The Effects of Finger-Walking in Place (FWIP) for Spatial Knowledge Acquisition in Virtual Environments

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Abstract. Virtual environments (VEs) can be used to study issues related to human navigation, such as spatial knowledge acquisition. In our prior work, we introduced a new locomotion technique (LT), named "Finger-Walking-in-Place (FWIP)", for navigation tasks in immersive virtual environments (IVEs). The FWIP was designed to map human's embodied ability for real navigation to finger-based LT. A two-hand based implementation on a multi-touch device (i.e., Lemur) was evaluated. In this paper, we introduce the one-handed FWIP refined from the original design, and its implementation on a Lemur and an iPhone/iPod Touch. We present a comparative study of FWIP versus the joystick's flying LT to investigate the effect of the mapping of the human's embodied ability to the finger-based LT on spatial knowledge acquisition. This study results show that FWIP allows the subjects to replicate the route more accurately, compared to the joystick LT. There is no significant difference in survey knowledge acquisition between two LTs. However, the results are useful, especially given that the FWIP requires small physical movements, compared to walking-like physical LTs, and has positive effect on route knowledge acquisition, compared to the joystick LT.

1 Introduction

Interaction techniques for navigation in virtual environments (VEs) are called "locomotion techniques" or "traveling techniques". Since our study is focused on the user's action/activity (i.e., locomotion in VEs), rather than the task (i.e., traveling in VEs), we use the term "locomotion techniques". LTs can be divided into natural LTs and abstract LTs based on the mapping method between users' input actions and locomotion control in VEs although there are several classifications of LTs.

Natural LTs are usually designed by directly using natural locomotion methods with least modification as much as possible. Examples include walking-like physical LTs and simulator-based LTs.

Abstract LTs are designed by mapping users' input actions abstractly to locomotion (output) in VEs. For example, when you want to move forward in VEs, an abstract LT can be designed by mapping the action, "pressing a button", to the "moving forward"

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control. Abstract LTs are usually realized with a keyboard or mouse for desktop VEs, or a joystick/wand device for immersive VEs (IVEs). A flying interaction technique with a joystick [3] is a type of abstract LTs, and commonly used to navigate in IVEs because of its simplicity and familiarity. Compared to natural LTs, most abstract LTs can be quickly designed and evaluated for a desired VE. In addition, there is much less body fatigue.

Walking-like physical LTs are a type of natural LTs, which are generally believed to support more accurate spatial knowledge acquisition by allowing users to use body-based senses (e.g., proprioception and vestibular cue) [15,20] with little or no cognitive mapping from the user. Walking in place (WIP) is a close match to the natural walking metaphor. There are various systems and interaction schemes to provide WIP-like LTs, e.g. WIP [17,18], the extensions (e.g., "Seven League Boots" [8]) and the use of treadmills [4,10]. These studies reported that users experienced higher levels of presence when using WIP. Thus, WIP is well-suited for VEs in which natural locomotion and a high sense of presence are required. However, these walking-like LTs still present several issues in terms of cost and usability [7]. The cheaper, simpler and more convenient LTs (i.e., abstract LTs) are preferred for most VE applications, while walking-like LTs are only used for special purposes,such as realistic training and rehabilitation. Such abstract LTs are often paired with navigation aids such as maps to give the user greater awareness of her spatial orientation in the virtual world [3]. Providing navigation aids requires for designers or researchers to make additional efforts in addition to developing an LT. Using those aids demands for users to spend extra cognitive load in addition to performing an LT.

Walking-like physical LTs are useful for spatial knowledge acquisition because they are based on our embodied resources [5,6] and over-learned body-based sensory and cognitive abilities, which are not available in abstract LTs. Can we leverage these abilities by using an alternative LT, rather than walking-like physical LT, for virtual navigation? To answer the question, we introduced an alternative LT, named "Finger-Walking-in-Place (FWIP)", in our prior work [12].

Finger-based interaction techniques can be realized by using several approaches. A sensing-glove can be used to control animation characters [13]. This approach is more suitable to the cases that need more detailed information from the joints of the hand and fingers. As a different approach, touch-based devices can be used to select and manipulate virtual objects [2]. Even though it is hardly found that touch-based devices are used for navigation in VEs, we chose to implement our FWIP on a multi-touch device [12], by observing how treadmill-supported WIP works.

