# A Unified Multi-touch Gesture based Approach for Efficient Short-, Medium-, and Long-Distance Travel in VR

by

Zhixin Yan

A Thesis

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Master of Science

in

Computer Science

April 2016

APPROVED:

Professor Robert W. Lindeman, Thesis Advisor

Professor David Brown, Thesis Reader

Professor Craig E. Wills, Head of Department

# Abstract

As one of the main topics in Virtual Reality (VR), travel interfaces have been studied by many researchers in the past decades. However, it is still a challenging topic today. One of the design problems is the tradeoff between speed and precision. Some tasks (e.g., driving) require a user to travel long distances with less concern about precise movement, while other tasks (e.g., walking) require users to approach nearby objects in a more precise way, and to care less about the speed. Between these two extremes there are scenarios when both speed and precision become equally important. In the real world, we often seamlessly balance these requirements. However, most VR systems only support a single travel mode, which may be good for one range of travel, but not others.

We propose and evaluate a new VR travel framework which supports three separate multi-touch travel techniques for different distance ranges, that all use the same input device with a unifying metaphor of the user's fingers becoming their legs. We investigate the usability and user acceptance for the fingers-as-legs metaphor, as well as the efficiency, naturalness, and impact on spatial awareness such an interface has.

# Acknowledgements

I would like to express my deepest gratitude to my advisor, Professor Robert W. Lindeman, who gave me great support on my research. Rob taught me how to design VR user interfaces and user studies with great patience. I got much valuable advice from him about research exploration as well as engineering and programming.

I would like to thank my thesis reader, Professor David Brown, who gave me many helpful comments, suggestions in depth, as well as encouragement, especially in my last semester.

I would like to thank our former and present HIVE lab members, from whom I learnt the whole process about experimental design, data analysis and discussion. It is thanks to them that I could be well prepared for my very first user study.

I would like to thank the 36 participants for their voluntary participation in our two experiments.

Finally, I would like to thank my parents and fiancé, who supported and kept encouraging me on my graduate study in the past years.

# Table of Contents

# List of Figures

# List of Tables

# 1 Introduction

Travel is one of the most basic and common Virtual Reality (VR) tasks. Designing a good travel interface to change the position and orientation of one's virtual representation from point A to B in a Virtual Environment (VE) is still a challenging problem. One of the problems is to effectively, efficiently, and realistically map the user's operation in the finite real-world space to locomotion in an infinite VE. However, in many applications, travel is not the goal, but a way to reach a location in order to perform other tasks like selection and manipulation [1]. A good travel interface should therefore produce low fatigue for long-term use. VR researchers and game developers have already implemented several low-fatigue travel solutions. The most popular one is WASD+Mouse which is the basic set in every FPS game. The drawbacks of this technique are also very obvious, in that it can only provide discrete speed control, both hands are occupied during travel, and the user can only travel where they are looking.

Another challenge to designing travel interfaces is scalability. In our real life, we have many different modes of transportation for different travel purposes. We would like to walk to a place nearby, drive to somewhere miles away, and take a flight to a different city. Similarly, in VEs, we also have different types of travel needs, such as short-distance, medium-distance, and long-distance. In addition, VR travel may also require moving in 3D (e.g., flying).

## 1.1 Our Work

In this research, we concentrate on integrating multiple travel metaphors into one unified travel framework using one device, a multi-touch pad with force sensing. The main idea is that by mapping one-handed gestures to lower body motion, users can travel in a low-fatiguing and intuitive way while working on other VR tasks, like picking up objects or moving virtual widgets, with the other hand.

## 1.2 Definition of Terms

- Devices: The devices we refer to in this thesis are the ForcePad, which is a multi-touch device with pressure sensing, and a traditional game controller (Gamepad).

- Interface/Travel Interface: An interface or travel interface in this thesis specifically means the device and techniques a user employs to complete travel tasks.

- Mode/Travel Mode: In this thesis, we have three types of modes in our travel interface: Walking, Segway, Surfing. . Each travel interface has at least one travel mode. Travel interfaces with multiple modes are called multi-mode travel interfaces. In our Experiment 2 (Section 4.3), we also introduce a single mode travel interface which could continuously change maximum speed to compare with our multi-mode travel interfaces.

## 1.3 Hypothesis

We formulated three hypotheses before conducting experiments.

**H1**: Participants using the multi-touch gesture-based travel interface will have a deeper sense of presence than participants using Gamepad.

**H2**: Participants will remember how to transition between the travel modes better while using multi-touch multi-mode travel interface than the Gamepad multi-mode travel interface.

**H3**: Participants will have better spatial awareness while using the multi-mode travel interfaces than using single mode travel interface.

For H1, since we are using two fingers to mimic the legs, we believe it will lead to a deeper sense of presence. In terms of H2, as the finger gestures for the different travel modes are vastly different from each other, and the mode switch for the Gamepad is pressing three buttons located close to each other, we believe participants using multi-touch multi-mode travel interface will remember the transitions better and be more aware of their current travel mode. In terms of H3, different travel modes could be helpful for the user to transfer their real life travel knowledge to the VE and have better sense of speed and distance during travel.

## 1.4 Contributions

In this thesis, we develop and describe a multi-touch gesture-based travel interface with which a user can seamlessly transit between different modes for different tasks. We also describe two user studies, and show that a finger-as-leg metaphor could help user remember transitions between modes better. The results of the studies can be taken to justify that multi-mode travel interface could be a good design choice. We believe these insights will help future researchers and developers to design multi-touch and multi-mode travel interfaces.

# 2 Related Work

In this section, we establish related work by listing and discussing the studies on virtual reality travel interfaces, including walking based travel interfaces and leaning based travel interfaces (both body driven interfaces), as well as multi-touch gesture based travel interfaces which are finger/hand driven.

## 2.1 Walking Based Travel Interfaces

According to research done by Slater et al. [2] and Usoh et al. [3], more natural locomotion can enhance the sense of presence. To overcome the problem of limited real-world space, some researchers have built mechanical systems to repeatedly place physical floor pieces under predicted foot locations [4][5][6], while others developed redirected walking technologies by taking advantage of the fact that users cannot sense the real-world movement as long as the system provides consistent and realistic visual, vestibular, and proprioceptive information [7][8].

## 2.2 Leaning Based Travel Interfaces

Leaning-based Travel Interfaces (LTIs) combine the advantages of real life walking interfaces with a virtual joystick interface to achieve immersion and efficiency at the same time. In essence, the user becomes the joystick. Beckhaus et al. [9] proposed a novel travel technique by using a tilting chair as an input device, but for most people it is hard to be very precise due to their inability to precisely control their center of mass. Wang and Lindeman [10][14] proposed their leaning based travel interfaces with the surfing metaphor, and conducted studies to compare the effects of postures (frontal vs. sidewise) and level of equilibrioceptive (isometric vs. elastic). Other similar work includes the PemRam motion base [11], the virtual Segway Patroller [12], and the Joyman interface [13].

## 2.3 Multi-touch Gesture Based Travel Interfaces

Kim et al. [15][16] proposed a multi-touch gesture-based travel technique which showed the potential of touch-based devices used for virtual locomotion in VR. Two different types of gestures were introduced in their system. One used the left hand for moving forward, backward, and strafing, and the right hand for rotation. The other approach only required one hand, but could only either walk or turn at one time. Benzina et al. [21] presented a similar touch-based virtual travel interface using smartphones.

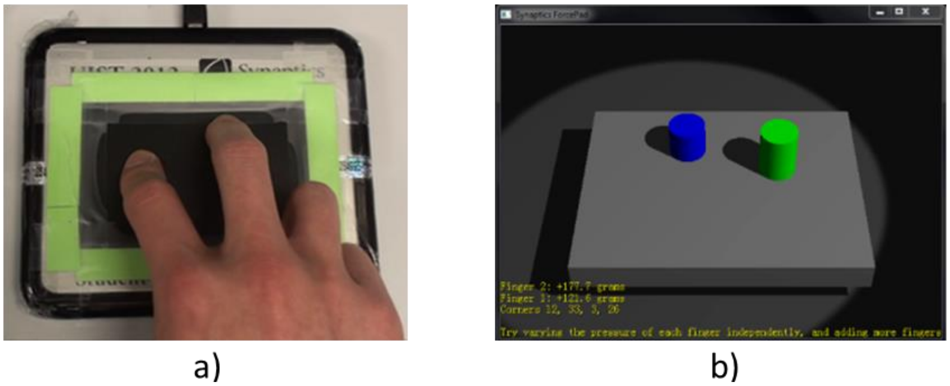
## 2.4 Pressure Based Interface

Wang & Lindeman [17] proposed two approaches for supporting Force Extension in 2D gestures, context force and shear force, to smoothly transition between position control and rate control. This interface was only used to extend 2D gestures like pinch-zoom, two-finger rotate, and one-finger swipe, however, and was not used for 3D movement. Our work uses the same device, but introduces the fingers-as-legs metaphor to support 3D movement.

# 3 System Design & Implementation

## 3.1 Device

The interface presented in this thesis is designed based on a multi-touch pad with force sensing, the Synaptics ForcePad (Figure 1), which can detect both the position and pressure of up to five fingers individually, and provide 6-bit resolution and up to 1000g of force sensing. The 2D touch and pressure data stream is received using the TUIO protocol [20]. With the 2D-touch + 1D-pressure information, we are able to map the user's two-finger gestures to virtual foot gestures and locomotion of the virtual character for the three different travel modes.



```
Finger 2: +177.7 grams
Finger 1: +121.6 grams
Corners 12, 33, 3, 26
Try varying the pressure of each finger independently, and adding more fingers
```

*Figure 1: ForcePad (a) and visualization tool (b). It can provide 3D touch information including 2D touch position and 1D pressure with 6-bit resolution and 1000g force, for up to five fingers.*

## 3.2 Walking Gesture

In our approach, walking is designated as a low-speed but high-precision surface travel mode. Based on this design goal, there are 3-DOFs of movement including forward/backward, left/right, and turning (yaw). We originally came up with a solution that maps all three DOFs to gestures. The first two DOFs, 2D translation on the ground surface, are controlled by a two-finger gesture mimicking a bipedal walking motion (Figure 2a). The trails of each finger on the ForcePad are translated into virtual-world locomotion on a 2D surface including forward, backward and strafing movement. This allows users to control the speed by the frequency and length of each "step." Unlike the first 2-DOF mappings which use position control, the third DOF (yaw) is a rate-controlled mapping, implemented by pressing on either the left or right side of the pad (Figure 2b). The amount of pressure on each side determines angular speed of turning left or right. The translation and rotation gestures are independent, and users are able to do both translation (with the index and middle fingers) and rotation (with the thumb and pinky) simultaneously, like our natural walking experience.

