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Leaning-based interfaces improve ground-based VR locomotion in reach-the-target, follow-the-path, and racing tasks

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

Abstract—Using standard handheld interfaces for VR locomotion may not provide a believable self-motion experience and can contribute to unwanted side effects such as motion sickness, disorientation, or increased cognitive load. This paper demonstrates how using a seated leaning-based locomotion interface –HeadJoystick– in VR ground-based navigation affects user experience, usability, and performance. In three within-subject studies, we compared controller (touchpad/thumbstick) with a more embodied interface ("HeadJoystick") where users moved their head and/or leaned in the direction of desired locomotion. In both conditions, users sat on a regular office chair and used it to control virtual rotations. In the first study, 24 participants used HeadJoystick versus Controller in three complementary tasks including reach-the-target, follow-the-path, and racing (dynamic obstacle avoidance). In the second study, 18 participants repeatedly used HeadJoystick versus Controller (8 one-minute trials each) in a reach-the-target task. To evaluate potential benefits of different brake mechanisms, in the third study 18 participants were asked to stop within each target area for one second. All three studies consistently showed advantages of HeadJoystick over Controller: we observed improved performance in all tasks, as well as higher user ratings for enjoyment, spatial presence, immersion, vection intensity, usability, ease of learning, ease of use, and rated potential for daily and long-term use, while reducing motion sickness and task load. Overall, our results suggest that leaning-based interfaces such as HeadJoystick provide an interesting and more embodied alternative to handheld interfaces in driving, reach-the-target, and follow-the-path tasks, and potentially a wider range of scenarios.

Index Terms—3D User Interface, Motion Sickness, Cybersickness, Locomotion, Travel Techniques, Virtual Reality

1 Introduction

Locomotion is a key element in many real-world experiences and tasks. Therefore, many virtual reality (VR) applications can benefit from a believable locomotion experience to achieve a convincing simulation of those experiences. For example, many VR games, architectural walk-through, and telepresence applications require the simulation of walking, running, and driving. However, it often is challenging to simulate a believable locomotion experience in VR, as real-world limitations usually do not allow for exploring large virtual environments (VEs) by actual walking or driving. Handheld interfaces (such as a gamepad or handheld VR controllers) do not provide embodied (proprioceptive and vestibular) self-motion cues. This could reduce the believability of locomotion, and can contribute to unwanted side-effects such as motion sickness, disorientation, and increased cognitive load [1], [2], [3].

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To address these challenges, researchers investigated embodied locomotion interfaces, which include physical motion cues during locomotion. *Leaning-based interfaces* are affordable embodied interfaces, where user-powered leaning controls the virtual motion, thus providing limited body-based self-motion cues. Leaning-based locomotion interfaces have been compared to handheld interfaces and showed advantages in terms of presence/immersion [4], [5], spatial awareness [2], [3], speed, ease of use or task load, and comfort/sickness [3]. However, compared to handheld interfaces, leaning-based interfaces often show lower accuracy/precision [4], [5], [6], [7], [8], [9], [10]. Therefore, leaning-based interfaces are often considered as more of a promising prototype for specific sets of tasks [11].

In this work, we study if leaning-based interfaces might be capable of providing a viable alternative to handheld interfaces in a wider range of scenarios. We investigate if a well-designed leaning-based interface could improve most if not all relevant measures, especially accuracy, for 2D (ground-based) locomotion. We recently introduced a leaning-based interface called ***HeadJoystick***, where users move their head toward the target direction to control their virtual velocity, that is speed and direction [12]. The user is seated on a regular swivel chair and controls virtual rotation by the physical rotation of the chair using a 1:1 mapping. Previously, we evaluated HeadJoystick for 3D (flying) locomotion and showed improvements in almost all relevant measures including accuracy/precision using a waypoint navigation task [12]. However, as we did not investigate HeadJoystick for 2D (ground-based) locomotion, it is yet an open question if the found advantages of leaning-based interfaces observed for 3D flying locomotion also generalize to 2D ground-based locomotion tasks, where handheld controllers are fairly easy to use due to more familiarity and less degrees of freedom (i.e., up/down motion). The current paper addresses this gap and research question by investigating three complementary ground-based locomotion task using diverse performance measures including throughput.

With the exception of the study by Buttussi and Chittaro [13], prior leaning-based interfaces have typically been investigated in only one specific task, or in terms of only a small subset of relevant measures. This limits generalization of their advantages/disadvantages over different tasks or in terms of other measures. For example, to the best of our knowledge, leaning-based advantages for 2D (ground-based) locomotion in terms of ease of use or task load, and comfort/sickness were only reported in a navigational search task [3] and thus it remains an open questions whether these advantages might or might not generalize to a wider ranges of tasks. To address this gap, we evaluated HeadJoystick over three different complimentary tasks that are capable of measuring accuracy/precision. For example, accuracy can be measured by proximity to the desired target when the user is asked to reach a target, or path when the user follows the path [14]. To address these types of tasks, we included both a ***reach-the-targets*** task, where users were asked to collect as many targets as possible; and ***follow-the-path***, where users were asked to follow and stay on a predefined path as best as they can. Unlike the generally used versions of these tasks, we adjusted them to get increasingly difficult to assess different levels of interface accuracy/precision. That is, in the reach-the-targets task, the targets' size was getting increasingly smaller [15], and in the follow-the-path task, the path was becoming increasingly narrow [16]. Moreover, as complex environment with obstacles and motion may produce strikingly different results on performance measures [17], we also evaluated HeadJoystick in a ***racing*** task, where users were asked to follow a road and overtake as many dynamically moving obstacles (cars) as possible without crashing into them or going off the road.

We conducted three user studies to thoroughly evaluate HeadJoystick in different scenarios: In Study 1, we evaluated HeadJoystick using reach-the-target, follow-the-path, and racing tasks. Study 2 evaluated repeated usage of HeadJoystick in a reach-the-target task for eight one-minute trials, to investigate how results might generalize to extended exposure. In Study 3, we evaluated potential benefits of different brake mechanisms when the user needs to stop at each target. Our pilot-testings showed that four (out of six) participants could not complete three tasks of Study 1 using a gamepad to control all three degrees of freedom due to severe motion sickness. Therefore, we excluded gamepad in all our three studies, and only compared two interfaces that control the virtual rotation with a 1:1 physical rotation. In the HeadJoystick condition, participants lean in the direction they want to translate. In the Controller condition, forward direction is determined by their chair (Study 1 and 2) or Controller (Study 3) yaw direction, i.e., touching top-side of the touchpad moves you in the forward direction of the chair or Controller. The user is always seated on a regular office swivel chair and controls their simulated yaw rotation with 1:1 physical rotation of the chair, identical to how rotations are controlled with the HeadJoystick. Previous work by Bowman and colleagues, in particular [14], [17], [18], [19], [20], suggests that an effective locomotion interface promotes eight factors including: speed, accuracy, spatial awareness, ease of learning, ease of use, information gathering potential, presence, and user comfort. We argue that these measures do no sufficiently reflect performance in our specific tasks, and thus included a number of new measures such as *vection intensity*, user's embodied sense of self-motion; *enjoyment*, user's enjoyment due to using the interface; *precision*, the ability of interface for fine movements without missing the target or colliding with the path or obstacles; *throughput*, which combines speed, accuracy, and precision [21], [22]. Detailed discussion of how we suggest expanding previous measures and why assessing each of our suggested factors is important for thoroughly evaluating a locomotion interface is summarized in the **??**-Appendix. The main contributions of this work are:

- We gain new insights into usability/performance and user experience of leaning-based locomotion interfaces by extending previously used measures (cf. **??**-Appendix). HeadJoystick showed significant and consistent advantages over hand-held controller conditions (touchpad and thumbstick) in terms of both behavioral performance measures (e.g., speed, accuracy, precision, overall score, and throughput), and additional usability and user experience measures.
- We address the extended measures by investigating locomotion techniques in three complementary tasks, reach-the-target, follow-the-path, and racing (cf. subsection 3.2) that contrast different navigation tasks and performance aspects. Overall, results indicate that HeadJoystick can be considered as an alternative solution for handheld locomotion interfaces in all these aforementioned types of tasks.
- We compare short-term usage with repeated usage of the locomotion interfaces to address if results generalize to repeated usage, which they did. While the number of targets reached improved with practice for both interfaces, the number of missed targets also increased substantially for the Controller, whereas for the HeadJoystick it remained constant and at a much lower level. Moreover, while motions sickness only slightly increased for HeadJoystick and remained fairly low, for the gamepad motion sickness increased to levels three times as high, where users noted limitations.
- Finally, we investigated if leaning-based interfaces might be suitable for tasks requiring the user to slow down and stop precisely at target position, e.g., to do other tasks such as interaction or manipulation. We investigated potential benefits of different brake mechanisms, and showed that with or without added braking options, leaning-based interfaces such as HeadJoystick outperformed the Controller over the course of 3 two-minutes trials.

2 Related Work

Convincing visual self-motion cues provided by head-mounted displays (HMDs) [23] can cause sensory conflict if not accompanied by aligned physical self-motion cues. Handheld interfaces such as touchpad/thumbstick and steering wheels (chapter 4 of [24]) lack body-based self-motion cues, which can cause sensory conflicts known to contribute to motion sickness [25] and disorientation (see chapter 1 of [26]). Sensory conflicts can be largely prevented by actual walking, as it provides full-scale body-based self-motion cues for both translation (changing position) and rotation (changing direction). However, full-scale translation is typically not feasible for large VEs due to space limitations or safety concerns. Therefore, various embodied interfaces have been designed and investigated for VR locomotion [27] that provide some of the non-visual sensory cues available in actual self-motion.

As our goal was to use a low-cost locomotion interface that would be suitable for broad general usage including VR home-users, many embodied interfaces might not be feasible for our purpose. For example, motorized walking platforms such as omni-directional treadmills, which bring a walking user back to their initial position (chapter 9 of [26]) or non-motorized walking platforms that use sliding shoes [28] are often costly, unreliable, or barely usable - section 6.4 of [20]). Moreover, walking platforms are not suitable for driving applications such as our *racing* task and other applications were users prefer to sit. Researchers also developed driving interfaces such as exercise bikes [29], [30] and motion base car driving simulators with steering wheels and pedals, or even full cockpits [31], [32], [33], but their cost, tie to specific locomotion tasks and technical complexity prevents wide-spread usage. In contrast, low-cost embodied locomotion interfaces often provide user-powered motion cues instead of relying on external actuation. Walking in place (WIP) is an example, where the user walks in place and the velocity and/or height of their steps control the velocity of locomotion - section 11.2 of [26]. While WIP showed advantages over handheld interfaces in terms of improved spatial orientation [34], [35], this technique usually does not allow for sideways or backward motion [36] and causes fatigue in long-term usage. Moreover, it could not be used for some ground-based locomotion tasks such as exploring large VEs or racing as velocities are limited to walking speeds. Another well-known locomotion paradigm is head-directed (often called gaze-directed) locomotion [8], [17], [37], [38], [39], [40], [41], [42], where the user controls forward/backward and sideways velocity using head tilt and pan respectively. However, this technique does not allow the user to naturally rotate their head to look around without changing their locomotion direction - section 8.5.1. of [20], section 11.2.2.1 of [26], and section 28.3.2 of [43].

2.1 Leaning-Based Interfaces

Leaning-based interfaces are another embodied locomotion technique, which use user-powered leaning to provide more convincing self-motion cues. Users simply lean toward the desired movement direction to control their virtual (translation) speed in that direction, typically using a velocity control paradigm. Leaning-based interfaces can track different parts of the user body such as head position [9], weight shift [2], [44], [45], upper body tilt while standing [3], [46], or tracking tilt of the chair/stool users are seated on [8], [47], [48]. Leaning-based interfaces free up users' hands, which allow them to more naturally use their hands for interaction such as manipulation tasks or communication [6], [7], [12], [46], [49], [50].

Some leaning-based interfaces also use a rate-control paradigm for rotations, where limited physical rotation of the user controls the simulated yaw rotation. This can be useful when using stationary (instead of head-mounted) displays [5], [47], when the physical setup cannot rotate [48], [49], or to prevent HMD cable entanglement for too many rotations [8], [51]. However, cable entanglement can be resolved by using wireless HMDs and controllers that have become widely available. Compared to limited physical rotation, full 360° physical rotation more closely resembles actual locomotion and associated cues. Thus, full-rotational leaning-based interfaces potentially could allow for higher believability along with lower motion sickness and disorientation. As an example, prior studies investigated how physical rotation alone (without translational motion cues) effects disorientation [52], and showed it's benefits [53], [54], [55], [56] such as improving navigational search task efficiency [3], [57]. We previously designed HeadJoystick as a full-rotational leaning-based interface, expanding on our prior design iterations [3], [7], [8], [12], [48], [49]. Different full-rotational leaning-based interfaces are juxtaposed and compared in **??**-Appendix, and reviewed in subsection 2.2.

2.2 Full-Rotational Leaning-Based Interfaces

Leaning-based interfaces have been designed for standing users [2], [3], [4], [44], [58] and seated user [7], [8], [13], [45], [47], [59], [60]. A standing body posture more closely resembles believable bipedal walking, but as we sought a universal VR interface for all 2D locomotion tasks, a standing posture might not be a natural posture for tasks such as racing, where users tend to sit [61]. Moreover, excessive uninterrupted standing posture could cause discomfort [62], leg swelling, and fatigue [63], with stronger motion sickness [64], [65] and postural sway during virtual accelerations [66], where the user could fall and get hurt. Therefore, we used HeadJoystick for seated users, even if it can easily be adapted for standing users as well [3]. In this section, first we review full-rotational leaning-based interfaces designed for standing body posture followed by interfaces for seated users.

Harris *et al.* introduced a leaning-based interface called Wii-Leaning [2], where the user stands on a Wii-balance board and shifts weight toward the target direction to control simulated velocity. Wii-Leaning improved spatial orientation compared to a handheld joystick in terms of reduced latency and pointing error toward previously seen virtual objects. Wii-Leaning also showed similar spatial orientation compared to walking-in-place, but with higher preference. Langbehn *et al.* designed Leaning-Amplified-Speed Walking-In-Place (LAS-WIP), where a standing user leans while walking in place to scale his/her virtual self-motion speed [58]. LAS-WIP showed higher preference compared to traditional WIP in a follow-the-path task, but was unfortunately not compared to handheld interfaces. Finally, Marchal *et al.* introduced the Joyman interface, where a user is standing on a trampoline surrounded by a safety ring and leans toward the target direction to control their simulated velocity [4]. Joyman was compared with joystick in a reach-the-target task, and showed lower efficiency (task completion time) but higher fun and presence.

