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NaviBoard and NaviChair: Limited Translation Combined with Full Rotation for Efficient Virtual Locomotion

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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. 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 cues and control: none (using the trackpad of the HTC Vive controller to translate), upper-body leaning (sitting on a "NaviChair", leaning the upper-body to locomote), whole-body leaning/stepping (standing on a platform called NaviBoard, leaning the whole body or stepping one foot off the center to navigate), and full translation (physically walking). Results showed that translational cues and control 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 NaviChair, NaviBoard, and actual walking. These results suggest that translational body-based motion cues and control from a low-cost leaning/stepping interface might provide enough sensory information for supporting spatial updating, spatial awareness, and efficient locomotion in VR, although future work will need to investigate how these results might or might not generalize to other tasks and scenarios.

Index Terms—Adaptive Control, Cognitive informatics, Human computer interaction, Human factors, User interface, Virtual reality

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 [1]. 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 all the mentioned locomotion interfaces are that they are affordable, compact and easy to set up. However, the simulation of self-motion offered by these locomotion interfaces is often unconvincing and frequently contributes to disorientation, unease, and simulator sickness [1].

Though various alternative locomotion interfaces have been proposed [2], [3], [4], disorientation and simulator sickness remain as challenges for VR locomotion that hinder efficient navigation in VR and thus reduce 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* [5]. Movement fidelity is only partially a technical constraint, as it involves complex interactions between various body-based sensory sources. Also, body-based sensory information, i.e., proprioception, has a strong impact on human spatial orientation in VR [5].

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1.1 Motivation

To investigate how body-based sensory information impacts human spatial updating and awareness in VR, a large body of research has compared various conditions with different 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 [1]. Each of these tasks assesses different aspects of human spatial orientation, e.g., landmark knowledge, route knowledge, environmental layout, or survey knowledge. 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 [6].

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: when we move in the real world, not only do we need to constantly update the knowledge of our position and orientation, but also our awareness of environmental elements and events in our immediate environment. The process that seemingly automatically updates our egocentric mental representation

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of our immediate environment when we move through it is referred to as *spatial updating* and is essential for enabling fast and low-cognitive-load spatial orientation [7]. *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 (when walking with an HMD) as well as they do in the real world (walking without an HMD) [8].

1.2 Navigational Search Experiments

Navigational Search has been used in a series of studies by Ruddle and Lessels [8], [9], [10], 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, while also increasing 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-only or visual-only conditions [9], [10]. 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, such as 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). Riecke *et al.* then revised the experimental design and re-ran the experiment with conditions avoiding the above confounds: joystick, real rotation, and walking [11]. 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.* [11]. They removed all orientation cues from the environment (e.g., the rectangular room) and salient landmarks (e.g., sun, clouds), which could have affected participant's spatial knowledge and prevented 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 revised navigational search experimental setup has since been used in several follow-up studies [12], [13], [14], [15].

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 [13]. In their study, an additional condition called "partial" was added, in which the rotation and translation was reduced to half of the actual motion to reduce the size of the tracked space needed. 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: it 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 differences between the conditions, likely because body-based sensory information is minimal when using a motorized platform instead of more 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 their study [13] 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 alone, including the vestibular cues provided by the wheelchair locomotion, were not sufficient to enhance performance. Unfortunately the study did not include a physical walking condition, so it is unclear how wheelchair locomotion compares 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 work investigating the contribution of body-based motion cues and control [9], [10], [11], [13]. For the purpose of this paper, we use the acronyms *translational cues and control* (TCC) and *rotational cues and control* (RCC) accordingly in the sense of vestibular, kinesthetic and proprioceptive cues as well as efference copies that are mapped to VR navigation beyond simple finger, hand, or arm movements. Table 1 shows

TABLE 1
Related studies and the body-based motion cues and control provided in each condition.

Study	Condition	RCC			TCC		
		N	P	F	N	P	F
Ruddle [9], [10]	Visual-only	■			■		
	Rotate			■	■		
	Walk			■			■
Riecke [11]	Joystick	■			■		
	Real Rotation			■	■		
	Walking			■			■
Fiore [13]	Visual-only	■			■		
	Rotate only			■	■		
	Partial		■			■	
	Full			■			■
Current study	Real Rotation			■	■		
	Upper-body			■		■	
	Whole-body			■		■	
	Walking			■			■

N = None; P = Partial; F = Full

our analysis of RCC and TCC provided by each condition in the navigational search studies mentioned above. We categorized each component into three levels, in which *none* signifies (almost) no motion cues and control, *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 of cues, control, and resulting virtual motion.

