

# **Design and Evaluation of 3D Multiple Object Selection Techniques**

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## Abstract

Few researchers have addressed the important issue of three-dimensional multiple object selection (MOS) in immersive Virtual Environments (VEs). We have developed a taxonomy of the MOS task as a framework for exploring the design space of these techniques. In this thesis, we describe four techniques for selecting multiple objects in immersive VEs. Of the four techniques, two are serial (where only one object can be indicated per operation), and two are parallel (where one or more objects may be indicated per operation). Within each of the two categories we also investigated two metaphors of interaction: a 3D spatial metaphor and the pen and tablet metaphor. Two usability studies were used to evaluate the four techniques, iterate their designs, and gain a deeper understanding of the design space of MOS techniques. The results from our studies show that parallel MOS techniques can select objects faster than serial techniques as the number of target objects increase. We also show that effective techniques for MOS in immersive VEs can be created using both pen and tablet and 3D metaphors.

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## Chapter 1 - Introduction

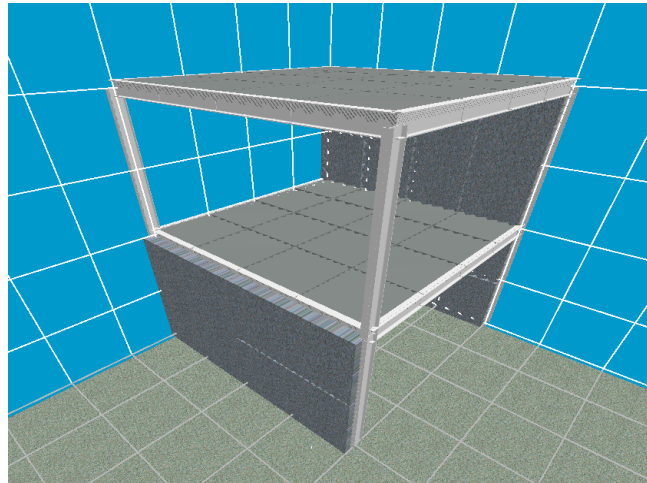
Virtual Environments (VEs) are computer generated three-dimensional worlds that are viewed through a first-person perspective. VEs allow users to visit locations and interact with environments that would be impossible to work with in the real world. VEs can be viewed on a desktop computer using a mouse and keyboard for input. A subset of VEs that use specialized hardware to view and interact with the environments is called immersive VEs. Immersive VEs typically use head-mounted or projection-based displays along with 3D tracking systems to immerse the user in the virtual world rather than view the world through a monitor. Immersive VEs have a distinct advantage over 2D desktop VEs for visualizing 3D information. In desktop environments navigation is performed using a mouse or other 2D input device whereas in immersive VEs users navigate through the virtual space by physically moving their body. Immersive VEs allow for more natural movement through 3D space allowing users to view virtual objects just as they would real objects. In this work we examine immersive VEs exclusively and for this paper the term VEs will refer to immersive VEs unless noted otherwise.

3D interaction is defined as: Human-computer interaction in which the user's tasks are performed directly in a 3D spatial context [Bowman et al. 2004]. Designing effective 3D interfaces for VEs is a challenging task that requires understanding of human cognition, ergonomics, VE technology, and a certain degree of creativity. The 3D interface should be easy to understand and allow the user to focus on their task. Good 3D interfaces should not overly fatigue the user or cause undue stress on their body. Current VE technology is limited in that input and output devices cannot accurately represent the real world. Creativity is needed to develop interfaces that use this technology and still be capable of powerful interactions. VEs allow users to perform actions that cannot be done in the real world, and creating interaction techniques that allow the user to perform these actions also requires creativity on the part of the designer.

An early application of VEs was for architectural walkthroughs. In these applications a computer model of a building is loaded into the virtual environment and architects can view the structure at the correct scale. Using a VE architects are able to visualize their designs without having to build physical models. Clients of the architects can visit the buildings before construction begins to be sure that the design fits their needs. By viewing the buildings virtually and locating problems in the designs before construction begins millions of dollars can be saved. The next generation of these applications, called immersive design applications, allow designers to create and modify their designs entirely in the virtual world. These new applications use more advanced 3D interaction techniques and can speed up the design process so that designers do not have to switch between their desktop computer and the immersive design system as often.



Virtual-SAP [Bowman et al. 2003] is an example of an immersive design application. Virtual-SAP allows architects to immersively create buildings and simulate the effects of earthquakes upon them. Architects arrange beams, columns, walls and floors to create building structures. The user can then run a simulation and see how the structure reacts to the forces of an earthquake. This immersive application is very compelling as it allows the user to visualize how a building will react to changes they make in the building's design.



**Figure 1 - Virtual-SAP Application**

Buildings, such as those created in Virtual-SAP, are very regular structures and contain many repeated patterns. From an architectural point of view the upper floors of a building are almost identical and creating each floor in a large building can be a tedious process. When designing the interface for Virtual-SAP we realized that an interaction technique was needed that could allow the designer to take advantage of these repeated patterns and to copy and paste entire sections of a building. The class of techniques needed for this application is called cloning techniques. Cloning is the process of creating multiple spatially distributed copies of an object or set of objects [Chen et al. 2004]. Without cloning techniques, users of Virtual-SAP must create and place each component of the structures one-at-a-time.

The most interesting cloning operations are those that allow groups of objects to be cloned in one operation. Single object cloning is important as well but it can be considered as a subset of multiple object cloning. To examine this problem we created a simple testbed to experiment with object cloning. To begin a multiple object cloning operation the user must first select the objects that they wish to clone. Our prototype technique selected multiple objects by manipulating a semi-transparent 3D box so that the box covered the desired objects. The prototype allowed the user to specify the number of clones and the distance between them using a 2D interface on a tablet. Our prototype multiple object selection (MOS) technique was limited in that it was only able to select objects that were grouped close together. Groups of objects that were

not aligned in a rectangular pattern also posed a problem for our technique. It was also very difficult to position the box so that it selected the desired set of objects. We quickly realized that designing 3D MOS techniques was much more challenging than we had anticipated and began this research effort to explore the problem.



**Figure 2 - Early Cloning Prototype**

### **1.1 Multiple Object Interaction**

Much research on 3D user interfaces has dealt with designing techniques for interacting with one object at a time [Bowman et al. 2004]. To date, most VE applications have contained relatively few manipulable objects and did not require techniques that could operate on many objects at one time. Repeatedly using one-at-a-time techniques to perform the same action on multiple objects quickly becomes tedious and is impractical as the number of objects to manipulate grows large. As VE applications become increasingly complex more powerful methods of interaction are needed.

### **1.2 Multiple Object Selection**

Environments in the domain of architecture typically contain more manipulable objects than in other common VE applications. Desktop 3D modeling and CAD applications allow for interaction with many objects in one operation. In order for immersive design applications to be successful new techniques need to be developed that can interact with many objects at one time. The application of multiple object interaction (MOI) techniques can be seen in the following scenario:

Consider Sally, an interior designer, who is designing a café for a client. Sally's employer has requested that the café feel small but still have adequate space for 15 tables. Sally designs her environment on her desktop computer and imports her design into an immersive design application. When she enters the VE she finds that the tables in the café are much too big for the space and need to be resized. She first selects all of the tables in the environment using a multiple object selection (MOS) technique. Sally then instructs the system to shrink the diameter of each tabletop by 10cm. She then walks through the environment and sits down at a table to confirm that she has created the appropriate feel for the space. Using an immersive VE, Sally reviewed her design and made changes without having to return to her desktop. Had she not been able to resize all of the tables in one action she may have returned to her desktop to use the more powerful interaction technique. Sally saved time by using a multiple object interaction technique in the immersive design application.

In this scenario Sally used a MOS technique to select her tables and a MOI technique to adjust their size. If Sally's application had not provided these MOI techniques she would have had to manipulate each object individually using single object interaction (SOI) techniques. The MOI technique is also more closely aligned with the way that Sally would think about the task of resizing the tables. Sally's thought process would lead her to decide that all tables should be 10cm larger. Sally would not decide that table one should be 10cm larger, table two should be 10cm larger, table three... etc.

Another important task in immersive design applications that could benefit from MOS techniques is the cloning of objects or groups of objects. When cloning large structures the selection task may take a significant amount of time using one-at-a-time selection techniques. With these *serial* selection techniques, selection of large groups of objects can be very time consuming. Here the lack of powerful MOS techniques can cause the user to become fatigued while attempting to perform a simple task. *Parallel* MOS techniques, such as 2D brushes and lassos, are very effective at cutting down time to select groups of objects on desktop environments. Extending these techniques to 3D applications, however, is a challenging task as issues such as occlusion, fatigue, and environment clutter are less of a problem in 2D environments. Overcoming these issues and creating effective 3D parallel MOS techniques is an important hurdle that must be passed before powerful interfaces can be created for interacting with the ever increasing number of objects in today's VE applications.

Multiple object selection does not only apply to the cloning task. Any technique that works with multiple objects must first specify which objects to interact with. Examples of other techniques where MOS is a prerequisite are: deletion of multiple objects, repositioning or reorienting of objects as a group, and aligning one group of objects with another group of objects. Tasks where MOS is needed are found in applications throughout most all domains where VEs are used.

### 1.3 Research Questions

Throughout the course of our research we developed several research questions regarding the design and use of 3D MOS techniques. We attempted to direct our research to answer the following questions.

*-What are the advantages of using parallel MOS techniques over serial MOS techniques?*

Parallel MOS techniques seem to be faster when selecting very large groups of objects. As the number of objects to select increases when is it more effective to use parallel MOS techniques rather than serial MOS techniques?

*-Can 2D selection techniques be used effectively to select objects in a 3D environment?*

By using desktop 2D metaphors in 3D environments users who are familiar with desktop applications can more easily learn their 3D counterparts. 2D techniques selection techniques can be used in VEs by first projecting the 3D scene onto a plane in the environment. This plane can then be treated as a 2D scene and objects may be selected using traditional 2D selection techniques. 2D techniques that are used in 3D environments are sometimes easier to use as they require manipulation of less degrees-of-freedom. Can these techniques be used in 3D effectively and if so for what scenarios are they best suited?

*-How can 3D MOS techniques be evaluated and compared?*

And by what criteria should we judge the effectiveness of MOS techniques? To answer this we need an understanding of when and how MOS is used. In what tasks would a user attempt to perform MOS? What do the desired objects look like and how are they arranged in the environments? Some MOS techniques may be better suited for selecting one set of objects than another. How can we differentiate and classify techniques so that designers of future applications require a MOS technique they know which they should use?

## 1.4 Hypotheses

We formed the following hypotheses about the behavior of 3D MOS techniques based on our initial experimentation with 3D selection techniques and our knowledge of 2D selection techniques.

*-Parallel MOS techniques become faster than serial MOS techniques as the number of target objects increases.*

We will attempt to show that parallel MOS techniques are faster than serial techniques for selecting large numbers of objects.

*-3D MOS techniques are faster at selecting objects in a 3D environment than 3D techniques that interact through a 2D plane.*

Techniques that use 3D input seem inherently better for selecting objects in a 3D environment. While 2D desktop techniques can be adapted to select 3D objects their difficulty at specifying the depth component would cause problems when selecting 3D objects.

*-3D MOS techniques that use 2D MOS metaphors are easier for users to learn than true 3D MOS techniques.*

Users who are familiar with 2D desktop selection techniques can become proficient with 2D MOS techniques more quickly than they can become proficient with 3D MOS techniques.

## 1.5 Approach

We used the following approach to answer our research questions and test our hypotheses.

*-Create a taxonomy to better understand the design space of 3D MOS techniques.*

A taxonomy of 3D MOS techniques will allow us to better understand the components of 3D MOS techniques.

Understanding how each component affects the usability of MOS techniques will allow for new techniques to be created with a desired set of properties.

*-Design, implement and evaluate 3D MOS techniques to examine the characteristics of various branches of our taxonomy.*

Using the taxonomy we will design and evaluate four MOS techniques to evaluate two branches of our taxonomy. The techniques will be chosen in an attempt to answer some of the above research questions.

*-Evaluate and improve the designs of the techniques gaining a better understanding on how to evaluate 3D MOS techniques.*

As we do not yet know how to best evaluate 3D MOS techniques we must experiment with this process as well. Deriving test environments from various application domains we evaluated our techniques in different scenarios to improve the design of the techniques as well as learn what properties of the environments affect the performance of 3D MOS techniques.

*-Perform a final evaluation of the techniques and compare their performance with a generic 3D MOS task.*

Using a generic environment and task generated from our analysis of the environments in the first experiments we will evaluate our MOS techniques.

## **1.6 Overview**

In this thesis, we examine the design space of 3D MOS techniques, focusing on the serial/parallel distinction. To aid in this exploration in chapter 3 we present a taxonomy of 3D MOS techniques. Chapter 4 details the four techniques we implemented representing different branches of our taxonomy. Two separate studies evaluate these techniques and compare their performance. The first study, described in chapter 5, was used to improve the designs of the untested techniques as well as to learn how more about how to evaluate 3D MOS techniques. A second, more formal, experiment (chapter 6) was used to evaluate the four techniques' effectiveness at selecting multiple objects. Finally, in chapter 7 we discuss the strengths and weaknesses of MOS techniques and present some guidelines for the design of future 3D MOS techniques.

## Chapter 2 - Related Work

The first pioneers of VR concentrated on developing the technology required to view the virtual worlds and thus early VEs did not allow for complex interaction with the environments. Interaction with these environments was often limited to user viewpoint navigation. Rarely were users of these early applications able to interact with the objects in the environments. When researchers first began developing three-dimensional user interfaces very little was known about how users interact with virtual objects in 3D space. Researchers in this new field learned how to develop powerful interaction techniques through a process of experimentation and refinement. An example of this process is the development of object selection and manipulation techniques. Early selection and manipulation techniques used simple metaphors of interaction such as pointing, touching and occlusion [Mine 1995, Poupyrev et al. 1996, Pierce et al 1997]. Evaluation of these techniques provided an understanding of the strengths and weaknesses of the metaphors. Using this knowledge new techniques were created that improved upon the earlier designs by combining the strengths of the previous designs [Bowman et al. 2001, Pierce et al. 1999]. This process of designing techniques in order to gain an understanding of a metaphor and using this understanding to develop new techniques has been repeated throughout the short history of 3D interaction techniques with great success.

### 2.1 Single Object Selection

Many researchers have investigated 3D single-object selection techniques, such as ray-casting [Mine 1995] and image-plane selection [Pierce et al. 1997] for immersive VEs. Ray-casting and image plane selection are both examples of techniques created by metaphor [Poupyrev and Ichikawa 1999]. With these techniques a metaphor for selection is chosen and then the techniques are designed with the metaphor in mind. The three main metaphors for 3D selection are pointing, virtual hand and World in Miniature (WIM). All three metaphors have been used to create effective selection techniques.

An alternative way of creating new selection techniques is the task decomposition approach. Bowman created a taxonomy of selection techniques by task decomposition where he presents the basic building blocks of selection techniques to be used to assemble new techniques [Bowman 2004]. By evaluating techniques built in this manner an understanding of the effects of each individual building block on the usability of the technique can be gained. Using this understanding, new techniques can be tailor made based on the needs of the application.

Single-object selection techniques can, of course, be used for MOS as well. Single-object selection techniques can be adapted for use as MOS techniques in two ways. The single-object technique may be used in succession to create a *serial*

MOS technique or the technique may be altered to specify a line, plane or volume wherein all objects are indicated for selection. We will use ray-casting as an example of both possibilities. A *serial* MOS technique adapted from ray-casting would function as follows: The user would point at objects one at a time pressing a button to select the object that first intersects the ray. A *parallel* version of ray-casting might be implemented like this: The ray projected from the user's hand would become a virtual skewer where all objects that the ray passes through are selected upon the push of a button. All single-object selection techniques may be adapted as *serial* MOS techniques but some techniques such as object touching may not be feasible as *parallel* techniques. In chapter four we describe our implementation of ray-casting for *serial* MOS.

## 2.2 Area Differentiation

There are many existing MOS techniques for 2D graphical user interfaces (GUIs). In Willis' [1996] framework, the task of area differentiation (the process of defining the area within which objects are indicated), is divided into two branches. *Brushes* are persistent areas where objects are continuously checked against the selection criteria. *Lassos* are single-use areas where the shape is cleared after the selection operation is performed. This simplification of the area differentiation task is appropriate for 2D WIMP interfaces but is not descriptive enough to adopt for 3D object selection. There are many other components of 3D volume differentiation that need to be examined. The position of the user's view is important for selection in 3D environments as problems such as object occlusion, size and shading/lighting can vary depending on the user's viewpoint. The creation and manipulation of the *brush* or *lasso* is also more complex in 3D environments. Specifying a 3D volume is more challenging than specifying a 2D area. Multiple viewpoints are often required for accurate specification of this volume and 3D input devices can be difficult to manipulate with the necessary precision.

Previous work on differentiation of 3D volumes for object selection has been rather limited in VEs. 2D techniques for desktop VEs have been successful in 3D modeling and design applications due to their ability to work with multiple views of a scene at one time and user familiarity with WIMP selection techniques. Applications that allow for volume definition with 3D input devices are rare. Liang and Green [1993] implemented cone-casting where a cone is projected from a 3D input device. The object closest to the center of the cone is selected. Steed and Parker [2004] extend this idea with shadow cone selection. Here, the user moves a cone through the environment and only objects that were surrounded by the cone throughout the manipulation are selected. Darrah et al. [2002] designed a MOS technique for the PHANTOM haptic pen that creates the selection volume using a convex hull algorithm. All these techniques have been effective in their given applications but none have been used for 3D multiple object selection in immersive VEs.



### 2.3 2D Interaction in VEs

Szalavári and Gervaultz [1997] presented an interface called the Personal Interaction Panel (PIP) which uses a tracked plexiglass tablet for interaction with a VE. Other researchers have used this metaphor to assist in defining 3D volumes for selection on workbenches [Schmalstieg et al. 1999; Haan et al. 2002]. In these interfaces the user holds the tablet in their hand and sweeps the tablet through the environment to define a 3D volume. All objects inside the volume are then considered for selection. This approach cannot be easily extended to more immersive setups for two reasons. First, the user can only effectively define volumes within arm's reach. As the technique was originally used on immersive workbenches, where the working area is limited by the size of the display, this limitation is not important. Selecting objects at a distance is impossible with this technique without stretching the user's virtual arm. Second, the techniques do not scale well for defining very large or very small volumes. The size of the plane defined by the tablet can be adjusted to select small or large volumes but these create new challenges. As the plane grows large, it becomes difficult to manipulate at arms reach and as the plane becomes small, manipulation is challenging due to tracker accuracy.

Angus and Sowrizal developed the Pen and Tablet metaphor [Angus and Sowrizal 1995] for using 2D interaction techniques in immersive environments. The Pen and Tablet metaphor displays a 2D interface onto a tracked tablet which the user then holds in their hand. A tracked pen device is then used to interact with the 2D interface in a manner similar to a PDA or tablet pc. In their work, with the PIP Schmalstieg et al. developed a method for using the tablet as a 2D surface through which the 3D world could be manipulated using the Pen and Tablet metaphor. In their interface, a view of the environment is mapped onto a handheld tablet creating a 2D representation of the objects in the environment. Using the pen the user could select and manipulate objects in the environment. Two forms of selection were used in this interface: touching the pen to the projected image of the desired object selected one object at a time, and drawing a lasso around a group of objects allowed for *parallel* selection of multiple objects. There are many exciting possibilities for interaction using the Pen and Tablet metaphor with projected views of the environment. We explore two techniques similar to those described above in chapter four.

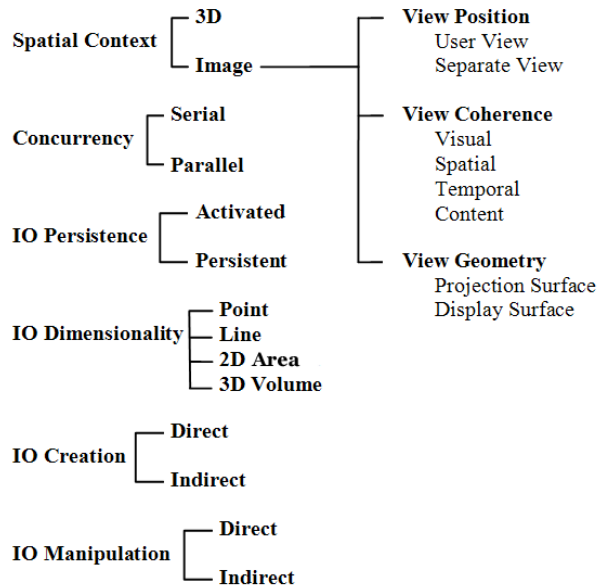
## 2.4 Multiple Views

CAD and 3D modeling applications commonly use multiple views for viewing and interacting with a 3D environment. As we discussed above, multiple views can also be used for interaction with immersive VEs. Designers must decide when using multiple views is appropriate for their application. Baldonado and Woodruff [2000] present a set of guidelines on when to use multiple views in information visualization applications. These guidelines are also helpful for determining when to use multiple views in VE applications. In their guidelines, the rule of diversity states that the designer should “Use multiple views when there is a diversity of attributes, models, user profiles, levels of abstraction or genres”. Diversity is key as multiple copies of the user’s current view of an object are not likely to be useful in most tasks. In VEs diversity can be attained with multiple views of an object from distinct angles, such as the orthogonal views in CAD and 3D modeling applications. Deciding which views to use and how to arrange them is an interesting problem which requires further study.

