Usability Evaluation of Behind the Screen Interaction

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ABSTRACT

A system (VizSpace) was evaluated that extends the conventional touch table interface by decoupling the display and placing it above the touch surface to create an interaction volume beneath the display. This physically situated setup enables touch and hand interactions beneath the display, allowing users to reach inside with their hands and interact in a 3D virtual workspace. This paper presents an empirical investigation of the performance and usability of such a system. Participants were asked to perform an object translation task that compares 2D drag with 3D grasp interaction techniques whilst also varying the height of the interaction volume. Results suggest that participants completed the task faster and more accurately with the 2D drag interaction mode compared to the 3D grasp interaction mode. More importantly, the size of the interaction volume did not affect task performance but system usability and subjective perception rankings were ranked lower for the least interaction volume with the clearest viewing area. Results suggest that a larger interaction area behind the screen is more important than a clearer viewing area.

CCS CONCEPTS

• **Human-centered computing → Mixed / augmented reality**; *User centered design*; Usability testing.

KEYWORDS

interactive 3D spaces, mixed reality, parallax, 2D drag, 3D grasp

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1 INTRODUCTION

Interactive tabletops are being used in public spaces [11] and for various applications in architecture, health and education. Conventional tabletops mainly rely on 2D touch for interaction and input on two-dimensional (2D) monoscopic displays. Recent work has focused on combining touch-sensitive display systems with stereoscopic three-dimensional (3D) technology [4, 9, 20–22]. This combination enables more intuitive and natural interaction for applications in archaeology, architecture, geo-spatial, urban planning, and education. Hence, research in this area has tended to focus on analyzing the relationship between the 3D positions of stereoscopically rendered objects, 2D touch points and mid-air interaction on the top of the touch surface. The mid-air interaction tends to be achieved by hand tracking technology, which has seen an increase in usage in recent years and enables virtual environments to track and recognize detailed hand motion using vision-based techniques on images obtained from sensors such as Microsoft Kinect[19] and Leap Motion [24]. Furthermore, stereoscopic visualization enables users to move around the interactive touchtable while the system adjusts the view to the user's head or eye position.

Objects in 3D stereoscopic scene can be behind or inside the screen (positive parallax), on the screen plane (zero parallax), or outside the screen (negative parallax). The placements of objects can have a significant impact on viewing experience in terms of viewer fatigue and discomfort. Parallax effects are discussed in [6, 18]. Usually, interaction with and visualization of a 3D environment are decoupled [18] because manipulation of stereoscopic content tends to take place in a different plane (usually zero or negative parallax) than the viewing plane where the objects of interest are placed. Objects placed at zero parallax work well with 2D touch interaction but do not work as well for objects that appear in front of or behind the screen [4]. When the viewing plane is in the positive/negative parallax plane, mid-air hand interaction is required which can lead to slight discomfort. In Void Shadows, each interactive object casts a shadow onto the zero parallax plane, allowing users to operate in the space below a tabletop display surface by interacting with the virtual shadows [8]. As such, this paper presents a concept that aims to enable fluid interactions in the positive parallax plane, i.e. between the surface of the multitouch table and the projection screen. The concept of interacting behind (or in this case, underneath) the screen has previously been demonstrated in SpaceTop [12]. The authors reported that a user commented that the physical setup of SpaceTop constrains his arm's movement which makes him easily exhausted. This raises a fundamental research question on the appropriate size of the interaction volume in such setups. There is a clear trade-off between the volume of the interaction space and the viewing comfort. As such, this paper's main contribution is a study design that varies the size of the interaction volume to study the trade-off between the interaction area beneath the screen and the viewing area on top of the screen.

Section 2 reviews related work. Section 3 describes the system design. Section 4 presents the experimental study and results, while section 5 presents the discussion. Finally, section 6 presents the conclusion and future work.

