LeanOn: Simulating Balance Vehicle Locomotion in Virtual Reality

Ziyue Zhao
School of Advanced Technology
Xi'an Jiaotong-Liverpool University
Suzhou, China

Yue Li*
Department of Computing
School of Advanced Technology
Xi'an Jiaotong-Liverpool University
Suzhou, China

Hai-Ning Liang
Department of Computing
School of Advanced Technology
Xi'an Jiaotong-Liverpool University
Suzhou, China

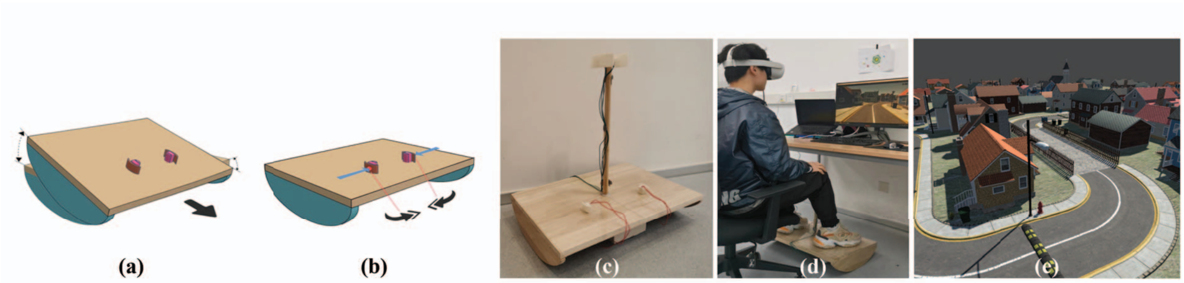


Figure 1: Illustrations of the (a) leaning-based locomotion and (b) feet-controlled orientation. (c) The prototype of the LeanOn locomotion device. (d) A user controlling the LeanOn to travel in (e) the experimental scene.

Abstract

Locomotion plays a critical role in user experience in Virtual Reality (VR). This work presents a novel locomotion device, LeanOn, which aims to enhance immersion and feedback experience in VR. Inspired by balance vehicles, LeanOn is a leaning-based locomotion device that allows users to control their location by tilting a board on two balance wheels, with rotation enabled by two buttons near users' feet. To create a more realistic riding experience, LeanOn is equipped with a terrain vibration system that generates varying levels of vibration based on the roughness of the terrain. We conducted a within-subjects experiment (N=24) and compared the use of LeanOn and joystick steering in four aspects: cybersickness, spatial presence, feedback experience, and task performance. Participants used LeanOn with and without the vibration system to investigate the necessity of tactile feedback. The results showed that LeanOn significantly improved users' feedback experience, including autotelic, expressivity, harmony, and immersion, and maintained similar levels of cybersickness and spatial presence, compared to joystick steering. Our work contributes to the field of VR locomotion by validating a leaning-based steering prototype and showing its positive effect on improving users' feedback experience in VR. We also showed that tactile feedback in locomotion is necessary to further enhance immersion in VR.

Index Terms: Human-centered computing - Human computer interaction (HCI) - Interaction paradigms - Virtual reality

1 Introduction

Locomotion shapes how users navigate through the virtual environment (VE), thus plays a pivotal role within Virtual Reality (VR) [3]. Many types of locomotion techniques have been designed to provide users an immersive travel experience, such as teleporting, steering, and a combined approach [54]. Martinez et al. [33] categorized locomotion techniques into walking-based, steering-based, selection-based, manipulation-based, and automated. Regardless of the type, the main purpose is to enable users to navigate and move within a VE in a natural, comfortable, and immersive manner [4].

*Corresponding author: yue.li@xjtlu.edu.cn

An inevitable challenge when navigating within VEs is the occurrence of cybersickness, a kind of motion sickness caused by the sensory conflict between the visual system and the vestibular perception [14]. Usually, the adverse effects led by cybersickness include nausea, headache, vertigo, disorientation, sweating, and eyestrain [29]. Recent research [6] showed that the cybersickness led by a locomotion technique is slighter when the technique is natural (e.g. real walking) or semi-natural (e.g. Virtusphere [36] and VR treadmill [7]). Many semi-natural locomotion techniques such as leaning-based locomotion have been introduced to reduce the effect of cybersickness in VR [22]. In addition, some research provided evidence that the appropriate tactile feedback mitigated users' cybersickness while traveling in VEs [15].

Motivated by the strength of leaning-based locomotion in reducing cybersickness [22], improving navigation performance [12], and enhancing self-motion perception [13, 27], we present a prototype that replicates a popular real-world vehicle, the balance vehicle, which utilizes a leaning-based mechanism for its operation. When using a balance vehicle, the rider's body is relatively static, while the optic flow of the view is continuously changing. This is similar to the continuous locomotion techniques in VR. Hence, we design a VR locomotion device with a mechanism similar to the balance vehicle to see if it can reduce cybersickness and increase immersion. This kind of device matches users' real-life experiences and reduces the unfamiliarity that might occur when traveling in VR. Considering these factors, we introduce a new leaning-based semi-natural locomotion interaction device called LeanOn. It allows users to steer in the VE by leaning the device forward or backward. Different from the other leaning-based locomotion techniques, LeanOn is a leaning-based steering and feet-controlled orientation device, which means it is hands-free for users (see Figure 1a-b). Unlike previous designs that did not have a real-world reference [26], LeanOn directly maps the structure and traveling mechanism of balance vehicles, which leverages users' life experiences in learning the VR locomotion. In addition, several studies have proven that tactile feedback synchronized with visual feedback is an important factor in increasing realism and immersion in VR, as well as the sense of body ownership and spatial presence [16, 17, 21]. Hence, a terrain simulation system is added to the LeanOn device to generate different levels of tactile feedback when users travel on different terrains in VE, similar to the real experience when users use balance vehicles to move on different roads.

2473-0726/23/$31.00 ©2023 IEEE
DOI 10.1109/ISMAR59233.2023.00056

We compared the LeanOn device with joystick steering in cybersickness, spatial presence, feedback experience, and task performance. Participants were asked to use joystick steering, LeanOn with and without terrain simulation to travel on a one-way route with four different terrains in a small town. The evaluation results showed that LeanOn contributed to a significantly higher feedback experience and kept the same level of spatial presence without increasing cybersickness. Our research contributes to the current locomotion research by 1) presenting a novel leaning-based locomotion technique with a terrain simulation system and specifying its operating principles, 2) evaluating the locomotion techniques and showing that the LeanOn device leads to enhanced feedback experiences to users without bringing in negative effects.

2 Related Work

2.1 Leaning-Based Locomotion Techniques in VR

Leaning-based steering (LBS) allows users to travel in VE by leaning their bodies, heads, or feet, which provides the probability of freeing users' hands when controlling the locomotion. Fairchild [11] was one of the earliest works on LBS. The technique mapped the head translation from a defined central point to the virtual translation in VE, and the leaning angle of the body determines the travel speed. Later, de Haan et al. [9] used the Wii Balance Board as an input device for a leaning-based steering technique. A translation in VE will be performed by leaning forward or backward, and leaning sideways controls strafing left or right. Rotation can be achieved by pressing on the toes and heel of opposing feet. According to their research, this device is intuitive to use and results in smooth movement. Wang and Lindemann [51] also used the Wii Board to create a leaning-based surfboard similar to the cartoon "Silver Surfer". The travel speed was controlled by an accelerometer sensor on the user's forward arm, and orientation was 2-DoF, which was performed by transforming the pitch and roll angles of the Wii to the rotation of the virtual avatar. Similarly, the NaviChair allowed users to sit on a chair and control the locomotion in VE by leaning their upper body in the direction they want to travel [23]; and the NaviBoard enabled users to travel in the VE by leaning their whole body or stepping forward [37]. A recent work [13] found that compared to joystick steering, the use of leaning-based locomotion improved user experience including enjoyment and spatial presence, and reduced motion sickness.

