Evaluation of Walking in Place on a Wii Balance Board to Explore a Virtual Environment

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In this work, we present a method of "Walking In Place" (WIP) on the Nintendo Wii Fit Balance Board to explore a virtual environment. We directly compare our method to joystick locomotion and normal walking. The joystick proves inferior to physically walking and to WIP on the Wii Balance Board (WIP–Wii). Interestingly, we find that physically exploring an environment on foot is equivalent in terms of spatial orientation to exploring an environment using our WIP–Wii method. This implies that the WIP–Wii is a good inexpensive alternative to exploring a virtual environment and it may be well–suited for exploring large virtual environments.

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1. INTRODUCTION

Finding ways to spatially navigate in virtual environments that perform comparably to the way we spatially navigate in the real world is a challenging and important problem that has received significant attention [Chance et al. 1998; Klatzky et al. 1998; Lathrop and Kaiser 2005; Ruddle and Lessels 2006, 2009; Riecke et al. 2010]. Two important concerns are if and how much physical motion is

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necessary to achieve good performance in a virtual environment. A significant body of work has shown the benefit of the proprioceptive cues of physical motion in spatial tasks [Bakker et al. 1999; Klatzky et al. 1998; Lathrop and Kaiser 2005; Pausch et al. 1997; Chance et al. 1998; Ruddle and Lessels 2006; 2009; Riecke et al. 2010] but there is some disagreement about whether the motion needs to be walking [Ruddle and Lessels 2009] or whether simple physical rotation would suffice [Riecke et al. 2010]. In this article, we explore an intermediate method, "Walking In Place" (WIP).

There are two issues with exploring a virtual environment by physically walking. First, an accurate room–sized tracking system is relatively expensive, difficult to set up, and not readily available to consumers. Second, foot exploration does not permit the free exploration of virtual spaces larger than the size of the tracked space. Thus, this work introduces a WIP method to explore virtual environment using a Nintendo Wii Fit™ Balance Board. Wii Balance Boards are readily available at retail stores and retail just under 100 USD. This makes the Wii Balance Board a potentially viable device for exploring virtual environments in homes, schools, and offices. Additionally, WIP on the Wii Balance Board (WIP–Wii) does not suffer space limitations. Our work focuses on Head–Mounted Display (HMD) technology because of its immersive qualities, wide availability, and relatively small expense as compared to other immersive virtual environment technologies. For example, a low, cost HMD can be purchased for less than 1500 USD. HMDs are typically mounted with an orientation sensor that updates the user's pitch, yaw, and roll in the virtual environment. A high–fidelity orientation tracker costs on the order of 1200 USD.

One obvious inexpensive solution to exploring a virtual environment using this type of HMD–based system is to use a joystick to translate freely in the virtual environment. However, this method has been shown inferior to physical locomotion [Chance et al. 1998; Ruddle and Lessels 2006; Lathrop and Kaiser 2002]. This work directly compares joystick translations with WIP–Wii. Other methods, for example, Razzaque et al. [2001], Engel et al. [2008], Nitzsche et al. [2004], Steinicke et al. [2010], Interrante et al. [2007], Williams et al. [2006], Usoh et al. [1999], Fernandes et al. [2003], Schwaiger et al. [2007], have also been proposed to explore a virtual environment, and we explore these in Section 2. We are not the first to look at WIP to explore a virtual environment. Much of the WIP work to date has involved using relatively expensive optical tracking systems that track knee and shin movement to infer locomotion [Feasel et al. 2008; Wendt et al. 2010]. Also, there seems to be no study that closely examines the WIP method in terms of the user's spatial orientation in the virtual environment. In contrast, this work employs an inexpensive implementation of the WIP method and examines the user's spatial orientation with respect to the virtual environment. As discussed in Section 2, current WIP research [Slater et al. 1995; Templeman et al. 1999; Feasel et al. 2008; Wendt et al. 2010] is focused on implementation details and usability studies.

This work relies on the investigation of humans' spatial orientation in a virtual environment. Spatial orientation refers to the natural ability of humans to maintain their body orientation and position relative to the surrounding environment. Spatial orientation relies heavily on visual information and whole-body information while moving in an environment [Wartenberg et al. 1998]. Prior work has shown that users can have difficultly maintaining spatial orientation in a virtual environment [Péruch et al. 2000]. The reasons for this are not well understood, but many cues are known to affect how well people can maintain their spatial orientation. These cues can be broadly classed as motion cues or environmental cues. As discussed in Section 2, many of the methods for overcoming physical space limitations in exploring large virtual environments seek to manipulate motion cues advantageously. What is critical for our goals is that such manipulations preserve, or degrade as little as possible, a user's spatial orientation [Rieser and Pick 2007].

