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# A new taxonomy for locomotion in virtual environments

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**A new taxonomy for locomotion in virtual environments**

by

**Laura Lynn Arns**

A dissertation submitted to the graduate faculty  
in partial fulfillment of the requirements for the degree of

**DOCTOR OF PHILOSOPHY**

Major: Computer Science

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**In memory of Russell Whisler and Beverly Nelson**

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## **CHAPTER 1. GENERAL INTRODUCTION**

The concept of virtual reality (VR) was first formally defined in 1965 when Ivan Sutherland introduced his Ultimate Display [Sutherland65]. The VR experience places a participant into a computer generated world, allowing the participant the unique experience of interacting with virtual objects that can simulate the physical world, but at the same time may not be bound by all the constraints of the physical world, such as the laws of physics and time. However, it is only recently that VR has begun to move outside the research lab and into mainstream use. Industry is beginning to accept VR as a tool that can be useful for performing work in a variety of application areas, including architectural walkthroughs, engineering, biology, chemistry, medicine, scientific visualization, art, and entertainment. Despite the increasing use of VR, there remain unresolved issues and limitations with the technology. In particular, the interaction of humans with virtual environments (VEs) presents some difficulties. Traditional desktop computer environments with graphical user interfaces (GUIs) have well-established guidelines and methods for performing interaction, such as pull-down menus, buttons, and windows. These GUIs cannot generally be transferred to VEs, resulting in new paradigms for interaction. VEs suffer from a lack of such standards and guidelines for design. The following two examples demonstrate the need for improved interaction with virtual environments.

## 1.1 Two Motivating Examples

### 1.1.1 VRGobi

As part of the author's Masters thesis work, experiments were performed using the C2<sup>1</sup> statistics application, VRGobi [Nelson99]. VRGobi was created as a three-dimensional, immersive version of XGobi [Swayne98], an XWindows application designed for analysis of multivariate statistical data, (i.e. data that has been sampled on more than two variables). For example, instead of measuring heights and weights of a group of people, we might measure height, weight, arm length, waist, shoe size, and inseam. Such information cannot easily be analyzed using a standard computer workstation because the workstation offers only two dimensions of visualization, significantly less than the number of variables sampled. We were curious as to whether using virtual reality, with its third dimension of visualization, could improve analysis of multivariate statistical data, so VRGobi was created.

In evaluating VRGobi, it was determined that there are two separate but important components for a user: *visualization* (understanding) of the data and *interaction* with data. Both of these components are necessary for a statistician to analyze a data set. When studying a data set, the statistician first visually observes the data, attempting to find important structures or features. Then he must interact with the data in order to mark or indicate the structures or features that he finds interesting. Marking the data points serves several purposes: allowing the user to differentiate between several sets of points with different characteristics, reminding the user of points that she wishes to study in more detail later, or making it easier to show another statistician points of interest. Because both of the steps involved in analysis are important, we decided to study them both in separate

experiments. (For more detailed information on the experiments and results, the reader is referred to [Nelson99].)

Four tests were designed for the experiment. Three of them were designed to study visualization tasks, and the fourth was to study interaction. In each visualization test, the test subject was to answer a specific question about the structure of the data set by simply viewing the data set for one minute. The interaction test required users to choose a paintbrush and then paint a group of data points. Subjects performed all four tests in both environments. A variety of data sets were available and chosen randomly with replacement.

Both the visualization test and the interaction test produced interesting results. In two of the three visualization tests, the VRGobi environment appeared to improve user performance on visualization tasks over the traditional XGobi environment. However, the results of the interaction task were somewhat discouraging, because most subjects performed the task more quickly using the desktop environment than the virtual environment. In the XGobi environment, subjects averaged 12.9 seconds to paint the group of data points. But in the VRGobi environment, subjects averaged 50.9 seconds to perform this task.

Further analysis of the VRGobi test results showed a large deviation in the painting times. Times ranged from 12 seconds to 120 seconds, with a standard deviation of about 30 seconds. Further analysis of the test results showed that subjects with previous VR experience performed significantly better in the VRGobi environment. They required only an average of 30 seconds to paint the data points, while subjects with no experience took twice as long, 61 seconds on average, accounting for the large deviation. This information indicates that experience with virtual reality, even very limited experience, leads to increased

---

<sup>1</sup> C2 is a 4-wall VR device in use at our laboratory. It is discussed in more detail in section 2.3.4.

performance in virtual environments. However, it is still unclear whether increased VR experience could completely account for the difference in performance between the virtual environment and the desktop environment.

In an effort to clarify the results of the interaction test, we conducted an additional experiment. This time, half of the subjects were experienced virtual reality users, with the other half being experienced computer users with no previous virtual reality experience. In addition, a few subjects were application experts. These subjects were experienced virtual reality users who also had substantial experience with the VRGobi application. The subjects performed the same painting task used for the previous interaction experiment.

The results of this experiment were somewhat surprising. In the virtual environment, the novice users outperformed the novice users from the previous experiment, possibly because of their increased experience with computers in general. However, the VR experts did not perform significantly better than the novice users. As expected, the application experts outperformed both the VR experts and the novice users. Unfortunately, even the application experts were still unable to complete the painting task as quickly in the virtual environment as with the desktop environment. This suggests that training and increased experience with virtual worlds may not always provide users with the ability to interact efficiently with a virtual world. Also, it is possible that our choice of interaction method was not appropriate for this task, and users may have performed the task more efficiently had we chosen a different interaction method.

The above example illustrates the need for better understanding of interaction between users and virtual environments. Often new users of VR come away from the experience impressed by the powerful visuals, but frustrated by their inability to easily

interact with the environment. Like the statisticians using VRGobi, they feel that to really accomplish useful work in the virtual world, they must interact with the data instead of simply viewing it. Many different types of interaction are needed, and the following example concentrates on one particular interaction that is common to many virtual worlds, travel.

### **1.1.2 Interactive Oil Field Exploration**

Another project that the author was involved with involved the use of a virtual environment to explore data about potential oil fields. In this application, domain experts such as geologists, geophysicists, and others use the virtual environment to view geological structures below the earth's surface, and then plan pathways for oil wells. It is often necessary to view an area from several different viewpoints to understand precisely how the planned well path will intersect the geological structures. This requires the ability to travel through the virtual space. In addition, the domain experts desired the ability to place themselves inside of planned wells and travel along their paths, as if riding inside the drill bit as it drills the well.

To provide users with these abilities, the application developers created a simple method of locomotion through the virtual surfaces. This worked fine during development, and the VR designers particularly appreciated the flexibility of this travel method, which gave them the ability to position themselves inside the virtual world with extreme accuracy. Unfortunately, when the domain experts used the new application, they were unable to control the locomotion. The same features of the locomotion that allowed the developers to maneuver into a wide variety of viewpoints also allowed the domain experts (who were not virtual reality experts) to unintentionally maneuver into viewpoints that were not useful to

them and were often disorienting (such as standing upside-down, or being unable to remain inside a well pathway while travelling along it).

Eventually, through trial and error, several different methods of travel were implemented in the environment. Users could select which method they used at any given time. This had the advantage that developers and end users could each choose a travel strategy that worked best for them, and different travel methods could be used for performing different tasks within the environment. However, the disadvantage is that a method had to be developed for indicating to the system which travel method the user desires. This introduced an extra complexity both for the user and for the application developers. Additionally, after a short time, it became obvious that many of the travel methods were never being utilized. Each method was added to the application because in the design phase it seemed to offer a useful ability, but when actually implemented it became obvious that some methods did not live up to their potential.

A better understanding of the navigation needs of the users, along with a classification of travel methods in virtual environments, was needed. With such a classification, the developers and the end users could have determined in advance what types of travel would be most useful for their application, then only implemented these few methods. This would have eliminated a large amount of frustration and wasted time, allowing the project to focus on other goals more directly related to the well planning.

Based on these two examples and other experiences, it is clear that there is a strong need to investigate interaction and travel methods in immersive environments.

## **1.2 Scope of Work**

The purpose of this work is to establish a classification system for travel in virtual environments. It is expected that such a classification will aid both designers of virtual environments and users of the environment by guiding the designer in his choice of travel method, shortening development time and allowing the user to most effectively perform his tasks in the virtual world. To achieve this goal, the research has been sub-divided into the following stages:

- 1) Review the methods currently used for travel in virtual environments, and analyze their advantages and limitations. (Covered in Chapters 1 through 5.1)
- 2) Review existing classification systems for travel in VEs. (Covered in Chapters 5.2 through 6)
- 3) Identify components common to all methods of travel in VEs. (Covered in Chapter 7)
- 4) Use these components to create a new taxonomy of locomotion that includes additional information and factors not present in existing classifications. (Covered in Chapter 7)
- 5) Experimentally validate selected portions of the new taxonomy. (Covered in Chapters 8 through 10)
- 6) Discuss how this taxonomy can be used by virtual environment developers to implement travel in their virtual worlds. (Covered in Chapter 9 through 10)
- 7) Discuss possible future work. (Covered in Chapter 10)

## **CHAPTER 2. VIRTUAL REALITY BACKGROUND**

The term virtual reality (VR) has been used in a wide variety of contexts.

Unfortunately the term is often misused by the popular media in reference to such activities as 3D movies, video games, or the World Wide Web. The entertainment industry has further clouded the public's understanding of virtual reality by presenting futuristic fantasies such as Star Trek's holodeck. New terms such as virtual world (VW), virtual environment (VE), and synthetic environment (SE) have been introduced in the research world in an effort to move away from the stereotypes associated with the term VR. But what do these new terms really mean?

In the work presented here, all of the above terms refer to "immersive, interactive, multi-sensory, viewer-centered, three-dimensional, computer-generated environments and the combination of technologies required to build these environments" [Cruz95 p2].

*Immersive* means that the user has the illusion of being a part of the environment, he is not just an observer on the outside looking into the computer-generated world. *Interactive* means that the user is able to affect the state of, and receive feedback from, the virtual world.

Chapter 3 discusses the ways in which a user can interact with the virtual environment. The rest of this chapter discusses the definition of VR in more depth, with emphasis on what hardware and software tools are needed to create a VE.

### **2.1 Overview of Virtual Reality Systems**

#### **2.1.1 Components of Virtual Reality Systems**

The main component most people associate with virtual reality is computer graphics, and the devices used to present them. Many people associate 3D vision with virtual reality.

This is the technique known as *stereoscopic graphics*, often referred to as “*stereo*”. The idea behind computer simulated stereo vision is to emulate natural human vision, in which each eye sees a slightly different view of the world due to their separation. For distant objects, such as a distant building, stereo has little impact [Barfield95]. But when an object is close, each eye sees the object from a slightly different angle, resulting in different views. The brain is able to fuse these two views into a single image that contains information about the depth of the object(s). This process is known as *stereopsis* [Burdea94]. When users view a computer screen, the result is usually *monoscopic* vision, as both the eyes view the same image on the screen. A variety of methods exist for emulating natural stereo vision for users of a virtual environment, such as liquid crystal display (LCD) shutter glasses, or polarized glasses. However, human factors researchers are unsure whether stereo vision is necessary for effectively performing tasks in the virtual world, or whether mono vision is sufficient ([Sollenberger91], [Ware93], [Ware96]).

A variety of graphics displays are available for use in a virtual reality system, several of them are discussed in Section 2.3. Because the different displays have many different characteristics such as brightness and field of view, it is important to consider the effects a display may have on users of the VR system. For example, an architectural walkthrough may require a display device with a large field of view so that the user is able to correctly perceive the size of the objects he is viewing in relation to his own size.

Because virtual reality is user-centered, and we want the user to feel that he is “inside” the virtual world, it is important that we know the user’s position and orientation. For example, when the user reaches out to grab a virtual object, we need to know the position of his hand to determine if his hand is intersecting the object or not. Also, it is important that

the position and orientation of the user's head is known because this information is used to create the visual representation of the virtual world from his point of view. Devices that can determine position and orientation are called *trackers*.<sup>1</sup> Most often, a user's head and hand will be tracked, but some applications may track additional body parts such as the feet [Iwata96]. A variety of tracking devices are available, including mechanical [Fakespace00], ultrasound [Burdea94], and electromagnetic [Ascension99], each with different abilities and limitations. For example, mechanical devices have a limited tracking area. Electromagnetic trackers can usually cover a larger area, but with less accuracy than a mechanical tracker.

From a human factors point of view, an important factor is the *latency* of a tracking device. Latency is the amount of time between when an action occurs and when that action is reflected in the virtual environment. High latencies can cause problems for users. For instance, when the user moves his hand, if there is high latency in the system, the virtual image of the user's hand will lag behind his actual movement. This has been shown to make interaction difficult ([MacKenzie93], [Ware94]). Mechanical devices tend to have very low latencies (the BOOM™ 3C specifications are 200ns latency [Fakespace00]), while EM trackers have much higher latencies (the Flock of Birds® has been reported to have a latency of 22msec [Burdea94]). However, mechanical trackers are often unusable for certain situations, such as when multiple body parts need to be tracked (the multiple linkages needed may interfere with each other). These factors must be taken into consideration when constructing a VR system in order to present the user with a system that is immersive and interactive.

---

<sup>1</sup> Except where stated otherwise, we consider tracking in virtual worlds to cover all six degrees of freedom.

Experiences such as 3D movies and most amusement park rides are not considered virtual realities in this research because they are not interactive. In order for the user to interact with the VE, the user must be able to send instructions to the computer that is controlling the VE. On traditional computer workstations, interaction is performed with a mouse and keyboard. For example, to move an icon on the desktop, the user moves the cursor to the icon, presses the mouse button, moves the mouse to a new location, and then releases the mouse button. In the same way, if the user wants to grab a virtual object and move it to a new location, it is not sufficient for the computer to simply know the user's hand position. There must be some indication to the system of "grab" and "release" the virtual object. A variety of devices exist for interacting with the virtual world. These devices are discussed in more detail in Section 2.2.

Our definition of VR states that it should be *multi-sensory*. Since VR is a user-centered experience, we wish to stimulate many of the available human senses (not just vision) to produce a better VE. Most commonly, VR systems include the sense of hearing and/or the sense of touch. Audio cues can contribute to a user's sense of immersion in the virtual world. Walking through a virtual jungle hearing animals all around is certainly more engaging than walking through the jungle hearing ambient noise from the current physical world (such as cars driving by or office doors slamming). Another human sense that is occasionally utilized in VEs is touch, called *haptics*. When a user reaches out to touch a virtual object, since the object does not physically exist, the user's hand will pass right through it. This decreases the user's sense that the virtual world actually exists. The human sense of touch covers a broad range, from feeling physical resistance when pushing against a wall, to running the fingers lightly over a surface such as sandpaper and feeling the texture.

Much work is being done in haptics in order to provide these sensations to VR users, but currently it is rarely seen outside the research lab.

All of the above hardware devices are integral to the creation of a virtual reality system. However, software is necessary to tie all of the devices together and make the system function as a whole. From operating systems, to device drivers, to libraries of common VR commands, through application programs, many software components must be integrated to create the VE. And small changes in software can affect user performance just as much as changes in hardware. For example, a tracking system may have an extremely low latency, but if the software is written inefficiently, and the tracking information does not reach the application quickly, long latencies will result, causing negative effects for the user. All of the hardware and software components discussed must be carefully chosen and integrated in the VR system to ensure the best experience for the user. The following section discusses some factors that can affect a user's experience, including frame rate, lag, and cables, along with some methods used to help evaluate the quality of the user's overall VR experience: presence, and simulator sickness.

### **2.1.2 Human Factors in Virtual Reality**

An important component of the computer graphics displayed is the rate at which they can be produced, also known as *frame rate*. Because the virtual world is interactive, we cannot know in advance exactly what parts of the world the user will view, or from what position he will view the world. This means that instead of creating all the computer images in advance and simply playing them back (like a movie), the images are generated in real-time as they are being displayed to the user. Frame rate is expressed in terms of frames per

second (fps). The higher the frame rate, the more smooth the display will appear to the user. Low frame rates produce graphics that are less interactive and appear “jerky” or “jumpy.” For architectural walkthroughs, 1 fps has been shown to make the application barely usable [Airey90]. Navigation can only be accomplished by using a 2D map. At 6 fps the illusion of being immersed in the virtual world begins to take effect, and 3D navigation is possible (but difficult). The interaction continues to improve quite rapidly up to about 20 fps where it begins to level off. At rates lower than 15-20 fps, user performance on interactive tasks begins to degrade [Burdea94]. In VR, this concept expands to include the time required to access information such as tracking data, draw the scene, and output the graphics to the display.

Also important to consider is the variance in the frame rate. It is often thought that a constant frame rate is necessary for good user performance in the VE, and that fluctuations in the rate can be detrimental. Many algorithms have been developed that attempt to maintain a constant frame rate in various ways such as reducing the number of polygons drawn. One such example is [Funkhouser93]. However, some studies have discovered that if the average frame rate is high enough, fluctuations in the frame rate may be acceptable. [Watson97] showed that at 20 fps, user performance on an interaction task was not significantly affected by variations in the frame rate.

In addition to the problems introduced by using machines to generate images, using machines to track movements can introduce difficulty for VR users. All interaction devices will have a *lag* associated with them. This is the time between when an input action takes place and when a output response is observed [MacKenzie93]. For example, when tracking a user’s hand position there is a slight delay between the time the user actually moves his hand

and the time that the virtual hand appears to have moved. If the lag is too great, it can make the user feel he is “dragging” his virtual hand along, instead of giving the desired impression that the virtual hand “is” his own hand. Users may complain the system feels slow, is unresponsive, or has a “sponginess” [MacKenzie93]. In addition, users’ performance on interaction tasks degrades in terms of both speed and accuracy when lag is increased. Around 75ms, users find hand lag to be quite noticeable [MacKenzie93], at 100ms users begin to move more slowly and carefully [Friedmann93], and at 225ms user performance degrades substantially [MacKenzie93]. In other experiments with fish-tank VR setups, [Ware94] found that lag in hand tracking is a critical factor in user performance on interaction tasks. At 200ms of lag, subjects used approximately 1.5 extra seconds when performing a selection task. For small targets, the time used was even greater, suggesting that in current VR systems, small targets should be avoided due to the lag currently present in most systems.

Another factor that can affect users in a VE are the cables present on many devices. Generally each interaction device will have at least one cable, as will all tracked objects, such as the user’s stereo glasses and his hand. It is not unusual for a user to have to contend with three or more cables. The cables can become twisted and tangled, restricting a user’s movements, or the user may become entangled in the cables. Keeping the cables under control can become a nuisance and detract from the user’s sense of immersion. Worse yet, users of head mounted displays (see Section 2.3.2) cannot see the cables, so these users may require a “helper” to follow them around so they do not trip over the cables [Usuh99].

Given the above factors that can influence a user’s VR experience, we would like to be able to measure the overall effectiveness of the system. One possible measure is the feeling of *presence* experienced by the user. Presence can be defined as “the subjective

experience of being in one place or environment, even when one is physically situated in another” [Witmer98, p225]. This is related closely to our definition of immersion, which we have already stated is one of the key components of VR. High feelings of presence indicate that a user is indeed immersed and involved in the VE, and the illusion is effective. There is a large body of research on the theory of presence in VEs including [Hendrix95], [Zeltzer92], [Sheridan92], [Heeter92], and [Steuer92]. Other researchers have developed questionnaires to measure presence, including the PQ (presence questionnaire) by [Witmer98]. Of course, presence (like immersion) is highly subjective and may vary widely from person to person. For this reason, [Witmer98] has also developed the ITQ (immersive tendencies questionnaire) to measure differences in individual tendencies towards immersion. Regardless of how presence is measured it is important to realize that presence generally gives an overall indication of the VR experience. Specific components such as interaction may need to be measured individually to discover how to improve the experience.

Impressions of presence can indicate what is “positive” about a VE. One factor that can indicate what is “negative” about a VE is *cyber-sickness*. Also referred to as *simulator sickness*, cyber-sickness is caused by exposure to VEs, and is similar to motion sickness, including many of the same symptoms such as: fatigue, disorientation, vertigo, headache, eyestrain, blurred vision, sweating, nausea, dizziness, burping, salivation, and others [Stanney95] [Kennedy93]. Because cyber-sickness has physical symptoms, it is slightly easier to measure than presence, and Kennedy has developed a questionnaire to measure its severity [Kennedy93]. It is estimated that 10-60% of all VR users experience some amount of simulator sickness [Stanney95]. Sickness resulting from use of a VE can be distracting for users, and may limit the length of time they stay in the environment. In the worst case,

symptoms may be severe enough to deter users from future use of the VE. Therefore it is important when designing a VE to consider the amount of cyber-sickness it may induce. For an extensive look at simulator sickness, the reader is referred to [Presence92].

## 2.2 Overview of Interaction Devices

### 2.2.1 Wands

One of the most common interaction devices used in virtual environments is the *wand*. The term wand is actually a generic description for a variety of devices. Generally a wand consists of a mouse-like or joystick-like device that the user holds in her hand. Buttons such as those found on a joystick or a mouse are usually found on the wand, and the user can perform various actions by clicking the buttons. Additionally, the wand is most often tracked. So for example, a user could grab a virtual object by moving the wand until his virtual hand appears to intersect the desired object, then clicking a button to select the object. Wands are useful for performing a variety of tasks, such as pointing, selecting, and navigating.

Figure 2-1 shows some examples of wands. Part c shows the current wand in use in the C2. The wands in parts a and b are wands that were previously used in the C2. It is important to note that the wands in part a and c are generally held in such a way that they lie parallel with the ground (like a mouse), while the other wand is held perpendicular to the ground (like a joystick). Even though the wands perform almost identical functions, the small difference between them could have a major impact on the user's ability to perform some types of tasks.

The wands in Figure 2 parts a and b were both individually adapted and modified to provide the desired functionality. As VR begins to move out of the research lab and into

commercial use, off-the-shelf, fully functional, commercial wands are becoming available, such as Wanda™ and NeoWand™ [Wanda00] [Fakespace00] [Russo99].

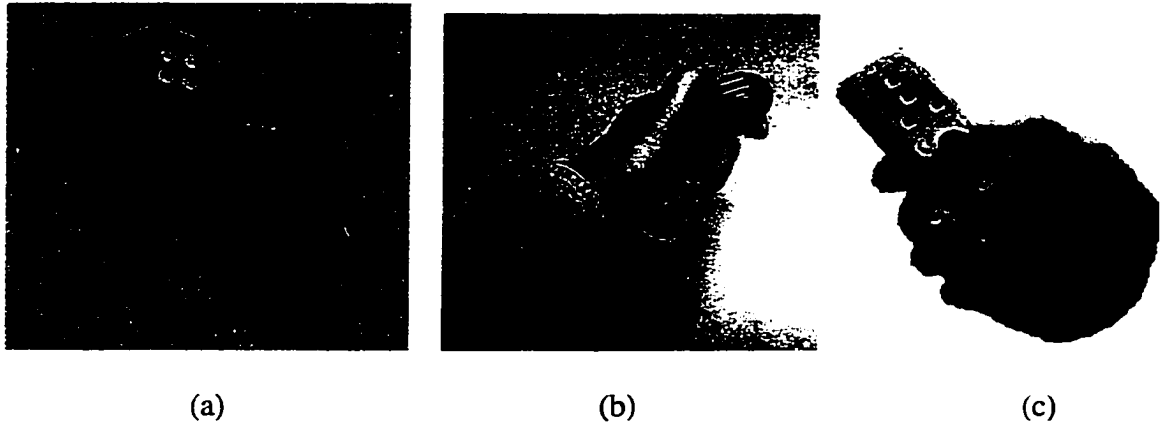


Figure 2-1: Wands: (a) The previous wand in use in the C2 system (b) The wand first used in the C2 (c) The wand currently used in the C2 and C6.

### 2.2.2 Gloves

Another common interaction tool is a *glove*. A few different types of gloves are available. One type is the pinch glove, so named because it can detect “pinching” type gestures. One line of pinch gloves is marketed by Fakespace ([Fakespace00]). Each fingertip, and the palm area, has a piece of conductive material on it. When the pieces of conductive material touch, such as when the thumb and index finger pinch together, the computer can detect this action. Another type of glove is the CyberGlove®, manufactured by Virtual Technologies, Inc. ([Virtex99]). Sensors run through the fingers of the glove and can detect changes in the bend at each joint. By measuring the bends at the joints, the CyberGlove® (and similar devices) can be used to recognize a variety of gestures such as a closed fist, or pointing with one finger. Regardless of the type of glove used, a tracking sensor is usually mounted on the glove so that the computer can detect the location of the user’s hand.

Because gloves allow a user to manipulate objects in a way that is familiar to most people, gloves are often considered a natural interface, useful for actions such as pointing and grabbing.

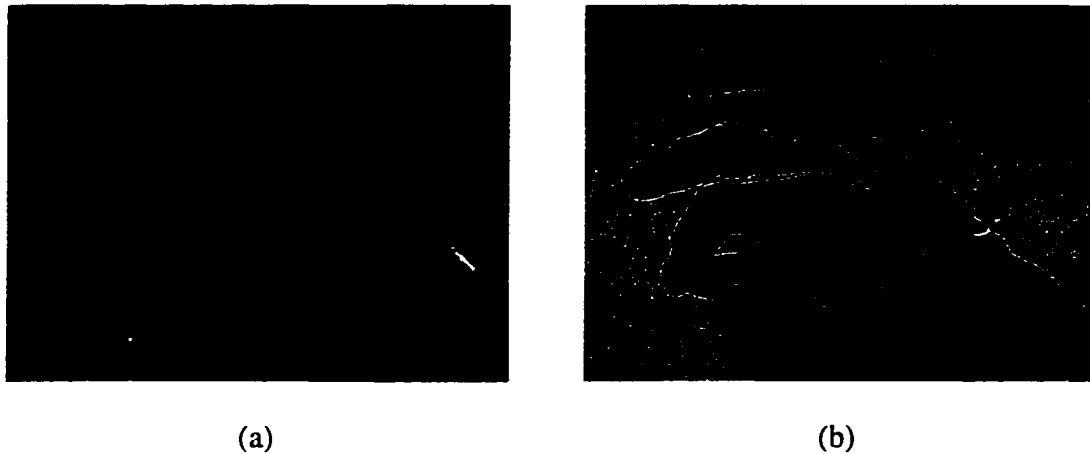


Figure 2-2: Gloves: (a) The CyberGlove® (b) A Fakespace PINCH™ glove

### 2.2.3 Mock-ups

A third type of interaction device is the *mock-up*, also referred to as a “*buck*”. These devices are generally used in situations where it is more appropriate to use part of the physical world than to model it. For example, in a simulation of driving a car, it may be preferable to have a physical steering wheel for the user to hold onto and control rather than a virtual one. Example of mock-ups used in our lab include: a flight seat including rudder and joystick controls, a tractor seat with steering wheel and other controls (shown in Figure 2-3), and a car with working steering wheel and pedals. Besides eliminating the need to render the components of the mock-up, the sense of touch is a major advantage for the user. Turning a physical steering wheel that pulls back when cornering too quickly provides better feedback

than a virtual steering wheel. However, mock-ups are usually very specialized for certain types of tasks such as driving or flying.

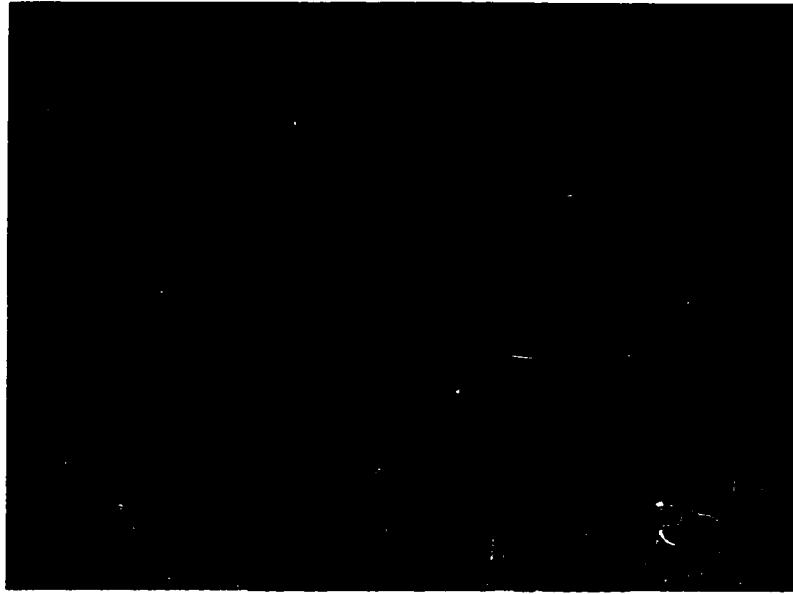


Figure 2-3: A tractor mock-up (Image courtesy of Deere & Co.)

#### 2.2.4 Others

Many additional interaction devices exist, and new ones are continually being introduced. Examples include ShapeTape™ [Balakrishnan99], CyberForce®, and CathSim® [Immersion02]. Some devices such as treadmills are uniquely suited to one specific type of interaction. A few devices designed specifically for travel (such as treadmills) are discussed later, in Chapter 7. Other types of interaction devices include palmtop computers, data suits, image-based gesture recognition tools, and many others. Because these devices are less widely used, and do not directly relate to this research, they have not been discussed here.

For additional information on these devices, the reader is referred to [Pimentel94] and [Kalawsky93].

## **2.3 Overview of Display Devices**

The main component of VR is the device that displays the visual representation of the virtual world. A wide variety of display devices are available for VEs. The following sections describe several of these devices, including the advantages and drawbacks of each.

### **2.3.1 Monitors**

Often, monitors are used to create a simple, inexpensive VR setup. Nearly every computer already has a monitor so developers do not have to purchase and configure a new piece of equipment to get their VR system up and running. Also, monitors generally have good resolution and a wide range of color. These desktop setups often include a head tracker and either a tracked glove or wand (occasionally only a regular 2D mouse is used). This type of setup is often called *fish-tank VR*, [Ware93] because users sometimes have the feeling that they are looking “into” the monitor to another little world. There are some drawbacks to fish-tank VR. The largest problem is that the display is fairly small and users can see the physical world around it. This leads to the user feeling he is looking through a window into the virtual world, but he does not feel that he himself is actually immersed in the virtual world. Due to the physical size of the display, it is not possible to explore many virtual worlds on a 1-to-1 scale, because only a small part of a virtual object will fit in the screen. Also, the user may receive conflicting depth cues when a virtual object is at the edge of the screen. The stereo graphics give the impression that the virtual object is located in front of the screen (or behind

the screen), but because the object is displayed against the edge of the display surface, so that the user can see the frame of the monitor, this gives the conflicting impression that the object is located at the same depth as the monitor.

### **2.3.2 Head Mounted Displays**

In many cases, a head mounted display (HMD) can provide the user with a better sense of immersion than a monitor. An HMD consists of a helmet with two small displays mounted inside, one for each eye. A tracking device is also usually attached to the HMD. When the user places the HMD on his head, the displays end up positioned so that each eye can only see one of them, making it easy to produce stereoscopic images. In most cases, the HMD blocks the user's view of the physical world, leading to an increased sense of immersion in the virtual world. Another type of HMD allows for *augmented reality* (AR), in which the physical and virtual worlds are simultaneously visible to the user. Throughout this work, we consider only standard HMDs and not AR HMDs unless noted otherwise. Unfortunately, it is usually necessary to have a "supervisor" who observes the person wearing the HMD to insure that he does not walk into a wall or other unseen physical object. This supervisor is also helpful for keeping the many cables free from tangles and out of the user's way. Historically, HMDs have had poorer resolution and more distortion than other displays such as monitors [Gigante93], but newer generations are improving [Chen99]. Additional human factors problems are mainly focused on user discomfort: the weight of an HMD can cause neck strain and reduce the amount of time that a user can utilize the display. Also, the device encloses the user's head, so it can become warm and uncomfortable, which may lead to hygiene issues. Nevertheless, HMDs are a fairly popular display tool.

### **2.3.3 Desks/Benches**

Another type of display offers the ability for users to work in the same metaphor they are already accustomed to: the desk. A variety of VR desks are available, including the The MD\_Table™ (seen in Figure 2-4), BARON, VersaBench™, and Immersadesk™ ([Mechdyne00], [Barco99], [Fakespace00]). Desks are approximately the same physical size as a standard office desk or a drafting table, about 2'-3' tall with a top surface about 4' by 6'. Head and hand tracking is usually employed, along with either active or passive stereo. Because the desk is larger than a monitor and thus covers a large portion of the user's view, it provides a greater level of immersion, without blocking out the physical world entirely. This type of display is often ideal for scientific applications, particularly medical simulations where the user is familiar with a horizontal working surface such as an operating table. An additional benefit is that many desks have the ability to be tilted so that the user can work at any angle she finds comfortable.

### **2.3.4 Projection Devices**

Another display technique makes use of a technology that has been used for many years for other purposes: projection. We commonly use projectors for displaying information to large groups of people, such as movies theaters or auditoriums. In this case, the projector is directly connected to the computer so it displays the virtual world on the projection surface. One obvious benefit is that we can now make use of a much larger surface than would be available through a monitor or HMD. This allows us to see a larger portion of a virtual world, or to view an entire object life-sized, instead of scaled to fit on a smaller presentation surface. A variety of projection displays are in use today.

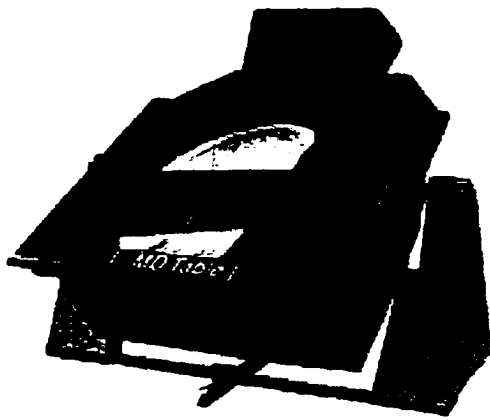


Figure 2-4. The MD\_Table™. (Image courtesy of Mechdyne)

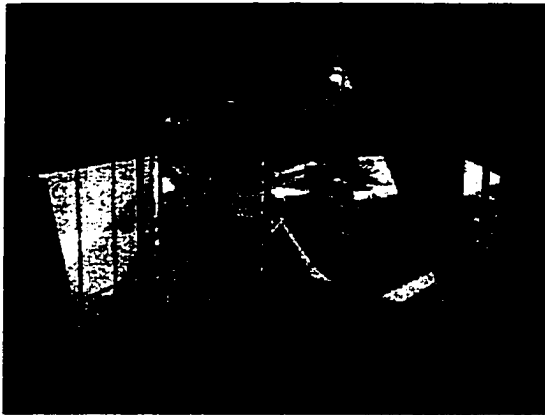
The simplest configuration for a projection display is a single screen, or wall. Commercial walls such as the MD Wall™ are readily available [Mechdyne00]. The drawback to a single wall display is that users may still feel they are outside the virtual world looking in, instead of feeling surrounded and immersed in the virtual world. They are unable to simply turn their head to the side and view other sections of the virtual world. Instead they turn their head and view the physical world, interfering with the sensation of immersion.

Larger screens are sometimes used for presentation settings, such as in a theater or auditorium. A single screen may still be used, but the size of the screen may require multiple projectors to display graphics across the entire screen. This type of display is particularly useful for presenting a virtual world to large groups of people (hundreds of viewers can easily and comfortably be seated in an auditorium). And because it often offers a wider field-of-view than a single wall with a single projector, users may be able to see more of the virtual world. However, auditorium and theater systems still are limited by the display being

present only in front of the viewer, preventing him from becoming more immersed in the virtual world.

The CAVE™ [Cruz93] helps solve this problem by using additional screens to surround the user. The original CAVE consisted of three walls (one each to the user's left, right, and front) and a floor, arranged as a partial cube, with images projected onto each surface. The back and top sides of the cube are left open. The user stands inside the cube and is more immersed in the virtual world. Additionally, several people (8-10) can be inside the device experiencing the virtual environment, unlike devices such as HMDs. Since its creation, a variety of other CAVE-like devices have been created, including the MD SSVR™ [Mechdyne00], C2 and C6 (shown in Figure 2-5) [Vrac00]. Some of these devices have smaller or larger screens, fewer screens, additional screens, or differently arranged screens. For example, the C6 has six screens, allowing the cube to be completely closed, immersing the user on all sides with the virtual world. Re-configurable devices such as the MD Flex™ (shown in Figure 2-6) [Mechdyne00], and the RAVE [Fakespace00] allow a single device to be used as either a CAVE-like device or an auditorium/theater presentation device.

We have now discussed the components that are used to create a virtual environment, and the ways in which they can affect a user's experience in the virtual world. In particular, we discussed how displays can be used to present an immersive, three-dimensional computer-generated world, and how tracking equipment can be used to make that world user-centered. Recall that we also desired a VE to be interactive. Section 2.2 presented a variety



(a)



(b)

Figure 2-5. VR systems at VRAC. (a) The C2. (b) The C6.

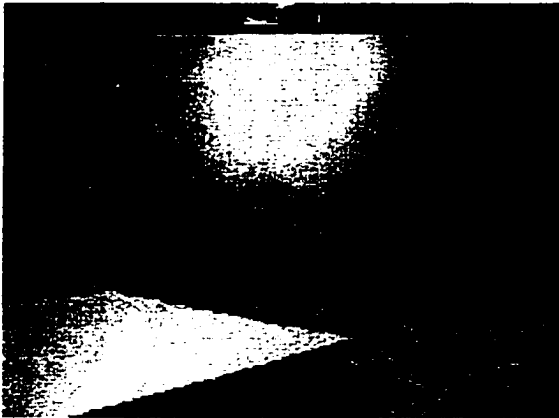


Figure 2-6. Part of the MD Flex™. Shown in the side walls open configuration. (Image courtesy of Mechdyne.)

of devices that can be used to interact with a virtual world. The following chapter discusses the types of interactions that can be performed with these devices.

### **CHAPTER 3. INTERACTION IN VIRTUAL REALITY**

One of the major “selling points” of virtual reality is that it allows a user to not only visualize information in three dimensions, but to interact directly and naturally with the data in three dimensions as well [Mercurio90]. An architect wants to be able to move walls in his virtual building, and an engineer may need to change the orientation of air vents in her virtual car to see how airflow is affected. Visually identifying a problem with the virtual model is most useful when the user can then proceed to fix the problem directly without leaving the VE to use traditional workstation based tools. Indeed, many of the applications found in research laboratories are extremely interactive, offering the ability to perform many different actions. However, even though virtual reality is beginning to gain acceptance as a useful tool, it is still most commonly seen in the research laboratories and not in actual commercial use. What is keeping all these useful applications in the lab, instead of the “real world”?

One of the main barriers to productive use of virtual environments is the lack of simple and effective interaction with the virtual worlds. Two of the best known applications of virtual reality: architectural walkthroughs and phobia exposure treatments, are probably widespread simply because there is little interaction required (and the interaction can be done by an expert user or guide, instead of by the individual users), making the applications very easy to use for most people ([Bowman98b], [Bowman99b]). In contrast, the applications seen in most research labs have interactions that are usually complex and can only be run by an expert VR user, in a sort of “demo mode”, while the application domain experts (architects, biologists, historians, geophysicists) just watch. The demo usually proceeds somewhat like the following: The VR expert maneuvers through a set of menus with indecipherable pictures and unreadable text, using a mass of complex combinations of button clicks and hand

gestures. Finally, some important result is achieved, the data has been manipulated and the visitors are duly impressed. However, when the domain experts take the controls, chaos often ensues. Objects are selected by mistake and mysteriously end up in new (and incorrect) locations; menus pop up all over and won't go away; the user suddenly finds himself flying along, upside down, at high speed, and shoots off the end of the world (which is never found again).

So, if VR is to make it out of the research area and into commercial use, the interaction must be improved so that most people can be productive in the environment, interacting quickly and easily but still performing a variety of tasks. [Bowman99b] defines three general types of interaction in virtual environments, which are discussed in the following sections: selection, manipulation, and viewpoint motion control.

### **3.1 Selection**

A common task in VR is to select an object, such as a button on a menu. This is often done by pointing at, or touching, the desired object. For example, the painting task of VRGobi (discussed in Section 1.1.1) could be considered a selection task: the user selects points to be painted by touching them. Many different methods for selection exist. Touching an object with the hand or finger is a natural method for selection, and this is often implemented with a glove. Unfortunately, this method only works for objects that are within an arm length of the user. And since different users can have different arm lengths, this must be taken into account when designing an application using selection by intersection with a virtual object.

One method for selection that allows users to select objects beyond their physical reach is ray-casting. A wand is often used in this case, and the user sees a sort of virtual laser pointer emanating from the wand. The user can orient the wand so that the ray intersects the desired object, and then performs an action such as a button press to complete the selection. Unfortunately, ray-casting can be difficult to use in some circumstances. When users have nothing stationary to rest or brace their hand against, they have difficulty maintaining a precise orientation, particularly if the pointing device is heavy. Additionally, noise can occur in the tracking data. These factors cause the ray to jitter, preventing precise pointing and making it difficult to select small objects, or objects at a distance [Forsberg96]. Also, virtual objects that are occluded by another virtual object cannot be selected.

Cone-casting is a similar technique in which a cone instead of a ray originates at the wand. Objects inside the cone's volume are selected. This makes it easier to select small or distant objects. Unfortunately, the increased volume also makes it more difficult to avoid selecting multiple objects simultaneously. Also, the cone must be drawn in such a way that objects inside the cone are still visible to the user, introducing additional complexity in the graphics rendering [Forsberg96].

The Go-Go technique attempts to resolve some of the problems with ray- and cone-casting. The technique is named for the cartoon character Inspector Gadget<sup>1</sup>, whose Go-Go-Gadget-Arms could extend to superhuman lengths. The Go-Go technique allows for both selection and manipulation. When a user's arm is located close to his body, the user can select and manipulate virtual objects directly. But when the user extends his arm past a pre-set threshold, his virtual arm extends farther from his body, enabling him to select and

manipulate objects at a distance. This technique enables the user to easily select a single object at a distance, even if it is occluded. And, it avoids the need to change between a mode for local direct selection and a mode for remote selection [Poupyrev96].

Another type of selection is occlusion selection, in which the user places his hand so that it occludes his view of the object he wishes to select. Several similar types of selection have been created that all rely on such line-of-sight interaction, including aperture selection [Forsberg96]. The major drawback to line-of-sight based selection is that it often leads to fatigue because users must hold their arms up in front of their face, rather than “shooting from the hip” as in ray- or cone-casting [Forsberg96] [Bowman99c].

We can see that there are several techniques available for selection of virtual objects. Each has its own advantages and limitations. As with all types of virtual interaction, there is no one technique that will maximize performance in all possible applications, so VE designers should use care when choosing which selection technique(s) to implement [Bowman99c].

### 3.2 Manipulation

An additional form of interaction in virtual environments is manipulation: changing some aspect of an object. One example would be changing the size or color of an engine part. Another example of manipulation would be grabbing a table in a virtual room and moving it to a new location. Notice that in most cases, selection must be done before manipulation. In the above case, the user would have to select which object in the room is going to be manipulated: the chair, the table, the wall... Many different methods of manipulation are

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<sup>1</sup> Inspector Gadget is the creation and property of DiC Entertainment.

possible. A new attribute may be selected from a list of presets, perhaps using a menu (ex: imagine that the chair comes in three different colors). Or the user may explicitly enter values using a device such as a keyboard (ex: place the table exactly three feet from the wall). Or a device such as the glove or wand may be used for a more direct style of manipulation (ex: grab the chair with your hand and drag it to any new position and orientation desired). Direct manipulation is often considered more “natural” because it more closely mimics the real world, and gives the user more freedom and control over the object being manipulated [Bowman99]. However, too much freedom can cause problems for the user, for example, if he only wants to translate the chair but not rotate it. It has been shown that under some conditions, a technique that appears completely unnatural and indirect may actually improve performance [Bowman99c].

### **3.3 Navigation**

The most common interaction in a virtual world is the task of viewpoint motion control. Viewpoint motion control is the task of moving from one location to another in the virtual world. In the virtual world, just as in the physical world, users want to explore the world by moving around to view the world from a different angle, or to view an object of interest at closer range. This is often referred to as navigation, and is the primary aspect of interaction that this thesis will be concerned with. Navigation in virtual environments can be accomplished by many different methods, which are covered in more detail in the following chapters.

## CHAPTER 4. NAVIGATION

Many applications such as architectural walkthroughs require the ability to walk or “fly” through an area. Often this is referred to as “navigating.” For example, we say that the user is navigating through the virtual world. Unfortunately, the term “navigate” is somewhat imprecise and is used to describe a broad range of activities. In the example of “navigating through the virtual world,” it is unclear which part of the user’s activities we are interested in. At least three possible interpretations present themselves: 1) Are we referring to his ability to mentally relate what he is seeing to some larger mental model of the world? (Think of looking at a map and determining where you are currently located.) 2) Are we interested in his ability to chart a path through the virtual world? (Think of tracing out on a map the roads that you want to travel to reach your destination). 3) Or are we referring to the actual process of moving from one place to another along the determined path? (Now think of actually getting in the car and driving to your destination). In various scenarios, each of these interpretations of “navigate” could be considered correct. Indeed, [Loomis93] defines five processes involved in navigation. These parts are:

- 1) Sensing
- 2) Creating a trace of the route
- 3) Forming a survey representation of the route
- 4) Computing desired trajectories
- 5) Executing the trajectories

Our three previous interpretations of “navigate” correspond roughly to parts 1, 2-4, and 5, respectively. As we can see from these examples, it is important to define some more precise

terms in order to effectively communicate about “navigation.” The following section covers three major components of navigation: path integration, piloting, and locomotion.

#### **4.1 Path Integration**

*Path integration:* This term is widely used in the psychology literature, and refers to the ability of humans (and many other mammals) to mentally update their “position and orientation using information about self velocity and self-acceleration over time” [Chance98, p168]. [Loomis93] states that this is also known as *dead reckoning* or *velocity based navigation* and [Péruch97] refers to it as *homing*. Path integration makes use of proprioceptive and vestibular information [Péruch97]. However, this term does not refer to the ability to update self location and orientation information relative to known distinct locations. It simply means, for example, that if an experimenter physically turns a blindfolded subject 90 degrees in place, the subject should be able to correctly turn the additional 270 degrees when asked to return to their original orientation.

Psychologists have studied path integration extensively in humans and other mammals. It appears from these studies that this process is not simply mental, but has a significant physical component, particularly when rotations are involved. For example, [Rieser89] had subjects memorize the location of several objects in a room. Subjects were then asked to close their eyes and point to the objects. Next, subjects were either physically rotated in place a fixed number of degrees, or they were asked to imagine rotating in place this same number of degrees (with their eyes still shut in either case). When asked to point to where objects should now be located, subjects were able to respond significantly more quickly and accurately if they had been physically rotated. When similar tests were

performed using translations instead of rotations, there was little difference between physical and imagined movements. Many other similar studies have shown similar results, including [May96] and [Presson94].