Nguyen-Vo *et al.* introduced NaviBoard [3], where a standing user can lean and step toward the target direction, and compared it to Controller and NaviChair, where a seated user leans on a swivel stool toward the target direction. Compared to Controller, the NaviChair and NaviBoard revealed improved navigational search task efficiency (task completion time) and reduced travelled distance for NaviChair and NaviBoard, as well as reduced task load and motion sickness for NaviBoard. Moreover, NaviChair and NaviBoard yielded performance and user experience levels of physical walking.

Hashemian and Riecke introduced a precursor to HeadJoystick called Swivel-chair, where the user controls forward/backward velocity by changing the tilt angle of the chair backrest, and controls the sideways motion by sideways motion of their head. Swivel-chair was evaluated in a follow-the-avatar task versus Joystick, RealRotation, and a different version of NaviChair, which used weight shifting [7]. Compared to the joystick, while NaviChair showed reduced accuracy (distance error), precise control, comfort, overall usability, and potential for long-term use, Swivel-chair interface showed only reduced precision of control. This could be due to the swivel-chair backrest support, which makes upper-body leaning more comfortable and easier to control compared to weight shifting in NaviChair condition [8]. As post-experiment interviews showed that controlling the chair backrest tilt in the swivel-chair condition might not be easy and accurate for users, we designed HeadJoystick, where the user controls the simulated motion only using their head position. Buttussi and Chittaro also investigated an interface similar to the Swivel-chair called *Leaning*, where a user seated in a swivel chair leans toward the target direction to control translation velocity [13]. This Leaning interface was compared with Joystick/Controller and teleportation techniques in a reach-the-target task. Leaning showed shorter task completion time compared to Joystick/Controller and reduced finger and arm fatigue, but no difference in motion sickness, presence, mental effort, or usability ratings, and increased physical effort and spine fatigue. Teleport also showed advantages over both Leaning and Joystick/Controller including higher speed, ease of use, usability, and reduced motion sickness. We did not use teleportation for this study as it cannot be used for maneuvering tasks where the actual path is important [20].

3 User Studies

While many studies showed clear benefits of leaning-based over hand-held interfaces for one specific task and several measures, there is a gap in literature in terms of comprehensive evaluations including a set of tasks needed to investigate more diverse aspects of locomotion interfaces, and a broader range of user experience, usability, and performance measures in both short-term and repeated usage. However, this would be needed to provide a compelling argument that leaning-based interfaces might be capable of providing a viable and affordable alternative to the prevailing hand-held controllers in more than just a few specific application scenarios. As a step towards addressing this gap in the literature, we investigated how translation using a leaning-based interface (HeadJoystick) versus handheld interfaces affects a broad range of diverse measures in a set of three complimentary short-term tasks (Study 1), and how these effects generalize over repeated usage (Study 2), and ecological validity including frequent stops (Study 3). HeadJoystick was introduced first in our prior work [12] and was evaluated in a fly through tunnels-in-the-sky task and later in a 3D navigational search [67] and showed several advantages compared to the gamepad including higher efficiency (number of passed tunnels), accuracy (lower distance error), precision (less collisions), enjoyment, preference, immersion, spatial presence, overall usability, ease of use, ease of learning, potential for long-term use and daily use, stronger illusion of self-motion (vection), while reducing motion sickness and task load.

3.1 Research questions

In this paper, we investigate how leaning-based interfaces for 2D (ground-based) locomotion affect relevant behavioral and introspective measures. This focus is addressed in four specific research questions (RQ):

RQ1: Do leaning-based interfaces improve locomotion accuracy/precision compared to handheld locomotion interfaces? Navigation performance is often measured by the *speed* (task completion time), *accuracy* (distance of the user from a desired position or path), and *precision* (how narrow a path could be for navigating with no collision) - section 1.3.2 of [68]. We assessed each of these three measures individually, as well as their combination as an overall performance score for each of our three tasks, as detailed in subsection 3.2 as well as interface throughput. Previous research showed higher performance of leaning-based interfaces compared to handheld interfaces in terms of improving spatial orientation [2] and spatial updating in a navigational search task [3]. A leaning-based interface similar to HeadJoystick already showed improved task completion time (speed) in a reach-the-target task [13]. However, leaning-based interfaces often showed reduced accuracy/precision compared to handheld interfaces [4], [5], [6], [7], [8], [9], [10]. As our prior study showed improved task completion time, accuracy, and precision for the HeadJoystick compared to handheld interfaces in flying [12], we predicted that the higher performance of the HeadJoystick over handheld interfaces would be generalized to 2D (ground-based) locomotion as well.

RQ2: Do leaning-based interfaces improve user experience and usability aspects compared to handheld locomotion interfaces? Design guidelines for locomotion interfaces usually suggest that leaning-based interfaces provide a more natural user experience compared to handheld standard interfaces [11]. For example, as for the user experience measures, previous works have shown a wide-range of advantages for leaning-based interfaces in terms of induced perception of self-motion (vection) [1], [44], [48], improved immersion [5], enhanced presence [4], and increased fun/enjoyment [4], [44]. As for the usability aspects, prior work reported advantages compared to the handheld interfaces in terms of improved spatial orientation [3], enhanced intuitiveness [5], reduced cognitive load and motion sickness [3] while other studies reported no significant improvement or lower ease of use [8], [13], [69] and ease of learning [44], [50], [69].

As prior studies typically tested only one specific task, and included often only a small subset of relevant measures, there is a limited understanding as to how these findings might or might not generalize to different tasks, and if a carefully optimized leaning-based interface (such as the HeadJoystick) might be able to show consistent benefits across a larger set of task that span the prototypical locomotion tasks outlined in Bowman's framework [14] as discussed in section 1. These gaps in the literature motivated the design of the current study and associated set of measures. Such broader benefits are, however, important if a novel interface is to provide an alternative and potentially replace established (hand-controller-based) locomotion interfaces.

RQ3: How do user experience, usability, and performance change over repeated usage of leaning-based interfaces vs. controller? Prior studies showed that the repeated usage of locomotion interfaces could significantly improve the performance by reducing the task completion time [4], number of errors [70], and distance error [7], but also increase unwanted side effects such as fatigue [63] and motion sickness - section 2.5 of [71]. Study 1 investigated short-term effects of leaning-based interfaces (i.e., HeadJoystick) across three complementary tasks. To address effects of repeated usage, Study 2 investigated how these findings might change over repeated usage of one of the tasks (reach-the-target). As our prior study showed that HeadJoystick's benefits for 3D flying were retained over repeated exposure [12], we hypothesize that the HeadJoystick's advantages will also continue to hold even after repeated exposure in 2D ground-based locomotion.

RQ4: How do leaning-based interfaces affect user experience, usability, and performance when users need to stop precisely at each target position? While our three complimentary tasks only focused on continuous motion, many real-world scenarios require users to slow down and stop at a specific location and remain sufficiently stationary, which could be useful for a number of tasks (interaction, manipulation, conversation/communication) or scenarios. Thus we designed Study 3 to investigate how leaning-based interfaces affect user experience, usability, and performance in a reach-the-target task, where the user needs to stop after reaching each target for one second before going for the next target. Prior leaning-based interfaces often allowed the users to stop simulated motion using a neutral/idle zone around the zero-point (i.e., initial position of the head when starting locomotion) [3], [4], [10], [70], which often reduced performance compared to the handheld controller with the exception of the study by Nguyen-Vo et al. [3]. However, as our prior study showed benefits of using HeadJoystick for 3D flying when the user needs to control their speed after reaching the target [12], [67], we hypothesize that the HeadJoystick's advantages will also continue to hold even with longer stops in 2D ground-based locomotion.

3.2 Tasks and Environment

The underlying motivation for selecting our tasks was to assess key performance measures of VR locomotion for leaning-based interfaces, extending findings of previous studies summarized above. As we want to investigate if leaning-based interfaces could potentially replace handheld interfaces by providing benefits across a fairly wide range of measures and scenarios, we focused here on three tasks that specifically assess locomotion aspects (especially accuracy) where leaning-based interfaces previously showed no consistent advantage.

Accuracy can be measured by proximity to the desired target or path when the user reaches a target or follows the path, respectively [14]. Therefore, we used reach-the-target and follow-the-path tasks for Study 1 to measure accuracy, speed, and precision (section 12.1.3.2 of [72]). We defined speed (i.e., task completion time) by the average time to reach-the-target and average velocity in the follow-the-path task. We measured accuracy by the size of the smallest target that participant managed to go through in a reach-the-target task and the average distance error from the center of a frame in a follow-the-path task. We measured precision in the reach-the-target task by the error rate i.e., ratio of failed over total attempts to reach a target, where We defined a failed attempt by passing 0.5 m proximity of a target without reaching it. In the follow-the-path task, we measure precision by the number of collisions with the door/frame tunnels' border. Other measures are discussed in detail for each task individually in more detail in subsubsection 3.2.1, 3.2.2, and 3.2.3, and are summarized in **??**-Appendix.

Many VR applications have a complex environment with obstacles and activity/motion, which may produce strikingly different results on performance measures [17]. Therefore, we decided to investigate HeadJoystick beyond basic reach-the-target and follow-the-path tasks in a more realistic travel task requiring accuracy/precision in a complex environment consisting of moving obstacles and activities/motions. Real-world travel tasks are usually categorized into three primary tasks including exploration, search, and maneuvering, where in particular maneuvering usually involves short, precise movements where the goal is to change the viewpoint slightly in order to do a particular task (section 12.4.3 of [72]). Therefore, as for the third task in Study 1, we selected racing, a maneuvering task, where users drive along a path/road as fast as possible while avoiding dynamically moving obstacles/cars. Following the categorization by Nilsson *et al.* that splits travel techniques into body-centric and vehicular control, reach-the-target and follow-the-path tasks evaluate HeadJoystick in body-centric control while racing task investigates if HeadJoystick findings are generalizable for vehicular control i.e., driving [36]. The racing task allowed us to assess performance-related measures such as speed by the average time to overtake a car and precision by the number of crashes with the cars.

3.2.1 Task #1: Reach-the-Target

The virtual environment of task 1 and 2 was a Sci-Fi space platform with sky-night and the earth background,

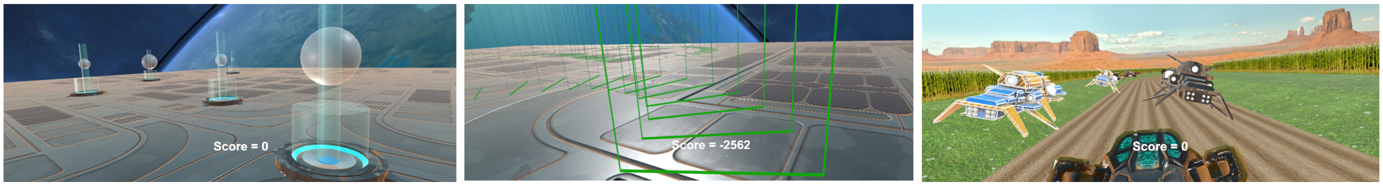


Fig. 1. Virtual environment used for this study. Left: reach-the-target environment for task$\#1$ from the participant view, where their head should reach inside white spheres. Middle: follow-the-path environment for task$\#2$, where their head should follow the path defined by the green frames. Right: Racing environment for task$\#3$, where participant should overtake other cars/obstacles without crashing into them or going off the road. Videos illustrating each task and condition are provided at http://ispace.iat.sfu.ca/project/headjoystick2d/

to provide rich visual self-motion cues and a compelling visual reference frame (cf. Figure 1). *Reach-the-target*[1] simply requires the user to reach as many targets as possible, where the path in-between targets is not important. Each target was scored and removed either immediately after contact (Study 1 & 2) or after one second in Study 3. Audio feedback was provided to inform reaching each target, with lower pitches indicating higher scores. The user had a limited time (90/60/120 s in Study 1/2/3) to reach as many targets as possible, represented as semi-transparent spheres, as illustrated in Figure 1 left. Targets' positions were randomized inside a 12 m$\times$12 m area with at least 2 m distance from each other and the user. As it was not easy to see the small targets, we placed each target at eye height above the center of a half transparent pillar over an easily visible platform. We presented five targets objects at the same time, and when the user reached and removed all of them in any order, five new targets appeared. Our reason for showing multiple targets at the same time was to make the simple reach-the-target task more mentally demanding, and require at least some basic spatial awareness to find all targets, efficient path-planning to reach them all as fast as possible, as well as the locomotion skills to follow that path.

As the required time to reach a target usually depends on its size and distance (i.e., how small and far is it) [15], we successively reduced target sizes to gradually increase task difficulty. Based on our pilot-testings, the first target had 0.8 m diameter, and the successive target's diameter was reduced by: 35% if it was between $0.4-0.8$ m; 15% if it was between $0.05-0.4$ m; 10% if it was between $0.015-0.05$ m; and 5% if it was below 0.015 m. Users' speed and accuracy was assessed using a performance score that was based on summing up the number of targets that the user successfully collected (by driving through it), each multiplied by a weighting factor of $50/diameter$ that increased for smaller (and thus harder to reach) target sizes. Therefore, higher scores represent better overall performance.

We also calculated interface throughput (TP), based on the following formula adapted from [21]:

$$\mathrm{TP} = \frac{\text{Effective index of difficulty}}{\text{Movement time}} = \frac{\mathrm{ID}_e}{\mathrm{MT}}$$

$$\mathrm{ID}_e = \log_2\left(\frac{A}{W_e}+1\right)$$

$$\mathrm{W}_e = \begin{cases} W * \frac{2.066}{\mathrm{z}(1-error/2)} & \text{if error} > 4\% \\ W * 0.5089 & \text{otherwise} \end{cases}$$

where MT is the movement time to the next target, A is the distance to the next target, W is the width of the next target, Z(x) is the z-score corresponding to the point where the area under the normal curve is x% [21]. Throughput calculation typically requires individual error rates for each target's distance and width [22], but as in our reach-the-target task, participants reached each target only once, we calculated error rate per participant as defined in subsection 3.2. Our formula is derived from Fitts' throughput formula [21], [22]. We argue throughput is a useful measure for navigation tasks to quantify human performance with different navigation techniques/devices by assessing the interrelation between speed, accuracy and error measures. We deliberately did not use throughput to predict (instead of compare) performance or use other Fitts' law measures as at the current state of research does not provide strong enough indications that these measures also apply to navigation tasks similar to ours.

