DEPTH PERCEPTION IN REAL AND VIRTUAL ENVIRONMENTS: AN EXPLORATION OF INDIVIDUAL DIFFERENCES

by

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Abstract

Virtual Reality Environments are becoming increasingly common in the design of automobiles and airplanes for their potential to reduce labourious and time intensive design processes. Unfortunately, variations in users' abilities to correctly perceive depth using virtual reality displays are a substantial obstacle to their use in industry. To examine this problem, a psychophysical experiment was conducted using a staircase method to observe how the difference threshold in a distance discrimination task varied in comparisons of real and virtual stimuli. A questionnaire was also used to explore whether the subject's background and previous training, or their ability to tolerate ambiguity could account for individual differences in performance. Results showed significant individual differences, and high variability but no effect was found for the subjects' distance thresholds, although some of the variation in subject response time appears to be related to distance, gender and the cognitive factor of tolerance of ambiguity.

Keywords: Depth Perception; Distance Perception; Virtual Reality; Individual Differences; Cognition; Human-Computer Interaction; Psychophysics

Subject Terms: Depth Perception; Individual Differences; Cognition; Virtual Reality; Human-Computer Interaction; Psychophysics

I tell you the most vivid experience of Virtual Reality is the experience of leaving it. Because after having been in the reality that is man-made, with all the limitations and relative lack of mystery inherent in that, to behold nature is directly beholding Aphrodite; it's directly beholding a beauty that's intense in a way that just could never have been perceived before we had something to compare physical reality to. And that's one of the biggest gifts that Virtual Reality gives us, a renewed appreciation of physical reality.

—Jaron Lanier interviewd by Adam Heilbrun for Whole Earth Review in 1988. Interview available at http://www.jaronlanier.com/vrint.html

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Chapter 1

Introduction

1.1 Research Area

In a 1992 interview for Virtual Reality Report, Dr. John Latta was asked what he believed was the greatest obstacle facing the Virtual Reality industry. His reply was "Lack of basic research. The issues of having the most intimate form of human computer interface in Virtual Reality necessitate a thorough understanding of human perceptual, muscle and psychological systems. Yet that research foundation does not exist." (as cited in Travis, Watson, and Atyeo (1994, p.43)). Fifteen years later, considerable research has been conducted with virtual reality displays (VR) but a thorough understanding of human response to the virtual interface is still lacking (Sherman & Craig, 2003; Patel et al., 2006). Despite this, successful applications of virtual environments have been made in areas such as rehabilitation, visualization, and training, (Hoffman, 1998; Ukai & Kato, 2002; Earnshaw, Vince, & Jones, 1995) and the potential of virtual reality has made it extremely attractive to industrial manufacturing and design companies. The automotive industry, in particular, has invested heavily in virtual reality displays, for their ability to rapidly create and modify computer models of vehicles. The potential of virtual models are extremely tempting to an industry that still relies heavily on expensive, time consuming and labourious physical models as cornerstones of their design processes (Ong & Nee, 2004; Smith, 2001). While many automotive manufacturers have incorporated virtual reality into their design processes, the systems have yet to replace physical models, or revolutionize the industry. Part of this slow return on investment stems from perceptual problems associated with the use of virtual reality environments for tasks requiring high detail and realism.

In 2004, General Motors Research asked our group of researchers and grad students at UBC and SFU to explore how depth perception functioned in virtual reality environments. Many automotive companies had begun investing in virtual reality to incorporate Computer-Aided Design (CAD) 3D models into their design processes, to allow for quicker design iterations, and to reduce their reliance on physical models. Virtual reality environments could also allow companies to collaborate on designs with their co-workers from around the globe (Smith, 2001). In order to accomplish this, General Motors Research developed their own rendering and interaction software called VisualEyes, with which they designed both interior and exterior vehicle simulations. For the interior view, the viewer sits in a real car seat and, ideally, perceives a realistic and geometrically accurate representation of a car interior (Figure 1.1).

Figure 1.1: An example of an interior automobile model in a virtual reality display at General Motors. Copyright 2007 GM Corps. Used with permission, GM Media Archive.

For the exterior car view, the cars can be viewed in a simulation of a courtyard or showroom (Figure 1.2). The displays are used by engineers, designers, and management to evaluate potential designs at full scale. However, GM encountered serious problems using virtual displays in their design process, as described by Baitch and Smith (2000):

> For a smaller number of individuals the interior fails to evoke a realistic perception. Some features are seen to be inappropriately large or small, they may seem to appear at the wrong distance, the three-dimensional space inside the vehicle may appear distorted, subjects may have difficulty with double vision,

> or may complain of image blur. These differences occur to persons with normal stereoacuity as well as to those with previously identified binocular vision disorders. (p.1)

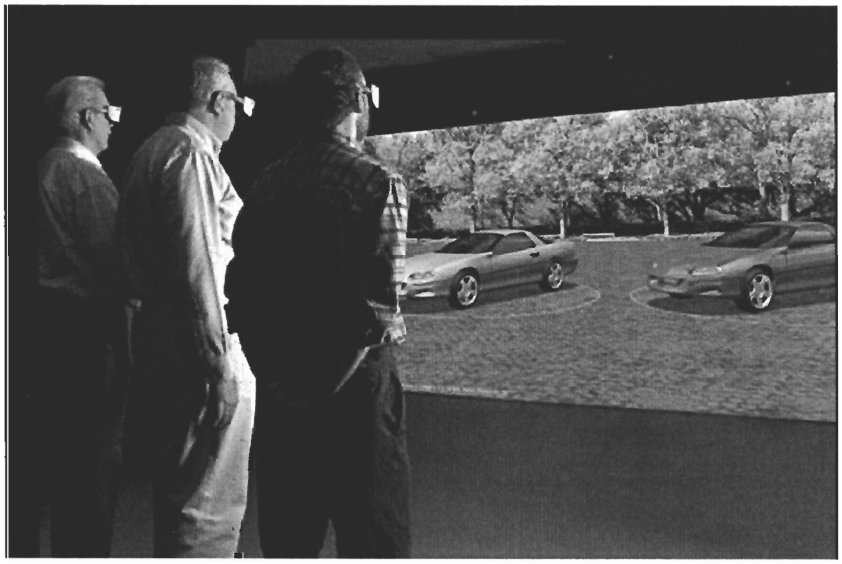


Figure 1.2: Exterior models of virtual automobiles displayed on a large-screen virtual reality display at General Motors. Copyright 2007 GM Corp. Used with permission, GM Media Archive.

GM's problems with virtual reality suggested that more basic science was needed to understand how depth perception functioned in virtual reality. In response to this problem, we conducted several perception experiments using psychophysical methods to compare the depth perception of real and virtual stimuli (these will be discussed in more detail in chapter 3). Each experiment showed significant individual differences among the subjects, which echoed GM's experience that some individuals were able to see the CAD stereo images correctly immediately, while others saw distortions even after several exposures to the environment (Baitch & Smith, 2000). It became clear that a more thorough assessment of individual differences was necessary.

This thesis presents a study that explores the causes of individual difference on depth perception in virtual environments by combining psychophysical methods and qualitative methods in an interdisciplinary approach. This work has drawn on methodology from Psychology, Human Computer Interaction (HCI), and the concept of Interaction Science.