Another type of homing task is triangle completion. Generally, subjects travel two segments of a triangle (with a turn between the segments) and are then asked to perform an appropriate turn and walk to complete the triangle. [Loomis93] performed triangle completion experiments using both blind and sighted individuals who were blindfolded for the tests. Generally, subjects performed fairly well on these tests, regardless of whether they currently were sighted. In fact, even subjects who were born without sight performed fairly well. This suggests that while sight is not necessary to perform homing or learn this skill, physical sensation alone is not sufficient to perform it perfectly.

[Péruch97] also performed tests using triangle completion. However, instead of using blindfolded subjects, these experiments tested subjects' homing ability using only visual stimulation. Subjects wore an HMD and performed a walk along a pre-determined path in a virtual environment, for two straight segments with a turn between them. They were then asked to complete the triangle. All movement in the virtual environment was performed using a joystick; the subjects did not physically translate or rotate themselves. Subjects generally performed more poorly on the triangle completion task than the subjects in [Loomis93]. In most cases, the subjects significantly underestimated the amount they needed to turn in order to face the origin of their movements. So it appears that vision alone is not as effective as physical motion alone in performance of homing.

[Klatzky98] had subjects perform a modified version of triangle completion. Subjects traveled two segments and the turn between them, and then were asked to simply turn to face

the origin of their walk. Some subjects were blindfolded and physically guided through the walk, others simply closed their eyes and imagined performing the walk which was described to them, others watched another person perform the walk and were told to imagine that person's perspective. Two additional groups of subjects wore an HMD that simulated the walk. In one HMD group, the subjects remained stationary while watching the walk, in the other HMD group subjects were physically rotated in place during the turn in the walk. Again, the two groups that actually performed the rotation gave the most accurate responses on this task. The group watching the walk in the HMD and turning in place performed as well as the group that physically walked the entire path. The other three groups, including the stationary HMD group all performed significantly more poorly on the homing task. Thus it appears that the ability to physically rotate is an important part of homing.

[Chance98] performed additional tests of dead reckoning ability, using only a virtual environment. In these tests, subjects "walked" a pre-set path through the virtual environment, and then were asked to indicate the direction towards objects in the virtual environment (which were no longer in view). Three methods were used for the virtual walking: subjects physically walked the path, subjects pressed a button to move forward in the direction they physically faced (real turn mode), or subjects pressed a button to move forward and used a joystick to perform turns (virtual turn mode). The last of these three methods of movement is very commonly used for traveling through virtual worlds. As expected, the physical walk mode produced the most accurate results. The real turn mode also produced good results (not statistically significant from physical walking). The virtual turn mode produced results that were significantly poorer than physical walking. Also, virtual turning produced more symptoms of simulator sickness. These results are discouraging when we consider the large

number of virtual environments currently in use that utilize a virtual turn mode of locomotion. However, there is still hope, because it is possible that the task of homing/path integration may not be the major component of navigation needed for effective navigation in virtual environments. There are other components of navigation that play a role, including piloting and locomotion, discussed in the following sections.

## 4.2 Piloting

*Piloting*: This term refers to the ability to update self position and orientation relative to other known locations. [Loomis93] refers to this as the use of external signals, and [Péruch97] notes that these signals are primarily visual. Being able to place yourself on a map as you move through town would be an example of piloting. This is also similar to the process [Darken96] refers to as *wayfinding*.

The basic goals of wayfinding are to understand where you are located within a world, determine where you want to go in the world, determine where the destination lies with respect to yourself and what lies in between, and create a path to take you to your destination. We can see that this covers parts 2-4 of the five sub-processes of navigation (creating a trace of the route, forming a survey representation of the route, computing desired trajectories). This process of developing a mental representation of the virtual environment is essential to successfully navigating in the virtual world. Darken ([Darken94], [Darken96], [Darken98], [Darken99]) has done extensive work in this area.

Several types of information are need for a user to perform wayfinding in large environments (either physical or virtual). Included are *landmark, procedural, and survey knowledge* [Darken96]. Landmark knowledge refers to information about a specific location.

Remembering what a particular building looks like is an example of landmark knowledge. Procedural knowledge is information about how to follow a route, built up by connecting pieces of landmark knowledge. Knowing how to get from your home to your office by following familiar landmarks such as “turn left at this building” is an example of procedural knowledge. Survey knowledge is an overall understanding of configurations or topologies. It includes information such as distances between objects. Such information can be geocentric (a global, map type view), or egocentric (based on a first-person view). Obviously, in most virtual environments, it is important that the user be able to acquire all three types of information in order to effectively move about the environment. Orientation is critical to this process. If a user becomes disoriented, he is often unable to process what he is viewing and use the information to perform wayfinding [Darken96].

The user may not always have a specific location in mind as his destination when performing navigation. At least three types of situations may occur [Darken96]. The user may be searching for a specific object but not know where in the environment it is located (imagine trying to find the grocery store in a new town). This is known as *naïve search*, and implies that the user may have to exhaustively search the entire environment to find the goal. If the user has information to guide him to the goal (imagine you asked the neighbor for directions to find the grocery store before leaving) this is a *primed search*. Or the user may simply *explore* the environment with the goal of simply obtaining information about the environment (imagine driving around the new town to see what kinds of stores are available and where they are located). It is important to consider what type of goal the user is pursuing when deciding on a scheme for navigation.

Once a user processes all the piloting information and makes a decision on where he wants to travel, he must put the plan into action. The plan could be as complex as following a path to desired target, or it may be as simple as “turn left now.” In the physical world she has a variety of methods available to her for performing the actual travel such as walking, driving, taking a taxi, train, or airplane. Similarly, in the virtual world, a variety of methods exist for moving through the world. These are discussed in the following sections.

### 4.3 Locomotion

*Locomotion:* The term locomotion has been used by [Chance98] and others to indicate a user’s control of movement through the virtual environment. This is also referred to as *travel* [Bowman98a], or *viewpoint motion control* [Bowman99b]. As has already been discussed, there are many ways for a user to change his viewpoint in the virtual world. In environments with head tracking, the user can simply move his head and thus change his viewpoint. Also, to some extent, a user can just physically walk around the virtual world. However, many virtual worlds are much larger than the space that a user can cover by these methods. Tracking devices have a limited range, and it just isn’t large enough for the user to explore a virtual cathedral by physical walking. Even if such a tracker existed, this would not necessarily be the best choice of travel technique. Imagine how tired users would become from walking great distances. One of the strengths of VR is the ability to do things that just aren’t possible in real life: travel great distances in only a few seconds, fly over a building like a bird to see how the support structure works, walk around inside a molecule. For these applications, physical walking simply doesn’t map directly to travel in the virtual environment. So, we have to develop and analyze alternative methods of travel in the virtual

world. The following chapter discusses possible methods for implementing travel in virtual environments.

## **CHAPTER 5. LOCOMOTION IN VIRTUAL REALITY**

Traditionally, locomotion in virtual environments has been studied using “metaphors” for different methods of navigation. The Section 5.1 discusses some of these metaphors, the benefits and drawbacks of each, and problems with the metaphor approach to studying travel in VR. Then Section 5.2 presents an alternative method for studying travel in VR.

### **5.1 Metaphors for Locomotion**

#### **5.1.1 Teleportation**

In the physical world, locomotion is often a time consuming process. We spend hours flying across the country or stuck in traffic. We have all wished at some time for the ability to point at a map and say “take me here”. and be instantly teleported to the new location. Teleportation would then seem to be an obvious choice for a locomotion method in VR. It provides a useful opportunity that is not possible in the physical world. Several methods have been implemented, allowing the user to specify his destination in various ways. For example, the user may have a map of the environment, and point to the desired destination on the map [Angus95]. Another possibility is to give the user a preset list of destinations from which to choose. This choice is helpful for new users of an environment but generally less desirable as it gives the user less freedom in where he may move. Unfortunately, studies have shown that teleportation is confusing and disorienting for the user [Bowman98a]. If the user is in a new environment he does not have an adequate mental representation of the environment to understand the relationship between the original location and the new location after the teleport. This is particularly troubling when the intent of the application is to convey information about the spatial layout of the environment, as in an architectural walkthrough.

### 5.1.2 Worlds In Miniature (WIM)

The Worlds In Miniature metaphor solves some of the problems created by teleportation. A World In Miniature, or WIM, is a small virtual model of the entire VE that the user “holds” in his hands [Stoakley95]. Using the WIM, the user specifies where it is he wishes to move to, and is then taken to that location via a smooth animation through the environment. The movement through the VE instead of instant teleportation allows the user to maintain his frame of reference, avoiding disorientation. An additional benefit of the WIM is that the user can rotate the WIM in his hands and view it from any angle, which can sometimes provide him with the desired information without having to actually travel through the VE. One drawback to the WIM is that users found it difficult to rotate the WIM without any haptic feedback, requiring the use of physical props that the user holds to manipulate the WIM. These props can lead to increased fatigue for some users. Additionally, this technique is less useful if the distance to be traveled is quite large, or if the path has obstacles that must be avoided while traveling [Pausch95].

Later work with WIMs led to the discovery that instead of flying *through* the full scale VE, it is useful to fly *into* the WIM. This is accomplished by simply scaling up the WIM as the viewpoint is changed. If a virtual human is placed inside the WIM at the location the user wishes to travel to, this type of movement gives the impression of the user “becoming” the virtual human [Pausch95].

### 5.1.3 Scene In Hand

Scene in hand navigation gives the user the impression that the entire VE is attached to her hand [Ware90]. When the user rotates or translates her hand, the entire VE moves

along with it, changing the user's viewpoint. The movement can be scaled so that a small movement of the user's hand creates a large change in the position of the VE, allowing the user to cover large distances quickly. Similarly, scaling can be used to provide the user with very fine movement control. When the scaling is one-to-one, travel over large distances can result in a "ratcheting" movement, where the user grabs the virtual world, moves it as far as physically possible, releases the world, then resets her arm to the original location before grabbing the world again. This may give the user the illusion of using handholds to pull himself through the virtual world, and displaying virtual handholds may help reinforce this illusion [Ware90]. This method appears to be most appropriate for travelling around objects, particularly objects that are smaller than the user. It is less effective for moving through interiors of buildings [Ware90]. Additionally, the ratcheting movement may cause fatigue and discomfort when used for extended periods of time.

#### **5.1.4 Eye In Hand**

The eye in hand metaphor is similar to the WIM method of navigation, except that the user must imagine the WIM, it is not presented visually to the user. The user is told to imagine that a small model of the virtual world is present just in front of him. The user's hand then acts as a virtual eyeball. By moving his hand through the imaginary model, the user can change his viewpoint in the virtual world, and feel he is moving through it. This type of navigation has been shown to be more difficult for users because it requires a conscious effort to concentrate on the locomotion instead of on other activities [Ware90]. Scene in hand has been shown to be easier to use than eye in hand [Ware88]. Many users

also felt that eye in hand metaphor required more physical effort than other types of locomotion [Ware90].

### **5.1.5 Flying Vehicle**

Unlike the two previous metaphors, in the flying vehicle metaphor, the virtual world is perceived as stationary, with the user “moving” through the world. In this metaphor, the user perceives that he is in some type of virtual vehicle that he can move around the virtual world. Many different devices can be used to implement this type of travel. A straightforward example is the use of a steering wheel and pedals. The user can manipulate these devices just like in a physical car, and use them to “drive” in the VE. Other implementations make use of a joystick or wand, which can be thought of as a flight stick for a virtual plane.

### **5.1.6 Leaning**

The leaning metaphor for travel has been implemented by [Fairchild93]. Two methods are possible: absolute and relative leaning. In both cases, when a user leans, she moves through the virtual world in the direction she is leaning. In absolute leaning, when the user straightens back up, she is returned to her original location within the virtual world. This is useful when the user wishes to grab a distance object and bring it to her current location. In relative leaning, the user remains at the new location in the virtual world, even after returning to a normal standing position. This is more useful for situations where the user actually wants to move through the virtual world, stopping at points of interest. The developers report that both novices and experts find the leaning-based locomotion easy to use. An additional benefit

is that the user's hands are not utilized in the locomotion, making it possible for the user to move while performing another task such as selection or manipulation.

### **5.1.7 Need for Classification**

Each of the techniques described above has advantages and limitations. For an application designer, it may be difficult to determine in advance which type of locomotion he should implement when designing a new virtual world. What is needed is a taxonomy, or classification, of the types of locomotion available for immersive environments, along with information that can guide the designer in choosing or creating an appropriate locomotion method. Such a classification system should include information on the methods for locomotion, the type of task to be performed, the interaction and display devices to be used, and the ways in which all these factors interact with each other.

Such a taxonomy provides additional benefits. It creates a framework for evaluating how well a particular travel technique works within a particular application. Existing metaphors for locomotion can be classified under the new system, enabling designers to more easily compare metaphors to see exactly how they are different and similar to each other. This information may reveal which components of a locomotion method are problematic, and allow designers to improve travel in an application by changing only small parts of the method, rather than implementing an entirely new method. Additionally, we can use the taxonomy to combine locomotion components together in new ways, to create new methods of travel.

In fact, one taxonomy has already been proposed [Bowman98a]. It is discussed in the following section. In Chapter 6 we will look at elements of this taxonomy that can be

improved upon. In Chapter 7 we will present a new taxonomy that takes these changes into account and expands on the existing taxonomy by incorporating additional information.

## **5.2 A Locomotion Taxonomy**

Bowman has described an extensive taxonomy of travel techniques in virtual environments [Bowman98a]. The taxonomy has three main components: direction/target selection, velocity/acceleration selection, and input conditions. There are several additional factors that can affect a travel technique. All of these components are discussed in the following sections.

### **5.2.1 Direction/Target Selection**

In order to travel somewhere, the user must specify *where* it is she wishes to go, or at least in what direction she wishes to go. The user may simply specify an exact target to move to, using a direct selection technique such as ray-casting, or a more indirect method such as selecting it from a menu or list. Or, the user may not specify an exact target, but instead a direction of movement, perhaps by pointing with a joystick, physically facing the desired direction, or turning a steering wheel. Once the user has decided where he is going, we need to worry about how quickly he will get there.

### **5.2.2 Velocity/Acceleration Selection**

Several methods exist for controlling *how fast* a user will travel in an environment. The user could just select a discreet speed (ex: slow, medium, or fast). Or a continuous range could be available (ex: a slider bar on a menu, or a “gas pedal”). Additionally, we need to

worry about how the user reaches this speed. A sudden jolt from no motion to 60mph will almost certainly be disconcerting and may cause disorientation or even simulator sickness. Similarly, it is often observed that users moving rapidly along will have balance difficulties if the virtual navigation is brought to an immediate halt. Worse yet are instantaneous switches from forward motion to backwards motion. So it may be beneficial to introduce the ability to accelerate or decelerate. However, this means we now need to worry about who will control this ability, will it be regulated by the application or will the user have control of it? If the application controls this, some decisions will have to be made about how long the acceleration/deceleration will take: will the user always accelerate at a constant rate until the desired velocity is reached, or must the acceleration fit into a specific length of time? If constant rate is chosen, what is the preferred rate? Or, if the acceleration must fit into a specified length of time, how long should that time be? Regardless of whether velocity and acceleration are handled by the application or the user, the user may still have to input some other actions to control the navigation.

### **5.2.3 Input Conditions**

Several types of inputs may be required for the user to perform the navigation. For example, an application may allow the user to continuously update the direction of her movement. Or, the user may simply indicate the target, and then do nothing further until the target has been reached. The second option is probably easier for novice users, but does not provide as much control as the first option, if for example the user changes his mind about where he wants to travel. Also important is how the motion is begun and ended. Perhaps movement only occurs while the user holds down a button. On the other hand, perhaps

movement always happens except when the user holds down the button. In the most extreme case, there may be no inputs from the user at all (including direction/target selection). This means that the travel would be completely controlled by the application, sort of a virtual tour of the environment. However, because this is not at all interactive and can be considered almost equivalent to watching a 3D movie, it does not really fit our definition of virtual reality. Only slightly less restrictive is the ability to simply choose the destination from a pre-set list and then be automatically navigated to the new location. While this type of travel has the advantage that users cannot become lost, turned upside-down, fly off the end of the world, etc., it limits the number of possible viewpoints. And the viewpoints a developer finds interesting may not be the same viewpoints a user finds interesting. Also, for many applications such as architectural walkthroughs, where the environment does not exist in reality, it may be difficult to determine ahead of time which viewpoints in the virtual world will be interesting.

#### **5.2.4 Task Characteristics**

Some of Bowman's initial experiments show that it is not sufficient just to compare different locomotion techniques, but instead we must study techniques relative to the type of task we are performing [Bowman98a]. For example, the task "move to the chair" is quite different from the task "move to a position where you can see the chair but not the desk."

Bowman lists the following task characteristics:

- Distance to be traveled
- Amount of curvature or number of turns in the path
- Visibility of target
- Number of degrees of freedom of motion required
- Accuracy required

- Complexity of the task; cognitive load induced on the user
- Information required of the user” [Bowman98a, p 13].

### **5.2.5 Environment Characteristics**

It is not only important to consider the type of task to be performed, but also the environment within which the task will be performed. Travelling around a large field with a few trees is quite different from moving around inside a room crowded with chairs, tables, and other objects. The environment characteristics given by Bowman are:

- “-Visibility within the environment
- Number of obstacles or distracters
- Activity or motion within the environment
- Size of the environment
- Level of visual detail and fidelity
- Homogeneity (amount of variation) in the environment
- Structure
- Alignment with the standard axes” [Bowman98a, pp13-14].

### **5.2.6 User Characteristics**

As we have seen in the VRGobi experiments, a user’s experience with virtual environments can affect her ability to perform tasks in the VE. Bowman suggests that many types of user differences can affect performance on travel tasks in VR. Important user characteristics include:

- “-Age
- Gender
- Visual acuity
- Height
- Reach
- Ability to fuse stereo images
- Experience with VEs
- Experience with computers
- Technical/non-technical background

-Spatial ability” [Bowman98a, p14].

### 5.2.7 System Characteristics

The last set of characteristics that Bowman believes can affect performance of travel techniques are system characteristics. The ones listed by Bowman primarily are related to the overall appearance of the application, including:

- “-Rendering technique
- Lighting model
- Frame rate
- Latency
- Display characteristics (stereo/mono, field of view, resolution, brightness. etc.)
- Collision detection
- Virtual body representation” [Bowman98a, p15].

Many studies have been conducted to study the influence of various system characteristics on user interaction, including travel and other interactions such as selection and manipulation. A partial list is shown in Table 5-1. However, more work remains to be done.

Table 5-1: Studies of various system characteristics

| System Characteristic | References                            |
|-----------------------|---------------------------------------|
| Frame Rate            | [Airey90], [Funkhouser93], [Watson97] |
| Latency/Lag           | [MacKenzie93], [Ware94]               |
| Field of View         | [Hendrix95], [Neale96], [Péruch97]    |
| Stereo/Mono           | [Ware93], [Sollenberger91]            |

It is interesting to note that the characteristics in Sections 5.2.4 through 5.2.7 were listed by Bowman as characteristics that can affect travel techniques, however we can see that most of them can also be applied to other parts of navigation such as piloting, or even other types of interactions as well. For example, pilots may prefer one type of navigation

aide, which may completely unhelpful for inexperienced users (user characteristic, piloting component of navigation). Another example would be selection, where a user's arm reach could be quite influential on performance (user characteristic, interaction other than navigation).

As we can see, there are many possible methods for travelling through a virtual world, and there is a need for a classification system for travel methods. Such a system would help designers to choose appropriate travel methods for their applications. Having discussed one such classification system, the next chapter focuses on proposed revisions and additions to improve the classification.

## **CHAPTER 6. PROPOSED LOCOMOTION TAXONOMY REVISIONS**

When designing a new virtual world that will require navigation, it is best if the preferred technique used for locomotion in the VE can be decided on before actually implementing the VE. This avoids the expense associated with testing performance of locomotion after implementation, and the possible expense of having to modify the implementation if the chosen technique does not perform well. A useful tool in the design of a locomotion technique is a method for “assembling” the technique from various parts that have well known behaviors in VEs. The existing taxonomy of Bowman [Bowman99a] is one such tool. Bowman considers the three main components of locomotion in VR to be direction selection, velocity selection, and input conditions. However, he also acknowledges that many other factors may affect the performance of a locomotion technique, including task, environment, user, and system characteristics. As discussed in Chapter 5, some of these characteristics have been studied in detail in an effort to determine how they affect virtual locomotion. In particular the area of system characteristics has been an area of much study (see Table 5.1).

Unfortunately, Bowman’s description of system characteristics is rather broad: “aspects of the hardware or software used to realize the virtual environment application” [Bowman98a p.15]. A great many aspects of VE development could fall into this category (operating system, programming language, tracking devices, etc.), but the primary ones listed by Bowman are characteristics of the graphics displayed, such as framerate, field of view, and brightness. Bowman further considers that these aspects of the system are not always under the control of the locomotion technique designer because design decisions made by others (operating system designers, hardware designers, etc.) may affect some of these

system characteristics. However, we believe that choices of interaction devices and display devices are usually under the control of the virtual environment developer, and are integral to the travel technique itself. Therefore, they should be considered part of the taxonomy's main components, instead of system characteristics.

One might argue that devices for display and interaction are not under the control of the application developer, that she must use whatever devices have already been provided. To some extent, this may be true, for example, in the research lab, applications are often developed for whatever type of VR system the lab already has on hand, without regard to the needs of the application. Unfortunately, most labs have only one or two VR systems and interaction devices, so applications are implemented on equipment that is not most appropriate. For example, using a "fish-tank" VR setup, with only a monitor for display, may not be the preferred device for an immersive architectural walkthrough. A better plan might be to use a different display device such as a projection system that can display the graphics on a much larger scale, surrounding the architect and giving him a realistic view of the building's size and layout. Similarly, if an application is to make use of a physical prop such as a steering wheel, an HMD may not be the best choice of display device as it will block the user's view of the prop, requiring a copy of the prop to be rendered in the VE. These difficulties occur because the research lab generally does not specialize in one type of application. The lab may support work in vehicle simulations, architectural walkthroughs, molecular biology, and other areas.

However, as VR begins to move out of the research lab and into the commercial arena, VR setups will become more specialized. An automobile manufacturer need not worry about implementing an architectural walkthrough on its VR equipment. The type of work that

will be done in the commercial environment is highly specialized, most likely only two or three classes of applications will need to run on the manufacturer's VR setup. Furthermore, the types of applications that will be developed will likely be known and designed in advance of the actual purchasing and construction of the VR facilities. So, equipment requirements can be taken into account from the very beginning, as part of the design of the applications. This puts interaction and display devices under the control of the application developers.

Why should devices be considered part of the actual locomotion taxonomy instead of being considered system characteristics that affect travel? Consider the following examples:

- 1) In this example, we choose to implement the same travel technique using two different methods of translation: physical translation and virtual translation. From Bowman's taxonomy, we choose to use gaze-directed steering with constant velocity (ie. either the user is moving at speed X or he is at a dead stop). Additionally, the user must provide continuous input to indicate that he wishes to continue moving. First we implement this travel technique using a wand: As long as the user holds down a button, he moves forward at constant velocity, in the direction he is looking. When the button is released, movement stops. We refer to this as virtual translation. However, this technique can also be implemented using a mechanism that allows the user to feel he is physically translating. [Iwata96] implemented such a device, using omni-directional sliding devices, worn on the feet. This setup allows the user to feel that he is physically walking, but his location in space does not change. Tracking information on the user's feet is used to determine when the user is "walking." Other similar walking techniques have been developed using devices such as a treadmill, or a harness that suspends the user while he walks. Under Bowman's taxonomy, the physical walking implementation is identical to

our wand implementation, because the user moves at constant velocity in the direction of gaze, as long as constant input is supplied. However, it seems intuitively obvious that these two implementations of travel lead to very different experiences for the user. For example, some people feel that the physical walking implementation more closely resembles “natural” human locomotion and is thus a more desirable method of locomotion in VR. However, Iwata states that some users are unable to move in a manner that the application can recognize as walking, meaning that these users cannot travel in the virtual world at all! In addition, this method may cause fatigue in some users, especially if the virtual world is large and requires extensive “walking.” For these users, this method of locomotion is obviously not the most desirable mechanism. We feel that these implementations should be considered to be different travel techniques.

- 2) Interaction devices used for locomotion may alter the locomotion method. Primarily, this happens when the choice of interaction device limits the types of locomotion that may be performed. As an example, a steering wheel provides the user with the ability to only rotate about one axis, while a tracked device such as a wand provides the user with the ability to rotate about all three axes. Additionally, because a steering wheel is usually mounted on a fixed base, the user always faces the same direction, with the virtual world rotating about him. Even when an interaction device does not limit the choice of locomotion methods, different interaction devices may produce locomotion methods that feel different to a user. It is even conceivable that two wands with different physical attributes such as shape or weight may produce different locomotion experiences.
- 3) The choice of a display device may also affect locomotion. For example, some display devices may make physical translation more difficult. With an HMD, physical translation

of the user often requires a “helper” to follow the user and prevent him from becoming entangled in cabling or running into walls. Requiring an extra person to assist with every VR experience may be undesirable. In other cases, some display devices may be incompatible with certain types of locomotion. Using a fish-tank VR setup with a gaze-directed method of locomotion will make it extremely difficult, if not impossible, for a user to travel freely in all directions. Since the user cannot visually observe the parts of the environment that are behind him or to the side, he would often be forced to navigate blindly. Even if a particular display device does not limit a user’s options for locomotion, it is possible that one style of travel may be more effective than another when using the display. It is even possible that each display device has an “optimal” locomotion technique associated with it.

## **CHAPTER 7. THE NEW TAXONOMY**

Locomotion in a virtual environment (VE) is typically composed of two major components, translation and rotation, which can operate jointly or independently of each other. By considering various methods for rotation in a VE and then combining these with various methods for translation in a VE, we can produce a variety of categories of locomotion. In this chapter, we will first discuss the major methods used for both rotation and translation, factors that can be used to determine sub-categories of rotation and translation. Then we discuss classification for interaction and display devices and discuss how these categories relate to the rotation and translation categories. Then we show how the various components can be combined to create methods of locomotion. Finally, several examples of traditional travel metaphors are given, and classified under the new taxonomy.

### **7.1 Rotation Categories**

When traveling through the physical world, we usually travel forwards, in the direction our body is facing. When we wish to travel in a different direction, we orient our body to the new direction. Occasionally we may change our direction of travel without changing our physical orientation (ex: stepping sideways or backwards), but such movement generally occurs over small distances and is less frequent. So, it seems logical that we should change our orientation in a virtual world by physically turning our body to face in the direction we wish to move.

However, in the physical world, we are limited by gravity, in that our body can only rotate around the vertical axis. We would have a difficult time trying to tilt our entire body 90 degrees sideways and then walk forward! In a virtual world, we are faced with the unique

situation in which it may in fact be desirable to travel in such a position. Since we are still subject to this physical limitation while using the VR system, and unable to fully rotate our body with respect to the virtual world, we can instead rotate the virtual world with respect to us. Rotation of the virtual world is most commonly performed using an interaction device such as a wand. Generally there is a “home” orientation for the device, so that when the device is in the home position no rotation of the virtual world occurs. However, when the interaction device is changed to a new orientation, it causes the virtual world to rotate around the user or the interaction device.

Thus we have defined two methods of rotation for the user of a VE: 1) rotating the self with respect to the world, and 2) rotating the (virtual) world with respect to the self. We will refer to these methods as, respectively, *physical turn/rotation* and *virtual turn/rotation*. A third possibility occurs for locomotion in a VE: *no rotation*. This is analogous to our earlier example of stepping sideways or backward without turning to face in the direction of travel.

## 7.2 Translation Categories

Similar to rotation, translation of the user’s viewpoint in a VE can be accomplished using two different methods, referred to as *physical translate* and *virtual translate*. Physical translation includes simply walking: we can walk forwards, backwards, and sideways in both the real and virtual worlds as a means of changing our viewpoint. However, because virtual worlds are often much larger than the physical area in which the user may walk (often due to device limitations), other methods may be employed that still allow the user to feel that he is physically walking as he translates through the virtual world, while actually remaining

stationary in the physical world. Some of these methods are discussed later in the Translation Sub-Categories section. Although these methods may make use of additional devices, we define physical translation to include them because of the way they “feel” to the user – they require the user to physically exert himself. Virtual Translation is similar to virtual rotation in that an interaction device is used to control the translation. A variety of devices can be used to perform the translation.

Although we have allowed for the case of no rotation, we do not allow for the case of no translation. This is because when no translation occurs, the user’s viewpoint cannot change location, only orientation, which is hardly “travelling” through the virtual world. Should the user wish to change their view in a VR system without translation, the user has two choices (assuming the VR system is user-centered and thus head tracked):

- 1) Change the orientation of his head with respect to the world, by simple rotation of his head.
- 2) Change the orientation of the virtual world with respect to himself through the interaction task of manipulation.

Because we are considering the term locomotion to refer to a change in the user’s location within the virtual environment, instead of simply a change in viewpoint, we do not consider either of these operations to be “locomotion”, as the user’s location with respect to the virtual world does not change.

We now have three methods for rotation and two methods for translation. These methods can be combined to form six different categories of virtual locomotion. The next section will cover several factors that can be used to create sub-categories within these six main categories.

### **7.3 Rotation Sub-Categories**

There are several additional factors that can affect the way in which rotation is performed in a VE. These factors can be used to distinguish among locomotion methods within the same category, in effect creating sub-categories. For physical rotation the factor is: which part of the body should be tracked? Sometimes the tracking device is placed on the user's torso, so that the rotation is performed when her body turns to a new direction. But, the tracking device can be placed on the head instead. This results in a "gaze-directed" travel technique, where the user moves in the direction she is looking, while the rest of the body does not have to move. Additionally, it is possible to implement a scaled form of physical rotation. For example, a user may only rotate himself 90 degrees, but a scaling function could be used that causes the user's viewpoint to appear to rotate 180 degrees. Such a scaling may be useful in situations where a display device does not normally allow a user to make use of physical rotation. One implementation of scaled rotation has been done by [LaViola01].

There are at least three factors that can affect virtual rotation. The first factor affecting virtual rotation is the degrees-of-freedom (DOF) afforded the user. The user may have full control of all three possible rotations, or the travel technique may have restricted the user's freedom in various ways. One or two degrees of rotation may not be available to the user at all. Or, the user may have access to all three types of rotations, but the access might be restricted, perhaps so that the user may only perform one type of rotation at a time. To the user, travel techniques with different DOF in rotation may appear quite different, even if they are otherwise identical.

The last two factors affecting virtual rotations come directly from Bowman's taxonomy of travel techniques. The first is Velocity/Acceleration Selection. This attribute

controls such things as: How fast can the user move? Is the user's rotation speed constant or can he accelerate? The second factor is Input Conditions. Input Conditions refers to the amount of input necessary from the user to control when travel happens. For example: Is the user in constant motion or can she stop? Does the user have to provide continuous input to continue rotating, or can she just enter a "start" command?

The categories for rotation are shown in Figure 7-1. Items joined by a solid vertical line indicate areas where a VR designer must make a choice. For example, "Physical", "Virtual", and "None" are joined because a locomotion method can only make use of one of these items at a time, it cannot simultaneously use more than one. However, to the right of "Physical" we see two sets of bracketed items. The designer may choose one item from each of the sets. For example, he may choose to implement scaled rotation that is gaze-directed. A similar convention is followed throughout this work.

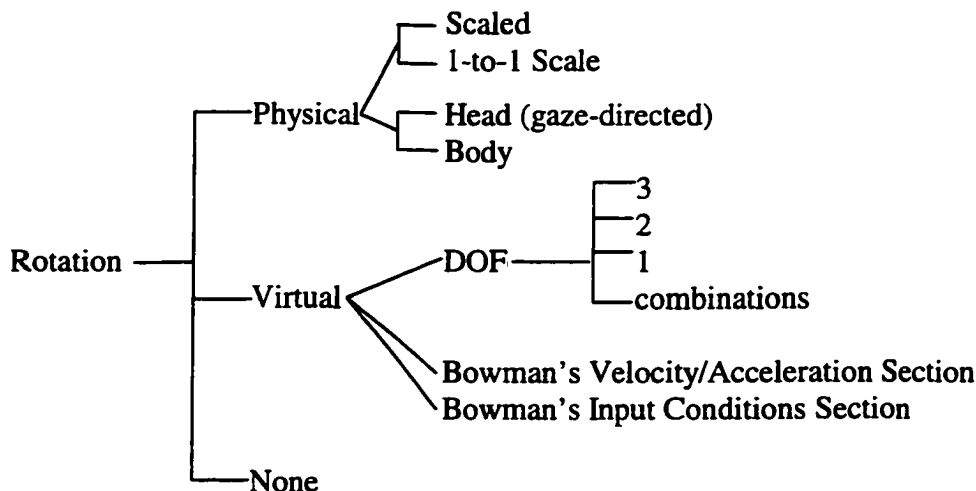


Figure 7-1. Rotation categories for locomotion.

## **7.4 Translation Sub-Categories**

The sub-categories of virtual translation are very similar to the sub-categories of virtual rotation: DOF, velocity/acceleration selection, and input conditions, so they are not discussed further. However, the sub-categories of physical translation are somewhat different. One method of physical translation is simple: the user physically walks around the environment within the range afforded by the tracking device and the display device. This form of locomotion is often used with HMDs, CAVE-like displays, and other VR systems. But when the VE is larger than the physical area in which the user may walk, other types of “physical walking” may be used. One option is to scale the user’s movement. Perhaps when the user physically moves forward one foot, the locomotion technique causes the user to move forward ten feet in the VE. Many scale factors can be used, allowing the user to cover very large distances quickly, or move with precision over small distances.

Another option is to have the user simply walk in place [Slater95]. The computer must then have an algorithm for detecting whether the user is walking in place or standing still. Still more possibilities exist by using a device to physically support the user so that he actually feels he is walking forward but is really still walking in place. Some such devices are discussed in the following section on interaction device categories. All of these methods of physical translation produce different locomotion techniques.

Figure 7-2 shows all the categories and sub-categories discussed for translation.

## **7.5 Interaction Device Categories**

A variety of devices can be used to interact with the virtual environment to perform translation or rotation. Each type of device will have its own unique “feel” to a user, and

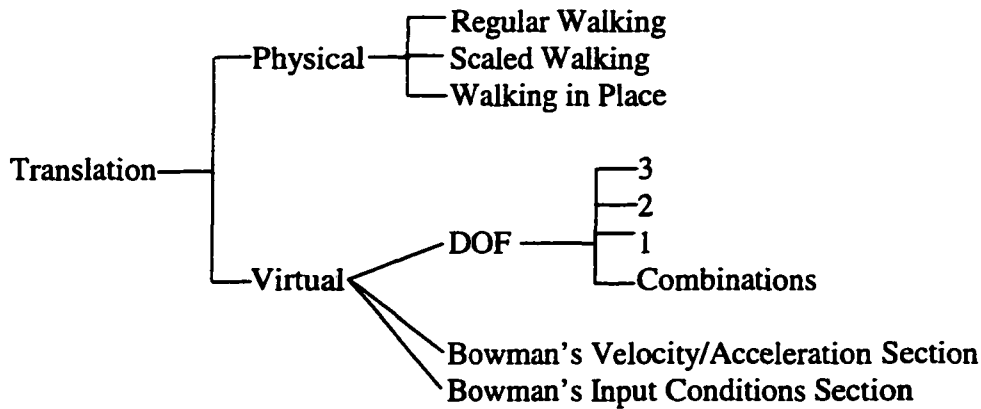


Figure 7-2. Translation categories for locomotion.

different devices may be more appropriate to some types of locomotion than others. Because new devices are developed regularly and many VR interaction devices are still “one-of-a-kind”, it would be difficult to attempt to describe and categorize them all. Instead, we focus on several common devices, some of which were already described in Section 2.2, and discuss how these devices relate to rotation and translation.

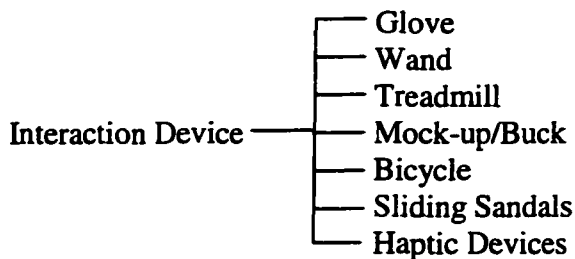


Figure 7-3. Interaction Device categories for locomotion

Wands and gloves can both be used with any type of rotation method and any type of translation method. Because they can be used for a variety of interactions, not just locomotion, these devices are commonly used in most VR installations. There are many

subdivisions that could be made beneath each device. For example, the “glove” category could be further broken down into the style of glove (pinch vs. Cyber), and the types of gestures used (closed fist vs. pointing finger) to perform rotation. These sub-divisions are beyond the scope of this paper but are still important to recognize when constructing a locomotion technique. Also, note that the devices in Figure 7-3 are joined by a vertical line on their left. As mentioned earlier, this indicates that the VR designer must generally choose only one of the options. In this case, it does not indicate that multiple interaction devices cannot be used together. However, in most cases, one device will be used for locomotion and the other device(s) for another type of interaction with the virtual world. Although it is conceivable that multiple devices could simultaneously be used by a single user for locomotion, it is not clear that this would be desirable.

Another commonly used device is the mock-up or buck. Because a user is generally seated in the buck, he does not have the ability to physically walk (or even emulate physical translation) in the virtual world. Also, the buck always faces in the same direction, interfering with physical rotation. Mounting the buck on a special motion platform can allow for physical translation or rotation. Because such an arrangement is possible but is not commonly done, these difficulties are represented by lines 1 and 4 in Figure 7-4. In Figure 7-4 and in other similar figures throughout this chapter, the following interpretation applies: A solid line between two objects indicates that they are limited and cannot generally be implemented together. A dashed line between two objects indicates that they are feasible only in certain circumstances that should be accounted for when attempting to implement them together. The absence of a line between objects indicates that they are fully compatible with each other.

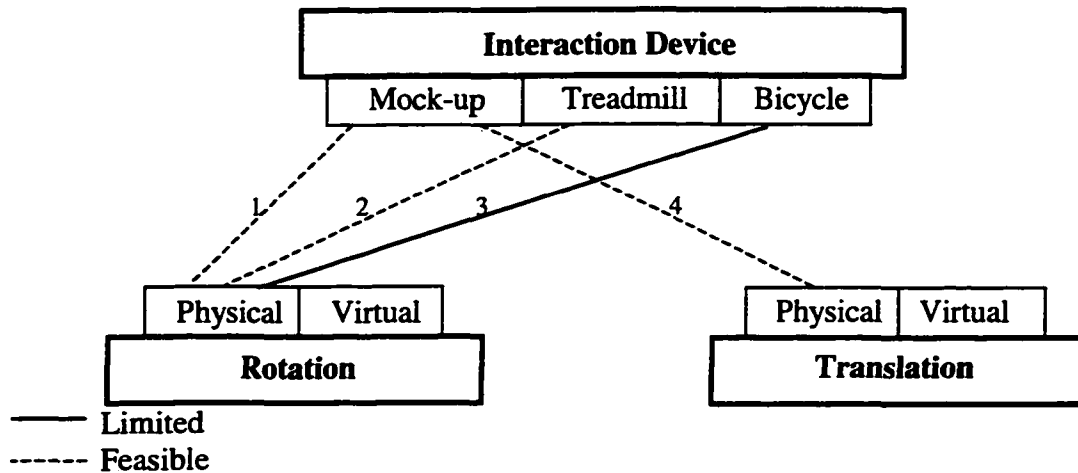


Figure 7-4. Interaction Device limitations.

In Section 7.4, we indicated that some devices can be used to create physical translation by simulating walking. An obvious possibility is to place the user on a treadmill or a specially mounted bicycle. Another choice is to suspend the user just above the floor with a harness, and have him wear roller-skates or similar devices on his feet [Iwata96]. A newer invention has the user wear sandals that slide on a special flooring material. A small ring encircles the user at waist level, and she can lean on this ring for support while “walking” on the special material. While these devices are intended to allow for physical translation, they do not generally preclude the use of virtual translation. However, the use of a treadmill or bicycle for physical translation does limit the ability to perform physical rotation in most cases, since the user must face “forward” on these devices to use them. One exception is found in [Noma00]. Lines 2 and 3 in Figure 7-4 show this relationship. Because we know of no implementations in which a bicycle has been adapted to allow for physical rotation, line 3 is solid instead of dashed. Also, because the treadmill and bicycle both allow the user to perform an action that emulates physical translation, there are no lines between these devices and the physical translation box in Figure 7-4.

## 7.6 Display Device Categories

In addition to the device used for interaction with the virtual world, we must choose a device for graphical display of the world. Several commonly used display devices have already been described in Section 2.3. We discuss here how these devices interact with other components of a locomotion method.

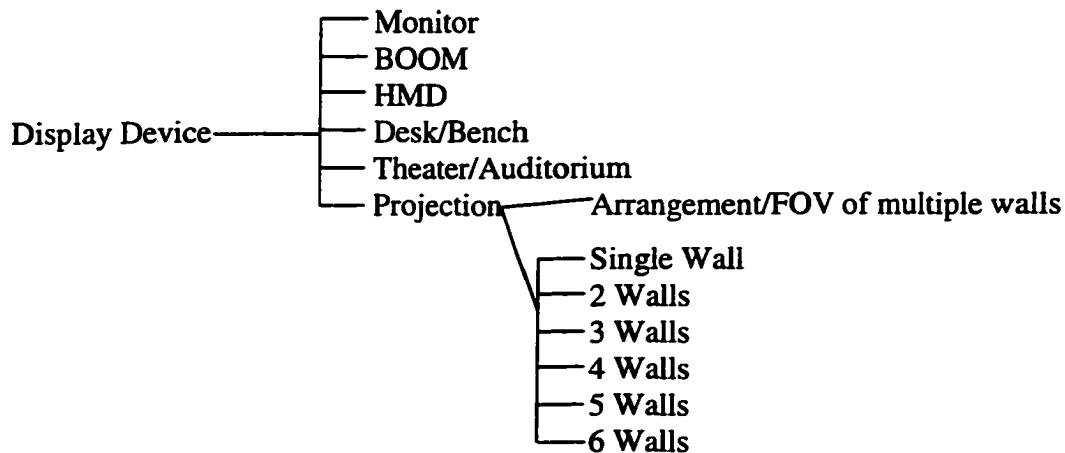


Figure 7-5. Display device categories for locomotion.

Several display devices can prevent the use of physical rotation, because they do not completely surround the user with graphics. For example, a monitor generally remains stationary on a desk, in front of the user. The user must continue to face towards the monitor if she wants to view the virtual world, thus preventing her from using physical rotation in the virtual world. Other devices with this limitation may include desks, auditoriums/theaters, and CAVE-like devices with only three or fewer side walls that do not provide a 360 degree field-of-view. These limitations are represented in Figure 7-6 by lines 1-4.

In addition, some display devices and interaction devices do not always work well together. The most obvious example here is the use of an HMD in combination with a mock-up. When wearing an HMD, the user's view of the real world is blocked, preventing him from seeing the mock-up. This makes it difficult for the user to manipulate the controls provided by the mock-up. However, some types of controls provide valuable touch feedback to the user, allowing such setups to be used effectively. This is represented in Figure 7-6 by line 12. Other combinations that can pose problems are interaction devices such as the sliding sandals (which are intended primarily for providing physical rotation) combined with display devices such as a monitor, which do not generally allow for physical rotation. However, it is possible for such interaction devices to be used with a virtual rotation method. Because such a combination is possible, but is likely not the usual or preferred locomotion for the device, this relationship is represented in Figure 7-6 by lines 8-11. Figure 7-6 illustrates limitations between display devices and other components of locomotion.

## **7.7 Major Locomotion Categories**

Having described the translation and rotation categories of locomotion, we now can combine these components into six commonly used methods of travel and show how the sub-categories, along with the display and interaction device categories, can be used to completely differentiate between different locomotion methods. Additionally, some of the locomotion metaphors described in Section 5.1 are classified under these new travel methods.

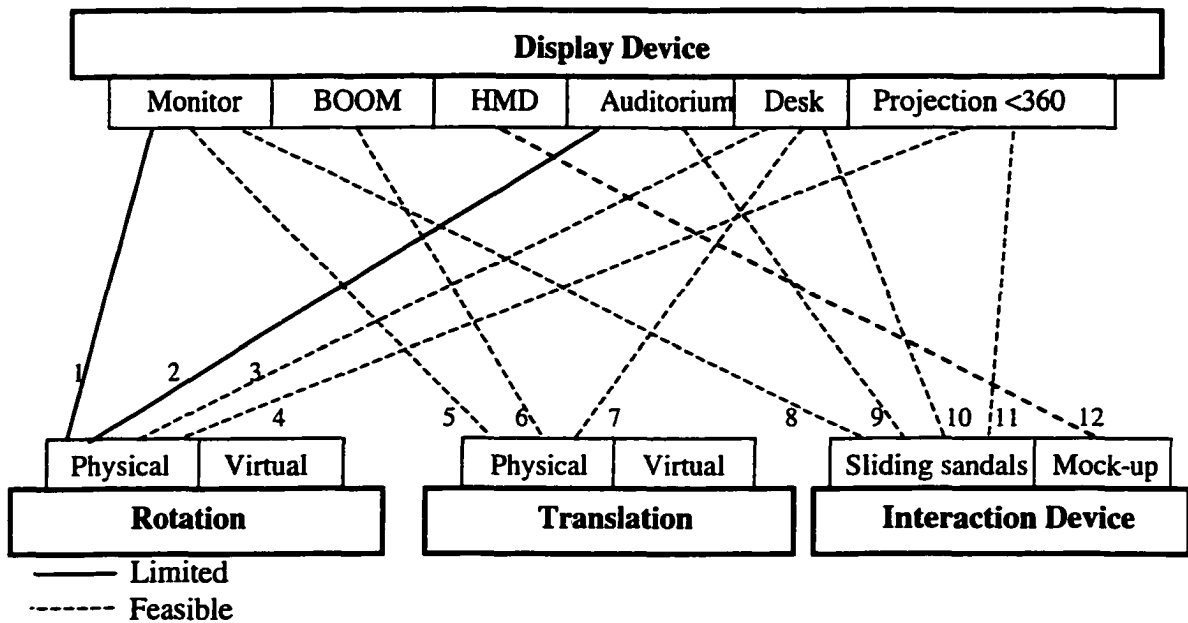


Figure 7-6. Display Device limitations.

### 7.7.1 Physical Rotation, Physical Translation

This type of locomotion occurs most commonly in environments where the user is simply free to walk about normally within the tracked area, using the head tracking information to determine the user's location and orientation within the virtual world. The sliding sandals example given above also falls in this category. Notice however that these two travel techniques fall in different sub-categories because they use different types of interaction device (a tracker would be considered the interaction device in the case where the user is simply walking).

