Comparing Leaning-Based Motion Cueing Interfaces for Virtual Reality Locomotion

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ABSTRACT

In this paper, we describe a user study comparing five different locomotion interfaces for virtual reality locomotion. We compared a standard non-motion cueing interface, **Joystick** (Xbox), with four motion cueing interfaces, **NaviChair** (stool with springs), **MuvMan** (sit/stand active stool), **Head-Directed** (Oculus Rift DK2), and **Swivel Chair** (everyday office chair with leaning capability). Each interface had two degrees of freedom to move forward/backward and rotate using velocity (rate) control. The aim of this mixed methods study was to better understand relevant user experience factors and guide the design of future locomotion interfaces. This study employed methods from HCI to provide an understanding of why users behave a certain way while using the interface and to unearth any new issues with the design. Participants were tasked to search for objects in a virtual city while they provided talk-aloud feedback and we logged their behaviour. Subsequently, they completed a post-experimental questionnaire on their experience. We found that the qualitative themes of control, usability, and experience echoed the results of the questionnaire, providing internal validity. The quantitative measures revealed the Joystick to be significantly more comfortable and precise than the motion cueing interfaces. However, the qualitative feedback and interviews showed this was due to the reduced perceived controllability and safety of the motion cueing interfaces. Designers of these interfaces should consider using a backrest if users need to lean backwards and avoid using velocity-control for rotations when using HMDs.

Keywords

Active locomotion; motion cueing; natural user interface; virtual reality; virtual locomotion

Index Terms: H.5.1 [Information interfaces and presentation]: Multimedia Information Systems - *Artificial, augmented, and virtual realities*

1. INTRODUCTION

Despite recent advancements in virtual reality (VR) technology, there is a need for effective and easy to use locomotion interfaces [1]. In particular, with affordable head-mounted displays (HMDs) such as HTC Vive, Oculus Rift, and Samsung GearVR quickly becoming more widespread, research in embodied navigation systems and techniques is especially relevant given the consumers' interest in these highly immersive experiences. Moreover, VR hardware is becoming easier to use with more consumer products available, more content generated, and more affordable systems. Yet, despite the latest HMDs coming with tracking systems allowing for small walking areas, moving through larger virtual environments remains an issue. In addition, a pervading challenge in VR is motion sickness, which can result in irritation, anxiety, and discomfort, ultimately reducing performance and user acceptance [2].

One possible solution for both increasing ease of movement and mitigating motion sickness is user-powered motion cueing – small, physical motions indicating that there is motion without having to actually move the complete distance, for example by leaning while seated or standing [3]–[6]. User-powered motion cueing can help create a simple and relatively inexpensive locomotion system, whereas the classic approach of using computer-driven and motorized platforms requires large and expensive setups to create motion that is similar to real-world motion. Moreover, interfaces that utilize user-powered motion cueing can be less dangerous and technically complex than large motorized platforms, which often require safety harnesses [7], [8] because they use simple perceptual deceptions instead of physically moving users in order to give them the feeling of movement. For example, Beckhaus and Riecke both developed seated interfaces with active motion cueing so that users could navigate in 3D environments without the space requirements of larger physical system or where walking was infeasible [9]–[12].

Our goal is to evaluate five different locomotion interfaces in order to better understand the most relevant factors for improving ground-based locomotion in VR, and thus to inform the design of flexible interface paradigms to support natural human spatial orientation and navigation in a variety of scenarios for both professional use and laypeople. We employ qualitative methods of semi-structured interviewing and observation in order to complement and deepen the understanding of our quantitative questionnaire. By collecting and analyzing user's self-reported experiences, we are able to generate themes and a richer data set that can give insight into relevant factors influencing ground-based locomotion and ultimately guide future design iterations. This is important because many past interface studies have used only behavioural measures as a way to assess usability [13]. However, due to the complex nature of these systems, often the results are either insignificant or inconclusive [10], [14], [15]. A qualitative approach to user experience allows researchers to understand on a deeper level why certain behaviour is occurring and how might the behavioural results be influenced by user's feelings towards a product, i.e., the experiential, affective, meaningful and valuable aspects of product use [16].

2. RELATED WORK

2.1 Spatial Updating and Self-Motion

Many researchers [17]–[20] argue that the perceptual and performance discrepancies between real and virtual movement stem from the lack of physical locomotion cues, such as vestibular and proprioceptive/kinaesthetic cues. These cues enable spatial updating – the largely automatized cognitive process that semi-automatically computes the spatial relationship between a person and their surrounding environment as they move based on

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perceptual information about their own movements [17]–[20]. Interfaces that utilize spatial updating, also known as *physical navigation interfaces*, have been shown to increase usability and spatial orientation [21]–[23]. In terms of self-motion, researchers investigating the integration of visual and vestibular sensory cues found that visual and non-visual cues are by themselves sufficient, but together are stronger in signaling self-motion [24], [25]. Moreover, researchers found vestibular and proprioceptive cues were tightly coupled, with interaction between motion detection and heading direction change playing a key role in motion perception [26]–[28]. Auditory cues, specifically with approaching and receding sound objects [29], [30], as well as tactile and biomechanical cues arranged in a matrix pattern around the torso [31] were also found to stimulate self-motion illusions.

2.2 Motion Cueing

Motion cueing has often been used for driving and flight simulations [32], [33], as well as for increasing the user's sensation of self-motion or vection [6], [11], [12], [34]. Motion cueing has also been widely studied, showing that it can enhance overall usability and user experience [21]–[23], enhance spatial perception and orientation [22], and reduce motion sickness [35]. Harris and colleagues [34] found passive physical motion, i.e., remaining inactive while the simulation moves the user, evokes an enhanced sensation of motion, but also tends to dominate other cues; and they found a complete match between visual and vestibular cues was not required to help induce self-motion. In another study [12], a force feedback, modified wheelchair where users moved the wheelchair slightly to initiate velocity controlled virtual movement, showed a clear enhancement of perceived self-motion, opposed to a mouse or joystick. Groen and Bles [36] systematically varied pitch amplitude to determine the minimum and maximum tilt amplitude required to generate linear self-motion, and found the simulation of linear self-motion was more realistic with the application of whole body tilt.

