Providing Embodied Self-Motion Cues Improve Flying and Ground-Based Locomotion Experience and Performance

by

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Abstract

This thesis contributes to Human-Computer Interaction (HCI) research and technology development with a focus on the design of locomotion interfaces for virtual reality (VR) applications. Using handheld locomotion interfaces does not provide embodied (vestibular and proprioceptive) self-motion cues, which are associated with disorientation and motion sickness. Therefore, previous research designed and investigated a wide range of embodied locomotion interfaces, which provide partial embodied self-motion cues. However, prior research often investigated embodied locomotion interfaces in only one specific task in terms of a small subset of locomotion-relevant aspects and showed their advantages (e.g., believability) with some disadvantages (e.g., effectiveness) compared to the handheld interfaces. We investigate if providing embodied self-motion cues can reduce adverse effects of using handheld interfaces while improving or at least matching other user experience and performance measures in a wide range of locomotion scenarios. Using four user studies, we designed and step-by-step refined a leaning-based interface - called HeadJoystick. HeadJoystick users sit on a regular office swivel chair and rotate it physically to control virtual rotation and control the simulated translation by moving their head toward the target direction. We conducted eight user studies to thoroughly evaluated HeadJoystick and its standing version (NaviBoard) versus handheld interfaces in a wide range of 2D (ground-based) and 3D (flying) locomotion scenarios. Our results showed that providing embodied self-motion cues using carefully optimized embodied interfaces (HeadJoystick and NaviBoard) significantly improved all performance measures and reduced adverse effects of using handheld interfaces in terms of unconvincing simulated motion, motion sickness, disorientation while also improving or at least matching all other locomotion-relevant measures. In addition, our results showed that these benefits were more pronounced if provided with 360° physical (instead of partial or virtual) rotation; repeated (instead of short-term) interface usage; in multitasking (instead of locomotion-only) scenarios; standing/stepping (instead of sitting) body posture; and increased locomotion difficulty (speed). From a theoretical perspective, our findings help researchers by extending our knowledge about the effects of providing vestibular and proprioceptive self-motion cues on VR locomotion. From an applied perspective, we also suggest design guidelines to user interface designers for improving user experience, usability, and performance of VR locomotion interfaces.

Keywords: 3D User Interface; locomotion; motion sickness; cybersickness; travel techniques; virtual reality

Dedication

To my wife Atefe who stood by me through all the difficulties in my path.

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Foremost, I want to thank my wife, who supported me with patience through all ups and downs in this long path. I love you more.

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Chapter 1

Introduction

Many real-life activities require travel, i.e., locomotion. Locomotion allows us to reach a target position usually by walking, driving, or even flying to perform other tasks. Locomotion happens in daily activities for different purposes such as exploring an environment, searching, or maneuvering - see chapter 8.2 of (Bowman et al., 2017). Locomotion can also be a simple reach-the-target or follow-the-path task or might accompany other tasks such as gathering information or interacting with environment in multi-tasking scenarios.

All these cases of locomotion can also happen in Virtual Reality (VR) applications, where prior research typically defined locomotion as viewpoint motion control - see chapter 4.3 of (McMahan et al., 2014). VR locomotion can be active (instead of passive) if the user controls the viewpoint motion using input devices AKA locomotion interfaces. In many current VR applications, users are typically able to actively locomote using handheld interfaces including mouse and keyboard, joystick, gamepad, and VR controllers. However, using handheld interfaces for VR locomotion provides no vestibular and minimal proprioceptive self-motion cues toward the intended locomotion direction (in the form of hand movements) as the rest of the user's body does not move physically toward the direction of simulated locomotion. In this thesis, we define the term embodied self-motion cues as vestibular self-motion cues that are aligned toward the intended travel direction with optionally also some levels of proprioceptive cues. The lack of vestibular self-motion cues when using handheld locomotion interfaces can enhance the visual-vestibular sensory conflict, which reduces believability of self-motion and exacerbates adverse side effects such as motion sickness (Reason and Brand, 1975) and disorientation (see chapter 1 of (Steinicke et al., 2013)). To help reducing visual-vestibular sensory conflict, prior research has designed and investigated a wide range of locomotion interfaces that provide vestibular with or without proprioceptive self-motion cues using partial body movements - see reviews (Boletsis, 2017; Al Zayer et al., 2020). While prior research defined the general terms of embodied interfaces as interfaces involving the user's body such as tangible and embodied interfaces (TEI), and examples include diverse body motions ranging such as cycling, rowing, and hammering (Clifton et al., 2016), in this thesis, we define the term embodied locomotion interfaces as

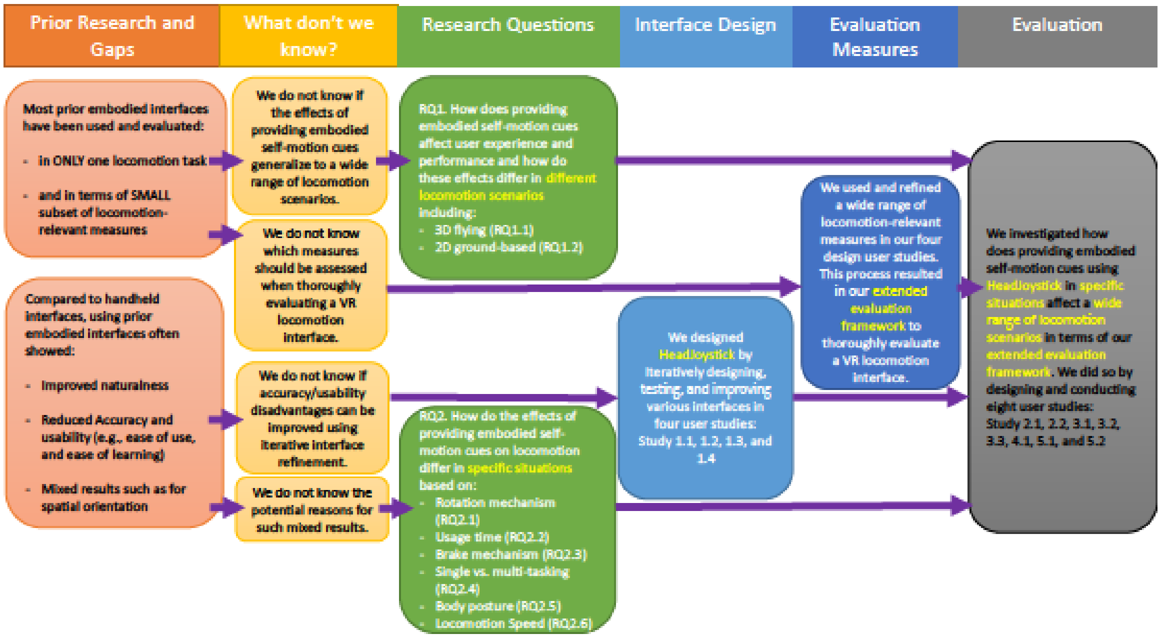


Figure 1.1: Overview of our research, which shows how the prior research and their gaps motivated our research questions, interface design, and evaluation user studies.

locomotion interfaces providing embodied self-motion cues using partial body movements such as motion cueing interfaces. These partial movements can be provided using complex motion platforms (such as omni-directional walking treadmills (Steinicke et al., 2013) or actuated/moving base motion flight/driving simulators (Knott et al., 2021)) or simply user-powered motions such as walking-in-place (WIP) (Nilsson et al., 2016), arm swinging, and leaning (Cherni et al., 2020).

Prior research typically reported that providing embodied self-motion cues using embodied locomotion interfaces can improve some locomotion-relevant aspects such as immersion and presence (Marchal et al., 2011; Freiberg, 2015; Kitson et al., 2015), self-motion perception (i.e., vection) (Kruijff et al., 2016; Riecke, 2006; Riecke et al., 2008), as well as fun/enjoyment (Beckhaus et al., 2005b; Kruijff et al., 2016; Harris et al., 2014; Marchal et al., 2011) compared to providing no vestibular and minimal proprioceptive self-motion cues when using standard handheld interfaces. However, most previous embodied locomotion interface prototypes have been typically tested in only one specific task, and included often only a small subset of locomotion-relevant measures. Therefore, there is a limited understanding as to how these findings might or might not generalize to different tasks. In addition, prior embodied locomotion interfaces often showed usability issues or reduced accuracy compared to the standard handheld locomotion interfaces (Steinicke et al., 2013). However, due to the limited research on each embodied locomotion interface, the question may arise if these disadvantages are inherent problems of embodied locomotion interfaces, or if they could be resolved with more rounds of prototype refinement. That is, we aimed to

Table 1.1: Overview of our 12 user studies for this research in chronological order. The first four user studies (in light-blue) were conducted to test and improve several embodied locomotion interface prototypes. After designing our embodied locomotion interface (HeadJoystick), we evaluated it using the next eight user studies (in gray) in a wide range of locomotion scenarios. My role is stated for each user study as well as their contribution to this research, publication (* submitted, ** short paper, otherwise published as a full paper), publication venue (* conference, otherwise journal), with reference to where they are presented in the thesis.

[illegible]	[illegible]	ctio	tib	lication	e	M
Interface Design	Study 1.1	Chapter 1 - Section 1.2.2	Evaluating a Seated Embodied Interface	[Kitson et al., 2015]	ACM SUI*	Co-Author
	Study 1.2	Chapter 1 - Section 1.2.2	Comparing Seated Embodied Interfaces	[Kitson et al., 2017a]	IEEE 3DUI*	Co-Author
	Study 1.3	Chapter 1 - Section 1.2.2	Evaluating Full-rotational Interfaces	[Hashemian and Riecke, 2017b]	SAVR*	First-Author
	Study 1.4	Chapter 1 - Section 1.2.2	Comparing Leaning Detection Techniques	[Hashemian and Riecke, 2017a]	HCI*	First-Author
Interface Evaluation	Study 2.1	Chapter 2 - Study 1	RQ1.1, RQ2.1	[Hashemian et al., 2022b]	IEEE TVCG	First-Author
	Study 2.2	Chapter 2 - Study 2	RQ1.1, RQ2.2			
	Study 3.1	Chapter 3 - Study 1	RQ1.2	[Hashemian et al., 2021]	IEEE TVCG	First-Author
	Study 3.2	Chapter 3 - Study 2	RQ1.2, RQ2.2			
	Study 3.3	Chapter 3 - Study 3	RQ1.2, RQ2.2, RQ2.3			
	Study 4.1	Chapter 4 - Study 1	RQ1.2, RQ2.2, RQ2.4, RQ2.5, RQ2.6	[Hashemian et al., 2022a]*	IEEE TVCG	First-Author
	Study 5.1	Chapter 5 - Section 5.1.1	RQ1.1, RQ2.2	[Adhikari et al., 2021a]	Frontiers in VR	Co-Author
	Study 5.2	Chapter 5 - Section 5.1.1	RQ1.2, RQ2.2	Adhikari et al., 2021c]**	IEEE VR*	Co-Author

investigate if providing embodied self-motion cues using a carefully optimized embodied locomotion interface can address the current challenges of handheld interfaces (unconvincing simulated motion, motion sickness, and disorientation) while improving or at least matching most other locomotion-relevant measures in a wide range of locomotion scenarios. To address this general research question (RQ), we decided to first conduct a series of user studies to carefully optimize an embodied locomotion interface prototype - called HeadJoystick, (see Section 1.2) and then evaluate it in a wide range of locomotion scenarios. These scenarios consist of different locomotion modes (2D ground-based vs. 3D flying), purposes (e.g., search and maneuvering), and tasks such as reach-the-target, follow-the-path, multitasking scenarios of locomotion and object interaction, and navigation i.e., aggregated task of locomotion and wayfinding (Blade and Padgett, 2015). Figure 1.1 provides an overview of our research depicting how the gaps in prior literature motivated each stage of our research. Table 1.1 shows the overview of the (12) user studies in this research for designing (four studies) and evaluating (eight studies) our embodied locomotion interface - called HeadJoystick (see Appendix A). Table 1.1 describes the contributions of these user studies to this research as well as their publication, publication venue, my role (first/co-author), with reference to where they are presented in this thesis.

In the remaining of this chapter, first we break our general RQ into specific RQs to be addressed in our evaluation user studies. Next, we discuss our expanded evaluation framework for thoroughly investigating the effects of providing self-motion cues. Then we explain our design process for a carefully optimized embodied locomotion interface and its iterative refinement process using our first four user studies i.e., Study 1.1, 1.2, 1.3, and

1.4 - see Table 1.1. Finally, we discuss our evaluation studies and how they addressed our specific RQs.

1.1 Research Questions

This thesis contributes to the design and evaluation of VR locomotion interfaces. As for our contribution toward designing a VR locomotion interface, we suggest design guidelines in Section 5.2.1 for such an interface as well as the design details for our interface (HeadJoystick) in the appendix A. As for our contribution toward evaluation of VR locomotion interfaces, we do so by investigating how providing embodied self-motion cues affects user experience and performance in a wide range of locomotion scenarios. Tackling this research question necessitates designing a VR locomotion interface prototype capable of providing embodied self-motion cues and then evaluating it in a wide range of locomotion scenarios. To this end, our first overarching research question is **how does providing embodied self-motion cues affect user experience and performance, and how do these effects differ in different locomotion scenarios (RQ1)**. We approach this research question by investigating it in different locomotion scenarios and then comparing those results. To do so, we divide this research question into two sub-questions, which categorise these scenarios into 3D (flying) versus 2D (ground-based) locomotion:

- RQ 1.1. How does providing embodied self-motion cues affect user experience and performance **in 3D (flying) locomotion?**
- RQ 1.2. How does providing embodied self-motion cues affect user experience and performance **in 2D (ground-based) locomotion?**

We do so because 3D locomotion has a higher level of complexity compared to 2D locomotion due to the need for controlling more Degrees of Freedoms (DoFs). We address RQ1.1 in Chapter 2 and RQ1.2 in Chapter 3 and Chapter 4.

In addition, prior research also reported mixed results when investigating embodied locomotion interfaces in different situations and scenarios. For example, while some prior studies reported that providing physical rotation without limited translational self-motion cues improves spatial orientation (Farrell and Robertson, 1998; Presson and Montello, 1994; Rieser, 1989; Klatzky et al., 1998; Ruddle et al., 1999) even comparable to actual walking (Riecke et al., 2010), others did not show such significant improvements (Sigurdarson et al., 2012; Sigurdarson, 2014). As we do not fully understand the potential reasons behind these mixed results, other factors might be responsible such as interface usage time, locomotion task difficulty, rotation control mechanism, brake mechanism, body posture, etc. Therefore, we decided to provide a *deeper understanding* on how these factors would affect locomotion when using embodied locomotion interfaces. That is, in our second overarching research question, we ask **how do the effects of providing embodied self-motion cues on**

user experience and performance differ in specific situations (RQ2). We approach RQ2 by further investigating six sub-questions:

- RQ 2.1. How does providing embodied self-motion cues affect user experience and performance **when using physical vs. virtual rotation**?
- RQ 2.2. How does providing embodied self-motion cues affect user experience and performance **for short-term vs. repeated interface usage**?
- RQ 2.3. How can **brake mechanisms** improve user experience and performance for leaning-based versus handheld interfaces?
- RQ 2.4. How does providing embodied self-motion cues affect performance **in single vs. multi-tasking** locomotion scenarios?
- RQ 2.5. How does providing different levels of embodied self-motion cues **for a sitting vs. standing/stepping** user affect user experience and performance?
- RQ 2.6. How does providing different levels of embodied self-motion cues affect performance **when increasing the locomotion task difficulty (speed)**?

1.2 Interface Design

1.2.1 Design Constraints

Our goal was to investigate if adverse effects of using handheld interfaces (reduced believability, motion sickness, and disorientation) can be addressed by providing vestibular self-motion cues in a wide range of locomotion scenarios. To design an embodied locomotion interface capable of providing such self-motion cues, our design constraints were:

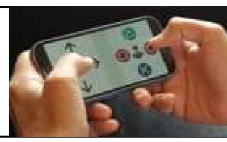
- **Affordability:** We aimed to address these adverse effects for the majority of VR users including home users, thus our first design constraint was to provide an affordable embodied locomotion interface that would be low-cost, easy to set up, and can be used in small spaces. Using this design constraint also helped us to speed up the refinement process by easily developing several interface prototypes due to their low cost and complexity.
- **Avoiding Specificity:** Providing embodied self-motion cues for a wide range of locomotion scenarios requires an interface compatible with different scenarios (e.g., walking, driving, and flying) rather than being tied to a specific scenario. This design constraint helped us to investigate our interface in a wider range of scenarios (e.g., walking, driving, and flying) and compare the effects of providing embodied self-motion cues in those scenarios.

- **Providing vestibular cues aligned with virtual locomotion:** To reduce the visual-vestibular cue conflict, we needed an embodied locomotion interface capable of providing motion cueing known to enhance vection, intuitiveness, etc.

Due to the first constraint (affordability), we chose embodied locomotion interfaces that simply use user-powered movements instead of providing body movements using motorized motion platforms. We did so as motorized motion platforms are often expensive with complex setup, specific hardware/software requirements, and safety hazards as summarized in (Viirre et al., 2015). Due to our second constraint (Avoiding Specificity), we tested locomotion interfaces that can be used in a wide range of locomotion scenarios. That is, we did not choose interfaces that are tied to specific locomotion scenarios such as driving (e.g., steering wheel (Sportillo et al., 2017)) and walking (e.g., walking in place (Nilsson et al., 2016), redirected walking (Razzaque et al., 2001), and arm swinging (McCullough et al., 2015)). As for the third constraint (providing vestibular cues aligned with virtual locomotion), we did not use gesture-based interfaces, where the user controls locomotion by body movement gestures that are not aligned to the simulated locomotion direction. As an example, based on our earlier pilot studies, Study 1.2 results, and this design constraint, we did not use head-directed (often called gaze-directed) steering, where the user controls forward/backward and sideways locomotion by tilt and pitch rotation of their head, respectively - section 28.3.2 of (Jerald, 2016) and section 11.2.2.1 of (Steinicke et al., 2013) and section 8.5.1 of (Bowman et al., 2017).

We designed our embodied locomotion interface prototype as a leaning-based interface, where the user leans toward the target direction to control their simulated speed using a rate-control paradigm. We chose leaning-based interfaces because of their reported benefits including reduced disorientation (Harris et al., 2014; Nguyen-Vo et al., 2019) and motion sickness (Nguyen-Vo et al., 2019) as well as increased enjoyment/fun (Marchal et al., 2011; Kruijff et al., 2016), spatial presence (Marchal et al., 2011), immersion (Freiberg, 2015), and vection intensity (Riecke, 2006; Kruijff et al., 2016; Riecke and Feuereissen, 2012a). However, compared to handheld interfaces, previous leaning-based interface prototypes typically showed reduced accuracy (Beckhaus et al., 2005b; Marchal et al., 2011; Hashemian and Riecke, 2017b,a; Kitson et al., 2017a; Freiberg, 2015; McMahan et al., 2012; Griffin et al., 2018) and usability (e.g., ease of use (Hashemian and Riecke, 2017b; Buttussi and Chittaro, 2019; Kitson et al., 2017a) and ease of learning (Hashemian and Riecke, 2017b; Kruijff et al., 2016; Zielasko et al., 2016)). Therefore, leaning-based interfaces are often considered as more of a promising prototype for specific sets of tasks (Bowman et al., 2012). To address these issues, we decided to design different leaning-based interface prototypes and compare them in a series of internal pilot-testings and user studies to iteratively improve the usability and accuracy of our prototype.

Table 1.2: Evaluation of our sensors for detecting body/chair leaning in our locomotion interface prototypes.

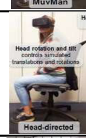
Body/ChairL eaning-detectionSensor		Advantages	Disadvantages
1-MicrosoftKinect		Noneedtobeattachedtothe user/chair	Detectsleaningwithdelay
2-TrackIR(Infrared) Kitsonetal.,2015 Kitsonetal.,2017a		Accuratedetectionwithnodelay	Needstobeattachedtothechair backrest-Notsuitablefor detecting360physicalrotation
3-PhidgetIMU Kitsonetal.,2017b		Detectsfullphysicalrotation	WireEntanglementproblem duringrotation-Inaccurateunder magneticnoises
4-Cellphone(IMU)		Wirelessandaccessibletomost users	Inaccurateundermagneticnoises
6-HTC-ViveContro ller HashemianandRiecke,2017a HashemianandRiecke,2017b		Wirelessandaccurate	Needstobeattachedtothechair backrestanduserscanonlyuse onecontrollerintheVR application
6-HTC-ViveTracker Hashemianetal.,2020 Hashemianetal.,2021 Adhikarietal.,2021		Wirelessandaccurateandeasy attachmenttothechairbackrest	Needstobeattachedtothechair backrest

1.2.2 Iterative Interface Refinement

We designed several leaning-based interface prototypes using different leaning detection sensors as shown in Table 1.2, and evaluated them using internal pilot-testings. Prototypes with higher usability were evaluated compared to the standard handheld interfaces in four user studies led by me (Study 1.3 and 1.4) and my colleagues (Study 1.1 and 1.2) with myself as a co-author as shown in Table 1.3. These user studies helped us to gain a better understanding of these prototypes' (dis)advantages and gather feedback for further rounds of iterative refinement. In the remainder of this section, we explain these four user studies.

In our first user study (Kitson et al., 2015) - Study 1.1, my colleagues and I investigated if motion cueing using a seated leaning-based interface can improve locomotion (and especially reduce disorientation and motion sickness). Previous research reported improved locomotion believability when using seated leaning-based interfaces based on a sit/stand stool called Swopper (Beckhaus et al., 2005b; Freiberg, 2015). Thus, in this study, we evaluated if using such interface can also address other adverse effects of using handheld interfaces such as disorientation and motion sickness. To this end, we designed a leaning-based interface - called **NaviChair**, where the user sits on the Swopper stool with limited tilt and yaw

Table 1.3: Our four user studies for the step-by-step improvement of our locomotion interface prototype.

Publication	InterfacePrototypes	MovementControl	Comparisonvs.Controller	Whatdidwelearn?
1-Kitsonetal.,2015	NaviChair 	Seattiltwith limitedrotation	Lowerusabilityandperformance comparedtoJoystickwith3DoF	SeatedLeaning-based interfacescouldprovide naturalexperience
2-Kitsonetal.,2017a	NaviChair 	Seattiltwith limitedrotation	Lowerusabilityand userratingsfor precisioncomparedtotheXbox controllerwith2DoF	1-Swivelchairhashigher usabilitycomparedto otherchairsdueto havingbackrest. 2-Leaning-basedinterfaces workbetterwithfullinstead of limitedphysicalrotation.
	Swivel- Chair 	Backresdttiltwith limitedrotation		
	MuvMan 	Seattiltwith limitedrotation		
	Head-directed 	Headtiltwith limitedrotation		
3-Hashemianand Riecke,2017b	Funky-Chair 	Weight-shiftingusing swivelchairandfull rotation	Highervect ionintensityandmotion sicknesswithlowereaseofuse,ease oflearing,precisecontrol,comfort, longevity,preference,enjoyment, andoverallusabilitycomparedtothe Joystickwith2DoF	Weight-shiftingonswivel chairhaslowusability thanbackresttilt
	Swivel-Chair 	Swivelc hairwith backresttilt	Noadvantages/disadvantages comparedtotheJoystickwith2DoF	
4-Hashemianand Riecke,2017a	NaviChair 	Seattiltwith fullrotation	Higherproblemswithinterfaceswith loweraccuracy,comfort,precise control,longevity,andoverall usabilitycomparedtotheJoystick with3DoF	Head-basedleaninghas higherusabilitythan backresttilt,sowen eedto useafull-rotationalhead-basedleaninginterface
	Swivel-Chair 	Backresttiltfor forward/backward headmovementfor sideways	Lowerprecisecontrolcomparedto theJoystickwith3DoF	

rotation to control virtual translation (i.e., forward/backward and sideways) and yaw rotation, respectively, using a velocity (rate) control paradigm. NaviChair was compared to a handheld interface (Joystick) in a pointing task toward previously seen targets. Our results showed that using NaviChair (instead of the Joystick) did not significantly reduce disorientation or motion sickness. In addition, while participants reported lower ease of use and accuracy of NaviChair compared to the Joystick, post-experiment interviews corroborated previous research (Beckhaus et al., 2005b; Freiberg, 2015) by showing that seated leaning-based interfaces can provide a more natural locomotion experience. Therefore, to improve our seated motion cueing interface, we decided to compare various seated leaning-based interfaces in our next (second) user study.

In our second user study (Kitson et al., 2017a) - Study 1.2, my colleagues and I evaluated various seated leaning-based interfaces with limited rotation in terms of locomotion experience measures. We did so by comparing a handheld interface (Xbox GamePad) versus NaviChair and three more seated leaning-based interfaces with limited tilt and yaw rotations using a velocity control paradigm. These were a sit/stand stool called **MuvMan**, a regular office **Swivel Chair**, and **Head-Directed**, where the user controlled virtual translation (forward/backward) and rotation (left/right) using tilt and yaw rotation of their head, respectively. We thoroughly assessed user experience and usability of our interfaces in a navigational search task using 13 subjective (but no behavioral) measures. Our results showed advantages of using Joystick compared to the MuvMan and NaviChair in terms of improved user ratings for precision and disorientation, but no significant difference was found between Joystick versus Head-Directed Steering and Swivel Chair. Among our leaning-based interfaces interfaces, participants preferred Swivel Chair over the other ones due to its higher usability, comfort, and having a backrest. In the post-experiment interview, participants suggested to design our seated interfaces with full 360° (instead of limited) physical rotation. As prior research also suggested that physical rotations reduce disorientation (Klatzky et al., 1998; Riecke et al., 2010; Riecke and Feuereissen, 2012a; Grechkin and Riecke, 2014), we decided to design and compare seated leaning-based interfaces using swivel chair with full 360° physical rotation in our next user studies.

As for our next, i.e., third user study (Hashemian and Riecke, 2017b) - Study 1.3, we evaluated seated leaning-based interfaces using a full rotational swivel chair in terms of locomotion experience and accuracy measures. For this study, we designed two full rotational leaning-based interface prototypes using swivel chair: Funky-Chair, where the user controls locomotion velocity using weight shifting assessed by a Wii-balance board under a swivel chair; and Swivel-Chair, where the user controlled locomotion speed using backrest-tilt. Both interfaces only controlled simulated forward/backward (but not sideways) motion using a rate control paradigm. To further investigate the effects of full physical rotation on locomotion, we compared our leaning-based interfaces (i.e., Swivel-Chair and Funky-Chair) with handheld interfaces using virtual and physical rotation called Joystick and Real-Rotation, respectively. Evaluating our leaning-based interfaces in a follow-the-avatar task showed that using Swivel Chair did not provide any significant differences compared to Joystick and RealRotation. In fact, compared to the Joystick, using Swivel Chair showed non-significant trends for improving eight (out of 12) measures. These were increased vection intensity, immersion, enjoyment, ease of learning, overall usability, overall preference as well as reduced motion sickness and problems using interface. Compared to the Joystick, Funky-Chair improved vection intensity but showed several disadvantages in terms of reduced ease of use, ease of learning, precise control, long-term use, enjoyment, comfort, overall usability, problems using interface, overall preference, and enhanced motion sickness. Overall, our results showed that full-rotational leaning-based interfaces such as Swivel-Chair (but not Funky-Chair) might be able to improve locomotion compared to the handheld controllers if designed with high usability. Therefore, we decided to investigate other mechanisms to control translation when using a swivel chair in our next user study.

In our forth user study (Hashemian and Riecke, 2017a) - Study 1.4, we evaluated full-rotational swivel chair with different mechanisms to control translation: backrest tilt, weight shifting, and head tracking. Due to the fairly low usability of the Funky-Chair in our third user study, we replaced Funky-Chair with a full-rotational NaviChair interface using weight-shifting to control forward/backward and sideways motion. As for Swivel-Chair, the user could control forward/backward and sideways motion with backrest tilt and head movement, respectively. Similar to Study 1.3, we compared our prototypes (i.e., Swivel-Chair and NaviChair) with handheld interfaces with virtual (i.e., Joystick) vs. physical (i.e., Real-Rotation) rotation in a follow-the-avatar task on an unpredictable curvilinear path. Compared to the Joystick, our results showed lower precision of Swivel-Chair as well as several disadvantages for NaviChair. These were increased problems with the interface and reduced accuracy, precise control, comfort, long-term use, and overall usability. As for how to improve our leaning-based interfaces, in the post-experiment interviews, participants stated higher usability of leaning using head motion compared to the backrest tilt or weight-shifting.

Together, these studies helped us to design an embodied locomotion interface for seated users (Study 1.1) using regular office swivel chair (instead of other sit/stand stools) (Study 1.2) with full (instead of limited-range) physical rotation (Study 1.3) and head-based translation (instead of trunk or weight-shifting) (Study 1.4). Later, we applied several other modifications to our leaning-based interface - called HeadJoystick, as discussed in Chapter 2. HeadJoystick design details and formulas are explained in Appendix A. Chapter 2, Chapter 3, and Chapter 4 describe our user studies to evaluate HeadJoystick in a wide range of locomotion scenarios. We also designed a standing/stepping locomotion interface with full physical rotation (Study 1.3) and head-based translation (Study 1.4) - called NaviBoard, with similar modifications as HeadJoystick as explained in (Nguyen-Vo et al., 2019) and evaluated in Chapter 4.

1.3 Evaluation Framework

In this section, we discuss the evaluation framework that emerged from our four design user studies (Study 1.1, 1.2, 1.3, and 1.4) and was used in HeadJoystick evaluation studies (Study 2.1, 2.2, 3.1, 3.2, 3.3, 4.1, 5.1, and 5.2). Prior research typically evaluated embodied locomotion interfaces in terms of only a few measures, and thus we do not know if embodied locomotion interfaces show consistent advantages in terms of a wide range of locomotion-related measures or not? We addressed this gap by using and refining a wide range of

Table 1.4: Overview of our suggested factors for evaluating VR locomotion interfaces as well as specific DVs and how to measure them - published as the Appendix in Chapter 3. Factors that go beyond Bowman's framework factors (Bowman et al., 1999) 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 e ects	I: Rating for ease of learning	"How easy was it to learn using the interface for the rst 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 [Hart, 2006]
		I: Rating for ease of use	"How easy was it to use the interface?"
	User Comfort	I:Ratedpotentialforlong-termuse	"Icouldimagineusingtheinterfaceforlongertimethanthestudytask"
		I:Ratedpotentialfordailyuse	"Icouldimagineusingtheinterfaceindailyapplicationsfrequently"
	Overall Usablity	I:Ratingforoverallusability	"Overallusability oft heinterface"
	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 ne movements [Mcmahan et al., 2014]	Average number of missed targets or crashes to unwanted objects
	Overall performance	B: Performance Score	De ned per task to combine its di erent performance measures
		B: Throughput [Roig-Maimó, 2017]	Ratio of e ective index of di culty over movement time
User Experience	Presence	I: Spatial presence	SUS Questionnaire of spatial presence [Slater et al., 1998]
		I: Immersion	"I felt immersed in the virtual scence (captivated by the task)"
	Self-motion perception	I:Vectionintensity	"Ihadastrongsensationofself-motionwiththeinterface"
	Motrion sickness	I: Motion Sickness	Simulator Sickness Questionnaire (SSQ) [Kennedy et al., 1993]
	Overall user experience	I: Enjoyment	"I enjoyed doing the task using this interface?"
		I:Overallpreference	"Overallpreferenceratings"

locomotion relevant measures in our step-by-step prototype evaluation studies (Study 1.1, 1.2, 1.3, and 1.4) as discussed in Section 1.2.2. We did so by assessing new measures in each study instead of less useful measures from the previous studies. For example, our evaluation framework does not include orientation ability (from Study 1.1) or precise control (from Study 1.3) as they can be assessed more accurately using behavioral measures. We also used general instead of specific measures such as overall usability instead of problems using interface (from Study 1.2) in our evaluation framework. In addition, we chose clearly-defined measures such as task load (Hart, 2006) and ease of use instead of unclear measures such as intuitiveness (from Study 1.4). Such process resulted in our own evaluation framework that we used in our later evaluation studies to more thoroughly evaluate our VR locomotion interfaces. Our evaluation framework is an expansion of previous evaluation frameworks for locomotion interfaces such as the work by Bowman and colleagues, in particular (Bowman et al., 1997, 1998, 1999; Bowman, 1999; Bowman et al., 2017). We adopted all factors from Bowman's framework in our extended framework as well as a wider range of factors, which are highlighted in green in Table 1.4. Shortcomings of the previous evaluation frameworks and the importance of our newly suggested aspects are discussed in the rest of this section.

Our suggested framework: As shown in Table 1.4, our extended framework consists of three categories (usability, user experience, and performance), where each category consists of four factors. Four usability factors are ease of learning, ease of use, user comfort, and overall usability; four user experience factors are spatial presence, self-motion perception, motion sickness, and overall user experience; and four performance factors are speed, accuracy, precision, and overall performance (cf. Table 1.4).

Usability Factors: Compared to the Bowman's framework, our framework includes more factors in each category to include more locomotion-relevant measures based on prior works. For example, as for the usability factors, Bowman's framework assessed user comfort mainly by assessing motion sickness (e.g., dizziness or nausea) (Bowman et al., 1999). However, we decided to assess motion sickness as a separate measure besides other types of discomfort such as fatigue, or feeling unsafe, similar to some recent studies (Pittman and LaViola, 2014; Viirre et al., 2015; Buttussi and Chittaro, 2019). We suggest separately assessing motion sickness as a user experience factor due to its critical role in user experience when evaluating a VR locomotion interface. As for the user comfort measures, we suggest measuring potential for long-term use in each session and the potential for frequent daily use. The potential for long-term usage per session helps assessing discomforts such as fatigue (Buttussi and Chittaro, 2019), which shorten the usage time per session. The interface potential for frequent daily usage helps assessing discomforts such as feeling unsafe or not being easy to set up (Viirre et al., 2015), which reduce the likelihood to use an interface in daily applications frequently. To assess these four usability factors, we also suggested data collection methods in our extended evaluation framework. For example, ease of learning can be measured by the subjective ratings of the user as well as the rate of performance improvement for new users over time. Ease of use can be measured by the overall rating of ease of use as well as detailed task load questions such as the first and commonly used part of the *NASA-TLX questionnaire* for locomotion and overall task load (Hart, 2006). Finally, we suggest the overall ratings for the usability of the interface to help better understand the priority of different usability aspects for each user. For example, if a user prefers ease of use over ease of learning for a locomotion interface or vise versa.

Performance Factors: As for the performance factors, we used two factors suggested by Bowman's framework: efficiency, which was measured using speed (i.e., lower task completion time); and effectiveness, which was measured using accuracy defined by the average proximity to the desired target or path. In addition, prior research suggested measuring precision defined by the ability to use the interface for fine movements - see section 1.3.2 of (McMahan et al., 2014). Precision can be measured by the average number of missed targets, going outside the path, or collisions with unwanted objects. Therefore, we also used precision as a new factor for measuring effectiveness. As for the overall performance, we also suggest defining and assessing it depending on the locomotion task to help prioritize different performance factors for that task. For example, Bowman's framework suggested two measures: spatial awareness and information gathering. However, we argue that spatial awareness/orientation could be defined as an overall performance measure. For example, spatial awareness/orientation can be measured in a pointing task toward previously seen objects using the (absolute) pointing error. Similarly, information gathering can be defined as the overall performance measure in an exploration task, where the user needs to gather information during exploration and later remembers them. However, in a maneuvering task, it might be better to combine speed, accuracy, and precision as one overall performance measure such as throughput (Fitts, 1954). Such an approach can help researchers to specifically design their tasks for assessing a locomotion interface in terms of a specific overall performance measure similar to what we did for each of our tasks in Chapter 2, Chapter 3, and Chapter 4.

User Experience Factors: As for the user experience factors, Bowman's framework assessed believability of a locomotion interface using presence (the user's sense of immersion or 'being within' the environment due to travel) (Bowman et al., 1998). Therefore, to assess presence factor, we suggested two subjective measures of spatial presence (feeling of physically being there in the environment) and immersion, which shows how much the user was mentally captivated by the task. Besides the presence factor, Bowman's framework did not suggested to assess believability of self-motion itself - an important factor for assessing locomotion interfaces - section 3.3.5 of (Badcock et al., 2014) and section 3.9.10 of (Jerald, 2016). Therefore, inspired by previous research (e.g., (Riecke, 2006; Riecke and Feuereissen, 2012a; Kruijff et al., 2016)), we decided to also assess how believable the perception of self-motion (vection) is, when using a locomotion interface. We suggest assessing vection based on the rated intensity of the users' self-motion sensation, i.e., how much the user sensed like she is moving inside the environment instead of the environment is moving around them. We also suggest assessing the overall user experience to help better understand the priority of different user experience aspects for each user. We suggest assessing the overall user experience by measuring user-ratings for enjoyment and overall preference measures. Enjoyment is an important measure for evaluating locomotion interfaces (Marchal et al., 2011; Kruijff et al., 2016) and the overall preference ratings helps us understand how much the user prefers this interface compared to any other possible interfaces.

We used our extended evaluation framework in all our eight evaluation user studies to thoroughly investigate the effects of providing embodied self-motion cues using our leaning-based interface (HeadJoystick) on locomotion as shown in Figure 1.2.

