Feel the Globe: Enhancing the Perception of Immersive Spherical Visualizations with Tangible Proxies

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ABSTRACT

Recent developments in the commercialization of virtual reality open up many opportunities for enhancing human interaction with three-dimensional objects and visualizations. Spherical visualizations allow for convenient exploration of certain types of data. Our tangible sphere, exactly aligned with the sphere visualizations shown in VR, implements a very natural way of interaction and utilizes senses and skills trained in the real world. In a lab study, we investigate the effects of the perception of actually holding a virtual spherical visualization in hands. As use cases, we focus on surface visualizations that benefit from or require a rounded shape. We compared the usage of two differently sized acrylic glass spheres to a related interaction technique that utilizes VR controllers as proxies. On the one hand, our work is motivated by the ability to create in VR a tangible, lightweight, handheld spherical display that can hardly be realized in reality. On the other hand, gaining insights about the impact of a fully tangible embodiment of a virtual object on task performance, comprehension of patterns, and user behavior is important in its own right. After a description of the implementation we discuss the advantages and disadvantages of our approach, taking into account different handheld spherical displays utilizing outside and inside projection.

Index Terms: Human-centered computing—Interaction paradigms—Virtual reality;

1 INTRODUCTION & MOTIVATION

While common drawbacks of VR regarding visual display issues, such as field of view, resolution, and latency are constantly improved, the concepts for tangible feedback are less straightforward. As Anthes et al. [2] state, a considerable variety of controllers exist, covering approaches for gestural input and methods for passive and active haptic feedback. However, it is still unclear which concept is best suited for which kind of application. A spherical display and controller shape accommodates numerous visualizations and provides a unified surface that can be represented by a (simple and cheap) tracked object. This opens the opportunity to investigate the role of accurate topological feedback on an established visualization paradigm as well as the possibility to prototype interaction with novel display technologies.

Besides its reproducibility, the simple and self-explanatory character of the shape and its natural affordance for rotation and focus, a spherical visualization provides multiple advantages that may even be amplified by tangible interaction. Spherical surfaces can, for instance, enhance the perception of structures and relationships in an information space, which can be useful for graph visualizations or representations of correlated elements as shown by Brath et al. [7]. For example, an inverse element can intuitively be mapped to the back side of the sphere while an element that is placed on the opposite edge of a plane cannot be identified distinctly as such a contrasting element. In a first step, we demonstrate the practicability of tracked spherical proxy objects that allow tangible interaction for spherical visualizations. Our implementation relies on common off-the-shelf VR hardware and is therefore easily reproducible. Second, we compare handling a fully tangible sphere to a closely related controller-as-proxy interaction technique and draw conclusions what types of spherical visualizations benefit from tangible interaction. We show that the perception of complex patterns in graph visualizations yield better results with fully tangible interaction.

Figure 1: We show how a fully tangible spherical object can be utilized in VR by tracking an acrylic glass sphere with commercial hardware. This allows for the examination of the effects of a topologically equivalent tangible proxy object (image captured with Microsoft Hololens).

2 BACKGROUND & RELATED WORK

Our work draws from various fields of research such as the interaction with handheld spherical objects, spherical visualizations in general (since they are not yet widely used in VR), and from tangible interaction as well as from display simulation techniques in VR.

2.1 Handheld Spherical Objects

While a considerable amount of research focuses on the interaction with static spherical displays [4,27,29], handheld spherical interaction objects are still rare. Recent advances have been made in the field of Handheld Perspective-Coupled Displays (HPCDs) [5,6,10]. This method tracks the user's position and the location of a spherical prop to project a perspectively correct image of an object from the outside onto its surface, which also makes it possible to display 3D objects that appear to be inside the sphere. Louis and Berard [18] compared an HPCD to an opaque Head-Mounted Display (HMD) on a docking task performed with a tangible sphere. They found that the HPCD approach was superior in terms of efficiency, user proprioception and the quality of visual feedback but acknowledged that the system had a number of drawbacks compared to the HMD—most prominently a limited and partially obstructed view of the sphere's projected content. Another interesting example is the work of Belloc et al. [3]. By positioning multiple calibrated high-performance

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Figure 2: For the purpose of tracking two differently sized acrylic glass spheres (diameters: 25cm and 40cm), a threaded rod with stabilization had to be fixed to the spheres so that a tracker could be mounted in the center. The complete hardware setup consisted of a total of four trackers, a VR headset, tracking gloves for selection, and two controllers. All components are commercially available.

laser pico-projectors inside the socket of a translucent sphere, they realized a handheld spherical display with support for multi-user interaction and stereoscopic 3D rendering. Both of the above examples demonstrate that the technology does not only require considerable effort in terms of costly or custom-built hardware, but yet cannot overcome a number of significant disadvantages.