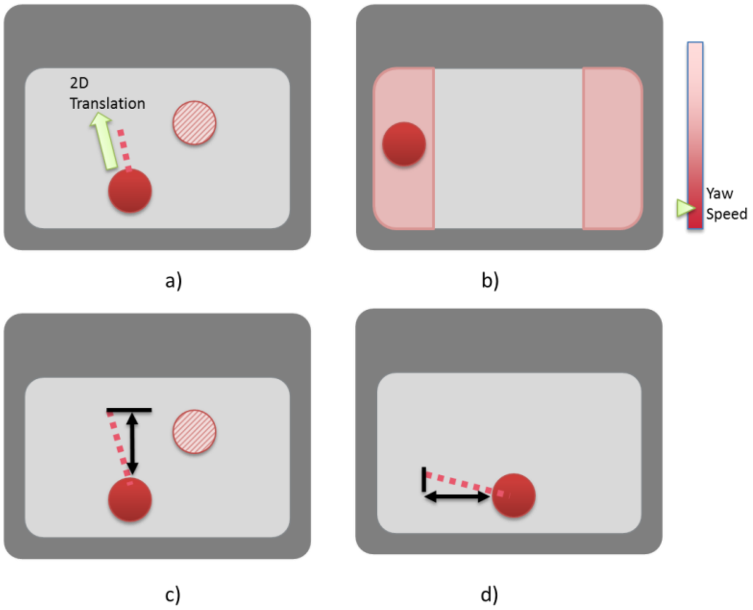


*Figure 2: Illustration of walking mode multi-touch gesture mapping. The first row and second row represents the first and second solution. a) and c) are translation mapping; b) and d) are rotation mapping.*

However, after a pilot study, we found that the first design was not an optimal solution, as users barely strafed during the study. Triggering left or right turning was also a problem, even after we attached tape on the rotation area to provide passive haptic cues; it cost extra time for users to find the correct area to place the fingers to rotate. Then we introduced our second solution which will be used in a later study. In the second solution, only two DOFs, forward/backward and yaw are mapped to the interface. We collect the finger trails of each touch. If the y component of the trail is dominant, the character will move forward/backward. The speed is controlled by the frequency and length of each step. Otherwise, the x component will be mapped to yaw angle, and the virtual character will rotate in-place. In the second solution, the users could only do rotation or translation at one time. The second solution uses fewer muscle groups than the first solution which might be potentially more efficient and less fatiguing, according to [22] and [23].

## 3.3 Segway Gesture

To achieve faster speed on the ground, the user can put both her index finger and middle finger horizontally aligned on the ForcePad to switch to Segway mode. As a vehicle, a Segway only has two DOFs. One is moving forward/backward, with the speed determined by how much weight the user puts on her toes or heels. The other, steering, is controlled by the difference between left and right-foot pressure.

In our framework, we implement two types of Segway mapping solutions. The first implementation is very similar to the idea of a real Segway, which is controlled by "foot" gestures. Moving forward or backward by leaning two fingers forward or backward, and pressing left or right to turn. However, after a preliminary evaluation of this interface, we found that users could not control the speed and orientation well at the same time by pressure only. We then developed the second implementation with a different mechanism. We define a baseline when the user triggers Segway mode (Figure 3a). The distance between the middle point of the two fingers and the baseline is mapped to the speed of moving forward or backward. Rotation mapping was first designed as mapping the Y-axis difference between the two fingers on the ForcePad to the angular speed, moving towards the desired Segway pose from the current perspective (Figure 3b).

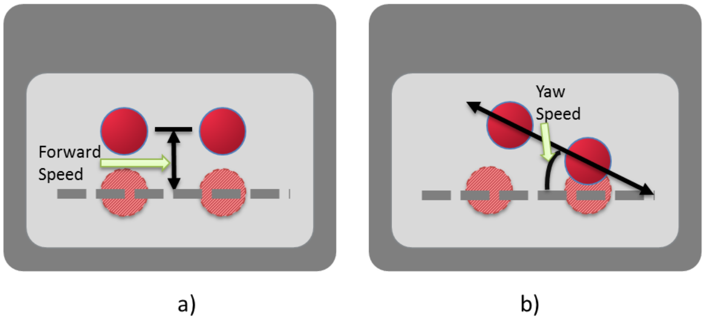


*Figure 3: Illustration of Segway mode multi-touch gesture mapping. a) is a rate-controlled forward speed mapping; b) is the first implementation for rotation mapping.*

## 3.4 Surfing Gesture

If the user wants to travel at a much faster speed than a Segway, say to travel to the other side of a map, or fly to somewhere across a very deep valley or river, he can switch to flying surfboard mode by placing his index finger and thumb in a vertical line on the touchpad (see Figure 4). Similar to the mapping proposed by Wang & Lindeman [14], the pressure difference between the front (index) finger and the back (thumb) finger is the pitch angle of the board. According to Wang & Lindeman [14], the mapping of pitch angle should be position control instead of rate control to prevent the user feeling confused. The X-axis difference between the two fingers is mapped to the angular (yaw) speed for steering. The third DOF, speed of moving forward, is controlled by the Y-axis difference between the two fingers on the ForcePad, similar to the idea of two-handed flying introduced by Mine et al. [18].

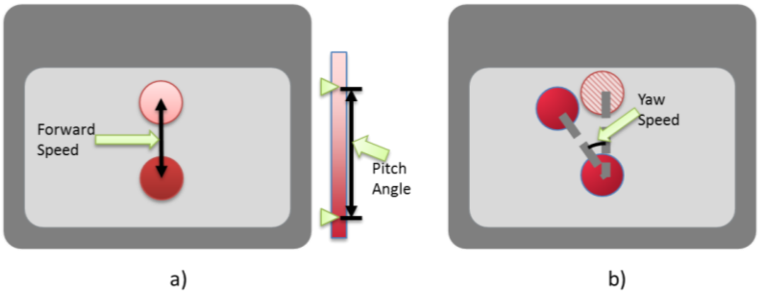


*Figure 4: Illustration of the surfing mode multi-touch gesture mapping. In a), forward speed is controlled by the distance between two fingers; pressure difference between the two fingers maps to pitch angle as a position-controlled mapping. b) is a rate-controlled rotation mapping*

# 4 Empirical Study

This section describes the design of a mixed-factorial user study including two experiments measuring the influence of the proposed interfaces on user performance and user cognition during travel. Participants would be asked to finish a pre-test training session, in which they had to meet a certain requirement (e.g. reach the goal within 60 seconds and 5 collisions), before the user performance experiment. After training, subjects would use the same devices for the cognitive experiment.

## 4.1 Control Group Devices

### 4.1.1 Multiple Mode vs. Single Mode

As our approach has three different travel modes, it would be interesting to compare our approach with a traditional single mode travel interface which could adjust speed for different tasks. We developed a gamepad based single mode travel interface (Figure 5). In this design, the left joystick was used to control the speed of moving forward and backward. The right joystick was mapped to character's yaw speed. The R2 button was used for continuously changing the maximum speed. When R2 was fully pressed, the speed of moving forward was four times faster than when it was released. So the user could always adjust the speed for different tasks.

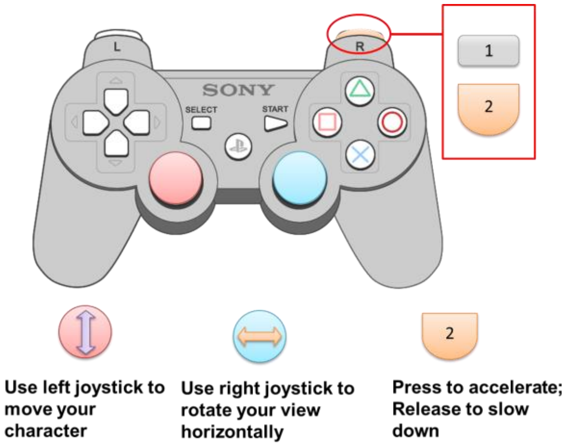
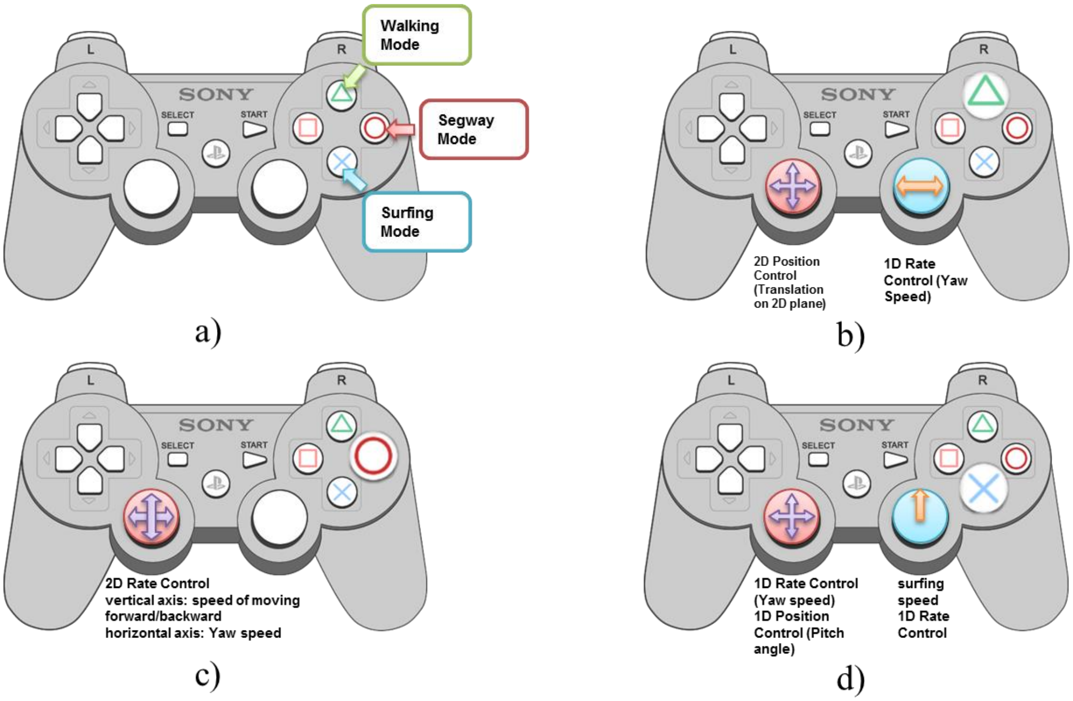


*Figure 5: Gamepad single mode mapping.*

### 4.1.2 Multi-touch Multi-mode vs. Gamepad Multi-mode

We also compared our multi-touch multi-mode travel interface with a traditional Gamepad interface. Figure 6 shows the mappings for the three Gamepad travel interfaces. Each used the same travel modes and same rotation and translation DOF control as the multi-touch, gesture-based mechanics. The main idea was to map the two joysticks on the Gamepad to locomotion, and to use the buttons on the right for switching between travel modes (Figure 6a). The main difference between the two interfaces was the muscle groups used during interaction. The Gamepad travel interface only required thumb movement, while the users had to use his or her wrist and fingers to interact with the ForcePad.



a) b) c) d)

*Figure 6: Gamepad control mappings. The buttons on the right switch between travel modes (a). (b) shows the controls for walking, (c) shows the controls for Segway, and (d) shows the controls for surfing.*

For the Gamepad walking interface (Figure 6b), the left joystick was mapped to rate-controlled 2D translation, and the horizontal axis of the right joystick was mapped to rate-controlled yaw rotation. The Gamepad Segway interface (Figure 6c) only used the left joystick, similar to traditional racing games control settings. The vertical axis of the left joystick used rate-controlled speed for moving forward and backward, while the horizontal axis of the left joystick was used for rate-controlled yaw rotation. The Gamepad surfing interface used a similar idea (Figure 6d), which treated the left joystick as the surfboard. The pitch and yaw of the joystick were mapped to pitch angle and yaw speed. The vertical axis of the right joystick was only used to control the speed of movement.

