Proceedings of Virtual Reality International Conference (VRIC 2010), 7-9 April 2010, Laval, France.
RICHIR Simon, SHIRAI Akihiko Editors. International conference organized by Laval Virtual.

Traveling in 3D Virtual Environments with Foot Gestures and a Multi-Touch enabled WIM

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Abstract

In this paper we demonstrate how foot gestures can be used to perform navigation tasks in interactive 3D environments and how a *World-In-Miniature (WIM)* view can be manipulated via multi-touch gestures in order to ease the way-finding task in complex environments. Geographic Information Systems (GIS) are well suited as a complex test-bed for the evaluation of user interfaces based on multi-modal input. Recent developments enable the construction of low-cost multi-touch sensors and relatively inexpensive devices for detecting foot gestures. In this paper, we describe an intuitive 3D user interface setup which combines multi-touch hand and foot gestures for interaction with spatial data and allows to exploit these input modalities for virtual reality environments.

Keyword: 3D user interface, 3D navigation, multi-touch interaction

I. INTRODUCTION

Navigation is one of the most basic and common interaction tasks in virtual environments (VEs). Many applications from different domains require intuitive metaphors and techniques to explore their underlying data. In particular, 3D geospatial data has grown in popularity and has been used widely in many different

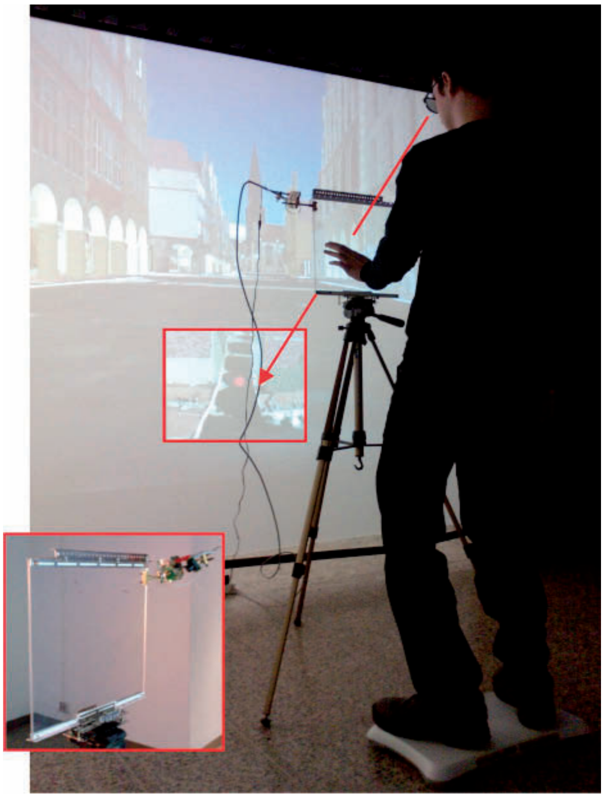

Figure 1. Subject using the multi-touch enabled Human-Transporter metaphor to travel through a virtual 3D city model displayed on a stereoscopic back-projection wall. The setup consists of a transparent FTIR-based multi-touch surface statically mounted on a camera tripod for hand input, and a Nintendo Balance Board for foot input.

application domains in recent years. While generating, processing and visualizing these complex data sets has been addressed through many sophisticated algorithms, current navigation and exploration techniques are often not sufficient for geospatial environments [1]. Navigation is often referred to as the combination of way-finding and travel [3]. Way-finding denotes the cognitive aspects of navigation in which users build a cognitive, mental representation of the environment. Way-finding determines how to get from one location to another, but does not involve the actual movement. In contrast, travel refers to the physical aspects of the navigation. In the context of virtual reality (VR) it denotes the physical action of changing the position and the orientation of the virtual viewpoint, according to the underlying metaphor.

Walking is the most intuitive and natural method to explore data from an egocentric point of view [18]. However, real walking introduces problems in setups with limited walking space, such as CAVEs. Locomotor simulators [10], omni-directional treadmills [14] and “redirected walking” [11, 15] provide certain solutions in this context, but often require a complex setup. Furthermore, real walking could be exhaustive for exploration of large datasets, such as virtual 3D city models or landscape terrains, especially if performed for extended periods of time. Similarly, many handheld 3D input devices for immersive VEs are complex and exhausting to use. This may divert the user’s focus from her primary task [1], or can result in the user losing orientation due to unnatural motion techniques or unintended input actions.