3.2.2 Task #2: Follow-the-Path

In the *Follow-the-path*[2] task users had a limited time (90 s) to follow a pre-defined path as far as they could while staying close to its center and inside its boundaries. As illustrated in Figure 1, the path was defined by a sequence of green doors/frames every 0.5 m, mimicking a tunnel. We gradually increased the task difficulty by linearly decreasing the tunnel width [16], and defined a performance score that weighted each successfully passed frame by the inverse of their width $100/width$, such that successfully driving through smaller frames resulted in higher scores. If users missed a frame by colliding with its boundaries, they were penalized eight times that frame's score. Therefore, higher scores represent better overall performance. The first frame had the largest width of 0.5 m and the consecutive frames' widths linearly reduced to 0 m over a path length of 152 m. To prevent participants from learning the path across the two interfaces, we balanced the order of the original versus horizontally mirrored layout across participants. Similar audio feedback was provided by bell and buzz sounds when passing and missing each tunnel frame, respectively, where lower pitch represented getting/missing a higher score.

3.2.3 Task #3: Racing

In *Racing*[3] users had 90 s to overtake as many cars as they could without crashing into them or driving off the road – see Figure 1 right. As motivation and scoring they received +10 points for overtaking each car, -100 points when crashing a car, and -10 points for being off the road for

1. Video for reach-the-target task (http://ispace.iat.sfu.ca/project/headjoystick2d/)

2. Video for follow-the-path task (http://ispace.iat.sfu.ca/project/headjoystick2d/)

3. Video for racing task (http://ispace.iat.sfu.ca/project/headjoystick2d/)

each 0.5 m path length. Thus, higher score represent better racing performance. We designed this task as a dynamic obstacle avoidance task to allow us to measure underlying constructs such as precise control of forward/backward and strafing velocity, path planning, anticipation of the obstacle movements, showing agility and maneuverability in avoiding obstacles, and deciding under time pressure if they should try and slip through the next obstacles or wait until there's an opening between obstacles. As illustrated in http://ispace.iat.sfu.ca/project/headjoystick2d/), obstacles/racers moved with a constant forward speed of 6 m/s, and a constant lateral oscillating motion (at 0.167 Hz) in pairs to allow for three overtaking choices on their left, middle, and right. Therefore, users had to match their speed with the next pair of racers and wait for them to open a possible path with their lateral motion, and then reach the opened path using sideways motion and overtake those racers by increasing speed before their way might be blocked by those racers later again. Despite adjusting speed to other racers might be seen as stopping relative motion, we evaluated true stopping behaviour mainly in the reach-the-target task.

As our interfaces (HeadJoystick and Controller) allowed for sideways strafing in both reach-the-target and follow-the-path tasks, we used the same motion model for all our three tasks to make it easier to generalize results and keeping things consistent. As most of current cars/bikes don't allow for sideways motion, we used a Star wars themed racing game with floating racers, which allow for controlling forward/backward and sideways (strafing) translation, and yaw rotation. Users saw themselves on a sci-fi racer, which was aligned with the direction of their chair/tracker – see Figure 1 right. We also provided audio feedback for overtaking or hitting each car or getting off-road.

3.3 Dependent Variables

??-Appendix describes our suggested factors and dependant variables (DV) to evaluate a locomotion interface. **??**-Appendix shows six (out of eight) factors from Bowman's framework [14] as well as six additional factors we propose to include: user comfort, assessed by the potential for long-term and frequent daily use; overall usability ratings; precision, assessed by the number of missed targets or collisions with path or obstacles; overall performance measures, assessed by throughput or defined as a performance score for each task individually; self motion perception, assessed by vection intensity; and overall user experience ratings assessed by enjoyment (for gaming interfaces) and overall preference. We further suggest assessing Bowman's factors using additional DVs, such as: ease of learning using both subjective and behavioral DVs; ease of use using a general rating and a detailed task load measure [73]; presence using both SUS questionnaire of spatial presence [74] and psychological immersion.

Out of the suggested DVs in **??**-Appendix, the only DVs we did not measure were information gathering potential and spatial orientation, as they are task-specific performance factors, which need to be assessed in specific tasks beyond this study's scope (e.g., [3]), which could be be assessed in the future studies. Besides the behavioral/performance scores for each task – explained in subsection 3.2 – we also measured 12 subjective DVs, including six user experience factors and six usability aspects described in **??**-Appendix, matching those used in our previous HeadJoystick study for flying in VR [12]. All our 12 DVs were measured with visual-analog scale answers between 0% to 100% except the SUS questionnaire of spatial presence [74], which used a Likert-based scale of $1-7$ and the simulator sickness questionnaire (SSQ) [75]. As for the SSQ, we calculated the post-pre motion sickness score by subtracting the total SSQ score obtained before from after exposure for each of the two conditions.

3.4 Apparatus

The environments used in our user study were developed using Unity3D 2018.2, rendered on a dedicated desktop PC (Intel Core-i7, 8GB RAM, NVIDIA GTX-1060) and displayed using an HTC-Vive HMD with a combined resolution of 2160×1200 pixels with binocular field of view about $110°$ diagonally. The HMD was connected to the PC using a wireless TPCast adaptor attached to the swivel chair to remove the constraint of cable entanglement during physical rotations. Participants controlled translations in the Controller condition using a Vive controller touchpad in Study 1 and a Valve Index controller thumbstick in Study 2. We also attached a Vive tracker to the chair's backrest using a tracker strap to measure the chair yaw rotation as depicted in Figure 2. A noise-cancelling headphone was used to present audio cues of each task as well as an ambient wind sound to avoid distractions from possible background noises.

3.5 Study 1

3.5.1 *Locomotion Modes*

Figure 2 shows the HeadJoystick and Controller interfaces used for this study. In the **Controller** condition, participants controlled their forward/backward and sideways velocity using a Vive controller's touchpad, where the forward direction was always aligned to the physical yaw direction of the swivel chair they were seated on. We mapped touchpad touched position to the virtual translation velocity using a linear transfer function to keep touchpad similar to standard handheld interfaces, and report findings generalizable to typical handheld interfaces. Both Controller and HeadJoystick had a unified maximum speed of 4 m/s for the simulated translation for reach-the-target and follow-the-path tasks, and 12 m/s for the racing task, all based on pilot-tests.

For **HeadJoystick**, users need to move their head toward the target direction to control their virtual translation velocity, similar to deflecting a joystick. That is, the further the user moves their head from zero-point the faster they move in VR. Participants typically combined head translation and upper body leaning, especially for faster desired velocities. The forward direction was determined by the chair direction similar to Controller. HeadJoystick design formulas have been explained in the appendix as well as our previously published research [12], which improved HeadJoystick precision by considering the below details:

High precision movements at lower speeds: based on extensive pilot testing and our prior works [3], [7], [8], [45],

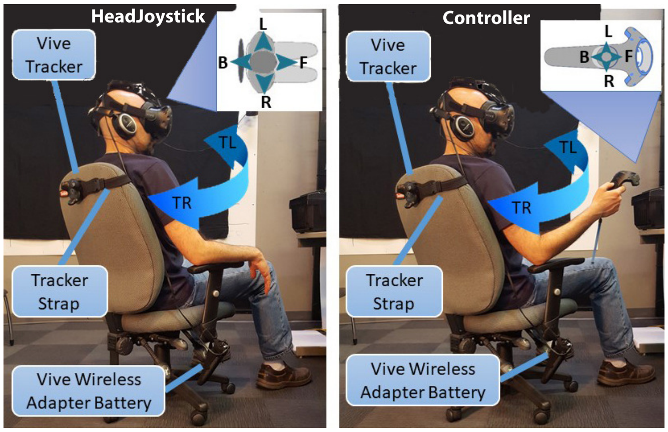


Fig. 2. HeadJoystick (left) and Controller (right) locomotion interfaces compared in Study 1. Each interface controls locomotion along the three degrees of freedom forward(F)/backward(B), left(L)/right(R), and yaw rotations turn-Left(TL)/turn-right(TR).

we used an exponential instead of a linear transfer function (with 1.53 exponent) to map the physical translation distance of the user head from zero-point to their virtual translation velocity, as it provides higher precision in lower speeds and makes it easier to stop travel.

Using high-precision muscles: Precise control of handheld interfaces requires usage of wrist/finger muscles, which is not hard due to a few reasons such as musculoskeletal configuration and movement dimensions, sensory bandwidth, and experience with I/O devices. In contrast, some leaning-based interfaces use large muscle groups – which are not often trained for precise fine movements – such as upper body muscles when weight shifting (e.g., Wii-Leaning [2] and NaviChair [7]) or body tilting (e.g., Joyman [4]), or tilting the chair/stool (e.g., Swivel-chair [7]). HeadJoystick uses head position, which requires controlling upper-body muscles for large changes in virtual speed, whereas for precise fine movements the neck muscles are used, a muscle group that is also trained for finer motions. As such, we hypothesized that this would allow for more precise and fine movements [76].

Body-based cues for zero-point: While handheld interfaces usually automatically return to zero-point when released (or even provide physical feedback for the zero-point), leaning-based interfaces usually expect the user to find zero-point using visual cues (nulling visual self-motion velocity). To makes it easier to find the HeadJoystick zero-point without relying on visual cues, we asked users to slightly touch the chair backrest with their back during the zero-point calibration before starting locomotion, to provide more intuitive and body-based cues for zero-point.

Preventing unintentional virtual translation during head rotation: other leaning-based interfaces that also use head position to control virtual translation often use the HMD position directly as the position of the head, such as human joystick [9], NaviChair, and NaviBoard [3]. However, as HMD position is not usually aligned with the head rotation center, head rotations during locomotion when using these interfaces can lead to unintentional speed changes, especially for precise motions. To allow for head rotation without unintentional speed changes or drift, we used a point defined by the average center of head rotation (instead of HMD position) as head position, which has an average 0.13 m behind the HTC-Vive HMD position for adults based on our pilot studies. Therefore, rotating the head during locomotion did not change the virtual translation velocity.

Preventing unintentional virtual translation during virtual rotation: Pilot studies showed that if the chair rotates or moves, the user could still find the zero-point and stop the motion easily if zero-point would be relative to the chair (not the room). Therefore, we used the position and orientation of a chair-attached tracker during travel to dynamically update the zero-point position with respect to the chair seat. To define the chair seat using the position and orientation of the tracker, we initiated a calibration process before starting locomotion and asked the user to push the chair backrest back, so we could calculate the center of the backrest tilt relative to the tracker's position and orientation. HeadJoystick calibration process and motion details are discussed in the appendix of [12].

3.5.2 Participants

Twenty-four students (11 females) between 19-26 years old ($M = 21.5, SD = 1.79$) participated in Study 1. Sixteen participants (66%) had corrected eyesight (glasses or contact lenses), 20 of them (83%) played 3D first-person view video games on a daily or weekly basis, six of them (25%) had no prior experiences with HMDs, and none of them had prior experience with any of our interfaces. Two additional participants did not finish the experiment due to severe motion sickness and were thus excluded from data analysis. The local ethics board approved this research (#2018s0649) and we compensated their participation time by course credit for 75 minutes.

3.5.3 Experimental Design

Using a within-subject design, each participant completed six practice trials and six main trials, consisting of a factorial combination of two interface conditions $\{$HeadJoystick vs. Controller$\}$ $\times$ three tasks $\{$reach-the-target, follow-the-path, racing$\}$. Each main trial was preceded by a practice trial, and we only analyzed the data from the main trial, as the length of practice trials varied per participant, and we wanted to compensate for initial learning effects. We counterbalanced the order of interface conditions across participants. The three tasks were always performed in the same order, blocked by interface.

3.5.4 Procedure

Participants started with reading and signing the informed consent form, and then answered an initial SSQ questionnaire on motion sickness [75]. Participants then performed tasks 1, 2, and 3 first with one interface, followed by the other interface. The order of tasks was always from simple to complex starting with task #1 (reach-the-target), followed by task #2 (follow-the-path) to allow for gradual learning of the interface for the final most-complex task #3 (racing). Note that the goals was to compare the interfaces not tasks, hence we did not vary task order. Participants completed two trials per task: a *practice trial*, where participants practiced the interface for the task until they felt comfortable, or 90 seconds passed, whichever came first,

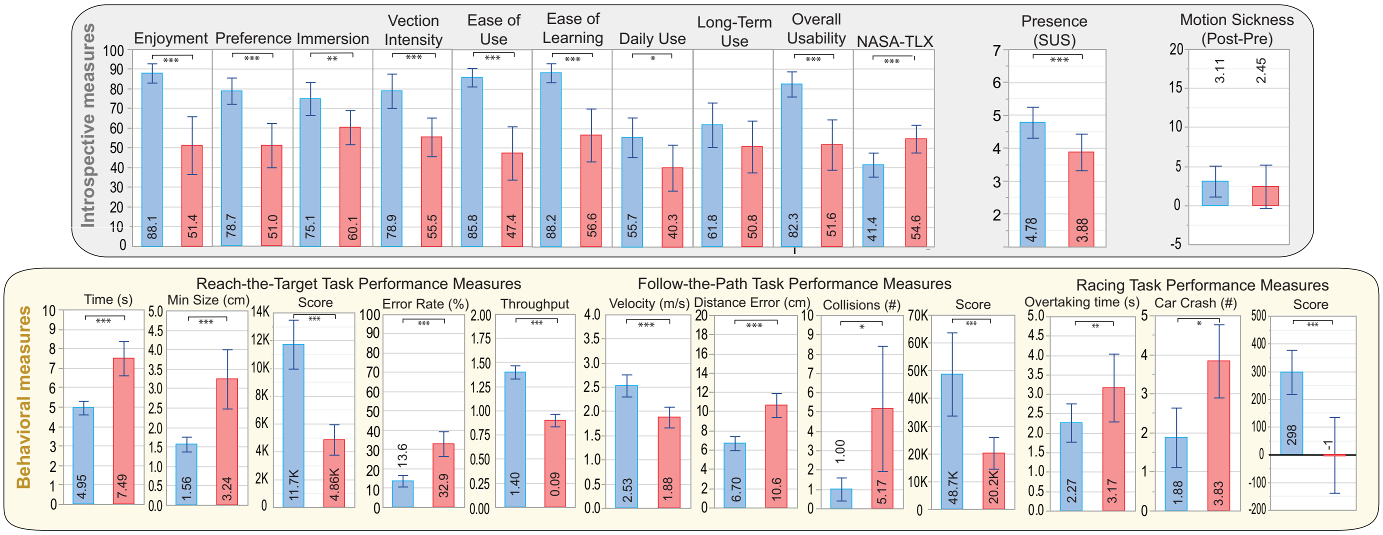


Fig. 3. Study 1: Mean data of user experience (top), usability (top), and performance (bottom) measures of HeadJoystick (in blue) versus Controller (in red). Error bars indicate confidence intervals ($CI = 95\%$), annotated bars represent significance levels of t-tests (* $p < .05$, ** $p < .01$, *** $p < .001$).

followed by a *main trial*, where participants had 90 s to perform the task and get as high a score as they could. After completing all three tasks, participants answered SSQ as well as an interface evaluation questionnaire to measure other usability and user experience aspects. After completing all tasks using both interfaces, we used a semi-structured interview to gain a deeper understanding and elucidate reasons behind participants' answers.

