Two Handed Selection Techniques for Volumetric Data

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ABSTRACT

We developed three distinct two-handed selection techniques for volumetric data visualizations that use splat-based rendering. Two techniques are bimanual asymmetric, where each hand has a different task. One technique is bimanual symmetric, where each hand has the same task. These techniques were then evaluated based on accuracy, completion times, TLX workload assessment, overall comfort and fatigue, ease of use, and ease of learning. Our results suggest that the bimanual asymmetric selection techniques are best used when performing gross selection for potentially long periods of time and for cognitively demanding tasks. However when optimum accuracy is needed, the bimanual symmetric technique was best for selection.

CR Categories and Subject Descriptors: H.5.2 [User Interfaces]: Input devices and strategies - Interaction styles. I.3.6 [Computer Graphics]: Methodology and Techniques – interaction techniques.

Additional Keywords: Bimanual interaction, 3D selection, 3D UI, volumetric data, splat-rendering, visualization.

1 INTRODUCTION

The complexity of visualizing 3D volumetric data can cause difficulty in interaction due to the added third degree of freedom, the type of rendering, or the overall functionality. Good 3D UI design is therefore critical for the success of 3D visualization applications. Visualization is a rapidly growing field that uses graphics to represent data in a more understandable way than in its raw form. Most of the applications in this field are domain dependent, thereby making it very difficult to develop standard visualization and interaction techniques. Not only does the developer need to create the interaction techniques specific to the domain, but the user must learn how to use the interaction techniques in addition to other aspects of the application.

Most 3D visualizations have some fundamental interactions, such as selection or manipulation, which can be dependent on the type of rendering. The primary interactions can be developed exclusive of the domain-dependent interactions. This can reduce the cognitive load on the domain experts by facilitating users to go from one 3D visualization application to another without needing additional training on basic interaction tasks. 3D visualization developers can then focus more effort on developing the visualization rather than the interaction.

In this paper, we focused on developing and quantifying selection techniques specifically for visualizations that use splat-based rendering [18][19][23]. Selecting a specific area from a splat-based volumetric rendering of data in this type of 3D visualization is difficult because the rendered objects are not precisely defined as polygonal objects. 3D visualizations using splat-based rendering represent data as clouds of various colors, sizes, shapes, opacities, levels of occlusion, and sparseness. These characteristics make it difficult to select areas for analysis using traditional selection techniques such as those incorporating point-based [24], ray-based [27][30], virtual hand [2][26][27], or aperture-based selection metaphors [8][28].

We propose three selection techniques that take advantage of the user's innate proprioceptive knowledge of hand positioning and orientation to reduce training. Since splat-based renderings of volumetric data can be of any size, shape, opacity, and level of occlusion and sparseness, traditional selection techniques may not be suitable for selection. For example when using a ray-casting technique, a virtual ray cast into space can easily select a defined object, such as a cup. However, casting a ray into a cloud of color may not select a volumetric area well. Our approach was to define a basic volume bound by a six-sided box. We believe that this approach offers advantages over point-based or virtual hand selection metaphors since the box encompasses a selected volume rather than a selected object. The selection box can be positioned, oriented, and scaled in any dimension. There are different ways to hold, position, orient, and scale the box. We chose to use two hands to hold and manipulate the box, as opposed to one, since it has already been shown for two-dimensional interaction that the use of two hands is more preferred and outperforms one [Latulipe 21]. We varied the techniques by assigning different tasks, of positioning, rotating, or scaling the selection box, to the dominant and non-dominant hands. Our hypothesis was that the selection techniques that assign the same tasks to each hand, as opposed to assigning different tasks, will be more accurate, quicker, and easier to use and learn but cause more fatigue.

2 BACKGROUND AND RELATED WORKS

2.1 Bimanual Interaction

Using both hands for 3D interaction allows users to transfer ingrained interaction skills and significantly increase performance on certain tasks and reduce training [3]. These benefits are demonstrated in various 2D interfaces [1] and 3D interfaces [3][16][32]. When creating two-handed interaction techniques, certain factors play a role in the division of labor among the two hands. According to Guiard's framework of Bimanual manipulation, there exist different classes of bimanual actions [14]. The Bimanual symmetric classification involves each hand performing identical actions either synchronously or asynchronously. The Bimanual asymmetric classification consists of both hands performing different actions but are coordinated to accomplish the same task. The three principles that characterize the roles of the hands in asymmetric division of labor are that 1) the non-dominant hand adjusts the spatial frame of reference for actions of the dominant hand, 2) the dominant hand produces fine-grained precision movements while the non-dominant hand performs gross manipulation [17], and 3) the manipulation is initiated by the non-dominant hand. We applied Guiard's framework of Bimanual manipulation to divide the labor among the non-dominant and dominant hands in each of our proposed selection techniques.

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2.2 Bimanual Devices

Many two-handed input devices have been developed. Veigl et al. implemented a wrist-mounted augmented reality panel made from a simple 2D touch pad. The device incorporates gestural interaction, such as pointing, grabbing or stretching [29]. The Cubic Mouse is a 3D input device that uses a six-degrees-of-freedom (6-DOF) tracker to control position and orientation [9]. Rods can be pushed and pulled to constrain the degrees of freedom. Although it is a two-handed device, it only tracks one distinct hand position and orientation. In our work we used devices that tracked both hands. Hinckley et al. developed a two-handed interaction prop-based device for neurosurgical visualization [16]. The non-dominant hand positions and orients a doll's head to correspondingly control the virtual head. The dominant hand holds a cross-sectioning clear plastic plate serves that as a virtual cross section tool.

Ebert el al. describes a minimally immersive volumetric interactive system for information visualization [7]. The SFA system uses glyph-based volume rendering, stereo-viewing and provides two interfaces. The bimanual interface uses two 3D magnetic trackers with buttons using direct manipulation. The non-dominant hand manipulates the position and orientation of the scene, while the dominant hand actually selects the glyphs.