One can see that in each of the previous studies, the motion cues and control vary between conditions in terms of both RCC and TCC. In the work presented here, we aim to keep one of the components constant and only change a single other component to investigate the effect of each individual component in isolation. From the spatial updating literature [16], [17], [18] and related work [9], [10], [11] 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 is mixed evidence as to whether full translation from walking is beneficial [9], [10] or not [11]. Moreover, there is a gap in the literature, as illustrated in Table 1, namely that the TCC has not yet been systematically investigated and isolated from the RCC.

1.3 Goal of this study

To address the above-mentioned gap, we decided to offer full RCC in all four conditions of our experiment and to systematically manipulate the TCC between the locomotion interfaces. We also added the characteristics of our current study to Table 1 to highlight similarities and differences between our experiment and previous work. All four studies mentioned in Table 1 have two common conditions: *real-rotation*, where participants have full rotation available but no physical translation; and *full-walking*, where users physically rotate and translate like they do in the real world, either by controlling an electric wheelchair with a joystick [13] or by walking in the current study and [9], [10]. Beside these two common conditions, we added two intermediate levels in our experiment, in which participants receive partial motion cues and control from either their *upper-body* or *whole-body* leaning/stepping when using the respective locomotion interfaces. This experiment design helps us to investigate the independent variable of TCC without changing the RCC and answer three research questions:

RQ1: How much translational cues and control is needed for efficient VR locomotion (improving performance and reducing disorientation)? Given full rotation, answering this question helps us to fill the gap in the literature about the role of TCC on spatial awareness and updating. If leaning-based TCC 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 VR 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 simulator sickness? This research question would allow us to test the sensory conflict theory [19], which explains simulator sickness symptoms by the mismatch in body-based self-motion information. Our leaning-based interfaces are designed 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 simulator sickness symptoms, and thus improve overall user experience.

RQ3: Does artificial interaction in locomotion interfaces cause higher task load? Though leaning-based interfaces might provide significant benefits in terms of better performance or less simulator sickness [1], its core interaction is (somewhat) artificial, which requires training to familiarize participants with it and might create a high task load for them. Answering this question also allows us to acquire more knowledge to inform guidelines for future designs of VR locomotion interfaces.

There are many open questions about the role of TCC in VR locomotion including: 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 TCC 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 directly applicable to other leaning-based interfaces.

2 Background

2.1 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 [5]. 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.

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 [17]. In VR, when an abundance of naturalistic landmarks are provided, physical motion cues seems not to matter much to participants' spatial updating [7], [20]. Yet, if such visual landmarks are missing and people cannot automatically re-orient, body-based sensory information becomes more relevant.

2.2 VR Locomotion Interfaces

In previous studies, body-based information provided by walking, has been shown to help people perform better in

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several spatial tasks, such as homing [21], spatial updating [16], estimating distance travelled [22], and pointing [23], compared with vision alone. Physical walking also improves participants' sense of presence, compared to walking-in-place (WIP) or flying [24], and allows them to maneuver in a virtual environment as they do in the real world [25]. 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, such as a supermarket or university campus. 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. Potential safety issues are another obstacle 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 [4], [26], redirected walking [27], [28], [29], gesture-based [30], [31], and leaning-based interfaces [32], [33], [34]. Each technique has some benefits over traditional interfaces, such as joystick-based steering or teleportation [35]. Gait negation interfaces, in particularly omnidirectional treadmills, such as the Cyberwalk treadmill [36], 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 [37], while joystick-based interface provide only minimal kinesthetic information. However, most studies did not systematically vary the amount of body-based self-motion cues and control 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.

As shown in Table 2, different interfaces provide different amounts of RCC and TCC. For example, redirected walking supports full translation but, during redirection, provides only distorted rotational cues, so we characterize it as having partial RCC. Except for redirected walking, most locomotion interfaces allow full rotation, as HMDs nowadays natively support 6DOF head tracking and wireless setups become increasingly available and affordable. Thus, traditional joystick/game pad interfaces tend to be replaced with head- or gaze-directed interfaces in VR.

While the presence of a RCC is obvious, the TCC is completely different between interfaces, i.e., completely missing in teleportation [35] and gaze-directed steering [39]; present to various degrees in arm swinging [3], walking-in-place [4], and leaning-based interfaces [15]. Arm swinging, walking-in-place, and leaning-based interfaces share a common characteristic, as they use embodied interactions with limited translational cues. Yet, the actual sensory information and its amount are different. Arm swinging and walking-in-place interfaces mimic the arm/leg movements of actual walking to simulate 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 [37]. These differences have not been thoroughly investigated in previous work. Hence, it is not known how much TCC might be "enough" for efficient VR locomotion, which motivated the design of our current study.

