

Leaning-Based Travel Interfaces Revisited: Frontal versus Sidewise Stances for Flying in 3D Virtual Spaces

Jia Wang

Robert W. Lindeman

HIVE Lab
Worcester Polytechnic Institute

ABSTRACT

In this paper we revisit the design of leaning-based travel interfaces and propose a design space to categorize existing implementations. Within the design space, frontal and sidewise stances when using a flying surfboard interface were compared through a user study. The interfaces were adapted and improved from our previous designs using a body-mounted, multi-touch touchpad. Two different experiments were designed and conducted that focus on user performance and virtual world cognition, respectively. The results suggest better user performance and user experience when using the frontal stance, although no better spatial orientation or virtual world cognition was identified. Further, user interviews revealed that despite the realistic simulation of skateboarding/snowboarding, the sidewise stance suffers from poor usability due to inefficient and inaccurate turning control and confusion between the viewing and movement directions. Based on these results, several guidelines are proposed to aid the design of leaning-based travel interfaces for immersive virtual reality applications.

Categories and Subject Descriptors

H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems – *artificial, augmented, and virtual realities*;
H.5.2 [Information Interfaces and Presentation]: User Interfaces – *evaluation/methodology, input devices and strategies, interaction styles, user-centered design*.

Keywords

Leaning-based travel interface; Stance; Navigation; 3D virtual spaces.

1. INTRODUCTION

Navigation, together with object selection and manipulation, system control, and symbolic input, is one of the basic building blocks of 3D user interaction in immersive virtual environments (VEs) [2]. A satisfactory travel experience is critical for the overall immersive experience a virtual reality (VR) application provides to the user. Although in many applications navigation is not the main goal, when a user is able to intuitively, efficiently, and easily travel in the VE, the portion of the user's cognitive load devoted to travel can be greatly reduced, freeing more

resources to invest on more important tasks such as the inspection of a virtual urban area or the training of cooperation skills on a virtual battlefield. Navigation in VEs combines the mental process of wayfinding and the physical process of transporting one's virtual body [2]. In terms of interface design, the latter is more challenging, mainly due to the demand of mapping from user motions in the limited real world space to a possibly infinite virtual world space. Based on the way the travel direction is specified, travel interfaces have been categorized into gaze-directed, pointing-directed, torso-directed, steering-based, and walking interfaces [2].

Inspired by real life transporters such as the skateboard, the snowboard, and the Segway, several leaning-based travel interfaces (LTIs) have been proposed that allow standing users to control virtual locomotion through leaning his/her body [8] or shifting his/her center of gravity (COG) [16]. The 2-DOF data from the devices are usually mapped to forward/backward motion and left/right turning in the VE to enable travelling on a terrain surface, although a flying surfboard interface has been proposed by adding an extra DOF [19]. LTIs are steering-based travel interfaces because the travel direction is always aligned with the platform, regardless of the user's body orientation. Prior work in this area has mainly focused on the design and implementation of the hardware and control laws, but little work has been done to systematically explore the various design options of LTIs except for our previous study that compared isometric and elastic implementations of the flying surfboard interface [19].

In this paper, we revisit the design space of LTIs with a focus on a comparison between the frontal and sidewise stances of using the interface. In skiing/snowboarding people can adapt to, and even master, both stances through practice. However in VR, stance may have a significant influence on task performance and VE cognition because of the degraded physical simulation of the real life metaphor, the narrow field of view of the display, and the lack of haptic and vestibular feedback that indicate the ongoing motion. In this paper, we raise this question to the level of 4-DOF flying control using an improved flying surfboard interface [19]. The goal is not only to find the better of these two design options, but more importantly, also to investigate the fundamental factors that affect the usability of LTIs in VR to provide guidelines that aid the selection and realization of LTIs for future VR research and applications.

2. RELATED WORK

Travel in VEs can be reduced to the continuous specification of a 3D vector. The aforementioned gaze-directed, pointing-directed, and torso-directed travel interfaces all use orientation sensors mounted on the user's head, hand, or torso to specify the direction of this vector in the VE [2]. The magnitude (the travel speed) can be controlled by buttons, hand gestures, voice commands, and so on [7]. These abstractions have been proven to be efficient by empirical studies in different travel scenarios [1]. However they do not represent how people travel in the real world and may therefore degrade the sense of presence in the VE.

WPI CS Dept., 100 Institute Road, Worcester, MA 01609, USA
{wangjia, gogo}@cs.wpi.edu

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Using vehicles in real life, people are able to travel long distances by applying body motion in a much more limited local space. This metaphor motivated the design and development of various vehicle simulators in VR for military training and entertainment purposes. LTIs are a sub-category of such interfaces and are mostly inspired by real life personal transporters, such as the PemRam motion base [4], the Hawai'i surf simulator, the virtual Segway Patroller [16], the Joyman interface [8], and the flying surfboard interface [19]. It should be stressed that our discussion of LTIs in this paper does not apply to interfaces that require users to turn their bodies [10], or make upper body postures to travel in the VE [5][18]. In other words, a LTI is defined only when whole body or at least lower body leaning is involved in controlling the virtual locomotion. Such LTIs can provide users with appropriate affordances and feedback without occupying large spaces.

