University of Nevada, Reno

HANDSFREE LOCOMOTION TECHNIQUES FOR MOBILE VR

A Thesis Submitted in Partial Fulfillment
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by
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ABSTRACT

Virtual reality is an area experiencing unprecedented growth due to the release of consumer-ready, affordable, and accessible head mounted displays. Many of these HMDs come in the form of low-cost smartphone adapters, such as Google Cardboard, that can turn any phone into a virtual reality device, paving the way for mass adoption of VR. However, input in mobile VR is typically limited to using head tracking or single button input, which makes it difficult to perform complex tasks like navigation. Walking-in-place (WIP) offers a natural and immersive form of virtual locomotion that can potentially reduce cybersickness. WIP, however, is difficult to implement in mobile contexts as it typically relies on bulky controllers or an external camera. This work presents a novel hands-free WIP technique usable for mobile VR, as well as an alternative hands-free input technique using head tilt. Two user studies are presented. In the first, we show that WIP is more immersive than another popular handsfree navigation method, without any loss in overall performance. In the second, we develop an extension of the WIP technique that uses head tilt and WIP, and compare that to a joystick and a tilt-only technique. These techniques allow users to explore an unlimited amount of virtual space, and are more immersive than traditional input methods, making them ideal for mainstream implementation in virtual reality applications.

ACKNOWLEDGEMENTS

This work would not be possible without the support and encouragement from my advisor, Dr Eelke Folmer. He introduced me to the world of VR, and pushed me to create tools that are immediately useful today. I'd also like to thank the members of my committee, Dr. Fang Jiang and Dr. Feil-Seifer. Finally, I'd like to thank my wife Katie, who put up with my constant worrying and helped me through my graduate school experience.

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CHAPTER 1

INTRODUCTION

Virtual reality (VR) has reached potential for mainstream adoption due to the introduction of consumer-ready, affordable head mounted displays (HMDs). These include low-cost smartphone adapters, such as Google Cardboard (Figure 1.2), that can transform any smartphone into a head-mounted VR display (also known as "mobile VR"), as well as higher-end HMDs like the Oculus Rift or HTC Vive (Figure 1.1), which connect directly to a computer. These devices immerse the user in exciting and new virtual worlds by offering full head tracking, which allows the user to look around as they would in the real world. However, the question of how people should actively move around in and explore these virtual worlds presents a major challenge for the VR field, as the real world and the virtual world often do not match up.

Cybersickness is a major concern to the mass adoption of VR [22] and is caused by –among other factors– a sensory mismatch between visual and vestibular stimuli [33]. Users experiencing cybersickness typically experience symptoms such as general discomfort, nausea, vomiting, and disorientation.

Walking-in-place (WIP) allows users to perform handsfree virtual locomotion using step-like movements while remaining stationary [30]. WIP resembles walking and offers a natural, immersive form of input [28]. When compared to using a controller, WIP allows for better spatial orientation [16] while approximating the performance of real walking [26]. Because WIP generates proprioceptive feedback, users are less likely to experience cybersickness than when using a conventional controller [13]. Unfortunately, current WIP implementations aren't feasible in mobile contexts, as they rely either on external cameras [27], which may require cali-

Figure 1.1: The HTC-Vive, a high end positionally-tracked HMD

Figure 1.2: A number of Google Cardboard devices.

bration, or expensive, bulky treadmill controllers [37].

This work addresses a need for a low-cost virtual locomotion technique [37] for mobile VR by presenting VR-STEP: a novel WIP implementation that requires no instrumentation beyond the sensors already present in smartphones. VR-STEP is immersive, has low latency, and is easy to learn. While the primary motivation for this work was to develop a locomotion system that would be usable with mobile VR, the findings are applicable to higher-end systems as well. Chapter 2 describes the general background of virtual locomotion, including other solutions and past implementations of WIP. Chapter 3 describes our implementation of WIP via smartphone gyroscope and accelerometer sensors. Chapter 4 describes a user study where VR-STEP was compared to another hands-free locomotion method. In Chapter 5, we augment VR-STEP and evaluate it in terms of motion sickness. Chapter 6 summarizes the overall results and gives a direction for future work.

This research has resulted in the following publications:

(1) Sam Tregillus and Eelke Folmer. 2016. VR-STEP: Walking-in-Place using Inertial Sensing for Hands Free Navigation in Mobile VR Environments. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (CHI ’16). ACM, New York, NY, USA, 1250-1255.

(2) Sam Tregillus. 2016. VR-Drop: Exploring the Use of Walking-in-Place to Create Immersive VR Games. In Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems (CHI EA ’16). ACM, New York, NY, USA, 176-179.

CHAPTER 2

BACKGROUND AND RELATED WORK

Exploring natural, immersive types of input for virtual locomotion is an active field of research (see [30] for an survey). There are a number of solutions, but first, it's important to gain an understanding of cybersickness.

2.1 Cybersickness

Cybersickness is a condition experienced during or after a virtual reality session that is similar to motion sickness, and includes symptoms such as nausea, disorientation, headaches, sweating, eyestrain, and more. While similar to motion sickness, cybersickness is generally induced only by visual perception of motion, and real physical motion is not necessarily present [17].

The term "cybersickness" is a somewhat new term used to describe problems specific to VR, but originally VR sickness was simply referred to "simulator sickness" [29]. Simulator sickness is a term used to describe the symptoms felt by many flight simulator pilots after their training sessions. However, there is evidence that cybersickness and simulator sickness differ in both the types of symptoms present and the severity of those symptoms. While simulator sickness and cybersickness are related, cybersickness is primarily characterized by disorientation, while oculomotor discomfort (eye strain, headache, difficulty focusing, blurred vision) is most associated with simulator sickness [9].

While there is not a consensus on the specific cause of cybersickness, the most popular explanation is called sensory conflict theory [33]. This theory posits that the sickness we feel comes from a conflict or mismatch between the visual system and the vestibular system. In the case of cybersickness, this generally means that the user visually perceives motion, but doesn't actually feel any motion because they are not moving in the real world.

2.2 Virtual Locomotion Solutions

Using a joystick for navigation is a simple and common approach. However, some studies have linked movement controlled by a joystick or similar input devices to an increased level of cybersickness [13, 7, 19]. Gaze based navigation with joystick control of locomotion speed was found to be superior to navigation using a joystick alone [26].

Real walking, where the user actually moves in real space and is positionally tracked in the environment, is the most natural and effective method for virtual locomotion [26, 34]. Real walking can be implemented using an optical tracking system [35, 34], but this approach doesn't scale very well since the tracked space and the virtual space need to be the same size. Real walking systems typically do a one-to-one mapping of the user's physical movements to the movement in the virtual environment. This typically means that there is very little risk of cybersickness, as there is no conflict between what is seen and what is felt, unless there is also some sort of additional movement separate from the player's own taking place in the VR application.