The implementation of FWIP on a Lemur [11] was evaluated in our previous study [12] that showed the similar action to treadmill-supported WIP, performed by fingers, can be used as robust interaction for virtual locomotion in an IVE (e.g., CAVE [19]). In this paper, we introduce the one-handed FWIP modified from the two-handed FWIP, and describe its implementation on a Lemur and iPhone/iPod Touch devices. We also present a comparative study of the introduced FWIP on a Lemur and an iPhone/iPod Touch versus the joystick LT to investigate whether our abilities learned for real navigation can be transformed to the alternate frame of finger-based LT.

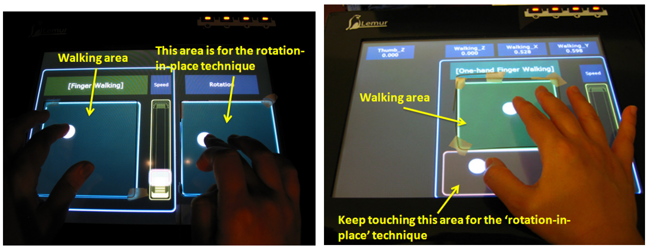
2 Two Locomotion Techniques

2.1 Finger-Walking-in-Place (FWIP) Technique

FWIP enables a user to navigate in a VE by translating and rotating a viewpoint as the user slides unadorned fingers on a multi-touch sensitive surface. In our prior work [12], three different viewpoint-rotation techniques (‘walking’, ‘dragging’ and ‘jog-dialing’) were introduced and separately operated from the viewpoint-translation technique. Since FWIP was designed to be separately operated on a multi-touch surface for viewpoint-translation and viewpoint-rotation, most participants used two hands to rotate and translate the viewpoint. We decided that two-handed operations are unnecessary because each technique for viewpoint-translation and viewpoint-rotation is touch-based. In addition, we observed that some of participants were confused with two separate operations, one assigned to each hand. Hence, we modified our original two-handed FWIP to one-handed FWIP combined with the ‘dragging’ viewpoint-rotation technique. ‘Walking’ and ‘jog-dialing’ techniques for viewpoint-rotation are excluded for one-handed FWIP because it is difficult that these two techniques are operated distinguishably from the ‘walking’ for viewpoint-translation. Figure 1 shows different user interface (UI) designs for two-handed FWIP (Figure 1(a)) and one-handed FWIP (Figure 1(b)) for implementation on the Lemur device.

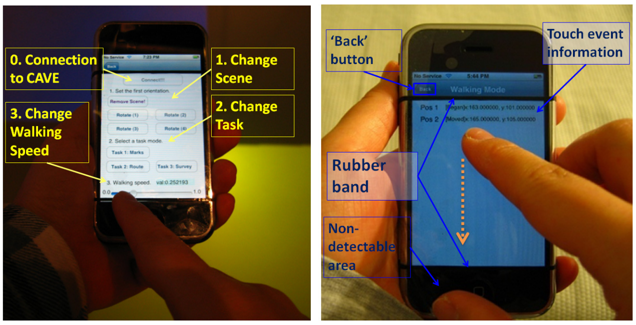
Another implementation of the one-handed FWIP has been tested on iPhone/iPod Touch [1]. The smaller size of the touch-screen was considered to refine the one-handed FWIP by merging the walking area and the touching area (Figure 1(b)). We used two modes for usability tests, the control mode for evaluators and the walking mode for test subjects. Evaluators can control the system setup specific to the experiment (Figure 2(a)). A test subject can perform finger-walking on the multi-touch screen for virtual navigation (Figure 2(b)). In the pilot study, we observed that most subjects accidentally touched the ‘back’ button or touch the non-detectable area while they are walking without looking at the screen. We attached the rubber bands to limit the walking-area on the iPhone screen (Figure 2(b)). Thus, FWIP can be applied to multi-touch devices with different sizes.