In our selection techniques, we use two 3D magnetic trackers with buttons similar to those used by Ebert [5]. However, in our system, both hands work together to size and position a box for selecting areas in splat-based volumetric rendering on a computer screen. In two of our selection techniques, the non-dominant hand manipulates the position and orientation of the selection box, not the scene, while the dominant hand controls the scale of the box. In our third selection technique, both hands control position, orientation, and scale of the box.

Bender is one example of a two-handed modeling system that uses two 3D magnetic trackers with buttons in order to interact with the system [22]. Grossman et. al developed a 3D model building application which integrates multi-finger gestural interaction with 3D volumetric displays [12].

2.3 Bimanual Interaction Techniques

Several studies have compared two-handed interaction techniques to one-handed techniques. Owen et al. investigated the relationship between two-handed manipulation and the cognitive aspects of task integration, divided attention, and epistemic action [25]. An empirical study compared a two-handed technique versus a one-handed technique for a curve matching task. They found that the two-handed technique resulted in better performance than the one-handed technique, and as the task becomes more cognitively demanding, the two-handed technique exhibited even greater performance benefits.

Buxton and Myers' two-handed input study shows that using a pair of touch-sensitive strips for jumping and scrolling with the non-dominant hand can result in improved performance [4]. In an experiment that compared a one-handed versus two-handed method for finding and selecting words in a document, they found that the two-handed method significantly outperformed the commonly used one-handed method by a number of measures. In another experiment the use of different devices to interact with an application for manipulating sculpting tools and dataset position and orientation were evaluated. User's preferred two-handed over one-handed input. Latulipe et al. created the symSpline technique, a symmetric, dual-mouse technique for manipulation of spline curves, and compared it to two asymmetric dual-mouse techniques and a standard single-mouse technique [21]. The symSpline outperformed the two asymmetric dual-mouse techniques and was most preferred by participants. Several other studies conducted showed this result of improved overall performance for bimanual interaction [10][20][32].

Several bimanual interaction techniques have been developed and evaluated. Zeleznik el al. explored bimanual techniques using two independent cursors to control camera navigation in 3D desktop applications [32]. A system was developed to allow a user to manipulate virtual models displayed on the Responsive Workbench with two-handed interactions that are coordinated and asymmetric [6]. Yee describes a system that overlays a touch-screen on a tablet display to support asymmetric bimanual interaction in which the preferred hand uses a stylus and non-preferred hand operates the touch-screen [31].

Grossman et al. explored 3D selection techniques for volumetric displays by conducting several experiments [11]. A ray cursor was found to be superior to a 3D-point cursor in a single target environment. The authors designed four new ray cursor techniques which provided disambiguation mechanisms for multiple intersected targets. The most successful technique was one in which users selected and disambiguated their target concurrently. This technique significantly reduced movement time, error rate, and input device footprint in comparison to the 3D-point cursor. Our selection techniques used a box metaphor rather than a ray-casting metaphor for selection.

3 EXPERIMENTAL DESIGN

Three selection techniques for volumetric data were evaluated in terms of accuracy, completion times, ease of use, mental and physical workload and ease of learning. We used splats as targets to evaluate selection for splat-based rendered 3D visualizations. Each splat is a colored volumetric sphere rendered at a set opacity. Some splats were indicated for selection while others were not. The splats indicated for selection were rendered in blue and changed to red when enclosed by the selection box (Figure 1). The splats not indicated for selection were dull yellow and changed to bright yellow when enclosed within the selection box. The participant's goal was to select all of the blue splats while selecting the least number of yellow splats. The same number of blue-to-red and dull-to-bright-yellow splats, with twice as many yellow splats than blue, was rendered for each trial per task. The size of each group of spats was determined by a volumetric space with the same predetermined width, height, and depth. A group of splats is created by individual splats randomly positioned within this space. For each of the four trials, a group of splats was positioned in one of each of the four corners of the screen and positioned in the center for the fifth. Each trial had different splat locations, but the same five trials were given for each task so no confound could result due to location of splats.

Each group of splats was arranged in different spatial locations within arm reach of the participant, and the size of the selection box was restricted to as large as the three-dimensional space between the two hands to eliminate travel and out-of-reach extension of the selection box. We kept the size of the spats constant among task types for this same reason. Further investigation will be conducted using travel or out-of-reach extension of the selection box to measure performance for various sizes and locations of the splats.

We exploited the different situations that can occur, by arranging the blue splats in different densities and occlusion. The densities ranged from being sparse, or spread out on the screen in three dimensions, to being clustered together. Blue-to-red splats were occluded or not occluded by dull-to-bright-yellow splats.

The variables of primary interest are as follows:

1. Selection Method (Hand-on-Corner, Hand-in-Middle, Two-Corners)
2. Density (Sparse vs. Clustered)
3. Occlusion (Occluded vs. Non-Occluded)

Density and occlusion were varied since they are primary characteristics of splat-based volumetric data and can be varied without travel or out-of-reach extensions. By varying the task difficulty, the performance of the methods is investigated under these conditions to generalize their performance with splat-based volumetric data in any variation of density and occlusion.

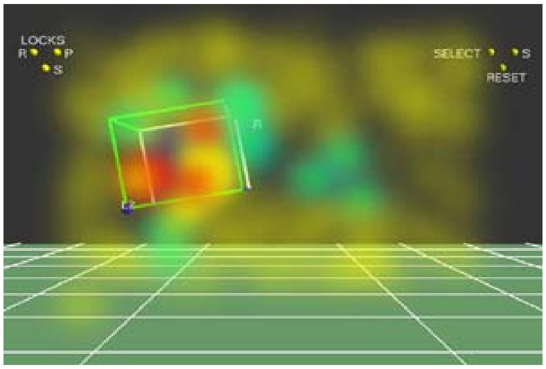


Figure 1: Performing a selection.

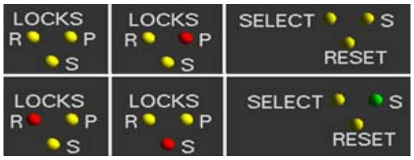


Figure 2: Feedback for buttons.

