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Selection Performance Based on Classes of Bimanual Actions

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ABSTRACT

We evaluated four selection techniques for volumetric data based on the four classes of bimanual action: symmetric-synchronous, asymmetric-synchronous, symmetric-asynchronous, and asymmetric-asynchronous. The purpose of this study was to determine the relative performance characteristics of each of these classes. In addition, we compared two types of data representations to determine whether these selection techniques were suitable for interaction in different environments. The techniques were evaluated in terms of accuracy, completion times, TLX overall workload, TLX physical demand, and TLX cognitive demand.

Our results suggest that symmetric and synchronous selection strategies both contribute to faster task completion. Our results also indicate that no class of bimanual selection was a significant contributor to reducing or increasing physical demand, while asynchronous action significantly increased cognitive demand in asymmetric techniques and decreased ease of use in symmetric techniques. However, for users with greater computer usage experience, accuracy performance differences diminished between the classes of bimanual action. No significant differences were found between the two types of data representations.

KEYWORDS: 3D selection, bimanual interaction, volumetric data, splat-based rendering, polygonal objects, visualization.

INDEX TERMS: I.3.6.[Interaction Techniques]:Methodology and Techniques; H.5.2.[Evaluation, Interaction Styles]:User Interfaces; H.3.3.[Selection Process]:Information Search and Retrieval.

1 INTRODUCTION

Interacting in three dimensions (3D) can be difficult due to the added third degree of freedom. It has been shown that bimanual interaction techniques can improve interaction in 3D over one-handed interaction techniques [4][8][17][18][20][22]. According to Guiard's framework of Bimanual manipulation, there exist different classes of bimanual actions [10]. The Bimanual symmetric classification involves each hand performing identical actions either synchronously (at the same time) or asynchronously (at different times). The Bimanual asymmetric classification consists of both hands performing different, but coordinated, actions to accomplish the same task [13]. Asymmetric actions can be performed synchronously or asynchronously as well. Therefore, four distinct classes of bimanual actions exist:

- Symmetric-Synchronous
- Symmetric-Asynchronous
- Asymmetric-Synchronous
- Asymmetric-Asynchronous

It is important to understand the advantages, disadvantages and relative performance characteristics of each of these classes in order to provide specific guidelines to designers and developers as to which class of bimanual interaction is appropriate to their design goals.

Although there has been previous work on bimanual interaction techniques [2], there is still a need to determine relative performance characteristics of these four classes. Research so far has also been limited to interaction with polygonal objects. Due to the differences in the properties of different data representations, these results may not generalize to other types of data, such as volumetric data used in many visualization applications. This study focuses on evaluating four selection techniques for volumetric data based on the four classes of bimanual action. The purpose is not necessarily to promote the use of one class of interaction or data representation in a system over the others, but rather to quantify the distinct performance characteristics of each. This information is useful to developers when making design decisions for new interaction techniques in the context of their application goals.

In addition, this study compares two different types of data representations: polygonal spheres and volumetric splats. Polygonal spheres are rendered as opaque, shaded objects with a well-defined volumetric bound. Splats are rendered as transparent, filled circles on a view-aligned plane simulating a three-dimensional cloud. In comparing these two data representations, this paper will also provide preliminary data on the interaction between selection techniques and data representation.

2 RELATED WORK

Several bimanual interaction techniques have been developed and evaluated. A two-handed system was developed using two 3 degrees of freedom (DOF) trackers to harness user's proprioceptive sense of 3D space and was found to be easy to use [5]. Zeleznik et al. explored bimanual techniques using two independent cursors to control camera navigation in 3D desktop applications [31]. 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 [5]. 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 [29]. Grossman et al. explored 3D selection techniques for volumetric displays by conducting several experiments [9]. 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 that 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. In this study, the authors evaluated single targets and not region selection. Our

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study focused more on a task that required the selection of regions.

Shaw evaluated a two-handed free form surface editor using a two-handed interaction style with 3 DOF trackers, called THRED, a two-handed interface using a keyboard and mouse, and a one-handed interface [25]. Shaw found that using a one-handed interface produced significantly more pain and fatigue than THRED. Our evaluation is different in that we are comparing four two-handed interaction styles with each hand holding the same 3 DOF tracker. Three bimanual selection techniques were designed and evaluated for 3D volumetric data [27]. It was shown that a asymmetric-synchronous selection technique was best used when performing gross selection for potentially long periods of time and for cognitively demanding tasks. However when optimum accuracy is needed, a bimanual symmetric-synchronous technique was best for selection. Though similar, our evaluation is different from this related work in that in that we specifically outline and evaluate four bimanual selection techniques, as opposed to three. The selection techniques we evaluated were based on the distinct bimanual classes of actions to determine what performance factors are credited by which classes of actions. Although the other study based their design of the selection techniques on Guiard's framework of bimanual action, these techniques were not developed such that interaction was completely restricted to the actions of each of the four bimanual classes. It is important to evaluate each distinct class in order to determine which properties of each class are affecting performance metrics. In addition, we evaluated the techniques using two different data representations for the target objects, as opposed to one. This evaluation is important to make sure that the performance results of interaction techniques are similar across multiple data representations.

