Spherical World in Miniature: Exploring the Tiny Planets Metaphor for Discrete Locomotion in Virtual Reality

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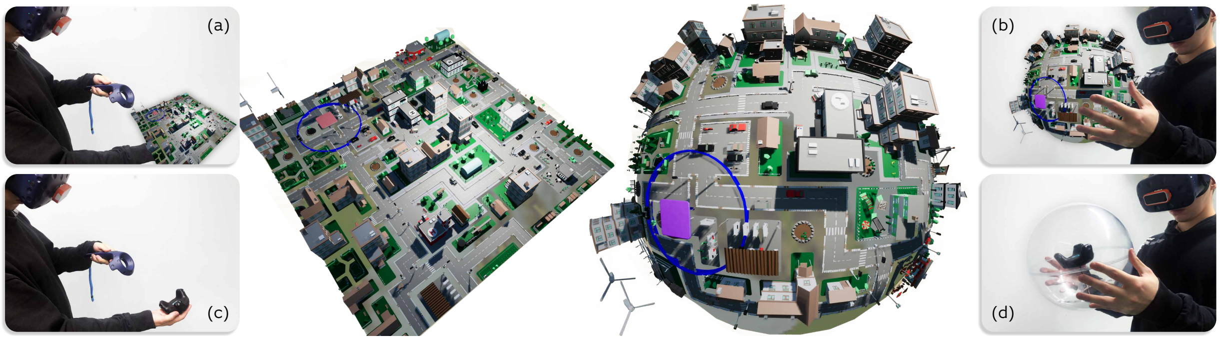

Figure 1: We compare two VR teleportation techniques: a planar (a) and a spherical (b) World in Miniature. The planar WIM relies on button-supported interaction (c) while the SWIM is solely controlled and embodied with a physical sphere (d). We evaluate both techniques with the tasks of scrolling, scaling, and teleportation, each with two different display sizes.

Abstract

We explore the concept of a *Spherical World in Miniature* (SWIM) for discrete locomotion in Virtual Reality (VR). A SWIM wraps a planar WIM around a physically embodied sphere and thereby implements the metaphor of a tangible *Tiny Planet* that can be rotated and moved, enabling scrolling, scaling, and avatar teleportation. The scaling factor is set according to the sphere's distance from the head-mounted display (HMD), while rotation moves the current viewing window. Teleportation is triggered with a dwell time when looking at the sphere and keeping it still. In a lab study (N=20), we compare our SWIM implementation to a planar WIM with an established VR controller technique using physical buttons. We test both concepts in a navigation task and also investigate the effects of two different screen sizes. Our results show that the SWIM, despite its less direct geometrical transformation, performed superior in most evaluations. It outperformed the planar WIM not only in terms of task completion time (TCT) and accuracy but also in subjective ratings.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction devices—Haptic devices; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms— Virtual reality

1 Introduction

VR technology enables intriguing ways to explore vast virtual environments. For instance, immersive geo information systems (GIS) such as Google Earth VR let us travel our planet by visiting detailed 3D-scanned places all around the globe in a matter of seconds. Environments enhanced with real-time lighting, e.g., live-rendered weather effects, can additionally increase the level of immersion [35]. However, locomotion in those vast VEs, despite the many existing approaches, poses a considerable challenge both for developers and users [14, 28]. The ability to quickly and precisely navigate a wide area is, for a usable and equally pleasant VR experience, as important as natural and situation-aware interaction.

We can split VR locomotion into two major paradigms: discrete or non-continuous locomotion as opposed to continuous locomotion [4]. While the latter is generally considered as more immersive and natural, techniques found in this field often lack the ability to cover a large space or to provide sufficient orientation and are likely to cause cybersickness [9]. Hence, discrete locomotion techniques, most notably the point and teleport technique [7, 9], are widely used in VR. The classical teleport approach requires users to directly point at the desired spot within their field of view (FOV). Methods incorporating navigation aids such as miniature versions of the virtual environment provide access to more distant virtual scenes and allow users to teleport there by placing a representation of their avatar in a miniature world.

While the general advantages of the WIM concept have been demonstrated [3], we see the recent developments in commercial VR hardware and tracking technology as an opportunity to explore novel interaction techniques that may support users in other intuitive ways when moving in VR.

In particular, we focus on the possible benefits of a physically embodied, spherical miniature world. This concept provides an easily understood metaphor for naturally controlling a small planet. This metaphor is inspired by a projection technique from photography [10] that is often described as a *Tiny Planets* projection. The concept appears to be exciting from many different angles: In addition to its comprehensible metaphor, the SWIM can be built at low expense [20] and, most importantly, allows us to utilize our natural skills in manipulating physical objects [26]. As a tangible spherical shape, it invites rotation and may intuitively convey [43] solutions to two inherent challenges of the WIM idea: scrolling and scaling.

