displayed 3D objects stereoscopically either in front of or behind a large vertical projection screen. They recorded user behavior when instructed to touch the virtual 3D objects on the display surface. They identified that users tend to touch between the projections for the two eyes with an offset towards the projection for the dominant eye. However, the results suffered from a large variance between subjects. Hence, it is unclear how far these results can be applied to different setups, such as mobile screens or tabletops, where users have an easy frame of reference due to the bezel. Also, they may engage in different touch behavior due to physical support and gravity.

So far, no comparative analysis exists for 2D and 3D touch interaction in stereoscopic tabletop setups. Thus, it remains unclear if 2D touch is a viable alternative to 3D mid-air touch.

3 Experiments

Here we describe our experiments in which we analyzed the touch behavior as well as the precision of 2D touch and 3D mid-air touches. We used a standard ISO 9241-9 selection task setup [19] on a tabletop surface with 3D targets displayed at different heights above the surface, i.e., with different negative stereoscopic parallaxes.

3.1 Participants

Ten male and five female subjects (ages 20-35, M=27.1, heights 158-193cm, M=178.3cm) participated in the experiment. Subjects were students or members of the Departments of computer science, media communication or human computer-interaction. Three subjects received class credit for participating in the experiment. All subjects were right-handed. We used the Porta and Dolman tests to determine the sighting dominant eye of subjects [22]. This revealed eight right-eye dominant sub-

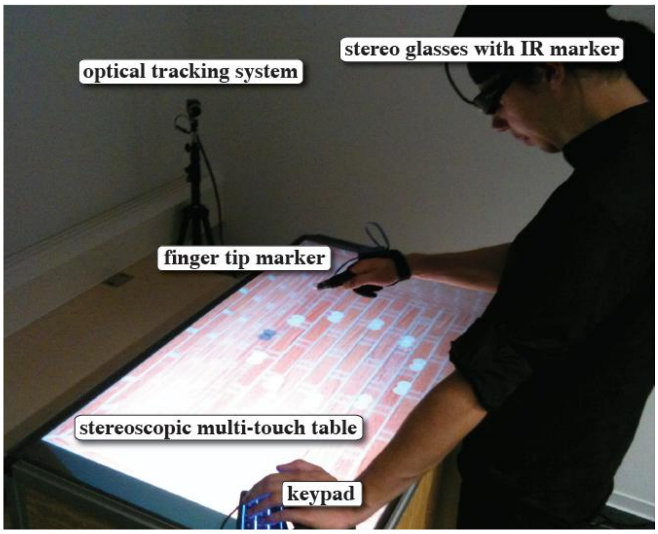

Fig. 3. Experiment setup: photo of a subject during the experiment (with illustrations). As illustrated on the screen, the target objects are arranged in a circle.

jects (7 males, 1 female) and five left-eye dominant subjects (2 males, 3 females). The tests were inconclusive for two subjects (1 male, 1 female), for which the 2 tests indicated conflicting eye dominance. All subjects had normal or corrected to normal vision. One subject wore glasses and four subjects wore contact lenses during the experiment. None of the subjects reported known eye disorders, such as color weaknesses, amblyopia or known stereopsis disruptions. We measured the interpupillary distance (IPD) of each subject before the experiment, which revealed IPDs between 5.8cm and 7.0cm (M=6.4cm). We used each individual's IPD for stereoscopic display in the experiment. 14 subjects reported experience with stereoscopic 3D cinema, 14 reported experience with touch screens, and 8 had previously participated in a study involving touch surfaces. Subjects were naive to the experimental conditions. Subjects were allowed to take a break at any time between experiment trials in order to minimize effects of exhaustion or lack of concentration. The total time per subject including pre-questionnaires, instructions, training, experiment, breaks, post-questionnaires, and debriefing was about 1 hour.

