TangibleSphere – Interaction Techniques for Physical and Virtual Spherical Displays

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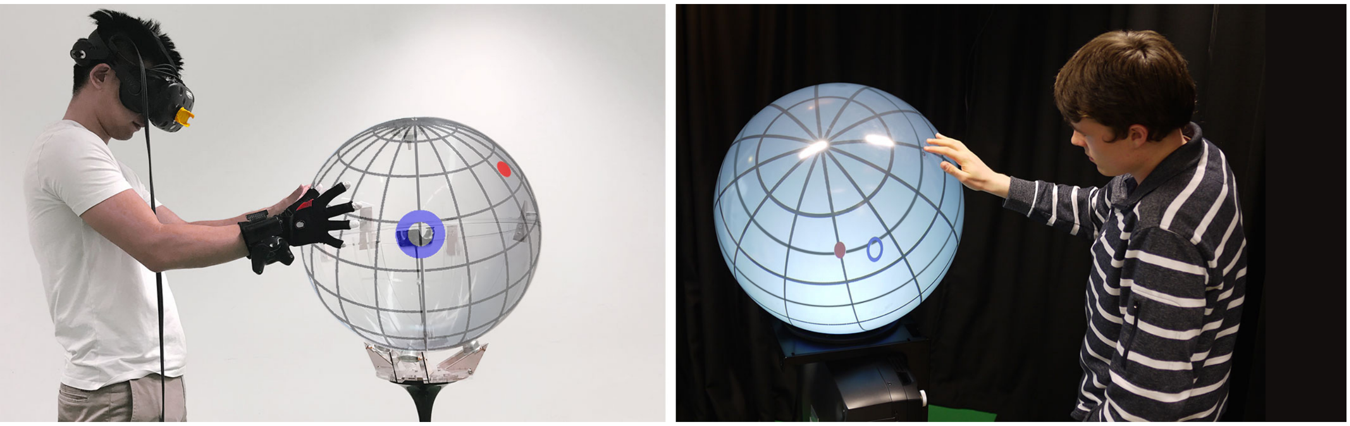

Figure 1: We present *TangibleSphere* – a setup that allows physical, interactive displays (in our case a spherical display with a diameter of 60 cm) to be simulated inexpensively in VR. We preserve the advantages of such displays' physical counterparts by enabling tangible interaction, such as free rotation in all directions. Comparing *TangibleSphere* to a purely virtual display, we found that allowing true physical rotation significantly improves accuracy and reduces task completion time.

ABSTRACT

Tangible interaction is generally assumed to provide benefits compared to other interaction styles due to its physicality. We demonstrate how this physicality can be brought to VR by means of *TangibleSphere* – a tracked, low-cost physical object that can (a) be rotated freely and (b) is overlaid with a virtual display. We present two studies, investigating performance in terms of efficiency and usability: the first study (N=16) compares *TangibleSphere* to a physical spherical display regarding accuracy and task completion time. We found comparable results for both types of displays. The second study (N=32) investigates the influence of physical rotation in more depth. We compare a pure VR condition to *TangibleSphere* in two conditions: one that allows actual physical rotation of the object and one that does not. Our findings show that physical rotation significantly improves accuracy and task completion time. These insights are valuable for researchers designing interaction techniques and interactive visualizations for spherical displays and for VR researchers aiming to incorporate physical touch into the experiences they design.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**.

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KEYWORDS

spherical displays, display simulation, virtual reality, tangible interaction, physicality

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1 INTRODUCTION

Interactive content has moved beyond flat displays to curved and 3D interfaces, for example, in the form of 360° videos and immersive 3D visualization [31]. Traditional input devices, such as keyboard and mouse, were not designed for interacting with non-planar content and common multi-touch input is not always suitable for curved and continuous surfaces. This asks for new, usable, and effective input techniques for non-planar surfaces. Yet, investigating such techniques is often challenging, as they require specialized and often expensive hardware.

We see significant potential in virtual reality (VR), as it allows technologies that are prohibitively expensive or infeasible in the real world to be (re-)created and investigated virtually. VR also provides greater flexibility for evaluation, e.g., when exploring different display configurations and sizes. While redesigning interaction techniques for modalities such as gaze or mid-air gestures may be straightforward in VR, techniques that require physical objects (e.g., a touch surface) pose a considerable challenge. To address this, VR user interfaces are often designed to be operated with controllers. However, this makes it difficult to transfer the study results obtained with VR prototypes to the real world.

To close this gap, we investigate the potential of VR to simulate high-fidelity non-planar displays in VR while preserving important characteristics of their real-world counterparts. As a use case, we focus on spherical touch displays. Spherical displays offer a compelling surface for interacting with existing types of non-planar visualizations. The shape provides a borderless but finite space, meaning content can be displayed continuously, both vertically and horizontally [48]. This property is essential for content such as geographical representations, 360° videos, and virtual environments, but also constitutes a novel way of presenting cyclic temporal data, which can be "wrapped" around the display. Finally, a sphere is a simple, familiar shape, the properties of which are easily understood, while complex non-planar shapes might be more difficult to model, perceive, and interact with. Spherical displays are available commercially, but the specialized nature of projection and display hardware is reflected in the price of commercial products. Although there are developments to reduce hardware costs (cf. Crespel et al. [12]), spherical displays generally require high-quality optics such as custom-made lenses, high-performance projectors and a significant expense in terms of assembly. This makes them an ideal candidate for being explored in a VR simulation.

In this paper, we demonstrate how an interactive device – in our case a spherical display – can be implemented in VR and how novel interaction techniques can be evaluated using our approach. In particular, we built a low-cost physical sphere (the *TangibleSphere*) made of acrylic glass, that is tracked in six degrees of freedom and enables tangible interaction. We then demonstrate that it is possible to re-create interaction techniques known from physical spherical displays in VR and that they perform comparably in terms of accuracy and task completion time. Therefore, we compare two interaction techniques – selection and alignment – on a commercial spherical display to *TangibleSphere*. Our research is complemented by an in-depth investigation of how the presence of a physical object and its properties enhances interaction with a spherical display in VR. In particular, we compare a virtual display with simulated rotation using a fixed tangible sphere to a virtual display with a freely rotating tangible sphere and a purely virtual display with no tangible feedback. We found that true physical rotation had a significant impact on accuracy and speed. Our work is valuable for designers of novel interaction techniques because it demonstrates the utility of simulating complex display types in VR. We hope to spark more research on prototyping novel interaction techniques in VR, particularly in situations where expensive hardware or physical constraints hinders development and evaluation.

2 BACKGROUND & RELATED WORK

Our work builds on prior research on spherical displays, display simulation, visualization, and interaction in VR, so we will briefly discuss each of these background fields.

2.1 Spherical Displays

Current spherical displays (both commercially available and research prototypes) almost exclusively use projection to display imagery. Projection can either happen from the inside or outside and while some displays can only show flat content on their surface, others can give the impression of a volumetric rendering inside the sphere by using techniques such as perspective correction [7, 18, 44, 50]. While a projection from the inside of the sphere often requires a fixed setup and thus hinders any form of physical rotation, projections from the outside can allow this type of physical manipulation and the haptic feedback it provides [11, 27]. However, this approach commonly suffers from other disadvantages, such as the support of a limited number of users, projection flaws, and shadowing from obstruction during interaction, as well as a restricted operation area. The user still needs to be instrumented for tracking or stereoscopic vision. In contrast, projecting spherical content onto domes places the user at the center of a spherical display [1, 3].