TABLE 2
Body-based motion cues and control in VR locomotion interfaces

Interface Type	RCC			TCC		
	N	P	F	N	P	F
Joystick-based [38]	■			■		
Teleportation [35]			■	■		
Gaze-directed [39]			■	■		
Hand gesture [30]			■	■		
Redirected Walking [27]		■				■
Arm swinging [3]			■		■	
Walking-in-place [4]			■		■	
Leaning-based [15]			■		■	
Physical Walking [10]			■			■

N = None; P = Partial; F = Full

3 METHOD

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).

3.2 Procedure

Participants began the study by reading and signing an informed consent form. Then they were presented with a video[1] explaining the navigational search task. Each participant completed two consecutive 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) [40], followed by NASA's Task Load Index (TLX)

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

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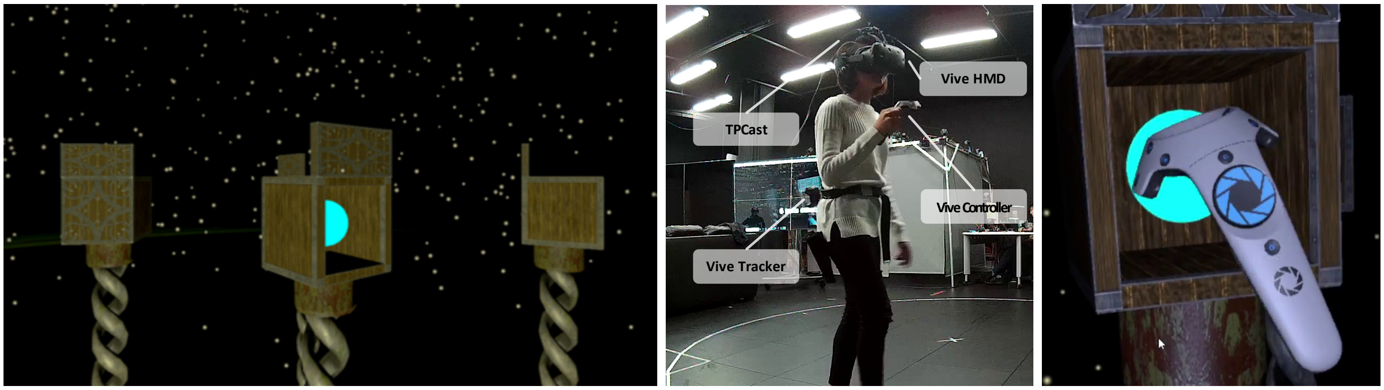

Fig. 1. Left: Environment from participant's view, where sight is limited to 2 meters. Middle: The setup with the wireless Vive HMD and the TPCast; Right: Ball collection from first-person view.

[41]. This also provided a break for participants to relax between trials and to recover from any potential simulator sickness. To further reduce the potential for simulator sickness affecting the results of the subsequent 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.

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 and not for locomotion control. To remove the constraint of cables, we used a TPcast wireless adapter for the Vive. Figure 1 (middle) shows the whole setup on a participant.

3.4 Stimuli and Apparatus

3.4.1 Virtual Environment

In a prior study, we observed that many participants tried to pre-plan their trajectory before they actually performed the task, by exiting out of the target area and looking back at the whole scene to get an overview of the environment's layout first [15]. This pre-planning 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 [42] and for memory-based tasks like this, even very brief visual information might suffice for the acquisition of spatial layout knowledge [43].

To address this issue and 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 being able to perceive recognizable landmarks. These fireflies moved independently and asynchronous, hence, they did not provide any illusory moving sensation (vection) while the user was stationary. This was confirmed in pilot tests with colleagues researching vection in VR, who agreed that there were no vection cues when stationary. Figure 1 (left) 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 every trial and every participant, independently. 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.

3.4.2 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 raised wooden banner on top of the box (see Figure 1 left). A box automatically opened when participants were close enough (within 90 cm 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 simulator sickness [19], 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 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.