2.2 Vibration Simulation in VR

Tactile feedback is an important interaction feedback to increase the immersion of VR, which can be simulated using vibration systems. Li et al.'s study [31] investigated the effects of whole-body tactile feedback on cybersickness and users' emotions when they used a controller to "walk" over different surface materials. The results showed that tactile feedback had no impact on cybersickness. Kruijff et al. [26] added combined audio, vibrotactor, and bass-shaker cues to a leaning-based locomotion device and found that these cues significantly improved users' sensation of self-motion. Jung et al. [15] developed a floor vibration system using audio transducers. Participants sat on this platform and experienced a driving journey in VE. The authors found that the system not only increased the level of realism but also significantly mitigated cybersickness. Similar to Jung et al.'s research, Sawada et al. [43] applied the vibration system to a VR motorcycle driving simulator. They investigated whether the whole-body tactile feedback and synchronized sound could mitigate cybersickness. Participants were asked to sit and hold the handlebars for five minutes to "drive" a motorcycle in VE. Their results showed that the combination of sound and vibration successfully reduced the motion sickness symptoms. In conclusion, the vibration feedback makes users feel more immersed in VE, but not all vibration systems mitigate cybersickness.

2.3 Cybersickness and VR Locomotion Techniques

Many theories, including but not limited to the poison theory [2], postural instability theory [40], and sensory conflict theory [14] provide insights into the underlying causes of cybersickness. Among them, sensory conflict theory is accepted by most researchers, which illustrates cybersickness as the sensory conflict between the sense of the visual system and the sense of the vestibular system [14]. Recent work also show that individual factors, such as age, gender, illness, and positioning, have an impact on cybersickness [8,25,28,53] and efforts have been made to predict cybersickness [35,38,50].

Locomotion techniques users used in VEs also affect the susceptibility to cybersickness [34]. Among various the locomotion techniques, non-natural continuous locomotion such as joystick steering [3] leads to more significant cybersickness than others. Natural locomotion techniques such as real walking lead to less cybersickness as the visual sensory feedback matches with the physical movements. Since the virtual scene is usually much larger than the tracking area of a VR HMD, it is challenging to map real walking with movements in VE. To preserve the self-motion cues and match the visual perceptions with movements in a limited space, several semi-natural locomotion techniques have been developed, such as leaning-based steering [37]. Nguyen-Vo et al.'s [37] research showed that leaning-based locomotion leads to significantly lower cybersickness than controller-based steering.

2.4 Spatial Presence and VR Locomotion Techniques

Spatial presence is a crucial factor that greatly influences user experience in VR [1]. Previous work has different illustrations of presence. Draper et al. [10] defined presence as a mental perception that users feel physically in the virtual environment. Slater's [46] theory identified two components that determine spatial presence. The first one is the sense of 'being there', or place illusion, signifying how users feel they are in a real place. The second one is the plausibility illusion, indicating users' sensation on something that happened in VR was actually happening. During the past few decades, various methods have been proposed for the measurement of presence [30,32,44,52], in which case spatial presence was often considered as a part of presence, together with other concepts such as copresence and social presence [45]. Vorderer et al. [49] proposed a measure of spatial presence alone, focusing on user perceptions on self-location and possible actions, and identified influencing factors such as attention allocation, spatial situation, and cognitive involvement.

Previous research showed that vestibular, proprioceptive and kinaesthetic cues between the real and virtual movement increase users' self-cognition and spatial presence [24]. According to the studies of Keshavarz et al. [19] and Riecke et al. [41], continuous locomotion techniques provide greater presence than discrete locomotion. Kitson et al.'s study [23] compared traditional joystick steering with motion cueing interfaces that involved users' body movements in the motion control. The results showed that the presence was not rated higher for the motion cueing interfaces. Similarly, Buttussi et al. [5] compared users' perceived presence among joystick steering, leaning-based steering, and teleporting, and the results indicated no significant difference among these techniques. Jung et al.'s study indicated that tactile stimuli can maintain the sense of presence when users sitting on a floor vibration plate [15]. Even though several studies have pointed out that leaning-based locomotion and tactile stimuli have minimal effect on increasing users' spatial presence, it lacks evidence of whether introducing tactile feedback to leaning-based locomotion can lead to higher spatial presence.

3 System Design and Implementation

3.1 LeanOn Structure Design

When designing the structure of LeanOn, we first referred to the existing balance vehicles on the market, such as the Xiaomi Millet

Nine Balance Car. The movement of this device is based on the leaning of the user, and the orientation is controlled by a lever around the knees. Similar to the structure of a balance vehicle, LeanOn consists of four parts: balance wheel, support board, support pillar, and orientation plates (see Figure 2a). The main material of this device is wood, except that the material of the orientation plates is polylactic acid, thermally stacked by Makerbot 3D printer. Two buttons were placed at the inner side of the two orientation plates, so that users can change their orientations by tilting their knees.

The initial design highly resembled the real balance vehicles. However, given that our device does not cause actual movements in the real world, instead of standing on the device, it was more natural to sit and use the device. Hence, we designed another structure for the device to be used for seated experiences, as shown in Figure 2b. We moved the two buttons and orientation plates around users' feet. The operation is similar to the previous design, except that the orientation control was via the feet. The prototype of the LeanOn device is shown in Figure 1c.

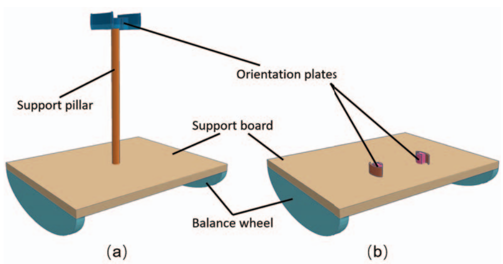


Figure 2: The 3D models showing the LeanOn structure design for (a) leg-controlled orientation and (b) feet-controlled orientation

3.2 Electronic Design

Several electronic components were used for the leaning-based locomotion control and the vibration simulation. An ESP32 development board was used as the main control board. We also included three vibration motors with different vibration frequencies (6000 RPM, 8500 RPM and 10000 RPM with an input voltage of 6V) to simulate bumpy terrain movements. We used an MPU6050, a 6-axis gyroscope, to detect the leaning of the device. Two buttons with 3D printed curved plates were connected to the development board to achieve the control of orientations. Figure 3 shows the implementation of these components on the LeanOn device. The total cost of the LeanOn prototype was ~20 USD.

3.3 System Control

We used Unity (version 2020.3.21f1c1) to implement the system control. The VR development was based on the Oculus Integration package. The Uduino package was imported to connect the development board with the Unity project. The information can be sent or received between PC and the development board by calling the functions encapsulated in this package. The VR system was built on a computer with an i7-10870H CPU, 32G RAM, and the NVIDIA Geforce RTX 3070 GPU. We used a Meta Quest 2 VR HMD, with a resolution of 1832*1920 per eye, and a refresh rate of 72Hz.