As first demonstrated by Grossman et al. [22] multi-touch interaction on spherical surfaces helps collaborative work greatly [21] and also allows a natural simulation of rotation [4]. Bolton et al. [6] examined how the spherical form factor can help preserve privacy in collaboration and derived interaction techniques for sharing information. Spherical displays can also support multiple users when deployed in public settings [48]. Williamson et al. have shown that such displays can be used for temporal visualizations that wrap naturally onto a spherical surface [49]. Differences between adults and children interacting with public spherical displays have been examined by Soni et al. [41].

2.2 Simulating Displays in VR

Part of our motivation for this work came from the desire to utilize and evaluate spherical display capabilities that were not available in any existing commercial display or research prototype (particularly physical rotation of the display). There is a rich history of simulating novel display technologies in VR prior to prototyping and implementing them [40] to better understand their properties and potential impact. For example, State et al. [43] built a simulator for their prototype parallax-free video-see-through head-mounted display (HMD) prototype. Arthur et al. [25] simulated a variety of head-up and head-worn display concepts for comparison purposes. Lee et al. [10] examined a volumetric display technology (depth-fused display) in all generality by simulation and optimized two-layer setups before building a physical prototype with two immaterial fog layers. Gabbard and colleagues [20] simulated outdoor AR in projection-based VR to evaluate text legibility in AR interfaces. Kim et al. [28] used a desktop VR system to simulate an AR windshield display. To study the effect of stereo cues, Fafard et al. [17] used VR to simulate a spherical fish tank display while Englmeier et al. [14, 15] explored applications for handheld embodied virtual spherical objects equally in a VR simulation. Other researchers employed mixed reality simulation (simulation of augmented reality or augmented virtuality applications in high-end VR) for controlled evaluation studies to better understand the immersion factors of AR [8, 33, 37].

2.3 Spherical Visualizations in VR

Traditional visualization techniques are often concerned with mapping abstract data sets to 2D displays. Immersive environments provide the opportunity to incorporate a variety of different display topologies [45]. Kwon et al. [30] propose mappings of abstract data to the surface of a sphere and show the benefits of such a mapping. Du et al. [13] propose a *Focus+Context* visualization, which is conceptually mapped onto the surface of a sphere. These two examples show how classical visualization concepts can be transferred and even extended when ported to a different display topology, which then, in turn, can be simulated in VR. Fully physical embodied visualizations and virtual objects have been envisioned in the context of an examination of organic interfaces by Holman and Vertegaal [24].

2.4 Interaction in VR and AR

While purely virtual interactions for *selection* and *manipulation* in VR have been found to lack the important quality of physical feedback, Schmalstieg et al. [38] showed how physical objects could remedy this lack and provide tangible interaction in VR. With their "Personal Interaction Panel", they augmented a planar wooden plate with a VR visualization and thereby created the impression of a physical object manipulated in the virtual world. Piper et al. [36] augmented an arbitrarily-shaped, malleable surface and thus turned it into a tangible display for scientific visualizations and simulated data. They also found benefits in the physical quality and tangibility of this type of physical display for virtual content.

Going back even further, Ware and Osborne [46] identified different manipulation techniques for the camera in virtual worlds and discussed different mappings of input to rotations of the camera. Their conceptual models are often implemented using a sphere surrounding the object of interest. Until today, this concept of a surrounding sphere forms the basis also for many other interaction techniques in virtual worlds, which in turn makes a physical sphere a very general and multi-purpose input object for VR.

2.5 Tangible Interaction with Physical Spheres

Previous research shows that tangible handheld spheres can be used for the rotation and inspection of 3D content with the object displayed on a 2D screen [19, 47]. Movable or even portable spheres that can display actual spherical visualizations are still rarely found, although VR provides the opportunity of projected spherical displays being used as a collaborative tool in immersive environments, as stated by Belloc et al. [2]. Mobile inside-projected spherical displays with a completely round shape have not been realized yet. However, handheld cubic prototypes have been implemented as demonstrated by the example of *Cubee* [23]. Louis and Berard [5, 34] demonstrated the feasibility of a low-latency outside-projected perspective-corrected handheld spherical display that performed better on a docking task when used in AR compared to a fully opaque VR condition. Another example of using a sphere as an input and output device supporting various kinds of physical interactions, such as throwing or kicking can be found in the work of Miyafuji et al. [35]. Apart from these examples, spheres also have a long history as a general interaction device in trackballs. Although Sperling and Tullis [42] have shown that the mouse often outperforms those devices in standard tasks, they have an advantage from an ergonomic point of view and for specific tasks, such as professional 3D media production [26, 29].

2.6 Summary

The related work we reviewed suggests that a spherical input device can support a wide variety of interaction techniques in VR. In addition, spheres are easily comprehensible and represent a simple, easily understandable familiar shape. Finally, providing a physical object with a size, mass, and resistance has often been found to be beneficial over purely virtual interaction techniques.

3 BUILDING A SPHERICAL DISPLAY FOR VR

As outlined above, a key motivation of this work is to enable interaction in VR that resembles interaction in the real world as closely as possible. We will now describe the hardware setup for our simulated spherical display. It had to meet three requirements: First, the sphere had to have the same size as the existing physical display to enable a direct comparison. Second, it had to provide an undisturbed line of sight for the infrared signals from the base stations to the Vive tracker enclosed within the sphere, but at the same time, it had to be robust enough for full physical rotation. Third, it needed to provide a smooth surface for an uninterrupted tangible sensation.

To achieve these objectives we used a light, two-piece acrylic sphere with a diameter of 60 cm from a manufacturer for decoration equipment, and modified it to fit our needs (Figure 2). We drilled two small openings at the "poles" and another four above the "equator" of the top half. For a smooth surface, these holes were cut in a cone shape in order for the screws to sink into the material. These screws hold the inner construction and connect the two hemispheres. The

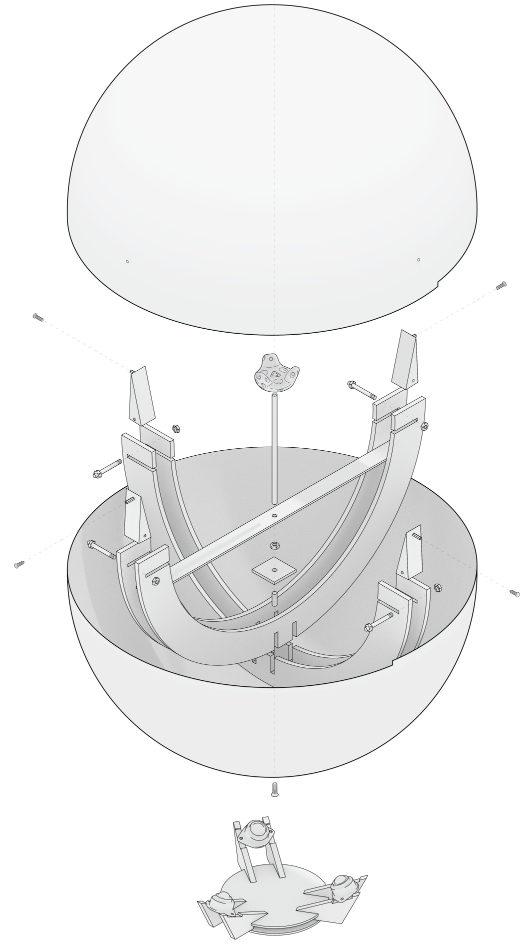

Figure 2: For the prototype of the simulated display, we fitted a large two-piece acrylic sphere with a scaffold holding the VR tracker at the center and providing stability to the construction. To allow physical rotation, the sphere sits on a ball bearing using 3 balls.

relatively light sphere was not rigid enough to fully retain its shape during rotation. We, therefore, constructed an inner frame of four laser-cut acrylic arcs in the lower hemisphere, that strengthened the structure, but also provided mounting points to attach the upper half.