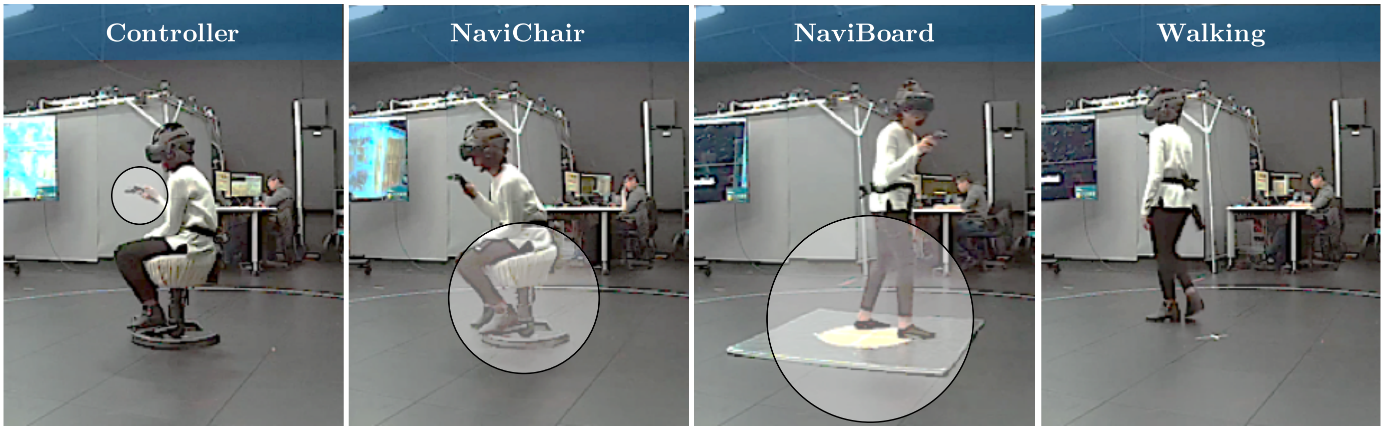

Fig. 2. A participant using all four locomotion interfaces corresponding to the four conditions of this experiment

3.5 Locomotion Modes

In our experiment, we compared four locomotion interfaces providing different amounts of TCC, as illustrated in Figure 2. RCC were provided in full, hence, view direction was set by tracked HMD pose in all conditions with no additional manipulation.

Controller condition relied on *real rotation*, and participants sat on a rotating stool. They could physically rotate with the stool while viewing direction was controlled by the tracked HMD pose. Note that the stool itself was not tracked in any condition. Participants used their finger to swipe on the Vive controller touchpad to translate. The movement direction was determined by their touchpoint on the touchpad, the forward direction of the trackpad was aligned with their view direction. The speed was continuous and exponentially mapped with rate control, based on the distance from their touch point to the center of the touchpad.

NaviChair was the second condition, in which participants could freely rotate with the stool, while their *upper-body leaning* controlled their movement direction and speed in VR. The mechanism is slightly different from the original NaviChair interface used in previous studies [14], [15], [34], [44], and is discussed in more detail in subsection 3.6.

NaviBoard is our new navigation interface that allows *whole-body leaning/stepping*, where participants can freely rotate while standing or stepping, and where the direction and amount of deflection from the board center controls the direction and speed of their simulated movement. We used the same motion control model as the NaviChair's, with different parameters as detailed in subsection 3.6 and Figure 3. Different from walking-in-place interfaces, NaviBoard requires 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 4 m diameter tracking area) and receive natural, *full TCC* through the body's sensory and control systems, including full vestibular and proprioceptive cues.

3.6 Motion Control Model

We developed a novel motion control model for both NaviChair and NaviBoard users. With it, simulated self-motions can be naturally controlled by the tracked HMD pose, while they are either sitting on a swivel chair/stool or standing on the designated platform. Users can easily control their movement direction and speed by adjusting their deflection from the physical interface's center.

The system has an *idle zone* centered on the physical locomotion interface, where positional tracking (including rotation) works normally and simulated motion is mapped identically to the physical one. In other words, when the user is inside this idle zone, the model does not apply any additional velocities or motions to them, and the simulated viewpoint is directly determined by the tracked HMD pose, just as in the walking condition. This zone is a cylindrical volume centered at the physical interface, as illustrated in Figure 3. The radius of this idle zone should match the size of the physical interface. Based on pilot testing, we chose $r_0 = 10$ cm for the NaviChair and $r_0 = 15$ cm for the NaviBoard in this work.

When users lean their body (or more specifically their head, which was tracked via the HMD) out of the idle zone, for example by taking a step onto the outer zone of the NaviBoard, 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 used directly, but transformed into a spherical coordi-

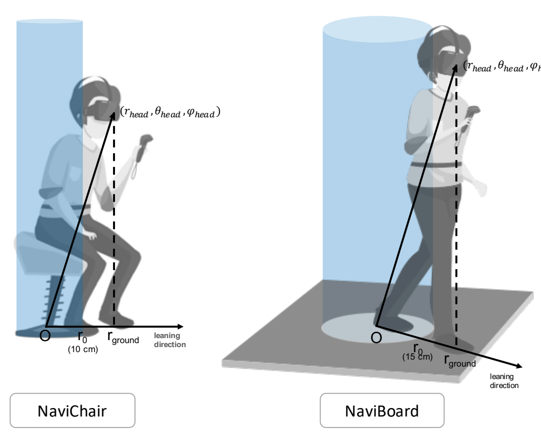

Fig. 3. Motion control model of NaviChair (left) and NaviBoard (right). Head pose is recorded through the HMD's tracking system (Valve's Lighthouse).