We designed two experiments (Section 4.2 and 4.3) to compare the three interfaces (also see Figure 7). In the first experiment, we fixed the travel mode during each trial, and compared the multi-touch multi-mode travel interface with the Gamepad multi-mode travel interface regarding performance of each mode separately. All the three modes, walking, Segway and surfing are included in the experiment. Then in the second experiment, users could freely switch between two modes, walking and Segway, at any moment with the two multi-mode travel interfaces. We also brought the Gamepad single-mode travel interface, which can continuously change maximum speed, into the experiment to compare user preference and performance between multi-mode and single mode travel interfaces.

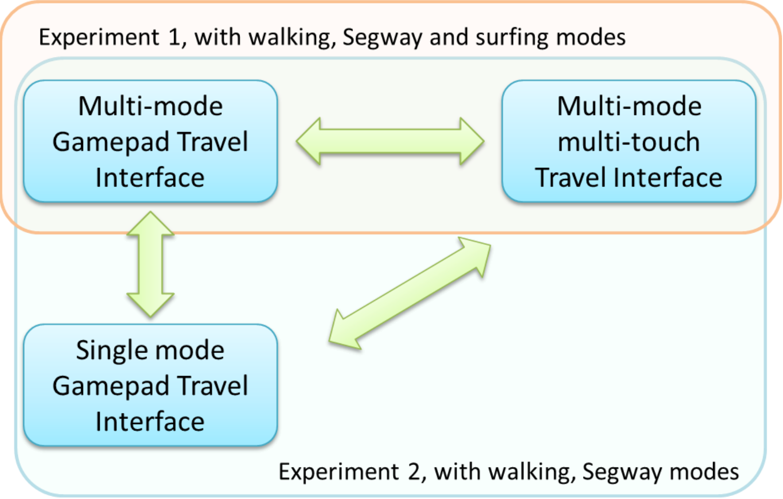


*Figure 7: Design space of two experiments.*

## 4.2 Experiment 1

A formal, mixed-factorial user study was designed to evaluate the usability of our travel framework by comparing it with a traditional Gamepad interface. The three Gamepad-based travel modes for walking, Segway, and surfing were modeled after typical game mechanics, and implemented to compete with our multi-touch, gesture-based travel interfaces. We conducted a single experiment combining an object-collection task for the walking interface, a path-following task for the Segway interface, and a breadcrumb-following flying task for the surfing interface. Each task had three difficulty levels, leading to nine trials per session. We asked every participant to do two sessions during the study with a break between the sessions. Each subject used only one of the interface devices, either ForcePad or Gamepad. Participants in the experiment group used multi-touch multi-mode travel interface with ForcePad; participants in the control group used Gamepad multi-mode travel interface with Gamepad.

### 4.2.1 The Virtual Environment

Our virtual world was developed using the Unity3D Game Engine. In the virtual world, there was a large maze with four platforms on the four corners. Trees, grass, and street lanes were included to increase the realism, provide motion cues, and imply valid paths in the maze (see Figure 8).

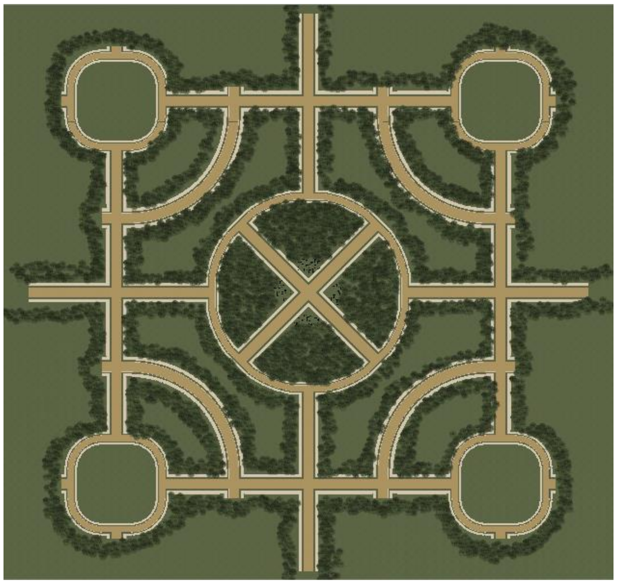


*Figure 8: Top-down view of the maze environment*

To aid in wayfinding during the study, we put an arrow right in front of the user's view to show the directions in walking and Segway tasks (see Figure 9). The arrow always pointed to the current target to collect (walking) or intersection to cross (Segway). For ForcePad subjects, we displayed a widget in the top-right corner to show the location and pressure of their fingers on the ForcePad. The harder subjects pressed their fingers, the more saturated (red) the color of the dots representing fingers became. Specifically for Segway trials, we drew the baseline on the widget to help subjects control the speed of movement and rotation.

*Figure 9: Directional arrow shown during the walking and Segway tasks*

### 4.2.2 Task Design

In the walking task, participants were asked to collect targets. A new target would appear only after the participant collected the previous one. The distance between each target was the same, while the angles to turn were chosen from 36, 72, and 108 degrees, depending on the difficulty level (Figure 10).

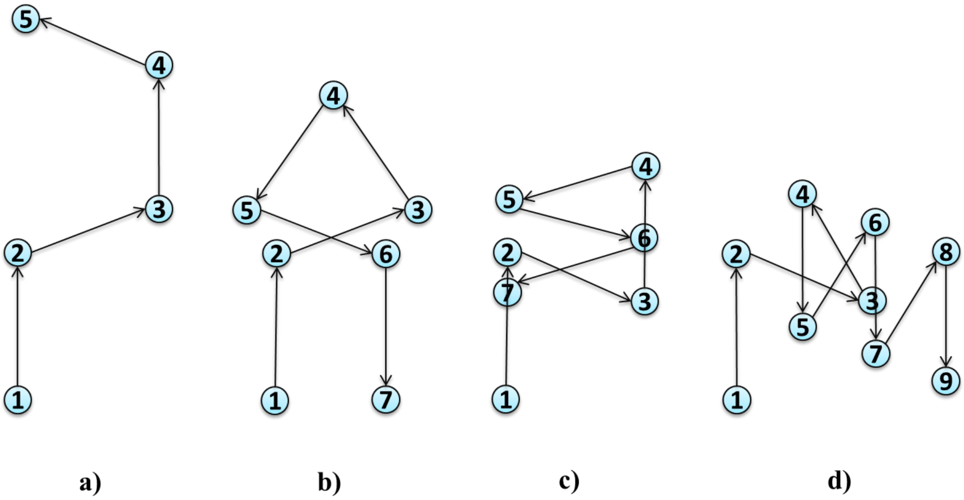


*Figure 10: Illustration of paths in the walking tasks. From a) to d) the difficulty levels are training, easy, medium, and hard. Higher difficulty levels had more targets and sharper turning angles.*

In the Segway task, participants had to follow a certain path in the maze to reach a goal as fast as possible while minimizing collisions with barrier tapes and trees along the road. We also designed three difficulty levels for Segway tasks based on the length of the path and number of sharp turns. The paths used in Segway are illustrated in Figure 11.

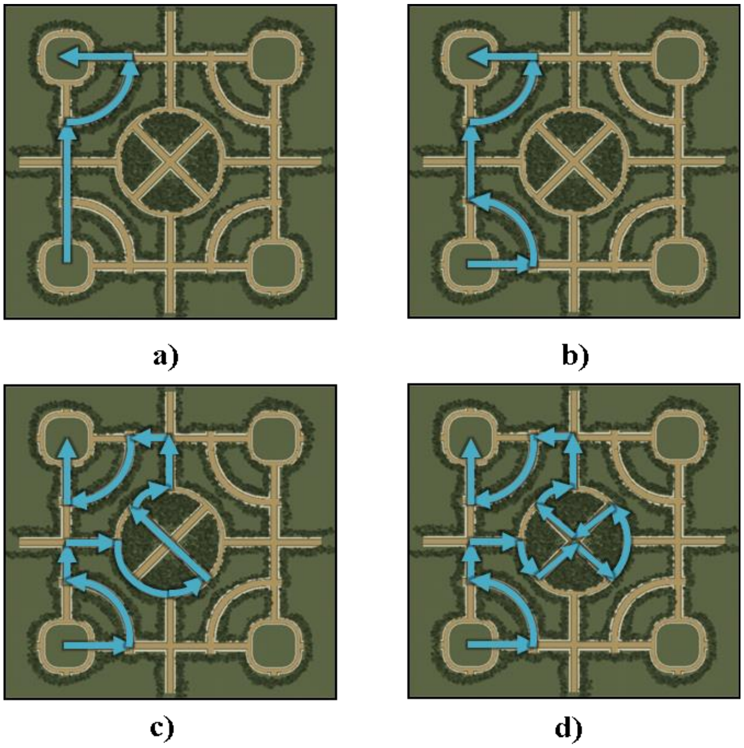


*Figure 11: Illustration of sample paths in the Segway tasks. From a) to d) the difficulty levels are training, easy, medium, and hard. Higher difficulty level had longer paths and sharper turns.*

In the surfing tasks, participants were asked to follow a path in the sky. Even though the flying path was designed with only pitch variation, both pitch and yaw controls were active, making it challenging for subjects in our pilot study. Adding yaw variation in the path might have made it more likely to cause motion sickness, and the performance data might have floor effects. Therefore, the breadcrumbs were all along a 2D path in a vertical plane, which only required pitch control, though both pitch and yaw control were available. The breadcrumb paths were generated using a bell-shape function with different height and climbing rates. The harder the task, the higher and faster participants had to climb during the study. The x and z values of points on the path were linearly interpolated from the start point to the end point. The y value could vary from Equation 1,

$$y = h * \frac{1}{(1+\left(\frac{p-0.5}{a}\right)^{2b})} \tag{1}$$

where *h* was the maximum height of the path, *a* and *b* were two variables to control the shape of the bell function. Variable *p* is calculated by dividing the distance between the start and end points by the distance already traveled.

### 4.2.3 Experiment Procedure

When a participant arrived, he was first asked to read and sign the IRB-approved consent form, then asked to fill out a general information form which included demographic questions such as gender, age, gaming experience, VR experience, FPS gaming experience, and a self-evaluation of solving maze puzzles. After that, the participant sat on a stationary chair, and wore the eMagin Z800 Head-Mounted Display (HMD). Participants in the control group used a Sony PS3 Controller held in their two hands, while those in the experiment group had a wooden board laid across their lap to provide a stable support platform for the ForcePad device. Then they were asked to face front to calibrate the inertial (SpaceFusion) tracker mounted on the HMD. The system setups for both groups are shown in Figure 12.