2.2 Spherical Visualizations

For the presentation of specific types of visualizations, a spherical surface can be more suitable than a planar surface. The shape can make complex data more understandable by facilitating the perception of spatial relationships. Consequently, a variety of spherical visualizations have been established, most prominently including geographic layouts. Apart from the inherent property of showing earth in its natural, undistorted shape, Vega et al. [25] stated that virtual globes—when coupled with statistical data—can convey complex scientific concepts to a wider audience by bridging the communication gap between discoveries and recognition.

A related visualization type is the origin-destination flow map that visualizes flows such as flight routes between different geographic locations. The findings of Jenny et al. [13] indicate that flow maps under consideration of layout principles are a powerful tool for representing global relationships. The research of Du et al. [9] shows that a spherical display can facilitate the interactive exploration of large graph visualizations. Spheres naturally support the focus and context technique that places important information close to the user while hiding distant nodes on the other side of the sphere.

Benko et al. [4] suggest to use a spherical layout for the presentation of omnidirectional content such as 360° panoramic images or videos that span across the entire display surface. The sphere can either be viewed from the outside to explore the recording by rotation or from the inside by looking around. Outside of VR, the latter method is often implemented with the help of projected dome environments [1] or CAVE-Systems [8] which place the user at the center of a surrounding visualization.

2.3 Immersive Spherical Visualizations

The approaches described above are often designed for use with real-world spherical displays or environments. The layouts are also well established and therefore inspired the use cases of our work. However, some conceptual properties of spherical layouts such as elevated flow-lines expanding beyond the surface are therefore difficult to implement in the real world. Following this insight, several approaches investigate spherical layouts in immersive environments. One of the most obvious characteristics of VR is that it allows the users to choose a suitable viewpoint from which the object of interest is perfectly visible by walking around and moving their head. However, the viewpoint from which the user looks at the visualization during exploration is not just important to avoid occluded items, especially for graph visualizations. It also enables the perception of depth and structures without requiring extensive spatial navigation. Kwon et al. [16] tried to solve the problem of finding an ideal viewpoint by placing the user in the middle of a sphere and presenting a graph on its surface. Consequently, the users viewpoint is equidistant to most of the display area that is equally accessible through simple angular motion. Yang et al. [28] recently obtained promising results by presenting origin-destination flow maps on 3D globes in an immersive environment. In several user studies, the authors found that a three-dimensional map with raised flows is well-suited for presenting regional flow data and outperforms a traditional two-dimensional origin-destination flow map.

2.4 Tangible Interaction

Previous research on tangible interaction constitutes another valuable resource. Our work seeks to investigate the positive effects of a fully tangible representation on the perception of spherical visualizations. In general, this interaction paradigm tries to make virtual information tangible by using physical artifacts. Thus, it addresses familiar senses and skills which are learned by interaction with the real world. Hurtienne et al. [12] define a technical system as intuitively usable when the users unconscious application of preexisting knowledge leads to effective interaction. It is important that the knowledge is applied unconsciously and without awareness of the user. Piper et al. [20] assume that such direct manipulation of physical objects supports the natural ability to discover solutions and allows to understand complex information or relationships more quickly and intuitively—a hypothesis our approach seeks to strengthen.

Schmalstieg et al. [22] and Weiss et al. [26] have shown that transparent objects can effectively provide tangible feedback on tabletops. Related not only by the nature of our props these findings back our expectations regarding beneficial effects created by a flexible adjustment of obstruction and opacity. While the opacity of the displayed content and the input devices (e.g the users' hands) can be freely set with our concept in VR the transparent material of the proxies also would allow for non-opaque visualizations in AR environments.

2.5 Display Simulation in VR

Because our spherical props can also be seen as handheld spherical displays that could, with all their features, theoretically become a reality in the future, we also looked at simulations of novel display technologies in VR. For instance, Kim et al. [14] used a desktop VR setup to simulate an AR heads-up windshield display in order to understand how the cognitive load on users could be reduced during interaction. Another example of simulating Augmented Reality systems was proposed by Lee et al. [17]. Their approach was focused on an investigation of the importance of latency while Ren et al. [21] explored future AR technology by simulating wide field of view capabilities in VR.