### **7.7.2 Physical Rotation, Virtual Translation**

The HMD experiments conducted by [Chance98] make use of this type of locomotion. However, this type of locomotion could also be extremely useful in the new C6, particularly for architectural applications. The user will be able to turn and face in any direction he wishes to travel, eliminating the concepts of “front” and “back” of the environment.

### **7.7.3 Virtual Rotation, Physical Translation**

One example of this type of travel is Brooks’ treadmill [Brooks86]. The user walks normally on the treadmill, but is provided with a pair of bicycle handlebars for steering. Another example is the harness (described previously in the Translation Sub-Categories section) that allows for physical translation by walking in place. Since the harness allows the user to face in only one direction, the user is provided with a tracked joystick that he may rotate to change direction. These two implementations also fall within different sub-categories based on the type of device used for the virtual rotation.

### **7.7.4 Virtual Rotation, Virtual Translation**

This is the type of locomotion most commonly used in the VRAC VR systems (one example is the architectural locomotion we refer to as “pfnav”). For “pfnav”, the user controls all travel through the wand. Many of the traditional metaphors for travel in VEs also fall into this category, including the scene-in-hand, eye-in-hand, and flying vehicle metaphors. Driving a virtual vehicle such as a plane or car using a mock-up also falls into this category. Even a more abstract method of travel such as using a pointing device to select

a destination from a menu can be placed in this category. Notice however, that all of these travel techniques can be placed into unique sub-categories through the use of the device and input conditions factors.

#### **7.7.5. No Rotation, Physical Translation**

This technique occurs infrequently. It is quite difficult to force a user to physically walk without changing his orientation, as this is how he is accustomed to moving. One interesting implementation makes use of a leaning technique [Fairchild93]. Both the user's torso and head are tracked. The application then uses this information to determine when the user is leaning, and in which direction he is leaning. The user then translates through the virtual world in the direction of the lean. While the user is not "walking" in the strictest sense, this is still making use of a physical translation according to our definition: No interaction device is explicitly manipulated by the user, and this does correspond to a "natural" method of locomotion (ex: leaning over to reach a nearby object that is just out of arm's reach).

#### **7.7.6 No Rotation, Virtual Translation**

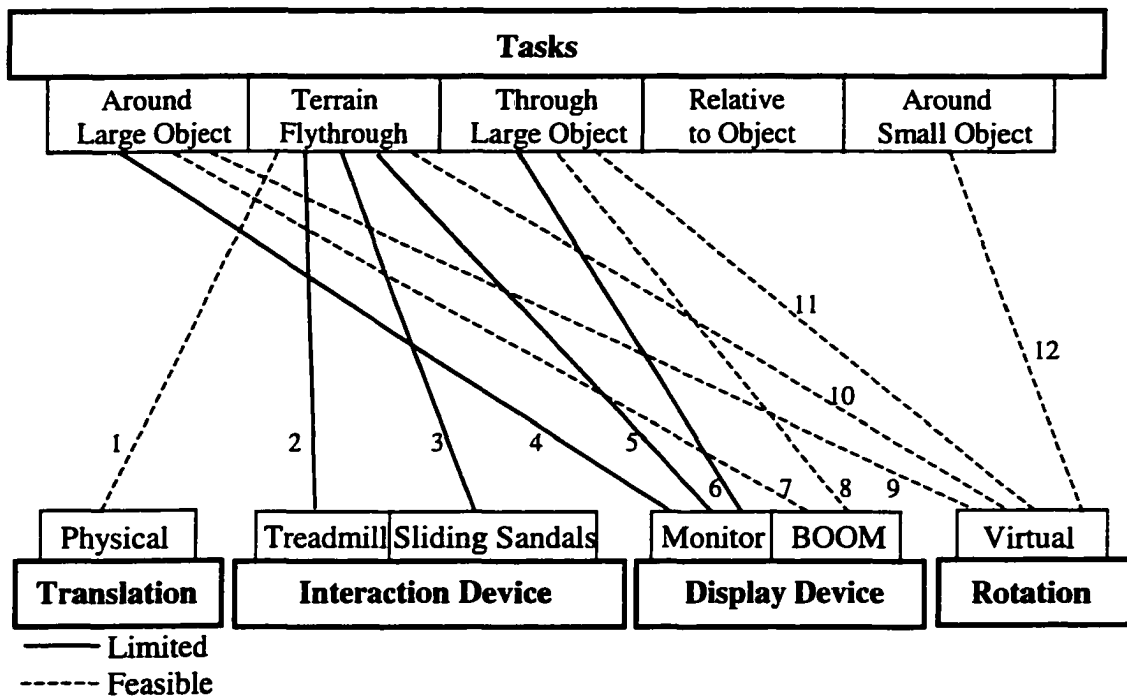
Some implementations of the scene-in-hand metaphor make use of this type of travel. The scene is still "attached" to the user's hand, and she can translate it in any direction, but rotation is not allowed, so that the user is always facing the same direction in the virtual world.

## **7.8 Task Categories**

The type of task the user needs to perform can affect what type of locomotion should be used [Bowman98a]. Traveling through the inside of a virtual molecule will likely require a different travel technique than flying an airplane over a virtual battlefield. However, most types of tasks requiring travel will fall into one of the following categories: move through the inside of a large virtual object (ex. interior architectural walkthroughs), move around the outside of a large virtual object (ex: exterior architectural walkthroughs), move relative to a virtual object, move around the outside of a small virtual object (ex: examine the design of a small vehicle part), move around a large area (ex: terrain flythroughs). The choice of what virtual objects are “large” is somewhat arbitrary, however we generally understand “large” objects to be those that are significantly larger than the user, such as a building. Such objects are also usually larger than the physical tracked area available to the user.

Some of these tasks are not compatible with other locomotion components. For example, when traveling around a large area of terrain, it may not be preferable to use physical translation, as the user can become tired trying to move over great distances. This is illustrated by line number 1 in Figure 7-7. This difficulty extends to devices such as treadmills that are intended primarily for physical translation (lines 2 and 3 in Figure 7-7). Also, display devices such as monitors may be inappropriate for traveling through or around large virtual objects, because the portion of the large object seen on the monitor may be quite small (due to the limited field-of-view). Lines 4-8 in Figure 7-7 represent this problem.

Virtual rotation can present difficulties when traveling around a small virtual object, as it usually appears to the user that the small object is actually circling around him, giving the impression that the object is being manipulated instead of the impression that the user is



traveling. This is represented in Figure 7-7 by line 12. For large objects and terrain flythroughs, virtual rotation may interfere with the user's spatial abilities. For some applications such as architectural walkthroughs, this obviously interferes with one of the user's main objectives. But for some applications such as entertainment, some degree of disorientation may be acceptable or even desirable. Lines 9 through 11 in Figure 7-7 represent this.

It is our belief that for many tasks, there is a "preferred" method of locomotion, including display and interaction device, that allows the user to most effectively perform the underlying task. We also believe that for tasks without a preferred locomotion method, there are some locomotion methods that will hinder the task performance and should be avoided. The experiments discussed in Chapter 8 and Chapter 9 will address this issue.

## **CHAPTER 8. EXPERIMENTAL METHODS**

The new taxonomy given in Chapter 7 provides a way to compare different methods of travel in virtual worlds. Because this classification system introduces new elements not found in previous work, we would like to provide evidence that the new distinctions made by this taxonomy between different locomotion methods are valid. This chapter describes an experiment designed to validate part of the taxonomy. In particular, the experiment is targeted to the impact of display devices and the distinction between physical rotation and virtual rotation.

### **8.1 General Description**

One of the most common activities performed in virtual environments is an architectural walkthrough. The goal of a walkthrough is usually to explore a building to discover interesting features and gain an understanding of the spatial layout of the building. Because architectural walkthroughs are so common, the activity each subject performed in this experiment was to simulate an architectural walkthrough by travelling along a preset path through an unfamiliar building. Subjects were told that they were going to experience and evaluate an architectural walkthrough. Each subject was first taught how to move through the environment using the selected travel method, and given three minutes in a practice environment to become accustomed to the experience. The subject then performed the locomotion task in the assigned test environment. Each test subject performed the locomotion task under only one experimental condition.

The locomotion task consisted of following a predetermined path through the environment. The path was indicated to the subject by arrows and signs positioned on the

floor, ceiling, and walls of the building. The arrows directed the user to a room within the building. Within the room, the user then had to pass over a circular red target on the floor. Once the user passed over the target, it turned green and a new set of arrows appeared directing the user to the next room. A total of ten targets were present along the path. When the user reached the final target, the travel automatically halted. Subjects were instructed to remember that their primary task as they moved along the path was to pretend they were architects studying the building. They were further instructed that they were being timed and should not spend excessive amounts of time wandering far from the path. However, instructions emphasized that the task was not a race and subjects should feel free to explore the rooms on the path.

The targets and arrows were present for several reasons. First, we wanted all the subjects to travel the same general path through the building so that they would have approximately the same virtual experience, making comparisons of results more straightforward. However, since we wanted subjects to develop their own understanding of the spatial layout of the building, it was not desirable to give them a map or building floorplan in advance. Thus, the arrows were added to direct subjects through the building. Arrows were placed in a variety of locations: on walls, hanging from ceilings, and mounted on posts. In this way subjects could obtain information from a variety of different locations, just as in the physical world. The use of targets helped to ensure that subjects did indeed follow the preferred path, and also served as a test of the user's ability to control fine movements, because several targets were located near walls or furniture. Finally, since some targets were not immediately visible upon entering a room, users were required to perform a search of the area. Piloting (see Section 4.2) is a strong component of an architectural

walkthrough as it is important for users to update their position relative to the virtual building. The instructions to subjects, combined with the targets and arrows, ensured that subjects performed all three of the sub-tasks associated with piloting: exploration, primed search, and naïve search [Darken96].

Figure 8-1 (a) shows the view the user is presented with when he first enters the virtual building. The arrow on the post and the two arrows on the wall are all directing the user into the first room on the walkthrough. Figure 8-1 (b) is a view from inside the first room. On the left is a large sculpture, and to the right are two pieces of furniture. The first target can be seen approximately halfway between the furniture and the sculpture.

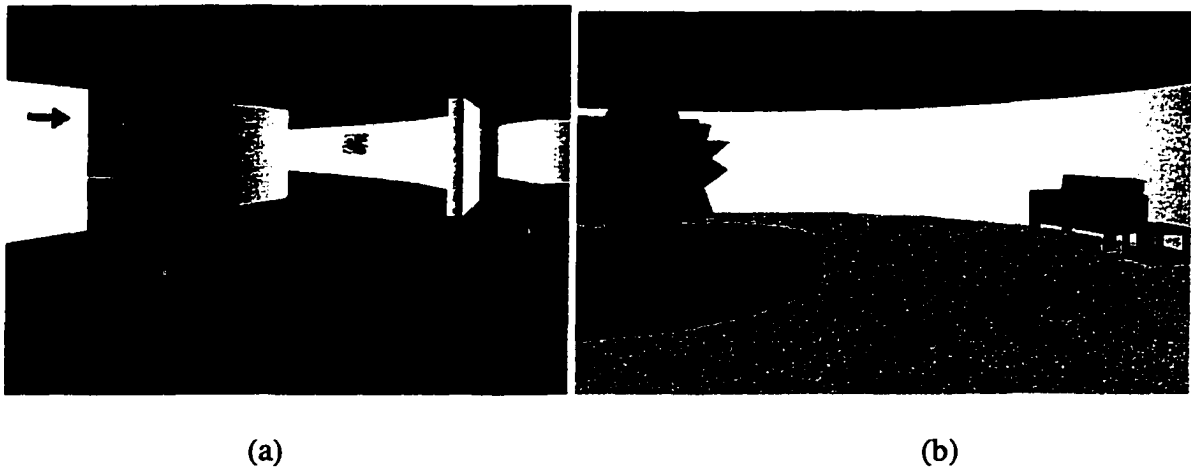


Figure 8-1: Views from the walkthrough.

Figures 8-2, 8-3, and 8-4 show additional views of the walkthrough. In Figure 8-2, the target in the room is located behind the trunk near the foot of the bed, and is difficult to see from the user's current location. This is the view almost every subject experienced when

entering the room, and demonstrates the need for subjects to occasionally search an area to find a target.



Figure 8-2.



Figure 8-3.

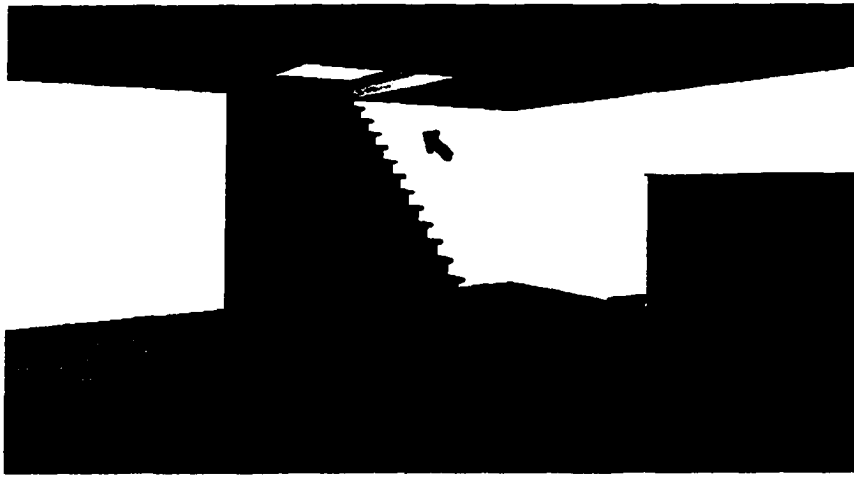


Figure 8-4.

## 8.2 Independent Variables

Eight different experimental conditions were possible: four types of display devices, with two different locomotion methods in each device. The display devices used were the C2 and C6 (described earlier in Section 2.3.4), an HMD, and a Barco Baron workbench (similar to the MD\_Table™ shown in Figure 2-4). These devices were chosen because they are representative of the wide variety of devices commonly in use at many VR facilities. In order to avoid introducing additional independent variables, all four systems used the same interaction device (shown earlier in Figure 2-1) and were driven by the same computer: a Silicon Graphics Onyx 2 with six Infinite Reality graphics pipes. Also, all the systems used an electromagnetic tracker for tracking head and wand location (the C6 uses an Ascension MotionStar®, the other three use Ascension Flock of Birds®).

The first type of locomotion used is virtual translation with virtual rotation. The second type of locomotion is virtual translation with physical rotation. Both of these types of locomotion are currently in use in our laboratory, and at other facilities. Also, the distinction

between virtual and physical rotation is one of the new elements introduced by our taxonomy so we believe it is important to test the validity of this distinction. It was hypothesized that the second type of locomotion would be too difficult for subjects to perform when using the workbench environment. This was confirmed through the use of pilot subjects. Table 8-1 shows the remaining seven experimental conditions. Throughout this work (usually in the appendices), the numbers shown in Table 8-1 may be used to refer to experimental conditions. For example, Condition 1 will be used to indicate virtual rotation in the C6. To avoid learning effects, each test subject completed the travel task in only one experimental condition.

Table 8-1. The experimental conditions.

|                                               | <b>C2</b> | <b>C6</b> | <b>HMD</b> | <b>Workbench</b> |
|-----------------------------------------------|-----------|-----------|------------|------------------|
| <b>Virtual Translate,<br/>Virtual Rotate</b>  | 7         | 1         | 6          | 5                |
| <b>Virtual Translate,<br/>Physical Rotate</b> | 3         | 4         | 2          | NA               |

Before performing the experiment, each subject completed a variety of questionnaires, including:

- 1) General background information questionnaire, found in Appendix A
- 2) Immersive tendencies questionnaire. This questionnaire is based on the work done by [Witmer98], and can be found in Appendix B.
- 3) Several tests of spatial abilities. From the Kit of Cognitive Factors: S-1, Card Rotations Tests; S-2, Cube Comparisons Test; SS-1, Maze Tracing Speed Test; SS-2, Choosing A Path; and SS-3, Map Planning Test. [Ekstrom76]

### 8.3 Dependent Variables

After traveling the entire path, the subject was asked to indicate the direction of the origin of their walk by pointing with the wand towards the doorway through which they had entered the virtual building (the doorway was no longer in view). This direction information was recorded and compared with the correct response to produce an error reading in the range from  $-180^{\circ}$  to  $180^{\circ}$ . A negative reading indicates that the subject did not rotate far enough, while a positive reading indicates that the subject over-rotated. Then subjects were asked to identify the floorplan of the virtual building they had observed from among 4 possible choices, shown in Figures 8-5, 8-6, 8-7, and 8-8, designated as choices A, B, C, and D, respectively. In each figure, the asterisks symbol represents the point where subjects began the walkthrough, and the stairs are shown as a series of small rectangles. Choice B (Figure 8-6) is the correct floorplan. These four floorplan choices were developed through the use of pilot subjects.

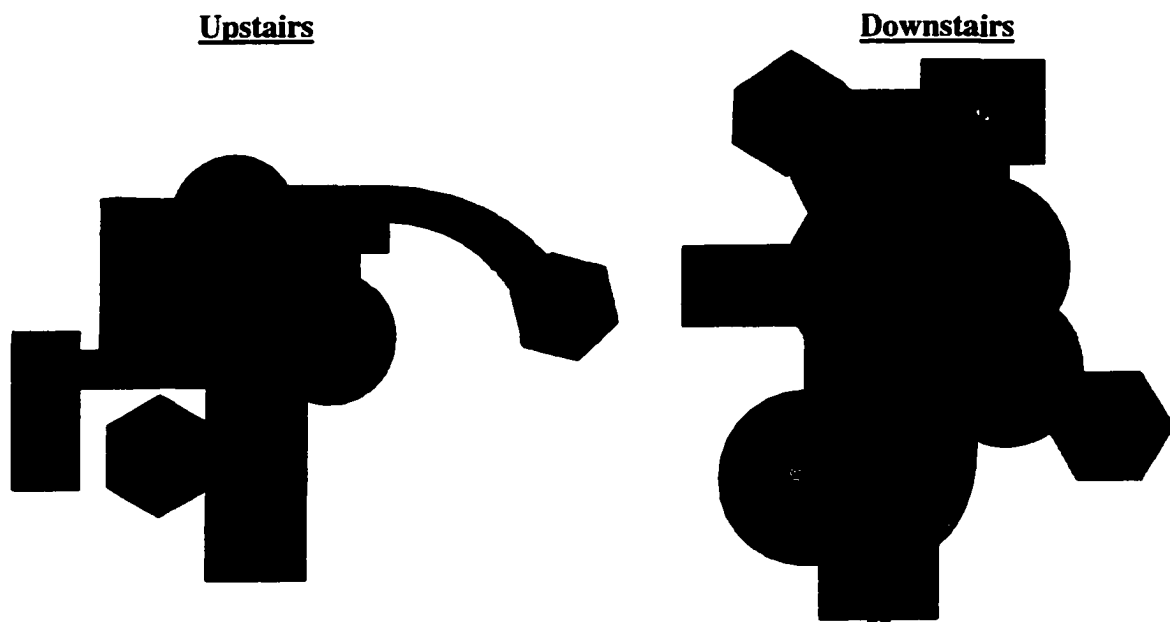


Figure 8-5: Floorplan A.

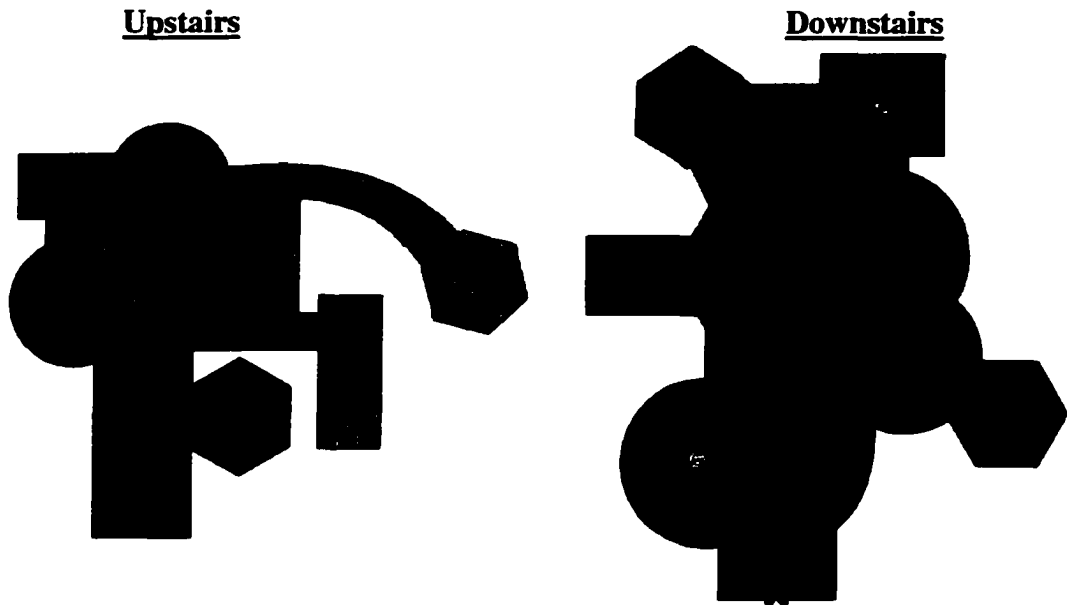


Figure 8-6: Floorplan B, the correct floorplan.

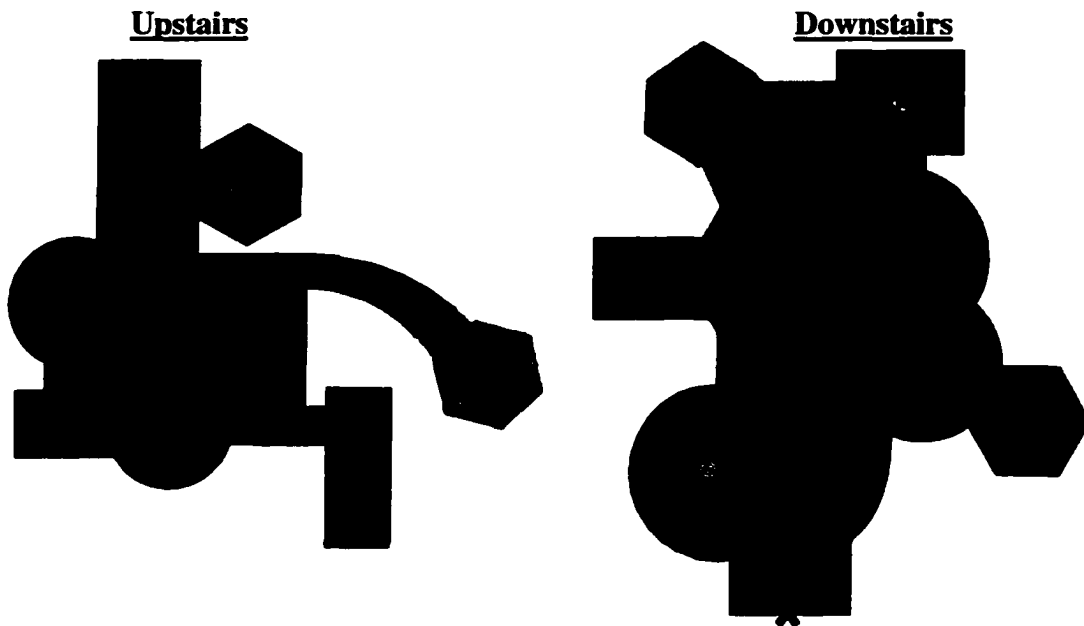


Figure 8-7: Floorplan C.

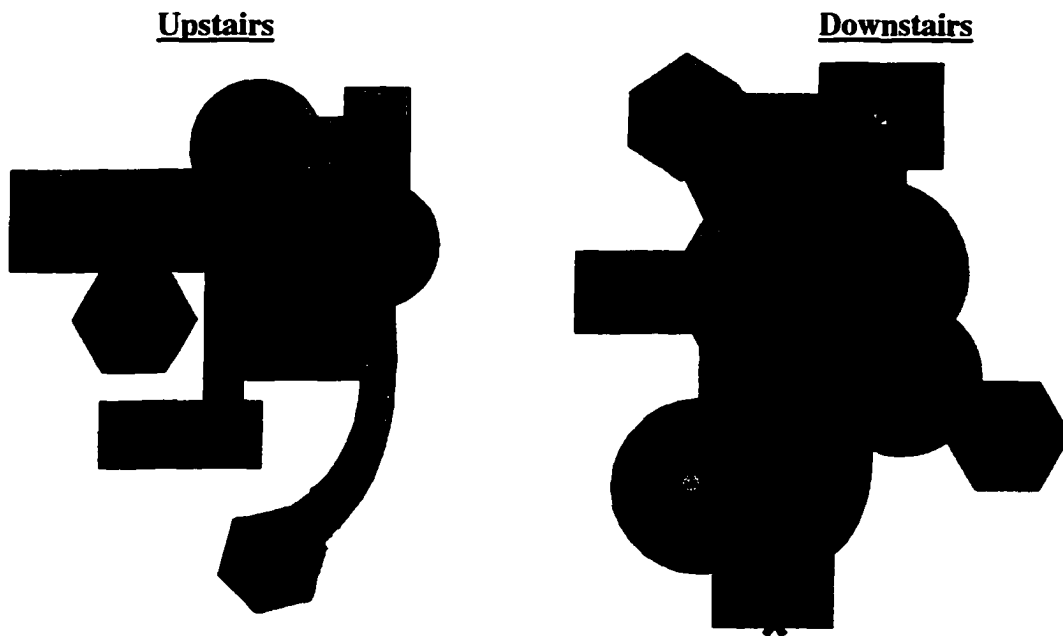


Figure 8-8: Floorplan D.

The time taken to complete the travel was recorded, along with the number of collisions with objects such as walls and furniture. These factors were chosen for study because in an architectural walkthrough it is important that the user be able to navigate quickly to locations of interest, while maintaining spatial information about the building. Collisions often increase the travel time and may also contribute to user frustration and disorientation.

Finally, subjects completed post-questionnaires, containing questions about cybersickness, presence, and the user's impressions of the locomotion. Copies of the questionnaires are found in Appendices C, D, E, and F.

#### **8.4 Test Subjects**

To recruit subjects, advertisements were placed in the campus and local newspapers, and fliers were posted throughout the campus area. Subjects were all unpaid volunteers. Many were college students, some were faculty, staff, or other community members. Full background information on subjects is given in Appendix G.

Because experimental conditions 1 and 6 are the conditions currently used in our laboratory, we restricted test subjects to be persons who had not previously operated the C2 or C6, in order to prevent learning effects. Additionally, because some of our early work indicates that even minimal exposure to virtual environments, such as playing a head-mounted display type game at an arcade, can influence subjects' performance [Arns99], any potential subjects reporting previous exposure to VR on the questionnaires were not used for the study. This left us with 77 usable test subjects, 42 male and 35 female.

Since it has been shown that scores on spatial abilities tests correlate with users' spatial perception in virtual environments [Neale96], subjects were grouped in such a way as to prevent individual abilities from skewing the results. The process used was as follows: subjects received a rank for each of the spatial abilities tests indicating their performance as compared to all other subjects. Then an overall ranking was computed by averaging the subject's rankings on all of the spatial abilities tests. Subjects with the lowest 7 overall rankings formed one cluster and were assigned to one of the 7 experimental conditions using random number tables, so that each experimental condition received one of these subjects. This process was repeated with the cluster of the next 7 lowest ranked subjects, until all 77 subjects were assigned, 11 to each experimental group. Additionally, after these assignments were made, groups were balanced by gender so that each group contained 6 males and 5

females. To accomplish this, a small number of subjects were “swapped” with another subject in a different experimental group. In all cases, the subjects within each swapped pair were both from the same cluster. The following lists show the ID numbers of the subjects assigned to each experimental condition:

Condition 1: 3, 5, 18, 21, 26, 29, 33, 35, 36, 77, 82

Condition 2: 1, 4, 8, 17, 40, 44, 46, 62, 67, 86, 96

Condition 3: 13, 14, 16, 25, 48, 59, 81, 91, 104, 106, 107

Condition 4: 22, 28, 30, 34, 41, 57, 61, 80, 83, 84, 109

Condition 5: 12, 15, 20, 23, 38, 49, 64, 73, 75, 94, 101

Condition 6: 6, 32, 39, 45, 50, 54, 68, 69, 89, 97, 100

Condition 7: 2, 9, 27, 52, 55, 58, 60, 63, 93, 99, 108

During the testing, a number of subjects (47) dropped out, failed to complete the experiment, or produced results that were unusable for various reasons such as hardware failure. More detailed information can be found in Appendix H. In order to maintain a large number of test subjects in each experimental condition, these subjects were replaced. A new group of test subjects was recruited and selected using the same procedures given above. In order to determine how to assign new subjects to an experimental condition, two assumptions were made:

- 1) That the subjects dropped from the original group were representative of the group as a whole.

- 2) That the new group of subjects was approximately equal to the original group in terms of general background and abilities.

Next, the new subjects each received an average ranking within the new subject pool, computed using the procedure given above for the original subject pool. Then, each new subject was assigned a percentile ranking within the group. Subjects from the original group were also assigned a percentile ranking within their group. Finally, for each original subject dropped from the experiment, a replacement subject was chosen by finding the closest percentile match (with appropriate gender) from the new subject pool. The replacement subject was then assigned to the same experimental condition as the original subject whom they replaced. Because more replacement subjects were recruited than were needed, we were able to repeat this process when any of the replacement subjects were dropped from the experiment. More information is available in Appendix I.

Table 8-2 shows the relationships among the original subjects and replacements assigned to experimental condition 1 (C6, virtual rotation). Tables 8-3, 8-4, 8-5, 8-6, 8-7, and 8-8 show this information for the other experimental conditions. In all of these tables, the following notation is used:

CS=Subject dropped out after experiencing cybersickness  
 M= Subject moved/graduated/left school before they could be tested  
 NR=Subject did not respond to contact attempts, was unable to schedule a testing time, or failed to appear for testing  
 T=Technical problems such as application crash or hardware failure  
 U=Subject was unable to learn how to control the travel and stopped the experiment after approximately 10 minutes without having made it to the 1<sup>st</sup> target  
 VR= Subject reported a VR experience between the time of filling out the initial paperwork and returning for testing

Table 8-2: Replacement subjects for experimental condition 1.

| Original Subject | Reason Dropped | Replacement Subject | Reason Dropped | Replacement Subject |
|------------------|----------------|---------------------|----------------|---------------------|
| 3                | NR             | 163                 | -              | -                   |
| 18               | NR             | 141                 | -              | -                   |
| 21               | CS             | 209                 | NR             | 137                 |
| 36               | T              | 220                 | -              | -                   |
| 77               | U              | 144                 | CS             | 208                 |
| 82               | NR             | 223                 | NR             | 113                 |

Table 8-3 Replacement subjects for experimental condition 2.

| Original Subject | Reason Dropped | Replacement Subject | Reason Dropped | Replacement Subject |
|------------------|----------------|---------------------|----------------|---------------------|
| 1                | T              | 181                 | -              | -                   |
| 8                | T              | 156                 | -              | -                   |
| 17               | NR             | 128                 | T              | 189                 |
| 44               | NR             | 198                 | T              | 145                 |
| 67               | T              | 217                 | T              | 134                 |
| 86               | NR             | 188                 | -              | -                   |
| 96               | NR             | 120                 | -              | -                   |

Table 8-4 Replacement subjects for experimental condition 3.

| Original Subject | Reason Dropped | Replacement Subject |
|------------------|----------------|---------------------|
| 14               | NR             | 125                 |
| 16               | T              | 129                 |
| 25               | NR             | 202                 |
| 107              | T              | 178                 |

Table 8-5 Replacement subjects for experimental condition 4.

| Original Subject | Reason Dropped | Replacement Subject |
|------------------|----------------|---------------------|
| 28               | NR             | 122                 |
| 30               | T              | 177                 |
| 41               | T              | 155                 |
| 57               | T              | 127                 |
| 80               | T              | 201                 |
| 83               | T              | 210                 |
| 84               | NR             | 142                 |
| 109              | T              | 159                 |

Table 8-6 Replacement subjects for experimental condition 5.

| Original Subject | Reason Dropped | Replacement Subject | Reason Dropped | Replacement Subject | Reason Dropped | Replacement Subject |
|------------------|----------------|---------------------|----------------|---------------------|----------------|---------------------|
| 20               | NR             | 140                 | -              | -                   | -              | -                   |
| 23               | NR             | 214                 | NR             | 170                 | VR             | 191                 |
| 49               | M              | 111                 | -              | -                   | -              | -                   |
| 75               | NR             | 151                 | -              | -                   | -              | -                   |

Table 8-7 Replacement subjects for experimental condition 6.

| Original Subject | Reason Dropped | Replacement Subject | Reason Dropped | Replacement Subject |
|------------------|----------------|---------------------|----------------|---------------------|
| 50               | T              | 124                 | -              | -                   |
| 54               | T              | 172                 | T              | 183                 |
| 97               | T              | 215                 | -              | -                   |
| 100              | NR             | 203                 | -              | -                   |

Table 8-8 Replacement subjects for experimental condition 7.

| Original Subject | Reason Dropped | Replacement Subject | Reason Dropped | Replacement Subject |
|------------------|----------------|---------------------|----------------|---------------------|
| 27               | NR             | 143                 | -              | -                   |
| 52               | NR             | 146                 | CS             | 206                 |
| 93               | CS             | 190                 | -              | -                   |
| 108              | T              | 197                 | -              | -                   |

The following lists show the ID numbers of subjects successfully tested in each experimental condition, after all replacements were made.

Condition 1: 5, 26, 29, 33, 35, 113, 137, 141, 163, 208, 220

Condition 2: 4, 40, 46, 62, 120, 134, 145, 156, 181, 188, 189

Condition 3: 13, 48, 59, 81, 91, 104, 106, 125, 129, 178, 202

Condition 4: 22, 34, 61, 122, 127, 142, 155, 159, 177, 201, 210

Condition 5: 12, 15, 38, 64, 73, 94, 101, 111, 140, 151, 191

Condition 6: 6, 32, 39, 45, 68, 69, 89, 124, 183, 203, 215

Condition 7: 2, 9, 55, 58, 60, 63, 99, 143, 190, 197, 206

### **8.5 Hypothesized Results**

We believed that the results of the experiments would validate two important parts of our new taxonomy. First, we hypothesized that within each display device, results in terms of presence scores, completion times, number of collisions, and/or error in the perceived direction of origin would differ by rotation method. This difference would indicate that the distinction in the new taxonomy between virtual and physical rotation is valid. Also, we believed a difference in results would be seen among different display devices. Such a difference would indicate the validity of the distinction in the new taxonomy of display device used.

## **CHAPTER 9. RESULTS**

Our original pool of volunteers produced 77 usable test subjects. Of these subjects, 37 did not produce usable data, for various reasons such as technical problems with equipment, or failure of the subject to show up for the experiment. More detailed information on these subjects is available in Section 8.4 and Appendix H. These 37 subjects were replaced with subjects from a new pool of volunteers, using a process described in Section 8.4. A careful examination of the data shows that the two assumptions made in Section 8.4 were valid, indicating that the replacement process did not affect the outcomes of the experiment. Detailed information on this analysis is found in Appendix J. The remainder of this chapter is concerned only with the 77 subjects (40 original subjects and 37 replacement subjects) that produced usable data.

Recall that the overall purpose of this experiment is to experimentally validate selected portions of the new taxonomy presented in Chapter 7. We would like to show that either display device or rotation method (or both) has an effect on users' experiences in a virtual environment. To achieve this we had users perform a walkthrough of a virtual building under one of 7 different treatment conditions (4 display devices, crossed with 2 rotation methods, with one of these 8 conditions not used). The next section of the chapter (9.1) covers the demographics of the subject pool. Section 9.2 covers the response variables collected: presence scores, completion times, number of collisions, missed targets, and pointing error in indicating the origin of the virtual walk. Section 9.3 discusses any effects demographics may have had on response variables. Section 9.4 covers observations made by test administrators. Section 9.5 covers other interesting interactions, and Section 9.6 covers subjects' responses on non-quantitative portions of the post-test questionnaires.

## 9.1 Demographic Information

### 9.1.1 Gender

As discussed in Chapter 8, groups were balanced for gender. Each experimental condition contained 5 females and 6 males, for a total of 35 females and 42 males.

### 9.1.2 Spatial Abilities

Table 9-1 shows the results for each of the individual spatial abilities tests. An overall ranking on the spatial abilities tests was also computed for each subject and used to assign the subjects to treatment conditions. This process was described in Section 8.4.

Table 9-1. Results from each of the spatial abilities tests. The highest possible score is shown in parentheses in the heading for each column.

|                           | <b>S1: Card<br/>Rotations<br/>Test<br/>(160)</b> | <b>S2: Cube<br/>Comparisons<br/>Test<br/>(42)</b> | <b>SS1: Maze<br/>Tracing<br/>Speed Test<br/>(48)</b> | <b>SS2:<br/>Choosing<br/>A Path<br/>(32)</b> | <b>SS3: Map<br/>Planning<br/>Test<br/>(40)</b> |
|---------------------------|--------------------------------------------------|---------------------------------------------------|------------------------------------------------------|----------------------------------------------|------------------------------------------------|
| <b>Average</b>            | 111.81                                           | 23.40                                             | 27.91                                                | 9.94                                         | 26.69                                          |
| <b>Standard Deviation</b> | 28.76                                            | 9.78                                              | 7.12                                                 | 9.14                                         | 8.22                                           |

### 9.1.3 Age

Figure 9-1 shows the ages of test subjects completing the experiment. From this figure it is obvious that the majority of the test subjects were fairly young (under 30 years of age). The average age of subjects completing the experiment is 27.57 years, with a standard deviation of 10.10. Table 9-2 gives average ages and standard deviations (shown in parentheses) for each group.

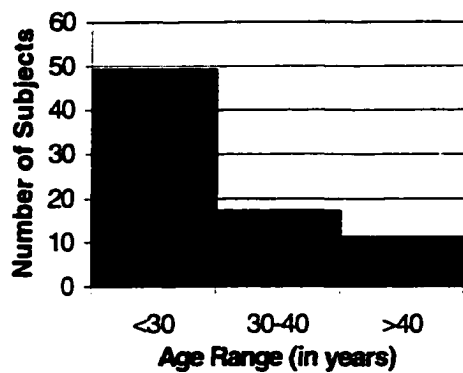


Figure 9-1. Ages of test subjects.

Table 9-2. Average ages (in years) of test subjects. Average is shown on the first line, standard deviation is on the second line of each cell.

|                                    | C2               | C6               | HMD              | Bench           | Per rotation method |
|------------------------------------|------------------|------------------|------------------|-----------------|---------------------|
| Virtual Translate, Virtual Rotate  | 30.82<br>(10.72) | 28.18<br>(11.77) | 31.00<br>(10.43) | 29.09<br>(9.71) | 29.77<br>(10.37)    |
| Virtual Translate, Physical Rotate | 27.55<br>(10.42) | 19.64<br>(3.83)  | 26.73<br>(10.38) | NA              | 24.64<br>(9.23)     |
| Per device                         | 29.18<br>(10.45) | 23.91<br>(9.60)  | 28.86<br>(10.39) | 29.09<br>(9.71) | 27.57<br>(10.10)    |

#### 9.1.4 Immersive Tendencies Questionnaire (ITQ)

Figure 9-2 shows the test subjects' scores on the ITQ. The average score is 67.34, out of a possible score of 112, with a standard deviation of 12.89. Table 9-3 shows the average ITQ scores for each group. Table 9-4 compares these results with those found in [Witmer98].

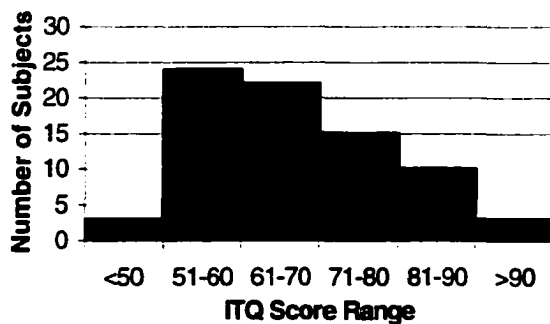


Figure 9-2. Subjects' ITQ scores.

Table 9-3. Average ITQ scores. Standard deviations are shown on the second line of each cell.

|                                           | <b>C2</b>        | <b>C6</b>        | <b>HMD</b>       | <b>Bench</b>     | <b>Per rotation method</b> |
|-------------------------------------------|------------------|------------------|------------------|------------------|----------------------------|
| <b>Virtual Translate, Virtual Rotate</b>  | 64.18<br>(11.36) | 70.55<br>(16.15) | 62.18<br>(10.93) | 65.91<br>(10.57) | 65.70<br>(12.41)           |
| <b>Virtual Translate, Physical Rotate</b> | 71.82<br>(12.21) | 67.91<br>(10.82) | 68.82<br>(17.22) | NA               | 69.52<br>(13.37)           |
| <b>Per device</b>                         | 68.00<br>(12.15) | 69.23<br>(13.48) | 65.50<br>(14.48) | 65.91<br>(10.57) | 67.34<br>(12.89)           |

Table 9-4. Average ITQ scores for all subjects compared with the results of [Witmer98]. The original ITQ from Witmer contained 2 questions more than our ITQ. The final column reflects the average score we would expect to attain from our subjects if the 2 additional questions had been included. This score compares favorably with Witmer.

|                           | <b>This work</b> | <b>[Witmer98]</b> | <b>Adjusted</b> |
|---------------------------|------------------|-------------------|-----------------|
| <b>Average</b>            | 67.34            | 76.66             | 75.75           |
| <b>Standard Deviation</b> | 12.89            | 13.61             |                 |

## 9.2 Response Variables

Due to the large amount of data collected, results not of statistical significance may not be discussed in this chapter. Full analysis of variance (ANOVA) tables and additional charts not discussed here may be found in Appendix L.

### 9.2.1 Presence Questionnaire (PQ)

Figure 9-3 shows the test subjects' scores on the PQ. The average score is 99.61, out of a possible score of 133, with a standard deviation of 13.68. Table 9-5 shows the average PQ scores for each group.

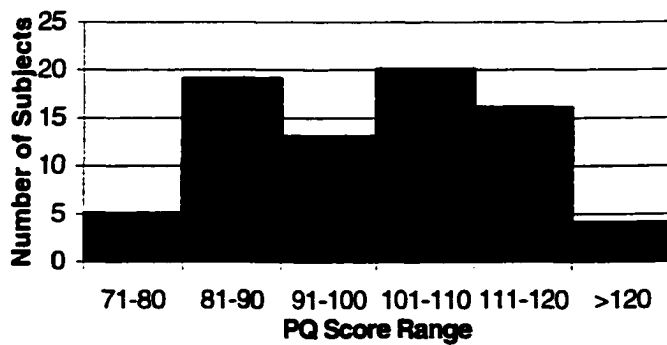


Figure 9-3. Subjects' PQ scores.

Table 9-5. Average PQ scores. Standard deviations are shown on the second line of each cell.

|                                           | C2               | C6                | HMD               | Bench           | Per rotation method |
|-------------------------------------------|------------------|-------------------|-------------------|-----------------|---------------------|
| <b>Virtual Translate, Virtual Rotate</b>  | 99.55<br>(8.94)  | 108.27<br>(12.13) | 95.18<br>(17.45)  | 90.73<br>(6.00) | 98.43<br>(13.23)    |
| <b>Virtual Translate, Physical Rotate</b> | 92.73<br>(15.38) | 108.00<br>(11.31) | 102.82<br>(12.58) | NA              | 101.18<br>(14.31)   |
| <b>Per device</b>                         | 96.14<br>(12.76) | 108.14<br>(11.45) | 99.00<br>(15.35)  | 90.73<br>(6.00) | 99.61<br>(13.68)    |

Table 9-6. Average PQ scores for all subjects compared with the results of [Witmer98]. Our results compare favorably with Witmer.

|                           | <b>This work</b> | <b>[Witmer98]</b> |
|---------------------------|------------------|-------------------|
| <b>Average</b>            | 99.61            | 98.11             |
| <b>Standard Deviation</b> | 13.68            | 15.78             |

Looking at the means in Table 9-5, the display devices appear to have quite different average PQ scores, with the C6 having the highest mean, almost 18 points higher than the device with the lowest mean (Bench). A one-way ANOVA indicates a significant difference ( $p < 0.001$ ) across display devices. The ANOVA table is shown in Table 9-7. A full

description of ANOVA tables is found in Appendix L. The differences in PQ scores are shown graphically in Figure 9-4.

Table 9-7. ANOVA Table for PQ scores by display devices

| Source         | DF | SS        | MS      | F     | PROB>F |
|----------------|----|-----------|---------|-------|--------|
| Display Device | 3  | 2740.948  | 913.649 | 5.810 | 0.001  |
| Error          | 73 | 11479.364 | 157.252 |       |        |
| Total          | 76 | 14220.312 | 187.109 |       |        |

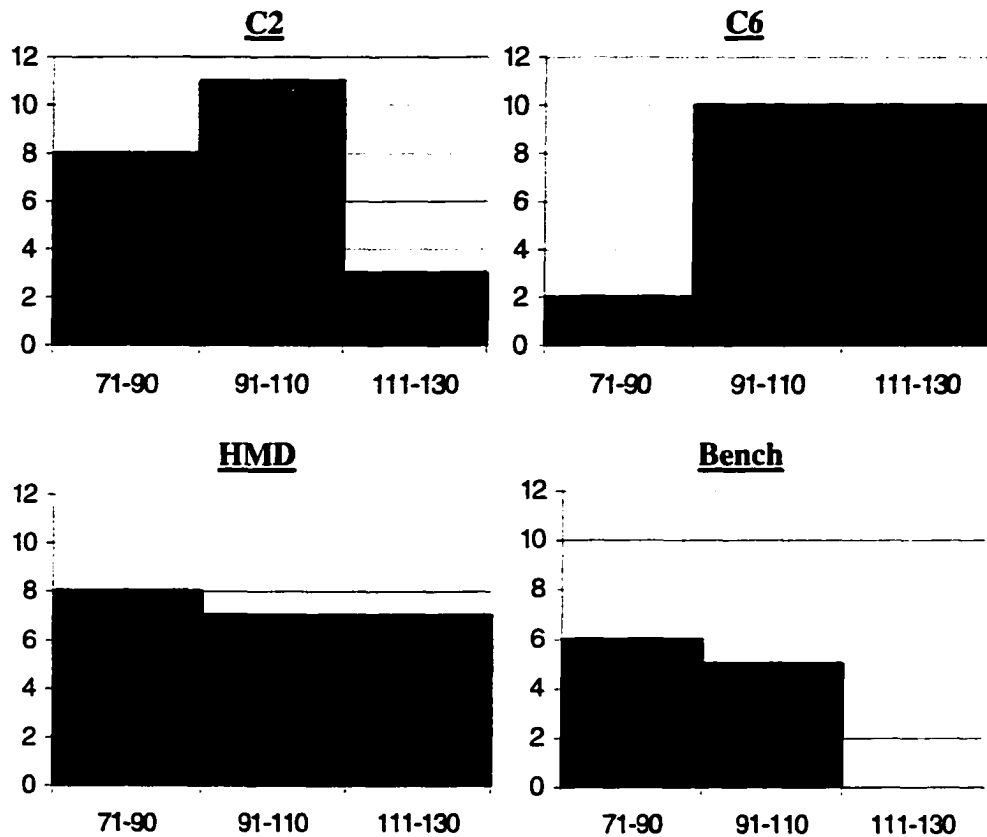


Figure 9-4. PQ Scores for each display device. Score range is displayed across the horizontal axis, and number of subjects is on the vertical axis.