2.3 Leaning Based Interfaces

Recent developments in 3D navigation interfaces have begun to take advantage of the power of body-centric physical cues [3]–[5], [11], [37], [38]. Beckhaus and colleagues [5] designed a stool based interface, called ChairIO, a chair-based computer interface that supports 3D motion – both directional and rotational. ChairIO is based on a commercially available stool, the Swopper™. ChairIO allows control along four axes: tilt left/right, tilt front/back, move up/down, and rotate left/right. To operate ChairIO, users sit on the device and shift their body weight to tilt and rotate the chair in any direction, and this physical movement is mapped to viewpoint/direction movement in the virtual environment. Users found ChairIO succeeds in navigation tasks, has a fast learning curve, is fun, and is natural to use. Another motion cueing interface, developed by De Haan and colleagues [37], used a Wii Balance Board™ as a virtual reality navigation input device, where users lean forwards/backwards and sideways left/right to move in that direction, and press on toes and heels of opposing feet to rotate. They found the Wii Balance Board™ to be suitable for navigation as a continuous input device. LaViola and colleagues took a similar approach and developed an interface, where users can lean to the side at their waist to move for a small to medium distance in that direction, which was combined with a foot-gesture interface to move larger distances [39].

Kruijff and colleagues [38] used a high resolution inclination sensor to measure user's leaning angle of their upper torso while seated and found that static leaning, i.e., keeping a constant forward torso inclination, increased the feeling of self-motion velocity but not vection per se. Dynamic leaning while seated using a "human joystick" metaphor, however, enhanced forward linear vection as well as user's involvement, engagement, and enjoyment compared to a joystick control. Passively tilting seated users in a moving-base simulator can also enhance self-motion perception [36]. Active leaning while standing on a force plate (Wii balance board) has also been shown to enhance self-motion perception for linear and curvilinear paths, even though participants feet remain stationary [6]. Zielasko and colleagues [40] developed and evaluated five different hands-free, seated navigation methods, and found that a leaning-based metaphor combined with an accelerator pedal performed best for navigating a large 3D graph. In another study, Riecke and Feuereissen [11] used a modified Gyroxus gaming chair, where leaning forwards and sideways controlled simulated translations and rotations, respectfully. Gyroxus is an off-the-self gaming chair where users sit with legs extended in a plastic, lounge-type chair with a joystick between their legs. When comparing active locomotion to passive locomotion, these researchers found self-motion intensity increased with active locomotion, although onset latencies of self-motion were increased. However, in another study, researchers using a user powering motion cueing stool interface (i.e., NaviChair, similar to the ChairIO [10], [41]) observed that users had issues with the lack of a backrest, no clearly defined forward direction, forward and backward speed, and finding the center zero-point of the stool to stop motion.

2.4 Our Design Approach

To address the above design issues of the NaviChair and ChairIO, we evaluated a similar interface, i.e., MuvMan, a taller stool with a slight backrest and more clearly defined tilting pitch and re-centering (see **Figure 2**). We also decided to exclude sideways (i.e., strafe) movement because a pilot test showed this type of movement can be confusing when used in conjunction with the other degrees of freedom and is less precise. Moreover, our other chair-based interface, the Swivel Chair, does not support strafing; therefore, we reduced the degrees of freedom for the other interfaces as well to allow for a fair comparison between all five interfaces. The Swivel Chair, however, is more affordable and designed with comfort and longevity of use in mind. We added a head-directed navigation interface to see if this type of head-based, rather than torso-based, locomotion interface is viable. Here, user's head or HMD orientation is tracked; users tilt their head forward/back and rotate their head left/right to move in those corresponding directions. The familiarity of the joystick interface may impact the results of any direct comparisons across interfaces. However, we intend to use the joystick as a "gold standard" due to users' familiarity with it. As such, we will compare the other four interfaces against the Joystick and we will keep this limitation in mind when interpreting any results.

We used motion cueing for rotation (i.e., velocity control, similar to a joystick), opposed to position control for several reasons: First, to compare and apply our interfaces to stationary screens and displays, which are still far more widely used than HMDs and allow for multi-user applications; Second, to design a simple set up without cables becoming entangled after longer rotations; Third, to implement a simpler tracking system that works with velocity control – unlike the Oculus Rift DK2, which does not support head tracking for 360° rotations.

3. STUDY METHODOLOGY

The goal of this study was to investigate which factors are most relevant for VR ground-based locomotion by evaluating five different types of low-cost locomotion interfaces in terms of user experience (i.e., comfort, immersion, motion sickness, controllability, ease of use, longevity of use, self-motion, and overall enjoyment) and receive feedback for the next phase of design iterations. To this end, we included a strong focus on qualitative and introspective data, as we aimed for a richer understanding of the specific factors that affect usability and user experience for VR locomotion interfaces – an aspect that many of the more behavioral and quantitative studies sometimes neglect. This work aimed to determine which types of locomotion interfaces were suitable for ground-based navigation in VR as well as understand any design issues with the interfaces before continuing with behavioural tasks.

3.1 Hypotheses

Based on previous studies, we hypothesized that the motion cueing interfaces would provide greater benefits over a non-motion cueing interface such as a joystick, for illusions of self-motion [6], [11], spatial perception and orientation [3], [4], enjoyment and engagement [3], [4], [6], as well as immersion and presence [3], [10], [41]. Conversely, we predicted the joystick control to yield higher accuracy, controllability, and ease-of-use and be less fatiguing than the motion cueing interfaces [3], [6], [10], [41]. However, these previous studies failed to provide a rich account of why the joystick was performing better than motion cueing interfaces in these categories, so we sought to provide insight through qualitative talk-aloud feedback, behavioural observations, and semi-structured post-experimental interviews.

3.2 Participants

We recruited 16 (six female) graduate students from the faculties of Engineering and Interactive Arts & Technology with an average age of 26.7 years (*SD* = 2.83). These participants had previous experience with VR, but had no prior experience with motion cueing interfaces. Participants had normal or corrected to normal vision and were made aware of the potential risk of motion sickness. The local ethics board approved this research.