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2 RELATED WORK

2.1 Interactive TableTops

Several interactive tabletops have been implemented over the last two decades. The Immersadesk [5] and the virtual workbench [25] were two of the earliest implementations of a stereoscopic tabletop. The Immersadesk was a stereoscopic table format VR display with a rear-projected screen at a 45 degree angle while the virtual workbench had a multimodal interface that used a 6D pen and a data glove for virtual manufacturing. The virtual workbench was also used for visualizing and interacting with 3D objects for scientific visualization [15].

There has been extensive research into natural and intuitive interaction techniques for this tabletop interfaces. Mockup Builder combines both hand and finger tracking in the space on and above a multitouch surface [7]. TractorBeam [17] was a hybrid point and touch interaction technique for tabletop computer displays that combines remote pointing and local touch. Remote pointing was found to be faster than stylus touch input for large targets, slower for small distant targets, and comparable in all other cases. Mendes et al. [14] explores mid-air interactions, which users found more efficient than the alternative touch based techniques. Virtual Reality headsets have been found to be more usable than the desktop interface for 3D grasp tasks with bare hands interactions [23].

MisTable combines a conventional tabletop surface with reach-through Personal Screens, built using fog [13]. In contrast with the setup proposed, the viewing space was also the interaction volume for the MisTable. Similar to the setup proposed in this paper, Toucheo combines multitouch and stereoscopic technology [9]. Although, the hand does not occlude 3D objects with Toucheo, it was behind a semi-transparent screen, which means that the user can see the hand through the 3D object. The same issue was evident in Holodesk [10], an interactive system that combines an optical see through display and Kinect camera to create the illusion that users are directly interacting with 3D graphics. Our proposed system implements virtual hands using hand tracking technology and thus avoids this issue. The close similarity of Toucheo did highlight some ergonomic issues which we investigated in this study. The authors highlighted that one of the limitations of their setup was the size of the stereoscopic volume and users had difficulties reaching the rear part of the touchscreen because of the mirror. The usability study in our paper made some findings that may be useful for deciding the size of stereoscopic volumes of such setup.

3 SYSTEM DESIGN

The system setup of VizSpace (Figure 1) includes three components: a multitouch table for multiple touch inputs; a 3D stereoscopic projector for visualization; and a Leap Motion controller [24] for hand tracking. A frame was designed around and over the touch table to mount the Leap Motion controller and a projection screen that receives the images projected by the 3D stereoscopic short-throw projector attached to the ceiling. The frame was designed in a 3D CAD Design software (Solidworks) and manufactured using a T-slot aluminum framing system.. The T-slot frame's adjustable upper half enables customization of the height, while also providing several mounting positions for the hand tracking controller to be adjusted or relocated depending on the application. Users place their hands in between the projection screen and the top of the touch table to interact with the applications whilst visualizing the application on the projection screen (Figure 1(b)).

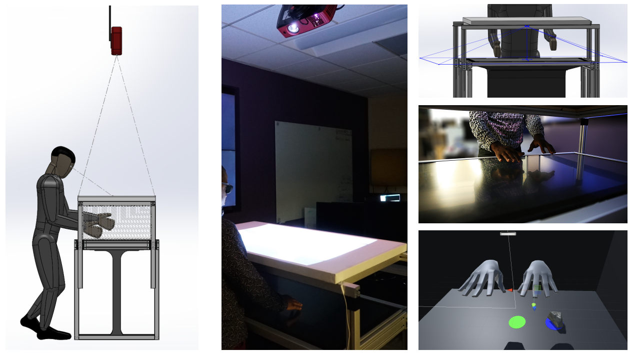
The touch interaction that was used to implement the 2D drag was achieved using a Platform 46 multitouch table. It has a 1080p HD LCD display panel and an integrated computer system (Intel i7 3.1GHz processor, 2GB Nvidia Graphics and 16GB RAM). The multitouch display comes with support for up to 60 simultaneous touch points (with palm rejection), a touch response time of 12ms and a height of 34 inches (86.36cm). The multitouch table's display was turned off and replicated through the 3D stereoscopic projector via the HDMI interface. The surface of the multitouch table also serves as a touch point of reference, which enables touch feedback, such as touching the surface of an object or picking up a virtual object placed on a virtual floor surface.

