Above Surface Interaction for Multiscale Navigation in Mobile Virtual Reality

Tim Menzner*  Travis Gesslein†  Alexander Otte‡  Jens Grubert§
Coburg University of Applied Sciences and Arts

Abstract

Virtual Reality enables the exploration of large information spaces. In physically constrained spaces such as airplanes or buses, controller-based or mid-air interaction in mobile Virtual Reality can be challenging. Instead, the input space on and above touch-screen enabled devices such as smartphones or tablets could be employed for Virtual Reality interaction in those spaces.

In this context, we compared an above surface interaction technique with traditional 2D on-surface input for navigating large planar information spaces such as maps in a controlled user study (n = 20). We find that our proposed above surface interaction technique results in significantly better performance and user preference compared to pinch-to-zoom and drag-to-pan when navigating planar information spaces.

Index Terms: Human-centered computing—Visualization—Visualization techniques—Treemaps; Human-centered computing—Visualization—Visualization design and evaluation methods

1 Introduction

Recent progress in Virtual Reality (VR) technology has enabled the possibility of allowing users to conduct knowledge work in mobile scenarios. While the vision of a spatial user interface supporting knowledge work has been investigated for many years (e.g. [84,85]), the recent emergence of consumer-oriented VR headsets now make it feasible to explore the design of portable user interface solutions [35].

Lately, commercial VR head-mounted displays (HMDs) are progressing to ‘inside-out’ tracking using multiple built-in cameras. Inside-out tracking allows a simple setup of the VR system, and

the ability to work in un-instrumented environments. Further, 3D finger tracking might be supported by traditional computing devices such as smartphones [114], which at the same time provide complementary high accuracy 2D touch input.

Given the capability of spatial hand and finger sensing, it is possible to see VR extending the input space of existing computing devices such as touch screens to a space around the devices, enhancing their usage. For example, knowledge workers can utilize existing 2D surface tools, new 3D tools, as well as using space around the devices and in front of the screen, reachable while sitting, to represent and manipulate additional information.

However, while VR is promising for mobile work it also brings its own additional challenges. For example, mobile information workers might many times be confined to a small space, such as the case of traveling in an airplane or a bus. While they can view potentially very large information spaces through their HMD, the ability to interact with those spaces might be limited in constrained physical spaces, restricting the suitability of ample spatial gestures [35]. Hence, we see it as important to examine interactions in potentially small input spaces. Also, while VR lends itself for interaction with three dimensional data, many knowledge worker tasks are still bound to two dimensional information surfaces [35].

In this context, this paper explores how to efficiently navigate multiscale information spaces in a small input space using a combination of VR HMD and a touch surface. Specifically, we explore the navigation of 2D planar information spaces such as maps using small spatial finger movements above a touchscreen while simultaneously allowing users to view beyond the boundaries of the touchscreen using a VR HMD.

Our contribution lies in the design and evaluation of such as spatial interaction technique for navigation of large planar information spaces. In a user study (n = 20) we show that the proposed technique outperforms traditional 2D surface gestures.

2 Related Work

Our work builds on the areas of spatial and around device interaction as well as multiscale navigation, which will be reviewed next.
2.1 Spatial Interaction

In the context of spatial user interfaces, a large number of techniques for selection, spatial manipulation, navigation and system control have been proposed [58]. Regarding object selection, Argelaguet et al. [4] presented a survey on 3D selection techniques. For a recent survey on 3D virtual object manipulation we refer to Mendes et al. [67]. Also, for spatial interaction across mobile devices (mostly in non-VR settings) recent surveys are available [18, 33].

For VR, spatial pointing techniques are of special interest, often relying on virtual hand or raycasting techniques. In the context of raycasting, Mayer et al. [66] investigated the effects of offset correction and cursor on mid-air pointing and Schwind et al. [94] showed that avatar representations can have an effect on ray-casting-based pointing accuracy. For virtual hand-based pointing, Barrera et al. [9] indicated effects of stereo display deficiencies. Chan et al. [21] explored the use of visual and auditory feedback for facilitating spatial selection. Teather et al. [109] also investigated visual aids for 3D selection in VR. Lubos et al. [64] and Yu et al. [119] investigated 3D selection in VR headsets, where Lubos found that visual perception has a larger effect on target acquisition than motor actions. Stuerzlinger and Teather proposed guidelines for targets in 3D pointing experiments [106]. The performance of 2D touch and mid-air selection on stereoscopic tabletop displays has been explored by Bruder et al. [16, 17]. Further, a number of techniques have been proposed for 3D object selection in the presence of object occlusion (e.g., [3, 11, 28, 102, 104]).

Besides, unimodal techniques, the combination of touch with mid-air, has drawn attention from researchers. For example, outside of VR, Müller et al. [70] investigated the use of touch and mid-air interaction on public displays, Hilliges et al. [44] studied tabletop settings. Multiple works have proposed to utilize handheld touchscreens in spatial user interfaces for tasks such as sketching, ideation and modelling (e.g., [5, 26, 31, 68, 83]), navigation of volumetric data [98], 3D data exploration [63] or system control [13]. Spatial manipulation has seen particular interest in single-user settings (e.g., [3, 48, 61, 65, 69, 107, 108]) but also in collaborative settings [32].