3.5.5 Results

We converted negatively skewed (toward zero) data to logarithmic scales [77] including average reach-the-target time, minimum target size, and throughput in reach-the-target task, average collisions in follow-the-path task, average time to overtake a car and number of car crashes in the racing task. Due to no or slight violation of normality assumptions (i.e., four violation cases in 24 Shapiro-Wilk tests, where $p > 0.023$), we analyzed all 24 (12 subjective and 12 behavioral) dependent measures using repeated-measures (paired) t-tests. Previous studies have shown the feasibility of performing parametric statistics on Likert data, even with small sample sizes, unequal variances, and non-normal distributions [78], [79]. Due to large number of dependent variables, we summarized t-test results in **??**-Appendix, with descriptive statistics in Figure 3.

HeadJoystick showed significant benefits over Controller in terms of 10 (out of 12) user experience and usability measures including significantly increased enjoyment, preference, immersion, vection intensity, daily use, overall usability, ease of use, ease of learning, spatial presence while reducing task load (see top row in Figure 3 and **??**-Appendix). Only motion sickness and long-term use showed no significant differences. HeadJoystick also showed advantages over Controller in terms of all 12 behavioral performance measures including significantly increased reach-the-target performance score, reach-the-target throughput, average velocity when follow a path, follow-the-path performance score, and racing performance score while reducing average time to reach a target, minimum reach-the-target distance, reach-the-target error rate, follow-the-path distance error, follow-the-path collisions, average time to overtake a car, and number of car crashes (see middle row in Figure 3). Effect sizes (Cohen's d) were small ($0.2 \leq d \leq 0.5$) for immersion, vection intensity, daily use, reach-the-target throughput, follow-the-path collisions, follow-the-path performance score, and number of car crashes and large ($d \geq 0.8$) for average time to reach a target, minimum reach-the-target distance, follow-the-path distance error, and medium ($0.5 \leq d \leq 0.8$) for the other 12 significant effects.

To investigate how **prior gaming experience** affected participants' results, we conducted an additional ANOVA analysis with **prior gaming experience** $\{yes, no\}$ as a between-subject factor and interface $\{HeadJoystick, Controller\}$ as within-subject factor. Results showed that prior gaming experience (daily or weekly) improved reach-the-target performance scores from 5.73 K ($SD = 3.33$ K) to 8.96 K ($SD = 5.03$), $F(1, 22) = 7.40, p = .013, \eta_p^2 = .252$ and immersion from 49.3% ($SD = 14.4\%$) to 72.7% ($SD = 19.6\%$), $F(1, 22) = 10.2, p = .004, \eta_p^2 = .317$ compared to non-gamers. Prior gaming experience also showed a significant interaction with the interface for the time to reach a target $F(1, 22) = 5.70, p = .026, \eta_p^2 = .252$, post-pre motion sickness $F(1, 22) = 5.00, p = .036, \eta_p^2 = .185$, and the long-term use $F(1, 22) = 7.74, p = .011, \eta_p^2 = .260$. That is, for gamers using the Controller (but not HeadJoystick) increased long-term usage ratings and reduced the time to reach a target and post-pre motion sickness.

3.5.6 Discussion

Our results showed that compared to handheld interfaces, leaning-based interfaces such as HeadJoystick could improve effectiveness factors including accuracy/precision in our reach-the-target, follow-the-path, and racing tasks. However, a 90 s trial might not be enough for a thorough evaluation of leaning-based interfaces, an issue we targeted in Study 2. For example, subjective reports of advantages of leaning-based interfaces after short-term usage could also reflect more of participants' first impression rather than providing a holistic picture of their pros/cons, as it could be affected by different reasons such as the interface novelty or initial learning effects, especially for the novel interface (HeadJoystick).

3.6 Study 2: Repeated Reach-the-Target

Study 2 was designed to investigate RQ3 and evaluate repeated usage of HeadJoystick versus Controller in a reach-the-target task similar to Study 1. We chose a reach-the-target task because it allows us to assess additional performance measures (e.g., throughput) compared to racing and follow-the-path. Our pilot-tests also showed reduced motion sickness when we tested repeated reach-the-target trials compared to follow-the-path and racing, which could be due to increased lateral visual motion cues from path frames or cars, respectively, and thus stronger sensory conflict during speed changes. Therefore, we used reach-the-target task to test repeated usage of the interfaces.

Generally, repeated interface usage can provide not only a beneficial learning effect but also increase fatigue and motion sickness. However, as our prior research showed that advantages of HeadJoystick over handheld interfaces hold over repeated usage in flying [12], therefore, here we hypothesised that the advantages of leaning-based interfaces (here HeadJoystick) hold over repeated usage in 2D ground-based locomotion as well. The overall design of the Study 2 was similar to the reach-the-target task of Study 1 apart from the changes described below.

Eight trials per interface: Instead of measuring the effects of our interfaces by one long trial, we used eight short (60 s) reach-the-target trials. The trial time was reduced from 90 s (in Study 1) to 60 s (in Study 2) to reduce the chance for motion sickness, after some participants dropped out of pilot-tests before completion due to severe motion sickness in the controller condition. Shorter trial length also allows for better detection of performance changes over time.

Post-trial questionnaire: To continually measure the changes in motion sickness and perceived task difficulty over time, participants were asked after each trial to take off their HMD, and verbally rate motion sickness and perceived task difficulty on a $0-100\%$ scale.

Using thumbstick instead of touchpad: In the post-experiment interviews of Study 1, participants stated that it was not easy to find the zero-point of the Vive controller's touchpad as it does not provide a physical force feedback for the zero-point. Therefore, we used a Valve index (instead of HTC Vive) controller for the Study 2, which uses a thumbstick. As prior studies showed lower accuracy of thumbstick compared to touchpad [80], using a thumbstick allows us to generalize our results to other VR HMDs as most of them use thumsticks instead of touchpad.

Smooth acceleration: Similar to our prior work, we smoothed the acceleration/deceleration by using Unity's SmoothStep function (see appendix of [12]) to provide a realistic inertial-like experience instead of abrupt speed changes, and to reduce the visual-vestibular sensory conflict and thus mitigate motion sickness.

Similar velocity transfer function for both conditions: In the post-experiment interviews of the Study 1, some participants mentioned high sensitivity of the touchpad especially in lower velocities. Therefore we used the same exponential transfer function to control the simulated velocity of both HeadJoystick and Controller conditions.

3.6.1 Participants

18 graduate students (seven females) between 25-40 years old $(M = 29.5, SD = 3.93)$ participated in Study 2. None had participated in Study 1. Five participants (28%) had corrected eyesight (glasses or contact lenses), nine of them (50%) played video games on a daily or weekly basis, eight of them (44%) had no prior experiences with HMDs, and none of them had prior experience with any of our interfaces. Two additional participants did not finish the experiment due to severe motion sickness after using controller interface and were thus excluded from data analysis. The local ethics board approved this research (#2018s0649) and we compensated their participation time (around 75 minutes) by offering a chance to try VR games for a couple of hours.

3.6.2 Results

We analyzed all 12 dependent measures using repeated-measures (paired) t-tests as our data did not violate normality assumptions. Due to the large number of dependent variables, t-test results are summarized in **??**-Appendix, with descriptive statistics in Figure 4 top row. HeadJoystick showed significant benefits over Controller in terms of 11 (out of 12) DVs (see Figure 4) except daily use, where the trend in the same direction did not reach significance. That is, compared to Controller, HeadJoystick yielded significantly increased enjoyment, preference, immersion, vection intensity, long-term use, overall usability, ease of use, ease of learning, and spatial presence, while also reducing task load and motion sickness. In terms of motion sickness, while HeadJoystick showed no significant increase in motion sickness before and after the eight trials (Figure 4 down-right plot), Controller showed a significantly increased motion sickness, $T(17) = 4.80, p < .001, Cohen'sd = 1.13$. Effect sizes (Cohen's d) were small $(0.2 \leq d \leq 0.5)$ for immersion, long-term use, ease of learning, task load, and post-pre motion sickness and large $(d \geq 0.8)$ for vection intensity and medium $(d \geq 0.5)$ for the other five significant effects.

To investigate how **prior gaming experience** affected participants' results, an additional ANOVA was conducted with prior gaming experience $\{Yes, No\}$ as a between-subject factor and interface $\{HeadJoystick, Controller\}$ as a within-subject factor. Results showed that prior (i.e., daily or weekly) gaming experience yielded improved ease of learning from 50.3% $(SD = 22.1\%)$ to 77% $(SD = 14.5\%)$, $F(1, 16) = 16.3, p = 0.001, \eta_p^2 = 0.449$, ease of use from 49.8% $(SD = 25.8\%)$ to 68.9% $(SD = 21.0\%)$, $F(1, 16) = 7.23, p = 0.016, \eta_p^2 = 0.535$, long-term use from 57% $(SD = 18.7\%)$ to 73.7% $(SD = 10.3\%)$, $F(1, 16) = 22.7, p < 0.001, \eta_p^2 = 0.332$. There were no other significant main effects of gaming experience or interactions with the factor interface.

To investigate how user experience (i.e., motion sickness and task difficulty) and performance (i.e., reach-the-target time, minimum size, overall score, number of reached targets, number of missed targets, error rate, and throughput) measures **change over trials**, we ran $2{\times}8$ repeated-measures ANCOVAs for the independent variables (IVs) interface

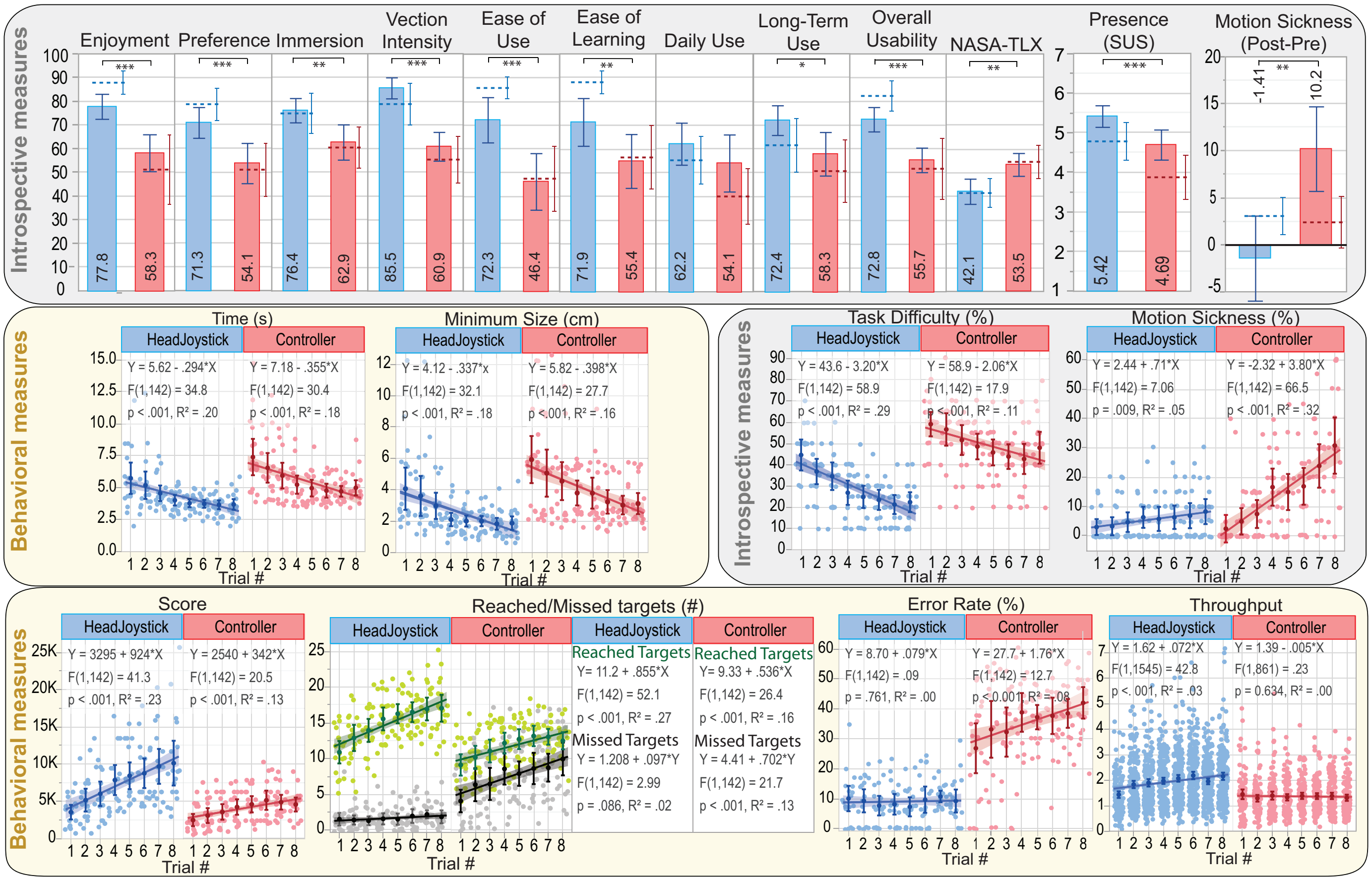


Fig. 4. Study 2: Mean data of user experience (top), usability (top), and per-trial performance (middle and bottom) measures of HeadJoystick (in blue), versus Controller (in red). Error bars indicate confidence intervals ($CI = 95\%$), annotated bars represent significance levels of t-tests (* $p < .05$, ** $p < .01$, *** $p < .001$). Means from Study 1 are added as blue and red dashed lines for HeadJoystick and Controller respectively in the top row for easier comparability. Middle and bottom plots show how performance and user experience changed over trials, including linear regression results. Blue and red pale dots indicate individual participants' data for HeadJoystick and Controller respectively. In the reached/missed targets plot, green lines and dots show the number of reached targets and the black lines and gray dots show the number of missed targets.

and trial number. Motion sickness, task difficulty, reach-the-target time, minimum size, number of missed targets, and overall score were analyzed as rank-transformed data, as Shapiro-Wilk tests indicated a violation of the normality assumption.

