# Leaning-Based Interfaces Improve Simultaneous Locomotion and Object Interaction in VR Compared to the Handheld Controller

Abraham M. Hashemian, Ashu Adhikari, Ivan A. Aguilar, Ernst Kruijff, Markus von der Heyde, and Bernhard E. Riecke

**Abstract**—Physical walking is often considered the gold standard for VR travel whenever feasible. However, limited free-space walking areas in the real-world do not allow exploring larger-scale virtual environments by actual walking. Therefore, users often require handheld controllers for navigation, which can reduce believability, interfere with simultaneous interaction tasks, and exacerbate adverse effects such as motion sickness and disorientation. To investigate alternative locomotion options, we compared **handheld Controller** (thumbstick-based) and **physical walking** versus a seated (**HeadJoystick**) and standing/stepping (**NaviBoard**) leaning-based locomotion interface, where seated/standing users travel by moving their head toward the target direction. Rotations were always physically performed. To compare these interfaces, we designed a novel simultaneous locomotion and object interaction task, where users needed to keep touching the center of upward moving target balloons with their virtual lightsaber, while simultaneously staying inside a horizontally moving enclosure. Walking resulted in the best locomotion, interaction, and combined performances while the controller performed worst. Leaning-based interfaces improved user experience and performance compared to Controller, especially when standing/stepping using NaviBoard, but did not reach walking performance. That is, leaning-based interfaces HeadJoystick (sitting) and NaviBoard (standing) that provided additional physical self-motion cues compared to controller improved enjoyment, preference, spatial presence, vection intensity, motion sickness, as well as performance for locomotion, object interaction, and combined locomotion and object interaction. Our results also showed that less embodied interfaces (and in particular the controller) caused a more pronounced performance deterioration when increasing locomotion speed. Moreover, observed differences between our interfaces were not affected by repeated interface usage.

**Index Terms**—3D User Interface, Dual Task, Continuous Interaction, Motion Sickness, Cybersickness, Locomotion, Travel Techniques, Virtual Reality

## 1 Introduction

In many real-world situations, walking is often not the main goal in itself; rather, walking supports other tasks such as exploration, gathering information or interacting with the environment. When simulating these multi-tasking situations in Virtual reality (VR) applications, we often use artificial locomotion interfaces such as handheld controllers because of real-world space limitations or the danger of colliding with obstacles, which often make unconstrained walking unfeasible. However, controller-based interfaces do not provide any vestibular and proprioceptive self-motion cue. Moreover, using hands for simultaneous control of both locomotion and object interaction can increase cognitive load and decrease performance [1]. Therefore, using controllers for locomotion can contribute to motion sickness, decreased believability and naturalness of locomotion, increased cognitive load and decreased performance [2], [3], [4].

To tackle these issues, researchers have designed and investigated embodied hands-free locomotion interfaces. These interfaces free users' hands and provide at least some vestibular and proprioceptive self-motion cues [2], [3], [4], [5], [6]. As an example, leaning-based interfaces require users to lean toward a target direction to control their locomotion speed using a rate-control paradigm. Leaning-based interfaces provide partial vestibular and proprioceptive self-motion cues mainly for the upper-body when seated [7], [8], [9], [10], [11], and can provide additional self-motion cues for the whole body while standing [3], [4], [12].

Earlier studies reported that leaning-based interfaces often provide higher presence and immersion but also often led to reduced effectiveness (i.e., accuracy/precision) compared to handheld controllers in both locomotion-only [8], [10], [13], [14] and locomotion and object interaction tasks [5], [12], [15], [16]. However, iterative refinements of our two leaning-based interfaces called **HeadJoystick** [17], [18], [19], [20] and **NaviBoard** [4] improved almost all relevant measures in locomotion-only tasks [4], [17], [18]. As shown in Figure 1-Bottom, HeadJoystick users sit on a

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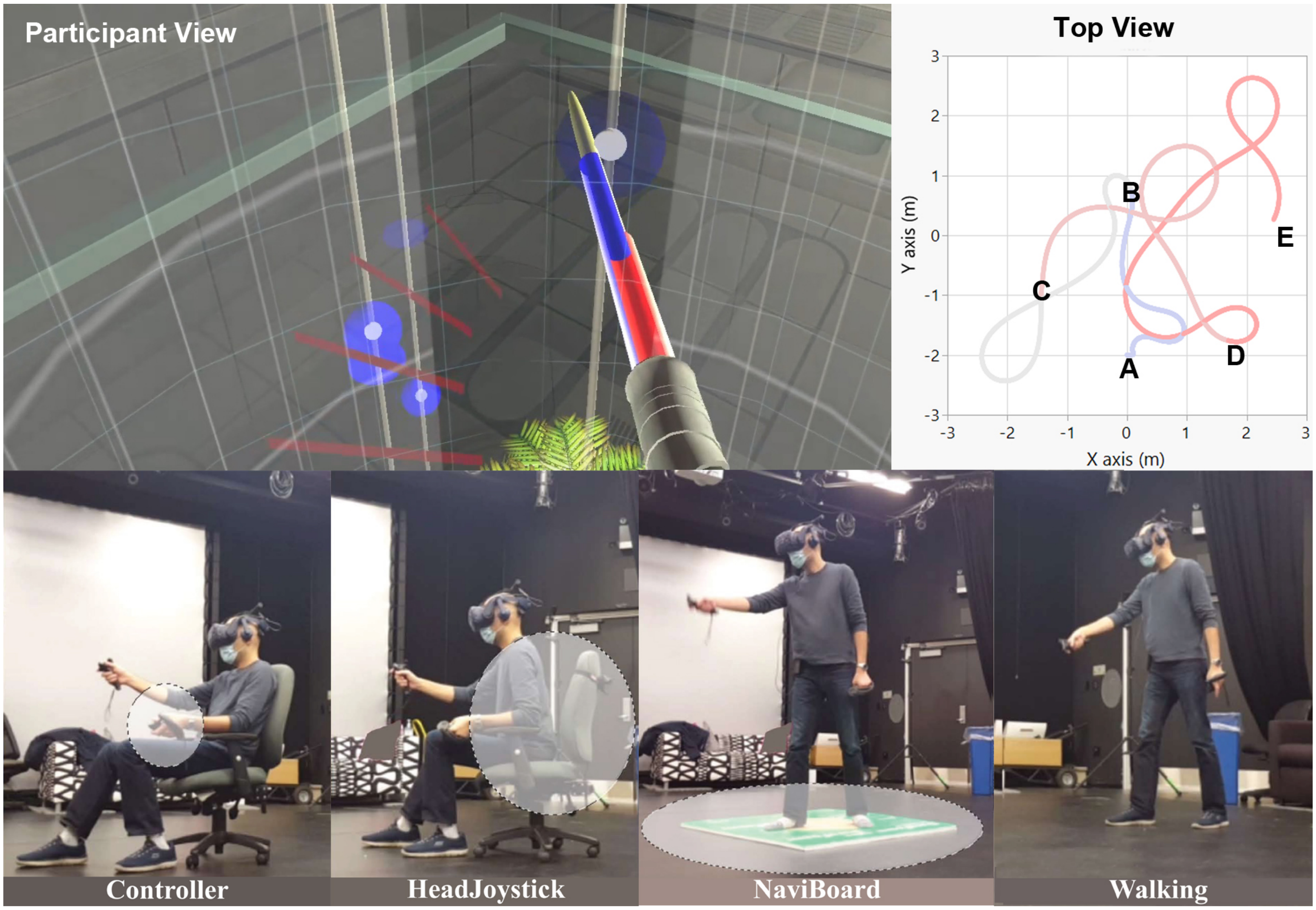


Fig. 1. Top-Left: Environment from participant view, where participants held a virtual lightsaber in their dominant hand, and were asked to fry vertically moving blue targets by intersecting them with the lightsaber as close as possible to the target's center. Participants were also asked to simultaneously follow a horizontally moving beam and keeping their head as close as possible to its center (see video at http://ispace.iat.sfu.ca/project/lightsaber/). Top-Right: Top view of one of the beam's paths randomly pre-generated within a $6 \times 6$ m tracked area. The locomotion task became more challenging every 24 s, as the minimum and maximum speed for beam's translation or rotation increased at locations A, B, C, D, and E - see Table 1. Bottom: All four locomotion conditions from left to right: Controller, where a seated user deflects Controller's thumbstick to translate in VR; HeadJoystick, where a seated user moves their head toward the target direction while leaning; Naviboard, where the user stands on a circular wooden plate surrounded by a Styrofoam platform and moves their head toward the target direction while leaning/stepping; and Walking.

regular office swivel chair while NaviBoard users stand on a wooden/Styrofoam platform. In both implementations, users control translational direction by moving their head (tracked via the HMD) toward the target direction and an exponential transfer function maps the head motion to translational speed.

In this paper, we investigate if these two leaning-based interfaces could improve also user experience, usability, and effectiveness when the locomotion task is accompanied by a continuous object interaction task. To study this, we designed a simultaneous locomotion and object interaction task and compared physical walking versus three locomotion interfaces. These interfaces provide different levels of self-motion cues: Controller provides no/minimal self-motion cues for a seated user; HeadJoystick provides self-motion cues mainly for the upper-body of a seated user; and NaviBoard provides self-motion cues for the whole body of a standing/stepping user. We used a regular office swivel chair for the seated conditions (i.e., Controller and HeadJoystick) due to its availability for most VR users. All conditions allow full 360° physical rotation.

Most prior studies on simultaneous locomotion and object interaction tasks [5], [12], [15], [21] often assessed general effectiveness measures (except [16]). These measures confound locomotion with interaction effectiveness, and thus we do not yet fully understand if and how using more effective locomotion interfaces might affect interaction, locomotion, and/or overall effectiveness. Thus, we addressed this issue by designing a novel task consisting of two simultaneous tasks. These tasks require effective locomotion *and* object interaction to assess locomotion, interaction, and overall effectiveness using similar yet separate measures. To do so, we asked the user to simultaneously control their locomotion to stay inside a horizontally moving semi-transparent enclosure ("beam") as well as collect upward moving target balloons with a virtual light-saber, as seen in Figure 1-top and the task video at http://ispace.iat.sfu.ca/project/lightsaber/.