Evolving from the magic lens [12] and tangible interaction concepts [112] tangible magic lenses allow to access and manipulate otherwise hidden data in interactive spatial environments. A wide variety of interaction concepts have been proposed within the scope of information visualization (for surveys we refer to [11, 111]). Both rigid shapes (e.g., rectangular [99] or circular [101] and flexible shapes (e.g., [103]) have been utilized as well as various display media (e.g., projection on cardboard [20, 27]), transparent props [15, 88], handheld touchscreens [36, 60], or virtual lenses [62] and sizes [72]. Also, the combination of touch and gaze has seen recent interest for interaction in spatial user interfaces (e.g., [45, 55, 99, 86, 93]).

Recently, Satriadi et al. and Austin et al. [68] investigated hand and foot gestures for map navigation within Augmented Reality in tabletop settings. Our work relates in the use of above surface interaction, but focuses on the interaction in constrained spatial environments.

Within this work, we concentrate on the use of mid-air interaction in conjunction with touch screen interaction for navigating potentially large planar information spaces such as maps.

2.2 Around Device Interaction

Along with the reduction of the size and weight of mobile and wearable devices, the need for complementary interaction methods evolved. Research began investigating options for interaction next to [72], above [30, 53], behind [25, 15], across [23, 89], or around [116, 123] the device. The additional modalities are either substituting or complementing the devices’ capabilities.

Different sensing solutions have been proposed such as infrared sensors (e.g., [19]), cameras (e.g., [71, 118]), acoustic sensing (e.g., [40], piezo sensors (e.g., [116]), depth sensors (e.g., [23, 54, 95]), electric field sensing (e.g., [124]), or radar-based sensing (e.g., [114]). Several approaches also investigated how to enable around-device interaction on unmodified devices (e.g., [34, 90, 96, 97]).

In VR, around device interaction has been studied in conjunction with physical keyboards for text entry (e.g., [68, 74, 75, 91]).

This prior work, alongside commercialization efforts (e.g., for radar-based sensing [114], which recently made its way into commercial products such as Google Motion Sens1) motivate us, that around-device interaction on mobile devices has the chance to become widely available for consumers.

2.3 Multiscale Navigation

To deal with large information spaces, multiscale interfaces [10, 39, 78] introduce the scale dimension, sometimes called 2D. Cockburn et al. [25] give a comprehensive overview of overview+detail, zooming and focus+context interfaces including techniques for multiscale navigation. Many techniques make use of a separate zoom/scale dimension and a scroll/pan dimension to select a target value in the multiscale space [47]. Prior work indicated, that multiscale navigation with 2D interfaces obeys Fitt’s law [38, 39]. Perluson et al. [77] investigated bimanual techniques for multiscale navigation. Appert et al. [2] investigated 1D multiscale navigation with a mouse-based zooming technique.

In VR, multiscale collaborative virtual environments have been studied (e.g., [29, 56, 59, 80, 81, 121]) and various metaphors (such as world-in-miniature) have been investigated for navigation tasks (e.g., [115, 117]). Further, Zhang et al. [57, 103, 120] introduced a progressive mental model supporting multiscale navigation and also indicated that navigation in multiscale virtual environments can be challenging [122].

For mobile devices, Jones et al. [47] investigated mid-air interactions for multiscale navigation afforded by mobile depth sensors and discussed design implications for mid-air interactions and depth-sensor design. Kister et al. [59] combined spatially-aware mobile displays and large wall displays for graph explorations. Kratz et al. [52] proposed a semi-automatic zooming technique as an alternative to multi-touch zooming but could not indicate significant performance benefits. For mouse-based interaction in desktop environments, Igarashi and Hinckley proposed rate-based scrolling with automatic zooming to obtain a constant perceived scrolling speed in screen space. To this end, when the user scrolled fast, the view automatically zoomed out. The authors indicated a comparable performance to the use of scroll bars.

Spindler et al. [100] compared pinch to zoom and drag to pan with mid-air spatial navigation utilizing absolute mappings and found that navigating a large information space by moving the display devices outperforms navigation with 2D surface gestures. Pahud et al. [76] compared 2D surface gestures with spatial navigation but derived at different findings (spatial navigation was slower than 2D navigation). Related, Hasan et al. [43] compared dynamic peephole pointing and direct off-screen pointing with on-screen 2D gestures for map based analytic tasks. They found that while the spatially aware techniques resulted in up to 30% faster navigation times, 2D onscreen gestures allowed for more accurate retrieval of work space content.

Our study also compares to a 2D surface gesture baseline technique, but compare it to relative-rate controlled above surface interaction technique, which is suitable for a wide variety of usage scenarios, including interaction in physically constrained environments such as trains or touchscreen places.

1https://www.blog.google/products/pixel/new-features-pixel4/ Last access November 21st, 2019

2In this paper, we use the words scale and zoom interchangeably.
Within this research, we set out to support efficient navigation of large information spaces using a potential small interaction space (such as the smartphone or a tablet) with a combination of spatial interaction and a touch surface. In this joint interaction space between touchscreens and VR headsets, the touchscreen can be utilized for fine grained 2D touch interactions, while the VR headsets allows to visualize content beyond the device boundary of the touchscreen. Within this scenario, spatial tracking of users’ hands and fingers could be achieved either by camera-based inside-out tracking on the VR headset (which at the same time could spatially track the position of the smartphone through marker-based or model-based tracking), by smartphone-integrated sensing, or a combination of both.