3.2 Materials

For the experiment we used a 62 x 112cm multi-touch enabled active stereoscopic tabletop setup as described in [7]. The system is shown in Figure 3 and uses rear diffuse illumination [24] for multi-touch. For this, six high-power infrared (IR) LEDs illuminate the screen from behind. When an object, such as a finger or palm, comes in contact with the diffuse surface it reflects the IR light, which is then sensed by a camera. We use a 1024x768 PointGrey Dragonfly2 with a wide-angle lens and a matching IR band-pass filter at 30 frames per second. We use a modified version of the NUI Group's CCV software to detect touch input on a Mac Mini server. Our setup uses a matte diffusing screen with a gain of 1.6 for the stereoscopic back projection. We used a 1280x800 Optoma GT720 projector with a wide-angle lens and an active DLP-based shutter at 60Hz per eye. We used an optical WorldViz PPT X4 system with sub-millimeter precision and sub-centimeter accuracy to track the subject's finger and head in 3D, both for 3D "touch" detection as well as view-dependent rendering. For this, we attached wireless markers to the shutter glasses and another diffused IR LED on the tip of the index finger of the subject's dominant hand. We tracked and logged both head and fingertip movements during the experiment.

The visual stimulus consisted of a 30cm deep box that matches the horizontal dimensions of the tabletop setup (see Figure 3). We matched the look of the scene to the visual stimuli used by Teather and Stuerzlinger [35, 36]. The targets in the experiment were represented by spheres, which were arranged in a circle as illustrated in Figure 3. A circle consisted of 11 spheres rendered in white, with the active target sphere highlighted in blue. The targets highlighted in the order specified by ISO 9241-9 [18]. The center of each target sphere indicated the exact position where subjects were instructed to touch with their dominant hand in order to select a sphere. For 3D touch this was the 3D position, and for 2D touch the center of the 2D projection. The size, distance, and height of target spheres were constant within circles, but varied between circles. Target height was measured as positive height from the level screen surface. Subjects indicated target selection using a Razer Nostromo keypad with their non-dominant hand. The virtual scene was rendered on an Intel Core i7 3.40GHz computer with 8GB of main memory, and an Nvidia Quadro 4000 graphics card.

3.3 Methods

The experiment used a 2 x 5 x 2 x 2 within-subjects design with the method of constant stimuli, in which the target positions and sizes are not related from one circle to the next, but presented randomly and uniformly distributed [11]. The independent variables were selection technique (2D touch vs. 3D mid-air touch), target height (between 0cm and 20cm, in steps of 5cm), as well as target distance (16cm and 25cm) and target size (2cm and 3cm). Each circle represented a different index of difficulty (ID), with combinations of 2 distances and 2 sizes. The ID indicates overall task difficulty [12]. It implies that the smaller and farther a target, the more difficult it is to select quickly and accurately. Our design thus uses four uniformly distributed IDs ranging from approximately 2.85bps to 3.75bps, representing an ecologically valuable range of difficulties for such a touch-enabled stereoscopic tabletop setup. As dependent variables we measured the on- as well as off-display touch areas for 3D target objects.

The experiment trials were divided into two blocks: one for the 2D and one for the 3D touch technique. We randomized their order between subjects. At the beginning of each block subjects were positioned standing in an upright posture in front of the tabletop surface as illustrated in Figure 3. To improve comparability, we compensated for the different heights of the subjects by adjusting a floor mat below the subject's feet, resulting in an (approximately) uniform eye height of 1.85cm for each subject during the experiment. The experiment started with task descriptions, which were presented via slides on the tabletop surface to reduce potential experimenter bias. Subjects completed 5 to 15 training trials with both techniques to ensure that they correctly understood the task and to minimize training effects. Training trials were excluded from the analysis.

In the experiment, subjects were instructed to touch the center of the target spheres as accurately as possible (either with 2D or 3D touch), for which they had as much time as needed. For this, subjects had to position the tip of the index finger of their dominant hand inside the 3D sphere for the 3D touch condition, or push their finger through the 3D sphere until it reached the 2D touch surface. Subjects did not receive feedback whether they "hit" their target, i.e., subjects were free to place their index finger in the real world where they perceived the virtual target to be. We did this to evaluate the often-reported systematical over- or underestimation of distances in virtual scenes, which can be observed even for short grasping-range distances [32], as also tested in this experiment. Moreover, we wanted to evaluate the impact of such misperceptions on touch behavior in stereoscopic tabletop setups. We tracked the tip of the index finger in both 2D and 3D touch conditions. When subjects wanted to register the selection, they had to press a button with their non-dominant hand on the keypad. We recorded a distinct 2D and 3D touch position for each target location for each configuration of independent variables, with a total of 20 circles and 220 recorded touch positions per participant.