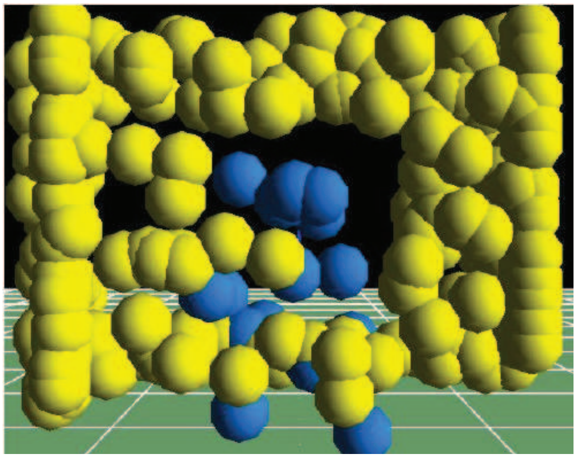

Figure 1. Polygonal Spheres Object Representations

3 EXPERIMENTAL DESIGN

A 4 x 2 mixed experimental design was used for this evaluation. We evaluated four two-handed selection techniques for interaction with volumetric data using a between-subjects study design. Each technique represented a unique combination of interaction between the hands with regard to symmetry and synchronicity. Participants were assigned to one of four conditions: symmetric-synchronous (SS), asymmetric-synchronous (AS), symmetric-asynchronous (SA), or asymmetric-asynchronous (AS). The task was to select a marked region of volumetric data. We also evaluated two types of target object representations for the volumetric data using a within-subjects study design. Objects were rendered either as opaque, polygonal spheres (Figure 1) or as transparent, volumetric splat-based representations (Figure 2). Participants were given each set of objects separately. Color differentiated the regions for selection from other regions. The techniques were evaluated in terms of accuracy, completion times, and workload levels.

For this evaluation, we hypothesized that asynchronous techniques would significantly reduce fatigue for selection techniques. We hypothesized that if we coupled asynchronous interaction with symmetric interaction, the symmetric-asynchronous technique would be significantly more accurate and allow significantly faster completion times than either asymmetric technique. In addition, we hypothesized that target object representations using polygonal spheres would allow for significantly more accurate selection for all techniques when compared to the splat-based representations.

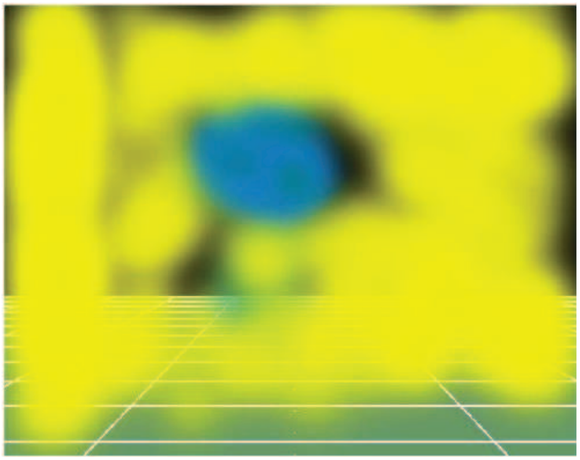

Figure 2. Splat-based Rendered Object Representations

3.1 Apparatus

The 3D input devices consisted of two Polhemus FastTrak magnetic trackers with 6 degrees-of-freedom (DOF), encased in plastic with three joystick buttons attached to each. One tracker was held in each hand (Figure 3). The evaluation was performed on a Dell Precision 380 with an Intel Pentium 4.40 GHz processor. The graphics card was a Quadro FX 4500 with 512 MB memory. Though the evaluation was run using mono-view, we used a NuVision 21MX-SL stereoscopic monitor by MacNaughton, Inc for the evaluation, with a resolution of 1280x1024.

