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Usability of immersive virtual reality input devices

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USABILITY OF IMMERSIVE VIRTUAL REALITY INPUT DEVICES

For the degree of Master of Science

Is approved by the final examining committee:

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Head of the Department Graduate Program

Date

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VIRTUAL REALITY INPUT DEVICES

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of

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by

Christopher G. Mankey

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Dedicated to everyone that
helped me make it here.

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ABSTRACT

Mankey, Christopher G. M.S., Purdue University, December 2014. Usability of Immersive Virtual Reality Input Devices. Major Professor: Patrick Connolly.

This research conducts a usability analysis of human interface devices within an Immersive Virtual Reality Environment. The analysis is carried out for two different interface devices, a commercially available Intersense© Wand and a home built pinch glove and wireless receiver. Users were asked to carry out a series of minor tasks involving placement of shaped blocks into corresponding holes within an Immersive Virtual Reality Environment. Performance was evaluated in terms of speed, accuracy and precision via the collection of completion times, errors made and the precision of motion during the experiment.

INTRODUCTION

Immersive Virtual Reality Environments have been around for some years now. Already several methods of interaction have been developed, as well as a variety of input devices for users to use to perform various different tasks within the virtual environments. Many researchers even today do not seem to put a lot of thought into what device they use for user input, rather they use what they have on hand, or one of the industry 'defaults' like a wand. How a user interacts with a system can be just as important as how the system interacts with them, for this reason, research is needed to advise users on what devices they should be using for their user input.

1.1. Significance

The core purpose of immersive virtual reality is to make the user feel that the environment or situation presented to them is real. However, when a component within this system proves to be too difficult or not intuitive to new users, this illusion starts to break down. This defeats the purpose of the system. For example, in reality, if a person wants to pick an object up, they need only reach out and grasp it with their hand. In many immersive virtual reality systems though, to pick up an object a user must use a device to essentially 'point & click' on the object within three dimensional space in order to pick it up. How much of the belief in this virtual reality is lost due to this method of interaction? If instead a device was used that allowed users to actually reach out and grasp the virtual object with their hand, how much more real would the simulation seem?

1.2. Statement of Purpose

This research performed an analysis of the usability of a wand device as compared to commercially available flex glove and a low cost ‘homemade’ pinch glove for user input in an immersive virtual reality environment to determine which one of these devices is easier for users to learn to use.

1.3. Research Question

“Does a flex glove and wrist tracker or a pinch glove and wrist tracker provide better usability than a traditional wand for user input in an immersive virtual reality environment?”

1.4. List of Assumptions

- Sufficient testing participants will be available to establish significance with the resulting data.
- All the necessary hardware will be functional and available for testing.
- By balancing all testing groups for both gender and handedness, it is assumed that biasing effects of these traits will be made insignificant amongst test participants (Kabbash, MacKenzie & Buxton, 1993).

1.5. Limitations

- Much of the real world object manipulation that we perform relies on our sense of touch and the haptic feedback that we receive back from an object as we manipulate it. In Virtual Reality Environments, we lack that sensation of touch and thus it becomes much more difficult to get a sense of an object as we move it in Virtual reality when a haptic device is not utilized as part of the user experience (Mine, Brooks & Sequin, 1997).

- For this research it was neither feasible nor practical to utilize a haptic device for user feedback of object manipulations (Mine et al., 1997).
- It was only possible to obtain right handed input gloves for this research. To eliminate bias against it, the wand will only be used with the right hand as well.

1.6. Delimitations

- All virtual objects that users are required to interact with in this research will be relatively close to each other and moderately sized, resulting in a constant context. For this reason, the ‘virtual hand’ interaction technique will be used for object interaction. Other techniques such as ‘ray casting’ or ‘go-go’ were not tested as they are unnecessary and would also add additional complexity to the research (Bowman, Gabbard & Hix, 2002) (Frees, 2010).
- All objects to be interacted with will be clearly presented to the user and within the range of the ‘real’ space of the Cave™, so navigation further within the environment will not be necessary (Poupyrev, Weghorst, Billinghurst & Ichikawa, 1997) (Bowman & Hodges, 1997).
- To keep testing sessions short to allow for as many testing participants as possible, spatial ability testing will not be included as part of the testing process in lieu of a larger testing group (Bowman et al., 2002).
- Testing times were relatively short, so effects of fatigue would be small and with high variability, so data on the effects of fatigue caused by the various devices was not collected (Zhai, 1998).
- Coordination, the efficiency with which a user moves an object from its starting position to its destination, was not tested for in this research. The system

requirements of recording this input could have compromised the computer's ability to collect data on more important variables (Zhai, 1998).

- Additional usability criteria such as: ease of use, ease of learning and sense of presence were not measured as they are highly qualitative and would have added significant time and complexity to the research (Poupyrev et al., 1997).
- Device persistence and device acquisition were not evaluated as these two usability criteria relate to releasing and reacquiring the devices, which were not expected to be done during testing (Zhai, 1998).

1.7. Definitions

- Virtual Environment – “A virtual environment (VE) is a computer-generated world in which a user can interact with computer-generated objects. Generating a virtual environment and the objects within it is done using multimedia technology with the purpose of providing the user with a certain experience while being immersed into a virtual reality” (Kjeldskov, 2008, p. 137).
- Cave™ – “Cave Automatic Virtual Environment (Cave™) is currently the display system that offers the greatest level of immersion into a virtual 3D environment. The user is placed in a small cubic room, measuring approx. 3 m on all sides, in which computer-generated images are back-projected on all four walls, the floor and the ceiling” (Kjeldskov, 2008, p. 140).
- One unique feature of Virtual Environments as opposed to real situations is that users can do actions that would be impossible in the real world. For the purposes of this research though, only ‘realistic’ object interactions are being evaluated (Poupyrev et al., 1997).

- Of the five basic interaction tasks in Virtual Environments: selection, position, orientation, text entry and quantity entry; text entry and quantity entry will not be evaluated (Poupyrev et al., 1997).
- Degrees of Freedom (DOF) – Refers to the number of ways in which an object is free to move. Translation in each of the three primary axes counts for one: X-axis, Y-axis, and Z-axis. Rotation in each axis of rotation also counts for one: Roll, Pitch, and Yaw. Most devices discussed in this research are 6 DOF Devices, meaning they are free to move in all three axis of translation and rotation.
- Head Tracking – “Tracking the position of the user’s head ensures that the correct visual perspective is calculated” (Kjeldskov, 2008, p. 140).
- Three Dimensional Vision (3D) – “The 3D experience requires shutter glasses to be worn by the user allowing separate images to be projected to the user’s left and right eye and thereby creating stereovision” (Kjeldskov, 2008, p. 140).
- Motion Parallax – “...head-tracked virtual environments, in which head movements generate a powerful alternative visual depth cue called motion parallax” (Werkhoven & Greon, 1998, p. 433).
- Wrist Tracking – Tracking of the user’s hand within a virtual environment via an attached device, used to calculate interactions with the virtual environment and virtual objects.
- Interaction Technique (IT) – The technique, usually matched to the particular requirements of the current task, by which a user interacts with a system (Bowman et al., 2002).

- Five basic interaction tasks – The five basic tasks that all interactions in VEs can be broken down into:

- “Position – the task of positioning an object”
- “Selection – the task of identifying an object”
- “Orient – the task of orienting an object”
- “Text – the input of a string of characters”
- “Quantify – the input of a numerical value” (Poupyrev et al., 1997, p. 22)

Only the first 3 basic interaction tasks will be tested in this research.