In order to control the translation and orientation in VE, PC will continuously receive signals from the development board. The device's tilt angle is conveyed through an analog signal, whereas the orientation signals from buttons are digitally based. Activating the orientation buttons results in a view rotation at a rate of 30 degrees per second. Given that the wheel was sensitive to rotation, we set a threshold ($\beta = 1$) for the tilt angle to limit the triggering of movements in VR. Only when the leaning angle of LeanOn is larger than the threshold, the movement will be activated. An angle

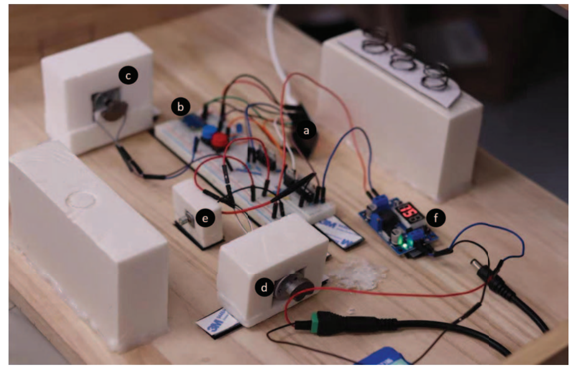


Figure 3: The hardware setup of the circuit. (a) ESP32 development board. (b) MPU6050 gyroscope. (c) 6000 RPM vibration motor. (d) 8500 RPM vibration motor. (e) 10000 RPM vibration motors. (f) LM2596 voltage converter.

bias $\omega = -4$ has been introduced, given that the the LeanOn device has a tilt angle ~-4 degrees when users place their feet on it in a natural posture. The speed of locomotion was set proportional to the leaning angle, so that users can move faster by increasing the angle. Suppose the leaning angle received by PC is α and the speed sensitivity is μ, then the travel speed (v) in VE can be expressed as

$$v = \begin{cases} 0, |\alpha + \omega| < \beta \\ \mu(\alpha + \omega), |\alpha + \omega| \geq \beta \end{cases} \tag{1}$$

Based on the pilot study during the device design, we set $\mu = 1$ in our experiment. The maximum travel speed was set to 3 m/s because it is more likely to induce cybersickness if the speed exceeds this value [47]. Thus, the effective leaning angle α ranged from 1 (moving forward) to 7 degrees (moving backwards). Angles surpassing these values indicates movements at the highest achievable speed.

3.4 Communication Protocol between ESP32 and PC

A communication protocol is needed to extract and decode the transmitted information between the ESP32 development board and the PC hosting the Unity project. The information sent by the development board to PC in each loop includes the current tilting angle of the LeanOn, the orientation state, and the working states of three vibration motors. The signal from the gyroscope and the state of the orientation buttons were processed by the development board and sent to PC. Distinguishing various terrains is achieved by collision detection. When users travel on particular terrains in VE, the PC will send corresponding signals to the development board to activate vibration motors. Figure 4 shows how the signal transfer between each device.

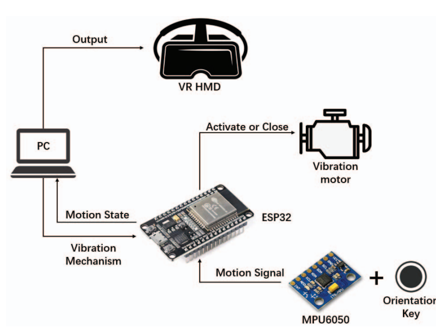


Figure 4: Illustration of the communication and system control.

4 Evaluation Study

As detailed in Section 3.1, two structures (leg-controlled and feet-controlled) were implemented during the prototype design, and tested among three participants in pilot studies in both standing and seated postures. We found it challenging to keep balance and control the locomotion while standing, and it was even more difficult when wearing the VR HMD. Seated with feet-controlled orientation was the most preferred method of control. Thus, we decided to evaluate the design of LeanOn with this method of control.

4.1 Research Questions and Hypotheses

In this study, we aim to answer the following research questions:

RQ1: Which method is the most comfortable and easiest to operate the LeanOn device?
RQ2: Can LeanOn reduce cybersickness in VR?
RQ3: Can LeanOn improve spatial presence in VR?
RQ4: Can LeanOn improve feedback experience in VR?
RQ5: Can LeanOn improve users' navigation performance in VR?

Based on the pilot study and related works, we hypothesize that:

H1: Sitting with feet controlled orientation is the most comfortable and easiest method to operate the LeanOn device.
H2: LeanOn will reduce users' cybersickness in VR [15, 37].
H3: LeanOn will improve the spatial presence in VR [12, 15].
H4: LeanOn will improve feedback experience in VR [20, 39].
H5: LeanOn will improve users' navigation performance in VR [12].

4.2 Study Design

To verify the pilot study results, we conducted a pre-study to collect empirical data about users' perceived comfort and ease of use with the four different operation methods (2 structures × 2 postures). We implemented a within-subjects design to compare users' perceived cybersickness, spatial presence, feedback experience, and control accuracy with three conditions: joystick steering (JS), LeanOn without vibration (LO), and LeanOn with vibration (LOV).

The experimental environment was a one-way route passed through a virtual town built in Unity (see Figure 5). There are four different terrains on this route: normal road, speed bump, rock road, and train track (see Figure 6 and Figure 1e). Each participant was asked to use three locomotion techniques to travel on the same route. A Latin square design was followed to eliminate the order effect of the used techniques. This study was approved by the University Ethics Committee at Xi'an Jiaotong-Liverpool University.

Figure 5: Experimental scene of the study. The whole route can be divided into 10 segments: 5 straight and 5 curved.

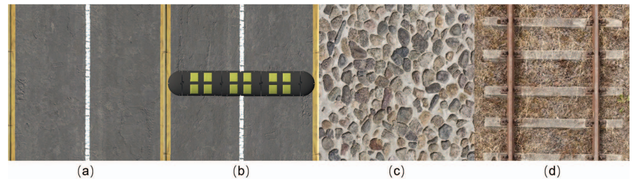


Figure 6: Four different terrains in the experimental scene: (a) normal road, (b) speed bump (8500 RPM, 3V), (c) rock road (6000, 8500, 10000 RPM, 2V), (d) train track (8500 RPM, 2V).

4.3 Implemented Locomotion Techniques

4.3.1 Joystick Steering (JS)

Joystick steering allows users to travel in a virtual environment by controlling the thumbstick on the right controller. The maximum steering speed is set to 3 m/s. The travel speed is higher when users push harder on the thumbstick. The orientation can be achieved by pushing the thumbstick on the left controller.

4.3.2 LeanOn without Vibration (LO)

As introduced in Section 3, the LeanOn device is a leaning-based locomotion technique. Users can lean the device forward or backward to control the translation in VE (see Figure 1a). Same to joystick steering, the travel speed varies from 0 m/s to 3 m/s depending on the leaning angle of the board. There are two orientation controllers that allow users to control the rotation (see Figure 1b). In the experiment, LO did not activate the vibration system. Participants used the seated with feet-controlled orientation method.

4.3.3 LeanOn with Vibration (LOV)

The setting of locomotion is the same as the previous technique. The only difference is that the vibration system is activated for LOV. When users travel on terrains with different textures, the vibration system will generate different levels of vibration to simulate realistic movements on the terrains.

4.4 Measures

4.4.1 Cybersickness

Cybersickness was measured by the Simulator Sickness Questionnaire (SSQ) [18]. It enumerated 16 possible symptoms into three categories: nausea (N), oculomotor (O), and disorientation (D). Participants needed to rate every symptom on a scale from 0 to 3, where 0 means asymptomatic and 3 means severe symptom. Items were repeatedly coded, leading to 7 items related to nausea, 7 items related to oculomotor, and 7 items related to disorientation. The score for each category and the total severity (TS) were calculated by multiplying a constant factor with the sum of the related symptom scores. The total severity of cybersickness is around three times greater than that of simulator sickness [48].

4.4.2 Spatial Presence

Spatial presence was measured by the MEC-spatial presence questionnaire (MEC-SPQ) [49]. We used the eight statements that directly measure spatial presence, with 4 items related to self-location and 4 items related to possible actions. The responses were recorded on a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree).