Inspired by the large amount of prior work, we followed an iterative approach with multiple design loops consisting of conceptualization, implementation and initial user tests (dogfood tests) [27][13]. For prototyping purposes we relied on an external outside-in tracking system (OptiTrack Prime 13) in conjunction with a HTC Vive Pro headset.

First, we explored an absolute, position-controlled mapping of finger height to the scale of the virtual information space. With this technique, the height of the finger above the smartphone display until a previous empirically determined maximum height (5 cm above the display) was directly mapped to a scale level of the virtual display. The scaling changed linearly between minimum and maximum finger height. While initial user tests indicated that this mapping felt natural, the accuracy of the technique is dependent on the the maximum scale of the information space.

To overcome this limitation, we implemented a relative, rate-controlled mapping, in which the scale level was constantly increased or decreased with a certain speed dependent of the height of the finger over the display (see Figure 1-a-d). For this approach, the volume above the smartphone display was separated into two smaller spaces of the same size. The first space extended from above the display to half a previous defined maximum height. The second area extended from this height to the defined maximum height. If the finger was in the lower volume, the scale level increased. If the finger was in the upper volume, the scale level decreased. The point between those areas at half maximum height, theoretically would result in a scale change of 0. We experimented with a “dead zone” in the center (i.e. expanding the volume in which no scale change would occur). Initial user tests, indicated that the scale change around the center was sufficiently low that no extended dead zone was necessary. We also experimented with a dead zone directly above the touch surface but came to similar conclusions.

For zooming out, a zoom base speed parameter determining the maximum reachable zoom speed was multiplied with the finger height above the display normalized between half maximum height and maximum height. The result was used to decrease the map size by this factor. Similarly, for zooming in, the height was normalized between half maximum height and the minimum finger height, see Figure 1. If the user touched the screen however, the zooming process was stopped so she could still conduct touchscreen input without constantly zooming in or moving on the other axes.

The movement on the two other axes in both techniques was handled equally. The position of the finger on the x axis or respectively the y axis relative to the display middle point was multiplied with a plane base speed parameter and was used to determine the speed in this direction, resulting in a rate-controlled change of the x,y position. In order to make sure that the user could always see where exactly the fingertip was hovering, a small flat white disc with a 5 mm diameter indicated where a ray cast perpendicular to the touch surface would hit the display. This point also functioned as the pivot point for zooming.

Initial user tests indicated that the rate-controlled mapping resulted in both in better performance (i.e. task completion time) and was more preferred than the absolute one. Especially, on the larger map we tested (1.392m * 0.655m and a touchscreen width to virtual map width ratio of 1:13.2 compared to 13.92m * 6.55m and a ratio of 1:132), the user would have to zoom more to get to the minimum scale level. Specifically, the range between the display surface and a physically possible maximum finger height was too small to provide a smooth scale change. A small change in finger height would map to a large scale change. This made accurate and precise navigation very difficult. Compared to this, the relative movement was perceived much more smooth and precise on all map sizes.

All base speed parameters were empirically determined. For the zoom base speed, this value was 0.05 and for the plane base speed, this value was 0.001. Please note that the zoom speed constant of 0.05 is dependent on the maximum finger height (in our case 5 cm) and the plane base speed parameter is dependent on the smartphone display size. For other finger heights or display sizes those parameters can be linearly interpolated. Also, the maximum finger height of 5 centimeters above the display empirically produced the best results for various users.

We aimed to compare the relative, rate-controlled mapping, which outperformed the absolute, position-controlled mapping in initial tests, with commonly used technique for navigating 2D information spaces on touch screens. To this end, we utilized the well known pinch-to-zoom and drag to pan known from mobile map applications. The parameters for pan and zoom were chosen to mimic the Google Maps pan and zoom experience on the smartphone used in the user study (see Apparatus section), including inertia and pivot point for zooming. The baseline technique utilized the smartphone touch screen for sensing. We also verified that the navigation performance when wearing a VR HMD matches performance when not wearing an HMD but interacting with a mobile phone only version of the application. A small white flat disc was used to visualize the pivot point of zooming, in this case the middle point between the two fingers used for zoom. The users’ fingers used for interaction (typically thumb and index finger of the dominant hand) were visualized as colored spheres with 10 mm diameter (same as the target size).

There were two map sizes: small map had a size of 1.45m * 0.69m resulting in ratio between touch screen width to virtual map width of 1:13.8. Large map had a size of 1.447m * 69.1cm resulting in ratio between touch screen width to virtual map width of 1:1380. In a pilot study, we evaluated an additional map size (with a touchscreen width to virtual map width ratio of 1:138), but found no additional insights compared to the large map size and, hence, excluded it from the main study.

Within each of the four conditions (2 interfaces * 2 map sizes), participants needed to select targets at three target distances: small distance, medium distance and large distance. The order of target distance was randomized within each condition, ensuring that each of the three target distances appeared exactly five times per condition. The target distances were defined relative to the length of the diagonal of each map size corresponding to 0.125 * map diagonal for small distance, 0.25 * map diagonal for
was highlighted. The new target was always selected to fit a certain distance to the previous target, respectively the origin for the first attempt, an error was logged. In order to progress to the next level. The active target was highlighted in blue, while all other potential targets were colored red. In order to click the target, the participant had to navigate close enough so that the target was inside the touch screen bounds (and at scale level 1:1). When this was achieved, it was possible to selecting it by dwelling the finger on the touch screen area of the smartphone is shown as semi-transparent blue rectangle with red border. The touch screen area of the smartphone was 139.2 mm 66.5 mm 8.9 mm (width x height x depth), with a touchscreen of size 105 mm x 60 mm. For 3D Tracking, we used an OptiTrack Prime 13 system, consisting of 8 cameras, of which 3 were Prime 13w wide field-of-view cameras and Motive Version 1.10.3. The main study application was a running on a PC with windows 10, an Intel Xeon E5 - 1650 CPU, a Nvidia GeForce GTX 1070 graphics card and 64 GB RAM. The VR Headset used was the HTC Vive Pro. Both applications, the one on the smartphone as well as the one running on the PC were created in Unity 2018.3.2f1. While the HTC Vive Pro and the fingertips of users could have been tracked with mobile sensing solutions [92] the HMD and fingers were equipped with retro-reflective markers for increased accuracy, see Figure 4.