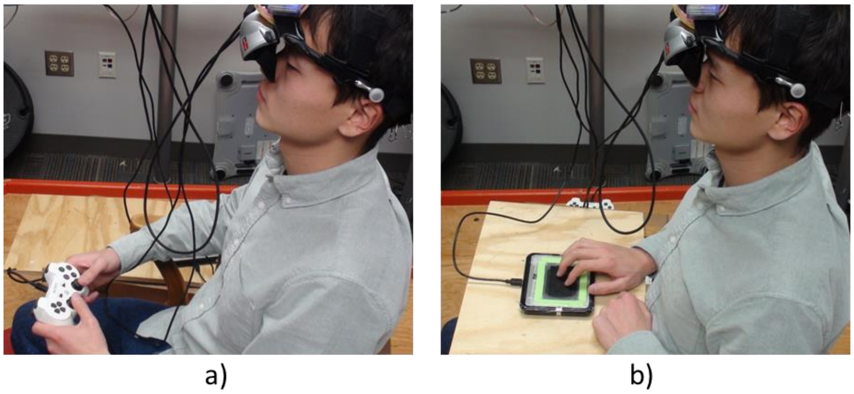


*Figure 12: Picture of system setup for both the control group (a) and the experiment group (b).*

A training session was designed to ensure at least a minimum level of proficiency for participants in each group. To complete the training session, participants had to finish the task within 80s for walking training, 120s for Segway training and 100s for Surfing training. Additionally, the Segway training tasks required participants to complete the task within five collisions, and to be within a tolerance of the breadcrumb path in the surfing training tasks. If a participant failed to pass one type of task, he had to do the particular task again until his performance met the minimum requirement.

In the study trials, participants were asked to complete nine trials with three levels of difficulty (easy, medium, and hard) using the three travel modes using one control device. We used a 9x9 Latin square to counterbalance the trials and minimize learning effects. We picked the row number of the Latin square by dividing their subject ID by two then taking its value modulo nine.

After the first session, participants had a short break of five minutes. Then they continued on to the second session of the study with another nine trials, but in a different order, and after a recalibration. The nine trials were generated in a similar way as the first session, but the row number was increased by four.

After completing both sessions, participants were asked to fill out a post-test questionnaire about realism, sense of presence, usability, and fun using six-point Likert scales for their general travel experience with the control device, as well as the three travel modes. A NASA TLX questionnaire [20] was also filled out after the study, mainly to measure the fatigue and mental/physical demands of the tasks. After the study and paper work were done, we also interviewed every participant to collect their comments about their travel experience. The whole study took about 45 minutes on average for each participant to complete.

The Institutional Review Board (IRB) approved the user study and 28 undergraduate students of our university were recruited with a reward of elective course credit. Four more graduate students were recruited with a reward of free soda. Out of 32 participants, four participants could not complete the study. Of the 28 subjects who successfully finished the study, 14 were males and 14 were females. Among the 14 participants in the control group, there were six males and eight females, eight of them often played video games, while in the experiment group there were eight males and six females, seven of whom often played video games. Their ages ranged from 18 to 35 years (mean = 20.9, SD = 3.8), and gaming experience from 1 to 6 points (mean = 3.3, SD = 1.5). By comparing gaming experience between the two groups, the p-value was 0.908, which showed that the groups were drawn from the same population.

### 4.2.4 Variables

In this experiment we used four independent variables: Travel interface, Travel mode, Difficulty, and Session.

- Travel Interface $\in$ {Gamepad, ForcePad} between-subjects

We used two different kinds of travel interfaces. Gamepad participants used a Sony PS3 controller. This is a device that is commonly used by mainstream gamers. The other was using ForcePad. Travel interface was a between-subjects variable, hence, each of the two groups of participants used only one of.

- Travel Mode $\in$ {Walk, Segway, Surfing} within-subjects

We used three different types of travel modes: walking, Segway, and surfing. Every participant in both groups had to perform all of the travel modes.

- Difficulty $\in$ {Easy, Medium, Hard} within-subjects

We used three difficulty levels for each of the travel modes. Hence, it resulted in 3x3 = 9 different trials. We used a 9x9 Latin square to counterbalance the trials.

### 4.2.5 Measures

Our measures included both objective and subjective ones.

#### 4.2.5.1 Objective Measures

In order to measure user performance, the following dependent variables were defined,

- **Completion Time**: time to complete each trial.

- **Path Deviation**: absolute distance between user's path and the optimal path.
- **Average Number of Over-Rotations**: average number of operations for correcting orientation after reaching each waypoint.
- **Number of Collisions**: number of collisions with obstacles in the maze.
- **Average Number of Overshoots**: average number of user going back and forth to correct overshoot.
- **Mode Switch Time**: time to switch to the correct travel mode

#### 4.2.5.2 Subjective Measures

Subjective data were also collected to measure user experience. As shown in Table 1, Q1-4 measured the sense of realism and presence, Q5 measured ease-of-use, and Q6 measured user enjoyment. We also asked them the mental load of remembering mode switching in Q7. Comments and a top-three ranking of the conditions were also collected at the end of the experiment. We also collected data using the NASA TLX scale form [19] to measure the mental and physical demand, performance, effort, and frustration.

*Table 1: subjective measurements and questions in post-test questionnaire*

| **Question Number** | **Subjective Measure** | **Question (range: 1-6)** |
|---|---|---|
| 1 | Realism | How close did the virtual world resemble the real world? |
| 2 | Realism | To what extent were there times during the experience when the virtual world became the "reality" for you, and you almost forgot about the "real world" outside? |
| 3 | Presence | To what extent did you experience the sense of "being there" while you were travelling in the VE, as opposed to being a spectator? |
| 4 | Presence | To what extent did you feel you were actually walking / riding a Segway / riding a surfboard, during the walking / Segway / surfing trials? |
| 5 | Ease-of-use | How easy was it to control your walking / Segway / surfing? |
| 6 | Fun | How much did you enjoy walking / the Segway / surfing? |
| 7 | Ease-of-Memory | How well could you remember which gestures/buttons to use to switch between walking, Segway, and surfing? |

### 4.2.6 Results

#### 4.2.6.1 Objective Results

We ran a mixed-factorial ANOVA on the objective data with each measurement dependent variable, and with control devices as the between subject factor. Travel mode, session, and difficulty level are set to within-subjects factors. The analyses that have statistically significant result are shown in Table 2.

*Table 2: Mean (M), Standard Deviation (SD) and F values for all objective measurements of three travel modes walking (W), Segway(S), surfing / flying (F).*

| | Control Group | | Experiment Group | | F | Df | $\eta^2_p$ |
|---|---|---|---|---|---|---|---|
| | M | SD | M | SD | | | |
| Completion time (W) | 12.1 | 3.2 | 20.9 | 2.5 | 36.1*** | 1/26 | .581 |
| Completion time (S) | 44.8 | 4.8 | 68.6 | 21 | 17.8*** | 1/26 | .406 |
| Completion time (F) | 15.1 | 6.4 | 25.6 | 5.8 | 20.8*** | 1/26 | .444 |
| Path deviation (W) | 6.67 | .63 | 7.55 | 1.1 | 6.74* | 1/25 | .212 |
| Overshoot (S) | .742 | .36 | .196 | .24 | 21.4*** | 1/24 | .472 |
| Mode Switch time (W) | 1.61 | .43 | 1.07 | .46 | 9.97** | 1/26 | .277 |
| Mode Switch time (S) | 1.61 | .43 | 1.00 | .46 | 13.2*** | 1/26 | .337 |

*p < 0.05, **p < 0.01, ***p < 0.001

From Table 2, we noticed a significant main effect of travel device on **completion time**. Gamepad was significantly faster than ForcePad: $F(1, 26) = 33.74$, $p<.001$, $\eta^2_p = .96$. There was a significant interaction effect of *travel interface* x *travel mode*: $F(2, 25) = 4.7$, $p=.02$, $\eta^2_p = .27$. While Gamepad was significantly faster than ForcePad in all three travel modes, the difference was more in the case of Segway than other modes (see Figure 13).

We also noticed a significant main effect of Session on completion time: $F(1, 26)=21.9$, $p<.001$, $\eta^2_p = .45$. Indicating a learning effect, the second session was faster than the first session. This improvement was more noticeable in the case of the ForcePad than the Gamepad. This effect is understandable as the ForcePad was a new device for the participants to use and they had more to learn with this device.

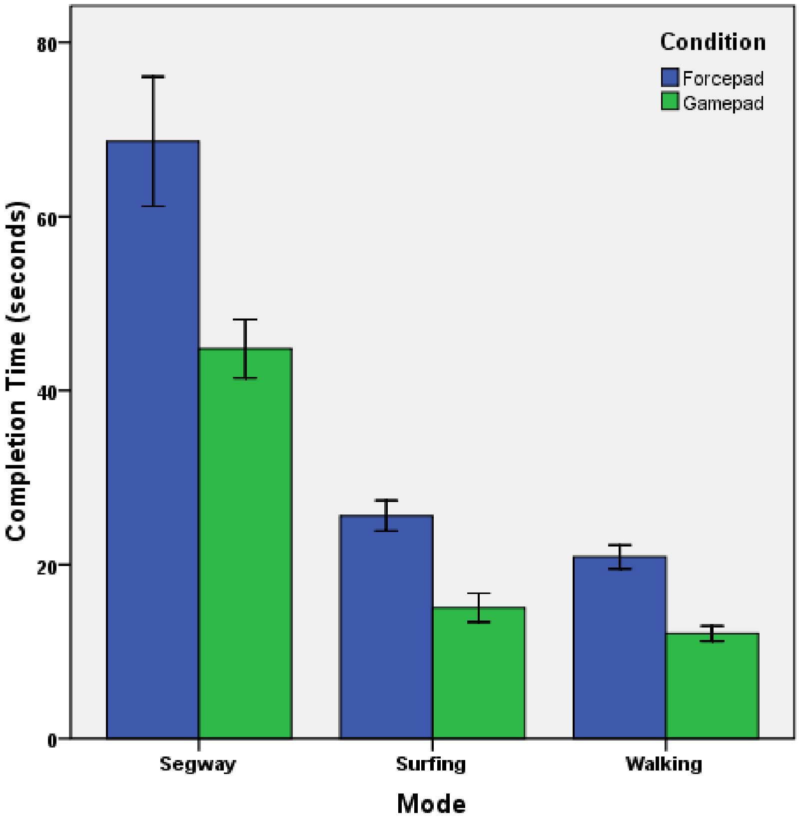


*Figure 13: In terms of task completion time, the Gamepad was significantly faster than the ForcePad and this difference was more for the Segway travel mode*

Participants using the Gamepad had significantly less **walking path deviation** (M = 6.67, SD = .63) than those using the ForcePad (M = 7.55, SD = 1.07): F(1, 25) = 6.739, p = .016, $\eta^2_p$ = .212. Regarding learning effects, there was no significant main effect of *session*. However, we noticed there was a significant interaction effect between *session* and *travel interface*: F(1, 25) = 7.35, p = .012, $\eta^2_p$ = .227. Participants in the control group performed better while those in the experiment group perform worse in second session.

During the experiment, we observed several users go back and forth at intersections of the maze in the Segway tasks. The behavior might be another indicator of how well participants could control their interaction with one of the control devices. We extracted velocity information from the raw data we collected to count the number of overshoots during Segway trials. The results show that participants in the experiment group were significantly less likely to overshoot during Segway sessions (M = .196, SD = .241) than the control group (M = .742, SD = .355): F(1, 24) = 21.44, p < .001 and $\eta^2_p$ = .472. The units were the average number of overshoots at each intersection. Other than the control device, all the within-subject factors including difficulty level and Session, and covariates including gaming experience and ability to solving maze puzzles were not significant.