Figure 3 illustrates the final design of FWIP. For viewpoint-translation, FWIP traces the trajectory of one-finger movement on the surface, as shown (Figure 3(a)). Until the touch ends, a user’s viewpoint is continuously translated in a virtual world using the



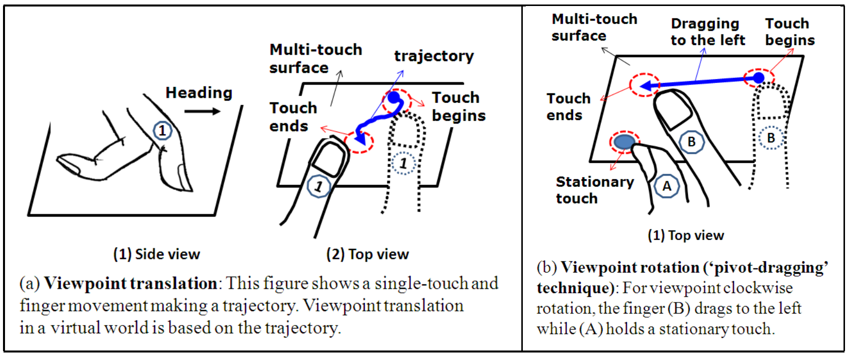
(a) Two-handed FWIP (b) One-handed FWIP

Fig. 1. Interface design for the two-handed and the one-handed FWIP LTs



(a) Control mode (b) Walking mode

Fig. 2. User interfaces for iPhone/iPod Touch



(a) **Viewpoint translation**: This figure shows a single-touch and finger movement making a trajectory. Viewpoint translation in a virtual world is based on the trajectory.

(b) **Viewpoint rotation ('pivot-dragging' technique)**: For viewpoint clockwise rotation, the finger (B) drags to the left while (A) holds a stationary touch.

Fig. 3. The final design of Finger-Walking-in-Place (FWIP) technique

trajectory. The virtual locomotion speed can be controlled by the speed and frequency of finger movement. This speed control mechanism is the same one used when walking by controlling leg-swinging.

FWIP requires multi-touch for viewpoint-rotation. For viewpoint-rotation, FWIP is designed considering the hand-constraint that cannot be fully rotated in place, so that it should be discretely realized. This is also found in the real world for rotation-in-place. When we rotate in place in the real world, we do not usually have a full rotation at a step. The full rotation is discretely realized with several steps. While one finger (A) holds a stationary touch (i.e., 'pivot' touch), another finger (B) can drag to the right or to the left (Figure 3(b)). The dragging distance is used to determine the rotation angle. The faster dragging movement is the faster rotation changes. For the full rotation of a viewpoint, a user needs to repeatedly drag in the same direction. Since this rotation technique needs a 'pivot' touch by a finger and 'dragging' by another finger, we call this technique 'pivot-dragging' technique. Thus, the action of FWIP is very similar to that of treadmill-supported WIP in terms of relative position and spatial direction of the executing body parts.

2.2 Joystick-Based Flying

Joystick-based flying is a common LT in VEs. It is usually based on the direction of a (hand-manipulated) wand or based on the head orientation. For the comparative study, we used a technique based on the wand orientation to determine the traveling direction. In other words, the joystick's direction is decoupled from the direction where a user's head is aiming to give more freedom to the user to look around during navigation. The joystick on the wand is used to translate and rotate the viewpoint. The buttons on the wand are used to control the flying speed.

While the action of FWIP is repetitively executed for movement in VEs as that of WIP is, the action of the flying is relatively stationary because users keep pushing the little stick and they only have force feedback.

3 Comparative Study

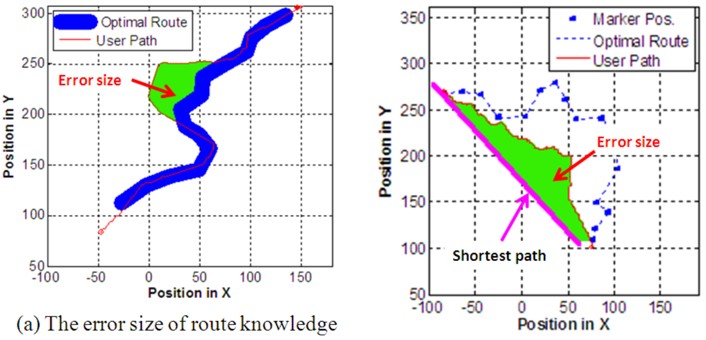
3.1 Methodology

We used the same experiment tasks and procedure presented by Peterson et al. [14], because their study was focused on the spatial knowledge acquisition. Their study was about the comparison of VMC and Joystick's flying techniques. In our study, the VMC is replaced with our FWIP and a multi-touch device.

