Improving Spatial Orientation in Virtual Reality with Leaning-based Interfaces

by

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Ethics Statement

Abstract

Advancement in technology has made Virtual Reality (VR) increasingly portable, affordable and accessible to a broad audience. However, large scale VR locomotion still faces major challenges in the form of spatial disorientation and motion sickness. While spatial updating is automatic and even obligatory in real world walking, using VR controllers to travel can cause disorientation. This dissertation presents two experiments that explore ways of improving spatial updating and spatial orientation in VR locomotion while minimizing cybersickness.

In the first study, we compared a hand-held controller with HeadJoystick, a leaning-based interface, in a 3D navigational search task. The results showed that leaning-based interface helped participant spatially update more effectively than when using the controller.

In the second study, we designed a "HyperJump" locomotion paradigm which allows to travel faster while limiting its optical flow. Not having any optical flow (as in traditional teleport paradigms) has been shown to help reduce cybersickness, but can also cause disorientation. By interlacing continuous locomotion with teleportation we showed that user can travel faster without compromising spatial updating.

Keywords: navigational search, spatial orientation, hyperjump, teleportation, iterative jumps, virtual reality, motion sickness, cybersickness, locomotion interfaces, leaning-based locomotion interfaces

Dedication

This thesis work is dedicated to my mother and father who encouraged me to pursue my interests, to my amazing teachers, who supported my pursuits of curiosities, to my partner and best friend, who has always been with me every step of the way. Thank you all. Your love, support and guidance made this possible.

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Chapter 1

Introduction

Spatial updating is a mental process of maintaining the spatial knowledge of our surroundings as we move around in our environment and self-to-object relationships constantly change. We can change our position in an environment through a simple activity like a walk or a complex activity like turning and diving to volley a ball. In any case, our mind automatically updates our spatial representation of where we are with respect to our immediate surroundings. This largely automated and low-cognitive-load process allows us to easily and effectively interact with our environment. We can accurately pass a soccer ball to our teammates during a match or return home after a stroll in a park.

However, only imagining those positional changes does not generate the same level of spatial updating. People are less accurate in estimating their location when they only imagine or view a travel compared to taking a real walk. This includes visually simulated self-motions in Virtual Reality (VR) with hand-held controllers. This limits the potential of VR applications, as the users' spatial awareness may be compromised when moving with a controller.

This issue can be addressed by complex platforms like omni-directional treadmills that allow users to walk almost like in the real world. However, they are either ineffective or expensive, take large spaces and have their own safety concerns. On the other hand, Nguyen-Vo et al. showed that even a partial body movement like leaning-based locomotion control can improve spatial updating and make it comparable to real walking in a navigational search task (Nguyen-Vo, Riecke, Stuerzlinger, Pham, & Kruijff, 2019).

In the first study of this thesis, we investigate if Nguyen-Vo et al.'s above-mentioned findings can be extended to 3D navigation. If such an affordable 3D locomotion interface could improve spatial updating, this could have substantial benefits for a variety of use cases in both VR and immersive telepresence and teleoperation (UAV/drone). With the advancement in both VR and drone technologies, affordable use cases across educational, commercial, health, and recreational sectors lie ahead.

As one of the contributions of this thesis, in the first study, we designed a task for assessing 3D spatial awareness in VR. We could not find an existing VR experiment designed to evaluate spatial updating in 3D. So, based on the advantages and limitations of existing ground-based navigational search tasks, we devised an experiment for 3D where users could fly in all directions. Then, we compared users' performance with and without a partial body movement (controller vs leaning). The users were instructed to find a number of hidden balls in free floating identical boxes with a virtual lamp attached to their avatar's head. In this experiment, the users' performance (spatial awareness and spatial updating) was compared through their ability to navigate efficiently and locate the balls. Further, we recorded and analyzed participants' travel paths, asked them to rate their experience on different measures and conducted open-ended interviews to understand the user experience better.

In the second study of this thesis, we propose a novel VR locomotion paradigm, HyperJump, that was designed to help users maintain their spatial awareness and orientation in large scale navigation while facilitating quick travel. HyperJump is a hybrid between continuous and discontinuous locomotion techniques. In traditional continuous VR locomotion, we continuously steer the travel direction as we move while discontinuous methods like teleportation takes user instantly from a current location to the (immediate) destination. Continuous locomotion more closely mimics real world travel. It can be more immersive and realistic. On the other hand, teleportation has been shown to break presence and cause disorientation. However, we can only apply a limited acceleration and speed to continuous locomotion without making users cybersick, while with teleportation, it is possible to jump to any distance without increasing the risk of cybersickness much or at all. Thus, teleportation can facilitate faster travel. HyperJump was designed to bring together the best of both worlds in one seamless interface, where users don't have to switch between different locomotion control modes and can travel quickly through both small and large environments while maintaining spatial awareness and orientation.

HyperJump uses continuous movement for short distances and seamlessly adds teleportation (iterative jumps every half a second) on top of the continuous movement when users would aim to travel at higher velocities that would likely cause cybersickness, thus effectively limiting the maximum amount of optic flow speed. By interlacing the continuous motion and jumps, we hypothesize that it will provide sufficient optical flow to maintain user's spatial awareness/orientation and a consistent sense of self-motion (vection) essential for eliciting automatic spatial updating while effectively limiting the optical flow to that of a lower velocity to reduce cybersickness. Compared to regular teleportation, the jump distances also tend to become much shorter and more regular, which we hypothesized might also help to reduce the negative side-effects of regular teleportation (in particular disorientation and breaks in presence). Thus, we designed a study to compare how leaning-based and controller-based interfaces support spatial updating with or without HyperJump.

In this second study, participants started from four different locations in a naturalistic virtual model of a city (Tübingen, Germany). They travelled to four new landmarks with each conditions and from each landmarks pointed back to all previously visited landmarks in random order. The pointing task was used to analyze spatial awareness. Further, we asked participants to rate their experiences on different measures and conducted open-ended interviews to understand their user experience better and improve the design of HyperJump for future use.

This is a cumulative thesis which consists of two studies investigating different aspects of an overall larger problem: how to more intuitively and effectively move through virtual spaces with low cognitive load and without getting disoriented or cybersick. Both studies explore how leaning-based interfaces might support spatial updating and how any changes (adding flight or iterative jumps) affect its functioning. Individual studies are reported as different papers. Therefore, the introduction, related works and motivation of each study are discussed in the relevant chapters below. In the following chapters, we will present the two studies (Chapter 2 and 3), then summarize their joint contributions, limitations and future works in Chapter 4.

- **Chapter 2 - Lean to Fly: Leaning-based Embodied Flying can Improve Spatial Orientation and User Experience in 3D Navigation:** This chapter investigates the role of partial body-based information in 3D navigation. A mixed method experiment was conducted to understand how partial body-based information affected the spatial awareness of users. It is being prepared for submission to *Frontiers in VR* at the time that thesis is being written.

  This user study investigates the following research questions:

  - RQ1: Does HeadJoystick improve spatial updating compared to a hand-held controller for 3D locomotion?
  - RQ2: Does HeadJoystick help to reduce motion sickness in 3D navigation?
  - RQ3: How do HeadJoystick and Gamepad affect the overall user experience and usability in 3D navigation?

- **Chapter 3 - Integrating Continuous and Teleporting VR Locomotion into a Seamless "HyperJump" Paradigm:** This chapter investigates how combining continuous motion with iterative jumps affects spatial updating. A quantitative method experiment with an open-ended design interview was conducted to understand and improve a design of a hybrid interface. It is being prepared for submission to *IEEE Transactions on Visualization and Computer Graphics.* A summary of findings from this study has also been presented at the *IEEE VR Workshop on Finding a way forward in VR locomotion* (Adhikari et al., 2021).

  This user study investigates the following research questions:

  - RQ1: How does adding HyperJump affect spatial updating when compared to continuous-only locomotion? How does it affect overall usability and user experience including cybersickness?
  - RQ2: How do leaning-based and controller-based interfaces effect spatial updating? How do they affect overall usability and user experience including cybersickness?
  - RQ3: Does HyperJump affect leaning-based and controller-based locomotion interfaces differently?

- **Chapter 4 - Conclusions and Future Works:** This chapter summarizes the contributions and limitations of the presented studies and points out the possible future improvements for these approaches.

Chapter 2

Lean to Fly: Leaning-based Embodied Flying can Improve Spatial Orientation and User Experience in 3D Navigation

Abstract: When users in virtual reality cannot physically walk and self-motions are instead only visually simulated, spatial updating is often impaired. In this paper, we report on a study that investigated if HeadJoystick, an embodied leaning-based flying interface, could improve spatial updating in VR. We compared it to Gamepad, a standard flying interface. For both interfaces, participants were seated on a swivel chair and controlled simulated rotations by physically rotating. They either leaned (forward/backward, right/left, up/down) or used the Gamepad thumbsticks for simulated translation. In a gamified 3D navigational search task, participants had to find eight balls within 5 minutes. Those balls were hidden amongst 16 randomly positioned boxes in a dark environment devoid of any landmarks. Compared to the Gamepad, participants collected more balls using the HeadJoystick. It also minimized the distance travelled, motion sickness, and mental task demand. Moreover, the HeadJoystick was rated better in terms of ease of use, controllability, learnability, overall usability, and self-motion perception. However, participants rated HeadJoystick could be more physically fatiguing after a long use. Overall, participants felt more engaged with HeadJoystick, enjoyed it more, and preferred it. Together, this provides evidence that leaning-based interfaces like HeadJoystick can provide an affordable and effective alternative for flying in VR and potentially telepresence drones.

2.1 Introduction

Spatial updating is a largely automated mental process of establishing and maintaining the spatial relationship between ourselves and our immediate surroundings as we move around (Wang, 2016). This ability allows us to navigate and interact with our immediate environment almost effortlessly (Loomis & Philbeck, 2008; McNamara, Sluzenski, & Rump, 2008; Wang & Spelke, 2002). Spatial updating can also support complex activities like driving, climbing, diving, flying, or playing sports.

While spatial updating is mostly automatic or even obligatory (i.e., hard to suppress) during natural walking, it cannot be deliberately triggered when merely imagining self-motions (Presson & Montello, 1994; Rieser, 1989; Farrell & Robertson, 1998; Wang, 2004). Similarly, spatial updating is impaired if self-motions are only visually simulated in virtual reality (VR) and people are not physically walking, especially when reliable landmarks are missing (Klatzky, Loomis, Beall, Chance, & Golledge, 1998). This has been demonstrated by comparing physical walking with a head-mounted display (HMD) to hand-held controller operated locomotion in VR (Klatzky et al., 1998; Ruddle & Lessels, 2006a; Riecke et al., 2010a). Moreover, a large percentage of participants completely fail to update rotations that are not physically performed but only visually simulated in VR (Klatzky et al., 1998; Riecke, 2008). This illustrates how critical it is to support reliable and automatic spatial updating in VR through, e.g., more embodied interaction and locomotion methods that can tap into such automatized and low-cognitive-load mechanisms.

While physical walking in VR is often considered the "gold standard" and can reliably elicit automatic spatial updating with low cognitive load, it is often not feasible due to restrictions on the available free-space walking area and/or safety concerns (Steinicke, Vissell, Campos, & Lecuyer, 2013). Moreover, walking does not allow for full 3D (flying or diving) locomotion, where there is currently no comparable or "gold standard" locomotion interface. To address this gap, we investigate in this study if an embodied leaning-based flying interface can improve spatial updating and other usability, performance, and user experience aspects in comparison to a commonly used dual-thumbstick flying interface. Recent research indicates that more embodied interfaces such as leaning-based interfaces can indeed improve spatial updating performance in a ground-based navigational search task, and almost reach the performance levels of physical walking (Nguyen-Vo et al., 2019). However, it remains an open research question if such benefits of leaning-based interfaces would generalize to full 3D locomotion (flying) where an additional degree of freedom (DoF) needs to be controlled. If such embodied and affordable 3D locomotion interfaces could indeed improve spatial updating, this could have substantial benefits for a variety of scenarios and use cases in both VR and immersive telepresence (UAV/drone) flying. These include training, disaster or emergency response management, embodied virtual tourism, or flying untethered (as no hand controllers are needed). With the advancement in both VR and drone technologies, affordable use cases across educational, commercial, health, and recreational sectors lie ahead.

To tackle this challenge, we conducted a user study to compare HeadJoystick, an embodied leaning-based flying interface adapted from (A. Hashemian, Lotfaliei, Adhikari, Kruijff, & Riecke, 2020) (discussed in detail in subsection 2.2.1), with Gamepad, a standard controller-based interface. We compared the interfaces' spatial updating ability in a novel 3D (flying) navigational search task. This task is a 3D generalization of a standard paradigm used to assess spatial updating and situational awareness in ground-based VR or real-world navigation (Ruddle, 2005; Ruddle & Lessels, 2006a, 2009; Ruddle, Volkova, Mohler, & Bülthoff, 2011; Ruddle, 2013; Riecke et al., 2010a; Nguyen-Vo, Riecke, & Stuerzlinger, 2018; Nguyen-Vo et al., 2019). Further, we investigated if using HeadJoystick could help to reduce motion sickness and task load. Finally, we triangulated our finding through a post-experiment questionnaire and open-ended interviews.

2.2 Related works

2.2.1 Locomotion in VR

In VR, hand-held controllers cannot provide physical self-motion cues that would normally accompany real-world locomotion. Since these non-visual cues, such as vestibular and proprioceptive cues, are missing, they cannot support the visual self-motion cues provided by the HMD, making it challenging to provide an embodied and compelling sensation of self-motion (vection) for the user (Riecke & Feuereissen, 2012; B. Lawson & Riecke, 2014). This lack of non-visual and embodied self-motion cues has also been shown to impair spatial updating (Ruddle & Lessels, 2009; Riecke et al., 2010a) and spatial tasks such as directional estimates (Chance, Gaunet, Beall, & Loomis, 1998), pointing (Waller, Loomis, & Haun, 2004; Ruddle, 2013; Klatzky et al., 1998), homing (Kearns, Warren, Duchon, & Tarr, 2002; Ruddle, Volkova, Mohler, & Bülthoff, 2011) and estimation of distance traveled (Sun, Campos, & Chan, 2004). Moreover, missing body-based sensory information has also been shown to increase cognitive load (Nguyen-Vo et al., 2019) and motion sickness (Aykent, Merienne, Guillet, Paillot, & Kemeny, 2014; B. D. Lawson, 2014).

To provide at least some of these essential body-based cues, a variety of systems have been proposed and investigated, including large omnidirectional treadmills for ground-based locomotion and full-scale VR flight simulators (Groen & Bles, 2004; Krupke et al., 2016; Perusquía-Hernández et al., 2017; Ruddle, Volkova, & Bülthoff, 2011). Although these simulators provide a more believable experience of walking/flying using vestibular/proprioceptive sensory cues, the cost and maintenance needs of the equipment, complicated setups, required extensive safety measures, and weight and space requirements of some designs make them unfeasible for general VR home users.

VR researchers have designed leaning-based locomotion interfaces as a low-cost alternative that provide embodied control system and partial body-based sensory information. In these interfaces, leaning towards the desired direction instantiates a virtual motion in that direction. User studies have shown promising results for ground locomotion, such as improvement in spatial perception and orientation (Harris, Nguyen, Wilson, Jackoski, & Williams, 2014; Kruijff, Riecke, Trekowski, & Kitson, 2015; Nguyen-Vo et al., 2019); the sensation of self-motion, i.e., vection (Kruijff et al., 2016; Riecke, 2006); immersion (Marchal, Pettré, & Lécuyer, 2011); presence (Kitson, Riecke, Hashemian, & Neustaedter, 2015); and engagement (Kitson et al., 2015; Kruijff et al., 2016; Harris et al., 2014). Leaning-based interfaces have also been adapted to 3D (flying) locomotion with similar effects. As we are mainly concerned with 3D locomotion in this experiment, we discuss these studies below in detail.

Flying in real/virtual environments with 2DOF leaning-based interfaces

Below we discuss several relevant leaning-based flying interfaces that allow users to control 2 DoF. While this is not sufficient for full control of 3D flight (which requires four DoF), they provide useful insights and inspiration.

Schulte *et al.* presented upper-body leaning-based flying interfaces using either the Kinect or Wii Balance Board (Schulte et al., 2016). Both interfaces rely on the (novel) metaphor of riding a dragon. Leaning in the sagittal and coronal planes controls the dragon's pitch and combined yaw and roll, respectively. Though it travels at a constant speed, a hand gesture with Kinect temporarily accelerates the speed as well.

Miehlbradt *et al.* suggested a similar upper-body leaning-based interface (Miehlbradt et al., 2018). Using Kinect, the user's torso motion is used to perform five distinct behaviors (constant forward motion, right-banked turn (roll), left-banked turn (roll), upward pitch, and downward pitch). Users' performance (accuracy) with the leaning-based interface was better than a joystick and comparable to Birdly, a commercial mechanical interface for flying like a bird in VR (Rheiner, 2014).

Rognon *et al.* designed an upper-body soft exoskeleton, FlyJacket, that controls a fixed-wing drone flying at a constant speed (Rognon et al., 2018). Participants use an HMD to view the real-world unmanned aerial vehicle (UAV) perspective, and control the pitch and roll through their torso leaning using an inertial measurement unit (IMU). Though FlyJacket showed no significant performance improvement compared to a standard two-thumbstick remote controller (RC), participants found it to be more natural, more intuitive, and less uncomfortable.

Flying in real/virtual environments with 4DOF leaning-based interfaces

Higuchi and Rekimoto developed a system, flying-head, that synchronizes a human head with UAV motions (Higuchi & Rekimoto, 2013). Users see the UAV's camera feed through an HMD, and control the UAV's horizontal movement by walking around, elevation by crouching, and orientation by physically rotating. In a user study, their interface was found to be better than a joystick in completion time, accuracy, ease of control, ease of use and enjoyment. However, the interface implements a position control paradigm (1:1 mapping of the user's head and UAV position). This makes long distance navigation of the UAV impractical as its movement is limited to the user's head movement in the real world.

Pittman and LaViola tried to solve that problem with their design 'Head-Translation' and 'Head-Rotation' (Pittman & LaViola Jr, 2014). In Head-Translation and Head-Rotation, a user controls the UAV's velocity (both magnitude and direction) in the horizontal plane by physically moving in the desired direction or tilting their head in the desired direction, respectively. In both interfaces, standing on tiptoe or squatting changes the elevation of the UAV, while returning the body to its original position halts the UAV. As they use velocity (i.e., rate) control, their interface supports long distance navigation. Among the six flying interfaces compared, Wiimote, a hand-held controller, showed the shortest completion time for passing through the waypoints. It also yielded better ratings for predictability, ease of use, and comfort. However, participants used a monitor instead of HMD with Wiimote. Excluding the Wiimote condition, the participants preferred Head-Rotation the most. However, participants had a hard time locating their original heading with Head-Translation and drifted away from their starting position.

Xia *et al.* also developed a VR telepresence UAV system with velocity control instead of position control (Xia et al., 2019). Similar to 'Head-Translation,' a user controls the UAV's velocity in the horizontal plane by moving in the desired direction. Their interface updates the reference point to mitigate the problem of drifting users. Whenever the user gets far away from the reference point, stepping in the opposite direction of the UAV flight automatically updates the stepped back position as the new reference point. The user no longer needs to keep track of the origin. However, during prolonged use, the reference point can keep moving away from the center of the tracked space and eventually out of the tracking space.

Hashemian *et al.* developed a seated leaning-based interface, 'HeadJoystick,' with a virtual quadcopter model (A. Hashemian et al., 2020). In their model, a user freely rotates the swivel chair to control the simulated rotation. The user leans in the direction they want to navigate. Further, they attach a tracker to the back of the chair to account for any difference between the head's resting position and the chair's center. The implementation, based on the tracker's orientation, updates the reference point as the chair rotates. This allows the user to rotate freely without worrying about the initial reference point. Assessing the interface in a maneuvering task, Hashemian *et al.* concluded that HeadJoystick improved both user experience and performance. They found the leaning-based interface to perform better than hand-held controllers in terms of accuracy, precision, ease of use, ease of learning, usability, long term use, presence, immersion, a sensation of self-motion, workload, and enjoyment.

To summarize, the studies mentioned above show that leaning-based interfaces can be a low-cost and relatively easy alternative for providing embodied control in VR. Hashemian *et al.*'s iteration of a flying leaning-based interface addresses the shortcomings of previous designs. However, Hashemian *et al.* only used a fast maneuvering (waypoint travel) task (A. Hashemian et al., 2020), and there seems to be no prior research investigating human spatial updating ability and situational awareness using embodied flying interfaces. Interfaces designed for maneuvering should support high precision of motion without compromising speed, while interfaces made for exploration and search should support spatial knowledge acquisition and knowledge gathering by freeing cognitive resources (D. Bowman, Kruijff, LaViola Jr, & Poupyrev, 2004). So, both kind of travels are important but require the interfaces to support different kinds of motion. This motivated us to design and conduct this study which will shed light on whether HeadJoystick is suitable for only maneuvering tasks, or it can support navigational search and the underlying automatic spatial updating processes as well.

2.2.2 Navigational Search

Navigational search is one of the established tasks for investigating spatial updating (Ruddle & Jones, 2001; Lessels & Ruddle, 2005; Ruddle, 2005; Ruddle & Lessels, 2006a, 2009; Ruddle, Volkova, Mohler, & Bülthoff, 2011; Riecke et al., 2010a; Nguyen-Vo et al., 2018, 2019). It is a complex spatial task with high ecological validity as it is equivalent to a person walking around a cluttered room looking for target objects (Ruddle & Jones, 2001). Ruddle and Lessels introduced a variant of a navigational search task in a series of experiments studying spatial updating (Lessels & Ruddle, 2005; Ruddle & Lessels, 2006a, 2009). In their version, participants were located in a virtual rectangular room with a regular arrangement of 33 pedestals. Sixteen of those pedestals had a box on top of them, and half of those boxes contained a hidden object inside. The objective was to collect all of those eight hidden objects while minimizing revisits to previously visited boxes. They showed that the task was trivial to perform in the real world (Lessels & Ruddle, 2005). Even when the field of view (FOV) was restricted to (20 × 16°) and thus much smaller than the FOV of current HMDs, performance for real world walking was not significantly reduced. However, when the task was performed in VR, performance was significantly reduced whenever visual cues provided via HMD were not accompanied by real walking, both in a real-rotation and visual-only condition (Ruddle & Lessels, 2006a, 2009).

Later, Riecke *et al.* pointed out that in Ruddle and Lessels' setup, navigators could use the room's geometry, a rectangular arrangement of the pedestals and the regular orientation of the objects to maintain global orientation (Riecke et al., 2010a). To avoid these confounds, they removed the surrounding room, removed the pedestals without the boxes, refrained from using a landmark-rich environment, and randomly positioned and oriented all objects for each trial in their experiment. With this modified experimental design, participants performed substantially better when they were allowed to physically rotate compared to visual-only simulation. Physical walking provided additional (but smaller) performance benefits.

Nguyen-Vo *et al.* showed that if a participant can walk out of the array of boxes and look at the whole scene, they could memorize the overall layout of the boxes and plan their trajectory (Nguyen-Vo et al., 2018). Studies also suggest that even a single viewing of the layout can help a user retain spatial orientation knowledge, including relative distances, directions, and scale (Shelton & McNamara, 1997; Zhang, Mou, & McNamara, 2011). This implied that participants just needed to memorize a pre-planned trajectory instead of needing to gradually build up their spatial knowledge as they navigated, especially if they could see the layout from an advantageous position in a fully lit room. To force gradual spatial updating in participants, Nguyen-Vo *et al.* later experimented in a dark virtual environment with a virtual headlamp attached to the avatar's head (Nguyen-Vo et al., 2019). The virtual lamp illuminated only half of the play area and prevented participants from ever seeing the overall layout and all boxes at once. Using this experimental design, Nguyen-Vo *et al.* compared four levels of translational cues and controls (none, upper-body leaning while sitting, whole-body leaning while standing/stepping, physical walking) accompanied by full rotational cues in all conditions. Their findings show that even providing partial body-based translational cues can help to bring performance to the level of real walking, whereas just using the hand-held controller significantly reduced both performance and usability.

In summary, the navigational search task has gone through numerous iterations. Each iteration addresses previously found confounds, making it a rigorous task for evaluating spatial updating. Here, we build on and expand on this task, by for the first time including vertical locomotion in a navigational search task to study full 3D locomotion, similar to what drones and many computer games provide.

