Evaluation of Hands-Free HMD-Based Navigation Techniques for Immersive Data Analysis

Daniel Zielasko* Sven Horn† Sebastian Freitag* Benjamin Weyers* Torsten W. Kuhlen*

Visual Computing Institute, RWTH Aachen University
JARA – High-Performance Computing

ABSTRACT

To use the full potential of immersive data analysis when wearing a head-mounted display, users have to be able to navigate through the spatial data. We collected, developed and evaluated 5 different hands-free navigation methods that are usable while seated in the analyst's usual workplace. All methods meet the requirements of being easy to learn and inexpensive to integrate into existing workplaces. We conducted a user study with 23 participants which showed that a body leaning metaphor and an accelerometer pedal metaphor performed best. In the given task the participants had to determine the shortest path between various pairs of vertices in a large 3D graph.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Evaluation/methodology

1 INTRODUCTION

The analysis of spatial data sets can benefit from their inspection in Immersive Virtual Environments (IVEs) [2, 22, 23, 30]. These are accessible via high fidelity projection systems such as CAVEs [9] or large display walls [14]. Another option are head-mounted displays (HMD) [37], which increasingly catch up to these large systems regarding disadvantages such as smaller field of view, lower resolution, heavy headgear and others [24]. Additionally, they are portable and easy to install. This is of special interest, as on the one hand, data analysts and domain experts do not always have access to large and expensive projection systems and on the other, these are not always easy to integrate into their usual workflows. In our opinion, the use of lightweight immersive display systems like HMDs that are directly integrable into the office workplace of the analyst and therefore into her usual workflow can create more acceptability and thus increase productivity.

The main focus of this work is that the user needs to navigate through spacial data, which is often too large to be observable from one view point. Classic device combinations for navigation, like mouse and keyboard, or devices like joysticks and gamepads are usually not an option, as they cannot be seen when wearing an HMD and additionally occupy the hands of the analyst. The latter prevents her from, e.g., manipulating objects in the virtual data space in a natural way at the same time [3, 35]. This reduces the immersion, which in case of virtual data analysis is different from immersing a user in a realistic virtual environment setting, but nevertheless adds to the user's ability to build a mental model of the data and finding her way [6].

To specifically address the analysis workflows of domain scientists working with desktop PCs or laptops, we decided to consider only navigation methods that can be used while seated. This again keeps everything easily integrable into the common workspace of an analyst and additionally is more comfortable and less fatiguing in longer periods of use [8]. In addition, different studies and theories report that a seated posture is less vulnerable to simulator sickness [29, 31], which supports potential longer usage times.

The sum of the aforementioned points led us to identify the following requirements for an HMD-based navigation technique that is applicable for efficient use on a daily basis within an application for virtual data analysis:

- **(R1)** keep the user's hands free
- **(R2)** be usable with the user sitting in an office chair
- **(R3)** simple and inexpensive installation and integration into analyst's existing workplace
- **(R4)** not only support ground-based navigation, but unrestricted flying

We conducted a survey of potential navigation methods that fulfill the named requirements and evaluated them against each other and against a standard navigation technique, realized with a gamepad. These methods include existing ones, namely a slightly adapted "Shake-Your-Head" [39] and a leaning metaphor [12, 27]; an adapted "Walking-in-Place" (WIP) metaphor [35] and finally two new developed accelerometer pedal metaphors.

The rest of the paper is structured as follows. We discuss the related work in section 2. In section 3, we introduce the different navigation techniques and their implementation. The evaluation of these techniques is described in section 4 and the main results are presented in section 5. Furthermore, we discuss these results in section 6 and close with a conclusion of this work and outlook on future work in section 7.

2 RELATED WORK

The most natural way to navigate through an IVE is real walking. But this needs a lot of space and is not easy integrable into the workplace of a data analyst. While WIP [35] or devices like an omnidirectional treadmill [7] dramatically reduce the necessary space, it remains questionable how high the reachable level of presence is by the use of a walking metaphor within an abstract data space, where the more convenient metaphor is flying. Nevertheless, many studies report that the integration of body motion cues increases presence [5, 33] and so the ability to orient oneself, and simultaneously decreases the effects of simulator sickness [4].

2.1 Walking-in-Place Techniques

Terziman et al. [39] showed that it is possible to realize WIP even while seated and with very restricted hardware. Their method, called "Shake-Your-Head", records the head movements of a user with a webcam and deduces how these relate to the body/head movements while walking. The computed speed then is applied in the user's viewing direction. The original implementation uses a non-stereoscopic setup and provided only ground-based navigation, but Terziman et al. stated that the technique is also applicable to HMDs. Thus, we slightly modified it by adding features for unrestricted flying (see section 3.4). Even though inspired by WIP,

*e-mail: {zielasko, freitag, weyers, kuhlen}@vr.rwth-aachen.de
†e-mail: sven.horn@rwth-aachen.de

it has to be noticed that this method differs in an important point from *real* WIP: While the user still can use her feet to move, she no longer has to. From this perspective, the technique can also be classified as a general body motion technique (see section 2.3).

Tempelman et al. [38] used sliding foot pedals in a seated HMD-based setting to mimic walking and control the speed of the user's movement in the direction given by a gamepad stick. Thus, this method uses very special hardware and is again ground-based. Additionally, their technique requires a joystick, which occupies the hands.

Kim et al. [19] introduced a WIP technique that is used while standing, but they detect the walking movements with the combined sensor data of two smartphones or one smartphone and a magnet that are attached to the user's legs. As today nearly everybody has a smartphone within reach, we hooked this idea in two of the evaluated methods that are driven by lower body movements: A seated WIP (see section 3.1) and an accelerator pedal metaphor (see section 3.2).