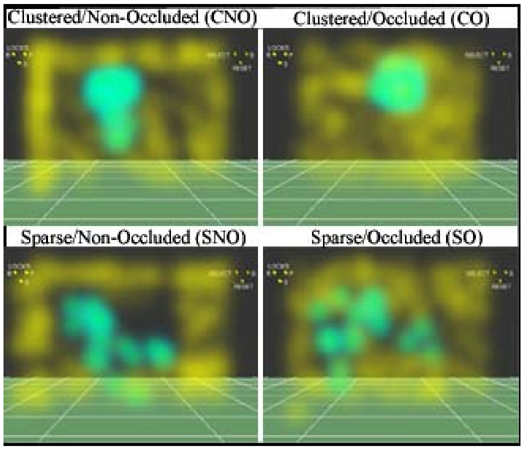


Figure 3: Splats rendered by task type.

The Selection Method was manipulated between subjects with each participant randomly assigned to one of three conditions:

1. Hand-on-Corner (HOC)
2. Hand-in-Middle (HIM)
3. Two-Corners (TC)

The levels of Density and Occlusion were combined to create a task variable with four different combinations of rendering the splats: Sparse/Occluded (SO), Sparse/Non-Occluded (SN), Clustered/Occluded (CO), and Clustered/Non-Occluded (CN) (Figure 3). The task variable was manipulated as a within subject variable and the following Latin square was used to determine the order in which the tasks were presented to the participants. An equal number of participants were randomly assigned to one of the four orderings of task type:

1. Task 1: SO, Task 2: SN, Task 3: CO, Task 4: CN
2. Task 1: CO, Task 2: SO, Task 3: CN, Task 4: SN
3. Task 1: SN, Task 2: CN, Task 3: SO, Task 4: CO
4. Task 1: CN, Task 2: CO, Task 3: SN, Task 4: SO

Varying the density of the splats will change the task difficulty if spats intended to be selected are clustered together, then task becomes easier to keep out splats that should not be selected, while if splats are sparser, or spread out, the task becomes harder to keep out splats that should not be selected. Varying the occlusion changes the task difficulty since it is easier to select the indicated splats if not occluded by splats that should not be selected and harder if they are.

Figure 4: Setup and apparatus.

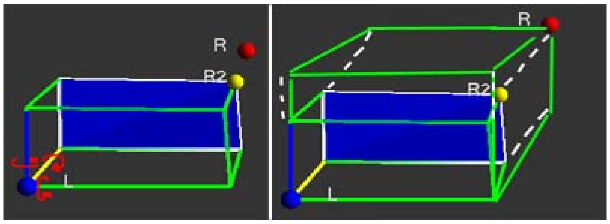


Figure 5: Positioning, orienting, and scaling box in HOC.

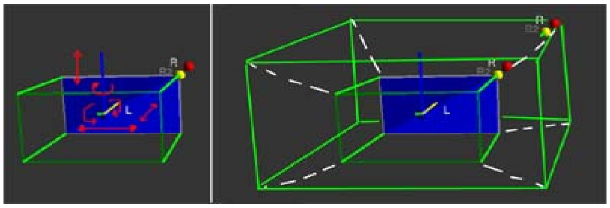


Figure 6: Positioning, orienting, and scaling box in HIM.

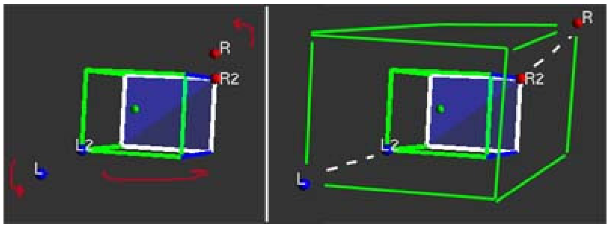


Figure : Positioning, orienting, and scaling box in TC.

For this evaluation, we hypothesized that the third condition of using both hands symmetrically to position, orient or resize the selection box will have better accuracy ratings, faster completion times, and higher ease of use and learning scores, but higher ratings of fatigue and overall workload. We hypothesized that the asymmetrical techniques will have worse accuracy ratings, slower completion times, and lower ease of use and learning scores along with lower ratings of fatigue and overall workload.

3.1 Experimental Setup

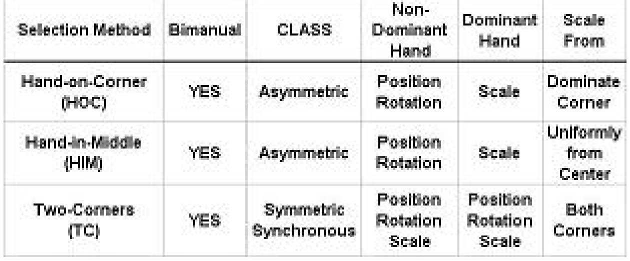
3.1.1 Apparatus

Two Polhemous FastTrak magnetic trackers with 6 degrees-of-freedom (DOF), encased in ping-pong balls with three joystick buttons attached to each, served as the 3D input devices (Figure 4). The participant held one tracker in each hand, clearly marked left or right on the device. The evaluation was performed on a Dell Precision 380 with Intel Pentium 4.40 GHz processor. The graphics card was a Quadro FX 4500 with 512 MB memory. Though the evaluation was run in a mono-view, we used a NuVision 21MX-SL stereoscopic monitor by MacNaughton, Inc for the evaluation, with a resolution of 1280x1024.

3.1.2 Visualization Environment

We used the Simple Virtual Environment (SVE) toolkit and OpenGL to render the testing environment. The environment was rendered in a 1280 x 1024 display resolution 30 FPS on average. The participant was presented with a view similar to Figure 1, where a series of splats were rendered and the selection box was displayed. Feedback for button functionality, located on each device controller, was displayed in the upper corners (Figure 1). Each controller's feedback was displayed on the corresponding side of the dominant and non-dominant hands. The non-dominant hand would press a button to lock, or disable, control of position, orientation, or scale the box. Spheres marked P, R, and S respectively, were displayed in the same arrangement as the buttons were on the device, and changed to red when locked (Figure 2). To scale the selection box, the dominant hand would press and hold the scale button marked S while moving the hand. The corresponding sphere changed to green when pressed. The dominant hand reset the box with the RESET button and executed selection with the SELECT button.

