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

Ashu Adhikari, Daniel Zielasko, Ivan Aguilar, Alexander Bretin, Ernst Kruijff, Markus von der Heyde, and Bernhard E. Riecke

Abstract—Continuous locomotion in VR provides uninterrupted optical flow, which mimics real-world locomotion and supports path integration . However, optical flow limits the maximum speed and acceleration that can be effectively used without inducing cybersickness. In contrast, teleportation provides neither optical flow nor acceleration cues, and users can jump to any length without increasing cybersickness. However, teleportation cannot support continuous spatial updating and can increase disorientation. Thus, we designed 'HyperJump' in an attempt to merge benefits from continuous locomotion and teleportation. HyperJump adds iterative jumps every half a second on top of the continuous movement and was hypothesized to facilitate faster travel without compromising spatial awareness/orientation. In a user study, Participants travelled around a naturalistic virtual city with and without HyperJump (equivalent maximum speed). They followed waypoints to new landmarks, stopped near them and pointed back to all previously visited landmarks in random order. HyperJump was added to two continuous locomotion interfaces (controller- and leaning-based). Participants had better spatial awareness/orientation with leaning-based interfaces compared to controller-based (assessed via rapid pointing). With HyperJump, participants travelled significantly faster, while staying on the desired course without impairing their spatial knowledge. This provides evidence that optical flow can be effectively limited such that it facilitates faster travel without compromising spatial orientation. In future design iterations, we plan to utilize audio-visual effects to support jumping metaphors that help users better anticipate and interpret jumps, and use much larger virtual environments requiring faster speeds, where cybersickness will become increasingly prevalent and thus teleporting will become more important.

Index Terms—Virtual Reality, Spatial Updating, Leaning, Teleportation, Locomotion, Semi-continuous locomotion

1 Introduction

Teleportation is a common metaphor for VR locomotion. In this metaphor, the user is discretely moved to a target destination as opposed to continuous travel methods where the users 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 with a controller. It is simple and effective. Further, it generally does not induce cybersickness, especially compared to controller-based continuous locomotion methods [1], [2]. Therefore, teleportation is commonly used as a target-based travel technique [3], [4], [5]. However, while comparing different travel techniques and metaphors, Bowman *et al.* [3] found that teleportation techniques, due to their abrupt view changes, can be disorienting compared to continuous travel techniques.

Spatial updating is a mental process of maintaining ("updating") the spatial relationship between ourselves and our surroundings during self-motion, where self-to-object relationships constantly change. It is important for effective navigation, spatial orientation, and situational awareness [6], [7], [8], [9]. This process is largely automated or even obligatory (i.e., hard to suppress) during natural walking and also occurs during more complex activities like driving, climbing, diving, flying, or playing sports. However, only imagining the self-motions does not generate the same level of spatial updating and does not seem to be able to elicit automatic or obligatory spatial updating [10], [11], [12], [13].

The discrete jumps in teleportation also remove any self-motion cues that could be used to path-integrate and thus support automatic spatial updating [5]. That is, for teleportation, one has to rely on other means to recover orientation, such as landmark-based piloting, which makes it less effective than using a combination of path-integration and piloting [14]. Conversely, dynamic translation information (either visual or body-based self-motion cues) provided by continuous travel methods has shown to help users perform better in spatial updating tasks [15].

On the downside, any continuous locomotion model provides continuous optical flow, which limits the maximum acceleration and speed that can be applied without causing cybersickness. As a result, large-scale navigation

- *A. Adhikari, I. Aguilar, A. Bretin, and B.E. Riecke are with the School of Interactive Arts & Technology, Simon Fraser University, Canada. E-mail: {ashua, ivan_aguilar, alexanderbretin, ber1}@sfu.ca*
- *D. Zielasko is with University of Trier, Germany. E-mail: zielasko@uni-trier.de*
- *E. Kruijff is with the Institute of Visual Computing, Bonn-Rhein-Sieg University of Applied Sciences, Germany and the School of Interactive Arts & Technology, Simon Fraser University, Canada. E-mail: ernst.kruijff@h-brs.de*
- *M. von der Heyde is with the vdH-IT and the School of Interactive Arts & Technology, Simon Fraser University, Canada. E-mail: info@vdh-it.de*

Manuscript received XXX.XX, 2021; revised XXX.XX, XXXX; accepted XXX. XX, XXXX. Date of publication XXX. XX, XXXX. For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below. Digital Object Identifier no. XX.XXXX/TVCG.XXXX.XXXXXXX

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 or locomotion speeds (like a regular controller-based or leaning-based interface). When users would aim to cover larger distances or travel at higher velocities that would likely engender cybersickness, HyperJump seamlessly adds teleportation (iterative jumps every half a second) to the continuous movement. Teleportation does not create any optical flow during the jumps, thus reducing the risk of cybersickness [3], [16]. Since the jumping distance is independent of optical flow, it 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 [3], [5], [17], we hypothesize that interlacing continuous movements with relative short repeated jumps might provide sufficient optical flow and predictability of one's post-jump location to help maintain users' spatial updating capabilities while effectively limiting the optical flow so that it does not exacerbate cybersickness during fast/long-distance travel. Bowman *et al.* [3] have already shown that the travel speed (continuous) 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 if the interface can provide sufficient optical flow to support spatial updating.

This paper proposes an experimental paradigm to assess users' spatial awareness and orientation in a naturalistic environment with a realistic task. We also conducted a user study to compare how leaning-based and controller-based interfaces support spatial updating with and without HyperJump. We included leaning-based interfaces, where the user leans in the direction they want to move because it provides at least some embodied locomotion cues compared to non-embodied stationary systems based on handheld controllers [18]. Compared to the commonly used hand-controllers that provide little if any embodied self-motion cues, leaning-based interfaces have not only been shown to improve navigational performance [19], [20], [21], [22], by providing body-based self-motion cues (in particular proprioceptive and vestibular translational cues), but also reduce cybersickness [20], [21], [23], [24], [25], enhance presence [26], immersion, enjoyment, and engagement [19], [27], [28]. At the same time, leaning-based interfaces perform comparably to standard controller-based/thumbstick-based interfaces (precision, completion time, error) or even better [23], [25], [29]. Leaning-based interfaces also do not rely on hand-controllers, thus freeing the hands to perform other tasks [30].

In our user study, participants travelled on four different non-intersecting paths with four different interfaces. Participants were instructed to point back to previously visited locations from each stop along the path. This allowed us to infer their spatial awareness and updating. We also asked participants to rate their experience on different measures and conducted open-ended interviews to understand underlying factors better and improve future locomotion interfaces.

2 Related works

Teleportation has been adopted as one of the most common locomotion interfaces for its simplicity, effectiveness, and reduction of cybersickness. However, it disrupts presence and cannot provide path integration cues, causing spatial disorientation [31], [32]. We found a few implementations aimed at understanding and improving situational awareness and spatial updating while using teleportation. Below, we present the implementation details and their advantages and disadvantages, which informed our design of HyperJump.

Weißker *et al.* compared spatial updating between teleporting a large distance (beyond vista space) and repeated teleporting within vista space [1]. 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 can see their current and target locations between each jump, they cannot update their spatial knowledge effectively. To address this shortcoming, users receive self-motion cues while using HyperJump.

LaViola et al. proposed a navigation interface where the user could teleport to their destination by stepping into a location on a map rendered at their feet [33]. Users could see their global location in an overview map, zoom in or out of the map, and also teleport to the desired location by standing in the position they wanted to teleport to. Users could also use continuous locomotion for short travel in this implementation. Though this implementation can show users' global position and facilitate moving from one point to another in a known map, this implementation is less useful for exploration tasks. Further, the interface uses two different interfaces discretely. It required users to manually activate and deactivate a metaphor before each use, which may discourage users to switch between the metaphors frequently. Our HyperJump metaphor can automatically and seamlessly transition between continuous and discontinuous methods to overcome this limitation.

In an attempt to solve the spatial updating problem of teleportation, Bolte *et al.* proposed the 'jumper' metaphor [34]. In this travel technique, the user could use real walking for small-range travel and virtual jumps for large-range travel, where the user's viewing direction would initiate a jump with smooth viewpoint animation. The interface used gaze-based target acquisition to avoid explicit target selection via additional input devices. Gazing at a location for 0.5 seconds, selected the target location. Target acquisition animation lasted for 2 seconds, and the user can deselect the target location by looking away at any point during that time. A map sketching task showed that while participants were significantly worse in map sketching with teleportation compared to real walking, they were only slightly (but not significantly) worse with the jumper metaphor. However, this method uses a gaze-based technique, predicted from the user's virtual head position and viewing direction. Though their gaze-based technique stops accidental triggering and supports information gathering at least to some degree, constant animation associated with gaze and needing to look away to avoid jumping could render it unsuitable for most practical applications that require exploration and information gathering. Our HyperJump metaphor is independent of looking direction to overcome this limitation.