3.3 Environment

The VE was a 19th century city from the Unity Asset Store as illustrated in **Figure 1**, and was modified so participants would not get stuck in tight corners or alleyways. Five red spheres were placed roughly equidistant apart for participants to find, and were used as an incentive to move around the environment.

Figure 1: 19th Century Town built in Unity. Participants are tasked to find five red spheres using five different locomotion interfaces, one sphere for each interface. Left: top-down view where circles represent the sphere's locations and the X is the starting point.

3.4 Experimental Design, Stimulus, Apparatus

In all five locomotion interfaces (see **Figure 2)**, simulated movement was constrained to two degrees of freedom to allow for comparability: yaw rotation and forward/backward movement. Participants could rotate and move forward/backward at the same time, resulting in curvilinear paths. Both rotations and translations used velocity (rate) control as is common with joystick-like interfaces, and simulated velocities were linearly related to deflections of the respective interface. That is, the further the participant moved the interface away from the zero-point (i.e., the point in the center of the interface where there is no movement in the x or y planes) toward forward/backward direction, the faster they travelled up until a maximum speed of 1 m/s. A "zero area" was piloted, but there were issues with knowing where the center was and we were limited by the constraints of the TrackIR: PRO sensor's field of view. For rotation, the further the participant turned the interface away from the default orientation toward left/right, the faster they rotated up until a maximum rotational speed of 15° per second. These values were selected based on pilot tests, unified across interfaces with the same minimum and maximum velocities, and were found to reduce the potential of motion sickness while also mimicking normal walking speeds.

We used a mixed methods approach to assess each locomotion interface. We chose to gather qualitative data through semi-structured interviews and observations in order to gain a "thick description" of users' experiences – a validated methodology that looks not only at human behaviour but also at its context, giving results external validity [42]–[44]. We applied a within-subjects design with five experimental conditions, defined by the five locomotion interfaces (see **Figure 2)**: **(1) Joystick**[1] – Xbox controller while the participant is seated on a four-legged office chair that does not rotate (not pictured in video). Because the joystick is the most widely used and familiar controller, we used this interface as a control or "gold standard" to compare against the other interfaces, even if its familiarity might affect the results; **(2) NaviChair**[2] – a user-powered stool chair called Swopper™, whose seat is mounted on springs. This chair acts as an input device where the user tilts the seat forward/backward by shifting their weight to move in that desired direction. The user controls simulated yaw rotations by rotating the chair slightly to the left/right away from the default forward direction. The degree of chair tilt was mapped to the simulated motion using a velocity (rate) control. That is, the simulated rotation speed was proportional to the amount of chair rotation away from the default forward orientation. This interface was introduced first on ChairIO [6], and we chose it in order to replicate and compare with another study that used the NaviChair [10]; **(3) MuvMan**[3] – another user-powered stool chair (similar to NaviChair), except the chair itself is stiffer, has a small backrest, and has a default forward inclination that allows the user to sit upright and control the chair's motion with less movement. MuvMan was positioned in low height mode instead of its normal high stool mode because participants in the pilot tests did not feel safe in the high stool mode, and had less control when pushing the chair seat backward. Although it has the same height as the NaviChair, there is a fundamental difference in the precision and smoothness of turning, and overall feel of the MuvMan that we think still warrants these two chairs as distinct locomotion interfaces worthy of investigation. We chose this interface because it seemed to solve the controllability issue of precise movement that was found with the NaviChair [10]; **(4) Head-Directed Interface**[4] – using head movement of the head-mounted display (HMD) to control

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[1] Video for the Joystick (https://youtu.be/fjYgVeqNo4k)

[2] Video for NaviChair (https://youtu.be/dZ7w9v4w0nQ)

[3] Video for MuvMan (https://youtu.be/msn6uc5IU98)

[4] Video for Head-Directed (https://youtu.be/vDBM1jGMg3Y)

Figure 2: The five interfaces tested in this user study. From left to right: Joystick, NaviChair, MuvMan, Head-Directed, and Swivel Chair.

movement, i.e., pitch head forward/backward to translate forward/backward and rotate head around yaw axis to turn. We chose this interface as an exploration of an alternative to torso-based locomotion because users reported in previous studies that there was a disorienting mismatch between head and torso direction; **(5) Swivel Chair**[5] – an everyday office chair where users tilt the chair forward/backward to move in that direction and rotate the chair to turn. We chose this interface because it is very accessible, i.e., already in the workplace, more affordable than the NaviChair and MuvMan, and feels very safe and comfortable with a high backrest.

Participants viewed the virtual environment through the Oculus Rift DK2, which has a resolution of 960 x 1080 per eye, a refresh and fixed update rate of 75 Hz, and 100° (nominal) diagonal field of view. For the NaviChair, MuvMan, and Swivel Chair, we used a TrackIR 4: PRO tracking system, an inexpensive and accurate optical motion tracking system, to measure two degrees of freedom about a central pivot point at each chair interface's base. Changes in yaw and pitch were read from the sensor placed at the base of the interface via a 3-point reflector mounted directly above on the chair's seat. For the Joystick, movement was tracked with an Xbox controller. The Head-Directed Interface was tracked using the inertial sensors built into the HMD.