Interaction science, though still in its infancy, calls for the scientific understanding of interaction in order to develop theories of perceptual cognition, and aims to ground its theory in use (Thomas & Cook, 2005). Researchers in Human-Computer Interaction (HCI) and Interaction Design have a keen interest in individual differences, as interfaces become too complex to be designed for a generic user (Chen, Czerwinski, & Macredie, 2000). Processes for addressing individual differences have been suggested, such as Egan's (1988) three-stage system that includes isolation, assaying, and accommodation. Isolation entails identifying the individual differences that affect the task being performed, assaying requires decomposing the task to determine which task components are causing performance variability, finally accommodation requires modifying the interface and eliminating or simplifying tasks that are causing individual differences. Due to their relative novelty and new interaction methods, the study of virtual reality environments requires a similar approach. This study will focus on isolating a distance perception task and examining whether personality variables or previous experience can account for any of the individual differences. Psychophysical methods, commonly used in Psychology, are well suited to this type of study as they provide important quantitative evidence of individual difference, while exploration of qualitative variables may help account for some of the causes of the differences.

1.2 Research Questions

The main research questions guiding this work are:

- How does distance perception based on binocular and oculomotor depth cues in virtual reality environments differ from depth perception in the real world?
- Can we isolate some of the causes of individual differences observed in virtual reality displays?

To explore these questions, an experiment was conducted using a psychophysical distance discrimination task comparing real and virtual low-cue stimuli to examine the first question, while the question of individual difference was explored using questionnaires on previous training and experience, and the personality trait of tolerance for ambiguity. It was hypothesized that individuals who have practiced tasks that recalibrate visual perception, will show effects of dual adaptation which may allow them to achieve increased accuracy in distance perception in virtual reality because they are more likely to be able to adapt their perception to different situations. Since the experiments use low cue stimuli and the virtual environment largely immerses the viewer in a virtual world, there is a substantial amount of ambiguity in the scene. It is possible that viewers who have a higher tolerance of ambiguity will have less difficulty accurately reporting distance discrimination in ambiguous depth situations than those with a lower tolerance of ambiguity. To test these hypotheses, the experiment included a questionnaire to measure the subject's experience with tasks that could have trained their visual perception, and given them greater flexibility in adapting to new visual environments. The second part of the questionnaire included questions to assess the subjects' tolerance for ambiguity, to determine whether there was a correlation between ambiguity tolerance and decreased accuracy in depth perception in virtual environments.

Three more specific research questions guiding this research included:

- How does the difference threshold of distance perception vary between the comparison of a virtual stimulus to real stimulus and the comparison of two virtual stimuli?
- Is there a significant interaction between a subject's previous experience with tasks that require perceptual learning and their distance perception performance in low cue virtual environments?
- Is there a significant interaction between a subject's ability to tolerate ambiguity and their distance perception performance in low cue virtual environments?

The data gathered presents an initial psychophysical and qualitative examination of distance perception in low cue virtual environments. It was expected that the data would show significant individual differences in the way that distance is perceived with virtual stimuli compared to real stimuli, particularly with the difference threshold of distance perception. It was also hypothesized that the use of qualitative questionnaires might shed some light on the causes of some individual differences in distance perception in virtual environments.

1.3 Thesis Organization

Chapter 2 reviews literature on depth perception including binocular and oculomotor depth cues, a definition of virtual reality, cue combination, monocular cues, metrics and other issues related to understanding depth perception in virtual environments. Chapter 3 presents the methods and results of previous work exploring depth perception in virtual reality environments. Chapter 4 presents the final study which focuses on individual difference. Chapter 5 discusses the results and implications of the research, and Chapter 6 summarizes the research and proposes future work.

Chapter 2

Literature Review

2.1 Depth Perception

Depth perception is the visual perception of a three-dimensional world (Howard, 2002a). Humans perceive depth in the world because we have two eyes that are set slightly apart. The distance between the eyes is known as interpupillary distance (IPD) and allows each eye to receive a slightly different view of the world. When light is reflected off of objects in the world and projected onto each eye's retina (Figure 2.1), the images from the retinas are sent to the visual cortex in the brain via the optic nerve and are recombined, providing a perception of a three-dimensional world. This perception of depth occurs even though the images projected on the retina are only two-dimensional. This is made possible by the difference between the overlapping views received by each eye, which is known as binocular disparity and forms the major cue to stereopsis, the impression of relative depth in the world. Binocular disparity is inversely proportional to the square of the object distance, so objects that are closer have a larger disparity than those farther away (Harris, 2004). When fixating on an object (i.e. the object is projected on the fovea, the most sensitive part of the retina), objects behind the point of fixation are viewed as having uncrossed disparity (the eyes have to move apart to look at objects that are farther away), while objects in front of the point of fixation have crossed disparity (i.e. the eyes have to move towards each other to look at closer objects) (Blake & Sekuler, 2006). Images that have neither crossed nor uncrossed disparity sit on the horopter, an imaginary line of all points in space that generate images at corresponding points on the retina (because of this they have no disparity) (see Figure 2.2). Objects around the horopter appear fused, and are located in

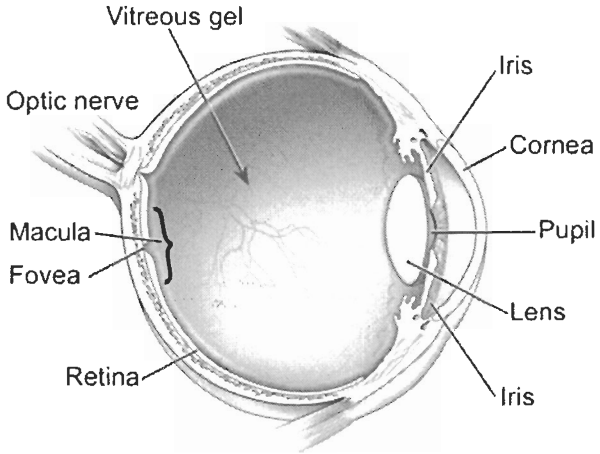


Figure 2.1: Eye diagram showing the retina and fovea. Credit: National Eye Institute, National Institutes of Health. *Note:* Copyright-free image. Retrieved from http://www.nei.nih.gov/health/eyediagram/eyeimages3.asp on February 2, 2007.

'Panum's fusional area', outside of which double vision (diplopia) occurs.

Aside from binocular disparity, several other depth cues contribute to our perception of a 3D world, including oculomotor cues (i.e. cues received from the eye muscles) and monocular cues (i.e. cues that can be seen with a single eye). Vergence and accommodation are oculomotor cues, while monocular cues include motion, occlusion, aerial and linear perspective, familiar & relative size, texture, lighting, and shading.

In order to quantify depth perception, research typically focuses on distance and size estimation. Depth cues provide a range of information on distance. Some cues provide absolute distance information that allows for an estimation of distance in units (e.g. feet or metres). While relative cues provide only ordinal information (e.g. information on which objects are behind or in front of other objects). In depth perception research, distance is commonly expressed in terms of exocentric and egocentric space. Exocentric space is the distance between objects (or their parts) as seen by the viewer. Egocentric space is measured in relation to the observer. Cutting and Vishton (1995) divide egocentric space into 3 further regions: personal space (0-1.5 or 2 metres), action space (2-30 metres), and vista space (30 metres or more). Judgments of egocentric distance require estimates of absolute distance

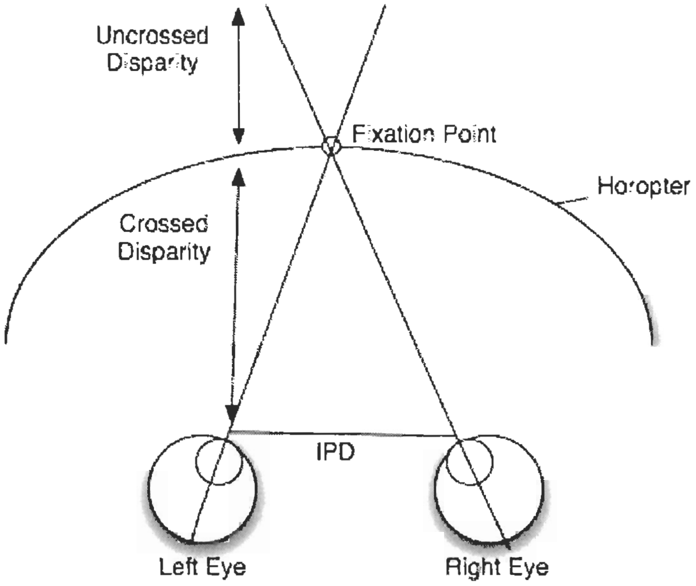


Figure 2.2: Crossed and uncrossed disparity in relation to the empirical horopter. Image credit: C. Akai.

because only depth cues are necessary to make a distance judgment, whereas exocentric judgments are relative depth judgments because the depths of two objects are compared (Mon-Williams & Tresillian, 1999b). Exocentric distance estimates tend to be more error prone (Loomis, Silva, Philbeck, & Fukusima, 1996).