4 Results

In this section we summarize the results from the 2D and 3D touch experiment. We had to exclude two subjects from the analysis who obviously misunderstood the task. We analyzed these results with a repeated measure ANOVA and Tukey multiple comparisons at the 5% significance level (with Bonferonni correction).

4.1 2D Touch

For the 2D touch technique, we evaluated the judged 2D touch points on the surface relative to the potential projected target points, i.e., the midpoint (M) between the projections for both eyes, as well as the projection for the dominant (D), and the non-dominant (N) eye, as illustrated in Figure 4. Figure 5 shows scatter plots of the distribution of the touch points from all trials in relation to the projected target centers for the dominant and non-dominant eye for the different heights of 0cm, 5cm, 10cm, 15cm and 20cm (bottom to top). We normalized the touch points in such a way that the dominant eye projection D is always shown on the left, and the non-dominant eye projection N is always shown on the right side of the plot. The touch points are displayed relatively to the distance between both projections.

As it is illustrated in Figures 4 and 5, we observed three different behaviors when subjects used the 2D touch technique. In particular, eight subjects touched towards the midpoint, i.e., the center between the dominant and non-dominant eye projections. This includes the two subjects for whom eye dominance estimates were inconclusive. We arranged these subjects into the group G_M. Furthermore, three subjects touched towards the dominant eye projection D, which we refer to as group G_D, and three subjects touched towards the non-dominant eye projection N, which we refer to as group G_N. This points towards an approximately 50/50% split in terms of behaviors in the population, i.e., between group G_M and the composite of groups G_D and G_N.

We found a significant main effect of the three groups (F(2,11)=71.267, p<.001, partial-eta^2=.928) on the on-surface touch areas. Furthermore, we found a significant two-way interaction effect of the three groups and target heights (F(8,44)=45.251, p<.001, partial-eta^2=.892) on the on-surface touch areas. The post-hoc test revealed that the on-surface target areas, see Figure 5, significantly (p<.001) vary for objects that are displayed at heights of 15cm or higher. For objects displayed at 10cm height group G_D and G_N vary significantly (p<.02). For objects displayed below 10cm we could not find any significant difference. As illustrated in Figure 5, for these heights the projections for the dominant and non-dominant eye are close together, and subjects touched almost the same on-screen target areas.

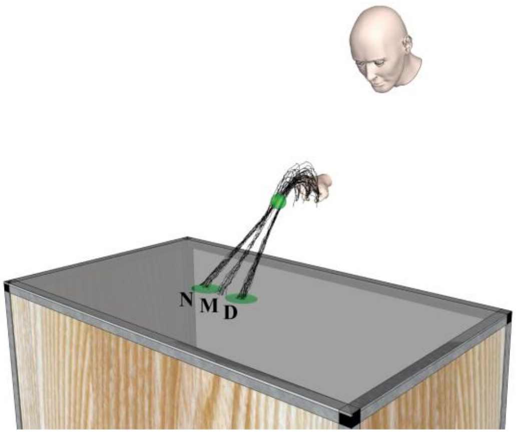

Fig. 4. Illustration of finger movement trails for eye user groups touching towards the dominant eye projection (D), non-dominant eye projection (N), or towards the midpoint. The trails have been normalized and are displayed here for a right-eye dominant user.