Table 1: Classification and functionality of selection methods.



Selection Method	Bimanual	CLASS	Non-Dominant Hand	Dominant Hand	Scale From
Hand-on-Corner (HOC)	YES	Asymmetric	Position Rotation	Scale	Dominate Corner
Hand-in-Middle (HIM)	YES	Asymmetric	Position Rotation	Scale	Uniformly from Center
Two-Corners (TC)	YES	Symmetric Synchronous	Position Rotation Scale	Position Rotation Scale	Both Corners

3.2 Selection Techniques

The selection techniques developed consist of two bimanual asymmetric techniques and one bimanual symmetric technique, with hands performing tasks synchronously (Table 1). All of the techniques developed incorporate a three-dimensional box for selection. The box is positioned, oriented, and resized differently for each technique. We chose very different methods for hand placement, positioning, orienting, and scaling for each technique so as to expose any strengths and weaknesses from characteristics of these methods, and begin to investigate what components are needed for accurate and comfortable volumetric selection. The selection area was the volume within the three-dimensional box. All techniques requiring specific tasks for the non-dominant and dominant hand were adjusted appropriately for right- and left-handed participants to prevent handedness as a possible confound.

3.2.1 Hand-on-Corner (HOC) Technique

The Hand-on-Corner technique is a bimanual asymmetric technique where the bottom front corner of the box, on the side of the non-dominant hand, is attached to the non-dominant hand (Figure 5). The non-dominant hand directly controls position and orientation. The top back corner of the box, on the side of the dominant hand, is attached to the dominant hand. The dominant hand directly controls the size of the selection box in all three dimensions by moving closer to, or further from, the non-dominant hand. This method was designed so the user holds the bottom front corner and scales from the opposing upper back corner to allow the hands to better sense the width, height, and depth of the box as physical space between the two hands. As an asymmetric technique, it enables one hand to rest while the other performs positioning and orienting, thus producing less fatigue.

3.2.2 Hand-in-Middle (HIM) Technique

The Hand-in-Middle technique is a bimanual asymmetric technique where the center of the box is attached to the non-dominant hand (Figure 6). The non-dominant hand directly controls the position and orientation. No part of the box is attached to the dominant hand. The dominant hand directly controls the size of the selection box by moving the hand closer to the non-dominant hand to uniformly decrease the size independently in each dimension and moving the hand away from the non-dominant hand to uniformly increase the size independently in each dimension. This method was designed to give more control in positioning and orienting the box. Since the hand holds the box from the middle, the user can place the hand in the center of the area to be selected and then adjust orientation and scaling outward. As an asymmetric technique, it enables one hand to rest thereby reducing fatigue.

3.2.3 Two-Corners (TC) Technique

The Two-Corners technique is a bimanual symmetric technique, with hands performing tasks synchronously (Figure 7). The bottom front corner of the box, on the side of the non-dominant hand, is attached to the non-dominant hand. The top back corner of the box, on the side of the dominant hand, is attached to the dominant hand. The combined position of both hands directly controls the position, orientation, and size of the selection box. Position of the box is the three-dimensional midpoint between the positions of the two hands. Orientation of the box is determined by the orientation of the vector defined by the positions of the two hands. Size of the box is calculated by the distance between the positions of the two hands independently in each dimension. This method was designed to hold the bottom front corner and scale from the opposing upper back corner to allow the hands the sense of physical space the box represents. As a symmetric technique, the method offers better control in how the box is being positioned, oriented, and scaled from the use of both hands.

3.3 Measures

3.3.1 Pre-Questionnaires

Participants were surveyed for demographic information such as age, gender, ethnicity, occupational status, major, colorblindness, sight, and device usage. A computer usage survey of eight questions was administered using seven point Likert-type scales (1= never, 7= a great deal) to determine the level at which each participant had been exposed to computer interaction in both 2D and 3D. Examples of these questions are 'To what extent do you play 2D computer games?' or 'To what extent do you use 3D modeling software (such as Maya®, 3D Studio Max®, or other)?'

Participants completed a handedness questionnaire [5] based on items from studies that tested handedness by asking which hand performed skilled activities with responses of left, right, or either. The score evaluates the strength of handedness and is determined by the number of "rights" multiplied by three, plus the number of "eithers" multiplied by 2, plus the number of "lefts". The score is interpreted as follows, 33 to 36 is strongly right-handed, 29 to 32 is moderately right-handed, 25-28 is weakly right-handed, 24 is ambidextrous, 20 to 23 is weakly left-handed, 16 to 19 is moderately left-handed, and 12 to 15 is strongly left-handed.

Participants completed the Guilford-Zimmerman (GZ) Aptitude Survey Part 5: Spatial Orientation [13]. Spatial Orientation is the ability to perceive of the arrangements of visual information in space. This test consists of 60 items, but a time limit of 10 minutes ensures that the vast majority of people cannot attempt all items. Each item shows two pictures and the participant has to select between a number of simple abstract representations of how the view changes from one picture to the other.

3.3.2 Performance Measures

Selection accuracy scores, completion times, and overall completion times were automatically logged for each trial per task. The percentage of good selection was determined by number of splats selected, that were indicated for selection, divided by the total number of splats indicated for selection, multiplied by 100%. The percentage of bad selection was determined by the number of splats that were not indicated for selection, that were selected, divided by the total number of splats not indicated for selection multiplied by 100%. Accuracy scores were determined by the subtracting half of the percentage of bad selection from the total percentage of good selection. Means for accuracy scores and task completion times for each task were computed from each participant across the five trials per task within each of the experimental conditions. Overall completion time was the amount time it took each participant to complete training and all tasks.