Omnidirectional treadmills [8] circumvent physical space limitations, but these are often expensive and bulky, which restricts their use in mobile contexts (Figure 2.1.

Figure 2.1: The Virtuix Omni, an omnidirectional treadmill

2.3 Walking-in-place

Walking-in-place [27] has many advantages over other methods for virtual locomotion. WIP can be used to control locomotion speed just as effectively as using a joystick [10], but WIP has also been found to be much more immersive [28]. Maintaining spatial knowledge of the virtual world is difficult in VR environments [24], but WIP was found to allow for better spatial orientation than when using a joystick [16]. WIP has also been found to be almost as efficient as real walking [26] but is not subject to space constraints and is therefore more cost effective to implement.

A challenge with implementing WIP is starting and stopping latency [30], i.e., how quickly a step is detected and translated into virtual motion, or how long it takes the virtual avatar to stop after the user stops taking any steps. High stopping and starting latency makes precise navigation challenging [10]. Latency can be a result of the step detection algorithm implementation, noise reduction, or damping based on which part of the body is being tracked. In general, step detection is most accurate when tracking motions closest to the feet [12]. The first WIP [27] implementation used an optical motion tracking system to track head movements to infer steps. However, due to “false steps" being detected, they did not start actual motion until 4 consecutive steps had been taken, which resulted in a large delay between walking and actually moving. Other implementations used optical tracking of knee or shin motions [30, 36], and had a latency of a “half-step", or about 400ms at a normal walking pace. Another method by Feasel [10] used a magnetic tracking system for detecting heel motions, with a starting latency of 138ms and stopping latency of 96ms.

The optical & magnetic tracking systems used in the above studies are typically expensive [10, 37], and their weight and size makes them difficult to employ in mobile contexts. Low-cost implementations have also been explored. To enable desktop VR, a basic webcam has been used to detect head oscillations, which are then interpreted for virtual locomotion [31]. A user study found this approach to be faster and more immersive than keyboard input when seated. A commercially-available pressure-sensitive game controller (Wii Balance Board) was explored for step detection [37]. A study found no significant difference in latency when compared with joystick and real walking input, but limitations included difficulty controlling small motions and a risk of users falling off the balance board. Other notable WIP implementations include using a Kinect [38] and a CAVE system [15, 25] but these implementations aren’t feasible in mobile contexts.

CHAPTER 3

IMPLEMENTATION OF VR-STEP

Inertial measurement units (IMU) have become ubiquitous in smartphones and typically consist of a 3-axis accelerometer and 3-axis gyroscope. Various studies have investigated the accuracy of pedometry for different smartphone/sensor placements on the body [6, 18] and found that steps can be detected most accurately for a sensor worn closest to the feet[12]. Rather than using an external sensor, VR-STEP uses the smartphone's accelerometer for step detection. Since the smartphone sits in the head-mounted adapter, latency is a major concern for effective virtual locomotion [10]. A challenge with our approach is that a smartphone worn on the head may dampen the acceleration signal (due to the larger distance from the feet), causing problems for accurate step detection. However, recent work [4] evaluated the accuracy with which pedometry can be achieved on a head-mounted display (Google Glass) and found no significant difference in accuracy on the head when compared with a smartphone worn on in the pocket or held in the hand, which supports the feasibility of our approach.

Though various step detection algorithms exist [6], we use a real-time algorithm proposed by Zhao [39]. This algorithm has little computational overhead and ensures the smartphone can maintain a high frame rate, which is important for VR simulations [20]. This algorithm averages every 5 samples to smooth the acceleration signal, which minimizes noise while still yielding a near real-time response of between 100-200ms. A step is detected if the accelerometer values pass a dynamic threshold level with a large enough negative slope. The dynamic threshold changes every 50 samples from the accelerometer to account for different step intensities. The slope acts as a sensitivity setting, which we can tune to make sure that small steps that the user uses to turn left and right are not translated into forward movement.

Once steps are detected, they need to be translated into virtual locomotion, in the direction of the user's gaze. A limitation of existing WIP implementations is that most provide few details on how virtual locomotion is implemented [10]. For our implementation, we wanted users to feel like they have precise control over their velocity, to be able to move reasonable distances quickly, but also be able to make small changes in position if needed. Because users walk in place, there is no way to detect the length of their stride to determine how far users might want to move. A discrete approach where every detected step is translated into moving a fixed distance forward leads to jarring and unnatural movement [10]. A high stopping latency can make users experience a frustrating sensation of gliding [10].

We query the accelerometer and gyroscope values to determine acceleration along the gravity axis, which we feed into the Zhao's algorithm described above. A sensitivity value, S, can be used to adjust the sensitivity of the algorithm. When a step is detected, an event is fired, which the step handler listens for. The step handler measures the time between steps, (t_{step}) to determine the virtual velocity (v). A large t_{step} indicates that the user is walking slowly, so we set v to a low value. A small t_{step} value indicates faster steps, so we set v to a higher value.

We establish a bounds on $t_{step} \in [I_{min}, I_{max}]$, and a maximum and minimum velocity, $[V_{min}, V_{max}]$. If $t_{step} > I_{max}$, it means that a step has not been detected in some time (the user has been standing still before they took this step), so we set v to V_{min}. $t_{step} < I_{min}$ is not possible, as it is filtered out by the step detector, but if $t_{step} < I_{min}$, velocity is set to V_{max}. If $t_{step} \in [I_{min}, I_{max}]$, we linearly interpolate v between $[V_{min}, V_{max}]$ according to: By modifying their WIP speed, users have precise control over their

Figure 3.1: User velocity based on time since last step

$$v = \frac{t_{step} - I_{min}}{I_{max} - I_{min}} * (V_{max} - V_{min}) + V_{min} \tag{3.1}$$

virtual speed. We also adjust the velocity of the avatar between steps by applying friction. This slows down the user between steps, giving a natural feeling of walking, and it reduces stopping latency, since the user begins slowing down immediately after taking their last step. If the user continues walking, the velocity is maintained.

CHAPTER 4

STUDY 1: COMPARISON WITH HANDSFREE NAVIGATION

4.1 Motivation

A number of studies have already compared WIP with joystick based virtual locomotion [26, 10, 28, 16, 37]. We also felt that comparisons to other WIP methods that involve extensive instrumentation weren't as useful, as users of mobile VR would not typically have access to such instrumentation. Because VR-STEP is hands free and requires no instrumentation, it is more meaningful to compare its performance with another hands free navigation method, "look down to move" (LDTM), which is used in several VR apps, such as the popular Oculus "Tuscany" demo [3]. Users toggle a button at their feet by briefly looking down at it, then back up. When activated the user will move with a fixed horizontal velocity in the direction of their gaze. Similar to other WIP evaluations [26, 10, 28, 16, 37, 5], we compare VR-STEP to LDTM by having users perform a number of navigation tasks.