- Gross Movement – After an object is selected, the initial movement of an object to bring it into the relative vicinity of its destination (Poupyrev et al., 1997).
- Correction Movement – After an object is within the vicinity of its destination, “a corrective motion to position the object on the terminal with the desired accuracy” (Poupyrev et al., 1997). “Precise positioning is more difficult than imprecise for unconstrained movement...” (Poupyrev et al., 1997, p. 23).
- Interactions in Virtual Environments – “...capability to detect and react to each user action executed with interaction techniques...” (Dubois, Nedel, Freitas & Jacon, 2005, p. 118).
- Proprioception – “... a person’s sense of the position and orientation of his body and limbs” (Mine et al., 1997, p. 1).

- Usability – “any characteristic relating to the ease of use and usefulness of an interactive software application, including user task performance, subjective satisfaction, user comfort, and so on.” (Bowman et al., 2002, p. 405).

1.8. Summary

Immersive Virtual Reality Environments is a relatively new area for both user experience and user input. To provide the user with the best experience possible, we must determine through research what are the new rules and guidelines of the experience that we must follow. Through experimentation like this we expand our knowledge of how to best direct our efforts when choosing an input device for a particular task.

LITERATURE REVIEW

The content of this research covers a variety of areas and technologies, it was decided that this literature review would best serve by breaking the relevant areas down into four areas each to be examined independently and in depth. These three areas of investigation are: Sensory Perception, Virtual Reality Environments, User Interaction within Virtual Reality Environments and Usability Evaluation of Virtual Reality Environments.

2.1. Perception in Virtual Environments

In order to understand how a person interacts with an Immersive Virtual Reality Environment, we must first understand how we perceive that virtual environment. If we are to understand that perception of the virtual environment, we must also first understand how our perception works in the real world.

Perception can be defined as the process by which a person gathers information from their senses, then interprets that information to form an internal representation of our environment and the things within it (Ward, Grinstein & Keim, 2010). It is critical for us to be able to undergo this process to some degree, otherwise we would be unable to understand our surroundings, how to interact with them, and above all our place within that environment.

Our perception of our world comes predominantly from our five external senses; sight, sound, smell, touch and taste. These senses do a wonderful job of allowing us to

see what's in front of us, reach out grab something, then pick it up and smell or taste it. But our sense of perception isn't limited to only our perception of our environment, but also of ourselves within that environment. In addition to our external senses, we also have our more internalized ones like our vestibular sense and our sense of proprioception. Our vestibular sense is derived from the structures and functions of the inner ear, these when working together, provide us with a sense of balance. This allows us to walk, run and carry out any number of activities in our daily lives. But this sense can be susceptible to error, when information coming from the other senses such as vision, touch or sensations of motion supply information that does not align with our vestibular sense, we can experience a "sensory conflict" (Sherman, 2002). In most people, this sensory conflict presents itself as motion sickness, which can be characterized by dizziness, vertigo and even nausea in extreme cases. Our sense of proprioception provides us with an impression of where our limbs and body lie in relation to each other. This sense is derived from a combination of inputs from our central nervous system, muscles, nerves and skin (Latiner & Sainburg, 2003).

When working in virtual reality environments, sensations of touch, taste as smell are difficult or outright impossible to simulate with the technology currently available. As such, our remaining external senses of sight and sound, as well as our internal vestibular and proprioception senses are left to work with. Our sense of vision is fairly straightforward to simulate, with proper inputs (head tracking) and with proper display devices (stereoscopic displays), we are able to simulate the typical elements in our visual experience of binocular vision, parallax and depth cues. For some users though, things like movement and rotation within a virtual environment can again cause the same sort of

“sensory conflict” that causes motion sickness. If a person experiencing a virtual environment is experiencing visual sensation of moving through an environment, while their vestibular sense is telling their brain that they are stationary, the resulting form of motion sickness in this case called “cyber sickness” can produce the same sensations of dizziness, vertigo and nausea just like when experiencing real environments (Nyberg, Lundin-Olsson, Sondell, Backman, Holmlund, Eriksson & Bucht, 2006). By giving users a way to interact with a virtual environment using their hands, we can also begin to simulate a sense of proprioception for them. If this input is accurate and intuitive enough we can hope to avoid both “sensory conflict” issues as well as other issues that might stem from their perception of their real hand not matching up with their perceived position of the virtual hand within the environment (Lateiner & Sainburg, 2003).

2.2. Virtual Reality Environments

Virtual reality environments, or VREs, exist in a variety of forms, implementations, and purposes. “Virtual environments are a relatively new type of human-computer interface in which users perceive and act in a three-dimensional world.” (Bowman et al., 2002, p. 404). Some examples of common hardware configurations used for VREs are: a desktop computer with a standard mouse and keyboard or some other input devices, a Head Mounted Display, or HMD, or a Cave Automatic Virtual Environment, or CAVE™. The goal for each of these configurations is the same: “Generating a virtual environment and the objects within it is done using multimedia technology with the purpose of providing the user with a certain experience while being immersed into a virtual reality.” (Kjeldskov, 2008, p. 137). While the goal is the same

for each configuration, the method and level of immersion that the user experiences varies greatly. The experience of immersion can “range from ‘looking at’ a virtual 3D world to ‘being in’ that virtual world (Shneiderman, 1987) (Kjeldskov, 2008, p. 137). While both desktop and HMD hardware gives users a decent experience of a VRE, the greatest level of immersion is experienced when using a CAVE™. In the case of a CAVE™, the user’s body actually exists within the projection space of the VRE, thus allowing them to get a sense that they exist within the virtual environment.

Over the years since they were first developed, VREs have been used for a variety of tasks, ranging from a purely entertainment purpose, to allowing exploration of other spaces, to observation of objects and processes that would not otherwise be possible, to training simulations for particular skills or procedures. “Studies on simulation show skills learned in VR can be successfully transferred to a real-world task.” (Johnson, Guediri, Kilkenny & Clough, 2011, p. 612). Based on this, it is likely that training simulations are probably the application of VREs that offer the greatest benefit to society for a variety of reasons. First, the user can be provided with a multitude of items that cost essentially nothing to duplicate for the user. If they were to train in a real environment, this could become exceedingly costly. Along the same lines, if the user desires the environment to be changed or modified in some way, this is a much cheaper and simpler task in virtual space than in a real environment. The process of removing or installing a wall is extraordinarily more complex and expensive than the simple series of button presses and mouse clicks that allow the changes to be made in a virtual world. Secondly, in VREs the user can be put into situations that could be dangerous or hazardous to carry

out in the real world. In a police or military live-fire training exercise, the scenario may be artificial, but the bullets being fired can do real harm to participants. Also, combatants with a variety of skills and equipment can also be supplied for the user to interact with. Thirdly, once a VRE has been established, the risks and cost of additional runs through the simulation are quite minimal; this can be of great benefit to the medical field. Both presently and historically, the typical method of educating new medical personnel is to observe the particular technique to be learned multiple times until the student has achieved a decent level of comprehension of the task (Johnson et al., 2011). Then the student is expected to “perform procedures for the first time on patients, exposing these to greater risk and discomfort as well as requiring more time to complete procedures” (Johnson et al., 2011, p. 613). Unfortunately this model of educating is flawed by “inefficiency, high risk, and high cost” (Johnson et al., 2011, p. 613). It exposes both the patient and institution to a high degree of risk, however, this practice stays in use because “it is widely accepted that visual observation alone does not lead to proficiency but that repeated deliberate practice is indispensably necessary for skill development, improvement, and maintenance” (Johnson et al., 2011, p. 613). In a VRE students could carry out a procedure many times in advance of performing the procedure on a real patient, thus hopefully reducing the risk and discomfort on the patient.