4.4.3 Feedback Experience

Feedback experience was measured by a group of questions modified from the haptic experience inventory [42]. We changed the word "haptic" to "feedback" to make it more general and applicable for all three conditions. Participants were instructed that the feedback include all sensory feedback they perceived during the experience, such as visual, auditory, and haptic feedback. For convenience, we name this questionnaire FEQ (Feedback Experience Questionnaire). Twenty questions measure 5 factors, 5 items for autotelic (A), 4 items for expressivity (E), 4 items for immersion (I), 3 items for realism (R), and 4 items for harmony (H) (see Table 1). The responses were recorded on a 5-point Likert scale.

Table 1: Questions to measure the feedback experience, adapted from [42].

A1. I like having the feedback as part of the experience.
A2. I like how the feedback itself feels, regardless of its role in the system.
A3. I disliked the feedback.
A4. I would prefer the system without the feedback.
A5. The feedback felt satisfying.
E1. I felt adequate variations in the feedback.
E2. The feedback changes depending on how things change in the system.
E3. The feedback reflects varying inputs and events.
E4. The feedback all felt the same.
I1. The feedback increased my involvement in the task.
I2. The feedback helped me focus on the task.
I3. The feedback helped me distinguish what was going on.
I4. I felt engaged with the system due to the feedback.
R1. The feedback was realistic.
R2. The feedback was believable.
R3. The feedback was convincing.
H1. The feedback felt disconnected from the rest of the experience.
H2. The feedback felt out of place.
H3. The feedback distracted me from the task.
H4. The feedback felt appropriate when and where I felt it.

4.4.4 Task Performance

During the experiment, we recorded the time participants spent completing the route and their travel distance. Their positions in VE were recorded every 0.5 seconds to track their travel route. To investigate the control accuracy of three locomotion techniques, we compared participants' travel routes with a reference route (a route in the middle of the road). Figure 5 shows the 10 segments of the road, with 5 straight and 5 curved. Given a user position (x_{user}, y_{user}), we selected the closest reference point point (x_{ref}, y_{ref}) to calculate the deviation. The deviation for each point was represented by the Euclidean distance, which could be calculated as

$$d = \sqrt{(x_{user} - x_{ref})^2 + (y_{user} - y_{ref})^2} \quad (2)$$

Then we added the deviations for each segment together to calculate the total deviation.

4.5 Procedure and Tasks

The experiment included the following four parts, lasting 35 to 40 minutes in total. The experiment procedure is shown in Figure 7. A Latin square design was followed to eliminate the order effect of the used techniques.

Briefing. Before the start of the experiment, we informed participants of the experimental procedure and the possible negative symptoms. Participants were allowed to stop the experiment if they feel uncomfortable. After participants read the information sheet and agreed, they were asked to sign an informed consent form and fill in a demographic questionnaire.

Pre-study and tutorials. There are four methods to operate the LeanOn device: (1) stand with leg-controlled orientation (DL), (2) stand with feet-controlled orientation (DF), (3) sit with leg-controlled (TL), and (4) sit with feet-controlled orientation (TF). Participants were invited to use these methods for the LeanOn device to travel in a pre-study scene. After each trial, they needed to fill in two questions on a 7-point Likert scale: 1) *"Do you think this operation method is comfortable?"* and 2) *"Do you think this operation method is easy to use?"*. Then, a tutorial scene was provided to help participants familiarize themselves with the three locomotion techniques (JS, LO, LOV). After participants indicated that they were familiar with the three techniques, they were asked to fill in a pre-exposure SSQ.

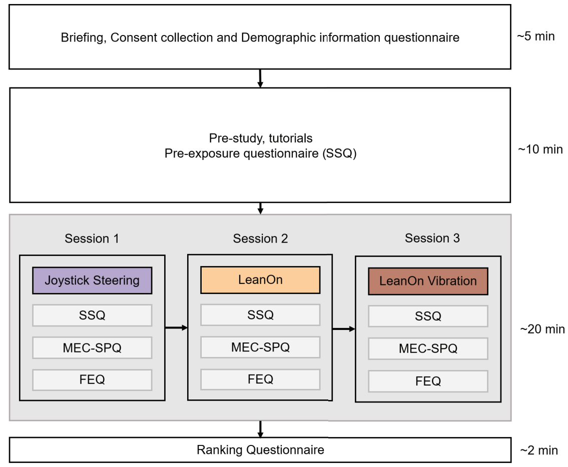


Figure 7: The experiment procedure of this study.

Experimental sessions. The experiment included three sessions, requiring participants to use different locomotion techniques to travel on the route in a virtual town. At the beginning of each session, participants were informed of the locomotion technique used in this session. When participants arrived at the end of the road, they needed to take off the VR HMD and fill in the questionnaires about cybersickness, spatial presence, and feedback experience. Participants were given a 2-minute break before the next session to relieve possible after-effects from the previous session. They could rest longer if requested.

Technique ranking. After all the experimental sessions were finished, participants were asked to give a ranking on the three locomotion techniques and provide a short explanation.

4.6 Participants

Twenty-four participants (15 males and 9 females) from a local university voluntarily signed up for the study. Their age ranged from 18 to 24 (*m*=21.86, *SD*=1.53). Six of them reported that they had 3D motion sickness. Fourteen participants had used VR devices before. All of them had used joystick steering, but none had used leaning-based locomotion. On a five-point Likert scale (5 = very familiar), participants were familiar with VR (*m*=3.5, *SD*=1.01).

5 Results

In total, we collected 96 sets of subjective measures on SSQ (4 sessions x 24 participants), and 72 sets of subjective measures on MEC-SPQ and FEQ (3 sessions x 24 participants). Data analysis was conducted in IBM SPSS Statistics.

5.1 Comfort and Ease of Use

In response to **RQ1**, Friedman tests showed significant differences in comfort ($\chi^2(3)$=50.489, $p<0.001$) and ease of use ($\chi^2(3)$=48.982, $p<0.001$). Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p<0.0125$. Except for the DL and TL pair, there were significant differences between other pair-wise comparisons in both comfort and ease of use (see Figure 8). Users found sitting with feet-controlled orientation to be the most comfortable and easiest to use method to operate the LeanOn device.

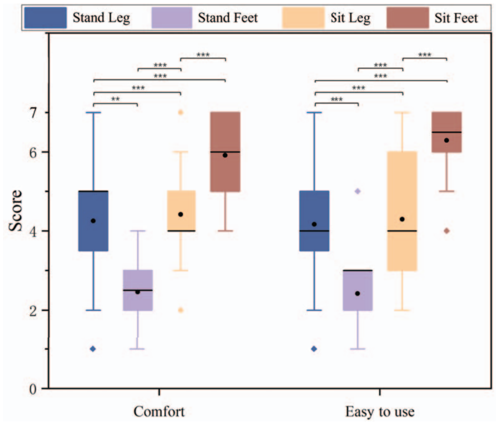


Figure 8: Box plot showing the results of comfort and ease of use. Dots in boxes indicate the mean value.

5.2 Cybersickness

In response to **RQ2**, Shapiro-Wilk tests showed that the distributions of nausea, disorientation, oculomotor, and total severity data were not normal ($p<0.001$). Friedman tests showed no significant differences in Nausea ($\chi^2(3)$=1.152, p=0.764), Oculomotor ($\chi^2(3)$=1.651, p=0.648), Disorientation ($\chi^2(3)$=3.774, p=0.287), or Total Severity ($\chi^2(3)$=4.617, p=0.202). Figure 9 presents the box plot of the simulator sickness score.

