sensory information becomes more relevant. Riecke *et al.* showed that rotation alone (without physical translation) might suffice for effective VR locomotion in a navigation search task [52]. In stark contrast, Ruddle *et al.* emphasized the importance of actual walking in VR, i.e., physical rotation and translation, in a series of studies [60, 61, 59]. Our current study was designed to address this discrepancy by comparing four interfaces that provide different amounts of body-based translational cues in a navigational search task adapted from [52, 60, 61, 59].

3.1.2 VR Locomotion Interfaces

In previous studies, body-based information, in the form of walking, has been shown to help people perform better in several spatial tasks, such as homing [20], spatial updating [28], estimating distance travelled [67], and pointing [69], compared with vision alone. Physical walking also improves participants’ sense of presence, compared to walking-in-place (WIP) or flying [70], and allows them to maneuver in a virtual environment as they do in the real world [73]. Despite these benefits, space for free walking is challenging to support. Currently, even the largest tracked spaces (e.g., 50m x 50m of WorldViz’s PPT) are comparatively smaller than common environments that we navigate in the real world (e.g., supermarket, university campus, or city). Moreover, such large spaces require very high effort to obtain/construct and incur cost for setup and maintenance, which most consumers or even research institutions cannot afford. There are also other factors, including safety issues, that are obstacles to building large tracked areas for free walking in VR.

For these reasons, several locomotion interfaces for VR have been proposed and investigated, such as walking-in-place [33, 65], redirected walking [41, 76], gesture-based [13, 74], and leaning-based interfaces [31, 16, 26]. Each technique has some benefits over the traditional interfaces such as joystick-based steering or teleportation [7]. Gait negation interfaces, in particularly omnidirectional treadmills, such as the Cyberwalk treadmill [62], were once thought to be ideal for VR locomotion. However, this concept has not been widely applied in real-world applications, as it requires substantial safety measures and the cost and technical complexity are extremely high. E.g., the Cyberwalk omnidirectional treadmill has been shut down for years as maintenance is too costly.

Though most locomotion interfaces aim to allow people to navigate virtual environments beyond a tracked space with less or even no physical walking, different cues embedded in each interface provide different body-based sensory information. For example, leaning-based interfaces often provide some vestibular, proprioceptive, and kinesthetic information [32], while joystick-based interface provide only minimal kinesthetic information.

However, most studies did not systematically vary the amount of body-based self-motion cues or did not look into the details of which motion cues or body-based sensory information were added through the proposed interfaces and how they contributed to users’ spatial updating.

Table 3.1: Body-based sensory information in VR locomotion interfaces

Interface Type	Rotation			Translation			Sample study that used...
	N	P	F	N	P	F	
Joystick-based	■			■			Fernandes and Feiner, 2016
Teleportation			■	■			Bozgeyikli <i>et al.</i> , 2016
Gaze-directed			■	■			Cardoso, 2016
Hand gesture			■	■			Ferracani <i>et al.</i> , 2016
Redirected Walking		■				■	Nescher <i>et al.</i> , 2014
Arm swinging			■		■		McCullough <i>et al.</i> , 2015
Walking-in-place			■		■		Skopp <i>et al.</i> , 2014
Leaning-based			■		■		Nguyen-Vo <i>et al.</i> , 2018
Physical Walking			■			■	

N = None; P = Partial; F = Full

To provide an overview of the body-based sensory information that different common locomotion interfaces provide, we analyze the rotational and translational components separately and summarize them in Table 3.1. For each component, we categorize the information into three levels, in which *none* signifies (almost) no sensory information, *full* describes a one-to-one mapping between physical motion and simulated motion, and *partial* involves distorted or transformed information, where users might perceive self-motion from sensory information, yet without a one-to-one correspondence. As shown in this table, different interfaces provide different amounts of rotational vs. translational cues. E.g., teleportation allows full rotation but no translation. Redirected walking enables full translation but provides only partial rotation. Except for redirected walking, most locomotion interfaces allow full rotation, as HMDs nowadays natively support 6DOF head tracking. Thus, traditional joystick/game pad interfaces tend to be replaced with head- or gaze-directed interfaces in VR.

While the presence of a rotational component for body-based information is obvious, the translational component is completely different between interfaces, i.e., translational information is entirely missing in teleportation [7] and gaze-directed steering [8]; It exists to various degrees in arm swinging [37], walking-in-place [65], and leaning-based interfaces [43]. Though arm swinging, walking-in-place, and leaning-based interfaces share a common characteristic, as they use embodied interactions with partial translational cues, the actual information and its amount are different. Arm swinging and walking-in-place interfaces mimic the arm/leg movements of actual walking to simulate the kinesthetic cues. Leaning-based interfaces provide kinesthetic information as well, but this information is

more targeted at the torso, instead of the limbs. Moreover, leaning-based interfaces provide vestibular cues that are more consistent with the simulated movement. These differences have not been thoroughly investigated in previous work. Hence, it is not known how much translational cues might be “enough” for efficient VR locomotion, which motivated the design of our current study.

3.2 Motivation and Goal

To investigate how body-based sensory information impacts human spatial updating and awareness in VR, a large body of research has compared different conditions of physical self-motion cues, e.g., joystick only (no physical motion cue), real rotation (without physical translation), and physical walking (full self-motion cues); using different spatial cognition tasks. Each task assesses different aspects of human spatial orientation, e.g., object identity, route knowledge, environmental shape, or survey knowledge [39]. For example, a pointing task is often used to assess landmark knowledge, spatial updating, or survey knowledge, while an estimate of distance traveled is more likely to be used for assessing route knowledge.

In this study, we are especially interested in spatial updating and situational awareness, as they are essential for spatial cognition and many real-world tasks such that when we move in the real world, not only can we update the knowledge of self position and orientation, but we can also maintain the perception of environmental elements and events with respect to the immediate environment that we are in. *Navigational Search* is a prototypical example of a complex spatial task that requires participants to combine spatial learning and spatial updating with the accumulation of situational awareness during locomotion. The task has been shown to have relatively high ecological validity compared to more abstract tasks, as there is experimental evidence that participants can perform the task in VR (walking with an HMD) as well as they do in the real world (walking without HMD) [58].

3.2.1 Navigational Search Experiments

Navigational Search has been used in a series of studies of Ruddle and Lessels [58, 60, 61], in which participants were in a room that contained 32 pedestals, half of which had closed boxes on top. Participants were asked to navigate in this environment and search for eight target objects hidden in the 16 closed boxes. The task required participants to maneuver in the environment, interact with objects (e.g., open a box, collect a ball), and at the same time learn object locations on the fly, and increase their situational awareness of locations and their status (e.g., checked or unchecked). In their studies, Ruddle and Lessels emphasized the benefits of physical walking with experimental results showing that people perform significantly better when they walk with the HMD than in rotation- or visual-only conditions [60, 61]. In the *rotation-only* condition, participants stood in one place, physically rotated to change orientation, but used buttons to control forward translation.

In the *visual-only* condition, participants viewed the VR simulation on a 21" monitor and controlled translation/rotation with a keyboard/mouse.

Later, Riecke *et al.* highlighted several confounds in Ruddle and Lessels work, e.g., different visual displays between conditions (HMD vs. monitor), different orientating cues from environmental geometry and object structure, and the choice of a discreet input device (which prevent participants from adjusting their velocity). They then revised the experimental design and re-ran the experiment with similar conditions: joystick, real rotation, and walking [52]. The results changed significantly, in that participants performed better with physical walking and physical rotation (without translation) conditions, compared to the joystick (visual-only) condition. The changed outcomes could stem from the revisions to the experimental design by Riecke *et al.* [52]. They removed all orientation cues from the environment (e.g., the rectangular room) and salient landmarks (e.g., sun, clouds), which could significantly affect participant's spatial knowledge and prevent the isolation of the effect of other variables. They also removed the 16 pedestals without boxes on top and used continuous input devices, which allowed participants to adjust their velocity. This revision of the navigational search experimental setup has been used in several follow-up studies [45, 14, 42, 43].

Of particular relevance to our work is a study by Fiore *et al.*, who used the navigational search paradigm to investigate the contribution of vestibular cues for vehicular travel [14]. In their study, they added an additional condition called 'partial', in which the rotation and translation was dampened by a half of the actual motion to reduce the size of the tracked space needed for the VE. They used a wheelchair-based motion platform controlled by a joystick for all four conditions. The difference between conditions was merely the movement of the wheelchair, in which the wheelchair did not move at all in the *visual-only* condition, rotated but not translated in the *rotate-only* condition, partially translated and rotated in the *partial* condition, and fully moved in the *full* condition. They did not find statistically significant results, probably because body-based sensory information was minimal when using a motorized platform instead of embodied interaction. However, the data showed a trend towards better performance for the full motion condition. Qualitative analysis of the path travelled also showed similarities between the full motion condition in this study and a physical walking condition in their previous work. Although the current study did not show any significant benefits, these outcomes suggest potential benefits of vehicle-simulation movement control with joystick locomotion. This implies that the physical motion cues including the vestibular cues provided by the wheelchair locomotion were not sufficient by themselves to enhance performance. Unfortunately the study did not include a physical walking condition, so it is unclear how wheelchair locomotion would have compared to physical walking.

While there are many other studies that used a navigational search paradigm to assess the efficiency of spatial updating in VR, we focus here specifically on those investigating

Table 3.2: Related experiments: the body-based sensory information provided in each condition

Study	Condition	Rotation			Translation		
		N	P	F	N	P	F
Ruddle and Lessel, 2006, 2009	Visual-only	■			■		
	Rotate			■	■		
	Walk			■			■
Riecke <i>et al.</i> , 2010	Joystick	■			■		
	Real Rotation			■	■		
	Walking			■			■
Fiore <i>et al.</i> , 2013	Visual-only	■			■		
	Rotate only			■	■		
	Partial		■			■	
	Full			■			■
Current study	Real Rotation			■	■		
	Upper-body leaning			■		■	
	Whole-body leaning			■		■	
	Walking			■			■

N = None; P = Partial; F = Full

the contribution of *body-based sensory information* [60, 61, 14, 52]. Table 3.2 shows our analysis of body-based motion cues provided in each condition of these studies. One can see that in each study, the motion cues vary between conditions in terms of both rotational and translational components. In our current study, we aim to keep one of the components constant and to only change a single other component to investigate each individual effect. From the spatial updating literature [28, 46, 57] and related work [60, 61, 52] we know that physical rotation is essential and that not providing it substantially reduces human performance in spatial cognition tasks, such as spatial updating and navigational search. However, there was mixed evidence as to whether full translation information from walking is beneficial [60, 61] or not [52]. Moreover, there was a gap in the literature, which can be seen in Table 3.2, namely that the translational component of body-based sensory information has not yet been systematically investigated and isolated from the rotational one.