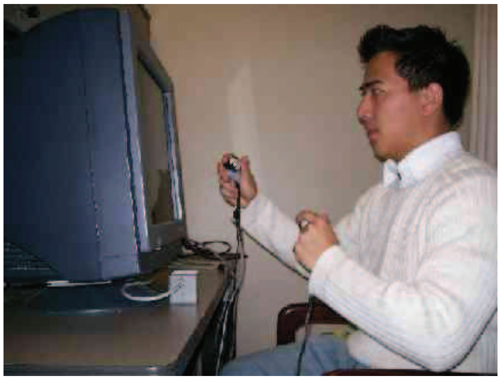

Figure 3. Experimental Setup

3.2 Region for Selection

The Simple Virtual Environment (SVE) toolkit and OpenGL were used to render the testing environment with a 1280 x 1024 display resolution at an average frame rate of approximately 60. For each trial, a set of 3D objects were displayed on the screen. Blue objects marked the region to be selected, while yellow objects marked the region that was not to be selected. Color of the objects changed when a region was selected: blue objects changed to red and yellow objects changed to green. Feedback was also given for button functionality. Three spheres were displayed on the left and right side of the screen corresponding to the buttons on the left and right controller (Figures 4 and 5). The buttons were labeled with the corresponding functionality and changed in color when pressed.

3.3 Selection Techniques

All selection techniques used a volumetric box for selection. All objects within the box were selected. For all techniques, the left and right hands held the box from opposite corners. The dominant held the box from the upper back corner on the dominate side. The non-dominant hand held the box from the lower front corner on the non-dominant side. The user's view of the environment was fixed for all selection techniques. This is an additional property of interaction and should be evaluated separately as it may induce confounds for this particular study.

3.3.1 Symmetric-Synchronous Technique

When using the symmetric-synchronous (SS) selection technique, the bottom two button on each controller for each hand were disabled and colored grey on the screen (Figure 5). The position of the box was changed by changing the positions of both hands at the same time. The orientation of the box was changed by rotating the hands around each other at the same time. Position and orientation of the box were controlled at the same time. The scale of the box was changed by holding the outer "scale" button and moving the hands apart from or closer to each other. When this button was released, changing scale was disabled. Position and orientation could still be controlled while modifying scale.

3.3.2 Asymmetric-Synchronous Technique

When using the asymmetric-synchronous (AS) selection technique, the bottom two buttons on each controller were disabled and colored grey on the screen (Figure 5). The position of the box was changed by changing the position of the non-dominant hand. The orientation of the box was changed by rotating the non-dominant hand. Position and orientation of the box were controlled at the same time. The scale of the box was changed by holding the outer "scale" button and moving the dominate hand. When this button was released, changing scale was disabled. Position and orientation could still be controlled while modifying scale.

3.3.3 Symmetric-Asynchronous Technique

When using the symmetric-asynchronous (SA) selection technique, the bottom two buttons on each controller were enabled on the screen (Figure 4). The left and right controllers were not permitted to be used at the same time. To switch control from the left to the right hand, the bottom right button was pressed, and the feedback label on the right changed to "on" while the one on the left changed to "off". To switch control from the right to left hand, the bottom left button was pressed, and the feedback label on the left changed to "on" while the one on the right changed to "off". The position of the box was changed by changing the positions of both hands one at a time. The orientation of the box was changed by rotating the hands around each other one at a time. Position and orientation of the box were controlled at the same time. The scale of the box was changed by holding the outer "scale" button and moving each hand, one at a time, apart from or closer to each other. When this button was released, changing scale was disabled. Position and orientation could still be controlled while modifying scale.

3.3.4 Asymmetric-Asynchronous Technique

When using the asymmetric-asynchronous (AA) selection technique, the bottom two buttons on each controller were enabled on the screen (Figure 4). The left and right controllers were not permitted to be used at the same time. To switch control from the left to the right hand, the bottom right button was pressed, and the feedback label on the right changed to "on" while the one on the left changed to "off". To switch control from the right to left hand, the bottom left button was pressed, and the feedback label on the left changed to "on" while the one on the right changed to "off". The position of the box was changed by changing the position of the non-dominant hand. The orientation of the box was changed by rotating the non-dominant hand. Position and orientation of the box were controlled at the same time. The scale of the box was changed by holding the outer "scale" button and moving the dominant hand. Since the dominant and non-dominant hand could not be used at the same time position and orientation could not be controlled while modifying scale.

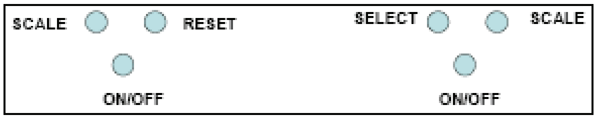

Figure 4. Button Setup for Asynchronous Selection Techniques

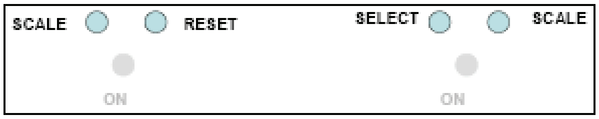

Figure 5. Button Setup for Synchronous Selection Techniques.

3.4 Measures

3.4.1 Pre-Experimental Measures

Demographic information was collected, such as age, gender, ethnicity, occupational status, major, colorblindness, sight, and device usage. Computer usage information was collected by a survey of eight questions 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)?'