The Leap Motion sensor was used to implement 3D grasp (pinch) by tracking users' hand and finger movements in 3D space. The sensor was mounted under the projection screen facing downwards and centered over the multitouch table (Figure 1(c)). The Leap Motion Controller's field of view (FOV) was 150 degrees wide and 120 degrees deep (averaging 135 degrees). The sensor uses two cameras and three infrared LEDs to capture images of the hands and fingers before performing computer vision algorithms on the resulting images in real time.

The Acer Predator Z650 projector with HD (1920 × 1080) resolution and short-throw projection (100" at 1.5m) was used. This Digital Light Processing (DLP) 3D projector use the built-in DLP LINK technology to synchronize the active shutter glasses with the display. Users wear 3D glasses to view the application in 3D stereoscopic mode. Stereo convergence was set to be in front of the 3D scene (objects of interest) within the 3D applications to achieve a positive parallax effect and enable users to see beneath the projection screen (as opposed to a "pop-out" effect). Head tracking was implemented using TrackIR to track users' head for view-dependent rendering. Stereoscopic parameters hare adjusted according to the adjustable height of the interaction volume and user characteristics such as inter-ocular distance, eye and head positions.

Touch and hand gesture tracking occurs in the adjustable interaction volume (Figure 1(c)). The tabletop surface has an area of 42 inches (106.68cm) by 25 inches (63.5cm) while the height of the interaction volume varies. In this study, heights of 11 inches (27.94cm), 13 inches (33.02cm) or 15 inches (38.1cm) from the tabletop surface were investigated. As users interact with VizSpace, they are able to see a 3D model of their hands within the 3D applications. The physical placement of the hand tracking sensor determined the active tracking area within the interaction volume.

A fundamental task when using the Leap Motion controller in an application was mapping the coordinate system values received from the controller to the application's coordinate system. The Leap Motion Controller provides coordinates in units of real world millimeters within the sensor's frame of reference. The origin was located at the top, center of the hardware. To obtain a matched interaction volume, the coordinates from the different input devices was converted into a unique reference space. The Leap Motion coordinate system was chosen as the primary coordinate system since it covers the interaction volume. The 2D touch positions on



(a) (b) (c)

Figure 1: (a) VizSpace illustration [16] (b) Setup and (c) Interaction Volume. In this depiction, the blue circle is on grid position 13 as depicted in Figure 2

the multitouch surface are converted to x-z axis while the y-axis was determined by the height of the interaction volume.

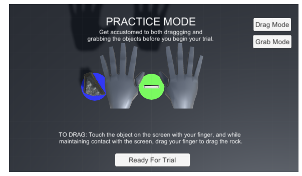
4 EXPERIMENT

4.1 Materials and Methods

4.1.1 Participants. Twelve unpaid participants (7 males and 5 females) made up of students and staff were recruited to take part in the study. Participants' age range was 18 to 29 years and the mean age was 22.1. All participants had normal vision and had a mean and median height of 5 feet 6 inches (167.64cm).

4.1.2 Experimental Design. The experiment used a 2 × 3 × 14 within-subjects design. The independent variables are interaction mode (2D drag and 3D grasp), height of interaction volume (11", 13" and 15") and grid positions (1 - 14). Using a counterbalanced measures design, the input and height conditions were mixed to reduce any confounding influence of the orderings such as learning effects or fatigue. The height of the interaction volume was the measurement between the touch and projection surfaces. Three heights were tested: (i) 11 inches (27.94cm); (ii) 13 inches ((33.02cm); and (iii) 15 inches (38.1cm).