3.2.2 Goal of this study

To address the above-mentioned gap, We decided to offer full rotation in all four conditions of our experiment and to systematically manipulate the translational information provided by

the locomotion interface. We also added the characteristics of our current study to Table 3.2 to highlight similarities and differences between our experiment and previous work. All four studies have two common conditions: *real-rotation*, where participants have full rotation but no physical translation; and *full-walking*, where they physically rotate and translate like they do in the real world, either by controlling an electric wheelchair with a joystick [14] or by walking in the current study and [60, 61]. Beside these two common conditions, we added two intermediate levels in our experiment, in which participants receive partial sensory information from either their *upper-body* or *whole-body* leaning/stepping when using the respective locomotion interfaces. These conditions help us to investigate the independent variable of translational body-based sensory information without changing rotational cues.

In this study, we aim to investigate the contribution of translational body-based sensory information in VR, given full rotation. Hence, we ran a study to systematically vary the amount of translational body-based cues ranging from *none* (just thumb movements on controller touchpad), *some* (upper-body or whole-body leaning to control velocity of simulated self-motions using a human joystick paradigm), to *full body-based motion cues* (using real walking without any redirection or scaling, as the ideal condition). These four levels of translational information will help us to answer three research questions:

RQ1: How much translational information is needed for efficient VR locomotion? Given full rotational cues, answering this question helps us to fill the gap in the literature about the role of translational cues on spatial awareness and updating. If leaning-based translational motion cues are enough to enable performance and user experience levels matching those of full physical walking, this would provide a useful guideline for future designs of more compact locomotion interfaces. Then, people might not need to invest in sophisticated omni-directional treadmill interfaces or costly large tracked spaces.

RQ2: Does reducing sensory conflict help reduce motion sickness? This research question would allow us to validate the sensory conflict theory [35], which explains motion sickness symptoms by the mismatch in body-based self-motion information. Our leaning-based interfaces are supposed to evoke vestibular cues in the qualitatively correct direction of visually simulated self-motion, which would decrease the conflict in sensory information and hence reduce motion sickness symptoms, and thus improve overall user experience.

RQ3: Does artificial interaction in locomotion interfaces cause higher task load? Though leaning-based interfaces could provide significant benefits in performance or motion sickness, its core interaction is artificial, which requires more training to get participants familiar with it and might create a high task load for them. Answering this question allows us again to acquire more knowledge/guidelines for future designs of VR locomotion interfaces.

There are many open questions about the role of translational motion cues in VR locomotion, such as: does synchronized translation provide more opportunities to maintain

spatial orientation in VR? Or how can we design an interface that supports embodied motion cues, without requiring as much physical activity as walking?. In this study, we used a mixed method approach to systematically compare the effects of translational body-based sensory information at different levels. We focus on the efficiency of spatial updating and situational awareness, and decreased simulator sickness and task load during VR locomotion. To ensure that our approach can be widely applied, we chose a spatial navigational search task, which requires participants to both maneuver in virtual environments and simultaneously acquire/update their spatial awareness. Also, we propose a new motion control model for leaning-based interfaces that is cost-effective, easy to adopt, and highly applicable to many leaning-based interfaces.

3.3 Method

3.3.1 Participants

Twenty-four participants (15 female and 1 preferring not to say), 19 to 38 years old ($M = 23.25$, $SD = 4.63$), took part in this experiment. 41.7% of participants had never used an HMD before, 54.2% reported playing video games on a weekly or daily basis. All participants finished the navigational search task in all four conditions. They were compensated with a soft drink and cookies at the end of the experiment for their efforts. The studies had approval of the SFU Research Ethics Board (#2015s0283).

3.3.2 Procedure

Participants began the study by reading and signing an informed consent form. Then they were presented with a video¹ explaining the navigational search task. Each participant completed two trials for each of the four interface conditions, where the first one was designed to familiarize the participant with the locomotion interface and to provide practice, while the second trial was the actual task where we collected data, which we later analyzed. The order of conditions was counter-balanced to account for order effects. Each trial lasted on average 73 seconds and at most a bit over 6 minutes.

After each condition, participants were asked to fill two questionnaires on a tablet: the Simulator Sickness Questionnaire (SSQ) [24], followed by NASA’s Task Load Index (TLX) [17]. This also provided a break for participants to relax between trials and to recover from any potential motion sickness. To further reduce the potential for motion sickness affecting the results of the next condition, we enforced a minimum break time of five minutes, even if participants finished both questionnaires in a shorter time. Participants were also encouraged to take a longer break if needed. After the last trial, participants were debriefed and thanked for their participation.

¹Task introduction video: <https://youtu.be/XjglwECr6bA>

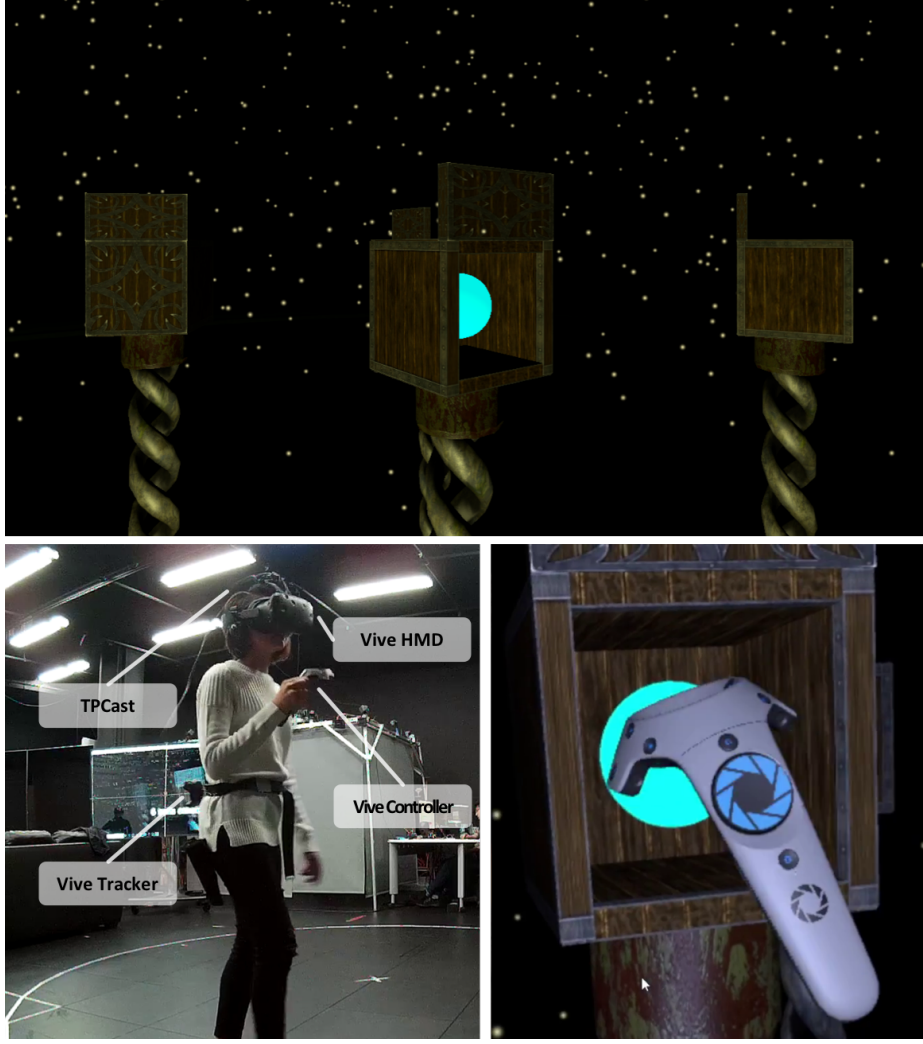


Figure 3.1: Top: Environment from participant’s view, where sight is limited to 2 meters. Left: The setup with the wireless Vive HMD and the TPCast; Right: Ball collection from first-person view.

3.3.3 Setup

In this experiment, the virtual scene was presented through an HTC Vive HMD with a binocular FOV of 110 degree diagonally and combined resolution of 2160×1200 . The simulation was built with Unity3D and rendered by a dedicated PC (Intel Core i7, Nvidia GTX-1080). Participants used a Vive controller to perform the task, i.e., collect balls. In addition, participants wore a dedicated belt with an attached Vive tracker at the back to track their torso movement, but the data collected was used only for behavior analysis. To remove the constraint of cables, we used a TPCast wireless adapter for the Vive. Figure 3.1(Left) shows the whole setup on a participant.

3.3.4 Stimuli and Apparatus

Virtual Environment

In a prior study, we observed that many participants tried to exit out of the target area and to look back at the whole scene to get an overview of the environment’s layout first, to then plan their trajectory before they actually performed the task [43]. This strategy substantially affects the measures, as performance is now influenced strongly by participants’ planning and spatial memory ability, instead of spatial updating and acquiring of situational awareness. Previous studies have shown that the layout of an environment, including relative distances, directions, and scales, can be accurately perceived and remembered from a stationary viewpoint [63] and for memory-based tasks like this, even very brief visual information might suffice for the acquisition of spatial layout knowledge [77].

To force participants to progressively build up their situational awareness of the environment during their locomotion, we carefully removed any landmarks or global orientation cues (such as skyboxes) and made an additional change to the design of the navigational search task: *putting the environment in darkness* where participants could only see boxes within two meters, thanks to a virtual head lamp attached to their avatar’s head. In order to maintain adequate visual self-motion information, i.e., optic flow, we added slowly moving simulated fireflies to the environment so that participants could easily perceive the optic flow due to their motion, without resorting to recognizable landmarks. Figure 3.1(Top) shows a participant’s view of part of the environment.

Participants started each trial from the center of a circular virtual area with 4 meters diameter. Sixteen pedestals with boxes on top were randomly positioned within this circular area for each trial. Eight of these 16 boxes contained green balls as target objects that participants had to search for. The other eight were empty and acted as decoys. Participants were asked to find all eight balls in the most efficient way, i.e., to minimize travel path, time, and revisits.

Interaction

To check if there was a ball inside a box, participants only needed to approach the box from its front side, which featured a banner (see Figure 3.1 Top). A box automatically opened when participants were close enough (within 90cm from the box’s center) and within a certain angle of the opening (45° in both directions from the box’s forward vector). To prevent motion sickness, there was no collision detection or response for the boxes. However, participants could not see the contents of a box if they moved through the box from the other side, i.e., when they did not approach from the side with the opening. Figure 3.1(Right) illustrates an example of opening a box. When they saw a ball, participants could collect it by touching it with a 6DOF wand controller.