2.2 Depth Cues

2.2.1 Binocular Depth Cues

The two major binocular cues to depth are binocular disparity and vergence (also considered an oculomotor cue). Binocular vision has been shown to provide a more accurate perception of distance than monocular vision (Loomis et al., 1996), which allows for improved visual detection, resolution, and discrimination (Howard, 2002a). Virtual Reality displays rely largely on horizontal binocular disparity, the difference between the horizontal angles subtended at the left and right eyes (Harris, 2004). Random Dot Stereograms, invented by Bela Julez in 1960, use only horizontal binocular disparity cues (i.e. and no monocular cues). The random dot stereograms showed that a strong perception of depth is possible with binocular disparity cues alone (Qian, 1997; Blake & Sekuler, 2006), and they continue to be one of the most commonly used tools to examine binocular vision. Vertical disparity is also possible, but is not considered a cue to depth, and relatively small amounts of vertical disparity can cause diplopia (double images) (Kalawsky, 1993).

In order to determine how accurately humans can perceive depth, a depth-discrimination threshold is measured. This threshold is the smallest depth interval that a viewer can perceive between two stimuli (Howard, 2002b). Humans are extremely sensitive to differences in binocular disparity, and have an average disparity threshold of 5 arcsec, a difference of 0.1mm at arm's length (Harris, 2004). Stereoacuity is the depth-discrimination threshold when binocular disparity is the only cue to depth. Stereoacuity is generally quite high, and 97% of the population has a stereoacuity of at least 2 arcmin, while 80% have a stereoacuity of 30 arcseconds (Ibid). Stereocuity can be difficult to measure since it can be affected by luminance, retinal location of stimuli (e.g. images sitting closer to the fovea will show greater stereoacuity), field of view, orientation, lateral motion and vertical disparity (Kalawsky, 1993).

Though the majority of people can perceive depth based on binocular disparity, those who are stereoblind cannot. Stereoblindness is often due to a misalignment of the eyes and it has been speculated that it affects 5-10% of the population (Blake & Sekuler, 2006). While total stereoblindness would prevent a user from achieving any stereopsis, it is also possible for people to be partially stereoblind. Based on studies done using Random-Dot Stereograms, Richards (1970); Richards (1971) found that there are three classes of wide-field disparity detectors in the brain, and that approximately 30% of the population may be subject to stereoanomalies. They can detect disparity but are unable to determine the direction of the disparity (i.e. whether it is crossed or uncrossed). This finding suggests that there are separate disparity processing mechanisms for crossed and uncrossed disparities. For those with significant stereoanomaly, there is little relationship between the amount of binocular disparity and the impression of depth. These anomalies appear to be genetic and correlate with the incidence of squint among adults. However, the anomalies are reduced with eye movement and when exposure to stimulus is increased. Two tests (one planar and one volumetric test) have been suggested to determine the extent of stereoanomaly (van Ee & Richards, 2002).

2.2.2 Oculomotor Depth Cues: Vergence and Accommodation

Vergence is the simultaneous movement of the eyes that ensures that objects being fixated are reflected on the fovea of the retina. To focus on objects nearby, the eyes converge, and they diverge to fixate objects that are farther away. Because vergence involves the muscles of both eyes, it is both a binocular and oculomotor cue. Vergence is a reliable cue from 10cm to 6m but is unreliable at large fixation distances (because the eyes are essentially parallel) and has been found to lead to contraction bias in reduced cue conditions (Mon-Williams & Dijkerman, 1999), though it is known to be a good source of egocentric distance information (Tresillian & Mon-Williams, 2000). Several studies have found that gaze angle/eye height can provide important proprioceptive information for distance estimates, especially in reduced cue environments (Gardner & Mon-Williams, 2001; Mon-Williams & McIntosh, 2001; Ooi, Wu, & He, 2001; Wraga, 1999). Philbeck and Loomis (1997) found that gaze angle had a significant effect on perceived distance in a real world task.

The second oculomotor cue is accommodation, the eye's ability to focus by adjusting the crystalline lens with the ciliary muscles. It is a monocular oculomotor cue because it does not require the use of both eyes. Accommodation is only effective for 2 metres or less and declines considerably with age (Howard, 2002a). Studies have found that accommodation is very accurate in conditions where several depth cues are available, but is not reliable when it is the only cue to distance (Mon-Williams & Tresillian, 2000; Fisher & Ciuffreda, 1988). Accommodation can provide some ordinal but not absolute distance information. Significant individual differences in subject accuracy have been found when accommodation is used as the predominant depth cue (in monocular task) (Fisher & Ciuffreda, 1988).

Vergence and accommodation are synkinetically linked, so that a change in one causes a change in the other. However, research has shown that vergence and accommodation have two separate feedback loops (Heron, Charman, & Schor, 2001). Vergence is open-loop, i.e. it does not use feedback, while accommodation is closed-loop and does incorporate feedback . Both vergence and accommodation provide depth information in the form of proprioceptive feedback from the ocular muscles. Signals sent from the ocular muscles to the brain are known as extraretinal inflow. Sources of extraretinal inflow include muscular feedback and internal monitoring of the muscle position (Shebilske, 1976). Extraretinal inflow from vergence is an important depth cue for distance perception, but can be perturbed by extending the eye muscles using an eccentric (angled) gaze (Mon-Williams & Tresillian, 1998). Holding an eccentric gaze for 30 seconds causes errors in perceived visual direction as well as pointing and throwing (Shebilske, 1994).

Blur is a general cue to depth related to accommodation. Objects that are fixated are in focus while those at other distances are blurred. Blur is a relatively unreliable depth cue, since its magnitude varies with pupil diameter and refractive state, as well as with depth (Mather & Smith, 2000). However, blur can provide important ordinal depth information at borders of objects at extreme blur values (Mather & Smith, 2002). In virtual displays when blur is combined with the depth cue of binocular disparity, disparity is the dominant cue (Mather & Smith, 2000).

2.3 What Is Virtual Reality?

Now that we have a basic understanding of depth perception in the real world, it is possible to examine depth perception in virtual environments. But first we must define virtual reality. The term "virtual reality" was reportedly coined by Jaron Lanier in 1987 (Encyclopedia Britannica Online, 2007). Virtual reality environments have been described as "interactive, virtual image displays enhanced by special processing and by nonvisual display modalities, such as auditory and haptic, to convince users that they are immersed in a synthetic space" (Ellis, 1994, p.17). Virtual reality has also been defined as "an advanced human-computer interface that simulates a realistic environment and allows participants to interact with it" (Latta & Oberg, 1994, p.23). To create this synthetic space, a strong emphasis is placed on binocular depth cues and multiple senses are engaged to give the user a sense of realism.