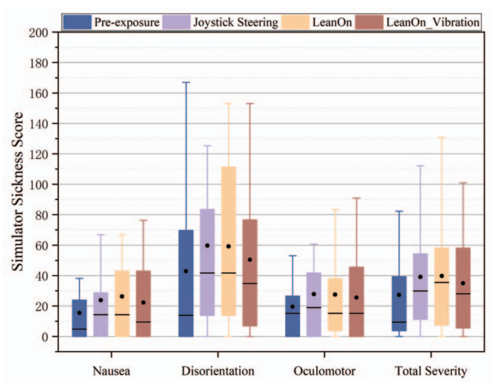


Figure 9: Box plot showing the SSQ results. Dots in boxes indicate the mean values.

5.3 Spatial Presence

In response to **RQ3**, Friedman tests showed no significant differences in SPPA ($\chi^2(2)$=1.542, p=0.463) or SPSL ($\chi^2(2)$=4.902, p=0.086). By comparing the mean score, LOV led to the highest SPPA (m=3.688, SD=0.848) and SPSL (m=4.052, SD=0.663) to participants (see Figure 10).

5.4 Feedback Experience

In response to **RQ4**, Friedman tests showed significant differences in autotelic ($\chi^2(2)$=9.956, p=0.007), expressivity ($\chi^2(2)$=8.615, p=0.013), immersion ($\chi^2(2)$=13.273, p=0.001), realism ($\chi^2(2)$=9.333, p=0.009), and harmony ($\chi^2(2)$=8.425, p=0.015). Post hoc analysis revealed that users' rating on the autotelics of LOV

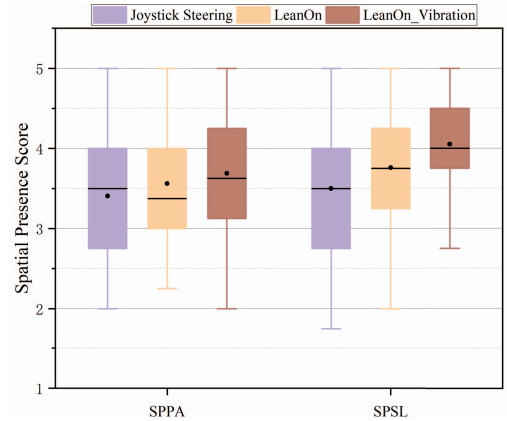
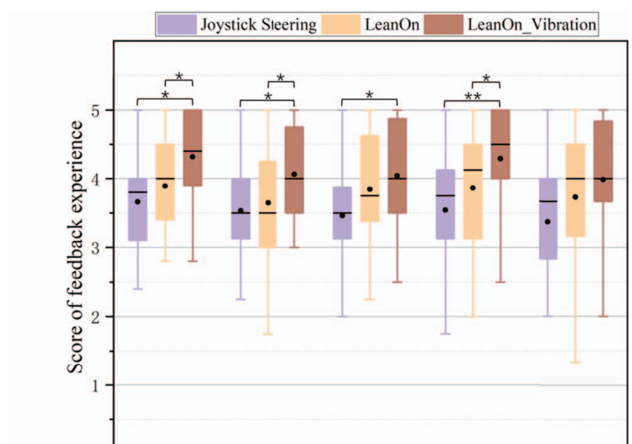


Figure 10: Box plot showing the MEC-SPQ results, including the spatial presence possible actions (SPPA) and the spatial presence self-location (SPSL). Dots in boxes indicate the mean values.

was significantly higher than JS (Z=-2.758, p=0.006) and LO (Z=-2.449, p=0.014); LOV provided significantly higher expressivity than JS (Z=-2.621, p=0.009) and LO (Z=-2.58, p=0.01); LOV provided significant higher harmony than JS (Z=-2.397, p=0.017); LOV led to significantly higher immersion than JS (Z=-2.983, p=0.003) and LO (Z=-2.495, p=0.013). However, the post hoc analysis did not show a significant difference in realism between pair-wise comparisons. Figure 11 presents the box plot and mean value of the feedback experience score.



	Autotelic	Expressivity	Harmony	Immersion	Realism
JS	3.658 (0.776)	3.5313 (0.863)	3.4583 (0.832)	3.5417 (0.926)	3.3750 (1.046)
LO	3.892 (0.9)	3.6458 (0.947)	3.8437 (0.793)	3.8646 (0.944)	3.7358 (1.054)
LOV	4.317 (0.643)	4.0625 (0.693)	4.0417 (0.786)	4.2917 (0.747)	3.9871 (1.028)

Figure 11: Box plot showing the results of the feedback experience questionnaire. Dots in boxes indicate the mean values. Means and standard deviations (in brackets) are shown in the table.

5.5 Task Performance

In response to **RQ5**, we compared participants' time spent, travel distance, and average speed when using JS, LO, and LOV to show the task performance. Shapiro-Wilk tests showed that the distributions of time ($p<0.001$), distance ($p<0.001$), and speed data (p=0.002) were not normal. Friedman tests showed significant differences in time ($\chi^2(2)$=27, $p<0.001$), travel distance ($\chi^2(2)$=25.2, p=0.047) and travel speed ($\chi^2(2)$=26.547, $p<0.001$). Post hoc analysis showed a significant difference in time spent, between LO and JS (Z=-2.429,

p=0.015), between LOV and JS (Z=-4.171, p<0.001), and between LOV and LV (Z=-2.857, p=0.004). For travel distance, the difference was significant between LOV and JS (Z=-2.448, p=0.013). Significant differences in travel speed were found between LO and JS (Z=-3.589, p<0.001), between LOV and JS (Z=-4.229, p<0.001), and between LOV and LO (Z=-3.057, p=0.002). Figure 12 presents the box plot of time spent, travel distance, and average travel speed. Joystick steering was the most efficient locomotion technique among the three, shown by the shortest time, the shortest travel distance, and the highest travel speed on average.

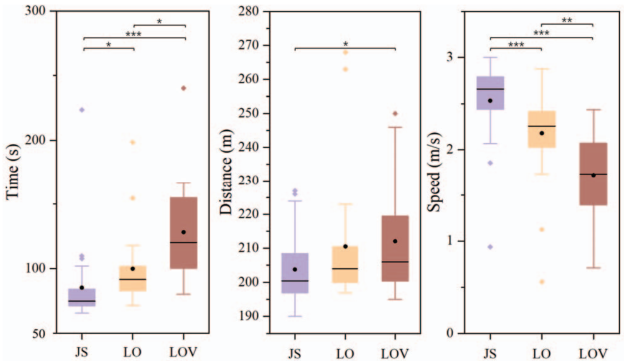


Figure 12: The box plot of time spent, travel distance, and average travel speed. Dots in boxes indicate the mean values.

5.6 Control Accuracy

We analyzed users' travel paths to investigate the control accuracy of three locomotion techniques. Specifically, we calculated users' travel deviations on straight segments and curved segments by comparing them against the central path. Shapiro-Wilk tests showed that the distribution of the deviation data was not normal (p<0.001). Friedman tests showed a significant difference in the deviation on straight segments ($\chi^2(2)$=14.434, p=0.001), but an insignificant difference in the deviation on curved segments ($\chi^2(2)$=0.867, p=0.648). Post hoc analysis showed significant differences in straight segments between JS and LO (Z=-4.166, p<0.001), and between JS and LOV (Z=-3.873, p<0.001). Figure 13 presents the box plot of the travel deviations on straight and curved segments.