Sophisticated 3D user interfaces, as they are provided by VR systems based on stereoscopic projection and tracked input devices, are rarely adopted by ordinary users or even by experts due to their overall complexity [24]. However, a major benefit of stereoscopy is binocular disparity that provides better depth awareness. When a stereoscopic display is used, each eye of the user perceives a different perspective of the same scene. This can be achieved by either having the user wear special glasses or by using special 3D displays. For this reason, VR systems using tracking technologies and stereoscopic projections of 3D synthetic worlds have a great potential to support a better exploration of complex data sets.

Multi-touch interaction has shown significant potential for exploring complex content in an easy and natural manner, and hand gestures allow precise input of point and area information. However, multi-touch surfaces exhibit limitations in the context of stereoscopically rendered projections, since the input interaction is constrained to a 2D plane. Furthermore, it is difficult to input continuous data with one or two hands for a long period of time.

Foot interaction, in contrast, can provide continuous input by just shifting the body weight on the respective foot. Since humans primarily use their feet to travel in real life, foot gestures have the potential to provide a natural and intuitive navigation metaphor.

Instead of using solely 3D hand-based input or physical locomotion systems, we propose to use a combination of hand and foot gestures for 3D traveling and to provide a *World-In-Miniature* (WIM) view [16], which can be manipulated by multi-touch input to support the user in the way-finding task.

The geospatial domain provides an interesting test-bed for multi-touch applications because the command and control of geographic space (at different scales) as well as selection, modification and annotation of geospatial data are complicated tasks and have a high potential to benefit from novel interaction paradigms [17].

In this paper we propose a navigation device based on a Nintendo Balance Board and a transparent *“frustrated total internal reflection (FTIR)”*-based [7] multi-touch surface for navigation through 3D geospatial data from an egocentric perspective, as well as a multi-touch enabled WIM approach to support the user’s orientation and the definition of long-distance travel paths. The multi-touch surface is separated from the main non-touch visualization display and could further be used as touch enabled transparent props for manipulation of arbitrary 3D objects in the scene. The work extends our previous setup in which we have simulated a Human-Transporter vehicle [23] by integrating a flying metaphor and extending the interaction possibilities with the WIM. Furthermore, we have conducted an initial user-study in order to verify if the user really benefits from the WIM and to which extent the WIM affects the grade of immersion into the proposed VE.

The remainder of this paper is structured as follows. Section II gives an overview about related work. Section III describes the proposed setup. The results of the conducted user study are presented in Section IV. The paper concludes in Section V and gives an overview about future work.

II. RELATED WORK

Many different approaches for exploring a virtual environment have been introduced in the last decades [2, 12, 19]. Some of them require the user to locomote through the real world while these movements are mapped to motions of the virtual camera [9, 15], other approaches make use of 2D or 3D input devices [6], which are used to specify motion parameters like direction, speed, start and stop [2, 12]. Several metaphors address the challenge of unlimited and efficient navigation in VEs by preventing a displacement of the user in the real world. In [18] some examples are presented and compared which show the benefits of natural navigation techniques in particular for egocentric navigation tasks.

The WIM metaphor is usually applied in VEs with egocentric view. It provides the user with an additional, third-person view perspective through a dynamic, hand-held miniature copy of the environment. WIM has been used successfully to accomplish common travel and navigation tasks [21, 22]. In the original paper [16] the miniature presented the whole VE, which has limited its application to simple environments. Trueba et al. [21] and Wingrave et al. [22] have proposed suitable methods to overcome these limitations. Although many different variations of a WIM metaphor have been proposed in recent years, to our best knowledge there is currently no implementation which can be manipulated through multi-touch gestures. Considering the successful application of multi-touch technology in related application areas, we want to explore the potential of such an approach.