This locomotion task required continuous maneuvering as the beam moved in a random curved path with varied levels of translational and rotational speed. This allowed us to evaluate effectiveness (accuracy and precision) of the interfaces for both the locomotion and object interaction task. We also thoroughly assessed how different interfaces/levels of self-motion cues affect locomotion-related aspects including different user experience, usability, and effectiveness measures. The main contributions of this study are:

- How different levels of embodied self-motion cues i.e., no/minimal (Controller), upper body of a seated user (HeadJoystick), whole body of a standing/stepping user (NaviBoard), and whole body of a walking user affect user experience, usability, and effectiveness in a simultaneous locomotion and object interaction task.
- The design of a novel simultaneous locomotion and object interaction task that allows to differentiate the effects of locomotion interfaces on locomotion, interaction, and overall effectiveness.
- Investigate whether the previously-observed advantages of leaning-based interfaces, such as HeadJoystick and NaviBoard which were used for 2D (ground-based) and 3D (flying) locomotion-only tasks, are generalizable to simultaneous locomotion and object interactions tasks.

## 2 Related Work

As providing full self-motion cues of physical walking is not possible without actual walking, prior research investigated a wide range of embodied interfaces, which provide different levels of physical self-motion cues. Examples include redirected walking, motorized/non-motorized walking platforms, walking in place (WIP), head-directed steering (often called gaze-directed), and leaning-based interfaces [6]. Some of these interfaces are not usable/affordable (cost and space) for a wide range of VR users and especially home users. Other embodied interfaces like WIP and head-directed steering might not provide vestibular and/or proprioceptive sensory cues matching the direction of virtual motion, cues known to help increase the believability of self-motion and reduce its unwanted side effects (e.g., disorientation and motion sickness) [4], [17], [18], [19], [22].

In the current study, we used leaning-based interfaces because they provide at least minimal translational self-motion cues matching the direction of virtual motion, and are easily accessible to most VR users without additional cost. Recent prior works also showed that leaning-based interfaces can improve almost all locomotion-relevant measures in locomotion-only tasks [4], [17], [18], [19]. That is, compared to handheld interfaces, recent leaning-based interfaces such as HeadJoystick and NaviBoard improved spatial orientation, speed (lower task completion time), accuracy, precision, enjoyment, preference, vection intensity, presence, immersion, ease of use, ease of learning, potential for long-term use, potential for daily use, and overall usability while reducing task load and motion sickness [4], [17], [18]. Leaning-based interfaces also free up the user's hands so they can interact with objects in the environment. This is a substantial advantage over handheld interfaces for simultaneous locomotion and object interaction [1], [7], [14], [17], [23], [24], [25].

While some prior research investigated locomotion and object interaction interfaces in separate or sequential tasks [26], [27], [28], in this paper, we focus on simultaneous locomotion and object interaction tasks. Prior research has investigated a wide range of user interfaces for simultaneous locomotion and object interaction such as physical walking [29], head-directed steering [15], [16], WIP [15], 3D (wand) controllers [30], glove-based hand gestures [31], mouse [32], [33], teleportation and Point of Interest [34], virtual gun [35], and omni-directional treadmill [21]. Many prior studies also investigated leaning-based interfaces in locomotion-only tasks [1], [2], [3], [4], [7], [10], [11], [13], [14], [17], [18], [19], [20], [36], [37], [38]. In the remaining of this section, we review previous research that investigated leaning-based interfaces for simultaneous locomotion and object interaction tasks.

Griffin *et al.* evaluated head-directed steering – called Tilt (direction and velocity of the movement is determined by the user's head tilt), WIP, teleportation, and controller (i.e., trackpad) by developing a First-Person-Shooter (FPS) game [15]. Though they did not use leaning-based interfaces, their Tilt interface is similar to leaning-based interfaces. In this study, participants were asked to collect ammunition while shooting at flying drones with both hands. The authors used four introspective measures including task load, usability, presence, and motion sickness, as well as a wide range of behavioral measures including the number of drones killed by the user, collected-ammunition, the number of shots the user took from the drone, number of hit over fired bullets as shooting/pointing accuracy measure for each hand, overall physical and virtual movement distance, and travelled time. The results showed that Tilt interface improved presence and task load but not performance over controller. That is, using controller over Tilt increased number of collected ammunition and travelled distance while reducing the damage taken and total physical movement.

Prithul *et al.* also evaluated head-directed steering versus handheld controller in a simultaneous locomotion and object interaction task [16]. Participants were asked to follow a path while popping balloons by touching them with their virtual hands. Results showed improved effectiveness of handheld controllers in terms of locomotion (reduced total time and more obstacles jumped) and object interaction (increased targets hit). In contrast, head-directed steering showed a significantly higher avatar embodiment.

Ha *et al.* investigated leaning-based interfaces to control a teleoperated ground-based mobile robot in a simultaneous locomotion and object interaction task [39]. In this study, leaning-based locomotion was used to move the robot by tracking the user's torso while they were seated on a chair. To provide rotational vestibular cues, users sat on an actuated chair - a rotating swivel chair using a DC motor, which provided yaw rotation in the direction they rotated their upper body. To manipulate objects, the user's hand position was tracked, which controlled the robot's end effector position and manipulator through the use of inverse-kinematics. To provide tactile feedback when manipulating objects, a cutaneous haptic device was used on the user's index finger and thumb which activated when the robot's end effector collided with an object. To evaluate this system, users were tasked with picking up and placing objects. Users rotated their body to reach the objects and place them at a designated location. Results showed a trend towards improved task performance (reduced task completion time), greater perceived ease of use, and reduced simulator sickness when using both chair actuated and cutaneous haptic feedback when compared to using one or none of them. While these findings illustrate the potentials of leaning-based interfaces for teleoperation, this study unfortunately did not compare leaning-based interfaces with any other locomotion methods.

Leaning-based interfaces have been investigated for projection screens by Beckhaus *et al.* in an informal study using the Unreal Tournament first-person shooter (FPS) game to evaluate ChairIO vs. handheld controllers (mouse/keyboard and joystick) [5]. To operate the ChairIO a user sits on the Swooper$^{TM}$, a stool with rotatable tilting seat, and tilts the stool in the desired direction of motion with their body. Users were asked to first shoot a non-moving target as practice, and then perform a death match against simulated bots. Results showed that compared to mouse/keyboard, ChairIO was rated for higher fun but lower subjective precision and perceived performance in the game. Unfortunately, this study did not assessed behavioral/performance measures.

Leaning interfaces have also been compared in desktop and six-sided CAVE conditions by McMahan *et al.* using an FPS-game (Quake III) to compare human joystick and handheld interfaces (mouse and keyboard) [12]. The authors designed ten scenarios to control for stereoscopy (bots appeared 3 m away from the user), field of regard (bots appeared 6 m away from the user in a surrounding fashion), aiming (eight bots appeared simultaneously), locomotion (bots retreat after being hit), and their combinations. While introspective results showed that using human joystick in CAVE provided higher presence, engagement, and usability over using handheld controllers on screen, behavioral performance measures showed improved performance of handheld controller on screen and human joystick in CAVE. That is, while human joystick improved speed in the CAVE, handheld controllers improved speed on screen. As for accuracy, handheld controllers on screen outperformed human joystick in both screen and CAVE, while for taken damage, human joystick in CAVE outperformed handheld controllers on both screen and CAVE.

Overall, all the aforementioned literature in simultaneous locomotion and object interaction tasks showed higher naturalness and fun but not higher performance and accuracy/precision of embodied interfaces in general and leaning-based interfaces specifically compared to the handheld interfaces.

## 3 Motivation and Goal

While prior research showed several benefits for providing self-motion cues in locomotion-only tasks, there is limited knowledge on their effects on simultaneous locomotion and object interaction tasks, which motivated this work. First, some research on simultaneous locomotion and object interaction tasks with embodied interfaces used WIP [15] and head-tilt interfaces [15], [16]. However, these interfaces might not provide proper vestibular or proprioceptive sensory cues due to not moving the head toward the target direction, as discussed in section 2. Prior research investigating leaning-based interfaces on simultaneous locomotion and object interaction tasks used projection screen [5], desktop, and CAVE [12], but not HMDs. Therefore, it is unclear if/how their findings generalize to HMDs as the display device (e.g., desktop, CAVE, HMD) likely affected user performance [40]. Moreover, prior work often used tasks which might not truly require simultaneous locomotion and object interaction as the players could, in principle, keep switching between locomotion and interaction tasks [5], [12], [15], [16]. Further, the overall effectiveness was only measured through combined locomotion and object interaction (such as number of precise pointing/shooting toward enemies or collected/intersected ammunition during locomotion). This does not allow to distinguish the effects the locomotion interfaces have on locomotion, object interaction, and overall effectiveness.

We have tried to address these limitations by making the following design considerations:

- We chose locomotion interfaces with varying degrees of translational self-motion cues.
- All the tasks use the same display device (HMD)
- We designed our task to require continued and concurrent locomotion and object interaction to ensure users cannot simply alternate between the two tasks.
- And, we use separate measures for assessing effectiveness of locomotion versus object interaction tasks.

Together, these changes should help us investigate how different locomotion interfaces that vary in the amount of provided self-motion cues affect effectiveness, user experience, and usability measures in a task requiring simultaneous locomotion and object interaction. We divide this general research question into three specific research questions:

**RQ1: How does providing partial self-motion cues improve effectiveness (accuracy/precision) in locomotion and object interaction tasks?** Though earlier leaning-based interface prototypes often reduced effectiveness compared to handheld controllers in locomotion tasks [7], [8], [10], [13], [14], our recent studies showed that iterative improvements of leaning-based interfaces can yield higher performance and effectiveness compared to Controller [17], [18], [19], [20]. Since we are following previously successful design guidelines, we hypothesize that using HeadJoystick improves locomotion effectiveness compared to the Controller.

As for interaction effectiveness, using hands for simultaneous control of both locomotion and object interaction is considered to increase cognitive load and thus reduce the interaction performance as well [1]. Both NaviBoard and HeadJoystick have been described as intuitive and easy to use by participants and showed improved ease of use and reduced task load compared to the handheld controllers [4], [17], [18], [19]. Thus, we hypothesize that hands-free leaning-based interfaces such as HeadJoystick and NaviBoard would reduce cognitive load and improve interaction effectiveness compared to the controller.

As for comparing NaviBoard with HeadJoystick, a recent study reported no significant differences between standing/stepping (NaviBoard) versus seated (NaviChair) leaning-based interfaces [4]. However, the results showed a general trend of participants performing better with NaviBoard compared to NaviChair. Therefore, we hypothesize the trend to continue and that adding embodied cues for whole body in standing/stepping posture using NaviBoard would further improve the effectiveness of locomotion compared to the Controller in our simultaneous locomotion and object interaction task.