On the other hand, to approach real walking in VR, walking-in-place (WIP) travel interfaces have been proposed in which the user wears multiple acceleration, orientation, and pressure sensors on special locations of the body, and steps, turns, and strafes in-place to control locomotion in the VE [14]. By designing the gestures to mimic real walking, WIP interfaces offer high proprioceptive but insufficient vestibular feedback because the user does not actually displace in the real world. Inspired by the treadmill, sophisticated mechanical systems have been built to rotate floor pieces from the back of the user to the front where he/she is going to step next [6]. These interfaces enabled limitless walking in a limited space. However, the systems were very expensive to build and maintain, very noisy to operate, and the user is forced to step very slowly and carefully to compensate for the time delay to mechanically displace the floor tiles.

The invention of large area tracking systems fully realized real walking in VR by tracking the user's position and orientation in a relatively large space to travel in a VE of the same size. Empirical user studies showed that this real walking technique significantly increases the sense of presence and the cognition of virtual spaces compared to WIP and joystick in immersive VEs [15][20]. To expand the reachable space in the VE, several redirected walking techniques have been proposed and evaluated which explore the effect of visual dominance [12] and change blindness [13] in VR. By imperceptibly manipulating the structure or the user's visual perception of the VE, such techniques are able to redirect the user to walk curved paths within a limited lab space without breaking presence in the virtual world. Despite the high cost to distribute the hardware systems, redirected walking techniques are by far the most successful solutions for terrain based VR navigation, especially in indoor VEs.

3. INTERFACE DESIGN

3.1 Leaning-Based Travel Interfaces

The motivations for using LTIs for travel in VE mainly include:

- **Hands-free navigation:** The lower-body controlled locomotion frees the hands for other tasks in the VE. For example, the virtual Segway Patroller frees both hands to do map navigation (wayfinding) on a multi-touch surface presented as a podium in front of the user [16]. However, the hands-free benefit is not available when designers choose to include hands as part of the travel interface design, either for safety concerns [8] or to extend the 2-DOF terrain travel to 3-DOF flying [19].
- **Ease of learning:** Because LTIs simulate real life personal transporters, they may require less time to learn, especially

for users with prior experience with skateboards, snowboards, or the Segway Patroller.

- **Rich equilibrioceptive feedback:** Because LTIs involve the user's whole body motion to control the platform, the user is able to perceive equilibrioceptive feedback from his/her balance system and become more aware of the state of the interaction, which results in more efficient travel control and a higher level of presence in the VE [8][19].
- **Space and cost effectiveness:** The building and maintenance costs and space requirements of LTIs are much lower than other types of travel interfaces such as real walking.

The challenges to making LTIs more usable mainly include:

- **Ergonomics:** Since the immersed user does not have vision of the real world, the consequences of falling off the platform can be very dangerous. Therefore designers have to include proper protection mechanisms, such as larger platform surfaces, surrounding guard bars, or handrails [8].
- **Fatigue:** Since most LTIs require the user to stand and use his/her whole body or at least lower body motion to control VE travel, fatigue becomes a significant problem in cluttered VEs that demand frequent changes in direction to navigate, or applications that require a long immersion time.
- **Lack of precision:** Because leaning is controlled by whole body motion, most LTIs have poor accuracy compared to gaze-, pointing-, or torso-directed interfaces in which more dexterous muscle groups are used.

It should be mentioned that the benefits and challenges listed above are targeted at general LTIs, and not specific implementations. When implementing a specific LTI, the designers have the following design options:

- **Isometric, elastic, and isotonic** platforms offer different types of equilibrioceptive feedback to the users [19]. One example of an isometric LTI is the virtual Segway Patroller [16] which uses the Nintendo Wii Fit Balance Board. The user has to apply isometric muscle tension to shift his/her COG on the static platform. On the other hand, isotonic LTIs, such as the Hawaii Surf Simulator and the Tony Hawk RIDE game board, tilt freely in all directions without giving any resistive feedback to the user. Between isometric and isotonic, elastic LTIs, such as the flying surfboard interface based on the Reebok Core Board [19], increase the strength of elastic resistant force as they tilt. Isometric and elastic implementations of the flying surfboard interface have been compared by the authors, and better user experience and presence were identified for the latter, although no performance difference was found [19].
- **Rate control, position control, the Go-go technique [11], and physics-based models** are all control laws that govern the mapping from the raw motion data from the devices to locomotion variables in the VE. The virtual Segway Simulator [16] and the Joyman interface [8] both proposed innovative control laws based the physical rules of their metaphors. The separation of rate controlled and position controlled pitch and yaw was addressed in the design of the flying surfboard interface through a pilot study [19]. The selection of control laws is highly relevant to the DOFs

implemented in the VE and no single option can be concluded to be the best for all scenarios.