Sherman and Craig (2003) describe four key elements to a virtual experience: a virtual world, immersion, sensory feedback and interactivity. A virtual world is defined as "1. an imaginary space often manifested through a medium. 2. a description of a collection of objects in a space and the rules and relationships governing those objects." (Sherman & Craig, 2003, p. 7). The virtual world is both what appears on the screen and what the viewer perceives in their mind. Immersion is described as the "sensation of being in an environment" or "immersion into an alternate reality or point of view." (Sherman & Craig, 2003, p.9) Immersion is closely related to the idea of "presence", which has been defined as "the subjective experience of being in one place or environment, even when one is physically situated in another"(Witmer & Singer, 1998, p.225). Immersion is reinforced through sensory feedback, and viewer's head movements are often tracked to give them the correct perspective. Users interact with the virtual environment through input devices like data gloves, wands or sensors (and of course, traditional mice and keyboards). The goal is for the viewer to feel that they are truly a part of the virtual world.

This document will define Virtual Reality as displays that allow viewers to perceive a three-dimensional (3D) image of a virtual environment. This is achieved by presenting stereoscopic images, i.e. two distinct but overlapping views of a virtual scene, each taken at a slightly different angle (Sherman & Craig, 2003).

Industrial design applications commonly use two types of virtual reality displays: displays viewed with stereo glasses and head-mounted displays. Displays viewed with glasses include small screen displays like FishTank VR and large screen projection displays composed of one or more screens (Ware, Arthur, & Booth, 1993). Large multi-screen displays are often arranged in a U-shape to form a Cave Automatic Virtual Environment (CAVE). Using a CAVE configuration provides a more immersive experience for the viewer, because the screens are large enough to fill the viewer's entire field of view (Cruz-Neira, Sandin, DeFanti, Kenyon, & Hart, 1992). Screen displays can be either passive or active. Passive displays can use anaglyph 3D, in which the stereo images are projected in different colours and require glasses with different coloured lenses (most 3D movies use red and blue lenses), or are based on circular polarization, which allows different orientations of the projected light waves to enter each eye when polarizing glasses are worn. To achieve a sense of depth, both systems ensure that each eye views a slightly different image. Active stereo displays use LCD shutter glasses that flicker on and off in sync with the projected image. Most active stereo displays also track the viewer's head position so they receive the correct image for their viewpoint. However, only a single viewer is provided with the correct viewpoint, while others see slight distortions of the scene.

The second type of virtual display commonly used is the Head-Mounted display (HMD). Head mounted displays are typically worn as helmets, with the stereo images projected directly onto each lens in the visor of the helmet (Figure 2.3). HMD's are similar to the active stereo displays in that they project synchronous stereo images. The have a field of view that varies between 40-80 degrees per eye. Each HMD is worn by a single viewer and occludes all vision of the outside world, providing for a highly immersive experience. However, this makes it more difficult to collaborate with other viewers (though not impossible if avatars are used), making large-screen active stereo displays the virtual display of choice for industrial design applications (Smith, 2001).

Figure 2.3: A user wearing a Head-Mounted Display (HMD) and using data gloves to interact with the display. Photo courtesy of NASA. *Note:* Copyright-free image. Retrieved from http://gimp-savvy.com/cgi-bin/img.cgi?ailsxmzVhD8OjEo694 on March 1, 2007.

Throughout this document, the terms virtual reality (VR), virtual environment (VE), virtual reality environment (VRE) and virtual display will be used interchangeably. This work will focus only on the visual experience provided by these displays, and will not examine the impact of head tracking, 3D sound or haptic feedback.

It is important to make a distinction between the term 3D graphics and stereo 3D. Three-dimensional graphics have volume and are drawn in x,y and z coordinates (width, height and depth). They also use monocular depth cues such as lighting, shading and camera view to simulate 3D objects in the real world, however, they are always perceived as being on the 2D surface of the screen because they do not use binocular depth cues. Stereo graphics usually are a form of 3D graphics but they require special hardware and the use of binocular depth cues to give viewers the perception that they are seeing a 3D object that appears as though it is leaping off or sitting behind the screen. Throughout this document the term 3D will refer specifically to stereo 3D graphics.

Figure 2.4: A viewer looking at a stereoscope that uses mirrors to project the two photographs to each eye separately so that the images are perceived in stereo. Photo courtesy of: US National Oceanic and Atmospheric Administration. *Note:* Copyright-free image. Retrieved from http://gimp-savvy.com/cgi-bin/img.cgi?noaaD3OKzLk1GHI4404 on March 1, 2007.

2.4 How Depth Perception is Re-created in Virtual Reality

In 1832, Sir Charles Wheatstone invented the modern stereoscope, which could generate a perception of three dimensions from two dimensional images (Howard, 2002a). Stereoscopes use mirrors set in a v-shape to reflect two images of different disparity (stereograms) into each eye (Figure 2.4). Stereoscopes are still commonly used in vision research today to examine the role of binocular disparity in depth perception.

Virtual displays work on a principle similar to stereoscopes. Binocular disparity is recreated by projecting two images of the same object, each taken from slightly different angles. The images are set laterally apart on the screen (with some overlap between the images) and various technologies are used to ensure that each perceives one of the two images (Figure 2.5). Once the images are projected onto the retinas, they are combined in the visual cortex just as images of the real world are. Binocular disparity is one of the major cues to depth in Virtual Environments, though most monocular depth cues are also available.

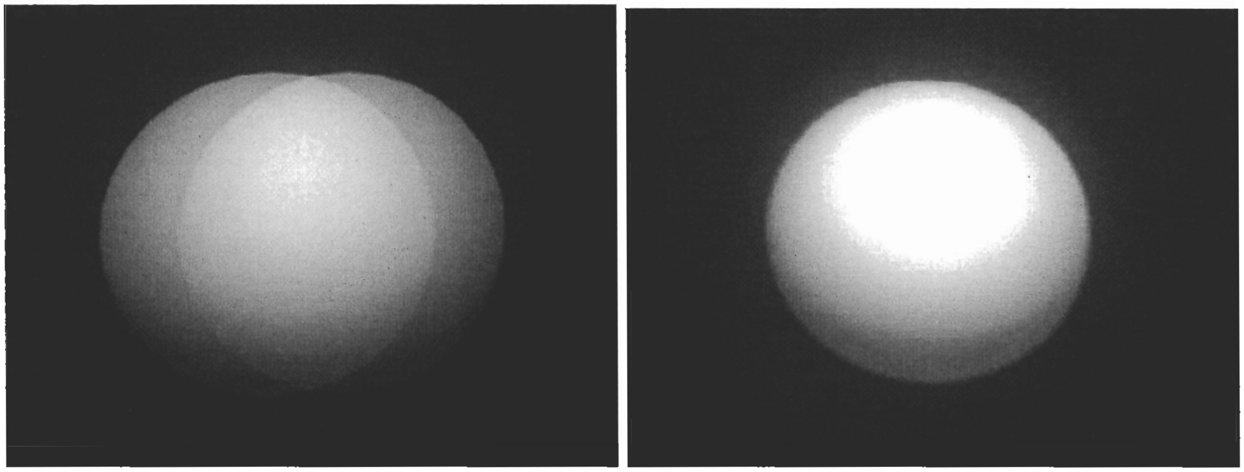


Figure 2.5: A virtual sphere projected on a 3D active stereo display. The image on the left shows the stereo view of the sphere when LCD shutterglasses are not worn. The image on the right is an approximation of what the sphere would look like when viewed with LCD shutterglasses. Image credit: C. Akai.

2.5 Studying Depth Perception in Virtual Reality

Re-creating depth in virtual reality has been found to be problematic, and several known perceptual issues associated with virtual reality are outlined in the literature. The first perceptual problem with virtual reality environments is that some users are not able to correctly view these displays due to stereoblindness. Approximately 5-10% of the population is stereoblind and unable to see stereo 3D in VR because they cannot use binocular disparity as a depth cue (Blake & Sekuler, 2006). Stereoblindness often occurs when strabismus (a misalignment of the eyes) is not corrected before a critical period of development in early childhood (Banks, Aslin, & Letson, 1975). However, this does not mean that those who are stereoblind are unable to perceive any depth in the world. They are still able to use monocular cues in both the real and virtual worlds. But in the virtual world, an inability to use binocular disparity as a depth cue makes it impossible for them to fuse the two projected stereoscopic images into one coherent 3D image.