3 A HANDHELD SPHERE AS AN INTERACTION OBJECT

Following Fishkin's taxonomy [11], the conception of our system fulfills the requirements for the level of full embodiment: The input and the output device are equivalent because the state of the input device (the spherical prop) is fully embodied in the output device (the head-mounted display). The spherical props for our prototype had to be robust, simple in construction, low cost, and provide a largely unobstructed and complete spherical surface. Another main goal of the construction and the hardware concept was to enable an effortless reproduction. Thus, we present an alternative to specialized and expensive hardware previously used in this field. The disadvantage of user instrumentation can obviously not be eliminated but the concept does not suffer from crucial drawbacks such as a limited view, a severely restricted operation area, obstruction of the visualization (e.g., shadowing by the users' hands or masking by tracking markers) or an incomplete spherical shape.

3.1 Construction & Hardware

We chose the HTC Vive lighthouse tracking system because it provides a low-latency, room-scale tracking with sufficient accuracy [19] at a refresh rate of 90 Hz. For tracking the spherical object, the commercially available Vive Tracker[1] is used. We found that the operation of the infrared-based tracking system was not restricted in any noticeable way when the tracker is placed behind transparent material. Consequently, we ordered two acrylic glass spheres (diameter: 25cm, 40cm) from a decoration equipment manufacturer. As seen in Figure 2, the spheres can be split into two halves and had to be fitted with a mount for the tracker. This was done by attaching a 1/4 inch threaded rod to one of the "poles" of the sphere with a countersunk screw from the outside. To achieve an optimal mapping to the virtual object and an unobstructed line of sight for the tracking system, we put the tracker at the center of the sphere. To center the rod and to avoid its vibration (and in turn the tracker's) we inserted a stabilization piece made of acrylic glass. Such a piece can be created with a laser cutter, 3D printer or simply with a jigsaw. When assembled completely, the smaller sphere has a total weight of 970g while the larger one weighs 2390g. For multi-touch input on the spheres' surfaces, we use the Noitom Hi5 VR Glove[2], which is designed for the integration with a Vive setup. We experienced that the system didn't work perfectly, but well enough to detect touch events on the surface as well as finger gestures.

3.2 Software Implementation

The implementation is exclusively done with Unity 3D using C#. The engine supports all necessary assets to integrate the head-mounted display, tracking devices and VR gloves. Therefore, no conversions from different coordinate systems, except a single rotation of 90° around the *x-axis* were needed.

1. **Virtual Globe:** The geographical visualization is realized by placing an earth texture in equirectangular projection on a spherical primitive. In order to make countries selectable, political borders were loaded in the background. A touch event occurs when a collision of the visible 3D hand model and the sphere is detected when the fingers form a pointing gesture. Accordingly, the index finger of either hand can be used to tap on interactive objects.

2. **Spherical Graph:** This visualization consists of a simple node-link-diagram. A graph consists of several small sphere primitives with four different colors that represent the nodes. Corresponding line objects that connect the nodes form the edges. The graph is wrapped around a slightly transparent sphere to enable full visibility at any time while ensuring a clear distinction between foreground and background.

3. **360° video:** The video is played simultaneously on a handheld sphere as well as on a sphere surrounding the user. The handheld sphere provides an additional tool for investigation, as it allows viewing parts of the video that are outside the users' field of view. Finally, a heatmap overlay showing data from previous viewers was added that provided a guide to important scene content as well as an opportunity for later evaluation.

4 REALIZED INTERACTION CONCEPTS

To allow for an investigation of the effects of tangible interaction provided by our setup, we compared this concept to a closely related technique that uses VR controllers. Both methods rely on absolute movement (6-DOF) of the virtual object: The output visualization performs the same transformation as the input device without any intermediate transformation [24].

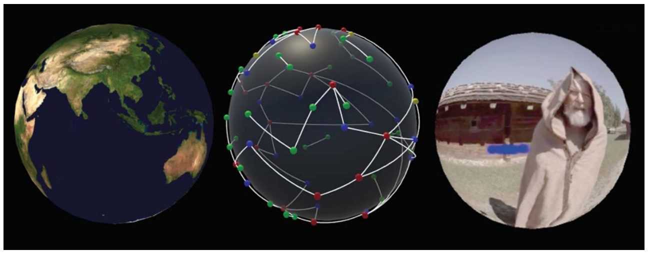

Figure 3: To analyze the effectiveness of our setup we used three spherical visualizations: a virtual globe (1), a spherical graph (2), and a 360° video (3). On the globe, users had to select a marked country, the graph was used for pattern detection and the video to investigate the comprehension of a virtual environment.