- **The DOF mapping** from the devices to virtual travel is highly relevant to the target application and is usually determined together with the control laws for each DOF. Most LTIs offer 2-DOF data (leaning in all directions on a horizontal surface) although by detecting a torque gesture, an extra DOF data can be extracted from the Nintendo Wii Fit Balance Board to control elevation of the virtual body [16]. Therefore, the possible DOF mappings for LTIs are 3-DOF (2-DOF leaning and 1-DOF torque) data from the device to 6-DOF control of the virtual locomotion (pitch, roll, yaw, and translation in three dimensions). It should be mentioned however, that including rolling in VE has been shown to be inappropriate because of motion sickness [17].
- **Passive and active LTIs** are different in whether the platform contains actuators in addition to sensors. An example of an active LTI is the PemRam motion base [4], while most other LTIs are passive devices driven only by user motion. Essentially, active LTIs open the tactile feedback channel for developers to program and can therefore provide a more realistic simulation of real life scenarios.
- **Frontal and sidwise stances** are the least discussed design pairs so far in LTIs. Most LTIs (with the exception of the flying surfboard interface [19]) use the frontal stance because people are used to walking frontally. However, no study has been done to investigate this assumption, which is also the focal point of this paper.

The design space above can be used to categorize LTIs. For example, the Joyman interface [8] is an elastic, passive, frontally used LTI that maps 2-DOF leaning data to a velocity vector on the terrain surface through a control law based on the Joyman metaphor. Different combinations in this design space can result in very different user performance and experience and may create additional benefits and problems. For example, an isometric, passive, sidwise used LTI that maps 2-DOF leaning to pitch and yaw in the VE made some users become nauseated. However, the possibility of motion sickness is lower when the isometric platform is replaced with an elastic one [19].

3.2 The Improved Flying Surfboard Interface

Figure 1 illustrates the DOF mapping and control law of the original flying surfboard interface [19]. The user wears an accelerometer on one arm to control speed by lifting the arm, and stands sidwise on the COG-sensing board to control his/her pitch and yaw in the VE. The speed control uses a control law adapted from the Go-go technique [11] to allow fine-grained control in local spaces and efficient navigation over long distances. Leaning on the long axis (B_x) maps to pitch by position control (PC) and leaning on the short axis (B_y) maps to yaw by rate control (RC).

The original interface had three main criticisms:

- **Fatiguing and unrealistic speed control:** In order to maintain a travel speed, the user had to keep his/her arm lifted. When the user relaxed the arm, the speed returned to zero instantly without any inertia, unlike in real life.
- **Inefficient elevation control:** The only way to change elevation was to pitch the board up and down while moving forward. This was very inefficient when the travel target was

right above or below the virtual body, in which case the user had to zigzag to reach the destination.

- **Inaccurate location control:** Although the Go-go-like technique [11] control law made speed control more fine grained in local spaces, the user still did not have direct control of his/her virtual body's location. Additionally, the method only supported moving forward. When the user's target was in a cluttered, small space and his/her initial moving direction was slightly off target, it was very easy to overshoot due to the lack of PC and very hard to readjust due to the lack of backward movement.

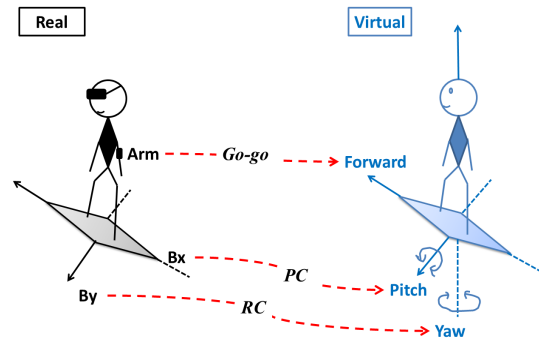


Figure 1. The original flying surfboard interface

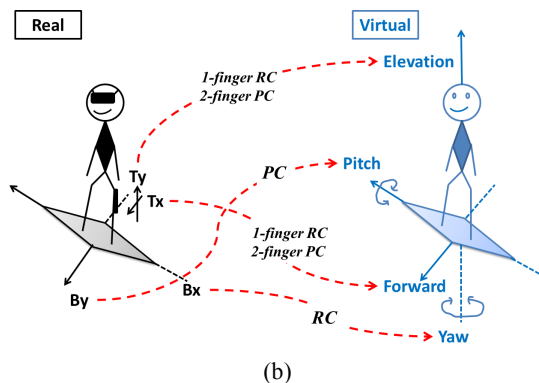
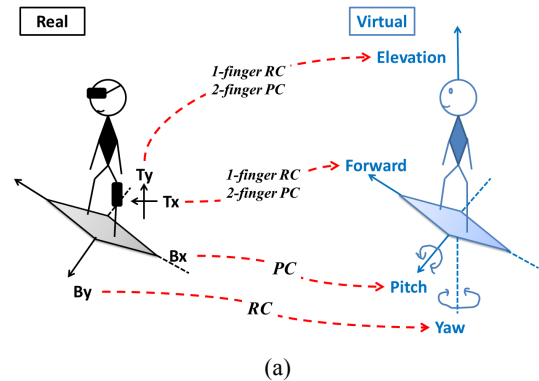