## 2.5 Summary

Many effective single object selection techniques have been developed for immersive VEs. These techniques can be adapted to become either *serial* or *parallel* MOS techniques. From 2D selection techniques we borrow the concept of area differentiation and show how it applies to selection in VEs. We also discuss how 2D interfaces have been used in VEs and how these interfaces can be used for selection. Finally, we discussed how multiple views can be incorporated into VEs and briefly described some of the challenges in doing so. Our 3D MOS techniques build upon existing 3D selection techniques as well as previous work using multiple views in VEs.

### Chapter 3 - Design Space of 3D MOS Techniques



**Figure 3 - A Taxonomy of 3D MOS Techniques**

Separate Understanding of the design space for a class of interaction techniques is important when designing new techniques. Bowman et al. [2004] used taxonomies to explore selection, manipulation and navigation techniques. Taxonomies are valuable as they enable the designer to understand what parameters of the technique can be modified to create new techniques. We present a taxonomy (Figure 3) of the task of area differentiation for 3D MOS techniques. We refer the reader to Willis' [1996] complete taxonomy of 2D selection to understand the possibilities of how objects can be chosen for selection after they have been indicated. We narrow our taxonomy to describe how objects are spatially indicated for selection in a 3D environment. Our taxonomy is a design space taxonomy which lists the various characteristics of a technique as well as the possibilities for each characteristic [Card 1990]. Using a design space taxonomy, new techniques may be created by making a selection from each main branch. Thus design spaces are useful for the exploration of interaction techniques. We present this taxonomy as our interpretation of the design space of MOS techniques and acknowledge that there are many other possible interpretations of the same task.

We use the term Indication Object (IO) to refer to the object manipulated by the user used to indicate the selection volume. In 2D interfaces this object often takes the form of a point at the tip of the mouse pointer or a rectangle specified when dragging the mouse. For 3D selection the IO may be a point, a line, a 2D area or a 3D volume. The method by which this IO is described is a key component of a selection technique. 2D applications only contain one viewpoint from which to view the environment. One of the powerful features of 3D applications is the ability to view the environments from many

viewpoints. This feature creates new challenges as the task of specifying the IO can vary in difficulty from different viewpoints thus the method of viewing the 3D environment is also an important component of a selection technique. In this taxonomy we describe possible methods in which a user may view the environment as well as the important properties of the IO in our breakdown of the selection task.

### 3.1 Spatial Context

The *spatial context* of the MOS technique refers to the dimensionality of the input used to specify the IO. Techniques using the *3D context* specify the IO directly in 3D space. This branch contains the more traditional 3D interaction techniques where a 3D input device is used to manipulate the IO. An important distinction of the 3D context branch is that the user must accurately manipulate the IO in three dimensions. Techniques using *image context* use a view of the environment mapped onto a 2D surface to specify the IO. There are several design choices when designing techniques using image context. Stoev and Schmalstieg [2002] outline the possibilities for through-the-lens techniques but we simplify the space for MOS into *view position* and *view coherence*. Selection can be done either through the user's *current view* of the world [Pierce et al. 1997], or by using a *separate view* of the environment. Views do not necessarily have to conform to the have the same properties as the user's view. Views can vary along several parameters: *visual* (lighting, color palette, rendering style), *spatial* (exploded view), *temporal* (slow motion, still image), and *content* (a subset of objects in the world is displayed). Mapped views can also have different *view geometry* where they are created using non-planar geometry for both the *projection surface* and for the *display surface*. An example of a non-planar projection surface would be a fisheye view displayed on a monitor. These can be useful for obtaining wide angle views of an environment. Displaying the projected view onto a sphere or hemisphere in the environment would be an example of a non-planar display surface. The value of choosing non-planar surfaces is not well studied but it is an important decision when using mapped views.

### 3.2 Concurrency

3D MOS techniques may have varying levels of *concurrency*. *Serial* techniques only allow one object selected per selection operation whereas *parallel* techniques allow one or more objects to be considered for selection. The usability and power of a technique is greatly affected by this design choice. In the example of ray-casting we discussed in the related work the ray can work as either a laser pointer, where only the first object is indicated, or as a skewer where all objects intersecting the ray are indicated. The parallel version of the technique allows for selection of multiple objects at one time possibly decreasing the time to complete a MOS task. The drawback of using a parallel version of ray-casting is that the ray may pass

through objects the user cannot see possibly causing unwanted selections. This important is an important tradeoff between serial and parallel selection techniques. Another tradeoff between serial and parallel techniques is the difficult manipulation required with many parallel techniques. Parallel techniques that use a volume to select multiple objects can be much more difficult to use than serial techniques. With the added power of parallel selection comes the greater difficulty in performing accurate selections. Serial techniques do not suffer from this as often as the restriction of only selecting one object allows the user to concentrate on the object they wish to select and not have to worry about selecting many unwanted objects.

### 3.3 IO Persistence

The specific properties of the IO are very important for MOS. The IO may be *persistent* in the world and continuously consider indicated objects for selection or the selection operation may only be *activated* at the user's explicit command. Persistent IOs are useful when precise control over the selection area is necessary or when the IO may need to be modified after initial selection. Activated IOs are more common than persistent IOs in desktop interfaces but may find more use in the 3D MOS task. Some examples of activated and persistent IOs from 2D desktop interfaces as are icon mouse click selection and Adobe Photoshop area selection. Using the mouse to select icons on a desktop interface creates an activated IO. The IO in this selection method is a point that is defined by the position of the mouse cursor and activated on click. Adobe Photoshop uses a persistent IO where the user defines an area under which all picture elements are selected. After creation the area can be modified at will using various tools allowing for precise selections.

Accurate definition of 3D objects often requires viewing the object from several angles. As persistent IOs remain in the world after creation modifications can be made to them to achieve the required accuracy. While modifications can be made to activated IOs while they are being created, once they are finalized they cannot be modified without performing another selection.

### 3.4 IO Dimensionality

The *dimensionality* of the IO is very important as IOs with a higher dimensionality may be able to select more objects in a single operation. IO's in VEs can range from a 1D point to a 3D volume. IO's with higher dimensionality are able to select larger numbers of objects as they can cover more space in the environment. The disadvantage of choosing a higher dimensionality is that these IO's are often more difficult to constrain than IO's with a lower dimensionality.

### 3.5 IO Creation and Manipulation

Lastly the IO may be created and manipulated either *directly* or *indirectly*. With direct manipulation the object is created or manipulated directly in the environment using the 3D input device. Indirect manipulation of the objects uses other means for this task. With indirect manipulation, the actions are not performed on the object itself but instead performed on a separate representation of the object or using menus. Indirect methods, such as numeric entry fields, may be better suited for tasks when very exact manipulation is required whereas direct manipulation techniques may be faster for less precise tasks.

### **3.6 Summary**

This taxonomy represents one interpretation of the design space of 3D MOS techniques. With this taxonomy MOS techniques can be categorized and compared based on their components. Through comparison the effects of each branch of the taxonomy on the usability of the techniques can be estimated. Using this knowledge, designers of new techniques will be able to create new techniques based on their needs. For example if through experiment it is found that serial techniques are more learnable than parallel techniques designers of applications used by novice users may choose to user serial techniques over parallel techniques. By exploring this taxonomy we hope to gain a better understanding of how each branch affects the usability of the created techniques. We begin to describe our exploration of two branches of this taxonomy in chapter four.

## Chapter 4 - Exploring the Design Space

		Concurrency	
		Serial	Parallel
Spatial	3D	Raycasting	Selection Box
Context	Image	Tablet Tapping	Tablet Lasso

Table 1. 3D MOS Techniques Evaluated in this Work

In order to explore the design space laid out in the previous chapter we designed four MOS techniques that represented different categories of our taxonomy. We were primarily interested in evaluating the effectiveness of parallel and serial techniques as we hypothesized that parallel techniques would be faster at selecting large numbers of objects. We also wished to explore the tradeoffs between techniques in both sub-branches of spatial context. Table 1 shows which category each our techniques fall under for concurrency and spatial context. Techniques in the image context branch can easily borrow 2D selection techniques while techniques using the 3D context can take advantage of true 3D input. All techniques were designed to be used in a head-tracked HMD with a 6-DOF wand device and a 6-DOF tracked tablet as a surface for displaying 2D interface objects. We used the Simple Virtual Environment (SVE) library to implement the four techniques as well as our testing framework [Kessler 2000]. Here we present the four techniques as originally designed. We later discuss our evaluation of these techniques and the improvements made on the designs.



Figure 4 - User Wearing a HMD while using a pen and tablet.

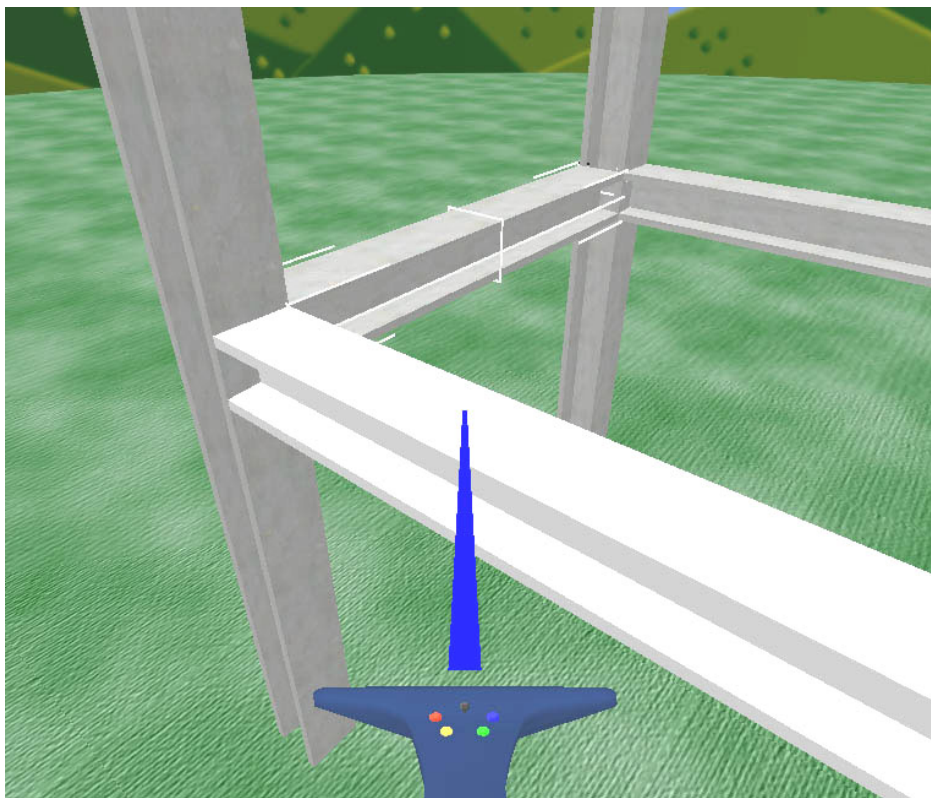
### 4.1 Serial Techniques

Serial techniques were adapted directly from existing single object selection techniques. Minimal modifications were needed to these techniques to turn them into MOS techniques.

## 4.1.1 Ray-casting

### 4.1.1.1 Design

Ray-casting [Mine 95] was an obvious choice for a serial technique in the 3D spatial context. Ray-casting has been shown to be efficient for selecting objects from a distance with good accuracy [Bowman et al. 1999]. Ray-casting has the advantage over arm extension techniques (such as the Go-Go technique [Poupyrev et al. 1996]) for MOS as it only requires 2-DOF control and does not require the user to hold his arm extended out from the body during long selection tasks. Ray-casting allows users to “shoot from the hip” and select objects with their hand close to their body thus minimizing fatigue. Our design of ray-casting was limited to select (or deselect) only the first object the ray intersects, classifying it as a serial MOS technique.



**Figure 5 - Raycasting**

### 4.1.1.2 Implementation

Most of the code necessary to implement ray-casting was available in the SVE library. A ray was attached to the pointer object and was represented by a blue line. SVE provided functions necessary to detect the collision of the ray with the objects in the environment. Once a collision was detected the color of the object was brightened to represent the indicated state. Pressing a button on the wand device toggled the objects selected state on and off. Audio feedback also informed the user as



to the status of the selection action. A chime sound played when an object was selected and a bass sound played when an object was deselected. These sounds were used for feedback in all of our selection techniques.

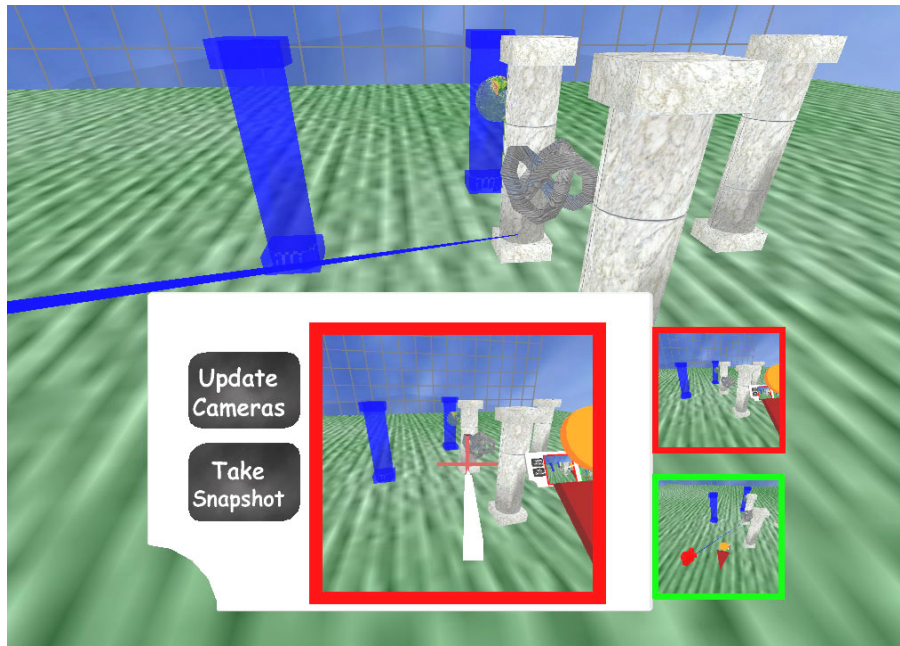
#### **4.1.2 Tablet Tapping**

##### **4.1.2.1 Design**

One of the powerful features of desktop 3D modeling and CAD software is the ability to interact with multiple views of an environment at one time. We adopted a similar approach by mapping a separate view onto the tablet to facilitate remote 2D selection. We made use of the Pen and Tablet metaphor [Angus and Sowrizal 1995] to interact through the separate views. A tracked plexiglass tablet provided a hard physical surface on which to place 2D widgets and extend 2D interaction techniques into 3D. In our design the user placed a camera object in the environment and positioned the camera to obtain the desired view of the target objects. The view of the camera object was mapped onto the user's tablet as a flat 2D image and was updated continuously. The user could then use the input device to interact with the camera view using 2D selection techniques similar to those found in modern desktop 3D modeling applications.

Positioning of the virtual cameras was accomplished by first traveling to the desired location of the camera. Pressing a button on the tablet started a three second countdown that was displayed on the viewplane. When the countdown finished the camera was moved to the exact position and orientation of the user's view. The three second countdown allowed the user time to precisely set their view before the camera was moved. We chose not to use camera in hand techniques [Ware and Osbourne 1990] because in our pilot testing they did not prove effective for use in large environments where navigation was required.

The serial selection technique for the tablet is easily adapted from 2D single object selection. As the user moves the input device close to the camera view on the tablet, the virtual representation of the device becomes semi-transparent and a red crosshair appears over the camera view on the tablet surface. The crosshair is positioned at the closest point on the camera view plane to the device and moves along with the device as it hovers above the tablet surface. A ray was also cast from the camera into the world to give a 3D representation of the crosshair's selection (see Figure 6). In our interface the crosshair appeared on the tablet so long as the device was within 10cm of the tablet; this gives the user the option of either touching the device to the tablet surface or hovering above the tablet. When the user presses a button on the device the object under the crosshair is selected (or deselected).



**Figure 6 - Tablet Tapping in a Testbed Prototype**

#### *4.1.2.2 Implementation*

To implement this design, we added functionality to the SVE library that allowed users to create multiple views in the environment which could then be mapped onto any surface. This was accomplished by adding a separate rendering callback which was called after each frame of the user's current view is rendered. During this callback any number of separate views could be rendered. The system then created a texture from the information in the video back buffer, which could then be mapped onto any surface. Our implementation allowed for any number of separate views of the environment. As this procedure required that extra viewpoints be rendered each frame, optimization was very important. The designer could adjust the resolution, field-of-view (FOV), and frequency in which the alternate views were updated. Dynamic update of the frames could also be turned off to allow for snapshot type views. With our test system we were able to achieve an acceptable frame rate of 30 frames-per-second (fps) with a main view at 640x480 resolution and one separate view at a resolution of 512x512.

The other views could then be bound to an object in the environment but adding the view as a child of the object in the scene graph. For our testbed we chose to use a movie camera object created in 3D Studio Max. As the camera object was moved through the environment so did the views bound to it. With this system the user could pick up and move the camera in one hand and watch the view move on the tablet in their other hand.

When the wand device was moved in proximity to the mapped view on the tablet, the system calculated the closest point from the pointing device to the mapped view. This point was then projected onto the viewplane of the virtual camera and a

ray was cast out from the eyepoint of the camera through the projected point. The projected ray was dynamically updated and moved as the wand moved in front of the mapped view. A button was used to perform the selection operation and test intersection as in the ray-casting technique described in section 4.1.2.1.

## **4.2 Parallel Techniques**

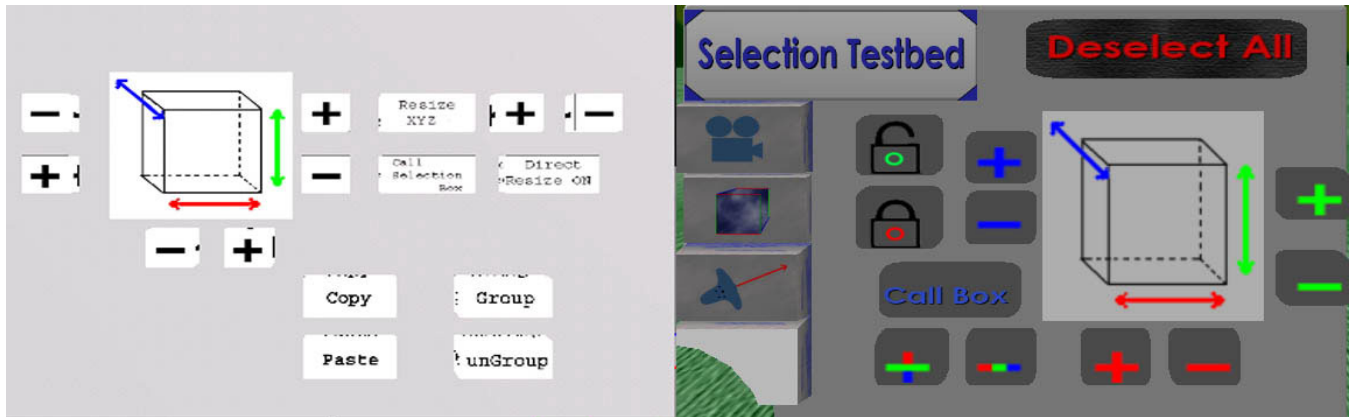
Our serial techniques both defined a one-dimensional ray to select objects in the environment. A ray can be used for selecting multiple objects in parallel but only if the target objects are aligned correctly. We designed two techniques that instead define 3D volumes for selecting multiple objects in parallel. We paid special attention to creating effective manipulation techniques for these volumes as we had predicted that a poor choice of manipulation technique would render the MOS techniques unusable.

### **4.2.1 Selection Box**

#### *4.2.1.1 Design*

Designing an effective 3D parallel MOS technique is a difficult task. To better understand the dimensions of a volume the user needs to be able to view the volume from multiple angles. When creating IOs that are 2D or 3D objects it is important to allow the user to use several viewing angles so that they may make an accurate selection. With this in mind we created a parallel 3D MOS technique using a persistent box as the IO. The box is semi-transparent and any objects touching or within the box are selected. We chose to implement this technique with a box but other shapes could work equally well depending on the structure of the environment and the shape of the objects to be selected.