Spatial orientation ability was determined by the Guilford-Zimmerman (GZ) Aptitude Survey Part 5: Spatial Orientation [11]. Spatial Orientation is the ability to perceive of the arrangements of visual information in space. Each item shows two images. The task is to select between a number of simple abstract symbols that match the view change from a pair of images. A 10 minute time limit ensures that all 60 items cannot be attempted.

3.4.2 Performance Measures

Selection accuracy scores, completion times, and tracker data were automatically logged for each trial. Accuracy was determined by the ratio of the amount of objects that were selected indicated for selection and to the amount of objects that were selected that were not indicated for selection. Means for accuracy scores and task completion times for each task were computed from each participant across all trials within each of the experimental conditions.

Workload was determined by the TLX workload Assessment questionnaire [12]. It is based on mental, physical and temporal demand, own performance, frustration, and effort. For each condition examined within subjects, 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 answer questions on a three questionnaires: self-perception of accuracy, ease of use, and user comfort. Each contained eight to ten items, for each within subjects' condition. These determined how well they thought they performed the task, how easy the system was to use, and how comfortable or fatigued they were when using the system.

3.4.3 Post-Experimental Measures

Ease of learning was determined by an eight-item questionnaire using a 7-point Likert scale (1=disagree completely, 7= agree completely) to rate how easy it was to learn to use the system. A qualitative open-ended questionnaire was given to debrief and interview participants about fatigue, ease of use, frequency of switching control to each hand (applicable only for asynchronous techniques), and other issues.

3.5 Experimental Procedures

Participants began by signing a consent form and completing all pre-experimental measures. The participants were then given instructions on how to hold and use the device. They were then guided through three sample trials along with instruction for their task. The number of practice trials was determined by a pilot study that found that performance of all of the selection techniques continued to increase until leveling off at the thirteenth trial, thereby indicating training was complete. Participants were asked to complete 13 additional practice trials and were permitted to ask questions during that time. Participants were then given two testing sessions with performance measures for each. Each testing session consisted of completing 28 selection trials for either type of object representation. Participants were given the option to rest after each trial. The order of which type they received first was balanced so not to introduce ordering confounds. Participants responded on performance questionnaires after each session. After the second session, participants were given post-experimental questionnaires and thanked for their time.

4 RESULTS

A 4 x 2 mixed multivariate analysis of variance (MANOVA) was used to test for the main and interaction effects of selection method and data representation. Data Representation was grouped into training session, testing session of polygonal spheres, and testing session of splat-based rendered objects. The F tests that are reported use $\alpha=0.05$ for significance. The post-hoc tests that were conducted were least significant difference (LSD) tests with $\alpha=0.05$ level for significance.

4.1 Participants

A total of 80 University students (17 females, 63 males, mean age= 22.08, SD= 6.01) participated in the study. All students were right-handed. Volunteers were recruited from the psychology department subject pool, and undergraduate and graduate computer science courses. All received credit points towards their class grade. Other volunteers that were recruited by word of mouth did not receive any compensation. The majors of 60 participants were some form of computing degree, while the majors of the other 20 were other degrees or undeclared. This might be one indication of higher computer usage and may lead to increased accuracy and completion time performance over all selection methods.

Table 1: Pre-experimental measures grouped by selection techniques: Symmetric-Synchronous (SS), Asymmetric-Synchronous (AS), Symmetric-Asynchronous (SA), and Asymmetric-Asynchronous (AA).

Pre-Experimental Measure	**SS M (SD)**	**AS M (SD)**	**SA M (SD)**	**AA M (SD)**
Spatial Ability Score (%)	**9.80 (5.90)**	**12.48 (5.91)**	**11.85 (6.49)**	**11.97 (7.40)**
Computer Usage in 2D	**4.95 (1.42)**	**4.45 (1.26)**	**4.60 (1.21)**	**4.55 (1.13)**
Computer Usage in 3D	**3.52 (1.43)**	**3.35 (1.61)**	**3.18 (1.53)**	**3.24 (1.34)**

4.2 Pre-Experimental Results

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, spatial ability, computer usage in 2D, or computer usage in 3D, with each F<1 (Table 1). It is however important to note that computer usage ratings overall groups in 2D (M=4.64, SD= 1.25) and 3D (M=3.32, SD= 1.46) were above average.