4.2 Methodology

4.2.1 Instrumentation

For our smartphone mount, we used a Zeiss VR One. The VR One features Zeiss precision lenses with a 100 degree field of view. The VR One features a strap and weighs 590 grams. We used an Android Nexus 5 smartphone with a Qualcomm Snapdragon 800 CPU (2.3 GHz quad-core) and an Adreno 330 GPU which can render 3D simulations with a high frame rate. The Nexus 5 features a InvenSense MPU-6515 six-axis (gyro + accelerometer) with a 50Hz sample rate. The user study was implemented using the Google Cardboard for Unity SDK and the Unity 5 engine.

Because LDTM uses a fixed velocity (V_{LDTM}), a precise quantitative comparison with VR-STEP is challenging, as VR-STEPallows variable locomotion speeds. Even if we limit V_{max} to be the same as V_{LDTM}, the average speed for VR-STEP will be smaller than LDTM unless the participant consistently runs at the highest speed. To allow for a fair comparison, we modified VR-STEP such that when $t_{step} < I_{max}$, we set v to V_{LDTM}. If no step has been taken for I_{max} seconds, we immediately set v to 0. This means that velocity is the same for both methods at all times when moving, but it does make stopping latency for VR-STEP equal to I_{max}, which causes a minor gliding issue, where after not taking any steps, you continue to move forward for I_{max} seconds. For the user study, we set I_{max} = .7s, and V_{LDTM} to 6 m/s.

4.2.2 Participants

We recruited 18 participants (9 female, average age 28.83, SD=7.93) to participate in our user study. None of the subjects self-reported any non-correctable impairments in perception or limitations in mobility. Individuals who had previously experienced cybersickness were excluded from participation as they were at a high risk of not completing the study. User studies were approved by an IRB. On average users had 4.97 years experience (SD=8.05) navigating 3D environments and 11 subjects had prior experience using a VR headset, such as the Oculus Rift.

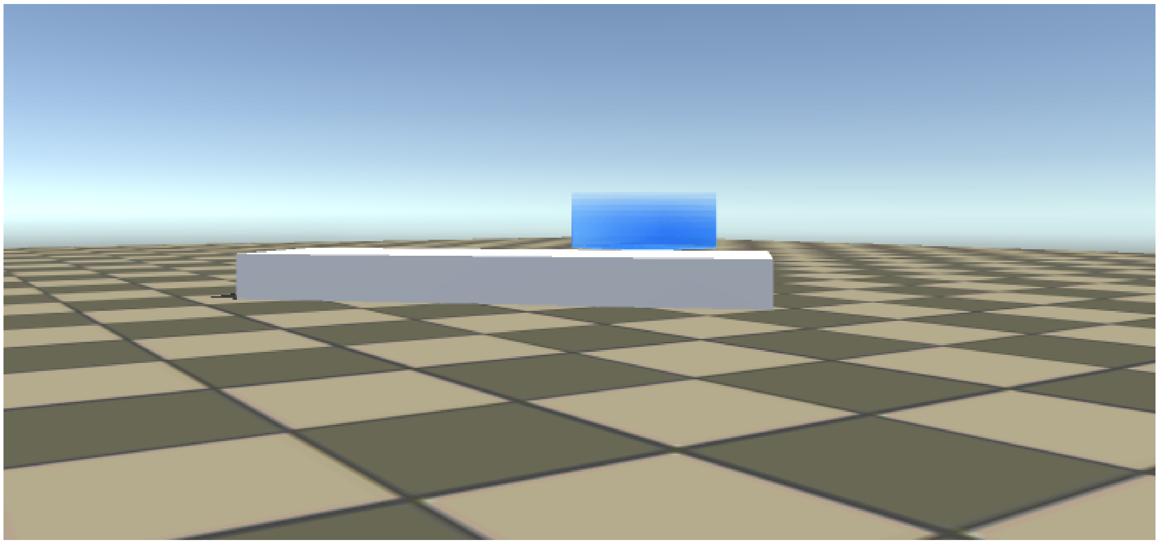

Figure 4.1: A view of the navigation task in the virtual environment

4.2.3 Procedure

A criticism of existing WIP studies is that they have mostly included navigation tasks that use a straight trajectory [32], which isn't very realistic for many VR applications. Our study had participants perform two different navigation tasks: an unobstructed navigation task with a straight trajectory, and an obstructed one requiring them to circumnavigate an obstacle. We designed our navigation task to be similar to one described by Bowman [5]. Our virtual environment consists of a flat plane featuring a checkerboard pattern. Participants must find a target zone (a blue transparent column), navigate to it, and remain inside the area for 2 seconds before the next target zone becomes visible. This column changes color when participants enter it, and auditory feedback indicates success.

The locations of the target zone were initially determined at random, with each new location a minimum distance of 10 meters away from the prior location. Obstructed navigation tasks feature a rectangular box (Size: 1x3 meters) halfway to the target zone. To decouple the visual search task from the navigation task, we started measuring time and distance traveled as soon as participants started moving. Each participant tests both navigation methods, but which method they use first is randomly assigned (half of the participants used VR-STEP first, then LDTM). Participants performed 20 navigation tasks for each navigation method with 10 tasks containing an obstacle. The specific locations of the target zones and the obstacle ordering was the same for all users and both methods. Before the data collection, participants were fitted with the VR One headset and we ensured the HMD was firmly attached to their head using the straps. Some participants with eyeglasses took them off but others kept them on. A built-in tutorial explained how each navigation method worked and let participants practice three navigation tasks.

After the trials, basic demographic and qualitative feedback was collected using a questionnaire. The entire session, including training and questionnaires, took about 10 minutes.

4.3 Results

Method-trajectory	**Time (s)**	**SD**	**Distance (m)**	**SD**
LDTM-straight	59.12	25.0	225.31	127.1
VR-STEP-straight	61.88	8.7	198.18	13.3
LDTM-curved	65.31	19.2	243.25	65.4
VR-STEP-curved	77.45	23.3	224.87	32.3

Table 4.1: Total time and distance traveled averaged per user.