From these histograms we see some patterns, for example, scores on the PQ for subjects in the C6 are mostly in the range 91-130, but scores for subjects in the C2 are mostly

the reverse, in the range 71-110. For the HMD, scores are spread relatively uniformly across all ranges, while scores for subjects using the bench are all in the lower range, 71-110. It should not be surprising that presence is strong when using the C6, as it completely obscures the physical world, a factor often believed to induce presence. The C2 and bench do not completely obscure the physical world, although the C2 does present a much larger view of the world than the bench, so it is not particularly surprising that these devices should create lower levels of presence than the C6, with the C2 showing some advantage over the bench. It is somewhat surprising that presence scores on the HMD are spread across the spectrum, and not mostly in the upper range. The HMD does completely block out the physical world, but this alone is apparently not a large enough factor to completely create a sense of presence.

Figure 9-5 shows the PQ scores for all 7 experimental conditions. Although a two-way ANOVA does not indicate any significant differences, we can still observe some interesting features of these diagrams. For the C6, rotation method appears to have almost no effect on the level of presence experienced. For the C2 however, we notice that most PQ scores are very consistent for virtual rotation, almost all are in the range 91-110. But for subjects using physical rotation, scores are more concentrated in the range 71-90, with just over half of the scores in this range, and a few scores in both the 91-110 and 111-130 ranges. This supports our assertion in Section 7.6 and Figure 7-6 that while physical rotation may be feasible in projection-based display devices with less than 360 degrees field-of-view, it is likely not the preferable means of locomotion, at least when trying to induce a sense of presence.

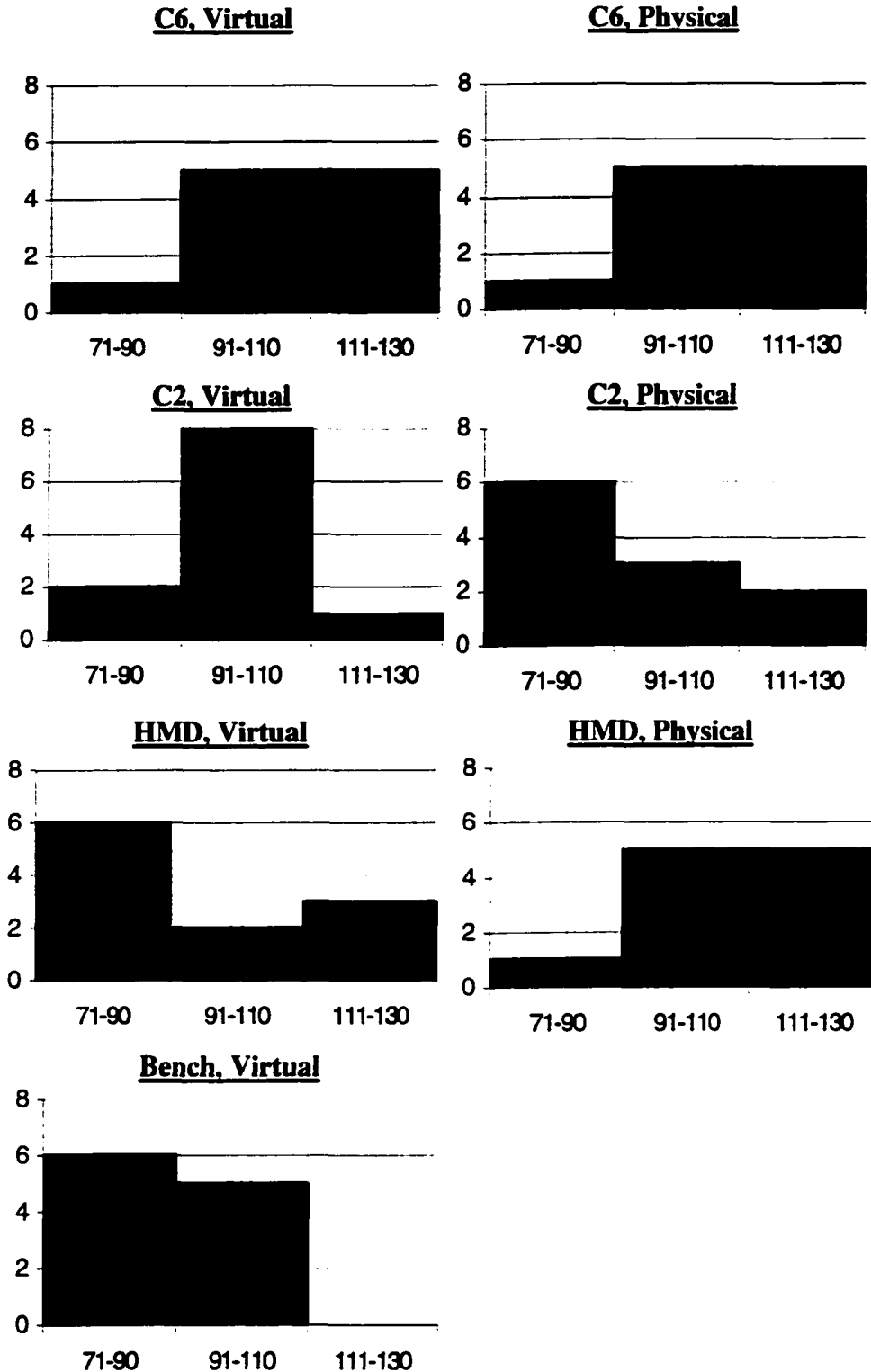


Figure 9-5. PQ scores for each experimental condition. Score range is on the horizontal axis, with number of subjects on the vertical axis.

### 9.2.2 ITQ and PQ Correlation

In [Witmer98], two studies indicated a strong correlation between ITQ and PQ scores, while two other studies did not. However, combining the data across all four of those experiments yielded a significant correlation between the two measures. Figure 9-6 shows a plot of ITQ scores vs. PQ scores for our data. It appears from Figure 9-6 that our ITQ scores and PQ scores are not linearly associated. The correlation between these scores is 0.11, which indicates that the scores on these measures do not show much correlation.

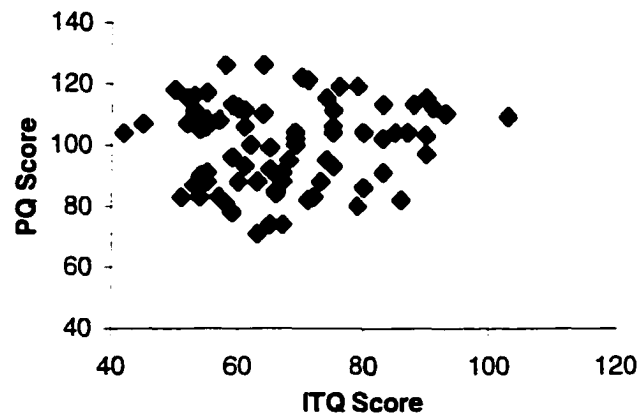


Figure 9-6. ITQ scores vs PQ scores.

### 9.2.3 Completion Times

Completion times for the walkthrough were recorded for each subject, and are shown in Figure 9-7. The mean completion times for each group are shown in Table 9-8. The average completion time for all subjects is 299.53 seconds, with a standard deviation of 127.98.

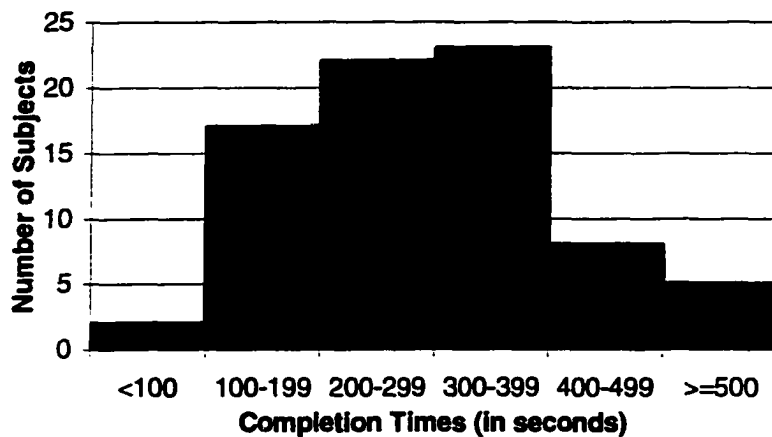


Figure 9-7. Completion Times for the walkthrough task.

Table 9-8. Average completion times for the walkthrough. Standard deviations are shown on the second line of each cell. All times are in seconds. \*One subject in this condition had an extremely large completion time (1046 seconds). This subject's data was not used in computing values shown in this table and Table 9-9. This did not affect statistical significance.

|                                           | C2                 | C6                 | HMD                 | Bench             | Totals per rotation method |
|-------------------------------------------|--------------------|--------------------|---------------------|-------------------|----------------------------|
| <b>Virtual Translate, Virtual Rotate</b>  | 274.00<br>(167.19) | 273.18<br>(105.01) | 349.36<br>(150.91)  | 327.55<br>(97.99) | 306.02<br>(133.16)         |
| <b>Virtual Translate, Physical Rotate</b> | 278.00<br>(97.21)  | 230.73<br>(80.68)  | 370.30*<br>(148.07) | NA                | 290.59<br>(122.03)         |
| <b>Totals per device</b>                  | 276.00<br>(133.47) | 251.95<br>(93.93)  | 390.55<br>(204.41)  | 327.55<br>(97.99) | 299.53<br>(127.98)         |

From Table 9-8, it appears that completion times are much lower for subjects using the C2 or C6. A one-way ANOVA reveals a significant difference ( $p < 0.012$ ) between devices. The ANOVA table is shown in Table 9-9. Figure 9-8 shows the completion times for each device. From this figure, it appears that completion times in the C6 are mostly in the range 100-300 seconds. Completion times for the other devices are spread across a wider

range, but times for the C2 still appear to be most concentrated in the lower to middle area, while HMD and Bench times are concentrated in the middle to upper time range.

Table 9-9. ANOVA Table for completion times by display devices.

| Source         | DF | SS          | MS        | F     | PROB>F |
|----------------|----|-------------|-----------|-------|--------|
| Display Device | 3  | 245622.110  | 81874.037 | 3.899 | 0.012  |
| Error          | 73 | 1532859.136 | 20998.070 |       |        |
| Total          | 76 | 1778481.247 | 23401.069 |       |        |

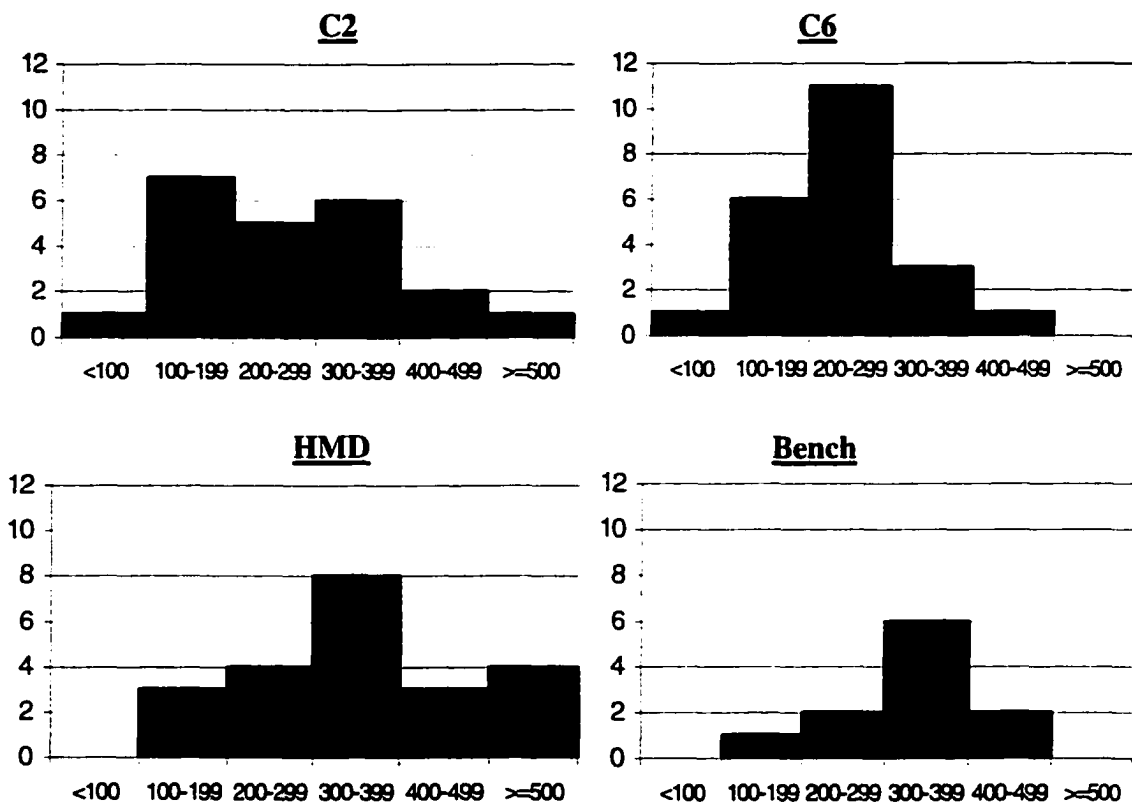


Figure 9-8. Completion times for each display device. Time (in seconds) is displayed across the horizontal axis, and number of subjects is on the vertical axis.

Although ANOVAs do not show a significant difference between rotation conditions, we notice from Table 9-8 that for some display devices, rotation method does appear to have an effect. Figure 9-9 shows histograms of completion times for each experimental condition. For the C6, both rotation conditions have many results in the range 200-299 seconds. However, for virtual rotation in the C6 the remaining results are mostly greater than 299 seconds, while for physical rotation in the C6 the remaining results are mostly less than 200. This can be observed graphically in Figure 9-9 by the first two histograms, which show stair-step patterns that are nearly reflections of each other. This also supports our assertion that for the C6, physical rotation may be the preferred method of rotation.

In the C2, while the overall means are quite similar, virtual rotation produced readings that are spread quite uniformly over the entire range of times, with a slight emphasis in the 100-199 range. Physical rotation produced results that are fairly uniform over the range 100-499, with a slight emphasis in the 300-399 range. This again supports Section 7.6 and Figure 7.6, indicating that physical rotation in the C2 device may not be the preferred method of travel.

Results for the HMD are quite dramatic, as virtual rotation resulted in completion times spread evenly over most of the entire range of times, but physical rotation produced many results in the range 300-399. Our taxonomy allows both rotation methods to be used with the HMD. It appears that virtual rotation may produce a lower completion time on average, while physical rotation may produce more consistent completion times. However, neither rotation method produces completion times that are, on average, as low as completion times for the C2 or C6.

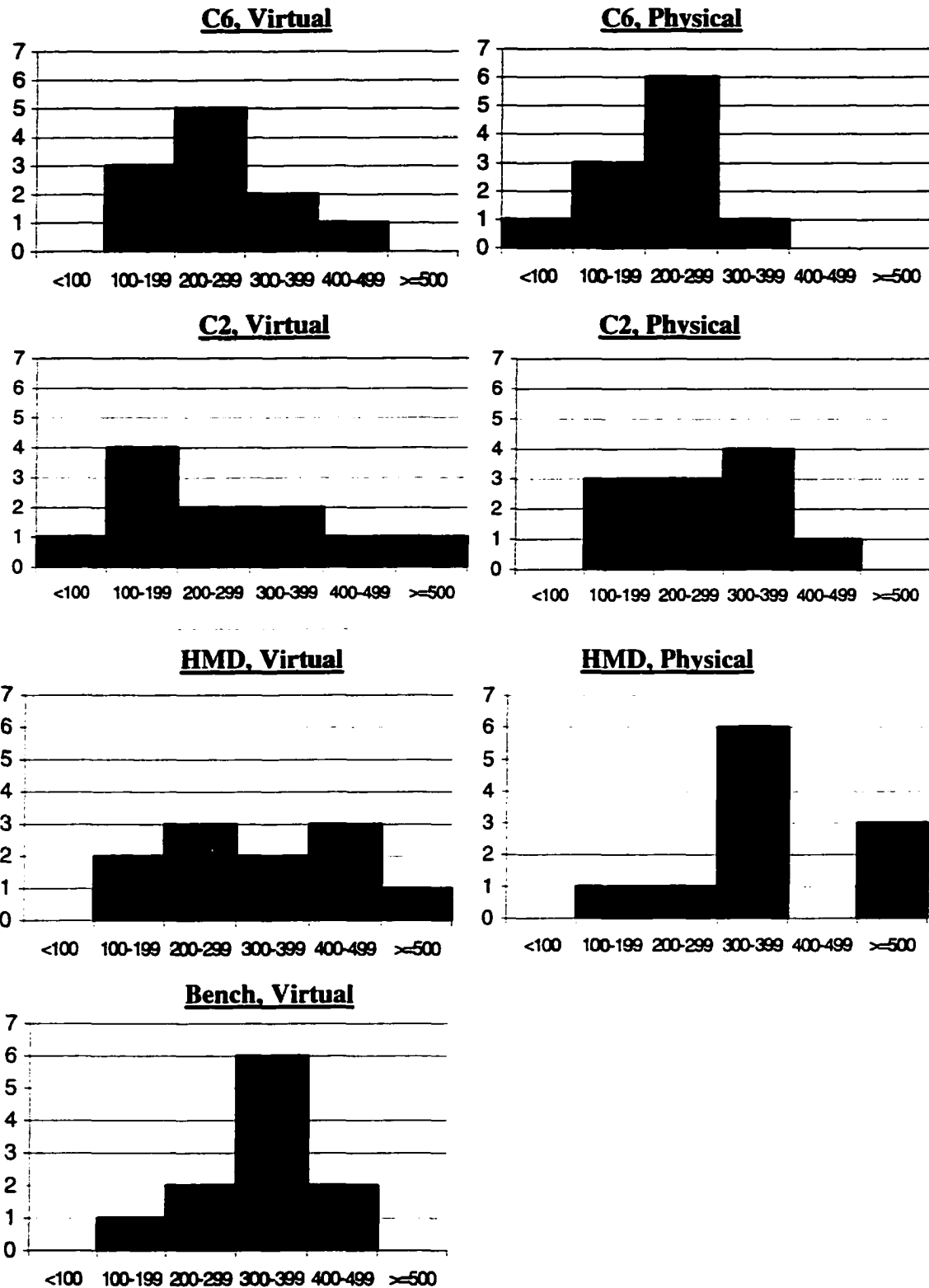


Figure 9-9. Completion times for each experimental condition. Time (in seconds) is displayed on the horizontal axis, with number of subjects on the vertical axis.

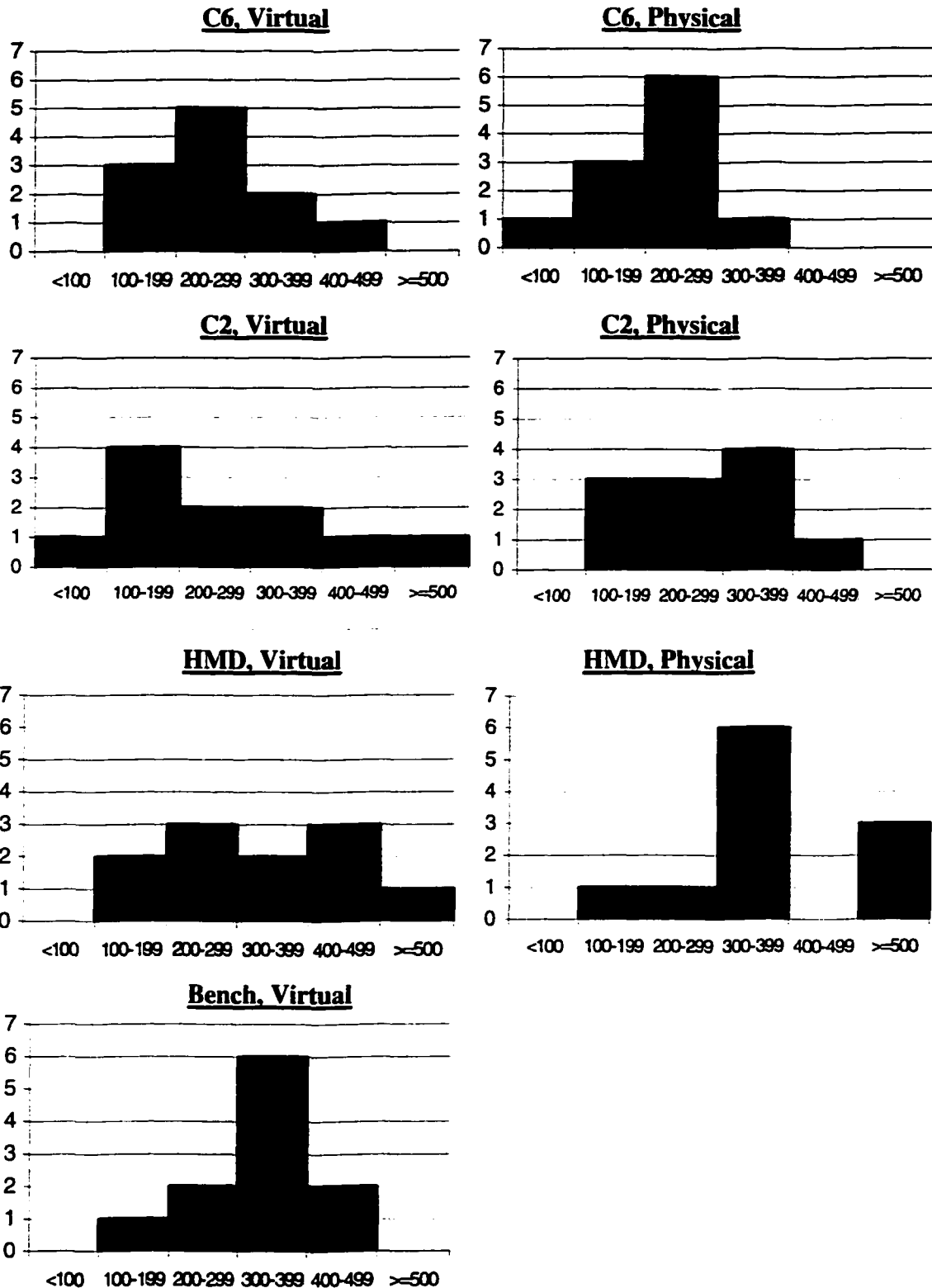


Figure 9-9. Completion times for each experimental condition. Time (in seconds) is displayed on the horizontal axis, with number of subjects on the vertical axis.

### 9.2.4 Collisions

As subjects walked through the virtual building, they occasionally collided with objects such as walls or furniture. The number of collisions was recorded. Figure 9-10 shows the number of collisions committed, and Table 9-10 shows the collisions data for all experimental conditions. The average number of collisions is 10.36, with a standard deviation of 9.35.

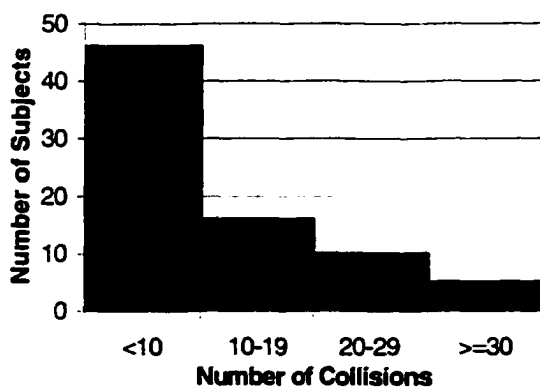


Figure 9-10. Number of collisions committed by subjects.

Table 9-10. Average number of collisions. Standard deviations are shown on the second line of each cell. \*One subject in this condition had an extremely large number of collisions (266). This subject's data was not used in computing values shown in this table and Table 9-11. This did not affect statistical significance.

|                                    | C2              | C6             | HMD               | Bench           | Totals per rotation method |
|------------------------------------|-----------------|----------------|-------------------|-----------------|----------------------------|
| Virtual Translate, Virtual Rotate  | 4.82<br>(5.25)  | 6.09<br>(8.49) | 13.55<br>(9.31)   | 11.91<br>(9.08) | 9.09<br>(8.75)             |
| Virtual Translate, Physical Rotate | 10.64<br>(7.12) | 7.64<br>(8.94) | 18.60*<br>(11.21) | NA              | 12.09<br>(10.01)           |
| Totals per device                  | 7.73<br>(6.79)  | 6.86<br>(8.54) | 15.95<br>(10.32)  | 11.91<br>(9.08) | 10.36<br>(9.35)            |

From this data we see that most subjects collided with very few objects during their walkthroughs. In fact, over one-third of all subjects had less than 5 collisions, over half had

less than 10 collisions, and over three-fourths had less than 15 collisions. However, subjects using the HMD or bench appear to have had more collisions than subjects in the C2 or C6. A one-way ANOVA indicates a significant ( $p < 0.004$ ) difference between display devices. The ANOVA table is shown in Table 9-11. This difference is shown graphically in Figure 9-11.

Table 9-11. ANOVA Table for collision by display devices.

| Source         | DF | SS       | MS      | F     | PROB>F |
|----------------|----|----------|---------|-------|--------|
| Display Device | 3  | 1104.592 | 368.197 | 4.858 | 0.004  |
| Error          | 72 | 5456.816 | 75.789  |       |        |
| Total          | 75 | 6561.408 | 87.485  |       |        |

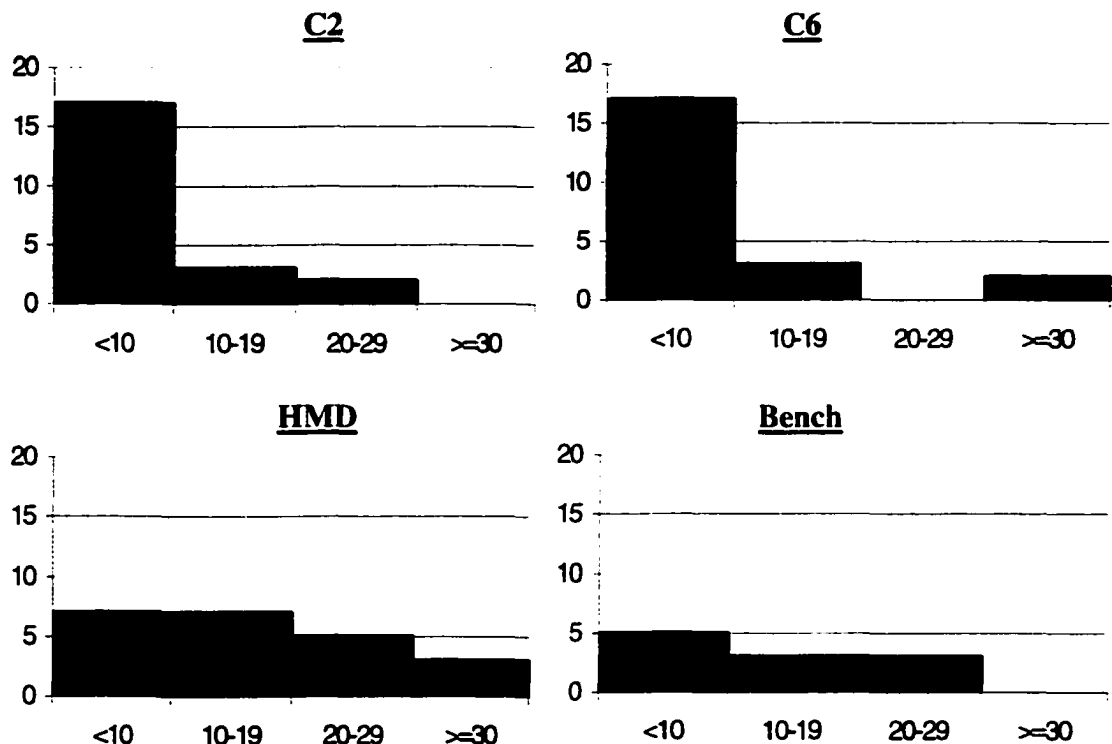


Figure 9-11. Collisions for each display device. Number of collisions is shown on the horizontal axis, with number of subjects on the vertical axis.

Figure 9-11 makes it quite apparent that the C2 and C6 both tended to result in fewer collisions, with most subjects having less than 10 collisions. Both the HMD and the bench

had more variability, with subjects being spread somewhat evenly across the entire range of resultant collisions. We believe this may be due at least in part to the large amount of peripheral vision afforded the user in the C2 and C6. Users in these devices can easily see to both sides, and the area around their feet, without requiring much head movement. This allows a user to notice if he happens to be standing partly inside a wall or other object. Although the HMD also allows a user to view the entire area around him, it has little peripheral view, and requires the user to make more head movements, so the user is less likely to notice these types of situations. This belief is reinforced by Figure 9-12, which shows collision data for all the experimental conditions. From this figure, we notice that the rotation method used has only a small effect on the number of collisions recorded in the C2 and C6. For the HMD, virtual rotation tends to produce only slightly fewer collisions than physical rotation. Overall, rotation method did not significantly affect the number of collisions.

### **9.2.5 Missed Targets**

To perform the walkthrough, subjects were supposed to follow arrows to guide them to each room, and then find a target within the room to walk over. Sometimes subjects did not walk over a target. This occurred for several reasons including: subject not seeing the target, and subjects believing they had crossed over the target when they had actually walked very close by to the target. Figure 9-13 and Table 9-12 show the number of missed targets. It is clear that most subjects did not miss any targets. And all but 2 subjects missed at most one target.

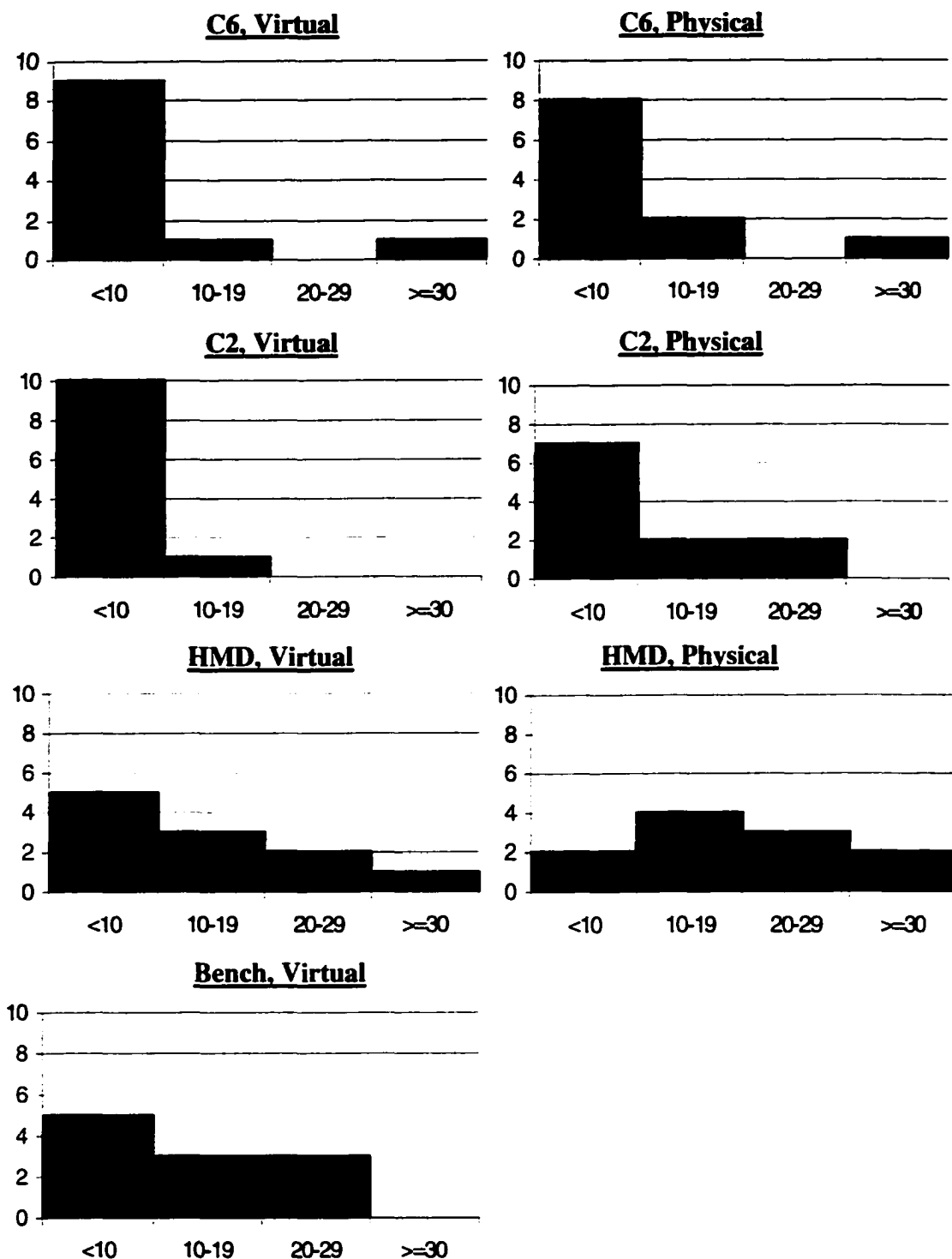


Figure 9-12. Collisions for each experimental condition. Number of collisions is displayed on the horizontal axis, with number of subjects on the vertical axis.

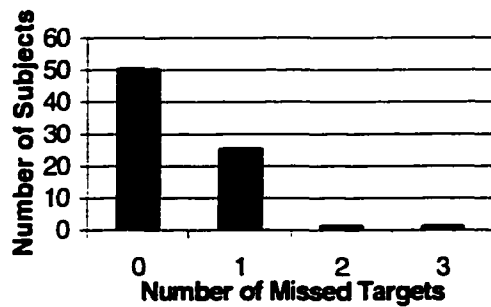


Figure 9-13. Number of missed targets.

Table 9-12. Average number of missed targets. Standard deviations are shown on the second line of each cell.

|                                           | C2             | C6             | HMD            | Bench          | Totals per rotation method |
|-------------------------------------------|----------------|----------------|----------------|----------------|----------------------------|
| <b>Virtual Translate, Virtual Rotate</b>  | 0.64<br>(0.50) | 0.36<br>(0.50) | 0.09<br>(0.30) | 0.55<br>(0.52) | 0.41<br>(0.50)             |
| <b>Virtual Translate, Physical Rotate</b> | 0.18<br>(0.40) | 0.45<br>(0.93) | 0.45<br>(0.69) | NA             | 0.36<br>(0.70)             |
| <b>Totals per device</b>                  | 0.41<br>(0.50) | 0.41<br>(0.73) | 0.27<br>(0.55) | 0.55<br>(0.52) | 0.39<br>(0.59)             |

ANOVAs show no significant differences among any factors. However, there are some interesting features shown in the table. For example, in the C2, subjects missed almost 4 times as many targets using virtual rotation as they did using physical rotation. This may be due to subjects' tendency to stand facing (and looking) only forward when using virtual rotation, but being forced to turn and look about when using physical rotation. For the HMD, the reverse situation occurs: subjects miss far fewer targets when using virtual rotation. This may be due in part to the smaller field-of-view of the HMD. Because subjects could see only a small portion of the virtual world, many of them stood in place and spun the entire virtual world around them several times to get a clear understanding of the environment. In the process they would be more likely to observe all targets and arrows. In the HMD, subjects

sometimes seemed uncomfortable with physically exploring the virtual world. They often simply looked straight ahead and did not make the connection that by turning their head they could view different parts of the virtual world. This is evidenced by some of the user comments, such as those from users 39 and 183 (see Appendix M and Appendix N) where the user wrote that she wished she could look up at the ceiling and down at the floor. With physical rotation method, such users physically rotated themselves only until they caught a glimpse of a target, and then headed for the target, often without even checking for arrows leading to the target. This caused problems in situations where a target (which is not the next desired target on the path) is visible, such as immediately after passing target #2.

### **9.2.6 Pointing Error**

At the end of the walkthrough, subjects performed a pointing task where they attempted to indicate (by pointing) the location of the doorway through which they entered the virtual building. An error was recorded in the range  $-180^{\circ}$  to  $180^{\circ}$ . Figure 9-14 shows the pointing responses for all subjects. In part a, a line connected to the very top of the circle would represent an error of  $0^{\circ}$ , indicating that the subject was able to correctly indicate the location of the doorway. A line to the very bottom of the circle would represent an error of  $180^{\circ}$ , indicating that the subject pointed directly away from the location of the doorway. Lines to the right edge of the circle represent positive errors (pointing too far to the right of the doorway) while lines to the left edge indicate negative pointing errors (pointing too far to the left of the doorway). From Figure 9-14 part a, it may appear that the errors are spread fairly evenly over the range  $-180^{\circ}$  to  $180^{\circ}$ , however part b shows that most of the responses were actually in the upper left quadrant: the range  $-90^{\circ}$  to  $0^{\circ}$ .

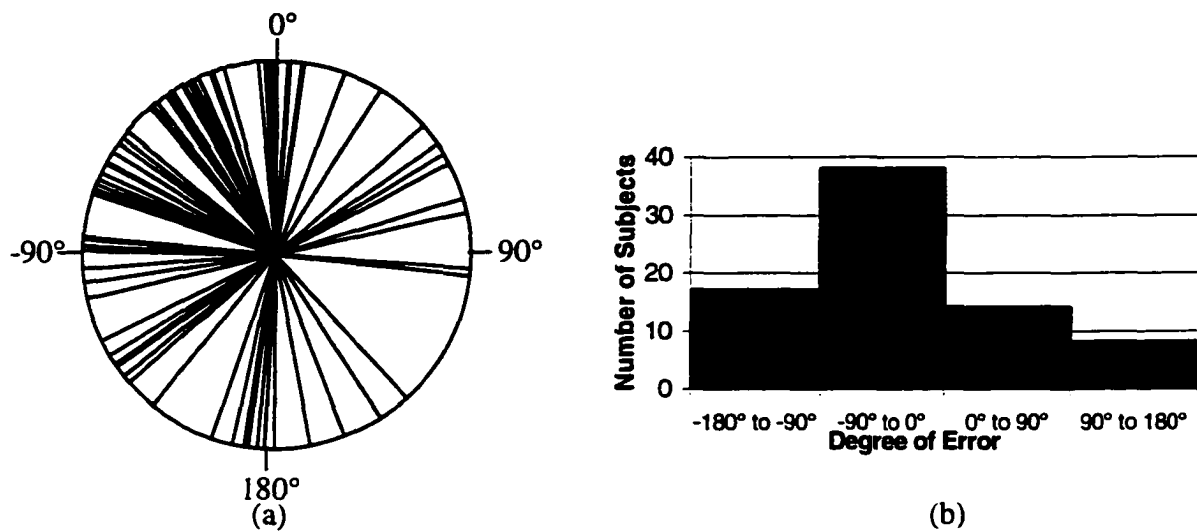


Figure 9-14. Pointing errors for all 77 subjects, (a) radially (b) by quadrant.

The average error on the pointing task at the end of the walkthrough is  $-32.39^\circ$ , with a standard deviation of 83.72. Table 9-13 shows the average pointing error for each of the experimental conditions.

Table 9-13. Average pointing errors and standard deviations. Averages are in the top row of each cell, with standard deviations on the second row.

|                                           | C2                 | C6                 | HMD                | Bench            | Per rotation method |
|-------------------------------------------|--------------------|--------------------|--------------------|------------------|---------------------|
| <b>Virtual Translate, Virtual Rotate</b>  | -12.15°<br>(87.71) | -48.34°<br>(76.41) | -70.06°<br>(45.26) | 1.30°<br>(93.82) | -32.31°<br>(80.63)  |
| <b>Virtual Translate, Physical Rotate</b> | -20.70°<br>(96.43) | -10.43°<br>(78.41) | -66.34°<br>(89.19) | NA               | -32.49°<br>(86.80)  |
| <b>Per device</b>                         | -16.43°<br>(90.06) | -29.38°<br>(78.00) | -68.20°<br>(69.04) | 1.30°<br>(93.82) | -32.39°<br>(83.72)  |

Table 9-13 shows some interesting features in the data. First, the HMD appears to have a much large pointing error average than the other display devices. A one-way ANOVA does show a significant ( $p < 0.082$ ) difference between display devices. The ANOVA table is

shown in Table 9-14. Figure 9-15 shows pointing errors for each device, in a radial format.

Figure 9-16 shows this information as histograms for each quadrant.

Table 9-14. ANOVA Table for pointing error by display devices.

| Source         | DF | SS         | MS        | F     | PROB>F |
|----------------|----|------------|-----------|-------|--------|
| Display Device | 3  | 46501.883  | 15500.628 | 2.327 | 0.082  |
| Error          | 73 | 486214.636 | 6660.474  |       |        |
| Total          | 76 | 532716.519 | 7009.428  |       |        |

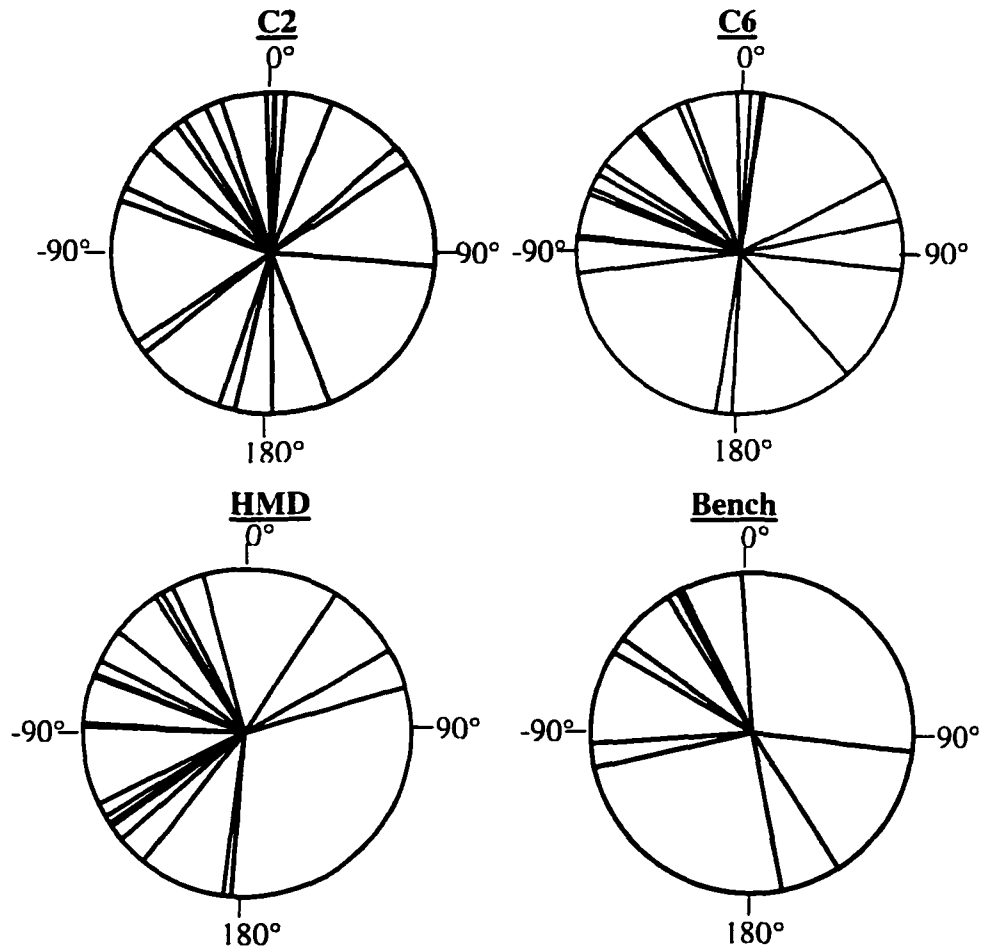


Figure 9-15. Pointing errors for each display device.

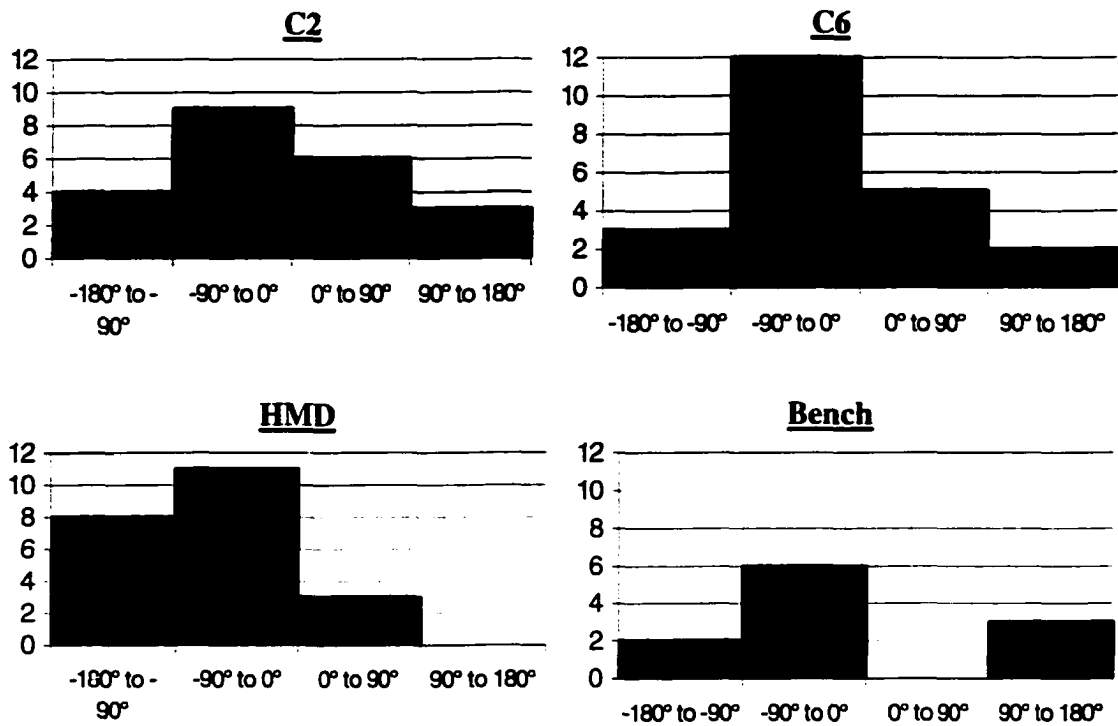


Figure 9-16. Pointing errors for each display device.