2.2 General Techniques Using Feet

There are several reasons not to use a walking metaphor. First of all, WIP suffers from the oscillating characteristic of natural walking that makes it difficult to keep a uniform movement speed. It is also difficult to immediately detect the start/stop of an intended motion, which is, e.g., addressed by Feasel et al. [13] and Wendt et al. [41]. Another reason could be, as mentioned before, that walking just does not match the related metaphor in the IVE, e.g., in non ground-based navigation scenarios. Nevertheless, using the user's feet as input for navigation without mimicking walking is very common, because it keeps the hands free for other interactions and is easier to use within a spatial context [10]. Beckhaus et al. [3] used, among others, a simple navigation metaphor realized with a dance pad. Alexander et al. [1] showed that different basic discrete and continuous foot gestures are in general applicable for navigation and interaction tasks. They tracked the user's feet with an accelerometer. Daibler et al. [10] used continuous foot gestures for a pan-and-zoom navigation within a non-immersive spatial analysis task. As input device, they used a Wii balance board. Tracked with a Microsoft Kinect, Simeone et al. [34] use foot gestures to steer a virtual camera in a 3D setting. All the mentioned techniques control translation and orientation with the feet, while Guy et al. [17] derived from their results that it is better to control different interactions with uncorrelated body parts. Additionally, all approaches, except the approach by Alexander et al. [1], have in common that they use special tracking hardware. We developed two acceleration pedal methods with simple tracking gear, which use a foot to control navigation's velocity magnitude and the user's head to control the direction (see section 3.2).

2.3 General Body Motions

Other methods do not use the feet, but the whole body or upper parts. A popular metaphor is to navigate in the direction of the body's center of gravity, which is achieved by leaning the whole body [12, 17, 27] or just parts of it [17, 25] into the desired direction. The leaning itself can be detected by standard tracking technology, e.g., optical or inertial tracking, or with special devices like force plates, such as the Wii balance board [11, 40] or special prototypes as the one constructed by Marchal et al. [27]. The leaning metaphor is feasible also while seated as Kitson et al. [20] and Riecke et al. [33] showed with the NaviChair and Beckhaus et al. [3] evaluated using the Swopper^{TM}, both special joystick-like chairs without backrests. With navigation chairs like these up to three degrees of freedom can be controlled, a 2D translation and turning around, which is enough for ground-based navigation. We used optical tracking to implement a leaning metaphor that additionally enables 5-DOF-flying (see section 3.3).

Guy et al. [17] evaluated different combination of pairs of body parts, excluding the hands, for a translation and rotation in a ground-based scenario. As mentioned before they found that users performed best when translation and rotation were controlled by uncorrelated body parts and furthermore, when the movement plane in the virtual environment corresponds to the used body plane.

2.4 Other

Smith et al. [36] implemented a partial gaze-based navigation in a video game, by tracking the eyes of the user. This can also be realized with head tracking, which is an integral part of modern HMDs. While head tracking allows looking around in the IVE, it is additionally possible to control the orientation of the user's virtual body, which we utilized (see section 3).

McNeil et al. [28] used speech input to enrich the navigation capabilities of a 2D GUI. But existing speech approaches alone do not allow smooth navigation through an IVE.

Finally, Fujisawa et al. [15] proposed an easy-to-learn EEG-based navigation technique. This technology is still in its beginning. The rate of recognition is around 80% and it is not clear if the mental workload is low enough that a user is able to perform a primary task at the same time.

3 Navigation Methods

We adapted or developed five different navigation methods that fulfill the requirements R1-R4. These are, a seated walking-in-place (**sWIP**, see section 3.1), two accelerator pedal metaphors (see section 3.2), where one allows flying backward (**biAP**) and the other does not (**AP**), a leaning method (**Lean**, see section 3.3) and a version of "Shake-Your-Head" (**SYH**) that is extended to free flying (see section 3.4). We evaluated these five against a standard gamepad control (**Pad**, see section 3.5).

All methods use a tracked HMD and partially (sWIP, AP, biAP) a smartphone that is carried in the user's pants pocket. A smartphone application sends the raw sensor data of the phone's inertial measurement unit to the main application via Wi-Fi.

The user is able to change the orientation of her virtual body around the yaw (360°) and pitch axis (restricted to 90° in up and to 90° in down direction). The roll axis is fixed so that the user is able to keep track of top and bottom, which supports orientation. To rotate, the user turns her head in the desired direction, i.e., she turns her head to the left and the body is accordingly rotated in the yaw axis, she looks up and the virtual body is accordingly rotated around the pitch axis. The only exception of this mapping is SYH. In the original implementation of Terziman et al. [39], the yaw of the virtual body was controlled by a roll of the real head and we kept the mapping this way.

When changing the orientation in the described way, the ability to look around is lost, i.e. independently turning the virtual head from the virtual body. For this reason we defined a deadzone, the extend of we gathered experimentally (see section 4.3). Within this deadzone, there is no change of the virtual body's rotation. Outside of the deadzone, the virtual body is rotated and the speed of the rotation increases linearly according to the distance to the deadzone's border. An overlayed visual representation (see Figure 1) shows the user whether she is inside or outside the deadzone. The translation of the virtual body is applied in the viewing direction. The translation's speed is also considered in the visual feedback (see Figure 1) and is set by the methods described in the following subsections. By design it is possible to simultaneously perform a rotation and translation of the virtual body.