4.1 Fully Tangible Interaction

For the tangible interaction method, the spherical props were used. Every time the position or rotation of the virtual tracker object changes (i.e., whenever the physical sphere is moved or rotated), the virtual sphere object changes accordingly. For the selection of a point on the surface, the user needs to wear the hand tracking gloves. By touching the sphere with an outstretched index finger while the other fingers of the same hand are flapped away, the touched point can be selected. This distinct gesture prevents triggering touch events when users just hold the sphere. Which of the two hands is used for selection is not important because the pointing gesture was implemented for both hands. We experienced some common drawbacks regarding room scale hand tracking in terms of precision and orientation of the hands. However, we found that the accuracy of the gloves was sufficient for the purpose of the study. In rare cases when users reported such problems, a repetition of the current task was allowed.

4.2 Controller Interaction

The controller interaction method is based on a technique used in popular VR applications such as Google Earth VR [23]. Users hold one controller in each hand while the spherical visualization is attached to one of them. To match the tangible variant, we decided to place the virtual sphere in the middle of the controller and to hide the 3D model of the input device. Point selection on the sphere can be performed with the other controller, to which a laser pointer is attached. A small dot becomes visible at the point where the laser hits the sphere. This supports comparability to the tangible interaction because the size of this marking is about the diameter of a fingertip. A selection is performed if the trigger or grip button on the controller is pressed. The decision whether the pointing device or the sphere controller was held in the dominant hand was, in line with the tangible method, left to the user.

5 USER STUDY

We completed a lab study to evaluate the usability of the fully tangible interaction technique with two different sphere sizes, we draw a comparison to the controller-based interaction and we evaluate our method qualitatively via a questionnaire.

5.1 Study Design

The study followed a mixed (within-subject- as well as between-subject) design. Half of the participants interacted by using the tangible sphere (*sphere* group) while the rest of the participants used the controller method (*controller* group). This design was chosen due to the observation that the second task generated a noticeable learning effect. Therefore we decided to split the participants into two groups in order to produce more unbiased results for this task. Respectively the within-subject-design was used for evaluating the

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[1] Vive Tracker: `https://www.vive.com/de/vive-tracker/`

[2] Noitom Hi5 VR Glove: `https://hi5vrglove.com/`

sphere size. Every user performed the globe task (find marker) and the graph task (detect pattern) on the two different sphere sizes in counterbalanced order. The video task (recall environment) was only carried out on the large sphere because we found that the surface of the small sphere offers too little space for presenting the video in a convenient size. Two different country markers and two different graphs with changed node positions and color-schemes were used along the two sizes to prevent a possible learning effect. The independent variables, which were manipulated during the study, are the interaction method and the size of the tangible sphere. The dependent variables, which were measured during the study, are the task completion time, the intuitive usability of the interaction method, the understanding and perception of the presented data as well as the users' preferences. By changing the interaction method from controller interaction to tangible interaction, we expected a positive effect on the dependent variables.

For the 32 participants in the study, the average age was 25.6 years in a range between 17 and 61 years. 62.5% of the subjects were female and 37.5% male. The average experience with virtual reality technologies was 4 on a scale from 1 (none) to 10 (very much) according to which the two test groups were balanced. The task succession, the independent variables and visualization variants were counterbalanced systematically to prevent any ordering effects. The study took about 30 minutes, including the questionnaire. Participants were rewarded with a voucher of an online store.

5.2 Tasks

For each of the three implemented visualizations the participants had to perform one predefined task:

1. **Explorative task:** Users had to find and select a country marker (orange cross) placed on the surface of the virtual globe. The marker was not visible from the starting position. Therefore, the task required rotation and selection.
2. **First analytical task:** For the spherical graph visualization users had to detect a specific pattern related to the color of the nodes without any prior knowledge (they were only told to look for any kind of abnormalities). In particular, one of four colors was exclusively connected to only one other color. We classified the users' solutions into three classes: detected, partly detected and not detected.
3. **Second analytical task:** Users had to watch a 360° video that was played on a surrounding sphere as well as on the smaller handheld tangible sphere. Afterwards, a questionnaire about the environment of the two consecutive scenes as well as the overlayed heatmap data had to be answered.