Another problem afecting virtual environments is a high incidence of eye strain and cybersickness (i.e. nausea and dizziness caused by exposure to VR) (Wann & Mon-Williams, 1997; Stanney, 1995). These side-effects severely limit the amount of time that users can comfortably spend in virtual environments. Thankfully, research on perceptual adaptation has found that subjects can adapt to virtual environments over time, reducing the severity of cybersickness symptoms with increased exposure (Regan, 1995).

The most commonly cited problem with depth perception in virtual environments is the conflict between accommodation and vergence (Wann & Mon-Williams, 1996; Watt, Akeley, Girshick, & Banks, 2005; Akeley, Watt, Girshick, & Banks, 2004; Wann & Mon-Williams, 1997). In virtual displays, all images are projected onto a screen (i.e., on a single focal plane) which requires our eyes to always be focused on the plane of the screen, but we perceive the images to be at different depths (because they appear to be leaping off the screen) which requires variations in vergence (i.e. our eyes are fixated at a different distance than the screen). In the real world, our eyes always converge on the object that we accommodate, so our eyes evolved so that accommodation and vergence were linked. In virtual reality, this link is broken, and because its influence on depth perception is still unclear (Eadie, Gray, Carlin, & Mon-Williams, 2000) it has been a major area of vision research. Akeley et al. (2004) have attempted to address the accommodation/vergence problem by creating a display with multiple focal distances so that the correct vergence and accommodation cues are available at several pre-determined distances. While the initial work is exploratory, their approach may one day be applicable to head-mounted virtual displays, thereby reducing some of the conflict between accommodation and vergence in virtual displays. Research in virtual environments has found that adaptations in the link between accommodation and vergence are possible in VR (Rushton & Riddell, 1999). Adaptation may be a result of prolonged exposure to a virtual reality stimulus and is likely related to a change in tonic adaptation (the dark/resting state of accommodation) (Eadie et al., 2000). In a virtual reality display, accommodative demand beyond the fixation distance will make targets appear farther away, but if fixation is farther than the accommodative demand targets are perceived as closer (Mon-Williams & Tresillian, 2000). Studies have shown significant individual differences in subjects' ability to accommodate while viewing a small screen stereo display with LCD shutterglasses (Miyao et al., 1996). They found that subjects with accurate depth perception tended to accommodate just in front of objects at farther distances, and seemed able to handle some discrepency between accommodation and actual distance.

The potential usefulness of blur cues are interesting to stereoscopic display researchers because they are absent in most virtual reality displays and are related to the accommodation/vergence conflict discussed previously (Akeley et al., 2004).

2.6 Other Cues Available in Virtual Displays

2.6.1 Monocular Depth Cues

Monocular depth cues are those that can be seen with a single eye, and are often called pictorial depth cues because they have long been used to provide a sense of three-dimensionality in art. Depth cues can be static or dynamic. Static depth cues include: occlusion, texture, lighting (and shading), familiar size, relative size, height in the visual field, aerial perspective, and linear perspective (Howard, 2002a; Cutting, 1997; Blake & Sekuler, 2006). Motion parallax and kinetic motion are dynamic monocular depth cues. All of these cues can be found in virtual reality displays, however, because the focus of this research has been primarily on binocular cues, monocular cues will only be described briefly. For a fuller survey of monocular depth cues see Howard (2002b).

Occlusion

The cue of occlusion (or interposition) is perceived when an object hides or partly covers another object from view. This cue provides unambiguous information ordinal depth information. Although occlusion cannot provide information on absolute distances between objects, it is the strongest cue to depth and its reliability does not decline with distance (Cutting, 1997).

Size

Familiar and relative size are two important depth cues in virtual environments because the size of familiar objects can provide an estimate of distance in uncertain situations, while relative size allows for size comparison between different objects and is reliable over a range of distances (Cutting & Vishton, 1995).

In perception research, Emmert's law, which says that an afterimage projected onto a surface in full cue conditions covers less of the surface as the object is brought nearer, is usually interpreted to mean that perceived size is proportional to perceived distance (Howard, 2002b). Emmert's law accounts for size constancy, the perception that size remains constant despite the fact that the size of the image projected on the retina (visual angle) varies as an object moves in distance. In reduced-cue conditions, a size-distance paradox can be observed, causing viewers to perceive smaller closer objects as farther away than more distant larger targets (Fisher & Ciuffreda, 1988). Tresillian and Mon-Williams (1999) found that a distance estimation task using verbal reports led to a response consistent with the size-distance paradox but when subjects responded by pointing the size-distance paradox did not occur. They concluded that the paradox was therefore a cognitive phenomenon (Mon-Williams & Tresillian, 1999a).

One of the most well known size constancy studies is that of Holway and Boring (1941), who examined size constancy in real world monocular and binocular viewing conditions. The task required subjects to adjust the size of a circle projected on a screen to match that of a circle set at a different distance. For both regular binocular and monocular cues, subjects were able to maintain size constancy, but in more constrained monocular conditions (e.g. those that used an artificial pupil), size constancy broke down and subjects relied on visual angle. They also found that the binocular condition resulted in a slight overestimation of target size, while monocular cues consistently resulted in underestimation. Eggleston, Janson, and Aldrich (1996) redid the Holway and Boring experiment using a Head-Mounted Virtual display. They tested the effect of viewing condition (binocular, monocular), resolution (1280x1024, 640x480), field of view (60x60 deg, 100x60 deg), luminance (single level vs. multiple levels), contrast, and distance. The size of the target was maintained at 1 deg of visual angle for each distance. They found that subjects relied on visual angle for each condition, including binocular. This variation from Holway and Boring's results suggest that size is perceived differently in virtual environments, though they were unsure of the cause.

Perspective Cues

Linear perpective cues are found when seemingly parallel lines appear to converge as they move towards a vanishing point in a 2-dimensional scene(Murray, 1994). Several studies have found that perspective cues are a very strong cue to depth across different displays (Hendrix & Woodrow, 1995; Waller, 1999; Cutting, 1997) . Surdick, Davis, King, and Hodges (1997) studied the effect of relative size, relative brightness, relative height, linear perspective, foreshortening, texture, and stereopsis in virtual displays at viewing distances of 1m and 2m. To achieve stereo, they used a Wheatstone Stereoscope, and found that the perspective cues were more effective across distances than other cues, while relative brightness was considerably less effective. Relative size, height and brightness all decreased in effectiveness as distance increased. They concluded that perspective cues were more valuable for depth perception than the other cues they tested. Hendrix and Woodrow (1995) found that in virtual environments perspective cues improved accuracy of distance judgments, though the most significant effect was found with perspective cues and droplines (i.e. when target objects had a dropline that extended from its base to a groundplane containing strong linear perspective cues).

Motion

Motion parallax, the relative motion of different points on an object at different distances, is caused by movement of the object (kinetic depth) or movement of the viewer (motion perspective) (Howard, 2002b; Cutting, 1997). In virtual reality, motion perspective is available to users being head-tracked in stereo displays or those wearing HMD's. Kinetic depth cues are only available when the virtual scene is animated, but are important cues to three-dimensional shape and interact with stereo disparity during early depth processing (Kontsevich, 1998). Motion parallax is an extremely important cue as it is one of the few that provide absolute distance information (Landy, Maloney, Johnston, & Young, 1995). Rogers and Graham (1979) found that motion parallax produced by observer or object movement in the real world provides a reliable and unambiguous perception of relative depth.