4.4 Apparatus

For capturing the touch input and sending it via WiFi to the main application on a PC, we used an Android application on an Amazon Fire Phone running Fire OS 4.6.3. The smartphone dimensions were 139.2 mm 66.5 mm 8.9 mm (width x height x depth), with a touchscreen of size 105 mm x 60 mm. For 3D Tracking, we used an OptiTrack Prime 13 system, consisting of 8 cameras, of which 3 were Prime 13w wide field-of-view cameras and Motive Version 1.10.3. The main study application was a running on a PC with windows 10, an Intel Xeon E5 - 1650 CPU, a Nvidia GeForce GTX 1070 graphics card and 64 GB RAM. The VR Headset used was the HTC Vive Pro. Both applications, the one on the smartphone as well as the one running on the PC were created in Unity 2018.3.2f1. While the HTC Vive Pro and the fingertips of users could have been tracked with mobile sensing solutions [92] the HMD and fingers were equipped with retro-reflective markers for increased accuracy, see Figure 4.

4.5 Participants

We recruited 20 participants from a university campus with diverse study backgrounds. All participants were familiar with touch sensitive screens. From the 20 participants (7 female, 13 male, mean age 24.4 years, sd = 2.973, mean height 175.8 cm, sd = 9.463, 15 indicated prior Virtual Reality Experience, 5 of those only once, 3 participants rarely but more than once, 5 participants occasionally and 2 often. Three participants indicated they don’t play video games, 1 participant only once, 4 rarely, 6 occasionally, 3 frequently and 3 very frequently. Five participants wore contact lenses or
4.6 Results

Statistical significance tests for log-transformed target acquisition time was carried out using general linear model repeated measures analysis of variance (RM-ANOVA) with Holm-Bonferroni adjustments for multiple comparisons at an initial significance level α = 0.05. We indicate effect sizes whenever feasible (η²p). We had to exclude performance data (target acquisition time and errors) for one participant due to logging errors.

For subjective feedback, or data that did not follow a normal distribution or could not be transformed to a normal distribution using the log-transform (errors), we employed the Aligned Rank Transform before applying RM-ANOVA.

The results in the following sections can be summarized as follows: Participants acquired targets significantly faster with 3D NAVIGATION compared to BASELINE. 3D NAVIGATION also resulted in significantly higher SUS scores, significantly lower demand ratings (as indicated by NASA TLX) and was preferred by more participants. No significant differences for the number of errors or for simulator sickness ratings were detected between conditions.

4.6.1 Target Acquisition Time

The times to acquire individual targets averaged over all target distances are depicted in Figure 3, left (for individual distances, see Appendix). An omnibus test revealed significance main effects of INTERFACE (F(1,18) = 59.91, p < .001, η²p = 0.77, 1 – β = 1.0), and (as expected) for MAP SIZE (F(1,18) = 199.05, p < .001, η²p = 0.92, 1 – β = 1.0) and TARGET DISTANCE (F(2,36) = 45.83, p < .001, η²p = 0.72, 1 – β = 1.0).

As expected, significant interactions have been indicated between INTERFACE and MAP SIZE (F(1,36) = 29.61, p < 0.001, η²p = 0.622, 1 – β = 0.99), MAP SIZE and TARGET DISTANCE (F(2,36) = 11.08, p > 0.001, η²p = 0.38, 1 – β = 0.99), but not between INTERFACE and TARGET DISTANCE (F(2,36) = 3.06, p = 0.059, η²p = 0.15, 1 – β = 0.56). We did not observe any asymmetrical effects [82].

Holm-Bonferroni adjusted post-hoc testing revealed that there were significant differences between each level for target distance (p < 0.001, as expected), map size (p < 0.001, as expected) and between BASELINE (mean target acquisition time over all map sizes and target distances: 59.62 seconds, sd = 23.95) and 3D NAVIGATION (mean target acquisition time over all map sizes and target distances: 33.52 seconds, sd = 8.10) (p < 0.001).

Also, Holm-Bonferroni adjusted pairwise t-tests between BASELINE and 3D NAVIGATION for each combination of MAP SIZE and TARGET DISTANCE indicated that 3D NAVIGATION resulted in significantly faster target acquisition times compared to BASELINE.

Similar results were obtained when excluding one participant whose target acquisition times were substantially larger than the times of the other participants (depicted as outlier in Figure 3 left). These results are omitted for brevity.

In other words, participants acquired targets significantly faster with 3D NAVIGATION compared to BASELINE.

4.6.2 Errors

We looked at two different error types. First, we looked at the number of wrongly selected targets. No target selection error was made in any condition. Second, we counted the occasions when a target was not hit at first touch down (i.e. the finger was dwelling outside of the target circle for more than a second), see Figure 3 right. No significant main effects or interactions were indicated.