2.3 Motivation and Goal

To close this gap in the literature, we are in this paper mainly concerned with investigating if leaning-based flying interfaces like HeadJoystick can not only improve maneuvering ability (A. Hashemian et al., 2020) compared to the standard 2-thumbstick flying interfaces, but also improve spatial updating, which is critical for effective and low-cognitive-load navigation and situational awareness (Klatzky et al., 1998; Rieser, 1989; Farrell & Robertson, 1998; Presson & Montello, 1994; Riecke, Cunningham, & Bülthoff, 2007). Further, we want to ground the applicability of the interface by studying its impact on motion sickness and task load, as well as diverse aspects of user experience and usability.

RQ1: Does HeadJoystick improve spatial updating compared to a hand-held controller for 3D locomotion?

In the HeadJoystick interface, the upper body is leaning in the direction of the simulated motion. This partial body movement of leaning in the right direction provides consistent vestibular cues. These translational cues have been shown to reduce disorientation in the 2D navigational search (Nguyen-Vo et al., 2019). Hence, we hypothesize that they should yield improved spatial updating for the HeadJoystick in 3D navigation as well (H1).

RQ2: Does HeadJoystick help to reduce motion sickness in 3D navigation? When physically stationary individuals view compelling visual representations of self-motion without any matching non-visual cues, it can cause unease and induce motion sickness (Cheung, Howard, & Money, 1991; Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990; Riecke, Feuereissen, Rieser, & McNamara, 2015). This can cause illness in the user or even incapacitate them, limiting the utility of VR (Hettinger & Riccio, 1992). Further, sensory conflict is most prominent during the change in velocity (acceleration/deceleration) (Bonato, Bubka, Palmisano, Phillip, & Moreno, 2008; Keshavarz, Riecke, Hettinger, & Campos, 2015).

Previous studies for ground-based locomotion have also shown that if virtual locomotion is accompanied by matching body-based sensory information similar to real-world locomotion, it can help to reduce motion sickness (Aykent et al., 2014; B. D. Lawson, 2014). However, the literature indicates mixed results for partial body-based sensory information. Some ground-based locomotion studies reported no significant difference in motion sickness between leaning-based interfaces and hand-held controllers (Marchal et al., 2011; A. M. Hashemian & Riecke, 2017a), while others reported significant reductions of motion sickness with a leaning-based interface (Nguyen-Vo et al., 2019). Further, as far as the authors know, the literature does not provide a definitive answer on whether the benefits of such implementation translate to flying locomotion. Rognon *et al.* hypothesized increased motion sickness with the remote controller to explain their results, but do not have explicit measurements. In Pittman and LaViola's study, participants using Wiimote reported significantly less motion sickness than those using head-rotation and head-translation, but Wiimote did not use an HMD. Further, only 5 out of 18 participants reported more than 10% of total SSQ score after the experiment. In Hashemian *et al.*'s study, participants found a significant difference (again, change of <10% of total SSQ score) in motion sickness between real-rotation with leaning-based translation and controller-based translation and rotation conditions; however, implementing real-rotation with both leaning-based and controller-based translation did not produce a change that was statistically significant (A. Hashemian et al., 2020).

Despite these conflicting findings, HeadJoystick is designed for providing vestibular and proprioceptive cues that aid the visual self-motion perception provided by the HMD. Hand-held controllers like a Gamepad cannot provide these physical self-motion cues. To change the velocity in HeadJoystick the user has to physically lean in the direction of acceleration, thus providing at least some vestibular self-motion cues in the correct direction and thus reducing the visual-vestibular cue conflict. Thus, we hypothesize HeadJoystick should reduce motion sickness and thus potentially allow for more extended headset usage (H2). We performed a planned contrast to see if there is any trend in change in motion sickness even if both interfaces should produce minimal motion sickness.

RQ3: How do HeadJoystick and Gamepad affect the overall user experience and usability in 3D navigation?

For the HeadJoystick interface, the simulated motion is consistent with the direction of the upper body. So, any point in the space can be reached by freely leaning towards that direction. However, each thumbstick on a Gamepad is constrained to control only 2 DoF. So, even with real-rotation, to control 3 degrees of translation simultaneously the user needs to proportionately combine inputs from those two thumbsticks to travel in the desired 3D direction. Alternatively, users could only use one thumbstick at a time and alternate their input to the thumbsticks, and keep switching their plane of movement until they reach the target. Hashemian *et al.*'s study also showed that participants found HeadJoystick to be easier to learn and use than Gamepad (A. Hashemian et al., 2020). Thus, we hypothesize that HeadJoystick should be more intuitive to use and learn, and users should be able to use HeadJoystick more effectively, even without any previous exposure (H3).

In addition to the three specific aspects mentioned above, we are also interested in more generally exploring how the two interfaces affect user experience and usability. In Hashemian *et al.*'s study, participants rated HeadJoystick as providing overall better user experience and usability than Gamepad (A. Hashemian et al., 2020). We hypothesize that these findings can be replicated even in a different environment with a different task (spatial updating instead of maneuvering).

2.4 Method

2.4.1 Participants

From 25 users whom participated in our experiment, we excluded three participants and performed analysis with remaining 22 participants (10 female), 19 to 32 years old (M = 24.0, SD = 3.70). 15 of them casually/regularly played video-games on a computer or a gaming console; 13 of them had used 3D navigation with video games, 3D modeling or flight simulator; and 15 of them had used a HMD before. Among the three excluded participants, one experienced motion sickness during the study and dropped the experiment. The other two excluded participants showed unusually high SSQ scores. Although we did not observe anything unusual during the experiment, we realized they reported high SSQ scores even before the start of the study. Due to this discrepancy and unreliability, we excluded their data as well. The studies had approval of the SFU Research Ethics Board (#2018s0649).

2.4.2 Virtual Environment and Task

As our main goal was to investigate how well different interfaces support participants' spatial updating and situational awareness, we carefully designed the virtual environment (Figure 2.1) and task to avoid potential confounds reported in prior works (see Section 2.2.2). Specifically, as our main focus was to investigate and compare locomotion interfaces

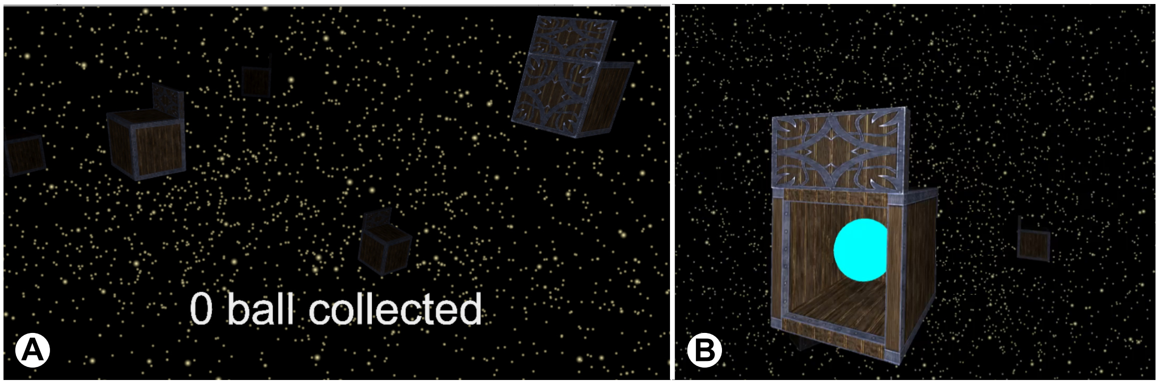

Figure 2.1: (A) A snapshot of a participant's view of the play area (6m × 3m cylinder) with the closed boxes. The light attached to the avatar's head lit half of the play area, 4.24m. Boxes became dimly lit as their distance increased from the player and stopped being visible when they were further than 4.24m. (B) The target, a blue ball, seen after approaching the box

and spatial orientation/updating performance, we carefully avoided all landmarks or global orientation cues. The experimental task was, apart from the changes described below, similar to the ground-based navigational search task in Nguyen-Vo *et al.*'s experiment, but generalized for 3D locomotion (flying) (Nguyen-Vo et al., 2019)[1]. To generalize for 3D, we tested different shapes and sizes of the play area prior to the main experiment. If the play area was too small, a user could quickly collect all eight balls without revisiting the boxes. If the virtual area was too big, they got easily lost in the vast void space with no global orientation cues (landmarks). We also observed that participants would keep going out of the play area when it was spherical. As a result of iterative pilot testing, we determined a cylindrical virtual area 6 meters in diameter and 3 meters in height would be a good fit for our experiment.

There were sixteen boxes scattered within this area, with eight of the boxes containing a blue ball (see Figure 2.1). The remaining eight boxes served as decoys. The participants' objective was to efficiently collect as many balls as possible. In our navigational search task, participants started each trial from the center of the cylinder. A trial ended when participants found all eight balls or the trial ran for 5 minutes. We chose to limit the trial length to reduce motion sickness.

Participants were explicitly told that the criteria for efficiency were the number of balls collected, the total distance traveled, and the number of revisits. Since it was possible to complete the game by collecting all the balls before 5 minutes, we also recorded the completion time.

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[1] `https:www.youtube.com/watch?v=xzTR_8sfZXA`

2.4.3 Interaction

To check if there was a ball inside a box, participants needed to approach it from its front side, indicated by an additional banner (Figure 2.1B). The box automatically opened when participants' viewpoints were close (within 90 cm from the box's center) and facing the front side (within ±45° from the box's forward vector). To prevent the accidental collection of the balls, the user needed to keep the box open for one second. The user was alerted through a ticking sound as the box opened, and it was followed by a 'ding' sound for collection.

As colliding with the boxes and any subsequent physics simulation would disorient the user and even induce motion sickness, we switched off collision detection for the boxes and the user could pass through them. However, to prevent participants from peeking into the boxes from the other sides, the ball became visible only when a box was approached from the front side.

2.4.4 Locomotion Modes

Hand-based controllers are still the most common interfaces for navigation in VR, especially when physical walking is not feasible. To choose among the hand-based controllers for the experiment, we compared the Vive controller that came with the headset and a gamepad. Through our pilot testing, we learned that the participants use their thumbs for controlling both kinds of controllers and release their thumbs to come to a halt. As a trackpad has no physical feedback that indicates the center, participants had difficulty providing proper input once they released their thumb, and as a result took time to adjust their input. A gamepad has thumbsticks loaded with springs that force the thumbsticks to come back to their center when released. Because of this, the user can locate the center much quickly. Further, a gamepad's thumbsticks are similar in design to the most common remote controller for drones. So, we chose to compare the HeadJoystick interface with a gamepad. Further, it adds comparability with Hashemian *et al.*'s original paper which proposed the HeadJoystick interface (A. Hashemian et al., 2020).

For both the Gamepad and HeadJoystick conditions, participants rotated the swivel chair they were sitting on to control the simulated rotations in VR. However, they translated in different manners. We chose to include only the interfaces that allow physical rotation because the importance of rotation in spatial updating has already been proved multiple times (Klatzky et al., 1998; Riecke et al., 2010a). Further, implementing physical rotations is no longer an issue, as HMDs are becoming increasingly wireless, and therefore have no cables to be entangled.

Gamepad Interface: For the Gamepad interface, the left control stick controlled horizontal translation velocities as illustrated in Figure 2.2. The right control stick controlled upward/downward translation speeds. Although physical rotation controlled yaw, for simplicity, we will refer to this interface as the Gamepad throughout the paper.

HeadJoystick Interface: In the HeadJoystick interface, head position determined the translation. The interface calibrated the zero-point before each use. Moving the user's head in any particular direction from that zero-point made the player move in the same direction. The distance of the head from the zero-point determined the speed of the virtual motion. To stop the motion, the user had to bring their head back to the zero-point. As a subsequent result, leaning forward and backward caused the user to move forward and backward, leaning left or right caused sideways motions, stretching their body up or slouching down created upward or downward motions, and coming back to the center stopped the motion.

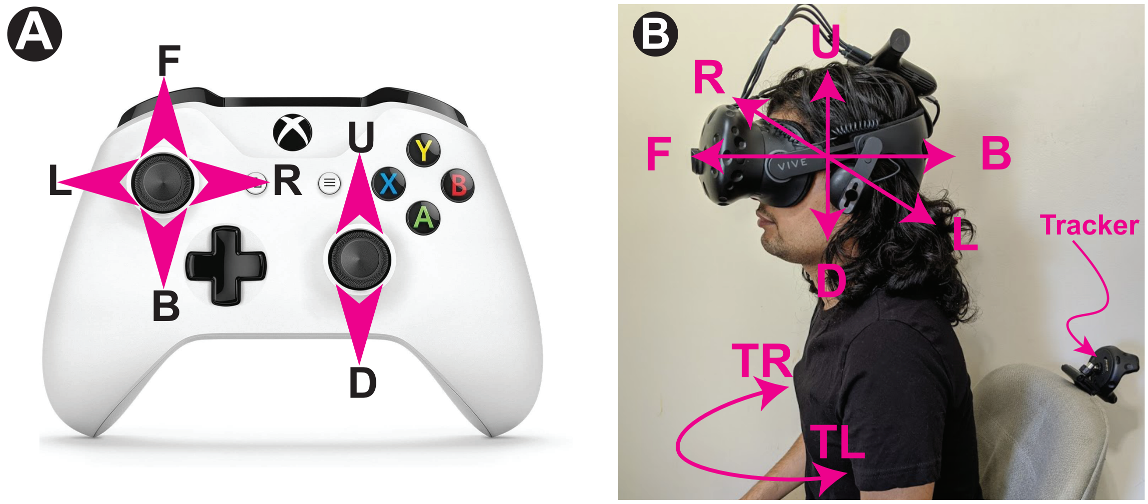


Figure 2.2: (A) In Gamepad, the left thumbstick controls the horizontal velocity (**F**orward, **B**ackward, **L**eft, **R**ight) and the right thumbstick controls the vertical velocity (**U**p, **D**own). (B) In HeadJoystick, the user's head position controls the velocity. In both cases, physical rotation (**T**urning **R**ight, **T**urning **L**eft) is applied.

The velocity calculation is based on a scaled exponential function, similar to the function for a smooth translation proposed by LaViola *et al.*'s study on leaning based locomotion (LaViola Jr, Feliz, Keefe, Zeleznik, et al., 2001).

$$F = \alpha e^{-\beta|\vec{head}\cdot\vec{V_{up}}|} \tag{2.1}$$

where α is the maximum speed factor, β controls the steepness of the exponential curve, $\vec{head}$ is a vector indicating the user's head orientation, and $\vec{V_{up}}$ is the vertical vector. Exponential implementation creates a smooth transition. It has been successfully implemented in other 2D interfaces (A. M. Hashemian & Riecke, 2017a; Nguyen-Vo et al., 2019). The same method also provides smooth translation in 3D when the projection of head orientation onto the plane $|\vec{head}\cdot\vec{V_{up}}|$ is replaced just with $|\vec{head}|$. It has successfully been implemented in Hashemian et. al's study. Please consult the appendix of Hashemian et. al (A. Hashemian et al., 2020) for a complete description of the HeadJoystick and its underlying mathematical model .

2.4.5 Experimental Design and Procedure

In this experiment, we compared the performance of the HeadJoystick and Gamepad interface. We collected the users' behavioral data while they were performing the tasks. After completing the trials, we asked them to fill out a questionnaire and performed a semi-structured open-ended interview. We deployed a 2-blocked, repeated measure experimental design. All participants performed the navigational search task twice for each interface, totaling 4 trials and thus up to 20 minutes of VR exposure in total. The order of the interfaces was counter-balanced to account for the order effects and maturation effects.

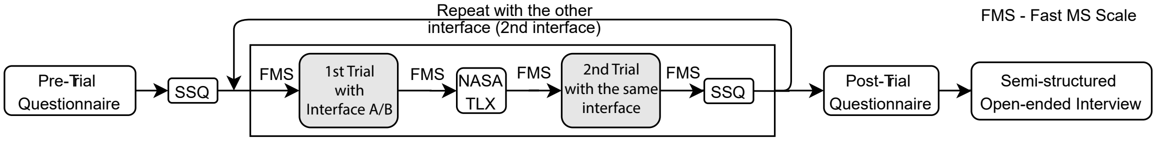


Figure 2.3: Experimental Procedure

2.4.6 Motion Control Model

The overall procedure is illustrated in Figure 2.3. After reading and signing the informed consent form, participants filled out a pre-experiment questionnaire before starting the experiment, asking about their age, gender and previous experience with video games and HMDs. Then, they were guided through the tasks and tried out both interfaces before the actual experiment started. Before they began the experiment, they filled out the Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane, Berbaum, & Lilienthal, 1993). They started with one of the two interfaces. They performed two trials with the first interface. Participants were asked to take off the HMD after the first trial and fill out NASA's Task Load Index (TLX) (Hart & Staveland, 1988) to reduce the potential for motion sickness. After completing the second trial, they filled out the SSQ again. The questionnaires were strategically placed between each trial to provide a short break between the trials. They repeated the same procedure including two trials with the interface they had not used in the first two trials.

Further, to assess motion sickness issues, we asked them to estimate their current state of motion sickness before and after each trial. They rated their motion sickness on a scale of 0-100. A rating of '0' meant 'I am completely fine and have no motion sickness symptoms' and '100' meant 'I am feeling very sick and about to throw up.' Based on their scale, we recommended that they go ahead with the trial, take a longer break or drop the experiment. This scale was adapted from the Fast Motion Sickness Scale (FMS), which goes from 0-20 (Keshavarz & Hecht, 2011).

Before switching the interface, participants were asked to take a minimum five-minute break, including the time required to fill out the questionnaires. In addition to taking a mandatory break, participants were encouraged to take a short walk or drink water.

After completing all four trials, they completed a post-study survey questionnaire (detailed in Section 2.5.2) and responded verbally to semi-structured open-ended interview questions. The whole study took, on average, about 1 hour to complete.

2.5 Results

2.5.1 Behavioral Measures

Six quantitatively measured behavioral data types are summarized and plotted in Figure 2.4. They were analyzed using 2 × 2 × 2 repeated-measures ANOVAs with the independent variables **interface** (HeadJoystick vs. Gamepad), **repetition** (1st vs. 2nd trial) and order of the interface assignment, **group** (GamepadFirst vs. HeadJoystickFirst). Since neither repetition, group, any interaction with the group, or the interaction between interface and repetition showed any significant effects for any of the dependent variables (all $p's > .05$), we only report the main effects of interface below. Unless stated otherwise, all test assumptions for ANOVA were confirmed in each case.

Participants collected significantly more balls when using HeadJoystick: Figure 2.4A. Participants collected all eight balls in 31 out of 44 trials with HeadJoystick and 26 out of 44 trials with Gamepad. All participants were able to collect at least 6 balls with HeadJoystick and at least 4 balls with Gamepad. On average, participants were able to collect more balls when using HeadJoystick ($M = 7.61, SD = .655$) than Gamepad ($M = 7.30, SD = 1.01$), $F(1, 42) = 4.51, p = .040, \eta_p^2 = .097$.

Task completion time did not differ between interfaces: Figure 2.4B. Participants reached the time limit of 5 minute in 13 trials when using the HeadJoystick vs. 18 trials when using the Gamepad. The fastest participant finished the task in 69 seconds with HeadJoystick and 48 seconds with Gamepad. Repeated measures ANOVA showed no significant difference in completion time between HeadJoystick ($M = 214\ s, SD = 76.5\ s$) and Gamepad ($M = 217\ s, SD = 84.6\ s$), $F(1, 42) = .119, p = .732, \eta_p^2 = .003$.

Participants travelled significantly less while using HeadJoystick: Figure 2.4C. Participants travelled from 33.5 m to 143.9 m with HeadJoystick and from 30.8 m to 277.4 m with Gamepad. ANOVA showed that participants overall travelled significantly less with the HeadJoystick ($M = 72.3\ m, SD = 28.3\ m$) than the Gamepad ($M = 116.8\ m, SD = 56.9\ m$), $F(1, 42) = 25.4$, $p < .001$, $\eta_p^2 = .378$

HeadJoystick marginally increased overall head, but not body rotations: Figure 2.4D&E. We recorded the users' body rotation (rotation of the chair) and head rotation (rotation of HMD) because it would inform us if either of the interfaces restricted or reduced looking around and thus potentially hindered situational awareness. The accu-

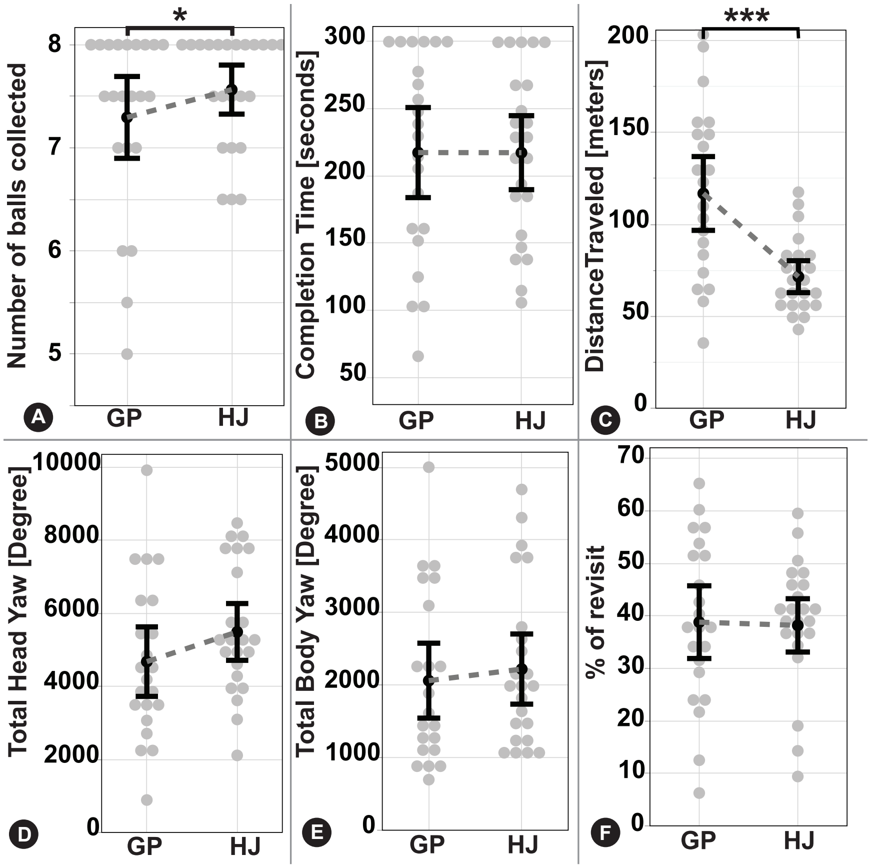


Figure 2.4: Behavioral data plot for Gamepad (GP) and HeadJoystick (HJ) with an overall mean (black dots), individual participants' average (gray dots) and error bars at 95% Confidence Intervals (CI).

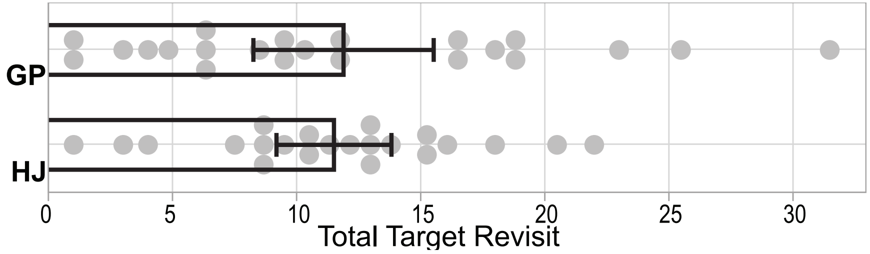


Figure 2.5: Total target (boxes) revisited by the participants with Gamepad and HeadJoystick

mulated body rotation for HeadJoystick ($M = 2255°, SD = 1360°$) and Gamepad ($M = 2061°, SD = 1260°$) did not differ statistically, $F(1, 42) = .782$, $p = .382$, $\eta_p^2 = .018$. The accumulated head rotation, however, showed a marginally significant effect $F(1, 42) = 3.88$, $p = .056$, $\eta_p^2 = .085$, indicating marginally larger accumulated head rotation for HeadJoystick ($M = 5520°, SD = 2410°$) compared to Gamepad ($M = 4670°, SD = 2490°$).