Texture

Texture gradient is an important cue to depth because the relative density of texture varies with distance, but does not require an accurate estimate of viewing distance, and therefore tends to be more realiable (Johnston, Cumming, & Parker, 1993). In studies examining the interaction between texture and stereopsis it was found that there is an interaction between the two, but texture is a weaker cue and appears to be weighted less heavily than stereopsis (Ibid). Cutting (1997) suggests that texture is not a particularly reliable depth cue but is an important component in perception of 3D shape. Research done with a head-mounted virtual display found that texture underneath an object provided more distance information than object texture, and that mid-density textures like brick patterns were more effective than lower density textures (e.g. carpet) and high-density textures (e.g. grass) (Sinai, Krebs, Darken, Rowland, & McCarley, 1999)

Lighting/Shading

Light reflectance and shading on objects provide important depth information,particularly for 3D shape. Objects that are lit cast shadows that supply information on the object's position and orientation (Murray, 1994). Shading can make an object appear concave (if shading is near botton of object) or convex (when shading is at the top of the object), which Ramachandran (1988) hypothesizes is due to our perception that the lighting comes from above, as it does in the real world from the sun. This effect is strongly influenced by the object's orientation, which can reverse the effect (i.e. objects that appear concave will appear convex when turned upsidedown). It has also been found that shading alone is a weak cue, and requires a strong outline to be effective (Ibid) and to resolve ambiguity.

Shape

While, not a monocular cue itself, perception of 3D shape is an important research area in virtual environments because shape perception is affected by distance (Todd, 2004). Perception of 3D shape is based on information from shading, texture, motion or binocular disparity (Todd & Norman, 2003). Shape distortion is not uncommon in the real world, particularly when perceived distance is misestimated (Bingham, Crowell, & Todd, 2004), and studies have found significant error and individual differences in the perception of 3D shape (Todd & Norman, 2003). GM noted the tendency for some viewers to perceive shapes within virtual environments as distorted (Baitch & Smith, 2000). It has been found that in the real world, binocular viewing has less shape distortion than monocular viewing, especially when the shape is presented on ground plane (Loomis, Philbeck, & Zahorik, 2002). Size and shape can also interact, making small shapes appear stretched while large shapes appear squashed (Champion, Simmons, & Mamassian, 2004). This effect varies by shape type, and was worse for rectangles than cylinders or ridge shapes.

2.7 Cue Combination

In both the real and virtual worlds, many simultaneous cues to depth are available, but understanding how different cues interact and how we process multiple cues is a complex problem that is still much debated. Researchers recognize that depth perception is more accurate when more cues are available, and that some cues are more dominant than others

(Beall, Loomis, Philbeck, & Fikes, 1995; Bruno & Cutting, 1988; Howard, 2002b). Theories on cue combination suggest that cues could be combined through summation (averaging), multiplication (interactions between cues), or selection (a single cue is used) (Bruno & Cutting, 1988). Research on vergence in the real world has found that if vergence conflicts with other cues or there is less vergence demand, less weight will be given to it perceptually (Tresillian & Mon-Williams, 2000). Other studies suggest that differential perspective and vergence angle are additive when combined as cues for scaling depth from horizontal disparities (Bradshaw, Glennerster, & Rogers, 1996). Hillis, Ernst, Banks, and Landy (2002) concluded that single cue information could be lost when cues from the same modality are combined, because cues of the same modality are always fused, but when different modalities are combined (e.g., haptics and vision) fusion is not manditory so single cue information is not necessarily lost. Key work in this area was done by Bruno and Cutting (1988), who examined the combination of relative size, height, occlusion and motion parallax. They found that subjects perceived these cues additively, so that one source could be substituted for another, and more depth cues provided a greater sense of depth. However, there has been some disagreement over these findings (Massaro, 1988).

Based on a visual illusion found during a study of vergence using prisms, Tresillian, Mon-Williams, and Kelly (1999) suggested a heuristic model of cue integration that uses a weighted averaging process. The model found that interactions between vergence angle, disparity and other cues can lead to increased distance estimates for both base in and base out prisms (which should lead to opposing perceptions of distance). Vergence becomes less reliable as distance increases, but as vergence angle increases its weighting increases. Landy et al. (1995) also describe a weighted averaging model they term "Modified Weak Fusion" a linear combination of separate cues. Cues interact to promote all cues to be absolute depth cues, and each cue has a reliability. These are input into the final fusion stage, which takes into account each cue's reliability and the discrepancies between cues. Weights of each cue should vary from location to location within a scene.

2.8 Other Factors Affecting Depth Perception in Virtual Reality

2.8.1 Field of View

Field of view (FOV) is an important aspect of depth perception research in virtual environments because FOV is more limited in virtual displays than in the real world. Our natural field of view is approximately 180-200 degrees with 120 degrees of binocular overlap (Sherman & Craig, 2003), while Head-Mounted Displays, typically have a FOV of 47 deg. horizontal by 36 deg. vertical (Loomis & Knapp, 2003). Large screen active stereo displays require glasses that can also limit FOV, (FOV will vary depending on the size of display and the type of glasses worn), though to a lesser degree than HDM's.

Research has shown that FOV can affect the perception of depth as increased FOV allows for increased accuracy of depth (Knapp & Loomis, 2004). HMD's consistently show distance underestimation that is inconsistent with the real world, so in a study comparing the impact of restricted FOV on distance perception using verbal report and blind walking metrics, Loomis and Knapp (2003) asked subjects to estimate the distance of a real target outdoors with unrestricted FOV and restricted FOV with a simulated HMD. They found no significant effect for FOV. Earlier, Psotka, Lewis, and King (1998) had attempted to address the question of why objects viewed on small non-stereo screens with a 10 degree geometric FOV appear much closer than in the real world. They suggest a 'Cognitive Frame theory', which hypothesizes that viewers of a virtual scene always base their distance estimates of any frame (e.g. screen frame) as if it were a full natural 180 degree hor. by 120 degree vertical FOV, which causes an underestimation of depth. In CAD models, a geometric field of view is determined by the clipping planes of the graphics and by the algorithm that can act similar to a camera lens. The geometric FOV is the visual angle of the model, not the display and can be manipulated like a camera. Objects in smaller frames are perceived as larger than objects in smaller frames, "there is a powerful tendency to base size judgments on a compromise between the absolute physical size of an object and its proportional size in the frame." (Psotka et al., 1998, p. 359). Results of their study did not completely support the frame theory but suggest that there is a 'telephoto bias', an apparent change in distance of objects in a truncated visual field, produced by media where the FOV is less than geometric FOV making objects appear nearer than they would in a normal field of view.

The seeming contradiction between the Loomis & Knapp and Psotka et al. papers may be a function of the fact that the task used by Loomis & Knapp used a simulated HMD, that restricted FOV but did not require the user to look through the usual HMD optics, or at a virtual scene.

2.8.2 Interpupillary Distance

Most stereo software allows individual interpupillary distance (IPD) to be set for each viewer to adjust the disparity correctly for the individual viewer. However, there is some question as to how much impact this setting actually has on depth perception in virtual environments. Rosenberg (1993) ran a study that varied IPD during a stereo alignment task and found that although average IPD is 6.3cm, no significant difference in performance was found with IPD's greater than 3cm. These results suggest that projecting stereo graphics with lower IPD's, which can reduce the incidence of diplopia (double-images) and eye-strain, can be done with little loss of performance. Surdick et al. (1997) found that a previously stereoanomalous subject could be trained to perceive with stereopsis by using a training program that consecutively presented images based on 1/4, 1/2, 3/4 of the subject's IPD. IPD is certainly an important factor in depth perception, but it's exact significance requires more study to be fully understood.