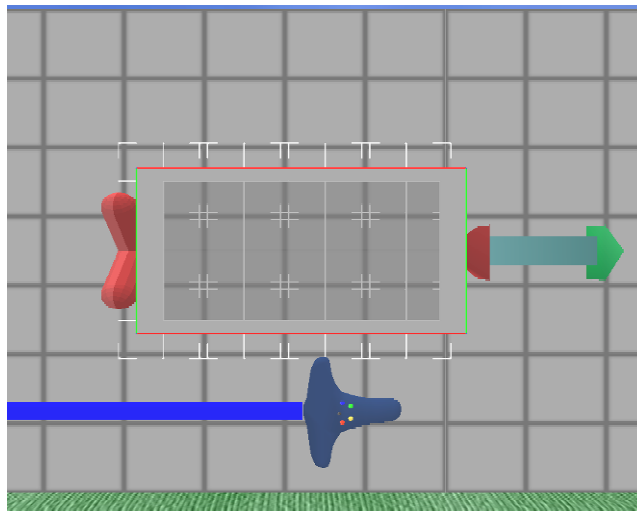
Go-Go object selection [Poupyrev et al. 1996] and manipulation is used for adjusting the position and orientation of the selection box. The Go-Go technique scales the movement of the virtual hand only after the user's physical hand moves past a set threshold. When the user's physical hand is close to their body the virtual hand moves with a 1-to-1 relationship with the physical hand. Once the physical hand passes a set distance from the user's body (approximated from the head position), the movement of the virtual hand is scaled increasingly as the distance between body and hand grows larger. Regardless of the hand's position, the rotation of the physical hand and the virtual hand is kept at a 1-to-1 ratio. Due to its dynamic scaling the Go-Go technique allows for the manipulation of distant objects. When working with objects that are spatially distant the selection box must be large in order to select all objects. Large objects are difficult to work with up close as they can occlude all other objects in the environment. We chose to use the Go-Go technique for manipulating the selection box as it allows for both up close and distant manipulation.



**Figure 7 - (Left) Early button resize interface. (Right) Final button resize interface.**

In our original prototype, resizing of the selection box was accomplished using a set of buttons on the handheld tablet. These buttons allowed the user to adjust the scale of the box in all three dimensions independently. A graphic representation of the box used colors to help users understand how the buttons correlated to the axes of the selection box. Pilot subjects were able to use the buttons to resize the box but the speed at which they could do so was not satisfactory. We realized that a direct manipulation technique would be beneficial to this task.

We developed a novel direct manipulation object resize technique called PORT (Pointer Orientation-based Resize Technique). PORT allows the user to independently position all six faces of the selection box. PORT (Figure 8) allows only one axis to be manipulated at a time and uses the orientation of the pointer to determine which direction to resize. PORT does not uniformly resize the object but stretches the object in the direction the pointer is oriented. This gives the user the sensation that they are pulling out or pushing in the sides of the object. The user simply needs to imagine that their pointer is contained inside the object and point at the face they wish to be stationary and the opposite face will be resized. Visual cues that indicate which side of the box will move and which side will not move are placed at the outer bounds of the object. Once the user has the desired axis selected the resize operation is performed one of two ways: by moving a joystick on the input device or by holding a button and translating the pointer along the pointer's direction vector.



**Figure 8 - Pointer Orientation-based Resize Technique**

After an initial evaluation of the selection box technique we realized that it was unable to avoid selecting objects that located were between two desired objects. The fact that the only objects touching the selection box were selected limited the potential of this technique. To allow for the selection of two separated sets of objects we added a locking feature to the selection box. Once an object, or set of objects, is selected pressing a button on the tablet interfaces locks the selection. When locked, the object(s) will remain selected even when the selection box is moved away. The lock feature allows the selection box to select any possible set of objects.

#### 4.2.1.2 Implementation

The selection box itself was a simple cube with 1 meter wide sides that was created in a text editor. A multicolored wire frame surrounded the box to allow for a better understanding of its dimensions. Each face of the box was made semi-transparent by assigning an alpha value of 0.5 to the faces' material. Implementation of the Go-Go technique was simple. The user's body position was approximated by subtracting .25 meters from the Y component of the user's head position. If the Euclidian distance between the body and hand was greater than .5 meters the scaling factor for the virtual hand was calculated as follows:  $((Hand - Threshold)^{2.25} + Threshold)$ . This scaling factor was then applied to the movement of the virtual hand to attain scaled manipulation.

We were able to take advantage of SVE's built in collision detection features when implementing the selection box. SVE provided a set of functions to test the intersection between the bounding boxes of two objects. As we did not plan on using any particularly complex objects bounding box collision was sufficient for our purposes. An animation callback checked for intersections with the selection box every frame. When an intersection was detected the object was checked to see if it was

selectable and if it was it was marked as selected by the system. The animation callback also checked to see that all previously selected objects were still intersected by the box and deselected those that were not.

With PORT, the system determined which of the object's axes the pointer is most closely aligned with by taking the dot product of the pointer's direction vector and the six direction vectors of the object's positive and negative x, y and z axes. The vector which was most coincident with the pointer's direction vector determines the axis on which resizing occurs. The indicator objects were placed slightly offset from the outer boundary of the selection box along the axis to be resized. The stretching of the selection box was performed by moving the selection box so that the side opposing the moving side was situated on the origin, adjusting the scale of the object, and then moving the object back to its original position. By moving and scaling the geometry of the object was never changed, only its position matrix was altered. This allowed the object to be reset to its original scale easily.

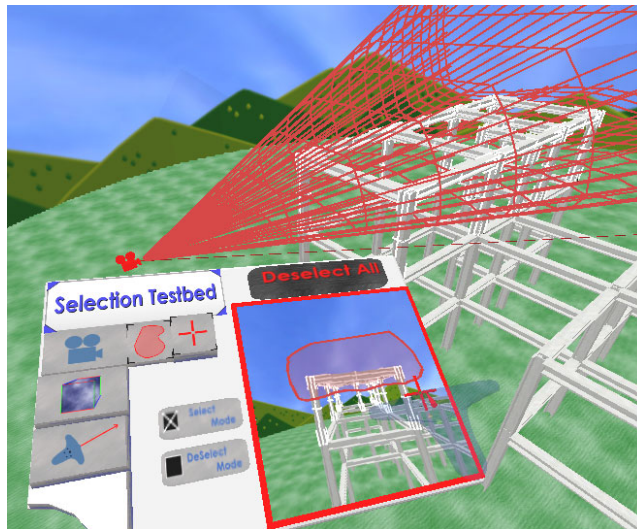
In the original design of PORT the user could resize the object in two ways. Both methods specified the direction of resize by orienting the pointer to specify the direction to resize, the difference between them was in how they initiated the resize action. With the first method the user held a button while moving the pointer in the direction to resize. This method was very direct but it sometimes required that the user move their arm in uncomfortable positions. The system determined the amount to resize by keeping track of how much the pointer moved along the resizing axis. This distance was then used to scale the selection box along that axis. The second, and more popular method, used a joystick on the pointing device to perform the resize action. Orienting the pointer in the desired direction and moving the joystick forward and backward adjusted the size of the selection box. With the joystick method a linear function was used to map the amount of joystick movement to the resizing factor.

## **4.2.2 Tablet Freehand Lasso**

### **4.2.2.1 Design**

Our final technique allows freehand 2D lassos (Figure 9) to be drawn on the camera view for parallel selection. This technique was inspired by lassos in Adobe Photoshop [Photoshop]. In Photoshop lassos allow the user to specify an area by drawing the boundary of the area using the pointing device. As images often have little structure the lasso tool allows for flexibility in selecting arbitrary shapes. Like images edited in Photoshop, camera views of an environment often have little or no structure. While the environment itself may have a given structure it is not always reflected in the camera view unless the view angle is set to take advantage of the structure.

To provide the user with maximum flexibility when creating 2D shapes freehand lassos were used rather than the standard box lassos found in most desktop applications. With the freehand lasso tool the user pressed a button and moves the crosshair to draw an arbitrary shape on the camera view screen. This 2D shape is then projected out from the camera into the environment to create a 3D volume. Like the ray-casting techniques, the selection operation toggles selection for indicated objects. We provided visual feedback from the last selection operation in the form of a wire frame “spider web” projected from the camera object (Figure 3).



**Figure 9 - Tablet Lasso Technique**

#### *4.2.2.2 Implementation*

The same camera views used in the Tablet Tapping technique were used for the Freehand Lassos. When the user initiated the technique by pressing a button and moving the pointer over the view surface the system recorded the 2D path on which the pointer moved. A line representation of this path was drawn on the view surface so the user could see their path. When the button was released and the line ended the more difficult calculations began.

First, the path was closed by connecting the first and last points. Points that were very close together were removed from the path to reduce the complexity of the shape and to save computation time later on. In order to turn the 2D shape into a 3D volume the path had to be converted into 2D polygons. Jonathan Shewchuk’s Triangle [Shewchuk 1996] application was used to create a 2D triangulation of the lasso path. The lasso points were input into Triangle and a list of 2D triangles representing the area inside the lasso was returned. This triangulation represented one side of the 3D polygon that would be used as the IO for selection.

To create the 3D polygon the 2D triangulation was moved from the mapped view surface to the view plane of the camera as with the Tablet Tapping technique. The other side of the polygon was found by projecting each point of triangulated polygon out from the camera's viewpoint. More polygons were added to connect the two sides together to form a solid 3D object. A limitation with SVE was that it could only test for collisions between the bounding boxes of two objects. Since any shape could be drawn with the lasso the resulting polygon was not guaranteed to be convex and bounding box collision would not provide enough accuracy for this technique. UNC's SWIFT++ library [Ehmann and Lin 2001] was capable of detecting intersections between convex polygons and was integrated into SVE specifically for this technique. Before runtime, all possible target objects in a scene had to be decomposed into convex hierarchy files which could then be loaded into SWIFT++. The transformation matrix of these target objects was combined with the hierarchy files at runtime and loaded into SWIFT++'s scenegraph. When the IO was created it was also loaded into SWIFT++ and a list of collisions was returned. Using this list of collisions the system determined which objects intersected the IO and were then processed for selection. A wire frame representation of the IO was left in the world between selections for visual feedback to the user.



## **Chapter 5 - Formative Evaluation**

Exploration and refinement were the two main goals in our first evaluation of the techniques. Ray-casting is a well established technique that had been evaluated many times before and has been used in many applications. Though it is very common as a single object selection technique there had been no formal evaluation of ray-casting as a MOS technique. There had also been little evaluation of tablet techniques as multiple selection techniques and there was no previous evaluation of the selection box. In order to be sure that our implementations of all four techniques were representative of the potential the techniques possess they all required evaluation and iteration. We designed an initial experiment to study the four techniques in various environments in order to learn how to improve their designs and how to best evaluate the techniques in future experiments.

### **5.1 Evaluation Platform**

#### ***5.1.1 Hardware***

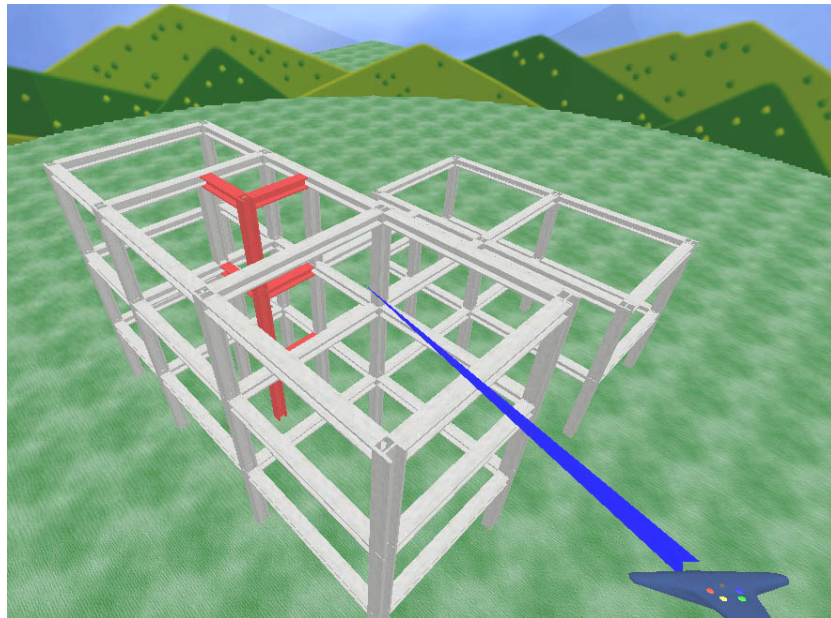
The experiment used a Virtual Research V8 head-mounted display (HMD) with 640x480 resolution and a 60° diagonal field of view. An Intersense IS900 tracking system provided tracking for the head, wand and tablet in a 10' x 10' area. The main input device was a tracked wand with four buttons and an analog joystick. For tablet interaction we used a custom designed 21" by 14" sheet of plexiglass that is held in the user's non-dominant hand. Graphics were rendered on a Pentium IV 2.4 GHz PC with a GeForce 4 TI 4600 128Mb graphics card running Windows XP.

#### ***5.1.2 Software Testbed***

We developed a software testbed that allowed us to evaluate all four techniques in various environments. Script files controlled the testbed and allowed us to create experiments by highlighting elements in an environment for selection and having the participants use a specific MOS technique to select them. The testbed was able to record the time to select a set of objects and was later extended to record more information regarding the selections.

The hardware system we used included an Intersense wand as the primary pointing device. This device had four buttons and a center mounted joystick. In our pilot studies we had difficulty explaining to participants which button was needed to perform a certain action. To solve this problem we created a 3D model of the wand device to be used as a virtual representation of the pointer. The buttons were colored to allow the experimenter to more easily explain which button the

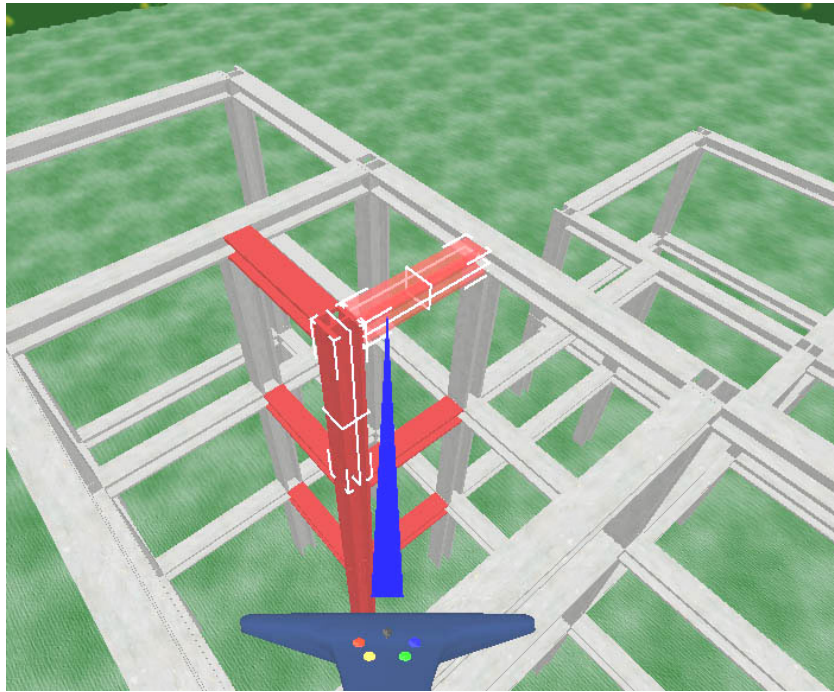
HMD user should push. This addition allowed the process of introducing the participants to go more smoothly and is recommended for future experiments.



**Figure 10 - Target objects in a building environment.**

A basic background environment was used for all environments in the testbed. The background was chosen to have minimal features with that the participants might confuse with the task environment. The background consisted of a ground (through which the user could not pass), a hemispherical sky, and a ring of hills. Navigation in the environment was accomplished with pointer directed flight. To fly the user points the wand in the direction they wish to move and by pressing a button the system moves them in the desired direction. This navigation was consistent throughout all techniques to avoid confusion.

The task for our experiment was to select a set of target objects in the environment. The system indicated a target object for selection by changing its color to red (Figure 10). No other red objects were used in the environments so that red objects would always be targets in the selection task. When selected a wire frame box surrounded the object to distinguish it from other objects (Figure 11). We experimented with other options for highlighting selected items such as changing the object's transparency but the wire frame solution proved the most effective as it was distinguishable regardless of the other objects in the scene.



**Figure 11 - Selected objects.**

The testbed provided a tablet interface for selecting from the four techniques. A set of raised buttons on were placed on the left side of the tablet for switching between techniques. The button for the currently active technique was recessed into the tablet to indicate its status. By moving the pointer over the button of the desired technique and clicking a button the active technique was changed. During the practice session participants were allowed to switch between the techniques at will. However, during the main experiment the system chose the technique according to the test script and participants could only use the technique selection buttons to determine which technique was currently active.

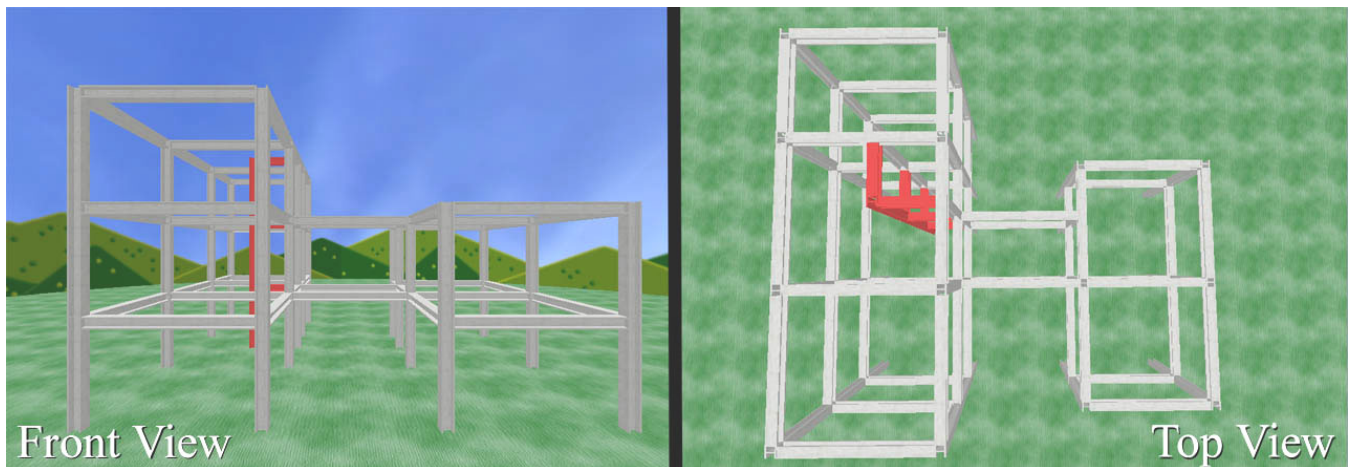
Audio feedback was especially important for this interface. Sounds were played as confirmation for most all actions the user performed. As we mentioned in chapter four specific sounds were used to indicate the selection and deselection of objects. The buttons on the tablet interface each played a sound when selected. The wand device we used in our experiment did not provide consistent tactile feedback when its buttons were pressed. The sound feedback substituted for the lack of tactile feedback very effectively.