5.3 Quantitative Results

We first present the quantitative findings regarding the three tasks, then we discuss the qualitative results from the questionnaires and report overall observations.

5.3.1 First task

The average time needed for selecting a country without instruction was 27.87 seconds for the *sphere* group and 29.91 seconds for the *controller* group. While in the first group, none of the participants needed assistance for operation, in the latter group, four of the sixteen participants needed advice or required a noticeably long trial time. The average time for finding the marker and selecting the corresponding country regardless of the spheres' size, was 12.88 seconds in the *sphere* group and 10.47 seconds in the *controller* group. As shown in Figure 4 the average times for the *sphere* group were 14.82 seconds (large) and 10.94 seconds (small) while the *controller* group scored 11.97 seconds (large) and 8.97 seconds (small). This close margin backs the insight of our method being comparable to established controller interaction and that in general the smaller sphere provides an advantage in terms of task performance for both approaches.

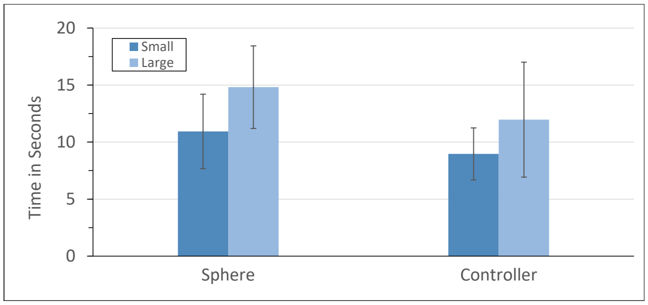

Figure 4: The smaller sphere led to marginally lower task completion times than the larger one for the first task (average task time with 95% confidence intervals).

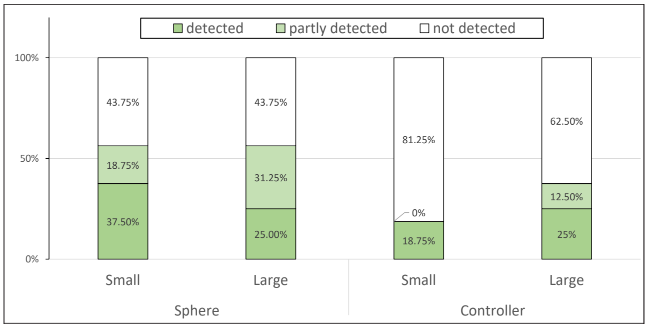

Figure 5: For the spherical graph (second task) the tangible proxies led to 18% better results regarding the frequency of detection for the smaller sphere while the larger spheres achieved the same result. If partial detections are considered the result of the *sphere* group improves even further.

5.3.2 Second task

For the graph visualization, a pattern in the connection of the colored nodes had to be detected. The users' answers were classified into three groups. The color pattern was detected if the user identified that the blue nodes could only be connected to the red nodes (first color scheme). The color pattern was partly detected if the user realized that blue and red were often grouped together. For all other answers, the color pattern was not detected. Per group, 16 detections were possible for each size which constitute the overall detection tasks as shown in Figure 5. When considering only full detections the smaller tangible sphere performed 18% better than the controller variant while the larger spheres performed equally. If partial detections are added to the result the *sphere* group outperformed the *controller* group by a total of 37,5%. When comparing the two groups independent from size and full or partial detection the *sphere* group scores a result of 56,25% of the 32 possible detections while the *controller* group scores 28,13%.

5.3.3 Third task

The users' descriptions of what they remembered from the scene were divided into the classes high, medium and low, indicating which amount of objects, people and details were recalled from the scene. Since every user described two scenes from the video, the overall number of descriptions is 64 (32 for each group). In the *sphere* group, the distribution was relatively balanced between the categories. The *controller* group provides a similar distribution.

Questions about the recall of the arrangement of objects in the scenes as well as on important parts indicated also did not show any noteworthy differences between the two groups. Thus, an in depth analyis was not necessary.

5.4 Qualitative Results

The final questionnaire consisted of Likert scales between 1 (agree) and 5 (disagree) about relevant topics such as intuitive usability or a level of immersion as well as questions with free text answers. The complete results are presented in Figure 6. In terms of subjectively reported cybersickness, there was not a strong feeling of sickness either for the outside perspective (earth and graph) or the inside perspective (video) content. The cybersickness ratings for the *sphere* group were overall better than those of the *controller* group.