The within–subject experiment presented in this work compares subjects' spatial orientation under normal walking, WIP on the Wii Balance Board (WIP–Wii), and joystick locomotion. In all three methods, subjects rotate physically. Rotation is updated in all three conditions using an orientation sensor. In both the WIP–Wii and joystick conditions, subjects translate in the direction that they are facing (or yaw angle). Facing direction is calculated from the orientation tracker. Thus, our WIP–Wii algorithm requires the use of an orientation tracker. Any immersive HMD system that updates orientation has some sort of orientation sensor. In the experiment presented in this work, spatial orientation is assessed by measuring errors and latencies in tasks where subjects turn to face a remembered object from their position in the virtual environments. Disparity is defined as the difference between the actual facing direction and the direction needed to face the target.

2. BACKGROUND

Previous research has explored various techniques of navigating a virtual environment. Haptic devices, such as a joystick or keyboard, allow users to virtually explore large environments [Ruddle et al. 1999; Bowman et al. 1999; Waller et al. 1998; Darken and Sibert 1996; Pausch et al. 1995]. However, studies have shown that using physical bipedal locomotion rather than haptic devices produces significantly better spatial orientation [Chance et al. 1998; Ruddle and Lessels 2006; Lathrop and Kaiser 2002]. Suma et al. [2007] show that using position and orientation tracking with an HMD is significantly better than using a system that combines the orientation tracking and a haptic device for translations. However, Riecke et al. [2010] found that joystick translations and physical rotations led to better performance than joystick navigation, and yielded almost comparable performance to actual walking in terms of search efficiency and time.

Williams et al. [2006] show that the translational gain of walking can be scaled by a factor of ten and that there is no significant difference in spatial awareness when compared to exploring an environment using normal bipedal locomotion. Additionally, this work directly compares joystick exploration with the gain of physical walking scaled by ten and finds that physical locomotion results in significantly better spatial awareness. Interrante et al. [2007] proposed a method called “seven league boots” in which they scale gain based on wand control. Another method of navigating a large virtual environment is manipulating rotation such that the locomotion of the subject fits within the limits of the tracking system [Razzaque et al. 2001; Engel et al. 2008; Nitzsche et al. 2004; Steinicke et al. 2010]. These methods require a large tracking area for the rotational manipulation to be imperceptible, and fail to form a complete solution because a situation could easily occur in which the physical limits of the tracking system are reached. All of the preceding methods of manipulating locomotion require the use of a relatively expensive tracking system to capture the physical position of the user. Virtual flying [Usoh et al. 1999] and teleporting are other ways of exploring large virtual environments, yet they lack locomotive feedback.

The present work examines exploring a virtual environment by “Walking In Place” (WIP). Different techniques of WIP to explore a virtual environment have been proposed [Slater et al. 1995; Templeman et al. 1999; Feasel et al. 2008; Wendt et al. 2010]. These works have focused on step detection algorithms. Slater et al. [1995] train a neural network to detect steps from head movement. This algorithm was slightly unnatural in that the algorithm had to detect four steps from the users before it would begin to translate the user with the idea that false-positive steps are more confusing than the prompt detection of a step. Also, virtual movement ceased when no steps were detected for two cycles. A usability study, Usoh et al. [1999] revealed that this method was better than virtual flying but not as good as walking. Templeman et al. [1999] use motion capture to detect a step when the knee reaches a certain position. This method has been shown to work well in a usability study testing path following tasks but has not been directly compared in a spatial orientation task with other methods. Feasel et al. [2008] track the user’s feet and knees to infer virtual steps. Their step finding method lacks the latency issues of previous methods. Participants move in the virtual environment according to a chest

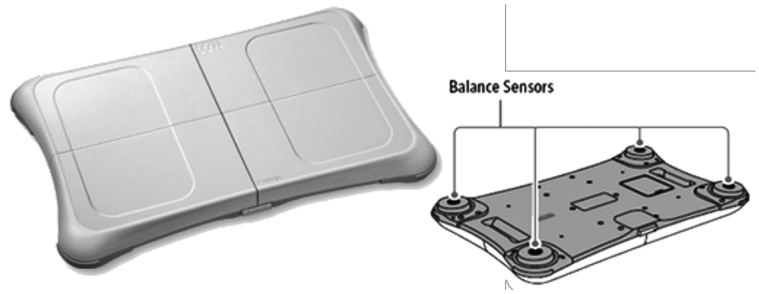

Fig. 1. This image shows the Nintendo Wii Fit Balance Board. The pressure sensors or balance sensors are located underneath the board at the corners of the board.