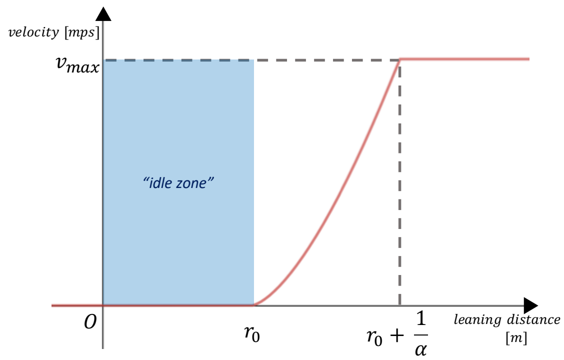

Fig. 4. Mapping function $v = f(r_{ground})$ consists of linear parts and an exponential part ($r_0 \leq r_{ground} \leq r_0 + \frac{1}{\alpha}$)

nate system ($r_{head}, \theta_{head}, \phi_{head}$), whose center is aligned with the physical interfaces, e.g., the stool or board center. Figure 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 $v = f(r_{ground})$ meter/second (Figure 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. We set the exponential factor to 1.53 based on the results of long-term iterative pilot testing with experienced VR researchers.

Pilots also identified that it was helpful for participants to have some subtle, intuitive awareness of the boundary between the different 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 or the hands/arms, which are used for interaction. For **NaviBoard**, participants stood on a board that was made out of two materials with different softness: the inner circle was wood and the outer square was styrofoam and thus much softer (see Fig 2 and 3). When participants lean their body out of the wooden circle, one of their feet naturally steps on the styrofoam, providing them with unobtrusive tactile feedback that they are crossing the boundary of the inner wooden circle. For **NaviChair**, the spring system of the chair itself combined with participant's leaning provided feedback about their deflection from the center.

This approach is substantially different from gaze-directed interfaces [39], as in our model, movement direction is determined by the leaning/stepping direction, rather than view direction. Hence, the user's view direction is completely independent of their movement direction. That is, participants could, e.g., look forward while backing up or moving sideways (strafing), and we observed such behaviors frequently. Our new approach is more similar to previous leaning-based interfaces [2], [32], [34], where users can use their torso to control the movement velocity: the more they lean, the faster they go.

4 Results

4.1 Behavioural Measures

The collected data of multiple dependent variables for user performance are summarized in Figure 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.

The number of perfect trials (trials with no revisit) was minimal. In each of the NaviBoard and Walking conditions, only three participants managed to complete the

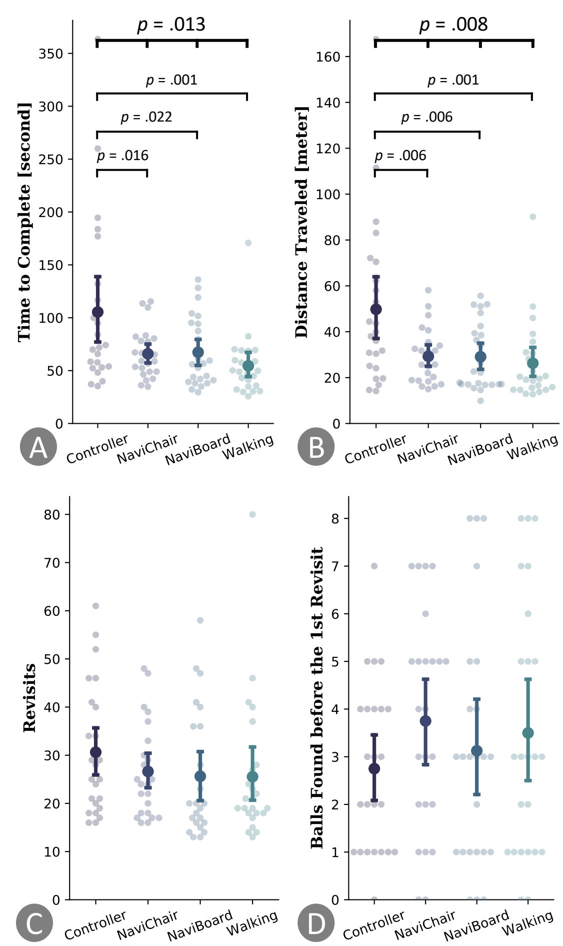

Fig. 5. Mean data of four dependent behavioral measures. Error bars indicate confidence intervals ($CI = 0.95$), gray dots indicate individual participants' data, annotated bars represent significance level of ANOVAs (top bar) and post-hoc tests (below).