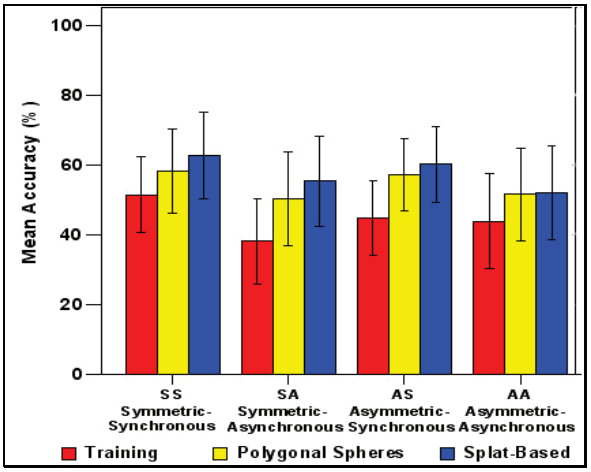

Figure 6. Mean Accuracy Scores by Selection Techniques and Data Representation

4.3 Accuracy and Completion Times Results

Mean accuracy and mean selection completion times were computed within each of the experimental conditions and averaged over all trials for each participant. Accuracy scores were measured as a percentage while selection completion times were measured in seconds. Although total accuracy scores and completion times were not significantly correlated r(240)= 0.12, p=0.07, correlation existed for accuracy scores and completion times grouped by data representation. The total accuracy scores and selection completion times were moderately correlated in the training session r(80) = 0.39, p<0.001, slightly correlated in the splats testing session r(80)= 0.22 p=0.05, and not significantly correlated in the spheres testing session r(80)= 0.16, p=0.16. The MANOVA revealed a significant main effect of selection methods F(6,456)=6.76, p<0.001, η2 = 0.08 and a significant main effect of data representation F(4, 456)=27.70, p<0.001, η2=0.19 (Figures 6 and 7).

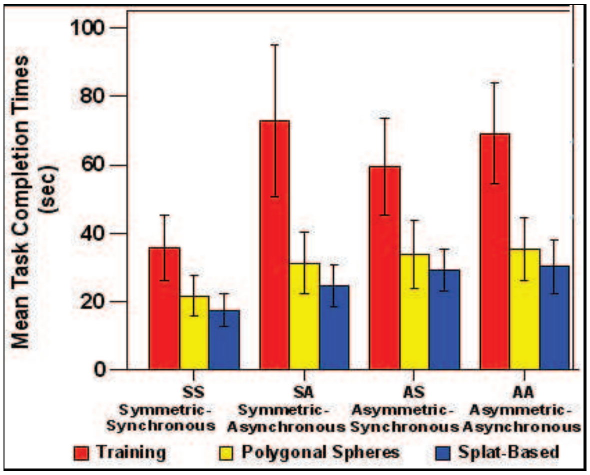

Figure 7. Mean Completion Times by Selection Techniques and Data Representation

4.3.1 Differences in Selection Techniques

The follow-up univariate tests for selection methods showed a significant main effect of selection methods on completion times F(3, 228) = 8.96, p<0.001, η2 = 0.11 (Figure 7) but not for accuracy scores F(3,228)= 1.71, p =1.67 (Figure 6). A LSD post-hoc test indicated that SS (M= 24.92 ,SD= 12.91) allowed for significantly faster selection completion times than AS (M= 40.77, SD= 26.04), SA (M= 42.88, SD= 28.91), and AA (M= 49.22, SD= 28.49).

4.3.2 Differences in Data Representation

The follow-up univariate tests for data representation showed a significant main effect for completion times F(2, 228)= 5.385, p= 0.005, η2 = 0.05 (Figure 7) and a significant main effect for accuracy scores F(2,228)= 48.22, p <0.001 (Figure 6). A LSD post-hoc test indicated that accuracy significantly increased from training (M= 44.60, SD= 25.47) to testing of splats data representation (M= 57.62, SD= 26.44) and to testing of spheres data representation (M=54.40, SD= 25.97). There was no significant difference in accuracy scores between the two testing sessions. A LSD post-hoc test also indicated that selection completion times significantly decreased from training (M= 59.32, SD= 36.19) to testing of splats data representation (M= 25.33, SD= 14.19) and to testing of spheres data representation (M= 30.46, SD= 19.04). There was no significant difference in completion times between the two testing sessions.

4.4 TLX Overall Workload

TLX Overall workload, TLX Cognitive Demand, and TLX Physical Demand measures were independently averaged for each participant across testing sessions.

4.4.1 Differences in Selection Techniques

A one-way ANOVA revealed a significant difference in TLX overall workload for selection methods F(3,159)= 3.43, p= 0.02 (Figure 8). A LSD post-hoc test indicated that the SS technique (M= 59.03, SD= 14.96) caused significantly less overall workload than the AS technique (M= 66.48, SD= 15.57) and the AA technique (M= 68.54, SD= 10.46). Overall workload ratings were not significantly different between any of the other techniques. TLX cognitive demand is one measure that composes the TLX workload survey. A one-way ANOVA found that there is a significant difference among selection methods for TLX cognitive demand F(3,159)= 3.17, p =0.03 (Figure 9). A LSD post-hoc test indicated that the SS technique caused significantly less cognitive demand (M= 53.50 SD= 23.46) than the AA technique (M= 68.13 SD= 17.23). TLX Physical demand is one measure that composes the TLX survey. A one-way ANOVA found no significant differences among the selection techniques for TLX physical demand, F<1.