3.1 Adapted Walking in Place (sWIP)

In sWIP, the user has to repeatedly move one leg up and down to control her navigation speed. The acceleration sensor in the smartphone registers this movements and the speed is adjusted with re-

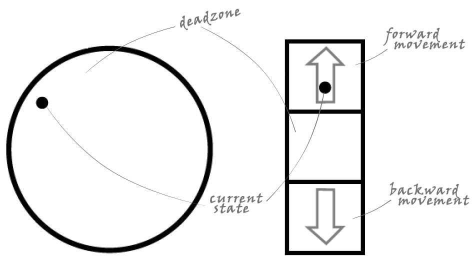

Figure 1: Visual feedback. The circle depicts the deadzone and the dot the state of the head's orientation, not leading to a rotation of the virtual body at the moment. In the right image the position of the dot relates to the state and magnitude of the translation's velocity: forward, zero (deadzone) and backward.

spect to the movement's frequency. Similar to Feasel et al. [13], the speed is scaled and smoothed. We defined a deadzone in this method too, to ignore small movements. As with the parameters for all implemented techniques, the size of the deadzone was chosen with respect to an empirical adjustment we performed (see section 4.3).

It is to mention that the only requirement for this method is that the user moves her thigh with the smartphone up and down. It does not matter how this movement is created. So the user can move both legs if this feels more realistic or just one, lift the whole leg or just seesaw on her forefoot.

3.2 Accelerator Pedal (AP & biAP)

The metaphor these methods are based on is an accelerator pedal, thus the user lifts and lowers the heel while the forefoot stands on the ground to control the translations speed. The different heights are tracked by the inertial measurement unit of the smartphone, which the user carries in her pants pocket. During a short setup, the user brings her heel into a comfortable position that is not on the ground, such that from this position it is possible to both, lift and lower the foot. This position is recorded and a deadzone is added. When the user leaves this zone downwards, she starts moving forward, with a speed that linearly relates to the distance to the deadzone's border. The same, but in the reverse direction, happens when she leaves the deadzone upwards. Of course, it is also possible to turn this mapping around as it might feel more natural for most of the people, but this mapping is our default as it is harder to lift the heel more out of a already lifted position then lowering it, and the forward movement is expected to be used more often.

After some initial testing, we got some comments from expert users that constantly lifting the heel could be exhausting after a while. Therefore, we added another method, where the reference position is a completely grounded foot whose heel can only lift. Thus, the user is only able to fly forward, which is closer to the metaphor of an accelerator method and therefore is named AP. As the first method allows bidirectional flying it is subsequently called biAP.

3.3 Leaning (Lean)

We determine whether the user sits up straight, leans forward or backward in her office chair by considering the distance to the HMD's tracking camera. The user's zero position is recorded before and can be adjusted quickly. A study conducted by Kruijff et al. [21] showed that static body leaning, i.e., the degree of leaning is directly mapped to a speed, generates a higher presence than a dynamic mapping. Thus we implemented a static body leaning method. This method also has a deadzone. When the user leans forward and leaves this zone, the speed increases linearly with the distance to the deadzone's border. The same holds for leaning backward, but in the reverse direction.

3.4 Shake Your Head (SYH)

We implemented SYH as introduced by Terziman et al. [39], but for the tracking of the head we used the tracking data of the HMD instead of a webcam. Furthermore, we added the possibility to rotate the virtual body around the pitch axis. This was not necessary in the original implementation as it was created as a ground-based navigation. To stay as close as possible to the original SHY, this is the only method that controls the yaw axis of the virtual body with the roll axis of the tracked head.

3.5 Gamepad Control (Pad)

The gamepad controls are defined as follows. The left analog stick rotates the virtual body around the yaw and pitch axes and the right one translates along the X and Z axes (ground plane). Additionally, the translation along the Y axis is possible with both right shoulder buttons. In the gamepad control the viewing direction is decoupled from the flying direction, which allows so called strafing, i.e. moving sideways.

4 Evaluation

The goal of this work is to find a suitable hands-free navigation technique for seated immersive data analysis. For this purpose, we evaluated the methods presented in section 3 against each other and a standard gamepad-control given as ground truth. In advance, we had some assumptions regarding secondary observations that we expected to make and list in the following:

(A1) Navigating with the gamepad is less exhausting than with all other techniques:
Because we do not use any body cues in the gamepad condition, we assume that the participants will report a higher grade of exhaustion with the tested techniques.

(A2) The awareness of being in the scene is lower with the gamepad:
For the same reason, namely the missing body cues, we expect a lower self awareness in the scene using the gamepad, as reported in different works of Grechkin et al. and Riecke et al. [16, 32]. Furthermore, this potentially can create more simulator sickness too, which also was observed by Llorach et al. [26].

(A3) SYH generates higher simulator sickness:
We expect SYH to cause more simulator sickness, first, because of the mismatch of virtual yaw to real roll axis and second, because of the continuous back and forth movement in the frontal body plane, where Guy et al. [17] strongly recommend to control a movement along the sagittal plane within the same.

(A4) SYH and sWIP are not as precise as the other techniques:
We assume that WIP-inspired techniques will have problems especially in small and precise movements as they work on a cyclic base, where state changes are harder to detect. This should be also visible in a worse overall task performance.

(A5) Techniques with the possibility to move backward (Gamepad, biAP, Lean) will profit from this:
Finally, we assume that the participants will use and benefit from the possibility to fly backwards where it is possible. For instance, they can correct a possible overshooting or get a better overview through a quick backwards movement. An interesting question in this context is also, if the backward movement is used in the same amount in the embodied methods as with the gamepad, because it could be perceived as costlier to induce this movement.