??-Appendix shows significant main effects of interface on all per-trial measures, and indicates a consistent advantage of using HeadJoystick over Controller in terms of reducing motion sickness, task difficulty, time to reach a target, minimum target size, number of missed targets, and error rate, while also increasing the number of reached targets, performance scores, and throughput. **??**-Appendix also shows significant main effects of trial on all DVs, indicating significant changes of all measures over time. That is, we observed a significant increase of motion sickness, overall score, number of reached targets, number of missed targets, error rate, and throughput, as well as a significant decrease of task difficulty, time to reach a target, and minimum target size reached as also illustrated in Figure 4. The significant main effects of interface and trial were qualified by significant interface-trial interactions for motion sickness, task difficulty, performance score, number of reached targets, number of missed targets, error rate, and throughput - as depicted in **??**-Appendix. As illustrated in Figure 4 and the linear regressions, these significant interactions show that the difference between the HeadJoystick and Controller over these measures became more apparent over time. Specifically, extended usage of the HeadJoystick instead of Controller leads to a smaller increase of motion sickness, number of missed targets, and error rate, as well as a larger decrease of task difficulty, and larger increase of number of reached targets, performance score, and throughput over time.

To gain a better understanding of how per-trial data changed between the first and last trial for each interface, we conducted additional planned contrasts (paired t-tests). Motion sickness increased moderately from the first to last trial from 3.06% ($SD = 5.46\%$) to 8.33% ($SD = 8.57\%$) for the HeadJoystick ($p = 0.01$), this increase was much more pronounced for the Controller, from 2.50% ($SD = 9.43\%$) to 30.8% ($SD = 19.3\%$), $p < 0.001$. Between the first and last trial, task difficulty decreased from 44.4% ($SD = 14.6\%$) to 22.2% ($SD = 9.43\%$) for the HeadJoystick, ($p < 0.001$), but only from 59.2% ($SD = 11.5\%$) to 48.1% ($SD = 15.1\%$) for the Controller, ($p = 0.001$). Similarly, time to reach a target decreased between the first and last trial from 5.74 s ($SD = 2.47$ s) to 3.67 s ($SD = 0.74$ s) for HeadJoystick, ($p < 0.001$), and from 7.41 s ($SD = 2.86$ s) to 5.01 s ($SD = 1.19$ s) for the Controller, ($p = 0.001$). Minimum target size reached also decreased from 4.17 cm ($SD = 2.81$ cm) to 2.90 cm ($SD = 0.898$ cm) for the HeadJoystick, ($p < 0.001$), and from 5.88 cm ($SD = 2.98$ cm) to 3.10

cm ($SD = 1.33$ cm) for the Controller ($p < 0.001$). The overall score increased from 3.55 k ($SD = 1.98$ k) to 10.1 k ($SD = 6.05$ k) for the HeadJoystick, ($p < 0.001$), but only from 2.49 k ($SD = 1.65$ k) to 4.58 k ($SD = 1.89$ k), for the Controller, ($p < 0.001$). Number of reached targets also increased from 10.9 ($SD = 3.16$) to 17.1 ($SD = 3.8$) for the HeadJoystick, ($p < 0.001$), and from 9.11 ($SD = 3.01$) to 12.5 ($SD = 2.41$) for the Controller, ($p < 0.001$).

However, whereas the number of missed targets increased for the Controller from 4.06 ($SD = 3.17$) to 9.94 ($SD = 4.62$), ($p < 0.001$) between the first and last trial, it did not increase significantly for the HeadJoystick. Similarly, error rate significantly increased for the Controller from 26.1% ($SD = 39.6\%$) to 41.8% ($SD = 11.1\%$), ($p < 0.001$), but not for the HeadJoystick. Finally, throughput only improved for the HeadJoystick from 1.29 ($SD = 0.535$) to 2.03 ($SD = 0.886$), ($p < 0.001$), but not for the Controller.

HeadJoystick showed overall similar effects compared to the Controller in both Study 2 and Study 1 as indicated in the top row of Figure 4 by added blue and red dashed lines for means and confidence intervals of HeadJoystick and Controller respectively. To investigate potential difference between user experience measures in Study 1 vs. 2, we ran an exploratory 2×2 ANOVAs with the factors Study {1 vs. 2} and interface {HeadJoystick vs. Controller}. Results showed no significant differences (main effects or interactions) between Study 1 and 2 values in terms of nine (out of 12) measures including preference, immersion, vection intensity, ease of use, ease of learning, daily use, long-term use, overall usability, and task load. There was only one significant main effect for spatial presence, which was rated higher overall for Study 2 compared to Study 1 ($p = 0.020$). There were, however, significant interactions between study and interface for enjoyment ($p = 0.043$) and post-pre motion sickness ($p = 0.002$), which revealed smaller enjoyment differences but larger motion sickness difference between interfaces in Study 2 compared to Study 1. The latter suggests that the more pronounced motion sickness-inducing effect of using the Controller vs. HeadJoystick becomes only fully apparent when using the interface for longer periods of time than the 90 s in Study 1.

3.6.3 Discussion

Overall the results of our second study showed that the advantages of leaning-based interfaces such as HeadJoystick over a hand-held controller do not decline over repeated usage. If anything, they became more pronounced over time, which is promising for a multitude of applications requiring longer or repeated usage. As illustrated in the ↑ task videos, there were 1-5 targets always visible, so there was little search involved, and thus our participants could and typically did not fully stop at a given target but drove through it toward the next target. Many applications, however, also require users to slow down and stop for at least a brief amount of time, for example to interact, look around, reflect, or communicate. Thus, we designed Study 3 to improve generalisability of our findings to a wider range of tasks and scenarios. Moreover, as not all HMDs or VR users have access to an additional tracker, Study 3 was designed to compare HeadJoystick with Controller without using an additional tracker.

3.7 Study 3: Brake Mechanisms

Study 3 was designed to investigate RQ4 and evaluate how leaning-based vs. controller-based interfaces affect user experience, usability, and performance when the user needs to repeatedly slow down and stop before continuing the locomotion. To this end, we modified our reach-the-target task such that users need to stop inside each target for one second to collect the score before moving on to the next target[4]. We hypothesized that the physical motion cues provided by leaning-based interfaces (e.g., HeadJoystick) during acceleration/deceleration help to extend their advantages over controllers as they did in 3D flying locomotion [12], [67]. Study 3 was designed similar to the Study 2 except for the following changes:

Modifications in task/environment: We improved the task and environment to address user feedback from our prior studies and pilot studies. For example, instead of continually reducing target sizes until they can become hard to see and focus on with both eyes without squinting, we only reduced target size down to 7 cm (the typical maximum distance between adult eyes). Also, we added two cylindrical grids around targets to help users know their location once inside a target, as illustrated in this ↑ video. To provide users with visual/auditory feedback when their head is inside the target, we added particle effect feedback and a visual charging bar accompanied by a charging sound.

Brake Mechanisms: As HeadJoystick users are constantly moving depending on the distance between their head and the zero-point, Study 3 pilot-tests showed that it might not be easy for users to stay inside small targets. Pilot-tests also showed that HeadJoystick users preferred neutral/idle zone instead of brake mechanisms to stop locomotion similar to prior leaning-based interfaces [3], [4], [10], [70]. Thus, we implemented a neutral/idle zone for the HeadJoystick condition, where the user would not start locomotion unless the distance of their head from zero-point goes beyond 5 cm. Moreover, we investigated potential benefits of providing two additional braking options in a "HeadJoystick+brake" condition (called soft and automated brake). **Soft brake** operates much like a normal vehicle brake in a car or bike, and allows users to reduce their simulated speed by gradually deflecting the controller's trigger, where the speed reduction rate linearly increases with trigger deflection. To prevent harsh decelerations that might exacerbate cybersickness, the maximum speed reduction was limited to 1 m/s (or 12% of the maximum speed of 8 m/s). That is, soft brake only completely stopped locomotion when users were already traveling relatively slowly. **Automated brake** allowed users to automatically slow down and stop locomotion (and disabling HeadJoystick) by pressing the 'A' controller button. Unlike soft brake, automated brake stops locomotion from any speed and then allows users to freely move their head without affecting locomotion. As harsh deceleration can enhance motion sickness, we used Unity's SmoothStep function to limit deceleration to 1.6 m/s^2, which stops maximum speed (8 m/s) in five seconds. To re-start locomotion, users need to move their head to the

4. Study 3 Videos: (http://ispace.iat.sfu.ca/project/headjoystick2d/)

desired zero-point and press the 'B' controller button.
Increasing maximum speed: Based on pilot tests and to prevent users from using maximum speed to reach a target and then stop inside it instead of accurately controlling the speed similar to many real-life scenarios (such as driving a car), we increased the maximum speed from 4 (Study 1 and 2) to 8 m/s, similar to fast cycling or slow inner-city driving speeds.
Study conditions: To evaluate potential benefits of adding braking options, we compared three conditions: HeadJoystick with no brake mechanism other than zero/idle zone; HeadJoystick+brake, where participants could use soft and/or automated brake based as they preferred besides using neutral/idle zone; and Controller, similar to Study 2 but with added soft brake option.
three 2-minute trials per interface: Based on pilot-tests and to compensate for the added time needed to slow down and stop at each target, we increased each trial's length from 60 s (in Study 2) to 120 s. To investigate affects of repeated usage and learning, each participant used each interface in three consecutive trials for a total of six minutes, which brought the whole HMD time to 18 minutes for three interfaces, similar to the 16 minutes in Study 2.
Simplified HeadJoystick interface: As not everyone might have a chair with a vertical backrest, a Vive tracker, or wants to go through a tracker calibration process [12], we also simplified the HeadJoystick interface to a software-only interface without requiring any additional chair-attached tracker or modification to the chair. Simplified HeadJoystick interface allowed us to investigate if leaning-based interfaces can be beneficial with an easier setup. Therefore, we asked participants to sit upright at the center of chair's yaw rotation to set it as their zero-point before starting locomotion. This way, users later could stop locomotion by siting upright again, which provided a simple embodied physical feedback for zero-point even if the user rotated the chair.
Modifying Controller condition: As we could no longer use the tracker on the chair to determine the forward direction for the Controller condition, forward deflection of the thumbstick moved the user toward the Controller's direction instead of the chair/tracker. Such a pointing-directed controller provided slightly more embodied control as shown in [81] and is used in many recent VR applications, thus helping to generalize our findings to more diverse controller-based locomotion conditions.

3.7.1 Participants

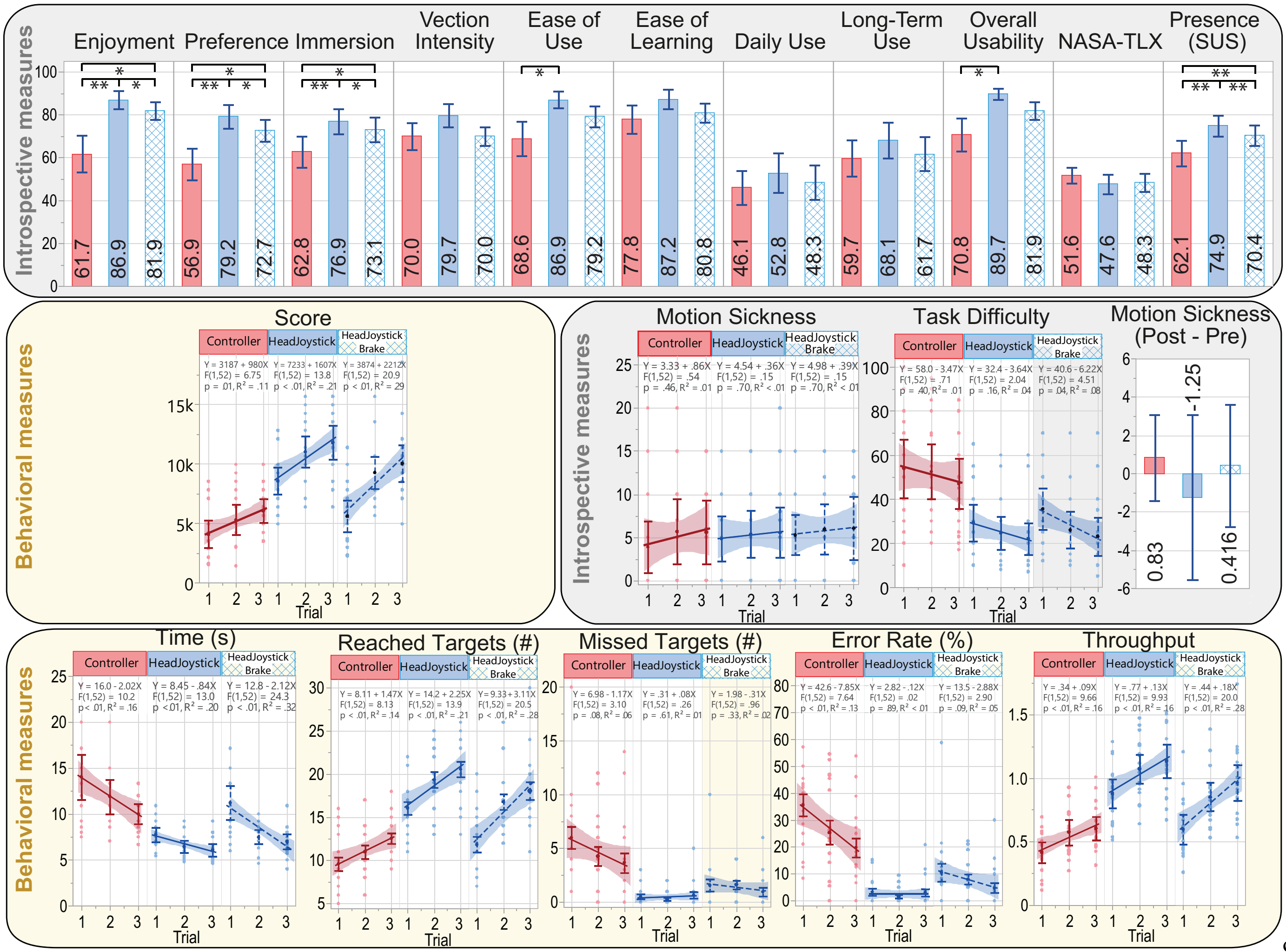
18 undergraduate students (10 females) between 19-34 years old ($M = 22.3, SD = 4$) participated in Study 3. None had participated in Study 1 or 2. 11 participants (61%) had corrected eyesight (glasses or contact lenses), six of them (33%) played video games on a daily or weekly basis, 11 of them (61%) had no prior experiences with HMDs, and three of them had prior experience with the HeadJoystick. Two additional participants did not finish the experiment due to severe motion sickness and were thus excluded from data analysis. The local ethics board approved this research (#20180649) and we compensated their participation time (around 75 minutes) by offering course credit.