Multi-touch technology is in the focus of several research projects, and it has been shown that it provides many benefits over traditional desktop systems, in particular, when it comes to natural 2D interactions. Tactile feedback provided by a multi-touch enabled surface is advantageous, especially in tasks where visual feedback is often occluded by the pointing device or graphical representations [5]. Furthermore, the combination of multi-touch input devices with a physics engine is shown to increase the naturalness for a range of interaction tasks [20]. Another advantage of multi-touch surfaces is that the user needs not to be equipped with any devices in order to interact in an intuitive way. However, until now challenges and limitations of multi-touch interaction in the context of 3D navigation, especially for stereoscopically rendered VEs, have rarely been considered.

One important observation of previous studies with multi-touch GIS is that users initially preferred simple gestures, which are familiar from systems with mouse input using the WIMP desktop metaphor [13, 25]. After experiencing the potential of multi-touch, users tended towards more advanced physical gestures to solve spatial tasks, but often these were single-hand gestures or gestures, in which the non-dominant hand just sets a frame of reference that determines the navigation mode, while the dominant hand specifies the amount of movement [20].

Embedding a 2D interaction metaphor in 3D VEs by using different types of physical or virtual props has been shown to be advantageous for many application domains [26, 27]. Recently, Looser et al. [28] have developed a flexible magic lens metaphor for augmented reality GIS applications. In their setup hand gesture and button input are used both to control the form of the magic lens and to interact with the virtual context. Schmalstieg et al. [29] have also proposed a 2D metaphor for interaction in 3D VEs. They used a transparent touch pad and a pen for interaction with GUI elements or 3D objects stereoscopically projected on a tabletop VR display.

The Balance Board introduced by Nintendo in the second half of 2007 contains multiple pressure sensors that are used to measure the user's center of balance and weight. Nintendo introduced several metaphors like a surfboard, magic carpet, or 2D transporter to use this board for traveling in games. Since the Nintendo Balance Board has been introduced, it has already been applied in some research projects. For instance, De Haan et al. [4] have applied the board to define an input device with 3 degrees of freedom (DOF), which they used to implement 3D rotations or a basic navigation technique. Schöning et al. [13] have examined simultaneous usage of hands and feet to manipulate two-dimensional GIS data sets.

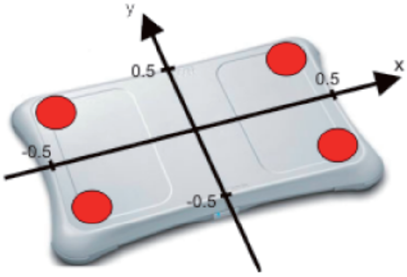

Figure 2. Illustration of the Balance Board and its four pressure sensors at its corners

By separating the tasks which have to be performed by hands or feet, they were able to achieve an improvement of the user's performance due to the parallel input from multiple channels. Hilsendeger et al. [8] proposed a navigation technique similar to a Human-Transporter. In their research different transfer functions for steering control, as well as differences between speed and acceleration control are evaluated and intriguing results are reported.

III. IMPLEMENTATION

In this section we explain how some traveling metaphors could be implemented as natural combinations of hand and foot gestures for 3D traveling. We use the multi-touch surface for discrete, constrained input gestures and the Balance Board for continuous input to navigate.

A. *Hardware Setup*

The hardware setup (shown in Figure 1) consists of a stereoscopic back projection display, a Balance Board and a transparent FTIR-based multi-touch surface. For the presentation of the VE a large-scale display with passive circular-polarized back projection is used. The multi-touch surface consists of an acrylic plate with a set of IR LEDs and a wide-angle (107°) camera mounted on its side. The camera is mounted outside the view frustum defined by the border of the acrylic plate and the user's head. Hence, the camera itself does not occlude objects behind the transparent surface. For finger detection ReacTIVision's TUIO server is used. In order to reduce fatigue for the user, the surface is mounted on a common camera tripod.

The Balance Board (see Figure 2) features a Bluetooth connection and contains multiple pressure sensors that are used to measure the user's *center of balance* as well as her weight. The *center of balance* is determined by the intersection between an imaginary line drawn vertically through the user's center of mass and the surface of the Balance Board.