Table 4.1 lists the results for all users. For our analysis, we used a two-way repeated measures ANOVA where we evaluate efficiency of each navigation method using time and distance traveled. There was no statistically significant two-way interaction between navigation type and trajectory for navigation time ($\boldsymbol{F}_{1,17} = 1.680$,

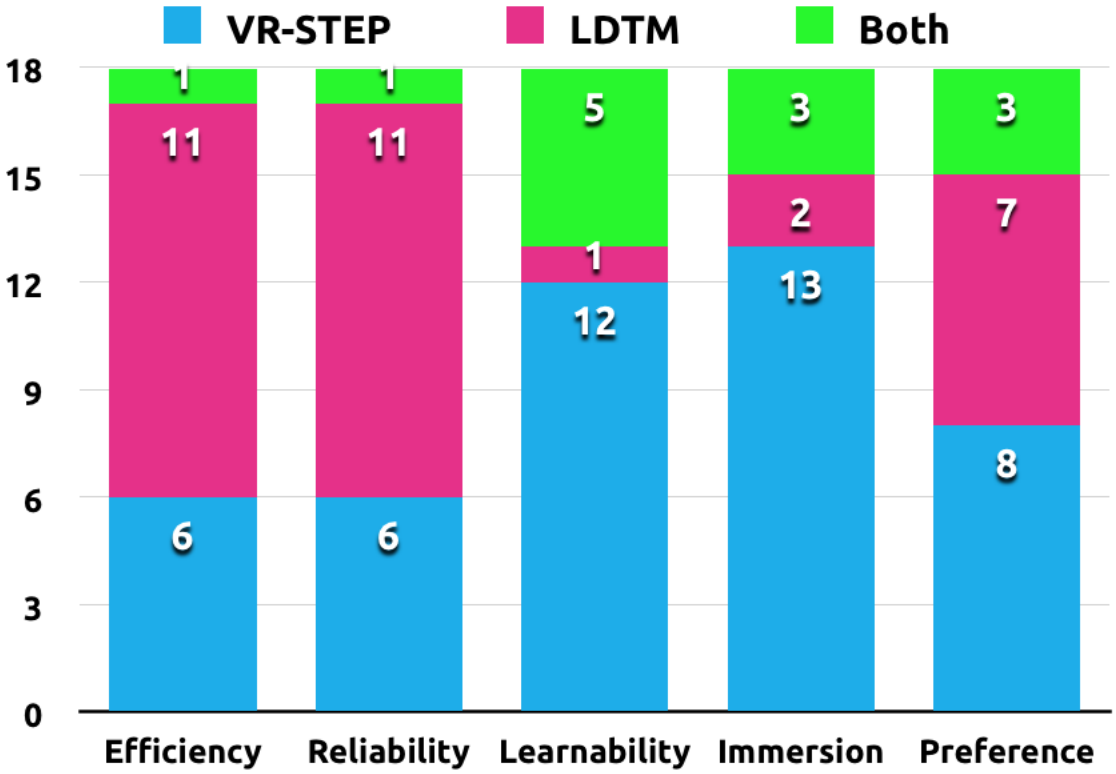

Figure 4.2: Ranking of navigation methods based on usability criteria

p = .212), or distance ($F_{1,17}$ = .107, p = .784). Pairwise comparisons using a Bonferroni correction found that LDTM was significantly faster for curved trajectories (p = .012) but not for distance traveled or straight trajectories.

After the trial, we let participants rank each navigation method based on a number of criteria which included: efficiency, reliability, learnability, immersion and overall preference. If participants had no preference, they could also select both as a 3^{rd} option. The summarized results are shown in Figure 4.2. A Chi square test found the rankings for learnability (p = .0023) and immersion (p = .0045) to be statistically significantly different.

Non-directed interviews with open-ended questions were used to collect general experiences and identify areas for improvement. For LDTM, ten participants stated that having to look down to activate the button was awkward or strenuous for their neck. Six participants suggested using a larger button or placing the button at eye level. For VR-STEP, eight participants said they found it difficult to stop precisely in the target zone due to gliding. Two participants wanted control over their velocity as they felt their avatar was moving too fast. Three participants wanted better step detection.

4.4 Discussion

Overall, we demonstrated the feasibility of VR-STEP as a low-cost virtual locomotion technique for mobile VR. Participants found VR-STEP more immersive and easy to learn than LDTM. Though LDTM was perceived to be more reliable and efficient, quantitative results only showed LDTM to be faster for curved trajectories. An analysis of paths revealed that some participants overshot the target zone, requiring them to turn around. Overshooting would occur with LDTM as well, but not as frequently as with VR-STEP. If users failed to stop, the switchback they took back to the target zone significantly increased both time and distance, leading to much larger standard deviation values for these metrics.

Ironically, the main user complaints about VR-STEP, high stopping latency (gliding) and no control over speed, are issues that are absent when variable locomotion speed is used. Though we wanted to be able to compare quantitative values, such as navigation speed, between the two methods, the changes we made to equate velocities ended up hurting user perception of efficiency and reliability. However, these results do highlight how stopping latency impacts user perception. Overshooting is very frustrating to the user, and enabling them to stop intuitively where they would like to is very important. LDTM can have large stopping latency, as users must stop looking at the world to look down at a button. Some participants found a way around this by looking forward and down while navigating, but if your goal is to create an immersive world, this is obviously not what you want your users to be doing. The trade off we made to allow for a fair comparison did clearly demonstrate participant's qualitative preferences for VR-STEP.

4.4.1 Limitations and Future work

VR-STEP requires users to stand and provide continuous stepping input. This may not be desirable when using mobile VR for longer periods of time. However, popular VR headset manufacturers recommend that users take regular breaks from using VR [2], so standing may not be a major issue. VR-step moves the user in the direction of their gaze, but this is rather limited compared to how humans navigate in real life. For future work, we will explore the use of head tilt to indicate a direction for navigation which may allow users to walk other directions. For step detection feedback, we will explore haptic feedback, since audio feedback may be obfuscated in gaming contexts. Besides detecting steps for walking, other feet related actions, such as jumps or stomps may be detected using acceleration. We were able to implement jumps in VR-STEP using a threshold for vertical acceleration. A promising application area of VR-STEP is exercise games [21]. Jogging-in-place has already been found to get users into moderate-to-vigorous levels of exercise [23]. In addition, bringing the immersion of VR to exergames could engage players for longer, which may stimulate larger health benefits. This may address some of the current criticisms of exergames that they don't provide sufficient health benefits [1].

CHAPTER 5

STUDY 2: OMNIDIRECTIONAL MOVEMENT AND CYBERSICKNESS

5.1 Motivation

In the previous study, users found walking-in-place input to be much more immersive than the auto-walk technique. However, that technique only allowed users to travel forwards, in the direction of their gaze. While forward motion is most frequently used, sometimes it is convenient to be able to move in other directions. For example, if a user approaches a door, but ends up walking a bit too close to it, it is much more convenient to be able to just walk backwards than it is to have to turn around, walk forwards, and then turn around again.

When humans walk, they tilt their body and head in the direction that they want to move [11]. Taking advantage of this existing natural mapping, this study presents an improved WIP implementation that explores the use of head-tilt and lets users use their head as a joystick to specify a direction to navigate to.