Bhandari *et al.* also proposed a 'Dash' metaphor similar to 'jumper', which adds a smooth viewpoint animation to teleportation [35]. They conducted a user study to compare participants' spatial updating with Dash and normal teleportation. In their study, participants teleported once or twice in one trial and pointed back to the origin from the final position. The user study showed that Dash allowed for better point-to-origin performance compared to normal teleportation while maintaining similar levels of cybersickness in both locomotion techniques. However, the Dash method requires participants to manually and constantly choose each target for travel. It does not support a smooth and continuous exploration of the virtual environment. To address those limitations, in our HyperJump implementation, the user can have continuous travel for short distance travel as well as a seamless transition to fast-paced travel without having to select jump locations or switch between interfaces. The virtual environment in their study was designed to be devoid of any landmarks, which likely reduced optical flow and diminished cybersickness. For our task, we chose a naturalistic environment with ample landmarks to make it closer to most real-world and simulated environments and provide a more realistic assessment of cybersickness.

Farmani and Teather [16] also investigated the impact of short repeated jumps, called viewpoint snapping, the closest technique to our proposal. They observed decreased cybersickness when discrete movements were applied to either rotational or translational viewpoint motion. Their study also found no significant difference in spatial awareness between translational snapping and 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, tasks, or environment sizes. Their implementation also requires users to have one hand on the mouse to control snapping and provides (from what we can tell from the paper) no indication of the future jump's location or path. Further, their experiment was mostly focused on cybersickness and did neither involve a complex naturalistic environment nor complex spatial orientation tasks. That is, their task consisted of 10 simplistic pointing tasks (pointing back to the origin after moving in a straight path) and four pointing back to the origin tasks after a 2-segment excursion. To complement their findings and investigate generalizability, our study chose a more complex maneuvering and spatial orientation task in a more naturalistic and ecologically valid environment.

Similarly, Rahimi *et al.* evaluated the importance of optical flow for spatial awareness by varying it in three different levels [36]. In an automated travel path, participants experienced teleportation (normal), animated interpolation (smooth viewpoint animation, similar to the jumper [34] and Dash [35]), and pulsed interpolation (similar to viewpoint snapping [16]). 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 cybersickness. Thus, the paper reiterates the importance of optical flow for improving spatial updating/awareness and its negative impact on cybersickness, adding motivation to our approach.

In sum, while prior research (and VR applications/games) include several teleporting/dashing implementations that can help to reduce motion sickness, they all require users to either manually select and trigger jumps/dashes, or do not provide full control over future jump/snapping locations, or don't work well across diverse distances.

HyperJump is the first system that combines continuous locomotion and self-motion perception (vection) at limited speeds (and optic flow), which is essential for spatial orientation and predictability/controllability, with teleporting into a seamless interface where users never have to switch locomotion interface or metaphor, yet can travel both extremely precisely (important especially for small-scale locomotion) and cover very large distances.

3 Experimental Evaluation

The main focus of our study was to investigate how HyperJump might affect the user's performance in a spatial orientation task that critically relies on spatial updating during excursion travel. 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 two continuous locomotion interfaces: a leaning-based interface because of its desirable traits as discussed in the section 1; and a standard handheld controller-based interface, as HMDs usually come with their own controllers, which are heavily used for locomotion.

RQ1: How does adding iterative jumps ('HyperJump') to continuous locomotion methods affect performance compared to continuous-only locomotion? How does it affect overall usability and user experience, including cybersickness?

We are mainly focused on evaluating if an interface can speed up travelling without negatively affecting the user's spatial orientation. Along with spatial orientation, we were also curious about how HyperJump might affect other aspects of usability and user experiences, such as cybersickness, task load, preference, and ease of use. In the following, we briefly review relevant prior studies that compared continuous travel with (modified) teleportation and on which we based our own hypotheses and predictions. Reduced cybersickness is observed when optical flow is reduced (jumps without viewpoint animation) [16], [36]. There were mixed results on time taken to complete a task, though, ranging from no significant time difference between the techniques [32], faster travel with continuous locomotion [37], [38], and faster travel with teleportation [39]. When participants compared different teleportation techniques using Likert scales, results were also mixed: Bolte *et al.* found no significant difference between real walking, jumper metaphor, and teleportation for ease of learning and ease of use [34]. 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 [35]. Rahimi *et al.* observed high variance in preference ratings among the interfaces [36]. In sum, findings are fairly mixed when comparing teleportation (standard and modified versions) with a continuous locomotion method. We expected our study to shed some light on the following measures:

Spatial updating, Cybersickness and speed: Bowman *et al.* were the first to show that teleportation negatively affects spatial awareness compared to continuous travel [3]. Subsequent studies have shown that adding animated viewpoint transitions to teleportation (”Jumper”, ”Dash”) can improve spatial orientation [34], [35], [36]. However, as Rahimi *et al.* demonstrated, adding optical flow to teleportation can be nauseating [36], negating or at least reducing the advantage of teleportation as a less sickening locomotion method. Later, Farmani and Teather demonstrated that iterative jumps could reduce cybersickness while not impairing spatial orientation in a simplistic point-to-origin task [16]. Based on these findings, we posited that the optical flow provided by interlacing continuous motion with iterative jumps would help maintain spatial orientation/awareness and facilitate spatial updating. We hypothesized there would be minimal performance difference when adding HyperJump to the continuous-only locomotion in a complex spatial updating task.

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 optimized for all interfaces to complete a trial. The trials were designed to be completed within a similar time for all conditions while minimizing cybersickness to avoid carryover effects. However, we still expected HyperJump to reduce optical flow, which might reduce cybersickness. Similarly, we did not expect all participants to travel with maximum speed at all times and expected to see some difference in task completion time. However, we did not have any directional hypothesis for travel time.

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

Overall usability and user experience: Finally, we wanted to compare the overall usability, and user experience with introspective measures using the extended Bowman’s effectiveness factors [29], [40] and semi-structured open-ended interviews. We hoped to thus better understand the underlying advantages and disadvantages of HyperJump to optimize a hybrid interface that integrates continuous locomotion with iterative jumps. In future studies, we plan to compare the performance of continuous locomotion with or without added HyperJump in much larger virtual environments which desire faster travel speeds.

RQ2: How does the locomotion interface (leaning-based versus controller-based) affect performance? How do they affect overall usability and user experience, including cybersickness?

Controller-based interfaces do not provide major embodied self-motion cues and fail to support spatial updating in a manner real-walking does [20], [41], [42], [43]. On the other hand, leaning-based interfaces have been shown to improve spatial awareness and orientation when compared to controller-based interfaces [26], even when physical rotation is present in both conditions [20], [21]. One leaning-based interface (NaviBoard) even reached performance levels comparable to walking [20].

Adding physical rotation to controller-based interfaces better supported spatial updating [43]. However, when physical rotation was introduced for controller-based interfaces, participants complained about the disjunction between the physical rotation and controller translation [21], [23], [44]. Further, the analysis of travelling path showed that participants often switched between travelling and turning, which confined the translational motion to a single axis or plane and could have impacted spatial updating [21]. 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 participants use only physical rotation or strafe via thumbstick use. With this implementation, users could change their steering direction by turning the controller, i.e., pointing in the desired direction with the controller. It still uses physical user rotation, which is highly desirable but allows a participant to perform smaller steering direction changes by just turning the controller or with partial rotation of their 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 more easily.

With this change, we expected to improve maneuvering ability for the controller-based interface (pointing-based steering instead of torso/chair-rotation based). It also added at least some minimal embodiment, i.e.; users would aim their hand (with the controller) in the direction they want to move. Hence, we expected the previously-observed clear spatial orientation benefit of leaning- vs. controller-based locomotion to be less pronounced or even no longer existent [20], [21]. Similarly, we expected it to improve the the controller-based interface’s overall usability and user experience.

RQ3: Does adding iterative jumps (‘HyperJump’) to continuous locomotion methods affect leaning- vs. controller-based locomotion interfaces differently? Users have different experiences with leaning-based and controller-based locomotion interfaces. Leaning provides a more embodied experience and, at least minimal, embodied self-motion cues. It improves presence, immersion, enjoyment, and engagement [21], [23], [26], [27], [28]. Partial body-based sensory information also makes the experience more naturalistic and realistic [21], [23]. On the other hand, leaning-based interfaces are relatively new methods with very little exposure compared to controller-based locomotion. As none of our participants had used leaning-based 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 [3], [5], [17]. We wanted to understand if the embodied nature and/or previous exposure made a difference while designing a hybrid system.

Fig. 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.

4 Method

4.1 Participants

Twenty users participated in our study. We excluded two participants due to incomplete experimental trials and one user because of a high level of 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 had previously used an HMD, and 12 had regularly used controllers to play video games on a computer or a gaming console. The study had the approval from the local Research Ethics Board.