Since the Vive Tracker uses a 1/4 inch thread for attachment, we fixed a rod with the matching thread to the lower hemisphere by using a custom-built adapter. This allowed us to use a smaller screw on the outside of the sphere. We used this adapter to simultaneously hold the inner frame in place. The upper hemisphere did not need its own frame since it was sufficiently stabilized when attached to the lower frame. This resulted in a largely unobstructed line of sight from the tracker to the base stations, as in [9, 16]. Lastly, we added a counterweight to the upper hemisphere for better balance during rotation and cut another tiny hole for turning on the tracking device without having to open the whole construction (Figure 3).

The stand of the sphere was built on a tulip-shaped base we took from an ashtray, designed by architect Eero Saarinen [32]. Due to its slim appearance, it provided little to no obstruction for users operating the display. On top of this stand, we mounted three triangular attachments in a tripod-like arrangement, which allowed for an easy switch between three ball bearings (needed for physical rotation) and three wooden blocks (needed for fixating the sphere).

4 STUDY METHODOLOGY

In order to investigate the efficiency of different input types, visual feedback methods, and selection techniques on spherical displays in the real world and in VR we completed two user studies. Since the setups were located in different labs, the studies were conducted at two different sites. Our first study investigated interaction with a fixed sphere. we compared (1) a commercial projected display in the real world and (2) a simulation in VR. The technically mature multi-touch surface of the commercial display served as the starting point to evaluate whether a VR simulation with touch input was generally feasible and how it compared regarding accuracy and speed.

After encouraging results, we conducted a second study comparing a non-tangible virtual sphere, a fixed tangible sphere with simulated rotation (same as the first study), and a fully rotating tangible sphere, all three using a VR display. All tasks and conditions were executed in counterbalanced order using the Latin Square Method to prevent possible learning or fatigue effects. Participants were different between both studies. They received a short oral explanation when dealing with a new condition or task. Upon completion, they were rewarded with a voucher from an online store. The first study took about 30 minutes while the second lasted about one hour. All studies were executed in concordance with the local ERB guidelines.

4.1 Research Objectives

Our primary objective was the comparison of different levels of physicality in terms of tangible spatial interaction techniques provided by our setups. As a general example task, we chose target acquisition on a spherical display, as it includes both manipulation and selection. In addition to a practical test of the VR-simulated spherical displays, we investigated the following aspects (as independent variables) through our two user studies:

Tangible Feedback: We compared three levels of physical feedback in order to evaluate performance on a target acquisition task: 1) simulated rotation on a fixed sphere; 2) real physical rotation on a turnable sphere; and 3) simulated rotation on a purely virtual sphere providing no tangible feedback.

Visual Feedback: We compared visual feedback in the foreground and background to support continuous control of the interface.

Selection Technique: We compared two selection techniques (selection by tap vs. alignment) for target acquisition on a spherical surface.

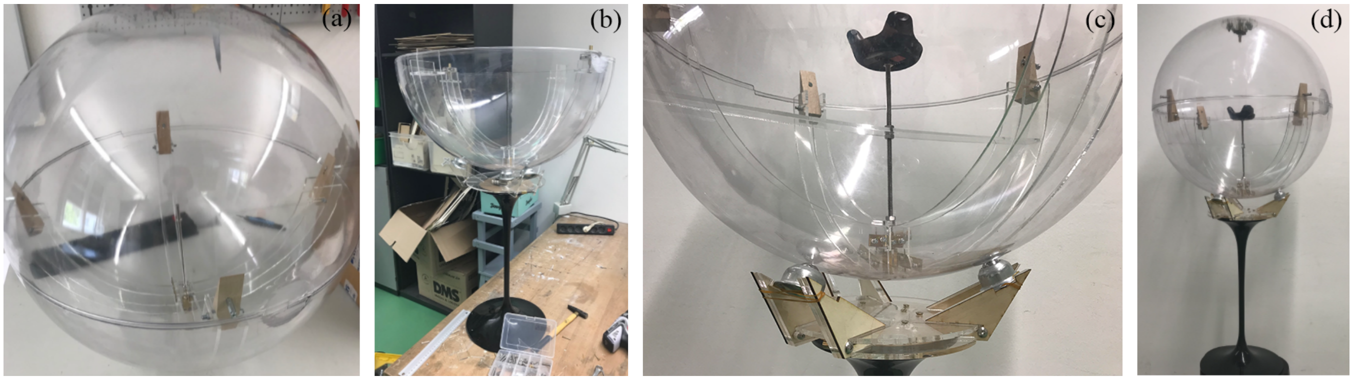

Figure 3: The tangible sphere was assembled in four steps (1-4 from left to right). First, we built a frame to join the two halves (a). Second, we created a stand (b) that allows the sphere to be held in a fixed position or to rotate it. We included a threaded rod (c) to firmly hold the VR tracker. Finally, we added a counterweight to the top part in order to balance the sphere during rotation (d).

5 STUDY ONE: REAL VS. VIRTUAL DISPLAYS

Our first study compares the efficiency of a virtual spherical display to current state-of-the-art projected displays that do not require user instrumentation for interaction. The commercial display we used as a baseline enables sophisticated multi-touch interaction. The device appears to be an ideal tool for exploring the general feasibility of our concept. Users did not see their hands in VR since we did not want to introduce side-effects through a virtual representation [39]. The system enables precise detection of the exact point where the sphere was touched and we provided visual feedback by a colored touch-point. This allowed us to compare the two display conditions independent of the input technology, and to carefully compare task performance in reality and in VR.

5.1 Hardware

In order to ensure a fair comparison, we exclusively used the spherical display as an input device. For visual output, we used either the real display itself or a VR headset.

5.1.1 Spherical Display. The projected display we used[1] provides multi-touch tracking across a fixed acrylic surface. It is made of rigid plastic that sits on an enclosed aluminum and steel stand. The display stands 1.47 m tall, with a diameter of 60 cm. A major advantage of this hardware is that it does not require user instrumentation and can be used as a free-standing display in a wide range of environments.

5.1.2 HTC Vive. In the VR display conditions we used a commercially available VR headset to visualize spherical content. The headset supports room-scale tracking with a 110° field of view and display refresh rates up to 90 Hz and a latency of about 20 ms.

5.2 Experimental Conditions

Our first study compared two different display conditions: the original projected spherical display and an overlaid VR display. All input was detected using the vision-based multi-touch surface of the commercial spherical display.

5.2.1 Condition 1: Fixed Sphere with Projected Display. Input was implemented as a simulated rotation across a fixed acrylic surface. This condition did not require any user instrumentation and represents the current state of the art in projected spherical displays.

5.2.2 Condition 2: Fixed Sphere with VR Display. Input was implemented as a simulated rotation as in the first condition but output was provided in a VR display. An HTC Vive HMD and tracking system was used for the VR simulation.