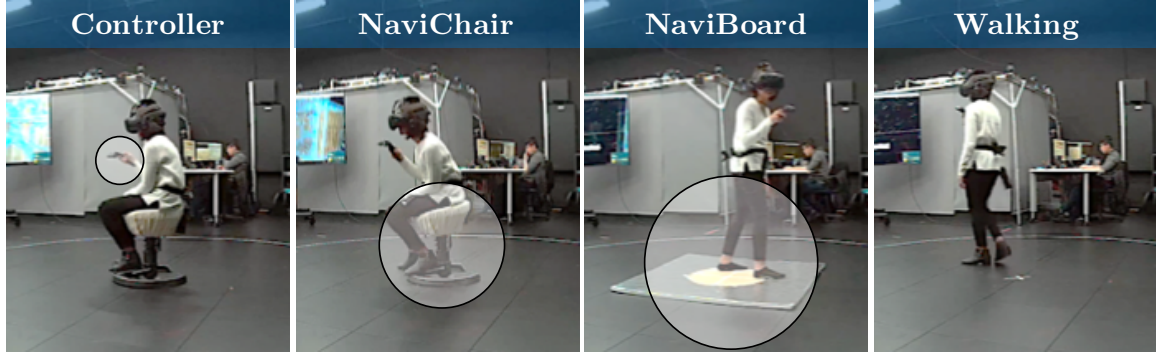


Figure 3.2: A participant used four locomotion interfaces corresponding to the four conditions of this experiment.

3.3.5 Locomotion Modes

In our experiment, we compared four locomotion interfaces providing different amounts of translational body-based sensory information, as illustrated in Figure 3.2 and described below in more detail.

The **Controller** condition relied on *real rotation*, and participants sat on a rotating stool. They could physically rotate on the stool to change orientation and use their finger to swipe on the Vive controller touchpad to translate forward/backward and sideways.

NaviChair was the second condition, in which participants could freely rotate on the stool and their *upper-body leaning* controlled the simulated translations. The mechanism is slightly different from the original NaviChair interface used in previous studies [43, 42, 27, 26], and is discussed in more detail in the Section 3.3.6.

NaviBoard is our new navigation interface that allows *whole-body leaning*, where participants can still freely rotate and where the amount of deflection from the center controls translational velocity. We used the same motion control model as the NaviChair’s, with different parameters as detailed in Section 3.3.6 and Figure 3.3. To provide unobtrusive tactile feedback about their physical location, participants stood on a board that was made out of two materials with different softness: the inner circle was made of wood and the outer square made of styrofoam (see Fig 3.2 and 3.3). When participants lean their body out of the wooden circle, their foot naturally steps on the styrofoam, providing them with unobtrusive feedback that they are crossing the boundary of the inner wooden circle. Inside the wood, head tracking is mapped 1:1, while the outer zone maps velocity non-linearly. Different from walking-in-place interfaces, NaviBoard required less muscular activity but still evokes translational sensory information, especially from the vestibular system.

Walking was used as the baseline and the most natural locomotion interface, where participants could simply physically walk (within a 4m diameter tracking area) and receive natural *full translational information* from the body’s sensory systems, including full vestibular and proprioceptive cues.

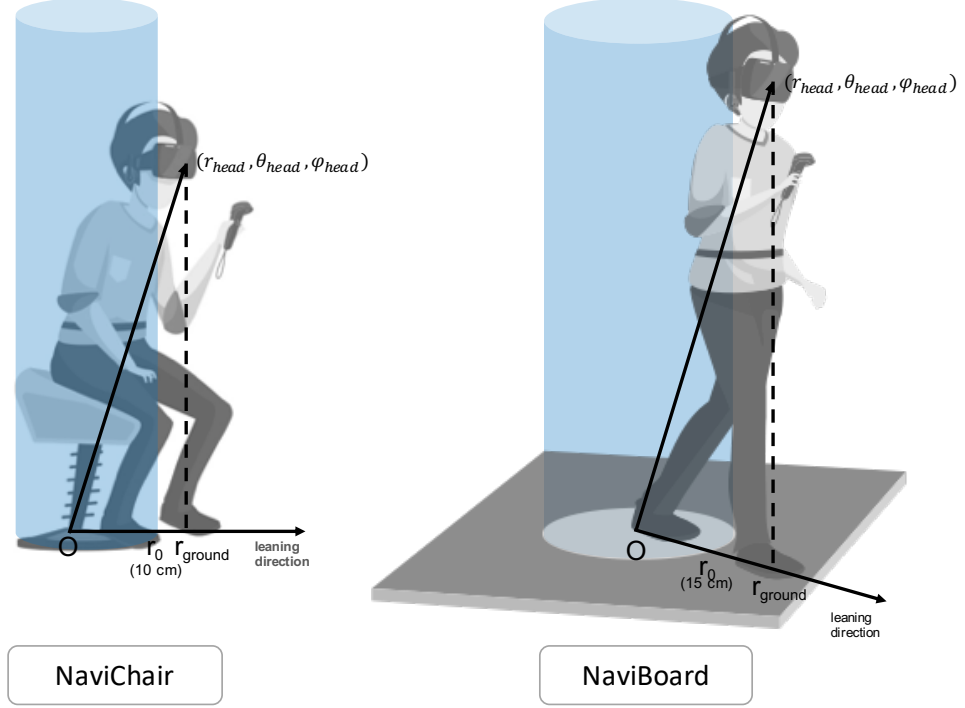


Figure 3.3: Motion control model of NaviChair (left) and NaviBoard (right)

3.3.6 Motion Control Model

We developed a novel motion control model for both seated NaviChair or standing NaviBoard users. With it, simulated self-motions can be naturally controlled by the user's head rotation or translation, while they are either sitting on a swivel chair/stool or standing on the designated platform. This approach is substantially different from gaze-directed interfaces [8], as in our model, translational movement direction is independent of user heading. That is, participants could, e.g., look forward while backing up or moving sideways, and we observed such behaviors frequently. Our new approach is more like previous leaning-based interfaces [26, 31, 5], in which users can use the leaning direction of their torso to control the translational velocity: the more they lean, the faster they go. Movement direction is also determined by the leaning direction.

The user has an *idle zone* centered on their physical locomotion interface, where positional tracking (including rotation) works normally and their simulated motion is mapped identical to their physical one. In other words, when the user is inside this zone, the model does not apply any additional velocities or motions to them, and the simulated viewpoint is directly determined by the HMD's positional tracking, just as in the walking condition. This zone is a cylindrical volume centered at the physical interface, as illustrated in Figure 3.3. The radius of this idle zone should match the size of the physical interface. Based on pilot

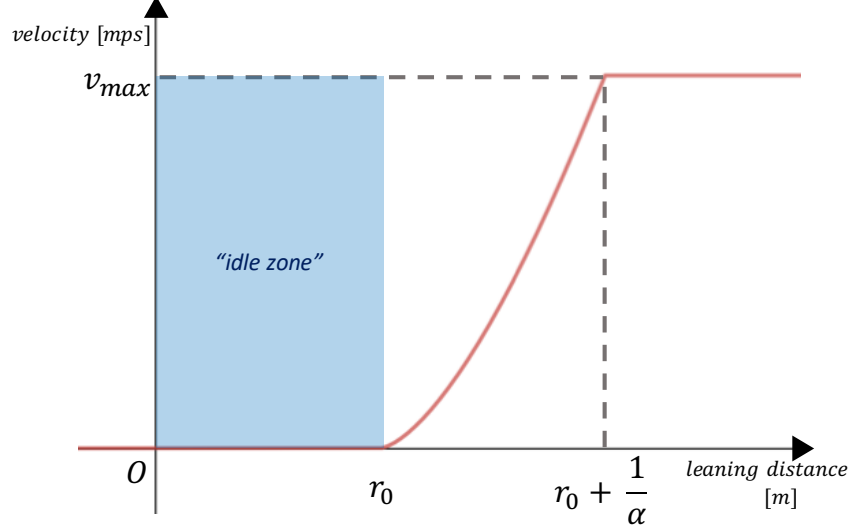


Figure 3.4: Mapping function $v = f(r_{ground})$ consists of linear parts and exponential part ($r_0 \leq r_{ground} \leq r_0 + \frac{1}{\alpha}$)

testing, we chose $r_0 = 10$ cm for the NaviChair and $r_0 = 15$ cm for the NaviBoard for the current study.

When users lean their body (or actually their head) out of the idle zone, a translational velocity aligned with the leaning direction is applied to them and added to the position tracking. The HMD's Cartesian position $(x_{head}, y_{head}, z_{head})$ was not directly used, but transformed into a spherical coordinate system $(r_{head}, \theta_{head}, \phi_{head})$, whose center is aligned with the physical interfaces, e.g., the stool or board. Figure 3.3 illustrates this model, where the displacement between the user's head and the center of the interface is annotated as r_{head} , the projection of r_{head} onto the ground is $r_{ground} = r_{head} \times \sin(\theta)$ where θ is the polar angle, the radius of the idle zone is r_0 , and the center is O . Velocity is then calculated using an exponential function $v = f(r_{ground})$ (Figure 3.4):

$$f(r) = \begin{cases} 0, & \text{if } r < r_0 \\ v_{max}(\alpha(r - r_0))^{1.53}, & \text{if } r_0 \leq r \leq r_0 + \frac{1}{\alpha} \\ v_{max}, & \text{otherwise} \end{cases}$$

where α is the sensitivity coefficient and v_{max} is the maximum velocity. If $\alpha = 2$, users would reach the max speed when $r_{ground} - r_0 = \frac{1}{2} = 0.5$ meters. Based on data collected in a pilot study, we observed that the users' leaning distance is usually less than 40 centimeters. Thus, we set $\alpha = 3 \approx \frac{1}{0.4-0.1}$ in our experiment (e.g., $r_{ground} = 0.4m$ and $r_0 = 0.1m$). In that pilot study we also measured the average speed of participants in the physical walking condition and the mean was 1.3 m/s. Hence, we set $v_{max} = 1.5$ in our experiment.

Pilots identified that it was helpful for participants to have some intuitive awareness of the boundary between the idle and the velocity control zones, without interfering with their experience and immersion/presence. Hence we decided against providing visual or auditory cues about that boundary, and instead focused on body-based cues as a different sensory channel not used by the HMD itself. For NaviBoard, users could easily sense the boundary between the hard wooden platter and the surrounding softer styrofoam when stepping. For NaviChair, the chair itself combined with participant’s leaning provided feedback about their deflection from the center.