2.9 Research Methods In Depth Perception

Perception researchers have used virtual reality as a tool to learn about depth perception in general, and to investigate how depth perception in virtual environments differs from the real world. Virtual environments have been especially useful in understanding distance and size perception under various conditions. Experimental design for research on depth perception requires careful consideration on the cue to measure, the environment to conduct the study in, and the method of measurement (metric) used.

2.9.1 Psychophysics

The most common approach to depth perception research is a psychophysical approach. Psychophysics requires isolating cues of interest and measuring subjects' responses to cues during specific tasks. Psychophysics was founded by Gustav Fechner, who published "Elemente der Psychophysik" in 1860. He described Psychophysics as "an exact theory of the relation of body and mind" (Fechner, 1860/1966, p.xxvii). Today, psychophysics is usually defined as "the scientific study of the relation between stimulus and sensation," (Gescheider, 1997, p.ix). In order to quantify the measurement of sensation, Fechner defined a concept called the threshold, which can be defined as "the point at which a stimulus or stimulus difference becomes noticeable or disappears" (Fechner, 1860/1966, p.199). Two types of thresholds are used in psychophysics: the absolute threshold and the difference threshold. The absolute threshold is the minimum stimulus intensity required to produce a sensation. The difference threshold is the smallest change in stimulus intensity needed to produce a noticeable change in sensation (i.e. a just noticeable difference) (Gescheider, 1997). Weber's Law says that the amount of change in stimulus intensity required for a just noticeable difference is a constant proportion of the original stimulus intensity. The most common types of tasks used in psychophysics include: detection, resolution, discrimination, categorization, identification, and description (Howard, 2002a).

Fechner described three psychophysical metrics for measuring sensation: the method of constant stimuli, the method of adjustment,and the method of limits. Each method varies depending on whether the absolute or difference threshold is being measured. Because this research is concerned only with the measurement of difference thresholds, the use of the three methods will only be described for the measurement of the difference threshold.

The method of constant stimuli presents two stimuli, one standard stimulus that changes only for defined levels (as selected by researcher), and a comparison stimulus whose intensity is selected randomly from a set of intensities around the standard. Several trials are completed for each intensity. Accuracy is then averaged by stimulus intensity and plotted with a psychometric function, a graph showing the proportion of correctly detected stimuli by stimulus intensity.

The method of adjustment requires the subject to adjust the intensity of the stimulus to match that of a standard stimulus. The Point of Subjective Equality (PSE) is the stimulus intensity at which the comparison stimulus is viewed as subjectively equal to the standard.

The method of limits compares a standard stimulus to a comparison stimulus. The intensity of the comparison stimulus is changed in steps, either ascending or descending in intensity. The series terminates when the subject's response changes (e.g. if judging light intensity, the subject's response might change from viewing comparison as brighter than standard, to dimmer than standard). A common variation of the method of limits is the forced choice method, which presents subjects with two (or more) stimuli and requires them to chose the one most representative of the cue being studied. The most common form of this task is two-alternative forced choice (2AFC). Another common modification of the method of limits is the staircase method (or up-and-down method), which presents the comparison stimulus in steps until the subjects response changes, the stimulus intensity is then reversed until the subject's response changes again (Cornsweet, 1962). This procedure continues for several reversals, with the stimulus intensity being recorded at each reversal. The threshold is often calculated as the average of the reversal points (Levitt, 1971). Because the intensity changes in a linear manner, subjects may be able to anticipate the next intensity level. To avoid this, multiple staircases are often used and interleaved (i.e. run concurrently with the stimulus intensity chosen randomly from one of the staircases), so that the subject cannot predict the next trial.

2.9.2 Metrics in Virtual Reality Research

Deciding on the appropriate metric for investigating depth perception is a critical issue in research. The metric used to measure the subject's response can add bias to the results, making it difficult to know if an effect was caused by the cue being measured or the measurement itself. When choosing a metric, the distance of interest is a key consideration. Studies by Patterson and Fox (1984) have shown that the metric used to examine stereopsis can make it seem as though some subjects have anomalies in their stereo vision under certain conditions, but that those anomalies disappear under different testing methods. A difficulty of determining the proper metric to use is the variety of methods for measuring depth perception used in the literature. This lack of standardization in metrics makes it difficult to compare results between studies (Surdick et al., 1997).

Metrics for judging distance in personal space often use pointing tasks or related motor tasks (Mon-Williams & Dijkerman, 1999; Bingham, Bradley, Bailey, & Vinner, 2001; Knill, 2005). Considerable VR depth research has explored the mid-range of action space using visually-directed action metrics, by allowing visual input before the task but removing it once the task is underway (Loomis, Fujita, Da Silva, & Fukusima, 1992). Walking metrics are the most common form of visually-directed action metrics. A variety of walking metrics are used in depth research including: visually directed walking, triangulated walking and pointing, blindfolded walking, and walking on treadmills (Loomis et al., 1996; Loomis et al., 1992; Proffitt, Stefanucci, Banton, & Epstein, 2003). Other less common metrics include throwing and imagined walking (Sahm, Creem-Regehr, Thompson, & Willemsen, 2005; Plumert, Kearney, Cremer, & Recker, 2005).

Chapter 3

Background: Previous Work

3.1 GM's Previous Work

Many applications of virtual reality, such as geological modeling, are used to visualize abstract graphics or models in a new way, in which case viewers have no preconceived notions of what they will see and can tolerate some distortion in the models. Unfortunately, the same does not hold true for virtual models of cars since viewers know what cars look like. Therefore, using VR for automobile design in a virtual environment requires extremely high realism and accuracy.

To examine the problems they had encountered with virtual reality displays, GM conducted an in-house experiment. They ran a study with 20 GM employees to examine visual acuity, convergence/accommodation relationships, refractive status and depth perception (Baitch & Smith, 2000). Several visual characteristics of the subjects were measured including: visual acuity, eye muscle testing (for phoria & strabismus), refractive status (myopic, hyperopic, presbyopic, etc), gradient AC/A (ratio of accommodative convergence to accommodative demand), Interpupillary Distance (IPD), stereopsis (gross and fine), binocular vergence, and accommodative status. The stimulus consisted of a 3D steering wheel (white with some texture) against a black background. Subjects wore goggles with prisms of varying powers to vary vergence and consequently distance and size perception. During each trial, subjects sat 75 cm from the screen and held two different sized wooden probes (one in each hand) where they perceived the outside edges of the steering wheel to be. Three measurements were taken for each of 4 prism powers, for a total of 12 measurements per subject.

Results showed that the geometry of the images was correct, and that the most salient relationship was between the measurements of the wheel and the results of the gross stereopsis (Titmus Stereofly test). They also found significant individual difference between subjects, and some subjects who were unable to perceive any depth in the stimulus across all conditions. It was also noted that there was less variation between measurements with different prisms than expected, which led them to suspect that their measurement technique may have biased the data.

Based on the results of GM's initial study and the known perceptual problems in virtual environments (as described in Chapter 2), our team of researchers at UBC and SFU decided to take a psychophysical approach to investigating distance perception in virtual reality with a focus on binocular and oculomotor cues. By removing extraneous cues, we ran three controlled studies using classic psychophysical methods to isolate how binocular and oculomotor cues affected distance perception in virtual reality compared to the real world.