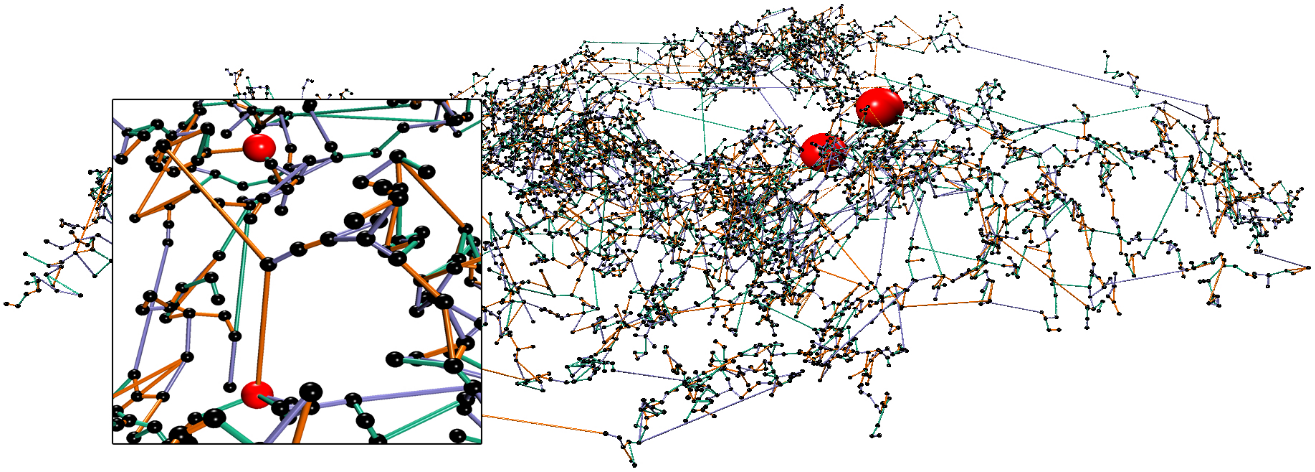

Figure 2: The graph that is used in the study. The task is to find the shortest path between a pair of vertices highlighted in red. In the detailed view on the left, the shortest path is 7. This path would also fulfill the requirement to include only orange edges. Additionally, the path length is difficult to determine only from this perspective and thus requires the use of navigation.

Figure 3: Experimental setup of the user study.

4.1 Apparatus

All experiments took place at a regular office desk, which the participant was seated in front of, on a rotatable and tiltable office chair with back- and armrests (see Figure 3). The IVE was projected by an Oculus Rift DK2. The HMD was tracked by its in-house infrared tracking system. Furthermore, the angle of one of the user's thigh was tracked by a regular android smartphone with an inertial measurement unit. The phone was worn in a front pants pocket or taped to the leg when the participant's clothes did not allow to place it in the described way. As gamepad, we used a Logitech RumblePad™ 2.

4.2 Virtual Environment

As virtual scene, we took a large 3D graph that depicts the solar systems of EVE Online[1] (5214 vertices) and the possible jump connections between them (6913 edges). In this game, every solar system has a security level, which is mapped to a color. It is more or less dangerous to include a system into a desired route from your current position to a target system. We were inspired by the analytic use case to find a route that optimizes the user's individual time to security ratio. Instead of coloring the graph's vertices, we randomly assigned one of three colors to each edge. The resulting graph is shown in Figure 2.

[1]space simulation MMORPG developed by CPP Games

4.3 System Calibration

We conducted a system calibration with 5 expert users to verify all methods and calibrate the method and system variables. This calibration includes the maximum translation and rotation speed, which is the same for all techniques and was set using the reference technique, the gamepad. Furthermore, these include method variables, such as the deadzones and the smoothing factor of the WIP techniques. All participants adjusted those parameters on the fly, i.e. while they were using the methods within the environment (see section 4.2). They were able to switch between the variables and the methods as long and as often as they were satisfied with the behavior of all techniques. They were asked to navigate long distances, i.e. in scale of the whole graph, as well as in a small scale, i.e. inspecting single vertex connectivities. As result we used the averaged variables in the study.

4.4 User Study

For the user study we used a 4×6 partial within-subject experimental design, i.e. every participant got 4 out of the 6 possible techniques, counter-balanced for order and frequency. At the beginning the participants received a written description of the procedure and saw a video describing their tasks. For each condition the participant than solved a training task followed by 6 real tasks (see section 4.4.2), resulting in $4 + 24$ trials in total. This design resulted in an HMD usage time per user of about 15 to 20 minutes, which we did not want to exceed because of potentially increasing effects of simulator sickness. Before the experiment, each participant filled out a demographic questionnaire and a Kennedy's simulator sickness questionnaire (SSQ) [18]. The SSQ was also filled out after the experiment. Additionally, the participants filled out Likert scale questionnaires and were asked to list advantages and disadvantages of the different methods in a free form and had space for general comments. In total the study took about 30 minutes.

4.4.1 Participants

23 subjects (4 female, mean age 29.5, SD = 10.4) finished the study, none of whom had participated in the system calibration. Additionally one participant prematurely canceled the experiment and

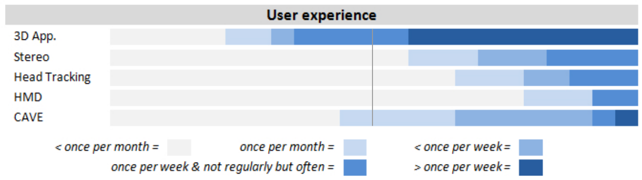

Figure 4: Distribution of the participants' experience with relevant technologies: 3D applications, stereo displays, head tracking, HMDs, CAVE-like systems.