3.4 Results

3.4.1 Behavioural Measures

Data of multiple dependent variables for user performance are summarized in Figure 3.5 and were analyzed using repeated-measures ANOVAs for general effects and Tukey post-hoc tests for pairwise comparisons. For measures whose data violate the sphericity assumption, Greenhouse-Geisser correction was applied.

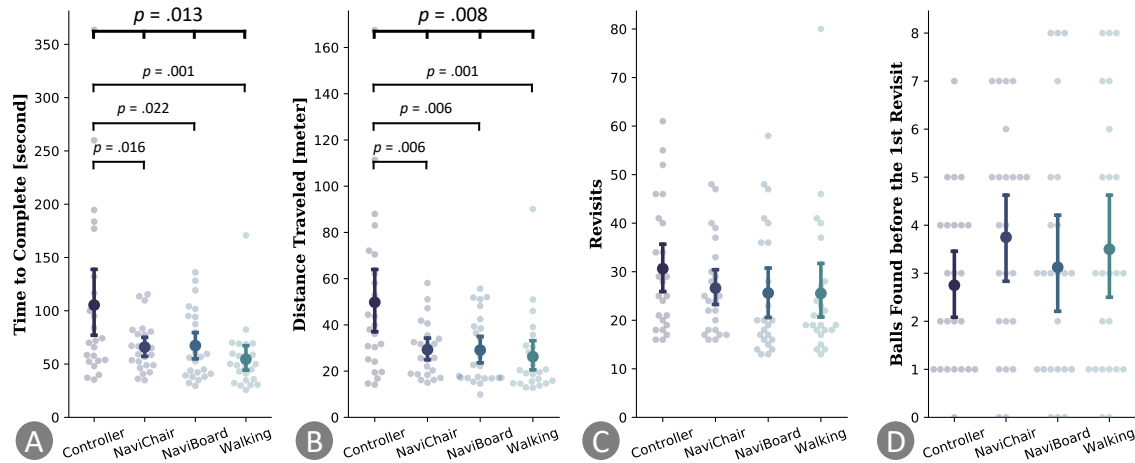


Figure 3.5: Mean data of different dependent measures for performance. Error bars indicate confidence intervals ($CI = 0.95$), gray dots indicate individual participants’ data

The number of perfect trials (trials with no revisit) was minimal. Only three participants in each of the NaviBoard and Walking condition managed to complete the navigational search task without revisiting any boxes. None managed to do so in the Controller and NaviChair conditions. These values are comparatively lower than those seen in related experiments [60, 61, 52, 14] and could be explained by the changes that we made to the navigational search paradigm, such as preventing participants from seeing all boxes from a single point and thus pre-planning their trajectories. Though these changes might make the task harder, they allow us to better assess the construct of spatial orientation/updating.

Participants performed the task faster when using locomotion interfaces that provided translational body-based information (Figure 3.5A). Analysis revealed a significant effect of locomotion mode on participant’s task completion time, $F(1.362, 31.329) = 5.925, p = .013, \eta_p^2 = .205$. Tukey post-hoc tests showed that participants finished the task significantly slower when using a Controller with no body-based translational information ($M = 105.39, SD = 79.65$); compared with the NaviChair ($M = 65.88, SD = 23.05$), $p = .016$; the NaviBoard ($M = 67.31, SD = 32.88$), $p = .022$; and Walking ($M = 54.52, SD = 29.19$), $p = .001$. There was no significant difference between other pairs.

Correspondingly, participants also traveled shorter distances when provided with translational body-based sensory information (Figure 3.5B). An ANOVA revealed a significant effect of locomotion mode, $F(1.495, 34.387) = 6.506, p = .008, \eta_p^2 = .220$. Tukey post-hoc tests showed the same pattern of results as for the task completion time, in that participants traveled a significantly longer path when using the Controller ($M = 49.78, SD = 35.90$), compared with the NaviChair ($M = 29.28, SD = 11.83$), $p = .006$; the NaviBoard ($M = 29.10, SD = 14.80$), $p = .006$; and Walking ($M = 26.25, SD = 17.25$), $p = .001$.

Participants made similar numbers of revisits in all conditions (Figure 3.5C). We counted the number of revisits as a measure of error, yet, there was no significant difference in this measure, $F(3, 69) = .908, p = .442, \eta_p^2 = .038$.

Participants made similar “progress” before their first mistake (Figure 3.5D). We recorded the number of balls found before the first revisit. There was no significant difference between conditions, $F(3, 69) = .735, p = .535, \eta_p^2 = .031$.

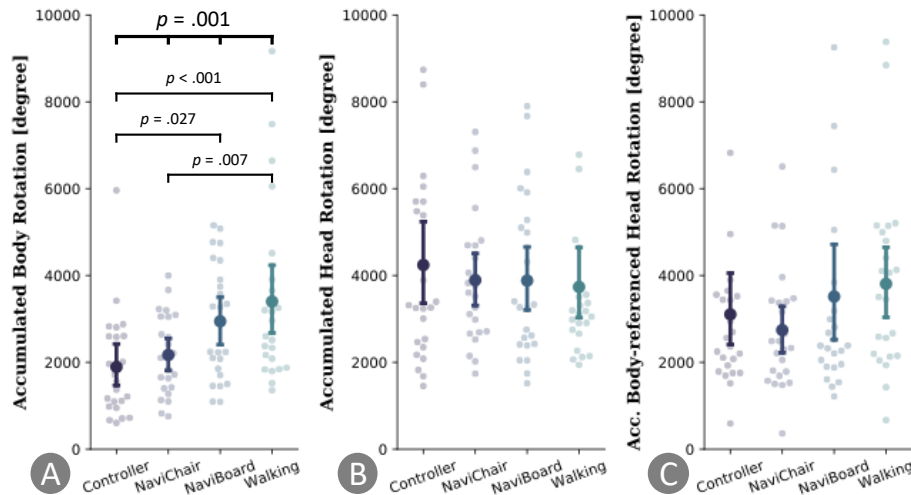


Figure 3.6: Mean data of two dependent measures for rotational behaviours. Error bars indicate confidence intervals ($CI = 0.95$), gray dots indicate individual participants’ data

Participants were more likely to rotate their body while standing (Figure 3.6A). We attached a 6DOF tracker to participants back to measure their torso motion. Analysis showed a significant effect of locomotion mode on body yaw, $F(2.262, 52.026) = 7.205, p = .001, \eta_p^2 = .239$. Tukey post-hoc tests showed that participants turned their body significantly less when using the Controller ($M = 1894.03, SD = 1204.43$), compared with the NaviBoard ($M = 2945.28, SD = 1343.75$), $p = .027$, and Walking ($M = 3401.93, SD = 2018.44$), $p < .001$. Also, participants turned significantly less in the NaviChair condition ($M = 2169.90, SD = 920.65$), than with Walking, $p = .007$.

Regardless of the locomotion interface, participants always used similar amounts of head rotation (Figure 3.6B). There was no significant difference in participants' overall amount of head rotations between the four conditions, $F(2.057, 47.313) = .323, p = .713, \eta_p^2 = .014$. As head rotation in world coordinates might contain both neck rotation and body rotation, we also measured the head rotation relative to the body (Figure 3.6C), but found no significant effect, $F(1.980, 45.533) = .433, p = .649, \eta_p^2 = .018$.

Participants tended to rotate their body together with their head when they were walking (Figure 3.6). Individual t-tests were used to compare the total amount of head versus body rotations for each condition. Interestingly, there was no significant difference between head and body rotations for the Walking condition ($t(23) = .054, p = .958$). In stark contrast, participants rotated their head significantly more compared to their body when using the Controller ($t(23) = 5.551, p < .001$), NaviChair ($t(23) = 7.908, p < .001$), and NaviBoard ($t(23) = 3.557, p = .002$).

3.4.2 Subjective Ratings

Simulator Sickness

We used the Simulator Sickness Questionnaire (SSQ) [24] to measure visually induced motion sickness in the experiment. The overall motion sickness was relatively low ($M = 19.14, SD = 21.26$) out of a possible 120. We were not only interested in the total score of the SSQ, but also the three individual components, i.e., nausea, disorientation, and oculomotor issues. The data are summarized in Figure 3.7 and were analyzed using repeated-measures ANOVAs for general effects and Tukey post-hoc tests for pairwise comparisons. Also, Greenhouse-Geisser correction was used for measures that violate the sphericity assumption.

Participants were less motion sick when more translational body-based information was provided (Figure 3.7A). Analysis showed a significant effect of translational body-based information on overall motion sickness ratings, $F(2.006, 46.127) = 3.506, p = .038, \eta_p^2 = .132$. Tukey post-hoc tests showed that participants were significantly less sick in the NaviBoard condition ($M = 14.79, SD = 18.94$), $p = .030$, and the Walking condition ($M = 15.42, SD = 22.74$), $p = .046$, compared with the Controller ($M = 25.69, SD = 20.98$).

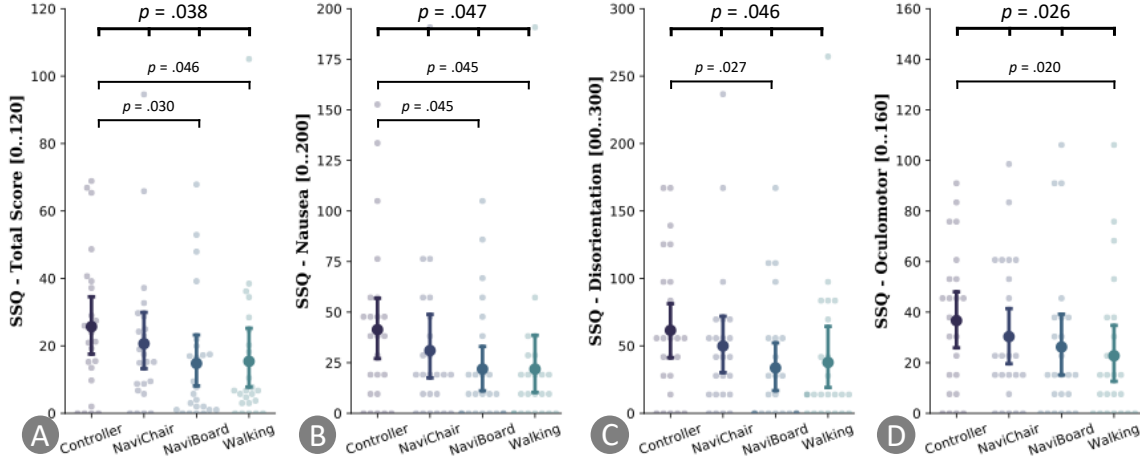


Figure 3.7: Mean data of the overall Simulator Sickness Questionnaire and its sub-components (nausea, disorientation, and oculomotor). Error bars indicate confidence intervals ($CI = 0.95$), gray dots indicate individual participants' data

Participants were less nauseous when using the NaviBoard or Walking (Figure 3.7B). An ANOVA revealed significant effects of locomotion mode on participants' nausea scores, $F(2.035, 46.797) = 3.249, p = .047, \eta_p^2 = .124$. Tukey post-hoc tests showed that participants were less nauseous when using the NaviBoard ($M = 21.86, SD = 29.70$), $p = .045$, and the Walking condition ($M = 21.86, SD = 39.02$), $p = .045$, compared with the Controller condition ($M = 41.34, SD = 41.22$).