There was no significant difference between % of revisit (ratio of revisited boxes to the total number of boxes visited): Figure 2.4F. Only 5 participants (2

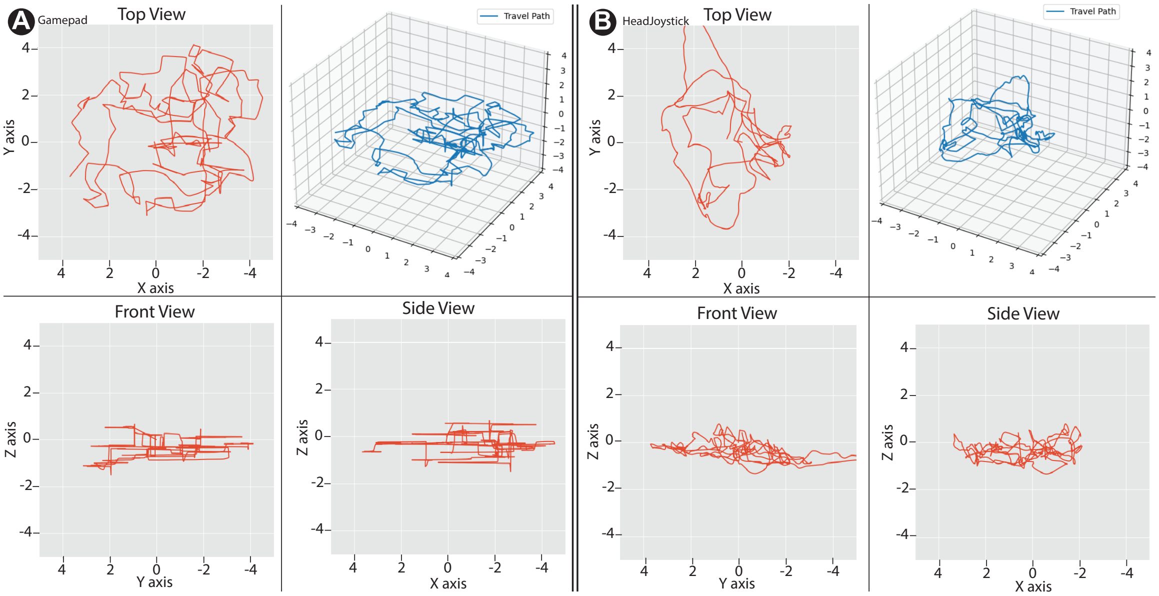


Figure 2.6: Representative travel path (isometric, top, front and side) for (A) Gamepad and (B) HeadJoystick

with Gamepad, 3 with HeadJoystick) had no revisits to the target boxes before the trial completed (note that this is not visible in Figure 2.5 as the graph is averaged over the two trials per interface). Some participants travelled slowly and visited only a few boxes. Others travelled quickly and visited as many boxes as possible. Since the total number of revisits depends on the total number of targets visited by the participants, we analyzed the ratio of revisited boxes to the total number of boxes visited by the participants. The mean % revisits was not significantly different, $F(1,42) = .018$, $p = .894$, $\eta_p^2 < .001$, between the HeadJoystick ($M = 38.3$, $SD = 18.7$) and Gamepad ($M = 38.8$, $SD = 18.8$).

We also recorded the travel path of the trials to investigate potential behavioral difference between the interfaces during navigation. Since putting the travel path of all the users and trials in a single graph created a dense path plot with impossible to distinguish travel instances, we show representative travel paths for Gamepad and HeadJoystick from a randomly selected participant (Figure 2.6). As the figure illustrates, with the Gamepad, participants restricted themselves to controlling no more than 2 translational DoF at a time, while with HeadJoystick, they controlled all available DoFs simultaneously. This is indicated by the straight horizontal and vertical lines with almost perpendicular turns with Gamepad (front and side views, Figure 2.6A) and curved paths with HeadJoystick in all projections (Figure 2.6B). Plots of almost all travel paths of individual trials showed similar trends.

2.5.2 Subjective Ratings

Motion Sickness

Simulation Sickness Questionnaire The **time** of SSQ measurement (participant's SSQ score before - 0, after completing the trials with the first interface - 1, and after completing the trials with the second interface - 2) was one of the independent variables (within-subject factor). The order of assignment of the first interface (**group** - HeadJoystick-First/GamepadFirst) was the second independent variable (between-subject factor). We chose to interpret the data with the time of SSQ measurement rather than the interfaces themselves because motion sickness accumulates over time. We performed a two-way mixed ANOVA using those two factors. Greenhouse-Geisser correction was applied whenever the assumption of sphericity was violated. As discussed in section 2.3, we also compared Pre-Experiment SSQ scores to SSQ scores after using the first and second interfaces as planned contrasts with Bonferroni correction, summarized in Table 2.1.

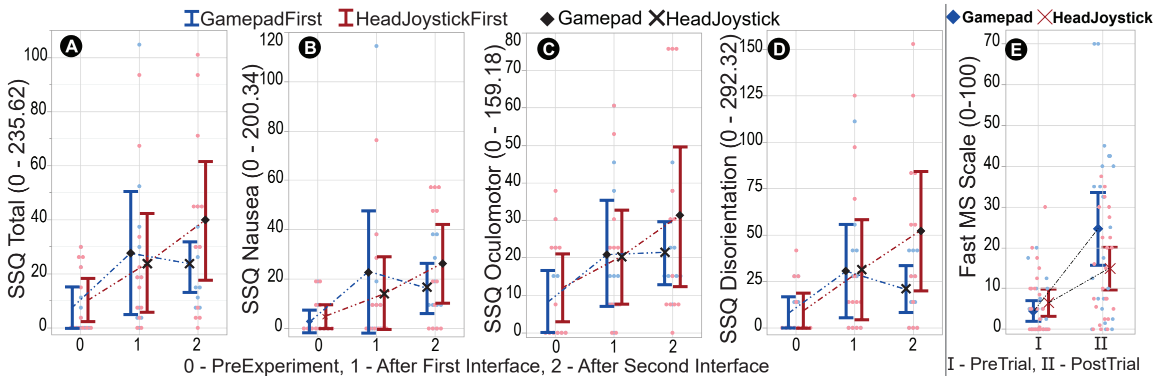


Figure 2.7: User's self-report of motion sickness using SSQ questionnaire before the experiment started ("Pre-Experiment"), after using the 1st interface, and after using the 2nd interface. Blue and red lines indicate an average participant using Gamepad and HeadJoystick as their first interface respectively. ♦ = Gamepad interface, X = HeadJoystick interface, $CI = 95\%$

Each trial produced only minimal motion sickness on average, and the average SSQ score after the experiment was 16.8% (or 39.7 in the SSQ scale from 0 to 235.32). The highest SSQ scores reached by any participant was 44.4% (104.7). We can see from Figure 2.7 that for an average participant, when they used Gamepad as their first interface (blue line), SSQ total and its sub-scales increased from Pre-Experiment to after using the Gamepad, and it stayed at the same level or even decreased after switching to HeadJoystick. For an average participant using HeadJoystick as their first interface (red line), not only did SSQ total and its sub-scales increase after using the HeadJoystick, it further continued increasing after switching to Gamepad. Inferential statistical analysis done below shows the same result.

Total SSQ scores increased significantly after using Gamepad and increased marginally after using HeadJoystick, Figure 2.7A. ANOVA revealed a main effect of time (Pre-Experiment, after the 1st interface, and after the 2nd interface), $F(1.85, 36.9) = 8.05, p = .001, \eta_p^2 = .287$. There was no effect of group (GamepadFirst/HeadJoystickFirst), $F(1, 20) = .457, p = .507, \eta_p^2 = .022$ as well as no interaction between time × group $F(1.85, 36.9) = 1.71, p = .197, \eta_p^2 = .079$. LSMeans (Least Squares Means) contrast showed that even with Bonferroni correction ($p < .025$ is significant) in the GamepadFirst group, the total SSQ score increased significantly from Pre-Experiment ($M = 7.48, SD = 10.7$) to Gamepad use ($M = 27.7, SD = 31.8$). However, the SSQ score dropped after switching to HeadJoystick ($M = 22.4, SD = 13.1$) as the second interface, and was no longer significantly higher than the Pre-Experiment score (blue line in Figure 2.7A). In contrast, for the HeadJoystickFirst group when using HeadJoystick for their 1st trial ($M = 24.0, SD = 28.7$) their motion sickness increased only non-significantly from Pre-Experiment ($M = 10.3, SD = 12.6$). When they switched from HeadJoystick to Gamepad, their motion sickness ($M = 39.6, SD = 34.5$) shot up and it was significantly higher than their Pre-Experiment scores (red line in Figure 2.7A).

Participants got significantly nauseous after using Gamepad while there was no significant change with HeadJoystick, Figure 2.7B. ANOVA revealed a main effect of time, $F(1.79, 35.8) = 5.67, p = .007, \eta_p^2 = .221$. However, there was no effect of group, $F(1, 20) = .031, p = .861, \eta_p^2 = .002$ as well as no interaction between time × group $F(1.79, 35.8) = 1.40, p = .260, \eta_p^2 = .065$. LSMeans contrast showed that in the GamepadFirst group, the nausea score increased significantly from Pre-Experiment ($M = 2.86, SD = 6.44$) to Gamepad use ($M = 22.9, SD = 34.6$), $F(1, 40) = 5.91, p = .020$. However, switching to HeadJoystick as the second interface reduced nausea scores ($M = 16.2, SD = 14.3$) and they were no longer significantly higher than the Pre-Experiment scores (blue line in Figure 2.7B). Similarly, for the HeadJoystickFirst group, nausea scores after their 1st trial with the HeadJoystick ($M = 14.3, SD = 23.2$) were not significantly elevated compared to their Pre-Experiment nausea scores ($M = 4.77, SD = 7.6$). When they switched from HeadJoystick to Gamepad, their nausea score increased ($M = 26.2, SD = 25.1$) and were significantly higher than their Pre-Experiment scores (red line in Figure 2.7B).

Participants had oculomotor issues after using Gamepad while there were mixed results with HeadJoystick, Figure 2.7C. ANOVA revealed a main effect of time, $F(1.99, 39.8) = 7.72, p < .001, \eta_p^2 = .279$, indicating an overall increase over trials as shown in Figure 2.7C. However, there was no effect of group, $F(1, 20) = .383, p = .543, \eta_p^2 = .019$ as well as no interaction between time × group $F(1.99, 39.8) = .853, p = .434, \eta_p^2 = .041$. LSMeans contrast showed for the GamepadFirst group a marginally significant increase in oculomotor issues (eye strain, blurred vision, difficulty focusing, etc.) from Pre-Experiment ($M = 8.34, SD = 11.6$) to Gamepad use ($M = 21.2, SD = 19.8$) (note: with Bonferroni correction, significant results require $p < .05$). Switching to HeadJoystick as the second interface did not change the ratings ($M = 21.2, SD = 11.7$) and the difference remained marginally significant from the Pre-Experiment score (blue line in Figure 2.7C). In contrast, for the HeadJoystickFirst group there was no significant increase in oculomotor issues from Pre-Experiment ($M = 12.0, SD = 14.25$) to their first trial ($M = 20.2, SD = 23.2$). When they switched from HeadJoystick to Gamepad, their ratings increased ($M = 30.1, SD = 29.3$) and were significantly higher than their Pre-Experiment ratings, (red line in Figure 2.7C).

Table 2.1: LSMeans Contrast was used to compare the Pre-Experiment SSQ score with SSQ score after Gamepad use and HeadJoystick use. Bonferroni correction was used for doubling the comparison. Significant differences ($p \leq 2.5\%$) are highlighted in green, and a lighter shade of green indicates marginally significant results ($p \leq 5\%$).

	GamepadFirst				HeadJoystickFirst			
	Pre vs Gamepad		Pre vs HJ		Pre vs Gamepad		Pre vs HJ	
	F(1,40)	p	F(1,40)	p	F(1,40)	p	F(1,40)	p
Total	5.62	.023	3.08	.087	14.2	<.001	3.11	.086
Nausea	5.91	.020	2.63	.113	8.14	.007	1.61	.212
Oculomotor	4.48	.041	4.48	.041	11.6	.002	2.18	.147
Disorientation	4.10	.050	1.30	.261	18.3	<.001	4.82	.034

Participants had disorientation issues after using Gamepad while there were mixed results with HeadJoystick, Figure 2.7D. ANOVA revealed a main effect of time, $F(1.92, 38.3) = 7.77, p < .002, \eta_p^2 = .280$ and marginal interaction between time × group $F(1.92, 38.3) = .280, p = .075, \eta_p^2 = .041$. However, there was no effect of group, $F(1, 20) = .948, p = .342, \eta_p^2 = .045$. LSMeans contrast showed that for the GamepadFirst group, the increase in disorientation was marginally significant from Pre-Experiment ($M = 8.35, SD = 11.7$) to Gamepad use ($M = 30.6, SD = 35.2$), $F(1, 40) = 4.10, p = .050$. Switching to HeadJoystick as the second interface decreased disorientation ($M = 20.9, SD = 17.7$) to a level that was no longer significantly different from Pre-Experiment scores, $F(1, 40) = 1.30, p = .261$ (blue line in Figure 2.7D). For the HeadJoystickFirst group, disorientation scores increased marginally from Pre-Experiment ($M = 9.28, SD = 14.9$) to their first trial using the HeadJoystick ($M = 31.3, SD = 42.4$), $F(1, 40) = 4.82, p = .034$. When they switched from HeadJoystick to Gamepad, their disorientation ratings increased ($M = 52.2, SD = 50.8$) and were now significantly higher than their Pre-Experiment ratings, $F(1, 40) = 18.3, p < .001$ (red line in Figure 2.7D).

Fast MS Scale

Participants reported higher FMS increase after using Gamepad than after using HeadJoystick, Figure 2.7E. Participants' self-reported motion sickness score (Scale: 0-100) given before and after each trial was analyzed using 2-factor repeated measures ANOVA. The results show that self-reported motion sickness score increased overall from before to after a trial, $F(1, 21) = 30.0, p < .001, \eta_p^2 = .588$ (Before: $M = 5.43$, $SD = 7.23$ | After: $M = 19.3$, $SD = 18.2$). However, as illustrated in Figure 2.7E, the interface × time interaction was also significant, $F(1, 21) = 21.1, p < .001, \eta_p^2 = .501$, indicating the degree of motion sickness increase from pre- to post-trial was larger for the Gamepad (Pre: M =

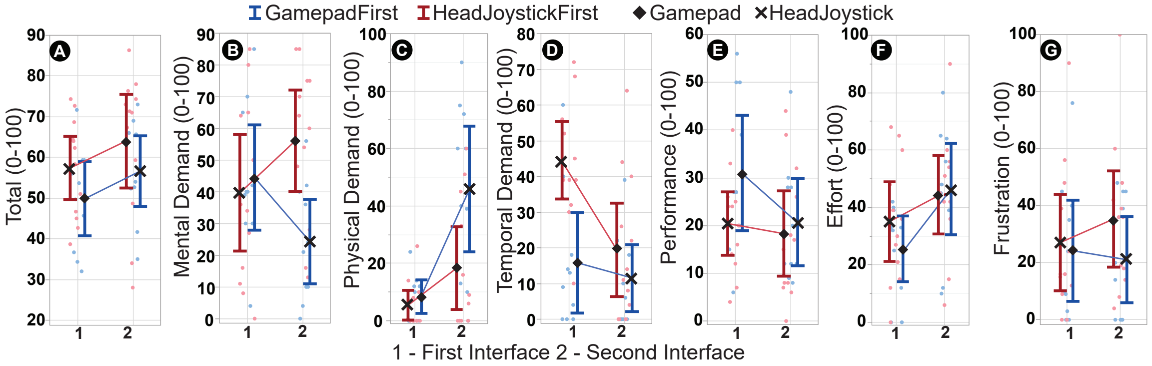


Figure 2.8: NASA TLX in %, after using the 1st interface then 2nd interface. The blue line and red line indicate participants using Gamepad and HeadJoystick respectively, for their first trial. ♦ = Gamepad interface, X = HeadJoystick interface, CI = 0.95

4.66, SD = 619 — Post: M = 25.0, SD = 21.7, a 436% increase) than for the HeadJoystick (Pre: M = 6.21, SD = 8.22 — Post: M = 13.6, SD = 12.1), where motion sickness only increased by 119%.

Task Load

The final weighted score as well as individual six sub-scores from the NASA Task Load Index (TLX) for the 2 factors, **time** (first vs. second interface), within-subject factor) and interface order (participant **group**: GamepadFirst or HeadJoystickFirst, between-subject factor) were analyzed with two-way mixed ANOVAs, with statistical results, means, and standard errors summarized in Table 2.2. We chose to analyze the TLX with time rather than interface as a main factor because it considers the effect of switching from HeadJoystick to Gamepad and vice versa. Further, this 2x2 ANOVA has factors with only two levels each. Therefore, the interaction between time and group (time × group) is equivalent to the main effect of interface in an ANOVA analysis with interface as one of the factors. To make the results' interpretation more easily understandable and comparable, we have scaled each measurement to 0-100.

The participants felt the task was overall more demanding with the second interface irrespective of the group, Figure 2.8A and Table 2.2. However, there was no significant effect of group and no significant interaction between time and group for total NASA TLX scores. This equivalently means that there was no significant main effect of the interface.

Participants felt HeadJoystick was mentally less demanding, Figure 2.8B. The analysis did not show a main effect of time or group. However, there was a significant interaction between time and group. Irrespective of the group, the mental demand with the first interface was around 50%. However, when the participants switched from Gamepad to HeadJoystick they found the mental demand to be significantly reduced, whereas in

Table 2.2: NASA Task Load demands for both interfaces are analyzed with ANOVA. Significant differences ($p \leq 5\%$) are highlighted in green, and a lighter shade of green indicates marginally significant results ($p \leq 10\%$).

Measures (%)	1st Interface				2nd Interface				Time (Within)			Group (First Interface/ Between)			Time x Group[1]		
	GamePad		HeadJoystick		Gamepad		HeadJoystick										
	Mean (M)	Standard Error (SE)	Mean (M)	Standard Error (SE)	Mean (M)	Standard Error (SE)	Mean (M)	Standard Error (SE)	F(1,20)	p	η_p^2	F(1,20)	p	η_p^2	F(1,20)	p	η_p^2
Total Task Load	49.8	12.7	57.3	12.2	64.0	18.1	56.6	12.1	4.50	.047	.184	2.07	.166	.094	.001	.973	<.001
Mental Demand	44.5	23.2	39.7	28.9	56.1	25.2	24.3	18.6	.072	.792	.004	3.00	.099	.130	6.70	.018	.251
Physical Demand	8.40	8.15	5.42	8.16	18.33	22.6	45.9	30.6	18.6	<.001	.482	6.38	.020	.242	4.43	.048	.181
Temporal Demand	15.8	19.7	44.5	17.1	19.4	20.6	11.5	13.1	8.48	.009	.298	9.96	.005	.332	4.24	.053	.175
Performance	31.0	16.9	20.4	10.4	18.3	14.0	20.7	12.8	2.47	.132	.110	2.28	.147	.102	1.09	.310	.051
Effort	25.6	16.0	35.1	21.8	44.4	21.5	46.4	22.2	8.96	.007	.309	.266	.612	.013	1.30	.268	.061
Frustration	24.2	24.8	27.1	26.6	35.3	26.6	21.1	21.1	.158	.695	.008	1.00	.329	.048	.766	.392	.037

[1] It is equivalent to the main effect of Interface (within) when the factors of ANOVA are Interface and Group

the group that switched to Gamepad from HeadJoystick, the mental demand ratings went significantly up for the second interface. This is corroborated by the significant overall effect of interface, with significantly higher mental demand ratings for the Gamepad ($M = 50.8, SD = 24.5$) than HeadJoystick ($M = 32.7, SD = 5.43$), $F(1,20) = 6.70, p = .018, \eta_p^2 < .001$.

Participants felt HeadJoystick was physically more demanding, Figure 2.8C. The analysis showed a main effect of time as well as group. The second interface was rated as more physically demanding ($M = 30.9, SD = 29.5$) than the first interface ($M = 6.77, SD = 8.11$) and the GamepadFirst group found the task to be more physically demanding ($M = 27.2, SD = 4.47$) than the HeadJoystickFirst group ($M = 11.9, SD = 4.08$). There was also an interaction between time × group. Thus, the physical demand of the HeadJoystick ($M = 23.8, SD = 29.4$) was rated higher than that of Gamepad ($M = 13.8, SD = 18.0$), $F(1,20) = 4.43, p = .048, \eta_p^2 = .181$.

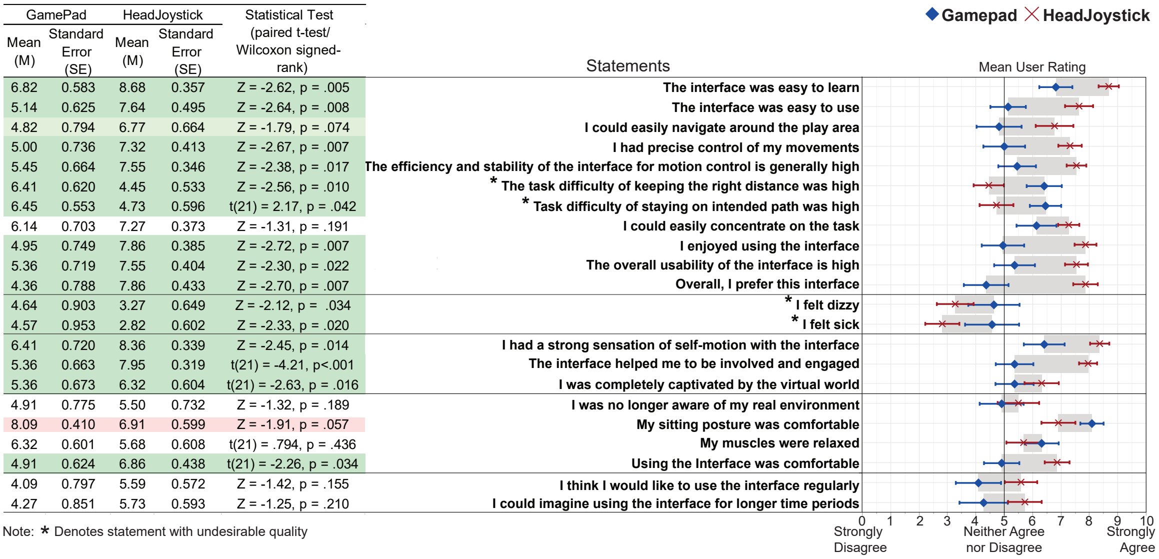
Participants found Gamepad to marginally decrease temporal demand (time pressure), Figure 2.8D. As with the physical demand, there was a main effect on time as well as group. In general, the second interface ($M = 15.8, SD = 17.7$) had lower temporal demand than the first interface ($M = 31.5, SD = 23.1$). In particular, the group that switched from HeadJoystick to Gamepad reported lower time pressure registering a marginally significant interaction; i.e., Gamepad ($M = 17.8, SD = 19.8$) had marginally lower temporal demand than HeadJoystick ($M = 29.5, SD = 22.6$).

The participants felt the task needed more effort in their second trial irrespective of the interface, Figure 2.8F. The second interface ($M = 45.3, SD = 21.3$) had significantly higher effort ratings than the first interface ($M = 30.8, SD = 19.6$). There was no significant difference between the groups or interaction between time and group.

There were no statistically significant main effects or interactions on performance or frustration Figure 2.8E&G.

Post-Experiment Questionnaire and Interview

Participants filled out a post-experiment questionnaire with 22 questions for each of the two interfaces, addressing different aspects like usability and performance, motion sickness, comfort, and immersion. The ratings were compared using t-tests, or Wilcoxon signed-rank tests whenever the assumption of normality was violated.