Since the first study did not evaluate cybersickness, we also added a focus to cybersickness for this study. Previous studies have linked any sort of artificial motion with cybersickness. Several VR developers have noted that sideways movement with a joystick is especially problematic. [2]

In this study, we expand upon VR-STEP and add directional control via head tilt. 3 different control techniques were compared: walking-in-place + tilt, tilt only, and joystick. We evaluated these control techniques for cybersickness, usability, performance, and immersion.

Figure 5.1: Samsung GearVR and joystick used for the experiment

5.2 Methodology

5.2.1 Instrumentation

As shown in Figure 5.1, we used the Samsung Galaxy S7 smartphone and the Samsung GearVR adapter. For the joystick condition, we used a SUNNYPEAK Wireless Bluetooth Gamepad Controller. For the actual VR app, we used the Unity game engine and the Google Cardboard SDK. The actual VR app is described below.

5.2.2 Participants

We recruited 24 participants (6 females, average age 26.33, SD 4.5) for our study. All participants were recruited locally from the university campus. All but 2 participants reported owning a smartphone, and 37% of them reported owning a VR headset. About 30% of the participants had no VR experience, about 58% of them had some VR experience while the rest had lots of VR experience.

5.2.3 Design

Our primary independent variable is navigation method. We had 3 different navigation methods - WIP-Tilt, Tilt-Only, and Joystick. The actual task that the participants did was the same for all methods, and is described in the procedure section.

WIP-Tilt

In this method, users walk or jog in place to move in the direction of their gaze. Users can also move in any other direction when they tilt their head towards that direction. A visual indicator is displayed to provide the users with visual feedback about the direction to which they are moving. For example, if the user tilts their head slightly to the left and walks in place, they will travel left (relative to their gaze) instead of forward. When standing straight up, the user walks forwards when they walk in place.

Tilt-Only

In this method, users tilt their head in the direction they want to move. The same visual indicator mentioned in the previous section is used to provide directional feedback. To move forwards, the user simply leans their body and/or head forwards.

Joystick

In this method, users use a joystick to control their motion. Pushing forward on the joystick will move the user forward while pushing the joystick sideways will move the users sideways.

Due to constraints on time and number of participants, we used a mixed design where we assigned participants to 3 different groups, each group testing and evaluating two of the navigation methods. Group 1 evaluated WIP-Tilt and Tilt-Only, group 2 evaluated WIP-Tilt and Joystick, and group 3 evaluated Tilt-Only and Joystick. Within each group, we controlled for order effects by counterbalancing the order of navigation methods.

Outside of VR, we recorded the results of the Simulator Sickness Questionnaire (SSQ) [14] after each task. The SSQ is a standardized questionnaire that attempts to quantify various aspects of simulation sickness. We also measured qualitative evaluations of each system for a number of different scales, and the results of a comparative questionnaire where users choose their favorite navigation method. During the experiment, we recorded the number of obstacles hit in the task and the amount of time it took to complete the main task.

5.2.4 Procedure

When participants arrived, they were told that they were helping to evaluate different methods of virtual locomotion. Participants were asked to fill the SSQ to get a baseline reading for cybersickness. Next, they were read a script that described the first navigation method that they will use, how training will work, and how

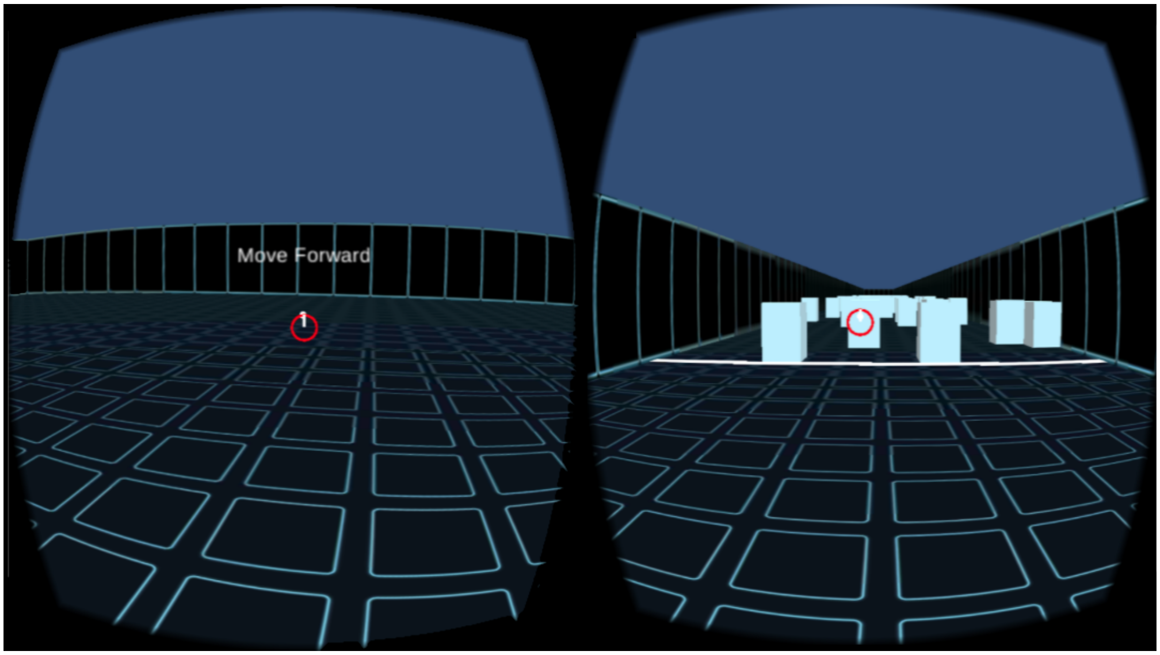

Figure 5.2: Participant tasks for study 2. The left side shows the training task, and the right side shows the navigation task. The red circle and line is the visual feedback shown to the user for directional input.

the task will work. Participants then were fitted with the VR headset and started the training task. After training, participants started the main task. Once this was done, participants stopped and filled the SSQ. They were then read another script that described the second navigation method. After they completed the training and main tasks for the second navigation method, they were asked to again fill the SSQ. Finally, participants were asked to fill a post-experiment questionnaire to provide their demographic information and their qualitative feedback about the two navigation methods they tried.

Training Task

In the training task, the participant wore the VR headset and was guided through a few navigation tasks. A direction appeared on the screen, and they had to navigate in that direction for a few seconds. Once they navigated in the 8 primary directions, the training ended and they moved on to the main task.

Main Task

In the main task, participants navigated through a large corridor with obstacles (chest-height rectangles) protruding out of the ground. These obstacles were positioned in a way that required users to move both left and right, not only forwards, so users were encouraged to use movement vectors other than straight forwards. When a user collided with an obstacle, a large amount of friction was applied, which meant that users were encouraged to move entirely left, right, or backwards to stop colliding with the obstacle. The obstacles were also placed so that there was always a minimum space of 2 obstacle-widths between obstacles.