orientation sensor. In a usability study, they find that "walking in place" is about as good as a joystick but a good deal worse than real walking. Interestingly, this finding is not consistent with our results. Wendt et al. [2010] also track the knees using an optical motion capture system. They can closely match the walking gait of real walking, although they have not compared their method with other forms of virtual locomotion. All of the mentioned WIP methods use relatively expensive tracking systems to track the position of the knees, shins, feet, or head. The Wii Fit™costs less than 100 USD. Our method of step detection is not as sophisticated as many of the preceding methods, but our results are compelling.

Other systems to explore a large virtual environment involve large-screen caves with a locomotion input such as a bicycle or treadmill [Plumert et al. 2004]. Cave–based systems are expensive, and most only contain three virtual walls. Treadmill systems are difficult and expensive to construct with enough degrees of freedom to allow for free exploration. Other expensive hardware solutions to explore a large virtual environment include the CyberSphere [Fernandes et al. 2003] and the CyberWalk [Schwaiger et al. 2007].

We directly compare participants' spatial orientation in a virtual environment when the environment is explored by a joystick, physically walking, and using our Wii-WIP method. One limitation of our work is that we did not do a real-world baseline comparison. Many studies [Bowman et al. 1999; Waller et al. 1998; Williams et al. 2007] have found a difference in virtual exploration versus real-world exploration. In this work, we were interested in seeing how well our WIP–Wii method compared to other methods of virtual exploration. However, we would like to follow up on this idea in future work.

3. WIP–WII IMPLEMENTATION DETAILS

The implementation details of our walking in place on a Nintendo Wii–Fit Balance Board (WIP–Wii) algorithm are discussed in this section. The Wii Balance Board contains four pressure sensors as show in Figure 1 at each of the four corners. Thus, our WIP–Wii method uses the weight measurements obtained from each of the four pressure sensors. The program translates the users forward according to how rapidly the users shift their weight from one corner of the board to the other. With our Wii–WIP algorithm, users walk in place in the direction their head is facing. Specifically, participants walked in place on the Wii Balance Board and translated in the virtual environment according to yaw direction that they were looking. The participant's pitch, yaw, and roll were updated using an orientation sensor. We performed several informal pilot usability studies and found that WIP was most natural when the direction of locomotion was controlled by facing direction. We experience some step detection lag with our WIP method. We estimate our method to be about a half of a step behind when starting to

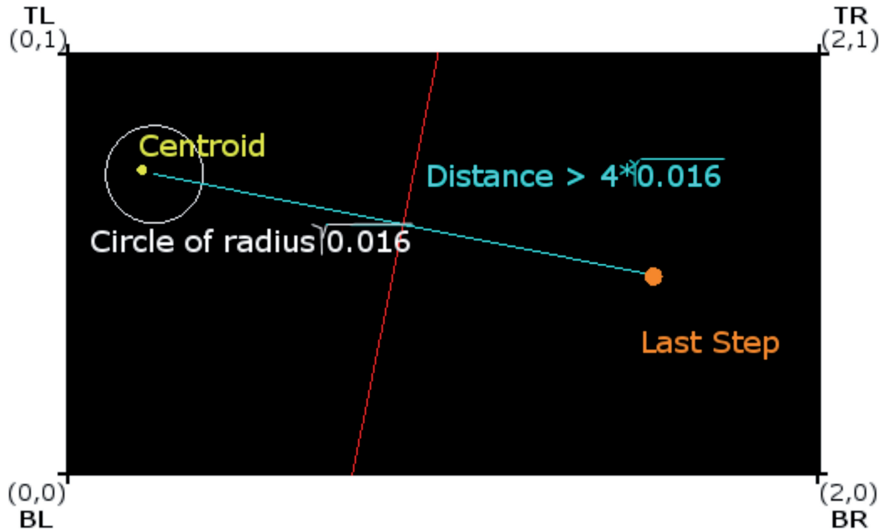

Fig. 2. This figure shows the basics of our WIP–Wii algorithm. The pressure sensors (TL, TR, BL, BR) are mapped to the four corners of 2×1 rectangle. The program calculates the centroid every 60 Hz. A step is detected when centroids lie within a $\sqrt{.016}$ of each other for a certain amount of time and the distance from the last step is greater than $4 * \sqrt{.016}$.

update the position of the user in the virtual environment. It is also approximately a half of a step behind ceasing the optical flow when a user stops walking in place. This delay is due to the limitations simulating walking from four weight sensors. Participants did not find this lag distracting.