Also, the average pointing error for the bench is quite small, which could lead to the belief that subjects performed very well on the pointing task when using the bench. However, a closer look reveals a very large standard deviation for this device. Table 9-15 shows the averages of the absolute values of the pointing errors for each condition. From this table, we see that the average for the bench is now 73.90°. Using Figures 9-15 and 9-16, we can see that many (8) users of the bench actually pointed in the range -90° to 0°. But the 3 other subjects committed pointing errors that balanced well against the range -90° to 0°, resulting in a very small average error but large standard deviation.

Similarly, although the C2 shows a smaller mean pointing error than the C6, we note that the C6 has a smaller standard deviation than the C2. From Figures 9-15 and 9-16 we can see that subjects were more consistent in the C6, with most subjects pointing in the range

Table 9-15. Absolute average pointing errors and standard deviations. Averages are in the top row of each cell, with standard deviations on the second row.

|                                           | <b>C2</b>         | <b>C6</b>         | <b>HMD</b>        | <b>Bench</b>      | <b>Per rotation method</b> |
|-------------------------------------------|-------------------|-------------------|-------------------|-------------------|----------------------------|
| <b>Virtual Translate, Virtual Rotate</b>  | 65.07°<br>(56.54) | 80.23°<br>(36.45) | 70.06°<br>(45.26) | 73.90°<br>(52.88) | 72.32°<br>(18.95)          |
| <b>Virtual Translate, Physical Rotate</b> | 71.03°<br>(64.96) | 50.98°<br>(58.38) | 30.79°<br>(96.81) | NA                | 72.94°<br>(61.10)          |
| <b>Per device</b>                         | 68.05°<br>(59.51) | 65.61°<br>(49.79) | 83.44°<br>(48.44) | 73.90°<br>(52.88) | 72.59°<br>(52.29)          |

–90° to 0°. In the C2, errors were spread more evenly over the entire range –180° to 180°, with slightly more errors in the range –90° to 0° than other areas.

Although the one-way ANOVA did not show a significant difference between rotation methods, from Tables 9-14 and 9-15 we notice that there appear to be some differences between rotation conditions within each display device. Figures 9-17 and 9-18 show the results of the pointing task for each experimental condition. For the C6, we notice that most users actually gave responses that are fairly grouped within each rotation method. For virtual rotation, 8 subjects gave responses in the range –98° to –38°. For physical rotation, 8 subjects gave responses in the range –61° to 10°. The average error for these 8 subjects is –66.92° and –17.29°, with standard deviations of 21.34 and 28.21, for virtual and physical rotation, respectively. This may indicate that in the C6, physical rotation allows for improved homing abilities over virtual rotation. Also note that these deviations are much smaller than for the devices overall.

In the C2 virtual rotation, there are also 8 subjects with responses fairly closely grouped, in the range –49° to 57° with an average of –0.915° and standard deviation of 40.87. For the C2 with physical rotation, the best grouping of 8 subjects results in an average of

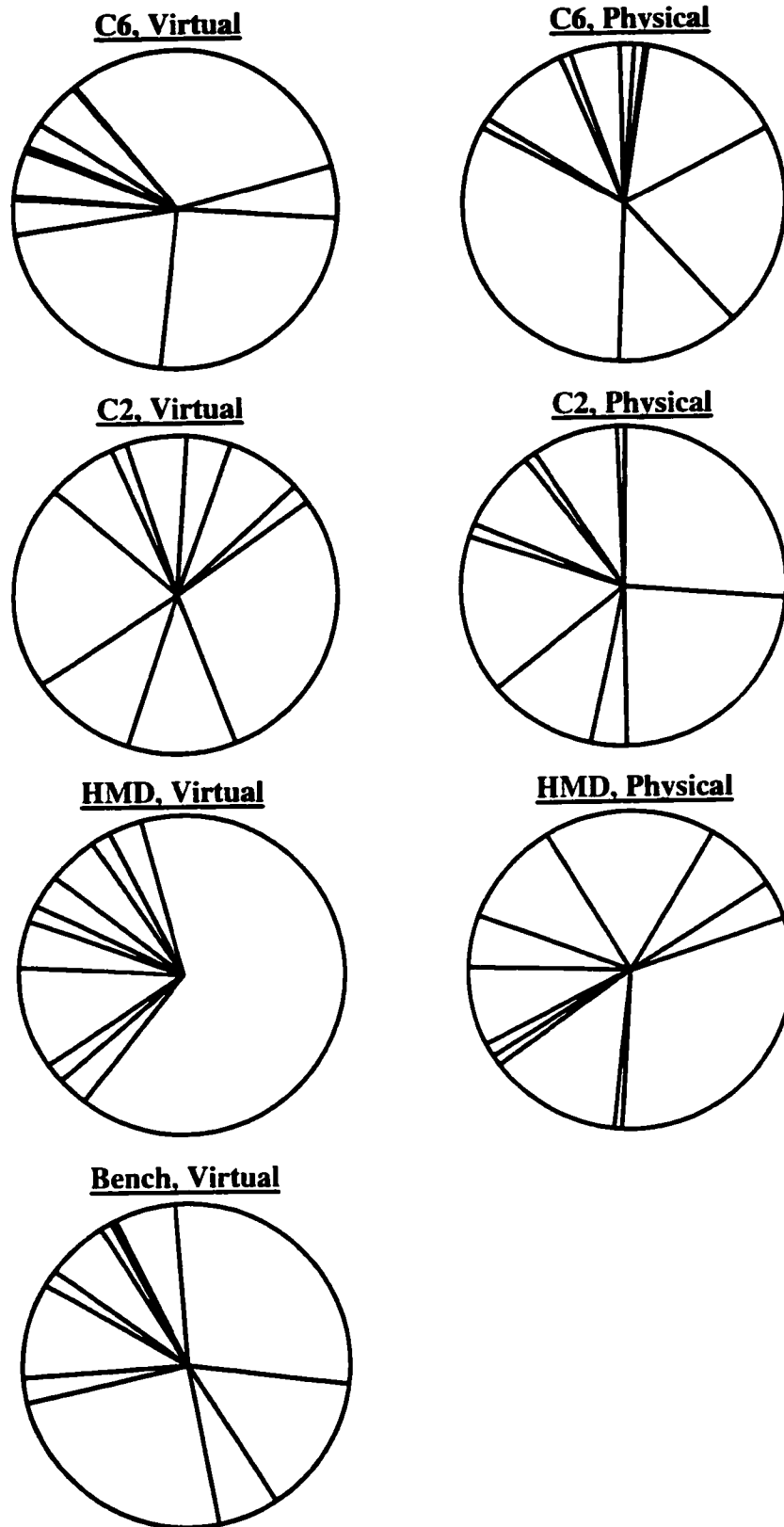


Figure 9-17. Pointing errors for each experimental condition.

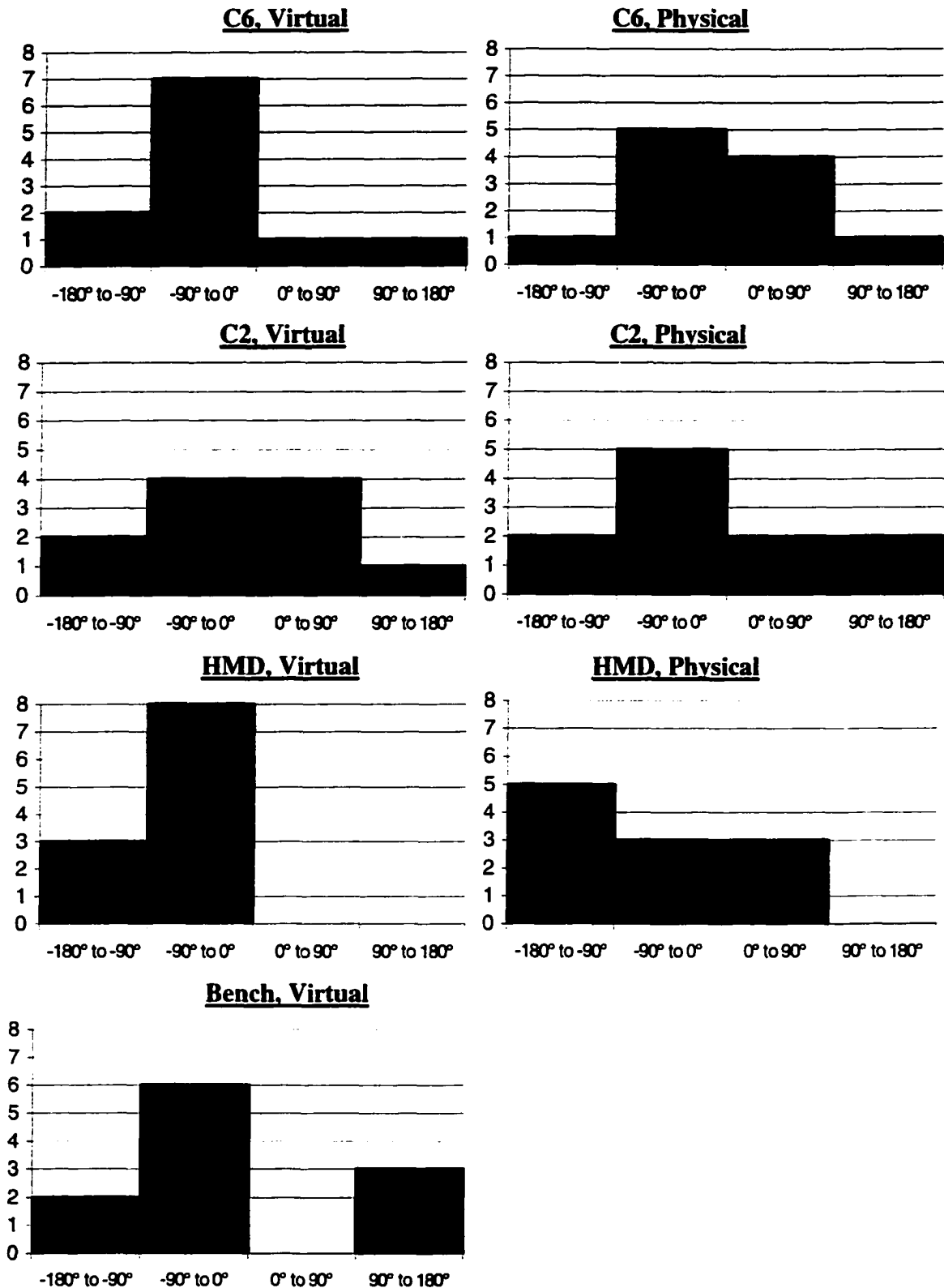


Figure 9-18. Pointing errors for each experimental condition. Degree of error is on the horizontal axis, with number of subjects on the vertical axis.

-41.79° and standard deviation of 45.34. This also supports our belief that virtual rotation is preferable to physical rotation when using the C2. Although these standard deviations are smaller than for the device as a whole, they are still larger than those computed above from the reduced set of subjects in the C6.

### 9.2.7 Floorplan Identification

After completing the walkthrough, each subject was asked to identify which one of four floorplan choices represented the building they saw. The available floorplans were previously shown in Chapter 8 (Figures 8-5 through 8-8). The correct choice is floorplan B. Figure 9-19 and Table 9-16 show the test subjects' responses to this question for each experimental condition. The group performed rather poorly on this task, with most subjects answering incorrectly. Only in one device (C2) did subjects answer correctly more than 50% of the time.

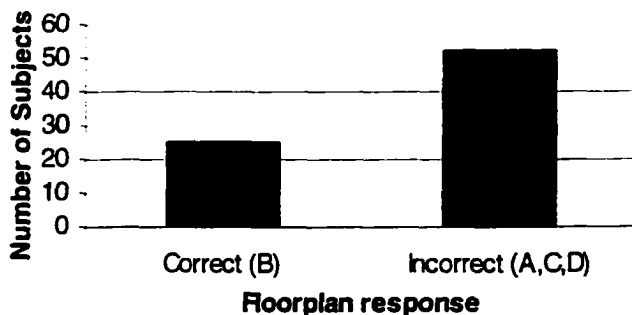


Figure 9-19. Subjects' responses to the floorplan question.

From Table 9-16, we notice that the C6 users performed especially poorly on this task. Figure 9-20 shows a mosaic plot of the responses. For each device, the width of the column in the plot indicates the number of responses, while the height indicates the

Table 9-16. Responses to the floorplan question. Number of correct responses is shown first, with number of incorrect responses below

|                                           | C2       | C6      | HMD     | Bench  | Per rotation method |
|-------------------------------------------|----------|---------|---------|--------|---------------------|
| <b>Virtual Translate, Virtual Rotate</b>  | 6<br>5   | 0<br>11 | 3<br>8  | 5<br>6 | 14<br>30            |
| <b>Virtual Translate, Physical Rotate</b> | 6<br>5   | 1<br>10 | 4<br>7  | NA     | 11<br>22            |
| <b>Per device</b>                         | 12<br>10 | 1<br>21 | 7<br>15 | 5<br>6 | 25<br>52            |

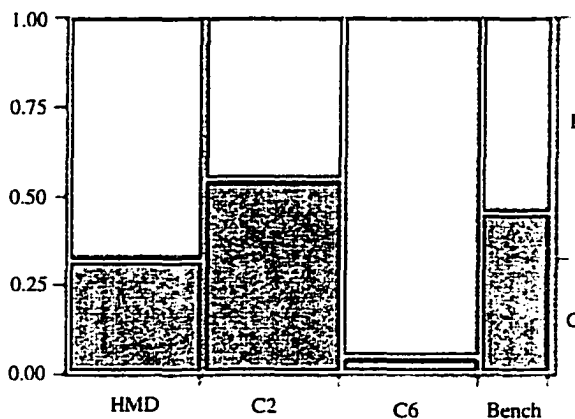


Figure 9-20. Mosaic plot of floorplan responses by display device.

percentage of responses in each category, correct or incorrect. A percentage scale is shown along the left edge of the plot. Correct responses are shown in the bottom portion of each column, by the darker grey area. The lighter grey at the top of the column indicates incorrect responses. A ChiSquare test shows the results to be significant ( $p < 0.0012$ ) by display device. The contingency table is shown in Table 9-17. Tests for significance between incorrect response choices A, C, and D indicate that incorrect responses are spread relatively evenly.

Table 9-17. Contingency table for floorplan choice, by display device.

|              | <b>Correct</b> | <b>Incorrect</b> |
|--------------|----------------|------------------|
| <b>HMD</b>   | 7<br>(9.09)    | 15<br>(19.48)    |
| <b>C2</b>    | 12<br>(15.58)  | 10<br>(12.99)    |
| <b>C6</b>    | 1<br>(1.30)    | 21<br>(27.27)    |
| <b>Bench</b> | 5<br>(6.49)    | 6<br>(7.79)      |
|              | 25<br>(32.47)  | 52<br>(67.53)    |

### 9.3 Effect of Demographics on Response Variables

As mentioned in earlier chapters, subject's backgrounds may affect their performance on tasks in virtual environments. Although we attempted to balance the groups for some background factors (gender and spatial abilities) it is possible that subjects' backgrounds may still have had some effect on our results. This section explores that possibility.

#### 9.3.1 Effect of Gender

Table 9-18 summarizes several response variables, by gender. Averages are shown on the first line of each cell, with standard deviations in parentheses below.

For presence scores, number of missed targets, and pointing error, we can see that the averages and standard deviations between men and women are quite similar. ANOVAs show no significant differences in these areas.

Because males have previously been shown to perform better than females on virtual environment tasks, we might expect males to complete the walkthrough more quickly than the females. However, the men performed the walkthrough only about 3 seconds faster on

Table 9-18. Response variables by gender. \*As discussed in previous sections, one subject had an extremely large completion time and number of collisions. That subject has been left out of the analysis of these two responses.

|               | <b>Presence<br/>Questionnaire</b> | <b>Completion<br/>Time</b> | <b>Collisions</b> | <b>Missed<br/>Targets</b> | <b>Pointing<br/>Error</b> |
|---------------|-----------------------------------|----------------------------|-------------------|---------------------------|---------------------------|
| <b>Female</b> | 98.06<br>(13.45)                  | 301.20<br>(106.89)         | 14.00<br>(10.49)  | 0.37<br>(0.55)            | -36.68<br>(80.87)         |
| <b>Male</b>   | 100.90<br>(13.90)                 | 298.01*<br>(144.90)        | 7.24*<br>(6.99)   | 0.40<br>(0.63)            | -28.81<br>(86.84)         |

average. A one-way ANOVA shows no significant differences. Of the 10 fastest completion times, 6 were by men (60%) and 4 were by women (40%). This is fairly representative of the group as a whole: 55% of all subjects were male, and 45% were female.

Men appear to have slightly outperformed women on the floorplan question. Nine women (25.71% of the women) correctly choose floorplan B, while 16 men (38.10% of the men) choose floorplan B. This means that of the 25 subjects correctly choosing floorplan B, only 36% were female and 64% were male. However, a ChiSquare analysis shows that the difference is not significant.

From Table 9-18, we see that on average, men committed far fewer collisions than women. An ANOVA shows a significant ( $p < 0.001$ ) difference between the genders. Table 9-19 shows the ANOVA table. We are unable to explain what may have caused this difference, particularly since performance between genders is so close for the other response variables.

Table 9-19. ANOVA Table for collisions by gender.

| <b>Source</b> | <b>DF</b> | <b>SS</b> | <b>MS</b> | <b>F</b> | <b>PROB&gt;F</b> |
|---------------|-----------|-----------|-----------|----------|------------------|
| <b>Gender</b> | 1         | 861.847   | 861.847   | 11.190   | 0.001            |
| <b>Error</b>  | 74        | 5699.561  | 77.021    |          |                  |
| <b>Total</b>  | 75        | 6561.408  | 87.485    |          |                  |

### 9.3.2 Effect of Age

Figure 9-21 shows plots of the effect of age on several of the response variables.

Table 9-20 shows the correlation between age and each of these variables. It appears from this information that age had only a small effect on subjects' completion time, and little effect on subjects' performances.

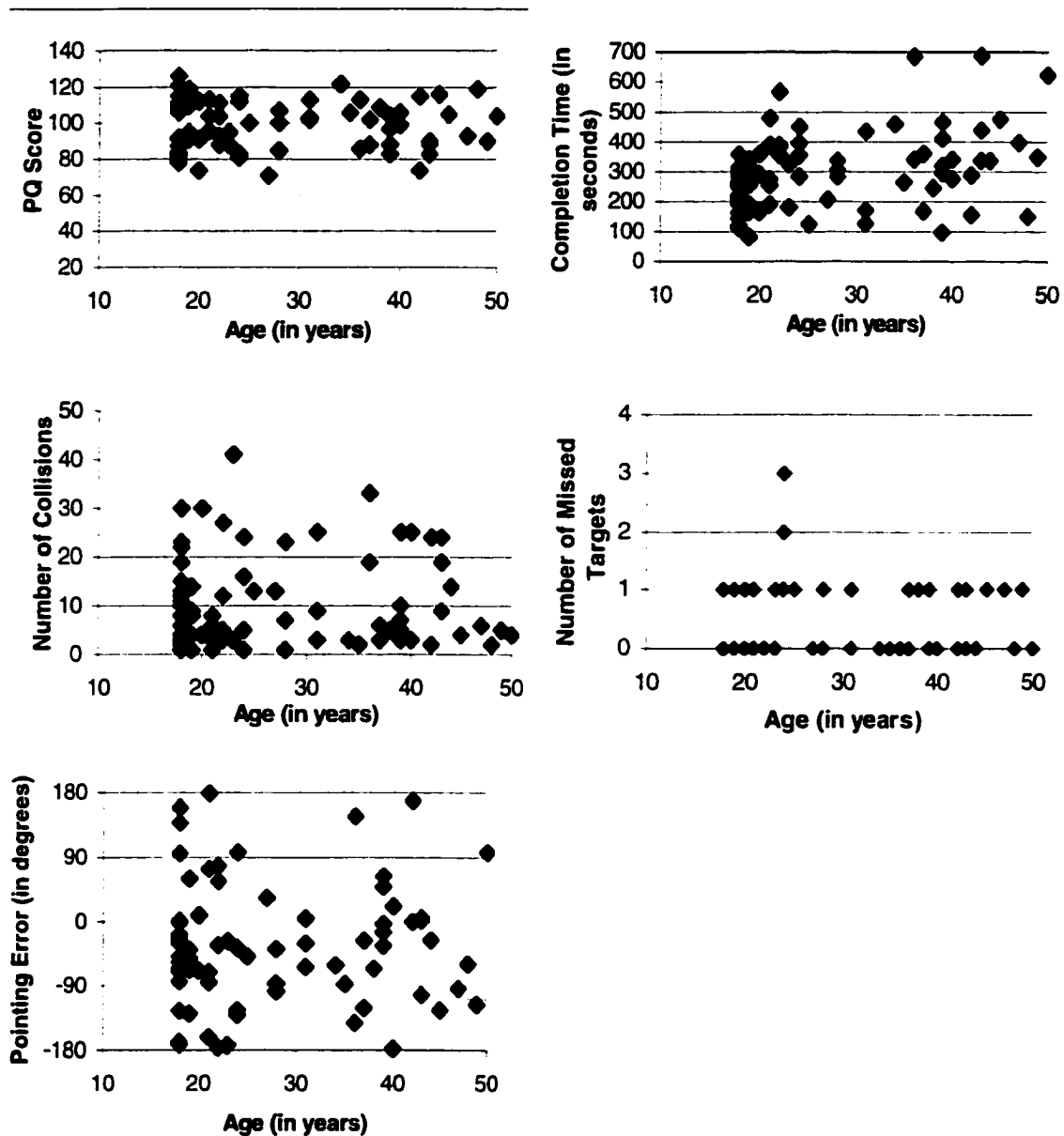


Figure 9-21. Plots relating subject age to response variables.

Table 9-20. Correlation between age and response variables. \*As discussed in previous sections, one subject had an extremely large completion time and number of collisions. That subject has been left out of the analysis of these two responses.

|                            | Presence<br>Questionnaire | Completion<br>Time | Collisions | Missed<br>Targets | Pointing<br>Error |
|----------------------------|---------------------------|--------------------|------------|-------------------|-------------------|
| Correlation<br>Coefficient | -0.08                     | 0.36*              | 0.01*      | 0.04              | 0.02              |

Subject age also does not appear to affect performance on the floorplan question.

Figure 9-22 shows a mosaic plot (similar to Figure 9-20) of responses to the floorplan question. A Chi-Square analysis shows no significant differences.

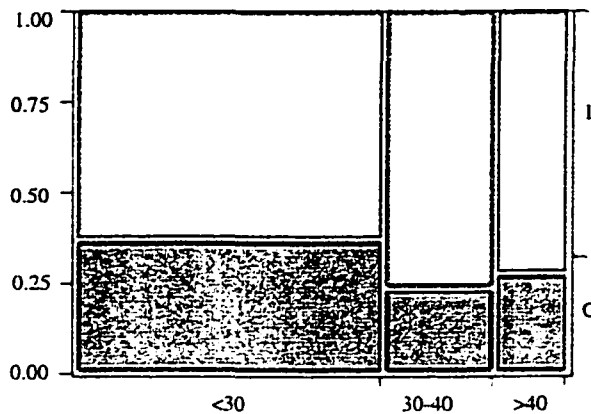


Figure 9-22. Mosaic plot of subject responses to floorplan question by age range.

### 9.3.3 Effect of Immersive Tendencies

Figure 9-22 shows plots of the effect of scores on the immersive tendencies questionnaire (ITQ) on several of the response variables. Table 9-21 shows the correlation between ITQ scores and each of these variables. It appears from this information that ITQ scores little effect on subjects' performances.

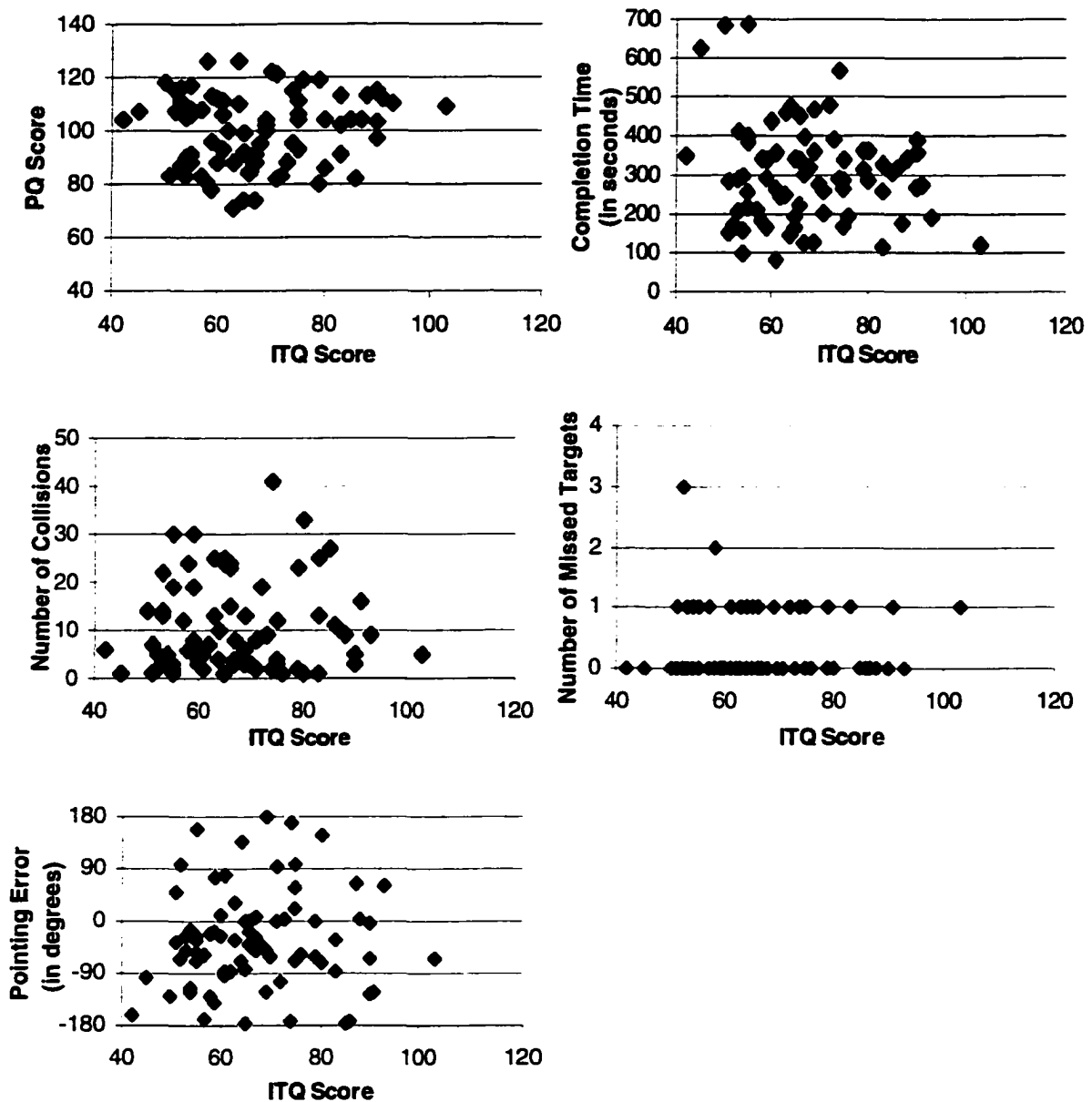


Figure 9-22. Plots relating ITQ scores to response variables.

Table 9-21. Correlation between ITQ scores and response variables. \*As discussed in previous sections, one subject had an extremely large completion time and number of collisions. That subject has been left out of the analysis of these two responses.

|                            | Presence<br>Questionnaire | Completion<br>Time | Collisions | Missed<br>Targets | Pointing<br>Error |
|----------------------------|---------------------------|--------------------|------------|-------------------|-------------------|
| Correlation<br>Coefficient | 0.11                      | -0.14*             | 0.04*      | -0.03             | 0.05              |

ITQ scores also had little effect on subjects' ability to choose the correct floorplan. The average ITQ score of subjects correctly picking floorplan B is 67.48, with a standard deviation of 12.39. The average and standard deviation on the ITQ for subjects choosing incorrect floorplans are 67.27 and 13.24, respectively.

#### 9.3.4 Effect of Spatial Abilities

It appears that in this case, spatial abilities had little effect on users' performances.

Table 9-22 shows the correlation between spatial abilities ranking (from 0 to 77) and several of the response variables. Figure 9-24 shows plots of this information.

Table 9-22. Correlation between spatial abilities ranking and response variables. \*As discussed in previous sections, one subject had an extremely large completion time and number of collisions. That subject has been left out of the analysis of these two responses.

|                                    | <b>Presence<br/>Questionnaire</b> | <b>Completion<br/>Time</b> | <b>Collisions</b> | <b>Missed<br/>Targets</b> | <b>Pointing<br/>Error</b> |
|------------------------------------|-----------------------------------|----------------------------|-------------------|---------------------------|---------------------------|
| <b>Correlation<br/>Coefficient</b> | -0.09                             | -0.03*                     | -0.10*            | -0.10                     | -0.08                     |

It would also seem sensible to believe that a subject's spatial abilities would affect his ability to correctly choose the floorplan of the building he walked through. However, this does not appear to be the case for this experiment. The average ranking on the spatial abilities tests (out of 77 subjects) is 38.96 for subjects who correctly choose floorplan B, with a standard deviation of 22.64. The average ranking is 39.02 for subjects who incorrectly choose floorplan A, C, or D, with a standard deviation of 22.46. Additionally, the subjects ranked in the top 10% on the spatial abilities tests (8 subjects) correctly choose floorplan B

only 25% of the time, worse than the group as a whole! Subjects ranked in the top third on the spatial abilities tests (25 subjects) answered correctly 36% of the time, only slightly better than the group as a whole. These very small differences indicate that subjects' spatial abilities were likely not a large factor in their ability to correctly identify the floorplan of the virtual building.

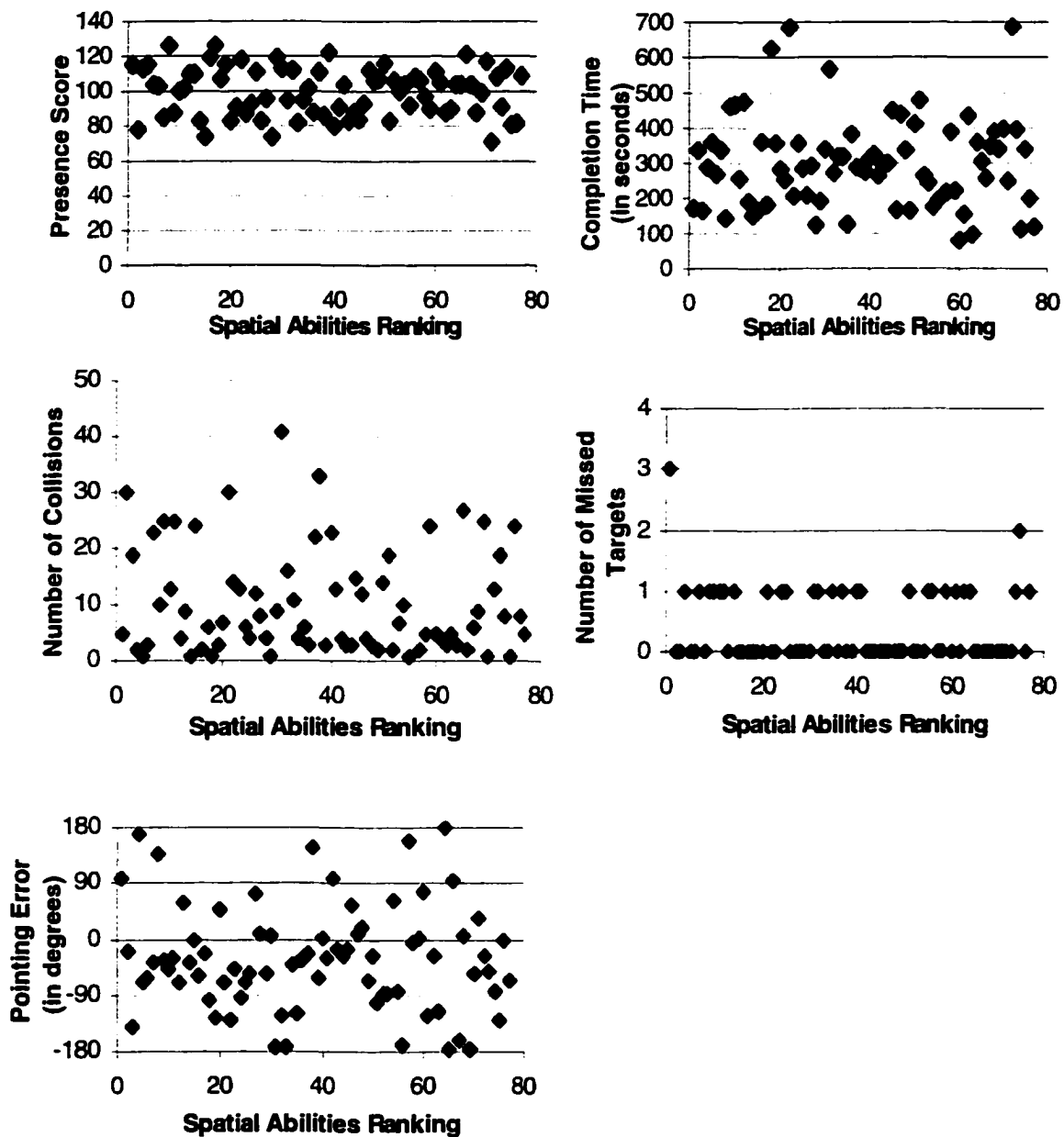


Figure 9-24. Plots relating ranking on spatial abilities tests to response variables.

#### **9.4 Effect of Observed Factors**

As subjects performed the walkthrough, test administrators made notes indicating subjects' performance, such as "traveling too quickly, unable to control travel." For 18 of the subjects, administrators noted that the subjects were exhibiting more attention to studying the building than average. These subjects followed the instructions most precisely, studying the building in detail. They often took extra measures, such as peering down hallways or into rooms that they did not enter, or walking up to windows to look out. The ID numbers for these subjects are: 5, 9, 15, 26, 33, 60, 62, 68, 73, 101, 106, 111, 122, 143, 155, 181, 203, and 206.

##### **9.4.1 Test Observations and Presence**

Subject scores on the presence questionnaire (PQ) are very similar regardless of how careful they were in studying the building. For careful subjects, the average PQ score is 102.32 with standard deviation of 12.73. For non-careful subjects, the average PQ score is 98.88 with standard deviation of 13.98. A one-way ANOVA indicates no significant differences.

##### **9.4.2 Test Observations and Completion Times**

Not surprisingly, subjects who carefully studied the building took a longer time on average to travel through the building, 399.39 seconds, with a standard deviation of 139.59. This is longer than for the group as a whole (299.53 seconds with standard deviation of 127.98), and for subjects not carefully studying the building (268.53 seconds with standard deviation of 107.77). A one-way ANOVA indicates this is significant ( $p < 0.0001$ ). The

ANOVA table is shown in Table 9-23. Figure 9-25 shows the completion times for subjects carefully studying the virtual building.

Table 9-23. ANOVA Table for completion times.

| Source      | DF | SS        | MS     | F       | PROB>F |
|-------------|----|-----------|--------|---------|--------|
| Careful/Not | 1  | 235214.2  | 235214 | 17.5236 | 0.0001 |
| Error       | 74 | 993280.7  | 13423  |         |        |
| Total       | 75 | 1228494.9 |        |         |        |

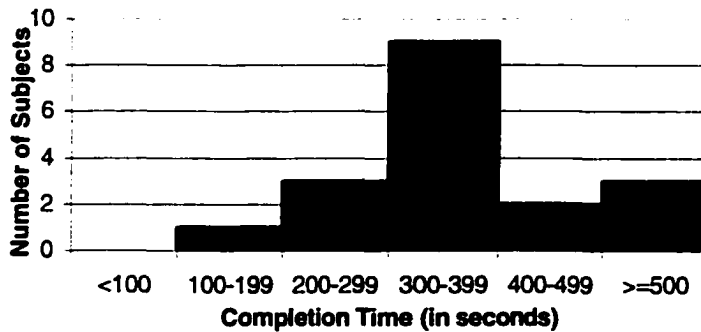


Figure 9-25. Completion times for subjects carefully studying the building.

### 9.4.3 Test Observations and Collisions

Subjects carefully studying the building tended to commit fewer collisions on average: 6.83 with standard deviation of 6.61. The group as a whole averaged 10.36 with standard deviation 9.35, and subjects not being careful averaged 11.45 with standard deviation 9.85. A one-way ANOVA indicates a significant ( $p < 0.0671$ ) difference. The ANOVA table is shown in Table 9-24. Figure 9-26 shows the collisions data for the careful subjects.

Table 9-24. ANOVA Table for collisions.

| Source      | DF | SS        | MS      | F      | PROB>F |
|-------------|----|-----------|---------|--------|--------|
| Careful/Not | 1  | 292.5631  | 292.563 | 3.4535 | 0.0671 |
| Error       | 74 | 6268.8448 | 84.714  |        |        |
| Total       | 75 | 6561.4079 |         |        |        |

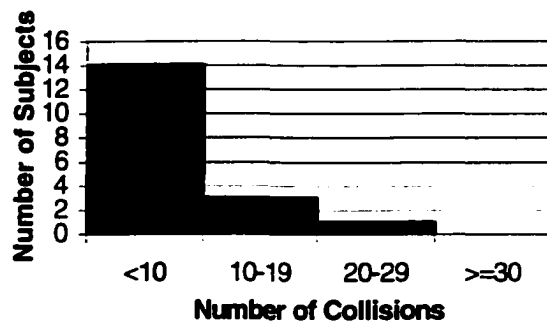


Figure 9-26. Number of collisions by careful subjects.

#### 9.4.4 Test Observations and Missed Targets

Careful subjects missed slightly fewer targets than those who did not carefully study the building. The average and standard deviation for the careful subjects are 0.33 and 0.49, respectively. This is slightly better than the group as a whole, but is not statistically significant.

#### 9.4.5 Test Observations and Pointing Error

Subjects who appeared to study the building carefully were able to perform the pointing task slightly more accurately. These 18 subjects had an average pointing error of  $-21.23^\circ$ , better than the group as a whole ( $-35.39^\circ$ ) and subjects not exhibiting careful studying behavior ( $-35.79^\circ$ ), but still having quite large standard deviation (86.48). A one-way ANOVA indicates that this difference is not significant.

#### 9.4.6 Test Observations and Floorplan Identification

Of these 18 special subjects, 10 (55.56%) correctly chose floorplan B. This is better than the response rate for the group as a whole (32.47%), and much better than for subjects not carefully studying the building (25.42%). Figure 9-25 shows a mosaic plot of this data. A ChiSquare analysis shows there to be a significant ( $p < 0.0196$ ) difference between subjects carefully studying the building and those not doing so. Thus it appears that each individual's level of concentration of studying the building may be one of the more important factors in determining whether he understands the spatial layout of a virtual building. The contingency table is shown in Table 9-25. It is important to note that test administrators noted this behavior *before* subjects completed the floorplan identification, and thus had no knowledge of subject performance on that task at the time the notes were made.

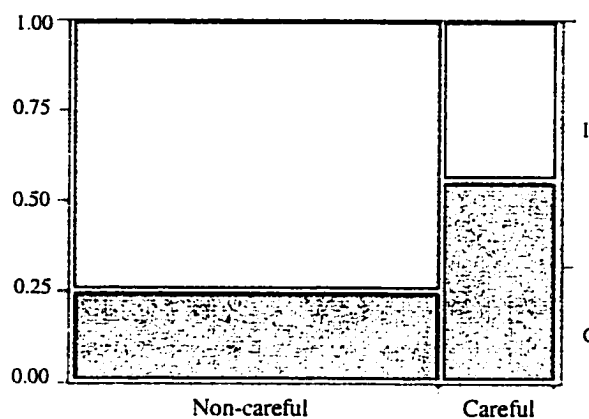


Figure 9-25 Floorplan choices of subjects studying the building carefully.

#### 9.5 Other Interactions

This section explores a few other relationships that we expected to occur between demographic variables and between response variables.

Table 9-25. Contingency table for floorplan choice.

|                    | <b>Correct</b> | <b>Incorrect</b> |
|--------------------|----------------|------------------|
| <b>Not Careful</b> | 15<br>(19.48)  | 44<br>(57.14)    |
| <b>Careful</b>     | 10<br>(12.99)  | 8<br>(10.39)     |
|                    | 25<br>(32.47)  | 52<br>(67.53)    |

### 9.5.1 Gender and Spatial Abilities

Table 9-26 shows average scores and standard deviations (in parentheses), by gender, for the spatial abilities tests. Because we believed that men would outperform women on the spatial abilities tasks, we balanced the experimental conditions for gender as well. However, it appears that women performed quite well on the tests, actually outperforming men on two of the tests. Only on one of the tests, SS2, did men perform significantly ( $p < 0.008$ ) better than women. The ANOVA table is shown in Table 9-27. Additionally, ANOVA show no significant differences between genders in overall ranking on the spatial abilities tests.

Table 9-26. Results from each of the spatial abilities tests. The highest possible score is shown in parentheses in the heading for each column.

|                | <b>S1: Card Rotations Test (160)</b> | <b>S2: Cube Comparisons Test (42)</b> | <b>SS1: Maze Tracing Speed Test (48)</b> | <b>SS2: Choosing A Path (32)</b> | <b>SS3: Map Planning Test (40)</b> |
|----------------|--------------------------------------|---------------------------------------|------------------------------------------|----------------------------------|------------------------------------|
| <b>Females</b> | 109.69<br>(29.16)                    | 22.57<br>(9.65)                       | 28.77<br>(5.12)                          | 6.94<br>(8.35)                   | 26.86<br>(8.25)                    |
| <b>Males</b>   | 113.57<br>(28.65)                    | 24.09<br>(9.94)                       | 27.19<br>(8.43)                          | 12.43<br>(9.12)                  | 26.55<br>(8.29)                    |

Table 9-27. ANOVA table for test SS2, by gender.

| Source | DF | SS       | MS      | F     | PROB>F |
|--------|----|----------|---------|-------|--------|
| Gender | 1  | 574.504  | 574.504 | 7.462 | 0.008  |
| Error  | 75 | 5774.171 | 76.989  |       |        |
| Total  | 76 | 6348.675 | 83.535  |       |        |

### 9.5.2 Floorplan Identification and Pointing Error

We would expect that identifying the virtual building floorplan and indicating the direction of the doorway where subjects entered the building would be in some way related tasks. It would seem that subjects who performed well on one task would do well on the other. This does not appear to be the case. Table 9-28 shows performance on the pointing task based on subjects' performance on the floorplan question. Although subjects correctly picking floorplan B had a lower standard deviation in pointing responses, they had a larger error overall than subjects picking an incorrect floorplan. A one-way ANOVA indicates no significant differences in performance. Figure 9-26 shows the pointing errors of subjects correctly choosing floorplan B.

Table 9-28. Pointing errors.

|                    | Subjects correctly choosing floorplan B | Subjects incorrectly choosing floorplans A, C, or D | All Subjects |
|--------------------|-----------------------------------------|-----------------------------------------------------|--------------|
| Average            | -42.91°                                 | -27.33°                                             | -32.39°      |
| Standard Deviation | 68.38                                   | 90.36                                               | 83.72        |

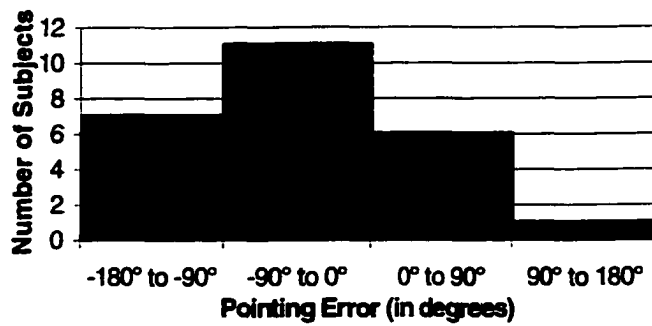


Figure 9-26. Pointing errors of subjects answering the floorplan question correctly.

### 9.5.3 Floorplan Identification and Completion Times

When considering how completion times may affect users' ability to correctly identify a floorplan of the virtual building, there are two possibilities that both appear logical:

- 1) Subjects with longer completion times will be more likely to correctly choose the correct floorplan. Possible reasoning could be that subjects intentionally took more time in an effort to better study the building, as shown in Section 9.4.6.
- 2) Subjects with shorter completion times will be more likely to correctly choose the correct floorplan. Possible reasoning could be that subjects who perform the walkthrough more quickly do so because they are more comfortable in the virtual world and/or can more effectively control the locomotion while still studying the building.

We do not consider the possibility that subjects with faster completion times have better spatial abilities and therefore are more likely to choose the correct floorplan, because we have previously shown that spatial abilities did not affect floorplan choice.

The average time taken by the 25 subjects who correctly picked floorplan B is 340.32 seconds, while the average time taken by the other subjects who chose floorplans A, C, or D is only 294.27 seconds. However, a one-way ANOVA indicates no significant difference between these groups. Thus it appears that the amount of time taken to perform the walkthrough does not significantly affect a subject's ability to correctly identify the layout of the building. Note that in Section 9.4.6 we showed that subjects carefully studying the building took a longer time to complete the walkthrough and also answered correctly more often on the floorplan choice. Combined with the information here, it seems that merely spending a longer time in the building is not sufficient to increase a user's understanding of the building – the user must be actively studying and exploring the building during that time.

#### **9.5.4 Video Game Effect**

Some of our previous work has shown that subjects with increased experience on computers and video games leads to increased performance in virtual environments. Question 12 on the Immersive Tendencies Questionnaire (ITQ) asks subjects how often they play video or arcade games. We believed subjects with higher scores (5, 6, or 7) on this question may have performed differently in our experiments than other subjects.

These 19 subjects did have a somewhat higher average ITQ score (76.26 with standard deviation of 14.07) than the other subjects (64.41 with standard deviation 11.12). A one-way ANOVA shows this difference to be significant ( $p < 0.003$ ). The ANOVA table is shown in Table 9-29. However, the PQ scores for this group were nearly identical to those for the non-game players, and were not significantly different.

Table 9-29. ANOVA table for ITQ score, by gaming experience.

| Source    | DF | SS        | MS       | F      | PROB>F |
|-----------|----|-----------|----------|--------|--------|
| Game Exp. | 1  | 2009.468  | 2009.468 | 14.202 | 0.0003 |
| Error     | 75 | 10611.753 | 141.490  |        |        |
| Total     | 76 | 12621.221 | 166.069  |        |        |

These subjects also completed the walkthrough task slightly faster than the group as a whole, with an average time of 264.37 seconds, and standard deviation of 133.73. A one-way ANOVA shows this difference to not be significant, likely because of the high deviation. As usual, subject #46 was left out of the analysis of this variable, and the collisions variable. Four subjects answered question 12 on the ITQ with the highest score (7). These 4 “game experts” performed the walkthrough extremely quickly, with an average time of only 172 seconds and a standard deviation of only 39.34. This difference is significant ( $p < 0.04$ ). The ANOVA table is shown in Table 9-30.