## **5.2 Environments and Tasks**

MOS techniques are applicable in an extremely wide variety of domains and applications. These applications can vary from being sparsely populated with only a few large objects to having millions of tiny data points. It is highly unlikely that

one MOS technique will be the optimal technique for every possible immersive application. Therefore it is important to evaluate the techniques in a range of environment and task situations so that VE designers can choose the appropriate technique or set of techniques for their applications. We designed four different environments within which to evaluate our techniques:

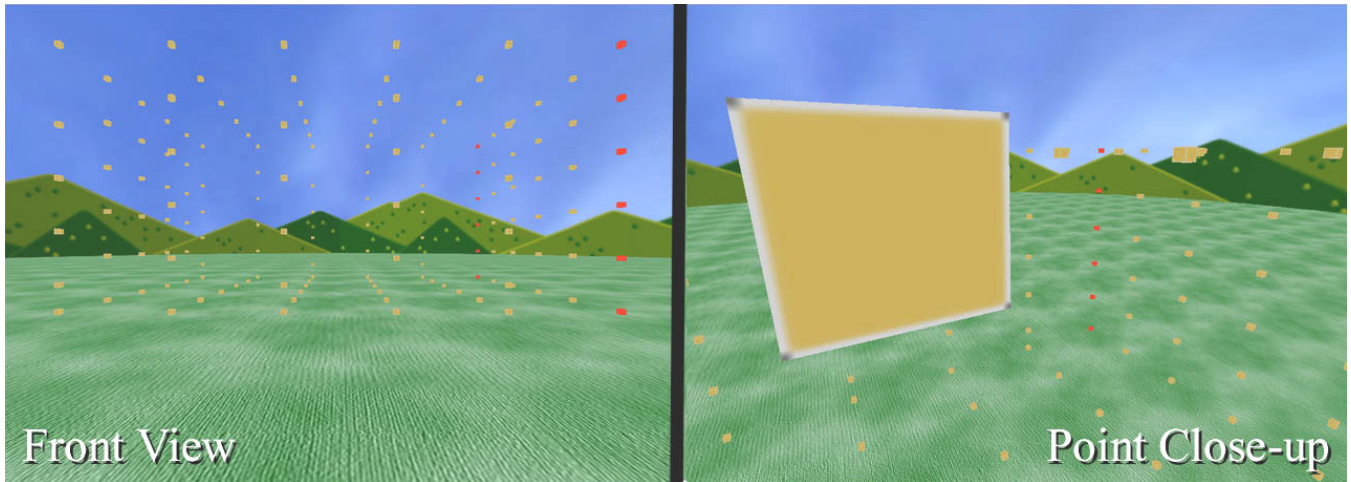
*-Building Environment:* The initial inspiration for our MOS work came when designing interfaces for Virtual-SAP [Bowman et al. 2003], an application for visualizing the forces of earthquakes on building structures. The building environment, similar to those in Virtual-SAP, was comprised of 98 beams and columns arranged to form the frame of a 3-story structure (Figure 3). The first target set for this environment was a central shaft of 12 objects (Figure 12 Below). This set was chosen as it was difficult to select with the camera techniques without using a top-down view. The second target set consisted of all elements of the top floor on the left section of the building and all elements of the bottom floor on the right side. The second set contained over 25 elements and required the participant to use the lock function of the selection box.



**Figure 12 - Building Environment**

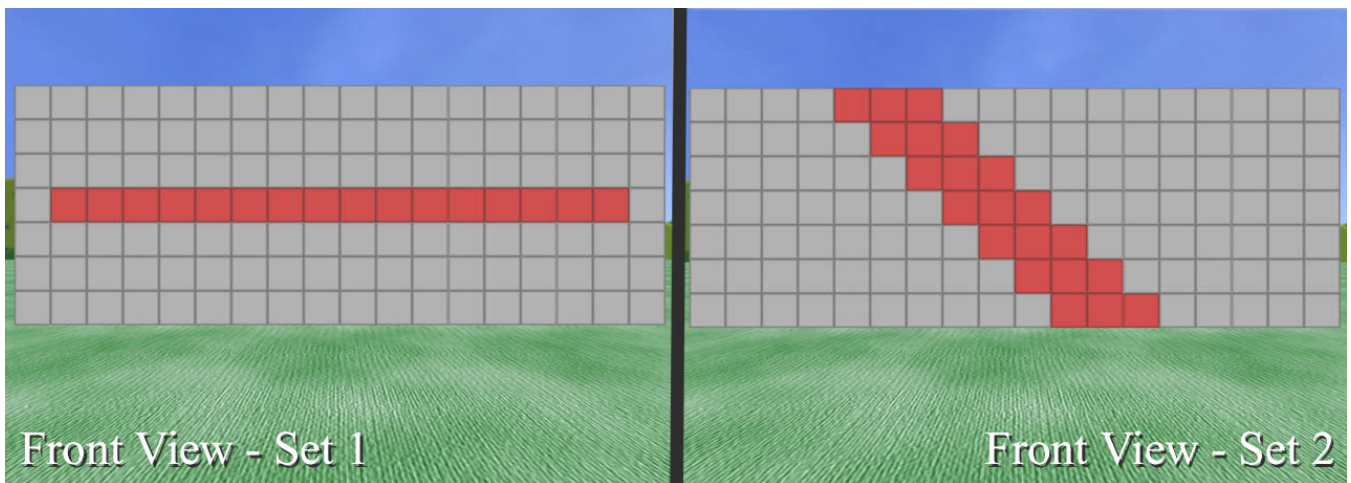
*-Point Box Environment:* Vertex editing in 3D modeling and CAD applications can be a challenging task as the objects are very small and are often positioned close together. To simulate this challenge our second environment was a point mesh that represented the faces of a 15m x 10m x 6m box. Points in the mesh were represented by 15cm cubes and were spaced 1.5m apart. The first target set (Figure 13 below) had the participant select two columns of points at corners of the box. As the two columns were shaped identically the participant could adjust the selection box to the correct size for one column and then re-use it to select the second. The second set required the participant to select 12 points along the wall of the point box.

This was challenging with the camera techniques as if the camera was positioned outside the box unwanted selections were difficult to avoid.



**Figure 13 - Point Box Environment**

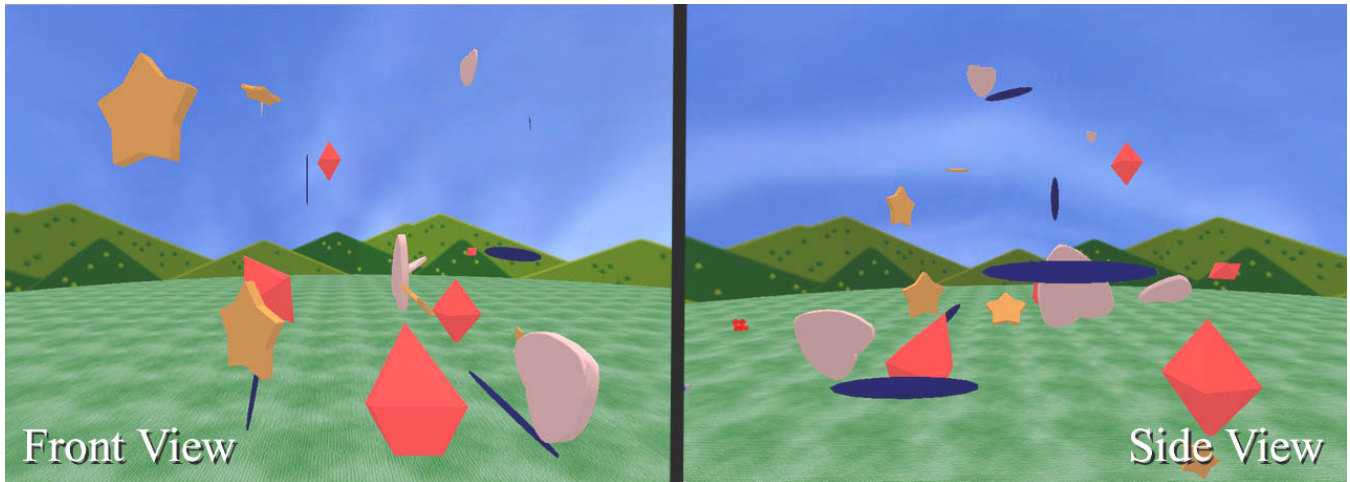
*-Tile Wall Environment:* In our experience, MOS techniques that use a 3D volume for selection had difficulty accurately selecting objects that were adjacent or very close together. For our third environment we created a 9m x 3m wall made of 50cm x 50cm tiles set adjacent to each other. The two target sets are pictured below (Figure 14) and were chosen to be challenging for the parallel techniques due to the objects proximity to each other.



**Figure 14 - Tiles Environment**

*-Pseudo-Random Environment:* Parallel MOS techniques tend to take advantage of the structure or patterns in an environment. We hypothesized that the lack of such structure would hinder performance of parallel techniques. Objects in the

environment were placed, oriented and scaled at random in a 20m x 20m x 15m area. First set for this environment was all of the diamond objects and the second set was the blue oval objects.



**Figure 15 - Pseudo-Random Environment**

Participants used all four techniques to select two sets of objects in each environment for a total of 32 trials. The number of objects in the target sets ranged from 5 to 30 objects with an average of about 10 objects. The target sets in each environment were the same for all subjects and were chosen to reflect common sets of objects that might be selected in a real application.

### **5.3 Participants**

We recruited 5 participants with VE experience ranging from VE expert to beginner. Participants self-reported their experience with VR, 3D games, and 2D MOS and had ranges from expert to beginner in all categories. One participant was female and four were male; all were graduate students. Their mean age was 24.

### **5.4 Procedure**

Before the experiment participants was asked to fill out a pre-questionnaire with questions regarding their age, occupation, VE experience and visual acuity. Participants were given training on the techniques in a generic environment until they were reasonably proficient with all techniques. Care was taken to only describe to the users how the techniques worked and not give them strategies for their use. The practice environment contained five columns for the participants to practice the techniques on. Appendix A details the practice procedure more thoroughly.

During the main experiment participants selected two target sets in each of the four environments using all four techniques for a total of 32 trials. The order of the environments was randomized with the order of the techniques and selections sets randomized within the environments. Participants were encouraged to think aloud during the trials and were told to explore different selection strategies rather than complete the trials quickly. After each trial, participants were asked to provide a subjective rating of the effectiveness of the technique for selecting the target set. A post-questionnaire was used to collect the participant’s final ratings of the techniques. All participants were interviewed to discuss the specifics of the techniques and to gain a deeper understanding of the challenges of each environment. The post-task questions and questionnaires are contained in Appendix A. With the training, trials and interview the experiment lasted approximately two hours.

### 5.5 Results

All subjective ratings were taken on a scale from 1 to 7 with 7 being the most preferable. In general, subjects preferred the serial techniques over their parallel counterparts in both the between trial ratings and the ratings collected in the post-questionnaire. Ray-casting was the clear winner in every category (Figure 4), participants found it easy to learn and versatile in all environments. Though ray-casting was the most preferred of the techniques participants often said that it was “tedious” or as one user commented “this technique requires lots of pointing”. Surprisingly, ray-casting was still rated as the least tiring of the techniques even though all users commented on the amount of pointing and clicking it required. Positive comments for ray-casting included “This ray makes me feel like I’m part of the world.” and “It’s easier to correct a problem if you mess up”.

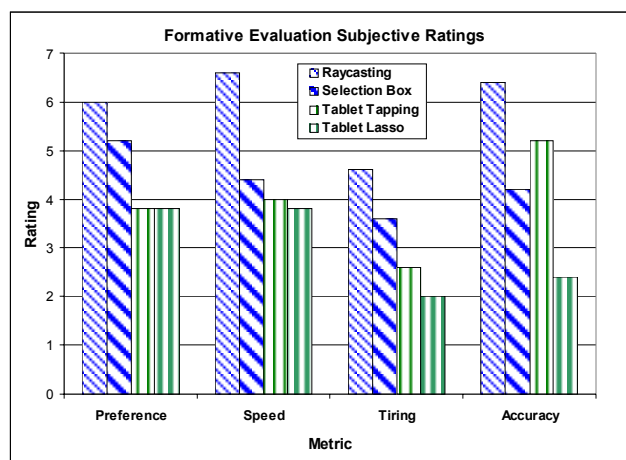


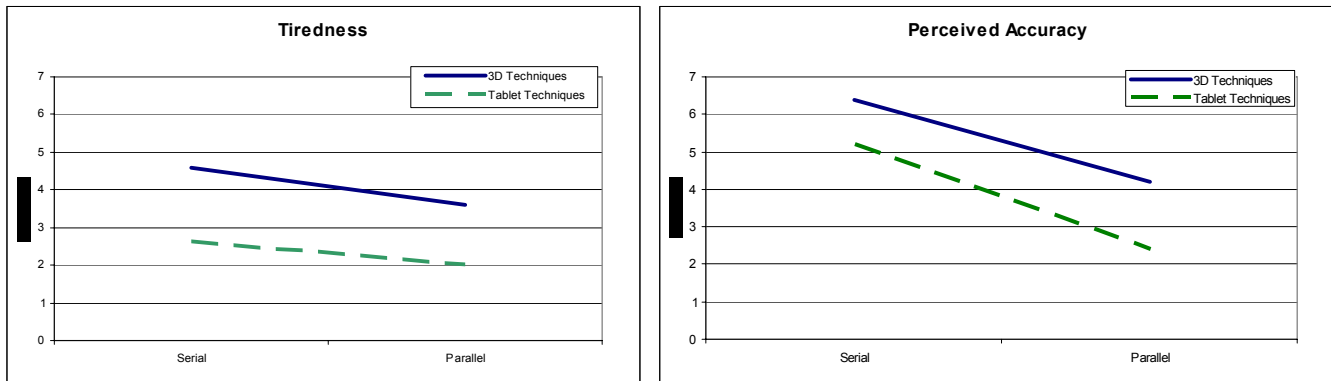
Figure 16 - Formative Evaluation Subjective Ratings

Participants felt that the selection box could be a very effective technique but all had difficulties precisely orienting the box. The selection box was rated as the second most frustrating technique and participants found that it was especially difficult to use when objects were very close together. It was also difficult for users to tell how far the back face extended when viewing the box from one side. There was often confusion when an object was behind the box but not selected. The transparency of the box allowed the user to see the desired objects but gave no sense of their distance from the far side of the box. Participants thought that selection box was a very intuitive concept but that it was limited by the lack of a precise manipulation technique.

Tablet techniques suffered from three main problems: the accuracy of the tracking system, the size of the camera screen, and the difficulty of positioning the camera. Precise manipulation on the tablet was very challenging due to jitter, which created large problems when selecting small objects or when trying to draw straight lines with the lasso. Drawing straight lines was particularly important when objects were very close together (such as in the tiles environment) and participants found tasks that required straight lines extremely frustrating. The limited size of the camera screen required users to position the camera very close to small objects to make selections with the tablet tapping technique. This limited the power of the techniques as fewer objects could be seen in one view and required more camera manipulation to select all targets. Camera positioning received the largest number of complaints because the user had to travel to the desired location and call the camera to this position when they arrived. Participants often commented that positioning the camera felt like an unnecessary step impeding the selection process. Our implementation of this technique did not take advantage of the camera's ability to obtain a view of the environment that was different from the user's current view. Aside from general camera issues the two tablet techniques both performed well. Participants were able to understand the mapping from the camera's view to the screen on the tablet and none had problems interacting with the screen as a 2D surface.

We did observe some trends in the answers to the questions in the post-questionnaire (Figure 16). Participants reported that the parallel techniques were more tiring to use than the serial techniques. We attribute this to the more complicated interaction required for constraining the volumes in the parallel techniques as well as the lack of refinement in the designs of the techniques. The participants also reported that the serial techniques were more accurate at selecting objects than the parallel techniques. This result does seem to make sense as a design goal of serial techniques is to provide fast accurate, selection of single objects whereas parallel techniques must first provide the ability to select many objects. This result was interesting and we hope to explore this difference more in future work.





**Figure 17 - Post-experiment questionnaire results for Perceived Tiredness and Accuracy.**

We found that the time to complete the tasks was largely dependent on the participants' strategies for selection. A prime example is for the second target set on the tiles environment (Figure 14). Four of the five participants created a small box the width of three tiles. The participants would then select three tiles lock the selection and repeat. Only one participant noticed the more optimal strategy of creating one large box and orienting it at an angle to perform the selection. The effects of poor strategies on the time to complete the tasks were significant with one participant completing a task a 3 minutes faster than another participant. This effect of strategy was so strong that the results gathered from the post-task questions varied depending on whether or not the user chose an effective strategy. Due to this strong variation we do not present those results here. In order to compare the performance of the techniques we realized that we needed to eliminate strategy as a variable in our study. We discuss more about how we did this later in chapter 6.

## 5.6 MOS Components

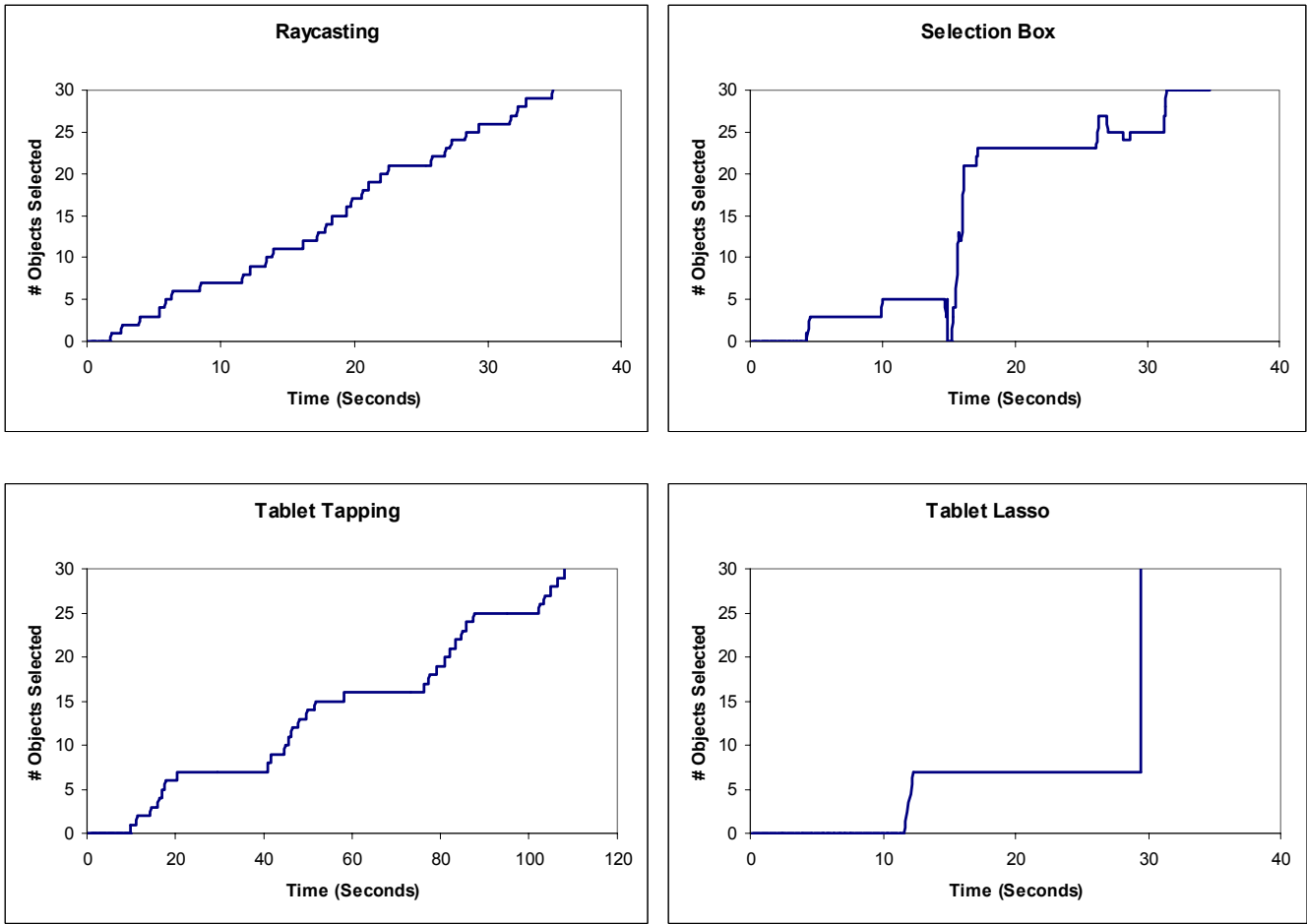
While observing users select objects with our techniques we made an important discovery. 3D MOS tasks are composed of three components:

- *navigation* to a location in the environment from where the technique can be performed
- *manipulation* of the IO to indicate the target objects
- *execution* of the selection operation

Depending on the specifics of the technique the time required to accomplish each component can vary greatly. Parallel techniques that specify a volume for selection require much more time to manipulate the IO than serial techniques such as ray-casting. The number of repetitions of this procedure will also vary greatly depending on the technique. Serial techniques will repeat this procedure once for every object selected whereas parallel techniques may only perform the procedure once

for the same set. The amount of navigation required and the number of repetitions of the procedure are highly dependent on the characteristics of the target set. Sets whose elements are very far apart will likely require more navigation than sets that are densely packed.

With this knowledge we instrumented our testbed to record the number of target objects selected as the task is performed. We then had an expert user select the second target set in the building environment with each selection technique. We chose this target set as it contained two smaller sets that were separated from each other requiring more travel and manipulation. By analyzing the graphs generated in the experiment (Figure 18) we can learn more about how each technique is used. In the graphs the X axis represents the time since the beginning of the task. The Y axis is the number of targets the user has selected. The vertical movements of the line are where targets were selected or deselected and therefore represent the execution of the selection operation. During the horizontal movements of the line the user is performing one of three actions: planning for the next selection, navigating to the desired location, and manipulating the IO. The expert user shown in these graphs had prior knowledge of the environment and target set and was given a selection strategy beforehand. We can therefore assume that the time spent planning for the next selection was minimal in this example.