We mapped the locations of the sensors to a 2×1 rectangular grid because the length of the board was roughly twice that of the width. This allowed us to treat the sensor data as if it were obtained from sensors on four corners of a square. This was important because it allowed participants to "walk in place" in any orientation on the Wii Balance Board. The bottom left (s_{BL}), top left (s_{TL}), top right (s_{TR}), and bottom right (s_{BR}) sensors were located at (0, 0), (0, 1), (2, 1), and (2, 0), respectively. The total weight of the user is calculated as follows:

$$weight = s_{TR} + s_{TL} + s_{BR} + s_{BL}. \tag{1}$$

In our algorithm, we used the position of the center of mass, or *centroid*, to calculate whether a user intended to walk. Thus, the values of the four sensors were combined to form the 2D centroid. The x and y coordinates of the *centroid* were calculated as follows.

$$centroid_x = ((s_{TR} + s_{BR})/weight) * 2, \tag{2}$$

$$centroid_y = (s_{TL} + s_{TR})/weight. \tag{3}$$

Again, $centroid_x$ is multiplied by 2 to match the rectangular shape of the balance board. The coordinates of the centroid were calculated every 60 Hz (the refresh rate of both the Wii Board and the HMD). A step was detected when the centroid moved a fixed distance and remained within a certain radius for a fixed amount of time. For this experiment, the time the centroid had to remain in a specified area was 0.15s before a step would be detected, and the area used was a circle of radius $\sqrt{0.016}$ units. This radius was derived from informal experimentation with several pilot subjects of different weights; it can be seen in Figure 2.

Thus, we introduce two variables, $elapsedTime$ and $avgCentroid$, to keep track of the time the centroid remains within radius distance away and the average center of the centroid over the elapsed time, respectively. We initialize $elapsedTime$ equal to 1/60s (the refresh rate of the HMD) and $avgCentroid$ equal to the initial centroid reading.

Thus, when the centroid was calculated every 60 Hz, $avgCentroid$ and $elapsedTime$ were updated. If the distance between the current centroid and the avgCentroid was less than $\sqrt{.016}$, then avgCentroid updated accordingly

$$avgCentroid = \frac{avgCentroid * elapsedTime + centroid * \frac{1}{60}}{elapsedTime + \frac{1}{60}}, \tag{4}$$

and $elapsedTime$ was increased by 1/60s. If the $elapsedTime$ reached a value of .15s, a step was detected. If the current centroid was not within $\sqrt{.016}$ units away from the $avgCentroid$, then $elapsedTime$ was set again to 1/60 sec and $avgCentroid$ was equal to the current centroid. If the calculated $centroid$ remains within the specified distance from the average value of the centroid for the specified amount of time, the algorithm detected a step. When a step was detected, the time when the step was detected was recorded along with the distance between the centroid's position at this step and the centroid's position at the previous step. The average centroid value and the time elapsed value were reset and the algorithm would not attempt to detect another step until the centroid had moved a distance of 4*$\sqrt{0.016}$ units away from the position where the last step was detected.

Once a step had been detected, the participant moved in the direction of their gaze in the virtual environment. The speed of that translation was determined by using the change of the position of the centroid. The rate of change at time i was calculated using the current value of the centroid, $centroid_i$ and the previous value of the centroid, $centroid_{i-1}$.

$$rateOfChange_i = \frac{\|centroid_i - centroid_{i-1}\|}{\frac{1}{60}}. \tag{5}$$

To correct for sudden changes in the rate of change, the last 10 calculations for the rate of change were recorded and summed together to form an average rate of change. The average rate of change was calculated as

$$avgRateOfChange_i = \frac{1}{10}\sum_{j=i}^{i+10} rateOfChange_j, \tag{6}$$

where i represents a recorded rate of change. The average rate of change, *avgRateOfChange*, was used to determine how far the user should move in the virtual environment per frame.