3.7.2 Results

As for comparing interfaces in terms of user experience and usability measures, four (out of 12) DVs did not violate Normality assumption in Shapiro-Wilk tests (vection intensity, task load, pre-post SSQ, and daily use) and were analyzed using repeated-measure ANOVA, but showed no significant differences between interfaces. The rest of these data, which violated the normality assumption in Shapiro-Wilk tests, were analyzed using pair-wise comparison of the interfaces using Wilcoxon signed-rank test with Bonferroni correction as summarized in **??**-Appendix, with descriptive statistics in Figure 5 top-row. That is, compared to the Controller, HeadJoystick showed increased ease of use, overall usability, presence, immersion, enjoyment, and overall preference (see **??**-Appendix and top-row of Figure 5). As depicted in top-row of Figure 5, other DVs showed non-significant trends toward HeadJoystick advantage. Top row of Figure 5 also shows that adding soft/automated Brake mechanisms to HeadJoystick significantly reduced its overall usability, immersion, enjoyment, and overall preference, but still showed significantly higher presence, immersion, enjoyment, and overall preference compared to the Controller - see **??**-Appendix.

We also analyzed how performance measures, motion sickness, and task difficulty changed over trials. For per-trial changes of motion sickness, task difficulty, number of missed targets, and error rate, Shapiro-Wilk test showed violated normality assumptions, thus we analyzed pair-wise comparison of the interfaces in terms of these measures using Wilcoxon signed rank test with Bonferroni correction as summarized in **??**-Appendix. To analyze other performance changes over trials (that did not violate normality assumptions), we conducted 2×8 repeated-measures ANOVAS for the IVs interface and trial number, and Tukey-HSD post-hoc tests as summarized in **??**-Appendix. Our statistical analysis showed significant main effects of interface on all per-trial measures except motion sickness. Specifically, pair-wise post-hoc tests showed consistent advantages of HeadJoystick over Controller in terms of lower task difficulty, average time to reach a target, number of missed-targets, and error-rate as well as higher overall performance score, number of reached targets, and throughput – see **??**-Appendix and **??**-Appendix. Our pair-wise post-hoc tests also showed that adding braking options to the HeadJoystick reduced overall performance score, reached-targets, and throughput and increased missed targets and error rate. However, compared to the Controller, HeadJoystick+brake still showed significantly increased overall performance score, reached targets, and throughput as well as less missed targets and reduced error rate. Other results such as motion sickness were no significant.

The ANOVA also showed significant main effects of trial, with later trials showing increased overall performance score, reached targets, and throughput, as well as reduced average time to reach a target – see **??**-Appendix and linear regressions in Figure 5. The significant main effects of interface and trial were qualified by significant interface-trial interactions for overall performance score, reached-targets, and average time to reach a target. That is, the difference between HeadJoystick with vs. without brake was



cf.

Fig. 5. Study 3: Mean data of user experience (top), usability (top), and per-trial performance (middle and bottom) measures of HeadJoystick (in blue), versus HeadJoystick+Brake (in hatched-blue) versus Controller (in red). Middle and bottom plots show how performance and user experience changed over trials, including linear regression results as well as their confidence intervals shown as shaded regions. Error bars indicate confidence intervals ($CI = 95\%$), and annotated bars (black lines on top of the top-row bar charts) represent significance levels of Wilcoxon Signed-rank tests for pair-wise comparison between the interfaces (* $p < .05$, ** $p < .01$). Blue and red pale dots indicate individual participants' data for HeadJoystick and Controller, respectively.

decreasing over time as corroborated by the steeper slope of the linear regression fit for HeadJoystick+Brake over HeadJoystick condition in Figure 5. Moreover, the significant interface-trial interactions and linear regressions in Figure 5 show that the advantages of HeadJoystick with/without brake over Controller became more apparent over time for the overall performance score and reached-targets, as corroborate by the steeper slope of the linear regression fit for HeadJoystick and HeadJoystick+Brake compared to the Controller in Figure 5. Specifically, between first to last trial, using HeadJoystick over Controller increased number of reached-targets by 55% and the overall performance score by 60%.

During the third (and last) trial of the HeadJoystick+brake condition, the majority of participants (14/18 or 78%) used soft brake when reaching targets, two participants (11%) used the automated brake, and two participants (11%) did not use any brakes. Nine participants (50%) also used soft brake when using the Controller condition. When asked about their most preferred brake mechanism in the post-experiment interview, 10 participants (56%) chose HeadJoystick without brake, six participants (33%) chose soft brake, and only two participants (11%) chose automated brake. Only one participant (5%) chose Controller over HeadJoystick as their most favorite interface and all other participants (95%) preferred HeadJoystick irrespective of brake mechanisms over Controller.

4 General Discussion

Both Study 1 and 2 showed conclusive advantages of leaning-based over handheld translation control for our tasks in terms of all user experience factors, usability aspects, and performance measures. In the remainder of this section, first we discuss results of Study 1 in the context of research questions RQ1 and RQ2 and then discuss short-term vs. repeated exposure effects of our interfaces in the context of RQ3 using Study 2 results, before discussing RQ4 and the effects of stopping in Study 3. Therefore, unless stated otherwise, we refer to Study 1 results when discussing RQ1 and RQ2, and refer to Study 2 and 3 results when discussing RQ3 and RQ4, respectively.

4.1 RQ1: Leaning-based interfaces improved locomotion accuracy/precision

Results confirmed our hypothesis about higher accuracy/precision of leaning-based interfaces such as HeadJoystick compared to Controller in both Study 1 and 2, with similar trends in Study 3. As prior leaning-based interfaces often showed reduced accuracy/precision compared to handheld interfaces [4], [5], [6], [7], [8], [9], [10], these findings are substantial as to the best of our knowledge this study is the first study that provides clear and thorough evidence that leaning-based interfaces could improve ground-based locomotion accuracy/precision compared to handheld interfaces. Our findings are especially interesting as other natural driving interfaces (such as a steering wheel) also reduced performance in terms of both efficiency (task completion time) and effectiveness (number of crashes with other cars) compared to handheld interfaces – see chapter 4 of [24]. As our previous study already showed higher accuracy/precision of HeadJoystick for flying [12], the current study shows that the previously reported benefits of leaning-based interfaces such as HeadJoystick in 3D flying do indeed generalize to different 2D (ground-based) locomotion tasks. That is, in both 2D and 3D locomotion, HeadJoystick showed similar performance benefits over handheld controllers (i.e., touchpad/thumbstick) in terms of improved accuracy, higher precision, and increased speed i.e., reduced task completion time.

The potential reasons for higher accuracy/precision of HeadJoystick compared to previous leaning-based interfaces both for 2D (ground-based) and 3D (flying) [12], [67] locomotion could be due to the precision considerations we applied when designing HeadJoystick as discussed in subsubsection 3.5.1. Participant explanations in the post-experiment interview also helped to elucidate potential reasons for HeadJoystick accuracy/precision. For example, using head/torso movements could make VR locomotion control easier and more intuitive than mapping finger position to the velocity change, as illustrated by P7: *"It was easier to control the speed with HeadJoystick, because I kind of felt the [Virtual] motion by my head motions."*. Six participants (25%) in Study 1 and four participants (22%) in Study 2 and five participants (28%) in Study 3 mentioned that the Controller was too sensitive, which confirms and extends findings from our prior HeadJoystick flying study [12]. For example, P20 said *"it [Controller] was so sensitive, but using head I could do it gradually."* and P14 stated *"It [HeadJoystick] felt like you have a lot more control on speed, and you can feel the speed increasing much more. But with Controller, if you move thumb a bit, you change your speed much more."*. Over-sensitivity of the Controller could be due to the lower movement range of thumb in comparison to head motion in Controller versus HeadJoystick control.

4.2 RQ2: Leaning-based interfaces improved user experience and usability aspects

Our results confirmed our hypothesis that leaning-based interfaces (here: HeadJoystick) improve user experience and usability aspects compared to a handheld controller. Relatively similar results patterns between Study 1, 2, and 3, as well as larger effect sizes and relatively small p-values for most of the significant effects ins Study 1 and 2 ($p <= .008$) (except for potential of long-term and daily use) show substantial benefits, which are unlikely to be caused by false positives due to testing multiple measures. HeadJoystick advantages in terms of ease of use and ease of learning are noteworthy as prior studies reported either no significant differences or a decrease in terms of ease of use [8], [13], [69] and ease of learning [44], [50], [69] for leaning-based 2D interfaces compared to handheld interfaces.

Our results also confirm previously reported benefits of leaning-based interfaces such as improved task completion times in reach-the-target tasks [13], more intense perception of self-motion (vection) [1], [44], [48], improved immersion [5], enhanced presence [4], and increased fun/enjoyment [4], [44]. However, prior studies often evaluated each leaning-based interface for only one task in terms of a small subset of relevant measures [2], [3], [4], [7], [58] although there are exceptions (e.g., [13]), and thus provided limited evidence about how generalizable and consistent their findings regarding leaning-based interfaces would be for other tasks and measures. Therefore, our consistent findings of both short-term and repeated usage benefits of leaning-based interfaces in terms of almost all user experience, usability and performance measures over three complimentary tasks address this gap, and suggest that the advantages of leaning-based interfaces such as HeadJoystick are actually generalizable to a wider range of tasks.

Participants' answers in the post-experiment interview suggested potential reasons for consistent HeadJoystick advantages in our user studies and prior research [12], [67]. For example, 11 of the 24 participants (46%) in Study 1, 11 of the 18 participants (61%) in Study 2, and four (22%) participants in Study 3 stated that HeadJoystick provided natural physical self-motion cues, similar to natural body leaning like, e.g., riding a skateboard (P13 in Study 2), or natural body movement on a motorcycle in a racing task (P23 in Study 1). The increased embodiment and more natural connection between real and virtual locomotion for the HeadJoystick was another reason mention - for example, P2 in Study 2 mentioned that *"HeadJoystick was easier for me to use, like doing everyday activities such as being careful to not hit your head to anything or deciding to hit your head to something. But when using controller, it was like controlling your head with your hands. However, your hands don't have any idea about your head size, position, and direction and they don't have any muscle memory about your head's information so it's not easy to control your head with your hands. For me using controller was like controlling a string puppet."* This hands-free interaction resulted in a more realistic, immersive, and unmediated experience as mentioned by four participants in Study 1 (17%), four participants in Study 2 (22%), and one participant in Study 3 (6%) e.g., *"Having a controller in hand feels like an unreal interface, but hands-free HeadJoystick helped me to be more immersed in the game"*(P9-Study 1), *"Using hand feels like you are sitting in the lab, but using head feels like a real situation."*(P13-Study 1), *"I like travelling with my body [using HeadJoystick] as it unites me with the virtual environment"*(P11-Study 2) and *"HeadJoystick removes requiring an extra hand-held tool as a proxy to communicate with the game world, and thus it feels like our body is actually part of the game world."*(P18-Study 2).

As for the potential reasons for why HeadJoystick is easier to use compared to Controller in our studies and previous research [12], [67], P5 said *"Controlling three interfaces [HMD, Chair, and controller] when using Controller was harder than controlling two interfaces [HMD, and chair], kind of like Juggling using two and three balls"*(P5). As another example, P20 explained *"Controlling chair and finger and head [in Controller] is complicated, and I forgot which direction is my left when using touchpad due to the difference between my head and chair direction."* and P16 stated *"[Using Controller] it is also hard to control your motion direction, and especially combining the chair rotation with my finger motion is very hard for me."*

Regarding potential reasons for why HeadJoystick is easier to learn than the Controller both for ground-based locomotion and flying [12], [67], 14 participants (58%) in Study 1, nine participants (50%) in Study 2, and two participants (11%) in Study 3 highlighted the intuitive control of HeadJoystick compared to using the touchpad/thumbstick. For example, P8 in Study 1 said *"I instinctively leaned left and right, when I wanted to lean left and right even when using the controller, probably because I thought it was the natural things to do."* and P12 in Study 1 stated *"HeadJoystick was kind of like walking, how to move in our daily walking, but in Controller I needed to use an extra touchpad to move, and so I needed to think about how should I move."*. Furthermore, P18 in Study 2 explained that *"[I preferred] HeadJoystick, because it feels like my in-game decisions are done in my muscle-memory level and does not require my conscious attention."*

As for motion sickness, four (out of six) pilot-test participants stopped the Study 1 pilot test after using the gamepad condition due to severe motion sickness. HeadJoystick also showed significantly reduced motion sickness compared to the Controller in Study 2. This corroborates and extends findings from our prior HeadJoystick flying study [12], where HeadJoystick reduced motion sickness compared to gamepad. Unlike prior studies on leaning-based interfaces, which generally did not show any reduction on motion sickness compared to gamepad/joystick [4], [5], [7], [8], [44], [69], our findings and similar results from a recent study [3] seem interesting and require further research to find the potential reasons for their effect on reducing motion sickness. Our findings also could inspire VR user interface designers to consider full rotation when designing leaning-based interfaces.

4.3 RQ3: Leaning-based interfaces continued to provide improved user experience, usability, and performance over repeated usage

Similar significant benefits of HeadJoystick over Controller in Study 1 vs. 2 and 3 confirmed our hypothesis that leaning-based interfaces such as HeadJoystick retain improved user experience and usability compared to hand-held controllers over repeated usage, even when in Study 2 and 3 we used the likely better controller (thumbstick) instead of the touchpad from Study 1. Eight minutes of interface usage time in Study 2 might not be considered long-term usage, but nevertheless all performance measures showed improvement for both interfaces similar to the repeated usage of the leaning-based interfaces in previous research (e.g., [4], [7], [70], [82], [83]). However, unlike these prior works [4], [7], [70], [83], our findings showed that the advantages of leaning-based interfaces over Controller rapidly become more pronounced over time - cf. **??**-Appendix, Figure 4, and Figure 5. Particularly, compared to the Controller, using HeadJoystick over the course of eight trials in Study 2 resulted in a three times slower increase in motion sickness, two times faster decrease in task difficulty, three times faster increase in the overall score, and two times faster increase in the number of reached targets. Unlike HeadJoystick, which showed a stable number of missed targets and error rate over time, using Controller more than doubled the number of missed targets and increased error rate by 60%. Moreover, unlike using Controller, which showed a stable throughput, using HeadJoystick increased throughput by 57% over the eight trials.

As for user experience factors and usability aspects, compared to Study 1, Study 2 did not reveal significant advantages of leaning-based interfaces over Controller in terms of daily use, but revealed new advantages of leaning-based interfaces in terms of long-term use and motion sickness. The significant interaction of interface and trial for motion sickness shows that motion sickness started similar for the two interfaces but increased much faster for the controller compared to the HeadJoystick, and reached motion sickness levels 3.7 times as high. This suggests that leaning-based interfaces could be more suitable for longer-term usage due to reduced motion sickness. The significant interaction of interface and trial for the overall performance score confirms participants' subjective ratings that HeadJoystick is easier to learn compared to the Handheld interfaces, and suggests that benefits of leaning-based interfaces can be further increased by moderate practice. Faster performance improvements for the HeadJoystick also shows that the performance advantage of leaning-based interfaces over Controller become larger over time and increased from 42% to 120%, which suggests that the full potential of leaning-based interfaces such as HeadJoystick might be even more apparent when allowing users to have sufficient practice, thus reducing initial novelty and learning effects. Altogether, these results show that the advantages of leaning-based interfaces over handheld Controller for our tasks does not seem to shrink over time, but if anything grow over extended usage, which is promising for many applications requiring longer usage.