Figure 2. The improved flying surfboard interface using the (a) sidwise and (b) the frontal stances

These issues are all addressed in our improved design of the flying surfboard interface, as illustrated in Figure 2, by replacing the arm-mounted accelerometer with a multi-touch touchpad. The Bamboo tablet being used is a rectangular, two-finger, multi-touch surface. The touchpad is always attached vertically with the

long edge pointing downwards. For each user, the touchpad location is adjusted so that the corresponding hand can cover the whole surface easily when the arm is at rest, which greatly reduces the fatigue of operating the touchpad. To make the best use of proprioception [8], the touchpad is also always aligned with the travel direction so that touching the touchpad (T_x and T_y) also moves the virtual body in the same direction. In other words, for the sidewise stance, the touchpad is attached to the front of the thigh (Figure 2(a)) whereas for the frontal stance, it is attached to the side of the thigh (Figure 2(b)).

The control laws of the touchpad are explained in Figure 2, Figure 3, and Equation (1) and (2). Vectors are represented in **bold** and *italic*. The touch position data on the touchpad is normalized to $[0.0, 1.0]$ from the top-left corner to the bottom-right corner so that delta touch position is a vector T ranging from $(-1.0, -1.0)$ to $(1.0, 1.0)$. The x and y components of this vector are mapped to forward/backward movement and direct elevation (moving straight up and down) using the body as a reference. Two gestures are defined to enable control over both the travel speed (one-finger RC) and the location of the virtual body (two-finger PC). As shown in Figure 3(a) and Equation (1), the one-finger RC mode maps T linearly to the travel speed S in the VE as long as the finger is in contact with the touchpad. A scale factor of 2 helps accommodate users who are used to starting touch gestures in the center of the touchpad, so that they can reach the maximum speed ($S_{max} = 150$ meters/second in our system) in all four directions while only covering half of the touch space. When the touch release event is detected, the last travel speed S_{last} decays linearly to 0 in t_d ($t_d = 2$ in our system) seconds.

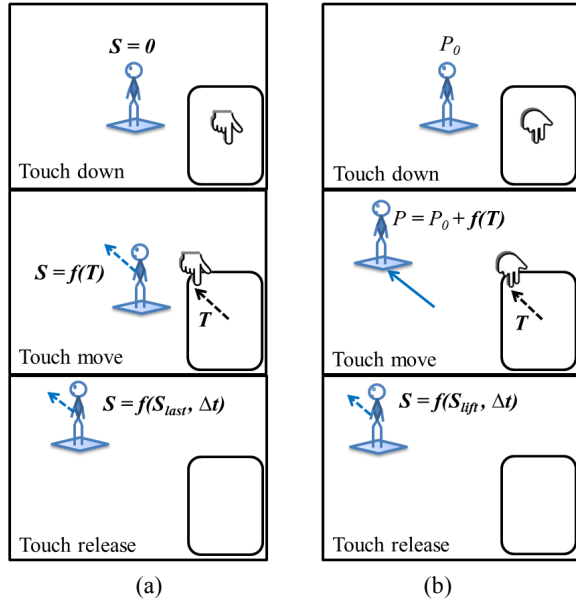


Figure 3. (a) One-finger RC mode controls travel speed. (b) Two-finger PC mode controls virtual body location.

Figure 3(b) and Equation (2) explain the two-finger PC mode designed to resolve the inaccurate location control issue of the previous interface. T is linearly mapped to virtual body translation ($\Delta P_{max} = 25$ meters in our system) in the VE as long as both fingers stay on the touchpad. When two fingers are released together, an instant speed S_{lift} is given to the virtual body based on the change between the last two reported touch positions, i.e., the touch releasing speed. This speed will also decay to 0 in t_d ($t_d = 2$ in our system) seconds. The purpose of including inertia when a

touch session ends is to make the speed control more realistic, answering the first criticism of the original interface.

$$\begin{cases} S = \hat{T} \max(2\|T\|S_{max}, S_{max}) & , (-1.0, -1.0) < T < (1.0, 1.0) \\ S = \hat{S}_{last} \max(\|S_{last}\| - \Delta t * \frac{\|S_{last}\|}{t_d}, 0.0) & , \text{when touch released} \end{cases} \quad (1)$$

$$\begin{cases} P = P_0 + \hat{T} \max(2\|T\|\Delta P_{max}, \Delta P_{max}) & , (-1.0, -1.0) < T < (1.0, 1.0) \\ S = \hat{S}_{lift} \max(\|S_{lift}\| - \Delta t * \frac{\|S_{lift}\|}{t_d}, 0.0) & , \text{when touch released} \end{cases} \quad (2)$$

The DOF mapping and the control laws of the board interface are kept the same as the original interface, meaning that leaning in the movement direction (B_x in sidewise stance and B_y in frontal stance) will pitch the virtual board using PC and leaning in the other direction will turn the virtual board using RC. Lastly, the input and output devices are all the same as the original interface. We use an elastic platform made by attaching a Nintendo Wii Fit Balance Board on top of a Reebok Core Board as the board interface, an eMagin Z800 head-mounted display (HMD) as the visual display, a SpacePoint Fusion sensor as the head tracker, and the TactaCage system to provide wind feedback. Figure 4 shows the complete system of both stances.