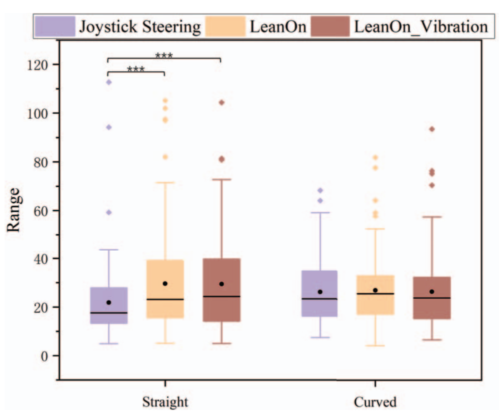


Figure 13: The box plot of the travel deviation on straight segments and curved segments. Dots in boxes indicate the mean values.

5.7 Participants' Preference

Friedman tests showed no significant difference in the rank of users' favorite locomotion technique ($\chi^2(2)$=5.083, p=0.079). Among all the 24 participants, 12 participants ranked first on LOV, 11 ranked on JS, and only 1 ranked on LO. The average rankings were 1.79 (SD=0.883), 1.833 (SD=0.868), and 2.37 (SD=0.575) for LOV, JS, and LO, respectively.

6 Discussion

We discuss our findings on the research questions and hypotheses, and provide design guidelines based on the user study.

Operation Usability. The results of the pre-study showed that the sit with feet-controlled orientation was the most comfortable method and the easiest to operate, which verifies **H1**. This finding is also consistent with the research results of Zielasko et al. [55], indicating that the majority of users tend to engage in virtual walking while in a seated posture. Although some participants thought the stand with leg-controlled orientation was more interesting, they reported that it was very uncomfortable to control the movement in the virtual environment. One participant (P8) suggested that *"standing on the LeanOn will be more stable if I can put my hands on the table."* However, such a way of use contradicts our intention of making the system hands-free, as we aim to ease the need for hand manipulation when traveling in virtual environments.

Cybersickness. The experiment results revealed that LeanOn did not significantly reduce users' perceived cybersickness compared to joystick steering, regardless of whether the vibration system was activated or not. This result does not agree with **H2**. The mean simulator sickness score of LeanOn with vibration was only slightly lower than that of the joystick and LeanOn. One possible reason for this difference is that both joystick steering and LeanOn involve continuous locomotion and rotation, resulting in similar optic flow on users' vision. Additionally, in Nguyen-Vo et al.'s study [37], the leaning-based approach adopted by NaviBoard and NaviChair involved users' movements of their upper body or the whole body. In contrast, LeanOn mainly involved users' feet movements. Thus, we speculate that the severity of cybersickness caused by leaning-based locomotion techniques varies depending on the different body positions involved in the leaning control.

Spatial Presence. We found no significant difference in spatial presence comparing LeanOn with steering (**H3** is not supported), which is consistent with some previous works [5, 15]. Nevertheless, LeanOn with vibration scored higher than the other two locomotion techniques in terms of mean and median scores. This result indicates that vibration feedback has the potential to enhance users' perception of the possible actions in the virtual environment. As for the factor of self-location, the two LeanOn techniques scored higher than joystick steering, which suggested that leaning-based steering helped users better judge their position in the virtual environment compared to controller-based steering, although the improvement was not statistically significant. We deem that the reason for the non-significant difference in spatial presence is that all three locomotion techniques involved continuous locomotion. There was no immediate change in the user's position that could cause cognitive dissonance or disorientation. The continuous changes in users' view during locomotion help maintain their sense of spatial presence. In contrast to steering which permits diagonal motion, the LeanOn device solely enables users to move straightforwardly. This limitation could contribute to the relatively modest enhancement of spatial presence observed with LeanOn. In addition, participants performed the same tasks in the same environment, the possible actions were limited in the controlled setting. The results may vary if the VR environment is exploratory and more interactions are allowed.

Feedback Experience. The experiment results demonstrated that LeanOn with vibration significantly improved users' feedback experience compared to joystick steering and LeanOn, in terms of autotelic, expressivity, and immersion. The higher feedback experience score indicated that tactile feedback effectively enhanced users' feedback experience. This result verifies **H4**. One participant (P15) mentioned that *"the vibration system of LeanOn gives me the feeling that I am actually walking on different roads. This feedback fits with what I've seen in the virtual scene."* This is consistent with the findings in [39] that vibrotactile feedback could improve realism. Although LeanOn had a higher feedback experience score than the joystick, the effect of leaning-based steering alone without vibration did not significantly improve the feedback experience. Participants mainly perceived visual feedback when using LeanOn and joystick steering, while LeanOn with vibration provided both visual and tactile feedback. In terms of realism, there was no significant difference between any groups. Since LeanOn with and without vibration had similar scores on the realism factor, we attribute this to the imperfections in the terrain simulation system used in our study. This system cannot perfectly replicate the road surface in the experimental scenario, leading to a discrepancy between the feedback experienced in the experiment and the real world. This conjecture also accounts for the insignificant result between them in the harmony factor.

Speed and Control Accuracy. The experiment results revealed that participants required more time when using LeanOn compared to joystick steering, and the vibration system caused significantly longer travel time. **H5** is not supported. While previous work showed that the leaning-based approach is more accurate than joystick in control [12], our work showed that the travel distance using LeanOn with vibration was longer than using joystick steering. Consequently, the travel speed of participants was significantly slower when using LeanOn than when using joystick steering, and the vibration system had a significant negative effect on speed. The demographic information showed that none of our participants had prior experience with the leaning-based locomotion technique, which may account for the slower travel speed while using leaning-based steering. We also observed that although technically, users could move and change the orientation at the same time, some participants tended to stop their movements before adjusting the orientations. Furthermore, the existence of tactile feedback caused participants unconsciously slow down their travel speed when passing rough terrains, such as rocky roads and train tracks. This is the primary reason for the significantly slower travel speed when using LeanOn with vibration. By comparing the travel deviations on the straight and curved segments, we discovered significant differences in the straight segments, but not curved segments. This is likely because joystick steering allows users to travel diagonally, while LeanOn only allows users to travel forward and backward. Hence, LeanOn lacks the ability to allow users to make slight adjustments to their positions without rotating their views. This may account for the lower accuracy of LeanOn on the straight segments.

Key Lessons. Seven key lessons are learned in this study: 1) The sit with feet-controlled orientation method was the most favorable way to operate our LeanOn device. It received significantly higher scores in terms of comfort and ease of use compared to the other three methods (stand with leg-controlled orientation, stand with feet-controlled orientation, and sit with leg-controlled). 2) The leaning-based locomotion technique and the terrain simulation system did not contribute to reducing users' perceived cybersickness. 3) Although the terrain simulation system did help users perceive a higher level of spatial presence, the difference was not statistically significant. 4) Compared to joystick steering and LeanOn without vibration, which only provide visual feedback to users, LeanOn with vibration with both visual feedback and tactile feedback has significantly improved users' feedback experience. The terrain simulation system contributed to the autotelic, expressivity, harmony, and immersion dimensions of the feedback experience. 5) The use of leaning-based steering resulted in lower travel speed, which was further reduced when the terrain simulation system was activated. 6) We observed that most participants were not familiar with leaning-based steering locomotion, which indicates the need for training and potentially more time to use the technique effectively. 7) LeanOn with only unidirectional movements has limited users' capability to fine-tune their movement directions on the go.

7 Limitations and Future Work

The current work has some limitations. First, our participants were mainly young adults who were not familiar with the leaning-based locomotion technique. This is not representative of the general population. It would be interesting to see if users' control accuracy could be improved if they are trained for a longer time and get experienced with this technique. The results should be generalized with caution to a different age group. Second, our study design did not consider the joystick with vibration condition, nor the use Wii balance board that has been used in previous works. In addition, we only had one trial for each condition. This decision was made to prevent user fatigue caused by excessive conditions and repetitive test runs. Still, follow-up studies with more number trials, different environments, types of trajectories, and tasks will contribute to a deeper understanding of the effectiveness of LeanOn. Nevertheless, the study design should take into account the possible impact of experiment duration and the exposure time on cybersickness. Third, the controls of translation and orientation were separated on the current LeanOn device. Future work could improve the design to use two foot pedals connected with a joint in the middle, so that users could tilt the pedals to lean forward, and twist the pedals to change their orientations. Subsequent research could also endeavor to enhance the fidelity of the design to accurately replicate movements while standing, similar to operating a balance vehicle. Finally, as a hands-free device, we did not investigate whether this design could make it easier for users to interact with objects in VR, especially when using hand gesture interaction. This will be examined in future studies.