If the user was standing still and shifting their weight from one side to the other, problems occurred with our algorithm. Thus, we decided to update the user's position only when a step was detected within two seconds of the last step. When the user takes the initial step to start translating or they take a step after waiting for more than two seconds, the position is not updated for that step. Instead, the program waits until the next step to start translating the position of the user. This was done to prevent the user's position from drifting due to small shifts in body weight on the Wii Balance Board while the user was standing still.

The speed at which the view moved depended on the rate of change of the centroid divided by the distance between the two previous steps. First, the average speed is calculated again to prevent sudden changes in the speed. This is done as follows:

$$averageSpeed = \frac{1}{6}\sum_{k=0}^{5} avgRateOfChange_k, \tag{7}$$

where $avgRateOfChange_k$ is the kth previously recorded average rate of change. Six previous values are recorded since this sufficiently smoothed the average speed so that there were no sudden jumps caused by a sudden change in the velocity. If a speed had a value lower than 0.03 or if the time elapsed since the last step was greater than 0.75 times the time between the second to last step and the last step, then the algorithm would record a speed of 0 once every two times the algorithm was updated. Recording a zero instead of the centroid's speed after 0.75 times the time between the two previous steps had the effect of slowing down the user's movement right before the next step or to stop which mimics real walking. The factor 0.75 was selected by informal testing since smaller values resulted in the user coming to a complete stop well before the next step and larger values resulted in the user drifting too far between steps and after the last step when the user desires to come to a stop.

Once the average speed, *averageSpeed*, was calculated, the final speed of the user, *finalspeed* was modified as

$$finalSpeed = averageSpeed/stepDistance, \tag{8}$$

where *stepDistance* is the distance between the centroid positions of the two most recent steps. The *averageSpeed* was divided by the *stepDistance* so that the user moved roughly the same distance per step no matter how far apart or close the last two steps were on the Wii Balance Board. Thus, the result of dividing by *stepDistance* disabled the user from going faster by spreading their feet farther apart on the Wii Board. Thus, taking quicker steps was the only way to increase the visual flow. Distance was calculated as

$$distance = finalSpeed * timeElapsed * 20, \tag{9}$$

where *timeElapsed* is the difference in time taken since the last update. Thus, the user moved *distance* in the direction they were facing. We multiplied the value by 20 to allow the movement to correspond with the movement observed by physical locomotion in the virtual environment. The number of steps needed to cross the virtual room (6m) by physically walking matched the number of steps using the WIP–Wii.

When users significantly change their facing direction, they often pick up their feet. We wanted to ignore this type of locomotion because it was not the user's intent to move forward, rather they wanted to turn their body to face a new direction. We ignored detected steps if the view was rotating at a rate greater than 20° per second. We arrived at 20° by informal pilot studies. When a user was turning compared to looking around while walking, they would rotate their head at least 20° per second when they were rotating their body to change direction, and they would rotate their head less than 20° per second when they were looking around while walking but not turning directions.

4. EXPERIMENTAL EVALUATION

This experiment compares locomotion interfaces that depend on three different motor actions to translate the subjects' perspective in virtual space, contrasting bipedal locomotion, joystick manipulation, and WIP on the Wii Balance Board (WIP–Wii). The results of the study compare learning and orientation in the three different conditions. To test subject orientation, subjects were asked to remember the locations of six objects in a virtual room, then were asked to move themselves (by walking, joystick, or WIP–Wii) to a new point of observation and instructed to turn to face the targets from memory without vision.

4.1 Participants

Twelve subjects participated in the experiment. Subjects were unfamiliar with the experiment and the virtual environments. Subjects were given compensation for their participation.

Fig. 3. This figure shows the virtual environment used in the experiment. Target objects appear on pillars. For each trial, subjects position themselves at the red cylinder facing the red arrow. Spatial orientation is assessed by measuring turning error and latency associated with facing target objects at different testing locations.

4.2 Materials

The experiment was conducted in a 9 by 7 m room. The virtual environment was viewed through a full-color stereo NVIS Visor SX Head-Mounted Display (HMD) with 1280 × 1 1024 resolution per eye, manufacturer's specification of a field of view of 60° diagonally, and an optical frame rate of 60 Hz. An InterSense IS-900 tracker was used to update the participant's rotational movements around all three axes. In the walking condition, position was interpolated by the WorldVIz PPT software using 4 optical cameras that track 2 LED lights mounted on the HMD. The tracking space used in this experiment was approximately 6m × 1 6m. The type of wireless joystick used in this experiment was the Logitech Freedom 2.4. The Nintendo Wii Fit^{TM}Balance Board was approximately 20.1"L × 1 12.4"W × 1 2.1"H.