Participants were less disoriented when using the NaviBoard (Figure 3.7C). Analysis showed that locomotion mode had a significant effect on participants' disorientation, $F(2.064, 47.473) = 3.261, p = .046, \eta_p^2 = .124$. Tukey post-hoc tests showed that participants were more likely to feel disoriented in the Controller condition ($M = 61.48, SD = 52.87$), compared with NaviBoard ($M = 33.64, SD = 46.06$), $p = .027$.

Oculomotor issues were more likely to occur in the Controller condition, compared with Walking (Figure 3.7D). ANOVA revealed a significant effect of locomotion mode on oculomotor issues, $F(3, 69) = 3.279, p = .026, \eta_p^2 = .125$. Tukey post-hoc tests showed that participants reported more oculomotor issues in the Controller condition ($M = 36.64, SD = 27.89$), compared with Walking ($M = 22.74, SD = 28.01$), $p = .020$. There was no significant difference between other pairs.

Task Load

We used the NASA Task Load Index (TLX) [17] to measure the workload participants experienced during the task and how it might depend on the locomotion interface. Beside the final weighted score, the six TLX subscores are also summarized in Figure 3.8 and were analyzed using repeated-measures ANOVAs for general effects and Tukey post-hoc

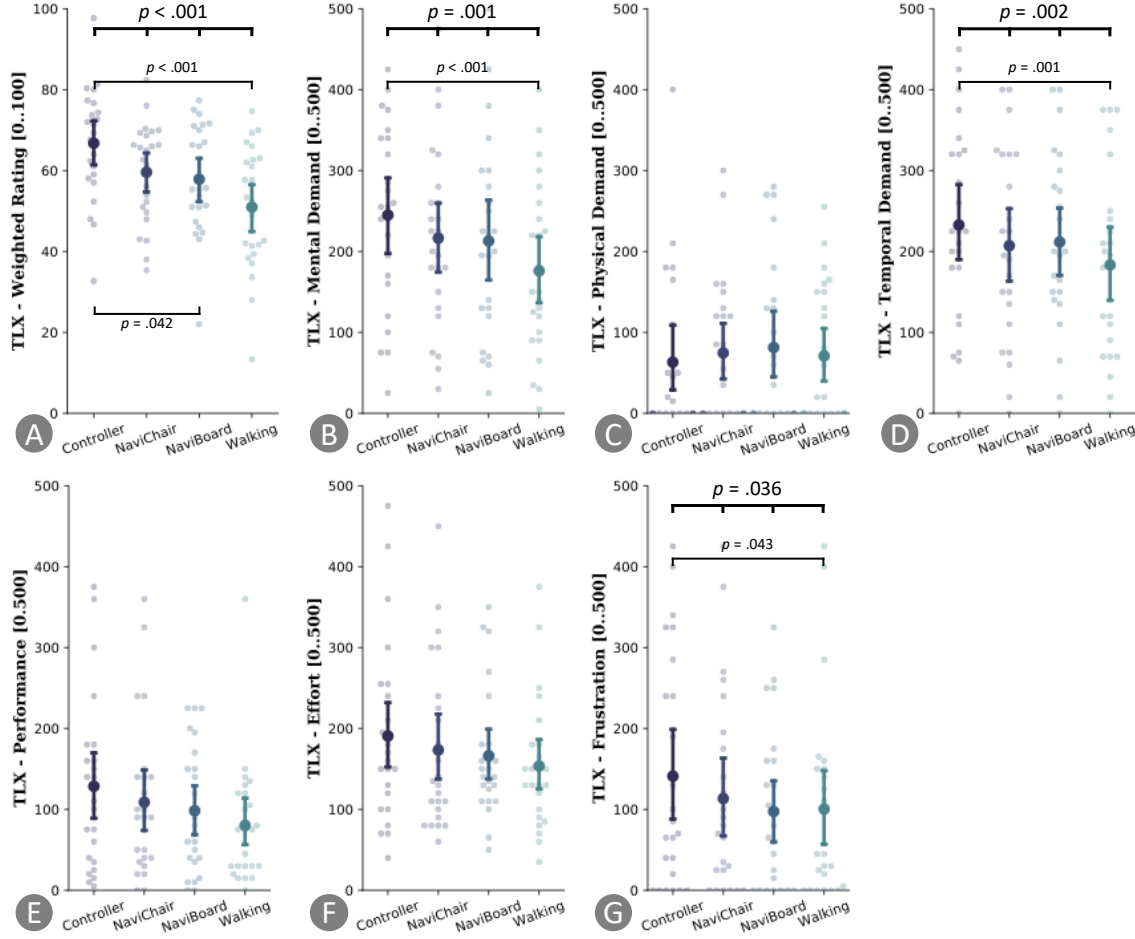


Figure 3.8: Mean data of the NASA Task Load Index. Error bars indicate confidence intervals ($CI = 0.95$), gray dots indicate individual participants' data

tests for pairwise comparisons. Results showed main effects of translational motion cues on the *overall weighted TLX score*, *mental demand*, *temporal demand*, and *frustration* as detailed below, but no significant difference was found for the other three, *physical demand*, *performance*, and *effort*.

Participants perceived lower workload when doing the navigational search task with NaviBoard or Walking (Figure 3.8A). An ANOVA showed a significant effect of locomotion mode on participants' perceived task load, $F(3, 69) = 7.770, p < .001, \eta_p^2 = .253$. Tukey post-hoc tests showed that participants experienced higher load in the Controller condition ($M = 66.74, SD = 13.76$), compared with the NaviBoard ($M = 57.85, SD = 13.41$), $p = .042$, and the Walking condition ($M = 50.96, SD = 15.34$), $p < .001$.

Participants perceived less mental demand when Walking, compared with the Controller (Figure 3.8B). An ANOVA revealed a main effect of locomotion mode on participant mental demand, $F(3, 69) = 5.888, p = .001, \eta_p^2 = .204$. Tukey post-hoc

tests showed that participants perceived significantly higher mental demand in the Controller condition ($M = 245.00, SD = 111.91$), compared with the Walking condition ($M = 176.04, SD = 106.05$), $p < .001$.

Temporal demand was reduced in the Walking condition, compared with Controller (Figure 3.8D). An ANOVA showed a significant effect, $F(3, 69) = 5.285, p = .002, \eta_p^2 = .187$. In a pattern similar to mental demand, Tukey post-hoc tests showed lower temporal demand for the Walking condition ($M = 232.71, SD = 121.75$) than the Controller condition ($M = 183.33, SD = 115.72$), $p = .001$.

Participant felt significantly more frustrated in the Controller condition, compared to Walking (Figure 3.8G). An ANOVA revealed a main effect of locomotion interface on this measure, $F(3, 69) = 3.00, p = .036, \eta_p^2 = .115$. Also, Tukey post-hoc tests identified significantly higher frustration when using the Controller ($M = 141.04, SD = 143.50$), compared to Walking ($M = 100.42, SD = 121.92$), $p = .043$.

3.5 Discussion

Though physical walking is considered as the locomotion gold standard in VR due to the full body-based sensory information, it is hardly used in actual application, as creating and maintaining a large tracked space is costly, space-demanding, and often infeasible. This motivated the design of various alternative locomotion interfaces that enable embodied interactions, which typically include at least some non-visual self-motion cues, such as walking-in-place, treadmills, or leaning-based interfaces. One of our contributions in this study is NaviBoard, a new paradigm for leaning-based locomotion interfaces. The board is made of common and affordable materials, and can be easily replicated at minimal cost. People can also apply its control model with another setup such as a swivel chair. In this study, we already applied the new model to the NaviChair to improve its usability. As our model requires no hardware, it is simpler than previous work that relies on sensing of weight shifting or tracking the chair motion [5, 27, 32, 43, 18]. NaviBoard was also highly preferred by participants, equal to or ranked right after the Walking condition:

“Walking is the most natural, after that is the one has a board on the ground [NaviBoard]. [For] that one, you don’t have to walk all around but it gives the impression that you can. It makes me feel more natural than the chair [NaviChair].”

“I prefer NaviBoard because it is so close to actual walking, you can feel it under your feet. The difference in material helps me to know where I am.”

“The NaviBoard is my favourite, because it gives me the ability to move my body, and it’s really natural in the way that I know how my movement maps to the movement in the game, really easy and intuitive. I didn’t have to worry about hitting something like when I was walking.”

From a scientific perspective, the literature has shown clear benefits of full rotational information for spatial updating [10, 52]. However, the importance of translational information is still under discussion, i.e., whether or not full translation (physical walking) is needed for efficient locomotion in VR.

While Ruddle *et al.* emphasized the role of physical walking [60, 61], Riecke *et al.* suggested full rotation might be enough [52]. In order to add to this debate, we combined full rotation with translational motion cues at different levels to investigate the role of translational body-based sensory information.

We observed a fairly consistent pattern of results, in that the Controller (which does not provide any body-based locomotion cues beyond thumb movements) performed not only worst in the different measures used, but yielded also the highest simulator sickness and task load scores. Conversely, the walking and standing-leaning (NaviBoard) conditions performed best and had the lowest simulator sickness and task load ratings, closely followed by the seated-leaning (NaviChair) condition. That is, in the current navigational search task, participants performed better when using a leaning-based translation control (while standing or sitting) or when they freely walked. This suggests that our leaning-based translation control might, at least in the current context, provide sufficient body-based sensory cues about translation, which helps us to answer our **RQ1** - *How much translational information might be enough for efficient VR locomotion?*. Note, however, that we only compared four different conditions here, and future work is needed to investigate the generalizability of the results to different tasks and interfaces.