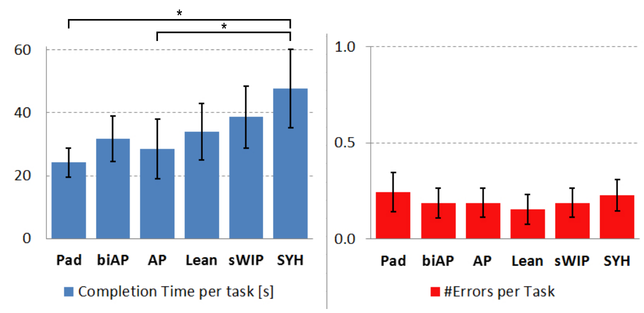

Figure 5: Results for the main dependent variables: Task completion time and errors per task. The error bars show the 95% confidence intervals. A * denotes statistical significance ($p < .05$).

was not considered in the analysis, because of incomplete data. As an incentive, three non-cash prizes with a total value of 25€ were awarded to the three best participants, i.e, with the least errors and than fastest time. Figure 4 shows the distribution of the participants' experience with relevant technologies. All of our participants had normal or corrected-to-normal vision.

4.4.2 Task

In every trial, the task consisted of determining the shortest distance (raging between 3 and 8) between two vertices in the graph (see Figure 2). To make them easier to find, they were both highlighted in red and linearly increased in size based on the participant's distance to them. We measured task completion time and errors. The maximum number of errors per task was one, reached when the participant reports the wrong path length. The correctness of an answer was not revealed to the participant. Before each task, the participant was shown which edge colors are allowed in this path using an image overlay, which ranged from a single color, over two, to all three of them. After the answer was given, the scene faded out and a new task started with the participant's virtual body reset to the start position. From there, she had an overview of the graph similar to the one in Figure 2. In total, we designed 28 tasks that fit into 4 complexity classes. As training task for each method, a task with complexity 1 was taken. The 6 real tasks per method were randomly composed of two of each of the complexity classes 2-4. The complexity classes should minimize the effect of not uniform distributed task difficulties. They are determined with respect to the distance from the starting point to the spheres, length of the path, degree of nodes on the path and number of parallel edges.

5 Results

We analyzed the results with a one-way ANOVA at the .05 significance level, using Welch's ANOVA instead where Levene's test indicated that the assumption of homogeneity of variances was violated. As Post-hoc test, we used Tukey's honest significant difference (HSD) or the Games Howell test, where the assumption of homogeneity of variances was violated. Throughout the paper, we

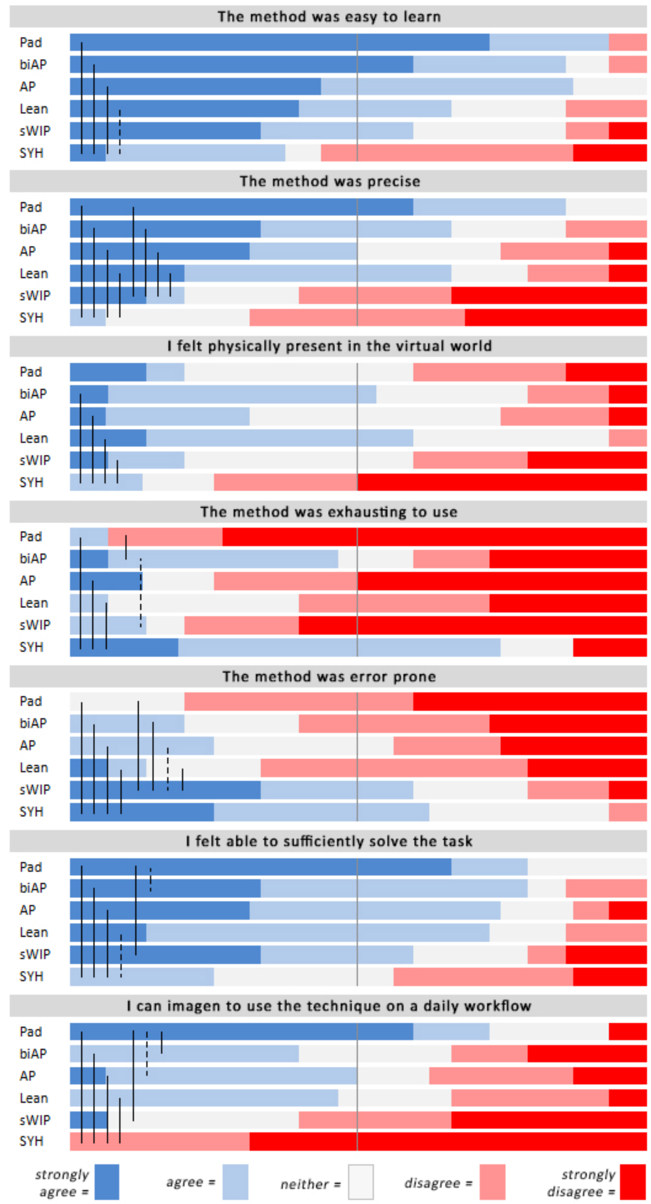

Figure 6: Answers to the subjective questionnaire. Lines denote a statistically significant difference ($p < .05$), dashed lines non-significant trends ($p < .1$).

report significant results at the .05 level and non-significant trends at the .1 level.