Finally, the SWIM technique obviously allows the accurate representation of actual planets, but due to the VR implementation, it can also show content expanding to the area around the sphere, which is more difficult for AR systems. This ability becomes important when 3D objects with a certain height need to be wrapped around the sphere, as illustrated in Figure 1, (b).

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2 BACKGROUND & RELATED WORK

Our work builds on existing work using sphere-shaped devices in VR and AR, particularly when applied in VR locomotion scenarios. We also discuss spherical visualizations and the development of the original WIM concept.

2.1 Handheld Spherical Devices in VR and AR

This field can be divided into Handheld Perspective Corrected Spherical Displays (HPCDs), and more generally passive tangible tracked spherical objects that are used to embody various virtual volumes in VR [20]. The first category of displays is, with few exceptions [1], implemented by projecting an image adjusted to the user's perspective from the outside to the surface of a handheld sphere creating an illusion of depth [2,30]. These handheld spherical fish-tank displays (FTVR) [5,40] are currently transitioning from mere showcases of a compelling technology to usable devices supporting a wide array of interaction techniques as shown by Miyafuji et al. [33] and recently by Louis et al. [31]. The latter paper reports on interaction ranging from selecting distant objects and menu items to scene scaling and continuous parameter control. Of particular interest to our work is the implementation of scaling and selection. The authors implemented scaling by rotating the sphere around a central axis and selection by casting a ray from a fixed cursor into the scene. While the first technique was also found to perform well for an equally mode-based object manipulation technique [17], the selection approach is in line with a study on VR display simulation that confirms that target alignment in combination with dwell time-triggered selection is a feasible approach for orb-shaped displays [19]. The selection technique appears promising for a buttonless device; however, we need to rely on a different approach for scaling. This is mainly due to the fact that for a natural experience, we would like to allow users to scroll and scale simultaneously without explicit mode-switching.

2.2 Spherical Devices for VR Locomotion

Examples of continuous locomotion techniques supported by handheld spherical devices exist, but we did not find any implementation utilizing such a device for discrete locomotion or teleportation. Hence, we see the concept of using a handheld sphere as a continuous locomotion device demonstrated by Englmeier et al. [18] as closely related, especially because they evaluated the use case of a perspective-corrected WIM that was, in contrast to our concept, fully enclosed by the device. However, it only served as a visual navigation aid. Although results showed no significant effects for the contained WIM, the metaphor of a rolling ball was well received and could, in combination with direct position manipulation, in a straight line task, outperform two controller-based techniques. Another example of a continuous implementation is the *VirtuSphere*, an omnidirectional treadmill that allowed users to virtually move by walking in a giant sphere [32]. Earlier implementations examined the use of stationary trackballs that showed comparable performance to joystick-based methods [36] or positive effects for impaired users [8].

2.3 Spherical Visualizations

While Vega et al. [39] outlined a number of general guidelines for visualizations on spherical displays, we consider those techniques spanning virtual content around a sphere as most relevant to our work. Kwon et al. [27] demonstrated different variants of wrapping graphs around a spherical surface with varying amounts of distortion. Spherical projections in general produce a natural fisheye effect [22] emphasizing and magnifying a certain focal area. Du et al. [15] explored this effect for a *Focus+Context* [11] technique mapping a sphere-projected graph to a 2D plane. Holman et al. [25] presented a vision of organic user interfaces, including the mapping of spherical visualizations to topologically matching physical props.

2.4 Implementations of the WIM Metaphor

Stoakley et al. [38] and Pausch et al. [34] initially introduced the WIM metaphor in 1995. The implementation builds on the use of two controlling devices: one is coupled with the WIM while another is used to set the avatar position by pointing or to select or manipulate objects within the scene. The *Scene in Hand* metaphor we use goes back to the work of Ware et al. [41]. The WIM idea has been explored in many different variants, often implementing extensions such as scrolling, scaling, or clipping that were discussed in the original publications. For novel interpretations, these challenges remain relevant. Therefore, we propose solutions that are tailored to the spherical shape of our prop, while we base both implemented techniques on the original WIM concept.

A wide-spread solution for the scrolling problem is the map dragging technique, as evaluated by Bowman et al. [6] that allowed users to drag an avatar on a 2D map with a stylus. This interaction paradigm of grabbing and manipulating an object while constant input is given has been ported to VR [37] and is often implemented using VR controllers. A version using hand gestures has been realized by Fittkau et al. [21].