GamePad Mean (M)	GamePad Standard Error (SE)	HeadJoystick Mean (M)	HeadJoystick Standard Error (SE)	Statistical Test (paired t-test/ Wilcoxon signed-rank)	Statements
6.82	0.583	8.68	0.357	Z = -2.62, p = .005	The interface was easy to learn
5.14	0.625	7.64	0.495	Z = -2.64, p = .008	The interface was easy to use
4.82	0.794	6.77	0.664	Z = -1.79, p = .074	I could easily navigate around the play area
5.00	0.736	7.32	0.413	Z = -2.67, p = .007	I had precise control of my movements
5.45	0.664	7.55	0.346	Z = -2.38, p = .017	The efficiency and stability of the interface for motion control is generally high
6.41	0.620	4.45	0.533	Z = -2.56, p = .010	* The task difficulty of keeping the right distance was high
6.45	0.553	4.73	0.596	t(21) = 2.17, p = .042	* Task difficulty of staying on intended path was high
6.14	0.703	7.27	0.373	Z = -1.31, p = .191	I could easily concentrate on the task
4.95	0.749	7.86	0.385	Z = -2.72, p = .007	I enjoyed using the interface
5.36	0.719	7.55	0.404	Z = -2.30, p = .022	The overall usability of the interface is high
4.36	0.788	7.86	0.433	Z = -2.70, p = .007	Overall, I prefer this interface
4.64	0.903	3.27	0.649	Z = -2.12, p = .034	* I felt dizzy
4.57	0.953	2.82	0.602	Z = -2.33, p = .020	* I felt sick
6.41	0.720	8.36	0.339	Z = -2.45, p = .014	I had a strong sensation of self-motion with the interface
5.36	0.663	7.95	0.319	t(21) = -4.21, p<.001	The interface helped me to be involved and engaged
5.36	0.673	6.32	0.604	t(21) = -2.63, p = .016	I was completely captivated by the virtual world
4.91	0.775	5.50	0.732	Z = -1.32, p = .189	I was no longer aware of my real environment
8.09	0.410	6.91	0.599	Z = -1.91, p = .057	My sitting posture was comfortable
6.32	0.601	5.68	0.608	t(21) = .794, p = .436	My muscles were relaxed
4.91	0.624	6.86	0.438	t(21) = -2.26, p = .034	Using the Interface was comfortable
4.09	0.797	5.59	0.572	Z = -1.42, p = .155	I think I would like to use the interface regularly
4.27	0.851	5.73	0.593	Z = -1.25, p = .210	I could imagine using the interface for longer time periods

Note: * Denotes statement with undesirable quality

Figure 2.9: User rating regarding statements about usability and preference, motion sickness, immersion, comfort, and long-term use. Green and lighter shade of green respectively indicate significant ($p \leq 5\%$) and marginally significant ($p \leq 10\%$) differences in favor of HeadJoystick. Lighter shade of red indicates marginally higher ratings in favor of Gamepad ($p \leq 10\%$). Note: * denotes statements with undesirable quality (reversed scale). Effectively, the green highlights in those statements with * indicate that HeadJoystick had lower task difficulty and made participants less motion sick. ⧫ = Gamepad interface, × = HeadJoystick interface, CI = 95%

Figure 2.9 summarizes descriptive and inferential statistics. As seen from the plot, while participants did not have a strong opinion about Gamepad for the majority of the statements (most averages were near 5, neither agree nor disagree), for HeadJoystick they had a stronger positive opinion (positive statements) or stronger negative opinion (negative statements). Compared to the Gamepad, the HeadJoystick interface was rated as **easier to learn**, **easier to use**, gave more **control**, and was more **enjoyable** and **preferable**. It also made them **less motion sick** than Gamepad while increasing **immersion** and **vection**. That is, all significant effects were in favour of the HeadJoystick over the Gamepad. Both interfaces were judged to provide a comfortable sitting position (Gamepad, M = 6.83, SD = .551 | HeadJoystick, M = 7.92, SD = .394), although the Gamepad provided a slightly (but only marginally significantly) more comfortable **sitting posture**.

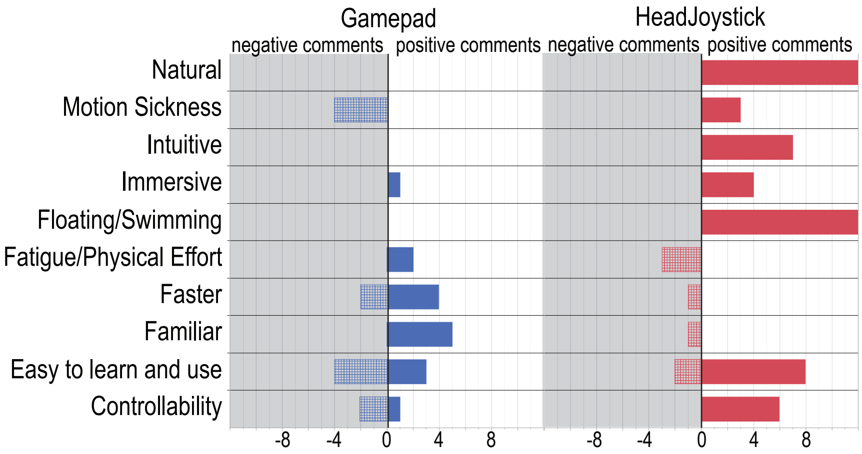


Figure 2.10: Thematic count of participants' response in post-experiment interview. The x-axis represents the number of participants mentioning the themes on the y-axis. Bars to the left (gray area) correspond to the number of negative comments about that topic whereas bars to the right (white background) represent the number of positive comments.

We performed semi-structured open-ended interviews with the participants after they completed the post-experiment questionnaire to get more insight into their choices and underlying reasons for those choices. 16 out of 22 participants mentioned in the interview that they preferred HeadJoystick over Gamepad. As seen in Figure 2.10, the recurrent themes among the participants for preferring the HeadJoystick over Gamepad were that HeadJoystick made them **less sick**, it was **easier to learn and use**, it was **intuitive**, it provided better **controllability**, it felt **natural**, there was a stronger sense of **self-motion (floating/swimming)**, and the virtual environment felt more **immersive**. Even though these participants preferred HeadJoystick over Gamepad, they still felt Gamepad had the advantages of familiarity, HeadJoystick would be fatiguing after a long use, and *"it would be hard to stand still with HeadJoystick"* [P13].

Five participants preferred Gamepad over HeadJoystick. The recurrent themes among the participants for preferring the Gamepad were **familiarity**, **ease of control**, **faster** and **less physical effort**. However, even among those who preferred Gamepad over HeadJoystick, some mentioned that the HeadJoystick made them less sick and a few appreciated the novel approach to VR locomotion.

Among the listed thematic counts in Figure 2.10, motion sickness turned out to be such a predominant concern with Gamepad that when we asked, *"How was your experience?"* as the first question after the experiment, several participants immediately responded:

> *"Felt like throwing up after using Gamepad"* {P03}
>
> *"Fun with the HeadJoystick but got dizzying after using Gamepad"* {P18}
>
> *"Gamepad was terrible... made me almost sick"* {P13}

> *"…Gamepad made me sick…"* {P25}

As we wanted to understand why they preferred one interface over the other we had also specifically asked *'What did you like about the locomotion interfaces?'*, the minimal cognitive load and intuitiveness of the HeadJoystick was one of the most consistent responses.

> *"HeadJoystick is more intuitive. You don't really have to learn to use it."* {P17}
>
> *"There was no cognitive load… with the HeadJoystick, motion was intuitive and [I] could concentrate more in the task."* {P13}
>
> *"Head one [HeadJoystick] is more intuitive. It feels like I am swimming."* {P23}

As for the Gamepad, participants liked that they were *"familiar"* {P16, P22} with its mechanics. However, they were split between *"easy to use"* {P12} due to its familiarity and *"difficult"* {P25} due to confinement in a single plane, i.e., *"moved in either vertical direction or moved in the horizontal plane"* {P01} as well as the apparent disjunction between *"two different kind of movements"* {P09, P23}, i.e., physical rotation and controller translation.

Other reasons for preferring one interfaces over the others included enjoyment, better control, naturalness and required effort:

> *"Because [HeadJoystick] was easier to learn. More enjoyable - feels like flying in VR."* {P05}
>
> *"[HeadJoystick] gives more control and [is] more precise."* {P09}
>
> *"[HeadJoystick] is more matched to the body. Felt similar to scuba diving."* {P14}
>
> *"HeadJoystick is easy to control and felt more immersive."* {P15}
>
> *"The Vive did not fit perfectly. It was also heavy. So, I was wary about moving properly for the HeadJoystick.* {P06}
>
> *"Gamepad made me dizzy, but still, it required less effort."* {P18}

We also asked specific question regarding their strategies with both interfaces. When we asked, *'Did you use any strategies? Were they different for the different interfaces?'*, many participants indicated using different search strategies depending on which interface they used. For Gamepad, they tended to first search horizontally, went up or down and then searched on that new level and so on, while avoiding motions that involved all three translational degrees of freedom. For example, P12 stated that they *"stayed in [the] same level, searched there then changed altitude"*. At the same time, for HeadJoystick they *"looked around in circle"* {P13}. Participants' descriptions of their travel strategies of moving in distinct planes for the controller but more fluidly through 3D space with the HeadJoystick mirrors the plots of their trajectories in Figure 2.6.

2.6 Discussion

This paper presents the first study exploring the effect of partial body-based self-motion cues, in the form of a leaning-based interface, on spatial updating while flying in virtual 3D space. Currently, flying is typically achieved through low-fidelity interfaces like a gamepad, joystick, keyboard, or point-and-click teleportation, or through high-fidelity interfaces with actuators or motors, like motion platforms (McMahan, 2011). We explore a relatively novel flying interface (HeadJoystick) that tries to bring together the advantages of both low- and high-fidelity interfaces: it is embodied, inexpensive, easy to set up, provides at least minimal translational motion cueing and full rotational cues, and is capable of controlling all four DoFs needed for full flight control, as discussed in more detail in (A. Hashemian et al., 2020).

Though past studies have shown that leaning-based interfaces can improve spatial perception and orientation in ground-based (2D) locomotion (Harris et al., 2014; Nguyen-Vo et al., 2019), leaning-based interfaces with the capability to control all four DoFs needed for full flight control have not been scrutinized in these contexts. We discuss the findings of our experiment in the context of our main research questions below.

RQ1: Does HeadJoystick improve spatial updating compared to a hand-held controller for 3D locomotion?

Indeed, participants collected significantly more balls with HeadJoystick, while being more efficient, i.e., travelling less distance. These quantitative findings indicate better spatial updating with the HeadJoystick.

We propose that the better performance of HeadJoystick for spatial updating can be mainly attributed to two factors. First, participants mention a strong sense of self-motion in our study when using the HeadJoystick. They felt they were *"actually floating"* [P19] and moving in the space. The importance of non-visual and embodied self-motion in a variety of spatial orientation and updating tasks has been shown through a number of studies (Ruddle & Lessels, 2009; Riecke et al., 2010a, 2015; Chance et al., 1998; Waller et al., 2004; Ruddle, 2013; Klatzky et al., 1998; Kearns et al., 2002; Ruddle, Volkova, Mohler, & Bülthoff, 2011; Sun et al., 2004; Harris et al., 2014), as discussed in subsection 2.2.1. Further, Nguyen *et al.* showed through their study that providing partial body-based sensory information (in particular, leaning-based minimal translational self-motion cues) can significantly improve spatial updating compared to controller-based locomotion, even when real rotation is applied in all cases (standing and sitting interfaces) (Nguyen-Vo et al., 2019). Together with these earlier findings, the current study confirms that the advantages of a well-designed leaning-based interface seen in spatial updating in ground-based locomotion do indeed generalize to 3D locomotion (flying), confirming our hypothesis 1.

Second, the Gamepad and HeadJoystick interfaces used in the current study facilitated different kinds of motions and subsequently led to different search strategies. For instance, HeadJoystick afforded changing the travel direction in all three axes with a single head motion while Gamepad required combination of two thumbsticks. Participants stated in the post-experiment interview that they searched on different horizontal levels with the Gamepad and searched in a more spiraling fashion with HeadJoystick. These statements are corroborated by the difference in travel paths between the interfaces illustrated in Figure 2.6. With the Gamepad, participants typically searched in distinct horizontal plane slices, moving from one level to another using straight vertical motions. However, with the HeadJoystick, their movements seemed to be less restricted to any plane or axis. This could be based on the limited usage of Gamepad: participants mostly controlled just one DoF (forward translation) in combination with full body rotations with their head mostly facing forward. However, based on participant quotes and qualitative differences in movement trajectories, the HeadJoystick seems to facilitate traveling in any direction and combining all three translational degrees of freedom. Moreover, using the HeadJoystick lead to a marginally significant increase in overall head (but not body) rotations, suggesting that participants might be looking around more and/or looking more into their periphery. This might contribute to an increased situational awareness with HeadJoystick.

The behaviour of being confined to planes or axes is quite common for input devices that separate control dimensions. Thereby, studies of user performance of 3D tasks with 2D input devices have shown performance decrements, especially for selection and manipulation tasks (Zhai, 1998). Basically, 6DOF need to be mapped to controllers that usually only afford 2DOF (e.g., a micro-joystick). While precision (accuracy) may be higher (an issue we will reflect on below), trials tend to take longer than with 3D input devices as different control axes have to be controlled independently and serially (e.g., in case of a mouse). Even when multiple axes can be controlled in parallel by being able to use two controllers at once with two hands (or fingers, e.g., by using a gamepad), analysis of the movement paths of such tasks still show jagged patterns (a sign of non-optimal movement paths), similar to our typical paths in Figure 2.6. Even more so, control also requires coordination between both hands. The comparison between HeadJoystick and Gamepad shows that HeadJoystick performs better for larger (course) movements as evident from our task (quickly traveling from one location to another while maintaining spatial orientation). Surprisingly, fine grained movement has also been shown to be better with HeadJoystick, compared to Gamepad, as shown in Hashemian *et al.*'s maneuvering task (travelling through narrow tunnels) (A. Hashemian et al., 2020). While some of these benefits have also been shown for specialized 3D desktop input devices (in contrast to handheld "free-air" input devices), these devices tend to require much training to precisely control them. In contrast, users of HeadJoystick did improve performance over time (steady learning slope), yet not as drastically as shown for 3D desktop input devices with a steep slope over multiple usage sessions, where users started with low performance (Zhai, 1998).

Despite these interface-specific locomotion strategies there was no significant difference in task completion time or revisit percentage to the boxes. The completion time is influenced by the auto-termination of the program after five minutes, terminating 13 HeadJoystick trials and 20 Gamepad trials. As for the revisits, the participants complained that the task was *"difficult"* {P14} and that they easily *"lost track"* {P1, P20, P25} with both interfaces. Removing any global orientation cues dropped the percentage of perfect trials (no revisits) in HMD with real walking from 90% in Ruddle and Lessels' studies (Ruddle & Lessels, 2006a, 2009) to 13.9% in Riecke *et al.*'s study (Riecke et al., 2010a). Further limiting overall visibility such that the whole layout of boxes could never be seen at once but had to be integrated during locomotion further decreased the percentage of perfect trials. There were no perfect trials without revisit in Nguyen *et al.*'s ground based locomotion study (Nguyen-Vo et al., 2019), and just 5.68% in this study (5 out of 88 trials). Thus, similar to the ground-based locomotion study, we did not find any difference between the interfaces for revisits.

RQ2: Does HeadJoystick help to reduce motion sickness?

Table 2.1 shows a clear advantage for the HeadJoystick in comparison to Gamepad interface. Gamepad caused a significant increase in motion sickness (for total SSQ and Nausea sub-scale) independent of whether it was the first or second interface. When Gamepad was used as the second interface, oculomotor and disorientation issues also significantly increased compared to Pre-Experiment scores. Further, oculomotor (p = .041) and disorientation (p = .050) issues showed a marginal increase compared to Pre-Experiment scores (that would be significant if we had not applied the fairly conservative Bonferroni correction), even with the Gamepad as first interface. Although HeadJoystick caused a marginal increase in oculomotor issues when it was the first interface and a marginally significant increase in disorientation when it was the second interface, there was no overall significant increase in overall motion sickness score or any of the sub-scales. In sum, there was a consistent increase in overall and some of the SSQ subscores for the Gamepad, and only marginal increases in oculomotor and disorientation scores for the HeadJoystick. This confirms our hypothesis 2.

The single-item Fast Motion-Sickness Scale (FMS) also showed a distinct difference in motion sickness between Gamepad and HeadJoystick. With a more straight-forward rating system of '0 - I am completely fine and have no motion sickness symptoms' and '100 - I am feeling very sick and about to throw up', the participants reported that their motion sickness increased significantly more with Gamepad than HeadJoystick. Further, one of the participants completed the tasks with the HeadJoystick but dropped it due to motion sickness after trying the Gamepad. Two more participants let us know after the trial that they were *"about to drop the trial"* [P03, P06] with the Gamepad before it auto-terminated due to the time limit.

These quantitative findings are corroborated by the participants' responses in open-ended interviews. Previous ground-based locomotion studies have shown that combining visual motion with body-based sensory information can help to make people less sick (Aykent et al., 2014; B. D. Lawson, 2014). However, the results have been mixed for leaning-based interfaces. Marchal *et al.*'s study (Joyman) (Marchal et al., 2011) and Hashemian and Riecke's study (SwivelChair) (A. M. Hashemian & Riecke, 2017a) showed no significant difference in motion sickness between a leaning-based interface and a hand-based controller. Nguyen-Vo *et al.*'s study (Nguyen-Vo et al., 2019) showed a significant motion sickness reduction for a standing interface (NaviBoard) as compared to a hand-held controller, but not for a sitting interface (NaviChair). Similarly, Hashemian *et al.*'s flying study (HeadJoystick) showed a significant reduction in motion sickness for real-rotation with leaning-based translation compared to controller-based translation and rotation conditions, but only varying the translation mechanism did not produce a change that was statistically significant (A. Hashemian et al., 2020). A closer look into Marchal *et al.*'s study show that a Likert scale of 7 was used to measure motion sickness, and both conditions barely caused any motion sickness (average of 6, where 7 meant no motion sickness symptoms). Further, Hashemian and Riecke's SwivelChair and Nguyen-Vo *et al.*'s Navichair were not compared with pre-experiment SSQ scores but only with SSQ scores after using Gamepad (HeadJoystick vs. Gamepad) (A. M. Hashemian & Riecke, 2017a; Nguyen-Vo et al., 2019). Hashemian *et al.*'s study compared the motion sickness of the interfaces by subtracting the pre-experiment values of SSQ from each interface (HeadJoystick - Pre-experiment vs. Gamepad - Pre-Experiment). In these three studies, the leaning-based interfaces (SwivelChair, NaviChair and HeadJoystick) showed a trend towards lower motion sickness than the controller condition, but were shy of statistical significance. In our study, we performed a planned contrast to compare all the conditions with pre-experiment SSQ scores (HeadJoystick vs. Pre-experiment and Gamepad vs. Pre-experiment). Combining this comparison with the results from FMS, post-experiment questionnaires and participants' testimony shows that Gamepad makes participants significantly more motion sick than HeadJoystick, and that the SSQ might be too conservative a measure for registering those differences. Even in the meta-analysis of the effectiveness of SSQ, in spite of having a strong correlation between SSQ scores and participant drop out, the dropped-out participant still rated only a 39.63 total SSQ score on average out of 235.62 (16.8%) (Balk, Bertola, & Inman, 2013). Thus, we recommend using the SSQ for comparing the pre- vs post-use motion sickness scores for each interfaces, rather than just comparing post-use motion sickness scores among the interfaces.

Therefore, our study, along with Hashemian *et al.*'s study indicates that a partial body-based locomotion interface can help to reduce motion sickness not only for ground-based locomotion but also for flying locomotion (A. Hashemian et al., 2020). In addition, participants also reported a significantly stronger sensation of self-motion with the HeadJoystick in the post-experiment questionnaire section 2.5.2. They described their HeadJoystick experience as *"natural"* in post-experiment interviews and compared it to *"swimming"* or *"floating,"* see Figure 2.10. This rejects the concern sometimes mentioned in the literature that increasing vection might also increase motion sickness (Hettinger et al., 1990; Hettinger & Riccio, 1992; Stoffregen & Smart Jr, 1998; Smart Jr, Stoffregen, & Bardy, 2002). Instead, our data show that increasing vection can, in fact, be accompanied by reduced motion sickness, e.g., if a carefully designed embodied interface like HeadJoystick is used. That is, vection is not in general a sufficient prerequisite or predictor for motion sickness, and often does not even correlate with motion sickness - see discussion in (Keshavarz et al., 2015; Riecke & Jordan, 2015).

RQ3: How do HeadJoystick and Gamepad affect the overall user experience and usability?

In terms of cognitive load, the participants felt HeadJoystick could be used with significantly lower mental demand than Gamepad. Users also rated HeadJoystick to be significantly easier to learn, easier to use, and more precise. Though some participants preferred Gamepad for its familiarity, others complained the apparent disjunction between physical rotation and controller translation. Previous studies have also documented participants complaining about the disjunction between the physical rotation and controller translation (A. Hashemian et al., 2020; A. M. Hashemian & Riecke, 2017b). All of these observations confirm our hypothesis 3, that HeadJoystick should be more intuitive to use and learn, and the user should be able to use HeadJoystick more effectively, even without any previous exposure.

Further, our participants highly and consistently preferred HeadJoystick over Gamepad for helping to reduce motion sickness, and for its ease of use, controllability, and learnability. They also found it more immersive, engaging and enjoyable. This mirrors the finding of previously discussed leaning-based flying interfaces in subsection 2.2.1. In Higuchi and Rekimoto's study, participants preferred the physical interface for ease of control, ease of use and enjoyment (Higuchi & Rekimoto, 2013). The participants in Pittman and LaViola's user study appreciated the Head-Rotation for being natural, intuitive and immersive (Pittman & LaViola Jr, 2014).

Hashemian *et al.*'s study also compared two interfaces on a number of user experience and usability factors including enjoyment, immersion, vection, long-term use, daily use, ease of use and ease of learning (A. Hashemian et al., 2020). The participants found 'HeadJoystick' to be better in all the criteria. Our findings echo most of these findings, except for long-term use where HeadJoystick in our study had a higher average but did not reach statistical significance. This suggests that leaning-based interfaces, if designed well, can provide a fairly clear affordance (Riecke & Zielasko, 2020) in multiple kind of environments and tasks, which can be further improved by providing a brief demonstration or showing a video of the interfaces as in (Nguyen-Vo et al., 2019).

We also explicitly asked participants about their reason for preferring one interface over the other. The recurrent themes, as summarized in Figure 2.10 and as also seen throughout the discussion participants, were mainly concerned with ease of learning and use, motion sickness, and familiarity. In particular, HeadJoystick was appreciated for being easy to learn and use, making them less motion sick, and providing a strong sensation of self-motion. Gamepad was preferred for familiarity, less physical effort and being faster.

One of the issues with leaning-based interfaces could be comfort and stability, especially when there is no backrest. Standing leaning-based interfaces or sitting interfaces without a backrest can make users wary of losing balance and falling (Badcock, Palmisano, & May, 2014; Kitson et al., 2015). However, in Kitson *et al.*'s paper, when the leaning-based interface was used with a swivel chair having a backrest, it was rated as the most comfortable interface. HeadJoystick had significantly higher comfort ratings in our study too, and there were no concerns about stability or falling. However, participants still rated the sitting posture of Gamepad as marginally more comfortable compared to HeadJoystick, which might be related to the need to constantly adjust one's posture during movement changes with HeadJoystick. Similarly, participants reported significantly higher physical demand and marginally higher temporal demand for HeadJoystick than the Gamepad. All of these issues might be related to us trying to make the interface stable and safe. In order to create a stable and safe interface suitable for diverse participants with a wide range of physical features, we designed the interface to require relatively large leaning postures for high speed. Therefore, either the participants leaned excessively to achieve high velocity and experienced higher physical demand and uncomfortable seating posture, or they leaned moderately but travelled slower and experienced higher temporal demand. Further fine tuning the mapping, or even allowing for personalized or context-dependent speed mappings (e.g., allowing for faster speeds in large or outdoor spaces), could help to address these issues.

In sum, our main research hypotheses were all confirmed: compared to the Gamepad, the HeadJoystick improved spatial updating (RQ1), helped to reduce motion sickness (RQ2), and resulted in improved user experience and usability ratings across all measures (RQ3).

2.7 Conclusion

The current study provides the first compelling experimental evidence that providing partial body-based self-motion cues through leaning/head-movements with full physical rotation can improve spatial updating capability of an interface in virtual flying. It also provides evidence that an interface with embodied control like the HeadJoystick can be intuitively learned and used effectively without any previous exposure or lengthy training or practice. Finally, it shows that partial body-based self-motion cues from leaning/head-movements can mitigate the conflict between visual information and vestibular cues observed in controller-based interfaces like a Gamepad, and thus arguably help to minimize motion sickness.