**Figure 18 - Technique component graphs**

The expert graphs show some interesting similarities between the techniques. The shape of the line for both the ray-casting and tablet tapping techniques is mostly linear with only a few large horizontal portions. This indicates that the user is spending much of their time executing the selection operation. The tablet tapping task took much more time for this task than ray-casting and thus the scale of the graphs is quite different. Even though the scale is different they both exhibit the same stair step pattern. The larger horizontal movements in the tablet tapping graph indicate that the user took longer to navigate, moving the camera to the next position. Minimizing the length of these horizontal portions is the goal when creating effective serial selection techniques. For our camera techniques this could have been accomplished by choosing a faster method for positioning the camera thus reducing the navigation component for that technique. Comparing the graphs for the selection box and tablet lasso we see that they both have two large vertical sections. These sections show that the expert used a strategy where they selected the objects in two parts corresponding to the two smaller sets in the target set. The horizontal portions of each graph are where the user was either moving the camera or manipulating the selection box. The jagged portions of the selection box graph are interesting in that they show objects being selected and deselected as the user attempts to position and

resize the box. The short distance between the jagged portions of this graph indicate that the user was able to correct the mistakes fairly quickly. The lack of jagged edges in the lasso graph show that the user was able to perform an accurate selection for both sets without having to make corrections. By choosing manipulation techniques for the selection box that allow for more precise movement the jaggedness of this graph could be reduced. Analyzing these graphs we were able to learn which components the techniques could use the most improvement and concentrate our efforts in those areas.

## 5.7 Design Iteration

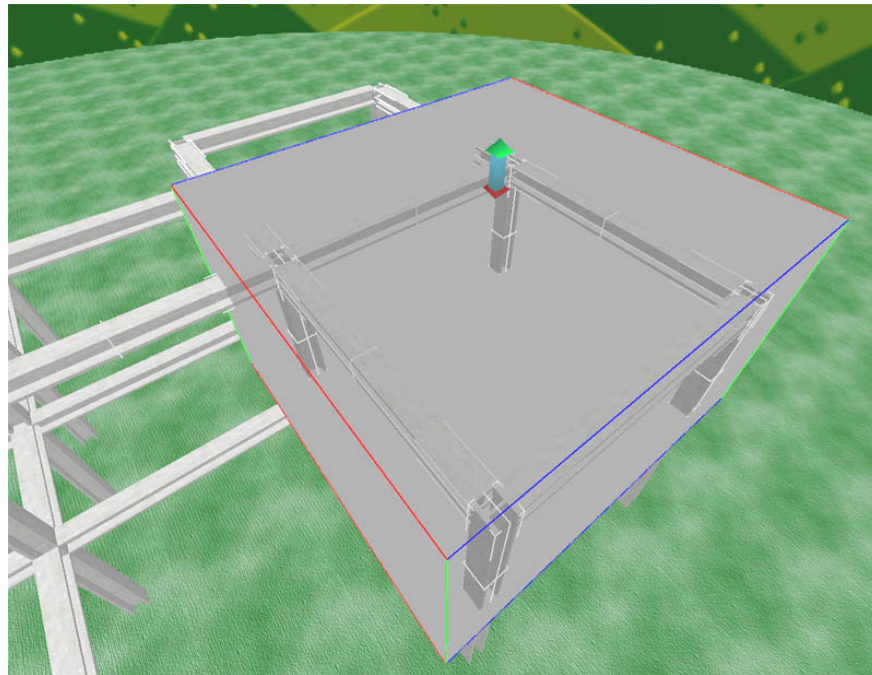
Using our observations and the participants' comments to improve our techniques we made several changes. Ray-casting required little iteration as its simple design limits the number of changes that can be made without transforming it into a different technique. Some users reported that it was difficult to tell when the ray intersected distant objects. The change in the object's translucency was difficult to see from a distance. To fix this problem we brightened the ray's color when it intersected an object.

The performance of the selection box technique was much lower than expected. Selecting the box with the Go-Go technique was challenging from a distance or when the box was small. Users also had great difficulty positioning and rotating the box at a distance. As these factors often frustrated our participants we realized that a new method for manipulating the box was needed. Go-Go did not allow the user to effectively manipulate the box at a distance and the box was almost completely useless when close to the user as it often occluded their view. We required a technique that allowed for: easy to select the box at a distance, could move the box large distances, precise positioning for final location, and fine control over object rotation.

We chose to implement HOMER [Bowman et al. 2001] for selection box manipulation. HOMER uses ray-casting to select the object allowing for easy selection of objects at a distance. Once selected, the virtual hand is moved to the position of the object. Movement of the user's hand is scaled to move the virtual hand and thus the object. There is a 1-to-1 mapping of the rotation of the user's hand to the object allowing for high rotational accuracy. In implementing HOMER we experimented with the scaling factors used for the object's movement and rotation. We ultimately found that the scaling factors used in the technique's original design worked well for manipulating the selection box.

To counteract the selection box's lack of occlusion cues we implemented a variant of the silk cursor [Zhai et al. 1994]. In our variant objects behind the box were completely occluded, objects inside the box were seen through a layer of silk, and

objects in front of the box were viewed as normal. With the silk cursor objects inside of the box were easily distinguished from objects outside of the box (Figure 19).



**Figure 19 - Iterated selection box design using the silk cursor.**

The size of the camera screen for the tablet techniques was increased by 24% in order to counteract some of the problems caused by tracker jitter. This also allowed users to position the camera further away from the desired objects and select more targets at one time. The lasso previously used a selection toggle operation and participants found this non-intuitive as well as frustrating. Select and de-select modes were added to the lasso technique; modes were changed with buttons on the tablet.

## Chapter 6 - Summative Evaluation

The most surprising result of our formative evaluation was the poor usability of the parallel techniques. Intuitively, parallel techniques should provide a distinct advantage when selecting a large number of objects. In our second experiment, we aimed to demonstrate these benefits and to determine why the parallel techniques were less successful in the first study.

### 6.1 Goals and Environment

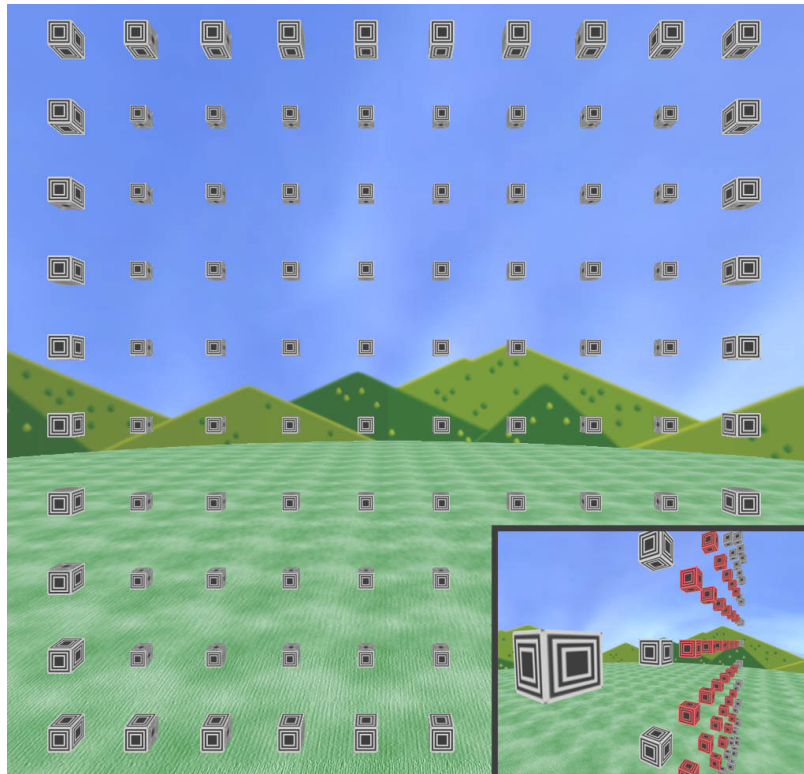
A limitation of our first experiment was that the number of objects in the target sets was rather small. With an average of 10 objects per set the advantage of parallel selection over serial selection was minimal. As the number of object approached 30 we began to notice a difference in performance between the serial and parallel techniques. For our second study we wanted to examine the effect of the number of target objects on task completion time with each technique more closely.

We found that the learnability of each technique was quite different with the serial techniques typically being easier for the participants to understand. However, what interested us most was what the performance of each technique would be when performed by users who were experienced with the techniques. We wanted to know which technique would be best in an application that was used daily by an expert user. We did not have a large subject pool of expert users nor did we have enough time to train every participant to the performance level of an expert user. Therefore, in this study we attempted to create a task that was simple enough so that novice users could perform at the level of expert users with moderate training.

Observations from our first study showed that time required for the navigation component of selection could vary greatly depending on the technique and the target selection set. As much is already known about navigation techniques we decided to eliminate this variable from our second study and seat the user in one place. The choice of navigation technique is very important and we believe that it will significantly affect the usability of the MOS technique but for our final study we choose to instead focus on the manipulation and execution components of the techniques. To eliminate the need for a navigation component we created an environment where there was no occlusion and objects were always in the user's view.

With these goals in mind we designed an environment (Figure 20) that consisted of a 13m x 13m wall made up of 100 cubes spaced 1.3m apart (center-to-center). The wall was positioned 10m away from the user so that it could be viewed without the user having to turn their head. The camera used in the tablet-based techniques was positioned so that all cubes were visible on the camera screen. The cubes were textured to contrast highly with the background. All sets of target cubes

were located in the center of the wall. The cubes along the perimeter of the wall served as a boundary so that tasks using volume based techniques had to be constrained.



**Figure 20 - Environment used for the summative evaluation.**

## 6.2 Variables and Tasks

We chose four independent variables for our trials: concurrency, spatial context, number of targets and target size. The first two variables corresponded with the portion of the MOS design space we are exploring with our four techniques. By varying the number of targets we expected to demonstrate that as the number of targets increases the performance gap between parallel and serial tasks increases. The size of the objects seemed to have a significant effect on the ease of selection for the serial techniques. Selecting small objects from a distance required more precise movement of the input device than that required to select large objects. We had also observed that our parallel techniques had difficulty selecting objects when the targets were very close together. When the space between targets was small participants would often unintentionally select non-target objects. We chose to use target size as a variable in our experiment so that we could better understand its effect on the techniques.

The task for this experiment was simple: select all of the red cubes on the wall and none of the grey cubes. When this condition was met the trial ended and a wall was placed in front of the user blocking their view. The target (red) cubes were always in the center of the wall forming a square. Grey cubes always bounded the target cubes so that the participants had to constrain the volume techniques for all tasks. Trials started when the participant pressed a button on the wand and ended upon selection of the entire target set. To cut down on experiment length we chose to use a mixed methods design. Participants were assigned either 3D or Tablet techniques and repeated all combinations of the other independent variables three times completing a total of 54 trials. Trials were blocked by technique; the ordering of the other variables was randomized.

The dependent variable for our study was time to select all targets. Values for the independent variables were as follows:

- Technique Concurrency: Serial, Parallel
- Technique Spatial Context: 3D, Tablet
- Number of targets: 9, 36, 64
- Target size: 30cm, 37.5cm, 45cm

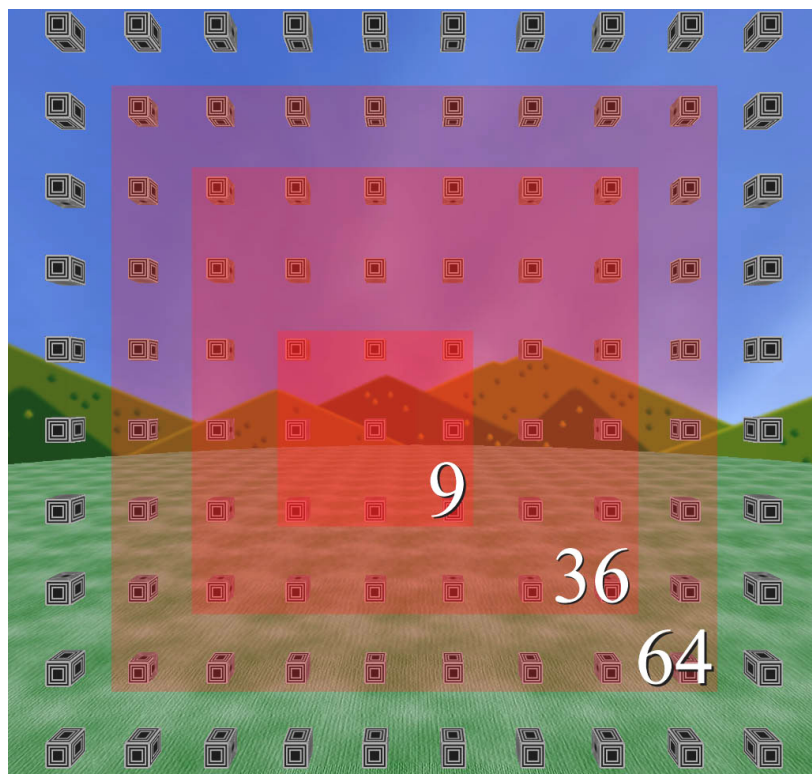


Figure 21 - 3 Target sets with medium size cubes.

### 6.3 Participants



Eighteen participants were recruited for the experiment. Nine subjects were assigned the tablet techniques and nine were assigned the 3D. Participant ages ranged from 20 to 35; six participants were female and twelve were male. Eleven subjects were computer science undergraduates and seven were from various other majors and professions.

## 6.4 Procedure

The procedure for the second experiment was more controlled than that of the first experiment. Participants were required to reach a minimum level of proficiency with both techniques before beginning the measured trials. Subjects were shown an effective strategy for selecting the objects during the training. Proficiency was measured by a minimum time to select a set of 36 medium-sized targets. The minimum time to complete the tasks was 1.5 times the recorded times of an expert user. Participants repeated the practice condition until they completed the task in less than the minimum time. During the experiment participants were asked to complete the trials as quickly as possible, holding questions or comments until breaks. A grey wall occluded the participants' view of the targets between trials so that they could not prepare for selection before starting the task. When ready participants pressed a button to remove the wall and begin the task. Once the task was completed the wall returned and the participant could rest or continue to the next task. Participants took rest breaks when they completed all tasks with their first technique as well as every fifteen minutes. As with the first experiment participants filled out a post-experiment questionnaire when finished.

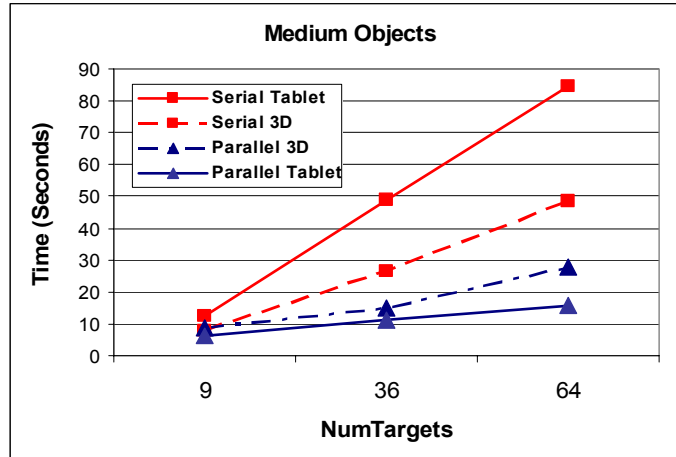
## 6.5 Objective Results

In chapter 2 we stated our hypotheses for 3D MOS techniques. Here we present our analysis of our data from the two experiments. We restate our three hypotheses here for convenience:

- *Parallel MOS techniques become can be performed faster than serial MOS techniques as the number of target objects increases.*
- *-3D MOS techniques can select objects faster in a 3D environment than 3D techniques that interact through a 2D plane.*
- *-3D MOS techniques that use 2D MOS metaphors are easier for users to learn than true 3D MOS techniques.*

To estimate the expert performance of the techniques we analyzed the data using only the fastest trials of each condition for each participant (Appendix D). While certainly not the most accurate measure of expert performance we felt that by

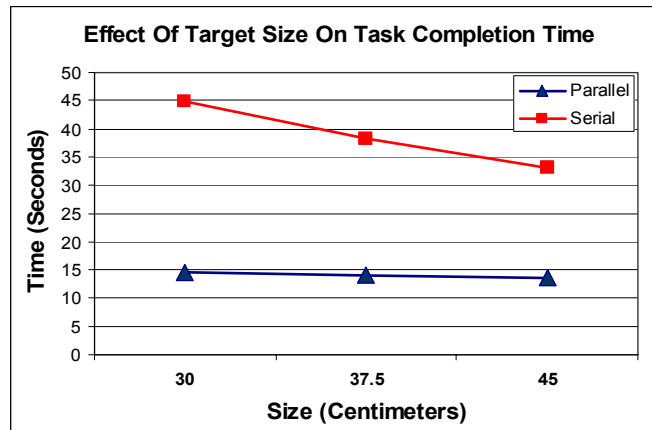
looking at the fastest trials we could estimate the potential of each technique when performed correctly. With the training requirements and the three repetitions most all participants were able to complete at least one repetition of each condition with no problems.



**Figure 22 - Best Trial Averages for Medium Targets**

We used a multi-factor analysis of variance (MANOVA) on the time data and found main effects of concurrency, target size, and number of targets. Figure 22 shows representative results from the medium object size condition. A very strong effect of concurrency ( $p < .0001$ ) indicates that the parallel techniques were significantly faster than their serial counterparts. We also found a strong interaction between concurrency and number of targets ( $p < .0001$ ). As the number of targets increased the performance gap between parallel and serial techniques widened. This result supports our first hypothesis that parallel techniques would be superior as the number of objects increases. A post-hoc least squares means test showed that there was still a significant effect of concurrency in the 9 target conditions. Both serial and parallel techniques performed well for the 9 target condition, but as the number increased the advantage of using parallel techniques became clear.

We also hypothesized that small objects would be harder to select using serial techniques. Our analysis showed that serial techniques were affected by changes in size whereas parallel techniques were not (Figure 23). A least squares means test did not show an effect of target size on parallel techniques ( $p = .4108$ ) and a large effect of size on serial techniques ( $p < .0001$ ).

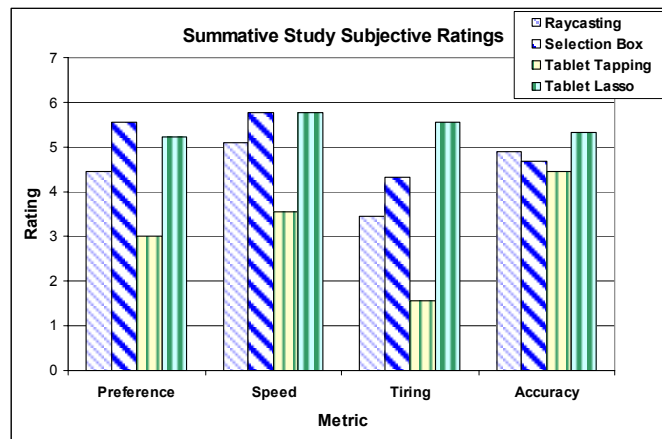


**Figure 23 - Effect of Target Size on Task Completion Time**

Our second hypothesis claimed that techniques using the 3D context would be superior to tablet techniques. We found no effect of spatial context in our results ( $p = .3378$ ). For the parallel techniques the lasso technique outperformed selection box, yet for the serial techniques ray-casting outperformed tablet tapping. Thus with this experiment we could not determine if 3D or tablet techniques were superior for this MOS task.

## 6.6 Subjective Results

Participants were asked to fill out a post-questionnaire identical to the questionnaire in the exploratory study. The results differed greatly from those of the first experiment in that the ratings of the parallel techniques had greatly improved (Figure 24). Parallel techniques received higher ratings than serial techniques in all categories except accuracy. Accuracy is a difficult metric to compare between serial and parallel selection. With serial techniques the accuracy is very highly affected by the accuracy of the tracking system whereas with parallel techniques this is not always the case. Participants commented that the accuracy of the selection box was greatly affected by the sensitivity of the joystick for resizing and the difficulty in determining the depth of the selection box. With the accuracy question we queried the participants' general feel for the accuracy of the technique but to truly gauge accuracy more thorough questioning would be required.



**Figure 24 - Subjective ratings in the summative evaluation**

From our observations we attribute the improvement of the parallel techniques to the iterated design of the techniques and to the optimal nature of the task for volume selection techniques. The lack of navigation in our tasks was noticed by the participants some of whom commented that ray-casting might be easier if they could move closer to the objects. The lack of camera manipulation also contributed to the improvement of the tablet techniques as this was a large portion of the time spent selecting in the first experiment.