However, VREs are not without drawbacks, while they do offer some lucrative benefits to users, some of the negatives about the systems, including cost, can overshadow the benefits. One drawback in VREs is that the manipulation of objects can be much more difficult for users since they lack the haptic feedback, or physical sense of

touch, that they are accustomed to when interacting with real objects (Mine et al., 1997).

The costs of setting up a VRE can be quite extensive, at the bare minimum a high end computer is required. At the upper end of the scale, multiple computers with cutting edge components along with a physical space of up to a thirty foot cube may be required.

Despite these drawbacks, VREs have excelled in a variety of areas, including but not limited to: Therapy, Aesthetics, Entertainment, Surgery, Military, Maintenance, Wayfinding, Architecture, Fluid Flow, Nano-surfaces, 3D Models and Cityscapes (Mine et al., 1997).

The experimental phase of this research was carried out at Purdue University's Envision Center for Data Perceptualization. This facility features a variety of high end graphics equipment, including a teleconferencing capacity, a tiled wall, a haptics research lab, a motion capture stage and the Flex CAVE™ VR Theater (Flex). The Flex is the cornerstone of the hardware used in this research. The Flex is a four-screened Cave™, featuring a floor screen, front screen and right and left screens. The Flex is named as such due to the flexible format of its displays, the right and left screens can be aligned flat to configure them as a thirty foot wide, eight foot tall screen, rotated in ninety degrees to function as an immersive ten foot cube that wraps around the user, and any angle in between. For the purposes of this research, the Flex will remain in the ten foot cube format to provide the highest level of immersion for the user.

2.3. Virtual Reality Interaction

VREs set themselves apart from other systems that produce a more passive experience in many ways, most important are the interactive nature of the experience and

VRE's methods of user interactions with the environment. "Instead of issuing an abstract command or specifying coordinates and rotation angles, users may reach out a hand, grab an object (using a button or a gesture), and move it around the virtual environment (VE) using natural, physical motions" (Bowman & Hodges, 1997, p. 35). Since the inception of VR technology, the matter of how to carry out user interaction has been the subject of much debate. In their 2005 paper, Dubois et al. defines interaction within a VRE as:

Interaction in virtual reality environments (VREs) is based on the responsive capability to detect and react to each user action executed with the interaction techniques, using some kind of special (data gloves, H3D glasses) or conventional (mouse, keyboard, screen) device. Interaction techniques support different kinds of user actions such as: executing commands and entering data to select virtual objects; manipulating them; specifying actions and navigating in the environment. (p. 118)

For a VRE interaction system to be effective, the system for user input into the VRE must allow to user to easily and quickly "navigate freely through a three-dimensional space, manipulate virtual objects with six degrees of freedom, or control attributes of a simulation, among many other things." (Bowman, Johnson & Hodges, 1999, p. 26) For a user to be able to quickly and easily interact with a VRE a level of precise control is needed, however, in direct contradiction to that drive there is the need for gross control when large movements or manipulations are desired (Frees, 2010). One method to help

enhance a user's level of precise movement is by adding constraints to the movements and manipulations of an object (Frees, 2010), this could be thought of as equivalent to resting one's elbow on a table to aid in making precise movements with the hand.

There are many different interaction techniques that have been developed over the years, each with its own benefits and drawbacks. For the purposes of this research, using head tracking and the 'virtual hand' interaction technique for object interaction were chosen. The results of Werkhoven and Greon's 1998 research support this decision:

Designers of highly interactive (immersive) 3D display systems in which task performance relies on the speed and accuracy of manipulations of the environment (e.g., design, training) should seriously consider implementing virtual hand control under stereoscopic conditions. (p. 442)

Since this experimental environment was interactive, immersive and stereoscopic, the use of the 'virtual hand' interaction technique is highly supported by these findings. Mine et al.'s 1997 research also supports the use of this technique by finding that "if a virtual object is located directly at the user's hand position, the user has a good sense of the position of the object (even with the eyes closed) due to proprioception, and thus a greater sense of control." (p. 2). Additionally Werkhoven and Greon's research also stipulated:

Another advantage is that virtual hand manipulation encourages active vision. Head movements during active vision provide motion parallax information, which is a powerful depth cue. (1998. p. 442)

This additional elaboration on the interaction technique supported using the head tracking system also available in the Envision Center's Flex CAVE™.

Just as the interaction technique used by a VRE must be matched to the action the user is trying to perform, so must the device used be matched to the interaction technique to achieve acceptable performance. A good example is using “a 3D mouse to manipulate an object into a 3D space is probably more suitable than a 2D mouse used in association with keyboard keys” (Dubois et al., 2005, p. 118). We must also keep in mind that the lack of a sense of haptic feedback from touching an object may additionally fatigue the user. The user tries to compensate by ‘feeling with their eyes’ this lack of haptic feedback can prematurely fatigue the user both physically and mentally (Mine et al., 1997, p. 1). This lack of haptic feedback also partially compromises our ability to make precise adjustments in VREs (Mine et al., 1997). While some input devices are able to incorporate more than others (head tracking, hands, buttons) all of these fall short of the input that we accomplish every day in the real world, so we regardless of what system we use we are being limited in our input into a virtual environment by at least a small margin (Mine et al., 1997). In order to accurately compare devices for usability, criteria for evaluation are needed. There are six predominantly used criteria used to evaluate six degree-of-freedom input devices for usability: Speed, Accuracy, Ease of Learning, Fatigue, Coordination, Device Persistence and Acquisition (Zhai, 1998). Due to the time

constraints of the experiment and the additional difficulty to measure, data for Ease of Learning, Fatigue, Coordination, Device Persistence and Acquisition was not collected.

Based on information collected during the literature review and technology available, three different user input devices were chosen to be compared and contrasted during the experimental process: an Intersense© Wand, a Flex Glove, and a Pinch Glove. The Intersense© wand is for the most part an industry standard for input devices in VREs. The flex glove and pinch glove were chosen for their high degree of naturalism or “how closely it mimics the real world” (Bowman et al., 1999, p. 27) interactions we carry out. The Pinch Glove is a ‘homemade’ glove constructed by the experimenter for low cost and easily replaced, versus the commercially available flex glove.

2.4. Usability Evaluation of Virtual Reality Environments

Criteria for usability evaluation of two dimensional interfaces have been in use for years. Each criteria evolving as time and technology goes on; however, most are not able to be accurately applied to VREs. So, new criteria have needed to be developed specifically for VRE applications but must still conform to the definition of usability; “‘ease of use’ plus ‘usefulness,’ including such quantifiable characteristics as learnability, speed and accuracy of user task performance, user error rate and subjective user satisfaction (Hix, Hartson, Shneiderman)” (Bowman et al., 2002, p. 404). As with any new technology it is critical that we do evaluate it, because “if humans cannot perform effectively in virtual environments, then further pursuit of this technology may be fruitless (Stanney)” (Poupyrev et al., 1997, p. 21).