B. *Simulation of a Human Transporter*

As mentioned above, we use the Balance Board for navigation in a virtual world. The steering and speed control are inspired by the Human Transporter vehicle (such as the one developed by "Segway"). Leaning forward or backward leads to forward or backward motion of the vehicle, while leaning left or right turns it in this direction. In order to implement such a control a 2D projection of the user's center of gravity, i. e., her *center of balance* c, is used to move a uniform mass across the board. This way we minimize the impact of different user weights.

1) Speed Control

For speed control we use the y-component c_y of the user's center of balance c. Moving the uniform mass along the y-axis of the board produces a rotational moment, which is proportional to the distance between its center of gravity and the vehicle's wheel axis. Since our coordinate system is aligned with the wheel-axis, the rotation moment is given by:

$$M(c_y) = -c_y \cdot F = -m \cdot g \cdot c_y$$

where m is the weight of the uniform mass, $g \approx 9.81 m/s^2$ is Earth's gravitational acceleration and $F = m \cdot g$ denotes the gravity force of the uniform mass. Applying reverse torque $M_R = -M$ to the wheels in order to compensate the declination of the platform results in forward (or backward for negative c_y) motion of the vehicle. In order to keep the calculations simple, we define the torque-to-speed function as $\omega = k \cdot M$ with a transmission coefficient k. Thus the speed of the left wheel ω_L and the speed of the right wheel ω_R resulting from shifting the user's body weight forward or backwards are equal and given by:

$$\omega_R(c_y) = \omega_L(c_y) = k \cdot c_y \cdot F = k \cdot m \cdot g \cdot c_y \qquad (1)$$

2) Steering Control

By leaning left or right the user moves her center of gravity, and hence her center of balance, along the vehicle's x-axis and thus the weight distribution between the two wheels changes. A weight applied to the board produces pressure on the wheels and therefore increases the rotational friction between the wheels and the ground. Changing the weight distribution between the wheels will result in different friction and thus in different rotational speed of the two wheels, i. e., the wheel to which more weight is applied will rotate slower than the other and a turn in this direction will result. For the calculation of the rotational friction force we use the equation:

$$F_{fr} = \pm 0.01 \cdot k_{fr} \cdot F$$

where k_{fr} denotes the friction coefficient between the wheels and the ground. Here F denotes the force applied perpendicularly to the two surfaces in contact. In our case this is the gravity force of the weight applied to the wheel. The multiplicative constant *0.01* is the empirically observed relation between rotational and sliding friction forces. Since the friction force takes effect against the motion direction and on the edge of the wheels, the rotational moment resulting from it is given by:

$$M_{fr} = -sign(c_y) \cdot 0.01 \cdot k_{fr} \cdot r \cdot F \ ,$$

where r denotes the radius of the wheel. If the vehicle's platform is a unit square, we can calculate the weight exerted on each wheel. With m as the weight of the uniform mass and c_x as the x-component of the user's center of balance we have:

$$\begin{aligned} m_R(c_x) &= (0.5 + c_x) \cdot m \\ m_L(c_x) &= (0.5 - c_x) \cdot m \end{aligned}$$

Here m_R is the weight exerted on the right wheel, and m_L is the weight exerted on the left wheel.

Finally, the rotational speed loss induced by the friction is given by:

$$\omega_{frR}(c_x) = -sign(c_y) \cdot 0.01 \cdot k_{fr} \cdot r \cdot m \cdot g \cdot (0.5 + c_x) \qquad (2)$$

$$\omega_{frL}(c_x) = -sign(c_y) \cdot 0.01 \cdot k_{fr} \cdot r \cdot m \cdot g \cdot (0.5 - c_x) \qquad (3)$$

The combination of (1) and (2) gives the final result for the wheel speed:

$$\begin{aligned} \omega_R(c) &= sign(c_y) \cdot m \cdot g \cdot \left(k \cdot |c_y| - 0.01 \cdot k_{fr} \cdot r \cdot (0.5 + c_x)\right) \\ &\approx sign(c_y) \cdot m \cdot g \cdot \left(k \cdot |c_y| + 0.01 \cdot k_{fr} \cdot c_x\right) \end{aligned}$$