Comments were in line with the subjective ratings: “the lasso was quicker but a little more inaccurate”, “the selection box was much faster, but ray-casting was OK for a few boxes”. One participant commented that manipulating the selection box was mentally tiring and that ray-casting was physically tiring. Some participants also suggested ways to improve the techniques. Many felt that moving the pointer over the tablet was difficult due to position in which the wand was held. One participant suggested holding the wand like a mouse against the surface, but the added friction made this difficult. A 3D pointing device with a flat side to be used on a flat surface, like a mouse, could be very well suited for tablet techniques. Many participants had difficult understanding which objects the ray intersected with the ray-casting technique. In our implementation the ray continued to pass through the objects to infinity. One participant suggested having the ray stop at the first intersected object to eliminate this confusion. We have since implemented this functionality with very good results.

We observed no significant difference in user strategies during the experiment. In the practice session participants were shown an effective strategy for all techniques and most all continued to use those strategies during the experiment. For the tablet lasso technique participants drew a U around the target objects and allowed the software to complete the selection. For the selection box participants moved the box to the upper left corner of the target set and resized the box right and down. This

was chosen most often as the PORT technique was easier to perform when resizing right and down then resizing left or up. The largest variation in strategy we observed was the order in which participants selected boxes with the serial techniques. Most participants selected the boxes in a zig-zag pattern but some experiments with block and spiral patterns. These strategies seemed to have little effect on the effectiveness of these techniques.

As subjects were divided into 3D and Tablet groups we could not directly compare the learnability of the techniques in this experiment. From our first experiment we found that the serial techniques were more easily learned than the parallel techniques and that result was seen again in the second experiment. Our third hypothesis was that tablet techniques would be easier to learn than 3D techniques and while we have no direct evidence of this due to our experiment setup we did notice that participants seemed more comfortable with the tablet techniques and tended to meet the training requirements more quickly than those who used the 3D techniques.

## 6.7 Discussion

Participants performed well when using both the 3D and tablet techniques. Participants were able to learn how select objects using both metaphors. The tablet techniques also constrained the movement of the pointer to the handheld 2D surface simplifying movement as well as benefiting from the user's proprioceptive sense. Tracker jitter was a problem for both tablet techniques and should be accounted for by designers. As mentioned in the user comments the way in which the wand was held made precise selection more challenging. The wand was held in the palm of the hand and supported between the thumb and index finger. Cutkosky [1989] labels this technique as the *power grasp* and studies have shown that this is best used for tasks where force is required to perform an action. The *precision grasp*, where the object is held at the tips of the fingers away from the palm, is better suited for tasks requiring precise movement. A device held in a precision grasp and constrained against the tablet would eliminate some of the issues with tablet techniques and perhaps improve their performance. Previous pen and tablet interfaces have used a stylus-like device for interacting with the tablet. Stylus devices are held with a precision grasp and are capable of precise movements. By choosing to use a wand device in our experiment we were able to use the same set of devices for all four techniques, with perhaps some cost of accuracy in the tablet techniques.

Extended use of the tablet also caused back and neck discomfort for the participants making it less than ideal as the primary mode of interaction. The participants typically held the tablet above their lap causing them to look down for extended periods of time. The weight of the HMD contributed to this fatigue and required participants to take rest breaks more often. Due to fatigue issues we recommend using tablet MOS techniques when the selection task is intermittent to

reduce strain on the user. Raising up the virtual representation of the tablet may reduce this fatigue at the expense of some proprioceptive confusion. By raising the virtual representation the user would not have to look down when interacting with the tablet; this has been done with the TULIP menus [Bowman, Wingrave 2001] with good success.

Our serial techniques both specified a 1D ray that was simple to manipulate using a 6-DOF input device. Due to the accuracy required to precisely orient the ray our techniques were greatly affected by the size of the target objects. The lower the dimensionality of the IO, the greater the effect of object size on the difficulty of selection. The parallel techniques that we implemented require much more navigation and manipulation before selection can occur. This is due partly to the higher dimensionality of the IOs specified with the parallel techniques. With both of the parallel techniques the IO is a 3D volume. Accurately describing a volume is a difficult task that requires powerful and expressive 3D interaction techniques. Parallel techniques can make up for their longer set-up time by requiring fewer repetitions to select a set. Parallel MOS techniques are not affected by object size but are affected by the shape of the target set and its proximity to non-target objects.

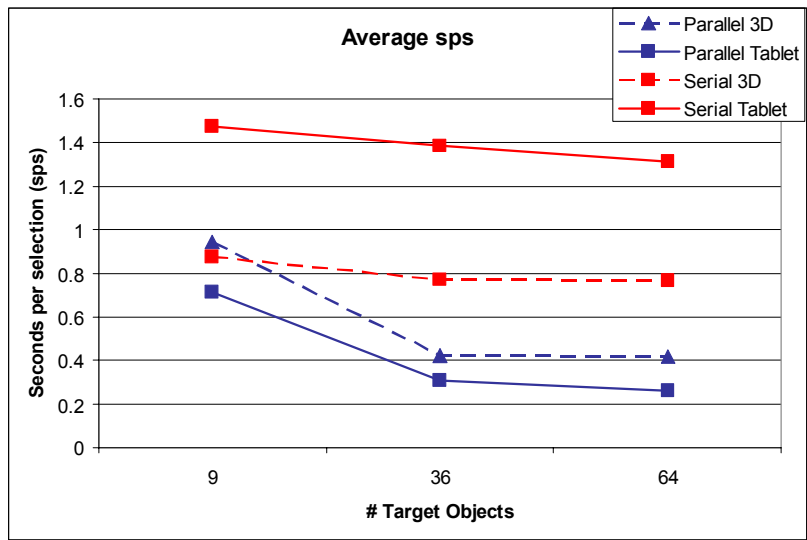


Figure 25 – Average sps for the techniques with the 3 target sets.

Serial MOS techniques, due to their nature, scale linearly as the number of target objects increases. Serial selection is very effective for selecting small numbers of objects as it often requires very little manipulation per selection. As the number of targets increases the number of selections and the time to complete the tasks increase. Parallel selection techniques require more manipulation before selection can begin but once the initial setup is performed the amount of time per object selected becomes very low. Thus the more objects selected with parallel selection techniques the smaller the time to select each object. We propose seconds per selection (sps) as a metric for evaluating MOS techniques. We averaged the selection times

for all trials in our experiment and found that the average sps for the parallel techniques decreased much more than the serial techniques as the number of objects increases (see Figure 25). We set out to show that parallel techniques are faster for selecting large groups of objects and we feel our results prove that they are a worthwhile addition when MOS is needed.

## Chapter 7 - Conclusions and Future Work

### 7.1 Summary

3D multiple object selection is an important and relatively unexplored interaction task. In our research, we have designed novel techniques for 3D MOS, developed a taxonomy to represent the design space for these techniques, and used the taxonomy as a framework for evaluating the techniques both formally and informally. Our first study showed that serial techniques are easier to understand and require less initial setup time. The usability of parallel techniques is much more subject to the effects of user strategy and sophistication. In our second study, however, we showed that parallel MOS techniques can be superior to serial MOS techniques when certain conditions exist:

- The number of target objects is large.
- The technique takes advantage of the environment's structure.
- When small target sizes make the use of serial techniques challenging.
- The time spent navigating or setting up camera views can be minimized.

Asking whether to use serial or parallel MOS techniques in an application is the wrong question. The important question is whether to use parallel techniques *in addition* to serial techniques. When the conditions outlined above are not met, parallel selection may add unneeded complexity to an application. On the other hand, in the right conditions adding parallel selection techniques to an application could greatly speed up selection tasks.

### 7.2 Contributions

Here we list our contributions to the field of 3D interaction techniques.

- We have presented a first look at the task of 3D multiple object selection with the hope that it will inspire future work in designing multiple object interaction techniques for immersive environments.
- We have created a taxonomy of the design space of 3D MOS techniques to aid future researchers in building new MOS techniques.
- We presented two novel MOS techniques, the 3D selection box and tablet lassos, and evaluated them against two existing MOS techniques, ray-casting and tablet tapping.
- We created a novel object resizing techniques called PORT for directly manipulating the size of objects in VEs.



- We developed a testbed for evaluating MOS techniques and made the code available to be used to evaluate future MOS techniques.
- We leave off with a list of questions that need to be researched in order for 3D MOS techniques to reach their full potential.

With more powerful interfaces, both the fields of Virtual and Augmented Reality can grow into new domains that were previously impractical with existing interaction techniques. We feel that our work advanced the state of the art of 3D interaction techniques and brought attention to the need of more powerful selection techniques.

### **7.3 Future Work**

One challenge we attempted to overcome in our research was that of a lack of experienced VE users to test our interaction techniques. As VE interaction techniques are developed that build upon existing techniques it becomes important to have subjects who are at least familiar with VEs and preferably familiar with how to interact with them. When designing interaction techniques that are going to be used by experienced users we need experienced users to test them. In this experiment we attempted to approximate expert performance by training less experienced users and by looking at their peak performances. Attempts should be made to find experienced users for VE evaluations but as this is very rarely possible future work should look into determining how to best evaluate more complicated interaction techniques using less experienced VE users.

We have only examined MOS based on the spatial attributes of the objects in the world. Selecting objects based on non-spatial attributes is another very powerful method for selection. Non-spatial attributes can range from color, to shape, or even relationships between objects. With the proper non-spatial attribute selection one could select all red placemats that sit on top of blue tables. Non-spatial attribute selection is especially helpful when combined with spatial selection. The combination is often referred to as filtering where objects can be removed from consideration with non-spatial selection techniques and the final selection is then made using spatial techniques. It is not known how to best use non-spatial selection techniques in VEs and future research should examine this problem as well as how to combine spatial and non-spatial selection techniques.

Our understanding of 3D MOS techniques is still very limited. The design space of 3D MOS techniques is very large and much exploration needs to be done in order to understand the advantages and disadvantages of the design choices for each

branch. The techniques we examined have proven effective for the generic environments in our experiments. A key challenge for the design of usable parallel techniques is to minimize the time to navigate and manipulate the IO. Potential solutions to these problems include: more specialized manipulation techniques for working with objects at a distance, constraining manipulation of the IO to a grid or embedding more depth information into the IO itself. Much can be adapted from 2D interfaces as far as IO manipulation. Photo editing software allows for complex area selections with specialized lassos and masks. These concepts could be adapted to 3D selection for advanced interfaces.

We hypothesize that a camera manipulation technique that allows for remote manipulation of the camera would be more effective than the technique that we chose. We also hypothesize that camera views would be effective for working with two separate areas of an environment simultaneously. Future work on camera based techniques should look into view management issues as well as compare the effectiveness of separate camera views with techniques that use the current view. Future research using techniques in the image context should also compare the effectiveness of freehand lassos with box lassos. We found that the precision of the trackers made freehand lassos difficult to draw and box lassos may eliminate this problem.

In our experiments we only examined selection using spatial attributes. Filtering objects from consideration using non-spatial attributes such as color or shape has been proven to be effective in 2D information visualization applications, and should be investigated for 3D MOS techniques. Other information visualization techniques such as linked views could be useful for selection in dense environments.

There has been little research in 3D MOS techniques. We have listed these research questions to inspire future research in a field with much potential.

## References

- ADOBE SYSTEMS, INC., PHOTOSHOP™ CS, 2004. COMPUTER PROGRAM.
- ANGUS, I., SOWIZRAL, H. 1995, EMBEDDING THE 2D INTERACTION METAPHOR IN A REAL 3D VIRTUAL ENVIRONMENT. *In Proceedings of SPIE (Stereoscopic Displays and Virtual Reality Systems)*, 282-293.
- BALDONADO, M., WOODRUFF, A., KUCHINSKY, A., 2000, GUIDELINES FOR USING MULTIPLE VIEWS IN INFORMATION VISUALIZATION, *Proceedings of the working conference on Advanced visual interfaces, ACM, 110 – 119.*
- BOWMAN, D., JOHNSON, D., HODGES, L. 2001, TESTBED EVALUATION OF VIRTUAL ENVIRONMENT INTERACTION TECHNIQUES. *Presence: Teleoperators and Virtual Environments, 10(1), 75-95.*
- BOWMAN, D. AND WINGRAVE, C. 2001, DESIGN AND EVALUATION OF MENU SYSTEMS FOR IMMERSIVE VIRTUAL ENVIRONMENTS. *Proceedings of IEEE Virtual Reality, 149-156.*
- BOWMAN, D. SETAREH, M., PINHO, M.S., ALI, N., KALITA, A., LEE, Y., LUCAS, J., GRACEY, M., KOTHAPALLI, M., ZHU, Q., DATEY, A., AND TUMATI, P. 2003, VIRTUAL-SAP: AN IMMERSIVE TOOL FOR VISUALIZING THE RESPONSE OF BUILDING STRUCTURE TO ENVIRONMENTAL CONDITIONS. *Proceedings of the IEEE Virtual Reality, 243-250.*
- BOWMAN, D., KRUIFF, E., LAVIOLA, J., POUPYREV, I. 2004, 3D USER INTERFACES: THEORY AND PRACTICE, *Addison-Wesley Professional*
- CARD, S., MACKINLAY, J., ROBERTSON, G., 1990 THE DESIGN SPACE OF INPUT DEVICES, *Proceedings of the SIGCHI conference on Human factors in computing systems: Empowering people, ACM, 174 – 124.*
- CHEN, J., BOWMAN, D., LUCAS, J., WINGRAVE, C. 2004, INTERFACES FOR CLONING IN IMMERSIVE VIRTUAL ENVIRONMENTS. *Proceedings of the Eurographics Symposium on Virtual Environments, 91-98,*
- M. R. Cutkosky, "On Grasp Choice, Grasp Models, and the Design of Hands for Manufacturing Tasks," *IEEE Trans. on Robotics and Automation, 5(3):269--279, 1989.*
- DARRAH, M., KIME, A., VAN SCOY, F. 2002, A TOOL FOR EDITING 3-D OBJECTS: IMPLEMENTED USING A HAPTICS DEVICE. *Proceedings of PHANTOM User Group Workshop.*
- EHMANN, S., LIN, M. 2001, ACCURATE AND FAST PROXIMITY QUERIES BETWEEN POLYHEDRA USING SURFACE DECOMPOSITION *Computer Graphics Forum (Proceedings of the Eurographics Symposium on Virtual Environments)*
- HAAN, G., KOUTEK, M., POST, F. 2002, TOWARDS INTUITIVE EXPLORATION TOOLS FOR DATA VISUALIZATION IN VR, *Proceedings of the ACM symposium on Virtual reality software and technology, 105-112*
- KESSLER, G., BOWMAN, D., HODGES, L. 2000, THE SIMPLE VIRTUAL ENVIRONMENT LIBRARY: AN EXTENSIBLE FRAMEWORK FOR BUILDING VE APPLICATIONS. *Presence: Teleoperators and virtual environments, 9(2), 187-208.*

- LIANG, J., AND GREEN, M. 1994, JDCAD: A HIGHLY INTERACTIVE 3D MODELING SYSTEM. *Computers & Graphics*, 18(4), 499-506.
- MINE, M., 1995, VIRTUAL ENVIRONMENT INTERACTION TECHNIQUES, *UNC Chapel Hill Computer Technical Report, TR95-01*.
- PIERCE, J., FORSBERG, M., CONWAY, M., HONG, R., ZELEZNIK, R., MINE, M., 1997, IMAGE PLANE INTERACTION TECHNIQUES IN 3D IMMERSIVE ENVIRONMENTS. *In Proceedings of SIGGRAPH Symposium on Interactive 3D Graphics, ACM, 39-44*.
- PIERCE, J., STEARNS, B., PAUSCH, R., 1999, VODOO DOLLS: SEAMLESS INTERACTION AT MULTIPLE SCALES IN VIRTUAL ENVIRONMENTS. *Proceedings of the 1999 symposium on Interactive 3D graphics, ACM, 141-145*
- POUPYREV, I., ICHIKAWA, T., 1999, MANIPULATING OBJECTS IN VIRTUAL WORLDS: CATEGORIZATION AND EMPIRICAL EVALUATION OF INTERACTION TECHNIQUES. *Journal of Visual Languages and Computing*, 10(1), 19-35
- POUPYREV, I., BILLINGHURST, M., WEGHORST, S., ICHIKAWA, T. 1996, THE GO-GO INTERACTION TECHNIQUE: NON-LINEAR MAPPING FOR DIRECT MANIPULATION IN VR. *In Proceedings of User Interface Software and Technology, 79 – 80*.
- SHEWCHUK, J. 1996, TRIANGLE: ENGINEERING A 2D QUALITY MESH GENERATOR AND DELAUNAY TRIANGULATOR, *In First Workshop on Applied Computational, ACM, 124-133*.
- SCHMALSTIEG, D., ENCARNACÃO, L., SZALAVÁRI, Z. 1999, USING TRANSPARENT PROPS FOR INTERACTION WITH THE VIRTUAL TABLE, *Proceedings of the 1999 symposium on Interactive 3D graphics, 147-153*
- STEED, A., PARKER, C. 2004, 3D SELECTION STRATEGIES FOR HEAD TRACKED AND NON-HEAD TRACKED OPERATION OF SPATIALLY IMMERSIVE DISPLAYS. *8<sup>th</sup> International Immersive Projection Technology Workshop*
- Z. SZALAVÁRI, Z., GERVAUTZ, M. 1997, THE PERSONAL INTERACTION PANEL - A TWO HANDED INTERFACE FOR AUGMENTED REALITY. *Computer Graphics Forum (Proceedings of EUROGRAPHICS'97), 16(3), 335–346*.
- STOEV, S., SCHMALSTIEG, D. 2002 APPLICATION AND TAXONOMY OF THROUGH-THE-LENS TECHNIQUES, *Proceedings of the ACM symposium on Virtual reality software and technology, 57-64*
- WARE, C., OSBORNE, S. 1990, EXPLORATION AND VIRTUAL CAMERA CONTROL IN VIRTUAL THREE DIMENSIONAL ENVIRONMENTS. *In Proceedings of the 1990 Symposium on Interactive 3D Graphics, Special Issue of Computer Graphics, Vol. 24, 175–183*.
- G. J. WILLS, 1996, SELECTION: 524,288 WAYS TO SAY "THIS IS INTERESTING", *PROCEEDINGS OF THE 1996 IEEE SYMPOSIUM ON INFORMATION VISUALIZATION, 54-60*.
- ZHAI, S., BUXTON, W., MILGRAM, P. 1994, THE "SILK CURSOR": INVESTIGATING TRANSPARENCY FOR 3D TARGET ACQUISITION, *In Proceedings of Computer Human Interaction, 459-464*.

## **Appendix A – Forms**

### **A.1 Formative Evaluation Introduction**

# **Multiple Object Selection Techniques Study**

## **Formative Evaluation – Introduction**

### **Introduction:**

To begin, thank you for volunteering to participate in our study. As you may know this study takes place in an immersive Virtual Environment using a head mounted display. If you are prone to motion sickness or dizziness please let the evaluator know before beginning.

The purpose of this study is to gain knowledge about the design space of 3D multiple object selection (MOS) techniques. You may be familiar with 2D MOS techniques from using window based user interfaces. An example of a 2D MOS technique is dragging a box around a set of icons to select them. We will try several different 3D MOS techniques for this study some of which may be similar to 2D techniques you may have used on your desktop.

First the evaluator will explain to you how to put on the HMD and how to move around in the environment. He will then explain to you how to use each of the selection techniques and give you some time to try them out. After you have had some time to practice the techniques the experiment will begin.

The task for this study will be to select the red highlighted objects in several different environments using each of the four selection techniques. You will be given instructions on when to start each task. For some tasks you may be asked to think-aloud, meaning to talk about how you go about the task, and for other tasks you may be asked to simply select the objects as quickly as possible.

The evaluator will be asking you questions about your experience throughout the experiment. Please answer the questions with as much detail as possible as your feedback will be directly used to improve these techniques.

It is important that you understand we are not evaluating your performance in the environment, but that we are evaluating the techniques themselves.

**Thanks for participating!**

**A.2 Formative Evaluation Pre-Questionnaire**

**Multiple Object Selection Techniques Study  
Pre-experiment Questionnaire.**

**Subject#** \_\_\_\_\_

**Pr1:** Age: \_\_\_\_\_

**Pr2:** Gender: M\_\_\_\_\_ F\_\_\_\_\_

**Pr3:** Please rate your experience level with immersive Virtual Environments.

- \_\_\_\_\_ Novice
- \_\_\_\_\_ Some Experience
- \_\_\_\_\_ Experienced
- \_\_\_\_\_ Expert

**Pr4:** Please rate your experience level with 3D modeling or CAD.

- \_\_\_\_\_ Novice
- \_\_\_\_\_ Some Experience
- \_\_\_\_\_ Experienced
- \_\_\_\_\_ Expert

**Pr5:** Please rate how often you play 3D video games.

- \_\_\_\_\_ Never play.
- \_\_\_\_\_ A few times a year.
- \_\_\_\_\_ A few times a month.
- \_\_\_\_\_ A few times a week.
- \_\_\_\_\_ A few times a day.