Table 9-30. ANOVA table for completion time, by gaming experts

| Source    | DF | SS          | MS        | F     | PROB>F |
|-----------|----|-------------|-----------|-------|--------|
| Game Exp. | 1  | 68665.836   | 68665.836 | 4.381 | 0.040  |
| Error     | 74 | 1159829.111 | 15673.366 |       |        |
| Total     | 75 | 1228494.947 | 16379.933 |       |        |

On the pointing task, the 19 subjects with more gaming experience performed somewhat better than the group as a whole, with an average error of  $-18.47$  degrees. However, the standard deviation was quite high, 93.29. A one-way ANOVA does not show any significance. The 4 game experts did not perform the pointing task any better than the rest of the group.

The 19 subjects also committed fewer collisions than the group as a whole, with an average of 7.05 and standard deviation of 6.37. This difference is significant ( $p < 0.075$ ). The ANOVA table is shown in Table 9-31. The 4 “game experts” committed very few collisions, with an average of 3 and standard deviation of 4. In fact, 3 of these experts had only 1 collision! The other subject had 9 collisions. This may be at least partly due to the subject using physical rotation in the C2.

Table 9-31. ANOVA table for completion time, by gaming experience.

| Source    | DF | SS       | MS      | F     | PROB>F |
|-----------|----|----------|---------|-------|--------|
| Game Exp. | 1  | 276.320  | 276.320 | 3.253 | 0.075  |
| Error     | 74 | 6285.088 | 84.934  |       |        |
| Total     | 75 | 6561.408 | 87.485  |       |        |

The collision information, combined with the completion time information, indicates that video game players are generally able to travel not only more quickly, but also with better control. We might expect that these subjects were actually racing through the walkthrough, without paying attention to the surroundings. Although the 19 subjects had a correct response rate of 36.84% on the floorplan question, slightly better than the group as a whole, a Chi-Square test does not show a significant difference. Of the 4 “game experts,” 3 correctly chose floorplan B. A Chi-Square test shows this to be significant ( $p < 0.0728$ ). Figure 9-27 and Table 9-32 show this information.

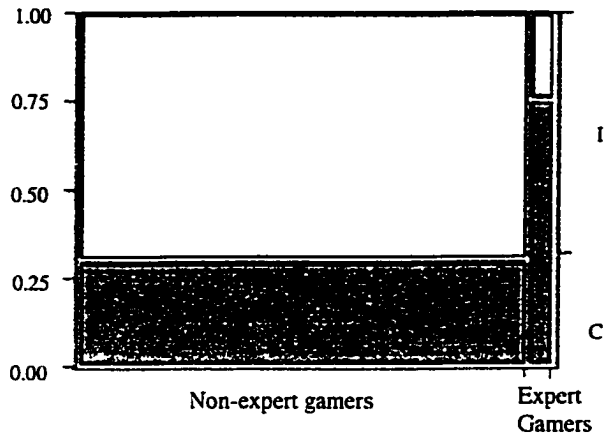


Figure 9-27. Mosaic plot of floorplan choices by gaming experience.

Table 9-32. Contingency table for floorplan choice by gaming experts.

|             | Correct       | Incorrect     |
|-------------|---------------|---------------|
| Not Careful | 15<br>(19.48) | 44<br>(57.14) |
| Careful     | 10<br>(12.99) | 8<br>(10.39)  |
|             | 25<br>(32.47) | 52<br>(67.53) |

These results support our opinion that video game players tend to outperform other subjects on tasks in a virtual environment. It is still unclear whether the video game experience “teaches” behaviors that are effective in virtual environments, or whether people who play video games tend to do so because they already possess skills and abilities that are helpful in both video game playing and in virtual environments.

## 9.6 Questionnaire Responses

This section covers user responses on the two post-questionnaires subjects filled out: the General Experience Questionnaire and the Locomotion Questionnaire. Copies of these

questionnaires can be found in Appendix E and Appendix F. This section summarizes responses that are of interest. Full subject responses can be found in Appendix M and Appendix N.

#### **9.6.1 General Experience Questionnaire**

Participants were asked whether they enjoyed their VR experience. Of the 77 subjects, 74 responded positively, with answers such as “yes”, “very much”, and “it was fun!” Two other subjects responded that they had mixed feelings – finding the experience new and exciting, but feeling somewhat motion sick. The other subject responded that the experience was interesting, but somewhat frustrating.

Many explanations were given as to why subjects enjoyed the experience. About a dozen subjects simply stated the experience was fun or enjoyable. Another 14 responded that the experience was interesting, and 13 more said it was enjoyable because it was something new. Seventeen found the environment to be realistic, or at least more realistic than they had anticipated. Many subjects used terms such as “amazing” or “surprising.” The few negative comments were focused mainly on problems with the control or other equipment. One subject felt the experience was not exciting enough, and three others thought it was too short.

The second question concerned negative effects of the experience, such as cybersickness. Recall from Chapter 8 that only 4 subjects experienced cybersickness severe enough for them to drop out of the experience. However, a surprising number of subjects reported experiencing at least some symptoms. Disorientation was reported most often, by 21 subjects. Eighteen subjects reported feeling dizzy, and 15 felt motion sickness. Twelve subjects reported feeling nausea, though this was often reported as being mild, or only

occurring at certain times such as when turning. Other symptoms reported include eye strain, headache, wooziness, and a feeling of warmth. Although some subjects did report multiple symptoms, the majority of subjects did report at least one symptom of cybersickness. Only 21 subjects reported no negative effects.

Surprisingly, no one display device appears to have caused more reports of cybersickness than the other devices. Approximately 70% of the subjects reported symptoms of cybersickness, regardless of display device used. Not surprisingly, virtual rotation tended to induce motion sickness slightly more often than physical rotation. Only 22 subjects experiencing physical rotation in the C2, C6, or HMD reported feelings of cybersickness. However, 28 subjects experiencing virtual rotation in the C2, C6, or HMD felt sick. An additional 8 subjects using virtual rotation on the workbench experienced cybersickness.

The third question asked subjects what they felt would improve the VR experience. The most requested feature (16 subjects) was improvements such as better colors, more textures, and other improvements to the visual quality in order to make things look more “real.” Almost a dozen subjects requested the addition of sound in the virtual world. An additional 12 were unhappy with the display device they were using. Seven of these subjects were C2 users. They all requested the addition of a back wall and/or a ceiling – essentially a C6 setup. All but one of these subjects used physical rotation in the C2. It is interesting to note that even though the C6 is considered our “premiere” device, user preconceptions can still affect user perceptions of a VR experience, as one C6 user requested that he would prefer a “full immersion” head mounted display. This same subject also scored 121 on the Presence Questionnaire, the 4<sup>th</sup> highest score overall, indicating that he was already quite immersed in the virtual world! Other requests included haptic feedback, wireless devices

(from C2 and HMD users), more features and interaction abilities, better fitting glasses, and a longer time in the virtual world. Several subjects also addressed problems with the controls. This issue is addressed further in the next section on the Locomotion Questionnaire.

### **9.6.2 Locomotion Questionnaire**

The first question asked subjects how easy they felt it was to learn to travel. Four choices were provided, such as “It was very easy and straightforward. I learned how to travel without difficulty.” A 5<sup>th</sup> choice “Other” was provided and asked subjects to explain their response. It appears that subjects found virtual rotation slightly easier to use. Twenty-one subjects (47.7%) chose the first option, the most positive and the example given above, compared with only 9 (27.3%) of the subjects using physical rotation. Most (60%) subjects using physical rotation chose the 2<sup>nd</sup> option, which was only slightly less positive. Surprisingly, subjects found virtual rotation easier to learn than physical rotation, regardless of display device. Overall, most subjects found travel easy to learn as only 6 subjects out of 77 chose options 3, 4, or 5, indicating they had difficulty learning to travel. The one subject (ID #106) who indicated she never became comfortable using the controls performed reasonably well, and was certainly not the poorest performer on any of the response variables. Subjects found the C6 slightly easier to use, with half the subjects choosing the first option. In the C2, C6, and workbench, all but 1 subject in each device chose one of the first 2 responses.

The second question asked subjects whether they felt the controls allowed them to effectively travel. Four choices were provided, such as “Yes, the travel controls allowed me to perform all the needed tasks.” Again subjects responded more positively to virtual

rotation, with 54.5% of the virtual rotation subjects choosing the above answer, compared with 45.5% of the physical rotation subjects. Overall, only 2 subjects did not respond with either the 1<sup>st</sup> option shown above, or the 2<sup>nd</sup> option, which was only slightly less positive. Subjects found the C6 most effective, with 77.3% of the subjects choosing the above option. The C2 and HMD were rated nearly equally in terms of effectiveness, with the bench finishing last. In both the C2 and HMD, users of virtual rotation rated it slightly higher than users of physical rotation. Both rotation methods were rated nearly equally by C6 users.

The first subjective question asked subjects whether they felt the controls for locomotion interfered with their spatial abilities. The majority (45 subjects) answered that the controls did not interfere with their abilities at all. Seventeen subjects using virtual rotation felt that the travel controls interfered with their spatial abilities, while only 11 subjects using physical rotation felt this way.

Just as 45 subjects felt the controls didn't interfere with their spatial abilities, 44 of the subjects responded that they either liked the travel controls, or felt they were "ok" or "fine". A variety of reasons were given for subjects dislike of the controls. Many (18) suggested different ways of using the wand, or different devices altogether, stating that the wand just didn't feel "realistic" to them. The buttons on the wand were also a source of some controversy, as some subjects felt the buttons were positioned poorly, were too sensitive, or were not sensitive enough. Other complaints included the wand and/or glasses being too large, too many buttons on the wand, a desire for wireless devices, and a desire for a different display device – usually one that offered more peripheral vision (from workbench, C2 and HMD users). Finally, four subjects requested the ability to travel in reverse, a situation not possible with virtual rotation. Several other subjects did not write this on their questionnaires,

but did express verbally to the administrator that they wished they could do this also.

Interestingly, 1 of the 4 subjects was using physical rotation, and thus should have had the ability to “back up.”

Subjects were next asked for suggestions to improve travel. These comments were quite similar to those for the previous question. It is interesting to note that some subjects using physical rotation (such as subject #142) made suggestions that would cause them to be using virtual rotation, while other subjects using virtual rotation (subject #143) wished for travel that used physical rotation!

When asked to rate how difficult they felt the pointing task was, six subjects felt it was “easy.” Another 20 rated it “not difficult,” “not too difficult,” or “not very difficult.” Seven subjects felt it was “pretty difficult” and 7 more felt it was “difficult.” Only 6 subjects wrote that they were completely lost or completely guessed, but several more verbally admitted this to the administrator. Of these 6, all were using virtual rotation.

The 26 subjects who did not find the pointing task particularly difficult did perform slightly better on the task, with an average error of only -8.41 degrees. However, the standard deviation was still quite high, 72.54. Of the 6 subjects ranking the test as “easy,” all but one performed quite well, with an average error of 34.54 degrees and standard deviation of 56.23. Leaving out the one subject who ranked the task as easy but who still performed poorly (subject #122) the remaining 5 subjects performed extremely well, with an average error of only 13.81 degrees and a standard deviation of 27.00. This indicates that subject self-ranking of performance on such tasks may be accurate in most cases.

Next subjects were asked if they became disoriented with respect to the physical world. Most (51) responded they did not. Nineteen responded that they were disoriented. Test

administrators noted that several subjects in the C6 expressed surprise when the rear wall opened, as subjects believed it was the “wrong” wall. Only one subject experiencing disorientation with the physical world was using the workbench. Surprisingly, six subjects in the C2 reported disorientation with the physical world, even though the ceiling and back wall were missing and subjects could have turned their heads to view the physical world. Of these 6 subjects, 5 were using virtual rotation. However, for subjects reporting disorientation with the physical world in the HMD and C6, all subjects were using physical rotation. Subjects using virtual rotation in these devices made comments such as “I was facing where I started I didn’t move my feet.” It is unclear why the same was not true of subjects using virtual rotation in the C2.

When asked for any other comments on the travel, most subjects had few comments. One subject using physical rotation in the C2 (#104) remarked, “I thought trying to move in the direction of the missing wall was very unnatural and difficult.” This matched our opinion of this travel method before conducting the experiment. However, we were quite surprised with how willing subjects were to ignore this potential problem and adapt to the constraints of the system. Some subjects initially remarked on this when first learning to travel, but quickly learned how to travel anyway and never mentioned it again, even on the questionnaires!

Finally, subjects were asked to rank their satisfaction with the travel, on a scale from 1 (low) to 5 (high). Most subjects were obviously fairly happy with whatever travel they were presented with, as the average is 4.1. The 2 rotation methods were rated fairly equally, with virtual rotation having a slight advantage overall. C6 users were most happy with travel,

with an average rating of 4.6. The C2 was next, followed by HMD and bench last. Both C2 and HMD users rated virtual rotation slightly higher than physical rotation.

## **CHAPTER 10. CONCLUSIONS**

As virtual reality becomes more commonly used in industry, it is increasingly important to design and develop effective interaction methods that can be reused for future applications, with a minimum of time and cost. Locomotion is an interaction inherent in the user-centered environment of VR, and is therefore key to most virtual worlds. Currently locomotion is still implemented far too often on a case-by-case, ad-hoc basis, with little consideration for the effects of various display and interaction devices, or the end effectiveness of the travel. Classification systems like the one defined in this dissertation can aid developers in choosing appropriate travel methods.

Previous taxonomies have focused primarily on the various sub-tasks a user must perform to achieve locomotion. We instead propose a taxonomy that incorporates display devices and interaction devices as key components to define effective locomotion techniques. Additionally, we divide travel into two sub-components: translation and rotation, and consider the various ways in which these sub-components can be performed. Finally, we include information on the type of tasks the user may wish to perform as part of his travel, and provide guidelines on how all of these components can be used together. This information can not only aid VR designers in choosing appropriate locomotion methods, but can even assist designers of a VR installation to choose appropriate display and interaction devices for the travel tasks they wish to perform. We conducted a large-scale experiment to experimentally validate selected portions of our new taxonomy. In particular, we studied the effect of display devices, and physical vs. virtual rotation, as these are novel elements our research introduces.

Our experiment had subjects perform an architectural walkthrough under one of seven different conditions. These conditions consisted of either virtual rotation or physical rotation for locomotion, and C2, C6, Workbench, or HMD display device (Workbench with physical rotation was not used). Test subjects filled out questionnaires and tests of spatial abilities before performing the experimental task. This data was used to balance the experimental groups by gender and spatial abilities. Eleven sets of good data were collected under each condition, for a total of 77 test subjects. Data collected includes time taken to complete the walkthrough, number of collisions, number of missed targets, and error in identifying the origin by pointing. Subjects also completed post-questionnaires to assess their level of presence and cybersickness, and to receive subjective feedback about the experience in general, and their opinions of the travel. This experiment produced many interesting results, most of which were statistically significant.

### 10.1 Display Device

The display device used had a large impact on many of the variables studied. Table 10-1 shows the p-values that indicate significance levels, for all the variables for which the effect of display device was significant. This data supports our addition of the display device category in our locomotion classification system.

Table 10-1. Significance of Display Device.

|                                       | <b>Presence<br/>Questionnaire</b> | <b>Completion<br/>Time</b> | <b>Collisions</b> | <b>Pointing<br/>Error</b> | <b>Floorplan<br/>Identification</b> |
|---------------------------------------|-----------------------------------|----------------------------|-------------------|---------------------------|-------------------------------------|
| <b>Display<br/>Device<br/>p-value</b> | .001                              | .012                       | .004              | .082                      | .0012                               |

The C6 created the greatest level of presence. The HMD was next highest, followed closely by the C2. The workbench finished last, with an average presence score 18 points lower than that of the C6. The C6 also had the fastest completion times for the walkthrough. C2 was next, followed by the workbench, with the HMD finishing last, nearly 140 seconds slower than the C6. Subjects collided with the least number of objects when using the C6, followed closely by the C2. The bench was next, with the HMD again finishing last, producing 9 more collisions on average than the C6.

On the pointing task, subjects at first appear to perform best when using the workbench, as the average error is quite small, with much larger errors when using the other displays. However, the deviation in responses for the bench is larger than for other display devices. When we instead look at the absolute values of the pointing errors, C6 users again performed more accurately, followed by C2 users and then bench users, with HMD users performing most poorly.

Subjects did not perform the floorplan identification task particularly well in any of the display devices. This is disappointing as one of the main goals of an architectural walkthrough should be to convey spatial information about a building. However, it is not completely surprising because we intentionally designed this virtual building to be somewhat confusing, with curved rooms and hallways, and few right angles. Subjects responded correctly most often when using the C2, followed by the HMD and the bench. Only one C6 subject identified the correct floorplan. We are unable to explain why the C6 should cause subjects to perform so poorly on this task, particularly since C6 subjects performed so well on the other measurements.

## 10.2 Rotation Method

The rotation method used for locomotion did not produce any significant overall effects. This is not surprising because we believe that for some display devices, physical rotation will be the preferred method, while for other display devices, virtual rotation will produce better results. Indeed, our results show interesting patterns in performance within each display device. These results support our addition of the rotation category in our locomotion classification system.

Presence levels in the C6 were not affected by rotation method, as average scores were nearly identical for both. However, C6 users completed the walkthrough more quickly when using physical rotation than when using virtual rotation. Not only did users perform over 40 seconds faster on average, but the variation in performance was also much lower for physical rotation.

C6 users generally performed the pointing task more accurately when using physical rotation, with average errors of  $-48.34^{\circ}$  for virtual rotation and  $-10.43^{\circ}$  for physical. Within each rotation method, there was a group of 8 subjects whose responses were tightly grouped. For virtual rotation, these subjects gave responses in the range  $-98^{\circ}$  to  $-38^{\circ}$ , while for physical rotation the subjects gave responses in the range  $-61^{\circ}$  to  $10^{\circ}$ . The average error for these 8 subjects is  $-66.92^{\circ}$  and  $-17.29^{\circ}$ , with standard deviations of 21.34 and 28.21, for virtual and physical rotation, respectively.

Rotation method did affect the presence scores of C2 users. Users of virtual rotation reported somewhat higher presence levels than users of physical rotation. This is likely because when using virtual rotation, the subject always faces the front wall, but users of

physical rotation often turn to face the missing back wall, and view the physical world of the lab environment, breaking the sense of presence in the virtual world.

In the C2, the overall average completion times are quite similar for both rotation methods, with virtual rotation producing only slightly lower average times. However, virtual rotation produced readings that are spread quite uniformly over the entire range of times, with a slight emphasis in the 100-199 range. Physical rotation produced results that are fairly uniform over the range 100-499, with a slight emphasis in the 300-399 range.

Rotation method also produced only a slight difference in number of collisions in the C2. Subjects had slightly fewer collisions when using virtual rotation. This is probably because with no back wall, subjects using physical rotation occasionally had to “walk blind” and were unable to see objects located in their path until it was too late to avoid a collision. Physical rotation produced the opposite effect on missed targets. Subjects missed almost 4 times as many targets using virtual rotation as they did using physical rotation. This may be due to subjects’ tendency to stand facing (and looking) only forward when using virtual rotation, but being forced to turn and look about when using physical rotation.

Although we believed that virtual rotation would be preferable to physical rotation for many tasks in the C2, we also believed that virtual rotation would probably interfere with users’ homing abilities. This does not appear to be the case. C2 users of virtual rotation had a lower average pointing error than users of physical rotation. Similarly to the C6, in the C2 there are also 8 subjects with responses fairly closely grouped for each rotation method. For virtual rotation these are in the range  $-49^{\circ}$  to  $57^{\circ}$  with an average of  $-0.915^{\circ}$  and standard deviation of 40.87. For physical rotation, the best grouping of 8 subjects results in an average

of  $-41.79^\circ$  and standard deviation of 45.34. This trend did not carry over to floorplan identification, as C2 users performed equally well under both rotation conditions.

We expected results for the HMD to be fairly similar to those for the C6, as both devices block out the physical world and thus would encourage physical rotation. In the C6, rotation method did not affect presence levels, but in the HMD, physical rotation created higher levels of presence than virtual rotation, with a difference of over 7 points on the Presence Questionnaire. Rotation method also affected completion times for the HMD differently than for the C6. In the HMD, completion times were about 20 seconds faster when using virtual rotation than when using physical rotation, but virtual rotation produced more variation. Physical rotation also tends to create slightly more collisions than virtual rotation for HMD users.

In the HMD, subjects miss far fewer targets when using virtual rotation. As stated earlier, this may be due in part to the smaller field-of-view of the HMD and subjects' reluctance to physically rotate to view the entire virtual world. Because subjects could see only a small portion of the virtual world, many of them using virtual rotation stood in place and spun the entire virtual world around them several times to get a clear understanding of the environment. In the process they would be more likely to observe all targets and arrow. In the HMD, subjects sometimes seemed uncomfortable with physically exploring the virtual world. With physical rotation method, such users physically rotated themselves only until they caught a glimpse of a target, and then headed for the target, often without even checking for arrows leading to the target.

As expected, subjects using physical rotation in the HMD tended to perform more accurately on the pointing task, but with more variation than subjects using virtual rotation.

Subjects using physical rotation performed only slightly better than virtual rotation subjects on the floorplan identification.

### **10.3 Demographic Effects**

As mentioned earlier, we balanced the experimental groups by gender and spatial abilities in order to prevent these factors from skewing our results. However, it appears this may have been unnecessary, as spatial abilities did not correlate with any of our performance measures. Gender also appears to have little affect on performance, as the only result of significance between genders was the number of collisions committed. Also unexpectedly, gender appears to have little impact on performance on the spatial abilities tests, with the exception of test SS2. Age and immersive tendencies did not affect any performance measures, including presence, which has previously been shown to correlate with immersive tendencies.

### **10.4 Subject Attention Effect and Video Game Effect**

Apart from the display device used, subject attentiveness to the task and previous video game experience of subjects may be the most importance factors in predicting performance. Subjects who followed the directions most exactly, exploring the building carefully, tended to have better results on the performance measures. Although these subjects did take significantly longer to perform the walkthrough, they also had significantly fewer collisions, and responded more accurately to the floorplan identification question. We also showed that in general, longer completion times did not lead to more accurate floorplan

identification. Thus we conclude that more actively studying the building (not merely spending more time in the building) leads to increased spatial understanding of the building.

Video game players also tend to perform better on these tasks. Subjects reporting that they play video games more than “occasionally” tended to have significantly shorter completion times, along with fewer collisions, indicating greater control over the virtual travel. Despite the very small completion times, the game players also tended to do better than average on the floorplan identification task, with 3 of the 4 video game experts answering correctly. Not surprisingly, game players had significantly higher immersive tendencies than the other subjects. It is still unknown whether video game experience can cause better performance in virtual environments, or whether subjects with skills leading to increased performance in VR also use those same skills to perform well at video games, leading to increased gaming experience.

### **10.5 The Winner?**

From all of this information, we might hope to draw a conclusion as to which display device and rotation method combine to produce the best overall locomotion method for architectural walkthroughs. Unfortunately, this depends heavily on precisely which part of the walkthrough task we wish to concentrate on. For inducing a sense of presence, the C6 is clearly the leader, regardless of rotation method. For fast completion times, the C6 with physical rotation is also the best choice. For a minimum of collisions, the C2 with virtual rotation comes out on top. However, C6 virtual rotation and C6 physical rotation are not far behind and would be acceptable choices if factors other than minimizing collisions were also under consideration. If we want to ensure subjects will miss the least number of targets, or

most accurately follow an established path, the HMD with virtual rotation is best. But the number of targets missed in other devices and rotation methods is also quite small, making them also acceptable choices. The pointing task is difficult to evaluate. Although the overall average error for the workbench is quite small, it is clear that this does not indicate good performance on this task by the workbench users. Instead it appears that physical rotation with the HMD or C6, or virtual rotation with the C2 will produce results that are more accurate and/or consistent. Finally, for tasks where floorplan identification is important, the C2 produces the best results, regardless of rotation method, but unfortunately no device produces outstanding results.

## **10.6 Future Work**

This experiment has clearly demonstrated the need for classification of display devices and rotation methods as part of our locomotion taxonomy. We also added another component to our taxonomy in Chapter 7: interaction device. We believe that additional experiments using different interaction devices will demonstrate the need for this part of our taxonomy. Our experiment used a wand for interaction, but future experiments could make use of several interaction devices, such as gloves, mock-ups, or other locomotion devices.

One particularly troubling result from this experiment is the poor performance on the floorplan identification task. Even more disturbing is the performance on this task by subjects using the C6, which produced very good results in other areas. Although this task was intentionally made difficult by the layout of our virtual building, we are unable to completely explain these findings. Future work could study this in more detail, such as comparing results

on floorplan identification in virtual environments against performance in the physical world, or performance on different types of floorplans.

Video game experience in VR users is an ever-present issue in virtual environments. Clearly, future work should recognize and account for differences arising from video game experience. But even more interesting are the issues concerning whether video games themselves help develop useful VR skills, or whether the innate tendencies that draw some people to video games also contribute to increased VR performance.

Finally, it is becoming increasingly important to develop software tools to quickly implement virtual environments. We would like to create a toolkit for VR locomotion that closely follows our taxonomy. Such a toolkit would consist of pre-coded modules, such as “virtual rotation module.” These modules could then be easily combined to quickly create fully implemented locomotion methods. Because creating a locomotion method for a new virtual environment only requires combining existing modules (re-using pre-written code), construction becomes quick and easy, with fewer chances of introducing coding errors. This modular approach also allows for easy extension, for example if a new interaction device becomes available. Additional components affecting locomotion (such as physics constraints, including gravity and friction) could be included in the toolkit. Advances in visual programming could allow even non-programmers to quickly and easily construct, implement, or modify a locomotion method for their virtual world.

## APPENDIX A: GENERAL PRE-QUESTIONNAIRE

Name: \_\_\_\_\_

Check One: ☐ Freshman    ☐ Sophomore    ☐ Junior    ☐ Senior  
☐ Grad Student, please list number of years in grad school: \_\_\_\_  
☐ Other, please explain: \_\_\_\_\_

Age: \_\_\_\_\_

Gender:    ☐ Female    ☐ Male

Is English your first language?    ☐ Yes    ☐ No

Will you be available to participate in the experiment during this summer?  
 (evenings/weekends are ok, but you must be able to travel to Ames.)    ☐ Yes    ☐ No

Is your vision in both eyes 20/20 or better? (mark yes if you wear glasses or contact lenses  
 which correct your vision to 20/20 or better)

☐ Yes-both eyes    ☐ Yes-one eye only    ☐ No    ☐ Not Sure/Don't Know

If you marked "No", please describe your vision (or vision with corrective lenses).

Have you ever visited Iowa State's C2 virtual reality device? If yes, how many times?

Have you ever visited Iowa State's C6 virtual reality device? If yes, how many times?

Have you ever seen a VR demonstration in ISU's Liu Lee Auditorium in Howe Hall? If yes,  
 how many times?

Have you ever used a head mounted display? If yes, how many times?

Have you ever used or visited any other virtual reality device? If yes, please describe these  
 experiences.

## APPENDIX B: IMMERSIVE TENDENCIES QUESTIONNAIRE

Indicate your preferred answer by checking the box corresponding to your choice on the seven point scale. Please consider the entire scale when making your responses, as the intermediate levels may apply. For example, if your response is "once or twice", the second box from the left (choice '2') should be marked. If your response is "many times but not extremely often," then choice '6' (second box from the right) should be marked.

1. Do you easily become involved in movies or tv dramas?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

2. Do you ever become so involved in a television program or book that people have problems getting your attention?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

3. Do you ever become so involved in a movie that you are not aware of things happening around you?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

4. How frequently do you find yourself closely identifying with the characters in a story line?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

5. Do you ever become so involved in a video game that it is as if you are inside the game rather than moving a joystick and watching the screen?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

6. How good are you at blocking out external distractions when you are involved in something?

|               |   |   |               |   |   |           |
|---------------|---|---|---------------|---|---|-----------|
|               |   |   |               |   |   |           |
| 1             | 2 | 3 | 4             | 5 | 6 | 7         |
| Not very good |   |   | Somewhat good |   |   | Very good |

7. When watching sports, do you ever become so involved in the game that you react as if you were one of the players?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

8. Do you ever become so involved in a daydream that you are not aware of things happening around you?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

9. Do you ever have dreams that are so real that you feel disorientated when you awake?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

10. When playing sports, do you become so involved in the game that you lose track of time?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

11. How well do you concentrate on enjoyable activities?

|            |   |   |                 |   |   |           |
|------------|---|---|-----------------|---|---|-----------|
|            |   |   |                 |   |   |           |
| 1          | 2 | 3 | 4               | 5 | 6 | 7         |
| Not at all |   |   | Moderately well |   |   | Very well |

12. How often do you play arcade or video games?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

13. Have you ever gotten excited during a chase or fight scene on TV or in the movies?

|       |   |   |              |   |   |       |
|-------|---|---|--------------|---|---|-------|
|       |   |   |              |   |   |       |
| 1     | 2 | 3 | 4            | 5 | 6 | 7     |
| Never |   |   | Occasionally |   |   | Often |

14. Have you ever gotten scared by something happening on a TV show or in a movie?

|       |   |              |   |   |       |   |
|-------|---|--------------|---|---|-------|---|
|       |   |              |   |   |       |   |
| 1     | 2 | 3            | 4 | 5 | 6     | 7 |
| Never |   | Occasionally |   |   | Often |   |

15. Have you ever remained apprehensive or fearful long after watching a scary movie?

|       |   |              |   |   |       |   |
|-------|---|--------------|---|---|-------|---|
|       |   |              |   |   |       |   |
| 1     | 2 | 3            | 4 | 5 | 6     | 7 |
| Never |   | Occasionally |   |   | Often |   |

16. Do you ever become so involved in doing something that you lose all track of time?

|       |   |              |   |   |       |   |
|-------|---|--------------|---|---|-------|---|
|       |   |              |   |   |       |   |
| 1     | 2 | 3            | 4 | 5 | 6     | 7 |
| Never |   | Occasionally |   |   | Often |   |

## APPENDIX C: WELL-BEING QUESTIONNAIRE

1. How mentally alert do you feel at the present time?

|           |   |            |   |   |             |   |
|-----------|---|------------|---|---|-------------|---|
|           |   |            |   |   |             |   |
| 1         | 2 | 3          | 4 | 5 | 6           | 7 |
| Not alert |   | Moderately |   |   | Fully alert |   |

2. How physically fit do you feel today?

|         |   |                |   |   |               |   |
|---------|---|----------------|---|---|---------------|---|
|         |   |                |   |   |               |   |
| 1       | 2 | 3              | 4 | 5 | 6             | 7 |
| Not fit |   | Moderately fit |   |   | Extremely fit |   |

Subjects answered these two questions immediately prior to testing, and again immediately after exiting the virtual environment.

## APPENDIX D: PRESENCE QUESTIONNAIRE

Characterize your experience in the environment, by checking the appropriate box of the 7-point scale, in accordance with the question content and descriptive labels. Please consider the entire scale when making your responses, as intermediate levels may apply. Answer the questions independently, in the order that they appear. Do not skip questions or return to a previous question to change your answer.

WITH REGARD TO THE EXPERIENCED VIRTUAL ENVIRONMENT:

1. How much were you able to control events?

|            |   |          |   |   |            |   |
|------------|---|----------|---|---|------------|---|
|            |   |          |   |   |            |   |
| 1          | 2 | 3        | 4 | 5 | 6          | 7 |
| Not at all |   | Somewhat |   |   | Completely |   |

2. How responsive was the environment to actions that you initiated (or performed)?

|                |   |                       |   |   |                       |   |
|----------------|---|-----------------------|---|---|-----------------------|---|
|                |   |                       |   |   |                       |   |
| 1              | 2 | 3                     | 4 | 5 | 6                     | 7 |
| Not responsive |   | Moderately Responsive |   |   | Completely Responsive |   |

3. How natural did your interactions with the environment seem?

|                      |   |            |   |   |                    |   |
|----------------------|---|------------|---|---|--------------------|---|
|                      |   |            |   |   |                    |   |
| 1                    | 2 | 3          | 4 | 5 | 6                  | 7 |
| Extremely artificial |   | Borderline |   |   | Completely natural |   |

4. How much did the visual aspects of the environment involve you?

|            |   |          |   |   |            |   |
|------------|---|----------|---|---|------------|---|
|            |   |          |   |   |            |   |
| 1          | 2 | 3        | 4 | 5 | 6          | 7 |
| Not at all |   | Somewhat |   |   | Completely |   |

5. How natural was the mechanism which controlled movement through the environment?

|                      |   |            |   |   |                    |   |
|----------------------|---|------------|---|---|--------------------|---|
|                      |   |            |   |   |                    |   |
| 1                    | 2 | 3          | 4 | 5 | 6                  | 7 |
| Extremely artificial |   | Borderline |   |   | Completely natural |   |

6. How compelling was your sense of objects moving through space?

|            |   |                       |   |   |                 |   |
|------------|---|-----------------------|---|---|-----------------|---|
|            |   |                       |   |   |                 |   |
| 1          | 2 | 3                     | 4 | 5 | 6               | 7 |
| Not at all |   | Moderately compelling |   |   | Very compelling |   |

7. How much did your experiences in the virtual environment seem consistent with your real world experiences?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not consistent

Moderately consistent

Very consistent

8. Were you able to anticipate what would happen next in response to the actions that you performed?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not at all

Somewhat

Completely

9. How completely were you able to actively survey or search the environment using vision?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not at all

Somewhat

Completely

10. How compelling was your sense of moving around inside the virtual environment?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not compelling

Moderately compelling

Very compelling

11. How closely were you able to examine objects?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not at all

Pretty closely

Very closely

12. How well could you examine objects from multiple viewpoints?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not at all

Somewhat

Extensively

13. How involved were you in the virtual environment experience?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not involved

Mildly involved

Completely engrossed

14. How much delay did you experience between your actions and expected outcomes?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Long delays

Moderate delays

No delays

15. How quickly did you adjust to the virtual environment experience?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not at all

Slowly

Less than one minute

16. How proficient in moving and interacting with the virtual environment did you feel at the end of the experience?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not proficient

Reasonably proficient

Very proficient

\*17. How much did the visual display quality interfere or distract you from performing the assigned tasks or required activities?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not at all

Interfered somewhat

Prevented task performance

\*18. How much did the control devices interfere with the performance of assigned tasks or with other activities?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not at all

Interfered somewhat

Interfered greatly

19. How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?

|   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|
|   |   |   |   |   |   |   |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Not at all

Somewhat

Completely

\*These two questions were scored in reverse. For example, an answer of "6" would be scored as 2.

## **APPENDIX E: GENERAL POST-QUESTIONNAIRE**

Please answer the following questions about your experience in the virtual environment. Your responses will not be associated with your name. Please feel free to elaborate on any of the questions or your responses. The more information you can provide, the more we can improve the experience for future users!

1. Did you enjoy your experience? Why or why not?
  
  
  
  
  
  
  
  
  
  
2. Did you experience any negative effects including, but not limited to:  
motion sickness, headache, nausea, eye strain, dizziness, disorientation? If so, please describe  
which ones and their duration.
  
  
  
  
  
  
  
  
  
  
3. What (if anything) would improve the virtual world experience?
  
  
  
  
  
  
  
  
  
  
4. Any additional comments?

## **APPENDIX F: LOCOMOTION POST-QUESTIONNAIRE**

The following questions refer to the way in which you moved through the virtual world (sometimes referred to as travel, locomotion, or navigation).

1. Which of the following best describes your experience in learning to travel through the virtual world? (please do not consider whether or not you “liked” the travel controls, consider only whether you were able to understand their operation)
  - It was very easy and straightforward. I learned how to travel without difficulty.
  - It was a little difficult to control at first, but I was able to learn how to travel during the practice environment.
  - It was difficult to learn how to travel. I did not feel comfortable with the controls until I was partway through the actual experiment.
  - I did not understand the travel controls. I never became comfortable with using them.
  - Other. Please explain:
  
2. Were you able to use the travel controls to effectively perform the requested tasks?
  - Yes, the travel controls allowed me to perform all the needed tasks.
  - Mostly, but there were a few things that were difficult to do (going through doorways, turning corners, etc) because of the travel controls.
  - No, the travel controls were inadequate.
  - Other. Please explain:
  
3. Did the travel controls interfere with your spatial abilities (that is, did the controls cause you to become disoriented or lose your way)?
  
4. Did you like the travel controls? If no, please explain.
  
5. How could travel be improved?
  
6. How difficult was the pointing task at the end of the experiment?
  
7. Did you become disoriented with respect to the physical world? (that is, if you were in the C6, was the exit wall in the place you expected?)
  
8. Overall, on a scale of 1 to 5 (with 5 most satisfied), how satisfied were you with the ability to travel in the virtual world?
  
9. Other comments related to the travel:

**APPENDIX G: EXPERIMENT SUBJECTS**

| <b>ID Num</b> | <b>Age</b> | <b>Gender</b> | <b>Designation</b> | <b>Major/Occupation</b>            |
|---------------|------------|---------------|--------------------|------------------------------------|
| 1             | 45         | M             | C                  | Computer Programmer                |
| 2             | 35         | F             | S                  | Instructional Designer             |
| 3             | 29         | F             | C                  | Technical Writing Support          |
| 4             | 40         | F             | C                  | Technical Writer                   |
| 5             | 40         | M             | C                  | Manager, Information Systems       |
| 6             | 39         | M             | C                  | Software Developer                 |
| 7             | 21         | F             | Sr                 | Computer Engineering               |
| 8             | 35         | F             | S                  | Radiographer                       |
| 9             | 50         | M             | C                  | Healthcare Technician              |
| 10            | 44         | M             | C                  | Management                         |
| 11            | 27         | M             | Sr                 | Elementary Education               |
| 12            | 48         | M             | P                  | Civil Engineer/Statistician        |
| 13            | 44         | F             | S                  | Lab Manager (Botany)               |
| 14            | 35         | M             | C                  | Computer Support                   |
| 15            | 22         | M             | Sr                 | Mechanical Engineering             |
| 16            | 50         | M             | C                  | Video/Multimedia Designer          |
| 17            | 31         | M             | C                  | Video Specialist/Graphic Artist    |
| 18            | 31         | F             | C                  | Teacher                            |
| 19            | 19         | M             | C                  | Marketing                          |
| 20            | 18         | F             | Fr                 | Undeclared                         |
| 21            | 41         | M             | C                  | Retail Sales                       |
| 22            | 31         | M             | G-3                | Chemistry                          |
| 23            | 24         | F             | G-1                | Public Administration              |
| 24            | 25         | M             | Sr                 | Computer Science                   |
| 25            | 35         | F             | G-5                | HDFS                               |
| 26            | 28         | M             | C                  | Business Owner                     |
| 27            | 23         | M             | C                  | Artist                             |
| 28            | 28         | M             | C                  | Retail Manager                     |
| 29            | 47         | M             | C                  | Dispatcher                         |
| 30            | 30         | F             | S                  | Counseling                         |
| 31            | 19         | M             | So                 | Computer Engineering               |
| 32            | 21         | F             | Se                 | Management Information Systems     |
| 33            | 45         | M             | C                  | Historian                          |
| 34            | 18         | F             | F                  | Biology                            |
| 35            | 37         | F             | NR                 | NR                                 |
| 36            | 19         | F             | So                 | Chemical Engineering               |
| 37            | 26         | F             | G-3                | CRP                                |
| 38            | 27         | M             | C                  | Police Officer                     |
| 39            | 39         | F             | C                  | NR                                 |
| 40            | 28         | F             | C                  | LMT                                |
| 41            | 20         | M             | J                  | Computer Science                   |
| 42            | 27         | F             | C                  | Homemaker                          |
| 43            | 29         | M             | C                  | Environmental Specialist/Biologist |

|    |    |   |     |                                 |
|----|----|---|-----|---------------------------------|
| 44 | 35 | M | S   | Computer Technician             |
| 45 | 43 | M | C   | Graphic Designer                |
| 46 | 18 | M | Fr  | Electrical Engineering          |
| 47 | 39 | M | F   | Philosophy Professor            |
| 48 | 36 | F | S   | Secretary                       |
| 49 | 49 | M | C   | Service Technician              |
| 50 | 37 | M | C   | Service Technician              |
| 51 | 19 | F | I   | Electrical/Computer Engineering |
| 52 | 20 | M | I   | Mechanical Engineering          |
| 53 | 21 | M | Sr  | MIS/International Business      |
| 54 | 33 | F | S   | Web Designer                    |
| 55 | 31 | M | S   | Agronomy                        |
| 56 | 29 | M | G-3 | Anthropology/Computer Science   |
| 57 | 20 | F | Jr  | Computer Science                |
| 58 | 38 | F | S   | Dietitian                       |
| 59 | 25 | M | C   | Engineering                     |
| 60 | 24 | F | C   | Marketing Coordinator           |
| 61 | 20 | F | J   | Agriculture                     |
| 62 | 36 | M | S   | Engineer                        |
| 63 | 42 | F | G-1 | NR                              |
| 64 | 23 | M | Sr  | Electrical Engineering/Physics  |
| 65 | 44 | F | S   | NR                              |
| 66 | 18 | M | Fr  | Engineering                     |
| 67 | 43 | F | F   | Agronomy                        |
| 68 | 43 | M | S   | Courseware Developer            |
| 69 | 23 | F | So  | Veterinary Medicine             |
| 70 | 52 | M | S   | Information Systems Management  |
| 71 | 41 | M | S   | Web Developer                   |
| 72 | 36 | M | F   | Agronomy                        |
| 73 | 39 | M | F   | Plant Pathologist               |
| 74 | 19 | M | So  | Computer Engineering            |
| 75 | 33 | F | Sr  | Nursing/Homemaker               |
| 76 | 20 | F | Jr  | Computer Science                |
| 77 | 40 | F | C   | Childcare Worker                |
| 78 | 52 | M | S   | Custodian                       |
| 79 | 50 | M | C   | MIS/Finance                     |
| 80 | 21 | F | Jr  | Architecture                    |
| 81 | 43 | M | G-1 | Agronomy                        |
| 82 | 22 | M | C   | Cook                            |
| 83 | 25 | M | So  | Political Science               |
| 84 | 20 | M | Jr  | MIS                             |
| 85 | 25 | M | C   | Sales                           |
| 86 | 25 | F | G-1 | Social Work                     |
| 87 | 42 | M | C   | Computer Support                |
| 88 | 22 | M | Sr  | Industrial Engineering          |
| 89 | 31 | F | C   | Project Manager                 |

|     |    |   |     |                        |
|-----|----|---|-----|------------------------|
| 90  | 35 | M | S   | Programmer             |
| 91  | 18 | F | Fr  | NR                     |
| 92  | 42 | M | S   | Systems Analyst        |
| 93  | 27 | F | C   | Computer Support       |
| 94  | 34 | F | NR  | NR                     |
| 95  | 22 | F | Sr  | Computer Engineering   |
| 96  | 22 | M | Sr  | NR                     |
| 97  | 27 | M | C   | Communications         |
| 98  | 27 | F | Sr  | Exercise Science       |
| 99  | 39 | M | C   | Welder                 |
| 100 | 22 | M | Sr  | English                |
| 101 | 28 | F | G-5 | Physics                |
| 102 | 19 | M | J   | Physics                |
| 103 | 36 | M | F   | Music Professor        |
| 104 | 24 | M | C   | Software Engineer      |
| 105 | 20 | M | J   | Architecture           |
| 106 | 22 | F | G-1 | Chemistry              |
| 107 | 28 | M | G-1 | Chemical Engineering   |
| 108 | 18 | M | Fr  | Architecture           |
| 109 | 18 | M | Fr  | Engineering            |
| 110 | 22 | M | Sr  | Advertising            |
| 111 | 24 | M | G-1 | Electrical Engineering |
| 112 | 18 | F | Fr  | Computer Engineering   |
| 113 | 19 | M | So  | Computer Science       |
| 114 | 18 | M | Fr  | Computer Engineering   |
| 115 | 18 | M | Fr  | Computer Science       |
| 116 | 19 | M | Fr  | Computer Engineering   |
| 117 | 19 | M | So  | Computer Engineering   |
| 118 | 19 | M | J   | Biology                |
| 119 | 18 | M | Fr  | Mechanical Engineering |
| 120 | 19 | M | Fr  | Computer Engineering   |
| 121 | 19 | M | So  | Business               |
| 122 | 18 | M | Fr  | Computer Engineering   |
| 123 | 35 | M | C   | NR                     |
| 124 | 18 | M | Fr  | Computer Engineering   |
| 125 | 18 | M | Fr  | Computer Engineering   |
| 126 | 18 | M | Fr  | Undeclared             |
| 127 | 18 | F | Fr  | Computer Engineering   |
| 128 | 18 | M | Fr  | Engineering            |
| 129 | 37 | M | G-1 | Transportation         |
| 130 | 31 | M | F   | Professor              |
| 131 | 21 | M | Sr  | JLMC                   |
| 132 | 18 | M | Fr  | Mechanical Engineering |
| 133 | 18 | M | Fr  | Engineering            |
| 134 | 20 | F | J   | Biology                |

|     |    |   |     |                                |
|-----|----|---|-----|--------------------------------|
| 135 | 19 | M | So  | Computer Engineering           |
| 136 | 44 | F | S   | Secretary                      |
| 137 | 19 | M | So  | Electrical Engineering         |
| 138 | 39 | M | S   | Webmaster                      |
| 139 | 23 | M | G-1 | Journalism/Mass Communications |
| 140 | 18 | F | Fr  | Pre-business                   |
| 141 | 18 | F | Fr  | NR                             |
| 142 | 19 | M | So  | Mechanical Engineering         |
| 143 | 20 | M | So  | Meteorology                    |
| 144 | 37 | F | S   | Graphic Designer               |
| 145 | 49 | M | F   | Professor                      |
| 146 | 19 | M | So  | Computer Engineering           |
| 147 | 19 | F | So  | Aerospace Engineering          |
| 148 | 23 | M | Sr  | Elementary Education           |
| 149 | 52 | M | C   | Postal Clerk                   |
| 150 | 19 | M | So  | Computer Engineering           |
| 151 | 39 | F | S   | Secretary                      |
| 152 | 31 | F | S   | Recruitment Coordinator        |
| 153 | 22 | M | J   | Electrical Engineering         |
| 154 | 19 | M | So  | Aerospace Engineering          |
| 155 | 19 | M | Fr  | Aerospace Engineering          |
| 156 | 19 | F | J   | Business/Marketing             |
| 157 | 21 | M | Sr  | Mechanical Engineering         |
| 158 | 22 | M | J   | Accounting                     |
| 159 | 18 | M | Fr  | Pre-Business                   |
| 160 | 18 | M | Fr  | Aerospace Engineering          |
| 161 | 19 | M | So  | Aerospace Engineering          |
| 162 | 18 | F | Fr  | Industrial Engineering         |
| 163 | 21 | F | Jr  | Journalism                     |
| 164 | 31 | M | S   | Graphic Designer               |
| 165 | 30 | M | NR  | Aerospace Engineering          |
| 166 | 39 | M | F   | Professor                      |
| 167 | 19 | F | So  | Mechanical Engineering         |
| 168 | 19 | M | So  | Aerospace Engineering          |
| 169 | 19 | M | Fr  | Industrial Engineering         |
| 170 | 20 | F | So  | Mechanical Engineering         |
| 171 | 19 | M | J   | Aerospace Engineering          |
| 172 | 22 | F | Sr  | Art                            |
| 173 | 18 | M | Fr  | Aerospace Engineering          |
| 174 | 21 | M | Sr  | Aerospace Engineering          |
| 175 | 22 | M | Sr  | Aerospace Engineering          |
| 176 | 19 | M | Fr  | Aerospace Engineering          |
| 177 | 18 | F | Fr  | Aerospace Engineering          |
| 178 | 18 | M | Fr  | Computer Science               |

|     |    |   |     |                                |
|-----|----|---|-----|--------------------------------|
| 179 | 18 | M | Fr  | Computer Science               |
| 180 | 18 | M | Fr  | Aerospace Engineering          |
| 181 | 22 | M | Sr  | Mechanical Engineering         |
| 182 | 18 | M | Fr  | Aerospace Engineering          |
| 183 | 18 | F | Fr  | Undeclared                     |
| 184 | 22 | F | G-2 | Industrial Engineering         |
| 185 | 19 | M | So  | Aerospace Engineering          |
| 186 | 40 | F | S   | Academic Advisor               |
| 187 | 19 | M | Fr  | Aerospace Engineering          |
| 188 | 22 | F | Sr  | Aerospace Engineering          |
| 189 | 21 | M | J   | Aerospace Engineering          |
| 190 | 21 | F | Sr  | ChE                            |
| 191 | 18 | F | Jr  | Genetics/Pre-Med               |
| 192 | 19 | F | So  | Materials Engineering          |
| 193 | 19 | M | Fr  | Computer Science               |
| 194 | 21 | M | Sr  | Aerospace Engineering          |
| 195 | 18 | M | Fr  | Computer Engineering           |
| 196 | 21 | M | Sr  | Aerospace Engineering          |
| 197 | 18 | M | Fr  | NR                             |
| 198 | 18 | M | Fr  | Aerospace Engineering          |
| 199 | 19 | M | Fr  | Computer Science               |
| 200 | 18 | M | Fr  | Aerospace Engineering          |
| 201 | 19 | F | Fr  | Marketing                      |
| 202 | 18 | F | Fr  | Aerospace Engineering          |
| 203 | 24 | M | C   | Information Technology Analyst |
| 204 | 36 | M | C   | Disability Examiner            |
| 205 | 19 | M | So  | Aerospace Engineering          |
| 206 | 21 | M | Sr  | NR                             |
| 207 | 18 | M | Fr  | Agronomy                       |
| 208 | 18 | F | Fr  | Interior Design                |
| 209 | 20 | M | Fr  | Aerospace Engineering          |
| 210 | 18 | M | Fr  | Aerospace Engineering          |
| 211 | 50 | M | S   | Manufacturing Consultant       |
| 212 | 21 | F | Sr  | Family & Consumer Sciences Ed  |
| 213 | 20 | M | Jr  | Computer Engineering/JLMC      |
| 214 | 43 | F | C   | Accountant                     |
| 215 | 42 | M | C   | NR                             |
| 216 | 18 | F | Fr  | Aerospace Engineering          |
| 217 | 22 | F | Sr  | Mathematics                    |
| 218 | 18 | M | Fr  | Aerospace Engineering          |
| 219 | 18 | M | Fr  | Aerospace Engineer             |
| 220 | 18 | F | Fr  | Biology                        |
| 221 | 18 | F | Fr  | Engineering                    |
| 222 | 18 | F | Fr  | Aerospace Engineering          |

|     |    |   |    |                    |
|-----|----|---|----|--------------------|
| 223 | 22 | M | Sr | Sport Management   |
| 224 | 19 | M | Fr | Aerospace Engineer |

Gender: F=Female, M=Male

Designation: F=Faculty, S=Staff, Fr=Freshman, So=Sophomore, Jr=Junior, Sr=Senior, I=Intern, C=Community member, G-#=Graduate student & number of years in graduate school, NR=No response

Subjects 1 through 109 were members of the original subject pool. Subjects 110 through 224 were recruited in the replacement subject pool.