Whereas Hashemian *et al.* (A. Hashemian et al., 2020) showed similar benefits of HeadJoystick over Gamepad for a gamified VR waypoint navigation (maneuvering) task, the current study shows that these benefits extend to a novel 3D navigational search task that requires spatial updating and building up and maintaining a mental representation of a large array of objects and thus situational awareness. Together, this suggests that our HeadJoystick locomotion interface can be useful in a wide range of 3D flying scenarios and applications, even if they require spatial updating and/or situational awareness, engaging novice users, or the need to minimize motion sickness.

Given that HeadJoystick's approach is compact and affordable, it can be easily integrated into existing systems without any additional cost or setup, provided a swivel chair is available. Though we attached the Vive tracker for detecting the center in a rolling chair, the interface also works efficiently without the tracker by fixing the chair in a place. Additionally, a pilot study showed that the interface could easily be used while standing, which might be more suitable for specific scenarios, or to provide more user engagement/movement abilities (Zielasko & Riecke, 2020). Further research could investigate this.

Moreover, as HeadJoystick implements four DoF control as in quadcopter drones, it also has the potential to be integrated with UAVs and used as a potentially more immersive, embodied, and intuitive control interface. In our future work, we want to investigate how the advantages of a leaning-based interface translate into immersive 3D telepresence scenarios in the context of flying experience, usability aspects, and performance measures.

Chapter 3

Integrating Continuous and Teleporting VR Locomotion into a Seamless "HyperJump" Paradigm

Abstract: Continuous optical flow provided by continuous locomotion methods in VR limits the maximum speed and acceleration that can be effectively applied without inducing cybersickness. On the other hand, there is no optical flow with teleportation, and users can jump to any length without increasing cybersickness. However, teleportation cannot support spatial updating, and can increase disorientation. Thus, we designed HyperJump in an attempt to merge continuous locomotion with teleportation (iterative jumps) and facilitate faster travel without compromising spatial awareness/orientation. In a user study, participants travelled around a virtual city with and without HyperJump added to continuous locomotion methods (controller- and leaning-based interfaces). They followed waypoints to new landmarks, stopped near it and pointed back to all previously visited landmarks in a random order as prompted by the program. The results show that participants travelled significantly faster with HyperJump, but it did not significantly affect their spatial knowledge as measured by pointing error. This provides evidence that optical flow can be effectively limited such that it facilitates faster travel without compromising spatial updating.

3.1 Introduction

The decreasing costs of stand-alone head-mounted displays (HMDs) have made virtual reality (VR) more accessible to a broad audience. These stand-alone devices are portable and can be set up in most living rooms without the need for an accompanying, let alone performant, computer, additional tracking systems, or cumbersome wires. However, a challenging problem still remains: how to make a user's movement in a virtual environment (VE) compelling and believable, while their physical body remains restricted to their physical space, which may be smaller than that of the VE they find themselves in? To address these challenges, there are currently different stationary locomotion techniques employed, which often rely on cumbersome hand-controllers, do not feel immersive, or can exacerbate cybersickness and be disorienting. This can negatively affect task performance, effectiveness, user experience, and overall enjoyment of the VR experience (A. Hashemian et al., 2020; A. M. Hashemian, Adhikari, Kruijff, von der Heyde, & Riecke, Submitted; Adhiakri et al., 2021; Kruijff et al., 2016).

The ideal interface should feel intuitive and natural, similar to walking, without evoking cybersickness (Cheung et al., 1991; Hettinger et al., 1990; Riecke et al., 2015; Hettinger & Riccio, 1992), which is crucial to ensure the enjoyability and long-term usability of VR. It should also support automatic spatial updating comparable to real-world navigation to help users maintain spatial orientation and situational awareness without increasing cognitive load (Loomis & Philbeck, 2008; McNamara et al., 2008; Wang & Spelke, 2002). Further, the ideal interface should allow performing additional actions while navigating, such as looking in directions different from the travel trajectory, or using one's hands for interaction, object manipulation or communication (Zielasko, Law, & Weyers, 2020).

Based on these criteria, leaning-based interfaces, where the user leans in the direction they want to move thus providing at least some embodied locomotion cues (Beckhaus, Blom, & Haringer, 2007), can be a favorable alternative to non-embodied stationary systems. Compared to the commonly used hand-controllers that provide little if any embodied self-motion cues, leaning-based interfaces have been shown to reduce cybersickness (Adhiakri et al., 2021; A. Hashemian et al., 2020; Bos, Bles, & Groen, 2008; Nguyen-Vo et al., 2019) by providing body-based self-motion cues (in particular proprioceptive and vestibular translational cues), improve navigational performance (Harris et al., 2014; Nguyen-Vo et al., 2019; Adhiakri et al., 2021), as well as enhance presence (Marchal et al., 2011), immersion, enjoyment and engagement (Harris et al., 2014; Kitson, Hashemian, Stepanova, Kruijff, & Riecke, 2017; Kruijff et al., 2016). At the same time, leaning-based interfaces perform comparably with standard controller-based/thumbstick-based interfaces (Zielasko, Horn, Freitag, Weyers, & Kuhlen, 2016). Leaning-based interfaces also do not rely on hand-controllers, thus freeing the hands to perform other tasks (A. M. Hashemian et al., 2021). On the downside, it is a continuous locomotion model that provides continuous optical flow, which limits the maximum acceleration and speed that can be applied to leaning-based interfaces without causing cybersickness. As a result, large-scale navigation might simply take too long or become annoying/boring.

To address this limitation, we propose 'HyperJump', a hybrid interface that uses continuous movement for short distances (just like a regular leaning-based interface) and seamlessly adds teleportation (iterative jumps every half a second) on top of the continuous movement when users would aim to travel at higher velocities that would likely engender cybersickness. Teleportation is one of the techniques that is not limited by optical flow. Jumps do not create any optical flow, thus reducing the risk of cybersickness (D. Bowman, Koller, & Hodges, 1997; Farmani & Teather, 2020). Since a jump's length is independent to optical flow, jump distances can also be adjusted to any desired length without effectively changing the risk of cybersickness. Though jumps can lead to breaks in presence and cause disorientation (Bakker, Passenier, & Werkhoven, 2003; D. Bowman et al., 1997; Riecke & Zielasko, 2021), we hypothesize that interlacing continuous movements with relative short jumps might provide sufficient optical flow to maintain users' spatial updating capabilities while effectively limit the optical flow so that it does not exacerbate cybersickness during fast travel.

In this paper, we propose an experimental design to assess users' spatial awareness in a naturalistic environment with realistic task. We also conducted a user study to compare how leaning-based and controller-based interfaces support spatial updating with HyperJump on and off. Finally, we asked participants to rate their experience on different measures and conducted open-ended interviews to improve the design of HyperJump for future use.

3.2 Related works

3.2.1 Spatial Updating

Spatial updating is a mental process of maintaining the spatial relationship between ourselves and our surroundings during self-motion. It is important for effective navigation, spatial orientation and situational awareness (Wang, 2016; Loomis & Philbeck, 2008; McNamara et al., 2008; Wang & Spelke, 2002). This process is largely automated or even obligatory (i.e., hard to suppress) during natural walking and also takes place during more complex activities like driving, climbing, diving, flying, or playing sports. However, only imagining the self-motions do not generate the same level of spatial updating and does not seem to be able to elicit automatic or obligatory spatial updating (Presson & Montello, 1994; Rieser, 1989; Farrell & Robertson, 1998; Wang, 2004). This includes visually simulated motion in VR with hand-held controllers (Klatzky et al., 1998; Ruddle & Lessels, 2006a; Riecke et al., 2010a), with the problem exacerbated if physical rotations are missing (Klatzky et al., 1998; Riecke, 2008). It demonstrates that current non-embodied interfaces fail to support automatic spatial updating, thus designing a better locomotion paradigm is warranted.

A number of different methods have been used for measuring spatial updating, including verbal recollections of spatial experiences, sketching an area map and arranging photos of route segments and landmarks in their correct order for assessing route knowledge and returning to the origin, pointing to the origin or other landmarks, and estimating distance traveled for assessing configurational knowledge (Witmer, Bailey, Knerr, & Parsons, 1996). Navigational search has also been effectively shown to assess spatial updating (Ruddle & Lessels, 2009; Ruddle, 2005; Ruddle & Lessels, 2006a; Riecke et al., 2010a; Nguyen-Vo et al., 2019). Since we wanted to quantitatively measure spatial updating while travelling in a large scale environment, we found pointing to the origin/landmarks to be the best fit for our experiment.

3.2.2 Teleportation

Teleportation is a common metaphor of VR locomotion in which the user is discretely moved to a target destination as opposed to continuous travel methods where the user continuously control or steer their travel direction along the way. The target destination can be chosen in multiple ways, including a common method of pointing using a controller. Due to its simplicity and effectiveness in reducing cybersickness, teleportation is commonly used as target-based travel technique (D. Bowman et al., 1997, 2004).

While comparing different travel techniques and metaphors under a comprehensive evaluation framework, Bowman *et al.* (D. Bowman et al., 1997) found that teleportation techniques due to its abrupt view changes can be disorienting compared to travel techniques with continuous optical flow. In another foundational contribution, the paper showed that the travel speed did not significantly affect spatial updating. This effectively shows that our ambition to design a fast travelling interface without compromising spatial awareness should be feasible given the interface can provide sufficient optical flow for spatial updating.

Weißker *et al.* compared the spatial updating between teleporting a large distance (beyond vista space) and repeated teleporting within vista space (Weißker, Kunert, Fröhlich, & Kulik, 2018). Their study showed that even visually seeing the target location each time before the jump did not improve spatial updating compared to large scale teleportation. This indicates that even when users are able to see their current and target locations between each jumps, they are not able to effectively update their spatial knowledge.

In an attempt to solve the spatial updating problem of teleportation, Bolte *et al.* proposed the 'jumper' metaphor (Bolte, Steinicke, & Bruder, 2011). In this travel technique, the user can use real walking for a small range travel and the user's viewing direction initiated a jump with smooth viewpoint animation. A map sketching task showed that while participants were significantly worse in map sketching with teleportation compared to real walking, with the jumper metaphor they were only slightly (but not significantly) worse. However, this method uses a gaze-based technique, predicted from the user's virtual head position and user's viewing direction. Though gaze-based technique allows implicit target acquisition for automated and smooth travel, it limits the users ability to look around for exploration or information gathering purposes, thus rendering it unsuitable for most practical applications. To overcome this limitation, our HyperJump metaphor is independent of looking direction.

Bhandari *et al.* also proposed a metaphor, Dash, similar to 'jumper' which adds a smooth viewpoint animation to teleportation (Bhandari, MacNeilage, & Folmer, 2018). They conducted a user study to compare participants' spatial updating with Dash and normal teleportation. In their study, participants travelled using either one or two teleportation/Dash instances and pointed back to the origin from the final position. The user study showed that Dash allowed for better path integration compared to a normal teleportation while keeping cybersickness comparable in both teleportation techniques. However, this method still requires participants to explicitly keep on choosing each target for travel. It does not support a smooth and continuous exploration of the virtual environment. To address that point, in our implementation the user can have a smooth continuous travel for short distance travel as well as seamlessly transition to fast-paced travel. Second, the virtual environment in their study was designed to be devoid of any landmarks which would have reduced optical flow and diminished cybersickness. Our virtual environment is closer to a normal application environment and should give a more realistic assessment of cybersickness.

Farmani and Teather (Farmani & Teather, 2020) also investigated the impact of short repeated jumps, called viewpoint snapping, very similar to our proposal. They observed decreased cybersickness when discrete movements were applied for either rotational and translational viewpoint motion. The study also did not find any significant difference in spatial awareness between the translational snapping and the continuous motion. However, in their design the jumps are fixed to a single length, which limits the interface from adapting to different kinds of paths or tasks. For instance, it is not very useful when a task requires travel of varying distances. Further, the experiment was mostly focused on cybersickness and did neither involve complex spatial orientation tasks nor complex naturalistic environment. The trial only consisted of 10 trivial pointing tasks (pointing back to the origin after moving in a straight path) and 4 pointing back to the origin after a 2-segment excursion.

Similarly, Rahimi *et al.* evaluated the importance of optical flow in spatial awareness by varying it in three different levels (Rahimi, Banigan, & Ragan, 2018). In an automated travel path, participants experienced teleportation (normal), animated interpolation (smooth viewpoint animation, similar to the jumper (Bolte et al., 2011) and Dash (Bhandari et al., 2018)), and pulsed interpolation (similar to viewpoint snapping (Farmani & Teather, 2020)). They found that among the three, animated interpolation allowed for the best spatial awareness performance as measured by pointing errors. However, it was also rated the worst in terms of sickness. Thus, the paper reiterates the importance of optical flow for improving spatial updating/awareness, but also its negative impact on cybersickness, adding motivation for our approach.

3.3 Motivation and Goal

The main focus of our study was to investigate how HyperJump might effect the user's spatial updating capabilities. Further, we wanted to study to what degree HyperJump might be able to support efficient navigation in terms of maneuvering accuracy, cybersickness, and ease of use. We chose to add HyperJump to a leaning-based interface because it has many desirable traits (see section 3.1). We also added HyperJump to one of the controller-based interfaces as HMDs usually come with their own controllers and are heavily used for locomotion.

RQ1: How does adding HyperJump affect spatial updating when compared to continuous-only locomotion? How does it affect overall usability and user experience including cybersickness?

Bowman *et al.* were the first to show that teleportation negatively affects spatial awareness compared to continuous travel (D. Bowman et al., 1997). Subsequent studies have shown that adding animated viewpoint transitions to teleportation ("Jumper", "Dash") can improve spatial updating (Bolte et al., 2011; Bhandari et al., 2018; Rahimi et al., 2018). However, as Rahimi *et al.* demonstrated, adding optical flow to teleportation can be nauseating (Rahimi et al., 2018), negating or at least reducing the advantage of teleportation as a less sickening locomotion method. Later, Farmani and Teather demonstrated that iterative jumps can reduce cybersickness while not affecting spatial orientation in a simplistic point-to-origin task (Farmani & Teather, 2020). Based on all these findings, we posited that the optical flow provided by interlacing continuous motion with iterative jumps would help maintain spatial orientation. We hypothesized there would be minimal difference in spatial awareness between continuous-only condition and HyperJump added to that locomotion interface in a complex spatial updating task.

Along with spatial updating, we were curious about how HyperJump might affect other aspects of usability and user experience, such as cybersickness, task load, preference and ease of use. Usability and user experience of some of the previous studies that compared continuous travel with (modified) teleportation can be summarized as following. Reduced cybersickness is observed with reduced optical flow (jumps without viewpoint animation) (Rahimi et al., 2018; Farmani & Teather, 2020). There were mixed results on time taken to complete a task. All combination of no significant time difference between the techniques (Langbehn, Lubos, & Steinicke, 2018), faster travel with continuous locomotion (Danyluk & Willett, 2019; Malekmakan, Stuerzlinger, & Riecke, 2020), and faster travel with teleportation (Buttussi & Chittaro, 2019) were observed. And when participants compared different teleportation techniques using Likert scales, results were mixed: Bolte *et al.* found no significant difference between real walking, jumper metaphor and teleportation for ease of learning and ease of use (Bolte et al., 2011). However, real walking and jumper both yielded improved user satisfaction compared to teleportation. Participants preferred Dash over normal teleportation, even though they rated regular teleportation to be more efficient (Bhandari et al., 2018). Rahimi *et al.* observed high variance in preference ratings among the interfaces (Rahimi et al., 2018).

In our task design, to allow a fair comparison between the conditions, the travel paths were kept deliberately short, travel speed low, and parameters were accordingly optimized for all interfaces to successfully complete a trial. The trials were designed to be completed within similar time for all conditions with minimal cybersickness in participants to avoid carryover effects. However, we still expected HyperJump to reduce optical flow, which might effect cybersickness. Similarly, we did not expect all participants to travel with maximum speed at all times and expected to see some difference in completion time. However, we did not have any directed hypothesis for travel time.

Further, we planned to compare the accuracy and precision of travel with HyperJump on and off. While traveling with HyperJump in high speed, the jump can be harder to control than continuous steering. Therefore, continuous condition could lead to more precise maneuvering than HyperJump condition, i.e., have less deviation from the center of the path. However, we expect the participants to still be able travel along an intended path and be able to reach their destination with ease.

Finally, we wanted to compare the overall usability and experience with introspective measures of extended Bowman's effectiveness factor (D. A. Bowman, Davis, Hodges, & Badre, 1999; A. M. Hashemian et al., Submitted) and semi-structured open-ended interviews. We hoped to understand the underlying advantages and disadvantages of HyperJump to optimize a hybrid interface that integrates continuous locomotion with iterative jumps. Later we want to compare the performance of continuous locomotion with or without added HyperJump in a much larger virtual environment requiring faster travel speeds.

RQ2: How do leaning-based versus controller-based interfaces effect spatial updating? How do they affect overall usability and user experience including cybersickness?

Controller-based interfaces don't provide any embodied self-motion cues and fail to support spatial updating in a manner similar to real-walking (Ruddle & Lessels, 2006a, 2009; Riecke et al., 2010a; Nguyen-Vo et al., 2019). On the other hand, leaning-based interfaces have been shown to improve spatial updating when compared to controller-based interfaces (Marchal et al., 2011), even when physical rotation is present in both conditions (Nguyen-Vo et al., 2019; Adhiakri et al., 2021). One leaning-based interface (NaviBoard) even reached performance levels comparable to walking (Nguyen-Vo et al., 2019).

However, when physical rotation was introduced for controller-based interfaces, participants complained about the disjunction between the physical rotation and controller translation (Adhiakri et al., 2021; A. Hashemian et al., 2020; A. M. Hashemian & Riecke, 2017b). Further, the analysis of travelling path showed that participants often switched between travelling and turning. That confined the translational motion to a single axis or a plane and could have impacted spatial updating (Adhiakri et al., 2021). Based on these observations as well as user feedback from our previous studies, in the current study we used a pointing-based steering controller instead of having the participants use only physical rotation or strafe by thumbstick. With this implementation, users could change their steering direction by rotating the controller i.e., pointing to the desired direction with the controller. It still uses physical rotation which is highly desirable but allows participant to to perform smaller steering direction changes by rotating the controller or with partial rotation of user's body, i.e., just turning the upper body to support the hand movement without rotating the whole chair. As an overall effect, we expected that users should be able to translate and rotate at the same time with more ease.

With this change, we expected to improve maneuvering ability for the controller-based interface as well as add at least some minimal embodiment as users would physically point in the direction they want to move. Hence, we expected the previously-observed clear spatial updating benefit of leaning- vs. controller-based locomotion to be less pronounced or even no longer existent. Similarly, we expected it to improve the overall usability and user experience of the controller-based interface.

RQ3: Does HyperJump affect leaning-based and controller-based locomotion interfaces differently?

Users have different experiences with leaning-based and controller-based locomotion interfaces. Leaning provides more embodied experience. It improves presence, immersion, enjoyment and engagement (Marchal et al., 2011; Kitson et al., 2017; Kruijff et al., 2016; A. Hashemian et al., 2020; Adhiakri et al., 2021). Partial body-based sensory information makes the experience more naturalistic and realistic as well (A. Hashemian et al., 2020; Adhiakri et al., 2021). On the other hand, leaning-based interfaces are relatively new methods compared to controllers with very little exposure. As none of our participants had used leaning-baseed interfaces before, we did not know how they would react to adding teleportation, an artificial phenomenon that has been shown to break immersion and presence (Bakker et al., 2003; D. Bowman et al., 1997; Riecke & Zielasko, 2021). We wanted to understand if embodied nature and/or previous exposure made a difference while designing a hybrid system.

3.4 Method

3.4.1 Participants

Twenty users participated in our study. We excluded two participants due to incomplete experimental trials and one user for high cybersickness. We performed the analysis with the remaining 17 participants (6 female, 11 male), 19 to 42 years old ($M = 23.3, SD = 5.34$). Ten of them had previously used an HMD and 12 of them had almost regularly used controllers to play video-games on a computer or a gaming console. The study had approval of the SFU Research Ethics Board.

3.4.2 Locomotion Modes

In this user study, we investigated the effect of adding iterative jumps to two continuous locomotion methods: leaning-based and controller-based. All interfaces were used while participants were seated on a swivel chair, thus allowing for physical rotation. The interfaces are explained in detail below. The boldface represents the shorthand for the interfaces.

Continuous Method of Locomotion

HeadJoystick: Participants lean their upper body as if it is a joystick to translate in the desired (i.e., leaning) direction (Adhiakri et al., 2021; Zielasko et al., 2016; A. M. Hashemian et al., Submitted; A. Hashemian et al., 2020). This is achieved through the tracking of HMD. When the program starts, users are asked to sit in a natural position, press and hold a button and rotate their head to the right and to the left for calibration. Then, we calculate the center of the head rotation and set it as the resting position of the head. When the user moves their torso (or their head for finer movements), we track the deviation from the resting position and assign a velocity exponential to the deviation for a smoother acceleration[1]. We limit the maximum virtual speed to 10 m/s mimicking inner city driving speeds.

Controller: Participants use the default Oculus controller thumbstick to translate in the desired direction up to a virtual speed of 10 m/s. We implement controller-directed steering where the controller's forward direction determines the forward direction of the movement i.e., the user can rotate the controller, physically rotate, or press the thumbstick sideways to change the moving direction. Similar to HeadJoystick, we exponentially mapped the deflection of thumbstick to velocity.

HyperJump: Hybrid Locomotion Method

HeadJoystick-Teleport: It works like a HeadJoystick up to the virtual continuous translation speed threshold of 5 m/s. Leaning further adds a jump of 1-8 meter every .5 second, on top of their continuous translation of 5 m/s. Leaning further increases jump distance, but not frequency[1].

Controller-Teleport: It works similar to HeadJoystick-Teleport but with a controller.

The threshold velocity and the range of the jump size was determined through a pilot study. With the above parameters, all the interfaces take exactly same time to travel a straight path with their maximum speed.

3.4.3 Virtual Environment

A virtual model of part of downtown Tübingen, Germany, was used to provide a naturalistic complex environment and avoid grid-like street patterns (see Figure 3.1A&B) (Anonymous,

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[1] `https://www.youtube.com/watch?v=raPNjAzIXh0`

n.d.). Four different non-intersecting paths were created so that participants travelled a unique path with each interface (see Figure 3.1).

Figure 3.1: (A) Participants traveled along the colored paths and performed pointing tasks from each white marker, which contained a distinct landmark. In each condition, they started from a white circle, moved to the subsequent white crosses and pointed back to all previously visited places (within that path) in random order as prompted by the program. (B) Top-down view of part of Tübingen on which path (A) is based.

Each trial began at one of four unique locations, as indicated by the white dots on in the map in Figure 3.1A. Participants followed 10 waypoints to the next landmark (see Figure 3.2A). The waypoints acted as both indicators of the path to the next landmark and a measure of travel accuracy. As they followed the waypoints and reached new landmarks, from each location, they would estimate the position and distance (see Figure 3.2B) of all previously visited landmarks in random order as prompted by the program[2] (Grechkin & Riecke, 2014).

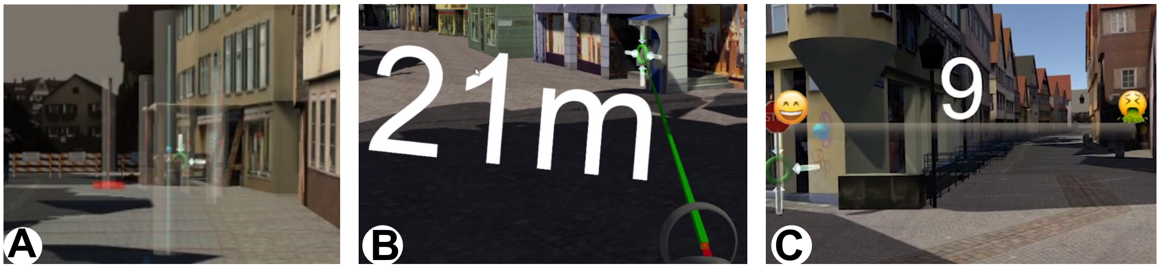

Figure 3.2: (A) Waypoint navigation task (B) Estimated distance to one of the landmarks, telephone booth. Landmarks are indicated by a green circle and white arrows for ease. (C) Participants' cybersickness state on the scale of 0-100

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[2] `https://www.youtube.com/watch?v=raPNjAzIXh0`

3.4.4 Experimental Design and Procedure

The experiment used a within-subject design where every participant took part in all four conditions with a different path for each interface (a single colored trace in Figure 3.1 is considered one path). Each path had a minimum of five turns of 90° or more. In total, they traveled to four different locations in each trial and performed to a total of 14 non-trivial pointings (to not directly visible landmarks). Each waypoint navigation task took about half a minute (four in a path/trial) and a trial took about seven to eight minutes.