4.2 Virtual Environment and Task

A virtual model of part of downtown Tübingen, Germany, was used to provide a complex naturalistic environment with ample landmarks and optic flow and avoid grid-like street patterns that might have supported undesired cognitive strategies such as counting turns (see Figure 1A&B) [45]. Four different non-intersecting paths were created, so participants travelled a unique path with each interface (see Figure 1). As all the participants were from the greater Vancouver area in Canada, none of the participants were familiar with the city.

Each trial began at one of four unique locations, as indicated by the white dots on the map in Figure 1A. Participants followed 10 waypoints to the next landmark (see Figure 2A). The waypoints acted as both indicators of the path to the next landmark and as a measure of travel accuracy. As participants followed the waypoints and reached new landmarks from each location, they would estimate the position and distance (see Figure 2B) of all previously visited landmarks in random order, as prompted by the program [46].

A number of different methods have been used to evaluate spatial awareness and updating. Oral recollections of spatial experiences, sketching an area map and arranging photos of route segments and landmarks in their correct order can assess route knowledge. Returning to the origin, pointing to the origin or other landmarks, and estimating the distance traveled can measure configurational knowledge [47]. Navigational search has also been effectively shown to assess spatial updating [20], [41], [42], [43], [48]. Since we wanted to quantitatively measure spatial updating while travelling in a large scale visually rich environment, we found rapid pointing to the origin/landmarks to be the best fit for our experiment.

4.3 Locomotion Modes

In this user study, we investigated the effect of adding iterative jumps to two otherwise 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.

4.3.1 Continuous Method of Locomotion

HeadJoystick: Participants lean their upper body as if it is a joystick to translate in the desired direction [21], [22], [23], [25], [29], [30]. This is achieved by using the HMD's built-in tracker, with no need for additional trackers. When the program starts, users are asked to sit in a natural upright position, press and hold a button and rotate their heads to the left and to the right for calibration. Then, we calculate the center of the head rotation and set it as the resting position of the head. When the user performs movements that also cause their heads to move, we track the deviation from the resting position and assign a velocity exponential to the deviation for smoother acceleration. Using an exponential transfer function reduces or even removes the need for a deadzone that is often necessary to compensate for minimal body sway in linear interfaces [25]. The maximum virtual speed was limited to 10 m/s,

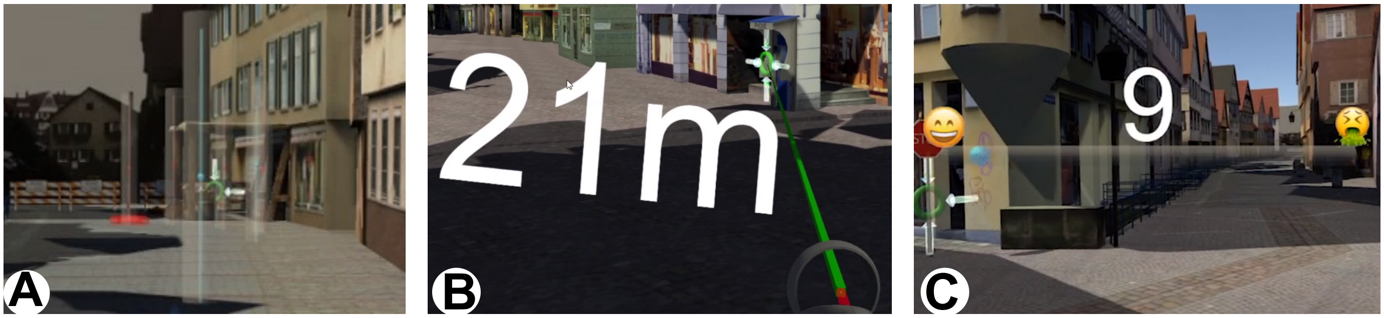


Fig. 2. (A) Waypoint navigation task, where participants need to travel through the white semi-transparent cylinders (5 blue followed by 5 red cores) until reaching the final (red) location where they were automatically stopped. (B) Distance estimation to one of the landmarks, telephone booth. Landmarks are indicated by a green circle and white arrows for ease of recognition. (C) Participants' cybersickness rating on a scale of 0-100

mimicking inner city driving speeds.

Controller: Participants used the Oculus controller thumbstick to translate in the desired direction up to a virtual speed of 10 m/s. We implement controller-directed (pointing-directed) steering, where the controller's forward direction determines the forward movement direction. That is, the user can physically rotate, point with the controller, or press the thumbstick sideways to change the moving direction. Similar to HeadJoystick, we used an exponential transfer function to map the input of the thumbstick deflection to translation velocity.

4.3.2 *HyperJump: Hybrid Locomotion Method*

HeadJoystick-Teleport:[1] Up to the virtual continuous translation speed of 5 m/s it works like the standard HeadJoystick implementation. Then, leaning further triggers a jump into the direction of travel every 0.5 s. The jump is added while maintaining the continuous translation of 5 m/s between jumps. Leaning further increases the jump distance between 1-8 m, but not the jump frequency. These parameters were chosen based on extensive pilot testing, which revealed that changing jump distance instead of jump frequency was perceived as more predictable and controllable.

Controller-Teleport: This works similarly to how the HeadJoystick-Teleport works but uses 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 the same time to travel a straight path at their maximum speed.

In this experiment, we were equally interested in understanding the spatial updating of the HyperJump method and its precision and accuracy for travel. It was not possible to assess teleportation accuracy unless we asked participants to teleport to the center of each waypoint or used teleportation only as if it were a velocity control method (i.e. a HyperJump method but without any continuous movement). Both felt unnatural teleportation methods and would require comparing teleportation with four other methods mentioned above in a different experimental task. With this, adding an experimental task or including different teleportation methods inthe current task, to make a fair comparison, would require us to extend the length of experiment sessions. It was already an hour long interaction with participants on two separate days in the midst of strict COVID-19 safety protocols. Therefore, we decided not to include a teleportation-only condition in our current study. However, comparing HyperJump, continuous locomotion, and teleportation-only conditions in the future as a separate study could provide a deeper understanding of their respective advantages and disadvantages and the generalizability of the current findings.

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

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 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 a total of 14 non-trivial pointings (to non-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.

The overall procedure is shown in Figure 3. Participants performed the trials with one of the interfaces (two conditions) on the first day and with the other interface (two conditions) 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 the simulator sickness questionnaire (SSQ) [49]. Then, they performed the first and second trial with one of the interfaces (leaning or controller) with HyperJump state switched between the two trials. Participants filled out an SSQ and a NASA task load index (TLX) questionnaire [50] after each trial while they took a mandatory break of 5 minutes. After completing the second trial, they filled out a post-trial questionnaire, detailed in subsubsection 5.2.3, which compared the interface with and without the use of HyperJump. On the second day, they followed the same routine with the interfaces they had not used yet and

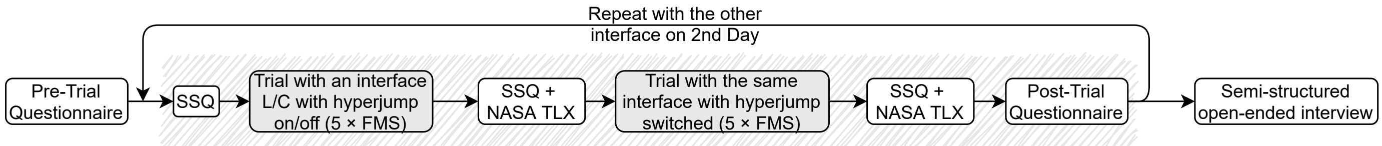


Fig. 3. Experimental Design

ended with a post-experiment open-ended semi-structured interview.

4.4.1 Experimental Tasks

During each trial, participants were tasked with the following tasks, as illustrated in this video.

Trivial Pointing Task: Participants started the trial with a trivial pointing task, i.e., by pointing to two directly visible landmarks (indicated with a green circle and white arrows), see video. Similarly, they finished the pointing task from each location with the trivial pointing to the adjacent (and the only directly visible) landmark. Though these trivial pointing tasks were not considered during the analysis, they both helped participants familiarize themselves with the task and ensured that they learnt the targets' names.

Waypoint Navigation Task: During the pointing phase, the locomotion interfaces were frozen. After completing the pointing tasks, 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 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 2A) of a waypoint they heard positive auditory feedback. Completely missing a waypoint caused a 'wrong' buzzer to sound and removed that 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 five blue waypoints (at least 8 m away from each other, except on turns) placed for assessing accuracy. The travel path ended with five red waypoints (1-5 m from each other) that oriented participants toward the new target as well as indicated that the navigation task was about to be completed.