METHODOLOGY

The experimental component of this research was conducted within the quantitative framework. Quantitative data was gathered directly by the computer performing the simulation. Research participants were chosen from the Purdue University, Computer Graphics Technology undergraduate student body.

3.1. Hypothesis

This research was based upon two possible resulting hypotheses:

H₁₀: The Null Hypothesis for this research was that there would be no significant difference between the precision, errors made and task times associated with using the wand versus the gloves for user input.

H_{1a}: The Alternative Hypothesis for this research was that there will be a significant difference between the precision, errors made and task times associated with using the wand versus the gloves for user input.

3.2. Task Choices

In order to maintain the highest possible level of external validity, the tasks chosen for the experiment would need to be at the “lowest cognitive and physical level” (Bowman et al., 2002, p. 407) to keep the experimental results as generalizable as possible (Bowman et al., 2002) (Poupyrev et al., 1997). For this reason, the chosen task was based on a children’s toy. When children are trying to learn to interact with their world, we give them toys that teach them to recognize which block will fit into a

particular hole, and then utilize their developing physical abilities to position and orient the object correctly so that it may enter the hole. Based on this premise, through the course of three tasks participants were provided with virtual blocks that they must insert into the appropriate virtual holes. Through this approach, the basic components of object interaction within a VE can be optimized so that in the future more sophisticated tasks and interactions can be carried out with greater efficiency (Poupyrev et al., 1997).

The first task for participants was focused on object selection and rotation. They were presented with a group of targets with four differently shaped holes in them. Suspended in front of each hole was the corresponding shaped block rotated to a random orientation which was kept the same for all participants to avoid providing participants with different starting scenarios. In order, blocks were indicated to be inserted into the corresponding holes in the wall via a color change from red to green. To minimize the impact of movement control needed from the user, for the first task each block is bound to the axis of its corresponding hole, essentially allowing a correctly oriented block to 'slide' into the hole along the axis. Only a correctly oriented block would be allowed to pass beyond the surface of the wall. In order to determine an allowable margin of error, initial testing was conducted with the input devices. A tolerance of five degrees of rotation offset was found to be fairly close to target, but still was an easily attainable accuracy. Once the block has been inserted into the hole correctly and released, it was locked against any further selection or manipulation.

The second experimental task was focused on object selection and movement. Within the VRE, the participant was supplied again with four differently shaped blocks and they were presented with a group of targets with four corresponding holes. The

blocks were again sequentially indicated to be inserted into corresponding holes in the wall. In this task, the orientation of the blocks was kept locked to eliminate the need for the participant to manage the orientation of the block. Only a block correctly positioned within approximately three centimeters of the hole will be allowed to pass beyond the surface of the wall. In this task, the virtual block was bound to the participant's real hand while grabbed. Once the block was inserted correctly, it was locked against any further selection or manipulation.

The third task for participants integrates object selection, orientation and movement. Once again participants were presented with a group of targets, but this time eight holes and eight corresponding blocks. Blocks must be both positioned and oriented correctly to complete the task. Since the participants now know how to use the device they were assigned to, it was hoped that the larger sample set for this task would provide results with a higher level of significance.

3.3. Task Breakdown

Events	Data Collected
Starting cue	
Number of empty selections (False Positive)	Object Selection Time (ST)
Number of wrong selections (Wrong Object)	
Correct object is grabbed	
Number of object drops (False Negative)	Object Contact Time (CT)
Number of empty selections (False Positive)	
Object contacts wall	
Contact distance to target (Gross Movement Accuracy)	Object Insertion Time (IT)
Contact rotation discrepancy (Gross Orientation Accuracy)	
Number of object drops (False Negative)	
Successful object placement	

Figure 1: Graphical Breakdown of Task Flow

Each task was broken down into three distinct stages for each block, marked by an event and also triggering the start/stop of a particular timer. Additional data was gathered by the computer; see the detailed description in a later section. See Figure 1 for a graphical breakdown of the tasks. The order that the blocks were inserted into the wall was the same for all participants to avoid time variances due to different block orders. All blocks started as red, then turned green to indicate the current block to be inserted, once correctly inserted the blocks changed to their ‘natural’ wood coloring. The beginning of each task was preceded by a brief set of on screen instructions detailing the task.

The first stage for any given block was the ‘Selection Stage,’ it was preceded by a brief five second on screen instruction asking the participant to hold their input device out in front of them to allow for a momentary recalibration of the device tracking. After that

period, the task began with the removal of the on screen instruction and changing of the color of the target block. Once the correct block had been selected, the selection timer stopped, and the second stage began.

The second stage, the ‘Contact Stage,’ represented the time after grabbing the block while the participant attempted to position and orient the block prior to contacting the wall. This initial low precision movement is ‘gross movement’ (Poupyrev et al., 1997). Once the block had contacted the wall, the second timer stopped and the third stage started.

The third stage, the ‘Insertion Stage,’ was the time from the initial wall contact until the block was successfully inserted into the hole. The much smaller, precise movements made in this stage are known as ‘correction movement’ (Poupyrev et al., 1997) and were aided by the contact with the wall to moderate them. Once the block has been released in the correct position, the next block or task is started.

3.4. Interaction Technique

First, one must recognize that “There is no single “best” technique because the technique that is best for one application will not be optimal for another application with different requirements” (Bowman et al., 2002, p. 414). So, a variety of different interaction techniques needed to be considered and evaluated based on their individual strengths and weaknesses. Through research, three predominant methods for object interaction were found. Each has its own strengths and weaknesses.

A common interaction technique, ‘ray-casting’, projects a virtual line (or ‘ray’) from whatever in the virtual environment represents the user’s hand straight out into the environment. This ray might be infinite or limited, and the precise implementation may

vary. In general though, the user is able to manipulate at range whatever object the ray intersects with in virtual space. This technique performs well at both short and long range, however, it can cause issues with ‘lever arm,’ difficulty to manipulate an object due to the distance from the user (Dubois et al., 2005) (Bowman et al., 2002) (Poupyrev et al., 1997).

The ‘virtual hand’ interaction technique creates a virtual representation of the user’s hand (either visible or not) within the virtual space and uses it to interact with objects. The virtual hand’s movements and actions are driven by the user’s hand via an input device of some form. Of these three common techniques it is the most intuitive and has been found to perform best with moderately sized objects located within arm’s reach of the user (Dubois et al., 2005) (Bowman et al., 2002) (Poupyrev et al., 1997). For these reasons it was chosen to be used for the experimental component of this research.

The third common interaction technique, usually referred to as the ‘Go-Go Technique’, it includes features of both the ray-casting and virtual hand techniques. For close objects, it performs very similarly to the virtual hand interaction technique; however, for interaction with distant objects it is quite different. As the user’s hand is extended away from the body, the virtual hand actually stretches to cross the distance between the user and the virtual object. While the least intuitive of the three techniques discussed here, for a skilled user it can be the most effective in VEs dealing with objects both close and far (Bowman et al., 2002) (Poupyrev et al., 1997).

3.5. Variables

Two relevant nuisance (or confounding) variables have been identified, participant gender and participant hand dominance (Poupyrev et al., 1997). Men and women are known to have statistically significant differences in spatial abilities (Sorby, 2009), which can effect performance in VEs. Left or right hand dominance can also affect performance in tasks relating to a single hand task (Kabbash et al., 1993). To compensate for these potentially confounding variables, these participant variables were balanced between both test groups for both gender and hand dominance in order to allow evaluation of only “a particular set of circumstances” (Bowman et al., 2002).