As discussed above, we wanted to exploit the sphere's shape for scrolling. Hence, the work by Wingrave et al. [42] demonstrating a *Scaled and Scrolling WIM* (SSWIM) is especially relevant. The authors realized scaling by using a mouse wheel, which they preferred over a button solution, and scrolling by moving the avatar position outside a dead zone. In a more recent study, Berger et al. [3] compared a WIM to continuous joystick movement and a point and teleport implementation in VR. They found that their WIM technique outperformed the other techniques for larger distances and in terms of motion sickness and spatial orientation. User positioning was implemented by performing a picking gesture by pressing and releasing a button and a controller trigger. While a visible ray indicated the dropping position of the avatar, the WIM was only shown if the dominant hand to which the WIM was attached was rotated upwards, facing the user's FOV. Elvezio et al. [16] presented a technique allowing users to set their avatar's orientation prior to executing teleportation.

Although we did not find any WIM approaches performing a spherical projection, examples of projecting a WIM to a plane exist. LaViola et al. [29] projected a WIM to the floor below the user in an AR setup. This made it possible to physically walk to a destination that then could be selected with a foot gesture. Coffey et al. [12] with the *Slice WIM* projected a 3D object to a 2D multitouch surface resembling a shadow [13] that was used to interact with a selected horizontal slice of a 3D representation.

3 DESIGNING A SPHERICAL WORLD IN MINIATURE

In this section we describe the key components and design decisions that define the implementation of a scrollable, scalable SWIM that works without buttons and explicit mode selection. The advantages of tangible interaction with spherical devices in comparison to simulated rotation have been shown by previous research [2, 19]. As stated, a Tangible User Interface (TUI) not only leverages acquired knowledge from the real world [26] but, in our case, may intuitively especially explain the scrolling but also the scaling functionality by mere interaction with the sphere. Hence, we decided for generally embodying the spherical visualization with a physical sphere.

3.1 Projection & Visualization

We project the planar WIM to the sphere with an inverse stereographic projection. This generates an appealing *Tiny Planet* without unnatural distortion, whose ground surface matches the surface of the physical sphere. The planar WIM is placed in a plane perpendicular to the vector from the HMD to the sphere's center. The projection center of the stereographic projection is where this camera vector intersects with the sphere. The WIM is only projected to the front hemisphere, but this creates the illusion of a fully covered planet because the user can't see the uncovered back side. Since this method would cause the SWIM to slightly move if the sphere's position changes in relation to the HMD, we stabilize the WIM like a billboard, creating a stable image of the *Tiny Planet*. The viewing window of the WIM only changes when the user scrolls it by rotating the sphere. Lastly, the projection also implicitly creates a *Focus+Context* visualization [11] due to the resulting magnification of the surface points closer to the camera. While this effect is mitigated by the clipping technique describe in Section 3.2 it can not be replicated by a planar WIM without unnatural distortion.

3.2 Clipping

As described by Stoakley and Pausch [34, 38], clipping the WIM in X and Y is straightforward. However, especially with a spherical projection, unwanted and overly strong distortion in Z can occur. We solved this problem by setting a maximum value for the scaling along Z. This results in uniform scaling up a predefined threshold, and from that point on, the WIM is only scaled along X and Y. The amount of distortion and scaling along Z may vary with the type of visualized content and, due to resulting occlusion, with the amount of desired visible context. We, therefore, leave that value to be set manually. However, since this method could lead to an advantage in an area with many occluding objects such as a city, we also applied it to the planar WIM to preserve a fair comparison.

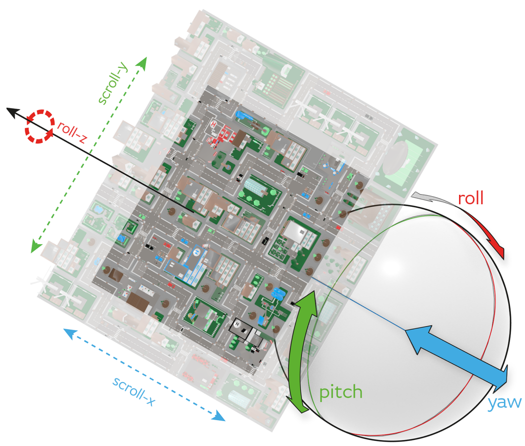

Figure 2: We align the planar WIM with a plane perpendicular to the camera vector (black). For a correctly rotating planet, we map the WIM's rotation in Z to the roll (red), the scrolling in Y to the pitch (green), and scrolling in X to the yaw angle (blue).