4.4.2 Differences in Data Representation

There were no significant differences between data representation for any of the measures TLX Overall Workload F(1,159)= 1.62, p= 0.21 (Figure 8), TLX physical demand F(1,159)= 2.52, p=0.12, or cognitive demand F<1 (Figure 9).

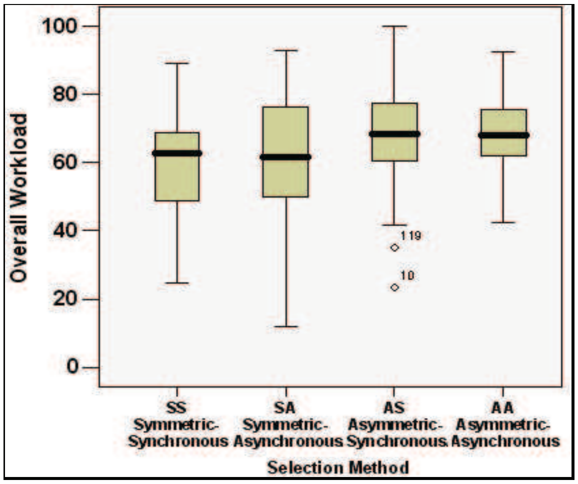

Figure 8. TLX Overall Workload by Selection Techniques

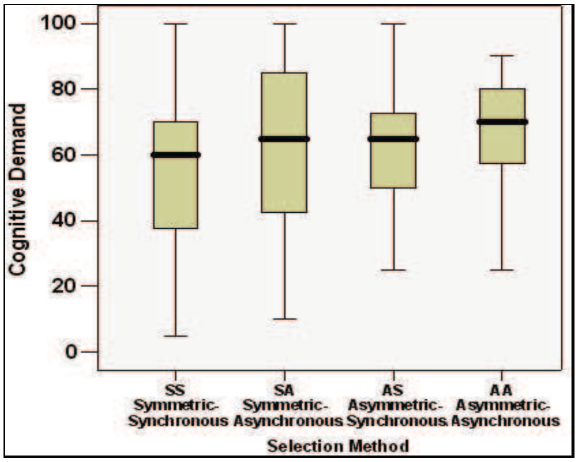

Figure 9. TLX Cognitive Demand by Selection Techniques

4.5 User Comfort, Arm Strain, and Ease of Use

User Comfort, Arm Strain, and Ease of Use measures were averaged for each participant across testing sessions. Arm strain was an item on the user comfort questionnaire.

4.5.1 Differences in Selection Techniques

A one-way ANOVA revealed a marginally significant effect in user comfort for selection methods F(3,159)= 2.58, p =0.056. A LSD post-hoc test indicated that the SS technique (M= 4.98, SD= 0.64) was significantly more comfortable than the AS technique (M=4.45, SD= 1.06). A one-way ANOVA revealed no significant difference of arm strain ratings between selection techniques, F(3,159)= 1.05, p =0.37 (Figure 10).

A one-way ANOVA revealed a significant difference in ease of use among selection techniques F(3,159)= 3.98, p =0.004. A LSD post-hoc test indicated that the SS technique (M= 3.98, SD= 0.96) is significantly easier to use than the SA technique (M= 3.39, SD= 1.08) and the AS technique (M= 3.22, SD= 1.01).

4.5.2 Differences in Data Representation

There were no significant differences between data representation for any of the measures User Comfort ratings, F<1, Arm Strain ratings, F<1, and Ease of Use ratings, F(1,159)= 1.20, p=0.28.

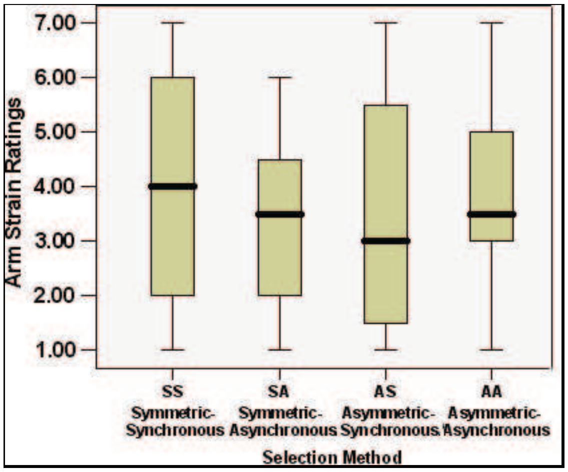

Figure 10. Mean Arm Strain Ratings by Selection Techniques

4.6 Ease of Learning

Ease of Learning ratings was one set of ratings and ratings were averaged for each participant. A one-way ANOVA found no significant difference for the differences in selection method for ease of learning.