At the beginning of each trial, we showed red text in the center of the screen to tell participants to user finger gestures or to press a button to use walking/Segway/surfing mode. We collected the time from when the system showed the text until participants gave the correct response. We believe this could be one measurement for how well participants could remember the activation of each travel mode for the two control devices. From the result, we noticed that participants using the multi-touch multi-mode travel interface responded to the mode switch instruction significantly faster in walking and Segway trials.

Besides the performance results, we also observe some interesting behaviors participants had during the study. We extracted the direction each participant was facing at each frame in walking trials and counted the number of frames they kept in the same direction. After comparing the dominant direction of both groups, we found that participants in the control group spent more time in the same direction (M = .323, SD = .170), while those in the experiment group spent a lesser portion of time in their dominant direction (M = .178, SD = .021). The unit of the measurement is the number of frames the participant was oriented in a certain direction (within -5 to 5 degrees) divided by the total number of frames for each trial. The effect is significant with F(1, 26) = 10.201, p = .004, $\eta^2_p$ = .282. The top two participants in the whole study (both from the control group) spent over 70% of the time in the dominant direction. The results are illustrated in Figure 14. In Figure 14a each heat ring is the average direction distribution from the six walking trials done by the same participant (redder is higher), which represents the distribution of directions each participant was facing. In a) each heat ring is the average direction distribution from the six walking trials done by the same participant (redder is higher). The rings are sorted based on the dominant direction. From left to right, the time spent in the direction increases (more red than yellow). The second row of each group is higher than the first row. In Figure 14b the max and mean are used to compare between two groups. Dots in the black boxes indicate the dominant direction.

Another interesting behavior we observed in the Segway trials was that some participants kept zigzagging during travel. We then extracted the data from all the Segway trials of every participant by averaging the absolute rotation speed at each frame. After analyzing it using a mixed ANOVA, we found that participants in the control group (M = .0347, SD = .005) zigzagged more than those in the experiment group (M = .0181, SD = .006). The units are the average angular speed in each Segway trial. The result was significant with F(1, 25) = 72.164, $p < .001$, $\eta^2_p = .743$. The main effect of Session, which indicates a learning effect, is also significant, with F(1, 25) =9.771, $p = .004$, $\eta^2_p = .281$. However, there is no significant interaction effect between Session and Control Device

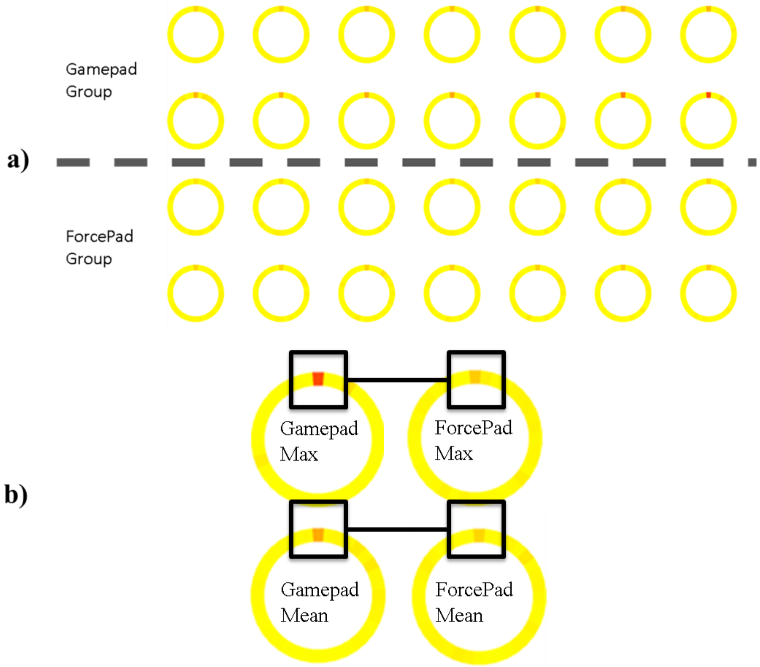


*Figure 14. Distribution of directions each participant was facing.*

#### 4.2.6.2 Subjective Results

We ran Mann-Whitney U tests to analyze the differences between the two travel devices as rated by the participants through the post-questionnaire. Surprisingly, we did not find any significant differences between the two travel devices (see Table 3). Hence, our first hypothesis was refuted. The ratings from the NASA TLX were analyzed using a one-way ANOVA for all questions (see Table 4). In the analysis of the NASA TLX, we noticed that, while other questions have no significant results, participants using the Gamepad had significantly less frustration than participants using the ForcePad: F(1, 26) = 128.571, p = .013, $\eta^2_p$ = .215.

*Table 3: The result of the post-questionnaire data analysis*

| | | Overall | | Walking | | Segway | | Surfing | |
|---|---|---|---|---|---|---|---|---|---|
| | | Ctrl. | Exp. | Ctrl. | Exp. | Ctrl. | Exp. | Ctrl. | Exp. |
| Realism | Mean | 3.8 | 3.4 | - | - | - | - | - | - |
| | SD | 1.1 | 1.4 | - | - | - | - | - | - |
| Presence | Mean | 3.5 | 3.6 | 2.5 | 2.7 | 3.2 | 3.9 | 3 | 3 |
| | SD | 1.2 | .93 | 1.2 | 1.1 | 1.4 | .95 | 1.3 | 1.2 |
| Ease of Use | Mean | 4.1 | 3.9 | 4.5 | 4.7 | 3.9 | 4.0 | 3.0 | 2.6 |
| | SD | .86 | .77 | 1.5 | .73 | 1.1 | 1.6 | 1.1 | .93 |
| Fun | Mean | 3.8 | 4.1 | 3.9 | 3.6 | 3.9 | 4.5 | 3.4 | 3.3 |
| | SD | 1.1 | 1.2 | .83 | 1.2 | 1.0 | 1.4 | 1.2 | 1.1 |
| Ease of Memory | Mean | 4.9 | 5.2 | - | - | - | - | - | - |
| | SD | 1.2 | .80 | - | - | - | - | - | - |

*Table 4: Result of the NASA TLX data analysis*

| Question | Control group | | Experiment group | | p-value |
|---|---|---|---|---|---|
| | Mean | SD | Mean | SD | |
| Mental Demand | 8.38 | 3.731 | 9.93 | 3.97 | 0.309 |
| Physical Demand | 2.57 | 2.138 | 4.14 | 4.167 | 0.220 |
| Temporal Demand | 8.93 | 3.496 | 8.36 | 4.413 | 0.707 |
| Performance | 8.07 | 4.463 | 8.0 | 4.332 | 0.966 |
| Effort | 9.43 | 3.413 | 10.86 | 4.605 | 0.360 |
| Frustration | **4.71** | **4.122** | **9.00** | **4.368** | **0.013** |

### 4.2.7 Discussion

Surprisingly, the subjective results refute **H1**. There is no significant difference between the two travel interfaces in participants' mind regarding presence, ease of use, or fun. However, the data from the NASA TLX questionnaire shows that the multi-touch, gesture-based interface is harder to interact with. Combining the results we got from informal interviews after the study, four out of 14 participants from the experiment group complained about the limited workspace; it was very easy to touch places outside the pad. And seven of 14 participants in the experiment group, but only four of 14 participants in the control group complained about surfing mode being too hard. As one of the participants explained, when he would like to lift the surfing board and increase the pressure of one finger, it started to turn left or right. This behavior is caused by the physical structure of our hands. It is neither symmetric nor rigid. Whenever the pressure changes, the touch point will shift as well. This brought frustration in surfing tasks for participants using the multi-touch, gesture-based interface.

The analysis of performance data shows that the Gamepad device, which has a more abstract design, is more efficient in time. The result is similar to the work of McMahan et al. [25], who hypothesized that natural interfaces might have more muscle groups involved and the system has more latency than the non-natural, or more abstract interfaces. In our case, though the multi-touch, gesture-based interface is very close to the Gamepad interface, there is still much more hand and finger motion involved than just moving both thumbs. Additionally, the gesture classification step brings additional latency to the system because we need a buffer of 10 recent frames to remove mode switch noise in order to improve recognition. This latency might be another reason for the poorer performance of multi-touch multi-mode travel interface compared to the Gamepad multi-mode interface.

Although Gamepad multi-mode interfaces are more efficient in time, we found that multi-touch multi-mode interfaces performed better in some of the measurements. In the Segway trials, we found participants in the control group often overshot at intersections and also kept zigzagging during the travel because the joystick on the Gamepad was either too unresponsive or too sensitive. Three participants from the experiment group said that operation, especially changing velocity, is very smooth in Segway mode, while no one in the control group especially liked Segway mode. The result indicates that multi-touch, gesture-based interfaces can be used for tasks needing subtle and precise operation. Compared to the joystick, although the two devices could both provide passive haptic feedback, the ForcePad had a larger workspace within which to map velocity.

The measurement of mode-switch time partially supports our hypothesis **H2**, which is about how well participants could remember how to switch. From the data analysis, we could see that participants using the multi-touch multi-mode interface responded to the mode switch instruction significantly faster in walking trials. However, participant response to surfing mode switch did not have significant differences. One of the reasons could be the extra latency the multi-touch, gesture-based interface caused due to gesture classification.

Another possible explanation is that there are not enough cues about the location of the ForcePad in the real world. The ForcePad was not bound to the user’s leg or arm due to its heavy housing. Instead, it was placed on a wooden board on the chair. Thus, the lack of proprioception might lead to an unexpected touch point. Walking trials were not affected because walking could be triggered once participants put a single finger anywhere on the ForcePad. However, for Segway and surfing mode, which required fairly precise two-finger touches to trigger them, once the fingers left the ForcePad, participants had to test the relative position of finger and ForcePad and then adjust their finger to the right position. To decrease the demand of looking for the control device, especially in immersive environments, proprioception should be use as much as possible, and additional passive haptic feedback could be helpful on locating the control devices.

During our study, two of 32 people (one in the control group, one in the experiment group) dropped out because of dizziness; two in the experiment group had encountered equipment failure, the HMD kept dropping from their head due to a loose strap. After watching recorded video of two participants, we found that they kept moving their heads in the direction of the ForcePad to locate the device. While they were doing that, as the strap was loose, the HMD then slipped on their head.

## 4.3 Experiment 2

In this experiment, we focus on comparing single mode with multi-mode travel interface, as well as exploring the timing of mode switching in a more complex environment. In Experiment 1 (Section 4.2), as we show in Figure 14, participants in the experiment group only chose to turn and then go forward if the target was not right in front. From the interview, with 14 participants in the experiment group. Four of them reported that walking and turning at the same time was hard; two reported that turning requires too much pressure. So, in the follow-up experiment, we used an updated version of walking travel interface for the ForcePad which was mentioned in Section 3.2. The three travel interfaces used in this experiment are the Gamepad multi-mode travel interface which only had the walking and Segway mode, the multi-touch multi-mode travel interface which also excluded surfing mode as there were no flying tasks, and the Gamepad single mode travel interface.

### 4.3.1 Experimental Design

We used the Unity 3D game engine to develop our virtual world (See Figure 15). There were two types of environments in the virtual world. One of them was a dynamic maze (see Figure 16). The two walls (inside the red box) could be set to transparent to provide shortcuts. This type of environment required more precise movement and more rotation operations. The other environment had long lanes connecting mazes (See Figure 17) which implied faster movement.