**APPENDIX H: ORIGINAL TEST SUBJECTS**

| <b>ID Num</b> | <b>Status</b> | <b>ID Num</b> | <b>Status</b> | <b>ID Num</b> | <b>Status</b> |
|---------------|---------------|---------------|---------------|---------------|---------------|
| 1             | T             | 38            | 5             | 75            | NR            |
| 2             | 7             | 39            | 6             | 76            | VR            |
| 3             | NR            | 40            | 2             | 77            | *             |
| 4             | 2             | 41            | T             | 78            | VR            |
| 5             | 1             | 42            | VR            | 79            | VR            |
| 6             | 6             | 43            | VR            | 80            | T             |
| 7             | VR            | 44            | NR            | 81            | 3             |
| 8             | T             | 45            | 6             | 82            | NR            |
| 9             | 7             | 46            | 2             | 83            | T             |
| 10            | VR            | 47            | VR            | 84            | NR            |
| 11            | VR            | 48            | 3             | 85            | VR            |
| 12            | 5             | 49            | M             | 86            | NR            |
| 13            | 3             | 50            | T             | 87            | VR            |
| 14            | NR            | 51            | M             | 88            | VR            |
| 15            | 5             | 52            | NR            | 89            | 6             |
| 16            | T             | 53            | VR            | 90            | VR            |
| 17            | NR            | 54            | T             | 91            | 3             |
| 18            | NR            | 55            | 7             | 92            | VR            |
| 19            | VR            | 56            | VR            | 93            | CS            |
| 20            | NR            | 57            | T             | 94            | 5             |
| 21            | CS            | 58            | 7             | 95            | VR            |
| 22            | 4             | 59            | 3             | 96            | NR            |
| 23            | NR            | 60            | 7             | 97            | T             |
| 24            | VR            | 61            | 4             | 98            | VR            |
| 25            | NR            | 62            | 2             | 99            | 7             |
| 26            | 1             | 63            | 7             | 100           | NR            |
| 27            | NR            | 64            | 5             | 101           | 5             |
| 28            | NR            | 65            | VR            | 102           | VR            |
| 29            | 1             | 66            | VR            | 103           | EYE           |
| 30            | T             | 67            | T             | 104           | 3             |
| 31            | VR            | 68            | 6             | 105           | VR            |
| 32            | 6             | 69            | 6             | 106           | 3             |
| 33            | 1             | 70            | VR            | 107           | T             |
| 34            | 4             | 71            | VR            | 108           | T             |
| 35            | 1             | 72            | VR            | 109           | T             |
| 36            | T             | 73            | 5             |               |               |
| 37            | VR            | 74            | VR            |               |               |

A number in the status column indicates that the subject was successfully tested under the corresponding experimental condition.

CS=Subject dropped out after experiencing cybersickness

EYE=Eyesight insufficient

**M=Subject moved/graduated/left school before they could be tested**

**NR=Subject did not respond to contact attempts, was unable to schedule a testing time, or failed to appear for testing**

**T=Technical problems such as application crash or hardware failure**

**VR=Subject reported previous experience with virtual reality**

**\* Subject was unable to learn how to control the travel and stopped the experiment after approximately 10 minutes without having made it to the 1<sup>st</sup> target.**

**APPENDIX I: REPLACEMENT TEST SUBJECTS**

| <b>ID Num</b> | <b>Status</b> | <b>ID Num</b> | <b>Status</b> | <b>ID Num</b> | <b>Status</b> |
|---------------|---------------|---------------|---------------|---------------|---------------|
| 110           | VR            | 149           | AGE           | 188           | 2             |
| 111           | 5             | 150           | VR            | 189           | 2             |
| 112           | VR            | 151           | 5             | 190           | 7             |
| 113           | 1             | 152           | VR            | 191           | 5             |
| 114           | EX            | 153           | VR            | 192           | VR            |
| 115           | VR            | 154           | EX            | 193           | VR            |
| 116           | VR            | 155           | 4             | 194           | EX            |
| 117           | VR            | 156           | 2             | 195           | VR            |
| 118           | VR            | 157           | VR            | 196           | VR            |
| 119           | VR            | 158           | VR            | 197           | 7             |
| 120           | 2             | 159           | 4             | 198           | T             |
| 121           | VR            | 160           | EX            | 199           | VR            |
| 122           | 4             | 161           | VR            | 200           | EX            |
| 123           | VR            | 162           | VR            | 201           | 4             |
| 124           | 6             | 163           | 1             | 202           | 3             |
| 125           | 3             | 164           | VR            | 203           | 6             |
| 126           | EX            | 165           | EX            | 204           | EX            |
| 127           | 4             | 166           | EX            | 205           | VR            |
| 128           | T             | 167           | VR            | 206           | 7             |
| 129           | 3             | 168           | VR            | 207           | VR            |
| 130           | VR            | 169           | EX            | 208           | 1             |
| 131           | VR            | 170           | *             | 209           | NR            |
| 132           | VR            | 171           | EX            | 210           | 4             |
| 133           | VR            | 172           | T             | 211           | VR            |
| 134           | 2             | 173           | VR            | 212           | VR            |
| 135           | EX            | 174           | EX            | 213           | EX            |
| 136           | VR            | 175           | VR            | 214           | NR            |
| 137           | 1             | 176           | VR            | 215           | 6             |
| 138           | VR            | 177           | 4             | 216           | VR            |
| 139           | EX            | 178           | 3             | 217           | T             |
| 140           | 5             | 179           | EX            | 218           | VR            |
| 141           | 1             | 180           | EX            | 219           | EX            |
| 142           | 4             | 181           | 2             | 220           | 1             |
| 143           | 7             | 182           | VR            | 221           | VR            |
| 144           | CS            | 183           | 6             | 222           | VR            |
| 145           | 2             | 184           | VR            | 223           | NR            |
| 146           | CS            | 185           | VR            | 224           | EX            |
| 147           | VR            | 186           | VR            |               |               |
| 148           | EX            | 187           | VR            |               |               |

A number in the status column indicates that the subject was successfully tested under the corresponding experimental condition.

AGE=Subject exceeded the age limit of 50 years old

CS=Subject dropped out after experiencing cybersickness

EX=Extra subject from the replacement pool who was not needed

NR=Subject did not respond to contact attempts, was unable to schedule a testing time, or failed to appear for testing

T=Technical problems such as application crash or hardware failure

VR=Subject reported previous experience with virtual reality

\* Subject reported a VR experience between the time of filling out the initial paperwork and returning for testing.

## **APPENDIX J: REPLACEMENT OF SUBJECTS**

In Chapter 8, the method used to replace test subjects was described. We made two assumptions when doing this:

- 1) That the subjects dropped from the original group were representative of the group as a whole.
- 2) That the new group of subjects was approximately equal to the original group in terms of general background and abilities.

We would like to determine the validity of these assumptions. The following sections discuss the gender, age, immersive tendencies, and spatial abilities of the original pool of usable subjects and the replacement subjects.

### **Gender of Dropped Subjects**

Of the original pool of usable test subjects, 35 (45.5%) were female and 42 (54.5%) were male. Of the 37 test subjects dropped from the original pool, 16 (43.2%) were female and 21 (56.8) were male. Because these numbers are fairly close, this information helps to support assertion 1 above. The replacement pool of 67 subjects contained 21 (31.3%) females and 46 (68.7%) males. However, dropped subjects were only replaced by replacement subjects of the same gender, in order to maintain a gender balance among experimental conditions.

### **Age of Dropped Subjects**

The average age of the original pool of usable test subjects was 31.14 years with a standard deviation of 9.34. The average age of test subjects from the original pool who were

replaced was 29.16 years with a standard deviation of 8.99. Because these averages are quite close (well within one standard deviation of each other), this information also helps to support assertion 1. The average age of subjects in the replacement pool was 22.07 years, with a standard deviation of 7.19. This difference is likely due to the fact that the original test subjects were recruited during the summer, while the pool of replacement subjects was recruited during the fall, when school was in session, resulting in more university students, and a lower age range. In any case, these averages are each within one standard deviation of each other, supporting assertion 2 above.

### **Spatial Abilities of Dropped Subjects**

Table \* shows the results of all groups on the five spatial abilities tests. Although in some cases the averages of the original group are higher than the averages of the dropped subjects and lower than the averages of the replacement subjects, all the averages are well within one standard deviation of each other, supporting both assertions 1 and 2 above.

|                                   | <b>S1</b> | <b>S2</b> | <b>SS1</b> | <b>SS2</b> | <b>SS3</b> |
|-----------------------------------|-----------|-----------|------------|------------|------------|
| <b>Original Pool</b>              | 103.23    | 20.90     | 26.21      | 9.94       | 25.39      |
|                                   | 36.34     | 11.10     | 7.15       | 8.94       | 9.13       |
| <b>Dropped Subjects</b>           | 95.35     | 18.92     | 25.86      | 9.00       | 23.89      |
|                                   | 38.66     | 11.45     | 7.99       | 9.93       | 8.44       |
| <b>All replacement subjects</b>   | 113.03    | 23.82     | 29.55      | 10.52      | 26.34      |
|                                   | 27.37     | 9.89      | 7.86       | 10.52      | 7.15       |
| <b>Final replacement subjects</b> | 113.19    | 24.14     | 29.41      | 9.00       | 26.59      |
|                                   | 23.90     | 8.91      | 7.66       | 10.31      | 6.49       |

Table \*. Spatial abilities test results. Averages are shown on the first line of each cell, standard deviations on the second.

### **ITQ of Dropped Subjects**

The average ITQ score of the original pool of usable test subjects was 65.43, with a standard deviation of 12.78. The average ITQ score of the test subjects dropped from the original usable pool was 67.59, with a standard deviation of 14.20. Again, because these averages are so close, this further supports assertion 1. The average ITQ score of test subjects in the replacement pool was 71.12, with a standard deviation of 13.49. Although this average is almost 6 points higher than the average of the original pool of subjects, the averages are within one standard deviation of each other. Additionally, the new average score of 71.12 is only 3.53 points higher than the average of the dropped subjects. Thus, we believe this supports assertion 2.

From these sections, it appears that both our previous assumptions are valid, and we therefore believe that the replacement process used did not affect the data collected during the experiment.

**APPENDIX K: SUBJECT PERFORMANCE**

| <b>ID</b> | <b>Experimental Group</b> | <b>Display Device</b> | <b>Rotation Method</b> | <b>Completion Time</b> | <b>Pointing Error</b> | <b>Collisions</b> | <b>Missed Targets</b> | <b>Floorplan Choice</b> |
|-----------|---------------------------|-----------------------|------------------------|------------------------|-----------------------|-------------------|-----------------------|-------------------------|
| 2         | 7                         | 2                     | V                      | 265                    | 5.21                  | 2                 | 0                     | C                       |
| 4         | 2                         | H                     | P                      | 341                    | -175.79               | 25                | 0                     | D                       |
| 5         | 1                         | 6                     | V                      | 276                    | -56.79                | 3                 | 0                     | A                       |
| 6         | 6                         | H                     | V                      | 297                    | -33.79                | 3                 | 0                     | B                       |
| 9         | 7                         | 2                     | V                      | 624                    | -23.79                | 1                 | 0                     | B                       |
| 12        | 5                         | B                     | V                      | 151                    | -27.79                | 1                 | 1                     | A                       |
| 13        | 3                         | 2                     | P                      | 338                    | -1.79                 | 3                 | 0                     | B                       |
| 15        | 5                         | B                     | V                      | 383                    | -3.79                 | 3                 | 0                     | B                       |
| 22        | 4                         | 6                     | P                      | 172                    | -18.79                | 5                 | 3                     | C                       |
| 26        | 1                         | 6                     | V                      | 285                    | -84.79                | 4                 | 1                     | D                       |
| 29        | 1                         | 6                     | V                      | 398                    | 97.21                 | 1                 | 0                     | C                       |
| 32        | 6                         | H                     | V                      | 389                    | -26.79                | 5                 | 0                     | C                       |
| 33        | 1                         | 6                     | V                      | 475                    | -171.79               | 4                 | 1                     | A                       |
| 34        | 4                         | 6                     | P                      | 264                    | -0.79                 | 4                 | 0                     | D                       |
| 35        | 1                         | 6                     | V                      | 361                    | -39.79                | 2                 | 0                     | C                       |
| 38        | 5                         | B                     | V                      | 207                    | -59.79                | 13                | 0                     | A                       |
| 39        | 6                         | H                     | V                      | 411                    | -123.79               | 14                | 0                     | D                       |
| 40        | 2                         | H                     | P                      | 306                    | -172.79               | 27                | 0                     | A                       |
| 45        | 6                         | H                     | V                      | 338                    | -63.79                | 30                | 0                     | A                       |
| 46        | 2                         | H                     | P                      | 1046                   | -115.79               | 266               | 1                     | D                       |
| 48        | 3                         | 2                     | P                      | 341                    | -70.79                | 9                 | 0                     | A                       |
| 55        | 7                         | 2                     | V                      | 126                    | -123.79               | 6                 | 1                     | A                       |
| 58        | 7                         | 2                     | V                      | 245                    | 21.21                 | 7                 | 0                     | C                       |
| 59        | 3                         | 2                     | P                      | 124                    | -36.79                | 4                 | 0                     | C                       |
| 60        | 7                         | 2                     | V                      | 357                    | -17.79                | 6                 | 1                     | B                       |
| 61        | 4                         | 6                     | P                      | 293                    | -60.79                | 8                 | 0                     | D                       |
| 62        | 2                         | H                     | P                      | 684                    | 33.21                 | 14                | 0                     | B                       |
| 63        | 7                         | 2                     | V                      | 156                    | -161.79               | 4                 | 1                     | D                       |
| 64        | 5                         | B                     | V                      | 326                    | 97.21                 | 13                | 1                     | C                       |
| 68        | 6                         | H                     | V                      | 687                    | -141.79               | 19                | 0                     | C                       |
| 69        | 6                         | H                     | V                      | 182                    | -69.79                | 6                 | 0                     | C                       |
| 73        | 5                         | B                     | V                      | 319                    | -53.79                | 4                 | 0                     | A                       |
| 81        | 3                         | 2                     | P                      | 438                    | -32.79                | 4                 | 0                     | A                       |
| 89        | 6                         | H                     | V                      | 435                    | -130.79               | 3                 | 0                     | C                       |
| 91        | 3                         | 2                     | P                      | 250                    | 1.21                  | 13                | 0                     | A                       |
| 94        | 5                         | B                     | V                      | 460                    | -25.79                | 25                | 1                     | C                       |
| 99        | 7                         | 2                     | V                      | 97                     | -48.79                | 5                 | 1                     | D                       |
| 101       | 5                         | B                     | V                      | 337                    | -31.79                | 23                | 1                     | B                       |
| 104       | 3                         | 2                     | P                      | 284                    | 1.21                  | 7                 | 0                     | B                       |
| 106       | 3                         | 2                     | P                      | 390                    | -65.79                | 9                 | 0                     | C                       |
| 111       | 5                         | B                     | V                      | 396                    | -102.79               | 8                 | 0                     | B                       |
| 113       | 1                         | 6                     | V                      | 192                    | -38.79                | 1                 | 0                     | A                       |

|     |   |   |   |     |         |    |   |   |
|-----|---|---|---|-----|---------|----|---|---|
| 120 | 2 | H | P | 318 | -120.79 | 11 | 0 | A |
| 122 | 4 | 6 | P | 359 | 138.21  | 3  | 1 | C |
| 124 | 6 | H | V | 201 | -26.79  | 8  | 0 | A |
| 125 | 3 | 2 | P | 313 | -128.79 | 23 | 1 | B |
| 127 | 4 | 6 | P | 144 | 4.21    | 10 | 0 | D |
| 129 | 3 | 2 | P | 167 | 95.21   | 12 | 0 | B |
| 134 | 2 | H | P | 166 | -68.79  | 19 | 0 | B |
| 137 | 1 | 6 | V | 165 | -83.79  | 2  | 0 | D |
| 140 | 5 | B | V | 257 | 147.21  | 25 | 1 | D |
| 141 | 1 | 6 | V | 120 | -67.79  | 5  | 1 | C |
| 142 | 4 | 6 | P | 81  | -56.79  | 5  | 0 | A |
| 143 | 7 | 2 | V | 360 | 159.21  | 1  | 0 | B |
| 145 | 2 | H | P | 349 | -87.79  | 6  | 0 | C |
| 151 | 5 | B | V | 466 | -93.79  | 13 | 1 | B |
| 155 | 4 | 6 | P | 258 | -22.79  | 2  | 0 | B |
| 156 | 2 | H | P | 341 | -30.79  | 24 | 2 | A |
| 159 | 4 | 6 | P | 217 | 9.21    | 2  | 0 | C |
| 163 | 1 | 6 | V | 255 | -97.79  | 30 | 1 | D |
| 177 | 4 | 6 | P | 285 | 8.21    | 33 | 0 | D |
| 178 | 3 | 2 | P | 191 | 179.21  | 9  | 0 | B |
| 181 | 2 | H | P | 357 | 60.21   | 3  | 0 | D |
| 183 | 6 | H | V | 164 | -14.79  | 24 | 0 | A |
| 188 | 2 | H | P | 567 | -124.79 | 41 | 1 | B |
| 189 | 2 | H | P | 274 | 74.21   | 16 | 1 | B |
| 190 | 7 | 2 | V | 479 | -48.79  | 19 | 1 | B |
| 191 | 5 | B | V | 301 | 169.21  | 3  | 0 | B |
| 197 | 7 | 2 | V | 113 | 49.21   | 1  | 1 | B |
| 201 | 4 | 6 | P | 176 | -177.79 | 10 | 0 | C |
| 202 | 3 | 2 | P | 222 | -167.79 | 24 | 1 | B |
| 203 | 6 | H | V | 450 | -51.79  | 15 | 0 | B |
| 206 | 7 | 2 | V | 192 | 56.21   | 1  | 1 | B |
| 208 | 1 | 6 | V | 268 | -65.79  | 3  | 0 | C |
| 210 | 4 | 6 | P | 289 | 63.21   | 2  | 1 | C |
| 215 | 6 | H | V | 289 | -86.79  | 22 | 1 | B |
| 220 | 1 | 6 | V | 210 | 78.21   | 12 | 0 | C |

Display Device: 2=C2, 6=C6, H=HMD, B=Workbench  
Rotation Method: P=Physical, V=Virtual

## APPENDIX L: ADDITIONAL ANOVAS AND HISTOGRAMS

### Description of ANOVA Tables:

The first column, headed "DF" indicates the degrees of freedom.

The second column, headed "SS" indicates the sum of squares calculated from the data.

The third column, headed "MS" indicates the values of the mean squares, calculated by dividing the sum of squares by its degrees of freedom.

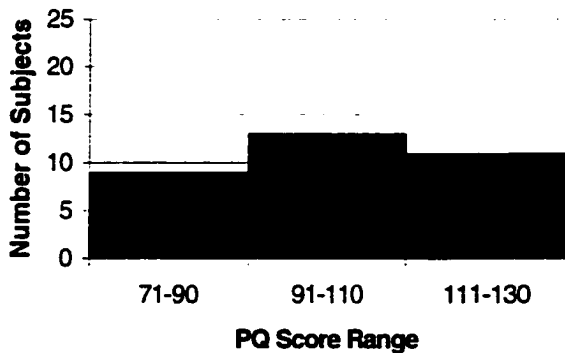
The fourth column, headed "F" indicates the F-value computed by the ratio of the MS between groups to the MS within groups.

The fifth column, headed "PROB>F" indicates the value at which the null hypothesis may be rejected (thus smaller values indicate greater significance).

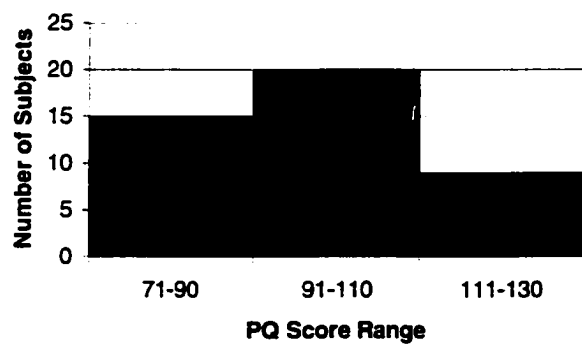
### Presence Questionnaire

ANOVA for Presence Questionnaire, by rotation method.

| SOURCE         | DF | SS        | MS      | F     | PROB> F |
|----------------|----|-----------|---------|-------|---------|
| Between Groups | 1  | 142.607   | 142.607 | 0.760 | 0.386   |
| Within Groups  | 75 | 14077.705 | 187.703 |       |         |
| Total          | 76 | 14220.312 | 187.109 |       |         |



(a)



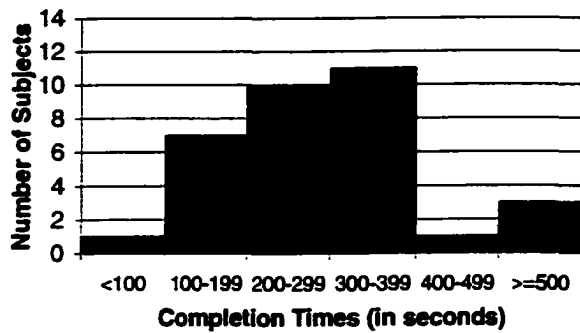
(b)

PQ scores of subjects assigned to (a) physical rotation and (b) virtual rotation.

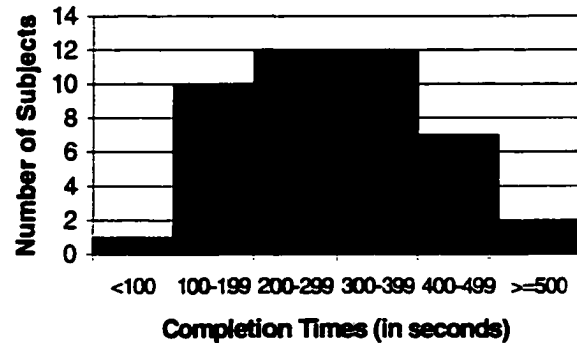
### Completion Times

ANOVA for Completion Time, by rotation method.

| SOURCE         | DF | SS          | MS        | F     | PROB> F |
|----------------|----|-------------|-----------|-------|---------|
| Between Groups | 1  | 1050.027    | 1050.027  | 0.044 | 0.834   |
| Within Groups  | 75 | 1777431.220 | 23699.083 |       |         |
| Total          | 76 | 1778481.247 | 23401.069 |       |         |



(a)



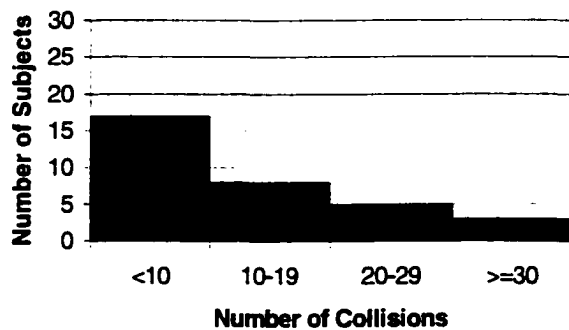
(b)

Completion times of subjects assigned to (a) physical rotation and (b) virtual rotation.

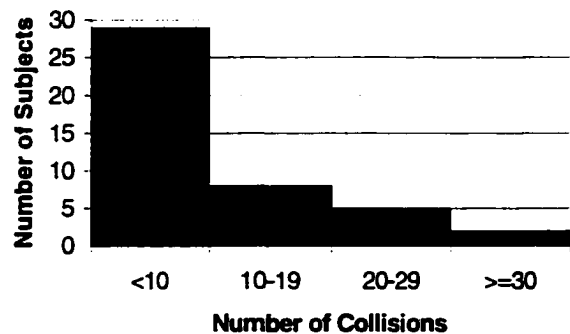
### Collisions

ANOVA for Collisions, by rotation method.

| SOURCE         | DF | SS       | MS      | F      | PROB> F |
|----------------|----|----------|---------|--------|---------|
| Between Groups | 1  | 167.053  | 167.053 | 1.9333 | 0.1686  |
| Within Groups  | 74 | 6394.355 | 86.410  |        |         |
| Total          | 75 | 6561.408 |         |        |         |



(a)



(b)

Collisions of subjects assigned to (a) physical rotation and (b) virtual rotation.

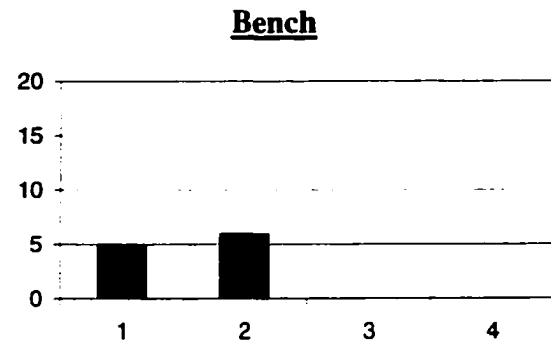
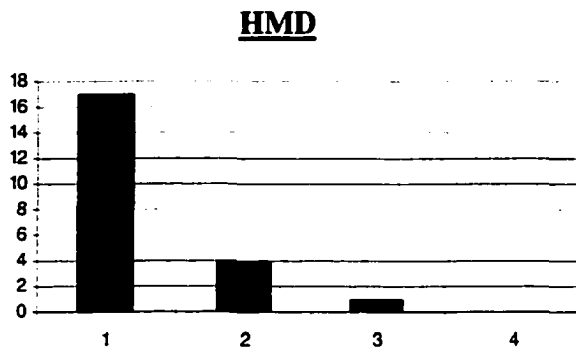
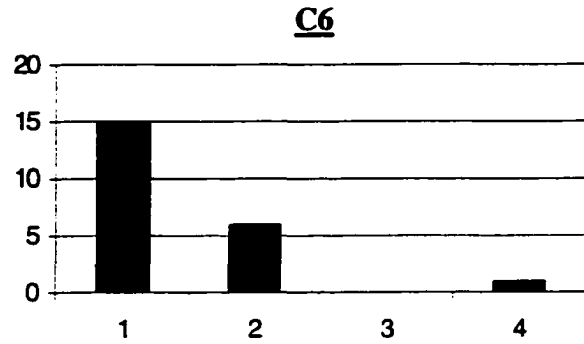
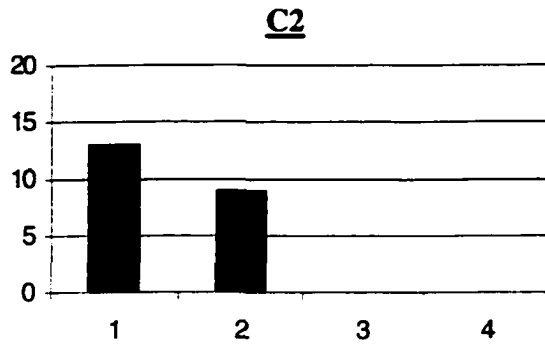
### Missed Targets

ANOVA for Missed Targets, by display device.

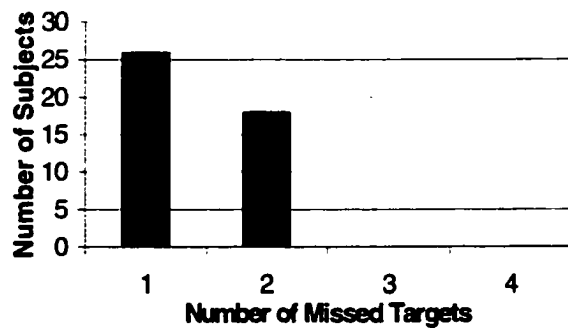
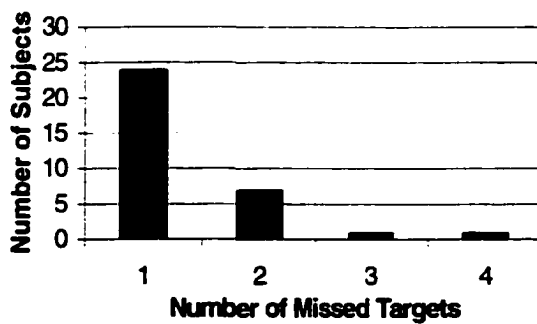
| SOURCE         | DF | SS     | MS    | F     | PROB> F |
|----------------|----|--------|-------|-------|---------|
| Between Groups | 3  | 0.584  | 0.195 | 0.553 | 0.648   |
| Within Groups  | 73 | 25.727 | 0.352 |       |         |
| Total          | 76 | 26.312 | 0.346 |       |         |

ANOVA for Missed Targets, by rotation method.

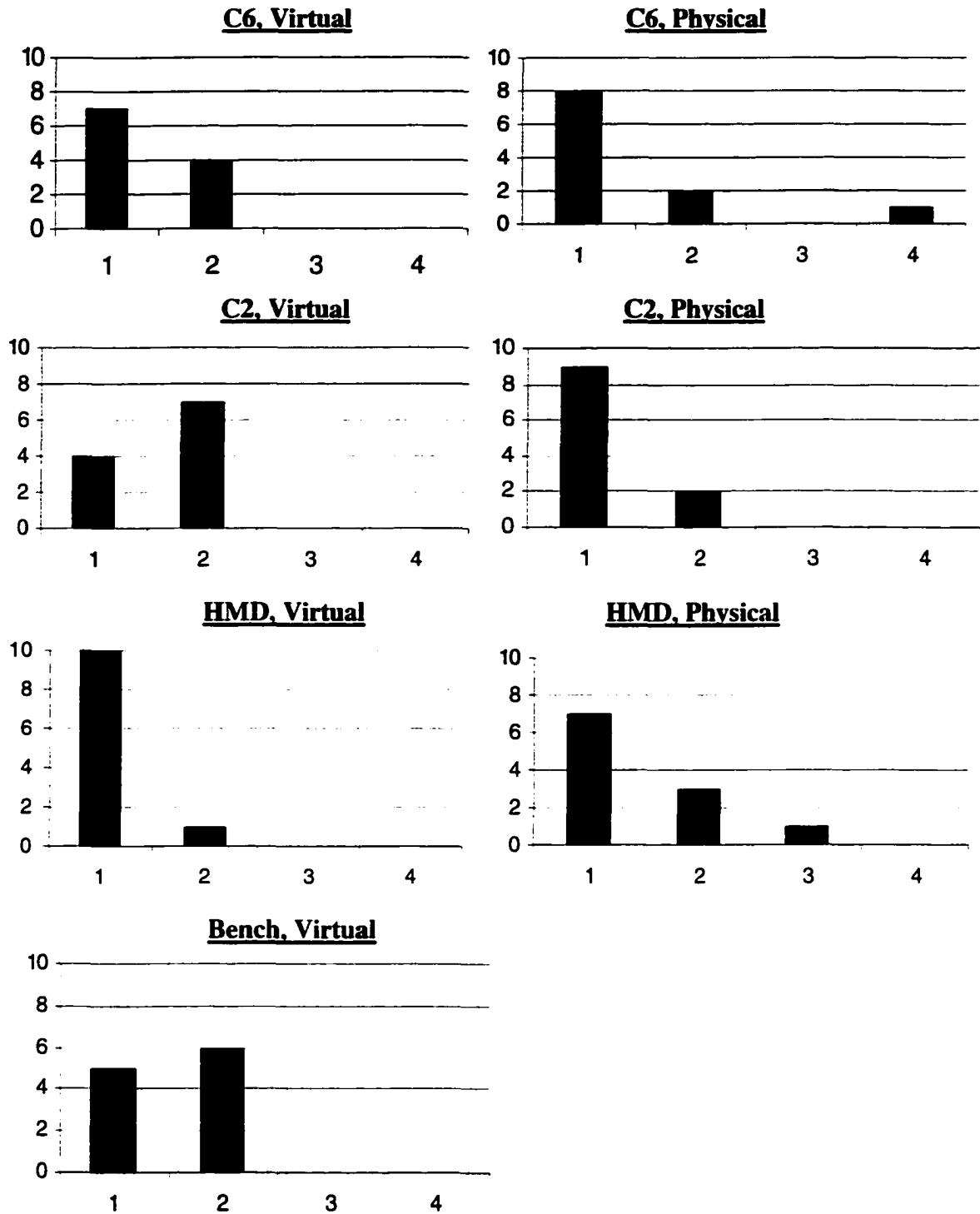
| SOURCE         | DF | SS     | MS    | F     | PROB> F |
|----------------|----|--------|-------|-------|---------|
| Between Groups | 1  | 0.039  | 0.039 | 0.111 | 0.740   |
| Within Groups  | 75 | 26.273 | 0.350 |       |         |
| Total          | 76 | 26.312 | 0.346 |       |         |



Missed Targets for each display device. Number of missed targets is shown on the horizontal axis, with number of subjects on the vertical axis.



Missed Targets of subjects assigned to (a) physical rotation and (b) virtual rotation.

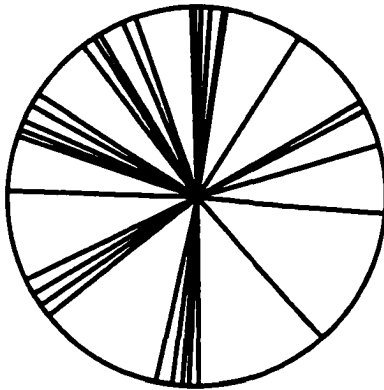


Missed targets for each experimental condition. Number of missed targets is displayed on the horizontal axis, with number of subjects on the vertical axis.

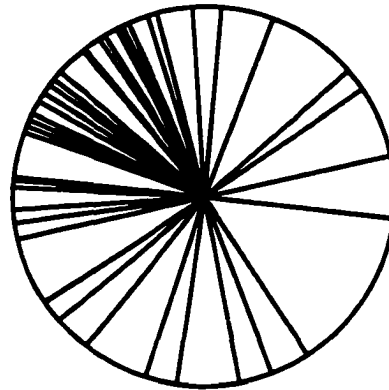
### Pointing Error

ANOVA for Pointing Error, by rotation method.

| SOURCE         | DF | SS         | MS       | F     | PROB> F |
|----------------|----|------------|----------|-------|---------|
| Between Groups | 1  | 0.573      | 0.573    | 0.000 | 1.000   |
| Within Groups  | 75 | 532715.947 | 7102.879 |       |         |
| Total          | 76 | 532716.519 | 7009.428 |       |         |

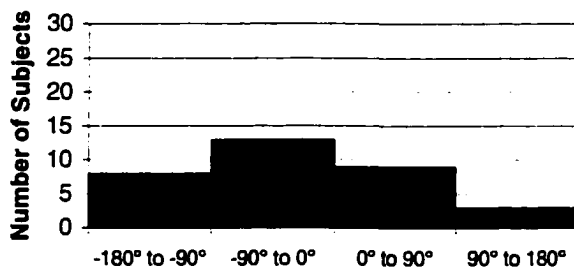


(a)



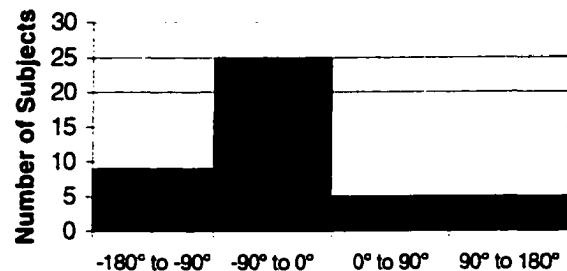
(b)

Pointing errors for (a) physical rotation (b) virtual rotation.



Pointing Error

(a)



Pointing Error

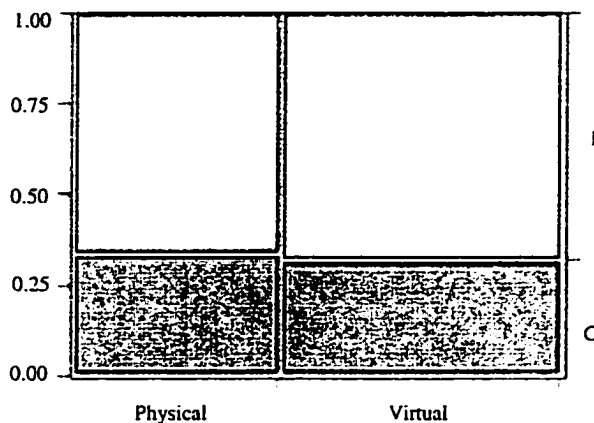
(b)

Pointing errors for (a) physical rotation (b) virtual rotation.

### Floorplan Identification

|          | Correct       | Incorrect     |
|----------|---------------|---------------|
| Physical | 11<br>(14.29) | 22<br>(28.57) |
| Virtual  | 14<br>(18.18) | 30<br>(38.96) |
|          | 25<br>(32.47) | 52<br>(67.53) |

Contingency table for floorplan choice, by rotation method.



Mosaic plot for floorplan choice, by rotation method.

### Effect of Gender

ANOVA for Presence, by gender.

| SOURCE         | DF | SS        | MS      | F     | PROB> F |
|----------------|----|-----------|---------|-------|---------|
| Between Groups | 1  | 154.807   | 154.807 | 0.825 | 0.366   |
| Within Groups  | 75 | 14065.505 | 187.540 |       |         |
| Total          | 76 | 14220.312 | 187.109 |       |         |

ANOVA for Completion Time, by gender.

| SOURCE         | DF | SS          | MS        | F     | PROB> F |
|----------------|----|-------------|-----------|-------|---------|
| Between Groups | 1  | 4128.028    | 4128.028  | 0.174 | 0.677   |
| Within Groups  | 75 | 1774353.219 | 23658.043 |       |         |
| Total          | 76 | 1778481.247 | 23401.069 |       |         |

## ANOVA for Missed Targets, by gender.

| SOURCE         | DF | SS     | MS    | F     | PROB> F |
|----------------|----|--------|-------|-------|---------|
| Between Groups | 1  | 0.021  | 0.021 | 0.061 | 0.806   |
| Within Groups  | 75 | 26.290 | 0.351 |       |         |
| Total          | 76 | 26.312 | 0.346 |       |         |

## ANOVA for Pointing Errors, by gender.

| SOURCE         | DF | SS         | MS       | F     | PROB> F |
|----------------|----|------------|----------|-------|---------|
| Between Groups | 1  | 1180.000   | 1180.000 | 0.166 | 0.684   |
| Within Groups  | 75 | 531536.519 | 7087.154 |       |         |
| Total          | 76 | 532716.519 | 7009.428 |       |         |

**Gender and Spatial Abilities**

## ANOVA for S1, by gender.

| SOURCE         | DF | SS        | MS      | F     | PROB> F |
|----------------|----|-----------|---------|-------|---------|
| Between Groups | 1  | 288.249   | 288.249 | 0.346 | 0.558   |
| Within Groups  | 75 | 62559.829 | 834.131 |       |         |
| Total          | 76 | 62848.078 | 826.948 |       |         |

## ANOVA for S2, by gender.

| SOURCE         | DF | SS       | MS     | F     | PROB> F |
|----------------|----|----------|--------|-------|---------|
| Between Groups | 1  | 44.329   | 44.329 | 0.460 | 0.499   |
| Within Groups  | 75 | 7220.190 | 96.269 |       |         |
| Total          | 76 | 7264.519 | 95.586 |       |         |

## ANOVA for SS1, by gender.

| SOURCE         | DF | SS       | MS     | F     | PROB> F |
|----------------|----|----------|--------|-------|---------|
| Between Groups | 1  | 47.716   | 47.716 | 0.941 | 0.335   |
| Within Groups  | 75 | 3804.648 | 50.729 |       |         |
| Total          | 76 | 3852.364 | 50.689 |       |         |

## ANOVA for SS3, by gender.

| SOURCE         | DF | SS       | MS     | F     | PROB> F |
|----------------|----|----------|--------|-------|---------|
| Between Groups | 1  | 1.829    | 1.829  | 0.027 | 0.871   |
| Within Groups  | 75 | 5128.690 | 68.383 |       |         |
| Total          | 76 | 5130.519 | 67.507 |       |         |

**Floorplan Identification and Pointing Error**

## ANOVA for Pointing Error, by floorplan choice correct/incorrect.

| SOURCE         | DF | SS        | MS      | F      | PROB> F |
|----------------|----|-----------|---------|--------|---------|
| Between Groups | 1  | 4098.96   | 4098.96 | 0.5816 | 0.4481  |
| Within Groups  | 75 | 528617.56 | 7048.23 |        |         |
| Total          | 76 | 532716.52 |         |        |         |

### Floorplan Identification and Completion Time

ANOVA for Completion Time, by floorplan choice correct/incorrect.

| SOURCE         | DF | SS          | MS        | F     | PROB> F |
|----------------|----|-------------|-----------|-------|---------|
| Between Groups | 1  | 35803.576   | 35803.576 | 1.541 | 0.218   |
| Within Groups  | 75 | 1742677.671 | 23235.702 |       |         |
| Total          | 76 | 1778481.247 | 23401.069 |       |         |

### Video Game Effect

ANOVA for PQ score, by gaming experience.

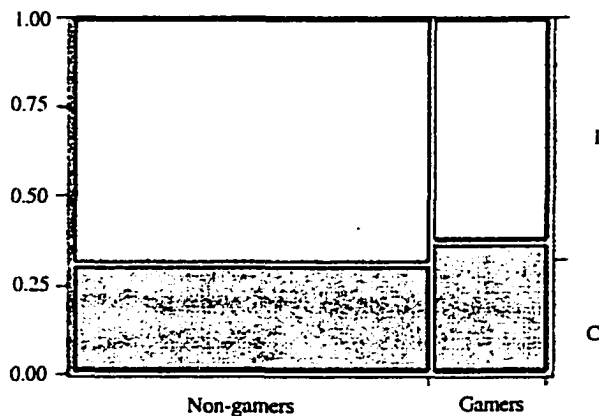
| SOURCE         | DF | SS        | MS      | F     | PROB> F |
|----------------|----|-----------|---------|-------|---------|
| Between Groups | 1  | 9.085     | 9.085   | 0.048 | 0.827   |
| Within Groups  | 75 | 14211.227 | 189.483 |       |         |
| Total          | 76 | 14220.312 | 187.109 |       |         |

ANOVA for completion time, by gaming experience.

| SOURCE         | DF | SS          | MS        | F     | PROB> F |
|----------------|----|-------------|-----------|-------|---------|
| Between Groups | 1  | 31313.965   | 31313.965 | 1.936 | 0.168   |
| Within Groups  | 74 | 1197180.982 | 16178.121 |       |         |
| Total          | 75 | 1228494.947 | 16379.933 |       |         |

ANOVA for pointing error, by gaming experience.

| SOURCE         | DF | SS         | MS       | F     | PROB> F |
|----------------|----|------------|----------|-------|---------|
| Between Groups | 1  | 4882.811   | 4882.811 | 0.694 | 0.408   |
| Within Groups  | 75 | 527833.709 | 7037.783 |       |         |
| Total          | 76 | 532716.519 | 7009.428 |       |         |



Mosaic plot for floorplan response, by gaming experience.