3.3 Scrolling & Rotation

Our projection technique also facilitated the implementation of scrolling: For a planet naturally rotating in sync with the tangible object, we mapped scrolling linearly to the yaw and pitch angles of the tracked sphere. Since the WIM is scrolled using these two degrees of freedom (DOF) only, the roll angle remained unused. However, we found that for a natural behavior, we also had to map the rotation of the plane in which we placed the WIM (see Section 3.1) to this angle. This means that, if the sphere is rolled, we rotate the WIM around the pivot point defined by the intersection of the camera vector and the WIM plane. The combination of these three angles results in natural rotational behavior as one would expect from a physical handheld globe, with the only difference that yaw and pitch do not actually rotate the sphere, but only generate this impression by scrolling the viewing window within the projected planar WIM (which itself can be of arbitrary size). Figure 2 illustrates this mapping.

3.4 Scaling

Since our approach uses all six degrees of freedom (3 for rotation and scrolling, 3 for positioning the object in the 3D space), we needed to find a different way to realize zooming without fundamentally changing the previous implementation. We first tested an implementation that mapped the roll angle to scaling [17, 31] instead of actual roll. However, we found that this strongly disturbed the impression of natural behavior of the embodied sphere and discarded the idea. We also rejected a mode-based approach because of inherent complexity and expected disadvantages in TCT [17].

Ultimately, we decided to base the scaling factor on the distance of the sphere from the HMD. This provides yet another easily understood metaphor: If users look closer at the object, as if inspecting it, the WIM is enlarged, and if pushed away, its size is decreased [24]. For both directions, we set a minimum and maximum value. To indicate when scrolling is possible, we show a simple scroll-bar at one side of the SWIM that consists of a blue dead zone, yellow scrolling areas, and a red indicator (Figure 3, (b)). Since the sphere's physical distance from the HMD is limited by the user's arm length, we needed to perform a quick preliminary calibration, which required users to hold the sphere in a neutral position. For both WIM and SWIM we applied the same logarithmic scale allowing for a homogeneous zooming behavior.

3.5 Teleportation

The teleportation mechanism is based on the selection by alignment technique that has been proven viable for spherical devices [19, 31]. We show a static target ring in the foreground of the spherical visualization that teleports the user to a position selected with a central dot. Selection works by keeping the sphere still for a dwell time of one second [17] while looking at the sphere. Selection is only triggered if the user looks at the sphere, keeps it still, and does not perform any zooming. This efficiently prevents unwanted teleportation. For constant visual feedback, we filled the selection circle progressively, and teleportation is only triggered when it is completely filled.

4 Experiment

To evaluate the SWIM concept in terms of performance, precision, and user ratings, we conducted a lab study comparing our implementation using embodied spheres of two different sizes (small, large) to an established technique using VR controllers. In the process, we also compared two different display sizes for the miniature world.

4.1 Study Design & Participants

We designed our experiment as a within-subjects study and followed the regulations of the local ERB regarding consent and data collection. Each participant completed a find-and-navigate task with all four conditions. We presented those in (incompletely) counterbalanced order following a Latin Square to prevent adverse learning or fatigue effects. Including a post-experiment questionnaire, the study took about half an hour. Participants could take a break between

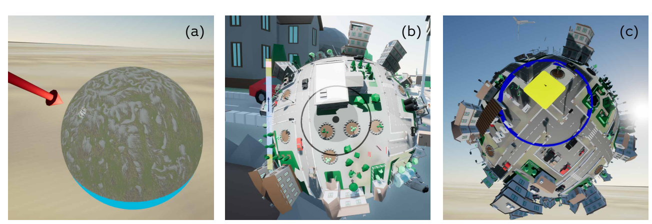

Figure 3: As a navigation aid, we supplied an arrow visible at smaller scales (a). The SWIM allowed teleporting by aligning a target, indicated with a square (c), for a dwell time with a static circle (b).

conditions to relax or recover from potential motion sickness and were finally awarded a $5 payment. They completed the task in a seated position in order to minimize the risk of motion sickness, which also was not our primary research focus.

We recruited 20 participants (mean age: 26.1, SD: 7.05), 13 of whom self-identified as male and 7 as female. They rated their VR experience on average at 1.25 (from 1 = no experience to 5 = expert).

4.2 Precautions & Limitations

In accordance with local laboratory guidelines for the SARS-CoV-2 pandemic, we took numerous precautions. These included adequate spacing, thorough disinfection of the user's hands and all touched objects and surfaces, continuous ventilation, mandatory face shielding (with optional removal during HMD usage) and a restriction of the study duration to 30 minutes. Due to the latter limitation, we had to limit the number of experimental conditions and opted for a shorter questionnaire specifically tailored to the focus of our study.