**RQ2: How does providing partial self-motion cues improve usability and user experience in simultaneous locomotion and object interaction tasks?** Though prior research revealed mixed results to this research question, there is a general trend of improved user experience with leaning-based interfaces. For example, leaning-based interfaces enhanced usability and presence [12] as well as increased enjoyment [5] compared to a handheld controller on simultaneous locomotion and object interaction tasks. Similarly, HeadJoystick versus controller also showed significant benefits of HeadJoystick in terms of some aspects (e.g., enjoyment, preference, immersion, ease of use, overall usability, and presence) [18]. However, the difference in some other aspects (e.g., ease of learning, long-term use, vection intensity, task load, and motion sickness) were inconclusive [18]. NaviBoard also reduced task load and motion sickness compared to a controller [4]. NaviBoard was even comparable to walking, the most natural user experience with the highest usability [29]. Considering these general trends, we tentatively hypothesize that using HeadJoystick and in particular NaviBoard interfaces will improve user experience and usability aspects in simultaneous locomotion and object interaction tasks.

**RQ3: When comparing leaning-based interfaces, how does standing/stepping vs. sitting on a chair affect effectiveness, user experience, and usability?** Prior research provided mixed results to this research question. For example, while the postural instability theory of motion sickness suggests higher motion sickness for standing over seated interfaces [41], [42], a recent study showed that a standing interface (NaviBoard) could reduce motion sickness compared to a seated interface (NaviChair) [4]. NaviBoard also improved performance over NaviChair, even though seated interfaces should generally provide higher precision than standing interfaces [43]. Compared to the seated posture, standing posture is also known to be less comfortable [44], [45], accessible [43], and safe [46]. In contrast, standing interfaces should provide more intense vection, higher engagement, and higher degrees of embodiment [43]. Overall, due to the similarities between HeadJoystick and NaviChair, we hypothesize similar benefits of standing interfaces (here NaviBoard) over seated ones (here HeadJoystick) in terms of motion sickness, performance, and believability.

## 4 Methods

### 4.1 Tasks and Environment

Our general LightSaber task is illustrated in videos at http://ispace.iat.sfu.ca/project/lightsaber/. It was inspired by the VR game Beatsaber, where participants used their lightsaber to intersect targets [47]. We revised this task for our user study by adding user locomotion. This allows us to assess effectiveness of locomotion and object interaction tasks using similar yet separate measures. To do so, participants were asked to actively follow a horizontally moving beam by keeping their head as close as possible to its center - see Figure 1 top-right. Participants were also asked to use their lightsaber to collect upward moving target balloons appearing to the beat of the music. To provide a continually demanding object interaction task, based on our pilot-testings, targets appeared at a rate of one target per second, and would be collected ("fried") if intersected with the lightsaber for at least 0.33 seconds. Otherwise, targets disappeared after reaching three meters above the floor. Based on our pilot-tests, the targets were programmed to appear in an area where participants could easily see and reach them with their lightsaber. That is, they appeared in a random distance between 1-2 m from the center of the beam in a $\pm 30°$ angular range around the beam's movement direction.

The effectiveness of locomotion and object interaction tasks was assessed using accuracy and precision measures. *Accuracy* was measured by the average distance of a user from a path/target - section 1.3.2 of [48], thus the accuracy scores for our locomotion and object interaction tasks were calculated by how close the participant's head and lightsaber were to the center of beam and target, respectively. At each frame, we standardized accuracy measures for locomotion and object interaction into a proximity percentage ranging between 0% (outside) to 100% (center) of the beam and target, respectively. To ensure that participants spent similar effort on both locomotion and object interaction tasks, we defined the overall accuracy score at each frame as the minimum score between the locomotion and object interaction scores of that frame. The locomotion, interaction, and overall (accuracy) scores of a trial were calculated by summing up the locomotion, interaction, and overall scores for each frame, respectively. *Precision* is the ability of an interface to support fine movements without missing the target or colliding with the path borders - section 1.3.2 of [48]. We assessed locomotion precision by the number of collisions with the beam's border, i.e., the number of times users left the beam. In addition, we also measured locomotion precision by the percentage of time users spent outside the beam. Interaction precision was assessed by the number of fried and missed targets.

Visual feedback for the locomotion and object interaction accuracy scores was provided at each frame by showing a red and blue bar over the lightsaber's blade, respectively, as shown in the task video at http://ispace.iat.sfu.ca/project/lightsaber/. As we wanted to assess participants' ability to effectively and efficiently locomote and interact, and not their ability to predict the locomotion path or target locations/movements, we showed the future path of the beam and locations where targets will appear using red and white lines on the floor, respectively. Targets also became visible under the floor one second before surfacing.

For the locomotion task, each trial had a different path, which was randomly pre-generated and tested to ensure that the beam would never move beyond the 6 m x 6 m area, as this was the size of the physical free-space walking area. The beam radius was 25 cm, based on pilot-testings. Music was played during each trial and spatialized to originate from the center of the beam to provide auditory feedback for locomotion accuracy, such that music amplitude and

TABLE 1
All levels in our task. The locomotion task became more demanding over time, as either rotation and translation speed were increased between levels.

| Difficulty | Time (s) | | *Translation Speed (m/s)* | | Rotation Speed (deg/s) | |
|---|---|---|---|---|---|---|
| Level | From | To | Min | Max | Min | Max |
| 0 | 0 | 23 | 0 | 0 | 0 | 0 |
| 1 | 24 | 47 | 0.15 | 0.3 | 15 | 30 |
| 2 | 48 | 71 | 0.3 | 0.6 | 15 | 30 |
| 3 | 72 | 95 | 0.3 | 0.6 | 22.5 | 45 |
| 4 | 96 | 119 | 0.4 | 0.8 | 22.5 | 45 |

direction provided an auditory cue about the beam's center location.

The beam's translational and rotational velocity was randomised when pre-generating its path - see Figure 1 top-right. As for determining minimum and maximum translational and rotational speed of the beam, prior user studies reported mixed results regarding if providing limited self-motion cues can improve locomotion performance in spatial orientation tasks [49]. For example, while some studies did not show improving spatial orientation when providing physical rotation without limited translational motion cues [50], [51], other studies showed that providing physical rotation could help the user to better stay spatially oriented [52], [53], [54], [55], [56]. Some previous studies even reported that providing physical rotation resulted in performance comparable to actual walking in a navigational search task when used with leaning-based interfaces [4] and handheld interfaces [57]. As the reasons behind such mixed results are not fully understood, and different factors such as translational and rotational speed could be responsible, we decided to compare our interfaces in different ranges of translational and rotational speeds. We did so by defining five levels of increasing speed and difficulty. Each level lasted for 24 s, after which the minimum and maximum speeds were increased for either the translation or rotation after each level to make the locomotion task more demanding over time [58], [59], [60] - as shown in Table 1.

As the interaction method was the same in all conditions, the beam did not move during the difficulty level 0 to allow comparing the interaction performance with locomotion to interaction without locomotion ("dual-task cost") for each interface. Note that all our interfaces provided different motion cues for translation but similar motion cues for rotation (i.e., full 360° physical rotation). Thus, we hypothesized that our results would show significant interactions between interface and translational speed changes, but no interactions between interface and rotational speed changes between levels.

Based on our pilot-study, the radius of each target was set to 7.5 cm. The lightsaber took 0.33 s to fry the targets when they were intersected at their center. However, if the lightsaber was not at the center, the frying time would be increased. That is, for each target, the 'remaining frying time' (FT) was initially set to 0.33 s, and after each frame of intersection with the lightsaber, we reduced FT by dFT obtained from the following formula:

$$\begin{aligned} \mathrm{dFT} &= \mathrm{eT} * \mathrm{IS} \\ \mathrm{IS} &= 1 - \mathrm{ID}/\mathrm{TR} \end{aligned}$$

where eT is the frame length (in seconds), IS in the interaction score, ID is the distance between lightsaber and the target, and TR is the target radius (0.075 m).

When frying a target, tactile feedback was provided by the controller's vibration. It vibrated more intensely if the light saber was closer to the center. In addition, the target gradually turned from blue to black upon frying, and produced a popping sound when the frying was complete. To provide rich visual self-motion cues including parallax cues as well as a compelling visual reference frame during locomotion, a futuristic-looking room was used as the virtual environment, with semi-transparent ceiling and floor (cf. Figure 1 top-left).

### 4.2 Dependent Variables

For this study, we used our previously introduced framework (see Appendix in [18]) to evaluate locomotion interfaces, which is an expansion of Bowman's framework [61], [62], [63], [64], [65] for assessing user experience, usability, and performance factors. User experience consisted of four subjective factors: *presence* - measured using the SUS spatial presence questionnaire [66] and psychological immersion (i.e., being captivated by a task); *vection intensity* - based on the rated intensity of the users' self-motion sensation; *motion sickness* - using the simulator sickness questionnaire (SSQ) [67]; and overall user experience - using *enjoyment* and the *overall preference* ratings for each interface. Usability consisted of four factors: ease of learning - measured by introspective ratings for *ease of learning* as well as the behavioral performance improvement over time; ease of use - including introspective rating for the *overall ease of use* as well as the first and commonly used part of the *NASA-TLX questionnaire* for locomotion and overall task load [68]; user comfort - measured by the user-ratings for the potential of *daily and long-term usage* of the interface; and *overall usability* ratings for the interface. Performance was assessed via two behavioral measures: *accuracy* was measured by the locomotion, interaction, and total scores; and *precision* for interaction and locomotion was measured by the number of missed and fried targets, number of times users left the beam, and the percentage of the time outside the beam, which have already been explained in subsection 4.1. All introspective questions were rated using visual-analog scale answers between $0\%$ to $100\%$, except for the SSQ, which uses a Likert-like scale of $\{$None, Slight, Moderate, Severe$\}$.

### 4.3 Apparatus

The virtual environment was created using Unity 2018.4 and rendered on a dedicated desktop PC (Intel-Core-i7, 8GB RAM, NVIDIA GTX 1060) and displayed on a HTC-Vive Pro Eye HMD. This HMD has a binocular field of view of about $110°$ diagonally with a resolution of $1400 \times 1600$ pixels per eye. We used a TPCast wireless adaptor to wirelessly connect the HMD to the PC to allow the user to freely walk in the $6 \times 6$ m tracked area, using four Vive V2 base stations, without any cable entanglement or length problem. As for the HeadJoystick interface, we used a tracker strap to attach a Vive V2 tracker to the swivel chair backrest. The game audio was played using the built-in HTC Vive Pro Eye headphones.

### 4.4 Locomotion Modes

Figure 1-bottom shows the four interfaces used in this study: Controller, HeadJoystick, NaviBoard, and Physical walking. In the **Controller** condition, translation velocity was controlled by the thumbstick deflection, where the forward deflection of the thumbstick moved the user toward the direction of the controller. Maximum translational velocity for all the artificial interfaces was 4 m/s, based on the pilot-testings. Thumbstick deflection was mapped to the translation velocity using an exponential transfer function with power of 1.53 to be consistent with HeadJoystick/NaviBoard input mapping as well as allowing for more precise control at lower velocities. To reduce motion sickness, we also used Unity's SmoothStep function to smooth out any harsh speed changes when artificial locomotion interfaces were used as detailed in the appendix of our previous study [17]. Participants used one controller to move and the other one to control the lightsaber, based on their choice. We asked participants to hold both controllers in all conditions for consistency.