1.4 Thesis Contributions and Overview

This thesis provides two main contributions to user interface design for VR. The first is addressing the gap in literature regarding (dis)advantages of providing embodied self-motion cues on different locomotion scenarios such as walking, driving, and flying: Prior research on locomotion interfaces typically evaluated each leaning-based interface prototype only in one specific task, and often included a small subset of locomotion-relevant measures. Thus, we do not fully understand how these findings might or might not generalize to different tasks? That is, we do not know if a carefully optimized leaning-based interface prototype might

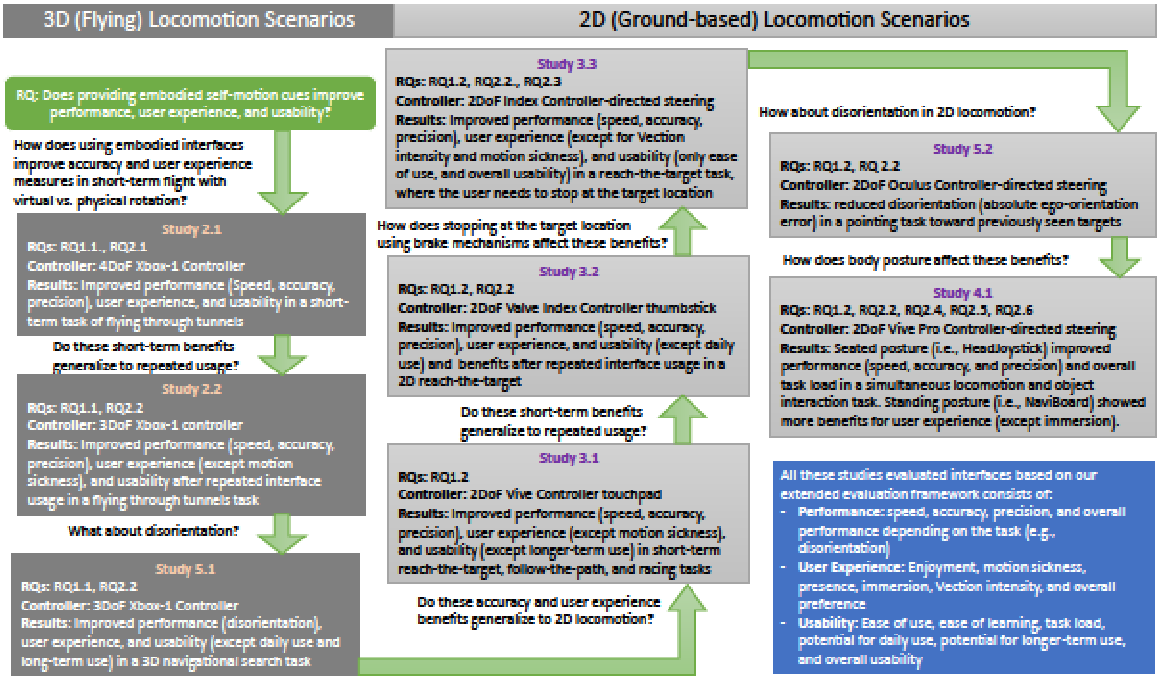


Figure 1.2: Our evaluation studies based on chronological order, and how the results of each study informed the next one.

be able to show consistent benefits across a larger set of task spanning the prototypical locomotion tasks. To address this gap, we carefully optimized a leaning-based interface (HeadJoystick) that provides embodied self-motion cues and then thoroughly investigated it for a wide range of scenarios in terms of a wide range of locomotion-related factors as depicted in Table 1.4.

The second contribution is in providing a deeper understanding of how do the effects of providing embodied self-motion cues on locomotion differ based on locomotion factors such as interface usage time and locomotion difficulty. Such findings can help us to understand the potential reasons behind prior mixed results regarding (dis)advantages of providing vestibular self-motion cues on locomotion such as disorientation (Ruddle, 2013). To address this gap, we evaluated our interface (HeadJoystick) versus handheld interfaces with different locomotion factors: interface usage time (short-term vs. repeated usage), simulated rotation control (physical vs. virtual), body posture (sitting vs. standing/stepping), locomotion difficulty (different speeds), brake mechanism, and locomotion with vs. without object interaction. The following chapters provide the details for six (out of overall eight) HeadJoystick evaluation studies that were conducted to address these research questions. These six user studies are published (Chapter 2 and Chapter 3) or submitted (Chapter 4) as three papers. Each chapter ends with an explanation of the individual contributions of its first and co-authors.

Chapter 2. HeadJoystick: Improving Flying in VR using a Novel Leaning-Based Interface (Hashemian et al., 2022b) In this chapter, we investigated how providing embodied self-motion cues affects 3D (flying) locomotion (RQ1.1). Prior studies often evaluated embodied flying interfaces in terms of limited measures and reported mixed results such as for accuracy (Pittman and LaViola, 2014; Rognon et al., 2018; Miehlbradt et al., 2018). Therefore, we do not know if providing embodied self-motion cues for 3D (flying) locomotion can address the current challenges of standard handheld interfaces such as unconvincing simulated self-motion and motion sickness while improving or at least matching other user experience and performance measures. To address this gap, we thoroughly evaluated HeadJoystick versus handheld interfaces using our extended evaluation framework Section 1.3. We did so by conducting two user studies investigating short-term and repeated usage effects of using HeadJoystick versus Controller in Study 1 and Study 2, respectively (RQ2.2). In Study 1, we also investigated the effects of using HeadJoystick with virtual vs. physical rotation control (RQ2.1). As for the task, we measured accuracy by designing a novel task of flying through a sequence of increasingly narrow tunnels in the sky. Our results showed conclusive advantages of providing embodied self-motion cues on 3D (flying) locomotion in terms of almost all measures. This will be presented as Chapter 2 of this thesis, and is published as a full paper in IEEE Transactions on Visualization and Computer Graphics (Hashemian et al., 2022b).

Chapter 3. Leaning-based interfaces improve ground-based VR locomotion in reach-the-target, follow-the-path, and racing tasks (Hashemian et al., 2021) In this chapter, we investigated the effects of providing embodied self-motion cues on 2D (ground-based) locomotion (RQ1.2). Prior studies on 2D locomotion often investigated each embodied locomotion interface in only one task and in terms of a small subset of locomotion-relevant measures. Therefore, we do not know if providing vestibular cues for 2D (ground-based) locomotion can reduce adverse effects of using handheld interfaces such as unconvincing simulated motion and motion sickness while improving or at least matching other user experience and performance measures. To address this gap, we thoroughly evaluated HeadJoystick versus handheld interfaces based on our extended evaluation framework Section 1.3 in three user studies (Study 3.1, 3.2, and 3.3). In our first study, we evaluated HeadJoystick in three complimentary tasks: reach-the-target, follow-the-path, and racing task to avoid dynamically moving obstacles (RQ1.2). In our second user study, we investigated how these effects differ during repeated usage of the interfaces (RQ2.2). In our third user study, we investigated how these effects differ when the user needs to stop at a target location (and remain stationary for a brief moment) using different brake mechanisms (RQ2.3). Overall, our findings addressed these research questions and showed that providing embodied self-motion cues in 2D locomotion can improve or at least match most user experience and performance measures compared to handheld interfaces (touchpad, thumbstick, and controller-directed steering). This will be presented as Chapter 3 of this thesis, and is published as a full paper in IEEE Transactions on Visualization and Computer Graphics (Hashemian et al., 2021).

Chapter 4. Leaning-based interfaces improve simultaneous locomotion and object interaction in VR (Hashemian et al., 2022a) In this chapter, we investigated the effects of providing embodied self-motion cues on single versus multi-tasking locomotion scenarios (RQ2.4). Many locomotion scenarios in our daily life or VR applications are multi-tasking scenarios, where we need to perform other tasks during locomotion such as interacting with the environment. Prior research often reported lower accuracy of leaning-based interfaces in multi-tasking scenarios (Beckhaus et al., 2005b; McMahan et al., 2012; Griffin et al., 2018). However, as most of these interfaces did not use Head-Mounted Displays (HMDs) (Beckhaus et al., 2005b; McMahan et al., 2012), we do not know if their results generalize to most VR users wearing HMDs. We addressed this gap by evaluating seated (i.e., HeadJoystick) and standing/stepping (i.e., NaviBoard) leaning-based interfaces versus handheld interfaces and physical walking (RQ2.5). As for our task, we designed and used a novel concurrent locomotion and object interaction task, where users need to keep touching the center of upward moving target balloons with their virtual sword AKA lightsaber, while at the same time actively following a horizontally moving platform and staying as close as possible to its center. This task allowed us to assess locomotion and object interaction accuracy using similar yet separate measures to gain a better understanding of how do locomotion versus object interaction accuracy interact together when using leaning-based interfaces. We also investigated how our results differ when varying locomotion difficulty by increasing the required locomotion speed (RQ2.6). Our results showed that while walking is clearly the best interface, providing higher levels of embodied self-motion cues with HeadJoystick and especially NaviBoard is capable of improving or at least matching most user experience and performance measures compared to a handheld interface. This will be presented as Chapter 4 of this thesis, and is currently submitted as a full paper to IEEE Transactions on Visualization and Computer Graphics (Hashemian et al., 2022a).

Chapter 5. Discussion and Conclusion In the final chapter, chapter 5, we return to our research questions and discuss the overall contributions of this thesis, design guidelines, limitations, and future directions for this research. Overall, while prior research often suggested limited advantages for embodied locomotion interfaces, our research shows that providing embodied self-motion cues using carefully optimized embodied locomotion interfaces is capable of improving or at least matching most locomotion-relevant measures compared to handheld controllers.

Chapter 2

HeadJoystick: Improving Flying in VR using a Novel Leaning-Based Interface

This chapter is published in IEEE Transactions of Visualization and Computer Graphics (September 30, 2020).

A. Hashemian, M. Lotfaliei, A. Adhikari, E. Kruijff and B. Riecke, "HeadJoystick: Improving Flying in VR using a Novel Leaning-Based Interface," in IEEE Transactions on Visualization and Computer Graphics, doi: 10.1109/TVCG.2020.3025084.

2.1 Abstract

Flying in virtual reality (VR) using standard handheld controllers can be cumbersome and contribute to unwanted side effects such as motion sickness and disorientation. This paper investigates a novel hands-free flying interface—*HeadJoystick*, where the user moves their head similar to a joystick handle toward the target direction to control virtual translation velocity. The user sits on a regular office swivel chair and rotates it physically to control virtual rotation using 1:1 mapping. We evaluated short-term (Study 1) and extended usage effects through repeated usage (Study 2) of the HeadJoystick versus handheld interfaces in two within-subject studies, where participants flew through a sequence of increasingly difficult tunnels in the sky. Using the HeadJoystick instead of handheld interfaces improved both user experience and performance, in terms of accuracy, precision, ease of learning, ease of use, usability, long-term use, presence, immersion, sensation of self-motion, workload, and enjoyment in both studies. These findings demonstrate the benefits of using leaning-based interfaces for VR flying and potentially similar telepresence applications such as remote flight with quadcopter drones. From a theoretical perspective, we also show how leaning-based motion cueing interacts with full physical rotation to improve user experience and performance compared to the gamepad.

2.2 Introduction

Flying has always been a fascinating dream for humanity, and despite current flying technologies such as planes, helicopters, paragliders, or wingsuits, flying is not yet easily accessible for most people. It also differs considerably from the long-held dream of bird-like, unencumbered and embodied flying experiences. As an alternative approach, virtual reality (VR) using head-mounted displays (HMDs) could provide a great opportunity to experience such embodied and unencumbered flying through virtual environments (VE), as VR can provide a first-person immersive and embodied experience. HMDs could also help provide a more compelling experience of flying in the real-world when used in telepresence/teleoperation scenarios, where the user controls an unmanned aerial vehicle (UAV), such as camera-equipped drones, and sees through its camera in real-time (Lima, 2012). UAV telepresence can be used for different applications such as virtual aerial tourism (Mirk and Hlavacs, 2015), surveillance, inspection, or search and rescue in disaster areas (Stepanova et al., 2017).

Flying interfaces usually require the user to control different degrees of freedom (DoFs) for changing position (translation) and direction (rotation) of the simulated flying camera or actual UAV. For example, flying interfaces for helicopters or quadcopters require controlling more DoFs (at least 4) than airplanes or fixed wing UAVs (at least 3), and thus allow for more control over the flight trajectory.

This paper investigates a simulated flying interface with four DoFs: forward/backward, up/downs, sideways, and yaw rotation, mimicking the controls used for quadcopter drones. Such an interface can be helpful in both simulations (e.g., video games and other VR applications) and telepresence applications (e.g., remote surveillance) due to its high maneuvering ability. For example, a well-designed 4DoF flying interface should allow users to reach their target position fast and accurately or rotate without translation to search for the next target position. A 4DoF flying interface could also help to control telepresence drones (which are predominately quadcopter-based) which allows the user to fly through pipes for inspection or through a wrecked building looking for survivors - chapter 8 of (Bowman et al., 2017).

VR and telepresence flying applications share similar challenges when the user needs to control four DoFs, though. The standard flying interfaces for video games and VR (gamepad and hand-held controllers) and telepresence (i.e., proportional remote controls like radio-controlled aka RC controllers) essentially use two thumbsticks for locomotion control, and are usually cumbersome and require extensive training sessions for proficient control (Miehlbradt et al., 2018). This motivated us to design a novel and more embodied and intuitive flying interface called "HeadJoystick", aimed to reduce cognitive load compared to the standard handheld flying interfaces. HeadJoystick uses the head as a "joystick," where users move their head (instead of deflecting the thumbstick) toward the target direction to control their simulated translation velocity. The user is seated on a regular office swivel chair and rotates it physically to control their simulated rotation using 1:1 mapping. This HeadJoystick was evaluated in two user studies focusing on short-term (Study 1) and extended usage effects (Study 2).

To this end, we designed a novel simulated drone racing task in HMD-based VR, where participants were asked to fly toward nine tunnel way-points and fly through the tunnels of decreasing diameter without colliding with the walls. Our test environment closely resembles operation of a UAV, to support transfer of our system and results to other usage domains besides standard VR environments. In our first study, 24 participants used four different interfaces to do this task, to tease apart the relative contributions of leaning-based translational cues versus full physical rotation cues: The *Gamepad*, which provided no physical motion cues beyond operating the thumbsticks, the HeadJoystick that provided leaning-based translational cues and full physical rotation cues, *RealRotation*, using the gamepad translation along with the chair physical rotation; and *LeaningTranslation*, using gamepad for rotation along with the leaning-based translation of the HeadJoystick. We measured performance, accuracy and precision and asked participants to compare these four interfaces in terms of different user experience aspects (e.g., enjoyment, presence, immersion, sensation of self-motion, preference) as well as usability measures (e.g., ease of learning, ease of use, motion sickness, task load). The second study was designed to investigate how results might generalize to extended exposure. To this end, a new set of 12 participants evaluated HeadJoystick versus RealRotation for doing eight rounds of the same 3D racing task. The main contributions of this study are:

- Introducing a novel low-cost leaning-based flying interface called HeadJoystick.
- Evaluating the HeadJoystick versus handheld controllers using a novel reach-the-target task combined with the tunnel-in-the-sky waypoint navigation task to comprehensively investigate diverse user experience, usability and the behavioral performance measures.
- Study 1 provides a deeper understanding of how leaning-based translation and full physical rotation each contribute to the overall user experience and performance.
- Study 2 investigates how repeated usage affects user experience and performance when using HeadJoystick versus handheld controllers, and corroborates the benefits of embodied (HeadJoystick) locomotion over hand-held controllers.

2.3 Related Works

In this section, we start with a general review of flying interfaces and then review flying interfaces similar to ours.

Various 4DoF flying interfaces have been investigated for immersive VR including handheld interfaces (Quigley et al., 2004), hand or arm-based gesture commands (Cauchard et al., 2015; Ikeuchi et al., 2014; Monajjemi et al., 2016; Pfeil et al., 2013; Sarkar et al., 2016; Stoica et al., 2014), voice commands (Krishna et al., 2015; Peshkova et al., 2016; Quigley et al., 2004), and even brain-computer interfaces (Yu et al., 2012). In general, these interfaces do not provide vestibular cues aligned with the visual motion direction of flight, which can reduce the believability of flying (Lawson and Riecke, 2014). Moreover, the mismatch between visual and vestibular/proprioceptive cues can cause or exacerbate visually induced motion sickness (VIMS), where the user feels motion sick without physically moving (Reason and Brand, 1975). VIMS is known as an unwanted side-effect in many virtual (Kennedy et al., 2010) or remote (van Erp et al., 2006) flight systems, and will be referred to as simple motion sickness in the present work as it can also occur when users are physically moving.

We use the term embodied flying interfaces here to refer to interfaces that provide a visual 1st person perspective accompanied by at least some physical (including vestibular) self-motion cues. While HMDs can provide convincing visual cues of self-motion (Riecke and Jordan, 2015), it is not possible to provide full physical cues of self-motion without actual flying (Lawson and Riecke, 2014). Therefore, embodied flying interfaces aim to create a believable flying experience by providing *limited* physical self-motion cues aligned with the vestibular/proprioceptive sensory cues in an actual flight. These physical self-motion cues can be provided by the mechanical setups (such as in actuated moving-base flight simulators (Groen and Bles, 2004; Miermeister et al., 2016)) or simply the user-powered body movements in leaning-based interfaces (Pittman and LaViola, 2014; Schulte et al., 2016; Miehlbradt et al., 2018).

While several embodied flying interfaces use complex mechanical setups to provide physical self-motion cues to the user's body, we chose to design a leaning-based interface due to their simplicity and affordability for the majority of VR users. As an example of complex mechanical flying interfaces, moving-base flight simulators use motors/actuators to apply limited physical motion cues to the user's body (Groen and Bles, 2004). Harnessing the user from ceiling is another fairly complex mechanical approach for embodied flying interfaces (Krupke et al., 2016; Perusquía-Hernández et al., 2017; Krupke et al., 2015). However, these mechanical interfaces usually have complicated setups and safety hazards, as summarized in (Viirre et al., 2015). Birdly is a mechanical interface for flying like a bird in VR (Rheiner, 2014) or telepresence applications (Cherpillod et al., 2017), and applies limited physical motions to a user lying face-down on it. However, Birdly is too expensive (more than a hundred thousand dollars) for most VR home users, professionals, and UAV pilots.

2.3.1 Leaning-Based Interfaces

Leaning-based interfaces usually deploy user-powered leaning toward the target direction to control their simulated translation velocity without the need for any additional actuators. These interfaces generally use a velocity control paradigm, where the more the user leans, the faster they travel. While a seated user can lean their upper body and/or tilt the chair/stool they are sitting on (Beckhaus et al., 2005b; Kitson et al., 2017a; Riecke and Feuereissen, 2012a), standing users can lean using their whole body (Marchal et al., 2011; Harris et al., 2014; Kruijff et al., 2016). In this section, we discuss leaning-based interfaces for 2D (ground-based) locomotion as they have been much more widely researched than 3D leaning-based interfaces, and also because our suggested interface (HeadJoystick) was originally designed for both 2D and 3D locomotion (Hashemian and Riecke, 2017b).

In this study, we investigate if leaning-based interfaces could be beneficial for flight (3D) control, given the diverse advantages of leaning-based over gamepad/joystick interfaces reported for ground-based (2D) locomotion. These advantages include an enhanced illusion of virtual self-motion (vection) (Kruijff et al., 2016; Riecke, 2006; Riecke et al., 2008), spatial perception and orientation (Harris et al., 2014), navigation performance (Nguyen-Vo et al., 2019), immersion and presence (Marchal et al., 2011; Freiberg, 2015; Kitson et al., 2015), enjoyment and engagement (Kruijff et al., 2016; Harris et al., 2014; Marchal et al., 2011), as well as reduced motion sickness and cognitive load (Nguyen-Vo et al., 2019). Additionally, leaning-based interfaces are hands-free, which allow us to use our hands for other tasks (such as pointing, interacting with objects, or communicating) in VR and teleoperation applications, similar to how we can freely use our hands in the real world while walking (Kitson et al., 2015; Beckhaus et al., 2005a; LaViola et al., 2001; Zielasko et al., 2016).

Leaning-based interfaces usually control the simulated rotations around the earth-vertical axis (yaw) either with the limited physical rotations using velocity control (Beckhaus et al., 2005b; Kitson et al., 2017a; Riecke and Feuereissen, 2012a) or full physical rotations with 1:1 mapping between physical and simulated yaw rotations (Marchal et al., 2011; McMahan et al., 2012; Hashemian and Riecke, 2017b; Nguyen-Vo et al., 2019). Although limited rotation might be better for stationary displays such as projection screens, where the user cannot see the screen if they fully rotate, full physical rotation provides natural physical self-rotation cues and thus remove the visual-vestibular cue conflict for yaw rotations, which might lead to more believable self-motion experiences. However, they do require an HMD or 360 surround screens, or a screen rotating with the user as in moving-base motion simulators. Additionally, full physical rotation may help in reducing motion sickness compared to limited rotation due to reducing the conflict between visual and vestibular cues. Therefore, we use a full physical rotation approach for our interface, where the physical rotation of the user in the real world controls the direction of simulated camera using 1:1 mapping.

Allowing for full physical rotation can help users remain spatially oriented (Farrell and Robertson, 1998; Presson and Montello, 1994; Rieser, 1989; Klatzky et al., 1998; Ruddle et al., 1999) by allowing them to more easily update their mental spatial orientation. Mixed results are reported about the importance of physical rotation for supporting spatial orientation when the user has no physical translation cues — as summarized in (Ruddle, 2013; Riecke et al., 2010). However, some researchers reported that providing physical rotation with no or leaning-based translation could reach almost the same efficiency as actual walk-

Table 2.1: Leaning-based flying interfaces. Note that all 2DoF interfaces used a fixed-wing (plane) locomotion paradigm, whereas the 4DoF interfaces used a quadcopter paradigm.

DoF	Body Posture	Interface	Rotation Control	Rotation Input	Translation Control	Translation Input
2	Seated	[illegible]	Velocity	Torso roll	Velocity	Torso pitch
2	Seated	[illegible]	Velocity	Torso yaw and position	Velocity	Torso position
2	Seated	[illegible]	Velocity	Torso roll	Velocity	Torso pitch
4	Standing	[illegible]	Position	Head yaw	Position	HMD position
4	Standing	[illegible]	Velocity	Head yaw	Velocity	Head pitch and roll
4	Standing	[illegible]	Velocity	Head yaw	Velocity	HMD position
4	Standing	[illegible]	Position	Torso yaw	Velocity	HMD position
4	Seated	[illegible]	Position	Chair yaw	Velocity	Head rotation center

ing in a navigational search task (Riecke et al., 2010; Nguyen-Vo et al., 2019). While there can be challenges with too many rotations if a cabled HMD is used, this problem will soon lose relevance with the increasing quality and affordability of wireless HMDs or trackers entering the market. As an example, we used a wireless HTC-Vive HMD in our study.

2D Leaning-based interfaces have been designed for both standing users (Kruijff et al., 2016; Guy et al., 2015; Langbehn et al., 2015; Wang et al., 2018; Marchal et al., 2011) and seated users (Beckhaus et al., 2005b; Kitson et al., 2017a; Silva and Bowman, 2009). For the current study, we chose a seated body posture due to comfort and safety reasons: As for comfort, seated users not only experience less discomfort, fatigue and leg-swelling in long-term usage (Chester et al., 2002), but they also experience less motion sickness compared to standing users (Merhi et al., 2007) as predicted by postural instability theory (Riccio and Stoffregen, 1991). Regarding safety, standing users might experience body sway during 3D virtual acceleration similar to VR roller coasters, and might fall and get hurt (Badcock et al., 2014). This motivated us to design a seated flying interface for the current study, even though our approach can easily be used for standing users as well if desired.

The aforementioned literature suggests that using a seated 4DoF flying interface with leaning-based translation and full physical rotation might be able to improve different aspects of 3D locomotion (e.g., vection, immersion, presence, enjoyment, and task-specific performance). However, there seems to be no prior published research that thoroughly investigate such an interface in terms of all these aspects as far as the authors know, apart from studies that investigated partially similar interfaces in terms of limited aspects, as detailed in sections 2.3.2 and 2.3.3 below (Schulte et al., 2016; Miehlbradt et al., 2018; Rognon et al., 2018; Pittman and LaViola, 2014). Therefore, this gap in the literature motivated us to design HeadJoystick and evaluate it in terms of a wide range of aspects.

2.3.2 Leaning-Based Interfaces Controlling two DoFs

Table 2.1 compares the HeadJoystick with other leaning-based flying interfaces. In this section, we review leaning-based interfaces that control two DoFs, which are investigated for airplane control in virtual flight or fixed-wing drone control in remote flight. For example, Schulte *et al.* developed an upper-body leaning-based “dragon-riding” interface to control pitch and yaw of a simulated dragon (Schulte et al., 2016) where a seated user leans backward or forward to pitch up or down respectively, and leans left/right to control their simulated yaw rotation. However, a dragon-riding interface might be unsuitable for most applications as the forward (translation) velocity was kept constant except when using a certain hand gesture to triple the speed for three seconds and then decelerating back to the normal speed. Dragon-riding interface was not compared with a standard controller such as RC remote controller or a gamepad.

Miehlbradt *et al.* suggested a similar upper-body leaning-based interface - called “torso strategy”, where the user moves their torso forward/backward and left/right to control the pitch and yaw/roll of a simulated fixed-wing airplane and thus fly up/down and turn left/right respectively (Miehlbradt et al., 2018). In a virtual flight task, participants were asked to control a simulated fixed-wing drone and fly through a series of simulated waypoints. The results showed that torso-strategy outperformed standard RC remote controller and reached a performance level comparable to the Birdly flight simulator. Participants also used torso strategy to control a real quadcopter with constant forward velocity and no strafing, which reduced its DoFs similar to a fixed-wing drone. However, in that implementation users could not directly control translation velocity, and thus cannot really start or land or slow down, which makes it unfeasible for most realistic applications.

Rognon *et al.* also suggested a similar upper-body leaning-based interface to torso strategy — FlyJacket, where the user wears a backpack that supports their arms’ weight and holds their arms up while the user was leaning (Rognon et al., 2018). The backpack was equipped with an inertial measurement unit (IMU), which enabled the user to lean forward/backward or left/right to control the pitch and yaw/roll of a drone, respectively. The participants were asked to fly a fixed-wing drone with constant forward velocity through several waypoints. Although FlyJacket had no significant improvement in performance compared to an RC remote controller, FlyJacket showed higher control on navigation, naturalness, and lower discomfort compared to the RC remote controller.

2.3.3 Leaning-Based Interfaces Controlling four DoFs

In this section, we review leaning-based interfaces that control four DoFs, which are investigated for VR applications or remote quadcopter control. Higuchi and Rekimoto (Higuchi et al., 2013) designed a telepresence interface called Flying Head, where a standing user controls the direction of the UAV with the direction of their head using 1:1 mapping, and the position of the UAV via the position of their head using 1:N mapping. Flying Head showed advantages over the joystick in two search and capture photo tasks in terms of ease of use, enjoyment, and the lower task completion time. However, because Flying Head uses a position control paradigm for simulated translation, the movement of UAV is limited to the user's head and body movements in the real world, which makes it not applicable to long-range flight and most realistic applications.

To the best of our knowledge, the only prior study that investigated leaning-based 4DoF flying interfaces and thus the most relevant prior work was done by Pittman and LaViola (Pittman and LaViola, 2014): 18 participants flew through rectangular waypoints for about 90 seconds to compare a Wiimote interface similar to a gamepad with five other interfaces including three leaning-based flying interfaces: Head-Rotation, where the user controls drone translation by tilting their head forward and/or sideways; Head-Translation, where the user controls drone translation by moving their head forward/backward and/or sideways; and modified flying-head, where the user controls drone translation velocity by moving their head forward/backward and/or sideways, and controls drone rotation by rotating whole their body using 1:1 mapping. While results showed that the Wiimote interface performed best along almost all measures such as task completion time, comfort, ease of use, predictability, enjoyment, naturalness, and overall preference, the authors stated several technical issues that likely contributed to the general disfavor of leaning-based interfaces that motivated our studies: (1) *calibration*: 39% of participants reported low precision of leaning-based interfaces due to reasons such as incorrect calibration, thus we simplified the calibration process. (2) *Pose*: While all the interfaces were tested when users were standing, a number of users commented that using leaning-based interfaces could be easier when seated. As standing body posture could lead to higher discomfort, severe motion sickness, with more safety hazards compared to the seated body posture, we designed all our interfaces for seated users. (3) *zero-point*: Multiple participants mentioned drifting and difficulty to return to the zero point when using head-translation and modified flying-head, due to lack of visual feedback for the zero-point. Therefore, we asked our participants to set the zero-point when their back touches the chair backrest, so later they could easily find this zero-point during flying without visual feedback. (4) *Technical issues*: Loss and oscillation of the drone's sensory information caused occasional stutter of the interface and side to side vibration of the drone during rotation when using modified flying-head. To address this, we used a virtual drone, which also allowed us to gradually reduce the size of waypoints (and thereby increased task difficulty) to study the achievable flying precision without and danger of crashing an actual drone.

While the aforementioned studies showed the potential of leaning-based interfaces for ground-based locomotion and 2DoF flying, it seems like leaning-based flying interfaces have not been investigated for 4DoF except the above-mentioned study (Pittman and LaViola, 2014), which had a few technical issues, and thus motivated us to design and conduct this study.

2.4 User Studies

2.4.1 Research Questions

This study aims to thoroughly evaluate leaning-based 4DoF flying interfaces through 5 specific research questions:

RQ1: Do leaning-based interfaces improve user experience compared to hand-held controllers? 2D leaning-based interfaces are known to improve different aspects of locomotion experience including stronger vection intensity (Kruijff et al., 2016; Riecke, 2006; Riecke et al., 2008), immersion and presence (Marchal et al., 2011; Freiberg, 2015; Kitson et al., 2015), as well as enjoyment (Kruijff et al., 2016; Harris et al., 2014; Marchal et al., 2011). As for leaning-based flying interfaces, while FlyJacket (Rognon et al., 2018) improved user experience compared to hand-held interfaces, the head-rotation and head-translation interfaces in Pittman *et al.* were rated lower than hand-held devices in almost all aspects. However, since many studies reported improved user experience for ground-based leaning-based interfaces, we hypothesize that flying experience should also be improved by HeadJoystick.

RQ2: Do leaning-based interfaces improve flying performance compared to hand-held controllers? Embodied interfaces are known to improve locomotion performance compared to hand-held interfaces if they provide exact self-motion cues (Bowman et al., 2012). For example, bipedal walking for 2D locomotion or mimicking head movements in 3D locomotion (i.e., flying-head interface (Higuchi et al., 2013)) can improve locomotion performance. However, compared to hand-held interfaces, embodied interfaces that provide partial motion cues of locomotion have shown mixed results. Bowman *et al.*, reported reduced performance for partial motion cues (Bowman et al., 2012). Similarly , FlyJacket (Rognon et al., 2018), flying-head, head-rotation, and head-translation showed no significant improvements or lower performance compared to hand-held interfaces in a reach-the-target task (Pittman and LaViola, 2014). Conversely, a torso-leaning-strategy showed higher performance than a hand-held device in recent studies of 3D flying controlling two DoF (Miehlbradt et al., 2018) and ground-based (2D) locomotion with 3 DoF control (Nguyen-Vo et al., 2019). Given the technical issues of flying head, head rotation, and head translation to control a real drone (Pittman and LaViola, 2014), we hypothesize that the HeadJoystick should show similar results to the torso-leaning-strategy (Miehlbradt et al., 2018) and should improve performance compared to a hand-held controller.

RQ3: Can adding full physical rotation and leaning-based translation cues help to reduce visual-vestibular sensory conflicts and thus motion sickness? Providing full-translational sensory cues for flying is not possible unless the actual flying motions are replicated, as in isomorphic simulations (Lawson and Riecke, 2014). Therefore, the maximum possible sensory data offered by an embodied flying interface (and without actually flying) could be full-rotational with partial-translational sensory data, similar to what the

HeadJoystick offers. Considering that hand-held controllers provide minimal sensory data for both translation and rotation (in the form of haptic cues from the thumbsticks), evaluating our four interfaces allows us to investigate how minimal versus maximum-possible sensory data for the flight translation and rotation affects motion sickness.

The literature indicates mixed results in terms of how leaning-based interfaces affect motion sickness. For instance, some 2D locomotion studies reported that leaning-based interfaces did not reduce motion sickness compared to hand-held interfaces (Marchal et al., 2011; Hashemian and Riecke, 2017b), while others reported significant reductions of motion sickness using leaning-based interfaces (Nguyen-Vo et al., 2019). Similarly, in 3D locomotion, flying-head, head-rotation, and head-translation did not reduce motion sickness using leaning-based interfaces (Pittman and LaViola, 2014), whereas FlyJacket reduced motion sickness (Rognon et al., 2018).

As the sensory conflict theory of motion sickness (Reason and Brand, 1975; Kennedy et al., 2010) suggests that reducing the cue conflict between different sensory cues indicating self-motion should reduce motion sickness, we predict that HeadJoystick (which was designed to reduce inter-sensory cue conflicts) should reduce motion sickness.

RQ4: How do leaning-based translation and full physical rotation each contribute to the overall user experience and performance? As far as the authors know, no prior research investigated how much leaning-based translation impacts the overall flying experience and/or performance with/without full physical rotation. Prior research on 2D (ground-based) navigation show mixed results regarding this research question (such as (Ruddle, 2013)). However, as full physical rotation could provide vestibular/proprioceptive sensory data similar to real-life like flying experience, we hypothesize that full physical rotation could improve the user experience and performance compared to limited/no physical rotation when using thumbsticks. As for the contribution of leaning-based translation without full rotation on the overall user experience and performance, there is mixed evidence: While Head-Translation (Pittman and LaViola, 2014) showed no improvement, FlyJacket (Rognon et al., 2018) improved the user experience, and torso-strategy (Miehlbradt et al., 2018) improved performance. Due to the similarity with (Rognon et al., 2018; Miehlbradt et al., 2018), we predict that leaning-based translation in our study should improve both user experience and performance.

RQ5: How do user experience, usability, and performance change over repeated interface usage? Proficient control of handheld flying interfaces are known to require extended training sessions (Miehlbradt et al., 2018). Prior research showed significant performance improvements during repeated usage of locomotion interfaces after a few trials in terms of speed (Wang and Lindeman, 2012b), accuracy (Hashemian and Riecke, 2017a), number of errors (McMahan et al., 2010), and the task completion time (Terziman et al., 2010; Marchal et al., 2011). Thus, we designed a second study to investigate how the findings of Study 1 which had relatively short exposure might or might not generalize to

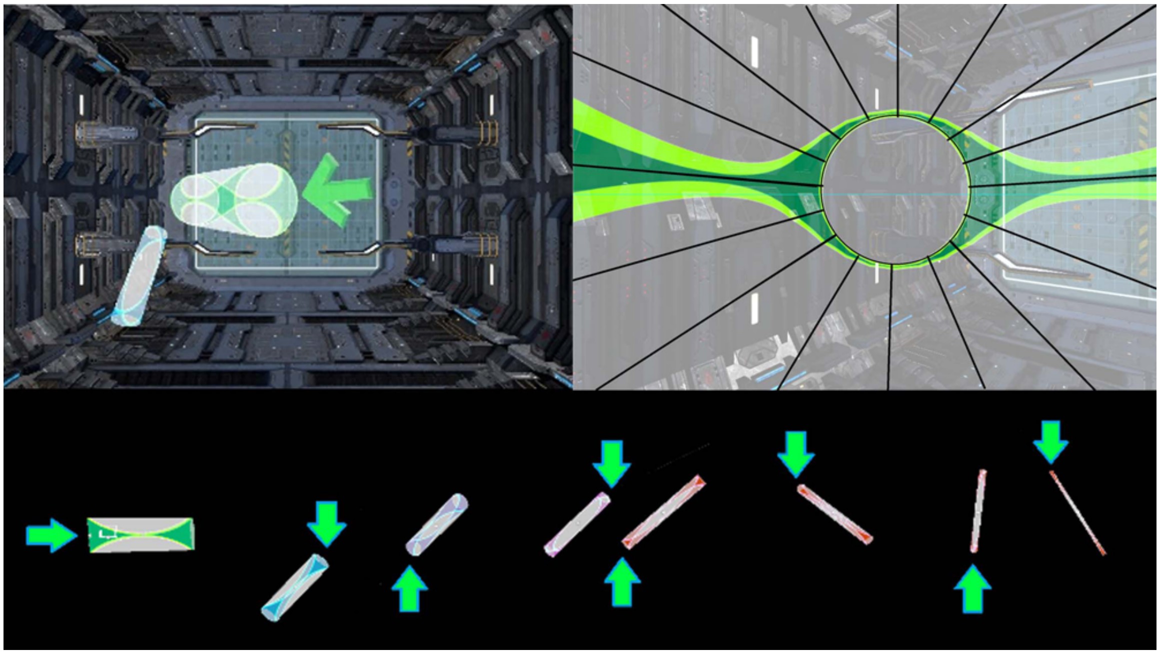


Figure 2.1: Virtual environment used for the tunnel-in-the-sky task: flying through tunnels inside a spaceship hangar. Top: Environment from participant view, where the green arrow shows the entrance direction of the next tunnel. Middle: Environment from participant view, inside a tunnel. The black lines are added to show the cylindrical structure of the tunnel. Bottom: Side view of all tunnels showing how they get narrower. Green arrows show the entrance of each tunnel, illustrating the amount of required rotation to do this task.

repeated and longer exposure. Especially, as motion sickness can build during continued exposure to VR - chapter 2.5 of (Lawson, 2014), we aimed to investigate how motion sickness might change over extended usage of the leaning-based vs handheld interfaces. We hypothesize in RQ1-3 that using HeadJoystick improves user experience (RQ1) and performance (RQ2) and reduces motion sickness (RQ3) – here we hypothesize that these benefits of HeadJoystick will continue to hold even for extended usage. We addressed RQ1-4 primarily by Study 1, while Study 2 was designed to specifically address RQ5, and corroborate RQ 1-3 for repeated usage.