Rapid Pointing Task (First Pointings): [1]

Once participants reached the last waypoint (represented with a red base - Figure 2A), the system applied a brake to slow down and stop the user at that location. Then, an auditory prompt instructed participants to "point up" so that their pointing always started from the same upright pointer orientation, thus avoiding any confounds with prior target directions. Next, an auditory prompt instructed participants to point as quickly and accurately to one of the previously visited landmarks along the current path. If the controller's pointing direction was less than 30 degrees from the horizontal and the controller was stable, the system would then register that as the pointing direction and indicated it 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 a more accurate response time [51]. 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 (Figure 2B). 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 held 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 tasks from a new location, the first pointing task can take longer than 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 [52]. 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 in investigating 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 2C. This is based on FMS scale adapted from Keshavraz and Hecht's FMS [53]. In both cases the participants adjust a slider between two extremes. However, in our pilot testing and previous study [21], we found that participants found a percentage scale to be more intuitive to use than a range from 0-20.

4.4.2 Performance measures

We measured the following dependent variables during the pointing tasks.

Absolute pointing error: It was used to assess 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

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

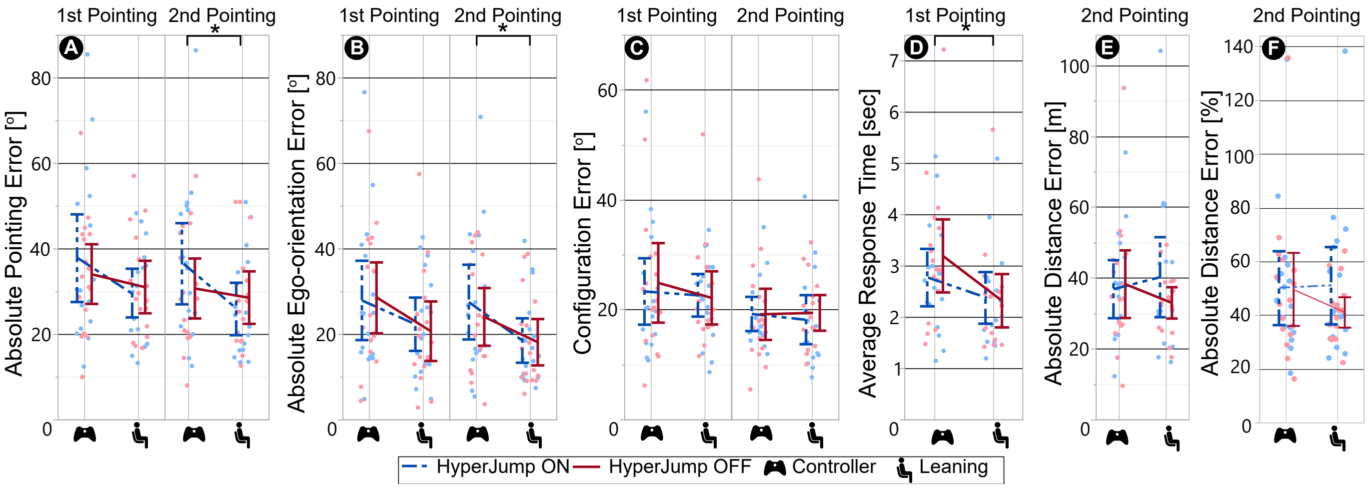


Fig. 4. (A) Absolute pointing error. (B) Absolute ego-orientation error. (C) Configuration Error while performing the first and second pointing tasks. (D) Average Response Time during the first Pointing. (E) Absolute Distance Estimation Error while performing the second pointing task. (F) Absolute Distance Estimation Error as percentage. Points with light shades show mean data for individual participants. Error bars indicate 95% confidence intervals (CI). * above the plot indicates $p < .05$

to a total of 14 non-trivial landmarks (non-trivial pointings). For each pointing, an absolute pointing error was calculated as the absolute value of the difference between the correct and the pointed yaw direction. Pointing measures can serve as a way to infer about the underlying spatial orientation and specifically spatial updating processes, although the task also requires other aspects such as maneuvering between targets, memorization of the targets, etc.

Absolute ego-orientation error: A part of absolute pointing error stems from participants' misperception of their ego-orientation, i.e., the difference between their actual and perceived orientation with respect to the landmarks [54]. An absolute ego-orientation error was calculated by taking the absolute circular mean of the signed pointing errors from each pointing location.

Configuration error: Is 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 [55], and can be used to assess participants' spatial awareness of the target layout (irrespective of any ego-orientation errors).

Response time: During the first pointing phase we instructed participants to point to each landmark as fast and as accurately as possible. We measured how long it took participants to stably point to a target after the system uttered that target's name. A shorter response time in rapid pointing tasks typically indicates the travel required less cognitive load, presumably because automatic spatial updating was better supported [12].

Absolute distance estimate error: The absolute difference between the target's real distance and participants' estimated distance. The use of the configuration error along with distance estimate helps us to assess participants' spatial awareness of the target layout and is easier to quantify and compare between interfaces/locomotion methods than alternative options, such as map drawing.

We measured the following performance-based dependent variables during the locomotion phase. Whereas the pointing measures are used to infer about spatial orientation/updating, the waypoint measures are a measure of maneuvering ability given the current interface and locomotion method.

Waypoint distance error: The absolute distance between the center of participants' head and the waypoints' center indicated by the sphere (see Figure 2, semi-transparent cylinders with a sphere in the middle).

Waypoint navigation time: 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.

5 Results

5.1 Behavioral Measures

Seven dependent variables (see subsubsection 4.4.2) 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 analysis of variance (ANOVA) were confirmed in each case.

5.1.1 *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 1.

TABLE 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 4. However, this trend did not reach significance for the absolute pointing error and configuration error, see Table 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.

5.1.2 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 the time participants needed to estimate the distance, because they quickly pointed in the approximate target direction and spent most of the time adjusting the distance estimate. As before, only the independent variable 'interface' showed any significant effects for the second pointing task, summarized in Table 2.

TABLE 2
Main effect of interface during pointing and distance measurement task. Green shading indicates significant ($p \leq 5\%$) differences.

	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
Distance estimate error (%)	46.1	3.70	49.9	4.50	.677	.423	.200

Similar to the first pointing phase, all dependent variables showed a trend towards improved performance for the leaning- when compared to the controller-based interfaces, see Figure 4 (Note: We include percentage of absolute distance error for reference) and Table 2. Though configuration error and distance estimation error showed trends towards improvement with leaning, it was not significant. The absolute pointing and ego-orientation errors did significantly decrease by 19% and 29%, respectively, when using the leaning- when compared to using controller-based interfaces.

5.1.3 Comparing 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 (and within 30° of the 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 trigger in a pressed state.

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 ANOVAs 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.

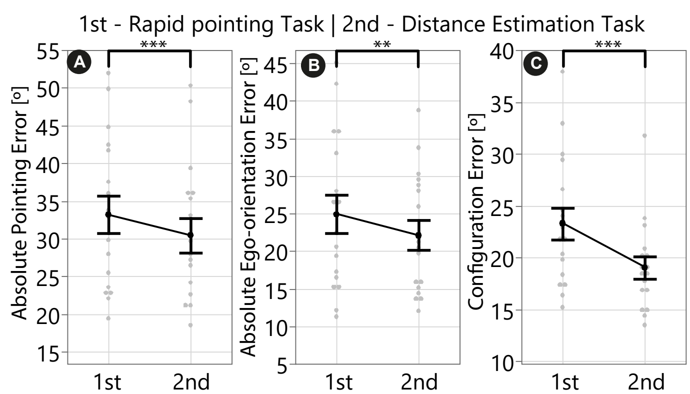


Fig. 5. (A) Absolute pointing error (B) Absolute ego-orientation error (C) Configuration Error while performing first rapid pointing task (1st pointing phase) and distance estimate and subsequent second pointing task. Light gray points show data for individual participants. Error bars indicate 95% CI. *, ** and *** indicate $p < .05$, $p < .01$ and $p < .001$ respectively

From Figure 5 and Table 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 for ANOVA results.