A latin-square design with blocking of partial-body-based interface (HeadJoystick, HeadJoystick-Teleport) and controller-based interface (Controller, Controller-Teleport) was used to account for ordering effect and varying path difficulties.

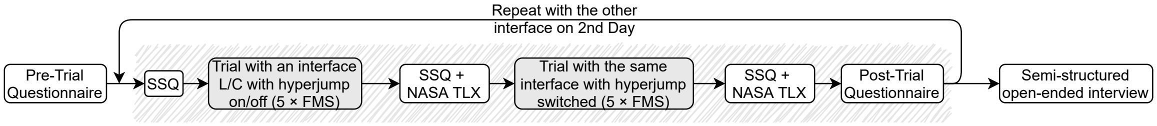

Figure 3.3: Experimental Design

The overall procedure is shown in Figure 3.3. They performed the trials with one of the interfaces (two conditions) on the first day and with the other interface after at least a gap of 24 hours. On the first day, participants started the experiment by filling out a pre-experiment questionnaire about their demographic information and simulator sickness questionnaire (SSQ) (Kennedy et al., 1993). Then, they performed the first and second trial with one of the interfaces (leaning or controller) with HyperJump state switched between the two trials. Also, they filled out the SSQ and NASA task load index (TLX) (Hart & Staveland, 1988) after each trial and took a mandatory break of 5 minutes. After completing the second trial, they filled the post-trial questionnaire detailed in section 3.5.2 comparing the interface with and without HyperJump. On the second day, they followed the same routine with the interfaces they hadn't used yet, and ended with a post-experiment open-ended semi-structured interview.

Experimental Tasks

During each trial participants were tasked with the following:

Trivial Pointing Task: Participants started the trial with a trivial pointing task, i.e., by pointing to two landmarks that were directly visible (indicated with a green circle and white arrows, see Figure 3.2B)[3]. Similarly, they finished the pointing task from each location with the trivial pointing to the adjacent (and the only directly visible) landmark. Though

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[3] `https://www.youtube.com/watch?v=raPNjAzIXh0`

these trivial pointing tasks were not considered during the analysis, they both helped participants to familiarize with the task and made sure that they learnt the targets' names.

Waypoint Navigation Task: After completing the pointing task, the program let go of the brake and participants were able to navigate again. They were instructed to follow a series of 5 waypoints (blue cylindrical posts with a spherical ball in the middle - Figure 3.2A) to a new location. Participants were asked to navigate through the waypoints as quickly as possible while trying to pass through the exact center of each waypoint. As long as participants passed through the white semi-transparent cylinder (see Figure 3.2A) of a waypoint they heard a positive auditory feedback. Missing a waypoint completely produced a 'wrong' buzzer sound and removed the waypoint from the scene. In the HyperJump mode, if the straight line jump went through the waypoint, it was counted as a successful attempt. In total there were 5 blue waypoints (at least $8m$ from each other except in turns) placed for accessing accuracy and 5 red waypoints (1-5 m from each other in a more strongly curved path) placed at the end to indicate to the participants that the navigation task is about to be completed.

Rapid Pointing Task (First Pointings): Once participants reached the last waypoint (represented with a red base - Figure 3.2A), the system applied a brake to slow down and stop the user at that location. Then, an auditory prompt instructed participant to "point up" so that their pointing always started from the same pointer orientation. Next, participants were asked to point as quickly and accurately to one of the previously visited landmarks along the current path, announced via headphones. If the controller's pointing direction was less than 30 degrees from the horizontal and the controller was stable then the system registered that as the pointing direction and indicated that to participants by laser shooting visual and audio cues. Riecke *et al.* used this technique of pointing without needing a trigger to reduce the interaction time with the interface and record more accurate response time (Riecke, Heyde, & Bülthoff, 2005). This rapid pointing procedure was repeated for all previously visited landmarks, in randomized order.

Distance Estimation Task and Subsequent Second Pointing Task: In this phase, participants were tasked to estimate both the direction and distance of all previously visited landmarks. Once the auditory prompt announced the target, they were instructed to turn the chair and face the direction of the target. When they pressed and hold the trigger, a white indicator appeared with its distance estimate from the user. Participants could move the white indicator with the thumbstick as long as they were holding the trigger and adjust their direction and distance estimate. They could let go of the trigger to indicate their final estimate. Riecke and McNamara had previously shown that when performing a series of pointing task from a new location, the first pointing task can take longer then later pointings, suggesting that the first pointing requires additional retrieval/mental transformation cost especially if participants' mental spatial representation of their surroundings was not already automatically spatially updated (Riecke & McNamara, 2017). This inspired us to task participants to perform pointing in two different phases. Even though participants gained no additional information between the two pointing phases, we were interested to investigate if previous pointing coupled with distance estimate might somehow help them improve their pointing and thus mental spatial representation.

Fast Motion Sickness Scale (FMS) Measurement: After completing all pointing tasks from a location, participants were asked to give us an estimate of their motion sickness state in a scale of 0-100, see Figure 3.2C. It is based on FMS scale adapted from Keshavraz and Hecht's FMS (Keshavarz & Hecht, 2011).

Dependent Variables

The following dependent variables were measured during the above tasks.

Absolute pointing error: It was used for assessing how well participants knew their location and orientation with respect to their surroundings. For each of the four locomotion conditions, participants pointed from 4 locations to a total of 14 non-trivial landmarks. For each pointing, the absolute pointing error was calculated as the absolute value of the difference between the correct and pointed yaw direction.

Absolute ego-orientation error: A part of absolute pointing error stems from participants' misperception of their ego-orientation, i.e., the difference between the direction they are supposed to be facing and their perceived orientation with respect to the landmarks (Riecke & Bülthoff, 2004). An absolute ego-orientation error was calculated by taking the absolute circular mean of the signed pointing errors from each pointing location.

Configuration error: It is defined as the mean angular deviation of the signed pointing error from each pointing location, and captures the consistency of participant' spatial knowledge of the pointing target locations (Wang, 1999).

Response time: During the first pointing phase we instructed participants to point to each landmark as fast and accurately as possible. We measured the time between the completion of target name's utterance and the stable pointing to that target. A shorter response time in rapid pointing tasks typically indicates the travel required less cognitive load (Farrell & Robertson, 1998).

Absolute distance estimate error: It is the absolute difference between the target's real distance and participants' estimated distance.

Waypoint distance error: It is the absolute distance between the center of participants' head and the waypoints' center indicated by the sphere, see Figure 3.2.

Waypoint navigation time: It is the time taken to travel between two blue waypoints.

To account for the difference in path difficulties, absolute pointing error, absolute ego-orientation error, response time and absolute distance estimate error were normalized per path before comparing them for different conditions. For normalization, we divided the individual trial data by path average and multiplied by total average.

3.5 Results

3.5.1 Behavioral Measures

Seven dependent variables (see section 3.4.4) were measured with three different tasks: rapid pointing task (first pointing phase), distance estimation task (including the second pointing), and waypoint navigation task. We present the descriptive and inferential statistics below. Unless stated otherwise, all test assumptions for ANOVA were confirmed in each case.

Rapid Pointing Task (First Pointing Phase)

Four dependent variables: absolute pointing error, absolute ego-orientation error, configuration error and response time were analysed using 2 × 2 repeated-measures ANOVAs with the independent variables interface (leaning vs controller) and HyperJump (on vs off). Since there were no significant main effects of HyperJump or any interactions between interface and HyperJump for any of the dependent variables (all $p's > .05$), we only report the main effects of the interface in Table 3.1.

Table 3.1: Main effect of interface during rapid pointing task. Green and light green shades indicate significant ($p \leq 5\%$) and marginally significant ($p \leq 10\%$) differences, respectively.

	Leaning		Controller		ANOVA		
	M	SE	M	SE	F(1,16)	p	η_p^2
Absolute pointing error	30.4°	2.50°	36.0°	3.48°	2.61	.126	.140
Absolute ego orientation error	21.6°	2.64°	28.3°	3.59°	3.23	.091	.168
Configuration error	22.4°	1.52°	24.2°	2.64°	.317	.581	.019
Response time	2.35s	.229s	2.98s	.271s	4.81	.043	.231

While performing the first rapid pointing task, all dependent variables showed a trend towards improved performance for the leaning- over controller-based interfaces, see Figure 3.4. However, this trend did not reach significance for the absolute pointing error and

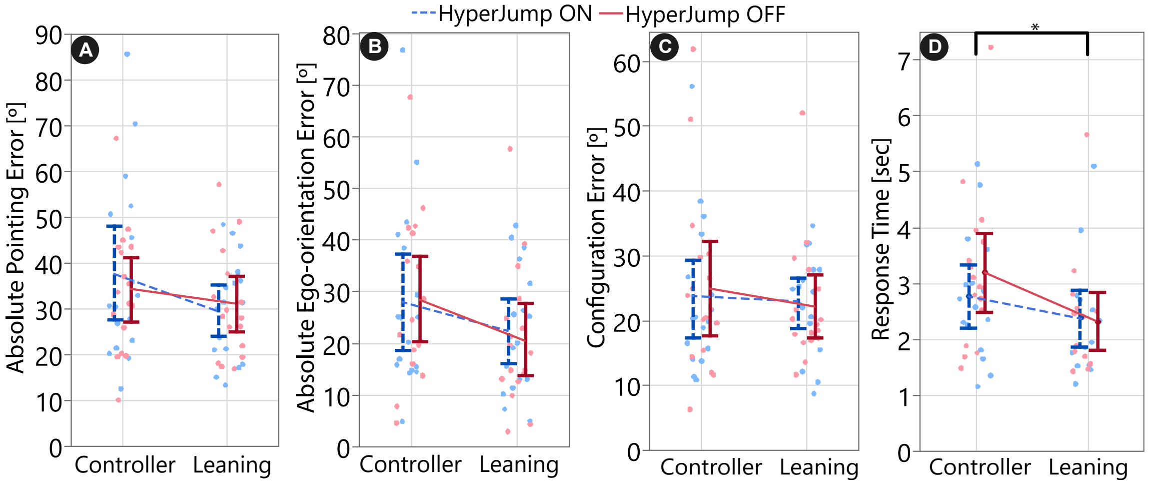


Figure 3.4: (A) Absolute pointing error (B) Absolute ego orientation error (C) Configuration Error (D) Response time while performing the first rapid pointing task. Points with light shades show mean data for individual participants. Error bars indicate 95% confidence intervals (CI)

configuration error, see Table 3.1. The difference in ego orientation was marginally significant, in favor of leaning interfaces which showed a 24% reduction in absolute ego-orientation errors. Similarly, participant pointed to targets significantly faster (by 21% or .63 seconds) with leaning interfaces than controllers.

Distance Estimation Task and Subsequent Second Pointing Task

Similar to the first rapid pointing task, we performed 2 × 2 repeated-measures ANOVAs with the independent variables interface (leaning vs controller) and HyperJump (on vs off) on four dependent variables: absolute pointing error, absolute ego-orientation error, configuration error and absolute distance estimate error. We did not analyse response time for this phase because participants spent only a minority of their time on in deciding the direction or fine tuning their distance estimate. It took a long time to reach to the approximate estimation values as distance estimation could only be changed linearly. Thus, the recorded response time failed to capture the exact time taken by the participants to make a decision in their estimate.

As before, only the independent variable interface showed any significant effects for the second pointing task. It is summarized in Table 3.2.

Similar to the first pointing phase, all dependent variables showed a trend towards improved performance for the leaning- over controller based interfaces, see Figure 3.5 and Table 3.2. Though the configuration error and distance estimation error showed trends towards improvement with leaning it did not reach to significance. The absolute pointing and ego-orientation errors did significantly improve by 19% and 29% when using the leaning-based interface over the controller.

Table 3.2: Main effect of interface during pointing and distance measurement task. Green shade indicates significant ($p \leq 5\%$) difference.

	Leaning		Controller		ANOVA		
	M	SE	M	SE	F(1,16)	p	η_p^2
Absolute pointing error	27.3°	2.21°	33.6°	3.07°	5.21	.037	.246
Absolute ego orientation error	18.4°	1.91°	25.8°	2.79°	7.66	.014	.324
Configuration error	18.9°	1.25°	19.2°	1.67°	.317	.581	.019
Distance estimate error	36.7m	3.08m	37.6m	3.80m	.084	.775	.005

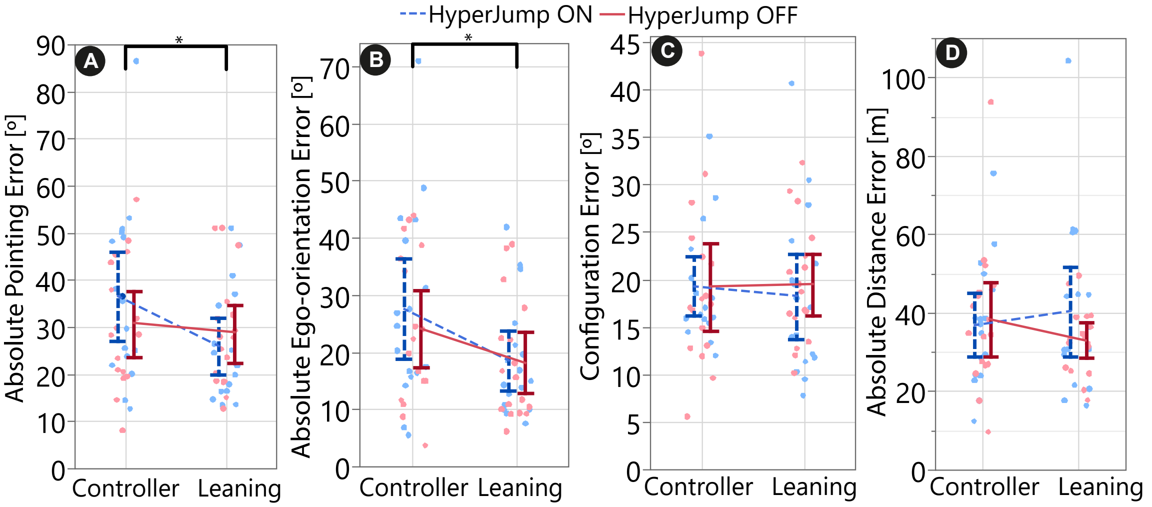


Figure 3.5: (A) Absolute pointing error (B) Absolute ego orientation error (C) Configuration Error (D) Absolute distance error while performing the distance estimation and subsequent second pointing task. Points with light shades show mean data for individual participants. Error bars indicate 95% CI

Comparing the performance in first and second pointing phases

During a trial participants pointed to the same landmark from the same pointing location twice. In the first pointing phase (rapid pointing task), they were instructed to point as quickly as possible and the program recorded the pointing direction as soon as their controller was stable (within 30° of horizontal plane). After completing the first pointing phase for all the landmarks from a location, they performed the distance estimation task. In the second phase, they were first asked to turn their chair and face the target's direction before pointing. In this phase, they could keep on adjusting their estimate as long as they were holding the pressed trigger.

To investigate how participants' performance and underlying spatial orientation might have changed between the first and second pointing phase, we ran additional 2 × 2 × 2 ANOVA with independent variables interface (leaning vs controller), HyperJump (on vs off) and pointing phase (first vs. second pointing phase). Since there were no significant interactions between the pointing phase and interface/HyperJump for any of the dependent variables (all $p's > .05$), we only report the main effects of the pointing phase below.

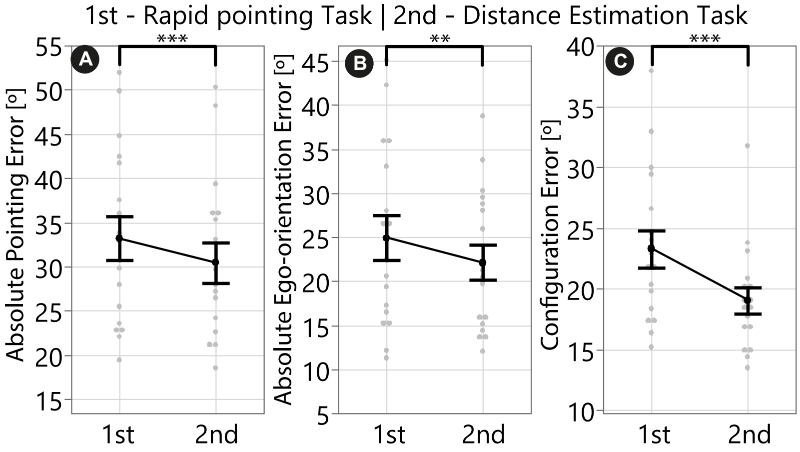


Figure 3.6: (A) Absolute pointing error (B) Absolute ego orientation error (C) Configuration Error while performing first rapid pointing task (1st pointing phase) and distance estimate and subsequent second pointing task. Points with light shades show data for individual participants. Error bars indicate 95% CI

From Figure 3.6 and Table 3.3 we can clearly see that participants always performed better during the second pointing phase. In the second pointing phase, absolute pointing error decreased by 9%, absolute ego-orientation error decreased by 11% and configuration error decreased by 18%. Each of those changes were statistically significant. Please refer to Table 3.3 for ANOVA results.

Table 3.3: Main effect of pointing phase. Green shade indicates significant ($p \leq 5\%$) difference

	1st Pointing		2nd Pointing		ANOVA		
	M	SE	M	SE	F(1,16)	p	η_p^2
Absolute pointing error	33.2°	2.49°	30.5°	2.28°	18.0	<.001	.529
Absolute ego orientation error	24.9°	2.50°	22.1°	1.98°	9.67	.007	.377
Configuration error	23.3°	1.53°	19.1°	1.06°	17.3	<.001	.519

Waypoint Navigation Task

We recorded the distance of the player from the waypoints while they were following the waypoints to the next location. We also recorded the time it took them to make that travel. Both the distance from the waypoints and the time taken were not normally distributed. So, we calculated the median distance of player's position from the waypoint and the median time taken for player to cross the waypoints for each condition. With HyperJump condition, participants made at least one jump between consecutive blue waypoints in 92% of the cases and crossed a waypoint with a jump in 45% of the cases.

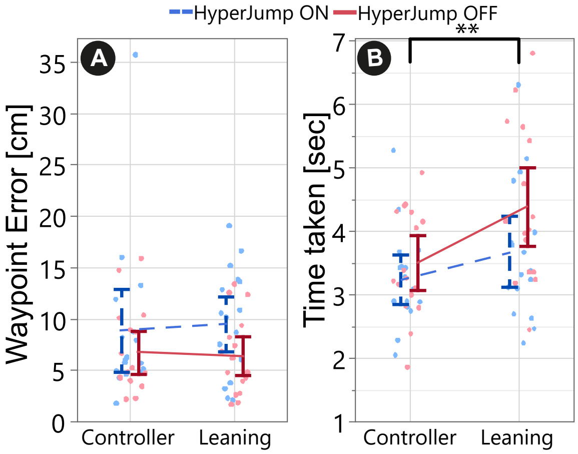


Figure 3.7: (A) Median absolute waypoint error (distance between the waypoint and player) in cm (B) Average time taken (in seconds) to travel between two consecutive blue waypoints. Points with light shades show mean data for individual participants. Error bars indicate 95% confidence intervals

On average, for all conditions the participants' median waypoint distance error was less than 10 cm, which is the width of the sphere in the waypoint, Figure 3.2A. This indicates that overall all of the locomotion conditions allowed participants to travel accurately enough to stay on the desired course. We performed further inferential analysis with interface and HyperJump as the independent variables. The ANOVA showed a marginally significant effect of HyperJump on waypoint distance error. Waypoint distance error was smaller (by 28%) without HyperJump than with HyperJump, see Figure 3.7A. However, there was no effect of the interface and no interaction between interface and HyperJump on Waypoint distance error, see Table 3.4. The number of missed waypoints also show a similar result. Participants missed a total of 14% of waypoints with HyperJump and only 8% without HyperJump. On the other hand, they missed 11% of waypoints with both leaning- and controller-based interfaces.

Table 3.4: ANOVA analysis of waypoint error and time taken to travel. Green and light green shades indicate significant ($p \leq 5\%$) and marginally significant ($p \leq 10\%$) difference respectively.

	Interface			HyperJump			Interface x HyperJump		
	F(1,16)	p	η_p^2	F(1,16)	p	η_p^2	F(1,16)	p	η_p^2
Waypoint Error	.021	.887	.001	4.35	.053	.214	.335	.324	.020
Time taken	9.33	.008	.368	6.43	.022	.287	1.02	.328	.060

The analysis of time taken to travel between two waypoints showed significant main effects of both interface and HyperJump but no interaction, see Table 3.4. The travel time was reduced by .48 seconds (12%) when participants travelled with controller-based interfaces compared to leaning-based, see Figure 3.7B. Similarly, they took less time with HyperJump on (reduced by 16%) compared to HyperJump off.

3.5.2 Subjective Ratings

Cybersickness

During the experiment, cybersickness was measured in two different ways. First, participants indicated their cybersickness while performing the task in a scale adapted from Keshavraz and Hecht's Fast Motion Sickness Scale (FMS) (Keshavarz & Hecht, 2011). After completing pointing task from each location within a trial, participants indicated cybersickness on a scale of 0-100. '0' meant 'I am completely fine and have no sickness symptoms' and '100' meant 'I am feeling very sick and about to throw up.' It allowed us to continually track participants' cybersickness and if required to intervene and stop the experiment. Second, after completing the trial with each interface they filled out the simulation sickness questionnaire (SSQ) (Kennedy et al., 1993).

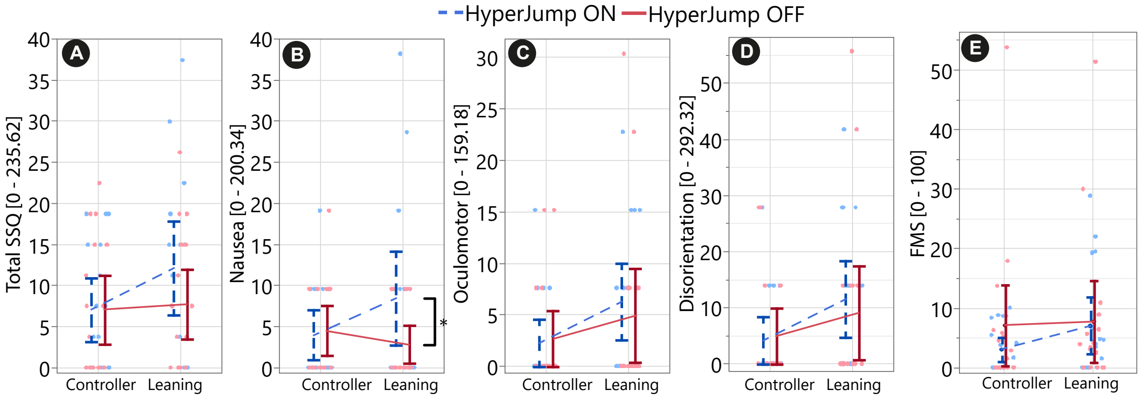


Figure 3.8: (A-D) SSQ with sub-scales and (E) FMS after performing the trials. Points with light shades show mean data for individual participants. Error bar indicates 95% CI

The total SSQ never exceeded 37.5 on a scale of 0 - 235.62 (16% of total) and on average stayed at 8.57 (3.63% of total), see Figure 3.8A. So, no participants complained about cybersickness or brought it up as a major factor of their experience, except for one additional participant who was highly susceptible to motion sickness (self rated motion sickness susceptibility - 69/100, average for rest of the participants - 25/100) and dropped the experiment after the first trial.

From the inferential statistics presented in Table 3.5, it is clear that there was no main effect of interface or HyperJump on the total SSQ, although there was a marginally significant interaction ($p = .81$), i.e., the leaning-based interface showed higher total SSQ scores with HyperJump ($M = 12.1, SE = 2.71$) than without ($M = 7.70, SE = 2.02$).

Table 3.5: ANOVA analysis of SSQ and FMS. Green and light green shades indicate significant ($p \leq 5\%$) and marginally significant ($p \leq 10\%$) difference respectively.