Peterson et al. used maze-traveling which is generally used to investigate navigation performance in IVEs. The study showed that the experiment design is appropriate for a between-subjects study, in terms of the temporal size and the spatial size, considered of the exposure time inducing sickness symptoms in IVEs. The participants maneuvered in two virtual mazes with different complexities. The investigation was based on the Landmark-Route-Survey (LRS) model [16] that describes the process of how spatial knowledge is acquired and represented. Even though there are some arguments about the developmental sequence of LRS knowledge acquisition [9], the experiment design in [14] is reasonable to test whether or not subjects acquire spatial knowledge about a certain route, and the orientation from the entrance to the exit about the space. The results include maneuvering performance, route knowledge (RK) acquisition, and survey knowledge (SK) acquisition. Maneuvering performance is measured by the control precision; RK acquisition is measured by subjective confidence and the route replication result; SK acquisition is measured by subjective estimation of direction to the exit and a straight path length to the exit [14].

3.2 Performance Metrics

In order to investigate the effect of each LT on spatial knowledge acquisition in VEs, we decided to use two metrics, route knowledge acquisition accuracy and survey knowledge acquisition accuracy. These two metrics are measured by using the quantitative errors produced by subjects in two tasks, route replication task and spatial orientation estimation (the deviation from a straight-line traversal from the entrance to the exit) task.



(a) The error size of route knowledge acquisition in the simple maze The thickness of the optimal route is determined by the width of the marker objects.

(b) The error size of survey knowledge acquisition in the complex maze.

Fig. 4. Two examples of the error sizes of route knowledge (RK) and survey knowledge (SK) acquisition

RK acquisition error size: The route error is measured as area between the optimal route (from the first marker to the last marker) and the path taken by the subject in the route replication tasks (Figure 4(a)). We denote this measure $\mathbb{E}_{RK}$.

Survey knowledge acquisition error size: The orientation estimation error is measured as area between the straight-line path (from the entrance to the exit) and the direct path taken by the subject (Figure 4(b)). We denote this measure $\mathbb{E}_{SK}$.

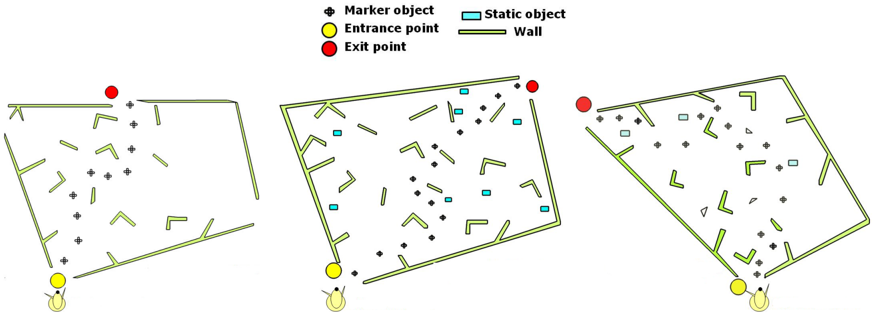
We chose the area between the optimal path and the one taken by a test subject to measure the performance as this is the cumulative deviation between the two loci. We excluded the distance traveled, which is used in [14] to evaluate SK acquisition, because it can be biased in some cases. For example, consider two users trying to find the shortest path. One of the users wanders a lot in a certain area close to the optimal path. The other user chooses a wrong direction, and travels far from the optimal path. If the first user had traveled longer distance than the second user, the distance traveled would not be an appropriate metric to evaluate their task performance.