4.3 Apparatus

In the following sections, we will discuss the hard- and software used to implement the SWIM and the methods we compared, and we will explain the design decisions that shaped each condition's implementation.

4.3.1 Hardware

For the HMD, we used an *HTC Vive Pro Eye* that provides a refresh rate of 90 Hz, and a 110° FOV. As the tangible outer shell of the SWIM, we used two acrylic glass spheres of different sizes (12 cm, 25 cm) and mounted a Vive Tracker in their center [17, 20]. For the planar WIM condition, we used a Vive Controller equipped with a directional touchpad and physical buttons as the pointing device and another Vive Tracker to move and rotate the WIM in 6 DOF. We also tested embodying the planar WIM with a clipboard as described in [34, 38], but found that such a rather large prop would make these conditions hard to operate. Instead we relied on the tracker that comfortably fits into the palm of a hand, as seen in Figure 1, (c).

4.3.2 Software

To create the rather large VE for our study, we used Unreal Engine 4 (UE4), version 4.25[1] and its built-in visual programming language as well as C++ for realizing the find-and-navigate task. To accurately resemble a GIS application we implemented a large terrain of about 100 km^2 that would require users to extensively pan and zoom the respective WIMs for acquiring the given targets.

We implemented the spherical projection as a custom shader that would stereographically project all vertices of the planar VE while we performed the mapping of the rotational axes (as described in Section 3.3) in the CPU program. As UI elements for the spherical conditions, we supplied a scrollbar, and a fixed target as seen in Figure 3, (b) while the planar WIM conditions for teleportation only required a visible ray cast and a target indicator (Figure 4, (a)). For the teleportation mechanism, we used the implementation of UE4's VR controller that represents an established method, found in many current VR applications and games. Pressing a button enables the teleportation mode and shows a ray for pointing to the target. Releasing the button executes the teleportation [9]. For both techniques, we indicated the avatar position on the WIMs with a small arrow pointing into the user's viewing direction.

4.4 Experimental Conditions

To evaluate the SWIM concept we tested it in combination with two different sphere sizes (small: 12 cm, large: 25 cm). In analogy, we supplied the planar WIM conditions with two equally sized planar WIMs that exactly matched the two SWIM sizes and showed the same viewing window. In total, this results in four conditions.

[1] https://www.unrealengine.com/

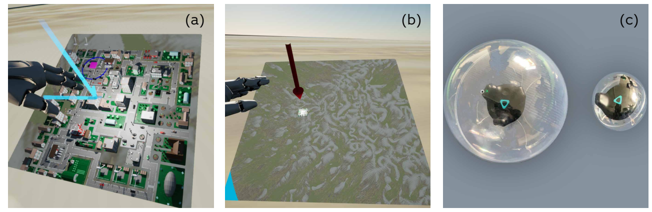

Figure 4: We based teleportation for the planar WIM on ray casting (a). At smaller scales, we also supplied a navigation aid (b). In contrast to the SWIM variants (c) it was embodied by an unenclosed tracker.

4.4.1 SWIM: Small

The first SWIM condition used the smaller physical sphere (diameter: 12 cm) with a total weight of 190 g. The sphere's size and the virtual buildings protruding from it made for a display size of about 15×15 cm. We implemented interaction as described in Section 3.

4.4.2 SWIM: Large

The second SWIM condition differed from the previous condition only in the use of the larger sphere (diameter: 25 cm) that weighed about 970 g and provided a total display size of about 31×31 cm.

4.4.3 WIM: Small

Just as with the original WIM concept, for the planar conditions we gave users a pointing device for teleportation and a Vive Tracker as a controller for the WIM. The Tracker seemed to be a good choice, since it could rest comfortably and flat in the user's hand. This made it easy, for example, to align the WIM with the floor. Participants could decide on their own in which hand to take the pointing device. In accordance with our expectations and the literature on bimanual interaction [23], a majority decided to point with their dominant hand. We implemented the teleportation method as described in Section 4.3.2 using UE4's VR controller. For scrolling, the controller's front trigger is held down. We indicated this by a closing virtual hand. Subsequently, the WIM can be grabbed and panned directly by moving the controller, also allowing a "clutching" technique.