Similarly, combining (1) and (3) gives:

$$\omega_L(c) \approx sign(c_y) \cdot m \cdot g \cdot \left(k \cdot |c_y| - 0.01 \cdot k_{fr} \cdot c_x\right)$$

The last equations show that the rotational speed of each wheel is controlled by the y-component of the user's center of gravity while the x-component adds a negative correction to it, i. e., it acts as braking. Once the rotational speed of the two wheels is determined, one can use a common differential steering equation [30] to determine the new position and orientation of the vehicle, as well as its motion speed.

The derived motion calculations differ considerably from the approach used in Segway's Human Transporter and therefore implement a significantly simpler method. The Segway's Human Transporter accelerates to compensate the user's tilt avoiding this way a potential slump, which cannot happen with a Balance Board.

C. A Flyer Metaphor

The "Flyer" metaphor provides the user with the ability to fly over the virtual 3D environment. As shown in many works, such a metaphor supports users by building a cognitive map of the environment, and it has been proven to be very helpful for spatial orientation and performing way planning/finding tasks. Because of the positive feedback which we have received in earlier work, we have decided to keep the steering concept of the Human Transporter unchanged for the Flyer metaphor. Nevertheless, this steering concept is extended in order to provide the additional degrees of freedom needed by a flying metaphor (i.e. changing the height of the virtual camera). Reflecting on the formulas given above, one could realize that if the user presses her toes on one side of the Balance Board and her heel on the diagonally opposite side, the vehicle will (counter-intuitively) not move, because the weight distribution between the two wheels remains the same and the forward and backward rotational moments compensate each other. Thus, we can use this particular gesture for changing the current height of the virtual camera. By utilizing this unused foot-gesture for height control and keeping the overall steering unchanged, we provide a user with the option of using both metaphors without switching between one another. In fact the Human Transporter metaphor becomes a subset of the Flyer in which the height of the virtual camera is constrained to a constant.

D. *World-In-Miniature Metaphor*

As mentioned above, we make use of a multi-touch surface, which consists of an acrylic plate with a set of IR LEDs and a camera mounted on its side. Since we can track both the user's head as well as the multi-touch surface, the transparency of the surface allows to display objects on a projection screen behind the surface in such a way that they appear either behind, attached to or in front of the multi-touch surface. In order to reduce fatigue for the user, the surface is mounted on a common camera tripod.

1) *Interface*

In order to support the user's orientation in the VE we provide a WIM view, which the user can control using multi-touch gestures. The WIM view is displayed as inset in the viewport that is used to render the egocentric view of the VE, which the user perceives on the projection wall. The position of this viewport is calculated separately for the left and the right eye according to the frustum defined by the user's head and the multi-touch surface in such a way, that the WIM appears attached to the multi-touch surface (illustrated in Figure 1). The WIM view itself is created by rendering the VE from the viewpoint of an additional (slave) camera, placed with an offset relative to the egocentric camera and directed to it (s. Figure 3). The scale of the WIM and the position of the slave camera can be manipulated using multi-touch gestures, such as pan, pinch, rotation, etc.

2) *Viewpoint Control*

Using the interactive surface the user can steer the virtual slave camera and modify the scale of the WIM view via single- and double-touch gestures. These gestures affect only the slave camera used to render the WIM, whereas the view on the projection wall is not altered.

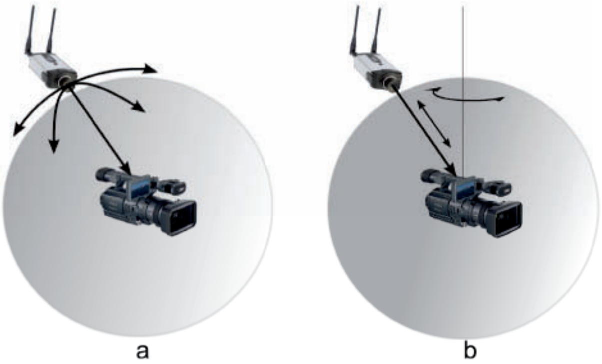

Figure 3. Illustration sketch of the WIM interaction: a) Single finger pan gestures map to azimuth and elevation of a virtual trackball control centered on the user's current position. b) Pinch and rotate gestures define scaling and rotation around the main-cameras up-axis.