8 Conclusion

In this paper, we present the design and evaluation of LeanOn, a novel leaning-based locomotion technique in Virtual Reality (VR). LeanOn allows users to lean the device to control the movements in the virtual environment (VE), and rotate the views by triggering the orientation control buttons near their feet. Furthermore, to increase users' immersion in VR, we implemented a terrain simulation system on this device. Three vibration motors of different frequencies were used to generate various levels of tactile feedback when users are passing through different terrains. To investigate the performance of the LeanOn device in users' perceived cybersickness, spatial presence, feedback experience, and task performance, we conducted a study comparing LeanOn with joystick steering. The results showed that LeanOn could not significantly reduce participants' cybersickness, and it could not lead to significantly higher spatial presence to users with or without the vibration system. However, LeanOn with the vibration system significantly increase participants' feedback experience and made them feel more immersed in VR. In terms of task performance, participants traveled slower when using LeanOn compared with joystick steering, and the speed was further slower when the vibration system was activated. Furthermore, participants found it difficult to control the LeanOn at the beginning of the experiment, but most of the deviations were not significant difference after they passed the first segment and adapted the operation of LeanOn. To conclude, our leaning-based locomotion device allows users to free their hands and leads to a better feedback experience for users in VR without causing higher cybersickness while maintaining the same level of spatial presence.

Acknowledgment

We would like to thank our participants for their time and valuable comments. This work is supported by the National Natural Science Foundation of China (62207022), Natural Science Foundation of the Jiangsu Higher Education Institutions of China (22KJB520038), and the Xi'an Jiaotong-Liverpool University (RDF-20-02-47).

REFERENCES

[1] B. Balakrishnan, D. Oprean, B. Martin, and M. Smith. Virtual reality: Factors determining spatial presence, comprehension, and memory. In *Proceedings of the 12th international conference on construction applications of virtual reality*, pp. 451–459, 2012.

[2] S. Bouchard, G. Robillard, P. Renaud, and F. Bernier. Exploring new dimensions in the assessment of virtual reality induced side effects. *Journal of computer and information technology*, 1(3):20–32, 2011.

[3] D. Bowman, E. Kruijff, J. J. LaViola Jr, and I. P. Poupyrev. *3D User Interfaces: Theory and Practice*. Addison-Wesley, 2004.

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

[5] F. Buttussi and L. Chittaro. Locomotion in Place in Virtual Reality: A Comparative Evaluation of Joystick, Teleport, and Leaning. *IEEE transactions on visualization and computer graphics*, 27(1):125–136, 2019.

[6] P. Caserman, A. Garcia-Agundez, A. Gámez Zerban, and S. Göbel. Cybersickness in current-generation virtual reality head-mounted displays: systematic review and outlook. *Virtual Reality*, 25(4):1153–1170, 2021.

[7] R. P. Darken, W. R. Cockayne, and D. Carmein. The Omni-Directional Treadmill: a Locomotion Device for Virtual Worlds. In *Proceedings of the 10th annual ACM symposium on User interface software and technology*, pp. 213–221, 1997.

[8] S. Davis, K. Nesbitt, and E. Nalivaiko. A Systematic Review of Cybersickness. In *Proceedings of the 2014 conference on interactive entertainment*, pp. 1–9, 2014.

[9] G. de Haan, E. J. Griffith, and F. H. Post. Using the Wii Balance Board™ as a low-cost VR interaction device. In *Proceedings of the 2008 ACM symposium on Virtual reality software and technology*, pp. 289–290, 2008.

[10] J. V. Draper, D. B. Kaber, and J. M. Usher. Telepresence. *Human factors*, 40(3):354–375, 1998.

[11] K. M. Fairchild, B. H. Lee, J. Loo, H. Ng, and L. Serra. The heaven and earth virtual reality: Designing applications for novice users. In *Proceedings of IEEE virtual reality annual international symposium*, pp. 47–53. IEEE, 1993.

[12] A. Harris, K. Nguyen, P. T. Wilson, M. Jackoski, and B. Williams. Human joystick: Wii-leaning to translate in large virtual environments. In *Proceedings of the 13th ACM SIGGRAPH international conference on virtual-reality continuum and its applications in industry*, pp. 231–234, 2014.

[13] A. M. Hashemian, A. Adhikari, I. A. Aguilar, E. Kruijff, M. von der Heyde, and B. E. Riecke. Leaning-Based Interfaces Improve Simultaneous Locomotion and Object Interaction in VR Compared to the Handheld Controller. *IEEE Transactions on Visualization and Computer Graphics*, 2023.

[14] L. J. Hettinger, K. S. Berbaum, R. S. Kennedy, W. P. Dunlap, and M. D. Nolan. Vection and Simulator Sickness. *Military psychology*, 2(3):171–181, 1990.

[15] S. Jung, R. Li, R. McKee, M. C. Whitton, and R. W. Lindeman. Floor-vibration VR: Mitigating Cybersickness Using Whole-body Tactile Stimuli in Highly Realistic Vehicle Driving Experiences. *IEEE Transactions on Visualization & Computer Graphics*, 27(05):2669–2680, 2021.

[16] S. Jung, P. J. Wisniewski, and C. E. Hughes. In limbo: The effect of gradual visual transition between real and virtual on virtual body ownership illusion and presence. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 267–272. IEEE, 2018.

[17] S. Jung, A. L. Wood, S. Hoermann, P. L. Abhayawardhana, and R. W. Lindeman. The Impact of Multi-sensory Stimuli on Confidence Levels for Perceptual-cognitive Tasks in VR. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 463–472. IEEE, 2020.

[18] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.

[19] B. Keshavarz, A. E. Philipp-Muller, W. Hemmerich, B. E. Riecke, and J. L. Campos. The effect of visual motion stimulus characteristics on vection and visually induced motion sickness. *Displays*, 58:71–81, 2019.

[20] H. Khosravi, K. Etemad, and F. F. Samavati. Simulating Mass in Virtual Reality using Physically-based Hand-object Interactions with Vibration Feedback. In *Graphics Interface 2021*, 2021.

[21] K. Kilteni, A. Maselli, K. P. Kording, and M. Slater. Over my fake body: body ownership illusions for studying the multisensory basis of own-body perception. *Frontiers in human neuroscience*, 9:141, 2015.

[22] A. Kitson, A. M. Hashemian, E. R. Stepanova, E. Kruijff, and B. E. Riecke. Comparing leaning-based motion cueing interfaces for virtual reality locomotion. In *2017 IEEE Symposium on 3d user interfaces (3DUI)*, pp. 73–82. IEEE, 2017.

[23] A. Kitson, B. E. Riecke, A. M. Hashemian, and C. Neustaedter. NaviChair: Evaluating an Embodied Interface Using a Pointing Task to Navigate Virtual Reality. In *Proceedings of the 3rd acm symposium on spatial user interaction*, pp. 123–126, 2015.

[24] R. L. Klatzky, J. M. Loomis, A. C. Beall, S. S. Chance, and R. G. Golledge. Spatial Updating of Self-Position and Orientation During Real, Imagined, and Virtual Locomotion. *Psychological Science*, 9(4):293–298, 1998. doi: 10.1111/1467-9280.00058

[25] E. M. Kolasinski. Simulator Sickness in Virtual Environments. 1995.