**HeadJoystick**'s design details and formulas have been explained in the appendix of [17]. To use HeadJoystick, participants were asked to press the trigger to set the zero-point when their back touches the chair backrest and then start the locomotion. During locomotion, the more participants moved their head towards the target direction, the more their velocity in that direction increased. Maximum velocity was reached by leaning 20 cm in a direction, leaning more than this did not increase the velocity further. Compared to other prior leaning-based interface prototypes, HeadJoystick had a few modifications to improve its effectiveness, as explained in the appendix of [17].

**NaviBoard** is a standing version of the HeadJoystick (cf. Figure 1-bottom) with a 15 cm natural/idle zone, where the user could move their head in this range without triggering simulated locomotion [4]. Moving beyond this range would trigger the simulated locomotion, where its direction and speed were determined based on the direction and horizontal displacement of the user's head from zero point, respectively. The maximum head motion range was 40 cm for NaviBoard. The NaviBoard platform consists of the inner circular wooden plate and the outer rectangular softer styrofoam ring providing tactile feedback about the neutral/idle and simulated locomotion zone, respectively. That is, moving the head beyond the neutral/idle zone to trigger simulated locomotion usually required the user to step on the soft outer styrofoam plate such that they receive unobtrusive tactile feedback from their foot. We asked participants to take off their shoes to more easily sense the tactile feedback (cf. Figure 1-bottom). The only change in our NaviBoard condition compared to its prior study was using the head rotation center instead of HMD's position as the user's head as shown in the appendix of [17], to be consistent with the HeadJoystick condition and allow for head rotations without affecting locomotion.

For the physical **Walking** condition, users could walk freely within the tracked $6 \times 6$ m area. Edges of the tracked area were shown as a green border on the floor in the virtual environment.

### 4.5 Participants

We recruited 24 participants (11 females) for this study, with ages ranging from 19 to 33 years ($M = 23.5, SD = 3.89$). Two additional participants stopped the study due to severe motion sickness and thus were excluded from analysis. 11 (out of 24) of the remaining participants reported moderate to severe symptoms of motion sickness in at least one of the SSQ questions, but all were okay to continue with the study. All participants were familiar with handheld controllers, but no one had prior experience with HeadJoystick or NaviBoard. None of the participants frequently used VR, seven of them (29%) never used VR. 11 participants (46%) play 3D first-person games on a daily/weekly basis and 13 participants (54%) had corrected eyesight (glasses or contact lenses). This research was approved by the local ethics board (#20180649) and course credit were offered as compensation for participating in the study.

### 4.6 Experimental Design

In this within-subject study, we compared controller with three embodied locomotion interfaces that used increasing levels of translational sensory cues including seated vestibular and proprioceptive translational information ("HeadJoystick"), standing/stepping vestibular and proprioceptive translational information ("NaviBoard"), and full translational information ("physical walking"). Each participant completed 12 trials consisting of a factorial combination of four interface conditions {Controller, HeadJoystick, NaviBoard, Walking} $\times$ three trials (i.e., repetitions) per interface, where each trial consisted of five difficulty levels. The order of interface conditions were counter-balanced across participants.

### 4.7 Procedure

After reading and signing the consent form, participants started the study by answering a demographic questionnaire as well as the pre-study SSQ. Then each participant performed the task for three consequent repetitions for each interface. Each repetition of the game took 120 s including five levels of increasing translational or rotational speed, where each level took 24 s. During each repetition, behavioral measures were recorded. After completion of all three repetitions, participants were asked to evaluate the interface by filling out the SSQ and introspective user experience and usability questionnaires. Upon completion of all the interfaces, we used a semi-structured open-ended interview to better understand the reasons behind participants' answers.

## 5 Results

11 (out of 21) dependent variables (DVs) showed no or only a slight violation of normality assumptions (i.e., two violation cases in 44 Shapiro-Wilk tests, where ($p > 0.024$)). We analyzed these 11 measures using repeated-measures ANOVA, as it has been shown to be robust against such slight violations of assumptions [69], [70]. These were all seven behavioral measures shown in Figure 2-bottom and four (out of 14) introspective measures (spatial presence, post-pre motion sickness, locomotion task load, and overall task load) and their sub-components depicted in Figure 3.

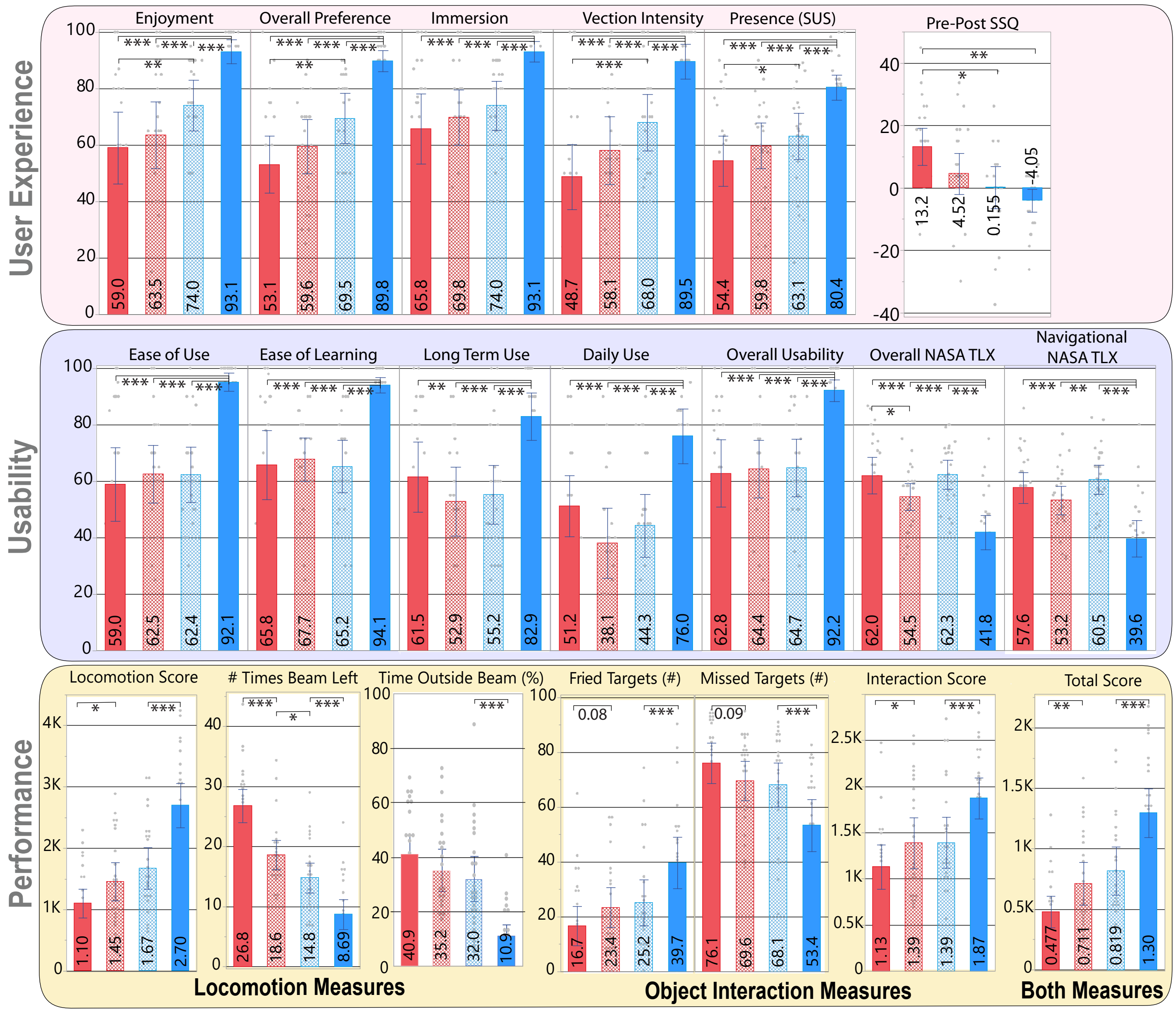


Fig. 2. Average data for user experience (top), usability (middle), and per-trial performance (bottom) measures for Controller (in red) vs. HeadJoystick (in hatched-red) vs. NaviBoard (in hatched-blue) vs. Walking (in blue). Seated conditions are color-coded in red to distinguish them from the upright conditions in blue. Error bars indicate confidence intervals ($CI = 95\%$) and dots show individual participants' data for each interface. Annotated bars represent significance levels in pairwise comparisons (* $p < .05$, ** $p < .01$, *** $p < .001$) for introspective (using Tukey post hoc tests) and behavioral (using planned contrasts) data. $p$-values were stated when marginally significant.

TABLE 2
ANOVA results for behavioral data comparing interfaces over trials and difficulty levels. Significant $(p \leq .05)$ and marginally significant $(p \leq .1)$ effects are highlighted in green and light green, respectively, and were always in the direction of improved aspects for physical walking followed by NaviBoard, and then HeadJoystick, and finally Controller.