3.5 Procedure

Before the study, participants were informed of the procedures and signed an informed consent form. The experimenter then demonstrated how to put on the HMD and how to operate the first interface. Each participant used all five different interfaces in five separate blocks, with the order of interfaces pseudo-balanced to account for learning or carry-over effects. The experimenter demonstrated how to use each interface between conditions. Participants were then seated on the first of five different interfaces and informed about the task they were to complete wearing the HMD. However, before finding the sphere, the participants were allowed 1-2 minutes to test out the interface in order to become more familiar with the controls. Participants' task was to find a red sphere in the 19th century city. These spheres were placed at different locations that were equidistant from the starting position of the user. While navigating the virtual environment, participants were instructed to give talk-aloud feedback. That is, participants were asked to voice what they were experiencing, what they thought of the interface, and how the interface compared to the other interfaces. Participants were further prompted with questions about the controllability and movement. However, the experimenter tried to allow participants the space to answer without prompts in order to not bias their responses. After completing the navigation task and removing the HMD, we started an open-ended interview with the question "what do you think?" and transcribed their responses. Open-ended questions in semi-structured interviews are designed to encourage a full, meaningful answer using the participant's own words without the experimenter imposing their own beliefs or biases [45]. Further prompts were given if the participant failed to provide feedback. These interview data and behavioural observations made by the experimenter were transcribed on the fly to text by the experimenter via a word document, and then later analyzed with NVivo through open and axial coding where core concepts, themes and ideas were identified. Two researchers coded the data independently in order to assess inter-rater reliability.

Next, participants completed a ten-minute online questionnaire to assess the following for each interface: comfort, ease of use, immersion, precise control, spatial orientation, presence, enjoyment, problems, longevity of use, sensation of self-motion, overall usability, motion sickness, and order of preference of the interfaces. The online questionnaire used an 11-point Likert scale asking participants to rate each question on a scale from -5 = strongly disagree, 0 – neither agree nor disagree, to 5 = strongly agree. Based on some usability issues reported in earlier studies using similar motion cueing interfaces (e.g., [11], [41], [46]) we designed a more detailed questionnaire to assess how the different proposed motion cueing designs compared to specific aspects of usability and user experience, and how they compare to the well-known joystick interface. The validity of this questionnaire was not assessed. The total time to complete the study was approximately one hour.

4. RESULTS AND DISCUSSION

4.1 Qualitative Data

First, two researchers independently open coded the transcribed interviews and observations. Next, the researchers axial coded the open themes, and three broad categories emerged: control, usability, and user experience (**see Figure 3**). The subcategories under **control** were controllability, rotation, looking and walking simultaneously, zero-point, speed and sensitivity, and backwards and strafe (see **4.1.1** for definitions). The subcategories under **usability** were comparison to other interfaces, intuitiveness and naturalness, comfort and stability, familiarity, and physical attributes. The subcategories under **user experience** were dizziness, nausea, and motion sickness; experiential; virtual environment. The two researchers compared codes and regrouped the open codes to create a higher order of themes. After the categories were agreed upon, the researchers selectively coded the data by finding the quotes that best illustrated the axial codes (categories) generated. These three main categories (i.e., control,

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[5] Video for Swivel Chair (https://youtu.be/xEhYU8JcDl8)

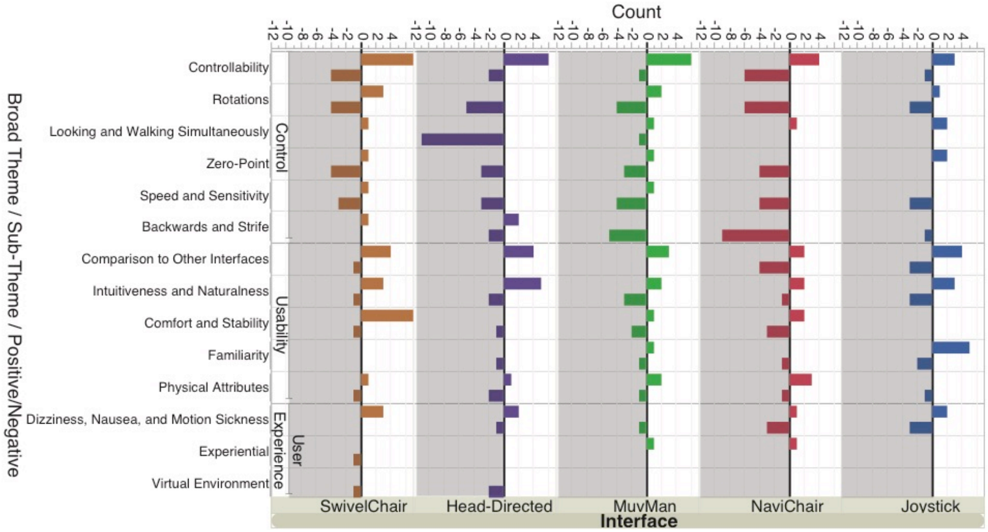

Figure 3: Visual representation of the qualitative themes and subthemes, showing the number of times each interface was coded for a specific theme in either a positive way (positive values) or negative way (greyshaded, depicted as negative values).

usability, and user experience) and their subthemes are discussed below and summarized in **Figure 3**. Participant quotes are representative statements based off experimenters' notes and are used to increase validity of the results [45]. "Px" denotes the participant number attributed to a quote, i.e., P1 means Participant 1. Direct quotes are used in order to increase validity and provide a more accurate account of participants' experiences without researchers imposing their own biases. When reporting on the different interfaces, we refer to the participant's rating of the interfaces, and not the interfaces themselves.

4.1.1 Control

Controllability: Participants reported that the Joystick and MuvMan interfaces had overall good controllability because they *"did not have loose control"* [P9]. The NaviChair, Head-Directed, and Swivel Chair interfaces were all difficult to control because they were *"not very precise"* [P3 & P14], it was *"hard to control speed"* [P15], and it was *"hard to control movement towards the target you aimed at"* [P5]. Motion cueing interfaces having less controllability over the joystick is consistent with prior literature [3], [10], [41].

Rotation**:** Participants reported that the Joystick's rotation was *"too fast"* [P2], though rotation speed was already quite slow at a speed of 15° per second – a value determined from pilot tests. The NaviChair, Head-Directed, and MuvMan interfaces were *"not very precise or accurate in their rotation"* [P5, P6, P7, P8, P13 & P15]. The Head-Directed interface was also *"too slow"* [P3 & P7]. For the chair-based interfaces, some participants reported confusion when they rotated their body in a direction and with a velocity that was not consistent with their head rotation velocity and direction. That is, there was a mismatch between perceived rotation and actual rotation.

Looking and Walking Simultaneously: All participants reported that the Head-Directed interface had a problem where they could not move and look around at the same time.