2.4.2 Task

A wide range of tasks have been used to evaluate flying interfaces, such as collecting objects (Wang and Lindeman, 2012b), navigational search (Trindade and Raposo, 2014), pointing tasks (Wang and Lindeman, 2012a), or capturing photos (Higuchi et al., 2013). We chose *reach-the-target*, a well-known task in drone racing contests, where the user has to reach predetermined circular waypoints and fly through them (Pittman and LaViola, 2014; Cherpillod et al., 2017; Perusquía-Hernández et al., 2017; Schulte et al., 2016; Sikstrom et al., 2015; Wang and Lindeman, 2012a; Krupke et al., 2015). Interface *accuracy* can be measured by the average distance from the desired path (McMahan et al., 2014). Since reach-the-target tasks have no predefined desired paths, we replaced the circular waypoints with a series of cylindrical *tunnels-in-the-sky* (de Vries and Padmos, 1997) that users were asked to fly through without colliding as illustrated in Figure 2.1. This allows us to quantify the interface accuracy as the average distance from the center of a tunnel when passing through it, because the most optimal and safest way (i.e., least chance of collisions) to pass through a tunnel without collision should be the one where participants fly through its center in a fairly straight line.

As interface *precision* when navigating through tunnels depends on how much the interface allows the user to navigate through a narrow tunnel without collision (McMahan et al., 2014), we also successively reduced the diameter of each tunnel, to make the task harder after passing each tunnel. The tunnel diameters were 6, 4, 3, 2.5, 2, 1.5, 1, and 0.5 meter (Figure 2.1, bottom). Participants were asked to fly through each tunnel in a specified direction without colliding with the tunnel walls. To impose precise flying, we penalized participants who collided with a tunnel's wall by asking them to fly through it again (Schulte et al., 2016), which meant they had to fly around it to enter it again from the same side. This allowed us to use the average collisions per passed tunnels as a measure for the interface precision.

2.4.3 Virtual Environment

The virtual environment was designed as a flying practice inside a spaceship hangar as shown in Figure 2.1, to provide rich visual self-motion cues and a naturalistic visual reference frame. Tunnels were laid out such that users had to perform substantial rotations to get from one tunnel exit to the entrance of the next tunnel. Subsequent tunnels also differed in their yaw and pitch orientations to ensure that users needed to control their movement in different directions and had to control more than one DoF simultaneously to pass tunnels. To prevent participants from learning the path, the tunnels' layout was mirrored per trial horizontally and/or vertically in a randomized order. We also added green arrows to the entrance of the next activated tunnel to be sure that users knew where to go next. We also provided audio feedback to inform users if they passed or failed a tunnel.

2.4.4 Dependent Variables

To thoroughly evaluate our interfaces in a wide range of aspects, we selected a total of 15 dependent variables (DVs). They consisted of three behavioral performance measures, and 12 subjective DVs to measure six user experience factors and six usability aspects using an online questionnaire. As for behavioral measures (McMahan et al., 2014), we recorded participants' performance during their flight in terms of *speed*, measured by the average time to pass a tunnel (Wang and Lindeman, 2012b); *accuracy*, measured by the average distance from the center of passed tunnels when flying through (de Vries and Padmos, 1997;

Cherpillod et al., 2017; Miehlbradt et al., 2018); and *precision*, measured by the average number of collisions with the tunnel per passed tunnel.

We measured six user experience factors including the *SUS* questionnaire for spatial presence (Slater et al., 1998) with 6 questions on a Likert-based scale of 1-7; the first (and usually used) part of the *NASA-TLX* questionnaire with six questions to measure the task workload (Hart, 2006) on a continuous 0-100% scale.; and four questions with continuous answers between 0% to 100% including *enjoyment*, by asking how much participants enjoyed using each interface; *immersion*, by asking how much participants felt immersed i.e., captivated by the flying task; *vection intensity*, where 100% means that the participant senses a compelling illusion of physical flight (self-motion) inside a stationary spaceship, while 0% means that the participant senses themselves stationary and the spaceship moves around them; and the *overall preference* by asking how much participants preferred the interface, where 0% means the worst interface, and 100% means the best interface they could imagine.

Our six usability measures consisted of the simulator sickness questionnaire (*SSQ*) (Kennedy et al., 1993) and five questions with a continuous answer between 0% to 100% including: *ease of use*, by asking how easy it was to use the interface; *ease of learning*, by asking how easy it was to learn using the interface; *long-term use*, by asking if the participant could imagine using the interface for a longer time than the study task; *daily use*, by asking to rate if they could imagine using the interface in daily applications; and the *overall usability*, by asking to rate the overall usability of the interface. A motion sickness (post-pre) score was defined by subtracting the total SSQ score obtained before exposure to any conditions from the total score obtained after exposure to each of the four conditions.

2.4.5 Apparatus

The virtual environments were presented using an HTC-Vive HMD with binocular field of view about 110° diagonally with a combined resolution of 2160×1200 pixels. The virtual environment was created using Unity3D 2018.2 and rendered on a dedicated PC (Intel Core-i7, Nvidia GTX-1060). The PC was connected to the HMD using a wireless TPCast adaptor to avoid entangling the HMD cable during physical rotations of participants (Figure 2.2). We attached the battery of the HMD wireless adaptor to the swivel chair and attached an additional Vive tracker to the chair backrest to measure chair orientation. We used a wireless Xbox-1 controller for the conditions that required a gamepad. Participants wore a noise-canceling headphone with an ambient sound of a spaceship to avoid distraction of possible background noises and to hear the audio cues if they passed or missed a tunnel.

2.4.6 Study 1

The goal of Study 1 was to investigate how using leaning versus thumbstick translation techniques, and physical versus thumbstick rotation techniques affects user performance and user experience (RQ1-4). Thus, we designed four different flying interfaces that differed

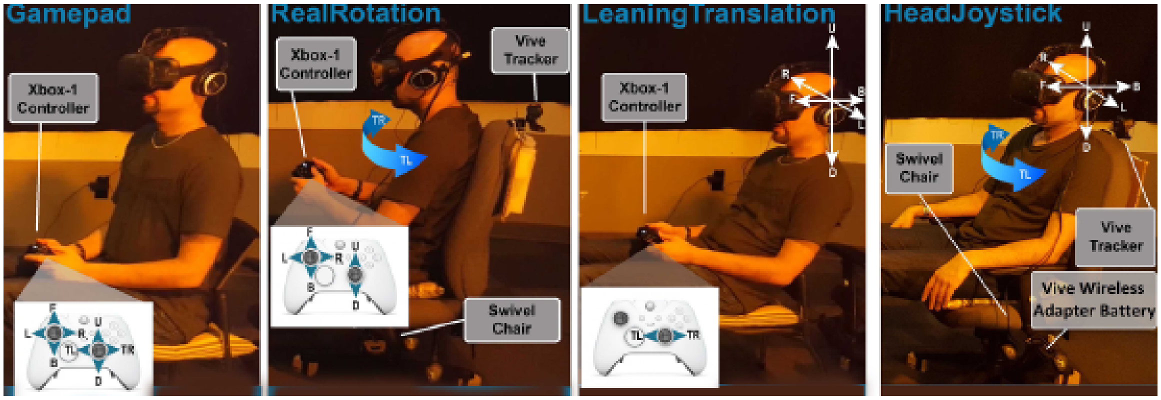


Figure 2.2: All four flying interfaces compared in Study 1. Each interface controls flying along four degrees of freedom including forward(F)/backward(B), left(L)/right(R), up(U)/down(D), and turn-Left(TL)/turn-right(TR).

Table 2.2: Flying interfaces in Study 1, using color coding as in Figure 2.3

Translation \ Rotation	Gamepad-based	Chair-based
Gamepad-based	*Gamepad*	*RealRotation*
Head-based	*LeaningTranslation*	*HeadJoystick*

in how a user controls translation and rotation. The techniques are named HeadJoystick, Gamepad, RealRotation, and LeaningTranslation, as shown in table 2. Each participant performed the task with all four interfaces. Due to our pilot tests, we limited the task completion time to 90 seconds (similar to the average task completion time in Pittman and LaViola (Pittman and LaViola, 2014)) to reduce the risk of severe motion sickness for inexperienced participants.

Locomotion Modes

This study compared four flying interfaces with different levels of physical motion cues for translation and rotation as illustrated in Figure 2.2 and Table 2.2, which are described below in more detail.

In the **Gamepad** condition, we used a classic controller scheme similar to (Pittman and LaViola, 2014; Pfeil et al., 2013). Participants moved the simulated camera forward/backward and sideways by pushing the left thumbstick forward/backward and sideways, respectively. The participants pushed the right thumbstick forward/backward and left/right to control Up/down movements and yaw rotations (left/right), respectively. The maximum translational velocity of the gamepad was 20m/s, the same as for all other interfaces. Based on pilot tests the maximum rotational velocity for the Gamepad and LeaningTranslation was set to $60°/s$.

For **RealRotation**, participants translated the simulated camera using an Xbox-1 controller as in the gamepad condition, but rotated the simulated camera by physically rotating the office swivel chair they were seated on. We attached a Vive tracker to the backrest of the swivel chair to measure its yaw direction and mapped it to the yaw rotation of the simulated camera using a 1:1 mapping. For example, flying forward moved the simulated camera toward in the yaw direction of the swivel chair (not the head).

In the **LeaningTranslation** condition, participants rotated the simulated camera using the right thumbstick, but translated by moving their head toward the target direction. That is, the direction and distance of their head's position from its initial position (when starting flight) controls the direction and velocity of their simulated flight, which will be added to the position tracking. That is, for both LeaningTranslation and HeadJoystick conditions, we only consider the translation (not the rotation) of the users' head to control the simulated translation. As none of our interfaces consider the direction of the user's head to control the simulated rotation or translation, users could rotate their head freely to see the virtual environment without affecting their simulated self-motion. The motion control model details are discussed in the appendix A.

For **HeadJoystick**[1], simulated rotation was controlled by the physical rotation of the chair as in the RealRotation condition. Participants controlled the simulation translation using head movements similar to the LeaningTranslation interface with one difference: While LeaningTranslation uses a static zero-point (initial position of the head), HeadJoystick uses a dynamic zero-point to compensate for chair movements. That is, HeadJoystick uses the position and orientation of the chair-attached Vive tracker to continually update the position and orientation of the zero point, to keep it stationary with respect to the chair (not the room). In other words, the user could always find the zero point and stop the simulated translation easily by sitting upright and touching the chair backrest, even after rotating the chair or accidentally moving it on the floor. Dynamic zero point allows the user to rotate without translating even if the global position of their head changes during the yaw rotation of the chair. The HeadJoystick motion details are discussed in the appendix A.

Participants

We recruited 24 students (12 females) between 19-50 years old ($M = 25.6, SD = 6.3$) for this study. 33% of participants had no prior experiences with HMDs, and 50% of them reported that they play video games on a daily or weekly basis using either online 3D PC games or gaming consoles. None of them had previous experience with any of our interfaces except the gamepad, which all of them were familiar with. Two additional participants did not finish the study due to motion sickness and were thus excluded from data analysis.

[1] Video for HeadJoystick (`https://youtu.be/zVOdu2ARV54`)

We compensated participation time by either course credit or 15 CAD$ for a 75 minutes experiment. The local ethics board approved this research (#2015s0283).

Experimental Design

This within-subject study compared gamepad control of a virtual drone with three more embodied interfaces that used either leaning-based translation ("LeaningTranslation"), full physical rotation ("RealRotation"), or both ("HeadJoystick"). Each participant completed 4 practice trials and 4 main trials, consisting of a factorial combination of 2 translation modes {embodied, gamepad} $\times$ 2 rotation modes {embodied, gamepad}. Each main trial was preceded by a practice trial and only data from the main trial was analyzed, as the length of practice trials varied per participant, and we wanted to compensate for initial learning effects. Interface conditions were counterbalanced across participants using a Latin-square design.

Procedure

After reading and signing the informed consent form, participants filled an initial SSQ questionnaire of motion sickness (Kennedy et al., 1993). Then each participant performed the fly-through-tunnels-in-the-sky task for each of the four interface conditions. Participants completed two trials per interface: a *practice trial*, where participants practiced the interface and flew through as many tunnels as they could until they felt comfortable, or one minute passed, whichever came first; This was immediately followed by a *main trial*, where participants had 90 seconds to fly through as many tunnels as they could. After completing the main trial with each interface, participants were asked to answer two Likert-based questionnaires including SSQ and other usability and user experience measures to evaluate the interface. Answering these questionnaires also provided participants a resting time before they used the next interface. After finishing all four interfaces, we explored reasons behind participant's answers in a semi-structured interview.

Results

Data were analyzed using 2×2 repeated-measures ANOVAs for the independent variables embodied translation {yes/no} and embodied rotation {yes/no}, and Tukey post-hoc tests for pairwise comparisons. We applied Greenhouse-Geisser correction when the sphericity assumption was violated. We analyzed ordinal data (i.e., number of passed tunnels) and ratio data that violated the normality assumption in Shapiro-Wilkes test (i.e., average collisions per passed tunnels and motion sickness post-pre scores) using Wilcoxon signed-rank test for main effects of embodied translation and embodied rotation. Due to the large number of DVs, we summarized main effects and interactions in Table 2.3, with post-hoc results presented together with descriptive statistics in Figure 2.3.

Table 2.3: Analysis of variance results for all dependent variables of the Study 1: Significant effects ($p \leq 5\%$) are written in bold, and were always in the direction of enhanced user experiences for embodied versus gamepad translation/rotation. The effect strengths partial Eta squared (η_p^2) indicates the percentage of variance explained by a given factor.

	Embodied Translation (yes/no)			Embodied Rotation (yes/no)			Interaction (Translation-Rotation)		
	F(1,23)	p	η_p^2	F(1,23)	p	η_p^2	F(1,23)	p	η_p^2
Enjoyment	**50.8**	**<0.001**	**0.688**	**8.50**	**0.008**	**0.27**	3.61	0.07	0.136
Preference	**45.4**	**<0.001**	**0.664**	**14.3**	**0.001**	**0.383**	2.08	0.16	0.083
Immersion	**26.8**	**<0.001**	**0.538**	**7.66**	**0.011**	**0.25**	0.056	0.815	0.002
Vection Intensity	**13.7**	**0.001**	**0.373**	**4.29**	**0.05**	**0.157**	0.098	0.757	0.004
Long-Term Use	**12.6**	**0.001**	**0.353**	**9.18**	**0.006**	**0.285**	0.761	0.392	0.032
Daily Use	**16.5**	**<0.001**	**0.418**	**7.41**	**0.012**	**0.244**	1.53	0.229	0.062
Overall Usability	**27.9**	**<0.001**	**0.549**	**6.30**	**0.02**	**0.215**	0.907	0.351	0.038
Presence (SUS)	**20.1**	**<0.001**	**0.466**	3.21	0.087	0.122	0.756	0.394	0.032
Ease of Use	**16.6**	**<0.001**	**0.42**	0.035	0.853	0.002	**9.67**	**0.005**	**0.296**
Ease of Learning	**11**	**0.003**	**0.324**	0.013	0.908	0.001	**5.53**	**0.028**	**0.194**
NASA-TLX	**16.6**	**<0.001**	**0.419**	1.57	0.223	0.064	**7.99**	**0.01**	**0.258**
Absolute Distance Error	**70.4**	**<0.001**	**0.754**	0.015	0.904	0.001	0.462	0.503	0.02
	Z	p		Z	p				
Motion Sickness (post-pre)	1.47	0.141		**2.49**	**0.013**				
Passed Tunnels	**4.30**	**<0.001**		1.55	0.120				
Collisions	**3.89**	**<0.001**		1.90	0.057				

Main effects and interactions: Providing **embodied (head-based) translation** showed a significant main effect and positively affected 14 measures (all but motion sickness) compared to the gamepad translation (see Table 2.3). As for the user experience factors, embodied translation yielded significantly increased enjoyment, higher spatial presence (SUS questionnaire mean), improved immersion, stronger vection intensity, higher preference ratings, and reduced task load (NASA-TLX scores). As for the usability measures, embodied translation also yielded significant benefits in terms of being easier to use, easier to learn, longer-term use, more potential for daily usage, and enhanced overall usability. As for the performance measures, embodied translation yielded significantly increased accuracy (decreased absolute distance error), as well as in increased number of passed tunnels, and reduced collisions.

Providing **embodied (physical) rotation** also showed significant main effects and improvements compared to gamepad rotation in eight out of 15 DVs (see Table 2.3). As for the user experience factors, embodied rotation yielded significantly increased enjoyment, improved immersion, enhanced vection intensity, and higher overall performance ratings. As for usability measures, embodied rotation also yielded significantly enhanced overall usability, longer-term use, and more potential for daily usage, while also reducing motion sickness. However, embodied rotation did not show a significant effect compared to the gamepad in terms of accuracy (absolute distance error), ease of use, ease of learning, task load, passed tunnels, and collisions. As for the absolute motion sickness levels, highest total SSQ scores were reported after using Gamepad ($M = 48.6, SD = 41.9$), followed by RealRotation ($M = 43.2, SD = 38.0$), then LeaningTranslation ($M = 41.1, SD = 36.3$), and finally HeadJoystick ($M = 31.5, SD = 27.7$). Note that for the ANOVA and Figure 2.3

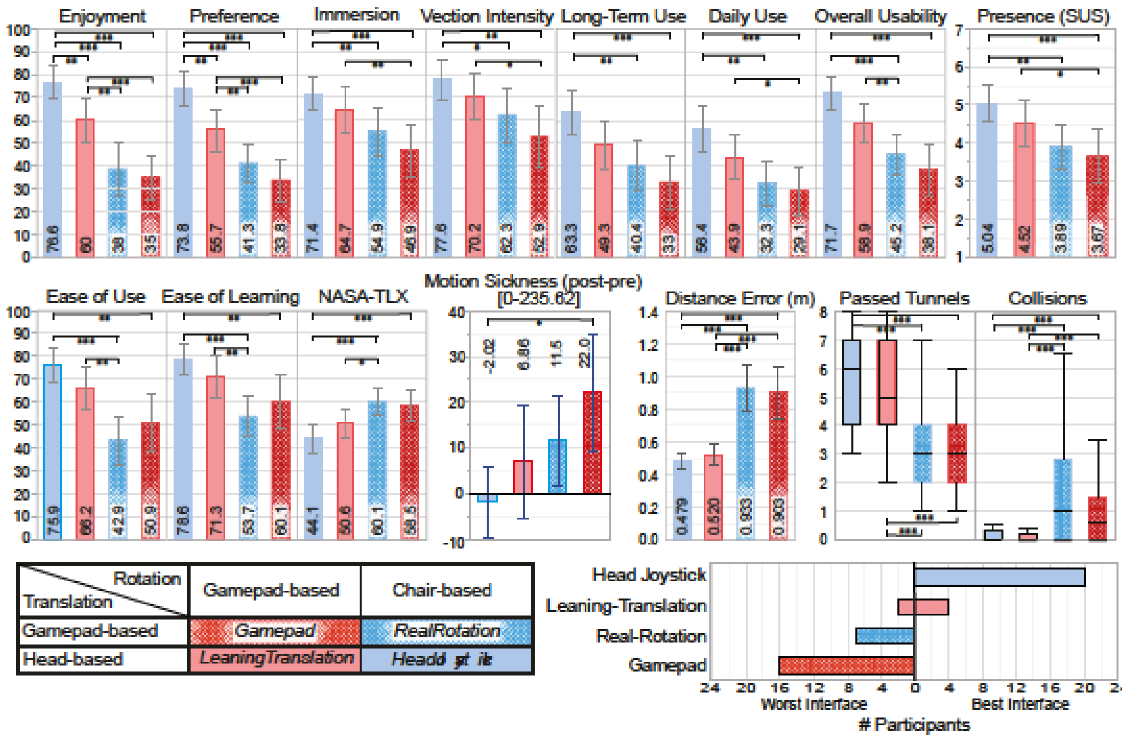


Figure 2.3: Study 1 results: Mean data of user experience and performance measures except *Passed Tunnels* and *Collisions* plots, which show medians. Error bars indicate confidence intervals ($CI = 95\%$), annotated bars represent significance levels of post-hoc and non-parametric tests (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). The bottom right plot shows the participants' rankings of best and worst interface from the post-experiment interview. For one participant, who chose both Gamepad and RealRotation as their worst interface, we included their answer in both ratings.

we used the difference between post and pre-scores instead of the absolute SSQ values to avoid carryover effects.

An **interaction between translation and rotation** qualified these main effects for three (out of 12) DVs including ease of use, ease of learning, and task load (NASA-TLX) as illustrated in Table 2.3 and Figure 2.3. That is, the effect of adding embodied (leaning-based) translations depended on whether rotations were performed by gamepad or physical rotations: when rotations were controlled by gamepad (red bars in Figure 2.3), switching to leaning-based embodied translations instead of gamepad translations provided no significant benefit for these measures (see also post-hoc analysis in Figure 2.3). Conversely, when virtual rotations were controlled by physical rotations (blue bars in Figure 2.3), switching to leaning-based embodied translations instead of gamepad translations provided more substantial and significant benefits in terms of increased ease of use and ease of learning, and reduced task load. To investigate if prior gaming experience improves performance, we conducted an additional ANOVA with the added between-subject factor of **prior gaming**

experience {yes, no}. Participants who played 3D first-person games on a daily or weekly basis passed more tunnels ($M = 5.10\%, SD = 1.94\%$) compared to non-gamer participants ($M = 3.35\%, SD = 1.79\%$), $F(1, 19.5) = 13.5, p = 0.002, \eta_p^2 = 0.381$. The performance of the participants with prior gaming experience was consistently better with every interface. Participants who played 3D first-person games on a daily or weekly basis also rated interfaces easier to learn ($M = 71.5\%, SD = 23.9\%$) compared to non-gamer participants ($M = 60.3\%, SD = 22.4\%$), $F(1, 22) = 4.87, p = 0.038, \eta_p^2 = .181$. The participants with prior gaming experience consistently rated all the interfaces easier to learn compared to non-gamer participants. Prior gaming experience showed no significant interactions or effects on any other DVs.

Post-hoc pairwise comparisons: **HeadJoystick** showed significant benefits in pairwise comparisons compared to both the RealRotation and Gamepad conditions in most of our 15 DVs (see Figure 2.3). The only exception was motion sickness, where using the HeadJoystick reduced motion sickness only compared to the gamepad, but not the RealRotation condition. That is, compared to RealRotation and Gamepad conditions, the HeadJoystick significantly increased enjoyment, preference, immersion, vection intensity, long-term use, daily use, overall usability, spatial presence, ease of use, ease of learning, and the number of passed tunnels, while reducing task load, absolute distance error, and average number of collisions. Compared to LeaningTranslation, HeadJoystick showed significantly higher enjoyment and preference. The other dependent measures showed only trends in the same direction that did not reach significance. In the post-experiment interview, 20 out of 24 participants (83%) chose HeadJoystick as the best (most favorite) interface, as illustrated in the bottom right plot of Figure 2.3.

LeaningTranslation showed significant benefits compared to using RealRotation and Gamepad in terms of nine out of 15 dependent measures (see Figure 2.3). Compared to using the RealRotation, LeaningTranslation yielded significantly increased number of passed tunnels, enjoyment, preference, overall usability, ease of use, ease of learning, with a reduced task load, absolute distance error, and average number of collisions. Compared to using the Gamepad, LeaningTranslation showed significantly increased number of passed tunnels, enjoyment, preference, immersion, vection intensity, daily use, spatial presence, as well as decreased absolute distance error and average number of collisions. In the post-experiment interview, 4 out of 24 participants (17%) chose the LeaningTranslation as the best (most favorite) interface while 2 participants (8%) chose it as the worst (least favorite) interface.

RealRotation did not show significant differences compared to the Gamepad in any of the 15 dependent measures, indicating that providing real rotations alone does not provide any benefits when translations are still controlled by gamepad (instead of leaning). In the post-experiment interview, 16 participants (67%) chose the gamepad and seven participants (29%) chose RealRotation as worst (least favorite) interface, while no participant chose any of them as the best (most favorite) interface.

Discussion

Study 1 provided evidence for the advantages of leaning-based over gamepad translation in terms of all user experience factors, usability aspects, and performance measures. However, using each interface only for 90 seconds might not be enough for a thorough evaluation of the interfaces, especially given that handheld flying interfaces (such as gamepad or RC controller) are known to require longer periods of time to be used efficiently (Miehlbradt et al., 2018). Moreover, due to the short duration of Study 1, participants' subjective responses might have been influenced by the novelty aspect of the embodied interfaces, which might change for prolonged or repeated usage. Study 2 was designed to address these concerns and gain a deeper understanding of how user experience, usability, and performance might change during repeated exposure, and if the observed benefits of the leaning-based interface (HeadJoystick) might replicate and generalize to extended usage without increasing motion sickness critically.

2.4.7 Study 2

Study 2 was designed to address RQ5 and investigate how usability, user experience, and performance might change over repeated interface usage, and if the observed benefits of leaning-based interfaces such as the HeadJoystick would generalize to multiple repetitions of the task. Repeated interface usage was expected to address initial learning effects and increase familiarity, which might benefit both the dual-thumbstick control scheme and the HeadJoystick which was a new interface for all participants. The overall experimental design and procedure of Study 2 was the same as for Study 1 apart from the changes described below.

Comparing leaning- vs. thumbstick translation: To reduce the potential for motion sickness, we excluded the two conditions from the first study that used thumbstick rotation, and only compared the two conditions using full physical rotation, where translations were controlled either by leaning (HeadJoystick) or thumbstick (RealRotation).

Eight trials per interface: Instead of one 90s trial per interface, we asked each participant to fly eight trials of 60s per interface to investigate how the different measures change over time due to learning/exposure effects. As our pilot studies showed some participants getting motion sick and dropping the experiment before completion, trial duration was reduced to 60s to reduce overall experiment duration while allowing for detection of learning/exposure effects.

Post-trial questionnaire: After each trial, we asked participants to verbally rate their motion sickness as well as perceived task difficulty on a 0-100% scale.

Reduced maximum velocity: As users in pilot studies stated that the controller thumbsticks were too sensitive and might induce severe motion sickness after a few trials, we reduced the maximum speed from 20 to 8 m/s, to reduce motion sickness and increase the usability of the thumbsticks.

Smooth acceleration: Based on user feedback about increased motion sickness during abrupt speed changes, we limited the possible accelerations/decelerations using Unity's SmoothStep function (see appendix A), resulting in smoother velocity profiles (almost like inertia). Limiting accelerations was intended to reduce visual-vestibular cue conflict and the potential for motion sickness, and make the flying experience more realistic.

Using controller instead of Gamepad: As most VR HMDs deploy two separate controllers for each hand instead of a gamepad, we asked participants to use two Valve Index controllers, which have a similar-sized thumbstick as the gamepad used in Study 1. To avoid confusion, we call this RealRotation condition in Study 2 the "Controller" condition. We used a thumbstick mapping similar to the gamepad in the RealRotation condition of Study 1, where the left thumbstick controls forward/backward and sideways and the right thumbstick controls elevation.

Similar velocity transfer function for both conditions: To address the feedback from Study 1 participants that lower speeds were harder to control with the thumbsticks (which used linear mappings in Study 1), we used the same exponential transfer function for both thumbsstick and leaning-based velocity control in Study 2.

Participants

We recruited 12 graduate students (5 females) between 25-37 years old ($M = 30.1, SD = 3.53$) for this study. Six participants (50%) had no prior experiences with VR HMDs, six of them (50%) reported playing 3D (first-person view) video games on a daily or weekly basis. They had no prior experience with our interfaces, and we compensated their time for a 75 minutes experiment by offering a chance to try VR games for a couple of hours. The local ethics board approved this research (#2015s0283).

Results

We compared HeadJoystick with Controller by analyzing 12 DVs using two-tailed repeated measures (paired) t-tests as the data did not violate the Shapiro-Wilk test of normality. Due to the large number of DVs, we summarized t-test results in Table 2.4 and descriptive statistics in Figure 2.3. HeadJoystick showed significant benefits over Controller in 11 of our 12 measures (see top row in Figure 2.4) except motion sickness, which showed no significant difference. Total motion sickness scores were overall relatively low after using both the Controller ($M = 27.7, SD = 19.4$) and the HeadJoystick ($M = 25.6, SD = 18.9$). That is, compared to Controller, HeadJoystick yielded significantly increased enjoyment, preference, immersion, vection intensity, long-term use, daily use, overall usability, spatial presence, ease of use, and ease of learning, while reducing task load. Effect sizes (Cohen's d) were large ($d \geq 0.8$) for all significant effects, indicating substantial benefits of the HeadJoystick even for prolonged usage, corroborating findings from Study 1.

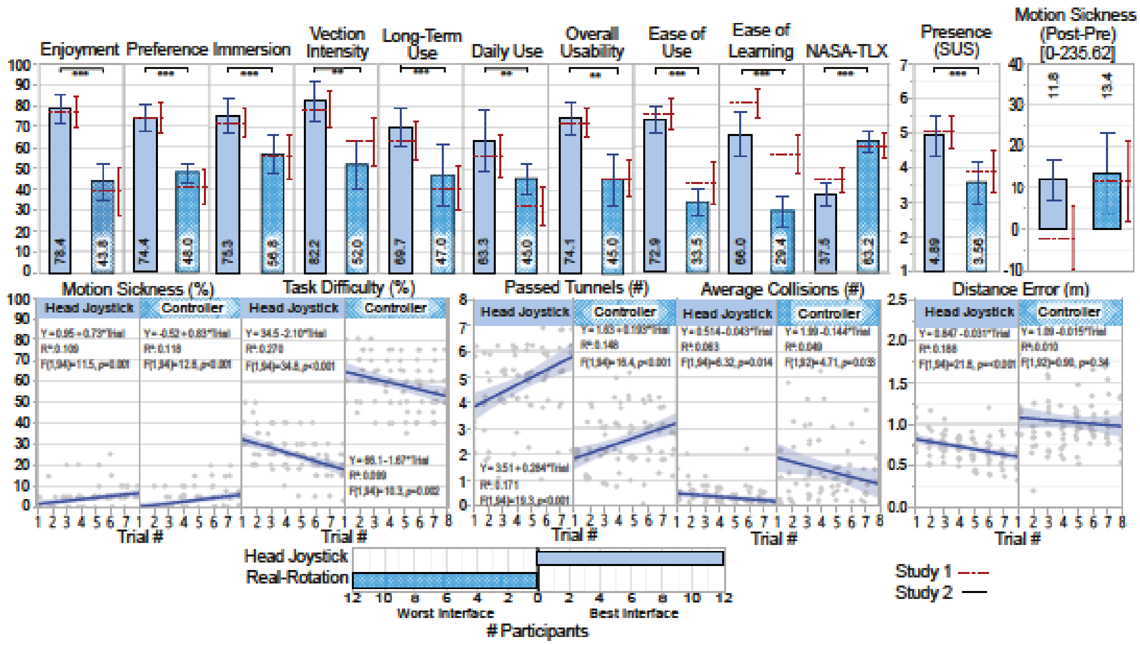


Figure 2.4: Study 2 results of comparing HeadJoystick (in solid blue) versus Controller (in hatched blue): Top row shows mean data of user experience, usability, and performance measures. Error bars indicate confidence intervals ($CI = 95\%$), annotated bars represent significance t-tests differences (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). Means from Study 1 are added as red dashed lines for easier comparability. Middle row shows user experience and performance changes over trials, including linear regression results. Gray dots indicate individual participants data and are jittered to improve visibility. The bottom plot shows the participants' rankings of best and worst interface from the post-experiment interview.

To investigate if **prior gaming experience** improves performance, we conducted an additional ANOVA with the added between-subject factor of prior gaming experience {yes, no} and interface as the within-subject factor. Participants who played 3D first-person games on a daily or weekly basis passed more tunnels ($M = 4.29\%, SD = 1.69\%$) compared to non-gamers ($M = 3.19\%, SD = 1.74\%$), $F(1, 10) = 5.42, p = 0.042, \eta_p^2 = 0.331$. None of the other DV showed any significant effects of gaming experience, though, and there were no significant interactions.

To analyze how HeadJoystick and Controller affect the per-trial measures of motion sickness, task difficulty, number of passed tunnels, and average collisions over time, we used 2×8 repeated-measures ANCOVAs for the independent variables interface and trial number. We analyzed ordinal trial data (i.e., number of passed tunnels) and ratio data that violated the normality assumption in Shapiro-Wilk tests (i.e., average collisions per passed tunnels and motion sickness) as rank-transformed data. We applied Greenhouse-Geisser correction when the sphericity assumption was violated. We summarized correlation results in the middle row of Figure 2.4. First and last trials were compared using planned contrasts.

Table 2.4: T-test results for dependent variables of Study 2: Significant effects ($p \leq 5\%$) are written in bold, 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(23)	*p*	*Cohen's d*
Enjoyment	**15.0**	**<0.001**	**4.33**
Preference	**11.5**	**<0.001**	**3.32**
Immersion	**4.89**	**<0.001**	**1.42**
Vection Intensity	**4.83**	**0.001**	**1.40**
Long-Term Use	**5.39**	**<0.001**	**1.55**
Daily Use	**3.21**	**0.008**	**0.924**
Overall Usability	**3.98**	**0.002**	**1.15**
Presence (SUS)	**6.81**	**<0.001**	**1.96**
Ease of Use	**12.4**	**<0.001**	**3.58**
Ease of Learning	**7.21**	**<0.001**	**2.08**
NASA-TLX	**7.63**	**<0.001**	**2.20**
Motion Sickness (Post-Pre)	0.114	0.742	0.099

Motion sickness showed a significant main effect of trial number ($F(1, 11) = 11.9, p = 0.005, \eta_p^2 = 0.459$), and linear regressions in Figure 2.4 corroborated significant increases in motion sickness over time for both the HeadJoystick ($p = 0.001, R^2 = 0.109$) and Controller ($p < 0.001, R^2 = 0.118$). Interface did not show any significant main effect or interaction with trial number. Motion sickness was overall low ($M = 3.73\%, SD = 5.35\%$) and increased from the first to the last trial from 2.08% ($SD = 3.34\%$) to 5.92% ($SD = 2.87\%$) for the HeadJoystick ($p = 0.041$), and from 0.42% ($SD = 1.44\%$) to 5.75% ($SD = 8.36\%$) for the Controller ($p = 0.007$).

Task difficulty was rated as overall lower for the HeadJoystick ($M = 25.0\%, SD = 9.31\%$) than the Controller ($M = 58.6\%, SD = 12.3\%$), $F(1, 11) = 114, p < 0.001, \eta_p^2 = 0.598$, and showed a significant main effect of trial number $F(1, 11) = 47.8, p < 0.001, \eta_p^2 = 0.229$. Linear regressions in Figure 2.4 indicate that task difficulty ratings decreased significantly over the course of the eight trials for both HeadJoystick ($p < 0.001, R^2 = 0.270$) and Controller ($p = 0.002, R^2 = 0.099$). More specifically, task difficulty decreased between the first and last trial from 31.3% ($SD = 8.56\%$) to 17.8% ($SD = 7.25\%$) for the HeadJoystick, ($p < 0.001$), and from 65.8% ($SD = 12.4\%$) to 53.7% ($SD = 11.5\%$) for the Controller ($p < 0.001$). There was no significant interaction between interface and trial number.

Performance was assessed in terms of the number of tunnels participants managed to pass in each trial, the number of collisions with the tunnel walls per passed tunnels, and the average distance error from the tunnel center while passing through. The **number of passed tunnels** showed a significant main effect of interface ($F(1, 11) = 53.4, p < 0.001, \eta_p^2 = 0.280$), with overall more tunnels passed for the HeadJoystick ($M = 4.79, SD =$

1.57) compared to the Controller ($M = 2.50, SD = 1.15$). Trial number showed also a significant main effect ($F(1,11) = 62.2, p < 0.001, \eta_p^2 = 0.188$), which was qualified by a significant interface-trial interaction ($F(1,11) = 6.47, p = 0.027, \eta_p^2 = 0.028$). As illustrated in Figure 2.4 and the linear regressions, this indicates significant performance improvement over the trials for both the HeadJoystick ($p < 0.001, R^2 = 0.171$) and the Controller ($p < 0.001, R^2 = 0.148$). Between the first and last trials the number of passed tunnels increased from 3.75 ($SD = 1.36$) to 5.83 ($SD = 1.53$) for the HeadJoystick ($p < 0.001$), and from 1.75 ($SD = 0.622$) to 3.08 ($SD = 1.08$) for the Controller ($p < 0.001$). The significant interaction suggests that the performance improvement was larger for the HeadJoystick compared to the Controller, which is corroborated by the steeper slope of the linear regression fit in Figure 2.4.

The **number of collisions per passed tunnel** showed a similar performance benefit (reduced collisions) for the HeadJoystick ($M = 0.319, SD = 0.398$) compared to the Controller ($M = 1.34, SD = 1.50$), $F(1,11) = 15.6, p = 0.002, \eta_p^2 = 0.167$. There was also a significant main effect of trial number $F(1,11.1) = 5.13, p = 0.045, \eta_p^2 = 0.071$, with collisions decreasing between the first and last trials from 0.413 ($SD = 0.500$) to 0.093 ($SD = 0.160$) for the HeadJoystick ($p = 0.505$), and from 1.83 ($SD = 2.40$) to 1.08 ($SD = 0.704$) for the Controller ($p = 0.125$). This performance improvement over the course of the eight trials was corroborated by significant negative linear regressions for both the HeadJoystick ($p = 0.014, R^2 = 0.063$) and the Controller ($p = 0.033, R^2 = 0.049$). There was no significant interaction.