5.1.4 Waypoint Navigation Task

We recorded the participant's distance from the waypoints while they were following the waypoints to the next lo-

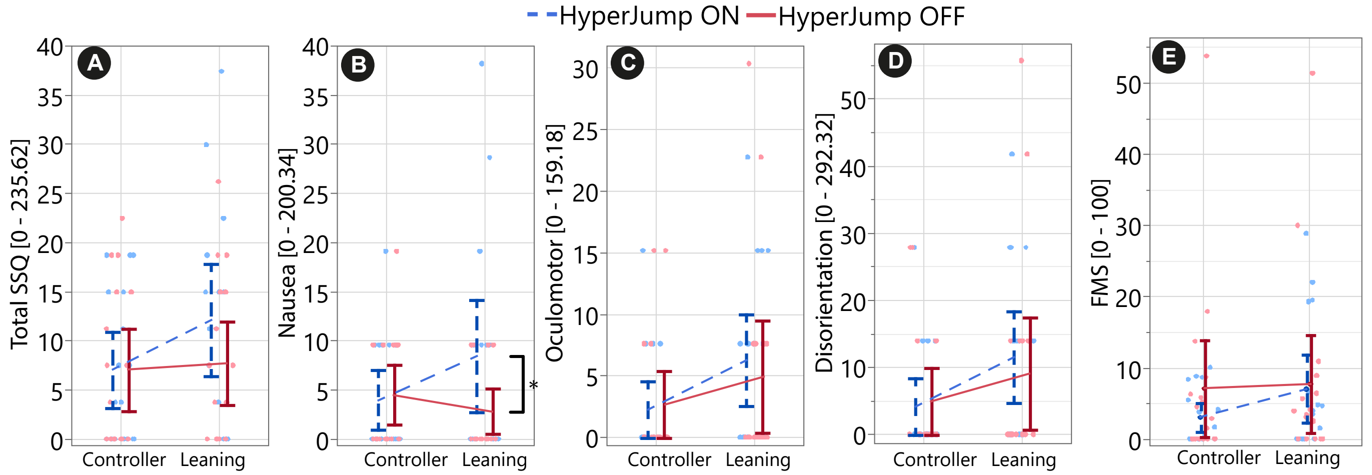


Fig. 6. (A-D) SSQ with sub-scales and (E) FMS after performing the trials. Points with light shades show mean data for individual participants. Error bar indicates 95% CI. * indicates $p < .05$

TABLE 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

cation. 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 the participant's position from the waypoint and the median time taken for the participant 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.

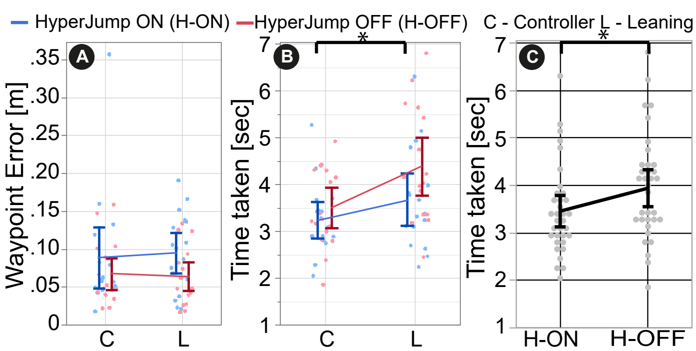


Fig. 7. (A) Median absolute waypoint error (distance between the way-point and player) in cm (B) Average time taken (in seconds) to travel between two consecutive blue waypoints. Points with light shades show mean data for individual participants. Error bars indicate 95% CI. * and ** indicate $p < .05$ and $p < .01$ respectively

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, see Figure 2A. This indicates that overall, all locomotion conditions allowed participants to travel accurately enough to stay on the desired course. We performed a further inferential analysis with interface and HyperJump as the independent variables. The ANOVA showed a marginally significant effect of HyperJump on waypoint distance error, see Table 4. Waypoint distance error was smaller (by 28%) without HyperJump than with HyperJump, see Figure 7A. However, there was no effect of the interface and no interaction between the interface and HyperJump on the Waypoint distance error, see Table 4. The percentage of missed waypoints showed that Leaning-based interface without and with the HyperJump performed best (5.5%) and worst (16.7%), respectively. Controller performed similarly without (11.6%) or with (11.4%) the HyperJump. Nevertheless, the chi-square test failed to find a significant difference between any conditions.

TABLE 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 4. The travel time was reduced by .48 seconds (12%) when participants travelled with controller-based interfaces compared to leaning-based, see Figure 7B. Similarly, they took less time with HyperJump on (reduced by 16%) compared to HyperJump off.

As participants took different times to complete the task with and without HyperJump, we tested if the average completion time correlated to any pointing or distance estimation task. However, there was no significant corre-

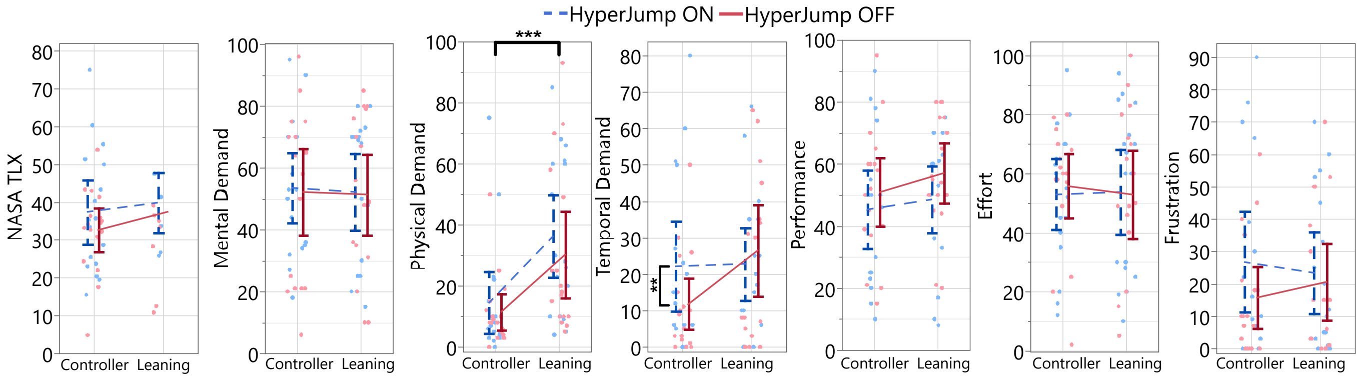


Fig. 8. NASA TLX with sub-scales while performing the trials. Points with light shades show mean data for individual participants. Error bar indicates 95% CI. *** indicates $p < .001$

lation between completion time and any other behavioral measurement (all $p's > .265$).

5.2 Subjective Ratings

5.2.1 Cybersickness

During the experiment, cybersickness was measured in two different ways. First, participants indicated their cybersickness while performing the task on a scale adapted from Keshavraz and Hecht's Fast Motion Sickness Scale (FMS) [53]. After completing the pointing task from each location within a trial, participants indicated cybersickness on a scale of 0-100, as illustrated in Figure 2 (C). '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 track participants' cybersickness continually and, if required, intervene and stop the experiment. Second, after completing the trial with each interface, they filled out the simulation sickness questionnaire (SSQ) [49].

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 6A. Furthermore, 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, the average for rest of the participants - 25/100) and dropped the experiment after the first trial.

TABLE 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^2_p	F(1,16)	p	η^2_p	F(1,16)	p	η^2_p
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

From the inferential statistics presented in Table 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 ($p = .081$), i.e., the leaning-based interface showed higher total SSQ scores with HyperJump ($M = 12.1, SE = 2.71$) than without ($M = 7.70, SE = 2.02$). 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 6A&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 6E. There were no significant main effects or interactions on FMS.

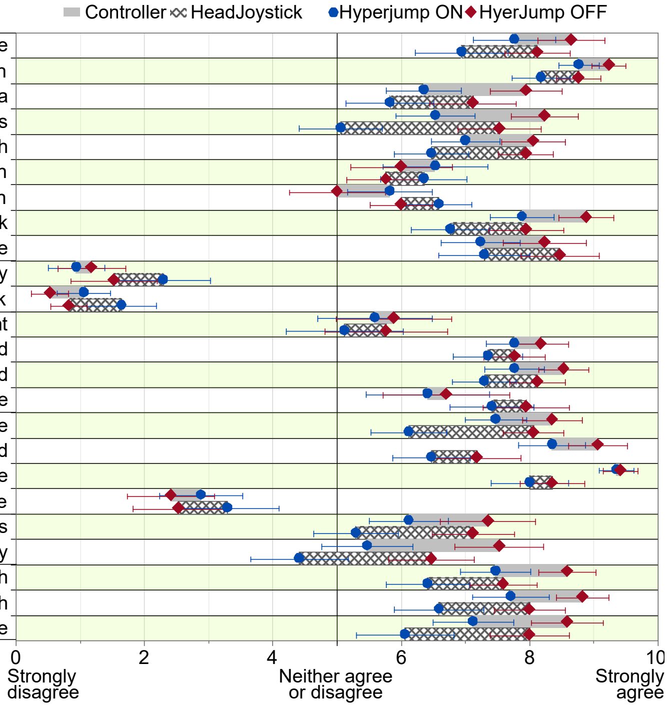
5.2.2 Task Load

There were no significant effects of any factor on the total NASA task load, see Table 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 8C. 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 8E&G. Finally, there was a significant interaction on temporal demand. Participants found Controller with no jump to have the least temporal demand compared to the rest of the conditions.

5.2.3 Preference and Post-Experiment Interview

In general, participants found all the conditions to have more 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 9 shows, however, that participants consistently preferred the HyperJump off condition ($M = 7.96, SE = .097$) to HyperJump on ($M = 6.87, SE = .107$),

HyperJump		Interface		
Z	p	Z	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

Fig. 9. 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 ().

TABLE 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

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 into 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 when using the controller felt *"no different than a computer scene"* {P09,P12} and they were not bothered much by them. But when using the leaning-based interface, the jumps were perceived as off-putting. They felt like they were *"tripping"* or *"falling"* when the jumps occurred and felt like they were *"about to hit the ground"* with those jumps {P09, P17}. In essence, these accounts also support that leaning-based interface provides a more realistic and natural experience of moving through the environment. 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 these 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*."