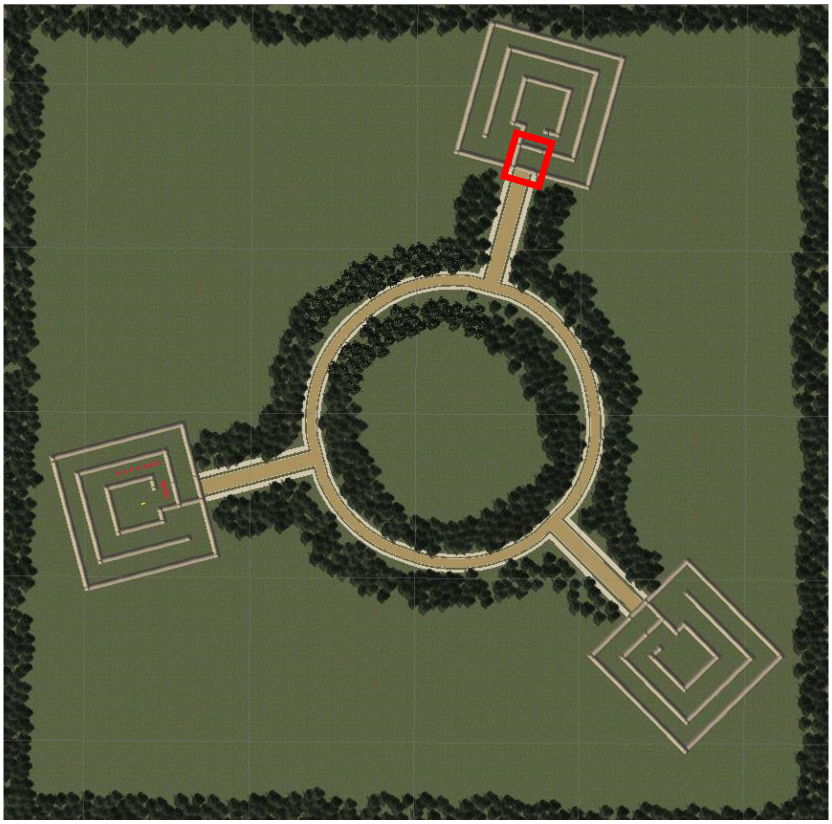


*Figure 15: Top-down view of our virtual environment.*

In this experiment, besides the yellow arrow as in the previous experiment, we also showed the user some red dots as way points to guide them the direction; especially in the dynamic maze in which the yellow arrow might be ambiguous. We also had the same widget for trials using the multi-touch multi-mode travel interface as in the previous experiment.

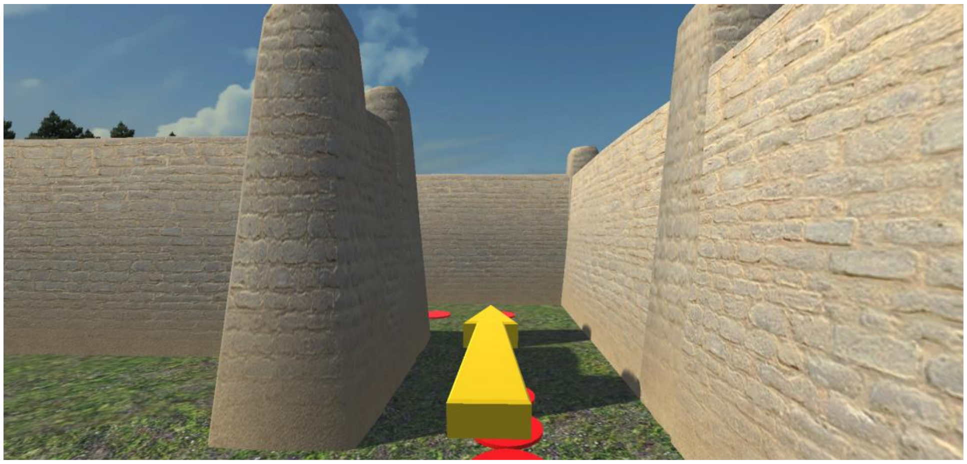


*Figure 16: maze-like virtual environment.*

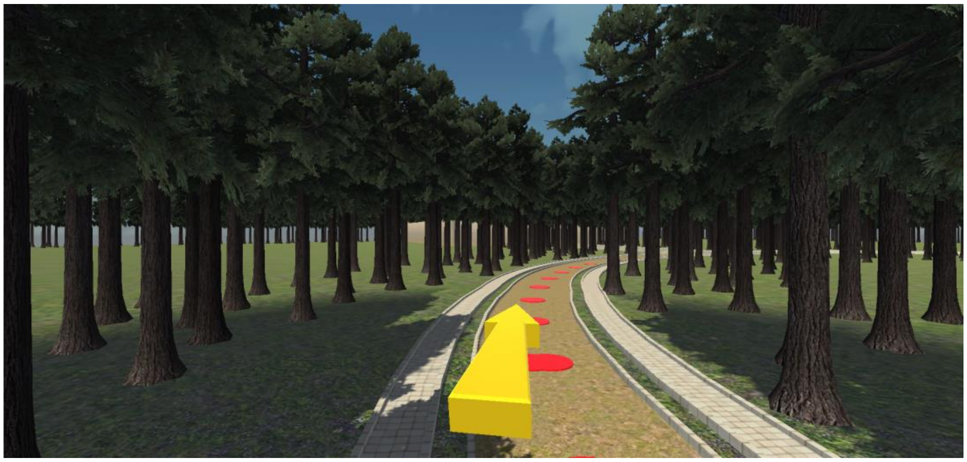
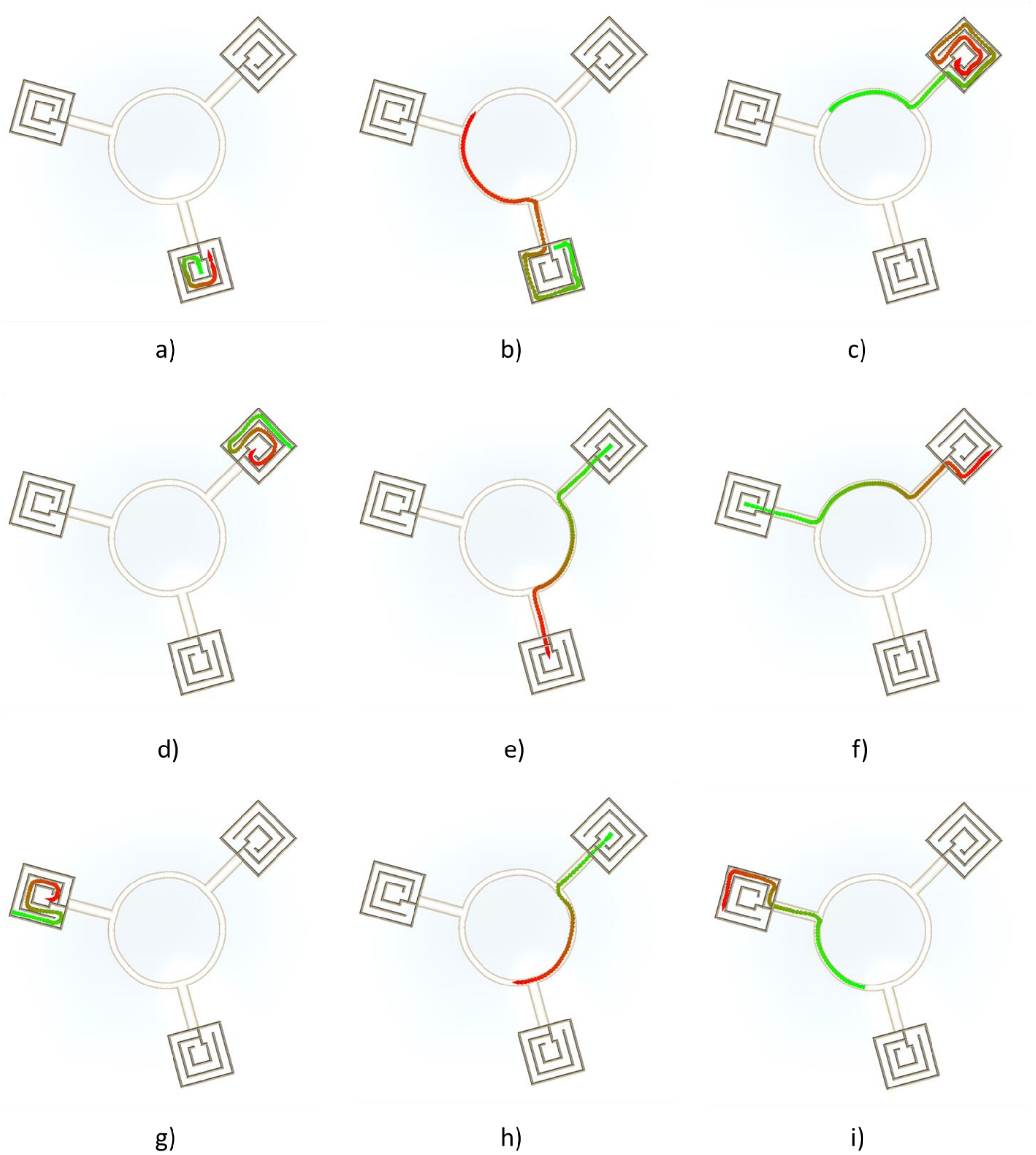


*Figure 17: lane-like virtual environment.*

### 4.3.2 Task Design

We designed three different types of tasks for the experiment. The first type of task was travelling in the maze, such as (a), (d) and (g) in Figure 18. There were 5 to 7 corners along the path which required the user to turn 90 degree angle smoothly. The paths in the second type of task only had long lanes, such as (b), (e) and (h) in Figure 18. There were very few sharp turns in this task. However, participants were supposed to finish the task in a relatively higher speed. The last type of task was the hybrid version of previous two, such as (c), (f) and (i) in Figure 18. The 9 paths could be grouped in 3 groups. The 3 paths in each row of Figure 18 is a complete trip from the center of one maze to the center of another maze. We ran a within-subject study that each participant could try all the three travel interfaces in 3 different groups of paths. Then we used a 9x9 Latin square to counterbalance the trials and minimize learning effects.



a) b) c)

d) e) f)

g) h) i)

*Figure 18: Nine paths used in the experiment. Each path starts with green triangles and ends with red triangles.*

### 4.3.3 Experiment Procedure

In our second study, the first thing a participant was asked to do was to read the consent form and completed the pre-test questionnaire about demographic questions. Then they did a Guilford Zimmerman Orientation Survey [24] as a pre-test of their spatial ability.

After all the pre-test is done, each participant tries 9 trials (3 sessions x 3 travel interfaces). In each session, at the beginning, we explain the travel interface they will use by showing them training slides. Then there are 4 training trials. Two of them are travelling in the maze, and the other two are travelling through the long lane. If a participant could not finish a training trial within 2 min and less than 10 collisions with the wall or forest, he or she then has to do the same training trail again. With this setup, we could assume participants have a minimum level of proficiency and understanding of the travel interfaces. In the following 9 formal trials, participants are required to complete the task as soon as possible while having fewer collisions with the obstacles in the environment. After each trial, we also ask the user to estimate the distance they have traveled to measure their spatial awareness. The order of the travel interfaces and paths are retrieved from a 9x9 Latin square by participants' ID from 0 to 8.