5.3 Tasks

For each condition, participants had to complete a set of tasks. In particular, we combined two selection techniques (selection by tap

Table 1: The tasks completed for each condition combined two target acquisition techniques (selection and target alignment) and two visual feedback techniques (Foreground Rotation and Background Rotation).

Task	BG Rotation FG Fixed	BG Fixed FG Rotation
Target Selection	BG: Grid and Dot, FG: None	BG: Grid, FG: Dot
Target Alignment	BG: Grid and Dot, FG: Ring	BG: Grid and Ring, FG: Dot

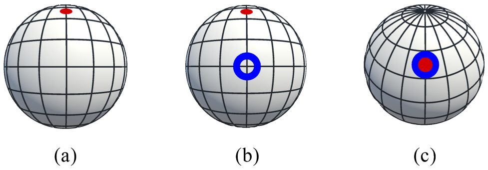

Figure 4: Users had to complete two types of tasks: selecting a target (a) and aligning an object (red dot) with a target (blue circle) (b, c).

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[1] PufferSphere M: https://pufferfishdisplays.com/

Figure 5: Duration of tasks in Study 1 for projected display and VR display conditions, values are given in seconds with 95% confidence intervals.

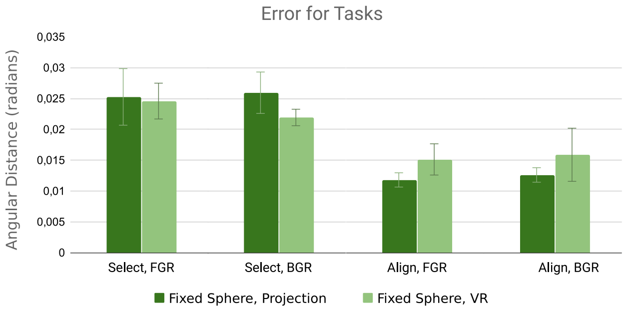

Figure 6: Accuracy of tasks in Study 1 for projected display and VR display conditions, values are given in distance from the target in radians with 95% confidence intervals.

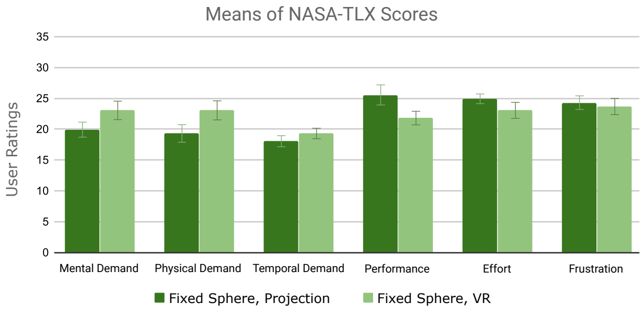

Figure 7: NASA-TLX results for Study 1 comparing the real, projected display to a condition simulating rotation using a VR display. Mean values of user ratings are given with 95% confidence intervals.

and by alignment) and two types of visual feedback (foreground and background), resulting in 2 × 2 = 4 tasks (see table 1). We presented tasks and conditions in (incomplete) counter-balanced order following a Latin Square.

For the first task type, users had to locate and tap a single red target point with a 10° diameter, as seen in Figure 4 (a). The second selection technique required users to locate the same kind of target and align it within a larger blue ring (20° diameter) fixed at the 0° longitude position (Figure 4 (b, c)). For each task, targets were chosen from six predetermined points which were located 45° below the north pole at 60° intervals. We chose these locations based on previous work that demonstrated this area as the most commonly used for content distributed across a spherical surface [48].

We placed interactive foreground elements on top of a black background grid enclosing a white sphere. Depending on the task (selection, alignment), the foreground elements consisted of either a single target point or a point and a corresponding target ring. In both methods, an additional dot (7° diameter) was supplied to indicate the user's touch position. The two visual feedback techniques implemented movement either in the foreground (FGR) or also in the background (BGR). FGR movement resulted only in the target points moving while BGR movement simultaneously rotated the target point and background grid. Each target was presented three times while users stood in a fixed place in front of the 0° longitude position on the display. Table 1 gives an overview of the tasks.

5.4 Results

Our results are based on a within-subjects evaluation with 16 participants (10 male). Participants' average age was 24.1 years with a standard deviation of 4.18 years. We completed our analysis based on usage logs of task time and task accuracy and NASA-TLX questionnaires.

5.4.1 Task Completion Time. We completed an ANOVA with repeated measures and multivariate analysis on our recorded task times. We found significant differences regarding display conditions: $F(1, 15) = 36.42$, $p < 0.001$. Bonferroni-corrected t-tests revealed statistically significant differences for the tasks *Align, FGR* and *Align, BGR* with $p < 0.001$. For both alignment tasks, the VR display caused significantly lower task completion times. This effect may be partially explained by small differences in rotation logic when implementing rotation as an azimuthal projection and a simulated sphere. Although we used standard motion constants based on commercially deployed spherical interfaces, this result suggests that further work is needed to optimize rotation logic for azimuthal projection on a multi-touch sphere. An analysis of visual feedback techniques and task types did not reveal any significant effect for task completion time. Figure Figure 5 gives an overview of the task completion times of the first study.

5.4.2 Accuracy. Figure Figure 6 gives an overview of the task accuracy for our four conditions, measured by the angular distance from selection targets in radians. A repeated measures ANOVA revealed that the conditions this time were not significantly different for accuracy: $F(1, 15) = 0.136$, $p = 0.72$. However, the task type had a statistically significant influence: Alignment tasks generated a higher accuracy with $F(1, 15) = 66.78$, $p < 0.001$. The two visual feedback techniques did not significantly influence completion times. Therefore we can only safely state that the accuracy was better for the two alignment tasks.

5.4.3 NASA-TLX. A quantitative analysis of the NASA TLX questionnaire using a Wilcoxon Signed Rank test (Figure 7) did not reveal any significant differences between the projected and VR display.

5.5 Limitations

While we took great care when implementing the conditions for the projected display and the VR display in such a way that they enabled a fair comparison, the robustness of the output hardware as well as the rotation logic might still have had a minor effect on our results.

5.6 Summary

The results from the first study show that there are differences between the projected display and the VR display regarding task completion time for alignment tasks. The selection technique only influenced accuracy, and the visual feedback technique had no significant effect on our measured values both for the simulated and the real display. While the absence of significant advantages for the real display does not prove comparability in any kind, this provides a rationale for further investigation of VR-simulated displays: The rather small effect sizes and the fact that we found significant benefits for the VR condition provide interesting prospects, just as the influence of task time on simulated rotation and the performance of the alignment technique in general.

6 STUDY TWO: DEGREES OF PHYSICALITY

A movable sphere affords a new kind of input that is not possible on current inside-projected displays. Our second study hence explores the impact of three different intensities of physical feedback: real physical rotation (*Rotatable Sphere, VR*), passive tangible feedback (*Fixed Sphere, VR*) and no tangible feedback (*Pure VR*). We compare these three types in terms of efficiency and overall usability.

6.1 Hardware

For output, in this study, we only used a VR headset. We detected user input by a finger tracking system and by tracking the physical rotation of our simulated display.