6 Discussion

This paper presents the first study comparing users' spatial orientation between a hybrid of teleportation and continuous locomotion versus continuous locomotion alone in a complex spatial updating task. While we can only travel with a limited acceleration and speed with continuous locomotion without causing cybersickness, teleportation makes it 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 [5] and facilitate perspective changes [56]. Continuous locomotion also supports path integration and can improve spatial awareness [17]. So, we proposed a hybrid interface that tries to retain both kinds of travel advantages.

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 also investigated if using pointing-based steering for the controller improves performance, usability, and user experience instead of just using its thumbstick. We discuss the findings of our experiment in the context of our main research questions below.

RQ1: How does adding iterative jumps ('HyperJump') to continuous locomotion methods affect performance compared to continuous-only locomotion? How does it affect overall usability and user experience, including cybersickness?

Our study showed a significant difference between the interfaces themselves (controller-based vs leaning-based) but adding HyperJump did not significantly affect how the underlying interfaces support user's spatial updating. Though a null hypothesis cannot be verified in this manner, we observed almost no negative effect of HyperJump on users' spatial orientation/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 is a promising area that can be further explored to capitalize on potential other benefits (such as reducing cybersickness and travel time) without a fear of compromising the user's 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 travel, even though it was limited to 5 m/s for the HyperJump conditions. Previous studies have already shown that modifying the teleportation technique by adding some optical flow to it can improve a user's spatial updating compared to teleportation techniques without any optical flow [16], [35], [36]. Bolte et. al found participants' 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 (virtual camera movement) to the jump itself [34], [35], [36]. 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 maneuvering accuracy. Participants managed to keep a 9.2 cm median distance from the waypoint with HyperJump, while without HyperJump it was only 6.5 cm, see Figure 7. Similarly, in their subjective ratings, participants indicated that HyperJump was not as precise to 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, the median distance between the waypoint and user's head center was less than 10 cm, which is the width of waypoint's center. That is, even with the added HyperJumps, participants were typically able to travel along the intended path in all conditions and successfully completed all the trials. Thus, if users want to get to a location 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 enough to switch to continuous mode.

The travel time between two regular (blue) waypoints reveals that participants travelled 14% faster with HyperJump. Though both conditions support the same maximum average speed, participants felt comfortable travelling with a faster average speed with HyperJump on than off (continuous speed capped at 5 m/s and 10 m/s with and without HyperJump). Past studies showed mixed results regarding completion times when comparing target-acquisition teleportation techniques with continuous locomotion [32], [37], [38], [39]. Our seamless technique proved to be faster than continuous locomotion, even in a setting designed for similar average speeds between both conditions and when cybersickness was not an issue. Hence, we are optimistic about its performance in much larger environments where teleporting will become more important, and we currently plan studies to investigate this.

The overall cybersickness during the experiment was very low and a number of factors likely contributed to this: The maximum travel speed was relatively low (10 m/s for continuous locomotion, similar to inner city car speeds), 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 potential benefits in sickness reduction of HyperJump. Adhikari *et al.* discussed in their paper how SSQ might be too conservative in detecting a difference between conditions in post-trial and how pre- vs. post-use SSQ scores might be more illuminating [21]. However, we blocked with and without HyperJump conditions on a single day, limiting us from comparing HyperJump with pre- vs. post-use SSQ scores. We are currently planning a follow-up study investigating HyperJump in a much larger environment (requiring higher speeds and/or longer travel times) which will help to better assess the potential benefits of HyperJump in terms of reducing cybersickness.

RQ2: How does the locomotion interface (leaning-based versus controller-based) affect performance? How do they affect overall usability and user experience, including cybersickness?

Our results also provided novel insights into how leaning versus controller-based interfaces support spatial orientation/updating. Both interfaces use physical rotation. In spite of that, leaning-based interfaces resulted in improved ego-orientation compared to the controller in both the first and second pointing phase. This shows that providing physical rotations (which were 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 [43], [57], [58]. Further, Nguyen-Vo *et al.* [20] demonstrated that despite having physical rotation in all conditions, partial body-based translation control through leaning could 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 through leaning.

The first rapid pointing phase showed a consistent trend of 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 [12]. Our results also show that these trends became more consistent with the second pointing. The performance benefit of leaning- vs. controller-based interfaces reached significance for both absolute pointing and ego-orientation errors. This effect somewhat surprised us, as participants had only additional time between the first and second pointing but no additional interface-related cues that could have helped them improve their performance.

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 with leaning-based interfaces, which contradicts our previous findings [20], [21], [23]. 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 a 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 could only run limited pilot tests, and we were not able to 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 - which we plan to implement in our future studies.

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 [20], [21], [23], [29] to pointing-based steering. These improvements for the controller condition likely contributed to reducing the previously-observed huge benefits of leaning-based over controller interfaces [21], [23], [29], and our participants now preferred controller as much as leaning in most of the conditions. As we mentioned in section 3, pointing-based steering allows users to make small turns with their hand and/or partial body turn, which might have made it more intuitive and easy. Pointing-based steering also added some minimal embodiment, in that users would point in the direction they want to move with their hand holding the controller. 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 were still there. Thus, comparatively, the controller was more preferred than observed in previous studies [21], [23], [29].

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 behavioural spatial orientating/updating data indicates that leaning-based interfaces still have performance advantages over controller-based interfaces. Further, participants expressed that leaning-based interfaces are more immersive and engaging than controller-based interfaces in the post-experiment interview.

Interestingly, we observed a considerable performance improvement between the first and second pointing. Several factors 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 used to improve their pointings. Even though previous studies have found a difference in response time between first pointing and subsequent pointing from the same location even in the same phase [52], 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, a ”pointing” was recorded and they could no longer change their mind. During the second phase, participants could physically rotate to face the target direction and had additional time to adjust their pointing direction during the distance estimation task. Finally, the distance judgment task might have triggered additional or different spatial cognition processes, including deliberately thinking more about the length of each part of the path, the route, or the overall spatial configuration. Future research is needed to pinpoint how these different factors 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.

RQ3: Does adding iterative jumps (‘HyperJump’) to continuous locomotion methods affect leaning- vs. controller-based locomotion interfaces differently?

The cybersickness result most prominently shows that there is a clear difference in how HyperJump affects the 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 and thus reduce carry-over effects and confounds. We limited overall travel time and speed not to cause any discomfort. As such, overall cybersickness was very low, with an average SSQ score of 7.04 for the controller, which is 3.14% of the scale. Due to this floor effect, we cannot draw any reliable conclusions about how HyperJump might have affected cybersickness in situations where overall sickness is higher, e.g., for faster 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 into this. Participants probably had challenges interpreting those abrupt jumps in an otherwise more immersive and naturalistic experience. They reported the sensation as a kind of “tripping” as it might have been the closest comparable experience in real life. This finding bolsters previous observations that leaning-based interface can provide a more immersive and realistic experience than handheld controllers [21], [23], [27], [29]. Meanwhile, 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, auditory, and/or haptic cues to help them interpret and anticipate them.

Though we did not explicitly ask if HyperJump impacted immersion or presence in our open-ended interview questions, the user ratings in the post-experiment questionnaire indicate changes in immersion and presence due to HyperJump with the leaning-based interface. Given that participants were not negatively affected by the HyperJump in our controller condition and that iterative jumps reduced cybersickness in previous studies [16], we believe a better metaphor supported by audiovisual and haptic cues will help to improve the user experience and performance with HyperJump, and potentially also reduce cybersickness. When we incorporated audio cues and blended the future and current location during the jump for a SIGGRAPH installation of HyperJumping in a large city model of virtual Vancouver, the initial pilot study showed that participants could spend extended periods of time moving across the environment even at a speed faster than what was used for this study [59]. This does not, however, rule out potential impacts of HyperJump on immersion and presence, and future studies are needed to explicitly investigate this, especially with more embodied interfaces.

Participants generally preferred the controller condition without HyperJump, which is also the only condition that most were familiar with (more than half of the participants had used HMD with a controller before). The current task failed to show any benefits of using HyperJump except for shortening travel time. Some users were frustrated by the novel interface, which did not add any perceived value to their experience – which might be related to cybersickness being extremely low for our study. 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 speeds. However, this experiment was deliberately conducted in a naturalistic inner city environment using typical inner city speed limits (10 m/s) so that all users could complete continuous locomotion without major cybersickness issues, 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 give us helpful insight to improve our design before we test it for larger environments and more prolonged travel.

7 Conclusion

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

Previous works have shown improved spatial orientation when using leaning-based interfaces compared to controller-based interfaces [19], [20], 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 insufficient to support spatial updating like leaning-based interfaces.