3.3 Design

We used three mazes, including a practice maze, with the different complexities (Figure 5). These mazes are based on [14]. As the complexity of the mazes increases, more turns are required (Table 1). The practice maze is used to familiarize the subjects with the experiment procedure used in the simple maze and the complex maze. We tried to eliminate any unnecessary head movement, such as looking down to find the markers. Consequently, the markers were taller than the subjects' height in a CAVE.

The experiment was performed in a CAVE [19] with a 10' by 10' Fakespace 4-wall CAVE display with shutter glasses, and an Intersense IS-900 VET-based head tracker.

Joystick subjects hold a wand device with a dominant hand and navigate by physically pointing the wand to indicate the forward direction of travel and employing the



(a) Practice maze. (b) Simple maze. (c) Complex maze.

Fig. 5. Top views of three virtual mazes. Each maze includes marker objects and walls. The simple/complex mazes include static objects that can be used to remember their traveling paths

Table 1. The characteristics of the virtual mazes

	Practice Maze	**Simple Maze**	**Complex Maze**
Number of markers	10	15	16
Size (units)	265 × 185	245 × 195	230 × 230
Path length (units)	213	310	377
Cumulative angle to turn (degrees)	337	479	699
Fog effect	Yes	Yes	Yes

joystick on the wand to specify specific movements with-respect-to that forward vector (Figure 6(a)). Lemur and iPhone devices are used for the purpose of a finger-walking surface and touch/position detection, and the navigation direction is only determined by finger-movements. In order to conduct the experiment with the constraint that the FWIP subjects would not physically move in the CAVE immersive space, we placed the Lemur and the iPhone/iPod Touch on a table to provide a persistent spatial reference. The FWIP subjects would stand on a floor next to the table. While the Lemur subjects would use only one-hand (Figure 6(b)), iPhone/iPod Touch subjects would hold the device with the non-dominant hand, align it with the vertical line of the front wall in the CAVE space, and move their fingers with the dominant-hand on the screen surface (Figure 6(c)).

(a) Joystick subject (b) Lemur subject (c) iPhone subject

Fig. 6. Experiment setup in VT-CAVE

Table 2. Demographic data of the subjects

Data	JS Group	Lemur Group	iPhone Group
Mean age (years)	24.5 (Std=5.797)	20.563 (Std=1.999)	19.13 (Std=1.0888)
Gender	Female:8, Male:8	Female:8, Male:8	Female:8, Male:8
VE Experience	Novice N=10, Experienced N=6	Novice N=10, Experienced N=6	Novice N=15, Experienced N=1

3.4 Procedure

48 college students participated in this experiment. They were assigned to three different interaction groups: the joystick LT group (JS group), the Lemur-based FWIP group (Lemur group), and iPhone-based FWIP group (iPhone group). The subjects were asked to fill out the pre-experiment questionnaire including demographic questions, such as age, gender, and VE experience level (Table 2). The instructions were:

1. Travel along the pre-defined route with marker objects five times (to have the experience of the maze environment): During five trials, the subjects were asked to pass right through every marker object until they reach the exit. After each trial, the subjects were automatically moved back to the entrance point.
2. Estimation: After each trial, the subjects were asked how confidently they can estimate the direction to the exit and how confidently they can replicate the same route without marker objects.
3. Route replication (for RK acquisition): After five trials, the subjects had two trials to replicate the same route without visible marker objects.
4. Travel along the shortest path (for SK acquisition): After the route replication, the subjects had two trials to find the shortest path. When finding the shortest path, the subjects were allowed to walk through internal walls (no collision detection).

After all the tasks in three mazes, the post-experiment questionnaire obtained subjective responses to the experiment and free-form comments. The subjects were asked to describe the strategies employed to replicate the route and to find the shortest path to the exit. They were required to take a break after completing the tasks in each maze.

4 Analysis and Discussion

4.1 Results

We normalized each of our $\mathbb{E}_{RK}$ and $\mathbb{E}_{SK}$ using the largest error score, such that $\bar{\mathbb{E}}_{RK} = \mathbb{E}_{RK}/\max(\mathbb{E}_{RK})$ and $\bar{\mathbb{E}}_{SK} = \mathbb{E}_{SK}/\max(\mathbb{E}_{SK})$ in our data analysis.