6.1.1 Tangible Sphere. As the main interaction device of the study, we used our custom-built sphere described above. It can be rotated physically while the hands of the user are tracked. User instrumentation (gloves and a headset) is required. The simulated display utilizes an HTC Vive Tracker[2] mounted inside the acrylic sphere (diameter: 60 cm). Placing the tracker inside the transparent sphere did not reduce tracking performance in any way and, therefore, allowed a precise and fast mapping of virtual visualizations. While the tangible sphere can either be rotated freely on three ball bearings or be fixed in place, the setup is held by a slim stand that is designed not to obstruct users while interacting with the device.

6.1.2 Hi5 VR Glove. We used a finger tracking system designed for the HTC Vive using two tracking gloves[3] that use local magnetic field tracking to determine finger positions. With that system, we were able to simulate a multi-touch surface for the simulated spherical display.

6.2 Software

For the VR conditions, we used Unity (C#). Touch events were generated by tracking the position of the index finger (invisible to the user) using the tracking gloves and detecting the collision with the 3D model of the sphere. This was indicated by a circular touch-point. If the interacting hand was raised the system would again wait for new input by either one of the user's two hands. We applied a small threshold of 5 mm for effectively detecting surface touch and to counter inaccuracies resulting from the gloves' tracking system and its calibration.

6.3 Experimental Conditions

Our second study compared three input techniques implementing three different degrees of physicality in VR. Due to the time required by the two main conditions (within-subject design), Condition 3 was carried out in a separate session (between-subject design).

6.3.1 Condition 1: Fixed Sphere with VR Display. This condition used the *TangibleSphere* with rotation disabled (equivalent to study one). We implemented user input as simulated rotation with finger tracking using the gloves (dragging) and also allowed selecting interactive elements by tapping on the surface.

6.3.2 Condition 2: Rotatable Sphere with VR Display. For this condition we used the *TangibleSphere* with physical rotation. Users physically turned the sphere to control rotation. Subsequently, we reduced touch input to clicking only.

6.3.3 Condition 3: Pure VR Display. To provide additional context for the main conditions, we investigated how users perform tasks when no tangible feedback was given at all. We detected user input again with the support of the tracking gloves that allowed users to interact (selection and rotation) when reaching with a hand towards the virtual sphere. Retracting the hand beyond the interaction threshold would cancel interaction. Therefore, the touch-point was the only feedback given to indicate possible interaction.

6.4 Tasks

We asked our users to perform the same tasks as in study one (selection/alignment task; foreground/background visual feedback), in the conditions that we designed for the *TangibleSphere* prototype.

6.5 Quantitative Results

Our results are based on a within-subject evaluation with 16 participants (none of the participants had taken part in study one) for the first two conditions. The participants' average age was 27.3 years, with a standard deviation of 3.3 years. Because these conditions required subjects to spend about an hour in VR, the third condition was performed by a comparable test group of the same size, with an average age of 27.1 years with a standard deviation of 3.9 years and five male participants. In order to examine the third condition, we performed a between-subjects evaluation utilizing Welch's t-test in contrast to a repeated measures ANOVA with multivariate analysis that we used to analyze the first two conditions. For the lack of space, we present the results in combined charts (Figure 8 - Figure 10) but would like to emphasize that the between-subjects

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

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

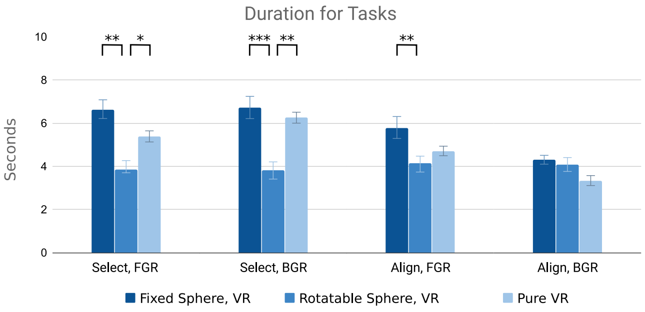

Figure 8: Duration of tasks in Study 2 for the three study conditions all using VR output, values are given in seconds with 95% confidence intervals.

evaluation only should serve for additional clues while the within-subjects evaluation provides the main source for the quantitative analysis in Study 2.

6.5.1 Task Completion Time. Figure Figure 8 gives an overview of the times taken to complete each task for the two main conditions and the additional condition. The repeated measures ANOVA revealed statistically significant differences for the main conditions: $F(1,15) = 13.42$, $p =< 0.001$. Subsequently, we completed pairwise comparisons using Bonferroni-corrected t-tests that revealed significant differences for the tasks *Select, FGR* with $p = 0.009$, *Select, BGR* with $p < 0.001$ and *Align, FGR* with $p = 0.01$. For the first three tasks, the tangible sphere with physical rotation produced significantly shorter task completion times. The Welch t-test discovered significantly higher task completion times for the third condition related to the second task *Select, FGR* and *Select, BGR* with $p = 0.038$ and $p = 0.005$. For the feedback techniques and task types we found no significant effects.

6.5.2 Accuracy. Figure Figure 9 shows an overview of the accuracy of each task. We again completed a repeated measures ANOVA with multivariate analysis for the main conditions which resulted in $F(1,15) = 34.19$, $p < 0.001$. The pairwise comparisons using Bonferroni-corrected t-tests showed that the condition *Rotatable Sphere* significantly improved task accuracy in task *Select, FGR* and *Select, BGR* with $p = 0.01$ and $p = 0.006$. As revealed by Welch's t-test the third condition was outperformed by the rotatable sphere in the tasks *Select, FGR*, *Select, BGR* and *Align, FGR* with $p = 0.03$, $p = 0.004$ and $p = 0.02$. A comparison between the task types revealed that the alignment tasks again produced a higher accuracy: $F(1,15) = 55.32$ $p < 0.001$.

6.5.3 NASA-TLX. Participants completed a NASA-TLX questionnaire for each condition to provide subjective ratings about the mental and physical demands of interacting with the system. We used the Wilcoxon Signed Rank test to compare participants' ratings between conditions. The full results of the NASA-TLX questionnaire are shown in Figure 10. Participants rated the interaction using the simulated rotation (virtual and tangible) as more mentally demanding than the physical rotation ($p < 0.05, W = 4.5$). Participants also rated the effort required to interact: The simulated rotations required more effort than the physical rotation ($p < 0.05, W = 4$).

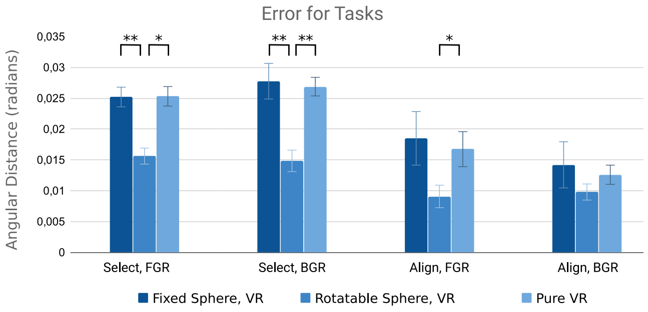

Figure 9: Accuracy of tasks in Study 2 for the three study conditions all using VR output, values are given in distance from the target in radians with 95% confidence intervals.