4.4 RQ4: Leaning-based interfaces improve user experience, usability, and performance for tasks requiring users to stop at each target

Similar to Study 1 and 2, the results of Study 3 confirmed our hypothesis regarding the advantages of leaning-based interfaces (here HeadJoystick) over Controller in terms of all performance aspects, and six (out of 12) user experience and usability measures. Note that the HeadJoystick in Study 3 did not require a chair-attached tracker, indicating that the HeadJoystick's benefit over the controller do not require any additional hardware or modification of the chair. Our results contradict prior studies that showed lower performance of leaning-based interfaces with a neutral/idle zone [4], [10], [70] and confirm recent studies such as [3], and expand the benefits of leaning-based interfaces to accuracy and throughput measures. Particularly, compared to the Controller, using HeadJoystick over the course of three 2-min trials increased the number of reached-targets by 55% and the overall performance score by 60%. This shows that the advantages of leaning-based interfaces over controller might grow over time.

Unlike Study 2, Study 3 did not show significant differences between Controller and HeadJoystick on a few DVs including ease of learning, long-term use, vection intensity, task load, and motion sickness. These reduced differences could be due to the shorter total interface usage time (6 min vs. 8 min in Study 3 vs. 2), and/or changes in HeadJoystick and Controller conditions: in Study 3, the Controller condition was more embodied because the forward deflection of thumbstick moved the user toward the controller (instead of chair) direction, which could explain improving Controller's ease of learning and ease of use [84]. Moreover, due to removing the chair-attached tracker in Study 3, we had added a neutral/idle zone to the HeadJoystick, such that vestibular cues of head movements were only directly coupled to simulated accelerations/decelerations when the user's head was outside of the neutral/idle zone, which might have contributed to the reduced benefit of HeadJoystick over Controller for vection and motion sickness.

As for the potential reasons for why using a neutral/idle zone was preferred over soft/automated brake by 10 participants, P10 said *"with head motion, I know how much I need to move to stop my motion"*, and *"it was easy to just compensate your error by tilting your head."*(P14). However as three participants (17%) mentioned, *"using my head sometimes makes me dizzy"*(P5). Soft brake was the preferred brake mechanism for six participants for reasons such as *"combination of returning my head to the zero-point and pulling the trigger is more precise for me"*(P7) even if for others *"the problem is that I don't know how much to press or when to press it"*(P10). Automated brake was the least favorite brake for reasons such as *"returning my head to the zero-point, press stop button, calibrate zero-point, and press another button to go was very demanding and too many things to think"*(P17) or *"more like a reset button not a brake"*(P2) or *"I forgot which button to press"*(P10) or *"I always push too soon or too late and really hard to control"*(P18). However, automated brake might be more suitable for different tasks and longer stops, as indicated by P13: *"I did not understand the purpose of automated brake, as in this game, we really don't need to stop totally."*, and *"maybe automated brake would be useful when I need to stop for a long time and I need to move my head without holding down the trigger for a long time."*(P5).

4.5 Limitations

To be able to run our studies in about 75 min per participant and study, we limited the total time for using each interface to 90 s in Study 1, eight minutes total (8×60 s) in Study 2, and six minutes total (6×120 s in Study 3. Future research is needed to investigate if and how our results might generalize to other scenarios and VR applications, where a user could be in VR for hours and thus be more likely to experience longer-term side-effects such as physical discomfort, fatigue, dry eye syndrome, or compounding motion sickness [85]. The familiarity of participants with the handheld controllers (but not the HeadJoystick) could also have affected our results, although Study 2 and 3 suggest that more extensive practice with both interfaces might, if anything, further enhance the relative performance advantage of the HeadJoystick. Note that both Controller and HeadJoystick locomotion metaphors in this study allowed for strafing (sideways motions) that is possible in real-world scenarios such as walking or flying a drone, but is not supported by some other real-world vehicles such as cars, motorcycles, bikes, or fixed-wing planes. Although our own pilot studies and some related literature [86], [87] suggests that leaning-based interfaces can provide a benefit in situations where strafing is not possible, this should be further investigated to test generalizablity of our findings to other locomotion paradigms and scenarios.

Our reach-the-target task was not primarily designed to look at Fitts's law and throughput measures, but was purposefully designed to have higher ecological validity and applicability. For example, instead of rapid aimed motions toward one visible target at a time in typical Fitts's law tasks, we included additional components including spatial awareness (e.g., searching for the targets and target selection between multiple targets), and path planning to find the shortest path. Thus, future research is needed to investigate how the observed throughput measures might generalize to different tasks, and compare accuracy/precision of HeadJoystick compared to Controller using more standard/ISO Fitts's law tasks [88], [89]. This could include reaching a series of visible targets of the same size and distance without any search or path-planning.

Future research is also needed to investigate how benefits observed for leaning-based locomotion paradigms such as the HeadJoystick might or might not generalize to more diverse tasks, scenarios, applications and user preferences, and how the various parameters might need to be fine-tuned and how much choice users should be provided with. For example, such scenarios involve tasks where the user does not continuously move but needs to occasionally slow down or stop to interact with the environment or gather information. In our reach-the-target tasks, we intentionally did not include a visual representation of any vehicle or self-avatar to reduce potential confounds – it might be interesting to investigate how such representations might interact with different locomotion paradigms, though. Future research could also explore different brake mechanisms or combinations thereof. For example, while Study 3 investigated combining neutral/idle zone with soft/automated brake due to our pilot-tests, future studies could investigate using soft/automated brake without neutral/idle zone, which might improve vestibular-visual sensory coupling, and strength the advantages of leaning-based interfaces over handheld controllers in terms of motion sickness, vection intensity, etc.

5 Conclusion

In this paper, we evaluated a locomotion interface using an extensive set of measures (cf. **??**-Appendix). We used our suggested framework to evaluate HeadJoystick, a precise leaning-based locomotion interface we introduced and evaluated on a 3D flying tasks in a previous papers [12], [67]. HeadJoystick was evaluated in Study 1 using three complimentary 2D navigation tasks including reach-the-target, follow-the-path, and racing to capture the key aspects of human locomotion experience. Due to severe motion sickness we had to exclude an initially planned additional controller condition that did not allow for physical rotations. Thus, HeadJoystick was compared to both touchpad (Study 1) and thumbstick (Study 2 and 3), where rotations were always physically performed, and HeadJoystick was chosen as the preferred interface by 100%, 89%, and 94% of participants in Study 1, 2, and 3 respectively. Study 2 extended HeadJoystick advantages over repeated usage, and Study 3 generalized observed advantages to scenarios where users need to stop frequently. In our studies, HeadJoystick showed significant advantages over touchpad and thumbstick in terms of behavioral performance measures (e.g., speed, accuracy, precision, overall score, and throughput), as well as ease of use, overall usability, presence, immersion, enjoyment, and overall preference. To the best of our knowledge, some of these advantages of leaning-based interfaces over handheld interfaces (e.g., ease of use, ease of learning, and accuracy/precision) have never been reported in prior work. Moreover, as far as we know, no prior research ever assessed the interface throughput for leaning-based self-motion control interfaces in VR. We argue that throughput can be useful for comparing accuracy of locomotion interfaces, as it combines speed, accuracy, and error rate, and thus provides a comparable measure between users with different speed and error rate.

As prior studies typically evaluated different leaning-based interface prototypes in terms of only one task for a small subset of key measures, findings of our current and prior [12] research show consistent benefits for both short-term and repeated usage of leaning-based interfaces over handheld interfaces in terms of six user experience factors, six usability measures, and three performance metrics (speed, accuracy, and precision), similarly across four complementary tasks (ground-based reach-the-target, follow-the-path, and racing in the current study, and flying (maneuvering in a waypoint navigation task) in [12] and 3D navigational search in [67]). These results contradict prior studies and design guidelines, which suggested limited usability of leaning-based interfaces for only specific tasks and factors [11]. That is, overall, our results show that leaning-based interfaces such as HeadJoystick could actually be considered as an alternative solution for handheld locomotion interfaces in tasks such as reach-the-target, follow-the-path, driving, and flying at least for home users and many professionals, while allowing for using hands/handheld interfaces for other tasks such as selection, manipulation, etc. These findings are substantial as they challenge decades of dominance of handheld locomotion interfaces for these tasks.

Although the current results are promising, future studies need to investigate leaning-based interfaces such as HeadJoystick in more depth and for other effectiveness factors such as spatial awareness/orientation [84] and information gathering. Future studies could also investigate how the current findings might generalize to larger and more diverse participant populations, longer and more sessions, as well as other tasks such as exploration, search, and multi-tasking, such as simultaneous travel and interaction.

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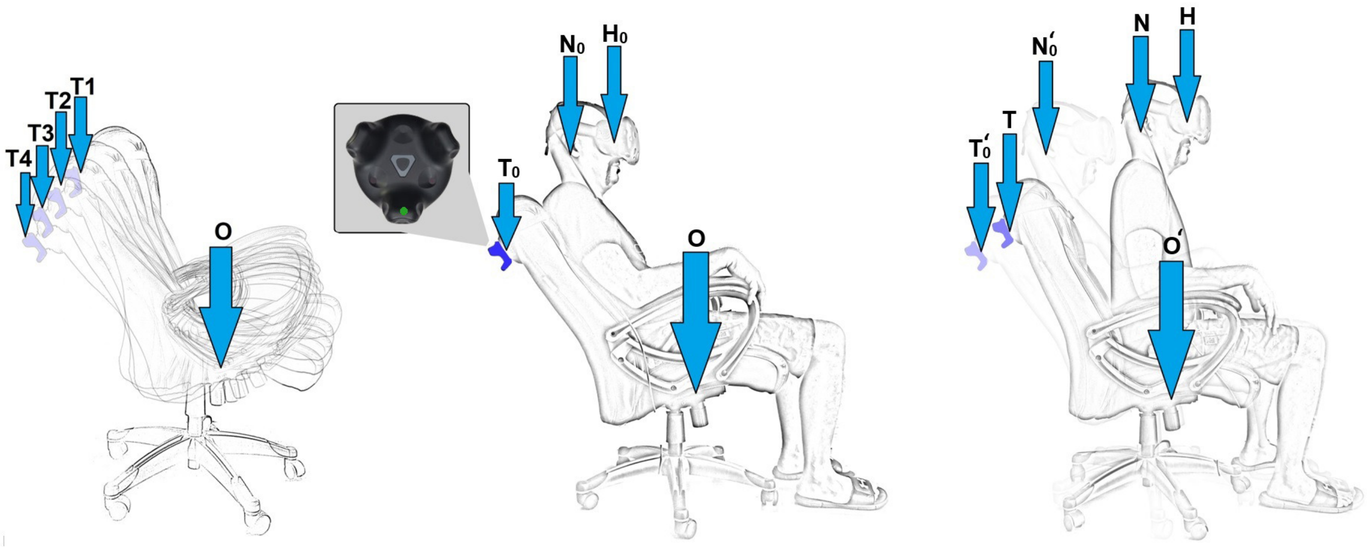

Fig. 1. HeadJoystick motion model: (Left) Tracker calibration process, (Middle) Setting zero-point when starting flight, (Right) Flight motion model. Position of Tracker (T), HMD (H), above the head rotation center in the neck (N), Center of chair backrest pitch rotation (O) are annotated in the figure, where T_0, N_0, and H_0 indicates the initial positions of tracker, head rotation center, and HMD when the flight starts. O', T_0', and N_0' are the estimated position for the backrest rotation center, initial position of the tracker, and head rotation center during flight.

1 APPENDIX

1.1 Motion Control Model

LeaningTranslation interface does not use a swivel chair, and thus has a *static* zero-point (initial head position) when the flight begins. However, because the HeadJoystick has a *dynamic* zero-point, it uses a tracker to track the backrest movements of a swivel chair including its yaw or pitch rotations, to update the zero-point relative to the center of the chair backrest pitch rotations. We call this the *chair center*, indicated as O in Figure 1. Tracking the chair center requires a tracker to be attached to the chair, and a calibration process is needed to calculate the chair center relative to the tracker position and orientation. Our calculations use orientation as $(pitch, yaw, roll)$ and the position in both Cartesian (x, y, z) and spherical (r, θ, ϕ) coordinates to make the equations easier to understand.