3.5.1. Independent

The independent variable for this research was the devices to be used by the participant to complete the tasks in the VE. The three test group device configurations were: head tracker and wand; head tracker, wrist tracker and flex glove; and head tracker, wrist tracker and pinch glove. With the exception of balancing due to confounding variables, as mentioned in the previous section, participants were assigned to their testing groups randomly.

3.5.1.1. Devices Used

In all test groups, the Intersense© head tracker was used to provide the computer with head tracking input. This allows the computer to alter the images projected on to the screens to simulate how they would change for the participant in a real environment.

For the wand testing group, the Intersense© wand was used to provide input tracking data into the computer for their hand position. The ‘trigger’ button on the bottom of the device (activated by the right index finger) was held to indicate a ‘grabbing’ action. The analog stick and other buttons on the device were disabled for this experiment.

For the flex glove testing group, the Intersense© wrist tracker was to be used to provide the computer with tracking data for the participant’s hand. By use of the flex glove, a ‘grabbing’ action could be made by the pinching of the thumb and index fingers together to indicate a ‘grabbing’ action.

For the pinch glove testing group, the Intersense© wrist tracker was used to provide the computer with tracking data for the participant’s hand. By use of the pinch glove, a ‘grabbing’ action could be made by the pinching of the electrical contacts on the right thumb and index finger to indicate a ‘grabbing’ action. Any contacts detected from any of the other fingers were disregarded.

3.5.2. Dependent

Dependent variables were automatically collected by the computer during the course of the experiment, and output to a text file for later review. Multiple completion times were collected for each task, each representing the time between each event in the task breakdown. Pauses between blocks and activities are not included in the times. Accuracy of block movements was recorded at the time of contact with the wall. In addition, error rates of false positives/negatives and wrong blocks selected were also recorded (Poupyrev et al., 1997).

Object Selection Time (ST) - The time between when a new block is designated to be selected for movement and when it is finally selected.

Object Contact Time (CT) – The time between when the block is selected, and when it first contacts the surface of the wall.

Object Insertion Time (IT) – The time between the block's first contact with the wall, and when it is released in the correct position and orientation.

Empty Selections – Number of times a button hold or pinch gesture registers while there is no blocks within the grab range of the virtual hand. (False Positive)

Object Drops – Number of times the block in hand is dropped before it reaches the correct destination. (False Negative)

Wrong Selections – Number of times that the user attempts to select a block other than the one currently designated for movement.

Gross Movement Accuracy – At the initial time of contact with the wall, how far is the block from the destination hole. (Measured in cm)

Gross Orientation Accuracy – At the initial time of contact with the wall, how far away from the correct orientation. (Measured in degrees)

3.6. Population

A goal of many researchers in VE technology is to bring this technology out of the research lab and into common use by the general public. However, for the time being the majority of users for VE technology are the researchers themselves. As such, research participant selection was focused on students with a background in computer graphics, one of the cornerstone fields of virtual reality. At the time of testing, due to

time and equipment constraints, insufficient participants were found in computer graphics studies alone, so recruitment also branched out into other areas.

3.6.1. Sample Population

The participants for this research were volunteers from the student body of Purdue University, predominantly from the Computer Graphics Technology (CGT) undergraduate program. This group was focused on for testing due to their easy availability to participate and due to their basic understanding of the technology involved.

3.7. Devices

3.7.1. Intersense© IS-900 Head Tracker



Figure 2: The IS-900 Head Tracker, attached to a plastic support for ease of use.

The Intersense© IS-900 Head Tracker, used in both device groups, provides the computer with a positional and rotational data for the user's head. The device is positioned above the eyes and secured similar to a pair of glasses. Tracking information is determined by use of a constellation of ultrasonic emitter bars suspended over the entire Cave™ offering full coverage. By use of two ultrasonic microphones on the device, it is able to determine its range from any given emitter. Given this information in

combination with some internal sensors, the device can be precisely located and oriented within the real and virtual space of the VE. This tracking information is then transmitted to the computer wirelessly using an attached transmitter worn around the waist on an elastic belt.

3.7.2. Intersense© IS-900 Wand



Figure 3: The IS-900 Wand, the 'trigger' used to grab blocks in the experimental tasks can be seen on the bottom of the device.

The Intersense© IS-900 Wand is a handheld device that operates based on the same principles as the head tracker. The same set of ultrasonic emitters is used to locate the device within the VE, though unlike the headtracker; this device uses four ultrasonic microphones to enhance tracking accuracy. In addition to the tracking data, the Wand also provides the user with more traditional input methods. This includes an analog stick and four buttons on the top of the device, all activated by the thumb, and a 'trigger' on the bottom of the device activated by the index finger.

3.7.3. Intersense© IS-900 Wrist Tracker



Figure 4: The IS-900 Wrist Tracker and Velcro strap to attach to the user's hand.

Just like the IS-900 Wand, the IS-900 Wrist Tracker uses four ultrasonic microphones and internal sensors to locate and orient itself within the VE. This device however does not provide any additional input methods such as buttons; additional input is expected to be handled by an additional device. To not impair the user's use of their hands, the device is strapped to the back of the hand using a Velcro elastic strap.

3.7.4. 5DT Data Glove 5 Ultra



Figure 5: The 5DT Data Glove, here the flex sensors can be seen along the top of each finger.

The 5DT Data Glove, or ‘Flex Glove’ as it is referred to in this experiment, provides user input to the simulation in conjunction with the wrist tracker. The glove functions by means of flexible fiber optic filaments embedded into the material on the backs of the fingers. By flexing the fingers, each sensor is also flexed, this varies the optical properties of the filament, thus the amount that the finger is flexed can be determined. This flex information can then be used to determine when a ‘pinch’ gesture is made. This information is transmitted to the computer wirelessly via an attached wireless transmitter.

3.7.5. Pinch Glove



Figure 6: The pinch glove, the electrical contacts can be seen along each finger.

The ‘Pinch Glove’ system used in this research was assembled at by the experimenter in an attempt to make a cheaper, more intuitive and more robust way to take input from user hand input. The system was assembled from two primary components, the glove and the transmitter. The glove itself was salvaged from an earlier set of hardware that had been in use at the Envision Center. The system had functioned via a wired control box that was no longer compatible with the present system that controlled simulations within the Envision Center’s VE. The glove functions to provide user input

via electrically conductive material covering each fingertip, by touching a finger to the thumb, an electrical circuit is completed. The electrical outputs from the glove were wired into a Logitech ® wireless gamepad and transmitted wirelessly to the simulation computer. The computer can then interpret input from the glove like any other button press from the gamepad.

Prior to experimental testing, the pinch glove was put through pilot testing with the simulation. With the combined input of the wrist tracker, the glove functioned well to provide user input to interact with objects in the environment.

3.8. Test Environment

Testing for this research was conducted at Purdue University's Envision Center for Data Perceptualization. At this facility there is a 'four walled Cave™,' it consists of three wall screens each meeting at ninety degrees and arranged in a 'U' shape. The fourth screen is the floor inside the 'U' and is projected onto from overhead. Each screen measures eight by ten feet, making the immersive environment approximate to a ten foot cube. Room lighting was kept low to avoid interfering with the shutter glasses. Intersense© emitter bars are located overhead to allow the Intersense© devices in use to be tracked within the zone of the simulator.