| Measures | Interface | | | Trial | | | Level | | | Interface * Trial | | | Interface * Level | | | Trial * Level | | | Interface * Trial * Level | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F(1, 23) | p | $\eta_p^2$ | F(1,23) | p | $\eta_p^2$ | F(1,23) | p | $\eta_p^2$ | F(1,23) | p | $\eta_p^2$ | F(1,23) | p | $\eta_p^2$ | F(1,23) | p | $\eta_p^2$ | F(1,23) | p | $\eta_p^2$ |
| Total Score | 36.4 | <0.001 | 0.624 | 32.1 | <0.001 | 0.593 | 63.0 | <0.001 | 0.741 | 1.17 | 0.322 | 0.051 | 3.51 | <0.001 | 0.138 | 0.705 | 0.646 | 0.031 | 0.810 | 0.689 | 0.035 |
| Locomotion Score | 42.5 | <0.001 | 0.659 | 32.1 | <0.001 | 0.593 | 75.3 | <0.001 | 0.774 | 1.26 | 0.280 | 0.054 | 3.59 | <0.001 | 0.140 | 1.27 | 0.276 | 0.055 | 1.19 | 0.264 | 0.051 |
| Interaction Score | 19.5 | <0.001 | 0.470 | 30.1 | <0.001 | 0581 | 31.1 | <0.001 | 0.585 | 0.503 | 0.805 | 0.022 | 3.63 | <0.001 | 0.142 | 1.02 | 0.418 | 0.044 | 0.970 | 0.494 | 0.042 |
| Fried Targets (#) | 12.3 | <0.001 | 0.360 | 24.6 | <0.001 | 0.528 | 32.3 | <0.001 | 0.595 | 1.655 | 0.137 | 0.070 | 1.46 | 0.164 | 0.062 | 0.633 | 0.703 | 0.028 | 1.13 | 0.325 | 0.049 |
| Missed Targets (#) | 13.0 | <0.001 | 0.372 | 24.1 | <0.001 | 0.522 | 26.9 | <0.001 | 0.550 | 1.82 | 0.136 | 0.076 | 1.79 | 0.072 | 0.075 | 0.506 | 0.803 | 0.022 | 1.05 | 0.401 | 0.046 |
| # Times Beam Left | 37.9 | <0.001 | 0.633 | 3.17 | 0.050 | 0.126 | 40.8 | <0.001 | 0.650 | 0.489 | 0.815 | 0.022 | 2.65 | 0.006 | 0.107 | 1.03 | 0.410 | 0.045 | 0.894 | 0.587 | 0.039 |
| Time Outside Beam (%) | 23.7 | <0.001 | 0.518 | 17.3 | <0.001 | 0.440 | 125 | <0.001 | 0.851 | 1.271 | 0.275 | 0.055 | 11.6 | <0.001 | 0.346 | 1.22 | 0.298 | 0.053 | 1.07 | 0.382 | 0.046 |

For pairwise comparison among these four introspective measures, we used Tukey-HSD post-hoc tests, and applied Greenhouse-Geisser correction whenever the sphericity assumption was violated in the Mauchly's test. As for the behavioral measures, we had specific hypotheses and thus used planned contrast to assess our hypotheses using three pairwise comparisons between interfaces: HeadJoystick versus Controller, to compare providing (i.e., HeadJoystick) versus not providing (i.e., Controller) embodied motion cues for a seated user; HeadJoystick versus NaviBoard, to compare the difference in embodied motion cues between standing/stepping (NaviBoard) versus seated (Head-

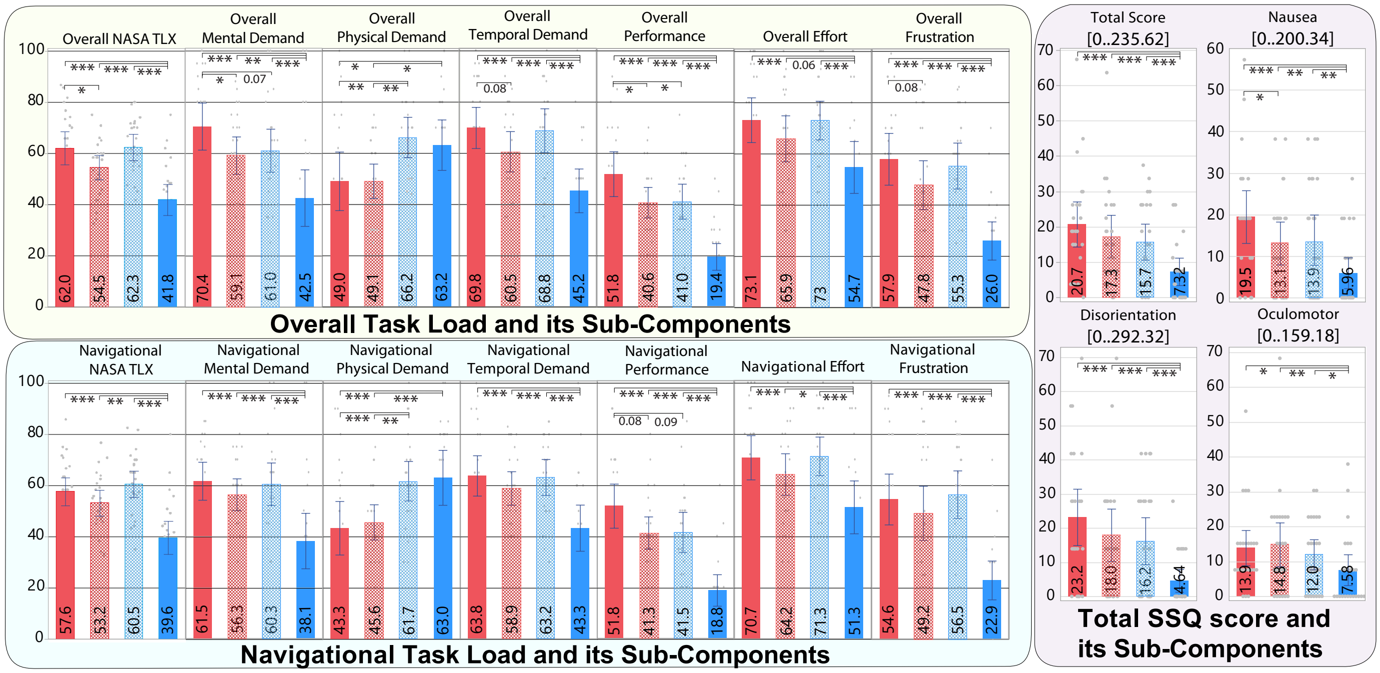


Fig. 3. Average data for overall NASA TLX (top-left), navigational NASA TLX (bottom-left), and SSQ score (right) and their sub-components for Controller (in red) vs. HeadJoystick (in hatched-red) vs. NaviBoard (in hatched-blue) vs. Walking (in blue). Seated conditions are color-coded in red to distinguish them from the upright conditions in blue. Error bars indicate confidence intervals ($CI = 95\%$) and dots show individual participants' data for each interface. Annotated bars represent significance levels in pairwise comparisons (* $p < .05$, ** $p < .01$, *** $p < .001$) using Tukey post hoc tests. *p*-values were stated when marginally significant.

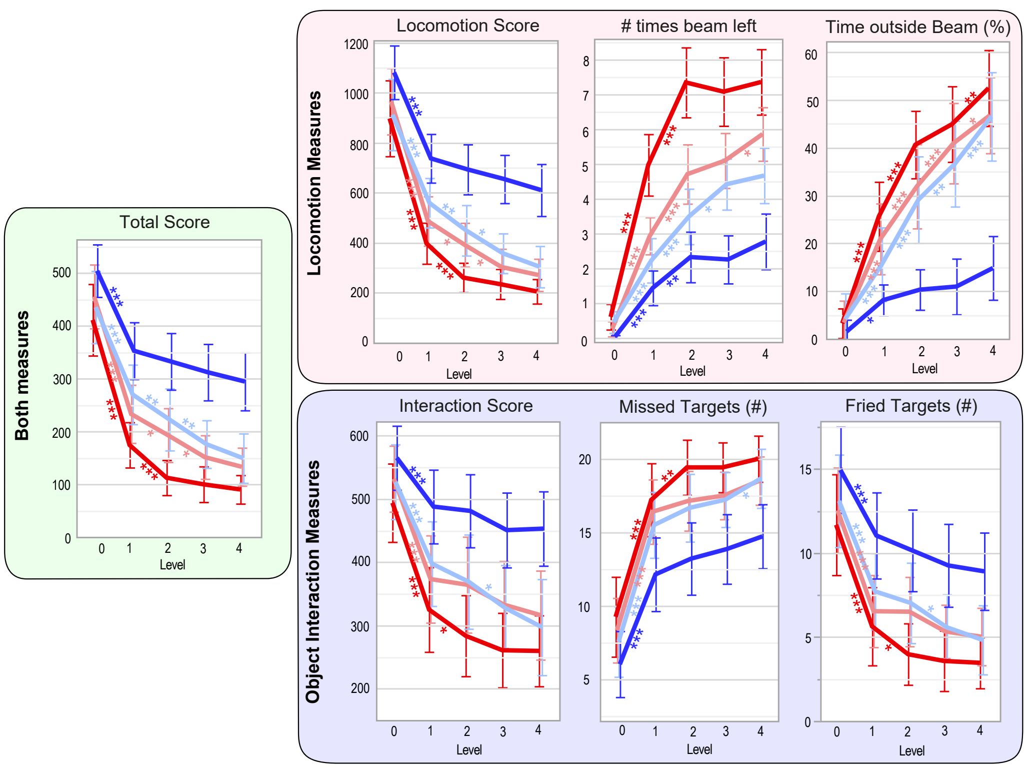


Fig. 4. Average data for performance measures over difficulty levels (locomotion speeds) for Controller (in red) vs. HeadJoystick (in hatched-red) vs. NaviBoard (in hatched-blue) vs. Walking (in blue). Seated conditions are color-coded in red to distinguish them from the upright conditions in blue. Annotated bars represent significance differences between behavioral measures in subsequent levels (* $p < .05$, ** $p < .01$, *** $p < .001$) using planned contrasts.

Joystick) leaning-based interface; and NaviBoard versus Walking, to compare partial (NaviBoard) versus full self-motion cues (Walking) for upright users. The rest of the data including ordinal data (i.e., favorite interface order ranking) and nine (out of 14) continuous introspective measures that violated normality assumptions were analyzed using Wilcoxon signed-rank test with Bonferroni correction. These were immersion, enjoyment, preference, vection intensity, daily use, long-term use, overall usability, ease of learning, ease of use.

**Behavioral data analysis methods.** We conducted $4 \times 3 \times 4$ repeated-measures ANOVAs for the independent variables interface, trial, and difficulty level for all behavioral measures. Due to the large number of DVs, ANOVA results are summarized in Table 2, with descriptive statistics and post-hoc tests summarized in Figure 2. As depicted in Table 2, our analysis showed significant main effects of interface, trial, and difficulty level on all behavioral measures, and significant interactions between interface and difficulty level for all but the fried/missed targets measures. The following paragraphs address individual questions based on these $4 \times 3 \times 4$ ANOVAs and post-hoc analyses:

**The effect of interface on performance and introspective measures:** Interface showed significant main effects on all introspective and behavioural measures, see Table 2, Figure 2, and Figure 3. Pairwise comparisons showed that physical walking improved all introspective and behavioral measures compared to all other interfaces ($p < 0.001$) except for the post-pre motion sickness, where walking showed no significant benefit over NaviBoard or HeadJoystick (see Figure 2). Although there was a consistent tendency for the NaviBoard to outperform the HeadJoystick, this trend reached significance only for the number of times users left the beam ($p = 0.025$). Compared to the controller, NaviBoard improved six (out of 14) introspective measures in terms of higher favorite interface order ranking ($p < 0.001$), enjoyment, preference, vection intensity, spatial presence as well as lower post-pre motion sickness (see Figure 2). HeadJoystick did not show any significant advantages on introspective measures compared to the Controller except higher favorite interface order ranking and the overall task load. However, HeadJoystick outperformed Controller in terms of most behavioral measures including significantly higher scores for locomotion, interaction, and combined accuracy as well as lower number of times beam left. In addition, HeadJoystick showed slight (but only marginally significant) advantages compared to the Controller in terms of more fried and less missed targets.