The **average distance error** also showed a similar performance benefit (reduced distance error) for the HeadJoystick ($M = 0.709m, SD = 0.163m$) compared to the Controller ($M = 1.02m, SD = 0.353m$), $F(1,10.7) = 30.4, p < 0.001, \eta_p^2 = 0.080$. There was also a significant main effect of trial number $F(1,10.2) = 18.6, p = 0.002, \eta_p^2 = 0.076$, with distance error decreasing between the first and last trials from $0.839m$ ($SD = 0.131m$) to $0.615m$ ($SD = 0.125m$) for the HeadJoystick, ($p = 0.013$), and from $1.14m$ ($SD = 0.322m$) to $.935m$ ($SD = 0.255m$) for the Controller ($p = 0.020$). This performance improvement over the course of the eight trials was corroborated by significant negative linear regressions for the HeadJoystick ($p < 0.001, R^2 = 0.188$), whereas the Controller showed no significant linear decrease in distance error ($p = 0.344, R^2 = 0.010$). There was no significant interaction.

The top row of Figure 2.4 illustrates that the observed differences between HeadJoystick and RealRotation/Controller showed similar data patterns (benefits for HeadJoystick) for both short-term usage (90s in Study 1, indicated as red dashed lines) and extended (repeated) usage in Study 2 (8 trials). Even the actual values were relatively similar between Study 1 and 2 for almost all subjective measures including enjoyment, preference, immersion, vection intensity, long-term use, daily use, overall usability, ease of use, task load, and presence. This is confirmed by running exploratory 2×2 ANOVAs with the factors Study {1 vs. 2} and interface {HeadJoystick vs. RealRotation/Controller}, which showed no significant main effects of study for any of these DV. Only ease of learning showed overall lower ratings in Study 2 vs. 1 ($p < 0.001$). There were, however, significant interactions between study and interface for vection intensity ($p = 0.044$), ease of learning ($p = 0.001$), and task load ($p = 0.024$), indicating more pronounced differences between HeadJoystick and RealRotation/Controller for extended usage in Study 2 vs. 1. Performance measures all showed improvements over repeated trials (Figure 2.4 middle-row), suggesting learning/practice effects as expected. In fact, after 8 trials participants in Study 2 managed to pass about as many tunnels in a 60s trial as participants in Study 1 in a 90s trial.

In the post-experiment interview, all 12 participants chose HeadJoystick as the best (most favorite) interface, which is shown in the bottom plot of Figure 2.4.

2.5 General Discussion

Both studies showed conclusive evidence for the advantages of leaning-based over thumbstick translation in general, and specifically HeadJoystick over handheld controllers in terms of most of the 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 our research questions RQ1-RQ4 and discuss potential reasons for the observed effects. Then we discuss short-term vs repeated usage effects of our interfaces in the context of RQ5 based on data from Study 2. Therefore, unless stated otherwise, we refer to Study 1 results when discussing RQ1-4, and refer to Study 2 results when discussing RQ-5.

2.5.1 RQ1: Leaning-based interfaces improve user experience

Results confirmed our hypothesis that leaning-based interfaces improve different aspects of user experience compared to using thumbsticks (see Figure 2.3). While previous research showed improved naturalness and control over flight trajectory when using a 2DoF leaning-based interface such as FlyJacket (Rognon et al., 2018), our findings extend knowledge by providing more thorough and conclusive evidence that 4DoF leaning-based interfaces can indeed improve a wide range of measures related to the user experience both in short-term (Study 1) and repeated usage of the interface (Study 2). Note that results patterns have been fairly consistent across Study 1 and 2, and effect sizes of all significant effects were all large ($\eta_p^2 > 0.14$ and Cohen's $d > 0.8$), and p-values were relatively small ($p < 0.008$), suggesting that effects (and the benefits of leaning-based interfaces) are substantial and not likely to be caused by false positives due to testing multiple measures. If anything, repeated usage of the interface in Study 2 showed more pronounced advantages of the HeadJoystick over Controller, indicating that the benefits observed in Study 1 generalize to more extended usage, and were not caused by initial novelty or first-exposure effects.

Compared to prior works, our conclusive results suggests that previously reported disadvantages of 4DoF (flying) leaning-based interfaces such as head-rotation and head-translation (Pittman and LaViola, 2014) might have originated from technical issues as discussed in section 2.3.3. For 2D (ground-based) locomotion, prior research showed benefits of leaning-based interfaces over hand-held controllers in terms of increased vection intensity (Kruijff et al., 2016; Riecke, 2006; Riecke et al., 2008), higher immersion and presence (Freiberg, 2015; Kitson et al., 2015; Marchal et al., 2011), and increased enjoyment (Harris et al., 2014; Kruijff et al., 2016; Marchal et al., 2011). Our findings show that these advantages can, in fact, generalize to 3D (flying) locomotion. Moreover, our results show additional advantages of leaning-based 3D interfaces in terms of usability measures such as ease of use, ease of learning, task load, long-term use, and daily use.

In the post-experiment interview, eight participants mentioned that HeadJoystick allowed for the most realistic experience of being in and moving through the virtual environment. For example, participants stated *"It [HeadJoystick] felt real. I am afraid of height, and using HeadJoystick, I could actually feel the height"*(p13), *"When I have more body motion, it feels like I am in a space station, but gamepad feels more like I am in a game"*(P8). The improved user experience and usability of HeadJoystick over thumbsticks may be due to the alignment of head translation direction (and associated vestibular and proprioceptive cues) with the resulting simulated translation. In fact, HeadJoystick was designed to mimic real-world self-motion cues during the movement initiation (initial acceleration), where we lean a bit in the direction of intended travel before taking a step in that direction. Note that most previous leaning-based seated interfaces used weight-shifting (e.g., dragon-riding (Schulte et al., 2016)), upper-body deflection (e.g., torso-strategy (Miehlbradt et al., 2018)), and/or tilting the chair/stool (e.g., swivel-360 (Hashemian and Riecke, 2017b), ChairIO (Beckhaus et al., 2005b) or different versions of the NaviChair (Freiberg, 2015; Kitson et al., 2015, 2017a; Hashemian and Riecke, 2017b)) to control simulated self-motions in VR and are thus largely independent of the user's head position in space. For the HeadJoystick interface, however, we chose to track the user's head and use it's position change to control simulated self-motions in VR for a number of reasons: Pre-tests showed that head movements seem to require less effort and are more precisely controllable than trunk movements, weight shifting, or chair/stool tilting, especially for smaller deflections. We hypothesized that this would contribute to overall usability, and support longer-term usage.

HeadJoystick also gives users the option to include as much or little upper-body movements and weight-shifting as they preferred and fit their body type and movement abilities. Finally, using head-tracking to control self-motion ensures that users always receive appropriate vestibular motion cueing signals in the direction of the virtual self-motion. We hypothesize that this helps to reduce visual-vestibular cue conflicts and in turn likely also motion sickness (Reason and Brand, 1975; Kennedy et al., 2010).

As for the potential reasons for lower usability aspects of thumbsticks compared to HeadJoystick translation, in the post-experiment interview P1 said *"It [HeadJoystick] was intuitive with my body movements."* and P13 stated *"HeadJoystick was my favorite interface, because it was easy to use and learn."* Conversely, six participants mentioned that it was not easy to control 3 translational DoFs using a gamepad. For example, P4 said *"Gamepad was the worst interface, because its hard to control the movement. You can't go toward different directions easily."* We suggest that the Gamepad design may have contributed to its disadvantages compared to the embodied interfaces: While the mapping between input and the simulated motion matches for the head-based translation, gamepad or RC controllers usually split the four DoFs between two hands/thumbs, and mapping between input and the simulated motion does not match for all DoF. For example, it might not be intuitive to control simulated up/down translation and yaw rotation using a thumbstick pitch/roll rotation. Unfamiliarity of participants with our controller scheme of using left thumbstick for forward/backward and left/right motion and using right thumbstick for elevation and yaw rotation might be another potential reason for the lower performance and user ratings, even though no participants in pilot-tests or in the post-experiment interview mentioned such a barrier when using gamepad.

2.5.2 RQ2: Leaning-based interfaces improve flight performance

Results confirmed our tentative prediction about higher performance of leaning-based interfaces compared to thumbsticks (see Figure 2.3). HeadJoystick and LeaningTranslation seem to be the first 4DoF leaning-based flying interfaces that outperformed the prevalent and often highly familiar dual-thumbstick handheld interfaces both for short-term (Study 1) and repeated usage of the interface (Study 2).

Note that prior work on 4DoF leaning-based flying interfaces (e.g., head-rotation and head-translation in (Pittman and LaViola, 2014)) showed no performance benefit over hand-held interfaces, which could be due to the lower precision caused by the incorrect calibration, drifting from the zero-point, and the technical issues of having an actual drone. Prior research on 2DoF leaning-based flying interfaces showed mixed results regarding this research question: while the FlyJacket interface (Rognon et al., 2018) did not improve performance, torso-strategy (Miehlbradt et al., 2018) improved only efficiency (more passed way-points). However, our results showed performance advantages of leaning-based flying interfaces in terms of not only efficiency (i.e., number of passed way-points) but also effectiveness including accuracy and precision.

Prior research on 2D (ground-based) leaning-based interfaces also showed mixed results in terms of improving navigation performance. For example, compared to 2D hand-held interfaces, the majority of 2D leaning-based interfaces did not improve navigation performance (e.g., (Beckhaus et al., 2005b; McMahan et al., 2012; Kitson et al., 2015, 2017a; Marchal et al., 2011; Hashemian and Riecke, 2017b)) except a few recent leaning-based interfaces (e.g., (Nguyen-Vo et al., 2019)) that reported improved performance in a navigational search task. Therefore, locomotion interface design guidelines usually suggested that 2D leaning-based interfaces provide reduced performance (e.g., (Bowman et al., 2012)). Together with results from (Nguyen-Vo et al., 2019), our findings suggest that leaning-based interfaces indeed have the potential to outperform standard hand-held controller-based locomotion interfaces in both efficiency and effectiveness if designed well, for not only 2D (ground-based) but also 3D (flying), even when all 4DoF need to be controlled. Unlike ground-based leaning-based interfaces, our flying leaning-based interfaces showed higher accuracy/precision compared to the handheld interfaces, which could be due to controlling additional DoFs, which could increase complexity and thus reduce the navigation accuracy/precision when using handheld interfaces.

To explore the potential reasons for poor performance of the gamepad vs head-based translation, in the post-experiment interview, five participants mentioned that the gamepad was too sensitive for the later narrow tunnels compared to using the head. For example, P17 said *"it [gamepad] was too sensitive and I could not go easily to the narrow tunnels."* Lower movement range of thumbstick versus HeadJoystick could be a potential reason for the higher accuracy/precision of the head-based over thumbstick translation, as it might not be easy to fly with extremely low velocity when using thumbstick.

2.5.3 RQ3: Combining full physical rotation and leaning-based translation cues reduce motion sickness

Even though we limited the exposure/trial duration in Study 1 to 90s intentionally to reduce motion sickness, HeadJoystick was the only interface that did not increase motion sickness (post-pre trial) and showed significantly lower motion sickness than the gamepad. This implies that while providing both rotational and translational physical self-motion cues can reduce motion sickness, neither of them alone might be enough to reduce motion sickness significantly. Our findings corroborate previous studies (e.g., (Rognon et al., 2018)) that reported that FlyJacket 2DoF leaning-based flying interface reduced motion sickness compared to a hand-held interface. In the post-experiment interview, P24 said *"Gamepad is so difficult to use and with the highest level of sickness."* Further research is warranted to more closely assess how translation and rotation cues interact and contribute to motion sickness.

2.5.4 RQ4: Contributions of full physical rotations vs. leaning-based translations

Results confirmed our prediction that **embodied (leaning-based) translation** should improve user experience and performance compared to thumbstick translation, by showing significant benefits for all DV apart from motion sickness in both Study 1 and 2, including user experience factors, usability aspects, and performance measures (see Table 2.3 and

Table 2.4). These findings are noteworthy as other promising leaning-based flying interfaces improved only a few user experience aspects (e.g., FlyJacket (Rognon et al., 2018)) or one performance measure (e.g., torso-strategy (Miehlbradt et al., 2018)). The observed advantages of leaning-based translation could be useful for improving locomotion interfaces in situations where users have no access to a swivel chair or simply prefer not to rotate physically, e.g., due to convenience or laziness (Ragan et al., 2017). For example, when the user is sitting on a couch or non-rotating chair, or when using a stationary display like a TV or projection screen instead of an HMD. LeaningTranslation (without physical rotation) in Study 1 showed significant benefits over the gamepad for nine out of 15 measures and was the most favoured interfaces for four (out of 24) participants, who preferred rotating with the gamepad (instead of a chair). As an example, P4 stated *"LeaningTranslation was my favorite interface, because rotating with controller is easier."*

Results also confirmed our prediction that **embodied (physical) rotation** should improve user experience and performance compared to gamepad rotation, by showing significant benefits (main effects) in seven out of 12 DVs in Study 1. This clear benefit of physical rotations could also be relevant from the applied perspective, as most of the recent leaning-based flying interfaces did not allow for physical yaw rotation, including Dragon-riding (Schulte et al., 2016), torso-strategy (Miehlbradt et al., 2018), FlyJacket (Rognon et al., 2018), Head-Rotation, and Head-Translation (Pittman and LaViola, 2014), although there are a few exceptions (e.g., modified Flying-Head (Pittman and LaViola, 2014)). Thus, the observed clear advantages of leaning-based interfaces when using 1:1 360° physical rotation suggest that flying interface designers might want to consider allowing for full physical rotation to improve the overall user experience and performance.

The interaction between embodied (head-based) translation and embodied (physical) rotation suggests that combining embodied translation with embodied rotation can make the interface easier to use, easier to learn, and reduce task load. These findings could also help to understand why prior work reported inconsistent results regarding the impact of full physical rotation on 2D (ground-based) navigation (e.g., (Ruddle, 2013; Riecke et al., 2010)). Our results showed that the advantage of physical rotation depends on which translation technique it is combined with. For example, when using gamepad translation, switching from gamepad to physical rotation improved none of the 15 measures. However, when using head-based translation, switching from gamepad to physical rotation not only improved enjoyment and preference ratings, but also revealed significant improvements in terms of ease of use, ease of learning, task load, long-term use, overall usability, and motion sickness. These results suggest that full physical rotation might improve the overall user experience only if it is combined with a suitable embodied translation technique, in the sense that both rotations and translations need to be embodied. This notion is corroborated by five participants mentioned in the post-experimental interview that controlling virtual translation with thumbs and virtual rotation with the body was confusing. For example, P2 explained that *"the worst interface was RealRotation, because it needs too much focus, both on your body and the gamepad."* These findings are aligned with prior concerns when using physical rotations with controller-based translations in 2D (ground-based) navigation such as (Hashemian and Riecke, 2017b) or informal observations of Grechkin and Riecke, (Grechkin and Riecke, 2014).

The importance of providing both embodied rotation and translation is corroborated by post-experimental interview feedback: Nine participants mentioned that controlling both simulated translation and rotation using their body (instead of their hands) was more similar to real-world movement inside an actual spaceship rather than a game. E.g., P1 state that *"HeadJoystick was my favorite interface, because I don't need to think which part to control with my head and which part to control with my hand."* Embodied control of both simulated translation and rotation could be a potential reason for the usability advantages of the HeadJoystick in terms ease of use, ease of learning, and the task load, and might be related to an improved affordance (Riecke and Zielasko, 2020). Moreover, embodied locomotion frees up users' hands so they can use them for interaction with the environment, which has been stated as another advantage of hands-free locomotion by prior research on 2D navigation (Kitson et al., 2015; Beckhaus et al., 2005a; LaViola et al., 2001; Zielasko et al., 2016). As we found no prior research on the contributions of embodied translation with/without embodied rotation on user experience or performance for flying, all our findings in this regard expand the knowledge by addressing this gap.

2.5.5 RQ5: Leaning-based interfaces retain improved user experience, usability, and performance over repeated usage

Study 2 confirmed our hypothesis that the benefits of a leaning-based interface over a handheld interface in terms of user experience, usability, and performance observed in Study 1 will continue to hold even after extended (repeated) usage. Similar to prior studies (e.g., (Wang and Lindeman, 2012b; Terziman et al., 2010; Marchal et al., 2011)), our study showed improved performance of leaning-based interfaces over repeated usage. However, unlike these prior works (Terziman et al., 2010; Marchal et al., 2011), our second study showed that leaning-based interfaces such as HeadJoystick could have a faster performance improvement compared to using thumbsticks. That is, while both Controller and HeadJoystick showed significant learning effects in Study 2, performance improvements were more pronounced for the HeadJoystick: Even though during the first trial participants passed already more than twice as many tunnels with the HeadJoystick than the Controller ($p < 0.001$), the subsequent learning effect and performance improvements were more pronounced for the HeadJoystick, indicated by the significant interaction between interface and trial number, and the steeper linear regression slope for the HeadJoystick (see Figure 2.4). Furthermore, linear regressions showed significant reductions of distance errors over the eight trials for the HeadJoystick, but not Controller. That is, even though participants were not familiar with the HeadJoystick, they already performed better with it in the first trials, and showed more pronounced improvements over time (as might be expected for novel interfaces) suggesting the full potential of leaning-based interfaces might be more apparent when allowing users sufficient practice.

While most of the measures for HeadJoysick and RealRotation/Controller were fairly similar between Study 1 and 2, extended usage in Study 2 showed more pronounced benefits of the HeadJoystick over RealRotation/Controller in terms of ease of learning, vection intensity, and task load. This might be related to the HeadJoystick being a novel interface for all participants and thus requiring more practice to reveal its full potential. That is, having sufficient time to learn the novel leaning-based interface and more intuitive control might allow users to more easily focus on their task and feel stronger vection, as they are less distracted by fiddling with the locomotion controls.

Study 2 showed a significant increase of motion sickness over the eight trials, similarly for both HeadJoystick and RealRotation/Controller. However, motion sickness overall remained fairly low ($< 6\%$) or < 28 for the total SSQ score, indicating that both interfaces are suitable for extended usage. The overall low motion sickness despite the fast-paced task and longer exposure in Study 2 suggests that the overall locomotion interfaces design and motion sickness mitigation measures of reducing maximum velocity, smoothing accelerations, and including embodied motion cues and thus reducing visual-vestibular cue conflicts were suitable, and can help guide future interface designs.

2.5.6 Limitations

While results from Study 1 and 2 are fairly consistent and show overall substantial effects and effect sizes, there are several potential limitations that could guide future research: Although Study 2 corroborated and largely replicated findings from Study 1 for repeated (extended) usage, we only ran 8 trials of 60s per interface. Future research is needed to investigate if/how our findings might extend to much longer durations or usage across several days/weeks, which can be relevant for real-world applications. All participants were familiar with the gamepad (but not the HeadJoystick), which could have affected our results too. As we designed this drone-racing task without using actual drones due to the high chance of colliding with the narrow tunnels, future research will need to test how the results generalize to telepresence applications with actual quadcopter drones.

2.6 Conclusion and Future Work

In this paper, we introduced HeadJoystick, a novel 4DoF leaning-based flying interface for VR applications. In previous work, leaning-based flying interfaces for 2DoF flying improved either user experience aspects (e.g., FlyJacket (Rognon et al., 2018)) or performance (e.g., torso-strategy (Miehlbradt et al., 2018)), but not both. In contrast, we showed that compared to handheld flying interfaces, HeadJoystick improved six user experience factors (i.e., enjoyment, taskload, immersion, presence, Vection intensity, and overall preference), six usability aspects (i.e., motion sickness, ease of use, ease of learning, long-term use, daily use, and overall usability,), and three performance measures (i.e., efficiency, precision, and accuracy). We did so in a VR-simulated drone waypoint navigation task. In addition, we corroborated these benefits under repeated exposure, with improved performance and only minimal increases in motion sickness over time. Together, this provides promising first evidence that leaning-based interfaces can improve performance and usability/user experience not just for 2DoF (fixed-wing) flight (Miehlbradt et al., 2018; Rognon et al., 2018), but also in 4DoF flying (similar to quadcopter drones). Our results could also benefit telepresence applications as they share similar challenges of using handheld controllers, even though we did not specifically investigate those.

From an applied perspective, HeadJoystick is easy to set up and affordable as it requires no additional hardware besides a swivel chair commonly found in most homes and offices, thus can be readily integrated into existing VR setups that provide 6DoF tracking. Although we only tested HeadJoystick with seated users, it can be easily adapted to standing, and pilot tests were promising. In applications where HeadJoystick could be used for tasks that require free body movements (such as conversation with a fellow visitor during virtual tourism), an “activate” switch for HeadJoystick could be considered, so users can choose to be completely stationary and move their body freely whenever they do not plan to locomote.

In situations where physical user rotation is not desired (e.g., due to convenience or laziness (Ragan et al., 2017)) or feasible (e.g., when sitting on a couch or on transit/planes, or using a projection or TV screen instead of a HMD), using LeaningTranslation provides considerable advantages over a gamepad in terms of six user experience measures as well as three performance measures. Compared to HeadJoystick and LeaningTranslation, other promising leaning-based flying interfaces (e.g., torso-strategy (Miehlbradt et al., 2018) and FlyJacket (Rognon et al., 2018)) might not be as suitable for daily real-life applications. For example, torso-strategy requires attaching several camera-based motion tracker markers to the user’s upper-body to measure the flexion/extension of the trunk muscles during flight (Miehlbradt et al., 2018), and FlyJacket requires the user to wear a backpack, which holds his/her arms up during flight (Rognon et al., 2018).

Future research is needed to investigate how the current findings and advantages observed for Head-Joystick and Leaning-translation might generalize to different virtual or telepresence tasks such as 2D navigation, driving, navigation with secondary interaction task (e.g., First-person shooter games), and 3D telepresence scenarios with quadcopter drones using RC controllers. Future studies can also investigate our suggested interfaces in more detail, such as standing as compared to sitting users (Zielasko, D. and Riecke, 2020), and more diverse participant samples. Overall, these findings extend our knowledge about the advantages of the leaning-based flying interfaces in general and specifically our suggested interface, HeadJoystick, as well as the contributions and interactions of embodied rotational versus translational cues.

2.7 Author Contributions

AH and BR conceived the main idea of the article. AH and BR conceived and developed the technical setup including interfaces and task, while AA, ML, and EK provided comments and suggestions to improve them. AH and ML collected all data. AH, AA, and ML carried data analysis. AH wrote the first draft of the manuscript, while AA, ML, EK, and BR contributed to the revising of the manuscript in many stages including giving feedback and suggestions regarding the issues related to the grammar, rhetoric, literature, arguments, and even rewriting major parts of the paper (in particular BR). BR supervised the entire work. All authors contributed to the manuscript, read, and approved the final version.

Chapter 3

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

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3.1 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.

3.2 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 (Riecke, 2006; Harris et al., 2014; Nguyen-Vo et al., 2019).

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 (Marchal et al., 2011; Freiberg, 2015), spatial awareness (Harris et al., 2014; Nguyen-Vo et al., 2019), speed, ease of use or task load, and comfort/sickness (Nguyen-Vo et al., 2019). However, compared to handheld interfaces, leaning-based interfaces often show lower accuracy/precision (Beckhaus et al., 2005a; Marchal et al., 2011; Hashemian and Riecke, 2017a; Kitson et al., 2017a; Freiberg, 2015; McMahan et al., 2012; Griffin et al., 2018). Therefore, leaning-based interfaces are often considered as more of a promising prototype for specific sets of tasks (Bowman et al., 2012).

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 (Hashemian et al., 2022b). 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 (Hashemian et al., 2022b). 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 (Buttussi and Chittaro, 2019), 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 (Nguyen-Vo et al., 2019) 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 (Bowman et al., 1999). 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 (Fitts, 1954), and in the follow-the-path task, the path was becoming increasingly narrow (Accot and Zhai, 1997). Moreover, as complex environment with obstacles and motion may produce strikingly different results on performance measures (Bowman et al., 1998), 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 (Bowman et al., 1997, 1998, 1999; Bowman, 1999; Bowman et al., 2017), 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 (Roig-Maimó et al., 2017; MacKenzie, 2018). 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 Table 1.4-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. Table 1.4-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. Section 3.4.2) 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.

3.3 Related Work

Convincing visual self-motion cues provided by head-mounted displays (HMDs) (Riecke and Jordan, 2015) 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 (McMahan, 2011)) lack body-based self-motion cues, which can cause sensory conflicts known to contribute to motion sickness (Reason and Brand, 1975) and disorientation (see chapter 1 of (Steinicke et al., 2013)). 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 (Boletsis, 2017) 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 (Steinicke et al., 2013)) or non-motorized walking platforms that use sliding shoes (Anthes et al., 2016) are often costly, unreliable, or barely usable - section 6.4 of (Bowman et al., 2017)). 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 (Carraro et al., 1998; Otte et al., 2011) and motion base car driving simulators with steering wheels and pedals, or even full cockpits (Lee et al., 1998; Nehaoua et al., 2008; Tudor et al., 2015), 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 (Steinicke et al., 2013). While WIP showed advantages over handheld interfaces in terms of improved spatial orientation (Williams et al., 2011; Wilson et al., 2014), this technique usually does not allow for sideways or backward motion (Nilsson et al., 2016) 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 (Mine, 1995; Bowman et al., 1998; Fuhrmann et al., 1998; Suma et al., 2007, 2009; Cardoso, 2016; Christou and Aristidou, 2017; Kitson et al., 2017a), 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 (Bowman et al., 2017), section 11.2.2.1 of (Steinicke et al., 2013), and section 28.3.2 of (Jerald, 2016).

3.3.1 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 (McMahan et al., 2012), weight shift (Kruijff et al., 2016; Harris et al., 2014; Nguyen-Vo et al., 2018), upper body tilt while standing (LaViola et al., 2001; Nguyen-Vo et al., 2019), or tracking tilt of the chair/stool users are seated on (Beckhaus et al., 2005b; Kitson et al., 2017a; Riecke and Feuereissen, 2012a). Leaning-based interfaces free up users' hands, which allow them to more naturally use their hands for interaction such as manipulation tasks or communication (LaViola et al., 2001; Beckhaus et al., 2005a; Kitson et al., 2015; Zielasko et al., 2016; Hashemian and Riecke, 2017a; Hashemian et al., 2022b).

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 (Beckhaus et al., 2005b; Freiberg, 2015), when the physical setup cannot rotate (Riecke and Feuereissen, 2012a; Kitson et al., 2015), or to prevent HMD cable entanglement for too many rotations (Fairchild et al., 1993; Kitson et al., 2017a). 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 (Ruddle, 2013), and showed it's benefits (Farrell and Robertson, 1998; Presson and Montello, 1994; Rieser, 1989; Klatzky et al., 1998) such as improving navigational search task efficiency (Riecke et al., 2010; Nguyen-Vo et al., 2019). We previously designed HeadJoystick as a full-rotational leaning-based interface, expanding on our prior design iterations (Kitson et al., 2017a; Hashemian and Riecke, 2017a; Hashemian et al., 2022b; Nguyen-Vo et al., 2019; Riecke and Feuereissen, 2012a; Kitson et al., 2015). Different full-rotational leaning-based interfaces are juxtaposed and compared in Table 3.1-Appendix, and reviewed in Section 3.3.2.

3.3.2 Full-Rotational Leaning-Based Interfaces

Leaning-based interfaces have been designed for standing users (Marchal et al., 2011; Harris et al., 2014; Langbehn et al., 2015; Kruijff et al., 2016; Nguyen-Vo et al., 2019) and seated user (Beckhaus et al., 2005b; Silva and Bowman, 2009; Kruijff et al., 2015; Kitson et al., 2017a; Hashemian and Riecke, 2017a; Buttussi and Chittaro, 2019; Nguyen-Vo et al., 2018). 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 (Zielasko and Riecke, 2020a). Moreover, excessive uninterrupted standing posture could cause discomfort (Zielasko, D. and Riecke, 2020), leg swelling, and fatigue (Chester et al., 2002), with stronger motion sickness (Riccio and Stoffregen, 1991; Merhi et al., 2007) and postural sway during virtual accelerations (Badcock et al., 2014), 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 (Nguyen-Vo et al., 2019). 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 (Harris et al., 2014), 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 hand-held 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 (Langbehn et al., 2015). 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 (Marchal et al., 2011). 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 (Nguyen-Vo et al., 2019), 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 (Hashemian and Riecke, 2017a). 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 (Kitson et al., 2017a). 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 (Buttussi and Chittaro, 2019). 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 (Bowman et al., 2017).

3.4 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 (Hashemian et al., 2022b) and was evaluated in a fly through tunnels-in-the-sky task and later in a 3D navigational search (Adhikari et al., 2021a) 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.

3.4.1 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 (McMahan et al., 2014). 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 Section 3.4.2 as well as interface throughput. Previous research showed higher performance of leaning-based interfaces compared to handheld interfaces in terms of improving spatial orientation (Harris et al., 2014) and spatial updating in a navigational search task (Nguyen-Vo et al., 2019). A leaning-based interface similar to HeadJoystick already showed improved task completion time (speed) in a reach-the-target task (Buttussi and Chittaro, 2019). However, leaning-based interfaces often showed reduced accuracy/precision compared to handheld interfaces (Beckhaus et al., 2005a; Marchal et al., 2011; Hashemian and Riecke, 2017a; Kitson et al., 2017a; Freiberg, 2015; McMahan et al., 2012; Griffin et al., 2018). As our prior study showed improved task completion time, accuracy, and precision for the HeadJoystick compared to handheld interfaces in flying (Hashemian et al., 2022b), 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 (Bowman et al., 2012). 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) (Kruijff et al., 2016; Riecke, 2006; Riecke and Feuereissen, 2012a), improved immersion (Freiberg, 2015), enhanced presence (Marchal et al., 2011), and increased fun/enjoyment (Kruijff et al., 2016; Marchal et al., 2011). As for the usability aspects, prior work reported advantages compared to the handheld interfaces in terms of improved spatial orientation (Nguyen-Vo et al., 2019), enhanced intuitiveness (Freiberg, 2015), reduced cognitive load and motion sickness (Nguyen-Vo et al., 2019) while other studies reported no significant improvement or lower ease of use (Hashemian and Riecke, 2017b; Buttussi and Chittaro, 2019; Kitson et al., 2017a) and ease of learning (Hashemian and Riecke, 2017b; Kruijff et al., 2016; Zielasko et al., 2016).

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 (Bowman et al., 1999) as discussed in Section 3.2. 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 (Marchal et al., 2011), number of errors (McMahan et al., 2010), and distance error (Hashemian and Riecke, 2017a), but also increase unwanted side effects such as fatigue (Chester et al., 2002) and motion sickness - section 2.5 of (Lawson, 2014). 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 (Hashemian et al., 2022b), 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) (Marchal et al., 2011; McMahan et al., 2010; Griffin et al., 2018; Nguyen-Vo et al., 2019), which often reduced performance compared to the handheld controller with the exception of the study by Nguyen-Vo et al. (Nguyen-Vo et al., 2019). However, as our prior

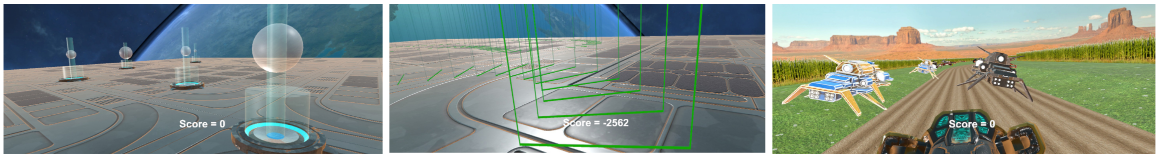

Figure 3.1: Virtual environment used for this study. Left: reach-the-target environment for task#1 from the participant view, where their head should reach inside white spheres. Middle: follow-the-path environment for task#2, where their head should follow the path defined by the green frames. Right: 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/`

study showed benefits of using HeadJoystick for 3D flying when the user needs to control their speed after reaching the target (Hashemian et al., 2022b; Adhikari et al., 2021a), we hypothesize that the HeadJoystick's advantages will also continue to hold even with longer stops in 2D ground-based locomotion.

3.4.2 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 (Bowman et al., 1999). 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 (Hale and Stanney, 2015)). 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 Section 3.4.2, 3.4.2, and 3.4.2, and are summarized in Table 1.4-Appendix.

Many VR applications have a complex environment with obstacles and activity/motion, which may produce strikingly different results on performance measures (Bowman et al., 1998). 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 (Hale and Stanney, 2015)). 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 (Nilsson et al., 2016). 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.

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, to provide rich visual self-motion cues and a compelling visual reference frame (cf. Figure 2.1). *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 2.1 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) (Fitts, 1954), 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

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

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 (Roig-Maimó et al., 2017):

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

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

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

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% (Roig-Maimó et al., 2017). Throughput calculation typically requires individual error rates for each target's distance and width (MacKenzie, 2018), but as in our reach-the-target task, participants reached each target only once, we calculated error rate per participant as defined in Section 3.4.2. Our formula is derived from Fitts' throughput formula (Roig-Maimó et al., 2017; MacKenzie, 2018). 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.

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 2.1, 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 (Accot and Zhai, 1997), 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

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

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.

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 2.1 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 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 2.1 right. We also provided audio feedback for overtaking or hitting each car or getting off-road.

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

3.4.3 Dependent Variables

Table 1.4-Appendix describes our suggested factors and dependant variables (DV) to evaluate a locomotion interface. Table 1.4-Appendix shows six (out of eight) factors from Bowman's framework (Bowman et al., 1999) 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 (Hart, 2006); presence using both SUS questionnaire of spatial presence (Slater et al., 1998) and psychological immersion.

Out of the suggested DVs in Table 1.4-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., (Nguyen-Vo et al., 2019)), which could be be assessed in the future studies. Besides the behavioral/performance scores for each task – explained in Section 3.4.2 – we also measured 12 subjective DVs, including six user experience factors and six usability aspects described in Table 1.4-Appendix, matching those used in our previous HeadJoystick study for flying in VR (Hashemian et al., 2022b). All our 12 DVs were measured with visual-analog scale answers between 0% to 100% except the SUS questionnaire of spatial presence (Slater et al., 1998), which used a Likert-based scale of $1 - 7$ and the simulator sickness questionnaire (SSQ) (Kennedy et al., 1993). 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.

3.4.4 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 2.2. 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.

3.4.5 Study 1

Locomotion Modes

Figure 2.2 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 A as well as our previously published research (Hashemian et al., 2022b), which improved HeadJoystick precision by considering the below details:

High precision movements at lower speeds: based on extensive pilot testing and our prior works (Hashemian and Riecke, 2017a; Nguyen-Vo et al., 2018, 2019; Kitson et al., 2017a), we used an exponential instead of a linear transfer function (with 1.53 exponent) to map the

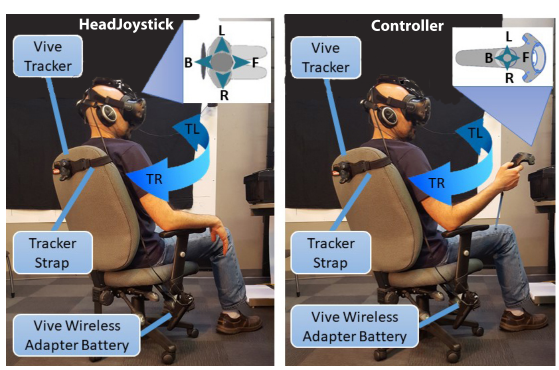

Figure 3.2: HeadJoystick (left) and Controller (right) locomotion interfaces compared in Study 1. Each interface controls locomotion along the three degrees of freedom forward(F)/backward(B), left(L)/right(R), and yaw rotations turn-Left(TL)/turn-right(TR).

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 (Harris et al., 2014) and NaviChair (Hashemian and Riecke, 2017a)) or body tilting (e.g., Joyman (Marchal et al., 2011)), or tilting the chair/stool (e.g., Swivel-chair (Hashemian and Riecke, 2017a)). 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 (Schärli et al., 2013).

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 (McMahan et al., 2012), NaviChair, and NaviBoard (Nguyen-Vo et al., 2019). 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 A.

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.

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} × 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.

Procedure

Participants started with reading and signing the informed consent form, and then answered an initial SSQ questionnaire on motion sickness (Kennedy et al., 1993). 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, 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.

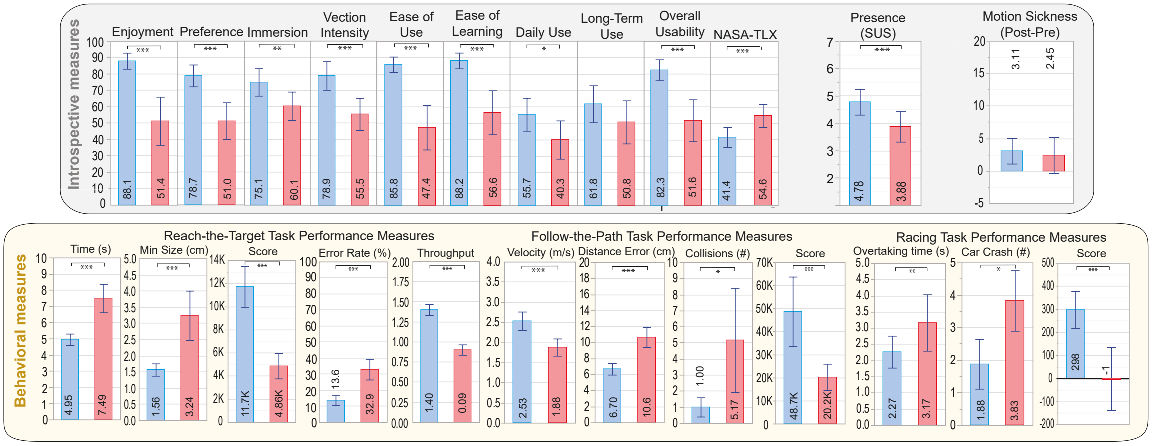

Figure 3.3: Study 1: Mean data of user experience (top), usability (top), and performance (bottom) measures of HeadJoystick (in blue) versus Controller (in red). Error bars indicate confidence intervals ($CI = 95\%$), annotated bars represent significance levels of t-tests (* $p < .05$, ** $p < .01$, *** $p < .001$).