The participants had to navigate to the end of the corridor. They were instructed to avoid running into the spikes, but also that they should try and run through the corridor as fast as they can. During this task, we measured the task completion time (seconds) and the number of collisions with the spikes. Each participant repeated this task 5 times (5 different corridors), and the positioning of obstacles was the same for all participants (each participant had the same corridor for trial 1, etc).

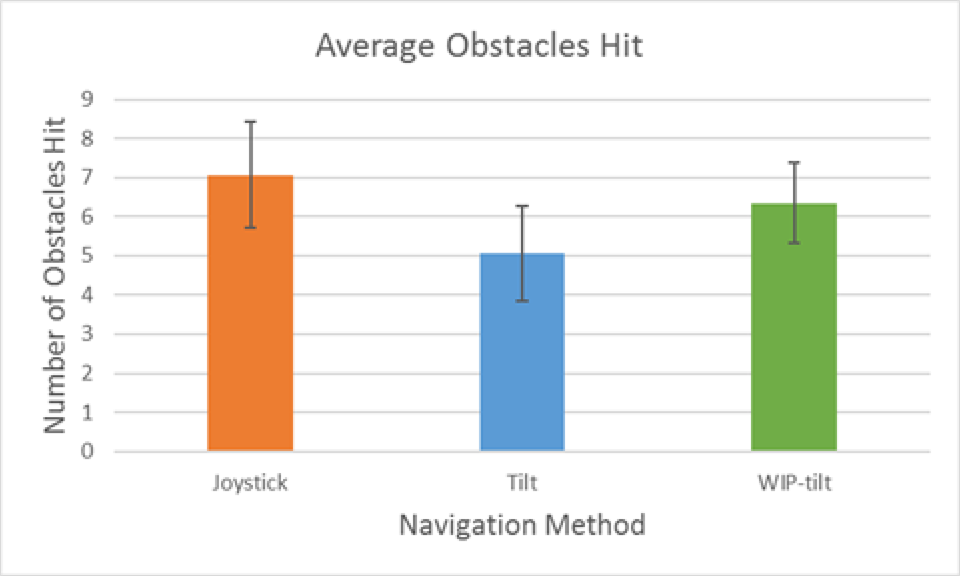

Figure 5.3: Average number of obstacles hit for each navigation method

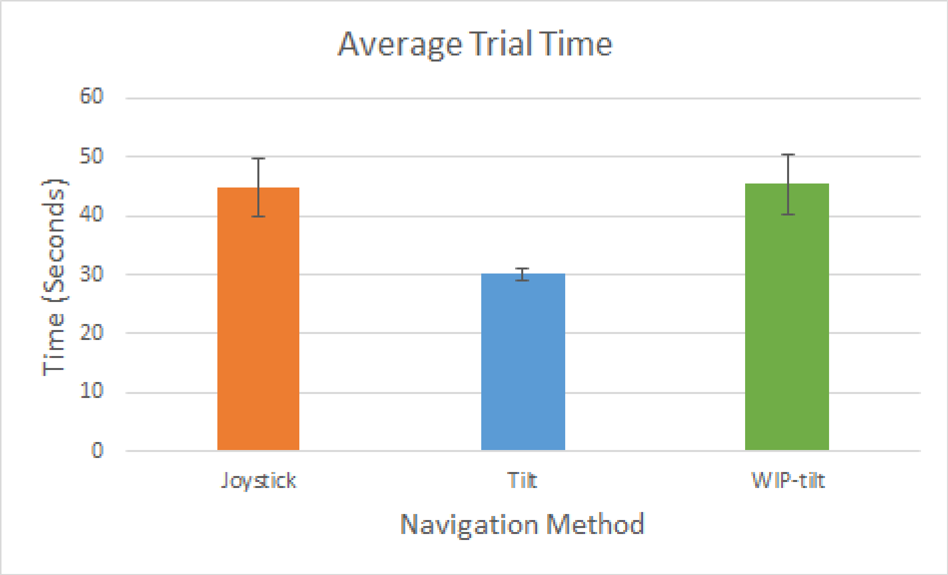

Figure 5.4: Average trial time for each navigation method

5.3 Results

5.3.1 Task Performance Results

For obstacles hit, the Joystick condition had the highest average obstacles hit per trial, followed by WIP-Tilt. Users using the tilt-only method were the fastest at the task. Figures 5.3 and 5.4 summarize the results.

There was a statistically significant difference between groups as determined by a one-way ANOVA ($F_{2,427} = 20.78$, $p = .00002$). Post-hoc tests found a significant difference between Tilt-Only and Joystick for both trial time and obstacles hit ($P < .05$ for both) and between Tilt-Only and WIP-Tilt for both trial time and obstacles hit ($P < .05$ for both).

5.3.2 Simulator Sickness Questionnaire

In the Simulator Sickness Questionnaire, each answer to a question was given a numerical value between 0 and 3. As directed by Kennedy et al. [14], these were then weighted and combined to form 3 subscales. The subscales are nausea, oculomotor discomfort, and disorientation. These are combined and weighted to get a value for total severity. The results for each method are summarized in Figure 5.5.

While the results do seem to show a general trend of joystick giving more simulation sickness across all scales, these differences were not significant. It's also important to note that these weighted scores are not high, and the averages shown would all fall between no simulator sickness and mild simulator sickness.