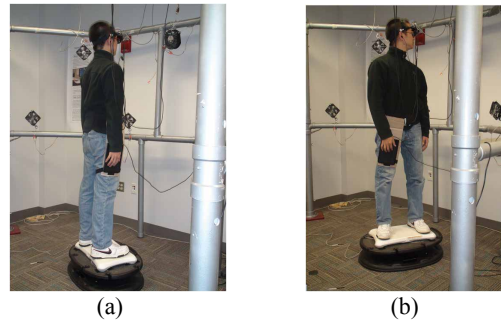


Figure 4. The complete system setup of (a) the frontal stance and (b) the sidewise stance

4. USER STUDY

4.1 Hypotheses

Both the frontal stance and the sidewise stance bear appropriate affordances and feedback based on their real life metaphors (skiing/Segway and snowboarding/skateboarding, respectively). However, we hypothesize a preference for the frontal stance, since the sidewise stance forces the user to twist his/her neck to one side in order to align the viewport with the movement direction, which more-negatively influences the user experience and even travel performance. Formally stated, we hypothesize the frontal stance will outscore the sidewise stance in questionnaire ratings, spatial orientation tests, VE cognition tests, and performance on 3D VE travel tasks.

4.2 Experiment Design

The VE in our experiments was created using the Unity3D game engine. Several graphical user interface (GUI) components were added to help the user with wayfinding [3]. In Figure 5(a), the 3D arrow at the lower center of the screen always pointed to the next target, the top left timer showed the elapsed time, and the bottom right counter showed the number of targets left in the current trial. In the zoomed-in view of the radar (Figure 5(b)), the yellow cone rotated around the center to show the direction of the viewport, the blue rectangle represented the surfboard, the red bar indicated the current travel speed, and the letter "N" gave the North direction within the VE. The red triangle indicated the location of

the next target relative to the user with its pointing direction showing its relative height, below the user when pointing down and above when pointing up.

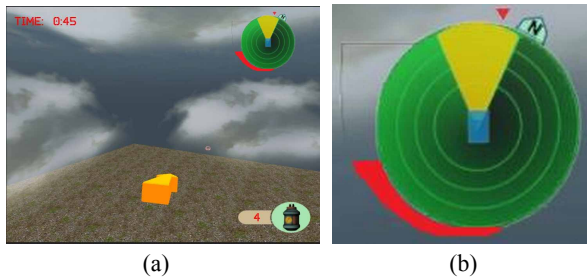


Figure 5. (a) The performance experiment. (b) The radar

Two experiments were designed and conducted to test our hypotheses. The first experiment compared user performance of the two stances on a simple reach-target task [1]. As illustrated in Figure 5(a), the targets were presented one after another to the subject in a specific order. When the virtual body and the current target collided, the target disappeared, and both the 3D arrow and the radar pointed to the next target positioned at a different 3D location. The task was complete when all targets had been visited. The total time was recorded as the metric of user performance. The VE for this experiment was a 2,000m X 2,000m flat textured terrain contained in a cube that was 2,000m X 2,000m X 500m. The inside faces of the cube were impenetrable cloud walls to assure the subject could focus on the task in a contained 3D space.

The second experiment was presented to the subject in the form of a mini game. The purpose was to investigate spatial orientation and VE cognition when navigating a large-scale 3D virtual world using the two stances. The role of the subject within the game was a mechanic whose job was to maintain windmills installed at different locations in the mountains. Figure 6 illustrates the task in detailed steps. The subject started from his/her base station, and used the 3D arrow and radar to move to the next windmill (Figure 6(a)). As the subject approached the windmill, he/she saw and heard the name of the windmill and corresponding feature objects (such as the wild flowers in Figure 6(b) and wood piles in Figure 6(c)). The blades of the windmill, as well as the cloud in the front, indicated the status of the windmill (red cloud and static blades for broken windmill, and white cloud and turning blades for working windmill). Regardless of its status, the subject needed to arrive at the cloud, which then froze the motion of his/her virtual body (turning was still enabled by leaning on the board). If the windmill was broken, the “fixing process” was triggered, which was a three-second timer. Otherwise, this step was skipped. Lastly the subject was asked to look in the direction of the previous station and confirm the answer with the experimenter (Figure 6(d)). Since the VE was large and complex and the view of the previous station was always occluded by mountains, we did not turn off the display or reduce the visibility of the VE while subjects were answering this spatial-orientation question. When the question was answered, the subject’s virtual body was unfrozen so he/she could continue to the next windmill. Once all the windmills were visited, the subject returned to the base station, after which he/she had three minutes to freely explore the VE. The session ended when the timer expired. The VE of this experiment was a 4,000m X 4,000m X 600m mountainous terrain. Landmarks in the VE included houses, roads, rivers, bridges, and tall standing rocks.