In other words, no significant differences between 3D NAVIGATION and BASELINE were detected.

4.6.3 Workload

The descriptive statistics for workload (as measured by the unweighted NASA TLX [22]) are depicted in Table 1. Significant main effects for INTERFACE were indicated for mental demand (F(1,19) = 4.71, p = 0.043, η²p = 0.20). physical demand
### Table 1: Mean and standard deviation (in parentheses) for the NASA TLX dimensions. 2D: BASELINE, 3D: 3D NAVIGATION, SM: SMALL MAP, LM: LARGE MAP. Bold headings indicate dimensions with significant differences.

| Dimension          | 2D-SM | 3D-SM | 2D-LM | 3D-LM |
|--------------------|-------|-------|-------|-------|
| Mental Demand      | 38.50 | 28.25 | 41.75 | 30.75 |
| (26.01)            | (16.33)| (23.64)| (19.89)|       |
| Physical Demand    | 26.00 | 19.50 | 32.75 | 18.5  |
| (21.56)            | (17.24)| (25.73)| (16.47)|       |
| Temporal Demand    | 41.00 | 31.50 | 55.50 | 30.25 |
| (25.00)            | (19.54)| (30.78)| (21.30)|       |
| Performance        | 37.75 | 32.25 | 58.25 | 25.25 |
| (23.98)            | (16.74)| (23.64)| (19.50)|       |
| Effort             | 35.75 | 25.25 | 49.5  | 24.75 |
| (25.41)            | (18.03)| (23.84)| (21.30)|       |
| Frustration        | 31.00 | 17.75 | 40.00 | 13.25 |
| (20.81)            | (12.41)| (19.53)| (12.08)|       |
| Overall Demand     | 35.00 | 25.75 | 46.29 | 24.13 |
| (16.96)            | (10.88)| (14.80)| (12.38)|       |

\( F_{1,19} = 6.42, \ p < 0.02, \ \eta^2_p = 0.25 \), temporal demand \( F_{1,19} = 22.82, \ p < 0.01, \ \eta^2_p = 0.55 \), performance \( F_{1,19} = 39.422, \ p < 0.01, \ \eta^2_p = 0.67 \), effort \( F_{1,19} = 18.30, \ p < 0.01, \ \eta^2_p = 0.49 \), frustration \( F_{1,19} = 66.18, \ p < 0.01, \ \eta^2_p = 0.78 \) and overall demand \( F_{1,19} = 39.95, \ p < 0.01, \ \eta^2_p = 0.68 \). For MAP SIZE a significant main effect was indicated for overall demand \( F_{1,19} = 5.44, \ p = 0.031, \ \eta^2_p = 0.22 \). No further main effects were indicated.

Significant interactions were indicated for performance \( F_{1,19} = 22.79, \ p < 0.01, \ \eta^2_p = 0.55 \), effort \( F_{1,19} = 7.78, \ p = 0.01, \ \eta^2_p = 0.29 \), frustration \( F_{1,19} = 4.89, \ p = 0.039, \ \eta^2_p = 0.20 \) and overall demand \( F_{1,19} = 11.77, \ p < 0.01, \ \eta^2_p = 0.38 \).

In other words, 3D NAVIGATION led to a significantly lower workload compared to BASELINE.

### 4.6.4 Usability

Results from the SUS questionnaire [14] are depicted in Figure 5. All conditions but BASELINE-LARGE MAP resulted above average SUS ratings > 68 (with BASELINE-LARGE MAP resulting in a mean score of 66).

A significant main effect for INTERFACE was indicated for the SUS score \( F_{1,19} = 28.14, \ p < 0.001, \ \eta^2_p = 0.60 \). A significant interaction between INTERFACE and MAP SIZE was also indicated \( F_{1,19} = 6.99, \ p = 0.02, \ \eta^2_p = 0.24 \).

In other words, 3D NAVIGATION resulted in significantly higher usability scores than BASELINE.

### 4.6.5 Simulator Sickness

Results from the simulator sickness questionnaire SSQ [49] are depicted in Figure 6. Omnibus tests revealed no statistically significant main effects or interactions for any SSQ dimension.

In other words, no significant difference for simulator sickness could be indicated between 3D NAVIGATION and BASELINE.

### 4.6.6 Preferences and Open Comments

When asked to rank the interaction techniques, all 20 participants preferred 3D NAVIGATION for LARGE MAP. For SMALL MAP, 15 participants preferred 3D NAVIGATION and 5 preferred BASELINE.

As benefits of 3D NAVIGATION, 8 participants mentioned it to be faster with one saying I have the feeling that it is faster" and two mentioning it was also fast to learn. Three participants mentioned that they felt it enabled more precise navigation. Five participants it was easier to learn and "more fluid" with one mentioning With 2D [BASELINE] I need more steps to zoom in or out. 3D [3D NAVIGATION] just feels better and four mentioning that using only a single finger for navigation felt more intuitive than the 2 finger pinch gesture.

Regarding drawbacks of the 3D NAVIGATION technique one participant mentioned that the fast zooming gave me slight dizziness on the large map, but all in all its better, because it is faster. Another participant mentioned I was losing the feeling on zoom range on single colored map parts and 2 participants mentioned that they accidentally touched the screen, which led to an interruption of the zoom process.