	Interface			HyperJump			Interface x HyperJump		
Measures	F(1,16)	p	η_p^2	F(1,16)	p	η_p^2	F(1,16)	p	η_p^2
Total SSQ	1.49	.241	.085	1.88	.189	.105	3.47	.081	.178
Nausea	.595	.452	.036	2.37	.144	.129	6.37	.023	.285
Oculomotor	4.15	.059	.206	.158	.696	.010	.557	.466	.034
Disorientation	4.15	.059	.206	.158	.696	.010	.557	.466	.034
FMS	2.47	.136	.134	.972	.339	.057	1.96	.181	.109

However, no such effect was seen for HyperJump on ($M = 7.04, SE = 1.97$) versus off ($M = 7.04, SE = 7.81$) for the controller. We observed a similar interaction for Nausea, with no significant main effects of interface or HyperJump, see Figure 3.8A&B.

There was a marginally significant effect of interface on the oculomotor and disorientation subscales. In general, leaning ($M = 5.57, SE = 1.37$) caused marginally higher oculomotor issues compared to controller ($M = 2.45, SE = .830$). Leaning ($M = 10.2, SE = 2.51$) also showed marginally larger disorientation ratings compared to controller ($M = 4.50, SE = 1.52$).

The fast motion sickness scale (FMS) also showed low cybersickness in participants and did not require us to intervene and stop any participants during the experiment. The overall average for FMS was 6.18 on a scale of 0 - 100, see Figure 3.8E. There were no significant main effects or interactions on FMS.

Task Load

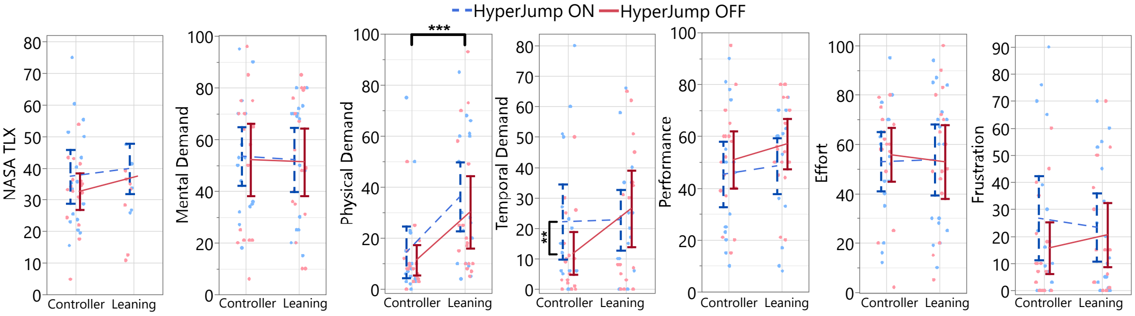


Figure 3.9: NASA TLX with sub-scales while performing the trials. Points with light shades show mean data for individual participants. Error bar indicates 95% CI

There were no significant effects of any factor on total NASA task load, see Table 3.6. However, there was a main effect of interface on physical demand. Participants reported that the controller required 60% less physical effort than the leaning-based interface, see Figure 3.9C. On the other hand, there were marginally significant main effects of HyperJump on performance and frustration: Participants rated HyperJump to be marginally less performant (17% less on average) while marginally increasing frustration (30% more on average) Figure 3.9E&G. Finally, there was a significant interaction on temporal demand. Participants found controller with no jump to have the least temporal demand compared to rest of the conditions.

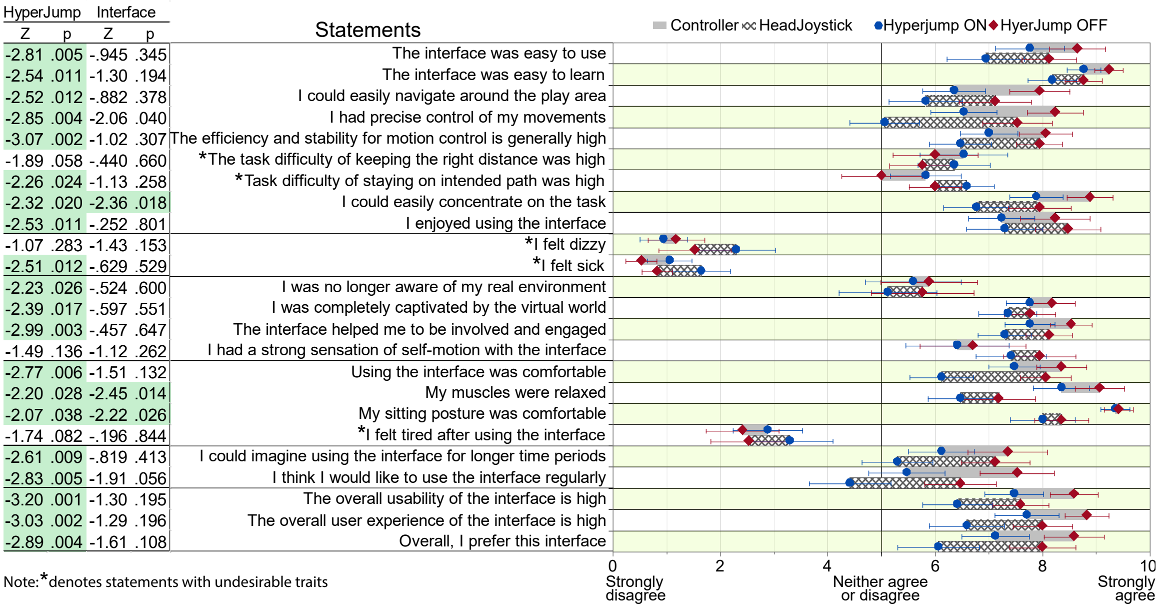
Table 3.6: ANOVA analysis of NASA TLX. Green and light green shades indicate significant and marginally significant difference respectively.

	Interface			HyperJump			Interface x HyperJump		
	F(1,16)	p	η_p^2	F(1,16)	p	η_p^2	F(1,16)	p	η_p^2
NASA TLX	.786	.388	.047	2.27	.151	.124	.345	.565	.021
Mental Demand	.078	.783	.005	.175	.681	.011	.013	.911	.001
Physical Demand	15.5	<.001	.493	1.93	.184	.108	.233	.636	.014
Temporal Demand	2.62	.125	.141	.824	.378	.049	11.1	.004	.411
Perfromance	.664	.427	.040	3.57	.077	.183	.126	.727	.008
Effort	.070	.795	.004	.025	.876	.002	.251	.623	.015
Frustration	.020	.890	.001	3.41	.084	.176	2.13	.164	.117

Preference and Post-Experiment Interview

In general, participants found all the conditions to have desirable traits than not, with an average of almost 75% in positive statements ($M = 7.41, SE = .074$ on a scale of 0-10). Figure 3.10 shows, however, that participants consistently preferred the HyperJump off condition ($M = 7.96, SE = .097$) to HyperJump on ($M = 6.87, SE = .107$), even though both of them have generally preferable scores, i.e., in almost all cases the scores for positive statements are higher than the ambivalent score of 5. Participants also significantly preferred controller over leaning-based interface in three factors, sitting posture, concentration on the task, and relaxed muscle. There were no significant differences for the remaining factors and conditions.

In the post-experiment open-ended interview, participants gave us an insight on their preferences and underlying reasons. Many of the participants thought that HyperJump was "*jittery*" {P01,P03,P17} or "*laggy*" {P13,P16} in contrast to continuous motion which they thought was "*smooth*". Some felt it even "*strained*" {P01, P07} their eyes. They also found it be "*unpredictable*" {P19}] and were "*startled*" {P04,P09,P17} by the jumps. For some the feeling was even worse with the leaning-based interface. Participants mentioned that they experienced the trials more like a *"computer game"* {P12} when using the controllers. With the leaning-based interface, however, they mentioned experiencing it to be more immersive and realistic. So, in their opinion jumps in controller felt "*no different than a computer scene*" {P09,P12} and they were not bothered much by them. But the jumps in leaning-based interface was perceived as off-putting. They felt like they were "*tripping*" or "*falling*" when the jumps occurred and felt like they are "*about to hit the ground*" with those jumps {P09, P17}. In essence, these accounts also support that leaning-based interface provide



HyperJump Z	HyperJump p	Interface Z	Interface p	Statements
-2.81	.005	-.945	.345	The interface was easy to use
-2.54	.011	-1.30	.194	The interface was easy to learn
-2.52	.012	-.882	.378	I could easily navigate around the play area
-2.85	.004	-2.06	.040	I had precise control of my movements
-3.07	.002	-1.02	.307	The efficiency and stability for motion control is generally high
-1.89	.058	-.440	.660	*The task difficulty of keeping the right distance was high
-2.26	.024	-1.13	.258	*Task difficulty of staying on intended path was high
-2.32	.020	-2.36	.018	I could easily concentrate on the task
-2.53	.011	-.252	.801	I enjoyed using the interface
-1.07	.283	-1.43	.153	*I felt dizzy
-2.51	.012	-.629	.529	*I felt sick
-2.23	.026	-.524	.600	I was no longer aware of my real environment
-2.39	.017	-.597	.551	I was completely captivated by the virtual world
-2.99	.003	-.457	.647	The interface helped me to be involved and engaged
-1.49	.136	-1.12	.262	I had a strong sensation of self-motion with the interface
-2.77	.006	-1.51	.132	Using the interface was comfortable
-2.20	.028	-2.45	.014	My muscles were relaxed
-2.07	.038	-2.22	.026	My sitting posture was comfortable
-1.74	.082	-.196	.844	*I felt tired after using the interface
-2.61	.009	-.819	.413	I could imagine using the interface for longer time periods
-2.83	.005	-1.91	.056	I think I would like to use the interface regularly
-3.20	.001	-1.30	.195	The overall usability of the interface is high
-3.03	.002	-1.29	.196	The overall user experience of the interface is high
-2.89	.004	-1.61	.108	Overall, I prefer this interface

Note: *denotes statements with undesirable traits

Figure 3.10: User rating states about usability and experience. Green shade indicates significant difference ($p \leq 5\%$), CI = 95%. In all significant cases, participants preferred HyperJump OFF (⧫) over HyperJump ON (●).

more realistic experience. However, the same realism made it harder for them to interpret or accept those sudden jumps.

Participants were split between the leaning- and controller-based interfaces regarding ease of use. Many of them mentioned they were "*used to*" {P02,P07,P08,P16} the controller and found it "*easy to use*" {P01,P02,P06,P07}, while others found HeadJoystick "*easy to learn and use*" {P05,P14,P15,P16}. However, participants had often shifted their upper body away from their neutral (upright) position while performing the pointing and distance estimation tasks - hence as soon as the brake was lifted they gunned towards the direction their body was leaning. Participants immediately noticed and corrected for this sudden movements and regained control quickly, but some participants {P07, P17} mentioned that these sudden movements caused some cybersickness. A few others mentioned that this made them wary of losing control and they concentrated a lot on "*balancing*" {P03,P07,P17,P18} their body while using leaning-based interfaces. On the other hand, controller afforded "*stop[ping] and look[ing] around*" {P01,P08}. This might have directly affected their preference ratings and even impacted the cybersickness results for leaning-based interfaces. Still, more than half of the participants thought leaning-based interfaces were more "*immersive and engaging*".

3.6 Discussion

This paper presents the first study comparing users' spatial orientation between a hybrid of teleportation and continuous locomotion vs continuous locomotion in a complex spatial updating task. While we can only travel with a limited acceleration and speed with continuous locomotion without causing cybersickness, with teleportation it is possible to jump to any distance without effectively increasing the risk of cybersickness. On the other hand, unlike teleportation, continuous locomotion supports vection (perceived self-motion) which can make a VR experience more immersive and realistic (Riecke & Zielasko, 2021) and facilitate perspective changes (Riecke et al., 2015). Continuous locomotion also supports path integration and can improve spatial awareness (Bakker et al., 2003). So, we proposed a hybrid interface which tries to retain the advantages of both kind of travels.

We proposed to combine continuous and teleportation locomotion methods into a hybrid interface to investigate if such a merging might help to mitigate the problems of the individual locomotion methods and create a better alternative. We were also investigating if adding a pointing-based steering to controller improves performance, usability and user experience. We discuss the findings of our experiment in the context of our main research questions below.

RQ1: How does adding HyperJump affect spatial updating compared to continuous only conditions? How does it affect usability and experience including cybersickness?

Our study showed a significant differences between the interfaces themselves (controller-based vs leaning-based) but adding HyperJump didn't significantly affect how the underlying interfaces support user's spatial updating. Though a null hypothesis cannot be verified in this manner there is almost no effect of HyperJump on user's spatial updating. Together with the fairly small effect size of HyperJump on all of the pointing errors ($\eta_p^2 < .1$), this suggests that adding HyperJump to different interfaces can be explored to capitalize on potential other benefits without a fear of compromising the users spatial orientation or spatial updating ability.

We posit that the overall similar performance of HyperJump compared to continuous only conditions might be mainly attributed to the optical flow that is always present during the travel, even though it was limited to 5m/s for the HyperJump conditions. Previous studies have already shown that modifying the teleportation technique by adding some optical flow to it can improve user's spatial updating compared to teleportation techniques without any optical flow (Farmani & Teather, 2020; Bhandari et al., 2018; Rahimi et al., 2018). Bolte et. al found participant's map sketching after using the "jumper" to be comparable even with real walking. Our study also shows comparable results between HyperJump and continuous locomotion in a complex spatial updating task in a realistic environment. All of these findings indicate that teleportation can be improved to support spatial updating by adding optical flow.

We would like to point out an interesting difference in the above approaches. Some of them ("jumper", "Dash", "animated interpolation") added animated optical flow to the jump itself (Bhandari et al., 2018; Rahimi et al., 2018; Bolte et al., 2011). Our implementation interlaces the jumps (without any optic flow) with continuous motion having continuous optical flow to avoid any acceleration/deceleration signals or change in optic flow that might contribute to cybersickness. And in both cases, the optical flow seems to have contributed to spatial updating, although future research is needed to test this hypothesis.

Based on the waypoint navigation task, there was a marginally significant effect of HyperJump on the accuracy of the travel. Participants managed to keep 9.2 cm median distance from the waypoint with HyperJump while without HyperJump it was only 6.5 cm, see Figure 3.7. Similarly, in their subjective ratings participants indicated that HyperJump did not allow for as precise control as continuous methods. HyperJump affected their performance and made them more frustrated.

However, the above data was taken during a relatively fast pace travel when jumps are present (at least one jump between the consecutive waypoints in 92% of the cases and crossed a waypoint with a jump in 45% of the cases). And even when jumps were present, median distance between the waypoint and user's center of the head was less than 10 cm, which is the width of waypoint's center. That is, even with the added HyperJumps participants were able to travel along the intended path in all conditions (passed through 89% of waypoints) and successfully completed all the trials. Thus, if users want visit a point quickly then HyperJump provides good enough control to travel along the intended path and reach the destination. Further, if more precise travel is required, users can always slow down to switch to continuous mode.

The travel time between two blue waypoints reveals that participants travelled 14% faster with HyperJump. Though we had optimized the parameters to allow for similar average maximum speed, participants felt comfortable travelling with a faster average speed with HyperJump on than with off (equivalent, continuous speed capped to 5 m/s with HyperJump). Past studies showed mixed results regarding completion times with target-acquisition teleportation techniques (Buttussi & Chittaro, 2019; Danyluk & Willett, 2019; Langbehn et al., 2018; Malekmakan et al., 2020). Our seamless technique proved to be faster than the continuous locomotion even in a setting designed for similar average speeds between both conditions. So, we are optimistic about its performance in a much larger environment where teleporting will become more important.

The overall cybersickness during the experiment was very low. The maximum travel speed was relatively low (10 m/s - inner city car speed), physical rotation was present in all conditions, each travel instance was short (less than a minute), each travel was followed by translationally stationary pointing tasks (each took about a minute) and both interfaces incorporated some embodiment (leaning or pointing to the travel direction). So, the instruments (SSQ and FMS) might not have been sensitive enough to assess the benefits in sickness reduction of HyperJump. We have already discussed in Chapter 2 how SSQ might be too conservative to detect a difference between conditions in post-trial and how pre- vs. post-use SSQ scores might be more illuminating. However, we blocked with and without HyperJump conditions on a single day limiting us from comparing HyperJump with pre- vs. post-use SSQ scores. A future study investigating HyperJump in a much larger environment (subsequently, a higher speed and/or longer travel time) can provide a more concrete findings regarding the benefits of HyperJump in cybersickness.

Finally, in the post-experiment questionnaire, participants indicated that HyperJump breaks immersion and provides less realistic experience. Further, the dislike for HyperJumps seems to be more pronounced in HeadJoystick and we discuss it in detail in RQ3.

RQ2: How do leaning-based and controller-based interfaces effect spatial updating? How do they affect overall usability and user experience including cybersickness?

Our results also provided novel insights into how leaning-based interfaces versus controller support spatial updating. Both interfaces use physical rotation. In spite of that, leaning-based interfaces resulted in improved ego-orientation compared to controller, in both the first and second pointing phase. This shows that providing physical rotations (which was identical in all interfaces) is not sufficient for properly updating one's orientation in VR, and that more embodied (leaning-based) ways to translate in VR can provide a significant spatial orientation benefit. Physical rotation had already been shown to be invaluable for spatial updating in previous studies (Klatzky et al., 1998; Riecke, 2008; Riecke et al., 2010a). Further, Nguyen-Vo *et al.* (Nguyen-Vo et al., 2019) demonstrated that in spite of having physical rotation in all conditions, partial body-based translation control through leaning can support spatial updating in a navigational search task. Here, we corroborate and extend these findings by showing that even our perceived orientation in our environment can benefit from a more embodied interface that provides partial translational body-based cues.

Looking at the first rapid pointing phase showed a consistent trend for improved performance for leaning-based translational control. This trend reached only marginal significance for the ego-orientation error. Participants, however, pointed significantly faster after traveling with the leaning-based interface. This indicates that their spatial representation of the self-to-target direction was more readily and easily available, and suggests that the cognitive load of spatially updating during locomotion was reduced (Farrell & Robertson, 1998).

As far as we know, this is the first paper that compares rapid pointing in a first pointing phase with rapid pointing in a second phase after providing a distance estimate. And our result shows that the trends became more consistent with the second pointing and the difference between the leaning- and controller-based interfaces reached significant for absolute pointing and ego-orientation errors. There were several factors that could have affected the performance in two phases. First, participants might have somehow used their knowledge from the previous task, even though they were never provided with any performance feedback that they could have been used to improve their pointings. Even though the previous studies have found difference in response time between first pointing and subsequent pointing from the same location even in the same phase (Riecke & McNamara, 2017), we could not find any literature comparing the performance between different phases with no additional information. Second, for the first pointing participants pointed rapidly to a given target without changing their physical orientation, sometimes having to point backwards. Moreover, once the controller was stable they could no longer change their mind. During the second phase, however, they were asked to first rotate to face the target direction, then providing a distance estimate, and only register the pointing direction after that, i.e., the pointing direction was registered only after the distance estimation was done and participants let go of their trigger. This provided them with additional time to reflect and adjust their pointing response for each target if desired. Finally, the distance judgment task might have triggered them additional or different spatial cognition processes, including to deliberately think more about the length of each part of the path, or the route, or the overall spatial configuration. Future research is needed to pinpoint how these different factor might have affected their spatial cognition processes and pointing responses. It is noteworthy, however, that even in a naturalistic scene that provides ample landmarks and spatial orientation cues, traveling with an interface that provides more embodied translation cues can provide not only a benefit directly after stopping, but even more so after having more time to reflect and also judge distances to the different targets.

Though there were no significant differences in total SSQ score and Nausea between the two interfaces, there was a non-significant trend for increased oculomotor issues and disorientation seems with leaning-based interfaces, which contradicts our previous findings (Adhiakri et al., 2021; A. Hashemian et al., 2020; Nguyen-Vo et al., 2019). However, this might have been caused by a shortcoming of our implementation of the leaning-based interface: As soon as the last pointing from a given location was completed, the brake was lifted and participants could travel again. However, as we mentioned before, participants were not in neutral (upright) position when the brake was lifted and they sped towards the direction their body was leaning, which created an abrupt motion and contributed to cybersickness according to participants' post-experimental responses. This issue did not show up in our pilot testing and only occurred while running the full study - but given the challenges of running human participants studies in the midst of the COVID-19 pandemic we were not able redo the whole study. Interestingly, though, the leaning-based interface nevertheless provided significant spatial orientation benefits. In hindsight, we could have asked participants to find the neutral position, given an auditory cue to finding the position, and only then release the brake.

Finally, based on participant feedback and more pilot testing, we changed the controller from the rotational velocity control used in some of our previous studies (Nguyen-Vo et al., 2019; A. Hashemian et al., 2020; A. M. Hashemian et al., Submitted; Adhiakri et al., 2021) to pointing-based steering. Huge gaps seen in favor of leaning-based interfaces in the previous studies are no longer existent and participants preferred controller as much as leaning in most of the conditions (A. Hashemian et al., 2020; A. M. Hashemian et al., Submitted; Adhiakri et al., 2021). Users can make small turns with their hand and/or partial body turn with pointing-based steering which might have made it more intuitive and easy.

As previously mentioned, there was an added disadvantage of shooting off in the direction of leaning with leaning-based interface. Participants mentioned that it made them conscious not to lose control of the interface and made it harder for them to concentrate on the task. Further, the disadvantages of leaning-based interfaces with sitting posture and tensed muscles from previous designs was still there. Thus, comparatively controller was more preferred than from previous studies (A. Hashemian et al., 2020; A. M. Hashemian et al., Submitted; Adhiakri et al., 2021).

In conclusion, the interfaces were comparable in user experience with no significant difference in their overall rating. However, even with similar user experiences in most cases, the spatial updating data indicates that in some performance measures leaning-based interfaces is still better than controller-based interfaces. Further, even when participants were pointing in the direction of their motion in controller-based interfaces, they explained to use in the post-experiment interview that leaning-based interfaces are more immersive and engaging.

RQ3: Does HyperJump affect leaning-based and controller-based locomotion interfaces differently? The cybersickness result most prominently shows that their is a clear difference in how HyperJump effect two different interfaces. It also helps explain other differences in user experience ratings.

For the controller, there was virtually no effect of HyperJump on cybersickness. The experiment was deliberately designed to limit cybersickness. We limited overall travel time and speed to not cause any discomfort. As such, overall cybersickness was very low, with an average SSQ score of 7.04 for the Gamepad, which is 3.14% of the scale. Due to this floor effect, at this point we cannot draw any reliable conclusions about how HyperJump might have affected cybersickness in situations where overall sickness is higher, e.g, for faster travel or longer periods of travel. We are currently planning studies to investigate this.

However, the HyperJump seems to have increased cybersickness with the leaning-based interface. The post-trial interviews gave some insight to this. Participants probably could not interpret those abrupt movements in an otherwise more immersive and naturalistic experience and could only find the sensation of tripping to be the closest experience in real life. This finding bolsters previous observations that leaning-based interface can provide a more immersive and realistic experience than hand-held controllers (A. M. Hashemian et al., Submitted; A. Hashemian et al., 2020; Adhiakri et al., 2021; Kitson et al., 2017). However, this also means that we need to find a better metaphor to help people understand and make sense of the jumps, and provide relevant visual and auditory cues to help them interpret and anticipate them. Given that participants were not negatively affected by the HyperJump in our controller condition, and that iterative jumps reduced cybersickness in previous studies (Farmani & Teather, 2020), we believe a better metaphor with supporting visual and auditory cues will help to improve the user experience and performance with HyperJump, and potentially also reduce cybersickness.

In general, participants preferred the controller condition without HyperJump the most which is also the only condition that was familiar to many of them (more than half of the participants had used HMD with controller before). The current task failed to show any benefits of using HyperJump, and some users were frustrated by the novel interface which did not add any perceived value to their experience. This highlights the challenge of creating novel locomotion paradigms that do not tap into participants' prior experience, and the importance of iteratively refining interfaces across multiple studies. As previously mentioned, we expect to see advantages of HyperJump in situations where cybersickness is more of an issue, e.g., when it is being used to travel for long distances, or with higher speed. However, this experiment was deliberately conducted in a small environment so that continuous locomotion would also take similar time to finish the task and we could have a fair comparison between the interfaces without the confound of different task difficulty or cybersickness. Nonetheless, the overall experience and usability data gives us useful insight to improve our design before we test it for larger environments and more prolonged travel.