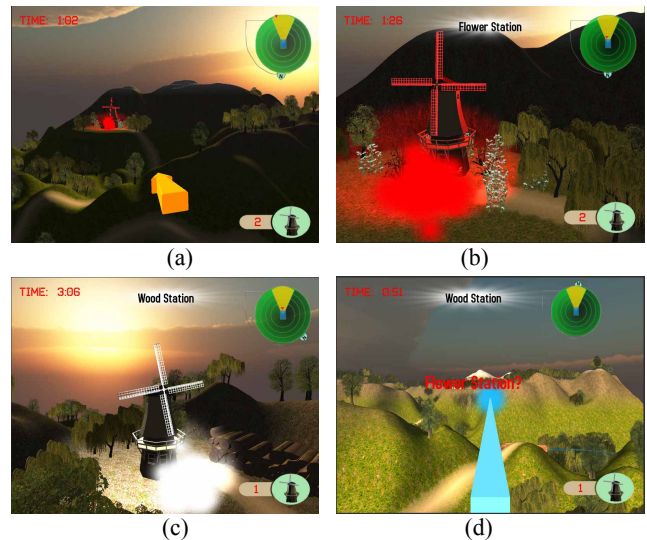


Figure 6. The cognition experiment in steps. (a) The user travels to the next windmill. (b) The user approaches a broken windmill. (c) The user approaches a working windmill. (d) The user indicates the direction to the previous windmill.

4.3 Study Procedure

The user study employed a within-subjects design, so each subject performed both experiments using both stances. The order of the stances was the same for both experiments for a given subject, but different between subjects to eliminate learning effects. When the study began, the subject completed a demographic form which included questions such as gender, age, dominant hand, height, weight, surfing stance (goofy or regular), real life Segway experience, real life board surfing experience, surfing-type video game experience, first person shooter video game experience, multi-touch interface experience, and VR experience. After that, the experimenter explained the flying surfboard interface and the experiment, and helped the subject to calibrate the board. The subject then traveled in a simple VE to test the calibration for both stances. The performance experiments started whenever the board was well calibrated (leaning in all directions was balanced). For each stance there were two trials, one training trial with five targets, and one study trial with ten targets to reach. The subject was asked to complete the task as fast as possible. When all four trials were completed, the subject took a five-minute break while the experimenter explained the cognition experiment.

After the break the subject began the cognition experiment, performing one training trial and one study trial for each stance. The training trial had a smaller VE (2,000m X 2,000m X 400m mountainous terrain) with one river, one wood bridge, one rock, one base station, and two windmills. The study trial had the normal size VE mentioned in the previous section with two rivers, five wood bridges, two stone bridges, three rocks, one base station, and four windmills. The geographical structure of the VE and the locations of the windmills were designed to be different between the two study trials to eliminate learning effects. The subject was asked to first complete the windmill task as fast as possible and then explore the VE for three minutes. After each study trial, the subject answered a cognitive questionnaire to test recollection of the VE. The first question listed ten windmill names and asked the subject to indicate if they were broken, working, or not visited, and also for the ones visited, the order of visitation. The second question gave a top-down view of the VE in black and white with the bridges, the rocks, the windmills, and the base station removed. The subject needed to add the missing

components as well as to specify the North direction. The last question asked the subject to rate his/her sense of orientation, feeling of being lost, and understanding of the VE during the experiment on six-point scales. Eventually after finishing all experiments, the subject was asked to answer a post-questionnaire to indicate his/her favorite stance and to rate the two stances on six-point scales about efficiency, accuracy, intuitiveness, ease of learning, ease of use, sense of presence, after effects (e.g., loss of balance), motion sickness, fatigue, and fun for traveling within the 3D VE. The whole study took about one and a half hours on average.

The user study was approved by the institutional review board (IRB) and 12 male students from the Computer Science Department at Worcester Polytechnic Institute were recruited with no remuneration. Three subjects had difficulty understanding the interface and started to show motion sickness symptoms after the training session, and were therefore stopped immediately. It should be mentioned that two of the three subjects had no first-person shooter video games experience and reported more severe discomfort when learning the sidewise stance due to confusion between the viewing and the movement directions. Furthermore, one subject spent quadruple the maximum time of the rest subjects on the performance experiment was therefore removed as an outlier during data analysis. The rest of the eight subjects successfully completed the study and the experimenter was able to balance the stance assignment so that half of them started with the frontal stance while the other half started with the sidewise stance. Of these eight subjects, four surfed using a goofy stance (right foot forward) and four with a regular stance (left foot forward), and seven used the touchpad using their right hands and one using the left hand (all subjects were right-hand dominant). Ages ranged from 18 to 32 years (mean = 24.0, SD = 3.9), height from 173 to 188 centimeters (mean = 178.8, SD = 4.4), and weight from 59 to 100 kilograms (mean = 79.3, SD = 11.9). Two subjects reported board surfing in real life once and the rest never. One subject used a Segway in real life yearly and the rest never. One subject played first-person shooter video games daily, four weekly, two monthly, and one once. Two subjects played surfing-type video games once (Wii Sports Resort) and the rest never. Six subjects used multi-touch interfaces daily, one weekly, and one monthly. One subject had VR experience yearly, six once, and one never.