In addition, simulator sickness is believed to largely originate from the mismatch between different sensory cues, in particular visual versus body-based information [35, 24]. By using leaning interaction to control the simulated velocity, we aim to provide at least minimal vestibular/body-based self-motion cues to reduce cross-sensory conflict and thus align the self-motion cues that participants perceive from visual cues (via the HMD) and vestibular cues (via physical movement). In terms of VR motion sickness, results showed a clear benefit of the body-based sensory information provided by the leaning-based locomotion interfaces. This result helps us to answer our **RQ2** - *Does reducing sensory conflict help reduce motion sickness?*. Our results suggest that adequate body-based sensory information might be needed to reduce visually-induced motion sickness symptoms. For example, in our experiment, the descriptive statistics identify a trend that motion sickness decreases as the locomotion interfaces change from the Controller, to the NaviChair, the NaviBoard, and the Walking condition. Yet, post-hoc tests did not show a significant difference between the Controller and the Navichair. This might be related to insufficient statistical power in the study. Or, it could also point to the leaning-based upper-body motion cues experienced while sitting not being quite sufficient to provide adequate translational body-based sensory information.

Another subjective measure affected by the locomotion modes is user-perceived task load. The data show that even when we applied some artificial interaction in a locomotion interface, i.e., leaning/stepping on a platform, this does not increase user task load, as long as the interaction is fairly simple, such as leaning forward to move. This result basically answers our **RQ3** - *Does artificial interaction in locomotion interfaces cause higher task load?*. Though NaviChair and NaviBoard use the same type of interaction, the TLX score of NaviBoard was more comparable to physical walking, which possibly means that more translational information also helps to reduce task load. Or, it could also mean that more training is needed for participants to get familiar with new interfaces/interactions. In this experiment, the only training participants got was from the first trial per interface, with an average of less than 90 seconds, while recent results has shown significant effects of training time on user performance in a leaning-based drone navigation task, with much longer training times [40].

3.6 Conclusion & Future Work

Whereas previous studies showed clear benefits of body-based sensory information in VR locomotion [28, 20, 67, 69, 59], especially in the real-world walking mode [60, 61], the current study provides first experimental evidence that partial translational information combined with full rotation can have significant benefits, i.e., improve user performance and reduce motion sickness and task load. These results suggest that, compared with traditional techniques that provide only rotation with minimal translational cues, allowing for full rotation combined with leaning-based control can provide not only better user performance for many applications that require significant locomotion, but also lower motion sickness and task load.

Moreover, our new approach is easily applicable in real-world situations where tracked space is restricted. People can thus set up an effective navigation interface with minimal effort and facilities, e.g., with any swivel chair (NaviChair-like) or a small circular platter or carpet (NaviBoard-like). While we attached a Vive tracker to the participant’s torso, we used this only for additional data collection in our work. Thus, HMD tracking is sufficient for real-world application with our new technique. Also, the NaviBoard platter is a passive element that does not require any motors or sensors. It basically provides only haptic cues for the participant to passively/automatically update their physical spatial awareness. Hence, any platter or mat might be used as long as it provides sufficient haptic cues.

One of the main limitations of this study is that we asked participants to perform only two trials per condition, one of which was practice. We identified this limitation before running the experiment. Yet, we decided to maintain this design as it was too risky to increase the number of trials per condition, which might expose participants to more severe forms of motion sickness and substantially affect the data even when participants can finish

the task. We made this decision also because there is previous evidence showing that a whole experiment needs to be redesigned or data become less interesting, just because too many participants got motion sick [43, 14]. Yet, even though participants had no prior experience with leaning-based interfaces, their performance levels already approached that of free-space walking after only two trials, and on average less than 3 minutes of total experience with an interface.

Another limitation is related to a technology constraint, in that we could only set up a free walking area of 4×4 meters. However, similar-sized areas have been used in Ruddell *et al.*'s [60, 61] and Riecke *et al.*'s [52] studies. Only Fiore *et al.* used a 7×7 meter area [14]. We aimed to address this problem through a dark environment with fireflies so that participants can still perceive enough optic flow from their motion, while preventing them from seeing the whole environment from a single point of view. According to Ruddell's classification [59], virtual environments like the one we used in this experiment can be considered as *large-scale*, where significant locomotion is required to fully acquire the spatial layout. Many studies of VR locomotion used stimuli that are sometimes simplified to the extreme, e.g., by using a *modal*- or *small-scale* environment, which (often unintentionally) decreases the ecological validity.

For the next steps, we plan to investigate if partial translational cues combined with full rotation might provide the same benefits in other conditions of environmental fidelity, e.g., when significant landmarks and environmental geometry is available. Though previous studies has shown that body-based motion cues might become less important when sufficient visual cues are available [53, 50], it is still interesting to identify the interaction effects of translational motion cues between the locomotion interface and the visual cues from the virtual environment, especially when only partial translational information is available. Investigating conditions under which user performance in a spatial task is improved will also deepen our understanding of human spatial cognition and guide the design of future VR simulations and locomotion interfaces. Investigating a locomotion interface that provides only partial translational information in different virtual environments of different fidelity levels is a planned step toward that goal.

Chapter 4

Conclusions and Future Works

VR Locomotion has always been an interesting topic in the research field of VR. On one side, people believe that VR enables the currently impossible locomotion modes in the real world such as teleportation and embodied flying; on the other side, people easily get sick or even lost when simply moving in VR with artificial interfaces. Though steering with a joystick or controller is supposed to be similar to real-life locomotion, and has been used in most video games for decades; people found it uncomfortable in VR (e.g., unconvincing simulated motion, motion sick, disorientation). These issues motivate us to understand human behaviors when they walk in VR and ultimately improve VR simulations so that people can efficiently navigate virtual environments with less or even no fatigue, discomfort, or safety concerns.

4.1 Summary and Main Contributions

In both studies presented in this thesis, we conducted mixed-methods within-subject experiments using a complex spatial task called navigational search, in which people can perform the task better if they maintain better spatial orientation and awareness.

In the first study, we designed two 3D rectangular wireframes whose behavior is slightly different from each other, representing different kinds of reference frame that people frequently use in real life, e.g., egocentric and allocentric. Results suggest that reference frames in virtual environment play an important role, even a very simple overlaid wireframe can improve user spatial orientation significantly. This study provides novel knowledge about simulated reference frame in VR and its effect on human spatial orientation.

In the second study, we proposed a motion control model that can be applied to multiple leaning interfaces, e.g., the NaviChair and the NaviBoard, which provides body-based sensory information in a mixed quantity: full rotation and partial translation. Together with two extreme conditions: controller (no translational information) and physical walking (full translational information), we had a 4-level independent variable of translational motion cues for our repeated-measures experiment. Results suggest that combining leaning with

full rotation might suffice for efficient VR locomotion and a standing-leaning interface such as the NaviBoard might even reduce motion sickness and task load.

4.2 Limitations

In the first study, we encountered a critical issue requiring us to change the experiment design, that is motion sickness. Because too many participants got sick in the pilot experiment, we had to cancel the joystick conditions, one of the two locomotion interfaces, in the main experiment to reduce the number of trials each participant had to perform. Therefore, we were not able to investigate the interaction effect of simulated reference frame and locomotion interface. That also reduced the external validity of the study as one can say that the effect might not be visible when using a locomotion interface other than the NaviChair. Also, we observed during the experiment that some participants tended to go out of the boxes area first, then look back to get a big picture of the boxes layout, and try to remember them before starting the task. This strategy likely helped them to perform the task better, however, altered our measures. As in this situation, participant performance is largely determined by their spatial memory and path planning ability instead of online spatial updating. In other words, people who perform the task better could be either those who maintain better spatial orientation, or those who have better spatial memory and path planning ability.

We tackled these limitations in our second study by improving the locomotion interfaces as well as the virtual environment so that participants get sick less with the locomotion and experimenters can collect more valid data. In the second study, all participants were able to finish all the trials completely (finding all eight balls) with seemingly no or very little motion sickness. However, there are still limitations in this study regarding the restricted virtual environment size. As we included an actual walking condition in this experiment, the virtual environment size cannot be larger than our physical tracked space, which is limited to 4×4 meter. Hence, we do not know if any measures would change if participants had to travel longer distances. Fortunately, the majority of related experiments also used the same 4 meter diameter circular area.

4.3 Methodological Improvements

Though both studies showed interesting results with significant roles of the investigated phenomena, one can identify a critical issue in the first study that there was a large portion of participants (44% in pilot testing and 28% in the main experiment) that got motion sick and could not complete the task. Interestingly, with the same task and similar conditions (e.g., no reference frame condition in the first study vs. NaviChair condition in the second study), there were no severe adverse symptoms observed during the second study. 100%

of participants in the second studies finished the task in all four conditions. They even provided positive feedbacks about the experiment and/or the task when being debriefed.

SSQ: We cannot directly compare the motion sickness data between these two studies as we only used a single general rating in the first study and used the standard Simulator Sickness Questionnaire (SSQ) [24] in the second study. This is one of the methodological improvements we have made after the first study. Not only does SSQ provide us hierarchical data with a total score and three subscores, it also allow us to compare the level of sickness with different studies that also used the SSQ.

Dark environment: As discussed in the second study, we blacked out the environment to ensure that participants acquire and build up their spatial awareness progressively instead of remembering and preplanning to perform the task. There might be a side effect of this change that when the environment is darker, there will be less visual cues and optic flow, consequently, participants might perceive less simulated self-motion (vection), and thus less sensory conflict, hence, less motion sick. More research is needed to test this hypothesis, however, the dark environment might have contributed to participants feeling less sick.

Smaller area: In addition to the lighting, in the second study, we also reduced the size of the play area (from 5m to 4m diameter) which actually reduce the whole area by 36%. We made this change because of the constraint in tracking technology. It is conceivable that this made the task easier as it does not require participants to move (translate) as much as in the first study. This could help reduce the chance that a participant gets sick, as they might finish the task before the first symptoms occur. However, note that the amount of required rotations did not decrease with the decreasing play area.

Minimum break: In the second study, we ensured that breaks between conditions were never less than 5 minutes, however, we did not enforce this in the first study. Therefore, some participants who rushed to finish might have ignored some slight sickness symptoms and decided to go to the next trials before sickness symptoms faded away, thus potentially contributing to accumulating motion sickness. Recognizing this issue after the first study, we included a minimum break of 5 minutes for the later study.

Speed limit: In the first study, we did not carefully control the maximum speed of the NaviChair. Therefore, participants could go quite fast, which might have contributed to motion sickness as well. In the second study, as we had a pilot study with actual walking, we applied the maximum walking speed to the main study, which prevented participants from moving too fast and thus might have contributed to the reduced motion sickness in the second study.