4.1.3 Task. The touch surface area of 42 × 25 inches was divided into 3 × 5 grid sectors of 8.4 × 8.33 inches (see table in Figure 2). Participants were instructed to move an object (3D model of a rock sample), as fast as possible, from each grid position to center position, X, as depicted in Figure 2. Participants moved the rock from the blue circle to the green circle. The rock and blue circle moves to the next position after every successful placement in the green circle. Six random orderings of the grid positions were used in the same sequence for each participant's trial runs to reduce any confounding influence of learning of the grid positions. Participants moved the rock using the 2D drag and 3D grasp interaction modes. Participants were randomly assigned to use the 2D drag interaction mode first followed by the 3D grasp mode, or used the mode in reverse order. Participants were allowed to interact with the left or right hand.



3	4	5	6	7
2	13	X	14	8
1	12	11	10	9

Figure 2: Image on the right shows experiment interface and table shows the grid positions of the touchscreen surface (participants stand at the double line)

4.1.4 Procedure. Participants were guided through the trials using steps implemented within the application that presented the different tasks in turn. Prior to starting the experiment, participants took part in a training phase that allowed one complete object movement per condition. Each participant participated in 84 trial runs that comprises 3 sessions. In each session, participants used both interaction modes, in turn, to move the rocks from all 14 grid positions to the center grid position for a height condition. At the end of each session, participants completed the System Usability Scale (SUS) questionnaire [3] and four additional height-specific questions on subjective perception, while the experimenter adjusted the height of the interaction volume for the next session.

4.2 Results

Three dependent variables were measured:

- Task completion time measures the total time that participants take to select the rock and move it to the center grid.
- SUS ratings were collected for each height condition.
- Four additional questions on subjective perception were collected and measured for each height condition. The questions asked the participants using a 5-points likert scale whether: (i) the height interfered with interaction; (ii) the height was comfortable; (iii) the 2D drag mode was easy to use at this height; and (iv) the 3D grasp mode was easy to use at this height. The scale ranged from 1 for "not true at all" to 5 for "completely true".

4.2.1 Task Completion Time. The dependent variable data (task completion time) was entered into a three-way repeated measures Analysis of Variance (ANOVA) with the three factors of interaction mode, height of interaction volume and grid position. There was a significant main effect of interaction mode, ($F_{(1,11)} = 67.48, p < 0.0001$) with longer task completion time for the 3D grasp (*Mean, M = 6.50s*) than the 2D drag mode (*M = 3.55s*). The 2D drag interaction mode had a significantly faster completion time than 3D grasp. The main effect of the height of interaction volume was not significant ($F_{(2,22)} = 1.52, p > 0.05$) with similar task completion time for heights of 11 inches (*M = 5.57s*), 13 inches (*M = 4.68*) and 15 inches (*M = 4.83*). Regardless of the height of the interaction volume, the task completion times did not significantly differ. Mauchly's test of sphericity was employed to validate that variances of the differences are equal. Mauchly's test indicated that the assumption of sphericity had not been violated ($\chi^2 = 5.13, p > 0.05$). There was a significant main effect of grid positions ($F_{(13,143)} = 5.25, p < 0.0001$). No other statistically significant interaction effect was found.

4.2.2 System Usability Scale. The SUS scores were computed from the 10-item SUS questionnaire ratings and entered into a one-way repeated measures ANOVA with one factor of height of interaction volume. Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated for the height ($\chi^2 = 4.02, p > 0.05$). There was no statistically significant main effect of the height of interaction volume on the SUS scores ($F_{(2,22)} = 1.02, p > 0.05$) with similar SUS scores for heights of 11 inches (*M = 68.75*), 13 inches (*M = 73.54*) and 15 inches (*M = 74.38*). Regardless of the height of the interaction volume, the SUS scores did not significantly differ. The residual errors satisfied the tests of normality with a Shapiro-Wilks test, and the hypothesis of normality was not rejected ($p > 0.05$) for all height conditions.