[26] E. Kruijff, A. Marquardt, C. Trepkowski, R. W. Lindeman, A. Hinkenjann, J. Maiero, and B. E. Riecke. On Your Feet! Enhancing Vection in Leaning-based Interfaces through Multisensory Stimuli. In *Proceedings of the 2016 Symposium on Spatial User Interaction*, pp. 149–158, 2016.

[27] E. Kruijff, B. Riecke, C. Trekowski, and A. Kitson. Upper Body Leaning can affect Forward Self-Motion Perception in Virtual Environments. In *Proceedings of the 3rd ACM Symposium on Spatial User Interaction*, pp. 103–112, 2015.

[28] J. J. LaViola Jr. A discussion of cybersickness in virtual environments. *ACM Sigchi Bulletin*, 32(1):47–56, 2000.

[29] B. D. Lawson et al. Motion Sickness Symptomatology and Origins., 2014.

[30] J. Lessiter, J. Freeman, E. Keogh, and J. Davidoff. A Cross-Media Presence Questionnaire: The ITC-Sense of Presence Inventory. *Presence*, 10(3):282–297, 2001. doi: 10.1162/105474601300343612

[31] R. C. Li, S. Jung, R. D. McKee, M. C. Whitton, and R. W. Lindeman. Introduce Floor Vibration to Virtual Reality. In *Proceedings of the 2021 ACM Symposium on Spatial User Interaction*, pp. 1–2, 2021.

[32] M. Lombard, T. B. Ditton, and L. Weinstein. Measuring Presence: The Temple Presence Inventory. In *Proceedings of the 12th Annual International Workshop on Presence*, pp. 1–15, 2009.

[33] E. S. Martinez, A. S. Wu, and R. P. McMahan. Research Trends in Virtual Reality Locomotion Techniques. In *2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pp. 270–280. IEEE, 2022.

[34] D. Monteiro, H. Chen, H.-N. Liang, H. Tu, and H. Dub. Evaluating Performance and Gameplay of Virtual Reality Sickness Techniques in a First-Person Shooter Game. In *2021 IEEE Conference on Games (CoG)*, pp. 1–8, 2021. doi: 10.1109/CoG52621.2021.9619145

[35] D. Monteiro, H.-N. Liang, X. Tang, and P. Irani. Using Trajectory Compression Rate to Predict Changes in Cybersickness in Virtual Reality Games. In *2021 IEEE international symposium on mixed and augmented reality (ISMAR)*, pp. 138–146. IEEE, 2021.

[36] M. Nabiyouni, A. Saktheeswaran, D. A. Bowman, and A. Karanth. Comparing the performance of natural, semi-natural, and non-natural locomotion techniques in virtual reality. In *2015 IEEE Symposium on 3D User Interfaces (3DUI)*, pp. 3–10. IEEE, 2015.

[37] T. Nguyen-Vo, B. E. Riecke, W. Stuerzlinger, D.-M. Pham, and E. Kruijff. Naviboard and Navichair: Limited Translation Combined with Full Rotation for Efficient Virtual Locomotion. *IEEE transactions on visualization and computer graphics*, 27(1):165–177, 2019.

[38] S. Palmisano, R. S. Allison, J. Teixeira, and J. Kim. Differences in virtual and physical head orientation predict sickness during active head-mounted display-based virtual reality. *Virtual Reality*, 27(2):1293–1313, 2023.

[39] Y.-H. Peng, C. Yu, S.-H. Liu, C.-W. Wang, P. Taele, N.-H. Yu, and M. Y. Chen. Walkingvibe: Reducing Virtual Reality Sickness and Improving Realism while Walking in VR using Unobtrusive Head-

mounted Vibrotactile Feedback. In *Proceedings of the 2020 CHI conference on human factors in computing systems*, pp. 1–12, 2020.

[40] G. E. Riccio and T. A. Stoffregen. An Ecological Theory of Motion Sickness and Postural Instability. *Ecological psychology*, 3(3):195–240, 1991.

[41] B. E. Riecke, J. Schulte-Pelkum, M. N. Avraamides, M. V. D. Heyde, and H. H. Bülthoff. Cognitive factors can influence self-motion perception (vection) in virtual reality. *ACM Transactions on Applied Perception (TAP)*, 3(3):194–216, 2006.

[42] S. N. Sathiyamurthy. Measuring Haptic Experience: Evidence for the HX model through scale development. Master's thesis, University of Waterloo, 2020.

[43] Y. Sawada, Y. Itaguchi, M. Hayashi, K. Aigo, T. Miyagi, M. Miki, T. Kimura, and M. Miyazaki. Effects of synchronised engine sound and vibration presentation on visually induced motion sickness. *Scientific reports*, 10(1):1–10, 2020.

[44] T. Schubert, F. Friedmann, and H. Regenbrecht. The Experience of Presence: Factor Analytic Insights. *Presence: Teleoperators and Virtual Environments*, 10(3):266–281, 2001. doi: 10.1162/105474601300343603

[45] R. Skarbez, F. P. Brooks, and M. C. Whitton. A Survey of Presence and Related Concepts. *ACM Comput. Surv. Article*, 50(96), 2017. doi: 10.1145/3134301

[46] M. Slater. Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 364(1535):3549–3557, 2009.

[47] R. H. So, W. Lo, and A. T. Ho. Effects of Navigation Speed on Motion Sickness Caused by an Immersive Virtual Environment. *Human factors*, 43(3):452–461, 2001.

[48] K. M. Stanney, R. S. Kennedy, and J. M. Drexler. Cybersickness is Not Simulator Sickness. In *Proceedings of the Human Factors and Ergonomics Society annual meeting*, vol. 41, pp. 1138–1142. SAGE Publications Sage CA: Los Angeles, CA, 1997.

[49] P. Vorderer, W. Wirth, F. R. Gouveia, F. Biocca, T. Saari, L. Jäncke, S. Böcking, H. Schramm, A. Gysbers, T. Hartmann, et al. MEC Spatial Presence Questionnaire. *Retrieved Sept*, 18(2004):2015, 2004.

[50] J. Wang, H.-N. Liang, D. Monteiro, W. Xu, and J. Xiao. Real-Time Prediction of Simulator Sickness in Virtual Reality Games. *IEEE Transactions on Games*, 15(2):252–261, 2023. doi: 10.1109/TG.2022.3178539

[51] J. Wang and R. W. Lindeman. Isometric versus elastic surfboard interfaces for locomotion in virtual reality. In *In Proceedings of 6th IASTED International Conference on Human-Computer Interaction*, 2011.

[52] B. G. Witmer and M. J. Singer. Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*, pp. 225–240, aug 1998.

[53] W. Xu, H.-N. Liang, Q. He, X. Li, K. Yu, and Y. Chen. "Results and Guidelines From a Repeated-Measures Design Experiment Comparing Standing and Seated Full-Body Gesture-Based Immersive Virtual Reality Exergames: Within-Subjects Evaluation". *JMIR Serious Games*, 8(3):e17972, Jul 2020. doi: 10.2196/17972

[54] Z. Zhao, Y. Li, L. Yu, and H.-N. Liang. TeleSteer: Combining Discrete and Continuous Locomotion Techniques in Virtual Reality. *2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pp. 755–756, 2023. doi: 10.1109/VRW58643.2023.00220

[55] D. Zielasko and B. E. Riecke. To Sit or Not to Sit in VR: Analyzing Influences and (Dis)Advantages of Posture and Embodied Interaction. *Computers*, 10(6):73, 2021.