Regarding benefits of BASELINE, one participant mentioned that this technique helped better in the final stage of the target acquisition phase by stating For me it was more precise because the frame is stable in the last step of target acquisition. Two participants mentioned that they liked that a hovering finger does not invoke zooming. Three participants mentioned that they like the technique because they were used to it and three mentioned that they felt the technique to be fast enough on the small map. In contrast, two participants also mentioned that the technique was too slow for navigating on the large map as well as to imprecise. Another participant mentioned my fingertips start to hurt if I touch the displays or things [in BASELINE] for too long, 3D on the other hand feels nice.

We further noticed differences regarding the amount of zooming used by the participants in the different conditions. Overall, the participants zoomed less on SMALL MAP for both interfaces. On
a normalized scale, where 0 equals the minimum zoom scale (i.e. the whole map is visible within the smartphone boundaries) and 1 equals the maximum scale, the average scale across all participants was 0.425 for 2D Navigation and 0.357 for 3D Navigation on SMALL MAP, compared to 0.065 and 0.064 for 2D Navigation and 3D Navigation on LARGE MAP (please remember that participants started the task at the maximum scale 1 and had to be at that scale in order to select a target). In 70 instances for BASELINE respectively 30 instances for 3D NAVIGATION on SMALL MAP, the participants found and clicked the highlighted target without zooming out at all. However, this was never the case in any of both conditions on LARGE MAP. Those differences can be attributed to the fact that on SMALL MAP, a larger proportion of the map was already in the participants field of view when zoomed in.

5 Discussion and Limitations

Our study indicated that the proposed relative, rate-controlled technique outperformed the BASELINE technique in terms of task completion time on both MAP SIZES. No differences in terms of errors were detected. While we assumed that potentially, differences between the conditions could appear for simulator sickness due to the faster scale change in 3D NAVIGATION, this assumption was not confirmed by the SSQ ratings.

The indications from workload and usability ratings were more nuanced. While for workload, 3D NAVIGATION resulted in significantly lower frustration and overall demand for both MAP SIZES, for the TLX dimensions temporal effort, performance and effort significant differences were solely indicated for the LARGE MAP. No significant differences were indicated for mental or physical demand. One potential explanation for this might be that while holding the finger in mid-air (even with support of the palm lying on a resting surface) might induce fatigue, so does the repetitive use of pinch-to-zoom gestures.

Also, regarding usability ratings, 3D NAVIGATION was solely rated significantly higher for the LARGE MAP. These quantitative results are also echoed by the qualitative feedback. While for LARGE MAP all participants preferred 3D NAVIGATION, for SMALL MAP, five out 20 preferred the BASELINE condition. This is also reflected by one participant stating "2D [baseline] on the small map is manageable but on the big map it is too much trouble".

With these findings in mind, we can still suggest the proposed relative, rate-control navigation technique can serve as viable option for navigating multiscale planar information spaces on and above touchscreens.

As a limitation we can see, that in the experiment, the smartphone was lying on a surface, which also functioned as a resting surface for both interaction techniques. While this represents well the intended target usage in physical constrained spaces such as an airplane seat with a tray, other use cases, such as free hand usage or usage while walking could result in other findings, specifically regarding expected fatigue of the techniques. Further, in such scenarios, approaches that utilize the touchscreen pose for spatially navigating an information space (such as the work by Spandler et al. [100]) could be used and potentially outperform the proposed approach. Also, the results might change if other form factors such as tablets will be employed. Further, while we took care to select a representative range of information space sizes, the results might change when investigating further scales. Finally, one could argue that given spatial finger tracking on modern VR headsets, there is no need for a supporting touchscreen at all. While this is true for spatial interaction, and, eventually for sliding motions on physical surfaces such as tables, selecting items through nuanced touches on the surface without touchscreens (or other contact-based sensors) will remain a challenge for the foreseeable future. Not using a touchscreen also strips away further potential interaction possibilities (which we did not investigate in this work) that could arise due to the tangible nature of smartphones and tablets [107].

6 Conclusion

The combination of physical touchscreen devices such as smartphones and tablets with Virtual Reality headsets enables unique interaction possibilities such as the exploration of large information spaces.

In this context, a controlled laboratory study with 20 participants indicated that a relative, rate-controlled multiscale navigation technique resulted in significantly better performance and user preference compared to pinch-to-zoom and drag-to-pan when navigating planar information spaces.

In future work, we plan to investigate the technique in further usage scenarios (such when standing or walking) and to explore the rich interaction space that opens up when combining traditional compute devices such as smartphones, tablets or notebooks with VR headsets capable of spatial tracking of the HMD, traditional input devices such as smartphones and the user’s hands.