A total of 10 participants (8 male) took part in the second experiment, while one of them felt dizzy and quit very early. Their ages ranged from 18 to 21 years (M = 19.89, SD = 1.364). Their gaming experience ranged from 1 (not frequently) to 6 (frequently) with M = 2.78 and SD = 1.394. In the Guilford Zimmerman Orientation Survey, their score range from 5 to 40 (M = 16.13 and SD = 11.529).

### 4.3.4 Measures

#### 4.3.4.1 Objective Measures

In order to measure user performance, the following dependent variables were defined,

- **Completion Time**: time to complete each trial.
- **Number of Collisions**: number of collisions with obstacles in the maze.
- **Consistency of Distance Estimation**: the correlation between the users' estimated distance and the distance they actually traveled.

#### 4.3.4.2 Subjective Measures

We also collected subjective data to measure user experience. There was one questionnaire rating after participants finished all the trials of one travel interface, which asked about the sense of presence and movement, etc.

As shown in Table 5, Q1-3 measured the sense of realism and presence, Q4 measured ease-of-use, Q5 measured user preference. Comments and a top-three ranking of the conditions were also collected at the end of the experiment. We also collected data from the NASA TLX scale form as for the previous experiment.

*Table 5: subjective measurements and questions in post-test questionnaire*

| **Question Number** | **Subjective Measure** | **Question (range: 1-6)** |
|---|---|---|
| 1 | Realism | How close did the virtual world resemble the real world? |
| 2 | Realism | To what extent were there times during the experience when the virtual world became the "reality" for you, and you almost forgot about the "real world" outside? |
| 3 | Presence | To what extent did you experience the sense of "being there" while you were travelling in the VE, as opposed to being a spectator? |
| 4 | Ease-of-use | How easy was it to use the system? |
| 5 | Fun | How much did you enjoy interacting with the system? |

### 4.3.5 Results

#### 4.3.5.1 Objective Data

As this study is a within-subject study, we used repeated measure ANOVAs with travel interfaces as an independent variable. From the analysis, we found that there are no significant differences between travel interfaces regarding completion time ($F(2, 16) = .271$, $p = .766$, $\eta^2_p = .033$). And it is also the case for number of collisions which has $F(2, 16) = 1.675$, $p = .218$ and $\eta^2_p = .173$. The descriptive data can be found in Table 6 and Table 7.

*Table 6: Descriptive statistics of completion time (in seconds)*

| | Maze Only | | Lane Only | | Hybrid | |
|---|---|---|---|---|---|---|
| | M | SD | M | SD | M | SD |
| Gamepad single-mode | 819.71 | 203.51 | 823.48 | 203.59 | 833.59 | 204.97 |
| Multi-touch multi-mode | 824.66 | 139.18 | 827.5 | 139.63 | 834.89 | 138.5 |
| Gamepad single mode | 659.34 | 202.21 | 663.05 | 200.74 | 674.94 | 201.05 |

*Table 7: Descriptive statistics of number of collision*

| | Maze Only | | Lane Only | | Hybrid | |
|---|---|---|---|---|---|---|
| | M | SD | M | SD | M | SD |
| Gamepad single-mode | 1.26 | .384 | 2 | .904 | 3.22 | 1.21 |
| Multi-touch multi-mode | 2.11 | .7 | 2.63 | 1.08 | 3.15 | 1.36 |
| Gamepad single mode | 1.48 | .64 | 2.04 | .89 | 2.37 | .96 |

We also asked participants to estimate the distance they traveled after they finished each trial. At the same time, we collected the actual distance they traveled. Then we computed the correlation between the estimated distance and the actual distance to see whether multi-mode could improve participants' spatial awareness. The results could be found in Table 8. If the correlation is closer to 1 and p value is closer to 0, the distance estimation would be more consistent, which represents high level of spatial awareness of the user during the study. We also apply a one-way MANOVA to analysis the effect of the spatial ability score from Guilford Zimmerman Orientation Survey. However, the result was not significant with $F(3, 4) = 1.444$, $p = .355$ and $\eta^2_p = .520$.

*Table 8: Correlations between estimated distance and actual distance*

| | Gamepad multi-mode | | Multi-touch multi-mode | | Gamepad single mode | |
|---|---|---|---|---|---|---|
| | Corr. | Sig. | Corr. | Sig. | Corr. | Sig. |
| Subject 0 | .386 | .305 | .562 | .116 | .594 | .092* |
| Subject 1 | .393 | .296 | .657 | .054* | .230 | .551 |
| Subject 2 | .032 | .935 | .049 | .901 | .367 | .332 |
| Subject 3 | .276 | .472 | .470 | .202 | .243 | .529 |
| Subject 4 | .415 | .267 | .628 | .070* | .686 | .041** |
| Subject 5 | .324 | .395 | .266 | .490 | .380 | .313 |
| Subject 6 | .145 | .710 | .193 | .620 | .423 | .257 |
| Subject 7 | .239 | .536 | .458 | .215 | .153 | .694 |
| Subject 8 | .768 | .016** | .722 | .028** | .246 | .523 |

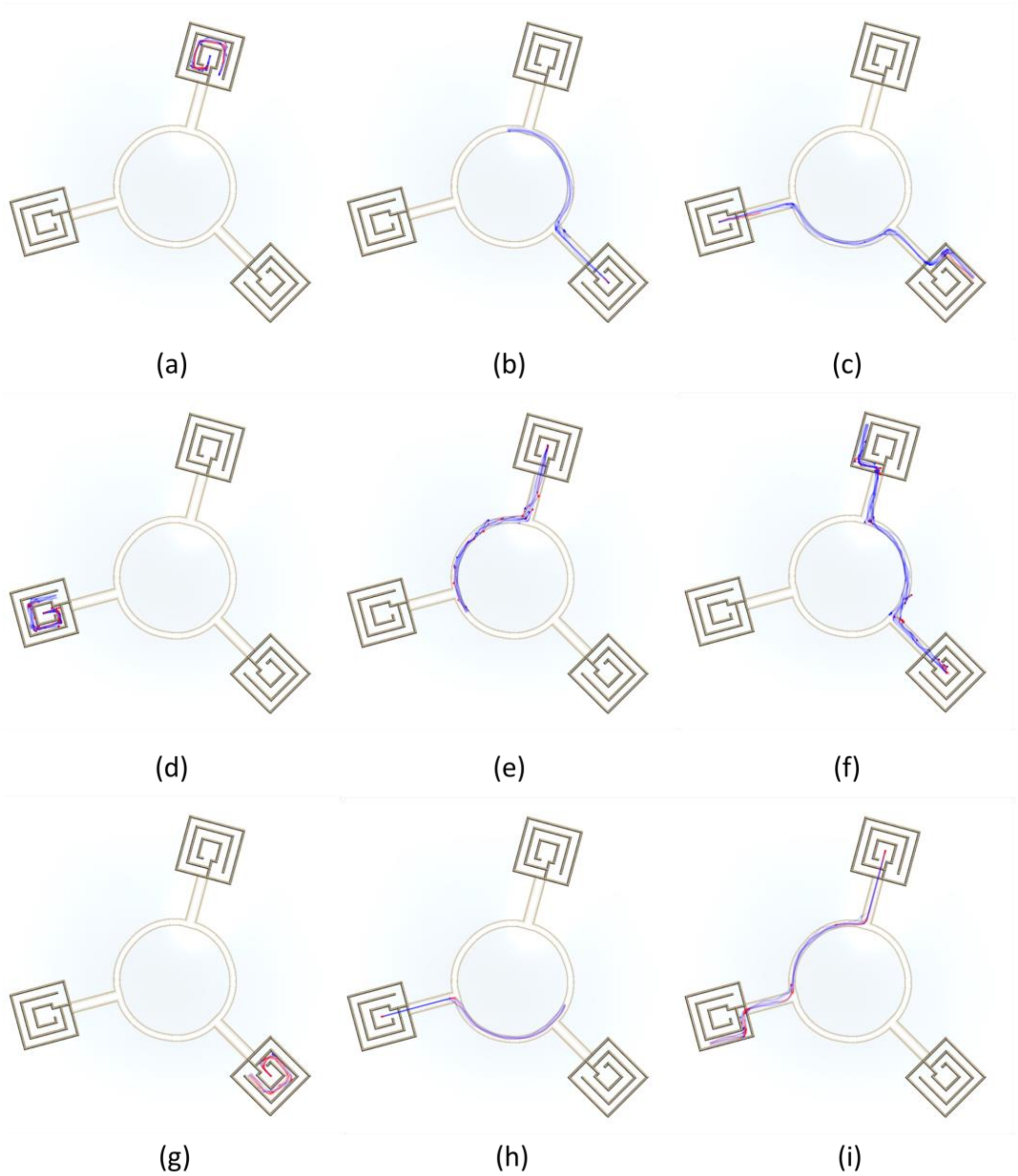


*Figure 19: Path visualization. Three rows represent three different travel interfaces. Three columns represent three different types of environments. (a), (b) and (c) are generated by Gamepad multi-mode travel interface; (d), (e) and (f) are generated by multi-touch multi-mode travel interface; (g), (h) and (i) are generated by Gamepad single mode travel interface. For the columns, (a), (d) and (g) are maze-only paths; (b), (e) and (h) are long lane only paths; (c), (f) and (i) are hybrid paths.*

We visualized the paths participants traveled during the second study. For each map, we rendered all the paths that every user traveled using the same travel interface on the same canvas with transparency 0.1 to combine them together. The results are shown in Figure 19. When the participants traveled in low speed mode or with lower maximum speed, the color of the paths are rendered in red. When participants traveled in high speed mode or with higher maximum speed, the paths are rendered in blue. From the blended paths, we could see some interesting user behavior which will be explained in Section 4.3.6.

#### 4.3.5.2 Subjective Data

We ran a Kruskal-Wallis H test on our post-test questionnaire data. The result showed that there were significant differences in ease-of-use between different travel metaphors, $\chi^2(2) = 10.694$ and $p = 0.005$, with a mean rank score 14.22 for Gamepad multi-mode travel interface, 7.94 for multi-touch multi-mode travel interface and 19.83 for Gamepad single mode travel interface.

Then we ran a repeated measure ANOVA on NASA TLX Scale data. From the analysis, participants reports significantly higher mental demand (pairwise p = .033 between multi-touch multi-mode and Gamepad multi-mode travel interface, and p = .006 between multi-touch multi-mode and Gamepad single mode travel interface) while using multi-touch multi-mode travel interface. The other two gamepad based travel interface did not show significant difference regarding mental demand. The descriptive statistics results were shown in Figure 20.