Given that HyperJump does not compromise user's spatial updating, helps them travel faster, and that discrete movements when interlaced with continuous motion are known to reduce cybersickness [16], it encourages us to improve further and evaluate the interface in much larger virtual environments that require high speeds, where cybersickness will become increasingly critical and thus teleporting will become more important.

References

[1] T. Weißker, A. Kunert, B. Fröhlich, and A. Kulik, "Spatial updating and simulator sickness during steering and jumping in immersive virtual environments," in *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, 2018, pp. 97–104.

[2] M. Al Zayer, P. MacNeilage, and E. Folmer, "Virtual locomotion: a survey," *IEEE transactions on visualization and computer graphics*, vol. 26, no. 6, pp. 2315–2334, 2018.

[3] D. Bowman, D. Koller, and L. Hodges, "Travel in immersive virtual environments: an evaluation of viewpoint motion control techniques," in *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality*, 1997, pp. 45–52.

[4] D. Bowman, E. Kruijff, J. J. LaViola Jr, and I. P. Poupyrev, *3D User interfaces: theory and practice, CourseSmart eTextbook*. Addison-Wesley, 2004.

[5] B. E. Riecke and D. Zielasko, "Continuous vs. Discontinuous (Teleport) Locomotion in VR: How Implications can Provide both Benefits and Disadvantages." Lisbon, Portugal: IEEE, 2021, pp. 1–2.

[6] R. F. Wang, "Building a cognitive map by assembling multiple path integration systems," *Psychonomic bulletin & review*, vol. 23, no. 3, pp. 692–702, 2016, publisher: Springer.

[7] J. M. Loomis and J. W. Philbeck, "Measuring spatial perception with spatial updating and action," in *Embodiment, ego-space, and action*, ser. Carnegie Mellon symposia on cognition. New York, NY, US: Psychology Press, 2008, pp. 1–43.

[8] T. P. McNamara, J. Sluzenski, and B. Rump, "Human Spatial Memory and Navigation," in *Learning and Memory: A Comprehensive Reference*, J. H. Byrne, Ed. Oxford: Academic Press, 2008, pp. 157–178.

[9] R. F. Wang and E. S. Spelke, "Human spatial representation: Insights from animals," *Trends in Cognitive Sciences*, vol. 6, no. 9, pp. 376–382, Sep. 2002.

[10] C. C. Presson and D. R. Montello, "Updating after rotational and translational body movements: Coordinate structure of perspective space," *Perception*, vol. 23, no. 12, pp. 1447–1455, 1994.

[11] J. J. Rieser, "Access to knowledge of spatial structure at novel points of observation." *Journal of Experimental Psychology: Learning, Memory, and Cognition*, vol. 15, no. 6, pp. 1157–1165, 1989.

[12] M. J. Farrell and I. H. Robertson, "Mental rotation and automatic updating of body-centered spatial relationships." *Journal of Experimental Psychology: Learning, Memory, and Cognition*, vol. 24, no. 1, p. 227, 1998.

[13] R. F. Wang, "Between reality and imagination: When is spatial updating automatic?" *Perception & Psychophysics*, vol. 66, no. 1, pp. 68–76, 2004.

[14] J. W. Kelly, A. G. Ostrander, A. F. Lim, L. A. Cherep, and S. B. Gilbert, "Teleporting through virtual environments: Effects of path scale and environment scale on spatial updating," *IEEE Transactions on Visualization and Computer Graphics*, vol. 26, no. 5, pp. 1841–1850, 2020.

[15] E. M. Barhorst-Cates, J. Stoker, J. K. Stefanucci, and S. H. Creem-Regehr, "Using virtual reality to assess dynamic self-motion and landmark cues for spatial updating in children and adults," *Memory & Cognition*, vol. 49, no. 3, pp. 572–585, 2021.

[16] Y. Farmani and R. J. Teather, "Evaluating discrete viewpoint control to reduce cybersickness in virtual reality," *Virtual Reality*, pp. 1–20, 2020, publisher: Springer.

[17] N. H. Bakker, P. O. Passenier, and P. J. Werkhoven, "Effects of head-slaved navigation and the use of teleports on spatial orientation in virtual environments," vol. 45, no. 1, pp. 160–169, 2003.

[18] S. Beckhaus, K. J. Blom, and M. Haringer, "Chairio–the chair-based interface," *Concepts and technologies for pervasive games: a reader for pervasive gaming research*, vol. 1, pp. 231–264, 2007.

[19] A. Harris, K. Nguyen, P. T. Wilson, M. Jackoski, and B. Williams, "Human joystick: Wii-leaning to translate in large virtual environments," in *Proceedings of the 13th ACM SIGGRAPH International Conference on Virtual-Reality Continuum and its Applications in Industry*. ACM, 2014, pp. 231–234.

[20] T. Nguyen-Vo, B. E. Riecke, W. Stuerzlinger, D.-M. Pham, and E. Kruijff, "Naviboard and navichair: Limited translation combined with full rotation for efficient virtual locomotion," *IEEE transactions on visualization and computer graphics*, 2019.

[21] A. Adhikari, A. M. Hashemian, T. Nguyen-Vo, E. Kruijff, M. v. d. Heyde, and B. E. Riecke, "Lean to fly: Leaning-based embodied flying can improve performance and user experience in 3d navigation," *Frontiers in Virtual Reality*, p. 120, 2021.

[22] D. Zielasko, Y. C. Law, and B. Weyers, "Take a Look Around – The Impact of Decoupling Gaze and Travel-direction in Seated and Ground-based Virtual Reality Utilizing Torso-directed Steering," in *Proc. of IEEE VR*, 2020.

[23] A. Hashemian, M. Lotfaliei, A. Adhikari, E. Kruijff, and B. E. Riecke, "HeadJoystick: Improving Flying in VR using a Novel Leaning-Based Interface," *IEEE Transactions on Visualization and Computer Graphics*, 2020, publisher: IEEE.

[24] J. E. Bos, W. Bles, and E. L. Groen, "A theory on visually induced motion sickness," *Displays*, vol. 29, no. 2, pp. 47–57, Mar. 2008.

[25] D. Zielasko, S. Horn, S. Freitag, B. Weyers, and T. W. Kuhlen, "Evaluation of Hands-Free HMD-Based Navigation Techniques for Immersive Data Analysis," in *Proc. of IEEE 3DUI*, 2016, pp. 113–119.

[26] M. Marchal, J. Pettré, and A. Lécuyer, "Joyman: A human-scale joystick for navigating in virtual worlds," in *2011 IEEE Symposium on 3D User Interfaces (3DUI)*, Mar. 2011, pp. 19–26.

[27] A. Kitson, A. M. Hashemian, E. R. Stepanova, E. Kruijff, and B. E. Riecke, "Comparing leaning-based motion cueing interfaces for virtual reality locomotion," in *2017 IEEE Symposium on 3D User Interfaces (3DUI)*, Mar. 2017, pp. 73–82.

[28] E. Kruijff, A. Marquardt, C. Trepkowski, R. W. Lindeman, A. Hinkenjann, J. Maiero, and B. E. Riecke, "On your feet!: Enhancing vection in leaning-based interfaces through multisensory stimuli," in *Proceedings of the 2016 Symposium on Spatial User Interaction*. ACM, 2016, pp. 149–158.

[29] A. M. Hashemian, A. Adhikari, E. Kruijff, M. von der Heyde, and B. E. Riecke, "Leaning-based interfaces improve ground-based vr locomotion in reach-the-target, follow-the-path, and racing tasks," *IEEE Transaction on visualization and computer graphics TVCG*, 2021.

[30] A. M. Hashemian, A. Adhikari, I. Aguilar, E. Kruijff, M. von der Heyde, and B. E. Riecke, "Is walking necessary for effective locomotion and interaction in vr?" *IEEE VR Workshop on Finding a way forward in VR locomotion*, 2021.

[31] J. Clifton and S. Palmisano, "Effects of steering locomotion and teleporting on cybersickness and presence in hmd-based virtual reality," *Virtual Reality*, vol. 24, no. 3, pp. 453–468, 2020.

[32] E. Langbehn, P. Lubos, and F. Steinicke, "Evaluation of locomotion techniques for room-scale vr: Joystick, teleportation, and redirected walking," in *Proceedings of the Virtual Reality International Conference-Laval Virtual*, 2018, pp. 1–9.

[33] J. J. LaViola, Jr., D. A. Feliz, D. F. Keefe, and R. C. Zeleznik, "Hands-free Multi-scale Navigation in Virtual Environments," in *Symposium on I3D*. NY, USA: ACM, 2001, pp. 9–15.

[34] B. Bolte, F. Steinicke, and G. Bruder, "The jumper metaphor: an effective navigation technique for immersive display setups," in *Proceedings of Virtual Reality International Conference*, vol. 1, 2011, pp. 2–1.

[35] J. Bhandari, P. R. MacNeilage, and E. Folmer, "Teleportation without spatial disorientation using optical flow cues." in *Graphics interface*, 2018, pp. 162–167.