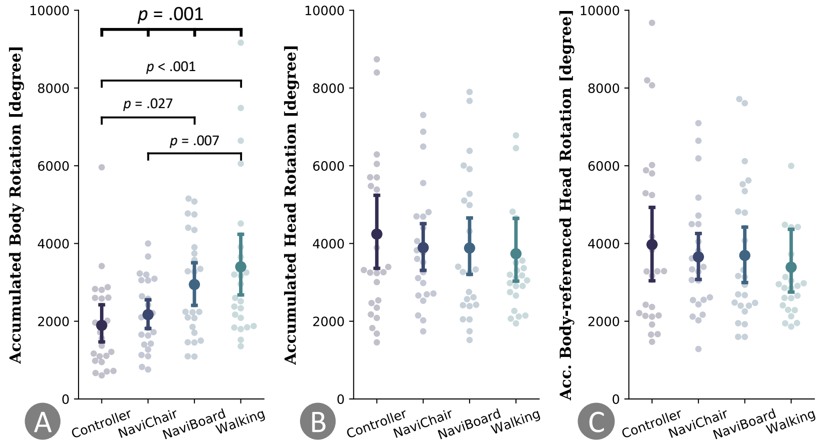

Fig. 6. Mean data of three dependent measures for rotational behaviours. Error bars indicate confidence intervals ($CI = 0.95$), gray dots indicate individual participants' data, annotated bars represent significance level of ANOVAs and post-hoc tests.

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 [9], [10], [11], [13] 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 TCC (Figure 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 TCC ($M = 105.39, SD = 79.65$); 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 TCC (Figure 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 to 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 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 5D). We recorded the number of balls found before the first revisit. There was no significant difference between conditions, $F(3, 69) = .735, p = .535, \eta_p^2 = .031$.

Participants were more likely to rotate their body while standing (Figure 6A). We measured torso motion through a 6DOF tracker attached to the participants' back. 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 ($M = 295, SD = 1343.75$), $p = .027$, 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 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 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 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 ($t(23) = 3.557, p = .002$).

4.2 Subjective Ratings

4.2.1 Simulator Sickness

We used the Simulator Sickness Questionnaire (SSQ) [40] to measure visually-induced motion sickness (VIMS) in the experiment. 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 7 and were analyzed using repeated-measures ANOVAs for general effects and Tukey post-hoc tests for pairwise comparisons. Also, Greenhouse-Geisser

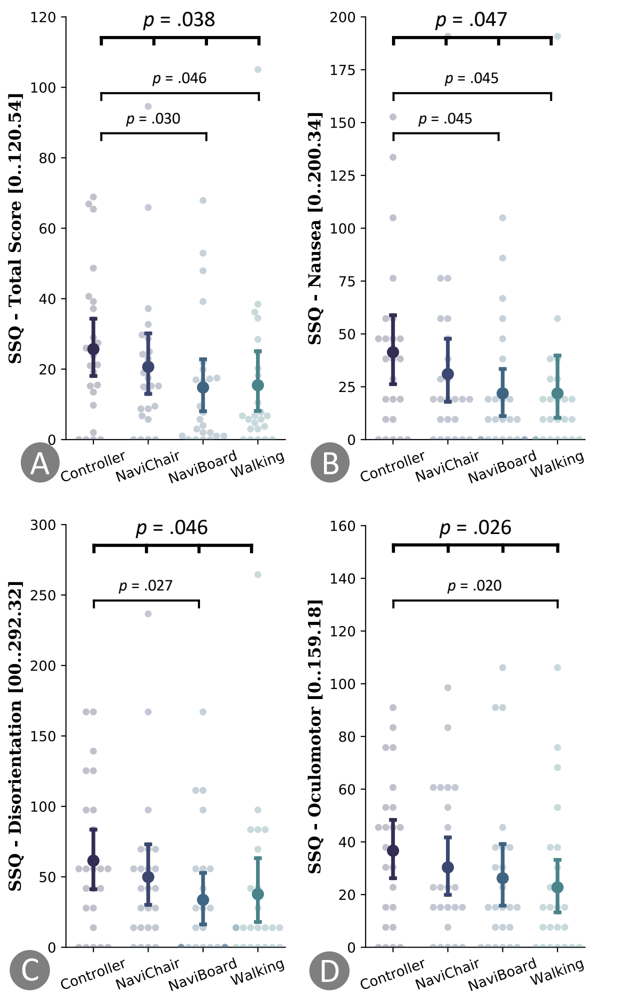

Fig. 7. Mean data of the overall SSQ and its sub-components (nausea, disorientation, and oculomotor). Error bars indicate confidence intervals ($CI = 0.95$), gray dots indicate individual participants' data, annotated bars represent significance level of ANOVAs and post-hoc tests.

correction was used for measures that violate the sphericity assumption.

Participants experienced less simulator sickness when more TCC was available (Figure 7A). Analysis showed a significant effect of TCC on overall simulator 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 ($M = 14.788, SD = 18.941$), $p = .030$, and the Walking condition ($M = 15.421, SD = 22.736$), $p = .046$, compared with the Controller ($M = 25.685, SD = 20.981$).