On the other hand, when using the Balance Board to move the egocentric viewpoint through the VE, the focus point for the WIM changes accordingly. This allows users to obtain additional information about the environment via the WIM while traveling using the Balance Board. Therefore, we map single finger pan gestures to azimuth and elevation of a virtual trackball control centered at the user's current position as used to render the egocentric view on the projection wall (Figure 3a). If two touch points are detected on the surface, we can define a line between them. Changing the position of one or both touch points defines a new line with different length and/or orientation. The difference of the length of these two lines and the angle between them is used for pinch and rotate gestures. The rotate gesture is used to rotate the slave camera around the main camera's up axis (Figure 3b). The pinch gesture is used to scale the WIM, providing users with the ability to get a detailed view of the current surroundings in an arbitrary direction or a broader overview of the environment. The transmission coefficient of the Human-Transporter, i.e., its speed sensitivity, is adjusted with the scaling factor of the WIM to provide an adequate motion speed according to the WIM view.

We also implemented long distance travel via the WIM. A user has to double-tap at the desired position in the WIM view, which places the main camera used for the projection wall at the corresponding position in the VE and aligns the WIM accordingly. Since direct "teleportation" often leads for the user to momentary loss of orientation, we have rather implemented a slow-in-slow-out type of space jump between the current and the desired location (as proposed in [22]).

Figure 4. A screenshot of the virtual 3D city model of the city of Münster, used as a VE in the evaluation study.

This aims to reduce this effect and to give some time to the user to adjust to the new surroundings. An alternative approach could be to calculate a reasonable trajectory between the two locations and to trigger a non-interactive flight between them. This could lead to an additional advantage of supporting a cognitive map building by the user. Such a flight could provide information about the position of the desired target in relation to the current position of the virtual camera. Such an approach may be addressed in the future.

IV. PRELIMINARY EVALUATION

In order to analyze the benefits and drawbacks of our proposed setup we performed a simple evaluation in which we presented the hardware setup and the metaphor in a typical VR environment.

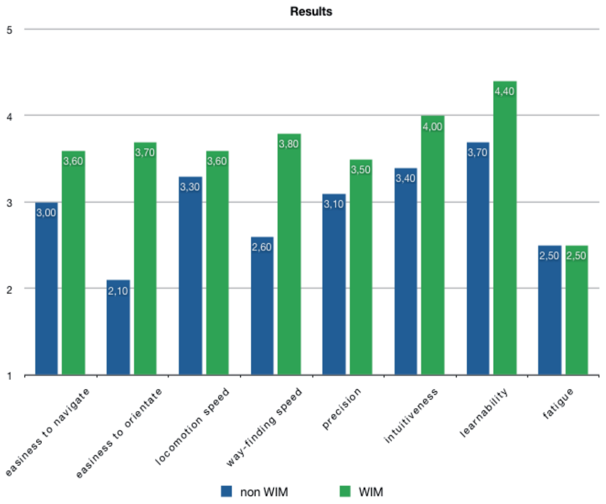

Figure 5. The average scores for the evaluated parameters under two conditions – one with the WIM metaphor enabled and one with the WIM disabled.

A. *Participants*

A total of 11 male (age 23 – 55, Ø: 29.27, height 172cm – 190cm, Ø: 184.27) subjects participated in this test. Subjects were students or members of the computer science department of the University of Münster. Two of them had no relevant 3D game experience, and the rest had some. All subjects had normal or corrected vision.

All subjects were naïve to the experimental conditions and had never used the device before. The total time per subject including pre-questionnaire, training, experiment, breaks, and debriefing took 30 minutes. Subjects were allowed to take breaks at any time.

B. *Procedure*

The subjects did not receive any instructions about the underlying locomotion or steering concept. We simply told them that they have to use the device in order to navigate through a virtual 3D city model. Therefore, we used a visualization application which supports the display of large scale city environments (see Figure 4).