[36] K. Rahimi, C. Banigan, and E. D. Ragan, "Scene transitions and teleportation in virtual reality and the implications for spatial awareness and sickness," *IEEE transactions on visualization and computer graphics*, vol. 26, no. 6, pp. 2273–2287, 2018.

[37] K. Danyluk and W. Willett, "Evaluating the performance of virtual reality navigation techniques for large environments," in *Computer Graphics International Conference*. Springer, 2019, pp. 203–215.

[38] M. Malekmakan, W. Stuerzlinger, and B. Riecke, "Analyzing the trade-off between selection and navigation in vr," in *26th ACM Symposium on Virtual Reality Software and Technology*, 2020, pp. 1–3.

[39] F. Buttussi and L. Chittaro, "Locomotion in Place in Virtual Reality: A Comparative Evaluation of Joystick, Teleport, and Leaning," *IEEE TVCG*, 2019.

[40] D. A. Bowman, E. T. Davis, L. F. Hodges, and A. N. Badre, "Maintaining Spatial Orientation during Travel in an Immersive Virtual Environment," *Presence: Teleoperators and Virtual Environments*, vol. 8, no. 6, pp. 618–631, Dec. 1999.

[41] R. A. Ruddle and S. Lessels, "For efficient navigational search, humans require full physical movement, but not a rich visual scene," *Psychological science*, vol. 17, no. 6, pp. 460–465, 2006, publisher: SAGE Publications Sage CA: Los Angeles, CA.

[42] ——, "The benefits of using a walking interface to navigate virtual environments," *ACM Transactions on Computer-Human Interaction (TOCHI)*, vol. 16, no. 1, pp. 1–18, 2009.

[43] B. E. Riecke, B. Bodenheimer, T. P. McNamara, B. Williams, P. Peng, and D. Feuereissen, "Do we need to walk for effective virtual reality navigation? physical rotations alone may suffice," in *International Conference on Spatial Cognition*. Springer, 2010, pp. 234–247.

[44] A. M. Hashemian and B. E. Riecke, "Swivel-Chair: Evaluating Seated Full-Rotational Interfaces for Virtual Reality Navigation." Vancouver, Canada: Software for Augmented and Virtual Reality (SAVR), Oct. 2017.

[45] Anonymous. "Virtual Tübingen," Cyberneum. [Online]. Available: https://www. cyberneum.de/30302/virtualtuebingen. [Accessed: 28-Jan-2021].

[46] T. Y. Grechkin and B. E. Riecke, "Re-evaluating benefits of body-based rotational cues for maintaining orientation in virtual environments: men benefit from real rotations, women don't," in *Proceedings of the ACM Symposium on Applied Perception*, 2014, pp. 99–102.

[47] B. G. Witmer, J. H. Bailey, B. W. Knerr, and K. C. Parsons, "Virtual spaces and real world places: transfer of route knowledge," *International journal of human-computer studies*, vol. 45, no. 4, pp. 413–428, 1996, publisher: Elsevier.

[48] R. A. Ruddle, "The effect of trails on first-time and subsequent navigation in a virtual environment," in *IEEE Proceedings. VR 2005. Virtual Reality, 2005.* IEEE, 2005, pp. 115–122.

[49] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal, "Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness," *The international journal of aviation psychology*, vol. 3, no. 3, pp. 203–220, 1993.

[50] S. G. Hart and L. E. Staveland, "Development of nasa-tlx (task load index): Results of empirical and theoretical research," in *Advances in psychology*. Elsevier, 1988, vol. 52, pp. 139–183.

[51] B. E. Riecke, M. V. D. Heyde, and H. H. Bülthoff, "Visual cues can be sufficient for triggering automatic, reflexlike spatial updating," *ACM Transactions on Applied Perception (TAP)*, vol. 2, pp. 183–215, Jul. 2005, aCM ID: 1077401.

[52] B. E. Riecke and T. P. McNamara, "Where you are affects what you can easily imagine: Environmental geometry elicits sensorimotor interference in remote perspective taking," *Cognition*, vol. 169, pp. 1–14, 2017.

[53] B. Keshavarz and H. Hecht, "Validating an efficient method to quantify motion sickness," *Human factors*, vol. 53, no. 4, pp. 415–426, 2011.

[54] B. E. Riecke and H. H. Bülthoff, "Spatial updating in real and virtual environments: contribution and interaction of visual and vestibular cues," in *Proceedings of the 1st Symposium on Applied perception in graphics and visualization*, 2004, pp. 9–17.

[55] R. F. Wang, "Representing a stable environment by egocentric updating and invariant representations," *Spatial Cognition and Computation*, vol. 1, no. 4, pp. 431–445, 1999.

[56] B. E. Riecke, D. Feuereissen, J. J. Rieser, and T. P. McNamara, "More than a cool illusion? functional significance of self-motion illusion (circular vection) for perspective switches," *Frontiers in psychology*, vol. 6, p. 1174, 2015.

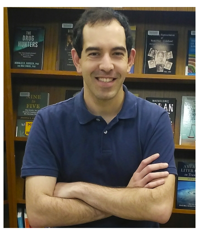
[57] R. L. Klatzky, J. M. Loomis, A. C. Beall, S. S. Chance, and R. G. Golledge, "Spatial updating of self-position and orientation during real, imagined, and virtual locomotion," *Psychological science*, vol. 9, no. 4, pp. 293–298, 1998, publisher: SAGE Publications Sage CA: Los Angeles, CA.

[58] B. E. Riecke, "Consistent Left-Right Reversals for Visual Path Integration in Virtual Reality: More than a Failure to Update One's Heading?" *Presence: Teleoperators and Virtual Environments*, vol. 17, no. 2, pp. 143–175, 2008.

[59] B. E. Riecke, D. Clement, D. Quesnel, A. Adhikari, D. Zielasko, and M. von der Heyde, "HyperJumping in Virtual Vancouver: Combating Motion Sickness by Merging Teleporting and Continuous VR Locomotion in an Embodied Hands-Free VR Flying Paradigm," in *Siggraph '22 Immersive Pavilion*. Vancouver, BC, Canada: ACM, 2022, pp. 1–2.

Ashu Adhikari has a Master's degree from the School of Interactive Arts and Technology (SIAT), Simon Fraser University (SFU). As an MSc student he joined the iSPACE team and has collaborated ever since. He pursues his interest in embodied locomotion interfaces in virtual reality.

Daniel Zielasko is currently a postdoctoral researcher and lecturer at the University of Trier's HCI group. He received his doctoral degree in 2020 at the Virtual Reality and Immersive Visualization group at RWTH Aachen University for studying desk-centered virtual reality. He has worked together with neuroscientists, psychologists, medical technicians, and archaeologists on projects such as the EU flagship project HBP (Human Brain Project) and the SMHB (Supercomputing and Modeling for the Human Brain). Today, he is working on the integration of VR technologies and methods into everyday life, such as existing professional workflows and entertainment.



Ivan A. Aguilar has a bachelor's degree in Computer Science and a master's degree in Media and Technology, both from the Sao Paulo State University (UNESP), in Brazil. He is currently a PhD student at the School of Interactive Arts and Technology (SIAT), Simon Fraser University (SFU), in Canada. His research has focused on the fields of augmented and virtual reality and in furthering human-computer interaction in these fields.

Alexander Bretin has a bachelor's degree in Cognitive Science from the University of Osnabrueck, Germany, and a master's degree in Intelligence and Movement from the University of Bielefeld, Germany. His research at the School of Interactive Arts and Technology (SIAT) at the Simon Fraser University (SFU), Canada, focused on locomotion in virtual spaces. He is now involved in creating interactive experiences for cultural spaces.

Ernst Kruijff Dr. Kruijff is an Professor for Human Computer Interaction at the Institute of Visual Computing, Bonn-Rhein-Sieg University of Applied Sciences. He is also adjunct professor at SFU-SIAT in Canada. His research has focused at the human-factors driven analysis, design and validation of multisensory 3D user interfaces.

Markus von der Heyde Dr. von der Heyde received his PhD in Computer Sciences from the University of Bielefeld, Germany for his work at the Max Planck Institute for Biological Cybernetics Tübingen. His approach to adopt biological principles into distributed computer applications in order to enhance stability and robustness was applied in national and international projects. For two decades he closely collaborates with various research labs. He also was appointed adjunct professor at SFU-SIAT in Canada.

Bernhard E. Riecke After researching for a decade in the VR Group of the Max Planck Institute in Tübingen, Germany and working as a post-doc at Vanderbilt and UC Santa Barbara, Dr. Riecke joined SFU-SIAT in 2008. His research combines multidisciplinary research approaches and VR/xR to investigate: Human spatial cognition/orientation/updating/navigation; Self-motion perception, illusions ("vection"), and simulation; Designing for transformative positive experiences, and rapid prototyping and agile researching in xR.