## APPENDIX M: RESPONSES TO GENERAL POST-QUESTIONNAIRE

All responses begin with the ID number of the subject making the response.

Responses within each question are ordered by subject ID number. All responses are as written by the subjects. Any corrections or comments by the author are in parentheses and preceded by the notation "lla:".

### 1. Did you enjoy your experience?

|                       |                 |                                  |
|-----------------------|-----------------|----------------------------------|
| 2: yes                | 63: Yes         | 143: Yes                         |
| 4: yes                | 64: yes         | 145: yes and no                  |
| 5: yes                | 68: Yes.        | 151: interesting                 |
| 6: yes                | 69: Yes!        | 155: Yes.                        |
| 9: enjoyed!           | 73: yes         | 156: Yes                         |
| 12: yes               | 81: Yes I did.  | 159: Yes.                        |
| 13: yes, very much.   | 89: Yes         | 163: Yes                         |
| 15: yes               | 91: yes         | 177: I did enjoy the experience. |
| 22: yes, very much    | 94: yes         | 178: yes                         |
| 26: yes, very much so | 99: yes         | 181: yes                         |
| 29: yes, very much    | 101: yes        | 183: yes                         |
| 32: yes               | 104: Yes.       | 188: yes                         |
| 33: It was fun!       | 106: Yes.       | 189: yes I did.                  |
| 34: yes               | 111: yes        | 190: yes                         |
| 35: yes               | 113: Yes I did. | 191: yes                         |
| 38: yes               | 120: Yes I did  | 197: yes                         |
| 39: yes               | 122: Yes        | 201: yes                         |
| 40: yes               | 124: Yes        | 202: yes                         |
| 45: yes               | 125: Yes        | 203: yes and no                  |
| 46: yes               | 127: yes.       | 206: yes                         |
| 48: yes!              | 129: yes        | 208: yes                         |
| 55: yes               | 134: yes        | 210: yes                         |
| 59: yes               | 137: yes        | 215: yes                         |
| 60: yes               | 140: yes        | 220: yes                         |
| 61: yes               | 141: yes.       |                                  |
| 62: yes               | 142: Yes.       |                                  |

### Why or why not?

- 2: It was unique! However feel somewhat motion sick and kept self too tense.
- 4: I was a bit nauseous. I did enjoy the experience though!
- 5: The motion was smooth and realistic
- 6: I enjoyed working with the new technology and trying the novel experience.
- 9: Fun to try something new. Interesting, stimulating. Also I felt a little unsure and self-conscious. Afraid to "walk" into a wall, etc.
- 12: it was new to me, and fun. I would have liked to "play" with it awhile longer. I think I had a sense of needing to get through it quickly, rather than looking around - I should have "played" more.
- 13: It was a very interesting very exciting thing to do. Very interesting to see how much your eyes control your body.
- 15: It was interesting and for the most part felt like walking through an actual building.
- 22: It is kind of realistic and a very beautiful building to see
- 26: I really felt as I was physically moving around.
- 29: colors, shapes, presence of texture, depth, illusion, very well planned out
- 32: It was neat to get a chance to try this out. I have heard a lot about it. It was better than I thought.
- 33: The only problem I had was with turning - the world turned very fast
- 34: I thought it was neat how you really felt like you were in the building.
- 35: it was great to try this out!
- 38: I haven't ever done anything like that before.
- 39: Interesting and fun. Pretty much like a video game
- 40: but I was more focused on the hand held mechanism. By the end I was more comfortable with it but ended too fast.
- 45: I had never done it.
- 46: I enjoyed it. It was something new and useful
- 48: What an amazing concept. This could provide opportunities to study places and things that are inaccessible to most people.
- 55: it gave me a chance to experience this firsthand. It was different than I thought, though. I really didn't have a good idea on what to expect.
- 58: Initially very enjoyable doing the practice - excited to try the technology; however became a little uncomfortable as I went too fast and became claustrophobic
- 59: video game like experience. Felt almost real
- 60: I could imagine using this "vr" tour to help people view new environments.
- 61: it was interesting to get a feel of what it was like in this type of environment.
- 62: Very interesting moving around. I was surprised how easy it was to use. After I felt more comfortable, I could move faster around the building.
- 63: Enjoyed testing my response/reaction to movement in the program
- 64: it felt like I was playing a game
- 68: The most interesting aspect of the control was being able to walk in one direction while looking in another. I was not "afraid" to "fall" out the window, but did not want to start over, looking for the arrows from the entry point. I thought there would only be direction arrows in the rooms/hall immediately adjacent to the next red spot. The

- movement was definitely more like being on an electric vehicle: more like a wheelchair than walking. I enjoyed going through the donut sculpture and over furniture. I think I should have tried to look around the outside of the building first then I would have found the tree, seen the orientation of windows, etc, then I could have determined my final position relative to the entrance.
- 69: It was neat to be able to look where I wanted, go where I wanted, etc. I like that I could clearly make out pictures on the walls and see out windows.
- 73: It was fun to test my navigation skills in the virtual reality environment.
- 81: I liked to "see and walk" around the building and to have the idea that was real.
- 89: It is something I have never experienced before
- 91: the stairs were a little weird trying to walk up
- 94: at first it was dizzying but after awhile it felt more like a gaming environment and I was beginning to feel better able to handle the control.
- 99: could be useful in a lot of ways
- 101: It was fun - kind of like a video game
- 104: It was the first time I've ever been in a VR experiment
- 106: It was interesting to see. I wish it could have been longer and perhaps a little easier to explore. It would be nice if it were a full cube
- 111: It was a first, more than anything. That, and I liked the building's décor.
- 113: The experience was like a 3D shooter on PCs, but much more impressive
- 120: it was neat to see how that works and enjoy it.
- 122: it was cool the way that I moved and went upstairs. I enjoyed how realistic it was looking out the windows.
- 124: My mind told me I was walking but my legs told me that I was not walking. The contradiction gave me a weird feeling that I liked kind of like a roller coaster.
- 125: it was really cool but it seemed kinda hard to turn around and the glasses were kinda big.
- 127: The simulation was very realistic. I liked how I could look around at everything.
- 129: gave a different perspective on movement
- 134: It was fun to me because I've never experienced VR here before.
- 137: It was an almost real experience, and it surpasses all the role playing video games I ever played
- 140: I have never had any experience with virtual reality before and I was really excited to get to participate. I really felt like I was moving part of the time and that was neat.
- 141: It was really interesting to feel like you're really walking around in another world. Especially going up steps and down steps quickly. It feels very real.
- 142: It was very impressive. I enjoyed being in control of my movement.
- 143: It was interesting how I could interact with what was going on: being able to control where I was going
- 145: new experience (and see next question)
- 151: made me a little "seasick"
- 155: very realistic. Very exciting the possibilities with such detailed VR environments.
- 156: it was fun to see a virtual world. The only thing I didn't like is that I couldn't move as freely in the virtual world as I would have in real life.

- 159: I did enjoy doing this but I wish there was something a little more exciting than walking around a house.
- 163: I enjoyed the experience because it was something totally new. The challenge of running over the red dots and trying to keep the shape in mind was stimulating.
- 177: It was like a giant video game. The longer I was there the more comfortable I was to have fun.
- 178: however it was a bit difficult missing an entire wall. Made me feel a blind spot.
- 181: It was a very interesting experience unlike anything I've ever done before. It felt like I was just gliding along. Very cool feeling.
- 183: it was fun to see the different environments
- 188: very interesting, I had never had any VR experience.
- 189: Realistic, nice to be in control, relatively free movement
- 190: It's amazing
- 191: enjoyable because it was a new experience. A little frustrating because I felt inept with the controls.
- 197: I'd never done anything like that before and it was smooth and the controls were easy to use.
- 201: it was like I was actually going through the building
- 202: because I have never done anything having to do with virtual reality and it was amazing to me how real it feels.
- 203: since I have never put on a VR headset before... that was interesting, but frustrating that I couldn't answer the questions better...
- 208: it was a very weird feeling, but a interesting experience
- 210: The images were very realistic. It was enjoyable to be able to look through a cathedral and see the detail VR is able to show.
- 215: it was interesting to "move" without any real sensation of movement, and to be able to walk off of a high place just for the heck of it.
- 220: but I became disoriented while upstairs

**2. Did you experience any negative effects including, but not limited to: motion sickness, headache, nausea, eye strain, dizziness, disorientation? If so, please describe which ones and their duration.**

- 2: some nausea when turned too fast (motion sickness). Little disorienting (only when turning and moving up
- 4: motion sickness and nausea the whole time. It also seemed a little out of focus, which may have been part of my problem.
- 5: very slight disorientation. I wanted to tip forward where I stopped
- 6: Some disorientation, especially when looking up or down, or when trying to look to the side while moving.
- 9: At one time I felt that I could become a little motion sick and slowed down.
- 12: disorientation. It was very difficult for me to maintain a sense of direction and distance traveled.

- 13: I experienced dizziness and momentary disorientation but I would not call it a negative experience any more than one might call riding a roller coaster a negative experience.
- 15: Slight eye strain. I think it would be worse with longer use.
- 22: When I hit the wall of the building, I did feel a little bit uncomfortable because, I think, it looks like a real building and I don't want to hurt myself and the building.
- 26: small amounts of nausea when near objects
- 29: disorientation: felt at time not sure of hand controller. Where fingers to hit correct buttons
- 32: motion sickness, headache, eye strain, not for very long - kinda felt like car sickness, but stopped once I took it off.
- 33: motion sickness, dizziness. I was ok until I had to turn more than 90 degrees. It was alright when I went in a straight line or turned slowly.
- 34: I felt a little dizziness at the very beginning
- 35: got a little woozy when I turned too fast. Or when the thing didn't keep up with me.
- 38: No, maybe a bit of disorientation
- 39: no
- 40: no. if I did it was more of a disorientation of combining the two
- 45: dizziness came and went depending on how fast I turned. Nausea the whole time, but not bad. Disorientation when turning too fast and I felt like I was being carried further than I should after I stopped
- 46: little eye strain
- 48: disorientation - brief: usually when "walking" through objects (furniture, walls)
- 55: A little bit of nausea when I got to moving too fast but very minor and for only a short duration.
- 58: motion sickness including slight nausea - throughout the experiment due to proceeding too fast on practice (spiral staircase); I have difficulty when what I see does not correspond to body's sensations.
- 59: no effects
- 60: A little nausea/motion sickness
- 61: yes, a little dizziness for about a couple minutes
- 62: None
- 63: dizziness - short, only when I hit a wall
- 64: no
- 68: The only negative experience was getting "stuck" next to/inside a wall a couple times where the red spots were very close to a wall. But I knew that software was "running" my environment, and that if I turned slowly and tried to move away from the wall, I could resume normal navigation, and that I did.
- 69: small bit of motion sickness, but not bad. Not enough to make me want to stop.
- 73: no
- 81: Disorientation for a few seconds.
- 89: A bit of motion sickness
- 91: I was not able to turn around easily without confusing myself of where I was
- 94: a little dizziness for less than 30 seconds
- 99: dizziness if you spun around in the building
- 104: A little disorientation for about half of a minute.

- 106: No
- 101: no
- 111: There was disorientation and it tended to last about 30 seconds before I got my bearings again.
- 113: None.
- 120: I felt just a little dizziness.
- 122: No
- 124: I felt a little disoriented at first but I feel I was improving at maneuvering. After the practice I was not ready for the curved walls they made me feel a little dizzy.
- 125: I started to get a headache about 10 min into it
- 127: Disorientation. My legs weren't moving, but my brain thought they were. It only lasted a few seconds.
- 129: None
- 134: Dizziness when I looked down at my feet in the VR and a little disorientation at the end. Slight headache after, but might have been from the head set.
- 137: Only during the experiment if I walk too fast or take sudden turns will I see a little dizzy, only lasts about 3 seconds.
- 140: Motion sickness and nausea (a little) it started at the end of the practice area.
- 141: I ended up spinning around once but that's the only time I felt dizzy.
- 142: No
- 143: Not really, but if I picked one thing it would be that my knees wanted to bend when I'd stop and turn around
- 145: queasiness
- 151: yes - motion sickness
- 155: Nope
- 156: I did feel disorientated in the maze. I couldn't tell where I was or where I should go. I was a little warmer during the experiment.
- 159: For brief periods I felt minor nausea when I was going fast and stopping quickly, or when I turn around too fast.
- 163: Yes. I experienced dizziness for about five minutes because I was moving and twirling too quickly. This also led to a little nausea, but it went down after a small break.
- 177: At first I was very disoriented. The floor and behind me confused me.
- 178: no
- 181: yes, mild dizziness and nausea. The dizziness went away as I got used to the equipment. The nausea got worse as I went along, but not to a very high level.
- 183: some motion sickness, not much at all though
- 188: dizziness and eye strain after I was done
- 189: No
- 190: when I hit the wall and climb the stairs at a faster speed I feel a little bit of dizziness
- 191: I was disoriented at times because of my limited means of movement (mostly the inability to back up) so I had to spin around in circles.
- 197: none
- 201: disorientation - I couldn't figure out where I was a couple of times.
- 202: motion sickness, just briefly
- 203: I currently feel some motion sickness

- 206: dizziness going up and down or whatever without actually moving is strange at first.  
Only lasted for a second
- 208: I felt motion sick pretty much through the whole thing
- 210: I didn't experience any negative effects.
- 215: Definitely disoriented, couldn't keep track, but that's no different from normal.
- 220: I became disoriented and felt like I could have been floating

### **3. What (if anything) would improve the virtual world experience?**

- 2: maybe more color - e.g. different colored walls?
- 4: I'd like to do it sitting down.
- 5: More texture to the surfaces
- 6: A more physically relaxed position (e.g. sitting) or some kind of tactile feedback.
- 9: I would have felt more comfortable sitting down.
- 12: More time becoming familiar with the controls, so that could have concentrated fully on the task during the search for red spots and following arrows. Better control over looking up and down would help.
- 13: no wires and some of the images were out of focus. I would like to see the virtual world seem a bit less flat and more like the natural world.
- 15: Sound and more smooth transitions at objects
- 22: I feel the color of everything I see is not "thick" enough. I feel it is kind of "transparent", but just a little bit.
- 26: More of a point to the experience, like a video game.
- 29: possible: add hidden features, possible cat running from room, ceiling fan - however that may add to some motion sickness
- 33: Perhaps a smaller change in the acceleration and brake controls
- 35: need a happy medium between 1 click and 2 click speed
- 38: Starting from outside the front of the structure.
- 39: I would have liked to "back up" instead of just being able to turn and go forward and to also be able to look up and down.
- 40: I guess just feeling more comfortable
- 45: It got to where I was looking for red dots rather than trying to analyze the space.
- 46: sometimes colors are too bright
- 48: more time!!!
- 55: Maybe a darker environment with more crisp projection to make it seem more real.  
Sounds to set the environment. I don't know if this is necessary for first-timers.
- 58: sitting down would have helped me
- 59: 6 walls, no cords
- 60: Sound could improve experience
- 61: I thought it went very well.
- 62: None that I can think of.
- 63: Picture seemed a little fuzzy - but that could be my eyes. Tables, furniture too easy to walk through
- 64: sound, like if I bumped into a wall or was walking on the floor

- 68: Make walls hard so I can't get stuck in them. Add sounds of my footsteps which are keyed to surface qualities, acoustics, and my speed. Ability to lean out a window and look up, down, left, right. Add interactive buttons (eg. Turn on the TV, get into an elevator, etc)
- 69: It would be fun to be able to see real places in the world through this.
- 73: surround image
- 81: The images. If it is possible to make them more clear, I think could be much better.
- 89: Nothing I can think of. It was very interesting.
- 91: Easier way of turning
- 94: Sound to go with (match) the environment
- 99: more sides and sharper image
- 101: More practice with controls would be nice.
- 104: Having a fourth wall.
- 106: It would be nice to see above and behind you.
- 111: Peripheral vision would make navigation and just enjoying the view vastly better. I suppose photo realism would tend to help if I experienced it all the time. A quick and easy pair of buttons to let you see the floor and ceiling could help too.
- 113: The corners of the cube were a tad disorienting, just the "wrap-around" effect. More effective controls would be useful too.
- 120: Being able to try it more.
- 122: Pressure gloves or suits so that you can touch things.
- 124: The walls and carpet being the same color at certain points makes it very hard to navigate maybe make them contrast each other. The graphics need to be improved so things don't look like they are made of legos.
- 125: If it went all around you, that way it would be easier to do a 180 degree turn without running off of the screen. Some of the obstacles didn't appear until I was right up next to them.
- 127: Some sounds to make it really realistic.
- 129: Directional arrows should stand out more.
- 134: I think maybe headphones because I could hear people talking, and that brought me out of the VR world.
- 137: I can see the difference of projectal light on walls and the ceiling; there is an "edge" and the color is a little different on walls and ceiling.
- 140: I think it would have been better if I had been a little shorter.
- 141: It looked like there was a slight vertical line on the right side of me, but that may not be a problem.
- 142: I can't think of anything
- 143: Being able to manipulate objects in the environment
- 145: sitting with steering wheel; remote
- 155: Full immersion head set... possible simple sounds?
- 156: More specific movements, so when I move, the virtual world would move exactly like me.
- 159: As said before, I wish it was something more exciting, but all-in-all I enjoyed it
- 163: Perhaps having a little cold water handy would help the dizziness. Keeping the shape in mind would be much easier if the walls had more structure/texture and more color.

Walking around the virtual church was much easier on the mind and eyes because one could look to landmarks to orient oneself in space.

- 177: I would change the equipment. The glasses need to fit better and if the controller were like a Nintendo paddle it would be easier. Also, sensors on the body would help.
- 178: a fourth wall, and maybe controls that do not involve acceleration and deceleration, but maybe a force button you have to hold down, or you should at least slow down as you move, or it gets to feel a bit out of control.
- 181: not much. Maybe being able to interact with the environment with my hands or feet.
- 183: make it easier to move around (the speed). I liked everything else though.
- 188: not so many tables and chairs in the way
- 189: A cordless head-set
- 190: sounds would be great
- 191: ability to "back up"
- 197: brighter color for objects up close. Walls and floor and ceiling different colors.
- 202: a fourth wall (if possible??)
- 203: A purpose other than "pretend you are an architect"
- 206: The ability to actually move and look all around
- 210: The only problem was that the 3D glasses were hard to keep on my eyes, they didn't fit well so I had to hold them with my free hand.
- 215: maybe sounds or more objects to look at.

#### **4. Any additional comments?**

- 2: pretty neat! Easy to use controls but they are slightly oversized for my hand.
- 6: I wish this questionnaire were on a computer so I didn't have to write responses by hand.
- 12: I rarely become disoriented outside, but I do often become disoriented inside, particularly if I'm with someone who is leading me around. I found my lack of familiarity with the maneuvering controls, and hence my concentration on moving around, to be distracting while I was moving through the building.
- 22: It's really a good program. Everything I saw is almost real.
- 26: Lots of fun!
- 29: for a first time experience I loved it!
- 40: It was hard after focusing on hitting the red dots. You focus on that. I was more looking at the furniture and art. I guess my mind was not quite on the building
- 48: Can I go again!?
- 55: Overall, a great first exposure! I love it... I wish I could show it off to my friends. It seemed like I had control of acceleration but the brake stopped me abruptly.
- 58: if motions/body sensations could correspond to visual it would be easier.
- 60: very interesting
- 62: I wish I would have knelt down to observe some of the artwork. I also get lost in buildings easy.
- 68: Advise users to cool off before putting on the headset: I was over heated from the walk to Howe Hall and had one foggy eyepiece during the first part of the experiment.
- 91: needs a back wall
- 99: enjoyed the experience

- 111: The world would be more convincing if there were other buildings, more trees, cars, streets, etc visible outside the window.
- 120: I thought this was neat experiment and was a little difficult, since I have not had any experience with virtual reality before.
- 122: It would be nice to play Quake.
- 127: Thanks for letting me do it!
- 134: I really enjoyed it. The graphics were nice.
- 140: I was surprised at how when I started "walking around" I was completely oblivious to what was actually going on around me. I was really into the experiment.
- 141: It was a great experience. I really enjoyed it! (11a: subject also verbally suggested elastic band to help hold glasses on)
- 143: It was really interesting how well I saw in 3D since I've never had good depth perception due to have one far and one near sighted eye
- 151: I was lost most of the time I was in the building
- 155: very realistic very cool
- 177: It was really fun and it would have been better if it were some type of a game.
- 181: lots of fun! Thanks for the opportunity!
- 183: Thank you for this opportunity!
- 191: the floorplan was totally confusing
- 210: I had fun!

## APPENDIX N: RESPONSES TO LOCOMOTION POST- QUESTIONNAIRE

All responses begin with the ID number of the subject making the response.

Responses within each question are ordered by subject ID number. All responses are as written by the subjects. Any corrections or comments by the author are in parentheses and preceded by the notation “lla:”.

1. Which of the following best describes your experience in learning to travel through the virtual world? (please do not consider whether or not you “liked” the travel controls, consider only whether you were able to understand their operation)
  - It was very easy and straightforward. I learned how to travel without difficulty.
  - It was a little difficult to control at first, but I was able to learn how to travel during the practice environment.
  - It was difficult to learn how to travel. I did not feel comfortable with the controls until I was partway through the actual experiment.
  - I did not understand the travel controls. I never became comfortable with using them.
  - Other. Please explain:

Subject responses to this question were recorded using the number representing their order within the above question. For example I=It was very easy and straightforward. I learned how to travel without difficulty.

|       |       |       |        |        |
|-------|-------|-------|--------|--------|
| 2: 1  | 29: 2 | 48: 1 | 69: 1  | 111: 2 |
| 4: 2  | 32: 1 | 55: 1 | 73: 2  | 113: 1 |
| 5: 1  | 33: 1 | 58: 1 | 81: 2  | 120: 2 |
| 6: 3  | 34: 2 | 59: 2 | 89: 2  | 122: 1 |
| 9: 2  | 35: 1 | 60: 2 | 91: 2  | 124: 2 |
| 12: 2 | 38: 1 | 61: 2 | 94: 2  | 125: 2 |
| 13: 2 | 39: 1 | 62: 2 | 99: 2  | 127: 2 |
| 15: 1 | 40: 3 | 63: 1 | 101: 2 | 129: 2 |
| 22: 1 | 45: 2 | 64: 1 | 104: 2 | 134: 2 |
| 26: 1 | 46: 1 | 68: 2 | 106: 4 | 137: 1 |

|                           |        |        |
|---------------------------|--------|--------|
| 140: 5 – I understand how | 156: 2 | 201: 2 |
| the controls work,        | 159: 2 | 202: 2 |
| but I think I             | 163: 2 | 203: 2 |
| needed a little           | 177: 3 | 206: 2 |
| more time to              | 178: 1 | 208: 2 |
| master them.              | 181: 1 | 210: 1 |
| 141: 1                    | 183: 1 | 215: 1 |
| 142: 2                    | 188: 3 | 220: 2 |
| 143: 1                    | 189: 1 |        |
| 145: 2                    | 190: 2 |        |
| 151: 2                    | 191: 2 |        |
| 155: 1                    | 197: 1 |        |

**2. Were you able to use the travel controls to effectively perform the requested tasks?**

- **Yes, the travel controls allowed me to perform all the needed tasks.**
- **Mostly, but there were a few things that were difficult to do (going through doorways, turning corners, etc) because of the travel controls.**
- **No, the travel controls were inadequate.**
- **Other. Please explain:**

Subject responses to this question were recorded using the number representing their order within the above question. For example 1=Yes, the travel controls allowed me to perform all the needed tasks.

|       |                       |        |        |                  |        |
|-------|-----------------------|--------|--------|------------------|--------|
| 2: 1  | 34: 4 – I felt they   | 62: 2  | 113: 1 | 155: 1           | 201: 1 |
| 4: 2  | were very effective   | 63: 2  | 120: 2 | 156: 2           | 202: 2 |
| 5: 1  | except at the stairs. | 64: 1  | 122: 1 | 159: 1           | 203: 2 |
| 6: 2  | 35: 1                 | 68: 1  | 124: 1 | 163: 2           | 206: 2 |
| 9: 1  | 38: 1                 | 69: 1  | 125: 2 | 177: 2           | 208: 2 |
| 12: 1 | 39: 1                 | 73: 2  | 127: 1 | 178: 1           | 210: 1 |
| 13: 1 | 40: 2                 | 81: 2  | 129: 1 | 181: 1           | 215: 1 |
| 15: 2 | 45: 2                 | 89: 2  | 134: 1 | 183: 1           | 220: 2 |
| 22: 1 | 46: 2                 | 91: 2  | 137: 1 | 188: 2           |        |
| 26: 1 | 48: 2                 | 94: 2  | 140: 2 | 189: 1           |        |
| 29: 1 | 55: 1                 | 99: 2  | 141: 1 | 190: 1           |        |
| 32: 2 | 58: 1                 | 101: 2 | 142: 1 | 191: 2           |        |
| 33: 1 | 59: 2                 | 104: 2 | 143: 1 | 197: 4 – Slowing |        |
|       | 60: 2                 | 106: 2 | 145: 2 | down was hard    |        |
|       | 61: 1                 | 111: 1 | 151: 2 | to get used to   |        |

**3. Did the travel controls interfere with your spatial abilities (that is, did the controls cause you to become disoriented or lose your way)?**

2: sometimes I moved too fast: causing problems. Not necessarily a control issue - just would need more experience/practice.

4: no

5: no

6: Not intrinsically. My source of disorientation was the inconsistency between the purely visual virtual world and my tactile sensations.

9: The wire attached to controls was a little distracting when I looked in that direction.

12: yes, the controls were unfamiliar, so concentrating on them made me less aware of the virtual world around me.

13: no

15: Somewhat. There is no peripheral vision, which makes it hard to see where you are in relation to objects.

22: no

26: only mildly

29: no

32: sometimes they moved too fast - especially turning

33: The controls didn't bother me - only some motion sickness

35: turning seem slow or fast compared to what I asked it to do sometimes

34: no

38: Just a lack of depth perception.

39: trouble finding a comfortable speed. Always too fast or too slow. But did not get disoriented within the hallway

40: At the beginning but halfway through the actual experiment I felt more comfortable

45: no

46: yes

48: no

55: no

58: no

59: no, it was more of not having 4 directions of view

60: no, somewhat opposite to this statement: braking/slowing down let me become more aware of my surroundings

61: yes, but only for a few seconds

62: No

63: No

64: I could not see what was to the side of me, so you had to stop to look around

68: Generally, no. except for the times I got stuck at a wall.

69: No, looking around and turning my head helped.

73: no

81: Not at all.

89: At times became disoriented

91: yes, I had problems turning and that confused me

94: No

- 99: you had to pay attention to the controls and that meant less time looking at what was going on.
- 101: For the most part no. I did have trouble turning sharp corners though. I got messed up once.
- 104: No
- 106: Somewhat. I ended up trying to figure out how to stop or start and ended up in places that were difficult to get out of.
- 111: Yes, mainly when trying to stop and turn around. It was a bit difficult to fully stop (and hard to tell when I'd stopped) and easy to turn too fast.
- 113: No
- 120: Not really. I was able to keep up for the most part.
- 122: No, it took a little to get used to the turning by pointing, but that was all.
- 124: Yes, sometimes when I turned my head to the right and the controller to the left it was a little disorienting the same happened when turning my head to the left and the controller to the right.
- 125: yes, I was walking along a wall and somehow I got outside through a doorway and I couldn't figure out how to turn around.
- 127: No. Sometimes it reacted more quickly than I anticipated, but I was always able to compensate.
- 129: No
- 134: Maybe just the cord from the headset, but the hand control was fine.
- 137: A little bit, since only my head was turning.
- 140: No, it was just an unfamiliar area and so I got lost a little
- 141: no, it felt very realistic and was easy to move around.
- 142: No, I found it quite easy to move through the building.
- 143: No
- 145: yes
- 151: no
- 155: No
- 156: A little because I was concentrating on the control instead of my own movement.
- 159: not really: but I wish it was something more natural for forwards and backwards, like a joystick
- 163: The speed of the "gas pedal" made it hard to take in the surrounding environment.
- 177: Only when I didn't pay attention below. Also, going through the walls was a little confusing.
- 178: it was difficult when thing I wanted to see (ie. Arrows) were behind me and I could not turn to see them
- 181: no
- 183: not at all
- 188: only when I ran into walls
- 189: No
- 190: no
- 191: the need to turn in circles all the time did contribute to my sense of disorientation
- 197: no
- 201: if I turned the control and not my body: it confused me some.

202: no  
 206: no I didn't think about them much  
 208: no  
 210: no, I felt at ease using the controls  
 215: no  
 220: slightly, I lost my way upstairs

#### **4. Did you like the travel controls?**

4: yes, they were fine  
 5: yes  
 6: no strong feelings either way  
 12: controls were ok (lla: except for changes suggested)  
 15: yes  
 22: yes  
 26: yes  
 29: okay  
 34: yes  
 35: yes  
 38: yes  
 39: okay  
 40: okay  
 46: no  
 48: The controls were fine  
 55: yes  
 59: no  
 60: yes  
 61: yes  
 62: Yes  
 63: Yes  
 64: yes  
 68: controls were "ok".  
 69: Yes  
 73: Not especially.  
 81: The travel controls are ok, I think is no problem with them  
 89: It was ok.  
 91: They worked well, besides turning  
 99: I could get use to them

101: They were ok.  
 104: Yes  
 106: They were okay.  
 111: I liked them overall.  
 113: The travel controls were functionally useful  
 120: Yes I thought they were fine  
 124: no opinion  
 129: yes  
 134: yes.  
 137: yes  
 140: yes  
 141: yes  
 142: Yes  
 143: Yes  
 145: no  
 151: No.  
 155: Yes  
 156: sure  
 163: yes  
 177: No.  
 178: no  
 181: yes, they seemed to work very well  
 183: no  
 188: fine  
 189: yes  
 201: yeah  
 208: yes  
 215: sure  
 220: yes

**If no, please explain.**

- 2: easy to use but sometimes I missed the brake button: oversized for my hand.
- 9: wireless control
- 12: I would have liked better control of looking up and down
- 13: I think that the move button and the stop button could both be more sensitive. I did not figure out until about ¼ of the way in to the experiment that I did not have to push the forward button at all times to go.
- 15: they were straightforward
- 22: it seems not very realistic somehow
- 29: possible for me not use to using hand controls. I felt my ability in hand eye coordination was poor.
- 32: the "go faster" and "go slower" buttons were good
- 35: (lla: subject remarked during test: "it feels like turning the whole big box around the corner, rather than just turning myself")
- 39: nice and simple
- 40: Took a little time to figure out
- 45: Had I grown up with video games I'm sure I would have felt at home with them. I have almost no video game experience and had to concentrate.
- 46: they are not well assigned for all directions
- 48: I would get a bit trigger-happy and zoom through rooms and/or objects
- 58: would have preferred a different way to slow down rather than the button: would forget it
- 59: the wires made it difficult to make corners of more than 90 degrees
- 61: very easy to handle
- 68: Although my arm did not tire from holding the control, I sometimes forgot that I could not relax my arm naturally because of the control.
- 73: A joystick (or 4-way arrow) would have been better for forward and backward movement.
- 89: had troubles at times (ex. Getting around steps)
- 94: The trigger worked fine. The stop button seemed to be in an awkward or non-intuitive location.
- 111: It seems a lot more natural to point in the direction you want to go than to push an arrow pad.
- 122: I didn't care for the cords, they can get in the way.
- 124: They were not anything special but they could have been like a gamepad which would not be as realistic as the controller
- 125: The remote was pretty easy to use but when I wanted to turn around, I would go off the screen.
- 127: It was a little awkward at first, but I got used to it.
- 141: the hand held device was very easy to use.
- 143: They were okay for steering as long as you stood straight up
- 145: depressing button briefly should yield position, not velocity
- 151: The stop button was harder to reach, so by the time I got over to it, I usually hit stop rather than slow.
- 163: they were similar to driving a car

- 177: I think as mentioned before, it should be a control paddle or motion sensors on the body.
- 178: at times it felt a bit too out of control, as if I was on ice
- 183: it didn't help me feel that much involved
- 189: due to simplicity
- 190: I guess it depends on the situation. I like it because we don't really need to do an actual travel but on the other hand, to touch the/sense it using our sense ability is good too.
- 191: I liked the stopping ability but there were a lot of buttons I didn't know what to do with
- 197: slowing down seemed to happen too fast, but everything else worked great
- 201: allowed me to move at a comfortable pace
- 202: the button to slow down would have been easier to use if it was bigger and in a more comfortable place.
- 203: more difficult to coordinate head and body movement
- 206: They seemed sluggish but overly responsive when they kicked in.
- 210: For straightforward, basic tasks, the controls were sufficient. They are very good to start out with to get oriented with VR.

## **5. How could travel be improved?**

- 2: smoother transitions
- 5: a little smoother acceleration and deceleration
- 6: gradual braking, rather than all-at-once
- 9: could this be done in a round room instead of one with square corners?
- 12: A sliding control for velocity, from zero to fast, might have helped.
- 13: no wires
- 15: Add peripheral vision
- 22: maybe better if I slow down
- 26: speed changes could be smoother
- 29: maybe different type of hand controller. For those who aren't used to them.
- 33: The controls worked fine - maybe just slow down the difference between each click
- 34: I felt the speed and brake created quite drastic changes.
- 35: need "brake" in a better position
- 38: By having peripheral vision to give some sort of depth perception
- 39: need to be able to back up and to look up and down.
- 40: I would feel comfortable if you could look that direct and push the button to go that way and stop not worry about tipping the control.
- 46: by assigning controls for all directions
- 48: 4 walls instead of 3
- 55: Controlled by walking movement on a treadmill device would seem more real where you could set your pace.
- 58: correlate body sensations to visual world
- 59: wireless, glasses that fit better
- 60: not sure, travel was somewhat easy

- 61: maybe have a smaller bag for the controllers (11a: likely referring to the backpack type bag that the tracker box is housed in, and the wand is connected to, which the user must wear)
- 62: Maybe some indicator that you bumped into something, such as a red dot in the upper right hand corner.
- 64: have two other screens on the sides to see what is next to me (peripheral vision)
- 68: Sitting down would seem more natural. Since my only form of locomotion when standing is using my legs, and since travel in the VR environment does not simulate walking, it would be better or the user to imagine being in/on some sort of vehicle.
- 69: Probably impossible, but it would be cool if I could look down and see my "feet".
- 73: add reverse movement (backup)
- 81: The part related with "reverse". When I turned back, I felt a little difficult to do it; but it could be due to my lack of experience using the control.
- 89: Things were blurry on the left at times. Maybe headset didn't fit properly.
- 91: turning
- 94: Perhaps a joystick operation vs a remote-control style device. Except for the trigger, it closely resembled my TV's remote control which I have a "memory" of how to use. This might interfere with my ability to use the travel controls.
- 99: maybe a trigger that stopped and slowed when released and could be pointed like a hand gun.
- 101: A trigger mechanism for both stop and go might be easier.
- 104: Adding a fourth wall
- 111: Maybe an all-stop button? But more than anything, it still comes back to peripheral vision.
- 113: Perhaps by having two controls, one for locomotion and one for directing point of view.
- 120: Maybe if you held it down that demonstrated walking the lifting up would stop.
- 122: By a glove with the motions built in and a sensor on a belt to automatically sense direction.
- 124: Wireless joystick that when tipped forward moves forward, tipped backwards moves backwards, etc.
- 125: Make the screen all the way around.
- 127: Getting rid of the hand controller and using another mechanism to direct the computer where to go.
- 134: I think the stop button, when pushed once, should be slow down. And to stop you would hold it down.
- 140: I got really confused when I went out the window: I don't think that should be allowed.
- 141: steps are kind of difficult.
- 142: Maybe if we could move without having to face the control in the direction we want to go.
- 143: Direction of travel controlled by where you look?
- 155: A wheel to control footspeed instead of button for set speeds.
- 156: more clear of a picture
- 159: going up and down stairs seemed very jumpy and the stairs looked vertical when I was close to them
- 163: Once again, the uniform color of the walls made the task more disorienting.

- 177: It would be more life-like. There wouldn't be the actually having to perform tasks eg. open a door. Delays.
- 178: put deceleration on automatically, so you slow down when not holding the trigger button
- 181: peripheral vision would be cool
- 183: turning your head to look around...
- 189: cordless handset
- 190: use some sound?
- 191: "backing up" and ability to look up and down (without actually changing one's body position, more like tilting)
- 197: gradual speed control, like a throttle
- 208: It was fine
- 210: The only way would be to have a treadmill like floor to have the person physically walk through the environment.
- 215: it would be nice to be able to look at something and then back-up
- 220: I'm not sure, this was my first experience.

#### **6. How difficult was the pointing task at the end of the experiment?**

- 2: easy
- 4: pretty difficult, because my nausea was making me want to finish faster, rather than pay close attention to where I was.
- 5: Performing the task was simple. But knowing where to point was difficult.
- 6: I was totally lost. I had a good sense of what was around me locally, but couldn't integrate a model of what was where outside line-of-sight.
- 9: I only had a mental hunch which way to point: just a felling. I really hadn't thought about it during the test.
- 12: not difficult
- 13: not difficult
- 15: very, I had no idea where I had gone in relation to the starting point.
- 22: if between 0 and 10, I would choose 8
- 26: very difficult
- 29: very difficult. I usually know north from south but lost track of which directions I was going
- 32: a little difficult because I wasn't thinking at where to go, just how to get there
- 33: I was pretty confused by where I'd been
- 34: I thought it was easy until the door opened!
- 35: I completely guessed!
- 38: not difficult
- 39: not
- 40: very. I was lost and I was looking at the pictures and worried about hitting the red buttons.
- 45: knowing where to point was a guess.
- 46: not very difficult

- 48: Difficult; I concentrated on finding the “dots” and had little regard for the actual “trip”
- 55: Not too difficult
- 58: not difficult
- 59: I was a little disoriented with direction
- 60: By going extremely slow (comfortable to me), the pointing task was fairly easy.
- 61: Not difficult
- 62: It was easy
- 63: somewhat
- 64: very difficult because I didn’t know I was supposed to remember that, so I didn’t even think about it until the end
- 68: Impossible. I think exploring the outside of the building would have enabled me to point to the entry.
- 69: Difficult because of the round rooms.
- 73: very difficult. If I would have known the objective I could have mentally mapped my location.
- 81: Was difficult because the travel was long and new for me.
- 89: very difficult
- 91: not at all
- 94: I wouldn’t say it was difficult but I’m not sure I answered it in the right manner.
- 99: very. I spun around in the building and was lost by that time
- 101: I wasn’t really paying attention to where I was going relative to the beginning, so I basically guessed.
- 104: Not difficult
- 106: It was difficult to figure out where the door was, since the passageways were curved.
- 111: I was really guessing. I wasn’t trying to map the terrain in my head as I went through. I think of architects as more worried about appearances than a floormap.
- 113: Not at all
- 120: Pretty difficult. I was a little disoriented
- 122: No problem
- 124: very difficult when I was in the VR I was concentrating on finding the red spot and navigating I gave no thought to the layout of the overall building.
- 125: It was pretty hard. I couldn’t really remember which way I came from.
- 127: Not very. Some corners I turned too quickly, but it was easy to make changes.
- 129: Not at all difficult
- 134: Not too hard except going up the stairs.
- 137: Somewhat difficult. I became involved with the task and almost lost track of direction.
- 140: It was made it more challenging but not impossible.
- 141: Pretty difficult. I wasn’t exactly sure which way to point.
- 142: Not very difficult
- 143: Not that difficult
- 145: not very
- 151: Very. If I had known I was supposed to memorize a floor plan, I could have done better. I was too busy looking around for architectural “abnormalities” which made me get lost.
- 155: Pretty hard, hard to remember after I got upstairs

156: very hard  
 159: not at all difficult  
 163: moderately difficult. About 90% off  
 177: It got worse. I wanted to just go, but I had to tell myself to point the controller.  
 178: using my sense of direction, very hard, but once I thought about it, I remembered which screen it started on (but pointed in the wrong direction anyway)  
 181: difficult, I hadn't kept track of where I was  
 183: on a scale of 1-10 (10 being hard) I'd give it a 5.  
 188: pretty difficult - easy to get disorientated  
 189: not too difficult  
 190: difficult, because I don't know which direction were I'm in.  
 191: I had no idea and just guessed  
 197: somewhat easy  
 201: pretty difficult.  
 202: somewhat difficult: I thought I was facing a different wall  
 203: more difficult than prior to the end  
 208: It was okay  
 210: It was moderately difficult because there was so many turns involved.  
 215: very  
 220: not especially

**7. Did you become disoriented with respect to the physical world? (that is, if you were in the C6, was the exit wall in the place you expected?)**

2: a little but I never moved my feet  
 4: no  
 5: no  
 6: No. I never changed my physical orientation.  
 9: No, not disoriented  
 12: No, I did not become disoriented.  
 13: yes I became disoriented but I don't think this the fault of the equipment rather my spatial skills.  
 15: no  
 22: if I didn't wear the head mounted display I wouldn't have been able to find the exit either because the building's kind of complex.  
 26: no  
 29: no  
 32: no  
 33: No, I didn't become disoriented in the physical world  
 34: I didn't really feel disoriented, more just surprised  
 35: no, I was fine  
 38: not disoriented  
 39: not

- 40: The door that I entered from the physical world I could tell but that was because the cable was wrapped around me. I was more comfortable (11a: rest illegible)
- 45: I felt I knew where I was by where my feet were. I was where I expected to be
- 46: no
- 48: no
- 55: yes, I didn't keep track of where I was at very well
- 58: no
- 59: no
- 60: It was disorienting for me.
- 61: I did not feel disoriented.
- 62: Not really disoriented. I was paying more attention to the architecture/artwork in the building than the actual path I traveled. I faced a different direction than expected.
- 63: Yes
- 64: no
- 68: No, I was quite aware of the physical surroundings, partly because hearing was reality; only sight was VR.
- 69: No, I didn't walk anywhere.
- 73: somewhat.
- 81: In this case, the facilities are not a cube, then, at the end, I did not have any problem of orientation.
- 89: no
- 91: did not become disoriented with respect of physical world
- 94: No - I was sitting down
- 99: No
- 101: No
- 104: No
- 106: No
- 111: No, the physical world felt like it was in the right place.
- 113: No. I remained stationary
- 120: No, I still had a sense of where I was.
- 122: I didn't even pay attention at first, so I had no idea where the exit was.
- 124: No. I was facing where I started I hadn't moved my feet
- 125: no
- 127: I didn't expect the exit wall to be right in front of me.
- 134: Yes.
- 137: I did not become disoriented in physical world
- 140: no
- 141: I was basically the way I expected to be.
- 142: It was in a different place than I expected for the practice run.
- 143: No
- 145: no
- 151: fairly disoriented in the world, totally oriented when I took off the mask.
- 155: No disorientation towards real world.
- 156: I wasn't at all where I expected to be. (about 180 degrees off of my assumption)
- 159: when I was done, I had no idea where the exit was

163: No

177: Yes. I had no idea what direction was where. It was almost relaxing to just go and not having to worry.

178: I felt it in the middle of the simulation a bit, I would expect another screen to my left and it wouldn't be there.

181: yes, I was 180 removed.

183: No

189: yes

190: don't know, I guess I was

191: no

197: no

201: yes - I was completely off

202: yes

203: No

206: Fine

208: no

210: yes, it very difficult to remember where the wall was. When concentrating in VR, you block out everything else.

215: no disorientation

220: No, I always knew where the door was (and so forth)

**8. Overall, on a scale of 1 to 5 (with 5 most satisfied), how satisfied were you with the ability to travel in the virtual world?**

|         |         |                       |          |
|---------|---------|-----------------------|----------|
| 2: 4    | 48: 5   | 111: 4                | 177: 4   |
| 4: 3    | 55: 5   | 113: 5                | 178: 4   |
| 5: 5    | 58: 3   | 120: 3                | 181: 5   |
| 6: 2.5  | 59: 2   | 122: 4                | 183: 3.5 |
| 9: 5    | 60: 5   | 124: 3                | 188: 4   |
| 12: 3   | 61: 5   | 125: (lla: illegible) | 189: 5   |
| 13: 5   | 62: 4.5 | 127: 5                | 190: 4   |
| 15: 4   | 63: 4   | 129: 4                | 191: 3   |
| 22: 4   | 64: 4   | 134: 4                | 197: 5   |
| 26: 5   | 68: 5   | 137: 5                | 201: 4   |
| 29: 5   | 69: 5   | 140: 3                | 202: 3.5 |
| 32: 5   | 73: 4   | 141: 5                | 203: 3.7 |
| 33: 4   | 81: 5   | 142: 4.5              | 206: 3   |
| 34: 5   | 89: 4   | 143: 5                | 208: 5   |
| 35: 5   | 91: 3   | 145: 4                | 210: 4   |
| 38: 3.5 | 94: 4   | 151: 5                | 215: 4.5 |
| 39: 5   | 99: 4   | 155: 5                | 220: 3.5 |
| 40: 3   | 101: 3  | 156: 3                |          |
| 45: 3   | 104: 3  | 159: 5                |          |
| 46: 4   | 106: 3  | 163: 3.5              |          |

## 9. Other comments related to the travel:

- 6: I hadn't realized how dependent I am on tactile/inertial feedback. I think of myself as a pretty visual person.
- 22: Wonderful. I really enjoy it! I wish I could travel in different scenes and at different speeds.
- 26: I almost fell over when I bumped into a table!
- 29: when does the home version come out?
- 34: It was fun! Thanks for the opportunity.
- 38: Hard to tell where you were in relationship to the structure. If you could enter the front door, I think it would be easier. Maybe that was part of the experiment!
- 40: I think I would have been more comfortable in that I was focusing on the task of the dots figuring out what to do. I also needed to move.
- 46: good, but please look into the controls
- 48: Thanks for the opportunity!
- 55: Although I offered some criticism in my review, I thoroughly enjoyed the experience and was satisfied with the experience.
- 60: This would make a 2D video game extremely more interesting.
- 68: I avoided going fast because I wanted to look all around.
- 81: It was an interesting experience.
- 91: It's a neat experience
- 99: This was a neat experiment with practice a person could travel with little thought. The images could be sharper but you could tell with no problem what they were.
- 104: I thought trying to move in the direction of the missing wall was very unnatural and difficult
- 113: None
- 120: Just a little difficult to get used to at first but it got better as I went along.
- 122: It was very interesting
- 127: The movements were smooth and flowed well. The area was easy to navigate.
- 140: It was difficult when you got stuck facing a wall, I got a little frustrated.
- 141: It wasn't difficult to move around and is very fun and exciting once you know how.
- 143: Traveling through the environment was quite interesting especially when compared with going through something on a flat computer screen.
- 155: very efficient, very clean and responsive.
- 163: Perhaps more practice with hitting marks in the practice session would make me a better travel controller later on.
- 177: Travel went well after I learned how to use the control. I think it would be neat if you actually had to walk up the stairs etc.

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