For zooming in, users needed to constantly push on the upper section of the touchpad while a push on the lower section would zoom out. Scaling used the same logarithmic scale as the SWIM conditions (including thresholds for minimum and maximum zoom level). We also considered repeated swiping on the touchpad [17] but found that to be impractical for the rather large zooming distances our VE required. Teleportation mode was engaged with the controller's grip buttons. Holding them down would bring up the pointing ray and releasing them would execute teleportation. To abort teleportation the ray just needed to be moved outside the WIM before releasing the grip buttons. We also indicated this by changing the color of the ray to red if it was not hitting the WIM. As noted above, the display size was equal to the first condition (*SWIM: Small*).

4.4.4 WIM: Large

The fourth condition only differed from the previous condition in terms of the display size, that here exactly matched the size of the second condition (*SWIM: Large*).

4.5 Task

The task consisted of a simple find-and-navigate exercise. Participants had to sequentially find five predefined targets placed within a city located on a 64 km^2 island surrounded by water. As a navigation aid, we provided a large arrow, pointing at the city (Figure 3, (a)). The targets consisted of blinking squares ringed by circles (Figure 3, (c)). Users began at one of five predefined starting positions with their view being zoomed in half the way. Subsequently, they first

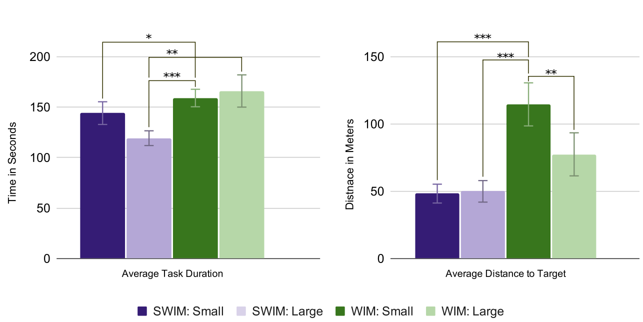

Figure 5: Total duration and accuracy for the navigation task. Values are given with 95% confidence intervals as accumulated average values for time in seconds and distance to target in meters.

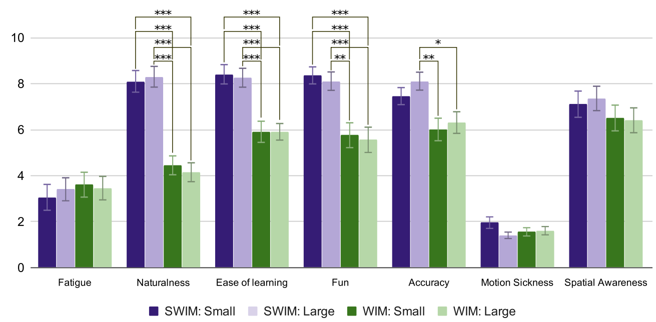

Figure 6: Users' perception ratings with 95% confidence intervals for the navigation task. Ratings were given on a 10-point Likert scale. Except for fatigue a higher rating represents a better result.

had to zoom out, locate the city, then zoom in to maximum scale, and eventually find and teleport to the targets. We repeated each target once, resulting in a total of 10 operations per condition. Users were given oral instructions before each controller condition and afterward could practice each condition until they felt comfortable with it. We also advised the participants to find the targets as quickly as possible and to teleport to the target's center as closely as possible. After they teleported to one target, a countdown of three seconds would show up allowing them to further improve their accuracy. Then, the next round started by resetting WIM and user position to the following predefined position. For uniform accuracy measurements, we only allowed teleportation after the maximum zoom level was reached. We explicitly explained this condition to the participants in the introduction, and they also practiced compliance with it during the training phases.

5 Results

First, we present the quantitative data we recorded on task performance (TCT, accuracy), and results from a post-experiment questionnaire. Then we discuss our documented qualitative findings.

5.1 Quantitative Results

To determine user performance, we recorded Task Completion Time (TCT) and accuracy. In total, the task took about 120-160 seconds. For accuracy, we measured the distance from the user's position to the target center. Last, we evaluate the given subjective ratings. To calculate the statistical analysis, we used IBM SPSS.

5.1.1 Task Completion Time

We ran a repeated measures ANOVA with multivariate analysis (a Greenhouse-Geisser corrected evaluation found equal significances). A Pillai's trace and Wilk's lambda test found statistical significance for the four main conditions: $F(3,17) = 18.107$, $p < 0.001$ with an effect size of $\eta^2 = 0.762$. For post hoc analysis, we ran pairwise comparisons and used a Bonferroni-corrected t-test. Thus, we report the corresponding corrected p-values. We found that users generated significantly lower completion times when interacting with *SWIM: Small* in comparison to *WIM: Small* with $t(38) = -3.321$, $p = 0.021$. The same effect showed for *SWIM: Large* that outperformed both planar WIM conditions with $t(38) = -3.895$, $p = 0.006$ (*WIM: Large*) and with $t(38) = -7.424$, $p < 0.001$ (*WIM: Small*). Figure 5, left gives an overview of these results.