Results

We converted negatively skewed (toward zero) data to logarithmic scales (Feng et al., 2014) 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 (Carifio and Perla, 2008; Norman, 2010). Due to large number of dependent variables, we summarized t-test results in Table 3.3-Appendix, with descriptive statistics in Figure 3.3.

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 3.3 and Table 3.3-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 3.3). 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.

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).

3.4.6 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

(Hashemian et al., 2022b), 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 (Ramcharitar and Teather, 2017), 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 A) 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.

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.

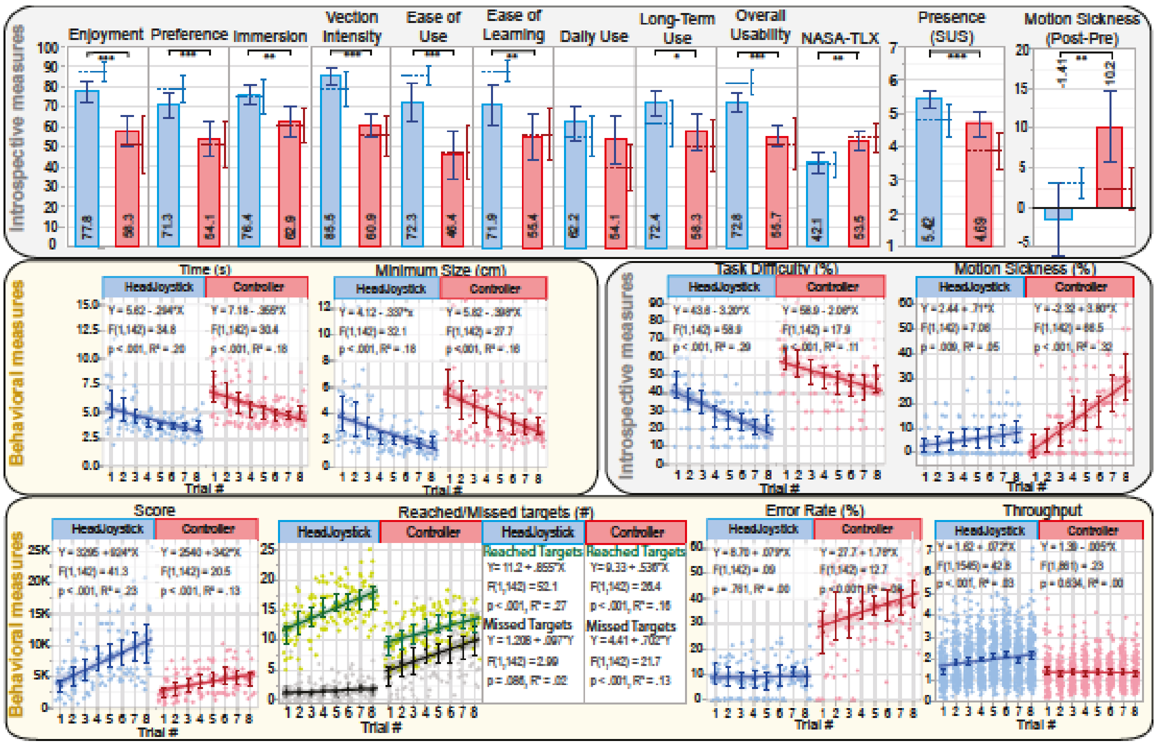

Figure 3.4: Study 2: Mean data of user experience (top), usability (top), and per-trial performance (middle and bottom) measures of HeadJoystick (in blue), versus Controller (in red). Error bars indicate confidence intervals ($CI = 95\%$), annotated bars represent significance levels of t-tests (* $p < .05$, ** $p < .01$, *** $p < .001$). 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.

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 Table 3.4-Appendix, with descriptive statistics in Figure 3.4 top row. HeadJoystick showed significant benefits over Controller in terms of 11 (out of 12) DVs (see Figure 3.4) 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 3.4 down-right plot), Controller showed a significantly increased motion sickness, $T(17) = 4.80, p < .001$, Cohen's d $= 1.13$.

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 2×8 repeated-measures ANCOVAs for the independent variables (IVs) interface 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.

Table 3.6-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. Table 3.6-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 3.4. 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 Table 3.6-Appendix. As illustrated in Figure 3.4 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 3.4 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.

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: `http://ispace.iat.sfu.ca/project/headjoystick2d/`, 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.

3.4.7 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 (Hashemian et al., 2022b; Adhikari et al., 2021a). 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: `http://ispace.iat.sfu.ca/project/headjoystick2d/`. 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 pre-

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

ferred neutral/idle zone instead of brake mechanisms to stop locomotion similar to prior leaning-based interfaces (Marchal et al., 2011; McMahan et al., 2010; Griffin et al., 2018; Nguyen-Vo et al., 2019). 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 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 (Hashemian et al., 2022b), 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 (Adhikari, 2021) and is used in many recent VR applications, thus helping to generalize our findings to more diverse controller-based locomotion conditions.

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.

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 Table 3.5-Appendix, with descriptive statistics in Figure 3.5 top-row. That is, compared to the Controller, HeadJoystick showed increased ease of use, overall usability, presence, immersion, enjoyment, and overall preference (see Table 3.5-Appendix and top-row of Figure 3.5). As depicted in top-row of Figure 3.5, other DVs showed non-significant trends toward HeadJoystick advantage. Top row of Figure 3.5 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 Table 3.5-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 tar-

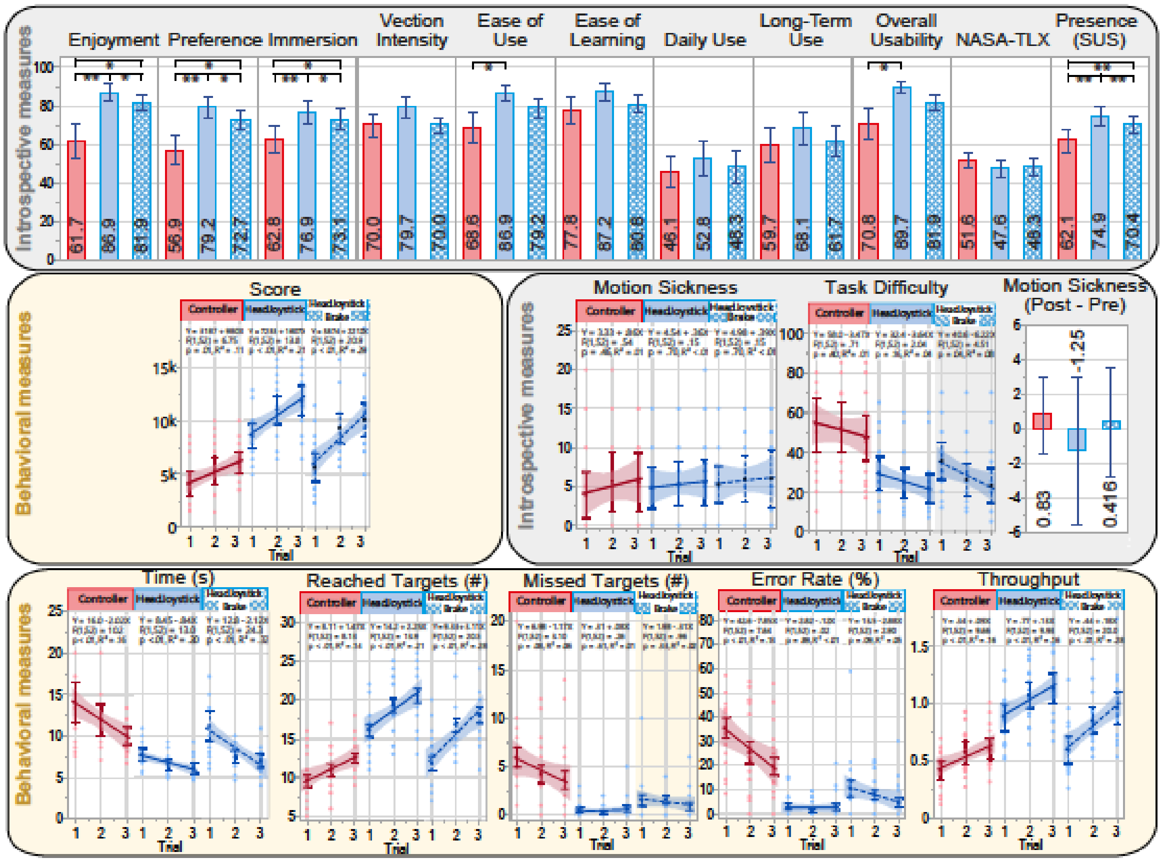

Figure 3.5: Study 3: Mean data of user experience (top), usability (top), and per-trial performance (middle and bottom) measures of HeadJoystick (in blue), versus HeadJoystick+Brake (in hatched-blue) versus Controller (in red). Middle and bottom plots show how performance and user experience changed 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.

gets, 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 Table 3.5-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 Table 3.7-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 Table 3.5-Appendix and Table 3.7-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 Table 3.7-Appendix and linear regressions in Figure 3.5. 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 decreasing over time as corroborated by the steeper slope of the linear regression fit for HeadJoystick+Brake over HeadJoystick condition in Figure 3.5. Moreover, the significant interface-trial interactions and linear regressions in Figure 3.5 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 3.5. 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.

3.5 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.

3.5.1 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 (Beckhaus et al., 2005a; Marchal et al., 2011; McMahan et al., 2012; Freiberg, 2015; Hashemian and Riecke, 2017a; Kitson et al., 2017a; Griffin et al., 2018), 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 (McMahan, 2011). As our previous study already showed higher accuracy/precision of HeadJoystick for flying (Hashemian et al., 2022b), 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) (Hashemian et al., 2022b; Adhikari et al., 2021a) locomotion could be due to the precision considerations we applied when designing HeadJoystick as discussed in Section 3.4.5. 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 (Hashemian et al., 2022b). 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.

3.5.2 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 (Hashemian and Riecke, 2017b; Buttussi and Chittaro, 2019; Kitson et al., 2017a) and ease of learning (Hashemian and Riecke, 2017b; Kruijff et al., 2016; Zielasko et al., 2016) 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 (Buttussi and Chittaro, 2019), more intense perception of self-motion (vection) (Kruijff et al., 2016; Riecke, 2006; Riecke and Feuereissen, 2012a), improved immersion (Freiberg, 2015), enhanced presence (Marchal et al., 2011), and increased fun/enjoyment (Kruijff et al., 2016; Marchal et al., 2011). However, prior studies often evaluated each leaning-based interface for only one task in terms of a small subset of relevant measures (Harris et al., 2014; Langbehn et al., 2015; Marchal et al., 2011; Nguyen-Vo et al., 2019; Hashemian and Riecke, 2017a) although there are exceptions (e.g., (Buttussi and Chittaro, 2019)), 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 (Hashemian et al., 2022b; Adhikari et al., 2021a). 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 (Hashemian et al., 2022b; Adhikari et al., 2021a), 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 (Hashemian et al., 2022b; Adhikari et al., 2021a), 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 (Hashemian et al., 2022b), 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 (Freiberg, 2015; Kruijff et al., 2016; Kitson et al., 2017a; Marchal et al., 2011; Hashemian and Riecke, 2017b,a), our findings and similar results from a recent study (Nguyen-Vo et al., 2019) 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.

3.5.3 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., (Wang and Lindeman, 2012b; Hashemian and Riecke, 2017a; McMahan et al., 2010; Terziman et al., 2010; Marchal et al., 2011)). However, unlike these prior works (Terziman et al., 2010; Hashemian and Riecke, 2017a; McMahan et al., 2010; Marchal et al., 2011), our findings showed that the advantages of leaning-based interfaces over Controller rapidly become more pronounced over time - cf. Table 3.6-Appendix, Figure 3.4, and Figure 3.5. 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.

3.5.4 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 (Marchal et al., 2011; McMahan et al., 2010; Griffin et al., 2018) and confirm recent studies such as (Nguyen-Vo et al., 2019), 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 (Adhikari et al., 2021b). 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).

3.5.5 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 (Steinicke and Bruder, 2014). 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 (Miehlbradt et al., 2018; Rognon et al., 2018) 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 (Fikkert et al., 2010; Aloraini et al., 2020). 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.

3.6 Conclusion

In this paper, we evaluated a locomotion interface using an extensive set of measures (cf. Table 1.4-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 (Hashemian et al., 2022b; Adhikari et al., 2021a). 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 (Hashemian et al., 2022b) 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 (Hashemian et al., 2022b) and 3D navigational search in (Adhikari et al., 2021a)). These results contradict prior studies and design guidelines, which suggested limited usability of leaning-based interfaces for only specific tasks and factors (Bowman et al., 2012). 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 (Adhikari et al., 2021b) 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.

3.7 Author Contributions

AH and BR conceived the main idea of the article. AH and BR conceived and developed the technical setup including interfaces and tasks, while AA, EK, and MvdH provided comments and suggestions to improve them. AH and AA collected all data. AH and AA carried data analysis. AH wrote the first draft of the manuscript, while AA, EK, MvdH, and BR contributed to the revising of the manuscript in many stages including giving feedback and suggestions regarding the issues related to the grammar, rhetoric, literature, arguments, and even rewriting major parts of the paper (in particular BR). BR supervised the entire work. All authors contributed to the manuscript, read, and approved the final version.

Table 3.1: 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 3.2: 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 (Bowman et al., 1999) 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"***

3.8 Appendix

Table 3.3: 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 3.4: 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 3.5: 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 3.5

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 3.6: 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 3.7: 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 3.5.

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

Chapter 4

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

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4.1 Abstract

Physical walking is often considered the gold standard for VR travel whenever feasible. However, limited free-space walking areas in the real-world do not allow exploring larger-scale virtual environments by actual walking. Therefore, users often require handheld controllers for navigation, which can reduce believability, interfere with simultaneous interaction tasks, and exacerbate adverse effects such as motion sickness and disorientation. To investigate alternative locomotion options, we compared **handheld Controller** (thumbstick-based) and **physical walking** versus a seated (**HeadJoystick**) and standing/stepping (**NaviBoard**) leaning-based locomotion interface, where seated/standing users travel by moving their head toward the target direction. Rotations were always physically performed. To compare these interfaces, we designed a novel simultaneous locomotion and object interaction task, where users needed to keep touching the center of upward moving target balloons with their virtual lightsaber, while simultaneously staying inside a horizontally moving enclosure.

Walking resulted in the best locomotion, interaction, and combined performances while the controller performed worst. Leaning-based interfaces improved user experience and performance compared to Controller, especially when standing/stepping using NaviBoard, but did not reach walking performance. That is, leaning-based interfaces HeadJoystick (sitting) and NaviBoard (standing) that provided additional physical self-motion cues compared to controller improved enjoyment, preference, spatial presence, vection intensity, motion sickness, as well as performance for locomotion, object interaction, and combined locomotion and object interaction. Our results also showed that less embodied interfaces (and in particular the controller) caused a more pronounced performance deterioration when increasing locomotion speed. Moreover, observed differences between our interfaces were not affected by repeated interface usage.

4.2 Introduction

In many real-world situations, walking is often not the main goal in itself; rather, walking supports other tasks such as exploration, gathering information or interacting with the environment. When simulating these multi-tasking situations in Virtual reality (VR) applications, we often use artificial locomotion interfaces such as handheld controllers because of real-world space limitations or the danger of colliding with obstacles, which often make unconstrained walking unfeasible. However, controller-based interfaces do not provide any vestibular and proprioceptive self-motion cues. Moreover, using hands for simultaneous control of both locomotion and object interaction can increase cognitive load and decrease performance (LaViola et al., 2001). Therefore, using controllers for locomotion can contribute to motion sickness, decreased believability and naturalness of locomotion, increased cognitive load and decreased performance (Riecke, 2006; Harris et al., 2014; Nguyen-Vo et al., 2019).

To tackle these issues, researchers have designed and investigated embodied hands-free locomotion interfaces. These interfaces free users' hands and provide at least some vestibular and proprioceptive self-motion cues (Beckhaus et al., 2005b; Riecke, 2006; Harris et al., 2014; Nguyen-Vo et al., 2019; Steinicke et al., 2013). As an example, leaning-based interfaces require users to lean toward a target direction to control their locomotion speed using a rate-control paradigm. Leaning-based interfaces provide partial vestibular and proprioceptive self-motion cues mainly for the upper-body when seated (Beckhaus et al., 2005a; Freiberg, 2015; Kruijff et al., 2016; Kitson et al., 2017a; Buttussi and Chittaro, 2019), and can provide additional self-motion cues for the whole body while standing (Harris et al., 2014; McMahan et al., 2012; Nguyen-Vo et al., 2019).

Earlier studies reported that leaning-based interfaces often provide higher presence and immersion but also often led to reduced effectiveness (i.e., accuracy/precision) compared to handheld controllers in both locomotion-only (Marchal et al., 2011; Hashemian and

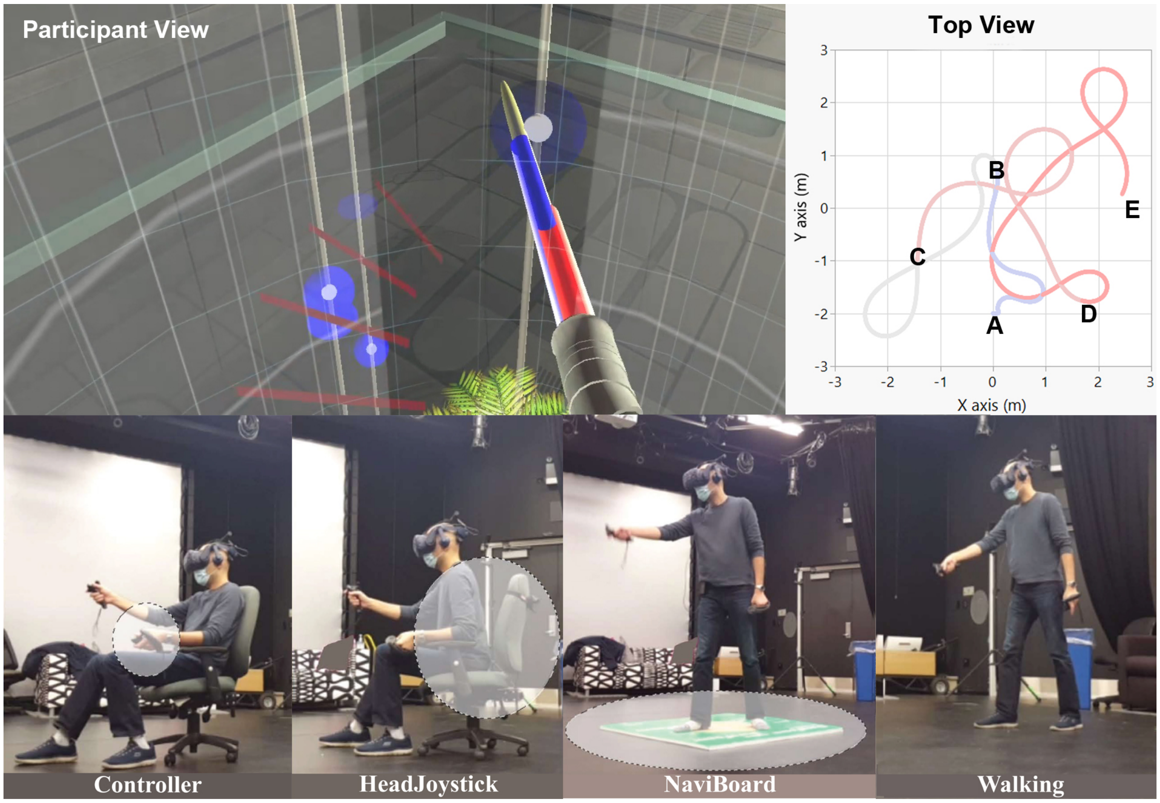

Figure 4.1: Top-Left: Environment from participant view, where participants held a virtual lightsaber in their dominant hand, and were asked to pop vertically moving blue targets by intersecting them with the lightsaber as close as possible to the target's center. Participants were also asked to simultaneously follow a horizontally moving beam and keeping their head as close as possible to its center (see video at `http://ispace.iat.sfu.ca/project/lightsaber/`). Top-Right: Top view of one of the beam's paths randomly pre-generated within a 6×6 m tracked area. The locomotion task became more challenging every 24 s, as the minimum and maximum speed for beam's translation or rotation increased at locations A, B, C, D, and E - see Table 4.1. Bottom: All four locomotion conditions from left to right: Controller, where a seated user deflects Controller's thumbstick to translate in VR; HeadJoystick, where a seated user moves their head toward the target direction while leaning; Naviboard, where the user stands on a circular wooden plate surrounded by a Styrofoam platform and moves their head toward the target direction while leaning/stepping; and Walking.

Riecke, 2017a; Kitson et al., 2017a; Freiberg, 2015) and locomotion and object interaction tasks (Beckhaus et al., 2005b; McMahan et al., 2012; Griffin et al., 2018). However, iterative refinements of our two leaning-based interfaces called **HeadJoystick** (Hashemian et al., 2022b, 2021; Adhikari et al., 2021a, 2022) and **NaviBoard** (Nguyen-Vo et al., 2019) improved almost all relevant measures in locomotion-only tasks (Nguyen-Vo et al., 2019; Hashemian et al., 2022b, 2021). As shown in Figure 4.1-Bottom, HeadJoystick users sit on a regular office swivel chair while NaviBoard users stand on a wooden/Styrofoam platform. In both implementations, users control translational direction by moving their head (tracked via the HMD) toward the target direction and an exponential transfer function maps the head motion to translational speed.

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

Most prior studies on simultaneous locomotion and object interaction tasks (Beckhaus et al., 2005b; McMahan et al., 2012; Griffin et al., 2018; Wiedemann et al., 2020) often assessed general effectiveness measures. These measures confound locomotion with interaction effectiveness, and thus we do not yet fully understand if and how using more effective locomotion interfaces might affect interaction, locomotion, and/or overall effectiveness. Thus, we addressed this issue by designing a novel task consisting of two simultaneous tasks. These tasks require effective locomotion *and* object interaction to assess locomotion, interaction, and overall effectiveness using similar yet separate measures. To do so, we asked the user to simultaneously control their locomotion to stay inside a horizontally moving semi-transparent enclosure ("beam") as well as collect upward moving target balloons with a virtual light-saber, as seen in Figure 4.1-top and this task video `http://ispace.iat.sfu.ca/project/lightsaber/`.

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

- How different levels of embodied self-motion cues i.e., no/minimal (Controller), upper body of a seated user (HeadJoystick), whole body of a standing/stepping user (NaviBoard), and whole body of a walking user affect user experience, usability, and effectiveness in a simultaneous locomotion and object interaction task.

- The design of a novel simultaneous locomotion and object interaction task that allows to differentiate the effects of locomotion interfaces on locomotion, interaction, and overall effectiveness.

- Investigate whether the previously-observed advantages of leaning-based interfaces, such as HeadJoystick and NaviBoard which were used for 2D (ground-based) and 3D (flying) locomotion-only tasks, are generalizable to simultaneous locomotion and object interactions tasks.

4.3 Related Work

As providing full self-motion cues of physical walking is not possible without actual walking, prior research investigated a wide range of embodied interfaces, which provide different levels of physical self-motion cues. Examples include redirected walking, motorized/non-motorized walking platforms, walking in place (WIP), head-directed steering (often called gaze-directed), and leaning-based interfaces (Steinicke et al., 2013). Some of these interfaces are not usable/affordable (cost and space) for a wide range of VR users and especially home users. Other embodied interfaces like WIP and head-directed steering might not provide vestibular and/or proprioceptive sensory cues matching the direction of virtual motion, cues known to help increase the believability of self-motion and reduce its unwanted side effects (e.g., disorientation and motion sickness) (Kruijff et al., 2015; Hashemian et al., 2022b; Adhikari et al., 2021a; Hashemian et al., 2021; Nguyen-Vo et al., 2019).

In the current study, we used leaning-based interfaces because they provide at least minimal translational self-motion cues matching the direction of virtual motion, and are easily accessible to most VR users without additional cost. Recent prior works also showed that leaning-based interfaces can improve almost all locomotion-relevant measures in locomotion-only tasks (Hashemian et al., 2022b; Adhikari et al., 2021a; Hashemian et al., 2021; Nguyen-Vo et al., 2019). That is, compared to handheld interfaces, recent leaning-based interfaces such as HeadJoystick and NaviBoard improved spatial orientation, speed (lower task completion time), accuracy, precision, enjoyment, preference, vection intensity, presence, immersion, ease of use, ease of learning, potential for long-term use, potential for daily use, and overall usability while reducing task load and motion sickness (Hashemian et al., 2022b, 2021; Nguyen-Vo et al., 2019). Leaning-based interfaces also free up the user's hands so they can interact with objects in the environment. This is a substantial advantage over handheld interfaces for simultaneous locomotion and object interaction (Wells et al., 1996; LaViola et al., 2001; Beckhaus et al., 2005a; Kitson et al., 2015; Zielasko et al., 2016; Hashemian and Riecke, 2017a; Hashemian et al., 2022b).

While some prior research investigated locomotion and object interaction interfaces in separate or sequential tasks (Sait et al., 2018; Wilson et al., 2018; Rogers et al., 2019), in this paper, we focus on simultaneous locomotion and object interaction tasks. Prior research has investigated a wide range of user interfaces for simultaneous locomotion and object interaction such as physical walking (Tedjokusumo et al., 2010), head-directed steering (Griffin et al., 2018), WIP (Griffin et al., 2018), 3D (wand) controllers (Lugrin et al., 2013), glove-based hand gestures (Yoon et al., 2010), mouse (Martel et al., 2015; Martel and Muldner, 2017), teleportation and Point of Interest (Mayor et al., 2019), virtual gun (Krompiec and Park, 2019), and omni-directional treadmill (Wiedemann et al., 2020). Many prior studies also investigated leaning-based interfaces in locomotion-only tasks (LaViola et al., 2001; Beckhaus et al., 2005a; Riecke, 2006; Marchal et al., 2011; Riecke and Feuereissen, 2012a; Harris et al., 2014; Langbehn et al., 2015; Kitson et al., 2017a; Hashemian and Riecke, 2017b,a; Buttussi and Chittaro, 2019; Nguyen-Vo et al., 2019; Hashemian et al., 2022b; Adhikari et al., 2022, 2021a; Hashemian et al., 2021). In the remaining of this section, we review previous research that investigated leaning-based interfaces for simultaneous locomotion and object interaction tasks.

Griffin *et al.* evaluated head-directed steering – called Tilt (direction and velocity of the movement is determined by the user's head tilt), WIP, teleportation, and controller (i.e., trackpad) by developing a First-Person-Shooter (FPS) game (Griffin et al., 2018). Though they did not use leaning-based interfaces, their Tilt interface is similar to leaning-based interfaces. In this study, participants were asked to collect ammunition while shooting at flying drones with both hands. The authors used four introspective measures including task load, usability, presence, and motion sickness, as well as a wide range of behavioral measures including the number of drones killed by the user, collected-ammunition, the number of shots the user took from the drone, number of hit over fired bullets as shooting/pointing accuracy measure for each hand, overall physical and virtual movement distance, and travelled time. The results showed that Tilt interface improved presence and task load but not performance over controller. That is, using controller over Tilt increased number of collected ammunition and travelled distance while reducing the damage taken and total physical movement.

Prithul *et al.* also evaluated head-directed steering versus handheld controller in a simultaneous locomotion and object interaction task (Prithul and Berhe, 2021). Participants were asked to follow a path while popping balloons by touching them with their virtual hands. Results showed improved effectiveness of handheld controllers in terms of locomotion (reduced total time and more obstacles jumped) and object interaction (increased targets hit). In contrast, head-directed steering showed a significantly higher avatar embodiment.

Ha *et al.* investigated leaning-based interfaces to control a teleoperated ground-based mobile robot in a simultaneous locomotion and object interaction task (Ha et al., 2015). In this study, leaning-based locomotion was used to move the robot by tracking the user's torso while they were seated on a chair. To provide rotational vestibular cues, users sat on an actuated chair - a rotating swivel chair using a DC motor, which provided yaw rotation in the direction they rotated their upper body. To manipulate objects, the user's hand position was tracked, which controlled the robot's end effector position and manipulator through the use of inverse-kinematics. To provide tactile feedback when manipulating objects, a cutaneous haptic device was used on the user's index finger and thumb which activated when the robot's end effector collided with an object. To evaluate this system, users were tasked with picking up and placing objects. Users rotated their body to reach the objects and place them at a designated location. Results showed a trend towards improved task performance (reduced task completion time), greater perceived ease of use, and reduced simulator sickness when using both chair actuated and cutaneous haptic feedback when compared to using one or none of them. While these findings illustrate the potentials of leaning-based interfaces for teleoperation, this study unfortunately did not compare leaning-based interfaces with any other locomotion methods.

Leaning-based interfaces have been investigated for projection screens by Beckhaus *et al.* in an informal study using the Unreal Tournament first-person shooter (FPS) game to evaluate ChairIO vs. handheld controllers (mouse/keyboard and joystick) (Beckhaus et al., 2005b). To operate the ChairIO a user sits on the Swooper^{TM}, a stool with rotatable tilting seat, and tilts the stool in the desired direction of motion with their body. Users were asked to first shoot a non-moving target as practice, and then perform a death match against simulated bots. Results showed that compared to mouse/keyboard, ChairIO was rated for higher fun but lower subjective precision and perceived performance in the game. Unfortunately, this study did not assessed behavioral/performance measures.

Leaning interfaces have also been compared in desktop and six-sided CAVE conditions by McMahan *et al.* using an FPS-game (Quake III) to compare human joystick and handheld interfaces (mouse and keyboard) (McMahan et al., 2012). The authors designed ten scenarios to control for stereoscopy (bots appeared 3 m away from the user), field of regard (bots appeared 6 m away from the user in a surrounding fashion), aiming (eight bots appeared simultaneously), locomotion (bots retreat after being hit), and their combinations. While introspective results showed that using human joystick in CAVE provided higher presence, engagement, and usability over using handheld controllers on screen, behavioral performance measures showed improved performance of handheld controller on screen and human joystick in CAVE. That is, while human joystick improved speed in the CAVE, handheld controllers improved speed on screen. As for accuracy, handheld controllers on screen outperformed human joystick in both screen and CAVE, while for taken damage, human joystick in CAVE outperformed handheld controllers on both screen and CAVE.

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

4.4 Motivation and Goal

While prior research showed several benefits for providing self-motion cues in locomotion-only tasks, there is limited knowledge on their effects on simultaneous locomotion and object interaction tasks, which motivated this work. First, some research on simultaneous locomotion and object interaction tasks with embodied interfaces used WIP (Griffin et al., 2018) and head-tilt interfaces (Griffin et al., 2018; Prithul and Berhe, 2021). However, these interfaces might not provide proper vestibular or proprioceptive sensory cues due to not moving the head toward the target direction, as discussed in Section 4.3. Prior research investigating leaning-based interfaces on simultaneous locomotion and object interaction tasks used projection screen (Beckhaus et al., 2005b), desktop, and CAVE (McMahan et al., 2012), but not HMDs. Therefore, it is unclear if/how their findings generalize to HMDs as the display device (e.g., desktop, CAVE, HMD) likely affected user performance (McMahan, 2011). Moreover, prior work often used tasks, which might not truly require simultaneous locomotion and object interaction as the players could, in principle, keep switching between locomotion and interaction tasks (Beckhaus et al., 2005b; McMahan et al., 2012; Griffin et al., 2018; Prithul and Berhe, 2021). Further, the overall effectiveness was only measured through combined locomotion and object interaction (such as number of precise pointing/shooting toward enemies or collected/intersected ammunition during locomotion). This does not allow to distinguish the effects the locomotion interfaces have on locomotion, object interaction, and overall effectiveness.

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

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

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

RQ1: How does providing partial self-motion cues improve effectiveness (accuracy/precision) in locomotion and object interaction tasks? Though earlier leaning-based interface prototypes often reduced effectiveness compared to handheld controllers in locomotion tasks (Beckhaus et al., 2005a; Marchal et al., 2011; Hashemian and Riecke, 2017a; Kitson et al., 2017a; Freiberg, 2015), our recent studies showed that iterative improvements of leaning-based interfaces can yield higher performance and effectiveness compared to Controller (Hashemian et al., 2022b; Adhikari et al., 2021a; Hashemian et al., 2022b; Adhikari et al., 2022). Since we are following previously successful design guidelines, we hypothesize that using HeadJoystick improves locomotion effectiveness compared to the Controller.

As for interaction effectiveness, using hands for simultaneous control of both locomotion and object interaction is considered to increase cognitive load and thus reduce the interaction performance as well (LaViola et al., 2001). Both NaviBoard and HeadJoystick have been described as intuitive and easy to use by participants and showed improved ease of use and reduced task load compared to the handheld controllers (Nguyen-Vo et al., 2019; Hashemian et al., 2022b; Adhikari et al., 2021a; Hashemian et al., 2022b). Thus, we hypothesize that hands-free leaning-based interfaces such as HeadJoystick and NaviBoard would reduce cognitive load and improve interaction effectiveness compared to the controller.

As for comparing NaviBoard with HeadJoystick, a recent study reported no significant differences between standing/stepping (NaviBoard) versus seated (NaviChair) leaning-based interfaces (Nguyen-Vo et al., 2019). However, the results showed a general trend of participants performing better with NaviBoard compared to NaviChair. Therefore, we hypothesize the trend to continue and that adding embodied cues for whole body in standing/stepping posture using NaviBoard would further improve the effectiveness of locomotion compared to the Controller in our simultaneous locomotion and object interaction task.

RQ2: How does providing partial self-motion cues improve usability and user experience in simultaneous locomotion and object interaction tasks? Though prior research revealed mixed results to this research question, there is a general trend of improved user experience with leaning-based interfaces. For example, leaning-based interfaces enhanced usability and presence (McMahan et al., 2012) as well as increased enjoyment (Beckhaus et al., 2005b) compared to a handheld controller on simultaneous locomotion and object interaction tasks. Similarly, HeadJoystick versus controller also showed significant benefits of HeadJoystick in terms of some aspects (e.g., enjoyment, preference, immersion, ease of use, overall usability, and presence) (Hashemian et al., 2022b). However, the difference in some other aspects (e.g., ease of learning, long-term use, vection intensity, task load, and motion sickness) were inconclusive (Hashemian et al., 2022b). NaviBoard also reduced task load and motion sickness compared to a controller (Nguyen-Vo et al., 2019). NaviBoard was even comparable to walking, the most natural user experience with the highest usability (Tedjokusumo et al., 2010). Considering these general trends, we tentatively hypothesize that using HeadJoystick and in particular NaviBoard interfaces will improve user experience and usability aspects in simultaneous locomotion and object interaction tasks.

RQ3: When comparing leaning-based interfaces, how does standing/stepping vs. sitting on a chair affect effectiveness, user experience, and usability? Prior research provided mixed results to this research question. For example, while the postural instability theory of motion sickness suggests higher motion sickness for standing over seated interfaces (Riccio and Stoffregen, 1991; Merhi et al., 2007), a recent study showed that a standing interface (NaviBoard) could reduce motion sickness compared to a seated interface (NaviChair) (Nguyen-Vo et al., 2019). NaviBoard also improved performance over

NaviChair, even though seated interfaces should generally provide higher precision than standing interfaces (Zielasko and Riecke, 2021). Compared to the seated posture, standing posture is also known to be less comfortable (Zielasko, D. and Riecke, 2020; Chester et al., 2002), accessible (Zielasko and Riecke, 2021), and safe (Badcock et al., 2014). In contrast, standing interfaces should provide more intense vection, higher engagement, and higher degrees of embodiment (Zielasko and Riecke, 2021). Overall, due to the similarities between HeadJoystick and NaviChair, we hypothesize similar benefits of standing interfaces (here NaviBoard) over seated ones (here HeadJoystick) in terms of motion sickness, performance, and believability.

4.5 Methods

4.5.1 Tasks and Environment

Our general LightSaber task is illustrated in videos at `http://ispace.iat.sfu.ca/project/lightsaber/`. It was inspired by the VR game Beatsaber, where participants used their lightsaber to intersect targets (BeatGames, 2019). We revised this task for our user study by adding user locomotion. This allows us to assess effectiveness of locomotion and object interaction tasks using similar yet separate measures. To do so, participants were asked to actively follow a horizontally moving beam by keeping their head as close as possible to its center - see Figure 4.1 top-right. Participants were also asked to use their lightsaber to collect upward moving target balloons appearing to the beat of the music. To provide a continually demanding object interaction task, based on our pilot-testings, targets appeared at a rate of one target per second, and would be collected ("fried") if intersected with the lightsaber for at least 0.33 seconds. Otherwise, targets disappeared after reaching three meters above the floor. Based on our pilot-tests, the targets were programmed to appear in an area where participants could easily see and reach them with their lightsaber. That is, they appeared in a random distance between 1-2 m from the center of the beam in a $\pm 30°$ angular range around the beam's movement direction.