Zero-Point: Participants had issues with all interfaces, except the Joystick, with finding the zero-point, i.e., the center position of the chair that is mapped to no movement: *"I struggle because I don't know where my zero point is, so I don't know how far to rotate or move"* [P14].

Speed and Sensitivity: With all interfaces, participants expressed the desire to travel faster. The NaviChair was reported as more sensitive than the Swivel Chair, MuvMan, and Joystick interfaces even though all interfaces were programmed with the same parameters. Participants reported it *"feels faster"* [P3 & P15] even though all speeds were programmed with a maximum of 1 m/s. The MuvMan *"needs to be more sensitive"* [P3] because there was less range of movement.

Backwards and Strafe**:** The Swivel Chair interface was reported having easy to use backwards locomotion. The Head-Directed interface had mixed feedback – participants reported it felt weird, but it was better than the MuvMan or Joystick interfaces*: "It's like a helicopter to go backward; this is better because you don't have the problem like the other one (head and body conflict)"* [P7]. Participants did not like moving backward with the NaviChair or MuvMan interfaces because it felt unstable and took more effort. There was no backrest for the NaviChair and a very small backrest for MuvMan, so participants had troubles knowing how far they were leaning back with the HMD on; and, some reported being concerned about falling backward.

4.1.2 Usability

Comparison to Other Interfaces: Participants reported the most negative comments with the NaviChair, followed by the Joystick. The Head-Directed interface had the most positive comments, followed by the Swivel Chair and MuvMan interfaces. *"I like chair interfaces better because my body moves with my virtual movements"* [P5].

Intuitiveness and Naturalness: Overall responses about the intuitiveness and naturalness of the interfaces were rather mixed, and all interfaces had some participants reporting they were natural and intuitive, and some participants who reported they were not. Overall, however, there were more positive comments for the Head-Directed, NaviChair, and Swivel Chair interfaces: *"The virtual movement [of Swivel Chair] reflects real movement"* [P14]*; "[The NaviChair] is a bit more intuitive than Joystick and Swivel Chair interfaces because I'm pushing my body forward to move forward. [The MuvMan] doesn't feel like real life because you never naturally lean backward when moving backward"* [P15].

Comfort and Stability: The Swivel Chair was by far rated as the most comfortable interface: *"I prefer Swivel because it's comfortable. There is a backrest, so you can balance better. Other chairs I feel like I'm falling off"* [P1]. The MuvMan and

NaviChair interfaces felt unstable to participants because there was no large backrest: *"It feels like I'm falling off, especially backward. I can't see where I really am in the outside world so I'm worried about falling"* [P5].

Familiarity: The Joystick was familiar to all participants, which allowed them to move around easily. Participants had the expectation that the Joystick would have the same affordances as in popular video games. The Swivel Chair interface is also familiar to participants because it is an everyday office chair and contributed to participants' comfort level. The other interfaces are new to all the participants.

Physical Attributes: The NaviChair was described as being too big and heavy and thus cumbersome to physically move the whole chair, though participants like its flexibility*: "It's more active than the others because I'm moving more"* [P2]. The MuvMan interface felt *"too tall and unstable"* [P3]. The Swivel Chair was not fully utilized because participants maximized velocity for the entire duration of the trial. Therefore, it is difficult to attest to the controllability.

4.1.3 Experience

Dizziness, Nausea, and Motion Sickness: Motion sickness occurred with the Joystick, NaviChair, and Swivel Chair: *"Moving left/right makes me a bit sick. I try to close my eyes when I rotate so I don't feel sick"* [P2]. *"When I want to stop, I still rotate and it makes me dizzy"* [P10]. One participant reported motion sickness with the MuvMan interface, and there were no reports of motion sickness with the Head-Directed interface. Surprisingly, two participants expressed that the Head-Directed interface made them less dizzy: *"It gives me more control and makes me less dizzy"* [P13].

Experiential: Overall, participants reported positive experiences with all interfaces, describing the experience as interesting, fun to do, and a novel way to move around: *"[The MuvMan] feels good, like I'm floating"* [P12]*; "This one [NaviChair] is fun to interact with for a short time"* [P5]. This result is consistent with prior literature that found motion cueing interfaces were more engaging and enjoyable than using a joystick [3], [4], [6]. One participant recounted that the virtual environment *"feels very real"* [P14]. One negative comment was expressed by [P6] who felt *"confused because of the difference between the natural and virtual environment. It's too much for me"*.

Virtual Environment: The VE itself had some problems with colliders and texture rendering distance. Participants reported that *"the texture rendering was too close"* [P2 & P7], and took them out of feeling immersed in the virtual world. Running into colliders forced the virtual observer to bounce off of them, creating a sense of disorientation, a problem did not present itself in pilot testing.

4.2 Quantitative Data

Here we present the results of the ratings for the questionnaire items, as summarized in **Figures 4-8**. Friedman tests were performed because assumptions of no significant outliers, normal distribution, and homogeneity of variances were violated. The independent variable was interface and the dependent variables were the individual questions from the questionnaire (see **subsection 2.3**). First, we compared each of the five interfaces against each other for each questionnaire item, and then we performed a second test between two groups: the Joystick (i.e., non-motion cueing) versus the remaining four interfaces grouped together (i.e., motion cueing) using a repeated measures Wilcoxon signed rank tests (non-parametric repeated measures t-test).