5.1.2 Accuracy

Regarding the precision of target acquisition we again found the main conditions to cause statistically significant differences for a repeated measures ANOVA with multivariate analysis (again, Greenhouse-Geisser corrected evaluation resulted in equal significances) followed by a Pillai's trace and a Wilk's lambda test: $F(3,17) = 10.646$, $p < 0.001$ with an effect size of $\eta^2 = 0.653$. The Bonferroni-corrected t-test revealed the following corrected p-values and significant differences between conditions: *SWIM: Small* led to significant better target acquisition when compared to *WIM: Small* with $t(38) = -5.519$, $p < 0.001$. A similar result was caused by *SWIM: Large* when compared to *WIM: Small* ($t(38) = -5.369$, $p < 0.001$). Finally, we found *WIM: Large* to generate significantly higher precision than *WIM: Small* ($t(38) = -4.274$, $p = 0.002$). Figure 5, right illustrates these results.

5.1.3 Questionnaire Results

For a subjective analysis of the SWIM technique we asked participants to answer a post-experiment questionnaire (10-point Likert scale). Then, we performed a Friedman test on the given ratings followed by a Dunn-Bonferroni post-hoc test. We discovered no significant influence of the main conditions for questions regarding fatigue ($\chi^2(3) = 6.414$, $p = 0.093$), motion sickness ($\chi^2(3) = 3.100$, $p = 0.376$) and spatial awareness ($\chi^2(3) = 2.842$, $p = 0.417$). However, we found strong significant differences for naturalness ($\chi^2(3) = 47.150$, $p < 0.001$), ease of learning ($\chi^2(3) = 38.180$, $p < 0.001$) and fun ($\chi^2(3) = 38.057$, $p < 0.001$). For these three questions both SWIM conditions received significantly higher ratings than the planar WIM conditions almost exclusively with $p < 0.001$ (standard z-scores between 3.797 and 5.083). The question for fun where *SWIM: Large* was rated higher than *WIM: Small* formed the only exception with $p = 0.005$ and $z = 3.368$. Finally, when asked about perceived accuracy ($\chi^2(3) = 16.263$, $p < 0.001$) participants rated *SWIM: Large* significantly higher than *WIM: Small* with $p = 0.005$, $z = 3.368$ and *WIM: Large* with $p = 0.016$, $z = 3.001$. Figure 6 gives an overview of the questionnaire results.

5.1.4 Summary of Quantitative Results

We can safely state that *SWIM: Large* achieved the best results. It outperformed the two planar conditions regarding TCT, while despite a larger difference in average TCT *SWIM: Small* only significantly outperformed *WIM: Large*. Regarding accuracy *WIM: Small* was outperformed by all other conditions, however most clearly by the SWIM conditions. The questionnaire results for the SWIM conditions were equally clear. Regarding Naturalness, Ease of Learning and Fun, both SWIM conditions reached significantly higher user ratings. For perceived accuracy again, only *SWIM: Large* was rated remarkably higher than both WIM conditions.

5.2 Qualitative Results

Qualitative observations and participant's comments also were in favor of the spherical WIMs. When asked what method they would prefer, none of the participants decided for the VR controllers. While the spheres were generally praised for their intuitiveness, users favoring the large sphere mentioned the better accuracy while the small sphere mainly was preferred for ergonomic reasons. Interestingly, we received no comments complaining about the distortion induced by the spherical projection. On the contrary, some users reported better spatial awareness. For example, one participant especially emphasized the arrow's spatial perception being easier when it rotated around a sphere. Regarding improvements, some users wanted to see their hands while others wished for a physical button on the spheres. Although the VR controllers were not rated significantly higher for fatigue in the questionnaire results, numerous users noted the WIM technique being more exhausting than the spheres.

6 Discussion and Implications

Before discussing the various implications, we would like to recall our study's goal of generally proving the viability of the SWIM concept focusing on the locomotion process. As unanimously positive as the results were for the SWIM technique, we would like to highlight that we base the discussion on the premise of the following limitations and subjects' overall low VR experience.

Limitations and Extensions. Due to the limited number of conditions (Section 4.2), we have to leave a detailed analysis of the influencing factors to future work. However, the results of our study clearly support an investigation that could further explain differences caused by the selection techniques (alignment with dwell time vs. pointer with button), scrolling techniques (grabbing and panning vs. continuous rotation), and zooming techniques (distance-based vs. button-based). While it is very likely that spheres may be the best choice for supporting scrolling by rotation, an extension of conditions would allow for deeper insights on the precise effects of the interaction paradigms on the results. Conditions including a non-tangible spherical WIM utilizing scrolling by grabbing and a planar WIM with distance-based zooming with or without a tangible sphere for scrolling appear as promising to provide such clarification.