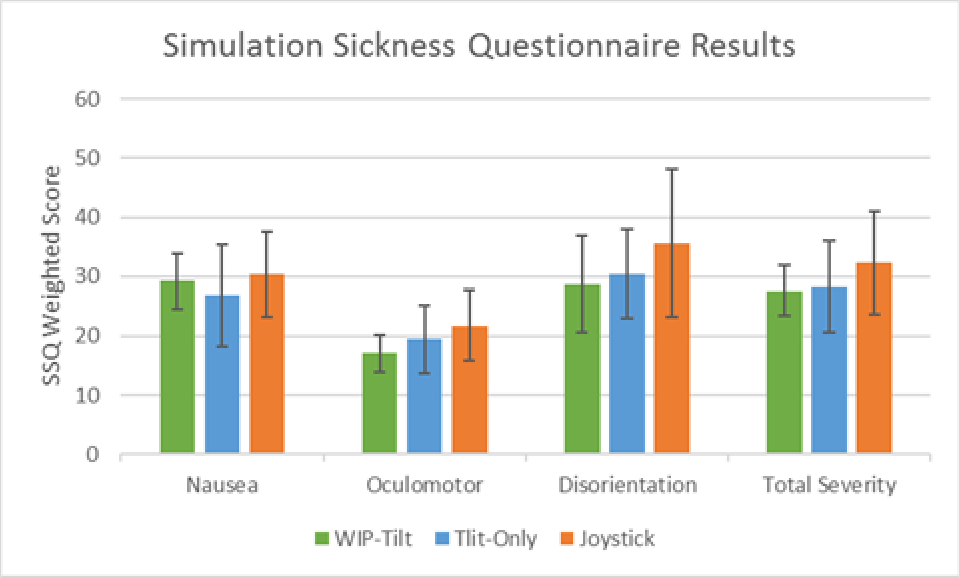

Figure 5.5: Results of the SSQ across the 3 subscales and total severity

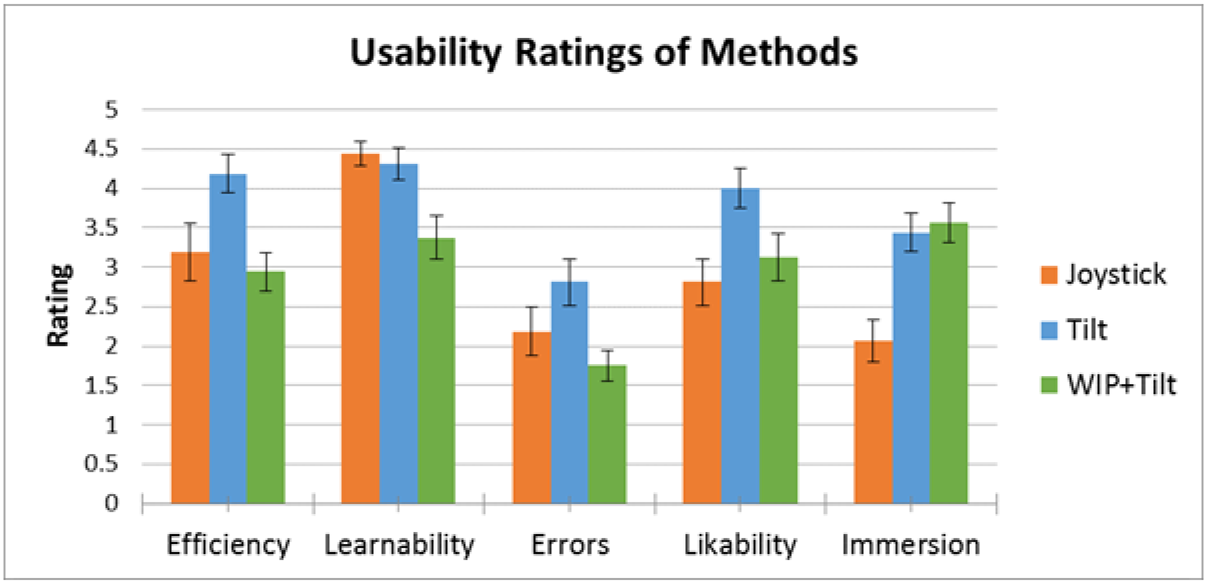

Figure 5.6: Likert score ratings of the navigation methods

5.3.3 Qualitative Ratings of Each Navigation Method

We asked users to rate each method that they used in terms of efficiency, learnability, accuracy, likability, and immersion. The results are summarized in Figure 5.6. Overall, people rated WIP-Tilt the highest for immersion, but seemed to give

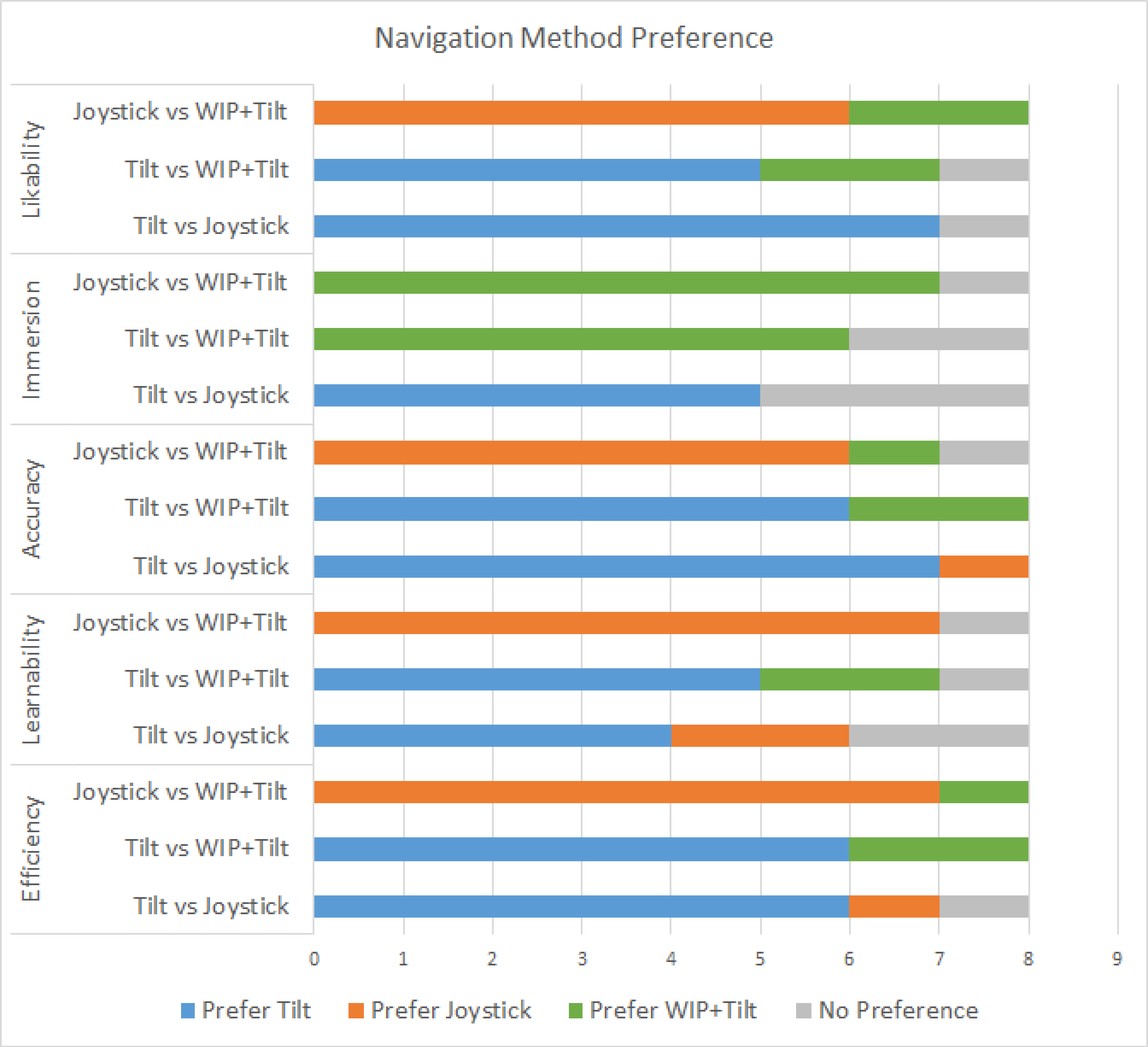

Figure 5.7: Number of participants who preferred each navigation method.