4.7 Debriefing Trends

4.7.1 Differences in All Selection Techniques

For all techniques, participants reported problems not relating to the selection techniques:

- "It was hard to see depth"
- "(I) didn't like not having control over space or view"
- "(I) found it hard to see"
- "It was hard to judge what was in the box"
- "sensitivity (of tracking) was too high"
- "I had to move my hand too much to move the box. It would be better to have a way to just move your wrist instead of your arm"

Depth was a problem due to the lack of depth cues and way to manipulate the view. Some participants also felt that tracking was too sensitive and others felt that it was not sensitive enough. These issues are not related to the selection technique itself. Most felt training was sufficient for the task, but several participants felt that more training might be needed for doing more complex tasks.

4.7.2 Symmetric-Asynchronous Observations

For the symmetric-asynchronous technique, a few participants suggested:

- "I would have liked to use my hands at the same time"
- "Maybe you could have something where you use your hands together"

An interesting observation of the participants using the symmetric-asynchronous technique was that sometime after training during the initial trials of the first testing session, participants began to switch control more and more quickly from hand to hand. As participants completed more trials, switching control between hands became so frequent that it seemed as though they were simulating the hands to work at the same time, or what would be the symmetric-synchronous technique. This was also affirmed by comments provided by the participants in this condition during debriefing when asked if they switched control from left to right and right to left:

- "I would click for the left and then click for the right, all I did was go back and forth a lot"
- " (I) tried to do everything with both hands at the same time"
- "Yes, I was doing it (controlling the box) simultaneously"

4.7.3 Debriefing Conclusions for Selection Techniques

In conclusion, the majority participants liked the symmetric or asymmetric techniques but did not like either asynchronous technique. The majority of participants attempted to simulate synchronous interaction when using an asynchronous technique.

4.7.4 Differences in Data Representation

Although each participant had opinions about each type of object representation and had personal preferences for one or the other, participants as a whole did not significantly prefer one type of representation of the objects over the other.

5 DISCUSSION

5.1.1 Differences in Selection Techniques

The symmetric-synchronous technique was found to allow significantly faster completion times than any of the other techniques. This indicates that symmetric and synchronous interactions may both contribute to faster task completion. We reject our hypothesis that if we coupled asynchronous interaction with symmetric interaction, the symmetric-asynchronous technique would be significantly more accurate and allow significantly faster completion times than either asymmetric techniques.

There were no significant differences for accuracy found between any of the four selection techniques in this study. This result conflicts with the result of one prior study which found that symmetric-synchronous techniques allowed for significantly more accurate selection than an asymmetric-synchronous and an asymmetric-asynchronous technique [27]. That study reported computer usage score means in 2D as 4.19 (SD= 1.09) , 4.43 (SD= 1.08), and 4.11 (SD=1.12) and in 3D as 2.02 (SD= 1.28), 2.07 (SD= 1.28), and 2.33 (SD= 2.33) for each of the three conditions [27]. One-way ANOVA tests found significant differences between those computer usage scores in 2D and 3D respectively with the higher computer usage scores of our subject pool in 2D, F(1,6)= 271.01, $p<0.001$ and in 3D, F(1,6)= 59.41, $p=0.001$. The lack of significant difference found in our study between selection methods for accuracy scores may have been due to the significantly higher usage scores found in our study and that 75% of the participants in this experiment have declared majors of some computing degree and the significant differences found for ratings of computer usage in both 2D and 3D would give all groups an advantage.

We reject our hypothesis that asynchronous interaction reduces fatigue in selection techniques. For TLX overall workload, the symmetric-synchronous technique produced significantly less overall workload than the asymmetric-synchronous technique and the asymmetric-asynchronous technique. When looking at a few major components of workload, no differences were found for TLX physical demand. However for TLX cognitive demand, the asymmetric-asynchronous technique caused significantly more cognitive demand than the symmetric-synchronous technique. In addition, there was no significant difference found for arm strain among selection methods. This means that symmetric interaction was not the main cause of arm or physical demand, counter to what was found in one previous study [27]. Further investigation would be required to determine the true source of what causes physical demand in bimanual selection techniques. The asymmetric-synchronous technique was found to be the significantly most cognitively demanding. When techniques were coupled with the asynchronous factor, more cognitive demand was produced as a result.