3.9. Virtual Environment

As the virtual environment in which participants carried out their tasks was somewhat similar to the real one, this was done to enhance believability and also eliminated the need navigation to be added to the simulation. The user was able to walk around within the Cave™, but since the virtual environment did not exist beyond the real walls, navigation was unnecessary. The virtual environment is ten feet across and lines

up with the cave walls. The targets with the holes for the blocks were located two feet in front of the front screen to allow it to be closer to the user.

Two volunteers were asked to take some measurements prior to the creation of the virtual environment so that objects with which users were to interact with could be located suitably for most people. The three primary pieces of information gathered from them were: a comfortable low bound for picking up objects, a comfortable high bound for picking up objects and finally their comfortable maximum lateral reach. The first volunteer was 4'11" and their comfortable low bound was 14", their comfortable high bound was 68" and their lateral reach was 30". The second volunteer was 6'3" and their comfortable low bound was 30", their comfortable high bound was 83" and their lateral reach was 32". According to these results, for user comfort, all objects should try to be within 30" of the user's starting position (center of Cave™), no less than 30" above the floor, and no more than 68" above the floor. Based on these findings, blocks were located approximately 18" in front of the user and 36" off the floor. Holes in the wall were located at 60" off the floor.

3.10. Procedures

Each participant signed up for a 30 minute time slot to conduct their testing. Each participant was given a waiver, included in Appendix A, detailing the risks associated with the testing and the testing procedure including what would be expected of them. Once all of this had been finished, the participant was placed into one of the two testing groups randomly (with exception to balancing for confounding variables as mentioned above.)

3.10.1. Device Group Procedures

Once a device group was decided for the user, they were equipped with the appropriate devices and given a brief explanation of how they worked; a brief explanation of how the Cave™ worked followed, after which any questions were addressed. The participant was then asked to step into the Cave™ so the experiment could begin.

3.10.2. Object Manipulation Task Procedures

With the exception of the device used, each participant carried out the same procedure. First, the computer would display on a series of on screen instructions containing an explanation of the tasks to be completed. Prior to each task, an on screen instruction would provide additional user instructions specific to each task. After a brief device calibration, the Selection Stage for the first block would begin. After the each block was correctly inserted into the wall, there would be a brief five second pause for calibration before beginning the next block. At the end of each task, there was a built in thirty second break to allow the user to recuperate and reorient themselves. At the conclusion of the last task, users were instructed to leave the Cave™ and return the devices to the experimenter.

3.10.3. Debriefing

Once the devices were returned, all participants were given a chance to ask any questions related to the experiment they had participated in, the devices they used, the other devices, data collected or any other relevant areas.

DATA

Testing for the research experiment began March 4th, 2014 and continued through March 13th, 2014. Testing was unable to be conducted over a longer period due to University holidays, and testing location availability. Participant recruitment was done via several emails to the department's student email list as well as in class announcements. During this period thirty one student volunteers participated in the study. Based on initial experiment design consulting with the university statistics department, a sample of at least forty participants would have been optimal. However, due to time, equipment constraints and student availability, these were all that were possible to include in the study.

At the time of testing, due to a hardware issue, the computer was unable to detect or interface with the flex glove for input. This problem could not be rectified in a timely matter, so the flex glove testing option was dropped from the experiment leaving only the wand and pinch glove options.

4.1. Testing Data Exclusions & Outliers

Of the thirty one testing participants, data for seven of the participants had to be removed from the data analysis after collection. Following are details of all seven cases of exclusion.

During testing for two of the participants (5, 10), the computer lost connection with the wand device and stopped receiving user input. One of these users (5) also lost

input from the glove device as well. By the time that the connection was reestablished, the user's data would have been an outlier in the data set so testing was ended at that time.

During testing for one of the participants (19), the cord leading from the pinch glove receiver to the computer was accidentally unplugged. Device input could not be regained, so the experiment could not be completed.

Testing for another participant (6) was interrupted at the beginning of task one, at that point the experimenter was made aware by the participant that they were colorblind, specifically in the red-green spectrum. As a result, they were unable to recognize the correct block to attempt to grab, and were unable to complete the task.

Testing for participant 23 also ended early due to a visual irregularity, the participant was unable to grab the blocks in the virtual environment. Due to what seemed to be an irregularity in their depth perception, they perceived the shaped blocks to be several feet from their actual location. The system was confirmed to be functioning properly by the experimenter before ending the testing session.

Data for participant 28 was also eliminated from analysis after the early stage of data analysis. The participant spent close to twice the time to complete the activity as any other participant, as such, their data was an outlier and was eliminated. A reason for the discrepancy could not be established.

Testing data for participant 18 was also eliminated due to also being an outlier from the rest of the group in their completion times. In this case a reason for the discrepancy was easily established. At approximately a dozen points during the timed

portions of the experiment, the participant attempted to initiate a conversation with the experimenter despite repeated reminders to not attempt conversation and to stay on task.

Of the thirty one original testing participants, data for twenty four participants remained after the above entries were removed.

4.2. Sample Population Characterization

Data for characterizing the sample population was obtained via a questionnaire given to testing participants prior to starting the experiment. This document can be found in Appendix B.

The sample population consisted of nineteen male testing participants and 5 female. Twenty participants were right-handed, the remaining 4 were left-handed. Student majors consisted of, fifteen Computer Graphics Technology students, two Electrical and Computer Engineering students, three undecided or undeclared, and one each of Computer Science, Finance, Animal Science and Apparel Design (recently left CGT). For student year, there were five Freshman, seven Sophomores, seven Juniors, one senior and two Graduate Students.

To gain some idea of what a participant's previous exposure to similar technologies, they were asked about any prior experiences in the questionnaire as well. Three participants had no experience with a Nintendo Wii Wiimote gaming controller (similar in function to the Intersense© wand used in the study). The remaining 21 ranged in experience from one, to approximately five hundred hours of Wiimote use, with an average of seventy nine hours. Participants were also asked about any previous experience with 'non-standard input devices' such as with an XBOX Kinect, Nintendo Wii Balance Board, Sony Playstation Eye Toy, or any other similar devices (these would

provide a similar experience to using the head tracker or pinch glove devices). Five of the participants had no experience, the remaining nineteen had between one and one hundred hours of experience, with an average of twenty two. Thirteen of the participants stated that they had no previous experience with an immersive virtual reality experience (such as the Cave™) as either an operator, or audience member. Eleven of the participants had at most an hour of previous experience with an IVRE as an audience member, sometime in the past two years. Nine of these were at the Envision Center, the remaining two were at amusement parks. Of these same nine, two had previous experience as the operator (the user wearing the head tracker and using the wand) of their experiences, both of which lasted approximately ten minutes.

4.3. Data Handling & Consolidation

For each of the participants, the raw data collected during the experiment contained two hundred thirty six data points. After meeting with a statistical consult, this was determined to be far too many data points to easily conduct a statistical analysis, so with the assistance of the consultant and committee input, the raw data was condensed down into an easier to manage number by value totals or averages depending on the data type collected.

Data for the gross movement accuracy of the block at the time of first contact with the target block was recorded in terms of both the X-axis and Y-axis displacement from the target. These were condensed into a single variable representing the linear displacement from the target by use of the Pythagorean Theorem.

Data collected for the gross orientation accuracy was recorded in terms of the absolute difference between the orientation of the block at time of first contact with the

target block and the target orientation across all three axis of rotation. These three values were summed to get a single variable representing the axial rotation offset from the target orientation.