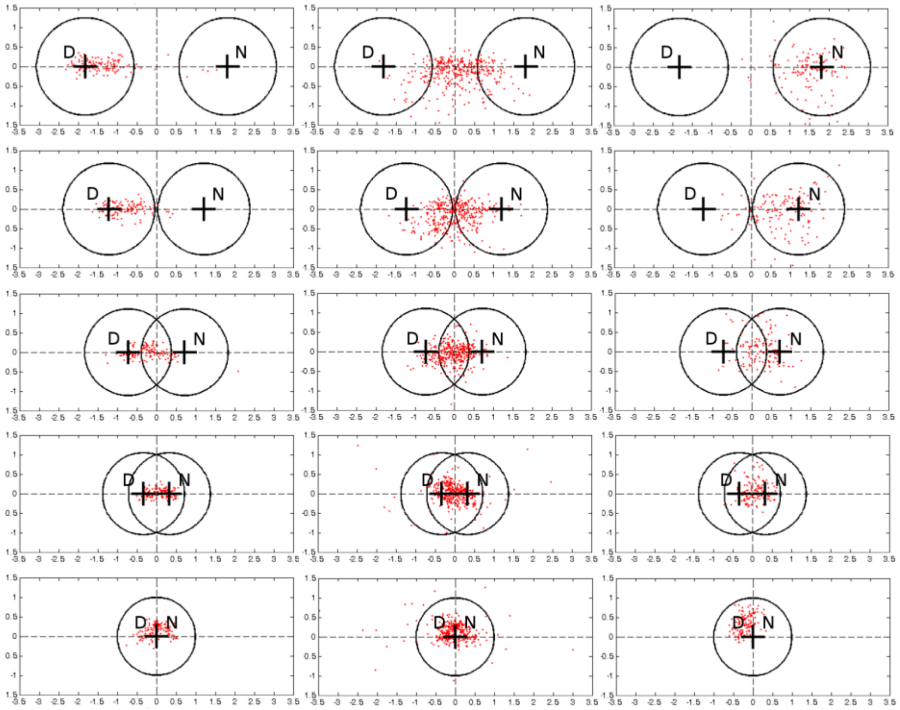

Fig. 5. Scatter plots of relative touch points between the dominant (D) and non-dominant (N) eye projections of the projected target centers on the surface for the 2D touch technique. Black crosses indicate the two projection centers. Black circles indicate the approximate projected target areas for the dominant and non-dominant eye. Top to bottom rows show results for 20cm, 15cm, 10cm, 5cm, and 0cm target heights. The left column shows subject behavior for dominant-eye touches (3 subjects), the middle for center-eye touches (8 subjects), and the right for non-dominant-eye touches (3 subjects). Note that the distance between the projection centers depends on the target height.

Considering the on-surface touch areas, we found that on average the relative touch point for group G_D was $0.97\mathrm{D}+0.03\mathrm{N}$ for projection points $\mathrm{D}\in\mathbb{R}^2$ and $\mathrm{N}\in\mathbb{R}^2$, meaning the subjects in this group touched towards the projection for the dominant eye, but slightly inwards to the center. The relative touch point for group G_N was $0.11\mathrm{D}+0.89\mathrm{N}$, meaning the subjects in this group touched towards the projection for the non-dominant eye, again with a slight offset towards the center. Finally, for group G_M we found that on average the relative touch point for this group was $0.504\mathrm{D}+0.596\mathrm{N}$. We could not find any significant difference for the different heights, i.e., the touch behaviors were consistent throughout the tested heights.

However, we observed a trend of target height on the standard deviations of the horizontal distributions (x-axis) of touch points for all groups as shown in Figure 5. For 0cm target height we found a mean standard deviation (SD) of 0.29cm, for 5cm SD 0.32cm, for 10cm SD 0.42cm, for 15cm SD 0.52cm, and for 20cm SD 0.61cm. For the vertical distribution (y-axis) of touch points and at 0cm target height we found a mean SD of 0.20cm, for 5cm SD 0.20cm, for 10cm SD 0.25cm, for 15cm SD 0.29cm, and for 20cm SD 0.30cm.

In summary, the results for the 2D touch technique show a significant effect for the different user groups on the on-surface touch area over the range of tested heights. These on-surface touch areas vary significantly for objects displayed at heights of 10cm and higher.

4.2 3D Touch

We analyzed the tracked physical 3D “touch” points where subjects judged the perceived center of the mid-air target spheres for the 3D touch technique in terms of their deviation from their actual position in the 3D virtual scene. Figure 6 shows scatter plots of the distribution of judged target positions in relation to the 3D target centers for the different target heights over all trials. The red dots indicate the center positions of the spheres as judged by the subjects. The black wireframe spheres illustrate the actual position and size of the objects. We normalized the judged positions relative to the optical view angle towards the target center. We found no significant difference in the judged positions for the three groups identified in Section 4.1 and pooled the data.

We analyzed the effect of target height on the subjects’ judgments. We found a significant main effect of target height on the distances of judged positions from the displayed target centers. Mauchly's test indicated that the assumption of sphericity had been violated for effects of height on the distances of judged positions ($chi^2(9)=62.388$, $p<.001$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (epsilon=.302). The results show that the distances of judged positions significantly differs for heights ($F(1.21,15.725)=12.846$, $p<.002$, partial-$eta^2=.497$).