Figure 3 shows the comparison between interfaces in terms of absolute motion sickness, navigational task load, and overall task load as well as their sub-components. These results show a similar pattern of consistent advantages of walking over all interfaces, except physical demand which was higher for walking compared to both Controller and HeadJoystick. NaviBoard showed a similarly increased physical demand compared to the Controller and HeadJoystick. As for other task load sub-components, compared to the controller, using NaviBoard improved user ratings for their overall performance and slightly (but only marginally significant) improved navigational performance ratings as well as reduced overall mental demand. Compared to the Controller, using HeadJoystick reduced overall mental load and improved performance ratings while reducing total nausea. Compared to the Controller, HeadJoystick also showed a marginally reduced overall temporal demand and frustration as well as significantly increased navigational performance ratings (see Figure 3).

**The effect of repeated interface usage on performance:** ANOVA results showed significant main effects of repetition (aka trial) on all performance measures (cf. Table 2), and pairwise planned contrast tests showed significant improvement with each successive trial. Together with the lack of any significant interaction between trial and interface, trial and level, or trial and interface and level, this indicates that repeated interface usage over three trials improved performance similarly for all four interfaces, and did not significantly modify the observed main effects of interface, level, or their interaction.

**The effect of difficulty level on performance:** Difficulty level showed significant main effects on all behavioral measures, and significant interactions between interface and difficulty level for all but the fried/missed targets measures, cf. Table 2. As illustrated in Figure 4, performance decreased as predicted with increasing difficulty level, but slightly differently for each interface. We were specifically interested in comparing interfaces between subsequent levels, and investigating the influence of single-task vs. dual-task (level 0 vs. 1), rotational speeds (level 2 vs. 3) and translational speeds (level 1 vs. 2 and 3 vs. 4) on performance measures. The following paragraphs address these individual questions.

*The effect of interface on performance in level 0 when participants are not moving:* As participants did not move in level 0, one might expect that they should perform similarly for all interfaces. However, pairwise comparison (i.e., planned contrasts) between interfaces showed that using more embodied interfaces (and in particular walking) improved performance compared to less embodied interfaces already in level 0. That is, compared to the NaviBoard, Walking showed significantly improved total accuracy score ($p = 0.005$), locomotion score ($p < 0.001$), as well as slightly (but only marginally significant) higher number of fried targets ($p = 0.078$). Comparing NaviBoard versus HeadJoystick in level 0 showed no significant differences for any performance measures, but HeadJoystick showed slightly (marginally significantly) improved total score ($p = 0.068$) compared to the Controller. Potential reasons for these results are discussed in subsection 6.1.

*The effect of locomotion on object interaction performance:* We conducted $4 \times 2$ repeated-measures ANOVAs for the independent variables interface $\{$Controller, HeadJoystick, NaviBoard, Walking$\}$ and level $\{0, 1\}$ on all behavioral measures. Significant main effects of level on all performance measures showed that adding locomotion for level 1 reduced all performance measures (cf. Figure 4, all $p's < 0.001$). However, as illustrated in Figure 4 this performance decrease tended to be more pronounced for less embodied interfaces. This is corroborated by significant interactions between interface and level for all behavioral measures (all $p's < 0.014$) except fried targets ($p = 0.052$) and missed targets ($p = 0.076$), which both showed marginally significant trends.

*The effect of increasing (doubling) translational speed on performance:* We conducted $4 \times 2$ repeated-measures ANOVAs for independent measures of interface $\{$Controller, Head-

Joystick, NaviBoard, Walking} and level {1, 2} on all performance measures. Our results showed that increasing (doubling) translational speed between level 1 and 2 lead to an overall performance deterioration (main effect of level, cf. Figure 4), for all measures (all $p's < 0.008$). As illustrated in Figure 4, this performance reduction for increasing translational speed was more pronounced for the less embodied interfaces (and in particular the controller). This trend was corroborated by a significant interaction between interface and difficulty level for locomotion measures including the number of times beam left ($p = 0.042$), time percentage outside beam ($p < 0.001$), and marginally significant for locomotion score ($p = 0.076$). Planned contrasts further showed that increasing translational speed between level 1 and 2 decreased performance over one, four, and six (out of seven) measures when using Walking, HeadJoystick/NaviBoard, and Controller, respectively (cf. Figure 4).

Further increasing translational speed between level 3 versus 4 showed overall similar performance deterioration (cf. Figure 2) and significant main effects of level for all measures except interaction score and fried targets (all $p's < 0.01$). Although this performance decrease when translating faster seemed more pronounced for the less embodied interfaces compared to the walking condition (where pairwise comparison showed no significant deterioration, see Figure 2), the interaction between interface and level did not reach significance for any performance measure.

*The effect of increasing (doubling) rotational speed on performance:* We conducted $4 \times 2$ repeated-measures ANOVAs for the independent variable interface {Controller, HeadJoystick, NaviBoard, Walking} and level {2, 3} on all performance measures. All ANOVAs results showed significant main effects of level (all $p's < 0.039$), indicating that all performance measures were significantly deteriorated when rotational speed was increased from level 2 to 3. These main effects were qualified by significant interactions between interface and level for total score and locomotion measures (all $p's < 0.035$). Figure 4 and the planned contrasts show that walking performance remained at the overall highest levels despite the rotational speed increase and did not decrease significantly. However, HeadJoystick and NaviBoard performance did decrease for several performance measures but remained overall above Controller performance. These were all performance measures except the missed targets for NaviBoard, and three measures for HeadJoystick including locomotion score, overall score, and the time percentage outside beam. Controller performance was already at the lowest level of all interfaces and did not decrease further significantly when rotational speeds were doubled.

**No effects of participant demographics.** Additional ANOVAs showed that participants' demographics did not affect any of the usability, user experience, and performance measures. That is, neither gender (male versus female), prior experience with first-person 3D games (daily/weekly versus monthly/less), HMD usage (sometimes versus rarely/never), nor vision (normal versus corrected) showed any significant main effects of demographics or interactions with the locomotion interface.

# 6 General Discussion

This paper presents the first study exploring the effects of providing partial translational self-motion cues for HMD-wearing users in a simultaneous locomotion and object interaction task. Extensive research on leaning-based interfaces when using HMDs [71] often investigated locomotion-only tasks. Thus, there is limited knowledge of their effects in multi-tasking situations, where users need to interact with the environment during locomotion. Moreover, despite extensive research on how providing rotational embodied self-motion cues affects locomotion [49], there is little understanding of how providing translational embodied self-motion cues affect locomotion either in locomotion-only tasks (except [4]) or multi-tasking situations. To tackle these gaps, we explored how using different levels of translational body-based self-motion cues using leaning-based interfaces can affect locomotion and/or interaction performance in simultaneous locomotion and object interaction tasks. Overall, our results showed that providing higher levels of translational body-based self-motion cues improve user experience, usability, and effectiveness measures. That is, providing full physical self-motion cues in the Walking condition showed conclusive advantages over all other conditions. Moreover, compared to a hand-held controller, providing more physical self-motion cues in HeadJoystick and especially NaviBoard improved effectiveness, usability, and user experience factors. In the remainder of this section, we discuss the findings of our experiment in the context of our main research questions.

## 6.1 RQ1: How does providing partial self-motion cues improve effectiveness in locomotion and object interaction tasks?

Overall, the results confirmed our hypothesis: While physical walking performs the best, providing partial translational self-motion cues using NaviBoard and HeadJoystick improves most effectiveness measures over Controller for both locomotion and object interaction measures (cf. bottom row of Figure 2). These findings corroborate recent user studies that reported adding different levels of embodied cues improve performance in a navigational search task [4]. Our study provides the first experimental evidence that those benefits can be extended to simultaneous tasks of locomotion and object interaction. While recent research showed that seated (i.e., NaviChair) and standing (i.e., NaviBoard) leaning-based interfaces performed almost comparable to walking [4], our findings showed a significant performance advantage of walking over all other interfaces. A potential reason for this include the dual-task of moving and interacting, other task differences, and the different difficulty levels in our study design. Overall, our findings suggest that although leaning-based interfaces outperform hand-held controllers, they might not be as good as walking, at least for more complex dual-tasks.

Our findings regarding higher effectiveness of HeadJoystick over Controller corroborate to recent research that reported improved locomotion effectiveness of HeadJoystick when compared to the Controller in locomotion-only tasks [11], [17], [18]. These findings provide the first experimental evidence that the benefits of providing partial self-motion cues are not limited to locomotion performance, but are able to either directly or indirectly improve object interaction performance in simultaneous tasks of locomotion and object interaction. A potential reason for why prior research on embodied interfaces using multi-tasking scenarios did not show such findings [5], [12], [15], [16] could be because our task really forced users to navigate and interact with objects at the same time. However, in those prior studies, the users could at least in theory switch between locomotion and object interaction task, which might explain why object interaction performance did not significantly deteriorate with the added locomotion task. Prior studies that compared leaning-based interfaces with handheld interfaces in multi-tasking scenarios also reported lower effectiveness of leaning-based interfaces compared to the handheld controllers [5], [12]. A potential reason for these contradicting results could be due to using mouse and keyboard instead of thumbstick. That is, while mouse and keyboard provide higher accuracy compared to a thumbstick [72], they are not easily usable when wearing an HMD. Another potential reason for these contradicting results could also be due to our design considerations (such as providing tactile feedback for the zero-point) for improving the effectiveness of our leaning-based interface prototypes (i.e., HeadJoystick and NaviBoard) as discussed in subsection 4.4.

Our findings regarding higher effectiveness of embodied interfaces over Controller for HMD-wearing users in multi-tasking scenarios also contradict prior research that used head-directed steering, where the user controls simulated self-motion by rotating their head [15], [16]. However, unlike leaning-based interfaces, head-directed steering does not require the user to translate their head toward the target direction. Therefore, using head-directed steering does not provide translational vestibular cues aligned with the virtual self-motion, which are known to improve locomotion believability and reduce motion sickness. Moreover, head-directed steering does not allow the user to freely look around during locomotion [73], see also section 8.5.1 of [65], section 11.2.2.1 of [6], and section 28.3.2 of [74]. In contrast, HeadJoystick and NaviBoard allowed users to freely rotate their head to look around without affecting virtual self-motion. In fact, to ensure that head rotation does not affect locomotion when using HeadJoystick and NaviBoard, we used the movement of the head's rotation center (instead of the HMD) to control locomotion when using HeadJoystick and NaviBoard - see HeadJoystick design details in the appendix of [17], [18].