Gamification: Last but not least, we included the ‘scoreboard’ gamification in the second study, in which we produced a performance score for every participant at the end of their session. The scores were published to our website and updated daily. Participants were announced about the cash prizes for the top three performers at the beginning of their session. According to a literature review about gamification [15], we believe that this factor

might motivate participants to perform better and help them overcome some minor adverse symptom of VR. On the other hand, one could also consider that this gamification might encourage participants to perform the task faster to get a higher score, which would predict increased motion sickness.

In summary, though the two studies share a within-subject experiment design and the navigational search paradigm, the second study includes substantial improvements in methodology, compared to its prior. All the changes, e.g., visual interface, locomotion, procedure, and gamification, originated from our observation and reflection after the first study and/or following pilot studies. Future research is needed to determine how much the different factors might have contributed to reducing motion sickness in the second study. The ultimate goal of these methodological improvements is to eliminate confounds which might affect user performance or even distort the collected data, preventing researchers from identifying the actual effects. This is also a contribution of this thesis, showing a progressive improvement in experiment design and providing practical experiences for future experiments using similar research methods and paradigms.

4.4 Future Works

For the next steps, we would fix the current limitations in these studies and extend them by coupling these variables of interest with other common factors such as high-fidelity virtual environments with embedded reference frames. It allows us to combine our findings in the current studies (simulated reference frames versus translational motion cues) to investigate their interaction effects and ultimately provide deeper knowledge of spatial cognition in VR, as well as improve future VR simulations.

Bibliography

- [1] Marios N. Avraamides, Roberta L. Klatzky, Jack M. Loomis, and Reginald G. Golledge. Use of cognitive versus perceptual heading during imagined locomotion depends on the response mode. *Psychological Science*, 15(6):403–408, November 2004.
- [2] Niels H. Bakker, Peter J. Werkhoven, and Peter O. Passenier. The Effects of Proprioceptive and Visual Feedback on Geographical Orientation in Virtual Environments. *Presence: Teleoperators and Virtual Environments*, 8(1):36–53, February 1999.
- [3] Steffi Beckhaus, Kristopher J. Blom, and Matthias Haringer. Intuitive, hands-free travel interfaces for virtual environments. In *New Directions in 3D User Interfaces Workshop of IEEE VR*, pages 57–60, 2005.
- [4] Steffi Beckhaus, Kristopher J. Blom, and Matthias Haringer. A new gaming device and interaction method for a First-Person-Shooter. *Proceedings of the Computer Science and Magic*, 2005, 2005.
- [5] Steffi Beckhaus, Kristopher J. Blom, and Matthias Haringer Introduction. ChairIO – The Chair-Based Interface. In *Concepts and Technologies for Pervasive Games: A Reader for Pervasive Gaming Research*, volume 1. Shaker Verlag, November 2007.
- [6] Doug A. Bowman, Ernst Kruijff, Joseph J. LaViola, and Ivan Poupyrev. *3D User Interfaces: Theory and Practice*. Addison Wesley Longman Publishing Co., Inc., Redwood City, CA, USA, 2004.
- [7] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. Point & Teleport Locomotion Technique for Virtual Reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play, CHI PLAY '16*, pages 205–216, New York, NY, USA, 2016. ACM.
- [8] Jorge C. S. Cardoso. Comparison of Gesture, Gamepad, and Gaze-based Locomotion for VR Worlds. In *Proceedings of the 22Nd ACM Conference on Virtual Reality Software and Technology, VRST '16*, pages 319–320, New York, NY, USA, 2016. ACM.
- [9] James Carifio and Rocco Perla. Resolving the 50-year debate around using and mis-using Likert scales. *Med Educ*, 42(12):1150–1152, December 2008.
- [10] Sarah S. Chance, Florence Gaunet, Andrew C. Beall, and Jack M. Loomis. Locomotion Mode Affects the Updating of Objects Encountered During Travel: The Contribution of Vestibular and Proprioceptive Inputs to Path Integration. *Presence: Teleoper. Virtual Environ.*, 7(2):168–178, April 1998.

- [11] E. Chang, I. Hwang, H. Jeon, Y. Chun, H. T. Kim, and C. Park. Effects of rest frames on cybersickness and oscillatory brain activity. In *2013 International Winter Workshop on Brain-Computer Interface (BCI)*, pages 62–64, February 2013.
- [12] Mark Heider Draper. *The Adaptive Effects of Virtual Interfaces: Vestibulo-ocular Reflex and Simulator Sickness*. PhD thesis, University of Washington, 1998. AAI9828482.
- [13] Andrea Ferracani, Daniele Pezzatini, Jacopo Bianchini, Gianmarco Biscini, and Alberto Del Bimbo. Locomotion by Natural Gestures for Immersive Virtual Environments. In *Proceedings of the 1st International Workshop on Multimedia Alternate Realities, AltMM '16*, pages 21–24, New York, NY, USA, 2016. ACM.
- [14] L. Puchalla Fiore, E. Coben, S. Merritt, P. Liu, and V. Interrante. Towards Enabling More Effective Locomotion in VR Using a Wheelchair-based Motion Platform. In *Proceedings of the 5th Joint Virtual Reality Conference, JVR '13*, pages 83–90, Aire-la-Ville, Switzerland, Switzerland, 2013. Eurographics Association.
- [15] Juho Hamari, Jonna Koivisto, and Harri Sarsa. Does Gamification Work? – A Literature Review of Empirical Studies on Gamification. In *2014 47th Hawaii International Conference on System Sciences*, pages 3025–3034, Waikoloa, HI, January 2014. IEEE.
- [16] Alyssa Harris, Kevin Nguyen, Preston Tunnell Wilson, Matthew Jackoski, and Betsy Williams. Human Joystick: Wii-leaning to Translate in Large Virtual Environments. In *Proceedings of the 13th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and Its Applications in Industry, VRCAI '14*, pages 231–234, New York, NY, USA, 2014. ACM.
- [17] Sandra G. Hart and Lowell E. Staveland. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In Peter A. Hancock and Najmedin Meshkati, editors, *Advances in Psychology*, volume 52 of *Human Mental Workload*, pages 139–183. North-Holland, January 1988.
- [18] Abraham M. Hashemian and Bernhard E. Riecke. Leaning-Based 360° Interfaces: Investigating Virtual Reality Navigation Interfaces with Leaning-Based-Translation and Full-Rotation. In Stephanie Lackey and Jessie Chen, editors, *Virtual, Augmented and Mixed Reality*, Lecture Notes in Computer Science, pages 15–32. Springer International Publishing, 2017.
- [19] Jason Jerald. *The VR Book: Human-Centered Design for Virtual Reality*. Association for Computing Machinery and Morgan & Claypool, New York, NY, USA, 2016.
- [20] Melissa J Kearns, William H Warren, Andrew P Duchon, and Michael J Tarr. Path integration from optic flow and body senses in a homing task. *Perception*, 31(3):349–374, 2002.
- [21] Jonathan W. Kelly, Marios N. Avraamides, and Timothy P. McNamara. Reference Frames Influence Spatial Memory Development within and Across Sensory Modalities. In Christoph Hölscher, Thomas F. Shipley, Marta Olivetti Belardinelli, John A. Bateman, and Nora S. Newcombe, editors, *Spatial Cognition VII*, Lecture Notes in Computer Science, pages 222–233. Springer Berlin Heidelberg, August 2010.

- [22] Jonathan W. Kelly and Timothy P. McNamara. Facilitated pointing to remembered objects in front: Evidence for egocentric retrieval or for spatial priming? *Psychonomic Bulletin & Review*, 16(2):295–300, April 2009.
- [23] Robert S. Kennedy, Julie Drexler, and Robert C. Kennedy. Research in visually induced motion sickness. *Appl Ergon*, 41(4):494–503, July 2010.
- [24] Robert S. Kennedy, Norman E. Lane, Kevin S. Berbaum, and Michael G. Lilienthal. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The International Journal of Aviation Psychology*, 3(3):203–220, July 1993.
- [25] Behrang Keshavarz and Heiko Hecht. Validating an Efficient Method to Quantify Motion Sickness. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 53(4):415–426, August 2011.
- [26] Alexandra Kitson, Abraham M. Hashemian, Ekaterina Stepanova, Ernst Kruijff, and Bernhard E. Riecke. Comparing leaning-based motion cueing interfaces for virtual reality locomotion. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 73–82, March 2017.
- [27] Alexandra Kitson, Bernhard E. Riecke, Abraham M. Hashemian, and Carman Neustaedter. NaviChair: Evaluating an Embodied Interface Using a Pointing Task to Navigate Virtual Reality. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction*, SUI ’15, pages 123–126, New York, NY, USA, 2015. ACM.
- [28] Roberta L. Klatzky, Jack M. Loomis, Andrew C. Beall, Sarah S. Chance, and Reginald G. Golledge. Spatial Updating of Self-Position and Orientation During Real, Imagined, and Virtual Locomotion. *Psychological Science*, 9(4):293–298, 1998.
- [29] Roberta L. Klatzky and Bing Wu. The embodied actor in multiple frames of reference. In *Embodiment, ego-space, and action*, Carnegie Mellon symposia on cognition, pages 145–177. Psychology Press, New York, NY, US, 2008.
- [30] Eugenia M. Kolasinski and U. S. Army Research Institute for the Behavioral and Social Sciences. *Simulator sickness in virtual environments*. U.S. Army Research Institute for the Behavioral and Social Sciences, 1995. Google-Books-ID: 7qwrAAAAYAAJ.
- [31] Ernst Kruijff, Alexander Marquardt, Christina Trepkowski, Robert W. Lindeman, Andre Hinkenjann, Jens Maiero, and Bernhard E. Riecke. On Your Feet!: Enhancing Vection in Leaning-Based Interfaces Through Multisensory Stimuli. In *Proceedings of the 2016 Symposium on Spatial User Interaction*, SUI ’16, pages 149–158, New York, NY, USA, 2016. ACM.
- [32] Ernst Kruijff, Bernhard Riecke, Christina Trekowski, and Alexandra Kitson. Upper Body Leaning Can Affect Forward Self-Motion Perception in Virtual Environments. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction*, SUI ’15, pages 103–112, New York, NY, USA, 2015. ACM.
- [33] Eike Langbehn, Tobias Eichler, Sobin Ghose, Kai von Luck, Gerd Bruder, and Frank Steinicke. Evaluation of an omnidirectional walking-in-place user interface with virtual locomotion speed scaled by forward leaning angle. In *Proceedings of the GI Workshop on Virtual and Augmented Reality (GI VR/AR)*, pages 149–160, 2015.