5.4.1 *Sphere* Group

When asked what they liked about the interaction method, the users in the *sphere* group answered that the technique was intuitively usable and provided a familiar feeling due to its similarity with interaction in the real world, especially the earth visualization that resembled a traditional globe. In addition, the interaction with the fingers instead of a device and the feeling that the direct touch helps in understanding and remembering information were mentioned positively. One point of criticism on the tangible interaction method was the heavy weight of the large sphere which required a stronger focus on the handling of the object. Also, the selection was described as difficult by some users because both hands were necessary for holding the sphere. For the video task, most of the participants did not realize that the tangible sphere could be used as an additional display and some of them even found it confusing because they were not able to concentrate on two displays at the same time. All participants preferred the small sphere size because they found the large sphere too heavy and also criticized that it had to be held far way from the body to see the whole visualization.

5.4.2 *Controller* Group

In the *controller* group, some of the participants criticized that it was not clear from the beginning which button had to be used for selecting a country. The rotation movement with the controller was characterized as not very natural and comfortable. In general users in the *controller* group named the ease of use and the light weight as characteristics they liked. In this group, 62.5% preferred the small sphere. The handy size which allowed to hold the sphere at a comfortable distance to the body and required less movement for rotating it was mentioned as an advantage as well. In general, users in the *controller* group named the ease of use and the light weight as characteristics they liked.

5.5 Observations and Interaction Strategies

Furthermore, some participants of both groups described the small sphere as more clearly arranged for an all-around view while the supporters of the large sphere found the greater display size beneficial to exploring details and selecting a point on the sphere. We observed that, especially for the larger sphere, users came up with alternative methods than just standing and holding the sphere. Some tucked it in against their body while others preferred placing it on the floor or sat down with it while placing the object on the lap (Figure 7).

6 DISCUSSION & LIMITATIONS

Our prototype shows that current VR technology can provide credible and fast visual feedback even though the tracking device is placed behind transparent material. Some current limitations are rooted in HMD technology. In addition to a high level of user instrumentation, users still remain quite isolated from their surroundings and the display resolution is not yet high enough to show elaborate detail. Since these limitations are of technical nature and likely to improve, we see great potential in the proposed method especially because it is not suffering from the various drawbacks that outside and inside projected handheld spherical displays have to deal with. One major advantage of placing the tracker inside the tracked object is the result of a completely unobstructed surface and visualization—a condition the HPCD approach as well as the inside projection method cannot maintain. The former is dependent on visible tracking markers on the surface and additional obstruction can occur when the user's body or hands get in the way of the projectors, while the latter needs a socket to which the sphere is mounted, strongly distorting its topology.

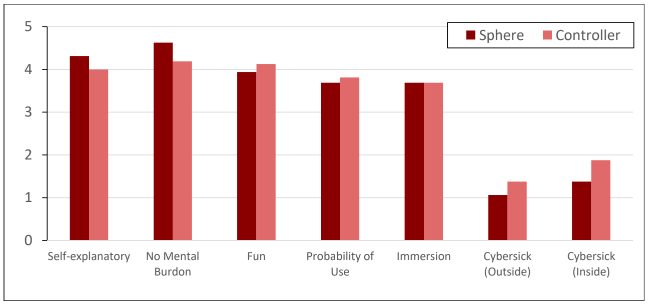

Figure 6: The evaluation of the qualitative results shows that both interaction methods performed within a close margin. No strong feelings of cybersickness were reported, with the spherical props scoring lower values. Values are given on a Likert scale from 0 to 5.

Figure 7: Some users applied unconventional strategies, especially for the large sphere, such as sitting on the floor and placing the sphere on their lap.

Additionally, the level of obstruction by the users' hands can be adjusted freely with our approach by either changing the opacity of the tracked 3D hand model or by completely disregarding hand tracking. Moreover, the visualization can be examined unrestricted from any viewpoint without any limitation. This is also not possible for HPCDs since the image is commonly projected from above the sphere and therefore only can cover the upper part. Developing HMD technology increasingly offers possibilities of blending between real and virtual world, mainly by the use of stereoscopic cameras, alleviating the isolation problem of VR environments. Therefore VR setups are likely to catch up on advantages of AR as they were investigated by Krichenbauer et al. [15]. We also believe collaborative interaction in VR could benefit from our approach taking into account the possibilty to show individual content on a shared sphere what at least for projected displays cannot be implemented without effort. We recognize that the weights of our prototype are yet not low enough to encourage long term usage. This is mainly due to the fact that we focused on a stable fixation of the tracker, but are confident that the mounting method can be improved, reducing the overall weight of the spheres.