A Tukey post-hoc test with Bonferroni correction revealed that subjects estimated the target centers significantly closer to the actual displayed target centers for the 0cm targets in comparison to targets displayed at 20cm height ($p<.002$). For all other heights the results suggest that the higher the targets are displayed, the larger are the deviations. Pooling over all subjects, we observed mean distances to target centers of M=0.56cm (SD=0.27cm) for 0cm target height, M=0.88cm (SD=0.53cm) for 5cm, M=0.97cm (SD=0.61cm) for 10cm, M=1.32cm (SD=0.93cm) for 15cm, and M=1.90cm (SD=1.48cm) for 20cm. The results suggest that the physical constraints provided by the touch surface at 0cm height reduced judgment errors for objects at zero parallax relative to the other heights. We found no significant difference when comparing to the results for the 2D touch technique at 0cm target height as presented in Section 4.1.

As it can be seen in Figure 6, subjects made larger errors along the view axis than along the orthogonal axes. For the mid-air target positions we found a mean standard deviation of 1.43cm along the optical line-of-sight, a mean SD of 0.36cm parallel to the touch surface, and a mean SD of 0.50cm orthogonal to the other axes. Furthermore, these deviations increased with increasing target heights. For the different target heights above the surface we observed standard deviations of judged positions along the optical line-of-sight of SD=2.20cm (for 20cm target height), SD=1.52cm (15cm), SD=1.05cm (10cm), and SD=0.94cm (5cm). On the other hand, we observed standard deviations of judged positions orthogonal to the view axis parallel to the touch surface of only SD=0.49cm (20cm), SD=0.39cm (15cm), SD=0.30cm (10cm), and SD=0.27cm (5cm). Finally, we found standard deviations of judged positions orthogonal to the other axes of only SD=0.70cm (20cm), SD=0.55cm (15cm), SD=0.41cm (10cm), and SD=0.35cm (5cm). We further analyzed the data to determine whether deviations in judged target positions result from under- or overestimation of distances from the observer to the mid-air targets [7,8]. We observed a mean distance underestimation of 0.25% (SD=2.93%). Surprisingly, we found a distance overestimation of M=0.4% (SD=2.00%) and M=1.0% (SD=2.25%) for heights of 5cm and 10cm, respectively. Yet, we found an underestimation of M=-0.54% (SD=2.67%) and M=-0.98% (SD=4.18%) for heights of 15cm and 20cm, respectively.

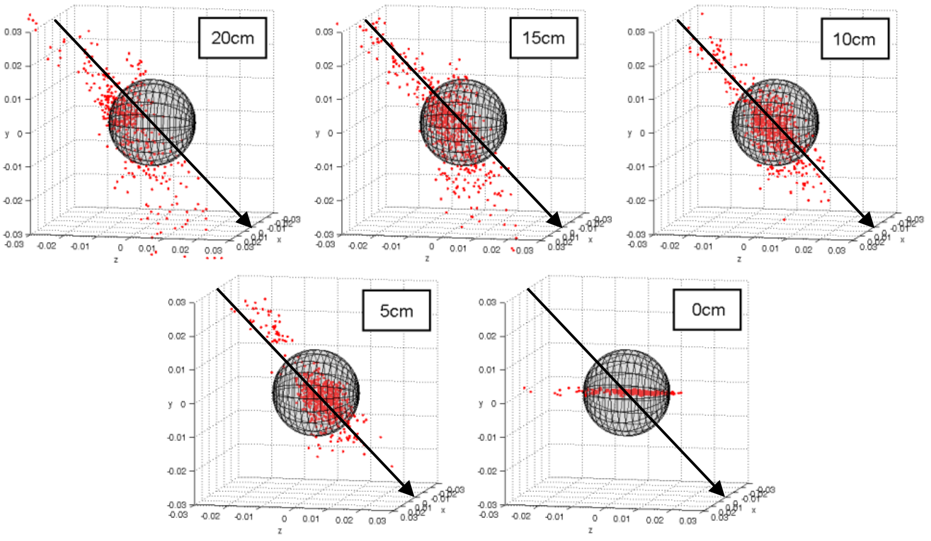

Fig. 6. Scatter plots of judged positions of the 3D target centers for the 3D touch technique over all subjects. Black wireframe spheres indicate the targets. The diagonal arrow illustrates the normalized view angle. The five diagrams show results for 20cm, 15cm, 10cm, 5cm, and 0cm target heights.