The averaged results of our dependent variables *task completion time* and *errors per task* are depicted in Figure 5. There was a statistically significant difference in the task completion time between groups as determined by an ANOVA (F(5,86) = 3.493, p = .006). Furthermore, a Tukey-HSD test revealed that the task completion time using SYH was significantly slower than using Pad (p = .004) or biAP (p = .033). There were no statistically significant differences between the number of errors per task as determined by a Kruskal-Wallis test (p = .687).

We were interested in the possibility to move backwards and its effects (A5), thus analyzed the data to that effects. Regarding the task completion time, an additional independent-samples t-test between the group of methods that allow flying backwards, namely

Pad, biAP and Lean (M = 28.1, SD = 13.5), and the ones that do not, AP, sWIP and SYH (M = 40.2, SD = 20.9), revealed a statical significant difference (T(79.0) = -3.304, p = .001). A Mann-Whitney-U test revealed no statistically significant difference between these groups regarding the number of errors per task (p = .773). All but one participant used the possibility to fly backwards where possible. Another independent-samples t-test regarding the distance moved backward, between the Pad condition (M = 24.2, SD = 24.2) and the two other methods allowing backward moving (M = 48.4, SD = 58.5), revealed that there was no statistically significant difference in the quantity of using backward movements (T(43) = -1.529, p = .134).

We measured a mean SSQ score of 12.6 (SD = 11.4) and a mean score of 40.0 (SD = 31.1) subsequent after the study. In the following we searched for effects in the SSQ score regarding the methods Pad (A2) and SYH (A3). A independent-samples t-test was conducted to compare the SSQ score of all participants that performed the Pad condition (withPad) with the score of all participants that did not perform the Pad condition (noPad). There was a non-significant trend (T(21) = 1.8, p = .086) in the scores for withPad (M = 48.1, SD = 33.5) and noPad (M = 24.8, SD = 19.4) conditions. In the same way, we compared the SSQ scores of all participants that performed the SYH condition (M = 39.0, SD = 23.6) with all that did not (M = 42.1, SD = 43.6) and found no statistically significant differences (T(21) = -.23, p = .821).

Figure 6 shows the results of the 5-point Likert scale subjective questionnaire. An ANOVA found a statistical significance between groups in all questions, *easy to learn* (F(5,39.7) = 5.464, p = .001), *precise* (F(5,86) = 15.219, $p < .001$), *presents* (F(5,86) = 5.628, $p < .001$), *tiring* (F(5,86) = 8.016, $p < .001$), *error prone* (F(5,86) = 8.047, $p < .001$), *able to successfully solve the given task* (F(5,86) = 6.374, $p < .001$) and *can imagine to use this technique on my daily work flow* (F(5,38.2) = 22.041, $p < .001$). The results of additional post-hoc tests are depicted in Figure 6.

6 Discussion

First, the results show a high error rate (about 25%), which validates that the tasks were difficult enough to make navigation necessary and thus obtain expressive results.

Starting with the two WIP methods, we found SYH to be significantly slower regarding task execution time than the control condition Pad and biAP and thus are not able to verify our assumption A4 in general. We would expect an overall increase of SYH's performance with a matched yaw axis (see section 3.4), but controlling translation and rotation of the virtual body with very similar movements of the head may also lead to problems. However, many participants graded and reported missing precision and susceptibility to errors in both walking-in-place methods. We found no significant effect on simulator sickness using SYH as expected in A3, even though many participants commented on the method causing discomfort. In sum, both methods were the slowest and were very poorly ranked in the subjective questionnaires. In our opinion, these effects were measured due to two reasons. First, it is harder to immediately control the movement speed and specifically the moment of starting and stopping. This is usually compensated by a feeling of more natural navigation, which second, does not longer hold in a flying scenario. Based on our results, we **do not recommend walking metaphors** for seated 5-DOF navigation using an HMD.

The accelerator pedal methods and the leaning method performed very well in general and were able to compete against the gamepad navigation on different levels. To our surprise, there was no significant effect of less exhaustion reported compared to the gamepad in general (A1). One limitation of the study should be considered here: the time of use (4 to 5 minutes per technique) was much less compared to a real scenario. Thus, this has to be investigated in more detail. However, as expected (see section 3.2), using AP was less exhausting than using biAP. Moreover, we did not expect AP being faster than biAP as the latter's functionality is nearly the same but more powerful. This would maybe change with more training, and thus experience, using biAP. Some participants reported that the allocation from up and down to forward and backward in biAP felt contra-intuitive to them. This can be adjusted individually, but was kept consistent throughout the study. The possibility to move backwards was reported as positive when possible and as negative where not possible by a majority of participants (A5). This is further supported by the fact that participants were faster with methods that allowed backwards travel, even though in our opinion moving backward was not that important in the given task as potentially in a real application. For instance, there was no real need of "zooming out" of the scene or perform a repositioning. This could be also an explanation why we did not find an effect on the amount of backward movements in comparison between the gamepad and the other two. We assumed that it could be perceived as costlier in the embodied methods to introduce a backward motion. This effect was probably not observable as the backward motion was only used to correct mis-navigation. In summary, **we recommend to use a method that allows moving backward**.

Confirming previous results [26], we also found a trend for a higher SSQ score when the participants used the gamepad. This supports A2, that the awareness of being in the scene is less with the gamepad and motion cuing may help feeling aware. However, this was not consolidated by the questionnaire.