4.4 Data Analysis

4.4.1 Questionnaire Measures

The six-point scale rating scores of the two stances were analyzed using two-sided Wilcoxon signed-rank tests with a threshold of 0.05 for significance on all questions. The three presence questions respectively asked the subjects about the sense of “being there”, whether “the virtual world became the reality”, and the sense of “not seeing, but visiting the virtual world”. The average scores and p-values are listed in Table 1 with statistically significant differences marked by stars (*) and shown in **bold**. The frontal stance was rated to be more efficient, more accurate, more intuitive, more fun, less tiring to use, and easier to learn. There was also a trend ($p < 0.1$) of easier to learn and more of a feeling of “the virtual world became the reality,” however these results were not significant. In addition, seven of the eight subjects preferred the frontal stance in general.

For scoring the windmill-status question and the windmill-visiting-order question, each of the four correctly answered windmills was worth two and one point, respectively. Because structured questions were used, the answers were graded by only one rater. On the other hand, the windmill map was graded by two

raters, whose results were averaged as the final scores. The subject needed to specify the positions of three rocks, seven bridges, four windmills, and one base station, as well as the North direction. Each of these components was worth two points adding up to 32 points in total. The inter-rater reliability was evaluated using Pearson’s correlation analysis and the result shows high agreement ($R = 0.975$). Lastly, the three subjective ratings regarding sense of orientation, feeling of being lost, and understanding the VE were analyzed using two-sided Wilcoxon signed-rank tests with a threshold of 0.05 for significance. The average scores and p-values are listed in Table 2. No statistically significant results were discovered in this part, although it is worth mentioning that seven of the eight subjects answered the windmill order question correctly when using the frontal stance compared to four when using the sidewise stance.

Table 1. The analysis result of the comparative rating scores

Ratings (1-6 scale)	Front	Side	Ratings (1-6 scale)	Front	Side
Efficiency*	4.6	2.9	Dizziness	1.3	1.6
	p = 0.021			p = 0.371	
Accuracy*	4.4	2.5	Nauseated	1.1	1.1
	p = 0.033			p = 1.000	
Intuitiveness*	4.8	3.1	Presence Question-1	4.4	4.1
	p = 0.034			p = 0.346	
Ease of Learning	4.8	3.4	Presence Question-2	3.6	3.0
	p = 0.099			p = 0.089	
Ease of Use*	5.0	3.3	Presence Question-3	3.8	3.5
	p = 0.034			p = 0.346	
Fatigue*	2.3	3.8	Loss of Balance	1.6	1.6
	p = 0.048			p = 1.000	
Fun*	4.5	3.3			
	p = 0.044				

Table 2. The analysis result of the windmill questionnaires

Ratings (1-6 scale)	Front	Side	Scores (min-max)	Front	Side
Oriented in VE	4.4	3.9	Windmill Order (0-4)	3.9	3.1
	p = 0.387			p = 0.181	
VE Understanding	4.1	3.9	Windmill Status (0-8)	7.1	6.8
	p = 0.784			p = 0.657	
Lost in VE	4.9	4.0	Windmill Map (0-32)	24.8	20.5
	p = 0.269			p = 0.167	

4.4.2 Performance Measures

The performance measures were analyzed using a single-factor ANOVA with a threshold of 0.05 for significance. The results are shown in Table 3. The total time spent to reach all 10 targets in the performance experiment was significantly shorter when using the frontal stance. For the cognition experiment, the time spent on travel was extracted from the total time by removing the time spent on exploration, fixing windmills, and pointing at previous stations. Additionally, the system recorded the pointing directions when the subject indicated the last visited windmills and computed the angular errors from the correct answer. The averaged angular errors were analyzed using a single-factor ANOVA. However, the differences between the two stances were not significant as shown in Table 3.

Table 3. The analysis result of the task performance data

	Front	Side
Time to reach all targets (seconds)*	214.3	280.3
	p = 0.002	
Time to reach all windmills (seconds)	189.4	221.4
	p = 0.438	
Average pointing deviation (degrees)	22.0	26.7
	p = 0.423	

5. DISCUSSION

Although only eight subjects successfully completed the study, the results clearly show advantages when using the frontal stance both objectively (shorter task completion time) and subjectively (rated as significantly more efficient, accurate, intuitive, easier to use, more fun, and less tiring). However, against our hypothesis, the use of different stances did not result in different levels of presence, spatial orientation, and VE cognition. To explore the causes of these results and gain a deeper understanding of LTI, we interviewed all subjects including the four who dropped out. Only one subject preferred the sidewise stance because of its realistic simulation of real life board surfing. According to this subject, it felt more like flying when using the sidewise stance to travel through large landscapes. However, like other subjects, he was frustrated by the sidewise stance when approaching targets.