In summary, the results for the 3D touch technique show a significant effect of stereoscopic parallax over the range of tested heights on the precision and accuracy of judging the position of a target object.

5 Discussion

Our results provide interesting guidelines on how touch interaction in 3D stereoscopic tabletop setups should be realized. First of all and in contrast to previous work [39], our results show evidence for a twofold diversity of 2D touch behaviors of users. As shown in Figure 5, roughly half of the subjects in our study touched through the virtual object towards the center between the projections, and the other half touched towards projections determined by a single eye. The second group roughly splits in half again depending if they touch the projection for the dominant or non-dominant eye. Our results differ from the findings by Valkov et al. [39]. Using a setup with a large vertical projection plane they observed that subjects touched towards the center projection, with a slight offset towards the dominant eye. With 3 subjects touching towards the dominant eye, and 3 subjects towards the non-dominant eye in our study, user behavior in tabletop environments cannot be explained by this model. As a guideline, we suggest that the center between the projection for the left and right eye can be used to detect selections of objects stereoscopically displayed with less than 10cm height, since we did not observe significant differences between subjects at such heights. In order to reliably detect selections for objects higher above the screen, i.e., with larger parallaxes, our results suggest that for each user a calibration would be required. Our results confirm that this approach is highly beneficial, since subjects touched *consistently* for all heights towards the dominant, center, or non-dominant projection.

For practical considerations and to evaluate the ecological validity of using the 2D touch technique for selections of targets at a height between 0cm and 10cm, we computed the minimal on-surface touch area that supports 95% correct detection of all 2D touch points in our experiment. Due to the similar distributions of touch points between the three behavior groups for these heights shown in Figure 5, we determined the average minimal 95% on-surface region over all participants. Our results show that an elliptical area with horizontal and vertical diameter of 1.64cm and 1.07cm with a center in the middle between the two projections is sufficient for 95% correct detection. This rule-of-thumb heuristic for on-surface target areas is easy to implement and ecologically valuable considering the fat finger problem [14, 40]. Due to this problem objects require a relatively large size of between 1.05cm to 2.6cm for reliable acquisition, even in monoscopic touch-enabled tabletop environments.

The results of our second experimental condition reveal that distinct differences exist between the 3D mid-air touch technique and the 2D touch technique. These differences impact the relative performance and applicability for interaction with objects displayed stereoscopically at different heights above the surface. We found no behavior groups or effects of eye dominance on the distribution of judged 3D target positions. Our results show that target height has an effect on precision and accuracy of 3D selections, with large errors mainly along the optical line-of-sight, which we believe to correlate with distance misperception. For 3D objects displayed close to the display surface up to 10cm, touching objects in 2D on the surface by touching "through" the stereoscopic impression is more accurate than 3D mid-air touching. Considering that much research has shown that 3D mid-air touches of virtual objects suffer from low accuracy and precision due to visual conflicts, including vergence-accommodation mismatch, diplopia, and distance misperception [7, 8], it is a promising finding that the reduction of 3D selection tasks to 2D input with the 2D touch technique can improve performance for tabletop surface with stereoscopically displayed objects. However, the results also show that the accuracy for 2D touching of objects displayed above the screen decreases significantly for large negative parallax. The findings are encouraging for stereoscopic visualization on (multi-)touch surfaces. They suggest that virtual objects do not have to be constrained exactly at the zero-parallax level, but may deviate up to 10cm before 2D touch accuracy is significantly degraded [38, 39]. For such distances, the 2D touch technique is a good choice and instrumenting users with gloves or 3D markers can be avoided. Overall, our results show that it is possible to leverage stereoscopic cues in tabletop setups for an improved spatial cognition.

As a guideline for future tabletop setups with direct 2D touch input, the results suggest that touch-enabled 3D objects should not be displayed above an interactive display surface at more than about 10cm height. Above that, the disadvantages outperform the benefits and 3D interaction techniques should be used in that region, as they will provide more accurate interaction possibilities.