The TLX workload Assessment questionnaire is based on mental, physical and temporal demand, own performance, frustration, and effort [15]. For each task, the participant rated pairs of these measures based on importance, giving a weight to each dimension of the overall workload. Afterwards, six questions were administered on a 20-point scale from low to high.

Participants used a 7-point Likert scale (1=disagree completely, 7=agree completely) to rate, on a three-part questionnaire with eight to ten items, how well they thought they performed the task, how easy the system was to use, and how comfortable and fatigued they were when using the system. Each item was averaged together per task, resulting in three measures per task: self-perception of accuracy, ease of use, and user comfort.

3.3.3 Post-Questionnaires and Debriefing

The participants used a 7-point Likert scale (1=disagree completely, 7= agree completely) to rate how easy it was to learn to use the system on an eight item questionnaire, and were averaged resulting in an ease of learning measure. Participants were debriefed and interviewed using a qualitative questionnaire asking the participants open-ended questions of ease of use, opinions of device and method, arm fatigue, and areas for improvement.

3.4 Experimental Procedures

3.4.1 Pre-experimental and Training Procedure

Participants initially completed the informed consent form and pre-experimental questionnaires. In the testing area, participants were first instructed on how to perform the task. They sat in a chair facing a computer screen holding one device in each hand. They were told how to hold the devices, the objective of the task, to change the position, orientation, and size of the selection box, to separately or simultaneously lock the position, orientation, and size of the selection box using the buttons, and led through two sample trials for each of the four combinations of density type and occlusion type pairings in the exact same ordering they would receive in testing. To reduce fatigue, after each trial a screen gave instructions to continue when ready thus allowing opportunity to rest before the next trial began. Participants were permitted to ask questions about the task and device only during this session.

3.4.2 Testing Procedure

Participants were given five trials for each of the four combinations of density type and occlusion type pairings. Before each of the five trials, the participant was told the objective of the task and to complete the task as quickly and as accurately as they could. After each trial, a screen appeared with instructions to continue when ready allowing them to rest before the next trial began to reduce fatigue. Participants could not ask questions during this session unless they concerned the need to rest or to discontinue the task. After each of five trials, the participant completed the TLX workload assessment, Self-Perception of Accuracy, Ease of Use, and User Comfort questionnaires.

3.4.3 Post-Experimental Procedure

After the testing session had been completed, the participants completed the Ease of Learning questionnaire. The participants were verbally given a short open-ended questionnaire, debriefed and thanked for their participation. The experiment took approximately one hour and ten minutes to complete.

Table 2: Pre-Experimental measures for selection methods: Hand-on-Corners (HOC), Hand-in-Middle (HIM), and Two-Corners (TC).

Pre-Experimental Measure	TC M (SD)	HOC M (SD)	HIM M (SD)
Spatial Ability Score	**11.63 (9.13)**	**13.91 (10.35)**	**14.66 (12.20)**
Computer Usage in 2D	**4.19 (1.09)**	**4.43 (1.08)**	**4.11 (1.12)**
Computer Usage in 3D	**2.02 (1.28)**	**2.07 (1.28)**	**2.33 (1.13)**

4 RESULTS

A 3 x 4 mixed analysis of variance (ANOVA) was used on each measure to test for the main and interaction effects of selection method and task. The F tests that are reported use $\alpha=0.05$ for significance and include the Geisser-Greenhouse correction to protect against possible violation of the homogeneity assumption.

4.1 Participants

A total of 60 University students (20 females, 40 males, mean age= 22.08, SD= 5.24) participated in the study. Of these students, 57 were right-handed (53 strongly right-handed, 4 moderately right-handed, 0 weakly right-handed), 3 were left-handed (2 strongly left-handed, 0 moderately left-handed, 1 weakly left-handed). Volunteers were recruited from the psychology department subject pool and undergraduate computer science courses. All received credit points towards their class grade.

4.2 Pre-Experimental

The Pre-Experimental measures were used to identify if there were any confounding factors affecting the results between the different selection conditions. None were evident as the results of one-way ANOVAs showed that there were no significant differences between participants that were grouped by selection method, for gender, spatial ability, computer usage in 2D, or computer usage in 3D, with each *F*<1 (Table 2). Handedness was controlled by using each participant's handedness score to determine which tasks were assigned to the non-dominant and dominant hands.

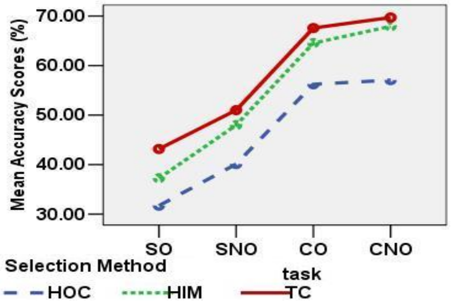


Figure 8: Accuracy scores for selection methods across task type: see figure 3 for task description

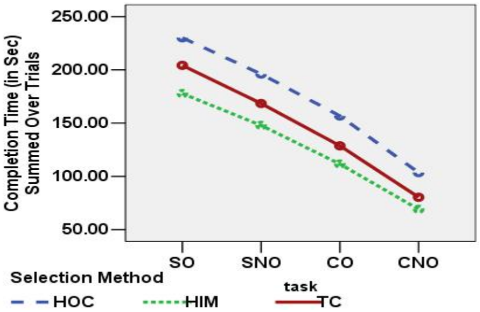


Figure 9: Completion Times (in Seconds) summed over trials for each task: see figure 3 for task descriptions.

4.3 Effects

4.3.1 Accuracy Performance on Selection

Mean accuracy scores for each task computed within each of the experimental conditions are presented in Figure 8. The ANOVA on these data showed a strong main effect of selection methods $F(2,57) = 3.22$, $p=0.05$, $\eta^2 = 0.93$.

The accuracy scores for the selection techniques ranged from highest to lowest: TC (M=57.86, SD=3.32), HIM (M=54.42, SD=3.32) and HOC (M=46.28, SD=3.32). A post-hoc test (least significant difference with $\alpha=0.05$ level for significance) indicated that TC was more accurate than HOC but was not significantly higher than the HIM technique. The two asymmetrical techniques (HOC and HIM) were not found to differ.