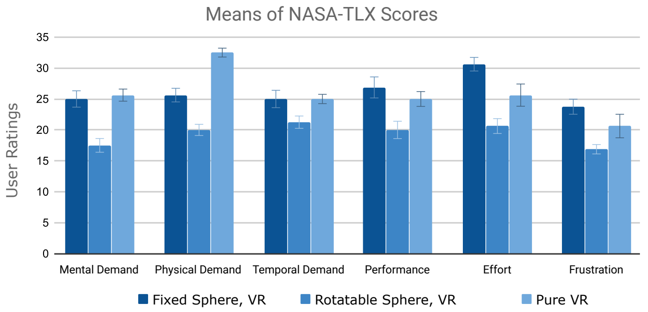

Figure 10: NASA-TLX questionnaire results for Study 2 comparing three conditions all using a VR display but different levels of physicality. Mean values of user ratings are given with 95% confidence intervals.

Given the increased friction necessary to interact when dragging the hand across a static surface and no possibility to rest their hands for the purely virtual condition, our results show that there is an increased effort for the *Fixed Sphere* and *Pure VR* condition. However, participants rate their performance higher in the simulated rotation conditions ($p < 0.05, W = 3$).

6.6 Qualitative Results

From our observations and informal discussions after the study we obtained a number of qualitative insights.

6.6.1 Rotation and Selection Strategies. An interesting finding was that people employed different strategies for selection and alignment. Some users first performed a horizontal movement of the sphere until the circle was vertically above the target and then rotated vertically. Others moved in on the target in a straight line. This fits the picture of the alignment strategy being a viable alternative for selection, in particular when paired with feedback from physical rotation. This is also backed by the observation that some users used one finger during selection tasks to provide a static target and then used the other hand to rotate the sphere to home in on the target, thus turning selection into alignment.

One advantage of the additional condition *Pure VR* is that the users do not need to follow the outline of the sphere but instead can reach into the sphere and perform the movement for rotation in a straight line. This may be an explanation for the lower task times that we found with the between-subject evaluation in comparison to the fixed sphere. This observation is in line with an inherent disadvantage of physical fish-tank VR displays: users cannot reach into the display to interact with content. Hence we focus on content that is displayed on (and possibly around) the surface of the display. However, this drawback appears to be negligible, especially since the comparison between the *Fixed Sphere* and *Pure VR* conditions resulted in no significant difference.

6.6.2 (Not so) Careful Interaction. While some people exercised great care when interacting with the sphere, others were so immersed that they performed very fast movements. This is in line with a slightly higher immersion we found from the questionnaires for physical rotation. Future work could investigate this in more detail.

6.7 Summary

Comparing the three conditions – fixed sphere, rotating sphere, and pure VR – we found that the rotating sphere led to a significantly increased accuracy and speed in all tasks (except the alignment with background visual feedback). Furthermore, the rotatable sphere led to lower perceived mental and physical demand, workload, effort, and frustration. Only in terms of perceived performance, it is rated lower than the other two conditions.

7 DISCUSSION

A virtual sphere is an attractive option for simulating spherical displays and prototyping new input techniques at a low cost. Our first study shows how it compares to a physical display, and that in some cases, it even outperforms it. Findings also demonstrate that with off-the-shelf technology, it is possible to simulate a viable tangible display in VR.

Simulating a spherical display made it possible to evaluate a new technique that uses physical rotation of the spherical surface, which would not be possible with a standard projected display. The fact that participants considered the physical demand for real rotation lower might also imply that VR is suitable for simulating objects that would have a certain weight to them in the real world. The tracked object only needs to provide the accurate outside shape of the respective object and its important characteristics (in our case rotation) and, therefore, can be noticeably lighter than its real display counterparts.

Alignment as a *selection technique* performs well on a spherical surface in terms of accuracy. In our physical display condition, this task performed best when users could see their hands. On the simulated display, the target alignment method outperformed the tapping technique especially when physical feedback was provided by real rotation.

Visual background *feedback* overall resulted in slightly better task performance, in particular for the real-world display, and also appears to be the right choice for the rotating simulated display, since it generates an image visually matching the sensation of rotation at the user's fingertips.

We were able to improve interaction with VR displays by adding *physical rotation* of a passive tangible sphere. Our study results show that physical rotation can have clear benefits for improving interaction in VR and with curved surfaces. Considering that the pure VR simulated sphere performed slightly better than the fixed sphere also suggests that the important factors of the rotating sphere are not necessarily only the shape, but also the sensation of rotation, moving mass, weight, and resistance. An evaluation of how this finding may affect interaction with real and simulated fish-tank displays, showing 3D content on the inside of a sphere, may offer a subject for future work.

Looking at possible *extensions*, in particular in the direction of (spatially separated) collaborative work, our prototype offers the interesting perspective of a shared, inexpensive physical object with a multi-touch surface that could display individually adjusted content for each user even at distributed locations. Although this was beyond the scope of our work, it might be an interesting topic for future research.

8 IMPLICATIONS AND OUTLOOK

Our experiments demonstrate that fully physical interaction as an input technique for spherical displays can significantly improve the usability of interacting with these devices. Although current projected displays have the advantage to not require any user instrumentation, most are not capable of tangible rotation. There are still many additional drawbacks regarding VR, such as a limited field of view, the challenges to seamless collaboration, and the isolation from the real world. However, the drawback of imprecise hand tracking could also turn into an advantage in the future and with improving technology, since our work shows that multi-touch interaction with well-known shapes is feasible even without the visibility of hands. Therefore, a dynamic adjustment of the opacity of the hand models and simultaneous control of the amount of visual occlusion could generate additional benefits. With advancing tracking technology, mixed-reality setups based on wide-angle high-resolution panels could continue to replace traditional physical displays to a greater extent, in particular in research.

Our results on comparing two selection techniques indicate that a target alignment task that involves more continuous movement may be better suited to the curved surfaces of a spherical display than traditional discrete selections.

Finally, this work demonstrates the value of virtual reality, not only as a simulation technology that can envision, prototype, and evaluate factors of future physical display technologies, but increasingly as an affordable and flexible display technology with general usability potential. The ergonomics of wearing a VR headset is still a major challenge for the time being. However, we believe that for exploring novel interaction techniques and special purpose applications, it may be still useful. Feedback from our users indicates that this technology can indeed succeed to establish itself as an exciting alternative and complement to physical display technologies.

REFERENCES

[1] Xavier Amatriain, JoAnn Kuchera-Morin, Tobias Höllerer, and Stephen Travis Pope. 2009. The AlloSphere: Immersive Multimedia for Scientific Discovery and Artistic Exploration. *IEEE MultiMedia* 16, 2 (2009), 64–75.

[2] O. R. Belloc, M. R. Nagamura, D. Fonseca, A. Rodrigues, D. A. R. Souza, C. S. Kurashima, M. M. Almeida, E. Z. Borba, R. D. Lopes, and M. K. Zuffo. 2017. OrbeVR: A Handheld Convex Spherical Virtual Reality Display. In *ACM SIGGRAPH 2017 Emerging Technologies* (Los Angeles, California) *(SIGGRAPH '17)*. Association

for Computing Machinery, New York, NY, USA, Article 19, 2 pages. https://doi.org/10.1145/3084822.3091104

[3] Hrvoje Benko and Andrew D. Wilson. 2010. Multi-Point Interactions with Immersive Omnidirectional Visualizations in a Dome. In *ACM International Conference on Interactive Tabletops and Surfaces* (Saarbrücken, Germany) *(ITS '10)*. Association for Computing Machinery, New York, NY, USA, 19–28. https://doi.org/10.1145/1936652.1936657