6 Example Application: Stereoscopic 3D Widgets

Our experiments have shown that the 2D touch technique has enormous potential as a new interaction paradigm for stereoscopic multi-touch surfaces as long as the objects are displayed with less than 10cm above the surface. In this region our 2D touch technique is the more accurate choice. While this constraint appears to limit the application scenarios in which one could use the 2D touch technique, it also ensures a simple implementation for interaction, in particular, a clear definition of on-display target areas as described in Section 5. Moreover, the size and scale of many virtual objects used in actual tabletop applications suit this constraint. For instance, 3D widgets can be displayed stereoscopically on any multi-touch surface and provide the user with a natural haptic feedback experience when she virtually touches them.

In order to evaluate the quality of the 3D touch technique in a real-world application, we adapted a simple visualization application for virtual caravans (see Figure 7). With this application customers can evaluate various types of caravans with several different features. The 3D widgets on the menu plane allow users to change the visual appearance of the caravan, lighting parameters, turn on signals, headlamps etc. We implemented the on-surface target areas of these 3D widgets as described in Section 5. The highest widgets, i.e., the 3D buttons on the menu panel, are displayed about 10cm above the surface. We used the same physical setup as described in Section 3.2. For this application we used the Unity3D game engine for the generation and rendering of the virtual scene. Unity3D provides a simple development environment for virtual scenes, animations and interactions. In order to synchronize virtual camera objects with the movements of a user, we integrated the MiddleVR for Unity software framework. MiddleVR supports streaming of motion data from our tracking system to Unity3D using the Virtual Reality Peripheral Network (VRPN) protocol. With this we stream head poses to Unity3D, resulting in a correct perspective from the user's point of view at all times.

We presented this application to four users, and made several interesting observations. First, all users acknowledged the stereoscopic display when viewing the 3D scene. Second, most users immediately understood that the menu panel with the 3D

Fig. 7. User interacting with a virtual scene in a stereoscopic multi-touch tabletop setup using touch-enabled 3D widgets. The widgets in the graphical user interface were rendered with negative parallax of up to 10cm height.

widgets provides a means to interact with the setup. Surprisingly, when users tried to “touch” the 3D widgets, they adapted their actions to the affordances provides by the widget. For instance, when they pressed the toggle switch, usually they touched its lifted part, although we did not distinguish between touch positions on the surface. We see this as further indication that stereoscopic display in combination with a touch-enabled surface does indeed support the notion of 3D physical interaction elements. Finally, none of the users complained about non-reactive 3D widgets, which might have occurred if they missed the on-surface target areas. This suggests that the shape and size of the on-surface touch areas, as determined by our above study, is sufficient for using stereoscopic 3D widgets in tabletop setups.

7 Conclusion and Future Work

In this paper we evaluated and compared 2D touch and 3D touch interaction techniques for scenes on touch-sensitive tabletop setups with stereoscopic display. We analyzed the differences of 3D mid-air touch input and a technique based on reducing the 3D touch problem to two dimensions by having users touch “through” the stereoscopic impression of 3D objects, resulting in a 2D touch on the display surface. We identified two separate classes of user behavior, with one group that touches the center between the projections, whereas the other touches the projection for the dominant or non-dominant eye. The results of the experiment show a strong interaction effect between input technique and the stereoscopic parallax of virtual objects.

The main contributions of this work are:

- We identified two separate classes of user behavior when touching “through” stereoscopically displayed objects.
- We compared precision and accuracy of 2D/3D direct touch input, which revealed that the 2D touch technique is a viable alternative to 3D touch interaction for object selection up to about 10cm height from the display surface.
- We determined on-surface target regions that support a simple implementation of the 2D touch technique. This enables intuitive touch input for 3D objects and widgets in stereoscopic 3D tabletop applications.

The results are encouraging for stereoscopic visualization in future touch-enabled tabletop setups, since no additional instrumentation and tracking technology is needed for objects with a small stereoscopic parallax. An interesting question for future work is if the results can be applied to portable setups, where the orientation of the touch-sensitive surface varies during interaction. We plan to further pursue these topics to provide compelling user experiences and effective user interfaces for touch-sensitive stereoscopic display surfaces. Moreover, we plan to investigate also how the 2D and 3D touch methods compare in terms of the speed-accuracy tradeoff.

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