Accuracy was also found to be strongly effected by task conditions, $F(2.59, 147.68) = 71.96$, $p<0.01$, $\eta^2 = 0.75$ with difficulty of the task ranging from most difficult to easiest: SO (M=37.36, SD=1.99), SNO (M=46.36, SD=2.24), CO (M=62.78, SD=2.75), and CNO (M=64.90, SD=2.34). To interpret this result, post-hoc contrasts tests were performed. There was a significant difference $F(2,57)= 12.70$, p<0.01 in comparing occluded to non-occluded tasks. There also was a significant difference $F(2,57)= 198.31$, p<0.01 in comparing sparse to clustered tasks. However, selection techniques did not interact with task conditions, *F*<1.

The ANOVA results for self-perception of accuracy further confirmed the strong main effect of selection methods among task type $F(3, 171) = 14.03$, $p<0.01$, $\eta^2 = 0.20$. Participants perceived a higher performance when using the TC symmetric technique than when using the HOC asymmetric technique. There was no significant difference between the two asymmetric techniques (HOC and HIM). Selection technique did not interact with task type, *F*<1, nor was there a main effect for task type, *F*<1.

4.3.2 Selection Completion Times

A one-way ANOVA determined no significant differences in overall completion time *F*<1, possibly due to a large variability between task type. Due to a technical error, task completion time data per trial per task type was only collected for 7 participants in HOC, 9 in HIM, and 20 in TC. As a result, we could not conduct a complete analysis on these data. Consider that the following partial analysis reveals trends only. In comparing the total completion times per task (Figure 9), individual completion times per trial summed for each task, there was a significant main effect due to selection method by task type $F(1.15,38.09)=256.83$, $p<0.01$, $\eta^2=1.00$ and no interaction effect of task type, *F*<1. Total completion times per task in seconds ranged from lowest to highest: HIM (M=126.54, SD=12.77), TC (M=145.42, SD=8.56), and HOC (M=171.59, SD=14.48). In assessing the average completion times per task, there were no significant main or interaction effects, *F*<1. Average completion times in seconds ranged from lowest to highest: HIM (M=25.31, SD=2.55), TC (M=29.08, SD=1.71), and HOC (M=34.32, SD=2.89).

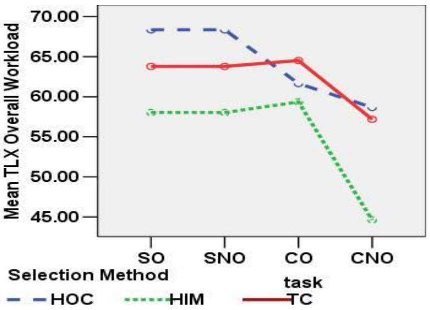


Figure 10: TLX overall workload for selection methods across task type: see figure 3 for task descriptions.

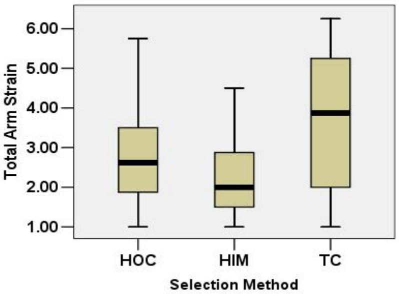


Figure 11: Arm strain measures for selection methods: Hand-on-Corners (HOC), Hand-in-Middle (HIM), and Two-Corners (TC).

4.3.3 Overall Workload

An ANOVA testing for TLX overall workload showed a main effect of task type $F(3,168)=9.36$, $p<0.01$, $\eta^2=0.14$. These measures range from highest to lowest, while matching the difficulty of the task ranging from most difficult to easiest: SO (M=63.39, SD=1.85), SNO (M=63.39, SD=1.85), CO (M=61.84, SD=2.03), and CNO (M=53.49, SD=2.31). There was also a significant main effect due to selection methods $F(2,56)=3.49$, $p=0.05$, $\eta^2 = 0.11$ (Figure 10). To interpret the main effect due to selection method, LSD post-hoc test (with $\alpha=0.05$ level for significance) indicated that TLX overall workload measures with HOC and TC selection techniques were significantly higher than with HIM technique. The interaction effect of selection method by task type was not significant, $F<1$. The mental demand dimension of the TLX workload assessment for difficult tasks, grouping SO and SNO, and easy tasks, grouping CO and CNO, were analyzed. An ANOVA revealed a strong main effect among selection methods $F(1,56)= 204.28$, $p<0.01$, $\eta^2 = 0.79$. The mental demand was the highest when HOC was used in both hard tasks (M= 16.49, SD=9.01) and easy tasks (M=13.96, SD=8.53). When HIM was used, ratings fell between the other two methods for both hard (M=15.02, SD=9.27) and easy tasks (M=12.86, SD=7.06). The mental demand was lowest for TC for both hard (M=11.32, SD=9.18) and easy (M=12.23, SD=8.53) tasks.

4.3.4 Arm, Hand, and Eye Strain

Arm, hand, and eye strain, each one item on the user comfort questionnaire, were averaged for each trial per task. An ANOVA testing arm strain found a main effect for task type, $F(3,171) = 3.24$, $p=0.02$, $\eta^2 = 0.05$. Arm strain measures ranged from highest to lowest: CO (M=3.07, SD=0.25), SO (M=2.88, SD=0.23), SNO (M=2.85, SD=0.25), and CNO (M=2.30, SD=0.18). There was also a significant interaction effect of task by selection methods $F(6, 171) = 3.18$, $p= 0.01$, $\eta^2 = 0.10$. There was a main effect due to selection methods $F(1,57) = 3.70$, $p=0.03$, $\eta^2 = 0.12$ (Figure 11). To interpret the result, LSD post-hoc test with $\alpha=0.05$ level for significance was used. When the TC was used, arm strain was significantly higher than HIM and was not significantly higher than HOC. There were no significant differences for task type or selection method in hand or eye strain measures, $F<1$.