**How does repeated usage of interfaces affect performance?** Our findings corroborate recent user studies that showed that the performance advantage of leaning-based interfaces over the Controller does not decline over repeated usage [17], [18]. However, unlike those earlier studies, where the performance advantages of HeadJoystick over controller became more prominent over time, repeated interface usage in this study improved performance similarly for all interfaces. A potential reason for that could be due to having less repetitions in this study (i.e., three) compared to the earlier studies (i.e., eight), which might not give users enough time to show learning benefits for the novel (leaning-based) interfaces. That is, they might have still been preoccupied with learning the (rather challenging) dual-task with not enough time to improve interface usage. Otherwise, we would expect higher performance improvement for less familiar interfaces such as HeadJoystick and NaviBoard compared to more familiar interfaces such as walking and Controller.

**Does participants' performance depend on the interface even in level 0 when they are not moving?** Though participants did not move in level-0, the embodied interfaces still had a better performance. How the trial started could be one of the potential reasons for this. Even though the level-0 should have included no locomotion, the participants were not at the center of the beam when the scene started. When they moved from the edge of the room and reached the center of the beam, the trial started. However, with the Controller they often overshot the target and needed to make adjustments before they could stay stationary and focus on the object interaction task. While adjusting themselves to the center of beam, they lost some locomotion scores as well as time to interact with the objects.

**How does object interaction with locomotion compare to interaction without locomotion?** As expected, performance levels dropped by almost 50% when users had to switch from an object-interaction-only task in Level 0 to a simultaneous multitasking of interaction and locomotion in level-1 (cf. Figure 2), presumably due to increased mental/task load. The significant interaction between interface and trial for every performance measure between level 0 versus 1 suggests that the performance cost of multitasking was more pronounced for less embodied interfaces. A potential reason for such findings could be that less embodied interfaces in our study required more mental resources due to their higher overall mental demand (cf. Figure 3-top). In particular, the controller seems to have required additional mental resources, especially for the dual-task, as corroborated by participants' exit interview feedback: E.g., *"using your head to look and move when using HeadJoystick is easier than to use your head for looking and your thumb to move."*(P9)) or *Controller required me to control moving my head, arm sword, joystick finger, and chair, which was too many things to control"*(P17). Interestingly, comparing Controller with HeadJoystick/NaviBoard in terms of navigational mental demand did not show a significant difference (cf. Figure 3-bottom). This could be because the locomotion task alone might not require much mental load as the path was smooth and predictable (by design) and locomotion speeds were fairly slow (i.e., 0.15-0.3 m/s). Further, separating tasks over separate hands could be another potential reason for the lower effectiveness of handheld over leaning-based interfaces [1] as *"It is confusing to use my left hand to move and right hand to hit targets."*(P10). The typically lower performance of the non-dominated hand when using the Controller could also have contributed [75].

Our findings are noteworthy as this study provides (from all we can tell) the first empirical evidence that using hands for controlling navigation can be detrimental to performance when also having to interact with objects. While prior research has claimed that overloading hands for navigational functionality is detrimental to performance when also performing other tasks [1], previous studies often did not show significantly reduced object interaction performance when using hands to control navigation [15],

[16]. A potential reason for our contradicting results could be that unlike the tasks in these previous studies, our task forced the users to use navigation and object interaction at the same time instead of allowing users to switch between them.

**How does increasing (doubling) translational speed affect performance?** Increasing (doubling) translational speed further widened the performance differences among our interfaces. Interestingly, it also significantly deteriorated the object interaction measures for the Controller but not other interfaces. A potential reason could be increased cognitive load of the Controller, which was rated as overall more mentally demanding (cf. Figure 3-top). As P21 explained it, *"it was not easy to use controller for multiple tasks. So, controller might be perfect for less accurate tasks, which you don't want to move your body a lot"*. Thus, when using embodied interfaces, increasing translational speed in level 2 still allows the user to keep performing the object interaction task with a non-significant performance decrease. P9 further provided body vs. hand/finger movements as additional potential underlying reasons: *"Using our physical body to move is easier than a controller, as I have more control over my physical body."* This is aligned with prior research that also reported enhanced intuitiveness [7], [8], [17], [18] and reduced cognitive load [4] of leaning-based interfaces compared to the Controller. Thumbstick sensitivity could be another contributing factor to the disadvantages of Controller compared to other interfaces, as P15 said *"Perhaps, because of the small range of controller thumbstick motion range, I always overshoot beam and so to stay at the center of the beam, I went forward and backward again and again."* Similar sensitivity issue of the controller for accurate movements have been reported by the participants in our prior user studies [17], [18].

**How does increasing (doubling) rotational speed affect performance?** When rotational speed increased (doubled) in level 3, most performance measures (6 out of 7) were reduced for HeadJoystick and NaviBoard but not for Controller or Walking (cf. Figure 4). As for the controller, most performance levels were already at a very low level and did not decrease further. For example, participants fried very few (3.5-4 out of 24) targets using Controller after level 2, where one third of participants fried less than one target on average (i.e., less than 5% of targets). However, for the leaning-based interfaces, participants still managed to fry 6.75 (out of 24) targets at level 2, which was significantly reduced to 4.9 (out of 24) targets at the most difficult level 4. The Walking interface showed a slight but non-significant decrease on all performance measures and stayed at a much higher level. Even at the most difficult level, walking participants were still able to fry 8.9 (out of 24) targets, which was more than twice as many as for the Controller.

### 6.2 RQ2: How does providing partial self-motion cues improve usability and user experience in simultaneous locomotion and object interaction tasks?

Our results showed that providing partial self-motion cues using HeadJoystick and NaviBoard improved user experience compared to the Controller, but not usability measures. That is, the NaviBoard provided significant benefits over the hand-held controller in five of the six user experience measures (enjoyment, overall preference, vection intensity, presence, and motion sickness) but none of the six usability aspects. HeadJoystick showed similar trends but did not show any significant subjective benefits over the controller except for the overall task load and favorite interface order ranking.

**How does providing partial self-motion cues affect user experience?** In contrast to our work, prior studies on simultaneous locomotion and object interaction tasks only investigated leaning-based interfaces for VR applications on projected screens [5], [12], not HMDs. Moreover, these prior studies often only measured a few introspective aspects. They reported limited benefits of leaning-based interfaces over controller including increased enjoyment [5], improved usability, and presence [12]. Our findings corroborate these enjoyment and presence benefits of the leaning-based interfaces and extend these benefits to other user experience measures, namely vection intensity, motion sickness, task load, and overall preference. Similar benefits have previously been reported for leaning-based interfaces in locomotion-only tasks [2], [4], [9], [17], [19], [76], [77], [78]. Our findings extend these benefits beyond locomotion-only tasks to simultaneous locomotion and object interaction tasks, which is relevant for numerous applications where users' goal is not just to locomote, but also interact with their environment or other people.

In post-experiment interviews participants provided several potential reasons for the user experience advantages of HeadJoystick and NaviBoard over the Controller, corroborating and extending earlier findings [17], [18]. Reasons mentioned include more natural body movements: *"Head movement was more natural than the controller"*(P19) and NaviBoard *"had more movement than HeadJoystick and Controller, which made me more energized"*(P8). Furthermore, P14 stated that *"NaviBoard was pretty much same as walking, and I could feel my whole body and feel the environment more. It feels more like a reality to me."*. Prior research stated that such levels of exertion could be enjoyable and motivating for users [79]. Another reason offered by participants is the alignment of head translation direction (and associated vestibular and proprioceptive cues) with the resulting simulated translation when using head-based leaning-based interfaces: P14 explained that *"using HeadJoystick, I could move my head and upper body (rather than only my finger when using controller) to feel actually traveling in the virtual reality. Controller does not feel like VR, its like playing a desktop game."*. Increased fun/enjoyment of natural interfaces over Controller thumbstick have been reported in prior research [3], [9], [13] and chapter 4 of [40].

**How does providing partial self-motion cues affect usability measures?** In contrast to our work, our previous user studies showed subjective benefits of HeadJoystick over Controller in almost all user experience and usability measures [17], [18]. Such contradicting results can have a combination of responsible factors. For example, we implemented controller-directed steering for the Controller condition, where the forward direction was determined by the yaw direction of the Controller (instead of body/chair). Using a similar controller-directed steering approach in one of our previous user studies showed non-significant differences with HeadJoystick in terms of vection intensity, ease of learning, task load, and potential for daily and longer-term usage [18]. Another potential factor could be the fairly small range of the locomotion speeds (i.e., 0.15-0.8 m/s), which does not reveal the usability issues (i.e., sensitivity) of the thumbstick for accurate speed control [17], [18]. Another potential reason could be because the task got quite hard for all conditions except walking at the last level, and none of other conditions were comparable with walking, which can be the reason participants rated the usability of other conditions not much different.

Participants also suggested other factors for the improved usability of the Controller: *"Controller is familiar for me due to regular games "*(P24) especially for participants with *"extensive game console experiences"*(P13); Controller's thumbstick *"automatically comes back to its center."*(P5); and controller does not require much physical effort (cf. Figure 3) as *"I did not need to use my body to move when using Controller"*(P20).

Overall, our results showed that while leaning-based interfaces can improve user experience and performance compared to the controller-based interfaces, further research is needed to better understand and improve their usability to be ready for daily use as an alternative to Controllers. Our previous works also showed the weakest advantage of HeadJoystick compared to the Controller in terms of the long-term and daily use [17], [18], [19].

### 6.3 RQ3: When comparing leaning-based interfaces, how does standing/stepping vs. sitting on a chair affect effectiveness, user experience, and usability?

Overall, the results confirmed our hypothesis: while the NaviBoard mostly showed non-significant trends for performance and user experience advantages over HeadJoystick, using NaviBoard instead of HeadJoystick showed more significant benefits over Controller (cf. Figure 2). In the following paragraphs, we discuss the seated vs. standing/stepping body posture in terms of different measures such as effectiveness, motion sickness, and naturalness.