Furthermore, a more versatile VR controller would need to support extensions such as object selection and manipulation, as outlined by Louis et al. [31]. This would bring the SWIM closer to being an alternative to established controllers that support interaction beyond locomotion. However, if we consider advances in (visual) finger tracking, interesting opportunities for exploring multi-touch interaction on a handheld object come to mind. Tracking errors were rare, yet, improvements in this area and even more light-weight props would certainly benefit the SWIM technique.

Implications from Usability and Visualization. The biggest surprise regarding the overall results was the very high perceived usability of the SWIM. We had expected the spherical projection to complicate spatial orientation and especially the scrolling functionality, to be not easily comprehensible for all users. However, this was not the case. Not only does the data clearly indicate that the participants could effortlessly navigate a large terrain, but they also explicitly reported a great sense for the environment no matter the zoom level. While this is easily understood for a zoomed-out view closely resembling a familiar globe, for the zoomed-in views, this was unexpected. A possible explanation could be the advantages a fully tangible object provides in terms of interaction and perception that seem to mitigate potential problems stemming from a spherical projection. In addition, the advantages of the fisheye effect (putting a focus on and magnifying closer surface points) may also play a role here. Since Cockburn et al. [11] state that this effect can also complicate target acquisition a closer investigation may provide an interesting topic for future work.

Implications from Interaction Metaphors. Another major advantage of the SWIM technique appears to be rooted in the scrolling behavior's continuous nature. While the planar WIM has to be grabbed and released for scrolling, thus applying a "clutching" technique, the SWIM, in contrast, is scrolled continuously in sync with the physical prop [19]. The characteristics of the spherical shape may especially support this technique. For the WIM technique, it also would have been possible to implement an approach of scrolling it by moving a controller indicator to the edges of the plane [42]. However, this appeared to be inferior to grabbing and panning which allows (as SWIM) for different scrolling speeds.

Figure 7: The SWIM concept comes closest to its corresponding photography technique when 3D scanned data (left) is mapped to a sphere (right), as shown by this example of a Tokyo area.

The device's self-explanatory character also seems to support the zooming metaphor. Although we feared the zooming behavior would be hard to learn in conjunction with scrolling, the opposite seems to be the case. Users didn't appear to have any problems simultaneously zooming and scrolling while homing in on a target or zooming out to improve their overview. A noticeable disadvantage of the zooming functionality was that on some rare occasions, users would knock the sphere slightly against the front of the HMD. However, this could easily be prevented by showing a distance warning.

We also further can confirm results on the selection technique by alignment and dwell time approach for handheld spherical devices [19, 31]. This observation is mainly backed by the superior results for accuracy the SWIM generated but also by user reports that specifically mentioned the precision of the larger sphere. For extensions, a comparison between the dwell time and a button-based solution would be promising. Even if it may be difficult to implement real physical buttons for the spherical devices, vibrotactile feedback simulating buttons when the surface was tapped [2, 31] at any point could provide an interesting option.

Implications from Display Size. An analysis of the results in regard to the display sizes reveals a positive effect for the larger displays. Yet, the larger WIM could not match both SWIM techniques but only outperformed its own smaller variant in terms of accuracy.

Implications from Accessibility. Finally, we want to emphasize again the ease with which the test subjects understood the concept. In the light of their overall low VR experience, a novelty effect as a possible explanation appears unlikely. The three kinds of interactions evaluated (scrolling, scaling, and selection) all seem to be efficient while being easily intelligible, even for novice users.

7 Summary and Future Work

In summary, we can state that the SWIM technique appears to be a usable and efficient alternative to the established planar WIM and its interaction concept based on two separate controlling devices. It has become clear that an embodied spherical object can be applied for discrete VR locomotion at various zoom levels enabling users to navigate large terrains fast, precisely, and intuitively. Whether the concept in combination with a wider variety of interaction techniques can be expanded to support a wider range of use cases is a topic for further investigation. However, we have shown that for discrete navigation in a large virtual environment, the concept is a viable approach and would only benefit from technical improvements or an application including real world 3D scanned data subsequently showing a *Tiny Planet* not just representing a fictional VE but its (more impressive) real world counterpart as seen in Figure 7. In this first study, we found clear evidence for the advantages of the tangible SWIM applied to discrete locomotion. Therefore, a following study of what factors precisely are causing those appears as a compelling topic for future exploration.

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