4.3.5 User Comfort, Ease of Use, and Ease of Learning

An ANOVA showed an interaction effect for user comfort of task type by the selection methods, $F(6, 171) = 3.20$, $p= 0.003$, $\eta^2 = 0.11$. Overall comfort ranged in the same order from highest to lowest in the most difficult task SO as HIM (M=5.57, SD= 1.02), TC (M=4.75, SD=1.26), and HOC (M=4.51, SD=1.48) and the easiest task CNO as HIM (M=5.32, SD=1.23), TC (M=5.25, SD= 1.10), and HOC (M=4.34, SD=1.33). There was no significant main effect due to task type or selection methods, $F<1$. An ANOVA analyzing ease of use revealed a significant interaction effect, $F(6, 171) = 2.30$, $p= 0.04$, $\eta^2 =0.08$. There was no main effect due to task type or selection methods, $F<1$. Comfort and ease of use were significantly correlated, $r=0.60$, $p<0.01$.

A one-way ANOVA tested the ease of learning measure and found no difference by selection method $F<1$. However, the ease of learning measures were above average (with average being 3.5) for all the selection techniques HOC (M= 4.45, SD= 1.28), HIM (M= 4.88, SD= 1.04), and TC (M= 4.79, SD= 0.83).

4.3.6 Debriefing Trends

For all techniques, participants reported frustration and that the locks were little or never used. Participants generally reported:

- (liked) “using both hands”, “had fun”
- “need more depth cues”
- “stressful at first, later got more easy, more natural”

Participants using the TC technique commonly reported arm strain, but liked the way they performed selection:

- “frustrated because couldn’t get box around blob, tried to look at background”
- “arms felt heavy”, “discomfort in arm”
- “easy to use”, “easy to navigate”, “felt natural”

Participants using the HIM technique commonly reported:

- (liked) “the fact that you could manipulate it in how you wanted to select the area”
- “easy to control”, “easy to get used to”, “felt normal”

Participants using the HOC technique commonly reported:

- “too many buttons”, “too many ways to hold”
- “ too complicated”, “felt unnecessarily hard”
- “mentally challenging”

The majority of participants reported that sufficient instructions and training time were given, while commenting on that they could have used more practice.

5 DISCUSSION AND CONCLUSION

The results on accuracy data suggest that TC (Refer to Table 1) significantly out performs HOC for all conditions: sparse, dense, occluded, not occluded. Results suggest that when the task is easy, accuracy ratings increase, and as the task becomes more difficult, the ratings decrease. The selection methods that are more mentally and physically demanding caused a reduction in task accuracy. This was similar to a result found by Owen et al in comparing one-handed to two-handed methods [25]. The results on time completion data suggest that if more participants’ data were collected, HIM technique performs tasks quickest, with TC and HOC following respectively. As more selections are made, the difference in total completion time grows between the methods. Also, as difficulty in task increases, completion time increases.

In the case of TLX workload assessment, HIM had significantly lower ratings than TC and HOC. HIM arm strain ratings were significantly lower than TC, with no significant difference between HOC and the other two methods. These results imply that since TC always requires the use of both hands, it causes more arm strain than methods which divide the labor of the hands that allow one hand to rest. Further investigation is required to assess what caused the arm strain and workload differences between the two asymmetrical techniques, as they differed in control point and scale procedure. Arm strain increases when selecting splats with occlusion and decreases without occlusion.

Difficultly of task did not effect overall comfort as in both easy and difficult tasks, HIM was the most comfortable, with TC and HOC following respectively. The ease of use ratings had a similar difference. According to participants in debriefing, HIM felt more comfortable and natural, and HOC was perceived to be the most complicated to use. In reflection of completion time results, to reduce time in selection design selection techniques to be more comfortable and require less physical and mental strain.

Participants did not have difficulty learning how to use our three selection techniques as found in the analysis of the ease of learning measure and debriefing. In other studies participants found the same device easy to use within 5-10 minutes [5][9].

We divided the tasks among the dominant and non-dominant following Guiard’s Bimanual Framework, with the assumption that the position and orientation of the selection box set the frame of reference for the selection tool. However, poor accuracy results may be a result of how the tasks were divided and requires further investigation. Comfort and fatigue ratings could have decreased for the symmetric technique had we integrated a way for the user to rest one hand. Future designers should consider these factors.

In conclusion, we found that the TC symmetric technique performs selection with the most accuracy. However, TC symmetric technique produced a statistically significant amount of arm strain as compared to the two asymmetric techniques (HOC and HIM). The HOC asymmetric technique was the least accurate, the most cognitively demanding, and slightly less physically demanding than TC. The HIM asymmetric technique was the least physically and cognitively demanding, and the most comfortable. Both asymmetric techniques (HOC and HIM) were the least accurate for selection. Therefore, when performing tasks that require long hours and gross selection, HIM asymmetrical technique is the best to use. This technique is also well suited for highly physically and mentally demanding tasks. However, TC symmetrical technique is the best technique to use if precise accuracy is required and if the time on task is relatively short (less than one hour). For longer tasks arm strain becomes an issue.

6 FUTURE WORK

Since a symmetric synchronous technique was most accurate, but an asymmetric technique was more comfortable, fastest, and least physically and mentally strenuous, we plan to integrate the best attributes of both, as a symmetric asynchronous technique, for best performance in all categories. A within subjects experiment comparing it with other techniques will gain users' preferences. We will further investigate how well these techniques perform in a stereo-view, or with other depth cues, and with large-scale data. We will develop more techniques, which use free-form selection volumes or change the division of tasks among the dominant and non-dominant hand, to reduce fatigue and increase accuracy. We plan to exploit characteristics of these selection methods to define a taxonomy for volumetric data selection, as well as explore travel and manipulation. These methods will be integrated in a weather visualization application that renders data using the splat-based technique.

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REFERENCES

[1] E. Bier, M. Stone, K. Pier, B. Buxton, and T. DeRose. Toolglass and magic lenses: The see-through interface. In *SIGGRAPH'93*, ACM Press, pages 73-80, 1993.