**Pr6:** Please rate your familiarity with 2D MOS techniques

- \_\_\_\_\_ Not familiar.
- \_\_\_\_\_ Somewhat familiar.
- \_\_\_\_\_ Very familiar.

**Pr7:** What is your occupation? If student please state your major. \_\_\_\_\_

**Pr8:** Is your vision 20/20 or corrected to 20/20 with glasses or contacts? \_\_\_\_\_

**Pr9:** Are you left or right handed? Left\_\_\_\_\_ Right\_\_\_\_\_

**A.3 Formative Evaluation Post-Questionnaire**

**Multiple Object Selection Techniques Study  
Formative Evaluation – Post Experiment Questionnaire**

**Question P1-4:** Please rate the techniques according to your personal preference:  
7: Liked a lot. 1: Did not like at all.

- P1**    \_\_\_ Raycasting
- P2**    \_\_\_ Selection Box
- P3**    \_\_\_ Tablet Tapping
- P4**    \_\_\_ Tablet Lasso

**Question P5-8:** Please rate the techniques according to how fast you were able to complete the tasks. 7: Very fast. 1: Very Slow.

- P5**    \_\_\_ Raycasting
- P6**    \_\_\_ Selection Box
- P7**    \_\_\_ Tablet Tapping
- P8**    \_\_\_ Tablet Lasso

**Question P9-12:** Please rate the techniques according to how tiring the techniques were.  
7: Very tiring. 1: Not tiring at all.

- P9**    \_\_\_ Raycasting
- P10**   \_\_\_ Selection Box
- P11**   \_\_\_ Tablet Tapping
- P12**   \_\_\_ Tablet Lasso

**Question P13-16:** Please rate the techniques according to how accurate selection with the techniques was. 7: Very Accurate. 1: Not Accurate at all.

- P13**   \_\_\_ Raycasting
- P14**   \_\_\_ Selection Box
- P15**   \_\_\_ Tablet Tapping
- P16**   \_\_\_ Tablet Lasso

**Thank You!**

#### A.4 Formative Evaluation Plan and Questions

### Multiple Object Selection Techniques Study Formative Evaluation – Plan and questions

#### **Intro:**

- Evaluator: Hello & Welcome
- Subject: Read Introduction & Intro Questionnaire
- Evaluator: Hardware introduction.

#### **Training (Columns Environment):**

- Subject: Put on HMD, left headphone down.
- Evaluator: HMD movement intro. Turning, Walking, Squatting.
- Subject: Pick up wand.
- Evaluator: Navigation intro. Dirs: Forward, back, up, down. Views: Front, Top, Back
- Evaluator: Home base intro. Have user do two laps around the environment.
- Evaluator: Raycasting intro. Indicate, select, deselect.
- Evaluator: Selection Box intro: Resize: 6 Dir Pull, Joystick. Select, Grab, Position, Drop
- Subject: Pick up tablet.
- Evaluator: Selection Box contd. Resize via tablet, call SB.
- Subject: Switch to Raycasting.
- Evaluator: Technique buttons. Deselect all button.
- Subject: Switch to tablet tapping
- Evaluator: Tablet intro. Point out camera, explain mapping. Explain tapping.
- Evaluator: Camera movement. Call camera, grab camera.
- Evaluator: Tablet lasso. Simple lassos, Explain wireframe, lasso timeout
  
- Subject: Exploration until they feel comfortable.
- Evaluator: Training End and questions.



**Building Environment (SB Resize Test):**

-Evaluator: Describe SB Resize test.

-Subject: Repeat 1 selection set with all 3 SB resize techniques.

*Question SBT1:* Please rate the 3 techniques from most favorite to least favorite.

*Question SBT2:* Please rate the 3 techniques from easiest to use to hardest to use.

**Environment 1:**

-Subject: Navigate through the environment.

-Evaluator: Explain desired set. Have subject navigate to home position.

-Subject: Select set using technique 1

-Evaluator: Post set questions.

Wash, Rinse, Repeat for all techniques and environments.

First set: Think aloud, time not important.

Second set: No think aloud, timing important.

Third set: Think aloud, final comments.

-Evaluator: Post technique questions.

After each set:

*Question ES1:* Did you feel this technique was an effective technique for selecting this set of objects? No 1 – 7 Yes

After each technique

*Question ET1:* Did you feel frustrated using this technique at any point?

*Question ET2:* For this technique rate your agreement with this statement from 1 to 7. I was able to select the objects I wanted with this technique.

*Question ET3:* For this technique rate your agreement with this statement from 1 to 7. I was able to avoid selecting the objects I did not want with this technique.

*Question ET3:* For this technique rate your agreement with this statement from 1 to 7. It was easy to find a location from where I could select all the objects I wanted.

*Question ET4:* How tiring was this technique to you? 1: Not tiring at all 7: Very tiring.

**A.5 Formative Evaluation Experimenter Evaluation Form**

**Multiple Object Selection Techniques Study      Subject# \_\_\_\_\_**  
**Formative Evaluation – Experimenter Observation Form**

**SB Resize Test:**

*Question SBT1:* Please rate the 3 techniques from most favorite to least favorite.  
Response:

*Question SBT2:* Please rate the 3 techniques from easiest to use to hardest to use.  
Response:

**Environment:** \_\_\_\_\_

**Technique 1:** \_\_\_\_\_  
Selection Strategies:

*Question ES1: Set 1: effective technique? Rating: \_\_\_\_\_*

*Question ES2: Set 2: effective technique? Rating: \_\_\_\_\_*

End of technique questions:

*Question ET1: Frustration*

*Question ET2: Positive Select*

Rating: \_\_\_\_\_

Comments:

*Question ET3: Negative Select*

Rating: \_\_\_\_\_

Comments:

*Question ET3: Location*

Rating: \_\_\_\_\_

Comments:

*Question ET4: Tiredness*

*Rating: \_\_\_\_\_*  
*Comments:*

**Technique 2:** \_\_\_\_\_

Selection Strategies:

*Question ES1: Set 1: effective technique? Rating: \_\_\_\_\_*

*Question ES2: Set 2: effective technique? Rating: \_\_\_\_\_*

End of technique questions:

*Question ET1: Frustration*

*Question ET2: Positive Select*

*Rating: \_\_\_\_\_*

*Comments:*

*Question ET3: Negative Select*

*Rating: \_\_\_\_\_*

*Comments:*

*Question ET3: Location*

*Rating: \_\_\_\_\_*

*Comments:*

*Question ET4: Tiredness*

*Rating: \_\_\_\_\_*

*Comments:*

**Technique 3:** \_\_\_\_\_

Selection Strategies:

*Question ES1: Set 1: effective technique? Rating: \_\_\_\_\_*

*Question ES2: Set 2: effective technique? Rating: \_\_\_\_\_*

End of technique questions:

*Question ET1: Frustration*

*Question ET2: Positive Select*

*Rating: \_\_\_\_\_*

*Comments:*

*Question ET3: Negative Select*

*Rating: \_\_\_\_\_*

*Comments:*

*Question ET3: Location*

*Rating: \_\_\_\_\_*

*Comments:*

*Question ET4: Tiredness*

*Rating: \_\_\_\_\_*

*Comments:*

**Technique 4:** \_\_\_\_\_

Selection Strategies:

*Question ES1: Set 1: effective technique? Rating: \_\_\_\_\_*

*Question ES2: Set 2: effective technique? Rating: \_\_\_\_\_*

End of technique questions:

*Question ET1: Frustration*

*Question ET2: Positive Select*

*Rating: \_\_\_\_\_*

*Comments:*

*Question ET3: Negative Select*

*Rating: \_\_\_\_\_*

*Comments:*

*Question ET3: Location*

*Rating: \_\_\_\_\_*

*Comments:*

*Question ET4: Tiredness*

*Rating: \_\_\_\_\_*

*Comments:*

## Appendix B – Formative Evaluation Subjective Results

### B.1 Formative Evaluation Comments and Observations

## Multiple Object Selection Techniques Study Formative Evaluation – Comments and Observations

### Pilot Subject:

#### Observations:

- User rarely used both the tablet and the world view in conjunction.
- User took 5 minutes to complete lasso selection on the large building set.
- User had problems with the lower frame rate on camera techniques.

### Subject 1:

Environment order: Building, Tunnel, Tiles, Random

Technique order: RC, TL, SB, TC

#### Observations:

- User only used addition selection for both volume techniques. Addition then subtraction techniques were not used except during errors.
- User often used both the camera view and the world view to confirm selection.

#### Comments:

On selection box:

- Subject initially preferred tablet controls, but eventually learned that the joystick resize could be more effective with practice.
- Subject stated that he would prefer that the direction be locked to one direction at the start of resize.
- “I like this one”
- Subject noted that it was difficult to perceive the depth at which the box started and stopped.

On Raycasting:

“mundane, tedious”

- Subject suggested placing a dot at the point the ray intersected the object. He was confused when the object became transparent and could see through the object.

On Tablet Lasso:

“tricky to not select objects that are not included in the selection set.”

- Subject noted that the lasso was very effective when objects were lined up in a row.

On Tablet Tapping:

- Subject was frustrated at having to switch viewpoint often.
- Subject noted that tracer jitter was a large problem in precise selection.
- “The right distance is very important”

### Subject 2:

Environment order: Random, Building, Tunnel, Tiles,

Technique order: TL, SB, TC, RC

#### Observations:

- User only used addition selection for both volume techniques. Addition then subtraction techniques were not used except during errors.
- Subject often went head first into the tasks without too much planning. Later commented on how most techniques required planning to be most effective.
- User often used both the camera view and the world view to confirm selection.

**Comments:**

On selection box:

“More intuitive”

“[initial] location very important”

“Once you get the first set, you kind of get the second set for free.”

(Regarding selecting 2 separate groups of similar size.)

-Subject noted that it was difficult to perceive the depth at which the box started and stopped.

On Raycasting:

“lots of pointing”

**Subject 3:**

20 minute training.

Environment order: Tiles, Random, Building, Tunnel

Technique order: SB, TC, RC, TL

**Observations:**

- User only used addition selection for both volume techniques. Addition then subtraction techniques were not used except during errors.
- Subject often went head first into the tasks without too much planning.
- Subject often switched focus between tablet and the world when using tablet selection.

**Comments:**

On tablet techniques:

-Subject wanted to grip the wand like a mouse.

-Subject often moved the tablet under the wand

“It’s easier to look in the environment and control the ray for the tapping”

On Raycasting:

“This ray makes me feel like im part of the world.”

**Subject 4:**

25 minute training.

Environment order: Tunnel, Tiles, Random, Building

Technique order: TC, RC, TL, SB

**Observations:**

- User only used addition selection for both volume techniques. Addition then subtraction techniques were not used except during errors.
- User often gave considerable thought into where he would position himself or the camera.

**Comments:**

On tablet techniques:

-User did not think the camera is best for spread out objects.

On Tablet Lasso:



“It would be easier if it did not select partial objects.”

“It was a mistake to try and find one view” Tiles environment.

On Selection Box:

“I think this would be one of the easier ones with some practice.”

On Raycasting:

“Easier to correct a problem if you mess up.”

## **Subject 5:**

25 minute training.

Environment order: Building, Tunnel, Tiles, Random

Technique order: RC, TL, SB, TC

### **Observations:**

-User only used addition selection for both volume techniques. Addition then subtraction techniques were not used except during errors.

-User rarely used both the tablet and the world view in conjunction.

-User often gave considerable thought into where she would position herself or the camera.

### **Comments:**

“Individually selecting objects was easier with 3D techniques. No camera movement was required.”

On Selection Box:

“The box was good because objects were aligned along 2 dimensions.”

-Subject wanted the box to snap to 90 deg angles.

Random environment: “I had to move around a lot.”

On Raycasting:

“It’s hard to select from far away.”

“It’s easy to use because you are pointing to move around anyway.”

On Tablet Lasso:

-Subject wanted to surround the objects with the lasso, not cross them.

## Appendix C – Summative Evaluation Forms

### C.1 Final Evaluation Plan and Questions

# Multiple Object Selection Techniques Study

## Final Evaluation – Plan and questions

### Intro:

- Evaluator: Hello & Welcome
- Subject: Read Introduction & Intro Questionnaire
- Evaluator: Hardware introduction.

### Training:

- Subject: Put on HMD, left headphone down.
- Evaluator: HMD movement intro. Turning.

### 3D Subjects

- Subject: Pick up wand.
- Evaluator: Raycasting intro. Indicate, select, deselect.
- Evaluator: Selection Box intro: Resize: 6 Dir Pull, Joystick. Select, Grab, Position, Drop
- Performance Tests:  
Min Time for Raycasting \_\_\_\_\_  
Min Time for Selection Box \_\_\_\_\_

### Tablet Subjects

- Subject: Pick up wand and tablet.
- Evaluator: Tablet intro. Point out camera, explain mapping. Explain tapping.
- Evaluator: Camera movement. Call camera, grab camera.
- Evaluator: Tablet lasso. Simple lassos, Explain wireframe, lasso timeout
  
- Subject: Exploration until they feel comfortable.
- Evaluator: Training End and questions.  
Min Time for Tapping \_\_\_\_\_  
Min Time for Lasso \_\_\_\_\_

## C.2 Final Evaluation Introduction

# Multiple Object Selection Techniques Study

## Final Evaluation – Introduction

### **Introduction:**

To begin, thank you for volunteering to participate in our study. As you may know this study takes place in an immersive Virtual Environment using a head mounted display. If you are prone to motion sickness or dizziness please let the evaluator know before beginning.

The purpose of this study is to gain knowledge about the 3D multiple object selection (MOS) techniques. You may be familiar with 2D MOS techniques from using window based user interfaces. An example of a 2D MOS technique is dragging a box around a set of icons to select them. We will try several different 3D MOS techniques for this study some of which may be similar to 2D techniques you may have used on your desktop.

First the evaluator will explain to you how to put on the HMD and how to move around in the environment. He will then explain to you how to use each of the selection techniques and give you some time to try them out. After you have had some time to practice the techniques the experiment will begin.

The task for this study will be to select the red highlighted objects using one of two techniques. You will perform this task in several times with varying conditions. You will be given instructions on when to start each task. You will be given training with the techniques before the experiment starts. In the training you are encouraged to think aloud and ask as many questions as you may need. **During the actual trials we ask that you try and select the target objects as quickly as possible.**

It is important that you understand we are not evaluating your performance in the environment, but that we are evaluating the techniques themselves.

**Thanks for participating!**

**C.3 Final Evaluation Pre-Questionnaire**

**Multiple Object Selection Techniques Study      Subject# \_\_\_\_\_**  
**Pre-experiment Questionnaire.**

**Pr1:** Age: \_\_\_\_\_

**Pr2:** Gender: M\_\_\_\_\_ F\_\_\_\_\_

**Pr3:** Please rate your experience level with immersive Virtual Environments.

- \_\_\_\_\_ Novice
- \_\_\_\_\_ Some Experience
- \_\_\_\_\_ Experienced
- \_\_\_\_\_ Expert

**Pr4:** Please rate your experience level with 3D modeling or CAD.

- \_\_\_\_\_ Novice
- \_\_\_\_\_ Some Experience
- \_\_\_\_\_ Experienced
- \_\_\_\_\_ Expert

**Pr5:** Please rate how often you play 3D video games.

- \_\_\_\_\_ Never play.
- \_\_\_\_\_ A few times a year.
- \_\_\_\_\_ A few times a month.
- \_\_\_\_\_ A few times a week.
- \_\_\_\_\_ A few times a day.

**Pr6-7:** Please rate your familiarity with these 2D multiple object selection techniques.

- P6** Box Lassos (Windows Explorer, Excel, Word etc.)  
Not Familiar 1-----2-----3-----4-----5-----6-----7 Very Familiar
- P7** Freehand Lassos (Photoshop, MS Paint.)  
Not Familiar 1-----2-----3-----4-----5-----6-----7 Very Familiar

**Pr8:** What is your occupation? If student please state your major. \_\_\_\_\_

**Pr9:** Please enter your visual acuity (i.e. 20/20)? If you wear glasses or contacts please enter your corrected visual acuity. \_\_\_\_\_/\_\_\_\_\_

**Pr10:** Are you left or right handed? Left\_\_\_\_\_ Right\_\_\_\_\_

C.4 Final Evaluation Post-Questionnaire

**Multiple Object Selection Techniques Study**  
**Final Evaluation – Post Experiment Questionnaire**

Subject# \_\_\_\_\_

*Question P1-3:* Please rate the techniques according to your personal preference.  
Please Circle your answer.

*P1* Raycasting Did not like 1-----2-----3-----4-----5-----6-----7 Liked A lot

*P2* Selection Box Did not like 1-----2-----3-----4-----5-----6-----7 Liked A lot

*P3 Comments?* \_\_\_\_\_

*Question P4-6:* Please rate the techniques according to how fast you were able to complete the tasks. Please Circle your answer.

*P4* Raycasting Very slow 1-----2-----3-----4-----5-----6-----7 Very Fast

*P5* Selection Box Very slow 1-----2-----3-----4-----5-----6-----7 Very Fast

*P6 Comments?* \_\_\_\_\_

*Question P7-9:* Please rate the techniques according to how tiring the techniques were.  
Please Circle your answer.

*P7* Raycasting Very Tiring 1-----2-----3-----4-----5-----6-----7 Not Tiring at all

*P8* Selection Box Very Tiring 1-----2-----3-----4-----5-----6-----7 Not Tiring at all

*P9 Comments?* \_\_\_\_\_

*Question P10-12:* Please rate the techniques according to how accurate selection with the techniques was. 7: Very Accurate. 1: Not Accurate at all.

*P10* Raycasting Not Accurate at all 1-----2-----3-----4-----5-----6-----7 Very Accurate

*P11* Selection Box Not Accurate at all 1-----2-----3-----4-----5-----6-----7 Very Accurate

*P12 Comments?* \_\_\_\_\_

**Thank You!**

**Multiple Object Selection Techniques Study  
Final Evaluation – Post Experiment Questionnaire**

**Subject#** \_\_\_\_\_

**Question P1-3:** Please rate the techniques according to your personal preference.  
Please Circle your answer.

**P1** Tablet Tapping Did not like 1-----2-----3-----4-----5-----6-----7 Liked A lot

**P2** Tablet Lasso Did not like 1-----2-----3-----4-----5-----6-----7 Liked A lot

**P3 Comments?** \_\_\_\_\_

**Question P4-6:** Please rate the techniques according to how fast you were able to complete the tasks. Please Circle your answer.