The positions and orientations of each block was identical across all users, which would allow for an analysis across users, however, this information would have been not very applicable to outside scenarios. For this reason, all common data points for each block within the same task were totaled, or averaged in the case of the movement and orientation accuracy.

Several new variable were generated totaling common variable across all three phases of each task, as well as across all three tasks themselves to give values that would be more representative of the participant's overall performance. This left a total of fifty nine data points per participant for analysis. These were divided into three groups to give representative data for the participant's speed, precision and accuracy or their performance with their input device.

RESULTS, CONCLUSIONS & FUTURE RESEARCH

5.1. Results

The data from the experiment was examined via ANOVA analysis between the two testing groups, the pinch glove users and the wand users. Data displayed in the figures in this section show the confidence interval of the analysis of the particular variable as well as the averages for both the pinch glove users (P) and the wand users (W). Confidence intervals are shaded related if they fall into either the 90% or 95% confidence interval ranges.

Due to the overwhelming majority of the sample population being right handed males, a comparative analysis was also made excluding either the left handed participants or the female participants. This exclusion of these participant's data from the sample population was not found to have any significant effect on any of the variables that were measured.

5.1.1. Analysis of Precision

Precision, in the case of this experiment being the preciseness with which users were able to control the gross movement and orientation of the blocks at the time they first contacted the plane of the front of the targets.

Table 1: Confidence Intervals and Average values for each of the variables collected relating to Precision

Precision			Average Gross Movement Accuracy per Block (cm)	Average Gross Orientation Accuracy per Block (deg)
Gender	Hand	Task		
M/F	R/L	Task 1		P: 49.93 W: 49.09
M/F	R/L	Task 2	0.539 P: 1.59 W: 1.58	
M/F	R/L	Task 3	0.459 P: 1.58 W: 1.58	0.259 P: 61.72 W: 59.84

Confidence Interval:

> 95%
> 90%

For the Gross Movement Accuracy, this data was not collected during the first task because the lateral and vertical movement of the blocks were locked. During the second and third task though this data was collected. In both of these cases, the averages were practically identical at approximately 1.58cm off target at time of contact, with the wand being very slightly closer in both cases. ANOVA showed that there was very little chance of a significant difference between the two testing groups.

For the data collected on Gross Orientation Accuracy during the first and third tasks, orientation was locked during task 2, again there is very little difference between the averages. With a difference in the averages of less than two degrees, ANOVA showed again that there was little chance of significance.

Based on the above analysis of the precision of the pinch glove and wand devices, the Alternate Hypothesis can be rejected and the Null Hypothesis accepted with a high degree of confidence as it relates to the precision of the two input devices. This is an

unsurprising conclusion though as the two input devices are both relying on the Intersense© tracking system for user input of orientation and position.

5.1.2. Analysis of Speed

Speed, as measured by the time interval that it took participants to complete each part of the experiment.

Table 2: Confidence Intervals and Average values for each of the variables collected relating to Speed

Speed			Average Selection Time per Block (sec)		Average Contact Time per Block (sec)		Average Insertion Time per Block (sec)	
Gender	Hand	Task						
M/F	R/L	Task 1	0.332	P: 4.49 W: 3.68	0.098	P: 5.41 W: 3.97	0.415	P: 4.08 W: 5.12
M/F	R/L	Task 2	0.161	P: 4.76 W: 3.92	0.913	P: 3.45 W: 3.39	0.461	P: 3.26 W: 3.96
M/F	R/L	Task 3	0.344	P: 3.57 W: 3.16	0.236	P: 4.60 W: 3.71	0.382	P: 4.61 W: 3.80

Confidence Interval:

> 95%

> 90%

For the average Selection times per block, the averages varied by less than a second between the two testing groups, and as such there was little significant difference found. Of note though, in all three task times, selection times for the wand were less than those for the pinch glove group. Not enough so as to be statistically significant, but at least consistent.

Average Contact time intervals per block were again all shorter with the wand than for the pinch glove. For Contact times though, in the first task, a confidence interval of over ninety percent was shown from ANOVA analysis. This, in addition to the rest of the analysis is beginning to show the wand as the superior input device.

For average Insertion times, the trend of shorter wand times was interrupted. For tasks one and two, the pinch glove group on average completed their precise movement faster, however, the corresponding p-values were high meaning that these numbers may not be able to be trusted.

Overall, with respect to the data collected on speed, the null hypothesis must be accepted. Again, this is to be expected in this area of data collection since the tracking system used for both groups of participants was the same, only the input device itself differed. While the wand users performed faster in most cases, it was by a narrow margin and with relatively high p-values. The appearance of two faster average times could also be seen to be of little significance, or it could be an indication of a longer learning curve for the wand users in regards to precise movement or orientation. More research would be required to make an accurate assessment.

5.1.3. Analysis of Accuracy

The Accuracy of the wand and pinch glove were evaluated by means of tracking how many errors participants made over the course of completing the three tasks.

Table 3: Confidence Intervals and Average values for each of the variables collected relating to Accuracy

Accuracy			Selection Phase				Contact Phase				Insertion Phase				Confidence Interval: <div>> 95% > 90% Unreliable Data</div>				
			False Positives (Empty Selections)		Wrong Object Selections		False Positives (Empty Selections)		Wrong Object Selections		False Negatives (Object Drops)		False Positives (Empty Selections)			Wrong Object Selections		False Negatives (Object Drops)	
Gender	Hand	Task																	
M/F	R/L	Task 1	0.116	P: 0.64 W: 1.77	0.006	P: 2.18 W: 0.39	-NA-	-NA-	0.122	P: 23.27 W: 0.69	0.369	0.216	0.253	P: 5.82 W: 0.54					
M/F	R/L	Task 2	0.826	P: 2.82 W: 2.62	0.235	P: 1.27 W: 0.39	-NA-	-NA-	0.061	P: 3.27 W: 0.39	-NA-	-NA-	0.780	P: 0.18 W: 0.23					
M/F	R/L	Task 3	0.852	P: 2.55 W: 2.39	0.002	P: 1.36 W: 0.15	0.287	-NA-	0.013	P: 8.36 W: 0.85	0.907	-NA-	0.097	P: 2.00 W: 0.69					

Three different types of errors were recorded. The first error type was classified as false positives, also called ‘empty selections,’ these were recorded any time that participants attempted to ‘grab’ a block while no blocks were in range of the hand. The second error type was classified as ‘wrong object,’ these were recorded any time that participants attempted to grab while any object was closer to the hand than the currently active block. The third type of error was false negatives, or ‘object drops’ these were recorded for each time the participant preemptively released the block anywhere but the target location. In the cases where a participant dropped a block, they almost always

immediately picked it back up again without moving at all. Only one or two participants made the error of a wrong object selection or an empty selection in the latter two phases of the tasks, and even those only made at most two of these errors. Because of this, out of a sample population of twenty four, data based on these one or two points of data was found to be unreliable, so was left out of the analysis.

In the Selection phase, the averages for empty selections had little significance. Interestingly though, task one had the lowest number of errors for both the wand and pinch glove. This might indicate that the participants took an extra moment to be sure that their hand was positioned over the blocks prior to grabbing. In tasks two and three, the higher number of errors may indicate that they were no longer taking their time to make sure they would grab an object.

In the same phase, the wrong object selections showed much more significance in the first and third tasks, both with over a ninety five percent confidence interval. In all three cases the wand had far fewer of these errors, this might be an indication that while the pinch glove would initially offer a better perception of roughly where the participant's hand is, the wand seems to offer a more precise perception of where their hand is.