From the comments of seven subjects, the causes of the sidewise stance's poor usability in local spaces can be summarized into three points. Firstly, left and right turning (yaw) in the VE was very difficult to control. This is because leaning forward and backward (as in sidewise stance) is harder to do than leaning side to side (as in frontal stance) and the rate control mechanism made it very slow to initiate turning and very easy to overshoot once reaching the desired direction. What was worse is that even when the desired heading was reached through careful maneuvering, it was very difficult to maintain it because the virtual board could not be "locked" and keeping the body balance absolutely centered on the board was very difficult. Secondly, the subjects felt easily confused and frustrated when the view and travel directions were not aligned. According to five subjects, it was not intuitive to figure out the heading of the board when starting to touch the touchpad. The virtual board indicated this information but it was far below eye level. The radar also showed the difference between the two directions but was hard to notice. The 3D arrow which pointed to the next target actually seemed to make things worse because sometimes the users thought it was an indication of travel direction. Consequently, the experimenter observed some extreme cases when a user was looking at a target and the 3D arrow was pointing at the same target. The user thought he/she would move towards the target and hence speeded up. However since the board was actually heading to the side of the view, movement dragged the user further from the target. To solve this problem, one subject suggested replacing the HMD with a TV or projection screen set up to the side of the board interface. Another subject suggested adding a cursor to the VE that was aligned with the front of the board, essentially bringing the virtual board to eye level, providing a constant visual cue about the forward direction.

On the other hand, seven subjects preferred the frontal stance because it partly resolved the two main issues of using the sidewise stance. Turning was still slow and easy to overshoot but leaning side to side was more accurate and less tiring to control. In addition, the movement direction was better predicated when

the user was looking forward. However, one subject did mention that standing on the heels (leaning backward) seemed harder for him when using the frontal stance, making pitch-up control slightly harder to use compared to elevation using the touchpad.

Regarding the two experiments, all eight subjects who completed both tasks commented that the advantages of the frontal stance were obvious in the first task because fine-grained, local-space maneuvering was necessary to reach the targets. However, the two stances seemed equal when performing the windmill task because of the large-scale VE. This explained the lack of differences in the corresponding data analysis. It is worth mentioning that based on these conclusions one may suggest a hybrid design to use the sidewise stance for long distance travel and the frontal stance for local space maneuvering. This would create problems as three subjects mentioned confusion when switching from one stance to the other during the user study.

Summarizing the discussions above, we make the following suggestions to designers who consider using similar LTIs in their immersive VR applications:

- **Fit to use cases:** Avoid using LTIs for applications which feature a small or indoor VE or which require high travel efficiency or accuracy. On the other hand, consider using LTIs to simulate realistic navigation in large-scale outdoor virtual worlds. Exemplary use cases include racing arcade games or virtual tourism such as Google Earth navigation.
- **Hybrid interfaces:** Consider mixing LTIs with local-space efficient travel interfaces. For example, the flying surfboard interface can be combined with real walking so that users can step on the board to fly through large landscapes as well as walk around in small local spaces to inspect details.
- **Better sidewise board surfing:** When using board-directed travel interfaces with an HMD, include visual cues at eye level to indicate the moving direction and pay special attention to existing visual cues to avoid confusing the user. Alternatively, replace the HMD with a projection screen installed in the moving direction. The fitness of CAVE systems in this scenario still needs further investigation.
- **Orientation lock:** When possible (not hindering intended orientation control), add a mechanism to lock the current travel direction to increase travel efficiency and precision.

Lastly, despite its complex control laws, the touchpad was complemented by all subjects to be a highly successful addition to the board interface. Seven subjects claimed that the two touch gestures were both necessary and complemented each other perfectly. The observed use pattern in the user study was one finger RC mode for long-distance travel (about 80% of time) followed by two-finger PC mode for local-space fine adjustment (about 20% of time). One subject suggested using the touchpad alone for controlling all DOFs. Two subjects liked the rich proprioception when the touchpad was aligned with the stance. Criticisms of the touchpad included its slippery surface and unclear touching boundaries.

6. CONCLUSION AND FUTURE WORK

To conclude, we revisited LTIs and proposed a design space to categorize their implementations. Within this design space the two stances of using LTIs were selected for further investigation through a user study. The frontal and sidewise stances for using

an improved flying surfboard interface were compared in the context of a performance task and a cognition task. The result revealed poor performance when using the latter to travel within local spaces because of inefficient and inaccurate turning control and confusion between looking and moving directions. Based on these findings we suggested six guidelines for using LTIs in immersive VR applications. For future work, we will further investigate the design space of LTIs and explore hybrid solutions such as combining LTIs and real walking in a CAVE. We will also consider using body-mounted multi-touch surfaces for other tasks in VR such as object manipulation and system control.

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