The effectiveness of locomotion and object interaction tasks was assessed using accuracy and precision measures. *Accuracy* was measured by the average distance of a user from a path/target - section 1.3.2 of (McMahan et al., 2014), thus the accuracy scores for our locomotion and object interaction tasks were calculated by how close the participant's head and lightsaber were to the center of beam and target, respectively. At each frame, we standardized accuracy measures for locomotion and object interaction into a proximity percentage ranging between 0% (outside) to 100% (center) of the beam and target, respectively. To ensure that participants spent similar effort on both locomotion and object interaction tasks, we defined the overall accuracy score at each frame as the minimum score between the locomotion and object interaction scores of that frame. The locomotion, interaction, and overall (accuracy) scores of a trial were calculated by summing up the locomotion, interaction, and overall scores for each frame, respectively. *Precision* is the ability of an interface to support fine movements without missing the target or colliding with the path borders - section 1.3.2 of (McMahan et al., 2014). We assessed locomotion precision by the number of collisions with the beam's border, i.e., the number of times users left the beam. In addition, we also measured locomotion precision by the percentage of time users spent outside the beam. Interaction precision was assessed by the number of popped and missed targets.

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

Table 4.1: All levels in our task. The locomotion task became more demanding over time, as either rotation and translation speed were increased between levels.

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

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

The beam's translational and rotational velocity was randomised when pre-generating its path - see Figure 4.1 top-right. As for determining minimum and maximum translational and rotational speed of the beam, prior user studies reported mixed results regarding if providing limited self-motion cues can improve locomotion performance in spatial orientation tasks (Ruddle, 2013). For example, while some studies did not show improving spatial orientation when providing physical rotation without limited translational motion cues (Sigurdarson et al., 2012; Sigurdarson, 2014), other studies showed that providing physical rotation could help the user to better stay spatially oriented (Farrell and Robertson, 1998; Presson and Montello, 1994; Rieser, 1989; Klatzky et al., 1998; Ruddle et al., 1999). Some previous studies even reported that providing physical rotation resulted in performance comparable to actual walking in a navigational search task when used with leaning-based interfaces (Nguyen-Vo et al., 2019) and handheld interfaces (Riecke et al., 2010). As the reasons behind such mixed results are not fully understood, and different factors such as translational and rotational speed could be responsible, we decided to compare our interfaces in different ranges of translational and rotational speeds. We did so by defining five levels of increasing speed and difficulty. Each level lasted for 24 s, after which the minimum and maximum speeds were increased for either the translation or rotation after each level to make the locomotion task more demanding over time (Cunningham et al., 2001; Zhai et al., 2004; de Winter et al., 2009) - as shown in Table 4.1.

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

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

$$\mathrm{dFT} = \mathrm{eT} * \mathrm{IS}$$
$$\mathrm{IS} = 1 - \mathrm{ID}/\mathrm{TR}$$

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

When frying a target, tactile feedback was provided by the controller's vibration. It vibrated more intensely if the light saber was closer to the center. In addition, the target gradually turned from blue to black upon frying, and produced a popping sound when the frying was complete. To provide rich visual self-motion cues including parallax cues as well as a compelling visual reference frame during locomotion, a futuristic-looking room was used as the virtual environment, with semi-transparent ceiling and floor (cf. Figure 4.1 top-left).

4.5.2 Dependent Variables

For this study, we used our previously introduced framework (see Appendix A) to evaluate locomotion interfaces, which is an expansion of Bowman's framework (Bowman et al., 1997, 1998, 1999; Bowman, 1999; Bowman et al., 2017) for assessing user experience, usability, and performance factors. User experience consisted of four subjective factors: *presence* - measured using the SUS spatial presence questionnaire (Slater et al., 1998) and psychological immersion (i.e., being captivated by a task); *vection intensity* - based on the rated intensity of the users' self-motion sensation; *motion sickness* - using the simulator sickness questionnaire (SSQ) (Kennedy et al., 1993); and overall user experience - using *enjoyment* and the *overall preference* ratings for each interface. Usability consisted of four factors: ease of learning - measured by introspective ratings for *ease of learning* as well as the behavioral performance improvement over time; ease of use - including introspective rating for the *overall ease of use* as well as the first and commonly used part of the *NASA-TLX questionnaire* for locomotion and overall task load (Hart, 2006); user comfort - measured by the user-ratings for the potential of *daily and long-term usage* of the interface; and *overall usability* ratings for the interface. Performance was assessed via two behavioral measures: *accuracy* was measured by the locomotion, interaction, and total scores; and *precision* for interaction and locomotion was measured by the number of missed and popped targets, number of times users left the beam, and the percentage of the time outside the beam, which have already been explained in Section 4.5.1. All introspective questions were rated using visual-analog scale answers between 0% to 100%, except for the SSQ, which uses a Likert-like scale of {None, Slight, Moderate, Severe}.

4.5.3 Apparatus

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

4.5.4 Locomotion Modes

Figure 4.1-bottom shows the four interfaces used in this study: Controller, HeadJoystick, NaviBoard, and Physical walking. In the **Controller** condition, translation velocity was controlled by the thumbstick deflection, where the forward deflection of the thumbstick moved the user toward the direction of the controller. Maximum translational velocity for all the artificial interfaces was 4 m/s, based on the pilot-testings. Thumbstick deflection was mapped to the translation velocity using an exponential transfer function with power of 1.53 to be consistent with HeadJoystick/NaviBoard input mapping as well as allowing for more precise control at lower velocities. To reduce motion sickness, we also used Unity's SmoothStep function to smooth out any harsh speed changes when artificial locomotion interfaces were used as detailed in the appendix A. Participants used one controller to move

and the other one to control the lightsaber, based on their choice. We asked participants to hold both controllers in all conditions for consistency.

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

NaviBoard is a standing version of the HeadJoystick (cf. Figure 4.1-bottom) with a 15 cm natural/idle zone, where the user could move their head in this range without triggering simulated locomotion (Nguyen-Vo et al., 2019). Moving beyond this range would trigger the simulated locomotion, where its direction and speed were determined based on the direction and horizontal displacement of the user's head from zero point, respectively. The maximum head motion range was 40 cm for NaviBoard.The NaviBoard platform consists of the inner circular wooden plate and the outer rectangular softer styrofoam ring providing tactile feedback about the neutral/idle and simulated locomotion zone, respectively. That is, moving the head beyond the neutral/idle zone to trigger simulated locomotion usually required the user to step on the soft outer styrofoam plate such that they receive unobtrusive tactile feedback from their foot. We asked participants to take off their shoes to more easily sense the tactile feedback (cf. Figure 4.1-bottom). The only change in our NaviBoard condition compared to its prior study was using the head rotation center instead of HMD's position as the user's head as shown in the appendix A, to be consistent with the HeadJoystick condition and allow for head rotations without affecting locomotion.

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

4.5.5 Participants

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

Table 4.2: ANOVA results for behavioral data comparing interfaces over trials and difficulty levels. Significant ($p \leq 5\%$) and marginally significant ($p \leq 10\%$) effects are highlighted in green and light green, respectively, and were always in the direction of improved aspects for physical walking followed by NaviBoard, and then HeadJoystick, and finally Controller.

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

the local ethics board (#20180649) and course credit were offered as compensation for participating in the study.

4.5.6 Experimental Design

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

4.5.7 Procedure

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

4.6 Results

11 (out of 21) dependent variables (DVs) showed no or only a slight violation of normality assumptions (i.e., two violation cases in 44 Shapiro-Wilk tests, where ($p > 0.024$)). We analyzed these 11 measures using repeated-measures ANOVA, as it has been shown to be robust against such slight violations of assumptions (Field, 2013; Schmider et al., 2010).

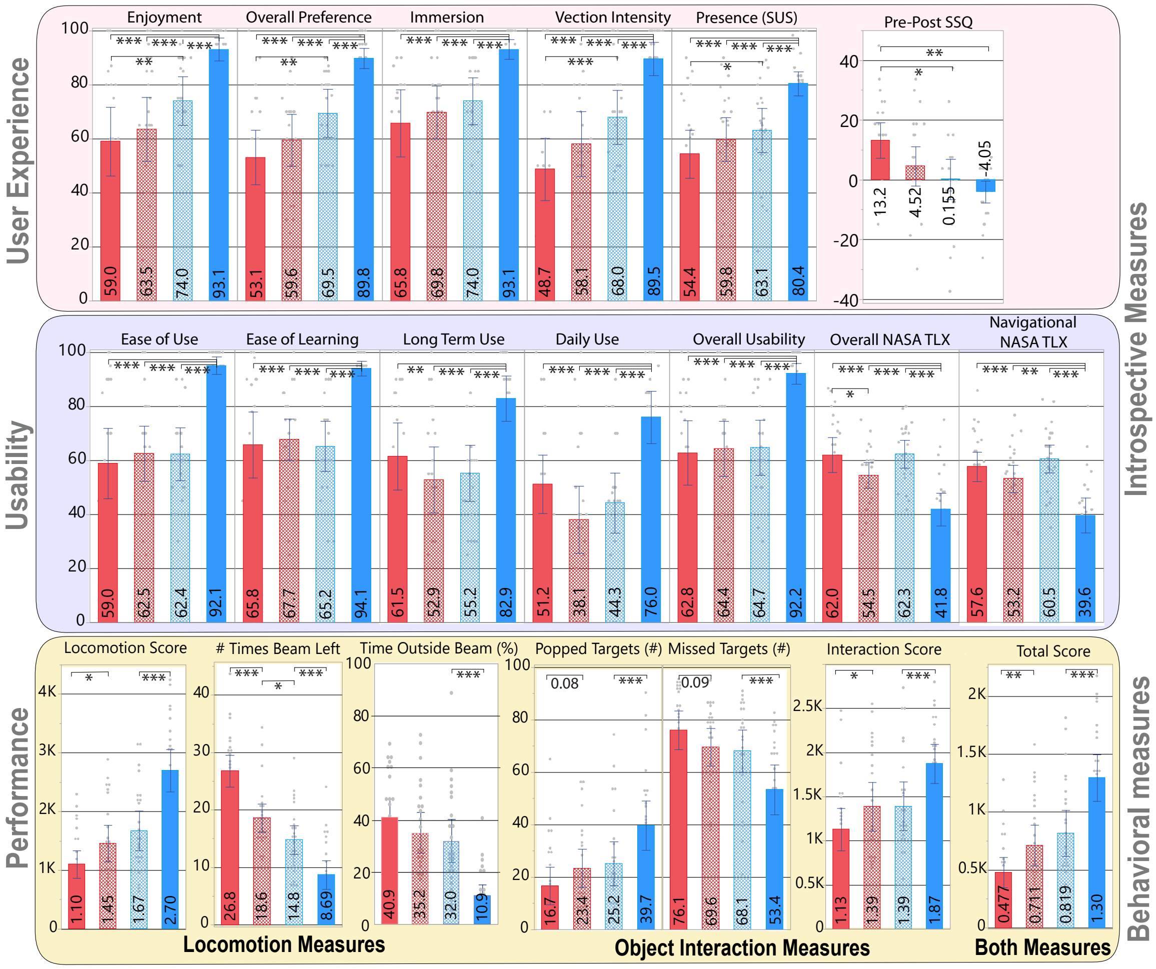

Figure 4.2: Average data for user experience (top), usability (middle), and per-trial performance (bottom) measures for Controller (in red) vs. HeadJoystick (in hatched-red) vs. NaviBoard (in hatched-blue) vs. Walking (in blue). Seated conditions are color-coded in red to distinguish them from the upright conditions in blue. Error bars indicate confidence intervals ($CI = 95\%$) and dots show individual participants' data for each interface. Annotated bars represent significance levels in pairwise comparisons (* $p < .05$, ** $p < .01$, *** $p < .001$) for introspective (using Tukey post hoc tests) and behavioral (using planned contrasts) data. p-values were stated when marginally significant.

These were all seven behavioral measures shown in Figure 4.2-bottom and four (out of 14) introspective measures (spatial presence, post-pre motion sickness, locomotion task load, and overall task load). For pairwise comparison among these four introspective measures, we used Tukey-HSD post-hoc tests, and applied Greenhouse-Geisser correction whenever the sphericity assumption was violated in the Mauchly's test. As for the behavioral measures, we had specific hypotheses and thus used planned contrast to assess our hypotheses using three pairwise comparisons between interfaces: HeadJoystick versus Controller, to compare providing (i.e., HeadJoystick) versus not providing (i.e., Controller) embodied motion cues

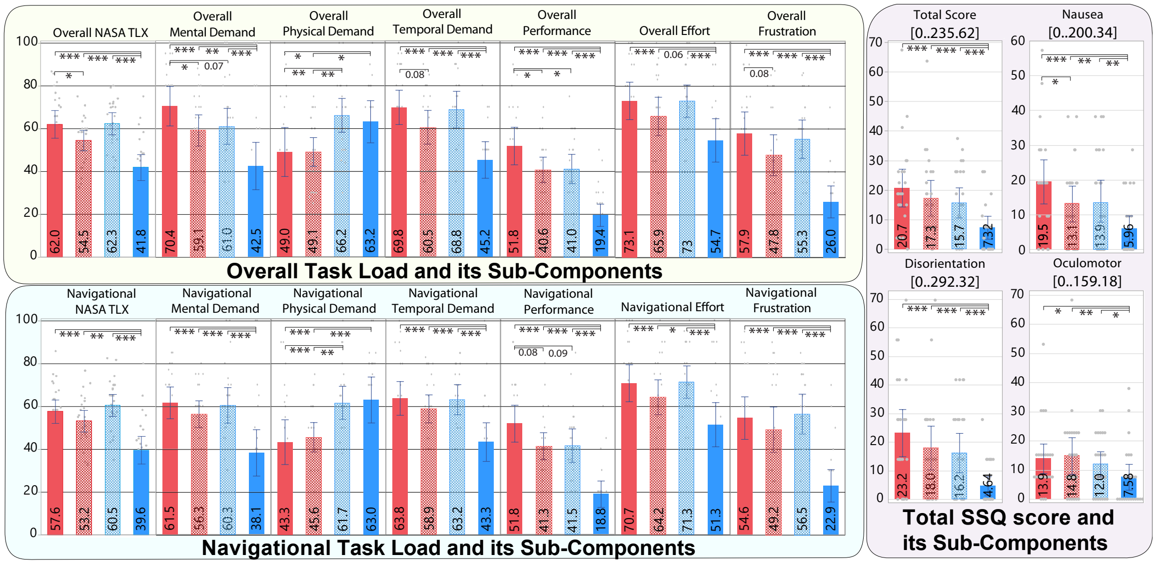

Figure 4.3: Average data for overall NASA TLX (top-left), navigational NASA TLX (bottom-left), and SSQ score (right) and their sub-components for Controller (in red) vs. HeadJoystick (in hatched-red) vs. NaviBoard (in hatched-blue) vs. Walking (in blue). Seated conditions are color-coded in red to distinguish them from the upright conditions in blue. Error bars indicate confidence intervals ($CI = 95\%$) and dots show individual participants' data for each interface. Annotated bars represent significance levels in pairwise comparisons (* $p < .05$, ** $p < .01$, *** $p < .001$) using Tukey post hoc tests. p-values were stated when marginally significant.

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

Behavioral data analysis methods. We conducted $4 \times 3 \times 4$ repeated-measures ANOVAs for the independent variables interface, trial, and difficulty level for all behavioral measures. Due to the large number of DVs, ANOVA results are summarized in Table 4.2, with descriptive statistics and post-hoc tests summarized in Figure 4.2. As depicted in Table 4.2, our analysis showed significant main effects of interface, trial, and difficulty level on all behavioral measures, and significant interactions between interface and difficulty level for all but the popped/missed targets measures. The following paragraphs address individual questions based on these $4 \times 3 \times 4$ ANOVAs and post-hoc analyses:

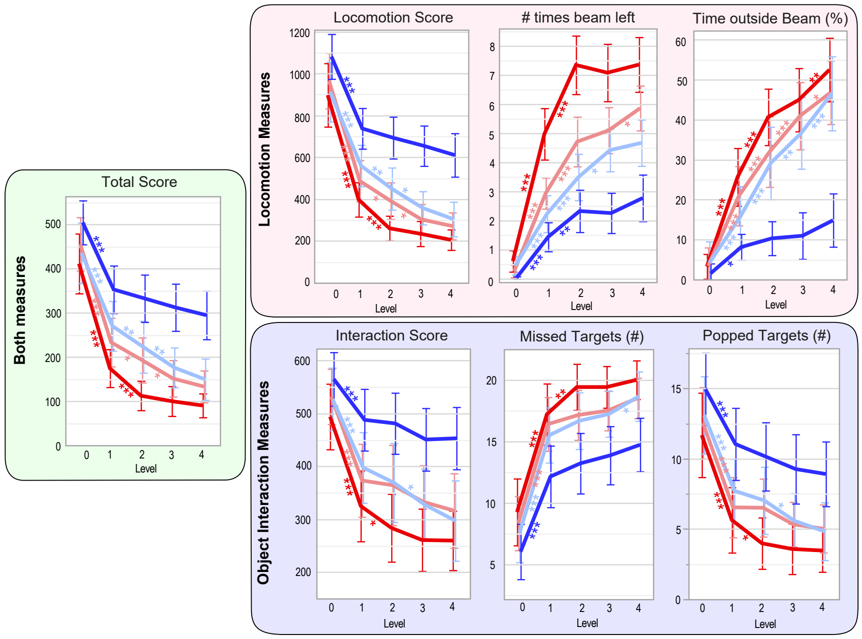

Figure 4.4: Average data for performance measures over difficulty levels (locomotion speeds) for Controller (in red) vs. HeadJoystick (in hatched-red) vs. NaviBoard (in hatched-blue) vs. Walking (in blue). Seated conditions are color-coded in red to distinguish them from the upright conditions in blue. Annotated bars represent significance differences between behavioral measures in subsequent levels (* $p < .05$, ** $p < .01$, *** $p < .001$) using planned contrasts.

The effect of interface on performance and introspective measures: Interface also showed significant effects also on all introspective measures. Interface showed significant main effects on all introspective and behavioural measures, see Table 4.2, Figure 4.2, and Figure 4.3. Pairwise comparisons showed that physical walking improved all introspective and behavioral measures compared to all other interfaces ($p < 0.001$) except for the post-pre motion sickness, where walking showed no significant benefit over NaviBoard or HeadJoystick (see Figure 4.2). Although there was a consistent tendency for the NaviBoard to outperform the HeadJoystick, this trend reached significance only for the number of times users left the beam ($p = 0.025$). Compared to the controller, NaviBoard improved six (out of 14) introspective measures in terms of higher favorite interface order ranking ($p < 0.001$), enjoyment, preference, vection intensity, spatial presence as well as lower post-pre motion sickness (see Figure 4.2). HeadJoystick did not show any significant advantages on introspective measures compared to the Controller except higher favorite interface order ranking and the overall task load. Figure 4.3 shows the comparison between interfaces in terms of the sub-components of the locomotion and overall task load. HeadJoystick outperformed Controller in terms of most behavioral measures including significantly higher scores for locomotion, interaction, and combined accuracy as well as lower number of times beam left. In addition, HeadJoystick showed slight (but only marginally significant) advantages compared to the Controller in terms of more popped and less missed targets.

Figure 4.3 shows the comparison between interfaces in terms of absolute motion sickness, navigational task load, and overall task load as well as their sub-components. These results show a similar pattern of consistent advantages of walking over all interfaces, except physical demand which was higher for walking compared to both Controller and HeadJoystick. NaviBoard showed a similarly increased physical demand compared to the Controller and HeadJoystick. As for other task load sub-components, compared to the controller, using NaviBoard improved user ratings for their overall performance and slightly (but only marginally significant) improved navigational performance ratings as well as reduced overall mental demand. Compared to the Controller, using HeadJoystick reduced overall mental load and improved performance ratings while reducing total nausea. Compared to the Controller, HeadJoystick also showed a marginally reduced overall temporal demand and frustration as well as significantly increased navigational performance ratings (see Figure 4.3).

The effect of repeated interface usage on performance: ANOVA results showed significant main effects of repetition (aka trial) on all performance measures (cf. Table 4.2), and pairwise planned contrast tests showed significant improvement with each successive trial. Together with the lack of any significant interaction between trial and interface, trial and level, or trial and interface and level, this indicates that repeated interface usage over three trials improved performance similarly for all four interfaces, and did not significantly modify the observed main effects of interface, level, or their interaction.

The effect of difficulty level on performance: Difficulty level showed significant main effects on all behavioral measures, and significant interactions between interface and difficulty level for all but the popped/missed targets measures, cf. Table 4.2. As illustrated in Figure 4.4, performance decreased as predicted with increasing difficulty level, but slightly differently for each interface. We were specifically interested in comparing interfaces between subsequent levels, and investigating the influence of single-task vs. dual-task (level 0 vs. 1), rotational speeds (level 2 vs. 3) and translational speeds (level 1 vs. 2 and 3 vs. 4) on performance measures. The following paragraphs address these individual questions.

The effect of interface on performance in level 0 when participants are not moving: As participants did not move in level 0, one might expect that they should perform similarly for all interfaces. However, pairwise comparison (i.e., planned contrasts) between interfaces showed that using more embodied interfaces (and in particular walking) improved performance compared to less embodied interfaces already in level 0. That is, compared to the NaviBoard, Walking showed significantly improved total accuracy score ($p = 0.005$), locomotion score ($p < 0.001$), as well as slightly (but only marginally significant) higher number of popped targets ($p = 0.078$). Comparing NaviBoard versus HeadJoystick in level 0 showed no significant differences for any performance measures, but HeadJoystick showed slightly (marginally significantly) improved total score ($p = 0.068$) compared to the Controller. Potential reasons for these results are discussed in Section 4.7.1.

The effect of locomotion on object interaction performance: We conducted 4×2 repeated-measures ANOVAs for the independent variables interface {Controller, HeadJoystick, NaviBoard, Walking} and level {0, 1} on all behavioral measures. Significant main effects of level on all performance measures showed that adding locomotion for level 1 reduced all performance measures (cf. Figure 4.4, all $p's < 0.001$). However, as illustrated in Figure 4.4 this performance decrease tended to be more pronounced for less embodied interfaces. This is corroborated by significant interactions between interface and level for all behavioral measures (all $p's < 0.014$) except popped targets ($p = 0.052$) and missed targets ($p = 0.076$), which both showed marginally significant trends.

The effect of increasing (doubling) translational speed on performance: We conducted 4×2 repeated-measures ANOVAs for independent measures of interface {Controller, HeadJoystick, NaviBoard, Walking} and level {1, 2} on all performance measures. Our results showed that increasing (doubling) translational speed between level 1 and 2 lead to an overall performance deterioration (main effect of level, cf. Figure 4.4), for all measures (all $p's < 0.008$). As illustrated in Figure 4.4, this performance reduction for increasing translational speed was more pronounced for the less embodied interfaces (and in particular the controller). This trend was corroborated by a significant interaction between interface and difficulty level for locomotion measures including the number of times beam left ($p = 0.042$), time percentage outside beam ($p < 0.001$), and marginally significant for locomotion score ($p = 0.076$). Planned contrasts further showed that increasing translational speed between level 1 and 2 decreased performance over one, four, and six (out of seven) measures when using Walking, HeadJoystick/NaviBoard, and Controller, respectively (cf. Figure 4.4).

Further increasing translational speed between level 3 versus 4 showed overall similar performance deterioration (cf. Figure 4.2) and significant main effects of level for all measures except interaction score and popped targets (all $p's < 0.01$). Although this performance decrease when translating faster seemed more pronounced for the less embodied interfaces compared to the walking condition (where pairwise comparison showed no significant deterioration, see Figure 4.2), the interaction between interface and level did not reach significance for any performance measure.

The effect of increasing (doubling) rotational speed on performance: We conducted 4×2 repeated-measures ANOVAs for the independent variable interface {Controller, HeadJoystick, NaviBoard, Walking} and level {2, 3} on all performance measures. All ANOVAs results showed significant main effects of level (all $p's < 0.039$), indicating that all performance measures were significantly deteriorated when rotational speed was increased from level 2 to 3. These main effects were qualified by significant interactions between interface and level for total score and locomotion measures (all $p's < 0.035$). Figure 4.4 and the planned contrasts show that walking performance remained at the overall highest levels despite the rotational speed increase and did not decrease significantly. However, HeadJoystick and NaviBoard performance did decrease for several performance measures but remained overall above Controller performance. These were all performance measures except the missed targets for NaviBoard, and three measures for HeadJoystick including locomotion score, overall score, and the time percentage outside beam. Controller performance was already at the lowest level of all interfaces and did not decrease further significantly when rotational speeds were doubled.

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

4.7 General Discussion

This paper presents the first study exploring the effects of providing partial translational self-motion cues for HMD-wearing users in a simultaneous locomotion and object interaction task. Extensive research on leaning-based interfaces when using HMDs (Cherni et al., 2020) often investigated locomotion-only tasks. Thus, there is limited knowledge of their effects in multi-tasking situations, where users need to interact with the environment during locomotion. Moreover, despite extensive research on how providing rotational embodied self-motion cues affects locomotion (Ruddle, 2013), there is little understanding of how providing translational embodied self-motion cues affect locomotion either in locomotion-only tasks (except (Nguyen-Vo et al., 2019)) or multi-tasking situations. To tackle these gaps, we explored how using different levels of translational body-based self-motion cues using leaning-based interfaces can affect locomotion and/or interaction performance in simultaneous locomotion and object interaction tasks. Overall, our results showed that providing higher levels of translational body-based self-motion cues improve user experience, usability, and effectiveness measures. That is, providing full physical self-motion cues in the Walking condition showed conclusive advantages over all other conditions. Moreover, compared to a hand-held controller, providing more physical self-motion cues in HeadJoystick and especially NaviBoard improved effectiveness, usability, and user experience factors. In the remainder of this section, we discuss the findings of our experiment in the context of our main research questions.

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

Overall, the results confirmed our hypothesis: While physical walking performs the best, providing partial translational self-motion cues using NaviBoard and HeadJoystick improves most effectiveness measures over Controller for both locomotion and object interaction measures (cf. bottom row of Figure 4.2). These findings corroborate recent user studies that reported adding different levels of embodied cues improve performance in a navigational search task (Nguyen-Vo et al., 2019). Our study provides the first experimental evidence that those benefits can be extended to simultaneous tasks of locomotion and object interaction. While recent research showed that seated (i.e., NaviChair) and standing (i.e., NaviBoard) leaning-based interfaces performed almost comparable to walking (Nguyen-Vo et al., 2019), our findings showed a significant performance advantage of walking over all other interfaces. A potential reason for this include the dual-task of moving and interacting, other task differences, and the different difficulty levels in our study design. Overall, our findings suggest that although leaning-based interfaces outperform hand-held controllers, they might not be as good as walking, at least for more complex dual-tasks.

Our findings regarding higher effectiveness of HeadJoystick over Controller corroborate to recent research that reported improved locomotion effectiveness of HeadJoystick when compared to the Controller in locomotion-only tasks (Buttussi and Chittaro, 2019; Hashemian et al., 2022b,b). These findings provide the first experimental evidence that the benefits of providing partial self-motion cues are not limited to locomotion performance, but are able to either directly or indirectly improve object interaction performance in simultaneous tasks of locomotion and object interaction. A potential reason for why prior research on embodied interfaces using multi-tasking scenarios did not show such findings (Beckhaus et al., 2005b; McMahan et al., 2012; Griffin et al., 2018; Prithul and Berhe, 2021) could be because our task really forced users to navigate and interact with objects at the same time. However, in those prior studies, the users could at least in theory switch between locomotion and object interaction task, which might explain why object interaction performance did not significantly deteriorate with the added locomotion task. Prior studies that compared leaning-based interfaces with handheld interfaces in multi-tasking scenarios also reported lower effectiveness of leaning-based interfaces compared to the handheld controllers (Beckhaus et al., 2005b; McMahan et al., 2012). A potential reason for these contradicting results could be due to using mouse and keyboard instead of thumbstick. That is, while mouse and keyboard provide higher accuracy compared to a thumbstick (Natapov et al., 2009), they are not easily usable when wearing an HMD. Another potential reason for these contradicting results could also be due to our design considerations (such as providing tactile feedback for the zero-point) for improving the effectiveness of our leaning-based interface prototypes (i.e., HeadJoystick and NaviBoard) as discussed in Section 4.5.4.

Our findings regarding higher effectiveness of embodied interfaces over Controller for HMD-wearing users in multi-tasking scenarios also contradict prior research that used head-directed steering, where the user controls simulated self-motion by rotating their head (Griffin et al., 2018; Prithul and Berhe, 2021). However, unlike leaning-based interfaces, head-directed steering does not require the user to move their head toward the target direction. Therefore, using head-directed steering does not provide translational vestibular cues aligned with the virtual self-motion, which are known to improve locomotion believability and reduce motion sickness. Moreover, head-directed steering does not allow the user to freely look around during locomotion - section 8.5.1 of (Bowman et al., 2017), section 11.2.2.1 of (Steinicke et al., 2013), and section 28.3.2 of (Jerald, 2016). In contrast, HeadJoystick and NaviBoard allowed users to freely rotate their head to look around without affecting virtual self-motion. In fact, to ensure that head rotation does not affect locomotion when using HeadJoystick and NaviBoard, we used the movement of the head's rotation center (instead of the HMD) to control locomotion when using HeadJoystick and NaviBoard - see HeadJoystick design details in the appendix of (Hashemian et al., 2022b,b).

How does repeated usage of interfaces affect performance? Our findings corroborate recent user studies that showed that the performance advantage of leaning-based interfaces over the Controller does not decline over repeated usage (Hashemian et al., 2022b,b). However, unlike those earlier studies, where the performance advantages of HeadJoystick over controller became more prominent over time, repeated interface usage in this study improved performance similarly for all interfaces. A potential reason for that could be due to having less repetitions in this study (i.e., three) compared to the earlier studies (i.e., eight), which might not give users enough time to show learning benefits for the novel (leaning-based) interfaces. That is, they might have still been preoccupied with learning the (rather challenging) dual-task with not enough time to improve interface usage. Otherwise, we would expect higher performance improvement for less familiar interfaces such as HeadJoystick and NaviBoard compared to more familiar interfaces such as walking and Controller.

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

How does object interaction with locomotion compare to interaction without locomotion? As expected, performance levels dropped by almost 50% when users had to switch from an object-interaction-only task in Level 0 to a simultaneous multitasking of interaction and locomotion in level-1 (cf. Figure 4.2), presumably due to increased mental/task load. The significant interaction between interface and trial for every performance measure between level 0 versus 1 suggests that the performance cost of multitasking was more pronounced for less embodied interfaces. A potential reason for such findings could be that less embodied interfaces in our study required more mental resources due to their higher overall mental demand (cf. Figure 4.3-top). In particular, the controller seems to have required additional mental resources, especially for the dual-task, as corroborated by participants' exit interview feedback: E.g., *"using your head to look and move when using HeadJoystick is easier than to use your head for looking and your thumb to move."*(p9)) or *"Controller required me to control moving my head, arm sword, joystick finger, and chair, which was too many things to control"*(P17). Interestingly, comparing Controller with HeadJoystick/NaviBoard in terms of navigational mental demand did not show a significant difference (cf. Figure 4.3-bottom). This could be because the locomotion task alone might not require much mental load as the path was smooth and predictable (by design) and locomotion speeds were fairly slow (i.e., 0.15-0.3 m/s). Further, separating tasks over separate hands could be another potential reason for the lower effectiveness of handheld over leaning-based interfaces (LaViola et al., 2001) as *"It is confusing to use my left hand to move and right hand to hit targets."*(P10). The typically lower performance of the non-dominated hand when using the Controller could also have contributed (van Mier, 2006).

Our findings are noteworthy as this study provides (from all we can tell) the first empirical evidence that using hands for controlling navigation is detrimental to performance when also having to interact with objects. While prior research has claimed that overloading hands for navigational functionality is detrimental to performance when also performing other tasks (LaViola et al., 2001), previous studies often did not show significantly reduce object interaction performance when using hands to control navigation (Griffin et al., 2018; Prithul and Berhe, 2021). A potential reason for our contradicting results could be that unlike the tasks in these previous studies, our task forced the users to use navigation and object interaction at the same time instead of allowing users to switch between them.

How does increasing (doubling) translational speed affect performance? Increasing (doubling) translational speed further widened the performance differences among our interfaces. Interestingly, it also significantly deteriorated the object interaction measures for the Controller but not other interfaces. A potential reason could be increased cognitive load of the Controller, which was rated as overall more mentally demanding (cf. Figure 4.3-top). As P21 explained it, *"it was not easy to use controller for multiple tasks. So, controller might be perfect for less accurate tasks, which you don't want to move your* *body a lot"*. Thus, when using embodied interfaces, increasing translational speed in level 2 still allows the user to keep performing the object interaction task with a non-significant performance decrease. P9 further provided body vs. hand/finger movements as additional potential underlying reasons: *"Using our physical body to move is easier than a controller, as I have more control over my physical body."* This is aligned with prior research that also reported enhanced intuitiveness (Beckhaus et al., 2005a; Freiberg, 2015; Hashemian et al., 2022b, 2021) and reduced cognitive load (Nguyen-Vo et al., 2019) of leaning-based interfaces compared to the Controller. Thumbstick sensitivity could be another contributing factor to the disadvantages of Controller compared to other interfaces, as P15 said *"Perhaps, because of the small range of controller thumbstick motion range, I always overshoot beam and so to stay at the center of the beam, I went forward and backward again and again."* Similar sensitivity issue of the controller for accurate movements have been reported by the participants in our prior user studies (Hashemian et al., 2022b, 2021).

How does increasing (doubling) rotational speed affect performance? When rotational speed increased (doubled) in level 3, most performance measures (6 out of 7) were reduced for HeadJoystick and NaviBoard but not for Controller or Walking (cf. Figure 4.4). As for the controller, most performance levels were already at a very low level and did not decrease further. For example, participants popped very few (3.5-4 out of 24) targets using Controller after level 2, where one third of participants popped less than one target on average (i.e., less than 5% of targets). However, for the leaning-based interfaces, participants still managed to pop 6.75 (out of 24) targets at level 2, which was significantly reduced to 4.9 (out of 24) targets at the most difficult level 4. The Walking interface showed a slight but non-significant decrease on all performance measures and stayed at a much higher level. Even at the most difficult level, walking participants were still able to pop 8.9 (out of 24) targets, which was more than twice as many as for the Controller.

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

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

How does providing partial self-motion cues affect user experience? In contrast to our work, prior studies on simultaneous locomotion and object interaction tasks only investigated leaning-based interfaces for VR applications on projected screens (Beckhaus et al., 2005b; McMahan et al., 2012), not HMDs. Moreover, these prior studies often only measured a few introspective aspects. They reported limited benefits of leaning-based interfaces over controller including increased enjoyment (Beckhaus et al., 2005b), improved usability, and presence (McMahan et al., 2012). Our findings corroborate these enjoyment and presence benefits of the leaning-based interfaces and extend these benefits to other user experience measures, namely vection intensity, motion sickness, task load, and overall preference. Similar benefits have previously been reported for leaning-based interfaces in locomotion-only tasks (Kruijff et al., 2016; Riecke, 2006; Riecke et al., 2008; Riecke and Feuereissen, 2012b; Rognon et al., 2018; Nguyen-Vo et al., 2019; Adhikari et al., 2021a; Hashemian et al., 2022b). Our findings extend these benefits beyond locomotion-only tasks to simultaneous locomotion and object interaction tasks, which is relevant for numerous applications where users' goal is not just to locomote, but also interact with their environment or other people.

In post-experiment interviews participants provided several potential reasons for the user experience advantages of HeadJoystick and NaviBoard over the Controller, corroborating and extending earlier findings (Hashemian et al., 2022b, 2021). Reasons mentioned include more natural body movements: *"Head movement was more natural than the controller"*(P19) and NaviBoard *"had more movement than HeadJoystick and Controller, which made me more energized"*(P8). Furthermore, P14 stated that *"NaviBoard was pretty much same as walking, and I could feel my whole body and feel the environment more. It feels more like a reality to me."*. Prior research stated that such levels of exertion could be enjoyable and motivating for users (Müller and Apps, 2019). Another reason offered by participants is the alignment of head translation direction (and associated vestibular and proprioceptive cues) with the resulting simulated translation when using head-based leaning-based interfaces: P14 explained that *"using HeadJoystick, I could move my head and upper body (rather than only my finger when using controller) to feel actually traveling in the virtual reality. Controller does not feel like VR, its like playing a desktop game."*. Increased fun/enjoyment of natural interfaces over Controller thumbstick have been reported in prior research (Marchal et al., 2011; Harris et al., 2014; Kruijff et al., 2016) and chapter 4 of (McMahan, 2011).

How does providing partial self-motion cues affect usability measures? In contrast to our work, our previous user studies showed subjective benefits of HeadJoystick over Controller in almost all user experience and usability measures (Hashemian et al., 2022b,b). Such contradicting results can have a combination of responsible factors. For example, we implemented controller-directed steering for the Controller condition, where the forward direction was determined by the yaw direction of the Controller (instead of body/chair). Using a similar controller-directed steering approach in one of our previous user studies showed non-significant differences with HeadJoystick in terms of vection intensity, ease of learning, task load, and potential for daily and longer-term usage (Hashemian et al., 2022b). Another potential factor could be the fairly small range of the locomotion speeds (i.e., 0.15-0.8 m/s), which does not reveal the usability issues (i.e., sensitivity) of the thumbstick for accurate speed control (Hashemian et al., 2022b,b). Another potential reason could be because the task got quite hard for all conditions except walking at the last level, and none of other conditions were comparable with walking, which can be the reason participants rated the usability of other conditions not much different.

Participants also suggested other factors for the improved usability of the Controller: *"Controller is familiar for me due to regular games"*(P24) especially for participants with *"extensive game console experiences"*(P13); Controller's thumbstick *"automatically comes back to its center."*(P5); and controller does not require much physical effort (cf. Figure 4.3) as *"I did not need to use my body to move when using Controller"*(P20).

Overall, our results showed that while leaning-based interfaces can improve user experience and performance compared to the controller-based interfaces, further research is needed to better understand and improve their usability to be ready for daily use as an alternative to Controllers. Our previous works also showed the weakest advantage of HeadJoystick compared to the Controller in terms of the long-term and daily use (Adhikari et al., 2021a; Hashemian et al., 2022b,b).