**P4** Tablet Tapping Very slow 1-----2-----3-----4-----5-----6-----7 Very Fast

**P5** Tablet Lasso Very slow 1-----2-----3-----4-----5-----6-----7 Very Fast

**P6 Comments?** \_\_\_\_\_

**Question P7-9:** Please rate the techniques according to how tiring the techniques were.  
Please Circle your answer.

**P7** Tablet Tapping Very Tiring 1-----2-----3-----4-----5-----6-----7 Not Tiring at all

**P8** Tablet Lasso Very Tiring 1-----2-----3-----4-----5-----6-----7 Not Tiring at all

**P9 Comments?** \_\_\_\_\_

**Question P10-12:** Please rate the techniques according to how accurate selection with the techniques was.

**P10** Tablet Tapping Not Accurate at all 1-----2-----3-----4-----5-----6-----7 Very Accurate

**P11** Tablet Lasso Not Accurate at all 1-----2-----3-----4-----5-----6-----7 Very Accurate

**P12 Comments?** \_\_\_\_\_

**Thank You!**

## Appendix D – Summative Evaluation Full Statistical Results

The Mixed Procedure

### Model Information

Data Set	WORK.MEAN
Dependent Variable	lntime
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Containment

### Class Level Information

Class	Levels	Values
ThreeDOrTablet	2	3D Tablet
Subject	18	s01 s02 s03 s04 s05 s06 s07 s08 s09 s10 s11 s12 s13 s14 s15 s16 s17 s18
SorP	2	Parallel Serial
Size	3	1 2 3
No_Targets	3	9 36 64
Task_no	57	1 3 5 7 8 9 11 13 15 17 19 21 23 25 27 29 31 33 34 35 37 39 41 43 45 47 49 51 53 56 58 60 62 64 66 68 70 72 74 76 78 80 82 84 85 86 88 90 92 94 96 98 100 102 104 106 108

### Dimensions

Covariance Parameters	4
Columns in X	145
Columns in Z	111
Subjects	1
Max Obs Per Subject	324
Observations Used	324
Observations Not Used	0
Total Observations	324

### Covariance Parameter Estimates

Cov Parm	Estimate
Subject(ThreeDOrTab)	0.02177
Task_no	0.001243
ThreeDO*Subject*SorP	0.01802
Residual	0.02259

### Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
ThreeDOrTablet	1	15	0.98	0.3387
SorP	1	15	323.80	<.0001
ThreeDOrTablet*SorP	1	15	88.53	<.0001
Size	2	200	34.43	<.0001
ThreeDOrTablet*Size	2	200	0.15	0.8640
SorP*Size	2	200	21.54	<.0001
ThreeDOrTa*SorP*Size	2	200	0.44	0.6458
No_Targets	2	200	2403.66	<.0001
ThreeDOrT*No_Targets	2	200	2.33	0.0997
SorP*No_Targets	2	200	245.69	<.0001
ThreeDO*SorP*No_Targ	2	200	2.50	0.0844
Size*No_Targets	4	200	0.44	0.7786
ThreeDO*Size*No_Targ	4	200	1.33	0.2597

SorP*Size*No_Targets	4	200	1.77	0.1357
Thre*SorP*Size*No_Ta	4	200	1.05	0.3836
tn	1	200	6.28	0.0130

Effect	t Value	Pr >  t	Least Squares Means				Standard Error	DF	
			Three DOr Tablet	SorP	Size	No Targets			Estimate
Thre*SorP*Size*No_Ta	24.92	<.0001	3D	Parallel	1	9	2.0915	0.08393	200
Thre*SorP*Size*No_Ta	32.31	<.0001	3D	Parallel	1	36	2.7122	0.08394	200
Thre*SorP*Size*No_Ta	38.97	<.0001	3D	Parallel	1	64	3.2714	0.08395	200
Thre*SorP*Size*No_Ta	25.49	<.0001	3D	Parallel	2	9	2.1389	0.08392	200
Thre*SorP*Size*No_Ta	31.66	<.0001	3D	Parallel	2	36	2.6571	0.08392	200
Thre*SorP*Size*No_Ta	38.84	<.0001	3D	Parallel	2	64	3.2661	0.08409	200
Thre*SorP*Size*No_Ta	25.38	<.0001	3D	Parallel	3	9	2.1349	0.08410	200
Thre*SorP*Size*No_Ta	31.71	<.0001	3D	Parallel	3	36	2.6690	0.08417	200
Thre*SorP*Size*No_Ta	36.92	<.0001	3D	Parallel	3	64	3.0994	0.08394	200
Thre*SorP*Size*No_Ta	25.82	<.0001	3D	Serial	1	9	2.1714	0.08411	200
Thre*SorP*Size*No_Ta	41.41	<.0001	3D	Serial	1	36	3.4807	0.08406	200
Thre*SorP*Size*No_Ta	47.93	<.0001	3D	Serial	1	64	4.0313	0.08411	200
Thre*SorP*Size*No_Ta	24.74	<.0001	3D	Serial	2	9	2.0803	0.08410	200
Thre*SorP*Size*No_Ta	38.90	<.0001	3D	Serial	2	36	3.2664	0.08396	200
Thre*SorP*Size*No_Ta	46.32	<.0001	3D	Serial	2	64	3.8870	0.08392	200
Thre*SorP*Size*No_Ta	22.46	<.0001	3D	Serial	3	9	1.8893	0.08411	200
Thre*SorP*Size*No_Ta	37.89	<.0001	3D	Serial	3	36	3.1805	0.08395	200
Thre*SorP*Size*No_Ta	44.32	<.0001	3D	Serial	3	64	3.7394	0.08438	200
Thre*SorP*Size*No_Ta	21.75	<.0001	Tablet	Parallel	1	9	1.8253	0.08392	200
Thre*SorP*Size*No_Ta	27.08	<.0001	Tablet	Parallel	1	36	2.2725	0.08393	200
Thre*SorP*Size*No_Ta	33.66	<.0001	Tablet	Parallel	1	64	2.8315	0.08412	200
Thre*SorP*Size*No_Ta	21.70	<.0001	Tablet	Parallel	2	9	1.8221	0.08398	200
Thre*SorP*Size*No_Ta	28.52	<.0001	Tablet	Parallel	2	36	2.3971	0.08405	200
Thre*SorP*Size*No_Ta	32.08	<.0001	Tablet	Parallel	2	64	2.6977	0.08409	200
Thre*SorP*Size*No_Ta	21.34	<.0001	Tablet	Parallel	3	9	1.7951	0.08413	200
Thre*SorP*Size*No_Ta	28.32	<.0001	Tablet	Parallel	3	36	2.3795	0.08402	200
Thre*SorP*Size*No_Ta	32.24	<.0001	Tablet	Parallel	3	64	2.7105	0.08408	200



Thre*SorP*Size*No_Ta 32.84 <.0001	Tablet	Serial	1	9	2.7589	0.08401	200
Thre*SorP*Size*No_Ta 48.32 <.0001	Tablet	Serial	1	36	4.0656	0.08414	200
Thre*SorP*Size*No_Ta 53.84 <.0001	Tablet	Serial	1	64	4.5328	0.08419	200
Thre*SorP*Size*No_Ta 29.80 <.0001	Tablet	Serial	2	9	2.5049	0.08406	200
Thre*SorP*Size*No_Ta 45.88 <.0001	Tablet	Serial	2	36	3.8629	0.08420	200
Thre*SorP*Size*No_Ta 52.64 <.0001	Tablet	Serial	2	64	4.4344	0.08424	200
Thre*SorP*Size*No_Ta 28.39 <.0001	Tablet	Serial	3	9	2.3873	0.08408	200
Thre*SorP*Size*No_Ta 44.14 <.0001	Tablet	Serial	3	36	3.7053	0.08394	200
Thre*SorP*Size*No_Ta 51.05 <.0001	Tablet	Serial	3	64	4.2849	0.08393	200

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Effect	Estimate	Standard Error	DF	t Value	Pr >  t
tn	-0.00139	0.000556	200	-2.51	0.0130

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The Mixed Procedure

Model Information

Data Set	WORK.MEAN
Dependent Variable	lntime
Covariance Structure	Variance Components
Estimation Method	REML
Residual Variance Method	Profile
Fixed Effects SE Method	Model-Based
Degrees of Freedom Method	Containment

Class Level Information

Class	Levels	Values
ThreeDOrTablet	2	3D Tablet

```

Subject      18      s01 s02 s03 s04 s05 s06 s07 s08 s09 s10 s11 s12 s13 s14 s15 s16
s17 s18
SorP        2      Parallel Serial
Size        3      1 2 3
No_Targets  3      9 36 64
Task_no     57     1 3 5 7 8 9 11 13 15 17 19 21 23 25 27 29 31 33 34 35 37 39
          41 43 45 47 49 51 53 56 58 60 62 64 66 68 70 72 74 76 78 80
          82 84 85 86 88 90 92 94 96 98 100 102 104 106 108

```

```

Dimensions
Covariance Parameters      4
Columns in X                46
Columns in Z                111
Subjects                    1
Max Obs Per Subject        324
Observations Used          324
Observations Not Used      0
Total Observations         324

```

Covariance Parameter Estimates

```

Cov Parm      Estimate
Subject(ThreeDOrTab)  0.02183
Task_no          0.001183
ThreeDO*Subject*SorP  0.01809
Residual         0.02260

```

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
ThreeDOrTablet	1	15	0.98	0.3378
SorP	1	15	322.93	<.0001
ThreeDOrTablet*SorP	1	15	88.25	<.0001
Size	2	221	34.53	<.0001
SorP*Size	2	221	21.43	<.0001
No_Targets	2	221	2409.00	<.0001
ThreeDOrT*No_Targets	2	221	2.35	0.0980
SorP*No_Targets	2	221	245.28	<.0001
ThreeDO*SorP*No_Targ	2	221	2.54	0.0812
tn	1	221	6.75	0.0100

Least Squares Means

Effect	Three DOr Tablet	SorP	Size	No Targets	Estimate	Standard Error	DF
ThreeDOrTablet*SorP	3D	Parallel			2.6709	0.06890	15
38.77 <.0001							
ThreeDOrTablet*SorP	3D	Serial			3.0807	0.06887	15
44.73 <.0001							
ThreeDOrTablet*SorP	Tablet	Parallel			2.3035	0.06890	15
33.43 <.0001							
ThreeDOrTablet*SorP	Tablet	Serial			3.6155	0.06891	15
52.46 <.0001							
SorP*Size		Parallel	1		2.5009	0.05170	221
48.37 <.0001							
SorP*Size		Parallel	2		2.4964	0.05173	221
48.25 <.0001							

SorP*Size		Parallel	3		2.4643	0.05169	221
47.67	<.0001						
SorP*Size		Serial	1		3.5068	0.05170	221
67.83	<.0001						
SorP*Size		Serial	2		3.3394	0.05174	221
64.54	<.0001						
SorP*Size		Serial	3		3.1981	0.05170	221
61.85	<.0001						
ThreeDO*SorP*No_Targ	3D	Parallel		9	2.1209	0.07296	221
29.07	<.0001						
ThreeDO*SorP*No_Targ	3D	Parallel		36	2.6793	0.07299	221
36.71	<.0001						
ThreeDO*SorP*No_Targ	3D	Parallel		64	3.2125	0.07297	221
44.02	<.0001						
ThreeDO*SorP*No_Targ	3D	Serial		9	2.0481	0.07301	221
28.05	<.0001						
ThreeDO*SorP*No_Targ	3D	Serial		36	3.3080	0.07296	221
45.34	<.0001						
ThreeDO*SorP*No_Targ	3D	Serial		64	3.8859	0.07297	221
53.25	<.0001						
ThreeDO*SorP*No_Targ	Tablet	Parallel		9	1.8142	0.07296	221
24.87	<.0001						
ThreeDO*SorP*No_Targ	Tablet	Parallel		36	2.3489	0.07297	221
32.19	<.0001						
ThreeDO*SorP*No_Targ	Tablet	Parallel		64	2.7474	0.07299	221
37.64	<.0001						
ThreeDO*SorP*No_Targ	Tablet	Serial		9	2.5504	0.07305	221
34.91	<.0001						
ThreeDO*SorP*No_Targ	Tablet	Serial		36	3.8788	0.07296	221
53.17	<.0001						
ThreeDO*SorP*No_Targ	Tablet	Serial		64	4.4173	0.07300	221
60.51	<.0001						

Tests of Effect Slices

Effect	Three DOr Tablet	SorP	Size	No Targets	Num DF	Den DF	F Value
Pr > F							
ThreeDOrTablet*SorP	3D				1	221	36.54
<.0001							
ThreeDOrTablet*SorP	Tablet				1	221	373.65
<.0001							
ThreeDO*SorP*No_Targ	3D				5	221	541.46
<.0001							
ThreeDO*SorP*No_Targ	Tablet				5	221	598.16
<.0001							
ThreeDOrTablet*SorP		Parallel			1	221	14.28
0.0002							
ThreeDOrTablet*SorP		Serial			1	221	30.26
<.0001							
SorP*Size		Parallel			2	221	0.92
0.4018							
SorP*Size		Serial			2	221	54.66
<.0001							
ThreeDO*SorP*No_Targ		Parallel			5	221	241.61
<.0001							
ThreeDO*SorP*No_Targ		Serial			5	221	835.46
<.0001							
SorP*Size			1		1	221	351.42
<.0001							
SorP*Size			2		1	221	247.70
<.0001							
SorP*Size			3		1	221	187.17
<.0001							
ThreeDO*SorP*No_Targ				9	3	221	31.98
<.0001							

ThreeDO*SorP*No_Targ <.0001	36	3	221	159.17
ThreeDO*SorP*No_Targ <.0001	64	3	221	187.57

---

Obs	Effect	Estimate	StdErr	DF	tValue	Probt
46	tn	-0.00142	0.000546	221	-2.60	0.0100

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Obs	Effect	SorP	Three DOr Tablet	Three DOr Tablet	Estimate	StdErr	DF	tValue
2 0.0018	ThreeDOrTablet*SorP 0.0088	Parallel	3D	Tablet	0.3674	0.09722	15	3.78
5 <.0001	ThreeDOrTablet*SorP 0.0003	Serial	3D	Tablet	-0.5348	0.09723	15	-5.50

---

Obs	Effect	Three DOr Tablet	SorP	_SorP	Estimate	StdErr	DF	tValue
1 <.0001	ThreeDOrTablet*SorP 0.0001	3D	Parallel	Serial	-0.4098	0.06779	15	-6.04
6 <.0001	ThreeDOrTablet*SorP <.0001	Tablet	Parallel	Serial	-1.3120	0.06787	15	-19.33

---

Obs	Effect	SorP	Size	_Size	Estimate	StdErr	DF	tValue
7 0.8777	SorP*Size 1.0000	Parallel	1	2	0.004541	0.02947	221	0.15
8 0.2147	SorP*Size 0.8145	Parallel	1	3	0.03659	0.02941	221	1.24
12 0.2798	SorP*Size 0.8876	Parallel	2	3	0.03205	0.02958	221	1.08
19 <.0001	SorP*Size <.0001	Serial	1	2	0.1674	0.02966	221	5.64
20 <.0001	SorP*Size <.0001	Serial	1	3	0.3087	0.02955	221	10.45
21 <.0001	SorP*Size <.0001	Serial	2	3	0.1414	0.02951	221	4.79

---

Obs	Effect	Size	SorP	_SorP	Estimate	StdErr	DF	tValue
9 <.0001	SorP*Size <.0001	1	Parallel	Serial	-1.0059	0.05366	221	-18.75

14	SorP*Size	2	Parallel	Serial	-0.8431	0.05357	221	-15.74
<.0001	<.0001							
18	SorP*Size	3	Parallel	Serial	-0.7337	0.05363	221	-13.68
<.0001	<.0001							

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Obs	Effect	SorP	No_Targets	Three DOr Tablet	Three DOr Tablet	Estimate	StdErr	DF
tValue	Probt	Adj						
27	ThreeDO*SorP*No_Targ	Parallel	9	3D	Tablet	0.3067	0.1029	221
2.98	0.0032	0.1216						
38	ThreeDO*SorP*No_Targ	Parallel	36	3D	Tablet	0.3304	0.1030	221
3.21	0.0015	0.0660						
48	ThreeDO*SorP*No_Targ	Parallel	64	3D	Tablet	0.4652	0.1031	221
4.51	<.0001	0.0006						
57	ThreeDO*SorP*No_Targ	Serial	9	3D	Tablet	-0.5023	0.1032	221
-4.87	<.0001	0.0001						
65	ThreeDO*SorP*No_Targ	Serial	36	3D	Tablet	-0.5708	0.1030	221
-5.54	<.0001	<.0001						
72	ThreeDO*SorP*No_Targ	Serial	64	3D	Tablet	-0.5314	0.1030	221
-5.16	<.0001	<.0001						

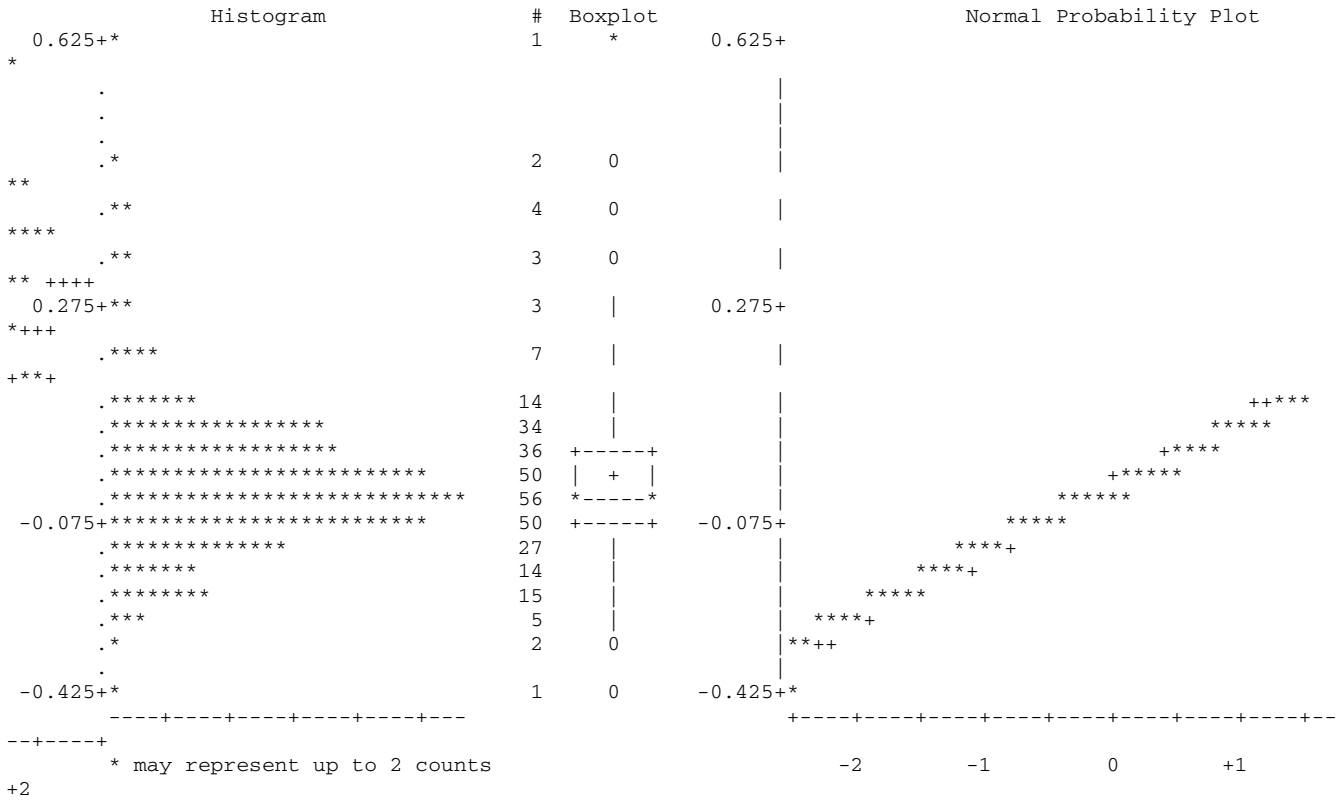
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Obs	Effect	Three DOr Tablet	No_Targets	SorP	_SorP	Estimate	StdErr	DF
tValue	Probt	Adj						
24	ThreeDO*SorP*No_Targ	3D	9	Parallel	Serial	0.07285	0.07584	221
0.96	0.3379	0.9983						
35	ThreeDO*SorP*No_Targ	3D	36	Parallel	Serial	-0.6287	0.07586	221
-8.29	<.0001	<.0001						
45	ThreeDO*SorP*No_Targ	3D	64	Parallel	Serial	-0.6734	0.07580	221
-8.88	<.0001	<.0001						
75	ThreeDO*SorP*No_Targ	Tablet	9	Parallel	Serial	-0.7362	0.07597	221
-9.69	<.0001	<.0001						
80	ThreeDO*SorP*No_Targ	Tablet	36	Parallel	Serial	-1.5299	0.07586	221
20.17	<.0001	<.0001						
84	ThreeDO*SorP*No_Targ	Tablet	64	Parallel	Serial	-1.6700	0.07600	221
21.97	<.0001	<.0001						

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Obs	Effect	Three DOr Tablet	SorP	No_Targets	_No_Targets	Estimate	StdErr	DF
tValue	Probt	Adj						
22	ThreeDO*SorP*No_Targ	3D	Parallel	9	36	-0.5583	0.04161	221
-13.42	<.0001	<.0001						
23	ThreeDO*SorP*No_Targ	3D	Parallel	9	64	-1.0916	0.04161	221
-26.23	<.0001	<.0001						
33	ThreeDO*SorP*No_Targ	3D	Parallel	36	64	-0.5333	0.04169	221
-12.79	<.0001	<.0001						
52	ThreeDO*SorP*No_Targ	3D	Serial	9	36	-1.2599	0.04181	221
-30.13	<.0001	<.0001						
53	ThreeDO*SorP*No_Targ	3D	Serial	9	64	-1.8378	0.04196	221
-43.80	<.0001	<.0001						

60	ThreeDO*SorP*No_Targ	3D	Serial	36	64	-0.5779	0.04170	221
-13.86	<.0001	<.0001						
73	ThreeDO*SorP*No_Targ	Tablet	Parallel	9	36	-0.5346	0.04173	221
-12.81	<.0001	<.0001						
74	ThreeDO*SorP*No_Targ	Tablet	Parallel	9	64	-0.9331	0.04153	221
-22.47	<.0001	<.0001						
78	ThreeDO*SorP*No_Targ	Tablet	Parallel	36	64	-0.3985	0.04167	221
-9.56	<.0001	<.0001						
85	ThreeDO*SorP*No_Targ	Tablet	Serial	9	36	-1.3284	0.04176	221
-31.81	<.0001	<.0001						
86	ThreeDO*SorP*No_Targ	Tablet	Serial	9	64	-1.8669	0.04175	221
-44.72	<.0001	<.0001						
87	ThreeDO*SorP*No_Targ	Tablet	Serial	36	64	-0.5385	0.04164	221
-12.93	<.0001	<.0001						



Plot of Resid\*Pred. Legend: A = 1 obs, B = 2 obs, etc.