A Wii Balance Board was connected to a remote computer through Bluetooth technology, and this computer was connected to the virtual reality system through a VRPN. The virtual room used in the experiment was a 6m by 6m corresponding closely with the size of the tracking room. Posters were placed on the walls of the room to give the participant a sense of size and scale. For each condition, a different set of six objects were placed on top of pillars at specific positions in the room as seen in Figure 3. These six target objects were arranged in a particular configuration, such that the configuration in all three conditions varied only by a rotation about the center axis. In this manner, the angles of correct response were preserved across each of the conditions. Examples of some of the target objects included a mug, sunglasses, a candle, and a hammer. Additionally, we used two different objects mounted on pillars to familiarize the participant with the setup of the experiment before the target memorization phase. A cylinder and an arrow as seen in Figure 3 were used to indicate the position and orientation of a participant needed for a particular trial.

4.3 Procedure

Each of the 12 participants explored each of the environments under the three different translational locomotion conditions, normal walking, WIP–Wii, and joystick locomotion. In all three conditions, rotation in the virtual environment matched rotation in the physical environment. In the joystick condition, participants used physical rotation and moved in the direction of gaze by joystick translations.

Using a joystick does not have a natural metric; that is, a given angle of the joystick does not map onto any corresponding amount of translation. To create a reasonably natural-seeming locomotion mode, we reasoned that pushing the joystick to its furthest extent should map onto a rapid, but relatively comfortable, walking speed. The maximum joystick translation rate was that of normal walking, 1 m/s. Subjects could go slower with the joystick just as subjects could walk more slowly than normal in the locomotion condition. In the WIP–Wii condition, participants also moved in the direction of gaze.

Since there were six orders of the three locomotion conditions, two subjects were tested in each order in a counter-balanced fashion. The experimental procedure was fully explained to the subjects prior to seeing the virtual environments. Before the subject saw the target objects in each condition, the participant was shown two objects on pillars that did not appear in our test set. Participants performed several practice trials in this environment so that they were familiar with the setup and the experimental design. After the subject understood the task and the condition, the practice target objects disappeared. The participant then practiced the locomotion condition by moving to various posters found on the wall. Once the participants were comfortable with this, they were asked to move to the center of the room where a set of six objects on top of six pillars was displayed. During the learning phase, subjects were asked to learn the positions of the six target objects while freely walking around the virtual environment. After about three minutes of study, the experimenter tested the subject by having them close their eyes, and turn to randomly selected targets. This testing and learning procedure was repeated until the subject felt confident that the configuration had been learned and the experimenter agreed.

Participants' spatial knowledge was tested from six different locations. A given testing position and orientation was indicated to the subject by the appearance of a red cylinder and a red arrow in the environment. Participants were instructed to locomote to the cylinder until it turned green and then turn to face the arrow until it turned green. When both the cylinder and arrow were green, the participants were in an appropriate position. When the subject reached this position, the room and the objects were hidden so that the participant only saw the cylinder and the arrow on a black background. After the participant was told which object to turn to face, the cylinder and arrow disappeared and the participant briefly saw the name of the target object. Specifically the subjects were told "turn to face the < *target name* >". Once the participant indicated that they had turned to face the object, the angle turned, the angle of correct response and the latency associated with turning to face the object were recorded. The cylinder and arrow reappeared and the participant then turned back to face the arrow until it turned green again. Then, the subject was instructed to face another target object. At each location, the subject completed three trials by turning to face three different target objects in the room, making 18 trials per condition. After completing three trials at a particular testing location, the participant was asked to face the arrow until it turned green before the room and objects were displayed again so that the participant would not receive any feedback. After the room and objects were shown again, the cylinder and arrow were moved to the next target location. Subjects were encouraged to reorient themselves after completing a testing location.

To compare the angles of correct responses across conditions, the same trials were used for each condition. The testing location and target locations were analogous in all three conditions, and targets varied randomly across the environments. The trials were designed so that the disparity [May 2004] was evenly distributed in the range of 20–180°. Also the testing locations were positioned in such a way that they would never turn to face a target object closer than 0.8m.