[2] D. A. Bowman, and L. F. Hodges. An Evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments. In *Symposium on Interactive 3D Graphics*. ACM. pages 35-38, 1997.

[3] D. A. Bowman, E. Kruijff, J. J. LaViola, and I. Poupyrev. *3D User Interfaces, Theory and Practice*. Addison-Wesley, 2005.

[4] W. Buxton, and B. Myers. 1986. A study in two-handed input. In *CHI '86,* ACM Press, pages 321-326, April, 1986.

[5] S. Coren. *The Left-Hander Syndrome: The Causes and Consequences of Left-Handedness*. Vintage Books 1993.

[6] L. D. Cutler, B. Fröhlich, and P. Hanrahan. Two-handed direct manipulation on the responsive workbench. In *Symposium on interactive 3D Graphics (SI3D'97),* ACM Press, pages 107-114, April, 1997.

[7] D. S. Ebert, C. Shaw, A. Zwa, E. L. Miller, and D. A. Roberts. Minimally-immersive Interactive Volumetric Information Visualization. In *IEEE Symposium on Information Visualization*. October, 1996.

[8] A. Forsberg, K. Herndon, and R. Zeleznik. Aperture based selection for immersive virtual environment. In *of UIST'96*, pages 95–96, 1996.

[9] B. Fröhlich and J. Plate, J., Wind, G. Wesche, and M. Göbel, Cubic-Mouse-Based Interaction in Virtual Environments. *IEEE Computer Graphics Applications 20*, 4, pages 12-15, July 2000.

[10] M. W. Gribnau, and J. M. Hennessey. Comparing single- and two-handed 3D input for a 3D object assembly task. In *CHI'98*. ACM Press, 1998.

[11] T. Grossman, and R. Balakrishnan, The design and evaluation of selection techniques for 3D volumetric displays. In *UIST '06*. ACM Press, pages 3-12, October 2006.

[12] T. Grossman, D. Wigdor, and R. Balakrishnan. Multi-finger gestural interaction with 3d volumetric displays, In *UIST '04*, ACM Press, pages 61-70, October 2004.

[13] J.P. Guilford, W.S. Zimmerman. The Guilford-Zimmerman Aptitude Survey. *Journal of Applied Psychology, 32*, pages 24-34, 1948.

[14] Yves Guiard. Asymmetric division of labor in human skilled bimanual action: The kinematic chain as a model. *In Journal of Motor Behaviour, 19*, pages 486–517, 1997.

[15] S. G. Hart, L. E. Staveland, Development of the NASA-tlx (Task Load Index): Results of empirical and theoretical research. In P. A. Hancock, N. Meshkati, Eds., *Human Mental Workload*. Elsevier, pages 139-183,1988.

[16] K. Hinckley. Passive Real-World Interface Props for Neurosurgical Visualization. In *CHI' 94*. ACM Press, pages 452-458, April, 1994.

[17] K. Hinckley, R. Pausch, and D. Proffitt. Attention and visual feedback: The bimanual frame of reference. In *SIGGRAPH' 97,* August, 1997.

[18] J. Jang, W. Ribarsky, C. Shaw, and N. Faust. View-dependent multiresolution splatting of non-uniform data. In *Symposium on Data Visualization*. pages 125-ff, 2002.

[19] D. Laur and P. Hanrahan. Heirarchical aplatting: A progressive refinement algorithm for volume rendering. In *SIGGRAPG'91*, pages 285-288, 1991.

[20] C. Latulipe. Symmetric Interaction in the User Interface. In *UIST '04,* 2004.

[21] C. Latulipe, S. Mann, C. S. Kaplan, and C. L. Clarke. symSpline: symmetric two-handed spline manipulation. In *CHI' 06*, ACM Press, April, 2006.

[22] I. Llamas, A. Powell, J. Rossignac, and C. Shaw. Bender: A Virtual Ribbon for Deforming 3D Shapes in Biomedical and Styling Applications. In *Symposium on Solid and Physical Modeling*. pages 89-99, 2005.

[23] J. Meredith, and Lwan-Liu Ma. Multiresolution view-dependent splat based volume rendering of large irregular data. In *IEEE Parallel and Large-Data Visualization and Graphics,* pages 93-155, 2001.

[24] A. Olwal and S. Feiner. The flexible pointer- An interaction technique for selection in augmented and virtual reality, In *UIST'03*, pages 81-82, 2003.

[25] R. Owen, R. Kurtenbach., G. Fitzmaurice, T. Baudel, and B. Buxton, When it gets more difficult, use both hands: exploring bimanual curve manipulation. In *Graphics Interface*, pages 17-24, 2005.

[26] J. Pierce, B. Stearns, and R. Pausch. Voodoo Dolls: seamless interaction at multiple scales in virtual environments. In *3DUI'99*, April, 1999.

[27] I. Poupyrev, M. Billinghurst, S. Weghorst, and T. Ichikawa. The go-go interaction technique: non-linear mapping for direct manipulation in vr. In *UIST '96*, 1996.

[28] A. Steed. Towards a general model for selection in virtual environments. In *3DUI'06*, pages 59-61, March 2006.

[29] S. Veigl, A. Kaltenbach, F. Ledermann, G. Reitmayr, D. Schmalstieg, "Two-Handed Direct Interaction with ARToolKit", In *First IEEE International Workshop on ARToolKit (ART02)*, IEEE, September, 2002.

[30] H. P. Wyss, R. Blach, and M. Bues. iSith- Interaction-based spatial interaction for two hands. In *3DUI'06,* pages 59-61, March 2006.

[31] K. Yee. Two-handed interaction on a tablet display. In *CHI '04*. ACM Press, pages 1493-1496, April, 2004.

[32] R. C. Zeleznik, A. S. Forsberg, and P.S. Strauss, Two pointer input for 3D interaction. In *Symposium on interactive 3D Graphics (SI3D'97)*. ACM Press, pages 115-ff, 1997.