Participants were less nauseous when using the NaviBoard or Walking (Figure 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 ($M = 21.863, SD = 29.703$), $p = .045$, and the Walking condition ($M = 21.863, SD = 39.029$), $p = .045$, compared with the Controller condition ($M = 41.340, SD = 41.218$).

Participants were less disoriented when using the NaviBoard (Figure 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 less likely to feel disoriented in the NaviBoard condition ($M = 33.640, SD = 46.061$), compared with Controller ($M = 61.480, SD = 52.873$), $p = .027$.

Oculomotor issues were more likely to occur in the Controller condition, compared to Walking (Figure 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 less oculomotor issues in the Walking condition ($M = 22.740, SD = 28.007$), compared with Controller ($M = 36.637, SD = 27.888$), $p = .020$. There was no significant difference between other pairs.

4.2.2 Task Load

We used the NASA Task Load Index (TLX) [41] 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 were analyzed using repeated-measures ANOVAs for general effects and Tukey post-hoc 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 and summarized in Figure 8, 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 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 ($M = 66.736, SD = 13.755$), compared with the NaviBoard ($M = 57.847, SD = 13.407$), $p = .042$, and the Walking condition ($M = 50.958, SD = 15.339$), $p < .001$.

Participants perceived less mental demand when Walking, compared with the Controller (Figure 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 with Walking condition, compared to the Controller (Figure 8C). 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 ($M = 183.33, SS = 115.72$), $p = .001$.

Participant felt significantly more frustrated in the Controller condition, compared to Walking (Figure 8D). 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 ($M = 100.42, SD = 121.92$), $p = .043$.

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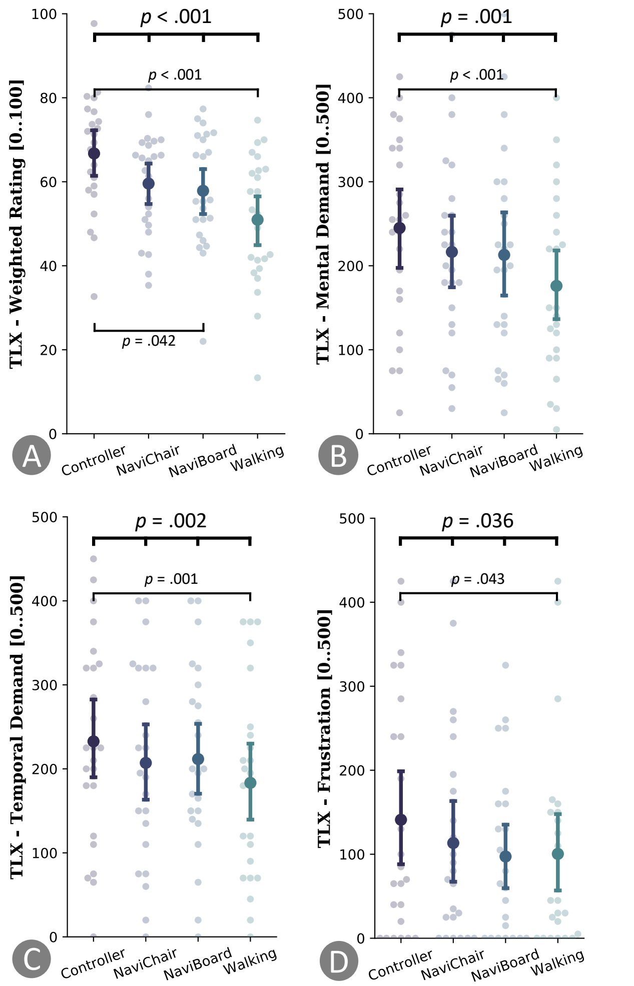

Fig. 8. Mean data of the NASA Task Load Index and three submeasures. Error bars indicate confidence intervals ($CI = 0.95$), gray dots indicate individual participants' data, annotated bars represent significance level of ANOVAs and post-hoc tests.

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 applications, 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 the contributions of our work is NaviBoard, a new method for stepping/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 additional hardware instrumentation, it is simpler than previous work that relies on sensing of weight shifting or tracking the chair motion [2], [15], [37], [44], [45].

NaviBoard was also highly preferred by participants, equal to or ranked right after the Walking condition, when being asked *"What did you like/dislike about the different locomotion modes?"*, and *"Which interface would you prefer?"* at the end of the study participants stated:

> *"Walking is the most natural, after that is the one [that] 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 [Navi]chair."*
> *"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 [11], [46]. 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 [9], [10], Riecke *et al.* suggested full rotation might be enough [11]. To add to this debate, we combined full rotation with different levels of translational motion cues and control to investigate the role of translational body-based sensory information.