References

[1] P. Abtahi, M. Gonzalez-Franco, E. Ofek, and A. Steed. I’m a giant: Walking in large virtual environments at high speed gains. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, p. 522. ACM, 2019.
[2] C. Appert and J.-D. Fekete. Orthozoom scroller: 1d multi-scale navigation. In Proceedings of the SIGCHI conference on Human Factors in computing systems, pp. 21–30. ACM, 2006.
[3] F. Argelaguet and C. Andujar. Efficient 3d pointing selection in cluttered virtual environments. IEEE Computer Graphics and Applications, 29(6):34–43, 2009.
[4] F. Argelaguet and C. Andujar. A survey of 3d object selection techniques for virtual environments. Computers & Graphics, 37(3):121–136, 2013.
[5] R. Arora, R. Habib Kazi, T. Grossman, G. Fitzmaurice, and K. Singh. Symbiosketch: Combining 2d & 3d sketching for designing detailed 3d objects in situ. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, p. 185. ACM, 2018.
[6] C. R. Austin, B. Ens, K. A. Satriadi, and B. Jenny. Elicitation study investigating hand and foot gesture interaction for immersive maps in augmented reality. Cartography and Geographic Information Science, pp. 1–15, 2020.
[7] D. Avrahami, J. O. Wobbrock, and S. Izadi. Portico: tangible interaction on and around a tablet. In Proceedings of the 24th annual ACM symposium on User interface software and technology, pp. 347–356. ACM, 2011.
[8] T. Babic, H. Reiterer, and M. Haller. Pocket6: A 6df0 controller based on a simple smartphone application. In SUI’18: 6th ACM Symposium on Spatial User Interaction, pp. 2–10, 2018.
[9] M. D. Barrera Machuca and W. Stuerzlinger. The effect of stereo display deficiencies on virtual hand pointing. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, p. 207. ACM, 2019.
[10] B. B. Bederson and J. D. Hollan. Pad++: a zooming graphical interface for exploring alternate interface physics. In Proceedings of the 7th annual ACM symposium on User interface software and technology, pp. 17–26. ACM, 1994.
[11] S. Bhowmick and K. Sorathia. Explorations on body-gesture based object selection on hmd based vr interfaces for dense and occluded dense virtual environments. 2018.
[12] E. A. Bier, M. C. Stone, K. Pier, W. Buxton, and T. D. DeRose. Toolglass and magic lenses: the see-through interface. In Proceedings of the 20th annual conference on Computer graphics and interactive techniques, pp. 73–80. ACM, 1993.
[13] D. A. Bowman and C. A. Wingrate. Design and evaluation of menu systems for immersive virtual environments. In Proceedings IEEE Virtual Reality 2001, pp. 149–156. IEEE, 2001.
[14] J. Brooke et al. Sus-a quick and dirty usability scale. Usability evaluation in industry, 189(194):4–7, 1996.
[53] S. Kratz and M. Rohs. Hoverflow: exploring around-device interaction with ir distance sensors. In Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services, p. 42. ACM, 2009.

[54] S. Kratz, M. Rohs, D. Guse, J. Müller, G. Bailly, and M. Nischl. Palmspace: continuous around-device gestures verus. multitouch for 3d rotation tasks on mobile devices. In Proceedings of the International Working Conference on Advanced Visual Interfaces, pp. 181–188. ACM, 2012.

[55] M. Kyō, B. Ens, T. Piumsomboon, G. A. Lee, and M. Billinghurst. Pinpointing: Precise head-and-eye-based target selection for augmented reality. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, p. 81. ACM, 2018.

[56] E. Langbehn, G. Bruder, and F. Steinicke. Scale matters! analysis of dominant scale estimation in the presence of conflicting cues in multi-scale collaborative virtual environments. In 2016 IEEE Symposium on 3D User Interfaces (3DUI), pp. 211–220. IEEE, 2016.

[57] J. J. LaViola Jr, D. A. Feliz, D. F. Keefe, R. C. Zeleznik, et al. Hands-free multi-scale navigation in virtual environments. SHD, 1.9–15, 2001.

[58] J. J. LaViola Jr, E. Kruijff, R. P. McMahin, D. Bowman, and L. P. Pouppeyev. 3D user interfaces: theory and practice. Addison-Wesley Professional, 2017.

[59] M. Le Chénchal, J. Lacoche, J. Royan, T. Duval, V. Gouranton, and B. Arnaldi. When the giant meets the ant an asymmetric approach for collaborative and concurrent object manipulation in a multi-scale environment. In 2016 IEEE Third VR International Workshop on Collaborative Virtual Environments (3D CVE), pp. 18–22. IEEE, 2016.

[60] S.-w. Leigh, P. Schoessler, F. Heibeck, P. Maes, and H. Ishii. Thaw: tangible interaction with see-through augmentation for smartphones on computer screens. In Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction, pp. 89–96. ACM, 2015.

[61] H.-N. Liang, C. Williams, M. Semegen, W. Stuerzlinger, and P. Irani. An investigation of suitable interactions for 3d manipulation of distant objects through a mobile device. International Journal of Innovative Computing, Information and Control, 9(12):4737–4752, 2013.

[62] J. Looser, R. Grassett, and M. Billinghurst. A 3d flexible and tangible magic lens in augmented reality. In 2007 6th IEEE and ACM International Symposium on Mixed and Augmented Reality, pp. 51–54. IEEE, 2007.

[63] D. López, L. Ochilberg, C. Doger, and T. Isenberg. Towards an understanding of mobile touch navigation in a stereoscopic viewing environment for 3d data exploration. IEEE Transactions on Visualization and Computer Graphics, 22(5):1616–1629, 2015.

[64] P. Lubos, G. Bruder, and F. Steinicke. Analysis of direct selection in head-mounted display environments. In 2014 IEEE Symposium on 3D User Interfaces (3DUI), pp. 11–18. IEEE, 2014.

[65] A. Marzo, B. Bossavit, and M. Hachet. Combining multi-touch input and device movement for 3d manipulations in mobile augmented reality environments. In Proceedings of the 2nd ACM symposium on Spatial user interaction, pp. 13–16. ACM, 2014.