At first, subjects had to step on the Wii balance board, and we allowed them to navigate for 1 minute in the virtual 3D city model without any instructions. Afterwards, we asked the subjects to navigate to certain locations in the city model. Subjects had to navigate from the start position via two stopovers to the end position. The length of the overall path was about 2.5 km. The maximum speed supported during this experiment was about 10 km/h. Since the target locations were global landmarks and all subjects were familiar with the displayed city environment, the way-finding component in this task was very simple. Therefore, subjects could concentrate on the traveling task with the metaphor. Nevertheless, since the participants have not been living in the city for the same length of time and have different basic orientation skills, we have not measured absolute performance values, such as time to completion, but rather constrained the maximal time for completion to 10 minutes.

We tested two different conditions in a within-subject design, i.e., all subjects performed the test with and without a WIM. Half of the subjects performed the experiment first with the WIM and then without a WIM, half of the subjects performed the test in reversed order. The results for those participants who were not able to perform the task within the 10 minutes constraint either for the WIM or the non-WIM condition were not taken into consideration.

After subjects had successfully completed the task, we interviewed them about their experiences during the test. Among other aspects they had to evaluate easiness to navigate and to orient, the locomotion and way-finding speed, precision, intuitiveness, learnability and fatigue. The subjects had to rate all aspects on a five point Likert-Scale, where 5 refers to positive evaluation, and 1 corresponds to negative evaluation.

C. Results

Overall, the feedback of the subjects was very positive. All 11 participants were able to perform the task within 10 minutes for the WIM condition, and one has failed for the non-WIM. Figure 5 shows the average values pooled over all subjects for both conditions, i.e., with and without WIM. We have further tested the results for significance using a two-sided t-test. The plotted results show that for all considered aspects, the condition in which the WIM is provided outperforms the non-WIM condition, except for level of fatigue, which is equal for both conditions.

One of the most remarkable differences for the two conditions is the easiness to orientate. The result for the WIM condition (average of 3.7) is significantly higher than for the non-WIM condition (2.1) with $p < 0.02$. Furthermore the way-finding speed rises on average by 1.2 points from 2.6 to 3.8 when providing a WIM view, the t-test has shown for this result a significance level of $p < 0.02$.

For all the other parameters no significant difference has been found. On average subjects evaluated the easiness to navigate under the non-WIM condition with 3.0, whereas subjects rated this aspect with 3.6 if a WIM is provided. The locomotion speed and the precision of the metaphor are also barely affected by the usage of a WIM view (locomotion speed: 3.3 vs. 3.6, precision: 3.1 vs. 3.5). Interestingly, intuitiveness and learnability of the traveling technique are also evaluated better for the WIM condition, though no significant difference has been found. Intuitiveness grows on average from 3.4 for the non-WIM to 4.0 ($p = 0.14$) for the WIM condition, and learnability from 3.7 to 4.4 ($p = 0.19$). Contrary to our initial expectation, fatigue of the navigation technique is evaluated on average to be relative high (though not affected by the WIM).

For both conditions all subjects remarked that after a short adaptation they were able to navigate easily through the virtual world, and they found the steering very natural. Furthermore, during the experiment all four subjects have tried out different options without being required to do so. Nevertheless, most subjects had particular problems to make a turn in place or within short distance. Furthermore, some of them remarked that it was difficult to maintain direction for a long time or to stay in place without moving in any direction. This could indicate a need for nonlinear speed control in our metaphor.

V. CONCLUSION AND FUTURE WORK

In this paper we have proposed a navigation metaphor based on a combination of a Nintendo Balance Board and a transparent FTIR-based multi-touch surface. The multi-touch surface was used to manipulate a WIM integrated into the proposed VE.

The results of the conducted evaluation motivate us to extend the proposed setup and to develop further interaction metaphors. Moreover, we want to incorporate other interaction metaphors, which make use of the multi-touch capability of the transparent surface, and to further investigate the combination of a WIM metaphor and multi-touch input.

ACKNOWLEDGEMENTS

The authors of this work are supported by the German Science Foundation DFG 29160938 and DFG 29160962.

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