4.2.1 Comfort

A Friedman test showed a statistically significant difference in comfort score between the different interfaces, $\chi^2(4) = 11.676$, $p = .020$, with a mean rank comfort score of 3.84 for Joystick, 3.47 for Swivel Chair, 2.91 for Head-directed, 2.34 for NaviChair, and 2.44 for MuvMan. Post hoc analysis with Wilcoxon signed rank tests revealed the Joystick was significantly more comfortable than the MuvMan ($Z = -2.024$, $p = .043$) **(see Figure 4)**. When comparing all motion cueing interfaces to the Joystick, a related-samples Wilcoxon signed rank test showed comfort was rated greater for the Joystick (mean rank score = 8.17) than for motion cueing interfaces (mean rank score = 8.58), $Z = -2.250$, $p = 0.024$ **(see Figure 4)**. These results mimic the qualitative findings. The Head-Directed, Swivel Chair, and Joystick were all using the same office chair, so it is perhaps not surprising that there was not a significant difference between them for comfort. Many participants also reported the Joystick as more familiar, which may have contributed to its added comfort level. According to the qualitative responses, the backrest of the office chair seemed to be an important contributor to the comfort level of the interfaces; both NaviChair and MuvMan interfaces lack a functional backrest, forcing participants to be more engaged with actively controlling their movement and posture. Studies that have looked at upper-body leaning have found that this engagement can be helpful in facilitating self-motion perception [36], [38]. Future studies will look into the effects of leaning.

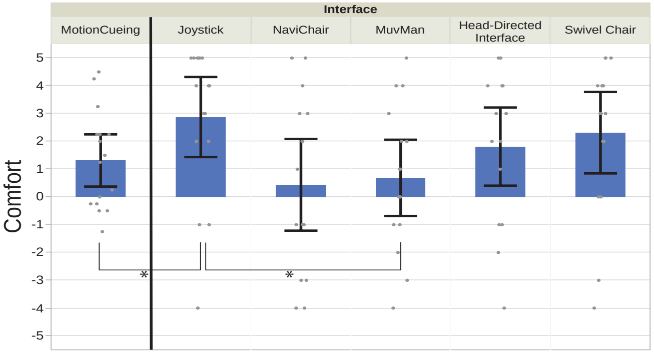

Figure 4: On a scale of -5 (strongly disagree) to 5 (strongly agree) participants rated "Using the [interface] was comfortable". Motion cueing represents all the motion cueing interfaces (MCIs) combined. Error bars were constructed using 95% confidence intervals of the mean and data points represent each participant (true for Figures 4-10).

4.2.2 Ease of Use

There were no significant differences in reported ease of use between interfaces. When comparing all motion cueing interfaces to the Joystick, ease of use was rated greater for the Joystick (mean rank score = 8.17) than the motion cueing interfaces (mean rank score = 7.96), $Z = -2.022$, $p = 0.040$ **(see Figure 5)**, which reflects prior literature [3], [10], [41]. These results reflect the qualitative responses, which were mixed in terms of positive and negative comments about each of the interfaces. One possible explanation for this mixed result is that the motion cueing interfaces (i.e., NaviChair, MuvMan, Swivel Chair, and Head-Directed) are all relatively new interfaces for participants, whereas the Joystick is highly familiar to use. There was also not much time to practice with each interface before giving feedback, which possibly contributed to the result of the Joystick being easier to use. In the future, we aim to give participants more time to get familiar with each interface before making a comparison to a more familiar platform, such as the Joystick.

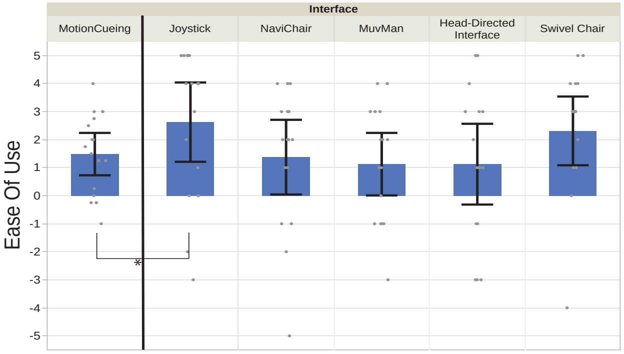

Figure 5: On a scale of -5 (strongly disagree) to 5 (strongly agree) participants rated “I thought the [interface] was easy to use”.

4.2.3 Precise Control

There was a statistically significant difference in precision of movement score between the different interfaces, $\chi^2(4) = 16.041$, $p = 0.003$, with a mean rank precision score of 4.25 for Joystick, 3.00 for Swivel Chair, 2.97 for Head-directed, 2.44 for NaviChair, and 2.34 for MuvMan. Post hoc analysis revealed the Joystick was significantly more precise than both MuvMan ($Z = -2.766$, $p = .006$) and NaviChair ($Z = -2.998$, $p = .003$) **(see Figure 6)**. When comparing all motion cueing interfaces to the Joystick, precision of movement was rated higher for the Joystick (mean rank score = 7.75) than for motion cueing interfaces (mean rank score = 8.61), $Z = -2.718$, $p = 0.007$ **(see Figure 6)**.

These results are consistent with the literature, which shows the Joystick is rated with higher precision over motion cueing interfaces [3], [10], [41]. Though pilot tests were conducted, there still arose some issues with control and precision that, according to the qualitative findings, might be affected by the users’ perceived reduced safety, comfort, and stability for the motion cueing interfaces. Both NaviChair and MuvMan were rated as not very precise, mirroring the qualitative findings. Some participants reported that the NaviChair felt too wobbly and it was difficult to know where the zero-point was located. MuvMan was reported as also not having good feedback on where the zero-point was located. Moreover, a Joystick requires the user to concentrate only on their finger position, whereas the other interfaces require knowing where your whole body is in space, thus may require more cognitive resources to use.

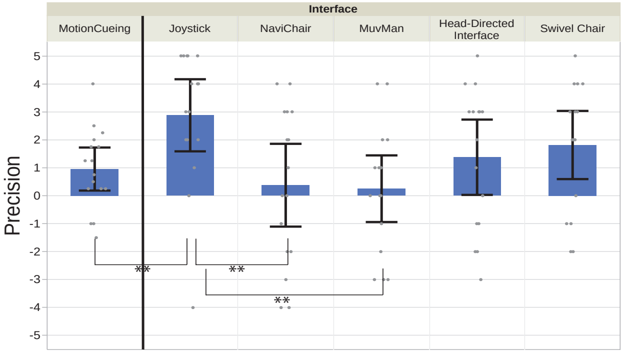

Figure 6: On a scale of -5 (strongly disagree) to 5 (strongly agree), participants rated “I could precisely control the self-motion with the [interface]”.