Riecke et al. [32] found indications for a partially embodied method even performing better than a joystick. We think that the same performance reached by gamepad is possible with the embodied methods, although the gamepad had two major advantages in our study. First, many people have prior experiences with a gamepad control and none with the embodied methods. Second, a major **limitation of our implementation** of the embodied methods **is that the navigation is applied in the viewing direction and thus does not allow to move sideways**. Furthermore, we did not want to also lock the gamepad translation to the viewing direction to maintain the comparability to a realistic gamepad control. Nevertheless, within a smaller group of conditions an additional restricted gamepad condition should be concerned in follow-up studies to isolate the effects of view-directed movement. The motivation for choosing the introduced implementations is that no further tracking device is needed to track, for instance, the user's upper body, which would allow to fly in the direction of the body's orientation. Additionally, this method probably would not work very well with the leaning metaphor. One of the advantages for leaning is that no additional tracking device is needed, such as the smartphone.

7 Conclusion & Future Work

We collected a survey of different hands-free, HMD-based navigation methods that can be used while seated in an analyst's usual workplace. Additionally, all methods can easily and inexpensively be integrated into existing workplaces. In the given spatial environment, we found that a body-leaning metaphor and an accelerometer pedal metaphor performed the best. Additionally, we could derive the recommendations to avoid using walking metaphors and including the possibility for traveling backwards.

In future work, we plan to validate our hypothesis that the methods with body cues perform at least as good as a gamepad or a joystick, assuming that learning effects can be reduced and that they gain the possibility to fly sideways. Additionally, we plan to observe and compare the dependent variables during a longer time-of-use.

Acknowledgements

The authors would like to acknowledge the support by the Helmholtz portfolio theme "Supercomputing and Modeling for the

Human Brain". The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 604102 (HBP). Furthermore, the authors want to thank CPP Games for providing and allowing to use the map of EVE Online's solar systems that was used as graph for the study.

References

[1] J. Alexander, T. Han, W. Judd, P. Irani, and S. Subramanian. Putting Your Best Foot Forward: Investigating Real-World Mappings for Foot-Based Gestures. *Proc. ACM Human Factors in Computing Systems*, pages 1229–1238, 2012.

[2] C. Armbrüster, M. Wolter, J. T. Valvoda, T. Kuhlen, W. Spijkers, and B. Fimm. Virtual Reality as a Research Tool in Neuropsychology: Depth Estimations in the Peripersonal Space. *CyberPsychology & Behavior*, (6):654, 2006.

[3] S. Beckhaus, K. J. Blom, and M. Haringer. Intuitive, Hands-Free Travel Interfaces for Virtual Environments. *IEEE Virtual Reality Workshop: New Directions in 3D User Interfaces*, pages 57–60, 2005.

[4] J. E. Bos, W. Bles, and E. L. Groen. A Theory on Visually Induced Motion Sickness. *Displays*, 29(2):47–57, 2008.

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

[6] D. A. Bowman and R. McMahan. Virtual Reality: How Much Immersion Is Enough? *Computer*, 40(7):36–43, 2007.

[7] T. Cakmak and H. Hager. Cyberith Virtualizer: A Locomotion Device for Virtual Reality. *ACM SIGGRAPH 2014 Emerging Technologies*, page 6, 2014.

[8] M. R. Chester, M. J. Rys, and S. A. Konz. Leg swelling, comfort and fatigue when sitting, standing, and sit/standing. *International Journal of Industrial Ergonomics*, 29(5):289–296, 2002.

[9] C. Cruz-Neira, D. J. Sandin, T. A. DeFanti, R. V. Kenyon, and J. C. Hart. The CAVE: Audio Visual Experience Automatic Virtual Environment. *Communications of the ACM*, 35(6):64–72, 1992.

[10] F. Daiber, J. Schöning, and A. Krüger. Whole Body Interaction With Geospatial Data. *Smart Graphics*, pages 81–92, 2009.

[11] G. de Haan, E. J. Griffith, and F. H. Post. Using the Wii Balance Board as a Low-Cost VR Interaction Device. pages 289–290, 2008.

[12] K. Fairchild, B. Lee, J. Loo, H. Ng, and L. Serra. The Heaven and Earth Virtual Reality: Designing Applications for Novice Users. *Proc. IEEE Virtual Reality*, pages 47–53, 1993.

[13] J. Feasel, M. Whitton, and J. Wendt. LLCM-WIP: Low-Latency, Continuous-Motion Walking-In-Place. *Proc. IEEE 3D User Interfaces*, pages 97–104, 2008.

[14] A. Febretti, A. Nishimoto, T. Thigpen, J. Talandis, L. Long, J. D. Pirtle, T. Peterka, A. Verlo, M. Brown, D. Plepys, D. Sandin, L. Renambot, A. Johnson, and J. Leigh. CAVE2: A Hybrid Reality Environment for Immersive Simulation and Information Analysis. *Proc. SPIE*, 8649:864903–864903–12, 2013.

[15] J. Fujisawa, H. Touyama, and M. Hirose. EEG-Based Navigation of Immersing Virtual Environment Using Common Spatial Patterns. pages 251–252, 2008.

[16] T. Y. Grechkin and B. E. Riecke. Re-Evaluating Benefits of Body-Based Rotational Cues for Maintaining Orientation in Virtual Environments: Men Benefit From Real Rotations, Women Don't. *Proc. Symposium on Applied Perception*, pages 99–102, 2014.

[17] E. Guy, P. Punpongsanon, D. Iwai, K. Sato, T. Boubekeur, R. Abdrashitov, J. Yao, K. Singh, J.-M. Thierry, and J.-M. Thiery. LazyNav: 3D Ground Navigation with Non-Critical Body Parts. *Proc. IEEE 3D User Interfaces*, pages 43–50, 2015.