RK Acquisition: Table 3 presents the mean error of each group and the results of our $\bar{\mathbb{E}}_{RK}$ analysis are shown in Figure 7.

Simple Maze: Since there were two outliers (one subject wandered too much and the other one was lost) in the JS group in the simple maze, we compared fourteen-subjects data for each interaction technique group. The mean error of the JS group is a little bigger compared to the other groups. Because three-group samples failed the normality test

Table 3. The $\bar{\mathbb{E}}_{RK}$ of the three groups

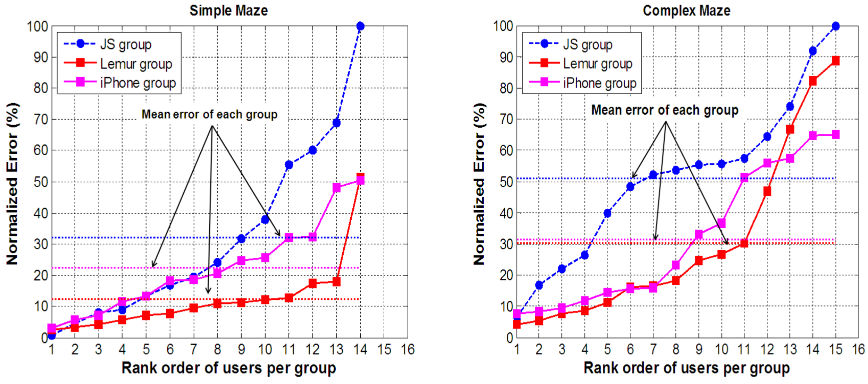
	JS Group	**Lemur Group**	**iPhone Group**
Simple maze	22.3(%)	8.63(%)	15.44(%)
Complex maze	50.1(%)	30.31(%)	31.45(%)

(Ryan-Joiner=0.789, 0.801, and 0.863, respectively, $p < 0.05$), we used the Kruskal-Wallis non-parametric test (H statistic). This test shows significant difference among three groups' means (H=7.34, $p < 0.05$).

Figure 7(a) shows that nine subjects in the JS group rank below the mean error (22.3 %), while 11 subjects in the Lemur group rank below the mean error (8.63 %). In addition, 12-th and 13-th subjects rank very close to the mean error, which is not the case in the JS group. Figure 7(a) implies that the Lemur group performed evenly well against the JS group in the simple maze. On the other hand, the iPhone group is placed between the JS group and the Lemur group. Since the iPhone device should be held in non-dominant hand, its alignment may be sometimes off the vertical line of the front wall in the CAVE space. We conjecture that it may affect the task performance.

Complex Maze: The mean error of the JS group is a little bigger compared to the other groups. Since the Lemur group samples failed the normality test (Ryan-Joiner=0.911, $p < 0.05$), we used the Kruskal-Wallis non-parametric test (H statistic). The statistical test showed no significant difference among the three groups. Figure 7(b) shows that the performance of RK acquisition was affected by the maze complexity.

Since we focus on the comparison of FWIP and joystick LTs, we are more interested in the two-group based results. When we compare the JS group vs. the Lemur group and the JS group vs. iPhone group using Mann-Whitney non-parametric test, the statistical tests show interesting results (Table 4). The table shows that the error size of the JS group is statistically greater than the error size of Lemur group in both mazes, while the



(a) Result in the simple maze (b) Result in the complex maze

Fig. 7. The comparison of $\bar{\mathbb{E}}_{RK}$ across our three groups. We added the line between data points to easily compare the results of three groups (neither interpolation nor extrapolation)

Table 4. Statistical test results for the comparison of RK acquisition

	$\lvert\, \mathbb{E}_{RK}$**(JS) –** $\mathbb{E}_{RK}$**(Lemur)** $\rvert$	$\lvert\, \mathbb{E}_{RK}$**(JS) –** $\mathbb{E}_{RK}$**(iPhone)** $\rvert$
Simple maze	W=281, $p < 0.05$	W=245, $p > 0.05$
Complex maze	W=284, $p < 0.05$	W=277, $p < 0.05$

Table 5. The $\bar{\mathbb{E}}_{SK}$ of the three groups

	JS Group	**Lemur Group**	**iPhone Group**
Simple maze	20.81(%)	21.85(%)	20.16(%)
Complex maze	54.27(%)	55.24(%)	57.0(%)

error size of the JS group is statistically greater than the error size of iPhone group in the complex maze.