4.2.4 Spatial Orientation

There was a statistically significant difference in spatial orientation score between the different interfaces, $\chi^2(4) = 10.629$, $p = 0.031$, with a mean rank spatial orientation score of 3.84 for Joystick, 3.44 for Swivel Chair, 2.59 for Head-directed, 2.66 for NaviChair, and 2.47 for MuvMan. Post hoc analysis revealed the Joystick is significantly better at supporting the perception of spatial orientation than both MuvMan ($Z = -2.353$, $p = .019$) and NaviChair ($Z = -2.064$, $p = .039$) **(see Figure 7)**. When comparing Joystick to all other interfaces (motion cueing interfaces), spatial orientation score was rated higher for the Joystick (mean rank score = 6.88) than for motion cueing interfaces (mean rank score = 9.04), $Z = -2.096$, $p = 0.036$ **(see Figure 7)**.

It is surprising that the non-motion cueing interface (i.e., Joystick) was rated as giving better sense of spatial orientation than the motion cueing interfaces because the literature suggests physically moving your body to cue virtual motion increases spatial orientation [3], [4], [34], [47]. One possible explanation could be that the mapping of the motion cueing interfaces caused more confusion than help in orientation, especially given that we used velocity (rate) control instead of position control (one-to-one mapping) for rotations. That is, even though the chairs could have rotated 360 degrees this was not used in the current study to ensure comparability. It is important to note that this study only looks at self-report measures of spatial orientation. However, Kozlowski and Bryant have shown that self-reports of sense of direction as a verbal expression of their estimation of their own spatial orientation ability reflect their actual spatial orientation ability [48]. Therefore, there is reason to suppose that behavioural measures of spatial orientation will reveal similar results, which we plan to investigate in the next iteration of this study.

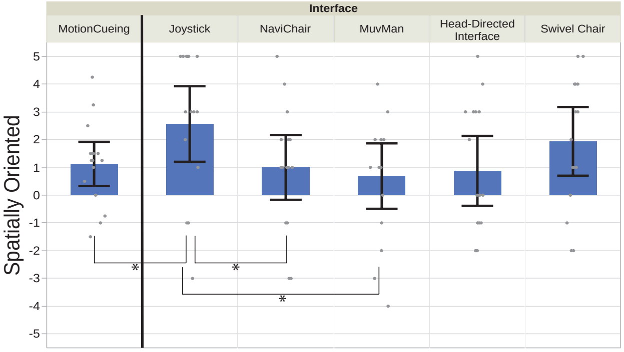

Figure 7: On a scale of -5 (strongly disagree) to 5 (strongly agree), participants rated “It was easy to remain spatially oriented with the [interface]”.

4.2.5 Sensation of Self-Motion

There were no significant differences in self-motion sensations between interfaces. There was a slight trend that the motion cueing interfaces are better at inducing self-motion than the Joystick when comparing all interfaces against each other. When comparing Joystick to all other interfaces pooled together (motion cueing interfaces), sensation of self-motion was rated higher for motion cueing interfaces (mean rank score = 9.50) than for the Joystick (mean rank score = 6.30), $Z = -1.892$, $p = 0.058$, though did not quite reach statistical significance.

The observed trend is consistent with the literature in that motion cueing can often enhance perception of self-motion [7], [11], [12], [25], [29], [46]. However, the lack of significant benefit of motion cueing on self-motion perception in the current study suggests the need for further development of these prototype-like interfaces. Also, a more formal and controlled vection study (e.g., with better controlled stimuli, movement velocities, and vection rating instructions) might help to reduce noise in the data and show clearer effects of user-powered motion cueing [6], [11], [12].

4.2.6 Problems Using the Interface

There were no significant differences in reported problems between all five interfaces. When comparing the Joystick to all other interfaces (motion cueing interfaces), problems using the interface score was rated higher for the Joystick (mean rank score = 8.42) than for motion cueing interfaces (mean rank score = 8.83), $Z = -2.148$, $p = 0.032$.

According to the qualitative results, most problems for the motion cueing interfaces were associated with controllability. Many participants became stuck in corners or could not control their virtual movement very precisely with the motion cueing interfaces. In addition, participants reported having problems with finding the zero-point, moving backwards and strafing, and controlling their speed. These problems also occurred in other studies using a similar interface [10], [41]. Therefore, more design iterations are needed in order for these motion cueing interfaces to be on a similar level as a very familiar and largely used device like the Joystick.

4.2.7 Immersion, Presence, Enjoyment, Longevity of Use, Overall Usability, and Motion Sickness

There were no significant differences between interfaces for the remaining variables. There is a slight trend that participants experienced more problems with the NaviChair and the least with the Joystick and Head-directed interface; there was also a non-significant trend that the Joystick and Swivel Chair (which both used a comfortable back rest) were more suitable for longer-term usage. These results reflect the qualitative statements on comfort, where the Swivel Chair was reported as most comfortable and the NaviChair and MuvMan were the least comfortable. In terms of motion sickness, all of the interfaces had a mean of close to zero reports of motion sickness or nausea. Together with the qualitative results, it appears that individual factors play a role in experiencing motion sickness because, on average, users were not sick though there were a few outliers who did experience motion sickness. A follow-up study suggests that the Joystick actually generates more motion sickness than leaning-based interfaces [49]. Therefore, it appears that the tracking of chair motions was not the issue for motion sickness, though further investigation is required.

Our results do not support prior literature where immersion and presence were rated higher for motion cueing interfaces over the Joystick, and longevity and overall usability were rated higher for the Joystick over motion cueing interfaces [3], [10], [41]. It is possible that participants did not understand what immersion or presence mean, so we plan to make these concepts clearer in future iterations. Also, participants did not use these interfaces for extended periods of time, so their reports on longevity may not be accurate. However, it is promising that for all interfaces, participants generally had high enjoyment ($M = 2.00$, $SD = 3.14$) and usability ($M = 1.94$, $SD = 3.21$), and low problems ($M = -1.56$, $SD = 3.12$) and motion sickness ($M = -1.56$, $SD = 3.46$).