For user comfort, the symmetric-synchronous technique was found to be more significantly comfortable than the asymmetric-synchronous technique. Examining the means, the symmetric-asynchronous technique had lower user comfort ratings than the symmetric-synchronous technique, but did have higher ratings than the asymmetric-asynchronous technique. The asymmetric-asynchronous technique had higher ratings than the asymmetric-asynchronous technique. Neither the symmetric interaction nor the synchronous interaction alone improved user comfort. Additionally, the ease of use results show that asynchronous action coupled with symmetric action and asymmetric action coupled with synchronous action can decrease ease of use. The results of the ease of learning measure indicated that all techniques were easy to learn how to use. In debriefing, the major result to address was that the participants adapted the asynchronous techniques to act more like synchronous techniques. This might mean that symmetric-asynchronous techniques are less easy and less natural to use. If the provided interaction is less natural or uncomfortable to use, users will adapt to use the interaction technique in a way that is more comfortable or natural even if it was not the intended use. Such behavioral observations could be very important for designers to use when modifying or creating new interaction techniques..

5.1.2 Differences in Data Representation

The significant difference found for accuracy and completion times for data representation were only the differences between training and testing. Splat-based rendered objects allowed for slightly faster completion times and slightly better accuracy, however these differences were not significant. This may have been due to the transparency of the splat-based rendered objects, allowing users to better view occluded objects. This study shows novel results that there were no significant differences for selection accuracy, completion times, overall workload, physical and cognitive demand, user comfort, arm strain, and ease of use measures between polygonal spheres object representations and splat-based rendered object representations. This may mean that selection techniques can be generalized by task type, meaning one technique could be used for multiple data representations as long as the selection task type is the same for all of them, however further investigation is required.

6 CONCLUSION

This study evaluated selection techniques across a number of performance factors with respect to the four basic bimanual classes of hand cooperation: symmetric-synchronous, symmetric-asynchronous, asymmetric-synchronous, and asymmetric-asynchronous. The conclusions of this evaluation can be summarized as the following:

- Symmetric and synchronous selection strategies both contribute to faster task completion, especially in training.
- No class of bimanual selection was a significant contributor to reducing or increasing physical demand for experienced users.
- Asynchronous selection techniques significantly increased cognitive demand, especially when coupled with asymmetric interaction.
- Ease of use significantly decreases for symmetric techniques when coupled with asynchronous actions, and are less natural to use.
- For experienced users, accuracy performance differences diminished between the classes of bimanual action.
- No significant differences in any measure were found between data represented as splats and data represented as polygonal spheres.
- When provided interaction techniques that are less natural, users' behavioral adaptation can provide clues for a more natural interaction.

This study has shown that the properties of each of the four distinct bimanual classes of action do not significantly induce or reduce fatigue for experienced users. Previous work has shown for novice users, that symmetric techniques produce more fatigue after an hour [27]. Providing multiple analysis of novice and expert users is important because differences in interaction performance can be identified for the different types of users. When designers create interaction techniques for a system, they can identify interaction strategies for specific users. For example, designers can incorporate symmetric interaction for high accuracy for all users, yet allow the option to switch to asymmetric interaction for novice users that may tire more quickly.

Also, since previous work did not explicitly compare interaction techniques that represented each specific class of bimanual actions, it is possible that other properties incorporated in the selection technique were causing the fatigue [27]. It is important for researchers to identify the extreme cases of interaction properties and evaluate them with all other properties remaining constant. Our work has shown the specific performance results from four selection techniques representing each class of bimanual actions. This does not mean that bimanual interaction should only incorporate these extreme classes of bimanual action. Various degrees of interaction in between those classes remain to be developed, but it becomes more difficult to evaluate those techniques and be able to discern the specific causes of the performance results. Our evaluation clearly shows the performance benefits of each class of bimanual action. Each class of actions has its own performance benefits. Designers can then use this information as a guide to combine interaction techniques and degrees of classes of bimanual actions to create new interaction techniques with a prediction of the performance level without evaluation of those specific techniques.

The following describes some examples of how the results from this study may guide designers and developers. If designers want to create an interaction technique that requires fast selection, symmetric, synchronous, or both types of interaction may be incorporated to increase selection speed. If the task is highly dependent on cognition, the designer would avoid any asynchronous-asymmetric interaction. For novice users, designers may incorporate symmetric-synchronous interaction because it is the fastest to learn, yet incorporate a switch for asymmetric interaction if fatigue becomes an issue.

7 FUTURE WORK

This work determines that no class of bimanual selection was the main cause of physical demand for users with higher computer usage ratings, however determines no specific cause when users have lower computer usage ratings. A direct extension of this work would be to run a study evaluating several plausible causes for physical demand to determine the major attributing factors. Another direct extension of this work would be to define the factors that could be generalized for selection techniques based on task type.

This work also shows the performance differences among selection techniques representing four distinct classes of bimanual actions. Designers and developers can use the performance metrics as a guide for predicted performance when incorporating various degrees of each class of bimanual actions in their interaction techniques. We plan to investigate all extreme cases of each factor of selection interaction to provide more performance metrics. This will enable designers and developers to add interaction properties and combine them while using the performance metrics as a guide of what the performance would be for their specific technique, without having to evaluate each specific interaction technique.

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