[4] Hrvoje Benko, Andrew D. Wilson, and Ravin Balakrishnan. 2008. Sphere: Multi-Touch Interactions on a Spherical Display. In *Proceedings of the 21st Annual ACM Symposium on User Interface Software and Technology* (Monterey, CA, USA) *(UIST '08)*. Association for Computing Machinery, New York, NY, USA, 77–86. https://doi.org/10.1145/1449715.1449729

[5] Francois Berard and Thibault Louis. 2017. 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* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4396–4404. https://doi.org/10.1145/3025453.3025806

[6] John Bolton, Kibum Kim, and Roel Vertegaal. 2011. Privacy and Sharing Information on Spherical and Large Flat Displays. In *Proceedings of the ACM 2011 Conference on Computer Supported Cooperative Work* (Hangzhou, China) *(CSCW '11)*. Association for Computing Machinery, New York, NY, USA, 573–574. https://doi.org/10.1145/1958824.1958912

[7] John Bolton, Kibum Kim, and Roel Vertegaal. 2011. SnowGlobe: A Spherical Fish-Tank VR Display. In *CHI '11 Extended Abstracts on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI EA '11)*. Association for Computing Machinery, New York, NY, USA, 1159–1164. https://doi.org/10.1145/1979742.1979719

[8] Doug A Bowman, Cheryl Stinson, Eric D Ragan, Siroberto Scerbo, Tobias Höllerer, Cha Lee, Ryan P McMahan, and Regis Kopper. 2012. Evaluating effectiveness in virtual environments with MR simulation. In *Interservice/Industry Training, Simulation, and Education Conference*, Vol. 4. I/ITSEC, Orlando, FL, USA, 44.

[9] Lila Bozgeyikli and Evren Bozgeyikli. 2019. Tangiball: Dynamic Embodied Tangible Interaction with a Ball in Virtual Reality. In *Companion Publication of the 2019 on Designing Interactive Systems Conference 2019 Companion* (San Diego, CA, USA) *(DIS '19 Companion)*. Association for Computing Machinery, New York, NY, USA, 135–140. https://doi.org/10.1145/3301019.3323904

[10] Cha Lee, S. DiVerdi, and T. Höllerer. 2009. Depth-Fused 3D Imagery on an Immaterial Display. *IEEE Transactions on Visualization and Computer Graphics* 15, 1 (jan 2009), 20–33. https://doi.org/10.1109/TVCG.2008.83

[11] Rick Companje, Nico van Dijk, Hanco Hogenbirk, and Daniundefineda Mast. 2006. Globe4D: Time-Traveling with an Interactive Four-Dimensional Globe. In *Proceedings of the 14th ACM International Conference on Multimedia* (Santa Barbara, CA, USA) *(MM '06)*. Association for Computing Machinery, New York, NY, USA, 959–960. https://doi.org/10.1145/1180639.1180850

[12] Thomas Crespel, Patrick Reuter, and Xavier Granier. 2017. A Low-Cost Multitouch Spherical Display: Hardware and Software Design, In SID Symposium Digest of Technical Papers. *SID Symposium Digest of Technical Papers* 48, 619–622. https://doi.org/10.1002/sdtp.11716

[13] Fan Du, Nan Cao, Yu-Ru Lin, Panpan Xu, and Hanghang Tong. 2017. ISphere: Focus+Context Sphere Visualization for Interactive Large Graph Exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 2916–2927. https://doi.org/10.1145/3025453.3025628

[14] D. Englmeier, J. Dörner, A. Butz, and T. Höllerer. 2020. A Tangible Spherical Proxy for Object Manipulation in Augmented Reality. In *2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, New York, NY, USA, 221–229. https://doi.org/10.1109/VR46266.2020.00041

[15] D. Englmeier, I. Schönewald, A. Butz, and T. Höllerer. 2019. Feel the Globe: Enhancing the Perception of Immersive Spherical Visualizations with Tangible Proxies. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, New York, NY, USA, 1693–1698. https://doi.org/10.1109/VR.2019.8797869

[16] D. Englmeier, I. Schönewald, A. Butz, and T. Höllerer. 2019. Sphere in Hand: Exploring Tangible Interaction with Immersive Spherical Visualizations. In *2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, New York, NY, USA, 912–913. https://doi.org/10.1109/VR.2019.8797887

[17] Dylan Fafard, Ian Stavness, Martin Dechant, Regan Mandryk, Qian Zhou, and Sidney Fels. 2019. FTVR in VR: Evaluation of 3D Perception With a Simulated Volumetric Fish-Tank Virtual Reality Display. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3290605.3300763

[18] F. Ferreira, M. Cabral, O. Belloc, G. Miller, C. Kurashima, R. de Deus Lopes, I. Stavness, J. Anacleto, M. Zuffo, and S. Fels. 2014. Spheree: A 3D Perspective-Corrected Interactive Spherical Scalable Display. In *ACM SIGGRAPH 2014 Posters* (Vancouver, Canada) *(SIGGRAPH '14)*. Association for Computing Machinery, New York, NY, USA, Article 86, 1 pages. https://doi.org/10.1145/2614217.2630585

[19] Bernd Froehlich, Jan Hochstrate, Verena Skuk, and Anke Huckauf. 2006. The GlobeFish and the GlobeMouse: Two New Six Degree of Freedom Input Devices for Graphics Applications. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Montréal, Québec, Canada) *(CHI '06)*. Association for Computing Machinery, New York, NY, USA, 191–199. https://doi.org/10.1145/1124772.1124802

[20] Joseph L. Gabbard, J. Edward Swan, and Deborah Hix. 2006. The Effects of Text Drawing Styles, Background Textures, and Natural Lighting on Text Legibility in Outdoor Augmented Reality. *Presence: Teleoperators and Virtual Environments* 15, 1 (feb 2006), 16–32. https://doi.org/10.1162/pres.2006.15.1.16

[21] Tovi Grossman and Ravin Balakrishnan. 2008. Collaborative Interaction with Volumetric Displays. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Florence, Italy) *(CHI '08)*. Association for Computing Machinery, New York, NY, USA, 383–392. https://doi.org/10.1145/1357054.1357118

[22] Tovi Grossman, Daniel Wigdor, and Ravin Balakrishnan. 2004. Multi-Finger Gestural Interaction with 3d Volumetric Displays. In *Proceedings of the 17th Annual ACM Symposium on User Interface Software and Technology* (Santa Fe, NM, USA) *(UIST '04)*. Association for Computing Machinery, New York, NY, USA, 61–70. https://doi.org/10.1145/1029632.1029644

[23] J. Grubert and M. Kranz. 2017. mpCubee: Towards a mobile perspective cubic display using mobile phones. In *2017 IEEE Virtual Reality (VR)*. IEEE, New York, NY, USA, 459–460.

[24] David Holman and Roel Vertegaal. 2008. Organic user interfaces: designing computers in any way, shape, or form. *Commun. ACM* 51, 6 (2008), 48–55.

[25] J. J. Arthur III, Lawrence Prinzel III, Kevin Shelton, Lynda J. Kramer, Steven P. Williams, Randall E. Bailey, and Robert M Norman. 2007. Design and testing of an unlimited field-of-regard synthetic vision head-worn display for commercial aircraft surface operations. In *Enhanced and Synthetic Vision 2007*, Jacques G. Verly and Jeff J. Guell (Eds.), Vol. 6559. International Society for Optics and Photonics, SPIE, Bellingham, WA, USA, 136 – 154. https://doi.org/10.1117/12.719695

[26] Lena Karlqvist, Eva Bernmark, Lena Ekenvall, Mats Hagberg, Anita Isaksson, and Tommy Rostö. 1999. Computer mouse and track-ball operation:: Similarities and differences in posture, muscular load and perceived exertion. *International Journal of Industrial Ergonomics* 23, 3 (1999), 157–169.