4.2.8 Order of Preference

Each participant ranked the five interfaces in order of preference (i.e., from 1 = most preferred to 5 = least preferred) **(see Figure 8)**. The interface with the lowest mean ranking and thus the most preferred interface overall was the Joystick (2.25), followed by the Swivel Chair (2.69), NaviChair (3.31), and Head-Directed and MuvMan (3.37).

Participants primarily preferred the Joystick interface because it is familiar, ease to use, and comfortable. However, the Swivel Chair was reported as the most comfortable interface. The Swivel Chair design incorporates an everyday office chair, so it could be that participants found sitting on it familiar, and it was also the only chair with a high backrest. Conversely, the NaviChair and MuvMan interfaces were very unfamiliar and were originally designed to actively engage its users while seated. While engagement can be good for correcting posture and increasing focus and involvement, it can also be tiring and feel unstable and potentially dangerous, especially while wearing an HMD. That is, the NaviChair and MuvMan and/or their velocity mapping would likely need to be modified to increase their comfort and perceived stability and safety. Note, however, that each of the interfaces ranked first for some of the participants. This suggests fairly diverse preferences and desires, and that there might not be one interface that is optimal for all, or even the majority, of users.

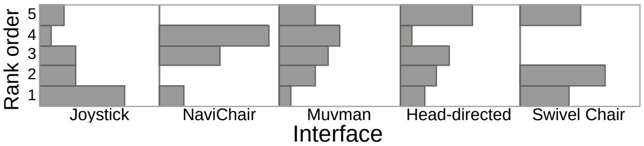

Figure 8: The preference rankings of each interface with each participant rating the interfaces from one through five, where one is the highest and five the lowest preference.

5. CONCLUSIONS

The results did not support the predictions of the literature that the **motion cueing interfaces** will provide greater benefits over a non-motion cueing interface such as the Joystick, for **illusions of self-motion** [6], [11], **spatial perception and orientation** [3], [4], **enjoyment and engagement** [3], [4], [6], as well as **immersion and presence** [3], [10], [41]. Instead, there were no significant differences between interfaces, except in the case of spatial orientation, which found the opposite effect. This could be because the mapping of the motion cueing interfaces caused more confusion than help in orientation, especially given that we used velocity (rate) control instead of position control (one-to-one mapping) for rotations, which we are currently exploring [49]. On the other hand, our predictions that the Joystick control would yield higher **accuracy**, **controllability**, and **ease-of-use** [3], [6], [10], [41] were supported by the results**.** However, there was no significant difference found that the Joystick was **less fatiguing** than the motion cueing interfaces.

The quantitative results showed the order for most comfortable and most precise interface was Joystick, Swivel Chair, Head-Directed, NaviChair, and MuvMan, although there was considerable variability in the data and individual preferences. When comparing the four motion cueing interfaces to the Joystick, the Joystick was rated to offer easier and more precise control, be more comfortable, and help participants feel more spatially oriented. Yet, the four motion cueing interfaces showed a trend towards providing a stronger sensation of self-motion. Our results indicated that the Joystick had a high familiarity, thus a training effect could account for its high preference. Moreover, the other interfaces are only in prototype stages and have yet to be fine-tuned. Given this limitation, participants still voiced they liked the motion cueing interfaces better than the Joystick because they were fun, engaging, more realistic, and had the natural feeling of moving. This preference for a more embodied interface is consistent with related interfaces, such as the ChairIO [5], Gyroxus gaming chair [11], or leaning interfaces like the Joyman [3], Wii balance board-based standing leaning interfaces [4], [6], [37], [50] or interfaces where users merely lean their upper body while seated on a stable chair [38]. In order to increase familiarity, we recommend a sufficiently long training phase for unfamiliar motion cueing interfaces before any systematic experiments or testing. The Swivel Chair was most favored out of the motion cueing interfaces because it was comfortable, felt safe and stable, and offered the most precise control. In particular, the backrest highly increased perceived safety and comfort. Participants valued these traits although this might depend on the specific task demands, and more fast-paced VR and gaming scenarios might yield different results.

Controllability was an issue for the motion cueing interfaces. While forward movement was smooth and was easy to learn, going backward by leaning backward felt awkward and unnatural for participants. Using velocity control for rotating instead of allowing for full 360° rotation with position control (one-to-one mapping) took some time to learn and adapt to; it was challenging to stop or return to the zero-point. Another challenge for rotation was that participants did not know where their bodies or forward trajectory was facing, and rotating the head while rotating the body (camera) at the same time caused confusion.

We are currently comparing velocity (rate) control to position control (one-to-one mapping), where participants can rotate 360° and the direction they face in the real world will correspond to the same in the VE. That said, a 360° approach only works for HMDs and not projection screens. We designed the majority of our interfaces without a 360° mapping because we wanted to allow for the option of using stationary (not head-mounted) displays, multi-user displays, and avoid issues with tangled cables. We also wanted to allow for comparable rotation and translation, which both use velocity mapping, and avoid a mix of velocity and position control. However, as the results show embodied rate-control rotation interfaces might not be a good fit for HMDs.

Overall, participants generally liked the motion cueing interfaces, but felt the interfaces needed modifications before they would switch from using a Joystick. In particular, perceived safety was a primary concern and we suggest the use of a backrest when users need to move backward to add comfort and safety. We will also improve upon our control mapping, increase awareness of forward direction, and create a more stable interface for MuvMan and NaviChair. Though we iterated and tested the controllability before running this user study, issues still arose. However, through the use of qualitative methods and the rich data gleaned from them, we were able to understand on a deeper level what users thought of the different interfaces, which is invaluable in the next stages of design iterations. This ground-based locomotion interface user study has some limitations that we will address in future experiments. For instance, the time to find each target and the participant's paths were not recorded or analyzed because this study focused on the user experience rather than on behavioural measures. It is important that we first collected rich qualitative data in order to better inform the next design iterations as well as ground our future behavioural studies that will record and analyze navigation and orientation in virtual environments.

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