3.7 Conclusion

We present a first study that evaluates user's spatial awareness when adding teleportation to continuous methods of travel in a complex spatial updating task. Our findings indicate that HyperJump allowed users to travel faster but did not negatively affect user's spatial updating capabilities compared to their respective continuous interfaces. It is not possible to prove through null hypothesis testing that the jumps do not have any effect on spatial orientation, but the effect size suggest a negligible difference when HyperJump is introduced to the interface. Our study corroborate previous findings that adding optic flow to teleportation improves user's spatial awareness and extends it to a more ecologically valid task and environment.

Though previous works have shown improved spatial orientation using leaning-based interfaces compared to controller (Nguyen-Vo et al., 2019; Harris et al., 2014), our experiment is the first to show a significant difference between the interfaces with a spatial updating pointing task in a realistic environment. Our study also shows that even adding some level of embodiment in controller-based interfaces through hand motions (pointing) and physical rotation, is still not enough for it support spatial updating in a manner similar to leaning-based interfaces.

Given HyperJump does not compromise user's spatial updating, helps to travel faster and discrete movements interlaced with continuous motion helps combat cybersickness (Farmani & Teather, 2020), it encourages us to further evaluate the interface in high speed, much larger scale virtual navigation where teleporting will become more important.

Chapter 4

Conclusion and Future Work

Virtual reality comes with many promises. It allows us to explore the world in ways that were not possible before, like flying untethered, or experiencing a dream-like state while fully awake. To fulfill the many potentials it bears, it should allow users to navigate freely and effortlessly through the virtual world. Spatial updating, an automatic process that happens naturally during our real world locomotion cannot be achieved with the same efficiency with VR controllers. This motivated us to design and investigate novel locomotion paradigms so that VR users could fly in VR or travel super fast in a VR world while maintaining spatial updating comparable to our real world.

4.1 Summary and Main Contributions

In both studies presented in this thesis, we conducted within-subject experiments using complex spatial tasks. We modified previous designs of navigational searches and rapid pointing tasks to adopt them suitably to our requirements. It allowed us to conduct an experiment with robust tasks that accurately determined how well the users could maintain their spatial orientation and awareness during virtual travel.

In the first study, we compared participants' spatial updating with 3D leaning-based interface and controller. Spatial updating is important for many 3D VR and telepresence (drone/UAV) applications. Since we could not find an existing VR experiment evaluating spatial updating in 3D, we designed one based on previous ground-based navigational search tasks (Nguyen-Vo et al., 2019; Ruddle, 2013; Ruddle & Lessels, 2006b; Riecke et al., 2010b). When tasked with finding a number of hidden balls in a pitch dark environment with a virtual lamp attached to their avatar's head, participants could search more efficiently with leaning-based interface compared to controller and find more hidden balls within a given time. This effectively provides the first experimental evidence that even though humans cannot fly, partial body-based interface is not only valuable for ground navigation, but also for 3D navigation and spatial orientation.

Further, travel path's analysis and post-experiment interview from the first study suggested that controller with physical rotation can make users avoid controlling more than 2DOF at the same time, leading them to travel in a single plane or axis (potentially impacting user's spatial updating). We suggested using pointed-based steering could overcome those limitations and improve user experience with controller-based interfaces.

In the second study, we compared user's spatial awareness and orientation while using leaning- and controller-based interfaces, with and without HyperJump. HyperJump is a design proposal aimed to solve the slow travel time of continuous locomotion in a large scale environment by merging it with teleportation. In a ground navigation task, participants travelled in a naturalistic environment (virtual model of Tübingen, Germany). Though using the pointed-based steering made the user experience comparable to leaning-based interfaces, participants still had better spatial orientation with leaning-based interfaces, i.e. they had better ego-orientation with leaning-based interfaces and could more accurately point to previously visited landmarks. Reducing optical flow with the HyperJump technique allowed them to travel faster but did not reduce spatial orientation performance in both leaning- and controller-based interfaces. Aiming to reduce cybersickness with HyperJump is still an open question due to a generally low cybersickness in the chosen conditions.

4.2 Limitations and Future Work

We identify comparing the leaning-based interfaces with only controllers as one of the major limitation of both studies. However, there are a myriad of interfaces designed at this point and it does not seem feasible to navigate through all the interfaces to find a universally accepted alternative or even best implementation of a controller, as seen by the findings of the first study. It makes it difficult to generalize the findings of leaning-based interfaces against all interfaces or other variations of leaning-based interfaces.

Second, we identify that the majority of participants were undergraduate and graduate students from our university representing a fairly homogeneous group in age and background. We tried our best to include both novice and experienced VR users to increase the generalizability of the results. But we acknowledge that though not intentional, we lacked participants from other particiapnt groups, such as older participants, or participants with disabilities or with chronic pain.

We also recognize that studying cybersickness raises ethical concerns. Participants' safety has been our utmost priority throughout the research. We constantly monitored users' comfort to intervene and stop the experiment if necessary, which was never required. A number of design choices including relatively low maximum speed and short translational task were made so that the overall cybersickness stayed very low during the experiments. In the second study our design choices induced such a low cybersickness that we could not even demonstrate if HyperJump helps to reduce cybersickness. The instruments (SSQ and FMS) were not sensitive enough to distinguish the difference in cybersickness with and without HyperJump.

In the first study, we demonstrated that in a dark environment devoid of global landmarks, leaning-based interfaces can help users update their spatial knowledge more intuitively. Though this experiment reduces the confound of visual information and helps us accurately judge the effect of body-based information, we would like to acknowledge that some real world scenarios will have a lot of visual information and global landmarks. So, it is important to investigate in the future, how these interfaces support spatial updating in real world use cases.

In the second study, we deliberately used an environment of a few hundred meters for a fair comparison between continuous conditions with and without HyperJump. However, HyperJump was designed for improving long distance travel. Given the promising results from this study, we want to conduct a future study investigating HyperJump in a much larger environment where the travel speed can be higher and/or travel time can be longer.

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Appendix A

Authors contributions to the manuscripts

Lean to Fly: Leaning-based Embodied Flying can Improve Spatial Orientation and User Experience in 3D Navigation

Authors: Ashu Adhikari, Abraham M. Hashemian, Thinh Nguyen-Vo, Ernst Kruijff, Markus von der Heyde and Bernhard E. Riecke

Ashu Adhikari, Bernhard E. Riecke and Thinh Nguyen-Vo conceived of the presented idea. Adhikari modified the existing experiment design and VR simulation from Nguyen-Vo's previous work under Riecke's guidance. Riecke, von der Heyde, Kruijff, and Hashemian provided feedback throughout the study. Adhikari collected and analyzed data. Adhikari wrote the first draft of the manuscript. All authors discussed the results and contributed to the final manuscript.

Study 2: Integrating Continuous and Teleporting VR Locomotion into a Seamless "HyperJump" Paradigm

Authors: Ashu Adhikari, Daniel Zielasko, Alexander Bretin, Markus von der Heyde, Ernst Kruijff, Bernhard E. Riecke

Ashu Adhikari, Bernhard Riecke, and Markus von der Heyde conceived of the presented idea. Adhikari, Riecke, Zielasko, von der Heyde and Kruijff contributed in experimental design. Adhikari and Zielasko designed the VR simulation and selected the parameters from pilot testing. All authors provided feedback throughout the study. Adhikari collected and analyzed data. Adhikari wrote the first draft of the manuscript. All authors discussed the results and contributed to the final manuscript.

Appendix B

Semi-structured open-ended interview questions (Chapter 2)

- How was your experience?
- How was your experience having to control 3 degrees of freedom + rotations at the same time?
  - Follow up:
    - What specifically made it difficult (or easy)?
    - Was it similarly difficult for the gamepad and the HeadJoystick? What were the differences? Can you explain?
    - Did you use any strategies? Were they different for the different interfaces?
  - What did you like about the locomotion interfaces?
- Which interface would you prefer? Why?
  - Follow up:
    - For what kind of tasks do you think each of the interfaces would be useful?
- Do you have any suggestions for things that could be changed/improved?
- Did anything bother you during the experiment?
- Any other comments?

Appendix C

Semi-structured open-ended interview questions (Chapter 3)

- How was your experience?
- What was your favorite interface?
  - Why was it your favorite?
- What was your least favorite interface?
  - Why was it your least favorite?
- Did hyperjump on vs off affect your spatial orientation in any way?
  - If yes, how?
- Did leaning vs controller affect your spatial orientation in any way?
  - If yes, how?
- Was the pointing task difficult or easy in any particular path?
  - If yes, why?
- Did hyperjump on vs off affect your cybersickness in any way?
  - If yes, how?
- Did leaning vs controller affect your cybersickness in any way?
  - If yes, how?
- Do you have any suggestions for things that could be changed/improved?
- Did anything bother you during the experiment?
- Any other comments?

Appendix D

Consent Form

Chapter 2: The user study done for the paper, *Lean to Fly: Leaning-based Embodied Flying can Improve Spatial Orientation and User Experience in 3D Navigation*, was approved by Simon Fraser University. Please find the attached consent form that participants read and signed before participating in this experiment.

Chapter 3: The user study done for the paper, *Integrating Continuous and Teleporting VR Locomotion into a Seamless "HyperJump" Paradigm*, was approved by Simon Fraser University. Please find the attached consent form that participants read and signed before participating in the experiment.

School of Interactive Arts + Technology (SIAT), Simon Fraser University Surrey
250 -13450 102 Avenue, Surrey, BC V3T 0A3 Canada
Tel: +1 778.782.7474 Fax: +1 778.782.7478 Web: http://www.surrey.sfu.ca

SIMON FRASER UNIVERSITY
Informed Consent by Participants in a Research Study

Title: Locomotion Interfaces, Spatial Orientation and Behaviour in Real and Virtual Environments (Lean to Fly: Leaning-based Embodied Flying can Improve Spatial Orientation and User Experience in 3D Navigation)

Who is conducting the study?

Principal Investigator:	Bernhard Riecke [redacted]
Co-investigators:	Ashu Adhikari <[redacted]>
	Abraham Hashemian <[redacted] >
Faculty Supervisor:	Bernhard Riecke, [redacted]

Who is funding the study?

Funding for this study is provided by an NSERC research grant.

Why are we doing this study?

We are doing this study to determine which interface would make the movement through virtual/augmented environments most intuitive, minimize discomfort and maximize spatial orientation. We will collect performance and physiological data as corroborative measures to compare how different interfaces effect user experience and spatial orientation. This is a largely unexplored research area and this study will contribute greatly to human perceptual and behavioural science.

Better understanding of how the parameters of the interfaces affect the user experience will help developers design more effective human-computer interfaces and virtual/augmented simulations. This can guide and lead to improved applications in diverse areas, from research to business (remote site visit), training (realistic vehicle simulation), and tourism (exploring places virtually).

We are inviting people who are at least 14 years old, and have no physical or cognitive disabilities.

Voluntary Participation

Your participation is voluntary. You have the right to refuse to participate in this study. If you decide to participate, you may still choose to withdraw from the study at any time without any negative consequences to the education, employment, compensation, or other services to which you are entitled or are presently receiving. if you choose to enter the study and then decide to withdraw at a later time, all data collected about you during your enrolment in the study will be destroyed.

What happens to you in the study?

If you say 'Yes,' here is how we will do the study:

This experiment takes about **60 minutes** in total and consists of a learning phase, experiment trials, an online questionnaire, an interview, and a short debriefing phase.

At the beginning, you will be given instructions on how to use the virtual reality equipment. Next, a virtual reality headset will be placed on your head to show you a simulated, audio-visual virtual environment. Subtle vibro-tactile feedback will be provided through a worn backpack.

We will ask you to wear BioPlux sensors that will monitor a patch of skin (typically on your arm or neck) for changes in temperature, texture, and moisture. We will also ask you to wear a heart rate sensor. We will be recording audio and video of you while you experience the content, and a recording will be taken of the first-person view of your display.

During the experiment you will be asked to navigate in a simulated, virtual environment with different interfaces (such as joystick, gamepad, or hand-held controller) and compare them afterwards. The experimenter will demonstrate how to use each interface. Then, in the learning phase, you will practice navigating through the virtual environment with the use of the custom interface, which will be followed by a set of experiment trials. Detailed instructions of the procedures are provided to you auditorily during the experiment; please follow them as well as you can.

After the experiment trials, you will be asked to fill out an online questionnaire about your demographic information and your experience during the experiment. This online survey will be hosted on SFU's recommended SurveyMonkey application where data are hosted in Canada.

We will also ask you questions about your experience during the experiment in a semi-structured interview, to compare the interfaces, which will be audio/video recorded with your permission.

Is there any way this study could be bad for you?

We do not think there is anything that could harm you or be bad for you. The risks of the study are expected to be minimal, or the same as when you ride a bike or play a video game. Some people may experience motion sickness, so please let the experimenter know right away if you experience motion sickness or you need to stop for any reason. For your safety, please remain in the seat after removing the headset until you are sure you do not feel motion sick.

What are the benefits of participating?

We do not think taking part in this study will help you directly, except the experience of interaction with new technologies. However, in the future, others may benefit from what we learn in this study.

Compensation

We will not pay you for the time you take to be in this study. If you are a student enrolled at SFU, you may have the option to gain course credit in return for your participation instead of payment, at a rate of one point (out of a hundred) per hour of participation. – please see your course instructor or TA.

How will your privacy be maintained?

Your confidentiality will be respected. Any information that is obtained during this study will be kept confidential. Participants are assigned an ID number known only to the researchers, with information disclosing your identity not to be released without your consent. Participants will not be identified by name in any reports of the completed study or any data that will be shared with other researchers. Physical data such as consent forms will be stored in our locked lab or office at the SFU Surrey campus and kept for at least 2 years. Recordings and other digital data will be stored on password protected storage devices or secure SFU servers and kept for at least 5 years. Data might be kept indefinitely. Aggregate data (but not consent forms, video/audio recordings of you, or any other identifiable information) may be uploaded to an open access data repository for others to use, and thus may be kept indefinitely; these data will be de-identified, meaning any direct and indirect identifying information will be removed or transformed.

The results of this study may be reported in a graduate thesis, online on websites such as our lab website http://ispace.iat.sfu.ca, and may also be published in other ways such as articles, books, and conferences. Additional research may be conducted where the data is used for future analyses within a different study, with any identifying information removed (de-identified) from the dataset.

The online survey is hosted by SFU's recommended and Canada-hosted SurveyMonkey system, which is US owned, and as such is subject to US laws including the US CLOUD Act and US Patriot Act. These laws allow government authorities to access the records of host services and internet service providers. If you choose to participate in the survey, you understand that your responses to the survey questions will be potentially accessed in the US, even though the data will be stored on Canadian servers. The security and privacy policy for the web survey company can be found at the following link: https://www.sfu.ca/itservices/publishing/surveys/surveymonkey_terms_of_service.html. The University and those conducting this research study subscribe to the ethical conduct of research and to the protection at all times of the interests, comfort, and safety of participants.

How will the results be used?

The results of this study will be reported in scientific venues, including books, conferences and journals or graduate theses. The results may also be reported in non-academic formats, such as forums, websites, and news articles.

Who can you contact to get your results or if you have questions?

The principal investigator keeps a repository of all publications on the lab website at http://ispace.iat.sfu.ca/publications/ so you can find study results there once they get published. For any additional questions, feel free to contact the student researcher Ashu Adhikari [redacted] or the principal investigator Dr. Bernhard Riecke [redacted]

Who can you contact if you have complaints or concerns about the study?

If you have any concerns about your rights as a research participant and/or your experiences while participating in this study, you may contact Dr. Jeffrey Toward, Director, Office of Research Ethics [redacted] or [redacted]

Future contact

	Yes	**No**
Would you like to be contacted to participate in future studies on this or related projects?	☐	☐

If yes, please provide the best means to contact you (enter all that apply):

Email:____________________________________Phone:___________________________

Acceptance of this Form

If you agree, we take video and audio recordings of you during the experiment and interview. This would allow us to more easily analyze the data later on and potentially use part of the video footage for scientific dissemination with your permission.

	Yes	**No**
1. Do you consent to being video recorded?	☐	☐
2. Do you consent to being audio recorded?	☐	☐
3. Do you permit the use of the video images and/or audio recordings in future research studies of the principal investigator and co-investigators?	☐	☐
4. Do you permit the use of your video image and/or audio recording in public dissemination (thesis, papers, conference presentations, etc.) directly related to this research project? (NOTE: Due to the nature of digital video images, once the video image is disseminated to the public, the researcher does not have any control over how the images are distributed and/or used.)	☐	☐
5. If you consent to the above question, do you wish that your image/voice be distorted before any public dissemination?	☐	☐

Taking part in this study is entirely up to you. You have the right to refuse to participate in this study. If you decide to take part, you may choose to pull out of the study at any time without giving a reason and without any negative impact on your employment, education (class standing), or services.

- *Your signature below indicates that you have received a copy of this consent form for your own records.*
- *Your signature indicates that you consent to participate in this study.*
- *You do not waive any of your legal rights by participating in this study.*

Participant first name:____________________ Participant last name: _____________________

Participant contact email: ___________________________ phone: _______________________

____

Participant Signature   Date (yyyy/mm/dd)

School of Interactive Arts + Technology (SIAT), Simon Fraser University Surrey
250 -13450 102 Avenue, Surrey, BC V3T 0A3 Canada
Tel: +1 778.782.7474 Fax: +1 778.782.7478 Web: http://www.surrey.sfu.ca

SIMON FRASER UNIVERSITY
Informed Consent by Participants in a Research Study

Title: Locomotion Interfaces, Spatial Orientation and Behaviour in Real and Virtual Environments – in-person study during Covid-19 restrictions (Integrating Continuous and Teleporting VR Locomotion into a Seamless "HyperJump" Paradigm)

Who is conducting the study?

Principal Investigator:	Bernhard Riecke [redacted]
Co-investigators:	Ashu Adhikari <[redacted]> Alexander Bretin < [redacted]>
Faculty Supervisor:	Bernhard Riecke, [redacted]

Who is funding the study?

Funding for this study is provided by an NSERC research grant.

Why are we doing this study?

We are doing this study to determine which interface would make the movement through virtual/augmented environments most intuitive, minimize discomfort and maximize spatial orientation. We will collect performance and physiological data as corroborative measures to compare how different interfaces effect user experience and spatial orientation. This is a largely unexplored research area and this study will contribute greatly to human perceptual and behavioural science.

Better understanding of how the parameters of the interfaces affect the user experience will help developers design more effective human-computer interfaces and virtual/augmented simulations. This can guide and lead to improved applications in diverse areas, from research to business (remote site visit), training (realistic vehicle simulation), and tourism (exploring places virtually).

We are inviting people who are at least 14 years old, and have no physical or cognitive disabilities.

Voluntary Participation

Your participation is voluntary. You have the right to refuse to participate in this study. If you decide to participate, you may still choose to withdraw from the study at any time without any negative consequences to the education, employment, compensation, or other services to which you are entitled or are presently receiving. if you choose to enter the study and then decide to withdraw at a later time, all data collected about you during your enrolment in the study will be destroyed.

What happens to you in the study?

If you say 'Yes,' here is how we will do the study:

This experiment takes about **60 minutes** in total and consists of a learning phase, experiment trials, an online questionnaire, an interview, and a short debriefing phase.

At the beginning, you will be given instructions on how to use the virtual reality equipment. Next, you will be instructed to place the virtual reality headset on your head to show you a simulated, audio-visual virtual environment. Subtle vibro-tactile feedback will be provided through a worn backpack.

We will be recording audio and video of you and the VR experience while you experience the content, and a recording will be taken of the first-person view of your display.

During the experiment you will be asked to navigate in a simulated, virtual environment with different interfaces (such as joystick, gamepad, or hand-held controller) and compare them afterwards. The experimenter will demonstrate how to use each interface. Then, in the learning phase, you will practice navigating through the virtual environment with the use of the custom interface, which will be followed by a set of experiment trials. Detailed instructions of the procedures are provided to you auditorily during the experiment; please follow them as well as you can.

After the experiment trials, you will be asked to fill out an online questionnaire about your demographic information and your experience during the experiment. This online survey will be hosted on SFU's recommended SurveyMonkey application where data are hosted in Canada.

We will also ask you questions about your experience during the experiment in a semi-structured interview, to compare the interfaces, which will be audio/video recorded with your permission.

COVID-19 risks

This study includes in-person research activities. While the research team will implement safety protocols, please note that COVID-19 can spread through close contact and through the air. While many of the characteristics of COVID-19 are still unknown, mild to severe illness have been reported for confirmed cases. Physical distancing will be maintained while you are in the lab. To mitigate risk, all individuals in the lab are required to wear a mask at all time, and will not be in direct physical contact with you. In addition, we are frequently disinfecting high-touch surfaces in the lab and disinfecting research equipment before and after each use.

Is there any way this study could be bad for you?

We do not think there is anything that could harm you or be bad for you. The risks of the study are expected to be minimal, or the same as when you ride a bike or play a video game. Some people may experience motion sickness, so please let the experimenter know right away if you experience motion sickness or you need to stop for any reason. For your safety, please remain in the seat after removing the headset until you are sure you do not feel motion sick.

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Compensation

We will not pay you for the time you take to be in this study. If you are a student enrolled at SFU, you may have the option to gain course credit in return for your participation instead of payment, at a rate of one point (out of a hundred) per hour of participation. – please see your course instructor or TA.

How will your privacy be maintained?

Your confidentiality will be respected. Any information that is obtained during this study will be kept confidential. Participants are assigned an ID number known only to the researchers, with information disclosing your identity not to be released without your consent. Participants will not be identified by name in any reports of the completed study or any data that will be shared with other researchers. Physical data such as consent forms will be stored in our locked lab or office at the SFU Surrey campus and kept for at least 2 years. Recordings and other digital data will be stored on password protected storage devices or secure SFU servers and kept for at least 5 years. Data might be kept indefinitely. Aggregate data (but not consent forms, video/audio recordings of you, or any other identifiable information) may be uploaded to an open access data repository for others to use, and

thus may be kept indefinitely; these data will be de-identified, meaning any direct and indirect identifying information will be removed or transformed.
The results of this study may be reported in a graduate thesis, online on websites such as our lab website http://ispace.iat.sfu.ca, and may also be published in other ways such as articles, books, and conferences. Additional research may be conducted where the data is used for future analyses within a different study, with any identifying information removed (de-identified) from the dataset.

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Additional information gathered during COVID-19

According to the Public Health Act, we may be requested to share contact tracing data if someone that has visited the lab presents with symptoms of COVID-19. If requested, we will share this data. Contact tracing is managed confidentiality and according to BC's Privacy Laws and is intended for your safety. Contact tracing data will be limited to your name, date present in the lab, and the contact information you provided to the research team. The log containing these data will be kept password protected on SFU's owncloud (sfuvault) server, and only members of Dr. Riecke's iSpaceLab will have access to it.

How will the results be used?

The results of this study will be reported in scientific venues, including books, conferences and journals or graduate theses. The results may also be reported in non-academic formats, such as forums, websites, and news articles.

Who can you contact to get your results or if you have questions?

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Acceptance of this Form

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	Yes	**No**
1. Do you consent to being video recorded?	☐	☐
2. Do you consent to being audio recorded?	☐	☐
3. Do you permit the use of the video images and/or audio recordings in future research studies of the principal investigator and co-investigators?	☐	☐
4. Do you permit the use of your video image and/or audio recording in public dissemination (thesis, papers, conference presentations, etc.) directly related to this research project? (NOTE: Due to the nature of digital video images, once the video image is disseminated to the public, the researcher does not have any control over how the images are distributed and/or used.)	☐	☐
5. If you consent to the above question, do you wish that your image/voice be distorted before any public dissemination?	☐	☐

Taking part in this study is entirely up to you. You have the right to refuse to participate in this study. If you decide to take part, you may choose to pull out of the study at any time without giving a reason and without any negative impact on your employment, education (class standing), or services.

- *Your signature below indicates that you have received a copy of this consent form for your own records.*
- *Your signature indicates that you consent to participate in this study.*
- *You do not waive any of your legal rights by participating in this study.*

Participant first name:____________________ Participant last name: _____________________

Participant contact email: ___________________________ phone: _______________________

____

Participant Signature Date (yyyy/mm/dd)

[note: for remote studies and during Covid-19 restrictions, the informed consent form will be provided through SurveyMonkey, and the last line with the signature and date will be replaced by the option [button] displaying

- “I agree and would like to proceed with the study”, or
- “I disagree, and wish to exit the study”.