- [34] William B. Lathrop and Mary K. Kaiser. Perceived Orientation in Physical and Virtual Environments: Changes in Perceived Orientation As a Function of Idiopathic Information Available. *Presence: Teleoper. Virtual Environ.*, 11(1):19–32, February 2002.
- [35] Ben D. Lawson. Motion sickness symptomatology and origins. In *Handbook of Virtual Environments*, 2nd ed., 2014.
- [36] Simon Lessels and Roy A. Ruddle. Movement around real and virtual cluttered environments. *Presence: Teleoperators and Virtual Environments*, 14(5):580–596, 2005.
- [37] Morgan McCullough, Hong Xu, Joel Michelson, Matthew Jackoski, Wyatt Pease, William Cobb, William Kalesky, Joshua Ladd, and Betsy Williams. Myo Arm: Swinging to Explore a VE. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception*, SAP '15, pages 107–113, New York, NY, USA, 2015. ACM.
- [38] Timothy P. McNamara. How Are the Locations of Objects in the Environment Represented in Memory? *Spatial Cognition III*, 2685:174–191, 2003.
- [39] T.P. McNamara, J. Sluzenski, and B. Rump. Human Spatial Memory and Navigation. In *Learning and Memory: A Comprehensive Reference*, pages 157–178. Academic Press, Oxford, 2008.
- [40] Jenifer Miehlebradt, Alexandre Cherpillod, Stefano Mintchev, Martina Coscia, Fiorenzo Artoni, Dario Floreano, and Silvestro Micera. Data-driven body-machine interface for the accurate control of drones. *PNAS*, 115(31):7913–7918, July 2018.
- [41] T. Nescher, Ying-Yin Huang, and A. Kunz. Planning redirection techniques for optimal free walking experience using model predictive control. In *2014 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 111–118, March 2014.
- [42] T. Nguyen-Vo, B. E. Riecke, and W. Stuerzlinger. Moving in a box: Improving spatial orientation in virtual reality using simulated reference frames. In *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 207–208, March 2017.
- [43] T. Nguyen-Vo, B. E. Riecke, and W. Stuerzlinger. Simulated reference frame: A cost-effective solution to improve spatial orientation in vr. In *2018 IEEE Virtual Reality (VR)*, 2018.
- [44] Geoff Norman. Likert scales, levels of measurement and the "laws" of statistics. *Adv Health Sci Educ Theory Pract*, 15(5):625–632, December 2010.
- [45] A. Nybakke, R. Ramakrishnan, and V. Interrante. From virtual to actual mobility: Assessing the benefits of active locomotion through an immersive virtual environment using a motorized wheelchair. In *2012 IEEE Symposium on 3D User Interfaces (3DUI)*, pages 27–30, March 2012.
- [46] Clark C. Presson and Daniel R Montello. Updating after rotational and translational body movements: Coordinate structure of perspective space. *Perception*, 23(12):1447–1455, 1994.
- [47] Jerrold Douglas Prothero. *The Role of Rest Frames in Vection, Presence and Motion Sickness*. PhD thesis, University of Washington, 1998.

- [48] J. Reason. Motion sickness: Some theoretical and practical considerations. *Applied Ergonomics*, 9(3):163–167, September 1978.
- [49] Anthony E. Richardson, Daniel R. Montello, and Mary Hegarty. Spatial knowledge acquisition from maps and from navigation in real and virtual environments. *Memory & Cognition*, 27(4):741–750, July 1999.
- [50] B. E. Riecke, D. W. Cunningham, and H. H. Bühlhoff. Spatial updating in virtual reality: the sufficiency of visual information. *Psychological Research*, 71(3):298–313, May 2007.
- [51] Bernhard E. Riecke. Consistent Left-Right Reversals for Visual Path Integration in Virtual Reality: More than a Failure to Update One’s Heading? *Presence: Teleoperators and Virtual Environments*, 17(2):143–175, 2008.
- [52] Bernhard E. Riecke, Bobby Bodenheimer, Timothy P. McNamara, Betsy Williams, Peng Peng, and Daniel Feuereissen. Do we need to walk for effective virtual reality navigation? physical rotations alone may suffice. In *Spatial Cognition VII*, pages 234–247. Springer, 2010.
- [53] Bernhard E Riecke, Markus von der Heyde, and Heinrich H Bühlhoff. Visual cues can be sufficient for triggering automatic, reflexlike spatial updating. *ACM Trans. Appl. Percept.*, 2(3):183–215, July 2005. ACM ID: 1077401.
- [54] Bernhard E. Riecke and Timothy P. McNamara. Where you are affects what you can easily imagine: Environmental geometry elicits sensorimotor interference in remote perspective taking. *Cognition*, 169:1–14, December 2017.
- [55] Bernhard E. Riecke, Joerg Schulte-Pelkum, and Heinrich H. Buelthoff. Perceiving simulated ego-motions in virtual reality: comparing large screen displays with HMDs. In *Human Vision and Electronic Imaging X*, volume 5666, pages 344–355, March 2005.
- [56] John J. Rieser. Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15(6):1157–1165, November 1989.
- [57] John J. Rieser and Elizabeth A. Rider. Young children’s spatial orientation with respect to multiple targets when walking without vision. *Developmental Psychology*, 27(1):97–107, 1991.
- [58] R. A. Ruddle. The effect of trails on first-time and subsequent navigation in a virtual environment. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pages 115–122, March 2005.
- [59] Roy A. Ruddle. The Effect of Translational and Rotational Body-Based Information on Navigation. In Frank Steinicke, Yon Visell, Jennifer Campos, and Anatole Lécuyer, editors, *Human Walking in Virtual Environments*, pages 99–112. Springer New York, January 2013.
- [60] Roy A. Ruddle and Simon Lessels. For Efficient Navigational Search, Humans Require Full Physical Movement, but Not a Rich Visual Scene. *Psychol Sci*, 17(6):460–465, June 2006.

- [61] Roy A. Ruddle and Simon Lessels. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction*, 16(1):1–18, April 2009.
- [62] Roy A. Ruddle, Ekaterina Volkova, and Heinrich H. Bühlhoff. Walking improves your cognitive map in environments that are large-scale and large in extent. *ACM Transactions on Computer-Human Interaction*, 18(2):1–20, June 2011.
- [63] Amy L. Shelton and Timothy P. Mcnamara. Multiple views of spatial memory. *Psychonomic Bulletin & Review*, 4(1):102–106, March 1997.
- [64] Salvar Sigurdarson, Andrew P. Milne, Daniel Feuereissen, and Bernhard E. Riecke. Can physical motions prevent disorientation in naturalistic VR? In *IEEE Virtual Reality*, pages 31–34, Orange County, CA, USA, 2012.
- [65] Nancy A. Skopp, Derek J. Smolenski, Melinda J. Metzger-Abamukong, Albert A. Rizzo, and Greg M. Reger. A Pilot Study of the VirtuSphere as a Virtual Reality Enhancement. *International Journal of Human-Computer Interaction*, 30(1):24–31, January 2014.
- [66] Kay Stanney, Robert Kennedy, and Kelly Hale. Virtual Environment Usage Protocols. In *Handbook of Virtual Environments*, volume 20143245, pages 797–809. CRC Press, September 2014.
- [67] Hong-Jin Sun, Jennifer L. Campos, and George S. W. Chan. Multisensory integration in the estimation of relative path length. *Exp Brain Res*, 154(2):246–254, January 2004.
- [68] Desney S Tan, Darren Gergle, Peter Scupelli, and Randy Pausch. Physically large displays improve performance on spatial tasks. *ACM Transactions on Computer-Human Interaction*, 13(1):71–99, March 2006.
- [69] Laura Telford, Ian P. Howard, and Masao Ohmi. Heading judgments during active and passive self-motion. *Exp Brain Res*, 104(3):502–510, June 1995.
- [70] Martin Usoh, Kevin Arthur, Mary C. Whitton, Rui Bastos, Anthony Steed, Mel Slater, and Frederick P. Brooks, Jr. Walking » Walking-in-place » Flying, in Virtual Environments. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH ’99, pages 359–364, New York, NY, USA, 1999. ACM Press/Addison-Wesley Publishing Co.
- [71] David Waller and Eric Hodgson. Sensory Contributions to Spatial Knowledge of Real and Virtual Environments. In *Human Walking in Virtual Environments*, pages 3–26. Springer New York, January 2013.
- [72] Ranxiao Frances Wang. Between reality and imagination: When is spatial updating automatic? *Perception & Psychophysics*, 66(1):68–76, January 2004.
- [73] M. C. Whitton, J. V. Cohn, J. Feasel, P. Zimmons, S. Razzaque, S. J. Poulton, B. McLeod, and F. P. Brooks. Comparing VE locomotion interfaces. In *IEEE Proceedings. VR 2005. Virtual Reality, 2005.*, pages 123–130, March 2005.

- [74] Preston Tunnell Wilson, William Kalescky, Ansel MacLaughlin, and Betsy Williams. VR Locomotion: Walking » Walking in Place » Arm Swinging. In *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry - Volume 1*, VRCAI '16, pages 243–249, New York, NY, USA, 2016. ACM.
- [75] Bob G. Witmer, John H. Bailey, Bruce W. Knerr, and Kimberly C. Parsons. Virtual spaces and real world places: transfer of route knowledge. *International Journal of Human-Computer Studies*, 45(4):413–428, 1996.
- [76] Markus Zank and Andreas Kunz. Where are you going? Using human locomotion models for target estimation. *Vis Comput*, 32(10):1323–1335, October 2016.
- [77] Hui Zhang, Weimin Mou, and Timothy P. McNamara. Spatial Updating according to a Fixed Reference Direction of a Briefly Viewed Layout. *Cognition*, 119(3):419–429, June 2011.

Appendix A

Contributions Statement

Study 1: Simulated Reference Frame: A Cost-Effective Solution to Improve Spatial Orientation in VR

Thinh Nguyen-Vo, Bernhard E. Riecke, and Wolfgang Stuerzlinger conceived of the presented idea. Nguyen-Vo developed the experiment design including the VR simulation under Riecke’s guidance. Stuerzlinger and Riecke provided feedback throughout the study. Nguyen-Vo collected and analyzed data. All authors discussed the results and contributed to the final manuscript.

Study 2: Do We Need Actual Walking in VR? Combining Physical Rotation with Leaning Might Suffice for Efficient Virtual Locomotion

Thinh Nguyen-Vo, Bernhard E. Riecke, and Ernst Kruijff devised the project with the main conceptual idea. The explicit experiment design was developed by Nguyen-Vo and Riecke. Thinh Nguyen-Vo and Duc-Minh Pham worked out almost all of the technical details, and performed the numerical calculations for the suggested experiment. After that, Nguyen-Vo conducted data analysis on his own. Results were discussed by Nguyen-Vo and Riecke. All authors contributed to the final manuscript.