[18] R. S. Kennedy, N. E. Lane, K. S. Berbaum, and M. G. Lilienthal. Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness. *Aviation Psychology*, 3(3):203–220, 1993.

[19] J. Kim, D. Gracanin, and F. Quek. Sensor-Fusion Walking-In-Place Interaction Technique Using Mobile Devices. *Proc. IEEE Virtual Reality: Short Papers and Posters*, pages 39–42, 2012.

[20] A. Kitson, B. E. Riecke, A. M. Hashemian, and C. Neustaedter. NaviChair: Evaluating an Embodied Interface Using a Pointing Task to Navigate Virtual Reality. *Proc. ACM Spatial User Interaction*, pages 123–126, 2015.

[21] E. Kruijff, B. Riecke, C. Trekowski, and A. Kitson. Upper Body Leaning can Affect Forward Self-Motion Perception in Virtual Environments. *Proc. ACM Spatial User Interaction*, pages 103–112, 2015.

[22] T. Kuhlen and B. Hentschel. Quo Vadis CAVE: Does Immersive Visualization Still Matter? *IEEE Computer Graphics and Applications*, 34(5):14–21, 2014.

[23] B. Laha, K. Sensharma, J. Schiffbauer, and D. Bowman. Effects of Immersion on Visual Analysis of Volume Data. *IEEE Transactions on Visualization and Computer Graphics*, 18(4):597–606, 2012.

[24] E. Lantz. The Future of Virtual Reality: Head Mounted Displays Versus Spatially Immersive Displays (Panel). *Proc. ACM Computer Graphics and Interactive Techniques*, pages 485–486, 1996.

[25] J. J. LaViola Jr, D. A. Feliz, D. F. Keefe, and R. C. Zeleznik. Hands-Free Multi-Scale Navigation in Virtual Environments. *Proc. ACM Interactive 3D Graphics*, pages 9–15, 2001.

[26] G. Llorach, A. Evans, and J. Blat. Simulator Sickness and Presence Using HMDs: Comparing Use of a Game Controller and a Position Estimation System. *Proc. ACM Virtual Reality Software and Technology*, pages 137–140, 2014.

[27] M. Marchal, J. Pettre, and A. Lecuyer. Joyman: A Human-Scale Joystick for Navigating in Virtual Worlds. *Proc. IEEE Symposium on 3D User Interfaces*, pages 19–26, 2011.

[28] M. McNeill, H. Sayers, S. Wilson, and P. Mc Kevitt. A Spoken Dialogue System for Navigation in Non-Immersive Virtual Environments. *Computer Graphics Forum*, 21(4):713–722, 2002.

[29] O. Merhi, E. Faugloire, M. Flanagan, and T. A. Stoffregen. Motion Sickness, Console Video Games, and Head-Mounted Displays. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 49(5):920–934, 2007.

[30] E. D. Ragan, R. Kopper, P. Schuchardt, and D. A. Bowman. Studying the effects of stereo, head tracking, and field of regard on a small-scale spatial judgment task. *IEEE Transactions on Visualization and Computer Graphics*, 19(5):886–896, 2013.

[31] G. E. Riccio and T. A. Stoffregen. An Ecological Theory of Motion Sickness and Postural Instability. *Ecological Psychology*, 3(3):195–240, 1991.

[32] B. E. Riecke, B. Bodenheimer, T. P. McNamara, B. Williams, P. Peng, and D. Feuereissen. Do We Need to Walk for Effective Virtual Reality Navigation? Physical Rotations Alone May Suffice. *Spatial Cognition VII*, pages 234–247, 2010.

[33] B. E. Riecke and D. Feuereissen. To Move or Not to Move: Can Active Control and User-driven Motion Cueing Enhance Self-motion Perception ("Vection") in Virtual Reality? *Proc. ACM Applied Perception*, pages 17–24, 2012.

[34] A. Simeone, E. Velloso, J. Alexander, and H. Gellersen. Feet Movement in Desktop 3D Interaction. *Proc. IEEE 3D User Interfaces*, pages 71–74, 2014.

[35] M. Slater, M. Usoh, and A. Steed. Taking steps: The influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction*, 2(3):201–219, 1995.

[36] J. D. Smith and T. Graham. Use of Eye Movements for Video Game Control. *Proc. ACM Advances in Computer Entertainment Technology*, 2006.

[37] I. E. Sutherland. A Head-mounted Three Dimensional Display. *Proc. ACM Fall Joint Computer Conference, Part I*, pages 757–764, 1968.

[38] J. Templeman, L. Sibert, R. Page, and P. Denbrook. Pointman - A New Control for Simulating Tactical Infantry Movements. *Proc. IEEE Virtual Reality*, pages 285–286, 2007.

[39] L. Terziman, M. Marchal, M. Emily, F. Multon, B. Arnaldi, and A. Lécuyer. Shake-Your-Head: Revisiting Walking-in-Place for Desktop Virtual Reality. *Proc. ACM Symposium on Virtual Reality Software and Technology*, pages 27–34, 2010.

[40] J. Wang and R. W. Lindeman. Silver Surfer: A System to Compare Isometric and Elastic Board Interfaces for Locomotion in VR. *Proc. IEEE 3D User Interfaces*, pages 121–122, 2011.

[41] J. Wendt, M. Whitton, and J. Brooks, F.P. GUD WIP: Gait-Understanding-Driven Walking-In-Place. *Proc. IEEE Virtual Reality*, pages 51–58, 2010.