In the Contact phase, in all three tasks the wand had far fewer drops than the pinch glove. The difference between the two testing groups was quite recognizable via a large discrepancy in the number of errors and in the high confidence interval from ANOVA. This, along with observations during testing of participant's having difficulty with the pinch glove most likely indicates a shortcoming of the pinch glove device itself. Over extended usage, participants were observed to have a difficult time maintaining a

constant pressure between the fingers to create a constant electrical connection while performing a pinch gesture with the glove, versus using a commercial product like the wand where holding a button down is all that is required. This is a definite area for future research using different or more robust devices.

Object drops during the Insertion phase also followed a similar pattern. In the first and third tasks, the wand made fewer errors with a high degree of significance. The second task actually had fewer errors with the pinch glove, but the low degree of significance for this value shows that this may be an unreliable number.

Taking all of these data points about accuracy into account together, in terms of accuracy the Null Hypothesis can be rejected. The number of errors showed in many cases that the wand and the glove do perform differently, even if it was due to a hardware shortcoming by the pinch glove.

5.2. Conclusions & Future Research

After examining the results of the experiment, in terms of the input device's speed and precision, the pinch glove and wand perform almost the same across all three tasks. In terms of accuracy, the pinch glove made significantly more errors than the wand. In a situation where both devices are available, the wand would be the logical choice for most immersive virtual reality environment input needs. However, if both devices are not already available, this would be an area where more research would be beneficial. In addition to the Intersense© tracking array, the Intersense© wand costs approximately five thousand dollars, and the pinch glove cost approximately fifty plus the wrist tracker for approximately two thousand. If money is of concern, it would very likely be worthwhile to use a cheaper tracking system, such as optical motion capture, and build your own

input devices such as remotes, controllers and gloves for thousands of dollars less at the loss of some tracking accuracy.

Due to the broad nature of the research for this experiment, there are a large number of areas that could stem from this as future research. In the area of input devices, there are dozens of 3D input devices commercially available in the market today. Testing using a haptic device (force feedback) would not allow the user of the freedom of a wireless interface, but it would give users a real feel for the object that they are interacting with, which could help to alleviate some of the mental strain posed on the user by a lack of the sensation of touch. Devices like the Razer™ Hydra would allow for two handed user input as well as access to a number of additional button and analog inputs. Tracking for 3D input could also be handled by a variety of other tracking methods, infrared, optical and magnetic would be viable options each with their own financial and technological considerations. A device like the Microsoft® XBOX Kinect would allow the use of full body input without the need of handheld or user mounted devices. Emotiv© has a variety of headsets available that actually cross the physical boundary and take input directly from a user's neural activity rather than their physical input. In addition to all the commercially available devices, there's a nearly infinite variety of home built devices created from combinations of all the different types of sensors available. In the area of output devices, CAVE™ simulators only account for a small part of the virtual reality output devices, head mounted displays (HMD) as well as other stereoscopic displays would make for other exciting and differentiated experiments. In this experiment, only the most basic of user task was considered, navigation as well as number and text entry were even intentionally excluded, more complex tasks with a

variety of different goals could be developed as testing scenarios. The population of experiment participants was made up exclusively of college students, without issues viewing stereoscopic imagery and without any physical ailments that would impair physical ability or range of motion. Testing user populations with a variety of educational backgrounds, areas of study as well as age or even those with physical ailments could all provide meaningful data for future experimentation and development with user input.

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APPENDICES

Appendix A: Research Participant Consent Form

RESEARCH PARTICIPANT CONSENT FORM

Usability of Immersive Virtual Reality Input Devices

Dr. Patrick Connolly

Purdue University

Computer Graphics Technology

Purpose of Research

The research you will be participating in is to determine how three different input devices compare against each other based on their performance and completion time for a given set of tasks.

Specific Procedures

You will be asked to carry out a series of 3 tasks in a virtual setting using the Envision Center's VR Simulator. Each task will require you to place a series of shaped virtual blocks into the associated holes in a series of virtual panels using one of three 6 degree of freedom input devices (A Wand, a flex glove or a pinch glove).

Duration of Participation

Prior to testing you will be asked to fill out a brief questionnaire about your demographic information. You will then be asked to carry out 3 tasks within the VR Theater, participation should require less than 30 minutes of your time. ***[30 minute period is the estimated time for completion of tasks]***

Risks

There is a minor risk of a breach of confidentiality if the included safeguards were insufficient, safeguards are specified below. Outside this, the risk is minimal, which is no greater than if you were to play a video game, or see a 3D movie. Your demographic information and the data collected during testing will be de-identified and have no association with your name or other personal information. All research files and data will be stored on local disk space, and will only be accessible to the researcher, a statistics consultant and viewable by the researcher's committee members. For future projects or

derivative research, the data collected from the experiment will be maintained for the foreseeable future in the form of a de-identified and disassociated archival spreadsheet only. Future resultant endeavors will require the spreadsheet be shared with co-researchers.

Benefits

At this time, there are no apparent benefits to participants.

Confidentiality

The project's research records may be reviewed by departments at Purdue University responsible for regulatory and research oversight.

Voluntary Nature of Participation

You do not have to participate in thesis research project. If you agree to participate you can withdraw your participation at any time without penalty.

Contact Information

If you have any question about this research project, you can contact:

Dr. Connolly (connollp@purdue.edu) or

Chris Mankey (cmankey@purdue.edu)

If you have concerns about the treatment of research participants, you can contact the Institutional Review Board at Purdue University, Ernest C. Young Hall, Room 1032, 155 S. Grant St., West Lafayette, IN 47907-2114. The phone number for the Board is (765) 494-5942. The email address is irb@purdue.edu.

Documentation of Informed Consent

I have had the opportunity to read this consent form and have the research study explained. I have had the opportunity to ask questions about the research project and my questions have been answered. I am prepared to participate in the research project described above. I will receive a copy of this consent form after I sign it.

Participant's Signature

Date

Participant's Name

Researcher's Signature

Date

1. What is your major?
CGT CGT Focus: _____
Other If 'Other' please specify: _____
2. Which year classification best describes your place amongst your peers in your major?
Freshman Sophomore Junior Senior Graduate
Student
3. What is your gender? _____
4. Are you: Right-Handed Left-Handed
5. Have you ever played a video game that used a Wiimote?
No
Yes If 'Yes' please specify how long: _____ hours (approx.)
6. Have you ever played a video game that used a non-standard input device? Such as a Kinect, a Wii Balance board, etc.
No
Yes If 'Yes' please specify: What device: _____
How long: _____ hours
(approx.)
7. Have you ever experienced an Immersive Virtual Reality Environment before?
No (Please return questionnaire to experimenter)
Yes, as a passive audience member (Please skip to question 8)
Yes, as operator (the person 'driving') (Please continue to next question)

8. Please answer the following about your experience OPERATING an Immersive Virtual Reality Environment:

How recent was your experience? 0-6 months 6-12 months 1 year
2 years or more

Where? _____

For how long did you use it? _____ hours (approximately)

What user input devices were used?

Head Tracker Wand Wrist Tracker Motion Capture

Other: _____

9. Please answer the following about your experience VIEWING an Immersive Virtual Reality Environment:

How recent was your experience? 0-6 months 6-12 months 1 year
2 years or more

Where? _____

For how long did you use it? _____ hours (approx.)