[27] Stefanie Kettner, Christopher Madden, and Remo Ziegler. 2004. Direct rotational interaction with a spherical projection. In *Creativity & Cognition Symposium on Interaction: Systems, Practice and Theory*. Creativity & Cognition Studios Press, Sydney, Australia.

[28] SeungJun Kim and Anind K. Dey. 2009. 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*. ACM Press, New York, New York, USA, 133. https://doi.org/10.1145/1518701.1518724

[29] M. Krichenbauer, G. Yamamoto, T. Taketomi, C. Sandor, and H. Kato. 2014. Towards Augmented Reality user interfaces in 3D media production. In *2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. IEEE, New York, NY, USA, 23–28.

[30] Oh-hyun Kwon and Kyungwon Lee. 2015. Spherical Layout and Rendering Methods for Immersive Graph Visualization. In *2015 IEEE Pacific Visualization Symposium (PacificVis)*. IEEE, New York, NY, USA, 63–67.

[31] Ed Lantz. 2007. A Survey of Large-Scale Immersive Displays. In *Proceedings of the 2007 Workshop on Emerging Displays Technologies: Images and beyond: The Future of Displays and Interacton* (San Diego, California, USA) *(EDT '07)*. Association for Computing Machinery, New York, NY, USA, 1–es. https://doi.org/10.1145/1278240.1278241

[32] Eric Larrabee and Massimo Vignelli. 1981. *Knoll design*. HN Abrams, New York, NY, USA.

[33] Cha Lee, Scott Bonebrake, Doug A. Bowman, and Tobias Höllerer. 2010. The role of latency in the validity of AR simulation. In *2010 IEEE Virtual Reality Conference (VR)*. IEEE, New York, NY, USA, 11–18. https://doi.org/10.1109/VR.2010.5444820

[34] Thibault Louis and Francois Berard. 2017. Superiority of a Handheld Perspective-Coupled Display in Isomorphic Docking Performances. In *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces* (Brighton, United Kingdom) *(ISS '17)*. Association for Computing Machinery, New York, NY, USA, 72–81. https://doi.org/10.1145/3132272.3134124

[35] Shio Miyafuji, Toshiki Sato, Zhengqing Li, and Hideki Koike. 2017. Qoom: An Interactive Omnidirectional Ball Display. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 599–609. https://doi.org/10.1145/3126594.3126607

[36] Ben Piper, Carlo Ratti, and Hiroshi Ishii. 2002. Illuminating Clay: A 3-D Tangible Interface for Landscape Analysis. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Minneapolis, Minnesota, USA) *(CHI '02)*. Association for Computing Machinery, New York, NY, USA, 355–362. https://doi.org/10.1145/503376.503439

[37] Donghao Ren, Tibor Goldschwendt, YunSuk Chang, and Tobias Höllerer. 2016. Evaluating wide-field-of-view augmented reality with mixed reality simulation. In *2016 IEEE Virtual Reality (VR)*. IEEE, New York, New York, USA, 93–102. https://doi.org/10.1109/VR.2016.7504692

[38] Dieter Schmalstieg, Anton Fuhrmann, Gerd Hesina, Zsolt Szalavári, L Miguel Encarnaçao, Michael Gervautz, and Werner Purgathofer. 2002. The studierstube

augmented reality project. *Presence: Teleoperators & Virtual Environments* 11, 1 (2002), 33–54.

[39] Valentin Schwind, Pascal Knierim, Cagri Tasci, Patrick Franczak, Nico Haas, and Niels Henze. 2017. "These Are Not My Hands!": Effect of Gender on the Perception of Avatar Hands in Virtual Reality. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. ACM, New York, NY, USA, 1577–1582. https://doi.org/10.1145/3025453.3025602

[40] Adalberto L. Simeone, Eduardo Velloso, and Hans Gellersen. 2015. Substitutional Reality: Using the Physical Environment to Design Virtual Reality Experiences. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 3307–3316. https://doi.org/10.1145/2702123.2702389

[41] Nikita Soni, Sayli Bapat, Schuyler Gleaves, Alice Darrow, Carrie Schuman, Hannah Neff, Peter Chang, Kathryn A. Stofer, and Lisa Anthony. 2019. Towards Understanding Interactions with Multi-Touch Spherical Displays. In *Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI EA '19)*. Association for Computing Machinery, New York, NY, USA, 1–6. https://doi.org/10.1145/3290607.3313063

[42] Barbra Wed Sperling and Thomas S Tullis. 1988. Are You a Better "Mouser" or "Trackballer"? A Comparison of Cursor-Position Performance. *SIGCHI Bulletin* 19, 3 (Jan. 1988), 77–81. https://doi.org/10.1145/49108.1046379

[43] A. State, K.P. Keller, and H. Fuchs. 2005. Simulation-based design and rapid prototyping of a parallax-free, orthoscopic video see-through head-mounted display. In *Fourth IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR'05)*. IEEE, New York, New York, USA, 28–31. https://doi.org/10.1109/ISMAR.2005.52

[44] Keita Ushida, Hiroshi Harashima, and Jun Ishikawa. 2003. i-ball 2: An Interaction Platform with a Crystal-Ball-Like Display for Multiple Users.. In *ICAT*. dblp, Tokyo, Japan.

[45] Karla Vega, Patrick Beard, Tassie Gniady, David Reagan, Michael J. Boyles, and Chris Eller. 2014. Visualization on Spherical Displays: Challenges and Opportunities. In *Proceedings of the IEEE VIS 2014 Arts Program, VISAP'14: Art+Interpretation*. IEEE, New York, NY, USA, 108–116. https://visap.uic.edu/2014/papers/12_Vega_SphericalDisplays_VISAP2014.pdf

[46] Colin Ware and Steven Osborne. 1990. Exploration and virtual camera control in virtual three dimensional environments. *ACM SIGGRAPH computer graphics* 24, 2 (1990), 175–183.

[47] Colin Ware and Jeff Rose. 1999. Rotating virtual objects with real handles. *ACM Transactions on Computer-Human Interaction (TOCHI)* 6, 2 (1999), 162–180.

[48] Julie R. Williamson, Daniel Sundén, and Keith Hamilton. 2016. The Lay of the Land: Techniques for Displaying Discrete and Continuous Content on a Spherical Display. In *Proceedings of the 5th ACM International Symposium on Pervasive Displays* (Oulu, Finland) *(PerDis '16)*. Association for Computing Machinery, New York, NY, USA, 38–44. https://doi.org/10.1145/2914920.2915005

[49] Julie R. Williamson, John Williamson, Vassilis Kostakos, Keith Hamilton, and Jeremy Green. 2016. Mobile Phone Usage Cycles: A Torus Topology for Spherical Visualisation. In *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI EA '16)*. Association for Computing Machinery, New York, NY, USA, 2751–2757. https://doi.org/10.1145/2851581.2892402

[50] Qian Zhou, Gregor Miller, Kai Wu, Daniela Correa, and Sidney Fels. 2017. Automatic calibration of a multiple-projector spherical fish tank vr display. In *Applications of Computer Vision (WACV), 2017 IEEE Winter Conference on*. IEEE, IEEE, New York, NY, USA, 1072–1081.