RQ1: We observed a fairly consistent pattern of results, in that the Controller (which does not provide any TCC 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 TCC, which helps us to answer our RQ1 - *How much TCC 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.

RQ2: Simulator sickness is believed to largely originate from the mismatch between different sensory cues, in particular visual versus body-based information [19], [40]. By using leaning/stepping interaction to control the simulated velocity, we aim to provide at least minimal vestibular/body-based self-motion cues to reduce cross-sensory conflicts 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 simulator sickness, results showed a clear benefit of the TCC provided by the leaning-based locomotion interfaces. This result helps us to answer our RQ2 - *Does reducing sensory* *conflict help reduce simulator sickness?* Our results suggest that adequate TCC might be needed to reduce sickness symptoms. For example, in our experiment, the descriptive statistics identify a trend that simulator 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.

RQ3: Another subjective measure affected by the locomotion modes is user-perceived task load. Data shows 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 similar types of interaction, the TLX score of NaviBoard was more comparable to physical walking, which possibly means that more TCC 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. Interestingly, recent work demonstrated significant effects of training time on user performance in a leaning-based drone navigation task, with much longer training times [47].

NaviChair vs. NaviBoard

Though NaviChair and NaviBoard shared the same motion control model (with different parameters), we observe that NaviBoard allowed participants to perform better overall. This might be related to the various differences between these two interfaces. We originally designed NaviBoard (only) as a full-body leaning interface, but our current implementation also allows the interaction of stepping (with or without leaning). Moreover, when stepping on the different materials of the NaviBoard, the user's sole likely acquires some haptic information, which has been revealed to affect VR users' spatial perception [32], [48]. Humans also modify their walking posture according to haptic information acquired through the sole [49]. Further research is needed to investigate the role of haptic information on the sole of the foot in VR locomotion interfaces.

Limitations

One of the main limitations of this work is that we asked participants to perform only two trials per condition, one of which was used for 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 simulator sickness and substantially affect the data, even when participants would be able to finish the task. Another factor is that previous evidence shows that a whole experiment might need to be redesigned or data become less informative, just because too many participants got simulator sickness [13], [15]. Yet, we can also state that 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 spatial and 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 Ruddle *et al.*'s [9], [10] and Riecke *et al.*'s [11] studies. Only Fiore *et al.* used a 7×7 meter area [13]. The dark environment with fireflies addresses this issue partially, as it prevents participants from getting an overview of the whole environment from a single point of view. According to Ruddle's classification [50], 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.

6 Conclusion & Future Work

Whereas previous studies showed clear benefits of body-based sensory information in VR locomotion [16], [21], [22], [23], [50], especially in the real-world walking mode [9], [10], the current study provides first experimental evidence that providing limited translational motion cues and control combined with full rotation can have significant benefits, i.e., improve user performance and reduce simulator sickness and task load. Note, however, that with the current experimental paradigm, we mainly focused on the context of spatial updating and situational awareness, and further research is needed and planned to investigate how these findings might generalize to other aspects (e.g., presence, affordances, and usability) and different tasks.

In other words, the current experimental results suggest that, compared with traditional techniques that provide full rotation but no physical translation, allowing for full rotation combined with leaning-based control can not only improve user performance, but also lower simulator sickness and task load. Our navigation interface could be used in many applications that require spatial updating and/or situational awareness.

Moreover, our new approach is easily applicable to VR systems where tracked space is restricted. People can thus set up an effective navigation interface with minimal effort and facilities, e.g., with any (NaviChair-like) swivel chair or a small circular platter or carpet (similar to the NaviBoard). While we attached a Vive tracker to the participant's torso, we used this only for additional data collection in our study, not for the control scheme. Thus, HMD tracking is sufficient for real-world application with our new technique. Also, both the NaviChair stool and the NaviBoard platter are passive elements that do not require motors or sensors. They basically provide only haptic cues (NaviBoard) or a centering force (NaviChair) for the participant to passively/automatically update their physical spatial awareness. Hence, any platter or mat might be used to create a NaviBoard-like interface and any swivel chair might be used for a NaviChair-like interface, as long as they provide sufficient cues.

For the next steps, we plan to investigate if limited translational cues and control combined with full rotational motion cues and control might provide the same benefits in conditions with higher environmental fidelity, e.g., when significant landmarks and environmental geometry are available. Though previous studies have shown that body-based motion cues might become less important when sufficient visual cues are available [7], [20], it is still interesting to identify the interaction effects of the translational motion cues and control for a locomotion interface and the visual cues from the virtual environment, especially when only limited translational cues and control are 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.

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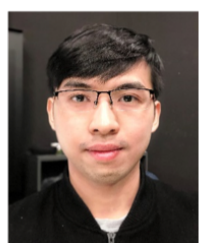

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