7 CONCLUSION & OUTLOOK

As illustrated, three-dimensional spherical visualizations in VR cannot only cover a wide field of applications but may also provide a convenient medium for data analysis, especially when fully embodied by a physical sphere. Due to its simplicity in hardware and construction, our approach is widely applicable for larger audiences. We were able to show for three types of applications that the feedback from a topologically equivalent object does grant benefits concerning analytical evaluation, user preference, and learnability. This may indicate beneficial future applications in education or for public VR technology demonstrations with first-time users.

A logical step for follow-up research is the extension to non-spherical visualizations that could also be controlled by spherical objects or a general approach in the direction of 3D object examination. An investigation of different perspectives (user position, mapping of the visualization onto the sphere) as well as concepts for more elaborate interaction, might also yield interesting insights. We plan to design and evaluate more complex UI elements, along with a further exploration of the importance of tangible feedback. Another intriguing future direction is presented by the ability to go beyond the capabilities of actual spherical physical displays while retaining tangible feedback, for example by showing simulated holographic content emanating from the sphere into the space around it.

The natural versatility of VR and AR technology combined with the simplicity of the tangible sphere interaction approach supports spherical visualization and data analysis in VR. Holding a tracked sphere can provide an interesting and beneficial alternative to established interaction techniques, addresses the haptic sense in a very realistic way, and may help in further bridging the gap between the physical and the virtual world.

REFERENCES

[1] X. Amatriain, J. Kuchera-Morin, T. Höllerer, and S. T. Pope. The allosphere: Immersive multimedia for scientific discovery and artistic exploration. *IEEE MultiMedia*, 16(2):64–75, 2009.

[2] C. Anthes, R. J. García-Hernández, M. Wiedemann, and D. Kranzlmüller. State of the art of virtual reality technology. In *Aerospace Conference, 2016 IEEE*, pp. 1–19. Ieee, 2016.

[3] O. Belloc, M. Nagamura, D. Fonseca, A. Rodrigues, D. Souza, C. S. Kurashima, M. Almeida, E. Z. Borba, R. Lopes, and M. K. Zuffo. Orbevr: a handheld convex spherical virtual reality display. In *ACM SIGGRAPH 2017 Emerging Technologies*, p. 19. ACM, 2017.

[4] H. Benko, A. D. Wilson, and R. Balakrishnan. Sphere: multi-touch interactions on a spherical display. In *Proceedings of the 21st annual ACM symposium on User interface software and technology*, pp. 77–86. ACM, 2008.

[5] F. Berard and T. Louis. The object inside: Assessing 3d examination with a spherical handheld perspective-corrected display. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 4396–4404. ACM, 2017.

[6] F. Berard and T. Louis. A low-latency, high-precision handheld perspective corrected display. In *Adjunct Proceedings of the IEEE International Symposium for Mixed and Augmented Reality 2018 (To appear)*, 2018.

[7] R. Brath and P. Macmurchy. Sphere-based information visualization: Challenges and benefits. In *Information Visualisation (IV), 2012 16th International Conference on*, pp. 1–6. IEEE, 2012.

[8] 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):64–73, 1992.

[9] F. Du, N. Cao, Y.-R. Lin, P. Xu, and H. Tong. isphere: Focus+ context sphere visualization for interactive large graph exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 2916–2927. ACM, 2017.

[10] F. Ferreira, M. Cabral, O. Belloc, G. Miller, C. Kurashima, R. de Deus Lopes, I. Stavness, J. Anacleto, M. Zuffo, and S. Fels. Spheree: a 3d perspective-corrected interactive spherical scalable display. In *ACM SIGGRAPH 2014 Posters*, p. 86. ACM, 2014.

[11] K. P. Fishkin. A taxonomy for and analysis of tangible interfaces. *Personal and Ubiquitous Computing*, 8(5):347–358, 2004.

[12] J. Hurtienne and J. H. Israel. Image schemas and their metaphorical extensions: intuitive patterns for tangible interaction. In *Proceedings of the 1st international conference on Tangible and embedded interaction*, pp. 127–134. ACM, 2007.