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

Overall, the results confirmed our hypothesis: while the NaviBoard mostly showed non-significant trends for performance and user experience advantages over HeadJoystick, using NaviBoard instead of HeadJoystick showed more significant benefits over Controller (cf. Figure 4.2). In the following paragraphs, we discuss the seated vs. standing/stepping body posture in terms of different measures such as effectiveness, motion sickness, and naturalness.

When comparing leaning-based interfaces, how does standing/stepping vs. sitting on a chair affect effectiveness? Prior research often suggested higher accuracy/precision of seated over standing leaning-based interfaces (Zielasko and Riecke, 2021). However, our results showed that accuracy/precision of leaning-based over controller can be improved if designed for a standing/stepping instead of a seated user. A potential reason behind the more apparent effectiveness benefits of NaviBoard over HeadJoystick could be the larger (i.e., doubled) motion range and thus enhanced translational vestibular/proprioceptive self-motion cues of NaviBoard compared to the HeadJoystick, which might have contributed to a more accurate control of the NaviBoard. Standing body posture could also help the interaction effectiveness due to the larger hand movement range when following a vertically moving target in a standing instead of seated body posture. However, such difference should provide effectiveness advantages for the NaviBoard over HeadJoystick even in level 0 with no locomotion, which our results did not show Figure 4.4. Some participants also found NaviBoard to be more intuitive than HeadJoystick. As P12 said, *"slight touch of walking felt better than Controller and HeadJoystick, because it made the control much easier."*

When comparing leaning-based interfaces, how does standing/stepping vs. sitting on a chair affect motion sickness? Prior research showed more severe motion sickness when using handheld controllers in standing (instead of sitting) posture (Merhi et al., 2007). This was attributed to the postural instability theory (Riccio and Stoffregen, 1991), which predicts increased motion sickness in unstable body postures such as standing over seated interfaces. However, in our study we found the opposite trend: while both leaning-based interfaces showed a trend towards reducing motion sickness compared to the (seated) controller, this benefit was more pronounced and reached significance for the standing/stepping (NaviBoard) but not the seated (HeadJoystick) interface. This confirmed the findings in a previous NaviBoard study (Nguyen-Vo et al., 2019). As motion sickness can accumulate across repeated sessions in within-subject designs, we also show the absolute motion sickness scores and sub-components in Figure 4.3. These absolute scores corroborate post-pre motion sickness results by showing an overall similar pattern for reducing motion sickness when providing higher levels of embodied self-motion cues, where using HeadJoystick significantly reduced absolute nausea scores when compared to the Controller. A potential reason for this could be that standing/stepping leaning-based interfaces (such as NaviBoard) are more natural compared to the seated ones (such as HeadJoystick) as they are more similar to actual walking in a limited area, and provide additional proprioceptive and vestibular self-motion cues aligned with the virtual translations, thus reducing sensory conflicts and motion sickness - and maybe even postural instability.

When comparing leaning-based interfaces, how does standing/stepping vs. sitting on a chair affect naturalness? Our results corroborated the previously reported benefits of standing over seated interfaces in terms of more intense vection, higher engagement, and higher degrees of embodiment (Zielasko and Riecke, 2021). For example, compared to the HeadJoystick, NaviBoard provided a more similar experience to Walking due to its standing body posture, as P9 said *"NaviBoard's standing position helps to feel I am in the interface, which is better than to be seated in a chair"*. Standing body posture when using NaviBoard provides motion cues for the whole (instead of upper) body when using HeadJoystick, which can improve presence/immersion and vection intensity as P21 explained *"NaviBoard was more accurate than the Controller, and more immersive as it was like a standing version of walking"*(P21). Stepping also improved NaviBoard's believability as it was *"like walking in a smaller area"*(P19), and *"NaviBoard felt more natural than HeadJoystick, and was like walking"*(P6).

How to improve usability aspects of standing/stepping leaning-based interfaces (i.e., NaviBoard)? Participants also suggested usability issues of the NaviBoard, which could be the potential reasons for why NaviBoard did not show significant advantages compared to the HeadJoystick, and could help to improve NaviBoard in future design iterations. For example, future design iterations might need to improve awareness of the zero-point as *"when I put both my feet on Styrofoam during fast rotations, I lost the zero-point."*(P15). Improving postural stability, intuitiveness, and perceived safety are additional design challenges for NaviBoard as participants reported *"as my feet did not automatically know how to always follow my head"*(P17) and *"once a while I was afraid to lose my balance."*(P22) specifically during rotations or in corners. For example, P17 said *"while moving forward, when the path rotated to the right, I started changing my direction by leaning a bit to right but forgot to adjust my feet, which then I felt like I am about to stumble."* and P10 said *"my foot just moving around and got in the way especially in the corners, and I did not know what to do with my feet."*.

Despite the aforementioned usability issues, from an applied perspective, our findings and recent research (e.g., (Nguyen-Vo et al., 2019)) suggest using standing/seated (instead of seated) leaning-based interfaces for natural simulation of physical walking in VR applications. However, due to the increasing accuracy and affordability of inside-out HMD tracking, free-space walking is becoming increasingly feasible and often preferred whenever there is sufficient free space that is safe for walking. However, the space that can be freely walked is often limited, and for larger distances users tend to prefer/require virtual locomotion due to reasons such as reduced travel times, effort, and fatigue. Therefore, combining free-space walking with leaning-based interfaces is a potentially fruitful avenue for future research, and we are actively working on this integration. For example, such integration can happen by switching between leaning-based interfaces and walking when pressing a designated button on a controller, using gestural or voice input depending on the context and technical options.

Seated leaning-based interfaces can also be used in scenarios where standing posture leads to fatigue and discomfort (such as long-term walking scenarios) or when there is an increased risk of falling due to large virtual accelerations (e.g., roller-coaster applications) (Badcock et al., 2014). Seated leaning-based interfaces can also be used by users who are unable to stand (e.g., wheelchair users), those that prefer to sit (Zielasko and Riecke, 2021), or when sitting better matches the locomotion metaphor (e.g., driving or flying).

4.7.4 Limitations

Due to the complexity of our tasks, our locomotion task required participants to move forward fairly slowly, and did not require much backwards or sideways motions, which could limit generalization of our findings to other types of locomotion tasks. Thus, future studies could assess how our results might generalize to other types of locomotion with faster speeds such as fast walking, running, or driving/flying speeds. As for the interfaces, participants' familiarity with using thumbstick (but not NaviBoard/HeadJoystick) could affect our results, and might have reduced potential effects. Future studies could also investigate generalizability of our results to other multi-tasking scenarios such as exploration, relative positioning (e.g., capturing photo), navigational search, and FPS games, which require designing other interaction mechanisms for leaning-based interfaces such as jumping/crouching. As for participants, our sample size (24) and statistical power might not be large enough to detect subtle effects, and thus we also reported marginally significant effects ($.05 < p < 0.1$). Further splitting participants based on demographics could be the reason why participant demographics did not show any significant effects on our results. Therefore, future studies with larger and more diverse participant populations are needed to find more conclusive answers. As for measures, while we assessed a wide set of locomotion-relevant measures in our study, our tasks was not designed to assess other constructs such as information gathering potential, spatial/situational awareness, or spatial orientation in simultaneous locomotion and object interaction tasks. Future works can also investigate how our findings might or might not generalize to different tasks, scenarios, and setups, and in particular if future design iterations might be able to improve the ergonomics and performance of hand-held controllers, hand-gestures, or hand-movements.

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

4.8 Conclusion

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

As far as the authors know, this work is the first study investigating leaning-based interfaces in an HMD-based dual task of simultaneous locomotion and object interaction. Furthermore, our findings contradict prior research investigating leaning-based interfaces in multitasking scenarios on projection screens (Beckhaus et al., 2005b; McMahan et al., 2012), by showing that using more embodied locomotion interfaces such as HeadJoystick and NaviBoard over Controller improves locomotion effectiveness and user experience measures. Moreover, while the previous research often measured only overall performance measures (such as number of kills in a FPS game), our newly designed paradigm of a gamified locomotion and object interaction task distinguished performance in locomotion versus object interaction and showed that providing higher levels of self-motion cues improves not only locomotion but also interaction effectiveness. Overall, our findings extend the effectiveness of leaning-based interfaces beyond locomotion-only tasks (Hashemian et al., 2022b,b; Nguyen-Vo et al., 2019) to simultaneous locomotion and object interaction tasks.

4.9 Author Contributions

AH and BR conceived the main idea of the article. AH and BR conceived and developed the technical setup including interfaces and tasks, while AA, IA, EK, and MvdH provided comments and suggestions to improve them. AH collected all data. AH and AA carried data analysis. AH wrote the first draft of the manuscript, while AA, IA, EK, MvdH, and BR contributed to the writing of the manuscript in many stages including giving feedback and suggestions regarding the issues related to the grammar, rhetoric, literature, arguments, and even rewriting of the major parts of the paper (in particular BR). BR supervised the entire work. All authors contributed to the manuscript, read, and approved the final version.

Chapter 5

Discussion and Conclusion

This thesis contributes to the design and evaluation of VR locomotion interfaces. While a large body of literature has been investigating the effects of providing embodied self-motion cues on locomotion (Steinicke et al., 2013; Boletsis, 2017; Cherni et al., 2020), most previous embodied locomotion interfaces have been evaluated in only one locomotion scenario and in terms of a small subset of locomotion-relevant measures with a few exception, e.g., (Buttussi and Chittaro, 2019). Therefore, we do not fully understand if their disadvantages can be improved with iterative interface refinement and their benefits generalize to a wider range of locomotion scenarios. To address this gap, first we designed an affordable embodied locomotion interface - called HeadJoystick (see Appendix A), which provides vestibular and proprioceptive self-motion cues for most VR users in a wide range of locomotion scenarios. My colleagues and I did so by iteratively designing, testing, and improving various interface prototypes using informal pilot-testings as well as four formal user studies as described in Section 1.2.2 (Kitson et al., 2015, 2017a; Hashemian and Riecke, 2017b,a). In addition, to thoroughly understand how using such a leaning-based interface (i.e., HeadJoystick) affects locomotion-relevant measures, we extended prior evaluation frameworks such as the work by Bowman and colleagues (Bowman et al., 1997, 1998, 1999; Bowman, 1999; Bowman et al., 2017) as discussed in Section 1.3.

Then, we investigated the effects of providing vestibular and proprioceptive self-motion cues using HeadJoystick based on our extended evaluation framework compared to handheld interfaces in a wide range of locomotion scenarios using eight user studies (Hashemian et al., 2022b, 2021, 2022a; Adhikari et al., 2021a, 2022). Six of these user studies are presented in Chapter 2, Chapter 3, and Chapter 4, which evaluated HeadJoystick in 3D (flying) and 2D (ground-based) locomotion-only tasks as well as simultaneous locomotion and interaction tasks, respectively. These six user studies allowed us to investigate adverse effects of handheld interfaces in terms of unconvincing motion and motion sickness, but not disorientation as our tasks only required very basic spatial orientation. Later, my colleagues conducted two more user studies with myself as a co-author to investigate how providing embodied self-motion cues for 3D (Study 5.1) and 2D (Study 5.2) locomotion using HeadJoystick versus controller affects spatial orientation and other aspects in our expanded evaluation framework.

Study 5.1 and 5.2: Study 5.1 used a 3D (flying) navigational search task for hidden target objects and showed HeadJoystick benefits in terms of most measures except potential for long-term and frequent daily usage, as using HeadJoystick could be more physically fatiguing after a long use (Adhikari et al., 2021a). Study 5.2 asked users to follow a path and then point toward previous positions (Adhikari et al., 2022). The results showed reduced disorientation of HeadJoystick compared to the handheld controllers but did not show significant differences in terms of any user experience and usability measures in terms of our extended evaluation framework. In this study, we also assessed new measures besides our extended evaluation framework. These were ease of navigation around the play area, precise control over movements, efficacy and stability for motion control, ease of concentration on the task, involvement and engagement, muscle relaxation, and comfortable sitting posture. Our findings regarding these measures showed significant advantages of using handheld controllers compared to the HeadJoystick: easier concentration on the task, higher relaxation of muscles, and more comfortable sitting posture.

Overall, our eight user studies addressed our research questions regarding (dis)advantages of providing embodied self-motion cues for a wide range of scenarios (RQ1) and how they would differ in specific situations (RQ2) as detailed in Section 1.1. In this final chapter, first, we revisit these research questions based on our findings. Then we discuss design guidelines and insights that emerged from our findings as well as limitations of our research and some suggestions for future work.

5.1 Revisiting Research Questions

5.1.1 RQ1: How does providing embodied self-motion cues affect user experience and performance, and how do these effects differ in different locomotion scenarios?

Prior research often reported a wide range of effects when evaluating embodied versus handheld locomotion interfaces. These effects include improved spatial orientation (Harris et al., 2014; Nguyen-Vo et al., 2019), reduced motion sickness (Nguyen-Vo et al., 2019), more intense vection intensity (Kruijff et al., 2016; Riecke, 2006; Riecke and Feuereissen, 2012a), improved presence/immersion (Marchal et al., 2011; Freiberg, 2015), improved enjoyment/fun (Kruijff et al., 2016; Marchal et al., 2011)), reduced accuracy (Beckhaus et al., 2005a; Marchal et al., 2011; McMahan et al., 2012; Pittman and LaViola, 2014; Freiberg, 2015; Griffin et al., 2018), reduced ease of use (Buttussi and Chittaro, 2019), and reduced ease of learning (Kruijff et al., 2016; Zielasko et al., 2016). However, most of these studies evaluated a different interface in each locomotion scenario using a different set of locomotion-relevant measures. Therefore, we do not fully understand if providing vestibular and proprioceptive self-motion cues can reduce adverse effects of using handheld interfaces (unconvincing simulated motion, motion sickness, and disorientation) while improving or at least matching most other locomotion-relevant measures in a wide range of locomotion scenarios. To address this gap, we designed and conducted eight user studies to thoroughly evaluate the same interface (i.e., HeadJoystick) in terms of the same measures (i.e., our extended evaluation framework) in a wide range of locomotion scenarios. In this section, first we discuss the locomotion scenarios and their underlying processes in each user study and then discuss their results in the context of prior research.

In Chapter 2, we investigated providing embodied self-motion cues for 3D locomotion (RQ1.1) using HeadJoystick in two user studies (Study 2.1 and 2.2) using a novel task of fly through a sequence of increasingly narrow tunnels in the sky. We designed this task as a combination of reach the target (next tunnel in the sky) task and follow the path (inside that tunnel) task. This task requires underlying processes such as basic spatial awareness (finding the entrance of the next tunnel), maneuvering (flying through tunnels), and path integration (integrating the paths inside and outside tunnels). Our task was designed for ecological validity and applicability over real-world locomotion scenarios such as drone-racing, pipe inspection, virtual tourism (Mirk and Hlavacs, 2015), and search and rescue through wrecked buildings (Lima, 2012; Stepanova et al., 2017).

In Chapter 3, we investigated providing embodied self-motion cues for 2D locomotion using HeadJoystick in three user studies using three complimentary ground-based locomotion tasks (reach-the-target, follow-a-path, and a complex dynamic obstacle avoidance racing) designed to particularly measure accuracy and precision. In our reach-the-target task, users were asked to reach as many targets as possible, where the targets become increasingly smaller. We showed five targets at the same time in this task to require underlying processes such as basic spatial awareness when finding all targets, path-planning when reaching them all as fast as possible, path integration when efficiently integrating paths to different targets as well as precise locomotion to reach small targets. In our follow-the-path task, users were asked to follow a curvilinear path becoming increasingly narrow. This task requires maneuverability and precise locomotion through the path. For the racing (driving) task, participants were asked to overtake moving target vehicles without crashing into them or going off the road. This racing task requires underlying processes such as predicting obstacle movements, path planning, precise control of forward/backward and strafing velocity to overtake obstacles, as well as maneuvering when avoiding obstacles.

In Chapter 4, we evaluated HeadJoystick and a standing version of it (NaviBoard) in a simultaneous locomotion and object interaction task. In this task, users were asked to follow a horizontally moving platform (i.e., beam) and stay as close as possible to its center while touching the center of vertically moving target balloons with their virtual lightsaber to pop them. This task requires underlying processes of basic spatial awareness to find the beam path, and maneuvering to stay at the center of the beam during locomotion. In addition, performing a simultaneous object interaction task requires splitting attention between two tasks (Charron and Koechlin, 2010) with underlying processes of basic spatial awareness to find targets and precisely intersecting with their center.

Our results showed that using HeadJoystick to provide embodied self-motion cues for 3D (Study 2.1 and 2.2) and 2D (Study 3.1 and 3.2) locomotion-only scenarios improved all performance and most (10-11 out of 12) subjective measures. As for the overall preference, 74 (out of 78) participants (95%) in these four studies (Study 2.1, 2.2, 3.1, and 3.2) preferred using HeadJoystick over Controller. As for the Controller condition in Study 2.1, 2.2, and 5.1 we used a standard dual-thumbstick controller (using XBox-1 gamepad). In Study 3.1 and 3.2, HeadJoystick was evaluated compared to the Vive Controller touchpad and Valve-Index Controller thumbstick, respectively, where the forward deflection of the thumbstick/touchpad moved the user toward the direction of their body/chair - called **body-directed steering**. As for our next three evaluation studies (Study 3.3, 4.1, and 5.2), we used a Controller interface - called **controller-directed steering**, where forward deflection of thumbstick moved the user toward the direction of the controller instead of the body/chair. We chose controller-directed steering due to its improved usability compared to body-directed steering in our pilot-testings, despite it only allowing for one-handed (instead of two-handed) interaction with the environment during locomotion (e.g., shooting in FPS games or popping targets in Study 4.1). Controller-directed steering does not provide vestibular self-motion cues aligned with the target direction, and thus we do not consider it as an embodied locomotion interface. However, it provides higher levels of embodiment (proprioceptive cues) because the user needs to aim their hand toward the target direction.

Comparing HeadJoystick with Controller-directed steering in these three user studies (Study 3.3, 4.1, and 5.2) also showed consistent performance benefits of using HeadJoystick to provide embodied self-motion cues. However, these studies showed mixed results regarding user experience and usability advantages of using HeadJoystick over Controller-directed steering. That is, subjective benefits of using HeadJoystick over controller-directed steering reached significance for six, one, and zero (out of 12) subjective measures in Study 3.3, 4.1, and 5.2 respectively. Therefore, while more participants (94% in Study 3.3 and 67% in Study 4.1) in these studies preferred using HeadJoystick instead of Controller, using HeadJoystick showed less subjective benefits compared to the Controller-directed steering.

Our findings regarding benefits of using leaning-based interfaces such as HeadJoystick in 3D flying (Study 2.1, 2.2, and 5.1) corroborate previously reported benefits of embodied flying interfaces. These are speed (Miehlbradt et al., 2018), naturalness and comfort (Rognon et al., 2018) when controlling virtual airplanes or fixed wing UAVs. In addition, our findings generalize these benefits to helicopter or quadcopter control paradigm. Our findings also showed that carefully optimized interfaces such as HeadJoystick could improve most other user experience and usability measures in Table 1.4. These are enjoyment, preference, vection intensity, immersion, ease of use, ease of learning, task load, motion sickness, spatial presence as well as potential for long-term and daily use. Prior research reported mixed results regarding the accuracy and usability of embodied flying interfaces. For example, while Pittman and LaViola reported inaccuracy and usability issues of "Head-Rotation" and "Head-Translation" interfaces (Pittman and LaViola, 2014), "torso strategy" (Miehlbradt et al., 2018) improved and "FlyJacket" (Rognon et al., 2018) did not change the flight accuracy compared to the handheld interfaces. However, Study 2.1, 2.2, and 5.1 showed consistent accuracy and usability advantages of using motion cueing interfaces such as HeadJoystick for VR flying. A potential reason for these contradicting results could be because the HeadJoystick became more accurate over the iterative refinement process. That is, both "torso strategy" (Miehlbradt et al., 2018) and "FlyJacket" (Rognon et al., 2018) interfaces control flight velocity using upper-body deflection similar to an early version of HeadJoystick - called Swivel-Chair, which showed no significant benefits in Study 1.2, 1.3, and 1.4. Head-Rotation and Head-Translation also showed usability issues such as incorrect calibration, drifting from the zero-point, and the technical issues of having an actual drone, which could lead to their perceptual instability and inaccurate control (Pittman and LaViola, 2014).

Our findings regarding benefits of using HeadJoystick in 2D locomotion scenarios (Study 3.1, 3.2, 3.3, 4.1, and 5.2) corroborate previously reported benefits of using embodied locomotion interfaces for 2D locomotion. That is, prior research reported that using embodied locomotion interfaces in 2D locomotion scenarios improves spatial orientation (Harris et al., 2014; Nguyen-Vo et al., 2019), Reach-the-Target speed (Buttussi and Chittaro, 2019), enjoyment (Beckhaus et al., 2005b; Marchal et al., 2011), immersion/engagement (McMahan et al., 2012; Freiberg, 2015), presence (Marchal et al., 2011; McMahan et al., 2012; Kruijff et al., 2016; Griffin et al., 2018), vection intensity (Kruijff et al., 2016), and usability (McMahan et al., 2012). Our findings corroborate these benefits when using embodied locomotion interfaces such as HeadJoystick and/or NaviBoard in spatial orientation (Study 5.2 and (Nguyen-Vo et al., 2019)), Reach-the-Target speed (Study 3.1, 3.2, and 3.3), enjoyment (Study 3.1, 3.2, 3.3, 4.1), immersion (Study 3.1, 3.2, 3.3), presence (Study 3.1, 3.2, 3.3, and 4.1), vection intensity (Study 3.1, 3.2, and 4.1), and usability (Study 3.1, 3.2, and 3.3). However, as prior studies reported these benefits for different embodied locomotion interfaces in different locomotion scenarios, our findings shows that all these benefits can be achieved using a carefully optimized embodied locomotion interface such as HeadJoystick or NaviBoard in reach-the-target (Study 3.1, 3.2, and 3.3), follow-the-path (Study 3.1), driving (Study 3.1), and multi-tasking (Study 4.1) locomotion scenarios.

As for the disadvantages of previous leaning-based interfaces in 2D locomotion, prior research reported either no significant difference or a decrease in several measures when comparing leaning-based versus handheld interfaces. These were accuracy (Kitson et al., 2017a; Hashemian and Riecke, 2017a; Beckhaus et al., 2005b; McMahan et al., 2012; Freiberg, 2015), ease of use (Beckhaus et al., 2005b; Freiberg, 2015; Griffin et al., 2018), ease of learning (Kruijff et al., 2016; Zielasko et al., 2016), task load (Griffin et al., 2018), and motion sickness (Kruijff et al., 2016; Griffin et al., 2018; Buttussi and Chittaro, 2019). However, our findings contradict these results by showing that using HeadJoystick or NaviBoard in 2D locomotion reduced motion sickness (Study 3.2, 4.1, and (Nguyen-Vo et al., 2019)) and task load (Study 3.1, 3.2, and 4.1) and improved accuracy (Study 3.1, 3.2, 3.3, 4.1), ease of use (Study 3.1, 3.2, and 3.3), and ease of learning (Study 3.1 and 3.2). A potential reason for these contradicting results could be the usability issues of prior leaning-based interfaces. For example, using NaviChair (Beckhaus et al., 2005a; Freiberg, 2015) reduced usability compared to an early version of HeadJoystick - called Swivel-Chair in Study 1.2 and 1.4. Head-Directed Steering (Griffin et al., 2018) also reduced usability compared to the Swivel-Chair in Study 1.2. The leaning interface in (Buttussi and Chittaro, 2019) was also designed based on Swivel-Chair, which did not reduce motion sickness compared to the controller in Study 1.2, 1.3, and 1.4. Human joystick (McMahan et al., 2012) was a standing leaning-based interface using head tracking similar to the NaviBoard, but without haptic feedback for the neutral/idle zone, which can drift the user from zero-point Pittman and LaViola (2014). Overall, these findings suggest that the accuracy disadvantages of embodied compared to handheld locomotion interfaces could be addressed via iterative interface refinement.

We also provided the potential reasons for the consistent performance benefits of providing embodied self-motion cues in Study 2.1, 3.1, 3.2, 3.3, and 4.1 using the participant answers in the post-experiment interviews. For example, participants' answers in all these studies (Study 2.1, 3.1, 3.2, 3.3, and 4.1) suggested over-sensitivity of the controller's thumbstick for accurate speed control due to its lower movement range of thumb compared to the head movement range using HeadJoystick. The fairly intuitive control of leaning-based interfaces compared to the controller was also mentioned by participants in Study 2.1 and 4.1.

The potential reasons for the mixed subjective advantages of using HeadJoystick compared to controller-directed steering could be due to the differences between these studies. One of these likely reasons can be the difficulty of using a handheld controller for locomotion scenarios in Study 3.3, 4.1, and 5.2. For example, a potential reason for reduced advantages of HeadJoystick over controller in our three later Studies (Study 3.3, 4.1, and 5.2) compared to earlier ones (Study 2.1, 2.2, 3.1, 3.2, and 5.1) could be higher usability of controller-directed steering compared to the body-directed steering due to its higher degree of embodiment. That is, it might be easier and more intuitive to holding the controller toward a target direction in controller-directed steering instead of deflecting the thumbstick when using body-directed steering. If this is the case, then evaluating HeadJoystick versus Controller-directed steering in our prior studies (Study 2.1, 2.2, 3.1, 3.2, and 5.1) should result in reduced advantages of HeadJoystick over Controller-directed steering. That is, while our flying studies (Study 2.1, 2.2, and 5.2) evaluated HeadJoystick versus Xbox gamepad (instead of controller-directed steering) to provide comparable results to similar previous research such as (Miehlbradt et al., 2018; Rognon et al., 2018; Higuchi et al., 2013), future research is needed to investigate HeadJoystick benefits in flying compared to controller-directed steering.

Study 3 used a more difficult locomotion task compared to Study 4.1 and 5.2, which could be a potential reason for the more pronounced advantages of HeadJoystick compared to the controller-directed steering in Study 3.3 compared to Study 4.1 and 5.2. That is, while Study 3.3 required accurate locomotion to reach increasingly narrow targets Study 4.1 required an easy (and slow) locomotion task to allow for easier interaction with the environment during locomotion. Such an easy locomotion task with a fairly small range of speeds (Fuller et al., 2008) did not require accurate thumbstick control, and thus did not reveal the usability issues of the thumbstick (e.g., over-sensitivity) for accurate speed control similar to our previous studies (Study 2.1, 2.2, 3.1, and 3.2). Study 5.2 used the easiest locomotion task in our evaluation studies as it only required participants to simply follow a path without any speed or accuracy requirements. Such an easy locomotion task could be a potential reason for showing significant advantages of controller-directed steering compared to the HeadJoystick in terms of three subjective measures. The potential reasons for the mixed results of Study 3.3, 4.1, and 5.1 and their implications for future research are discussed in more depth at the end of our next research question (RQ2).

We also provided participants' answers in post-experiment interviews to help elucidate potential reasons behind the mixed advantages of HeadJoystick over Controller in terms of user experience and usability. For example, providing vestibular self-motion cues can lead to a fairly realistic experience of being in and moving through the virtual environment according to the participants' answers in all user studies. The similarity between NaviBoard and walking in a limited area as well as between HeadJoystick leaning and riding a skateboard or motorcycle was also mentioned by participants as another potential reason in Study 3.1, 3.2, 3.3, and 4.1. Hands-free locomotion was mentioned as another potential reason for natural locomotion with leaning-based locomotion interfaces in Study 3.1, 3.2, and 3.3. Conversely, participants who preferred using handheld controllers instead of HeadJoystick suggested reasons such as being more familiar with controllers (in Study 2.1, 3.1, 3.2, 3.3, and 4.1) and not leading to much body exertion (in Study 4.1).

Together these findings address our general research question by showing that providing embodied self-motion cues can reduce adverse effects (unconvincing simulated motion, motion sickness, and disorientation) of using handheld interfaces while improve or at least matching other locomotion-relevant measures. That is, as for unconvincing simulated self-motion, our results showed improved believability of locomotion when using HeadJoystick/NaviBoard instead of Controller, which reached significance for more intense perception of self-motion (except in Study 3.3), spatial presence (except in Study 5.1) and psychological immersion (except in Study 4.1). As for motion sickness, our results showed a consistent trend for reducing motion sickness using HeadJoystick/NaviBoard over Controller, which reached significance in Study 2.1, 3.2, 5.1, and Nguyen-Vo et al. (2019). As for disorientation, using HeadJoystick/NaviBoard consistently reduced disorientation in all our spatial orientation studies i.e., Study 5.1, 5.2, and (Nguyen-Vo et al., 2019). However, our results show that these benefits might not yet be enough to substitute controller-directed steering for frequent daily usage in most VR locomotion scenarios. Such results were supported by non-significant differences between our embodied locomotion interfaces (HeadJoystick and NaviBoard) with controller-directed steering in terms of potential for frequent daily usage in Study 3.3, 4.1, 5.1, and 5.2. Such results necessitate further iterative interface refinement for embodied locomotion interfaces such as HeadJoystick and NaviBoard as discussed in Section 5.2.1.

5.1.2 RQ2: How do the effects of providing embodied self-motion cues on user experience and performance differ in specific situations?

Prior research showed mixed results about how providing vestibular self-motion cues affects locomotion in different situations. As an example of these mixed results, our findings in Study 3.3, 4.1, and 5.2 showed different subjective advantages of using HeadJoystick over controller-directed steering in different locomotion tasks. Another example of these mixed results can be seen in prior research that investigated the performance benefits of providing vestibular and/or proprioceptive self-motion cues in spatial orientation tasks (Ruddle, 2013). That is, while some previous studies reported that providing physical rotation without limited translational self-motion cues improves spatial orientation (Farrell and Robertson, 1998; Presson and Montello, 1994; Rieser, 1989; Klatzky et al., 1998; Ruddle et al., 1999) even comparable to actual walking (Riecke et al., 2010), others did not show such significant improvements (Sigurdarson et al., 2012; Sigurdarson, 2014). As we do not fully understand the true reasons behind such mixed results, different factors might be responsible such as interface usage time, locomotion speed, body posture, rotation control, etc. Understanding how these factors can affect (dis)advantages of providing embodied self-motion cues in specific situations helps us to generalize our findings across a wider range of locomotion tasks and factors. We revisit this general research question after revisiting its six sub-questions:

RQ2.1. how does providing embodied self-motion cues affect user experience and performance when using physical vs. virtual rotation? Previous user studies evaluated embodied locomotion interfaces with virtual (Schulte et al., 2016; Miehlbradt et al., 2018; Rognon et al., 2018; Pittman and LaViola, 2014), limited (Beckhaus et al., 2005b; Riecke and Feuereissen, 2012a), and full physical (Marchal et al., 2011; McMahan et al., 2012) rotation. Our early interface prototypes used limited-range physical rotation to prevent problems such as cable entanglement during rotation (Study 1.1 and 1.2). However, participants suggested using full instead of limited-range physical rotation in Study 1.2. Therefore, our later interface prototypes controlled simulated rotation using full 360°

physical rotation Study 1.3, 1.4, and Kitson et al. (2017b) with 1:1 mapping. Comparing the evaluation results for our later versus earlier locomotion interface prototypes showed more pronounced benefits of embodied locomotion interfaces with full instead of limited rotation. For example, using Swivel-Chair with full (Study 1.3) instead of limited (Study 1.2) rotation showed more (eight instead of one) non-significant subjective benefits compared to the Joystick.

Despite the benefits of full rotational embodied locomotion interfaces, full physical rotation might not always be an option for VR users. For example, physical rotation might not be an option due to accessibility issues (e.g., when sitting on a non-rotating chair), usability issues (e.g., when using a wired HMD or projection screen), or simply user preference (e.g., convenience or laziness (Ragan et al., 2017)). Therefore, in Study 2.1, we investigated how using HeadJoystick to provide embodied self-motion cues for 3D (flying) locomotion affects user experience and performance with physical versus virtual rotation. Our results showed that while embodied locomotion interfaces with virtual rotation improve locomotion, such benefits were more pronounced with full physical rotation. That is, using HeadJoystick to provide embodied self-motion cues with full physical (instead of virtual) rotation improved 14 (instead of nine) out of 15 measures.

Our results also showed that while providing both limited translational self-motion cues and physical rotation showed several subjective benefits, neither of them alone might be enough to show these benefits. These were motion sickness, task load, ease of use, ease of learning, potential for daily use, and overall usability. These findings suggest lack of physical rotation can be one of the potential reasons for why prior embodied locomotion interfaces with limited instead of full 360° physical rotation did not improve these aspects. For example, lack of using full 360° physical rotation could be a potential reason why using ChairIO (Beckhaus et al., 2005b), NaviChair (Freiberg, 2015; Kitson et al., 2017a), Head-Translation, Head-Rotation (Pittman and LaViola, 2014), MuvMan, and Swivel-Chair (Kitson et al., 2017a) did not reduce ease of use compared to the handheld interfaces. As another example, lack of full 360° physical rotation could be a potential reason why using Leaning was not easier to learn compared to the Joystick (Kruijff et al., 2016). As for motion sickness, lack of full 360° physical rotation can be a potential reason for why using Leaning (Kruijff et al., 2016), NaviChair (Freiberg, 2015; Kitson et al., 2015, 2017a), MuvMan, and Swivel-Chair (Kitson et al., 2017a) did not reduce motion sickness compared to a handheld controller.

In fact, our findings can be noteworthy for improving the usability of several previous seated embodied locomotion interfaces by allowing for full physical yaw rotation. Some examples are torso-strategy (Miehlbradt et al., 2018), FlyJacket (Rognon et al., 2018), Dragon-riding (Schulte et al., 2016), Wheelchair (Riecke, 2006), Shake-Your-Head (Terziman et al., 2010), and Gyroxus (Riecke and Feuereissen, 2012a). Our findings suggest that using these interfaces with full physical rotation might improve their usability and performance.

In Study 2.1, we suggested that a potential reason for the advantages of full (instead of limited or virtual) rotation could be due to providing full rotational self-motion cues. That is, full rotational motion cues can remove the visual-vestibular cue conflict for yaw rotations, and thus leading to more believable self-motion experiences Chapter 2. In the post-experiment interview of Study 2.1, participants also suggested that full rotational leaning-based interfaces allow for a fairly natural control of both translation and rotation using our body leaning and rotation. In contrast, Leaning-translation (a leaning-based interface with virtual rotation) required controlling simulated translation and rotation using our head and controller, respectively, which might be less natural.

Overall, our findings address this research question by showing more pronounced benefits of full physical rotation instead of limited (Study 1.2) or virtual (Study 2.1) rotation. In addition, our findings showed benefits of using embodied locomotion interfaces with virtual rotation in terms of performance and six (out of 12) subjective measures if full physical rotation is not possible or preferred. Limitations of our research and some suggestions for future work are discussed in Section 5.2.2.

RQ2.2. How does providing embodied self-motion cues affect user experience and performance in short-term vs. repeated-usage? Due to the familiarity of handheld interfaces for users, comparing them with embodied locomotion interfaces in short-term versus repeated interface usage can lead to mixed results due to the learning effects. As this can be a potential reason for prior mixed results regarding the benefits of providing embodied self-motion cues, we decided to compare the short-term versus repeated usage of embodied locomotion interfaces for 3D (in Study 2.1 versus 2.2) and 2D (in Study 3.1 versus 3.2). Previous user studies evaluated embodied locomotion interfaces after 90 seconds (Higuchi et al., 2013; Pittman and LaViola, 2014; Rognon et al., 2018; Miehlbradt et al., 2018) (with a few minutes of prior practice) up to 10 minutes (Marchal et al., 2011; McMahan et al., 2012) of interface usage time. Therefore, we assessed user experience and performance in Study 2.1 and 3.1 after short-term (90 seconds) for 3D and 2D locomotion after a practice round. Then, in Study 2.2 and 3.2, we assessed user experience and performance after eight minutes of repeated interface usage in the same 3D and 2D locomotion tasks.

Our findings in Study 2.1, 2.2, 3.1, and 3.2 showed that using HeadJoystick to provide embodied self-motion cues improve user experience and performance after a short-term usage and retain or even pronounce those benefits after repeated interface usage in both 3D and 2D locomotion scenarios. In addition, Study 3.3 and 4.1 corroborated these results by showing that the performance benefits of using HeadJoystick and NaviBoard would not shrink after repeated usage. Such findings indicate that the short-term benefits of providing vestibular and proprioceptive cues for self-motion generalize to more extended usage, and were not caused by initial novelty or first-exposure effects. A potential reason for showing such fast and steady performance and user experience improvement could be due to the naturalness of embodied locomotion interfaces, which could have contributed to their significant benefits in most our user studies in terms of ease of use (except Study 4.1), ease of learning (except Study 3.3 and 4.1), and task load (except Study 3.3).

Overall our results addressed this research question by showing that using embodied locomotion interfaces such as HeadJoystick and NaviBoard showed benefits after a short-term interface usage, which do not diminish over repeated usage. These findings are specifically interesting as they show that extensive experiences with handheld interfaces are not nearly enough to outperform novel embodied locomotion interfaces with a few minutes of training. These findings also help us to hypothesize that if future embodied locomotion interface prototypes show similar short-term advantages compared to the handheld interfaces in our short-term tasks (e.g., in Study 2.1 and 3.1), these benefits will likely be retained over repeated interface usage (such as in Study 2.2 and 3.2).