**When comparing leaning-based interfaces, how does standing/stepping vs. sitting on a chair affect effectiveness?** Prior research often suggested higher accuracy/precision of seated over standing leaning-based interfaces [43]. However, our results showed that accuracy/precision of leaning-based over controller can be improved if designed for a standing/stepping instead of a seated user. A potential reason behind the more apparent effectiveness benefits of NaviBoard over HeadJoystick could be the larger (i.e., doubled) motion range and thus enhanced translational vestibular/proprioceptive self-motion cues of NaviBoard compared to the HeadJoystick, which might have contributed to a more accurate control of the NaviBoard. Standing body posture could also help the interaction effectiveness due to the larger hand movement range when following a vertically moving target in a standing instead of seated body posture. However, such difference should provide effectiveness advantages for the NaviBoard over HeadJoystick even in level 0 with no locomotion, which our results did not show (Figure 4). Some participants also found NaviBoard to be more intuitive than HeadJoystick. As P12 said, *"slight touch of walking felt better than Controller and HeadJoystick, because it made the control much easier."*

**When comparing leaning-based interfaces, how does standing/stepping vs. sitting on a chair affect motion sickness?** Prior research showed more severe motion sickness when using handheld controllers in standing (instead of sitting) posture [42]. This was attributed to the postural instability theory [41], which predicts increased motion sickness in unstable body postures such as standing over seated interfaces. However, in our study we found the opposite trend: while both leaning-based interfaces showed a trend towards reducing motion sickness compared to the (seated) controller, this benefit was more pronounced and reached significance for the standing/stepping (NaviBoard) but not the seated (HeadJoystick) interface. This confirmed the findings in a previous NaviBoard study [4]. As motion sickness can accumulate across repeated sessions in within-subject designs, we also show the absolute motion sickness scores and sub-components in Figure 3. These absolute scores corroborate post-pre motion sickness results by showing an overall similar pattern for reducing motion sickness when providing higher levels of embodied self-motion cues, where using HeadJoystick significantly reduced absolute nausea scores when compared to the Controller. A potential reason for this could be that standing/stepping leaning-based interfaces (such as NaviBoard) are more natural compared to the seated ones (such as HeadJoystick) as they are more similar to actual walking in a limited area, and provide additional proprioceptive and vestibular self-motion cues aligned with the virtual translations, thus reducing sensory conflicts and motion sickness - and maybe even postural instability.

**When comparing leaning-based interfaces, how does standing/stepping vs. sitting on a chair affect naturalness?** Our results corroborated the previously reported benefits of standing over seated interfaces in terms of more intense vection, higher engagement, and higher degrees of embodiment [43]. For example, compared to the HeadJoystick, NaviBoard provided a more similar experience to Walking due to its standing body posture, as P9 said *"NaviBoard's standing position helps to feel I am in the interface, which is better than to be seated in a chair"*. Standing body posture when using NaviBoard provides motion cues for the whole (instead of upper) body when using HeadJoystick, which can improve presence/immersion and vection intensity as P21 explained *"NaviBoard was more accurate than the Controller, and more immersive as it was like a standing version of walking"*(P21). Stepping also improved NaviBoard's believability as it was *"like walking in a smaller area"*(P19), and *"NaviBoard felt more natural than HeadJoystick, and was like walking"*(P6).

**How to improve usability aspects of standing/stepping leaning-based interfaces (i.e., NaviBoard)?** Participants also suggested usability issues of the NaviBoard, which could be the potential reasons for why NaviBoard did not show significant advantages compared to the HeadJoystick, and could help to improve NaviBoard in future design iterations. For example, future design iterations might need to improve awareness of the zero-point as *"when I put both my feet on Styrofoam during fast rotations, I lost the zero-point."*(P15). Improving postural stability, intuitiveness, and perceived safety are additional design challenges for

NaviBoard as participants reported *"as my feet did not automatically know how to always follow my head"*(P17) and *"once a while I was afraid to lose my balance."*(P22) specifically during rotations or in corners. For example, P17 said *"while moving forward, when the path rotated to the right, I started changing my direction by leaning a bit to right but forgot to adjust my feet, which then I felt like I am about to stumble."* and P10 said *"my foot just moving around and got in the way especially in the corners, and I did not know what to do with my feet."*.

Despite the aforementioned usability issues, from an applied perspective, our findings and recent research (e.g., [4]) suggest using standing/seated (instead of seated) leaning-based interfaces for natural simulation of physical walking in VR applications. Nowadays, due to the increasing accuracy and affordability of inside-out HMD tracking, free-space walking is becoming increasingly feasible and often preferred whenever there is sufficient free space that is safe for walking. However, the space that can be freely walked is often limited, and for larger distances users tend to prefer/require virtual locomotion due to reasons such as reduced travel times, effort, and fatigue. Therefore, combining free-space walking with leaning-based interfaces is a potentially fruitful avenue for future research, and we are actively working on this integration. For example, such integration can happen by switching between leaning-based interfaces and walking when pressing a designated button on a controller, using gestural or voice input depending on the context and technical options.

Seated leaning-based interfaces can also be used in scenarios where standing posture leads to fatigue and discomfort (such as long-term walking scenarios) or when there is an increased risk of falling due to large virtual accelerations (e.g., roller-coaster applications) [46]. Seated leaning-based interfaces can also be used by users who are unable to stand (e.g., wheelchair users), those that prefer to sit [43], or when sitting better matches the locomotion metaphor (e.g., driving or flying).

### 6.4 Limitations

Due to the complexity of our tasks, our locomotion task required participants to move forward fairly slowly, and did not require much backwards or sideways motions, which could limit generalization of our findings to other types of locomotion tasks. Thus, future studies could assess how our results might generalize to other types of locomotion with faster speeds such as fast walking, running, or driving/flying speeds. As for the interfaces, participants' familiarity with using thumbstick (but not NaviBoard/HeadJoystick) could affect our results, and might have reduced potential effects. As for the controller condition, future research could also investigate how sitting versus standing body posture might affect locomotion when using hand-held controllers. Our study investigated hand-held controller using controller-directed (instead of torso-directed) steering, where the forward deflection of the thumbstick moves the user toward the direction of the controller (instead of torso). However, as prior research showed that using torso-directed (instead of controller-directed) steering can improve path anticipation during navigation [80], future research could also investigate multi-tasking locomotion scenarios using controllers with torso-directed versus hand-directed steering. Future studies could also investigate generalizability of our results to other multi-tasking scenarios such as exploration, relative positioning (e.g., capturing photo), navigational search, and FPS games, which require designing other interaction mechanisms for leaning-based interfaces such as jumping/crouching.

As for participants, our sample size (24) and statistical power might not be large enough to detect subtle effects, and thus we also reported marginally significant effects ($.05 < p < 0.1$). Further splitting participants based on demographics could be the reason why participant demographics did not show any significant effects on our results. Therefore, future studies with larger and more diverse participant populations are needed to find more conclusive answers. As for measures, while we assessed a wide set of locomotion-relevant measures in our study, our tasks was not designed to assess other constructs such as information gathering potential, spatial/situational awareness, or spatial orientation in simultaneous locomotion and object interaction tasks. Future works can also investigate how our findings might or might not generalize to different tasks, scenarios, and setups, and in particular if future design iterations might be able to improve the ergonomics and performance of hand-held controllers, hand-gestures, or hand-movements.

Due to COVID-19, we conducted our study in one 75 minute session, which limited the interface usage time to 6 minutes per interface. Our findings showed that the differences between our interfaces did not decrease over this relatively short interface usage time. However, future studies could assess how our findings might generalize to longer-term usage per interface and/or multiple sessions. Given that the leaning-based interfaces were novel to all our participants (whereas they were familiar with hand-held controllers), we would tentatively predict that the observed performance differences between leaning- and hand-held interfaces might, if anything, further increase once novelty and initial learning effects are overcome. As another example, using four interfaces in one session could potentially also lead to accumulating motion sickness due to carry-over effects, even though we asked participants to spend 5-10 minutes answering questionnaires after using each interface as a resting time before they used the next interface. Due to limitations during the COVID-19 pandemic it was unfortunately not feasible to run a full between-subject design or invite participants to come to the lab on 4 different days. Nonetheless, given that we used a counterbalanced design, there were breaks between VR exposures, and that the post-pre and absolute motion sickness scores showed overall similar differences between interfaces, potential carry-over effects might have added noise to the data and reduced the observed motion sickness differences between interfaces. However, future research is needed to investigate how our results compare to between-subject experimental designs or testing on separate days.

## 7 Conclusion

In this paper, we investigated how different levels of translational self-motion cues might affect effectiveness, user experience, and usability in simultaneous locomotion and object interaction tasks in VR. We compared four locomotion interfaces that provide increasing levels of self-motion cues, namely Controller, HeadJoystick, NaviBoard, and physical walking. Our results showed that while physical walking is the gold standard locomotion interface and clearly outperformed all other interfaces, providing some non-visual self-motion cues using leaning-based interfaces such as HeadJoystick and especially NaviBoard could still provide benefits in most effectiveness and user experience measures compared to minimal/no self-motion cues (Controller). Besides improving effectiveness, providing self-motion cues for the whole body of a standing/stepping user using NaviBoard instead of Controller improved most user experience measures including enjoyment, preference, vection intensity, spatial presence, and reduced post-pre motion sickness. Comparing these results over three consecutive trials also showed that these effects remained over repeated interface usage.

As far as the authors know, this work is the first study investigating leaning-based interfaces in an HMD-based dual task of simultaneous locomotion and object interaction. Furthermore, our findings contradict prior research investigating leaning-based interfaces in multitasking scenarios on projection screens [5], [12], by showing that using more embodied locomotion interfaces such as HeadJoystick and NaviBoard over Controller improves locomotion effectiveness and user experience measures. Moreover, while the previous research often measured only overall performance measures (such as number of kills in a FPS game), our newly designed paradigm of a gamified locomotion and object interaction task distinguished performance in locomotion versus object interaction and showed that providing higher levels of self-motion cues improves not only locomotion but also interaction effectiveness. Overall, our findings extend the effectiveness of leaning-based interfaces beyond locomotion-only tasks [4], [17], [18] to simultaneous locomotion and object interaction tasks.

To the best of our knowledge, this study provides the first empirical evidence that using hands for controlling navigation can reduce interaction performance in simultaneous locomotion and object interaction scenarios. While this might seem obvious, several prior studies failed to observe this detrimental effect of effect hand- or controller-based navigation on interaction performance (e.g., [15], [16]). This could be due to the challenge of designing true multi-taking scenarios where users cannot "cheat" by switching between tasks. Therefore, we would suggest future research to consider the below guidelines when aiming to design true multi-tasking scenarios:

- **Enforce multi-tasking:** Design tasks so users cannot alternate or switch between tasks, e.g., by requiring continuous control for both tasks.
- **Carefully test:** Carefully and thoroughly test (ideally with experienced observers) that it is really not possible to "cheat" by switching between tasks.
- **Vary task difficulty:** As some effects can be subtle and hard to detect, and different participants might have different skills for the tasks to be investigated, we suggest to vary task difficulty in at least one of the tasks that comprise the multi-tasking scenario.

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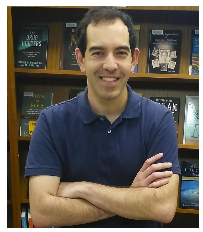

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