To assess the degree of difficulty of updating orientation relative to objects in the virtual environment, latencies and errors were recorded. Latencies were measured from the time when the target was identified until subjects said they had completed their turning movement and were facing the target. Unsigned errors were measured as the absolute value of the difference in initial facing direction

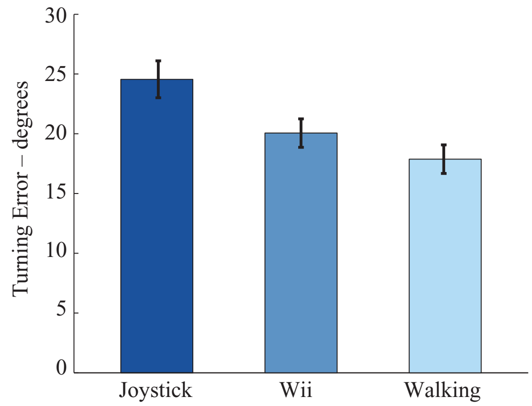

Fig. 4. Mean turning error for the joystick, Wii, and walking conditions. Error bars indicate the standard error of the mean. As discussed in Section 4.4, condition has a significant effect on turning error.

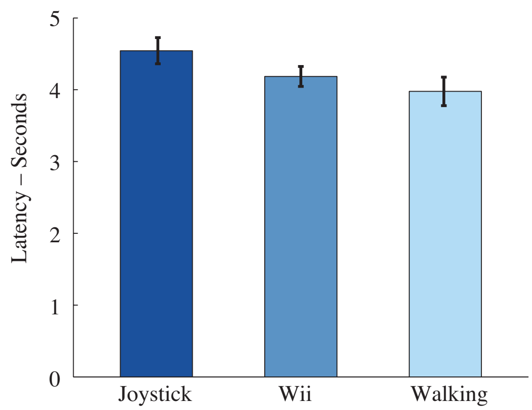

Fig. 5. Mean latency for the joystick, Wii, and walking conditions. Error bars indicate the standard error of the mean. As discussed in Section 4.4, condition was not significant on latency.

(toward the arrow) minus the correct facing direction. The subjects indicated to the experimenter that they were facing the target by verbal instruction, and the experimenter recorded their time and rotational position. The time was recorded by computer, and the rotational position was recorded using the InterSense tracker. Subjects were encouraged to respond as rapidly as possible while maintaining accuracy.

4.4 Results

Figures 4 and 5 show the subjects' mean turning errors and latencies by locomotion condition in the virtual environment. We performed a one-way repeated measures ANOVA on the turning errors with the three conditions (joystick, WIP-wii, walking) as the within-subjects factor and find a main effect of condition $F(2, 22) = 7.4$, $p = .006$. Performing pairwise comparisons using Fisher's LSD test revealed that the joystick condition was significantly different from walking, $p = .007$, and from WIP–Wii, $p = .007$, but that the walking condition was not significantly different from the WIP–Wii condition. A separate analysis was conducted to see whether there was an effect of the order of the different testing conditions on the turning errors, and results revealed no effect of order. People made fewer errors if they explored the virtual environment physically or with WIP–Wii than with the joystick. Participants performed equally well in the walking and WIP–Wii conditions. We performed a similar one-way repeated measures ANOVA on latencies with the three conditions, but the effect of condition was not significant. A separate analysis confirmed taht there was no effect of order on latencies. The response times for participants were approximately the same across the conditions.

5. DISCUSSION

This article presents "walking in place" on a Wii Fit Balance Board (WIP–Wii) as a method of allowing users to freely locomote through a virtual environment. An experiment directly compares joystick locomotion, our WIP–Wii method, and normal walking. We showed that joystick locomotion results in higher turning error (on the order of $5 - 8^{\circ}$ difference) than both the walking and WIP–Wii conditions. Thus, participants' spatial awareness of a virtual environment is significantly improved using their own physical locomotion or WIP–Wii over joystick locomotion. More importantly, our results show that participants' spatial orientation was similar in physical walking and WIP–Wii conditions in terms of turning error and latency. This finding suggests the Wii Fit Balance Board is a great inexpensive alternative to exploring a virtual environment.

It is important to note that our WIP–Wii method employs an orientation sensor. However, using some sort of orientation sensor is necessary to update the pitch, yaw, and roll of the user. Orientation sensors are commonly used with HMDs. We used this sensor in all three conditions to update the orientation of the participant.