From an applied perspective, our findings show that carefully optimizing embodied locomotion interfaces can lead to an alternative for handheld interfaces for both short-term and long-term locomotion scenarios. In addition, such fast and consistent performance benefits of using embodied locomotion interfaces could be helpful in reducing extensive training sessions, which are currently necessary for proficient control of handheld interfaces in 3D locomotion (Miehlbradt et al., 2018). Previous training could actually make the users more comfortable with a locomotion interfaces. For example, previous studies reported benefits of embodied locomotion interfaces mostly for inexperienced users rather than users with extensive gaming experiences (Beckhaus et al., 2005b). Our studies showed a similar pattern, but nevertheless very few of the participants with extensive gaming experience preferred handheld controllers over HeadJoystick or NaviBoard. That is, while 64 participants (53%) in our six evaluation studies (Study 2.1, 2.2, 3.1, 3.2, 3.3, and 4.1) reported playing 3D first-person view video games on PC or consoles on a daily or weekly basis, only seven of these gamers (11%) preferred their highly trained-on interface (i.e., handheld controllers) over HeadJoystick. This means that while users with extensive gaming experience might be more comfortable with using handheld interfaces, embodied locomotion interfaces can still be their preferred interface if optimized carefully.

As for the effects of repeated versus short-term interface usage on benefits of 3D embodied locomotion interfaces, Study 2.2 showed more apparent benefits of HeadJoystick in terms of vection intensity, ease of learning, and task load (ease of use) compared to Study 2.1. That is, using embodied flying interfaces becomes more convincing, easier to learn, and easier to use compared to the handheld controllers after repeated interface usage. These findings are noteworthy as most previous studies evaluated 3D embodied locomotion interfaces only in 90 s (Higuchi et al., 2013; Pittman and LaViola, 2014; Rognon et al., 2018; Miehlbradt et al., 2018). Our findings suggest that these studies might observe more intense perception of self-motion with higher usability (ease of learning and ease of use) of 3D embodied locomotion interfaces compared to handheld interfaces after repeated interface usage.

As for the effects of repeated interface usage on 2D locomotion, Study 3.2 revealed smaller enjoyment differences but larger motion sickness differences between HeadJoystick and Controller after repeated interface usage. This means that while enjoyment benefits (and novelty) of using embodied locomotion interfaces become less apparent over time, their benefits in terms of reducing motion sickness become more apparent. These findings are noteworthy as previous studies often reported non-significant differences between embodied and handheld locomotion interfaces in terms of motion sickness. Some examples are Study 1.1, 1.2, 1.3, 1.4, and (Marchal et al., 2011; Griffin et al., 2018; Buttussi and Chittaro, 2019; Kruijff et al., 2016). Our findings suggest that these studies can expect significant motion sickness-inducing effect when using handheld controllers after longer periods of interface usage time.

Overall, our findings showed that repeated usage of embodied locomotion interfaces such as HeadJoystick might show less enjoyment benefits over time (Study 3.2), but using such interfaces over time becomes easier to learn and use (Study 2.2). Our findings also showed that repeated usage of embodied locomotion interfaces such as HeadJoystick intensifies their benefits for addressing adverse-effects of using handheld interfaces in terms of unconvincing locomotion (Study 2.2) and motion sickness (Study 3.2).

RQ2.3. How can brake mechanisms improve user experience and performance for leaning-based versus handheld interfaces? Unlike Study 2.1, 2.2, 3.1, 3.2, and 4.1, which required continuous locomotion, many real-life scenarios might require the user to stop after reaching the target position to perform other tasks. Therefore, in Study 3.3, we investigated if and how the observed benefits of embodied locomotion interfaces generalize to locomotion scenarios where the user needs to stop after reaching a target. Considering HeadJoystick users always move depending on the distance between their head and the zero-point, HeadJoystick requires a mechanism to help stop locomotion. We addressed this problem by adding a neutral/idle zone for HeadJoystick to prevent locomotion if the distance of the user head from zero-point is less than 5 cm. We used neutral/idle zone to stop locomotion as it was used for most previous leaning-based interfaces (Marchal et al., 2011; McMahan et al., 2010; Griffin et al., 2018; Nguyen-Vo et al., 2019).

In addition, we implemented and evaluated two brake mechanisms. First mechanism is called soft brake, where the user can reduce the speed by 10% of the maximum locomotion speed with pressing and holding the controller trigger. Such brake mechanism only completely stops locomotion when users are already traveling relatively slowly to prevent harsh decelerations that might exacerbate motion sickness. The second brake mechanism was called automated brake, where users can disable and enable HeadJoystick by pressing controller buttons A and B, respectively. We evaluated HeadJoystick with versus without (soft and automated) brake mechanisms in a reach-the-target task, where the user was asked to stop inside each target position for a second before traveling to the next, i.e., smaller target.

Our results showed that using HeadJoystick improved all performance measures as well as 4-6 (out of 12) user experience measures compared to controller-directed steering irrespective of if there was a brake mechanism. Potential reasons for why using HeadJoystick conditions did not significantly improve 6-8 (out of 12) subjective measures compared to the controller could be due to changes in HeadJoystick and Controller conditions. That is, as for the controller condition, we used controller-directed steering due to its higher usability compared to body-directed steering in our earlier studies (Study 2.1, 2.2, 5.1, 3.1, and 3.2). As for the HeadJoystick condition, we used a simplified HeadJoystick interface without tracker or chair backrest to investigate if leaning-based interfaces can be beneficial even with an easier setup.

Post-experiment interviews revealed that neutral/idle zone was preferred over soft and automated brake by most (56%) of the participants. Participants also suggested automated brake for longer-term brakes after reaching a target (such as for a few minutes instead of the one second stop in our task) to allow users moving their head freely without affecting locomotion. For example, using automated brake could allow participants in a virtual conference to stop locomotion after reaching other participants or the next poster using HeadJoystick and then freely look around without affecting any virtual locomotion. Our findings regarding higher preference of neutral/idle zone over soft or automated brake corroborate the usability benefits of using neutral/idle zone in previous leaning-based interfaces such as Joyman (Marchal et al., 2011), human joystick (McMahan et al., 2010), head-directed steering (Griffin et al., 2018), and NaviBoard (Nguyen-Vo et al., 2019). Our post-experiment interviews also suggested potential reasons behind the advantages of neutral/idle zone compared to soft and automated brake. For example, stopping locomotion using soft/automated brake requires controlling hands/finger besides head, which might get confusing as participants sometimes forgot when or how much they should press the controller's trigger/buttons.

Our findings showed that the benefits of embodied locomotion interfaces generalize to locomotion scenarios that require the user to stop after reaching the target to do other tasks. These findings are specifically noteworthy for prior research that only investigated embodied locomotion interfaces in locomotion scenarios without stops. Some examples are Study 1.3, 1.4, (Marchal et al., 2011; McMahan et al., 2010; Kruijff et al., 2016; Griffin et al., 2018; Buttussi and Chittaro, 2019). For example, Kruijff *et al.* showed that the benefits of embodied locomotion interfaces in terms of improving locomotion believability (vection intensity, presence and involvement) become more apparent by incorporating walking-related feedback. These feedback were visual cues of simulating bobbing head-motions from walking, auditory cues of footstep sounds, and vibrotactile cues via vibrotactile transducers and bass-shakers under users' feet (Kruijff et al., 2016). As other examples, Buttussi *et al.* reported higher performance of embodied over the handheld locomotion interfaces in a reach-the-target task (Buttussi and Chittaro, 2019), and Griffin *et al.* reported improved presence and task load when using embodied instead of handheld locomotion interfaces in FPS games (Griffin et al., 2018). While none of these tasks required the user to stop after locomotion, our findings help generalizing those results to locomotion scenarios that require the users to stop, e.g., after reaching the target to do other tasks.

Overall, our findings suggested that the benefits of using embodied locomotion interfaces (such as HeadJoystick) generalize to locomotion scenarios that require the user to stop after locomotion to do other tasks. In addition, post-experiment interviews in Study 3.3 suggested using neutral/idle zone for short-term stops and automated brake for long-term stops.

RQ2.4. How does providing embodied self-motion cues affect performance in single versus multi-tasking scenarios? Many real-world locomotion scenarios require the user to perform other tasks such as gathering information or interaction with the environment during locomotion. Prior research on multitasking scenarios reported reduced accuracy when using seated (Beckhaus et al., 2005b) and standing (McMahan et al., 2012) leaning-based interfaces as well as head-directed steering (Griffin et al., 2018). However, as these leaning-based interfaces were evaluated for projection screen (instead of HMD) and head-directed steering does not provide full embodied (vestibular) self-motion cues, we do not know if and how these results generalize to most VR users using HMD. To address this gap, in Study 4.1, we designed a novel simultaneous locomotion and object interaction task. We asked users to follow a horizontally moving platform while intersecting vertically moving target balloons with their virtual lightsaber to pop them. Such task helped us to evaluate accuracy of both locomotion and object interaction using separate yet similar measures. To investigate how single versus multi-tasking scenarios affect performance (accuracy), we evaluated our embodied locomotion interfaces (HeadJoystick and NaviBoard) in an object interaction task with versus without locomotion.

Our results showed that providing higher degrees of embodied self-motion cues using HeadJoystick and especially NaviBoard improved performance and six (out of 12) user experience and usability measures in simultaneous locomotion and object interaction scenarios. These results contradict prior research evaluating embodied locomotion interfaces in multitasking scenarios such as ChairIO (Beckhaus et al., 2005b), human joystick (McMahan et al., 2012), and Head-directed steering (Griffin et al., 2018). The design considerations for our leaning-based interfaces could explain these contradicting results. For example, both ChairIO (Beckhaus et al., 2005b) and Head-directed steering (Griffin et al., 2018) reduced usability compared to an early version of the HeadJoystick - called Swivel chair in Study 1.1, 1.2, and 1.4. Human joystick (McMahan et al., 2012) is also a standing/stepping leaning-based interface similar to the NaviBoard, but without haptic feedback for the zero-point, which could reduce its usability due to losing zero-point during locomotion as shown by prior research (e.g., (Pittman and LaViola, 2014)).

In addition, our results showed a higher dual-task cost for the Controller compared to HeadJoystick and NaviBoard, which intensified the performance benefits of using embodied locomotion interfaces in multi-tasking scenarios. Such results are in alignment with hypotheses such as switching from single to dual-task scenarios increases the overall task difficulty where less embodied locomotion interfaces (and especially Controller) experience more performance deterioration as we discuss in RQ2.6. These findings also corroborate the role of task difficulty as a potential reason for the mixed results in Study 3.3, 4.1, and 5.1. That is, increasing locomotion difficulty from a fairly slow 2D locomotion task in Study 4.1 to a faster 2D locomotion in Study 3.3 could be a potential reason for why using HeadJoystick shows more significant benefits in Study 3.3 compared to Study 4.1. Similarly, increased task difficulty in 3D locomotion in Study 5.1 compared to the 2D locomotion in Study 3.3 can be a potential reason for more significant benefits of using HeadJoystick in Study 5.1. Other implications of these findings are discussed at the end of this section.

RQ 2.5. How does providing different levels of embodied self-motion cues for a sitting versus standing/stepping user affect user experience and performance? Prior research designed a wide range of embodied locomotion interfaces for sitting (Beckhaus et al., 2005b; Riecke and Feuereissen, 2012a; Schulte et al., 2016; Rognon et al., 2018; Miehlbradt et al., 2018; Buttussi and Chittaro, 2019) and standing/stepping (Marchal et al., 2011; McMahan et al., 2012; Harris et al., 2014; Kruijff et al., 2016) body postures. Prior research reported some mixed results when comparing sitting versus standing embodied locomotion interfaces (Zielasko, D. and Riecke, 2020). For example, prior research reported that standing posture can contribute to more severe motion sickness compared to the seated body posture (Riccio and Stoffregen, 1991; Merhi et al., 2007; Zielasko and Riecke, 2021). However, a study by Nguyen-Vo *et al.* reported reduced motion sickness when using a standing/stepping embodied locomotion interface (NaviBoard) but not a seated one (NaviChair) compared to the handheld controller (Nguyen-Vo et al., 2019). To address this gap, in Study 4.1, we investigated the effects of providing different levels of embodied self-motion cues using four conditions: handheld Controller, with no/minimal self-motion cues; HeadJoystick, which provided embodied self-motion cues for the upper-body of a seated user; NaviBoard, which provided embodied self-motion cues for the whole body of a standing/stepping user; and physical walking, which provided the full self-motion cues.

Our results showed that while walking performed the best, providing higher levels of embodied self-motion cues for standing/stepping (instead of sitting) body posture showed more pronounced benefits compared to the handheld interfaces. That is, using HeadJoystick and NaviBoard showed one and six significant user experience advantages compared to the controller, respectively. Our findings corroborated prior research suggesting that standing body posture could provide more intense vection and higher engagement compared to the seated posture (Zielasko and Riecke, 2021). As for motion sickness, while both HeadJoystick and NaviBoard showed a trend for reducing motion sickness compared to the controller, this trend reached significance only for NaviBoard but not HeadJoystick. Such similar results to the first research on NaviBoard generalizes pronounced benefits of standing/stepping (compared to seated) embodied locomotion interfaces in terms of motion sickness to both spatial orientation (Nguyen-Vo et al., 2019) and maneuvering (Study 4.1) scenarios. Such similar findings contradict prior research reporting induced motion sickness of standing interfaces (Riccio and Stoffregen, 1991; Merhi et al., 2007; Zielasko and Riecke, 2021) compared to the seated ones. A potential reason for such contradicting results could be due to using a carefully optimized standing/stepping embodied locomotion interface (NaviBoard) in our studies. That is, similarity between NaviBoard and physical walking in a limited area and providing additional proprioceptive and vestibular self-motion cues aligned with the virtual translations could reduce sensory conflicts and motion sickness.

Together, our findings from Study 4.1 and (Nguyen-Vo et al., 2019) addressed RQ2.5 by showing more pronounced benefits of using standing/stepping (instead of sitting) body posture when using optimized embodied locomotion interfaces such as NaviBoard (instead of HeadJoystick). These results can suggest potential reasons for some previous results. For example, the improved usability of controller-directed steering compared to body-directed steering could be due to providing higher levels of embodiment when using controller-directed steering. As another example, prior research reported a deeper impact of VR experiences on users when using embodied instead of handheld locomotion interfaces (Antle et al., 2013). Such a deeper impact could be due to the improved usability of the embodied locomotion interfaces, which allowed users to have a more real-life-like experience and thus increased their involvement and engagement with the VR experience, which led to a deeper impact instead of being distracted by the user interfaces when using handheld interfaces.

RQ 2.6. How does providing different levels of embodied self-motion cues affect performance when increasing the locomotion task difficulty (speed)? As mentioned in RQ1, we hypothesized that one of the potential reasons for more pronounced benefits of using HeadJoystick over Controller-directed steering in a Study 3.3 versus Study 5.2 could be due to the increased difficulty of locomotion in Study 3.3 due to requiring higher speed and accuracy. To explore this potential reason, we decided to investigate how providing different levels of embodied self-motion cues affects performance when increasing locomotion task difficulty. As prior research showed a close association between locomotion speed and task difficulty (Fuller et al., 2008), we decided to increase the required locomotion speed to increase task difficulty in the Study 4.1. That is, in Study 4.1, we investigated how using embodied locomotion interfaces affect performance when increasing locomotion speed.

Our results showed more pronounced performance deterioration for less embodied locomotion interfaces (and in particular the Controller) when increasing locomotion difficulty (speed). That is, while walking outperformed all other interfaces in all locomotion speeds, providing vestibular and proprioceptive self-motion cues for sitting (HeadJoystick) and especially standing (NaviBoard) body posture showed less performance decrease compared to the Controller when increasing locomotion speed. A potential reason for more pronounced performance deterioration of less embodied locomotion interfaces could be because they required higher overall mental demand as shown in Study 4.1 results. Our findings can suggest varied task difficulty as a potential reason for why providing embodied self-motion cues in prior research sometimes showed benefits comparable to actual walking (Riecke et al., 2010) and sometimes not (Sigurdarson et al., 2012; Sigurdarson, 2014). Therefore, to thoroughly evaluate other embodied locomotion interfaces, we suggest future research to use locomotion scenarios with varied levels of task difficulty. For example, we increased the task difficulty by reducing target and path size in Study 2.1, 2.2, 3.1, 3.2, 3.3 and increasing locomotion speed in Study 4.1.

Prior research often used a wide range of locomotion speeds when evaluating previous embodied locomotion interfaces in 2D (e.g., 0.6-1.4 m/s (Marchal et al., 2011), 1.5 m/s (Nguyen-Vo et al., 2019), 3 m/s (Harris et al., 2014)) and 3D (e.g., 12 m/s (Rognon et al., 2018; Cherpillod et al., 2017)) locomotion scenarios. Thus, we also evaluated HeadJoystick in a wide range of locomotion speeds ranging from 0.3-0.8 m/s (Study 4.1), 4 m/s (Study 3.1, 3.2, and 3.3), 8 m/s for flying (Study 2.2), 12 m/s for driving (Study 3.1), and 20 m/s for flying (Study 2.1). This helps us to better generalize benefits of providing embodied self-motion cues to different locomotion speeds.

Overall, our findings regarding RQ2.6 (effects of task difficulty) and RQ2.4 (effects of single versus dual task) corroborated each other by showing more pronounced benefits of embodied locomotion interfaces when increasing task difficulty. Such findings provide a more clear explanation to our mixed results regarding the benefits of embodied locomotion interfaces in different locomotion scenarios (RQ1). That is, as shown in RQ2.6 and RQ2.4, reducing locomotion difficulty (speed) from Study 3.3 to 4.1 reduced the number of significant benefits of providing embodied self-motion from six to one measure. Similarly, the locomotion task in Study 5.2 had no speed and accuracy requirements, which could be a potential reason why using controller-directed steering instead of the HeadJoystick not only showed no significant difference in terms of our expanded evaluation framework measures but also showed three other subjective advantages.

The positive relationship between task difficulty and benefits of embodied locomotion interfaces can also help us to predict the benefits of embodied locomotion interfaces in other locomotion scenarios. For example, As 3D locomotion requires controlling more DoFs compared to 2D locomotion, we can predict that providing higher degrees of embodied self-motion cues would provide more pronounced benefits in 3D as compared to 2D locomotion tasks. As another example, due to the increased complexity of relative motion tasks such as photo capture (Higuchi et al., 2013) compared to absolute motion tasks such as reach-the-target (Bowman et al., 1997), using embodied locomotion interfaces could provide more pronounced benefits in relative compared to absolute motion tasks. Similarly, we can predict much more benefits of using embodied (instead of handheld) interfaces in complex multi-tasking scenarios. For example, where the user needs to interact with the environment using both her hands (e.g., simultaneous shooting at two enemies in different directions) during locomotion. As another example, more benefits of embodied locomotion interfaces can be expected in FPS games that require the user to shoot toward an enemy while looking at another enemy in a different direction and simultaneously moving in a third direction to avoid being hit.

Together, our findings regarding RQ2 showed consistent benefits of providing vestibular and proprioceptive cues toward virtual travel direction using carefully optimized embodied locomotion interfaces (such as HeadJoystick and NaviBoard) in different situations: with physical and virtual rotation (in Study 2.1); in short-term (in Study 2.1 and 3.1) and repeated interface usage (in Study 2.2, 3.2, 3.3, and 4.1); with brake mechanism such as neutral/idle zone (in Study 3.3); in multi-tasking (Study 4.1) and locomotion-only (Study 2.1, 2.2, 3.1, 3.2, and 3.3) scenarios; for seated and standing/stepping body posture (in Study 4.1); and in different locomotion speeds (in Study 4.1).

5.2 Key Insights and Future Directions

In this section, we describe key insights that emerged from the different stages of working on this thesis. We also discuss the limitations of our work and offer some suggestions for future work that can advance research.

5.2.1 Design Guidelines

Various benefits of providing vestibular and proprioceptive self-motion cues in our eight evaluation studies (Study 2.1, 2.2, 3.1, 3.2, 3.3, 4.1, 5.1, and 5.2) compared to no significant benefits in our early four design studies (Study 1.1, 1.2, 1.3, and 1.4) can be due to our design considerations when refining HeadJoystick and NaviBoard. Therefore, we list our design considerations that are based on participants' answers in post-experiment interviews as well as the findings from our evaluation studies as design guidelines for designing future **leaning-based interfaces**:

- **Design Guidelines for Providing Embodied Self-Motion Cues**
  - **Leaning Detection:** Consider detecting leaning by tracking head (instead of upper-body or trunk) to ensure providing vestibular self-motion cues to improve locomotion believability, reduce motion sickness while increasing movement accuracy according to participants' answers in the post-experiment interview in Study 1.4 and improved benefits of our final head-based leaning-based interfaces (HeadJoystick and NaviBoard) compared to our early leaning-based interfaces such as Swivel-Chair, NaviChair, MuvMan, etc.

- **Rotation Control:** Consider using full physical rotation to control simulated rotation in VR whenever possible. Use virtual rotation only when full physical rotation is not possible. Use virtual rotation if users are not able to physically rotate or simply prefer not to, e.g., due to convenience or laziness (Ragan et al., 2017). For example, when the user is sitting on a couch or non-rotating chair or when they use a wired HMD or a stationary display like a TV or projection screen.
- **Body Posture:** Consider designing standing/stepping leaning-based interfaces when simulating walking scenarios to reduce motion sickness and increase locomotion believability including presence and vection intensity in Study 4.1 and (Nguyen-Vo et al., 2019). Use seated leaning-based interfaces for scenarios where standing posture leads to fatigue and discomfort (such as long-term walking scenarios) or when users simply prefer to sit as compared to standing. Use seated leaning-based interfaces also in scenarios where standing posture would reduce believability, such as driving or flying scenarios that are intended for seated users in the real-world. Other factors should also be considered when choosing between sitting and standing body postures, such as users' safety, engagement, accessibility requirements, and movement abilities (such as requiring crouching, jumping, crawling) (Zielasko, D. and Riecke, 2020). That is, prior research showed that sitting (instead of standing) posture can lead to increased safety, reduced sensation of self-motion, reduced engagement, and improved accessibility (Zielasko and Riecke, 2021). Despite these factors, VR applications should also consider other factors such as users' intentions by allowing them to choose their preferred body posture based on their comfort and/or prior activities (Zielasko and Riecke, 2020b).

- **Design Guidelines for Improving Usability**
  - **Hands-free Locomotion:** Consider using hands-free instead of hands-busy interfaces for VR locomotion. Participants in the post-experiment interviews of all our evaluation studies (Study 2.1, 2.2, 3.1, 3.2, 3.3, and 4.1) suggested higher usability of hands-free over hands-busy locomotion interfaces. As an example, P9 in Study 4.1 stated that *"using your head to look and move when using HeadJoystick is easier than to use your head for looking and your thumb to move."* Using hands-free locomotion interfaces also frees hands for interaction. As an example, post-experiment interviews in Study 4.1 showed that stopping locomotion by pressing a button on the controller was more confusing for the users compared to moving their head to the neutral/idle zone. Using hands only for object interaction but not locomotion is also more consistent with our everyday experiences in the real world.

– **Comfortable Interaction:** Consider designing comfortable interactions for the user to improve usability. For example, use a swivel chair with backrest instead of sit/stand stools to increase comfort, overall usability, and potential for longer-term use according to our findings and post-experiment interviews in Study 1.2. Study 5.2 results showed that controller-directed steering could provide more comfortable interaction compared to the HeadJoystick in terms of muscle relaxation and comfortable sitting posture. These advantages of handheld controllers over HeadJoystick could suggest a potential reason for why using HeadJoystick instead of the controller did not show a significantly higher potential for frequently daily usage.

– **Feedback Provision:** Consider providing non-visual feedback for zero-point (i.e., initial position of the head when starting locomotion) to help users know the direction of locomotion and how to stop locomotion according to previous research (e.g., (Pittman and LaViola, 2014)), which was confirmed by our evaluation studies. For example, when using HeadJoystick with a tracker in Study 2.1, 2.2, 3.1, 3.2, and 4.1, we asked users to set the zero-point when their back touched the chair backrest, so later they could easily find this zero-point during locomotion. As another example, when using HeadJoystick without tracker in Study 3.3, we asked users to sit upright at the center of chair's yaw rotation to set it as their zero-point. This way, users later could stop locomotion by siting upright again, which provided a simple embodied physical feedback for zero-point even after rotating the chair. As for the NaviBoard, haptic feedback for the neutral/idle zone was provided to the user's feet when standing on the central wooden plate.

– **Decouple intended motion controls:** Consider allowing users to easily rotate their head and body without affecting locomotion direction or speed. We tracked the movement of head rotation center (instead of the HMD position) to allow users rotating their head without affecting locomotion velocity. Allowing for head rotation without affecting simulated locomotion also reduces the visual-vestibular sensory conflict by minimizing the vestibular signals in the otolith system and maximizing the signals in the canal system of the inner ear. We also attached a tracker to the chair's backrest to update zero-point and keep it stationary with respect to the chair (not the room) during yaw rotation of the swivel chair. This allows the user to always find the zero point and stop the simulated locomotion even after rotating the chair. Details are discussed in the appendix A.

– **Ability to stop and dwell:** Consider allowing users to easily stop locomotion in VR when using leaning-based interfaces. For example, use neutral/idle zone for short-term stops to increase usability of hands-free locomotion (according to

Study 3.3 results) and use automated brake by disabling/enabling leaning for longer-term stops (according to the post-experiment interviews in Study 3.3).

5.2.2 Limitations and Future Directions

As we discussed the specific limitations of each study and their internal validity issues in Chapter 2, Chapter 3, and Chapter 4, here we discuss cross-study limitations of all 12 user studies for addressing our research questions (cf. Table 1.1).

embodied locomotion interfaces: To address our general research question, we only used leaning-based interfaces to provide embodied self-motion cues, and thus our results might not generalize to other embodied locomotion interfaces such as omni-directional walking treadmills or actuated moving-base driving/flight simulators. Similar to leaning-based interfaces, these complex embodied locomotion interfaces previously showed similar naturalness benefits (e.g., (Groen and Bles, 2004; Berger et al., 2010)) despite their usability and performance disadvantages (e.g., (McMahan, 2011; Viirre et al., 2015)). Therefore, it would be interesting to investigate if the usability and performance disadvantages of other types of embodied locomotion interfaces can be resolved using iterative interface refinement. As an example, a flying interface - called Birdly (Rheiner, 2014) showed improved user experience and performance compared to the handheld controllers (Cherpillod et al., 2017). Future studies are also needed to extend our refinement process method by investigating which steps in our refinement process are able to systematically improve embodied locomotion interfaces. For example, are these steps always applicable and beneficial to other embodied locomotion interfaces, and why?

Participant sample: Overall, 224 SFU students were recruited (14-24 participants per study) from the School of Interactive Arts & Technology as participants in all 12 user studies (Table 1.1). As these students might be more familiar with new technologies compared to the average VR users or the general population, their results might or might not be generalizable to a wider range of participants. Thus, future studies could investigate generalizability of our findings with more diverse participant populations and larger participant samples per study.

RQ1- Locomotion Scenarios: As for evaluating embodied locomotion interfaces in a wide range of locomotion scenarios, prior research classified locomotion scenarios into three purposes: exploration, search, and maneuvering. Our user studies investigated 2D (Study 5.2) and 3D (Study 5.1) search scenarios as well as 2D (Study 3.1, 3.2, and 3.3) and 3D (Study 2.1 and 2.2) maneuvering tasks, but we did not investigate any exploration scenarios. Therefore, we have a limited understanding of how using embodied locomotion interfaces affects user experience and performance (e.g., the user's ability to gather information during locomotion) in exploration scenarios (Bowman et al., 1999). Future studies could also investigate other specific locomotion tasks, such as capturing photo task for assessing relative positioning (Higuchi et al., 2013).

RQ2.1- Rotation Control: Our findings showed more pronounced benefits of embodied locomotion interfaces with full (instead of virtual or limited) rotation. However, we did not compare embodied locomotion interfaces such as HeadJoystick with limited versus virtual rotation. Therefore, we do not fully understand which rotation mechanism (i.e., virtual or limited) works better with HeadJoystick when full physical rotation is not an option, e.g., when sitting on a non-rotating chair, using a projection screen or wired HMD, or simply user preference. Future research could address this gap by comparing different rotation mechanisms including limited rotation, virtual rotation, and Ratcheting (instantaneous turns of, e.g., 30°) - see Chapter 18.3 of (Jerald, 2016).

RQ2.2- Interface Usage Time: We conducted all our studies in one session, and thus interface usage time was limited to 1.5, 8, 1.5, 9, 6, and 6 minutes in Study 2.1, 2.2, 3.1, 3.2, 3.3, and 4.1, respectively. While our results showed that the benefits of using embodied locomotion interfaces remained over repeated interface usage, future research is needed to investigate if and how our findings might extend to hours or several days/weeks similar to many real-world applications. Such research also needs to assess adverse effects such as fatigue, dry eye syndrome, physical discomfort, or compounding motion sickness (Steinicke and Bruder, 2014).

RQ2.3- Brake Mechanisms: Future research could investigate other brake mechanisms. In addition, as we evaluated our brake mechanisms for short-term (one second) stops, future research can investigate automated brake for longer-term stops. We also evaluated soft/automated brake only with neutral/idle zone, and thus future studies can evaluate soft brake without neutral/idle zone to investigate if it could improve visual-vestibular sensory coupling, and pronounce the benefits of embodied locomotion interfaces in terms of induced vection intensity, reduced motion sickness, etc.

RQ2.4- Multi-tasking Scenarios: We evaluated our embodied locomotion interfaces in a dual-task scenario of simultaneous locomotion and object interaction (Study 4.1). Future studies are needed to investigate how our results might generalize to other multi-tasking scenarios from our daily life or common VR applications such as First-Person Shooter games, which have been used in prior research (Beckhaus et al., 2005b; McMahan et al., 2012; Griffin et al., 2018). Such locomotion scenarios might require designing extra interactions for embodied locomotion interfaces such as jumping or crouching.

RQ2.5- Body Posture: We only evaluated standing/stepping and seated leaning-based interfaces in a short-term dual-task scenario. Therefore, future studies can investigate the effects of body posture (seated, standing/stepping, etc.) when evaluating embodied locomotion interfaces in longer-term and wider range of 2D or 3D locomotion scenarios.

RQ2.6- Locomotion Speed: While our evaluation study used a fairly wide range of maximum locomotion speed (4-20 m/s), we investigated this RQ in Study 4.1 using a dual-task scenario. Due to the complexity of our dual-task scenario, our locomotion task required a fairly slow speed (less than 0.8 m/s) without backward or sideways motion with a small range of speed changes (0.15-0.8 m/s). Therefore, future research needs to investigate if our findings generalize to faster 2D and 3D locomotion or with backward and sideways motion.

Outlook: We aim to continue an iterative interface refinement process to further improve the usability of our embodied locomotion interface prototypes. As for current usability issues of the HeadJoystick, our evaluations showed that when HeadJoystick users follow a target by translating (instead of rotating) their head, their locomotion direction and speed changes, which could increase motion sickness. Such situations could happen when a target goes outside the head rotation range such as when looking back at a missed target. To address this usability issue, future research could prevent unwanted velocity changes in these situations or suggest alternative techniques to the users such as rotating the chair to look back. As for the usability issues of the NaviBoard, participants reported that they forgot where the zero-point is if they put both their feet on Styrofoam (e.g., during fast translations). Future interfaces can address this issue by finding better ways to indicate the center of NaviBoard to the user such as using a hard foam indicator of the center of the board, as we did in Riecke et al. (2022). As another usability issue of the NaviBoard, participants reported losing balance when their feet cannot automatically follow their head during rotation or in corners. A potential solution for that could be to allow and instruct the user to comfortably step/walk on the NaviBoard Riecke et al. (2022) instead of always keeping a foot at the center of NaviBoard to not lose its zero-point.

We also aim to personalize our embodied locomotion interfaces (HeadJoystick and NaviBoard) for specific locomotion scenarios. For example, using embodied locomotion interfaces for VR games requires implementing specific interactions such as jumping and crouching. We also aim to implement other hands-free brake mechanisms such as a foot-based brake.

5.3 Conclusion

In this thesis, we investigated if providing embodied self-motion cues during locomotion in VR can address adverse effects of current standard handheld locomotion interfaces such as unconvincing simulated motion, motion sickness, and disorientation for most VR users in a wide range of locomotion scenarios. To do so, we iteratively designed, evaluated, and refined different embodied locomotion interfaces in several internal evaluations as well as four formal user studies (Study 1.1, 1.2, 1.3, and 1.4). Once our interface prototypes (HeadJoystick and NaviBoard) showed higher usability compared to the handheld controllers in our pilot-testings, we conducted eight more user studies to evaluate them in different locomotion scenarios as presented in Chapter 2, Chapter 3, Chapter 4 as well as Study 5.1 and 5.2. Overall, our findings showed that providing vestibular and proprioceptive cues toward the simulated travel direction using carefully optimized leaning-based interfaces (such as HeadJoystick and NaviBoard) can help reducing adverse effects of using handheld interfaces while improving or at least matching most other locomotion-relevant measures in a wide range of locomotion scenarios.

As for addressing disorientation, three other user studies were conducted and led by my colleagues for evaluating HeadJoystick and NaviBoard for 2D (Nguyen-Vo et al., 2019) and 3D navigational search (Adhikari et al., 2021a) as well as pointing toward previous positions (Adhikari et al., 2022). These user studies showed that using both HeadJoystick and NaviBoard to provide embodied self-motion cues significantly improved spatial orientation. Our findings contradict prior studies that reported using embodied locomotion interfaces reduced accuracy (Beckhaus et al., 2005b; Marchal et al., 2011; McMahan et al., 2012; Pittman and LaViola, 2014; Freiberg, 2015; Griffin et al., 2018). In addition, our results showed consistent benefits of providing embodied self-motion cues in different situations: with physical and virtual rotation; in short-term and repeated usage; with and without neutral/idle zone to stop locomotion; in locomotion-only and multitasking scenarios; for a seated and standing/stepping user; and in different locomotion speeds. However, despite consistent performance benefits of using our HeadJoystick over handheld controllers, using HeadJoystick instead of controller-directed steering did not significantly improve user experience in easy (slow and/or inaccurate) locomotion scenarios. Overall, our findings show that iterative refinement of embodied locomotion interfaces can ultimately end the dominance of standard handheld locomotion interfaces (at least for difficult locomotion scenarios) by providing an alternative in a wide range of locomotion scenarios.

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Appendix A

HeadJoystick Motion Model

Using HeadJoystick with virtual (instead of physical) rotation (LeaningTranslation) does not require using a swivel chair, and thus has a *static* zero-point (initial head position) when the locomotion begins. However, using HeadJoystick with 360° physical rotation requires a *dynamic* zero-point to be updated during chair rotation. To do so, full-rotational HeadJoystick 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 A.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 A.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 (Beyer, 1987):

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

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

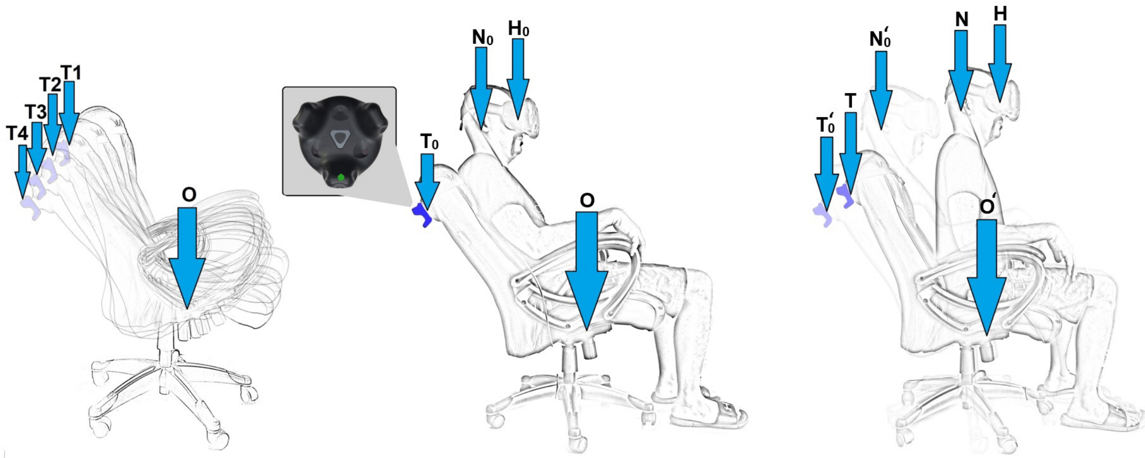

Figure A.1: HeadJoystick motion model: (Left) Tracker calibration process, (Middle) Setting zero-point when starting flight, (Right) Flight motion model. Position of Tracker (T), HMD (H), above the head rotation center in the neck (N), Center of chair backrest pitch rotation (O) are annotated in the 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.

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 A.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:

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

Flight Motion: As depicted in Figure A.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):

$$\begin{aligned}
\Delta pitch &= pitch_T - pitch_{T_0} \\
\overrightarrow{\text{O'T}}(r,\theta,\phi) &= (r_{\overrightarrow{OT_0}}, \theta_{\overrightarrow{OT_0}}, \phi_{\overrightarrow{OT_0}} + \Delta pitch) \\
O' &= T - \overrightarrow{\text{O'T}} \\
T'_O &= O' + \overrightarrow{OT_0} \\
N'_0 &= T'_0 + \overrightarrow{T_0 N_0}
\end{aligned}$$

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 ($\vec{D}$) 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).

$$\begin{aligned}
\overrightarrow{\text{HN}}(r,\theta,\phi) &= (0.13m, yaw_H, pitch_H) \\
N &= H + \overrightarrow{\text{HN}} \\
\vec{D} &= N - N'_0 \\
\vec{D} &= \vec{D} \cdot \alpha \\
y_{\vec{D}} &= y_{\vec{D}} \cdot \beta
\end{aligned}$$

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.

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

Smooth Acceleration: To prevent abrupt speed changes and reduce the motion sickness, we can smoothly apply 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.

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