[13] B. Jenny, D. M. Stephen, I. Muehlenhaus, B. E. Marston, R. Sharma, E. Zhang, and H. Jenny. Design principles for origin-destination flow maps. *Cartography and Geographic Information Science*, 45(1):62–75, 2018.

[14] S. Kim and A. K. Dey. Simulated augmented reality windshield display as a cognitive mapping aid for elder driver navigation. In *Proceedings of the 27th international conference on Human factors in computing systems - CHI 09*, p. 133. ACM Press, New York, New York, USA, 2009. doi: 10.1145/1518701.1518724

[15] M. Krichenbauer, G. Yamamoto, T. Taketomi, C. Sandor, and H. Kato. Augmented reality vs virtual reality for 3d object manipulation. *IEEE Transactions on Visualization and Computer Graphics PP*, 99:1–1, 2017.

[16] O.-H. Kwon, C. Muelder, K. Lee, and K.-L. Ma. A study of layout, rendering, and interaction methods for immersive graph visualization. *IEEE transactions on visualization and computer graphics*, 22(7):1802–1815, 2016.

[17] C. Lee, S. Bonebrake, D. A. Bowman, and T. Höllerer. The role of latency in the validity of ar simulation. In *Virtual Reality Conference (VR), 2010 IEEE*, pp. 11–18. IEEE, 2010.

[18] T. Louis and F. Berard. Superiority of a handheld perspective-coupled display in isomorphic docking performances. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces*, pp. 72–81. ACM, 2017.

[19] D. C. Niehorster, L. Li, and M. Lappe. The accuracy and precision of position and orientation tracking in the htc vive virtual reality system for scientific research. *i-Perception*, 8(3):2041669517708205, 2017.

[20] B. Piper, C. Ratti, and H. Ishii. Illuminating clay: a 3-d tangible interface for landscape analysis. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pp. 355–362. ACM, 2002.

[21] D. Ren, T. Goldschwendt, Y. Chang, and T. Höllerer. Evaluating wide-field-of-view augmented reality with mixed reality simulation. In *Virtual Reality (VR), 2016 IEEE*, pp. 93–102. IEEE, 2016.

[22] D. Schmalstieg, L. M. Encarnação, and Z. Szalavári. Using transparent props for interaction with the virtual table. In *Proceedings of the 1999 symposium on Interactive 3D graphics*, pp. 147–153. ACM, 1999.

[23] B. Streppel, D. Pantförder, and B. Vogel-Heuser. Interaction in virtual environments-how to control the environment by using vr-glasses in the most immersive way. In *International Conference on Virtual, Augmented and Mixed Reality*, pp. 183–201. Springer, 2018.

[24] J. Sweetser, A. Grunnet-Jepsen, and G. Panchanathan. Absolute pointing and tracking based remote control for interactive user experience. In *Proceedings of the 1st international conference on Designing interactive user experiences for TV and video*, pp. 155–164. ACM, 2008.

[25] K. Vega, E. Wernert, P. Beard, C. Gniady, D. Reagan, M. Boyles, and C. Eller. Visualization on spherical displays: Challenges and opportunities. *Proceedings of the IEEE VIS Arts Program (VISAP)*, pp. 108–116, 2014.

[26] M. Weiss, R. Jennings, R. Khoshabeh, J. Borchers, J. Wagner, Y. Jansen, and J. D. Hollan. Slap widgets: bridging the gap between virtual and physical controls on tabletops. In *CHI'09 Extended Abstracts on Human Factors in Computing Systems*, pp. 3229–3234. ACM, 2009.

[27] J. R. Williamson, D. Sundén, and J. Bradley. GlobalFestival: Evaluating Real World Interaction on a Spherical Display. *Proceedings of the Joint International Conference on Pervasive and Ubiquitous Computing and the International Symposium on Wearable Computers (Ubicomp/ISWC'15)*, pp. 1251–1261, 2015.

[28] Y. Yang, T. Dwyer, B. Jenny, K. Marriott, M. Cordeil, and H. Chen. Origin-destination flow maps in immersive environments. *IEEE transactions on visualization and computer graphics*, 2018.

[29] Q. Zhou, G. Hagemann, S. Fels, D. Fafard, A. Wagemakers, C. Chamberlain, and I. Stavness. Coglobe: a co-located multi-person ftvr experience. In *ACM SIGGRAPH 2018 Emerging Technologies*, p. 5. ACM, 2018.