Tracker Calibration: The tracker has to be calibrated after the tracker is attached to the chair and before the flight starts. The user does not need to repeat the calibration process as long as the tracker remains attached to the chair and does not move with respect to the chair. As shown in Figure 1-left, the calibration process requires the user to lean back to change the backrest pitch. We recorded four different positions of the tracker - called T_1, T_2, T_3, T_4, with at least $2.5°$ pitch differences to calculate the chair pitch rotation center (O). Considering the tracker (T) has a constant distance from the chair center, we used the W.H. Beyer approach, which finds the center of an sphere using any four points on it by solving the below equation [1]:

$$\det \begin{vmatrix} (x_O^2 + y_O^2 + z_O^2) & x_O & y_O & z_O & 1 \\ (x_{T_1}^2 + y_{T_1}^2 + z_{T_1}^2) & x_{T_1} & y_{T_1} & z_{T_1} & 1 \\ (x_{T_2}^2 + y_{T_2}^2 + z_{T_2}^2) & x_{T_2} & y_{T_2} & z_{T_2} & 1 \\ (x_{T_3}^2 + y_{T_3}^2 + z_{T_3}^2) & x_{T_3} & y_{T_3} & z_{T_3} & 1 \\ (x_{T_4}^2 + y_{T_4}^2 + z_{T_4}^2) & x_{T_4} & y_{T_4} & z_{T_4} & 1 \end{vmatrix} = 0$$

Set Zero-Point: To start the flight, we asked users to sit comfortably and centered on the chair. Then we asked them to gently lean backwards until they touch the backrest, without pushing it backwards, after which they press a button to set the zero-point before starting the flight. This way, the user gets physical feedback for their zero-point when their back touches the backrest during flight. Pilot studies showed that this makes it easier than using visual cues to stop the flight. To ensure that users can rotate their head freely without initiating a virtual translation, we did not use the initial position of the HMD (H_0) as the zero-point, but instead calculated through pilot testing the approximate rotation center of the head (N_0) as indicate in Figure 1-middle. This allows the user to rotate their head left/right or up/down to view the VE without affecting their flight direction or speed. Our pilot tests showed that Vive HMD has an average of 0.13m horizontal distance with the typical head rotation center, for adults i.e., $\overrightarrow{H_0N_0}$. We also calculated the head rotation center distance from tracker (T_0), so we could later update the head rotation center position based on the tracker movements:

$$\overrightarrow{H_0N_0}(r, \theta, \phi) = (0.13m, yaw_{H_0}, pitch_{H_0})$$
$$N_0 = H_0 + \overrightarrow{H_0N_0}$$
$$\overrightarrow{T_0N_0} = N_0 - T_0$$
$$\overrightarrow{OT_0} = T_0 - O$$

Flight Motion: As depicted in Figure 1-right, we measured the position of the tracker (T) during flight, to estimate the position of the chair center (O'), the initial position of the tracker (T_0'), and the initial user's head rotation center position (N_0'):

$$\begin{aligned}
\Delta pitch &= pitch_T - pitch_{T_0} \\
\overrightarrow{\mathrm{O'T}}(r,\theta,\phi) &= (r_{\overrightarrow{OT_0}}, \theta_{\overrightarrow{OT_0}}, \phi_{\overrightarrow{OT_0}} + \Delta pitch) \\
O' &= T - \overrightarrow{\mathrm{O'T}} \\
T_O' &= O' + \overrightarrow{OT_0} \\
N_0' &= T_0' + \overrightarrow{T_0 N_0}
\end{aligned}$$

As the next step, we predicted the head rotation center position (N) using the HMD position (H), yaw (yaw_H) and pitch ($pitch_H$). Then we found the head rotation center displacement (D) using its initial position (N_0') and the current position (N). To calculate the speed, we then multiplied the displacement to a sensitivity coefficient of α, which we determined as 8 in our pilot testings. Moreover, because users usually have lower range for their vertical head movement compared to their horizontal head movement, we multiplied the vertical sensitivity to a higher sensitivity coefficient (β) determined as 3 based on our pilot testings. This makes the overall vertical sensitivity coefficient as 24 $(3 * 8)$.

$$\begin{aligned}
\overrightarrow{\mathrm{HN}}(r,\theta,\phi) &= (0.13m, yaw_H, pitch_H) \\
N &= H + \overrightarrow{\mathrm{HN}} \\
\vec{D} &= N - N_0' \\
\vec{D} &= \vec{D} * \alpha \\
y_{\vec{D}} &= y_{\vec{D}} * \beta
\end{aligned}$$

Then, we calculated the user's simulated speed ($\vec{S}$) using an exponential transfer function. Pilot testing showed us that using 1.53 as the exponential factor makes it easier for the user to find the zero-point and control their movements accurately in lower speeds. Finally, we apply the speed limit (v_{max}), because our pilot testings showed that high speeds could make the user dizzy. We used ($\vec{S}$) as the speed of moving the user's view-point in study 1.

$$\vec{S}(r,\theta,\phi) = (\min(r_{\vec{D}}^{1.53}, v_{max}), \theta_{\vec{D}}, \phi_{\vec{D}})$$

Smooth Acceleration: To prevent abrupt speed changes and reduce the motion sickness, we smoothly applied the simulated speed ($\vec{S}$) to the current simulated speed of the user ($\vec{K}$) using SmoothStep function in Unity with an acceleration smoothness factor (δ) determined as 0.12 based on our pilot testings.

$$\begin{aligned}
x_{\vec{K}} &= Mathf.SmoothStep(x_{\vec{K}}, x_{\vec{S}}, \delta) \\
y_{\vec{K}} &= Mathf.SmoothStep(y_{\vec{K}}, y_{\vec{S}}, \delta) \\
z_{\vec{K}} &= Mathf.SmoothStep(z_{\vec{K}}, z_{\vec{S}}, \delta)
\end{aligned}$$

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TABLE 1

2D (ground-based) leaning-based interfaces with full 360° physical rotation and their significant differences compared to handheld interfaces such as gamepad and touchpad. The last row shows the current study and its results to facilitate direct comparison.

Body Posture	Interface Name	Translation Input	Task	Compared with	Significant Advantages	Significant Disadvantages
Standing	*Wii-Leaning [2]*	Weight Shifting	Pointing	Joystick	Lower latency, turning error	
				WIP		Higher turning error and latency
Standing	*LAS-WIP [58]*	Torso Leaning angle	Follow-the-path	WIP	Higher Preference	
Standing	*Joyman [4]*	Torso Leaning angle	Reach-the-target	Joystick	Higher fun, presence, and rotation realism	Lower speed, accuracy, intuitiveness, and higher fatigue
Standing	*Naviboard [3]*	HMD position	Navigational search	Controller	Higher search speed, lower taskload, travelled distance, and motion sickness	
Seated	*NaviChair [3]*	HMD Position	Navigational search	Controller	Higher search speed, with lower travelled distance	
Seated	*NaviChair [7]*	Weight Shifting	Follow-the-avatar	Real-Rotation		higher distance error, lower precision
				Joystick		higher distance error, lower precision, comfort, long-term use, usability, higher usability problems
Seated	*Swivel-Chair [7]*	Chair Backrest Tilt and HMD Position	Follow-the-avatar	Joystick		Lower precise control
Seated	*Leaning [13]*	HMD position	Reach-the-taregt	Joystick	Higher speed, lower finger & arm fatigue	Higher spine fatigue
				Teleport		Lower speed, usability, comfort, ease of use, higher motion sickness
Seated	*Head Joystick [Current Study]*	Position of the head rotation center	Reach-the-target, Follow-the-path, and racing	Real-Rotation	Lower motion sickness and higher speed, accuracy, precision, throughput, enjoyment, preference, vection intensity, immersion, usability, ease of use, ease of learning, presence, long-term use, daily use, and lower task-load	

TABLE 2

Overview of our suggested factors to evaluate a locomotion interface, including suggested DVs and how to measure them. Factors that go beyond Bowman's effectiveness factors [2] are highlighted in green. "I" stands for introspective measures and "B" for behavioral measures.

	Factor/Construct	Dependent Variable	Research Instrument/measure
Usability (I) and Performance (B)	Ease of learning / learning effects	*I: Rating for ease of learning*	*"How easy was it to learn using the interface for the first time?"*
		B: Performance improvements over time	Comparing the overall performance improvement of interfaces over repeated trials of using each interface based on the linear regression
	Ease of Use	*I: Taskload*	*NASA-Task load index questionnaire [73]*
		I: Rating for ease of use	*"How easy was it to use the interface?"*
	User Comfort	***I: Rated potential for long-term use***	***"I could imagine using the interface for longer time than the study task"***
		I: Rated potential for daily use	***"I could imagine using the interface in daily applications frequently"***
	Overall Usablity	***I: Rating for overall usability***	***"Overall usability of the interface"***
	Speed	B: Task completion Time	Average time to complete the task
	Accuracy	B: Proximity to the desired target or path	Average absolute disrance error from the desired target or the path
	Precision	**B: The ability of technique for fine movements [68]**	**Average number of missed targets or crashes to unwanted objects**
	Overall performance	**B: Performance Score**	**Defined per task to combine its different performance measures**
		B: Throughput [21], [22]	**Ratio of effective index of difficulty over movement time**
User Experience	Presence	*I: Spatial presence*	*SUS Questionnaire of spatial presence [74]*
		I: immersion	*"I felt immersed in the virtual scence (captivated by the task)"*
	Self-motion perception	***I: Vection intensity***	***"I had a strong sensation of self-motion with the interface"***
	Motrion sickness	*I: Motion Sickness*	*Simulator Sickness Questionnaire (SSQ) [75]*
	Overall user experience	***I: Enjoyment***	***"I enjoyed doing the task using this interface?"***
		I: Overall preference	***"Overall preference ratings"***

TABLE 3

Study 1: t-test results for all dependent variables: Significant effects $(p \leq 5\%)$ are highlighted in green, and were always in the direction of enhanced user experiences for HeadJoystick over Controller. The effect size *Cohen's d* indicates the magnitude of the effect i.e., the difference between two means expressed in standard deviations.

	t(23)	*p*	*Cohen's d*
Enjoyment	30.8	<.001	.572
Preference	26.9	<.001	.539
Immersion	11.6	.003	.335
Vection Intensity	15.4	<.001	.402
Long-Term Use	2.07	.163	.083
Daily Use	5.13	.03	.182
Overall Usability	24.7	<.001	.518
Presence (SUS)	35.2	<.001	.605
Ease of Use	38.6	<.001	.627
Ease of Learning	27.4	<.001	.543
NASA-TLX	21.9	<.001	.605
Post-Pre Motion Sickness	.285	.6	.012
Reach-the-Target Average Time	69.6	<.001	.865
Reach-the-Target Minmum Size	51.6	<.001	.802
Reach-the-Target Overall Score	56.8	<.001	.712
Reach-the-Target Error Rate	43.4	<.001	.653
Reach-the-Target Througput	54.7	<.001	.362
Follow-the-Path Average Velocity	66.2	<.001	.742
Follow-the-Path Distance Error	68.5	<.001	.944
Follow-the-Path Collisions	5.71	.030	.456
Follow-the-Path Overall Score	16.1	<.001	.411
Racing Average Overtaking Time	14.5	.001	.638
Racing Car Crashes	5.67	.030	.415
Racing Overall Score	29.5	<.001	.562

TABLE 4

Study 2: t-test results for all user experience and usability measures: Significant effects $(p \leq 5\%)$ are highlighted in green, and were always in the direction of enhanced user experiences for HeadJoystick over Controller. The effect size *Cohen's d* indicates the magnitude of effect i.e., the difference between two means expressed in standard deviations.

	t(17)	*p*	*Cohen's d*
Enjoyment	32.1	<.001	.654
Preference	18.5	<.001	.521
Immersion	13.8	.002	.448
Vection Intensity	132	<.001	.886
Long-Term Use	7.33	.015	.301
Daily Use	2.22	.155	.115
Overall Usability	27.2	<.001	.615
Presence (SUS)	41.0	<.001	.707
Ease of Use	18.8	<.001	.525
Ease of Learning	13.3	.002	.439
NASA-TLX	21.9	<.001	.452
Pre-Post Motion Sickness	8.90	.008	.334

TABLE 5

Study 3: Wilcoxon signed-ranked test results for user experience and usability measures. Significant effects $(p \leq 5\%)$ are highlighted in green, and were always in the direction of enhanced user experiences for HeadJoystick followed by HeadJoystick+brake and then Controller, as illustrated in Figure **??**

Measures	Controller vs HeadJoystick		HeadJoystick+Brake vs HeadJoystick		Controller vs HeadJoystick+Brake	
	Z	*p*	Z	*p*	Z	*p*
Enjoyment (%)	100	0.003	48.0	0.030	92.0	0.013
Preference (%)	97.5	0.005	84.5	0.043	99.0	0.025
Immersion (%)	78.0	0.002	36.0	0.011	36.0	0.011
SUS Presence (%)	120	0.001	88.0	0.003	114	0.002
Long-Term Use (%)	63.5	0.489	58.5	0.360	40.5	0.906
Overall Usability (%)	61.0	0.130	48.0	0.320	65.5	0.161
Ease of Use (%)	89.0	0.021	37.5	0.073	74.5	0.166
Ease of Learning (%)	44.5	0.336	67.0	0.132	59.0	0.683
Motion Sickness (%)	20.0	0.779	34.0	0.929	41.0	0.477
Task Difficulty (%)	4.50	<0.001	31.0	0.177	3.00	<0.001
Missed-Targets (#)	1.00	<0.001	12.0	0.002	7.00	0.001
Error Rate (%)	1.00	<0.001	6.00	0.001	5.00	<0.001

TABLE 6

Study 2 Statistical analysis for per-trial data, with significant effects shown in green. Significant main effects of interface and interface-trial interactions were always in the direction of enhanced user experience and performance for HeadJoystick versus Controller.

Measures	HeadJoystick		Controller		Interface			Trial			Interface * Trial		
	M	SD	M	SD	F(1,17)	p	η_p^2	F(1,17)	p	η_p^2	F(1,17)	p	η_p^2
Motion Sickness (%)	5.63	7.48	14.8	15.5	7.13	0.016	0.005	39.9	<0.001	0.243	14.3	0.002	0.103
Task Difficulty (%)	29.2	13.6	49.6	14.2	64.3	<0.001	0.201	670	<0.001	0.241	2.68	0.018	0.039
Time to reach a target (s)	4.30	1.52	5.59	1.94	99.0	<0.001	0.187	61.2	<0.001	0.187	0.736	0.372	0.038
Minimum Target Size (cm)	2.61	1.80	4.03	2.26	101	<0.001	0.110	80.3	<0.001	0.173	1.83	0.087	0.041
Overall Score (K)	7.45	4.48	4.08	2.21	86.2	<0.001	0.108	109	<0.001	0.214	10.8	0.004	0.082
Reached Targets (#)	15.0	3.79	11.7	3.12	18.2	<0.001	0.118	45.1	<0.001	0.241	14.6	0.002	0.093
Missed targets (#)	1.65	1.56	7.57	4.43	36.0	<0.001	0.202	22.0	<0.001	0.134	8.04	0.005	0.054
Error Rate (%)	9.06	7.14	35.6	14.1	241	<0.001	0.250	80.3	<0.001	0.058	2.60	0.016	0.064
Throughput	1.96	1.01	1.48	0.795	20.0	<0.001	0.002	80.3	<0.001	0.029	2.57	0.017	0.064

TABLE 7

Study 3 Statistical analysis for per-trial data, with significant effects shown in green. Significant main effects of interface and interface-trial interactions were always in the direction of enhanced user experience and performance for HeadJoystick followed by HeadJoystick+Brake and then Controller, and performance improvement over the course of the three trials per interface, as illustrated in Figure **??**.

Measures	HeadJoystick		HeadJoystick+Brake		Controller		Interface			Trial			Interface * Trial		
	M	SD	M	SD	M	SD	F(1,17)	p	η_p^2	F(1,17)	p	η_p^2	F(1,17)	p	η_p^2
Overall Score (K)	10.4	2.37	8.30	2.59	5.15	2.05	40.4	<0.001	0.704	82.5	<0.001	0.829	5.25	0.001	0.236
Reached Targets (#)	18.6	3.31	15.6	3.70	11.1	2.89	41.2	<0.001	0.708	80.7	<0.001	0.826	5.92	<0.001	0.258
Average Time (s)	6.76	1.25	8.57	1.98	12.0	3.34	31.3	<0.001	0.648	42.6	<0.001	0.715	4.61	0.008	0.213
Throughput	1.03	0.22	0.805	0.210	0.532	0.159	78.8	<0.001	0.822	49.8	<0.001	0.746	1.88	0.125	0.099