4.2.3 Subjective Perception. For each of the four questions, a non-parametric Friedman test of repeated measures was conducted to test between the responses for the three height conditions. Results are reported below:

- There was a statistically significant difference in participants' perception of whether the heights interfered with interaction ($\chi^2(2) = 9.556, p = 0.008$) with a median rank of 5 (11 inches), 1 (13 inches) and 3 (15 inches). Dunn-Bonferroni post hoc tests found a statistically significant difference between 11 and 13 inches ($p = 0.017$).
- There was no statistically significant difference in participants' perceived comfort of the height ($\chi^2(2) = 5.097, p = 0.078$) with a median rank of 2 (11 inches), 4 (13 inches) and 4 (15 inches).
- There was no statistically significant difference in participants' perception of the ease of use of 2D drag ($\chi^2(2) = 4.957, p = 0.084$) with a median rank of 4 (11 inches), 5 (13 inches) and 5 (15 inches).
- There was a statistically significant difference in participants' perception of the ease of use of 3D grasp ($\chi^2(2) = 6.400, p = 0.041$) with a median rank of 2 (11 inches), 4 (13 inches) and 4 (15 inches). Dunn-Bonferroni post hoc tests found no significant differences between all pairs ($p > 0.05$).

5 DISCUSSIONS

In the experiment, participants performed a selection and movement task that was designed to explore the interaction volume. The study aimed to investigate the usability of the system, given that the viewing area was decoupled from the interaction volume.

The analysis of the results revealed that task completion times were not affected by the variations in the height of the interaction volume. However, it was noted that the SUS scores for the height levels of 13 inches and 15 inches were over 70 (a score of 70 and over indicates promising acceptability in the field [1, 2]) while the lowest height level of 11 inches was below the acceptable standard. This was confirmed by the findings of the subjective perception questionnaire, which found that the lowest height interfered with participants' ability to interact with the system (median rank of 5 - completely true). Although, the subjective findings of the SUS conflicted with the objective results, we conjecture that this discrepancy was due to the simplicity of the set task. One of the limitations of this system was the limited size of the active tracking area within the interaction volume. The active tracking area becomes even more limited at the lower heights and that could have affected the tracking of the hands at the diagonal edges.

It should also be noted that the limited viewing space above the projection screen for the highest height did not affect usability of the system or task performance. Contrasting this with the finding for the smaller space, this suggests that the size of the interaction volume was a more important design factor than viewing comfort. In other words, as long as participants can see the display, accessibility of the interaction volume was perceived as a more important feature.

The analysis of the study revealed that the task completion times was faster with the 2D drag interaction mode than the 3D grasp mode. The task completion time was a combination of the time it took participants to select and move the objects to the target location. The limitation of the active tracking area within the interaction volume likely affected the task completion times for the 3D grasp interaction mode. This depends on the user behavior, if they picked up the object and raised their hand too high, it could move out of the active tracking area. Besides, tracking with the Leap Motion can be challenging on reflective screens such as the tabletop display. Furthermore, 3D grasp interaction requires an explicit acquire and release action which takes more time and cognitive effort. Also, the user has to control three degrees of freedom for the 3D grasp, as opposed to two for the 2D drag interaction mode.

6 CONCLUSIONS AND FUTURE WORK

In this paper, an interactive 3D visualization system was presented that has been designed to enable a user to use touch or hand interaction with a 3D stereoscopic experience behind the display screen. The interaction modes enable a user to simulate reaching inside and interacting with an object in a 3D virtual workspace. This paper evaluated the system's usability and interactive capabilities. The main finding and recommendation of the study is that designers of these systems should consider allowing more space for the interaction volume at the expense of the viewing area.

A limitation of this study is the sample size and the robustness of the 3D grasp implementation. Future work will focus on exploring a more appropriate placement of the tracking sensor within the interaction volume. The findings on the comparisons of the grid positions requires a larger sample size for further analysis. In future, we plan to test users' acceptance of the system such as the level of agency with the realism of the virtual hands and the plausibility of interacting in the 3D space. We will also focus on improving usability by evaluating the use of a height-adjustable ergonomic standing stool to account for users of varying heights for maximum comfort. Additionally, the system has the potential to provide a collaborative workspace, as multiple users' hands and heads can be tracked simultaneously, enabling transfer of control of the viewing frustrum to different users, as well as the ability to utilize the multi-touch functionality.

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