[66] S. Mayer, V. Schwind, R. Schweigert, and H. Henze. The effect of offset correction and cursor on mid-air pointing in real and virtual environments. In Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, p. 653. ACM, 2018.

[67] D. Mendes, F. M. Caputo, A. Giachetti, A. Ferreira, and J. Jorge. A survey on 3d virtual object manipulation: From the desktop to immersive virtual environments. In Computer Graphics Forum, vol. 38, pp. 21–45. Wiley Online Library, 2019.

[68] T. Menzner, A. Otte, T. Gesslein, J. Grubert, P. Gagel, and D. Schneider. A capacitive-sensing physical keyboard for vr text entry. In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp. 1080–1081. IEEE, 2019.

[69] A. Mossel, B. Venditti, and H. Kaufmann. 3dtouch and homer-s: intuitive manipulation techniques for one-handed handheld augmented reality. In Proceedings of the Virtual Reality International Conference: for Virtual and Augmented Reality, p. 12. ACM, 2013.

[70] J. Müller, G. Bailly, T. Bossuyt, and N. Hillgren. Mirrortouch: combining touch and mid-air gestures for public displays. In Proceedings of the 16th international conference on Human-computer interaction with mobile devices & services, pp. 319–328. ACM, 2014.

[71] R. Nandakumar, V. Iyer, D. Tan, and S. Gollakota. Fingerio: Using active sonar for fine-grained finger tracking. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, pp. 1515–1525. ACM, 2016.

[72] I. Oakley and D. Lee. Interaction on the edge: Offset sensing for small devices. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, CHI ’14, pp. 169–178. ACM, New York, NY, USA, 2014. doi: 10.1145/2556288.2557138

[73] J.-y. Oh and H. Hua. User evaluations on form factors of tangible magic lenses. In 2006 IEEE/ACM International Symposium on Mixed and Augmented Reality, pp. 23–32. IEEE, 2006.

[74] A. Otte, T. Menzner, T. Gesslein, P. Gagel, D. Schneider, and J. Gru bert. Towards utilizing touch-sensitive physical keyboards for text entry in virtual reality. In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), pp. 1729–1732. IEEE, 2019.

[75] A. Otte, D. Schneider, T. Menzner, T. Gesslein, P. Gagel, and J. Gru bert. Evaluating text entry in virtual reality using a touch-sensitive physical keyboard. In 2019 IEEE International Symposium on Mixed and Augmented Reality Adjunct (ISMAR-Adjunct), pp. 387–392. IEEE, 2019.

[76] M. Pahud, K. Hinckley, S. Iqbal, A. Sellen, and B. Buxton. Toward compound navigation tasks on mobiles via spatial manipulation. In Proceedings of the 15th international conference on Human-computer interaction with mobile devices and services, pp. 113–122. ACM, 2013.

[77] S. Peluron and L. Nigay. Bimanual input for multiscale navigation with pressure and touch gestures. In Proceedings of the 18th ACM International Conference on Multimodal Interaction, pp. 145–152. ACM, 2016.

[78] K. Perlin and D. Fox. Pad: An alternative approach to the computer interface. In Proceedings of the 20th Annual Conference on Computer Graphics and Interactive Techniques, SIGGRAPH ’93, pp. 57–64. ACM, New York, NY, USA, 1993. doi: 10.1145/166117.166125

[79] K. Pfeuffer, B. Mayer, D. Mardanbegi, and H. Gellersen. Gaze+pinch interaction in virtual reality. In Proceedings of the 5th Symposium on Spatial User Interaction, pp. 99–108. ACM, 2017.

[80] T. Piumsomboon, G. A. Lee, B. Ens, B. H. Thomas, and M. Billinghurst. Superman vs giant: a study on spatial perception for a multi-scale mixed reality flying telescreen interface. IEEE transactions on visualization and computer graphics, 24(11):2974–2982, 2018.

[81] T. Piumsomboon, G. A. Lee, A. Irliti, B. Ens, B. H. Thomas, and M. Billinghurst. On the shoulder of the giant: A multi-scale mixed reality collaboration with 360 video sharing and tangible interaction. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems, p. 228. ACM, 2019.

[82] E. Poulton and P. Freeman. Unwanted asymmetrical transfer effects with balanced experimental designs. Psychological Bulletin, 66(1):1, 1966.

[83] D. Ramanujan, C. Piya, K. Ramani, et al. Mobisweep: Exploring spatial design ideation using a smartphone as a hand-held reference plane. In Proceedings of the TEI’16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction, pp. 12–20. ACM, 2016.

[84] R. Raskar, G. Welch, M. Cutts, A. Lake, L. Stevin, and H. Fuchs. The office of the future: A unified approach to image-based modeling and spatially immersive displays. In Proceedings of the 25th annual conference on Computer graphics and interactive techniques, pp. 179–188. ACM, 1998.

[85] J. Rekimoto and M. Saitoh. Augmented surfaces: a spatially continuous work space for hybrid computing environments. In Proceedings of the SIGCHI conference on Human Factors in Computing Systems, pp. 378–385. ACM, 1999.

[86] K. Ryu, J.-J. Lee, and J.-M. Park. Gg interaction: a gaze–grasp pose interaction for 3d virtual object selection. Journal on Multimodal Interface, pp. 1–11. 2019.

[87] K. A. Satriadi, B. Ens, M. Cordei, B. Jenny, T. Czauderna, and W. Willett. Augmented reality map navigation with freehand gestures.