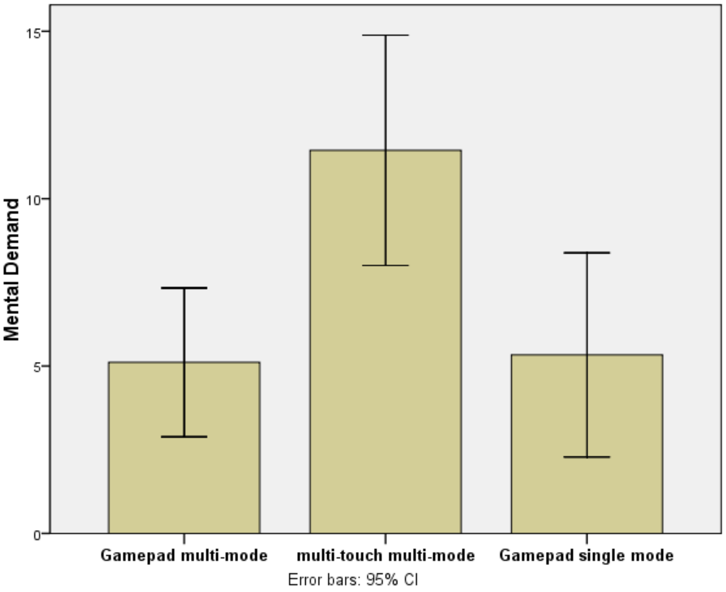


*Figure 20: Descriptive statistics of self-assessed mental demand*

Participants also reported the effort of using multi-touch multi-mode travel interface significantly higher than Gamepad single mode travel interface with pairwise p = .008. And the results also showed a strong trend that while using multi-touch multi-mode travel interface, users made more effort than Gamepad multi-mode travel interface (pairwise p = .069). Then descriptive statistics results of self-assessed effort were showed in Figure 21. There are no significant differences between three travel interfaces regarding other measures.

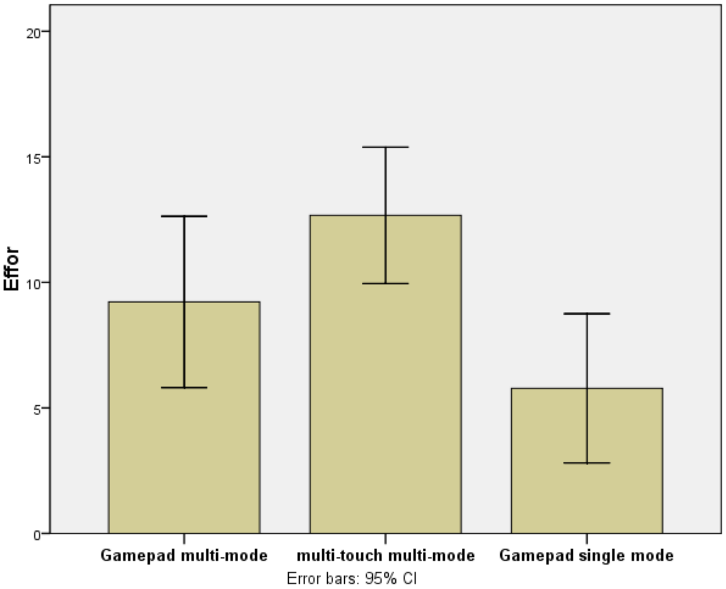


*Figure 21: Descriptive statistics of self-assessed effort*

### 4.3.6 Discussion

By analyzing the subjective data collected from this experiment, we found that participants had significant higher mental demand and effort regarding the multi-touch multi-mode travel interface. However, in our objective data analysis, we found that there were no significant differences between the three travel interfaces. This suggests that the multi-touch multi-mode travel interface would be an alternative device of gamepad with similar level of performance, presence and fun. However, it requires more effort to learn the interface as it is a brand new travel interface comparing to interfaces using Gamepad.

In terms of H3, we did not find any interesting phenomenon from the correlation between user estimated distance and actual distance. Most of the participants cound not estimate the traveled distance in a relatively consistent manner. There might be several reasons. The first reason might be because our experiment is not a fully immersive environment. The other reason might be the lack of other cues, such as sound cue and vestibular cue, to assist speed and orientation status estimation.

From Figure 19, we could see the path segments inside mazes are mostly red, especially around 90 degree corners, while those on the long lanes are mostly blue. It indicates that participants prefer low speed mode when they encounter sharp turns. Even when they were using gamepad single mode travel interface, their operations followed a binary pattern which were either full speed or low speed, although the R2 button could provide continuous value. It might suggest that multi-mode might be a better choice than a single mode with continuous maximum speed if the travel modes are well designed. If we included surfing mode, which could support flying, with the walking and Segway modes, it would be even harder to design a good single-mode travel interface to support both efficient ground travel and flying experience.

# 5 Conclusion

In this thesis, we present a multi-touch, gesture-based travel interface for VEs adopting a unified approach where multiple travel modes can be achieved seamlessly using a ForcePad device. We have compared this technique with a commonly used two Gamepad travel interfaces (multi-mode and single mode).

Our results were encouraging, showing that our multi-touch, gesture-based interface was qualitatively rated similar to the commonly used Gamepad based travel interfaces. Although we noticed participants reported higher mental demand and frustration using our multi-touch multi-mode travel interface, it is understandable that learning and using a new technique in a short amount of time may lead to more mental load causing frustration. From the Experiment 1 result analysis, we could see that user could remember mode switch gestures better when they are using our multi-touch multi-mode interface. That means, even though using finger gestures might not improve the sense of presence and enjoyment, it could help people build mental model of the travel interface easier. Additionally in the second experiment, the results showed that even when participants were using single mode Gamepad based interface, they tended to use only the slowest and fastest mode which might suggest that multi-mode travel interface could be a good choice if the transition between modes are smooth and intuitive.

We would like to improve the finger-based interactions in the future, and with better touch and pressure sensitivity of the hardware, we believe we can significantly improve the usability of this type of travel metaphor. It will be interesting to integrate other interactions, such as shooting, together with travel in a use case and evaluate how users can manage multiple tasks through this interaction method. We believe this work provides innovative design ideas for interactions with virtual environments.

# References

[1] D. A. Bowman, E. Kruijff, J. J. LaViola, and I. Poupyrev. *3D User Interfaces: Theory and Practice*. Addison, 2004.

[2] M. Slater, M. Usoh, and A. Steed. Taking steps: The influence of a walking technique on presence in virtual reality. *ACM Trans. Comput.-Hum. Interact.*, 2(3):201–219, Sept. 1995.

[3] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks, Jr. Walking > walking-in-place > flying, in virtual environments. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '99, pp. 359–364, New E. Catmull.

[4] H. Iwata, H. Yano, H. Fukushima, and H. Noma. CirculaFloor: A Locomotion Interface Using Circulation of Movable Tiles. In Proceedings of IEEE Virtual Reality Conference'05, Bonn, Germany, pp. 223–230, 2005.

[5] H. Iwata, H. Yano, and F. Nakaizumi. Gait master: A Versatile Locomotion Interface for Uneven Virtual Terrain. In *Proceedings of IEEE Virtual Reality Conference'01*, Yokohama, Japan, pp. 131–137, 2001.

[6] H. Iwata and Y. Yoshida. Path Reproduction Tests Using a Torus Treadmill. *Presence: Tele-operators and Virtual Environments*, vol. 8(6), pp. 587–597, 1999.

[7] S. Razzaque, Z. Kohn, and M. C. Whitton. Redirected walking. *In Proceedings of Eurographics*, pp. 289–294, 2001.

[8] F. Steinicke, G. Bruder, T. Ropinski, and K. Hinrichs. Moving towards generally applicable redirected walking. In *Proceedings of the Virtual Reality International Conference (VRIC)*, pp. 15–24, 2008.

[9] S. Beckhaus, K. J. Blom, and M. Haringer. ChairIO – the Chair-Based Interface. Ed. Magerkurth und Rotzler, *Shaker Verlag*, 2007.

[10] J. Wang and R. W. Lindeman. Leaning-based Travel Interfaces Revisited: Frontal Versus Sidewise Stances for Flying in 3D Virtual Spaces. *Proc. of ACM Symposium on Virtual Reality Software and Technology (VRST) 2012*, pp. 121-128.

[11] P.R.M Denne. The PemRam – an Electromagnetic Linear Actuator. *IEEE Colloquium on Actuator Technology: Current Practice and New Developments*, London, UK, 1996.

[12] D. Valkov, F. Steinicke, G. Bruder, and K. H. Hinrichs. Traveling in 3D Virtual Environments with Foot Gestures and a Multi-Touch enabled WIM. In *Proceedings of IEEE Virtual Reality Conference'10*, Waltham, MA, USA, pp. 171–180, 2010.

[13] M. Marchal, J. Pettré, and A. Lécuyer. Joyman: a Human-Scale Joystick for Navigating in Virtual Worlds. In *Proceedings of IEEE Symposium on 3D User Interfaces'11*, Singapore, pp. 19-26, 2011.

[14] J. Wang and R. W. Lindeman. Comparing isometric and elastic surfboard interfaces for leaning-based travel in 3d virtual environments. In *3D User Interfaces (3DUI)*, pp. 31–38. IEEE, 2012.

[15] J. Kim, D. Gračanin, K. Matković, and F. Quek. Finger walking in place (FWIP): A traveling technique in virtual environments. In *Smart Graphics*, pp. 58–69. Springer, 2008.

[16] J. Kim, D. Gračanin, K. Matković, and F. Quek. IPhone/iPod touch as input devices for navigation in immersive virtual environments. In *Virtual Reality Conference'09*, pp. 261–262. IEEE, 2009.

[17] J. Wang and R. W. Lindeman. ForceExtension: Extending isotonic position-controlled multi-touch gestures with rate-controlled force

sensing for 3d manipulation. In *Symposium on 3D User Interfaces'13*, pp. 3–6. IEEE, 2013.

[18] M.R. Mine, F.P. Brooks Jr, and H.S. Carlo. Moving objects in space: exploiting proprioception in virtual-environment interaction. In *Proceedings of the 24th annual conference on Computer graphics and interactive techniques*, pp. 19–26. ACM Press/Addison-Wesley Publishing Co., 1997

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

[20] M. Kaltenbrunner, T. Bovermann, R. Bencina, and E. Costanza. Tuio: A protocol for table-top tangible user interfaces. In *Proc. of the The 6th Intl. Workshop on Gesture in Human-Computer Interaction and Simulation*, pages 1–5, 2005.

[21] A. Benzina, A. Dey, M. Tonnis, and G. Klinker, Gudrun. Empirical evaluation of mapping functions for navigation in virtual reality using phones with integrated sensors. In *Proceedings of the 10th Asia Pacific Conference on Computer Human Interaction*, pages 149-158. 2012

[22] R. Balakrishnan, and I.S. MacKenzie. Performance differences in the fingers, wrist, and forearm in computer input control. In *Proceedings of the ACM SIGCHI Conference on Human factors in computing systems*, pp. 303-310. ACM, 1997.

[23] S. Zhai. Human performance in six degree of freedom input control. *PhD diss., University of Toronto*, 1995.

[24] M. Kyritsis, S. Gulliver. Guilford Zimmerman Orientation Survey: A Validation, *ICICS*, 2009.

[25] R. P. McMahan, A. J. D. Alon, S. Lazem, R. J. Beaton, D. Machaj, M. Schaefer, M. G. Silva, A. Leal, R. Hagan, and D. Bowman. Evaluating

natural interaction techniques in video games. *Proc. of the 2010 3D User Interfaces (3DUI) Symp.*, pp. 11-14.