SK Acquisition: We analyzed our $\bar{\mathbb{E}}_{SK}$ dataset in the same way we did the $\bar{\mathbb{E}}_{RK}$ evaluation. The statistical test showed no significant difference in JS vs. Lemur groups and JS vs. iPhone groups. Table 5 shows that the SK acquisition is not much affected by the interaction technique but the maze complexity.

4.2 User Behaviors

We observed that most users are focused on trying to find their better strategies to complete route replication and shortest path finding tasks. They showed a common strategy which they tried to use landmarks knowledge developed during the first five trials with marker objects. Some joystick users tried to change their physical postures/movement (e.g., physical body-rotation by fixing the wand's position on the body-chest, only use of the device without physical body-rotation, and horizontal swing of the arm as well as physical body-rotation). Some FWIP users tried to memorize the number of steps and turns at specific positions (e.g., original positions of the marker objects) in relation to some static objects (e.g., box objects or walls). Thus, we may assume that using the same action of that of walking may help the users to recall some wayfinding strategies that might already be learned from the real world.

4.3 Discussion

This experiment showed that the Lemur group's users acquired more accurate route knowledge in both mazes and the iPhone group's users acquired more accurate route knowledge in the complex maze, compared to what the joystick group's users did. This result implies that there are some benefits to remember and recall the subjects' route knowledge when using FWIP for navigation in VEs. In other words, our embodied resources related to spatial knowledge acquisition can be utilized by FWIP. This result is also useful, especially given how far FWIP is removed from actual walking and turning.

However, there is no significant difference for survey knowledge acquisition in the Lemur versus the joystick groups and the iPhone versus and joystick groups. Regarding this, we realized that survey knowledge is usually acquired from more exploration in an environment. In our experiment we provided insufficient exploration opportunity to users for survey knowledge acquisition in each maze. We need further experiment to measure survey knowledge acquisition with some methodological improvements, such as providing more exploration opportunity of the maze (e.g., traveling several different routes or searching several objects placed in the maze).

We also found that our experiment design included some confounding factors as follows,

- The rotation technique of the iPhone-based FWIP is different from that of the Lemur-based FWIP due to some time-constraint at the time when we performed the experiment with the iPhone-based FWIP.
- Since the iPhone subjects held the device in non-dominant hand, its heading direction may be sometimes off the vertical line of the front wall in the CAVE space.
- While the users in the JS group kept holding a device, the users in the Lemur group used a table to place the Lemur device.
- For the wand device (to which the joystick is attached), the absolute angle of rotation is determined by a tracking system. Hence, hand rotation and body rotation cannot be distinguished. Body rotation has concomitant direction implication which hand rotation does not. We allowed only joystick-users to physically rotate in place because we understand that this conflation is typical for wand/joystick users without adequate understanding of how this conflation influences 3D interaction. On the other hand, the action of the FWIP for rotation has some constraints, compared to WIP and the joystick's flying because we cannot fully rotate our wrist on which the fingers depend.

In order to thoroughly investigate the effect of FWIP on spatial knowledge acquisition, we need to remove these factors in the next experiment.

5 Conclusion and Future Work

We described a touch-based, one-handed FWIP and its implementation on a Lemur and an iPhone/iPod Touch. We conducted a comparative study of FWIP versus the joystick's flying LT to investigate the effect of the mapping of the human's embodied ability to the finger-based LT on spatial knowledge acquisition.

The basic finding of this study is that FWIP designed by the similar action to that of walking helped the subjects to acquire more accurate route knowledge in virtual mazes with different complexity, showing that this mapping may provide positive effect on human spatial knowledge acquisition in VEs. In order to support this observation, we will find some theoretical foundations as well as to perform further experiment.