In the work presented here, we have participants explore a virtual environment that was approximately the size of the tracking area of our HMD system. Our motivation was to directly compare physical locomotion with WIP–Wii. Ruddle and Lessels [2006, 2009] explore the importance of physical locomotion in exploring a virtual environment; Riecke et al. [2010] find physical rotation but not locomotion to be a key component. Other work [Chance et al. 1998; Ruddle and Lessels 2006; Lathrop and Kaiser 2002] has shown that physical waking is better than using a joystick. We hypothesized that the WIP–Wii method would fall between physical walking and joystick locomotion in terms of spatial awareness. WIP–Wii superiority over the joystick seems to suggest that WIP does provide the user with some of the proprioceptive cues of walking. Interestingly, we did not find a significant difference in the spatial awareness of the virtual environment when the environment was explored on foot or by WIP–Wii. Our finding is also not in line with a prior implementation of WIP, that of Feasel et al. [2008]. Their system is quite different, employing chest orientation sensors to track orientation and tracking heel positions for locomotion, which perhaps impacts spatial orientation differently.

There are several possible reasons for these results. As mentioned previously, our work joins a body of prior work [Chance et al. 1998; Lathrop and Kaiser 2002; Ruddle and Lessels 2009; Riecke et al. 2010] indicating that joystick locomotion is inferior to motion in which physical movement occurs. These findings are consistent with work showing people have difficulty updating headings given only visual stimuli [Klatzky et al. 1998; Gramann et al. 2005], which may be due to underlying neural representations [Gramann et al. 2010; Plank et al. 2010]. Physical movement may prime the sensorimotor system to more easily adopt an underlying spatial representation in which task performance can be enhanced. If sensorimotor priming is responsible for performance differences between joystick and physical movement, it is perhaps less surprising that WIP–Wii and walking conditions had equivalent performance, since the idiothetic cues of movement are likely dominated by vision. What is interesting is that WIP-Wii can stimulate such cues. One participant reported that the WIP–Wii condition "seemed very adaptable. It didn't take me long to get the hang of it." Another subject stated that the WIP–Wii condition "feels like you are moving around because the feet are moving." The notion of visual dominance over physical movement has been previously exploited in much of the "redirected walking" literature [Williams et al. 2006; Razzaque et al. 2001; Engel et al. 2008; Nitzsche et al. 2004; Steinicke et al. 2010; Xie et al. 2010]. Williams et al. [2006] scale the translational gain of walking so that one step forward in physical space carries one several steps forward in virtual space. They find no significant difference in spatial awareness when the translational gain of walking is scaled by two and by ten as compared to normal bipedal locomotion. Additionally, work has been done [Razzaque et al. 2001; Engel et al. 2008; Nitzsche et al. 2004; Steinicke et al. 2010] that imperceptibly rotates the virtual environment so that the physical locomotion of the user fits within the confines of the tracking system. Again, researchers are able to successfully manipulate the mapping between normal physical walking and visual flow in such a way that benefits spatial orientation and provides the user with an opportunity to explore a virtual space larger that the tracking space of the HMD. However, we should not discount the possibility that the WIP–Wii and the walking condition could have been performed similarly because subjects found the HMD tether in the walking condition distracting. One subject commented that the cord sometimes seemed a little heavy. Clarifying these issues is the topic of future work.

There were a few criticisms of our WIP–Wii method. One participant found it “hard to control small movements” in the WIP–Wii condition. Also, a few comments revealed that the Wii Balance Board “seemed rather small.” However, none of the subjects unintentionally moved off the board during the experiment. One subject did intentionally step off the board to turn to face the different objects in the environment. From observing the subjects perform the experiment, we found that subjects’ feet would sometimes land on corners of the board. They seemed to quickly correct themselves and move their feet to the center of the board. Interestingly, there were not many missteps. A little over half the participants took off their shoes for the WIP–Wii condition. They were instructed that they could do so if they were inclined. One hypothesis for the subjects’ ability to turn around freely and walking in place on this relatively small board without unintentionally stepping off the board could be that the subjects had prior experience with the Wii–Fit Balance Board. However, only two out of the twelve subjects had ever been on a Wii–Fit Balance Board.

We think the WIP–Wii method could be a viable method for exploring a large virtual environment, that is, an environment that cannot easily be explored on foot because of the limits of the tracking system. Other methods to explore large virtual environments [Razzaque et al. 2001; Engel et al. 2008; Nitzsche et al. 2004; Steinicke et al. 2010; Interrante et al. 2007; Xie et al. 2010; Usoh et al. 1999; Fernandes et al. 2003; Schwaiger et al. 2007] suffer being relatively expensive and employ technology that is not readily available to the public. In contrast, the Wii Fit Balance Board is readily available to consumers and is inexpensive. Thus, we plan to explore this idea in the future.

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