Tilt-Only higher ratings for the other categories. Joystick scored much lower than the other methods for immersion, but aside from that scored about the same as Tilt-Only for learnability and WIP-Tilt for the other categories.

We also asked each user to compare the 2 methods that they used and indicate which one they liked better for a number of different categories. We show the overall preferences for all 3 methods in Figure 5.7 below. Because each participant only did 2 out of 3 navigation methods, results are split based on which group they were in.

Overall, people who used it seemed to like the Tilt-Only method the most across all scales other than immersion. WIP-Tilt was preferred for immersion when used, otherwise people preferred Tilt-Only.

5.3.4 User Comments

We asked each user to give feedback about each method. Generally, users liked the joystick's ease of use and familiarity, but felt like the joystick did not feel realistic, and felt that the joystick was more "jerky" and less smooth when compared to head tilt. Users also commented that the joystick used seemed to be low quality, and had issues going directions other than forward.

For tilt control, some users said that they felt like they needed to lean forward more than they would like, and some commented that it didn't feel realistic, but they generally thought that it was easier to use accurately. Several users commented that it was initially hard to learn, but they adjusted quickly and felt good about using it. Some expressed a desire to be able to control their speed by leaning more or less in the desired direction.

For Walking in place input, participants liked how natural and realistic it felt, but some participants had a hard time staying in one place, and felt nervous walking when not being able to see the real environment. Some felt that the walking input accelerated them too fast, and they couldn't stop if they made an error. Many commented that it made them feel much more immersed in the world, but that also resulted in them feeling nervous about moving too much in the real world.

During the experiment in the WIP-Tilt condition, users tended to drift from their original physical location quite a bit, but the amount that they drifted varied wildly. Some users had no problems staying relatively stationary when moving, some moved a little bit but self-corrected when they sensed that they had moved too far, and others moved so much that they had to be stopped and repositioned during the experiment.

5.4 Discussion

We did not expect to see any significant differences for performance, so it was interesting to see how much better the Tilt-Only method performed. On average, the Tilt-Only method finished each trial 15 seconds faster and with 1-2 fewer obstacles hit than the other two methods. With the Tilt-Only method, users only needed to lean forward to move, and lean left or right to make small corrections, while with the WIP-Tilt method they had to actively step in a way that the VR-Step algorithm detected in order to maintain speed. The joystick used also was of somewhat low quality, which may have resulted in unintentional stops. However, the overall performance of the Tilt-Only suggests that it may be a viable control method for handsfree locomotion.

We did not find any significant differences for cybersickness between the three conditions. The data did trend towards what we expected (most cybersickness in the disorientation subscale overall, higher values for joystick control), but without statistical significance it's hard to draw any major conclusions. We did have two participants who had a much stronger sickness reaction to virtual reality than others, but that reaction did not seem to have any correlation with a navigation method, and was likely just a general reaction to VR. This does seem to be contrary to other studies [13, 7, 19], which were able to find higher simulator sickness scores with joystick controls than with other control methods. We may have not had users stay in VR long enough to experience the cybersickness, or our implementation of joystick controls may not have been comparable to other studies. For example, we did not allow users to control their orientation with a joystick, only their movement.

Overall, people seemed to like the tilt-only control method the most across all scales other than immersion. Joystick controls seemed to be rated the lowest. People felt like the WIP-Tilt method had the best immersion, but surprisingly felt that it was harder to learn and was the least accurate. Participants felt comfortable with the joystick controls, but surprisingly performed the worst with them. Some participants complained about the quality of the joystick, though we had chosen the most popular joystick that is used in mobile VR.

Our WIP-Tilt input did require participants to walk deliberately with a "bounce" in their step, which may not have felt natural for everyone. Some participants also tended to drift from a central position while walking-in-place, sometimes moving so far that we had to actually stop them mid-trial and reposition them. This might have lead to higher average task completion times. We noticed this drift in our original WIP study [12], but we observed much higher amounts of movement drift with the WIP-Tilt method. It's possible that by requiring the user to tilt their head in a direction, we offset their natural balance enough to exacerbate the movement drift problem.

Our results show that Tilt-Only control may be a good alternative to joystick motion, and that more research is needed to evaluate walking-in-place input with tilt. As expected, the WIPTilt method had the highest immersion ratings, but we weren't able to show significant improvements towards reducing cybersickness or improving general performance.

While the tilt-only controls were liked by the participants, it's important to note that this control method may not be ideal for all VR situations. In VR applications that require the user to look vertically to see targets or to just experience the environment, the tilt-only control does not work as any rotation of the head up or down will result in motion. However, that could be offset by requiring the user to push a button to move, and allowing them to control their direction with the head tilt.

CHAPTER 6

CONCLUSION

6.1 Summary

This work documents a novel implementation of walking-in-place for virtual reality. This system is especially useful for mobile VR, but could also be implemented for any VR system. This system has has many advantages over other handsfree input methods or joystick input: it requires no external instrumentation, it does not require a large amount of space for the user, it allows the user to explore an unlimited amount of virtual space, and it is more immersive than most other input options. With the head-tilt extension, VR-STEP also doesn’t differ functionally from joystick input, making it a viable candidate for mainstream use.

We were unable to show any effect on cybersickness in our studies. While some participants did experience mild cybersickness, and a couple had a large amount, their reactions seem to be more from just using VR than from a particular locomotion method.

6.2 Future Work

Our system could be vastly improved by improved step detection. The system does require users to walk in a way that their head bounces up and down. While some users find this intuitive, other users seemed to default to a much more "flat" walking pattern. A better step detection algorithm could dramatically decrease user frustration. We also observed that users are most frustrated with WIP when they can't stop as quickly as they like. While it's difficult to tell when the user actively wants to stop and when they are just between steps, it's possible that we could allow the user to stop more quickly by sampling the magnitude of the accelerometer and using extremely low values on that to more quickly slow down the user.

A promising application area of VR-STEP is exercise games [21]. Jogging-in-place has already been found to get users into moderate-to-vigorous levels of exercise [23]. In addition, bringing the immersion of VR to exergames could engage players for longer, which may stimulate larger health benefits. This may address some of the current criticisms of exergames that they don't provide sufficient health benefits [1].

For step detection feedback, we will explore haptic feedback, since audio feedback may be obfuscated in gaming contexts.

Finally, we'd also like to investigate a possible integration of VR-Step with a real walking system like Valve's Roomscale technology. This would allow users to walk in real space for smaller, precise movements, and jog in place to travel longer distances. Since these systems typically show the boundaries of your playspace inside virtual reality, this mixed implementation may also solve the drifting problem observed in both studies.

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