In Introduction Section, we raise a question, "can we leverage these abilities by using an alternative LT, rather than walking-like physical LT, for virtual navigation?". Even though the study result shows some positive effect, we cannot fully answer to this question. In order to show that the effect of FWIP on spatial knowledge acquisition would not be significantly different from that of walking-like physical LTs for spatial knowledge acquisition, we will perform another type of comparative study, i.e., FWIP versus walking-like LTs (e.g., WIP or walking).

References

1. Apple Computer, Inc. iPhone User's Guide For iPhone and iPhone 3G (2008)
2. Benko, H., Wilson, A.D., Baudisch, P.: Precise selection techniques for multi-touch screens. In: Proceedings of the SIGCHI conference on Human Factors in computing systems (CHI 2006), pp. 1263–1272. ACM, New York (2006)
3. Bowman, D.A., Kruijff, E., LaViola Jr., J.J., Poupyrev, I.: 3D User Interfaces: Theory and Practice. Addison-Wesley, Boston (2004)
4. Darken, R.P., Cockayne, W.R., Carmein, D.: The omni-directional treadmill: A locomotion device for virtual worlds. In: UIST 1997: Proceedings of the 10th annual ACM symposium on User interface software and technology, pp. 213–221. ACM Press, New York (1997)
5. Dourish, P.: Where the Action Is: The Foundations of Embodied Interaction. The MIT Press, Cambridge (2001)
6. Fishkin, K.P.: A taxonomy for and analysis of tangible interfaces. Personal Ubiquitous Computing 8(5), 347–358 (2004)
7. Gabbard, J.L.: Taxonomy of Usability Characteristics in Virtual Environments. MS's thesis, Virginia Polytechnic Institute and State University (1997)
8. Interrante, V., Ries, B., Anderson, L.: Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments. In: Proc. of IEEE Symposium on 3DUI, pp. 167–170 (2007)
9. Montello, D.R., Hegarty, M., Richardson, A.E., Waller, D.: Spatial Memory of Real Environments, Virtual Environments, and Maps. In: Allen, G. (ed.) Human Spatial Memory: Remembering where, pp. 251–285. Lawrence Erlbaum, Mahwah (2004)
10. Iwata, H., Yoshida, Y.: Path reproduction tests using a torus treadmill. Presence: Teleoperators & Virtual Env. 8(6), 587–597 (1999)
11. JazzMutant. Lemur User Manual 1.6. JazzMutant (January 20, 2007), `http://www.jazzmutant.com/download/Lemur_v1.6_Manual.pdf`
12. Kim, J., Gračanin, D., Matkovic, K., Quek, F.: Finger Walking in Place (FWIP): A Traveling Technique in Virtual Environments. In: 2008 International Symposium on Smart Graphics, pp. 58–69. Springer, Heidelberg (2008)
13. Komura, T., Lam, W.-C.: Real-time locomotion control by sensing gloves. Journal of Visualization and Computer Animation 17(5), 513–525 (2006)
14. Peterson, B., Wells, M., Furness III, T.A., Hunt, E.: The effects of the interface on navigation in virtual environments. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, pp. 1496–1505 (1998)
15. Ruddle, R.A., Lessels, S.: The benefits of using a walking interface to navigate virtual environments. ACM TOCHI 16(1), 5:1–5:18 (2009)
16. Siegel, A.W., White, S.H.: The development of spatial representations of large-scale environments. In: Reese, H.W. (ed.) Advances in Child Development and Behavior, vol. 10, pp. 9–55. Academic, New York (1975)
17. Slater, M., Usoh, M., Steed, A.: Taking steps: the influence of a walking technique on presence in virtual reality. ACM Transactions on Computer-Human Interaction (TOCHI) 2(3), 201–219 (1995)
18. Templeman, J.N., Denbrook, P.S., Sibert, L.E.: Virtual locomotion: Walking in place through virtual environments. Presence: Teleoperators & Virtual Env. 8(6), 598–617 (1999)
19. Virginia Tech. VT-CAVE, `http://www.cave.vt.edu/` (last accessed, February 2010)
20. Waller, D., Loomis, J.M., Haun, D.B.M.: Body-based senses enhance knowledge of directions in large-scale environments. Psychonomic Bulletin and Review 11, 157–163 (2004)