3.2 Our Previous Work

3.3 Experiment 1

In our first study we were interested in examining factors associated with the accommodation/vergence mismatch. Because virtual reality requires vergence to be disassociated with accommodation, we hypothesized that errors in the estimation of depth could be due to a bias of the signals sent from the extraocular and ciliary muscles to the brain (known as extraretinal inflow). The extraocular muscles control vergence through six muscles that control the movement of each eye in its socket. The ciliary muscles control accommodation by adjusting the crystalline lens in the eye. In order to test this hypothesis, we biased the extraretinal inflow signal using a Minor Motor Anomaly (MMA), which Shebilske (1994) describes as 'dysfunctional states of slight misalignment or misregistration of body part positions' (Shebilske, 1994, p. 331). The MMA's were induced by getting subjects to view the stimuli with an eccentric (angled) gaze, which has been found to cause a misregistration of eye position (Ibid) and would further perturb vergence. We hypothesized that if the extraretinal inflow signal was affecting perception in VR, further biasing the signal should increase that error. In order to maximize the observer's use of the extraretinal signal, we removed any kind of visible probe that might allow subjects to compare binocular disparities with the target during a trial. This required an open-loop (no feedback) test. In the literature, many open-loop tasks use indication with an unseen hand (e.g. Mon-Williams and Tresillian (2000)). However, because we were interested in distances farther than arms length, including those behind the screen, we asked subjects to make absolute distance estimates of target distance.

3.3.1 Materials and Methods

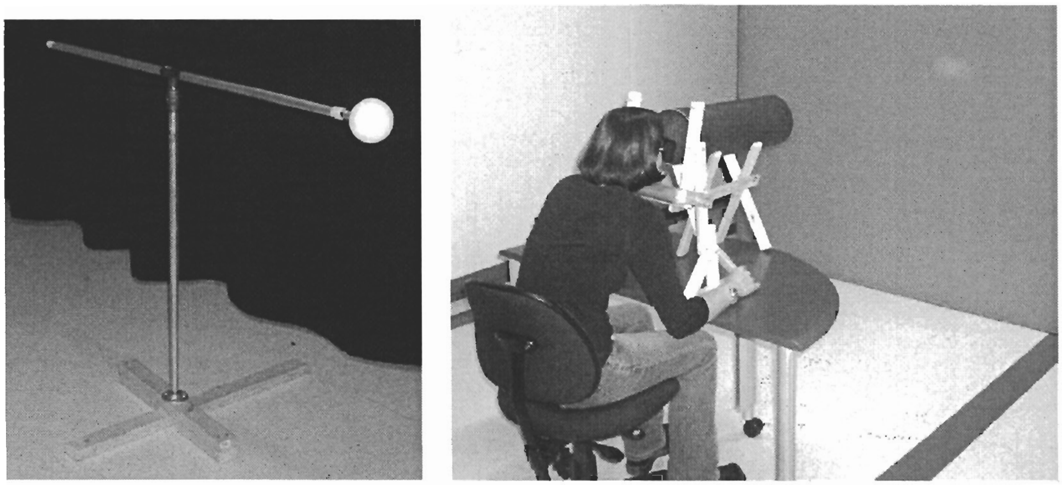
Participants

Five adults between the ages of 25 and 35 years participated in the experiment. Three of the subjects were male and two were female. Two of the subjects were naive to the experiment goals, and three of the subjects were familiar with the experimental design. The two naive subjects were paid $20 for their participation. All subjects had normal or corrected to normal vision, and were tested with the Titmus StereoFly test to ensure they were not stereoblind.

Apparatus

For both the virtual and physical conditions, subjects were required to rest their head on a chin and forehead rest to eliminate motion parallax as a depth cue. In order to reduce other cues within the viewing environment, particularly those in the subject's peripheral vision, the majority of trials were viewed through a tube. The tube was approximately 20 inches long and 8 inches in diameter and was painted matte black on the inside and outside. The tube was mounted on an adjustable wooden stand so that it stood at eye-level, and was adjusted for each subject (see Figure 3.1(b)). For one condition, two subjects were permitted to view the stimuli without the tube in order to reduce eyestrain.

Physical Environment The physical environment consisted of a hand-built stand that held an extendable pole (Figure 3.1(a)). Targets were white Styrofoam spheres that could be mounted at the end of the pole and set to different distances. In order to remove texture as a distance cue, the Styrofoam spheres were covered in polyfilla and sanded to remove their texture. The following sizes of spheres were used: 6.4 cm, 7.6 cm, 10.2 cm, 12.7 cm, 15.2 cm and 20.3 cm. The spheres were placed at distances ranging from 100 cm-305 cm. Subjects viewed the targets through a tube that was surrounded by a large black curtain



(a) Extensible pole used to adjust the distance of the real sphere.

(b) Setup for the virtual condition that required subjects to make absolute distance judgments while viewing the stimulus through a tube to remove extraneous cues. Image credits: C. Akai.

Figure 3.1: Apparatus used in Experiment 1.

so they could not see the stand. The stand on which the targets were mounted was also covered with black felt so that subjects could not see the bottom of the stand. Behind the stand was a black fabric backdrop with no texture. The targets were lit with a small LED light that was moved each time the distance changed and was focused on the target. This lighting was very similar to the lighting of the target in the virtual display. Otherwise there was no other illumination in the room.

Virtual Environment The virtual environment consisted of a two-screen Fakespace RAVE display and a table for the tube and chin rest to sit on. Targets were white spheres projected onto the centre of one of the screens. The spheres had the same range of sizes as the physical setup and were placed at the same distances. The subjects sat at a distance of 2 meters from the screen. The targets were displayed with a program called VisualEyes, written by General Motors Research and generously provided for this experiment. VisualEyes was used to set the proper distances and sizes of the spheres. All subjects wore a pair of CrystalEyes shutterglasses in order to view the images in stereo. The glasses have a field rate of 96 Hz, which is split between the two lenses giving a rate of 48 Hz per eye.

3.3.2 Procedure

Five experimental conditions were used: physical environment with normal gaze (all subjects), physical environment with eccentric gaze (all subjects), virtual environment with normal gaze (all subjects), virtual environment with normal gaze but without the tube (2 subjects), and virtual environment with eccentric gaze (3 subjects). Subjects were asked to estimate the target's absolute size and distance. Answers were recorded on scale sheets. To insure they were comfortable with the measurement units, subjects could choose to use a scale sheet in centimetres or in inches. Three of the subjects chose inches and two chose cm. Scales on the cm sheets ranged from 0-315 cm for the distance estimates, with increments of 5 cm. For the diameter of the target, the scale ranged from 0-25 cm with increments of 1 cm. Scales on the inches scale sheet ranged from 0-12 feet for distance estimates with increments of 4 inches. For the diameter of the target, the scale ranged from 0-12 inches with increments of 1/4 inch. The size/distance combinations (in cm) for the spheres were: (6.4cm, 127cm), (7.6cm, 101cm), (10.2cm, 203.2cm), (12.7cm, 170.2cm), (15.2cm, 304.8cm), (20.3cm, 271.5cm). In order to test whether size constancy was upheld across the conditions, distances were chosen such that three spheres of different sizes would subtend the same retinal angle: 4.3 degrees for the 7.6cm, 12.7cm and 20.3cm balls and 2.86 degrees for the 6.4cm, 10.2cm and 15.2cm balls. For each condition, subjects ran through four preview trials during which they were given feedback on the correct size and distance of the target. Experimental trials consisted of 6 different sized spheres, repeated 3 times, with 18 trials per condition, for a total of 72 trials. Subjects were allowed to view the targets as long as needed, however the target was removed from view when subject recorded their response. All subjects ran both physical conditions, and the virtual normal condition. However, only three subjects ran the virtual eccentric condition, while only two ran the virtual normal condition without the tube. This was because two subjects found using an eccentric gaze very uncomfortable and complained of eyestrain. To aleviate their discomfort, they were permitted to use a normal gaze without the tube in the virtual condition and did not use an eccentric gaze in the virtual condition.

3.3.3 Results

Analysis of the distance estimation task was conducted using a General Linear Model MANCOVA in SPSS (version 11 for Mac) on distance and size estimates using Visual Angle as a

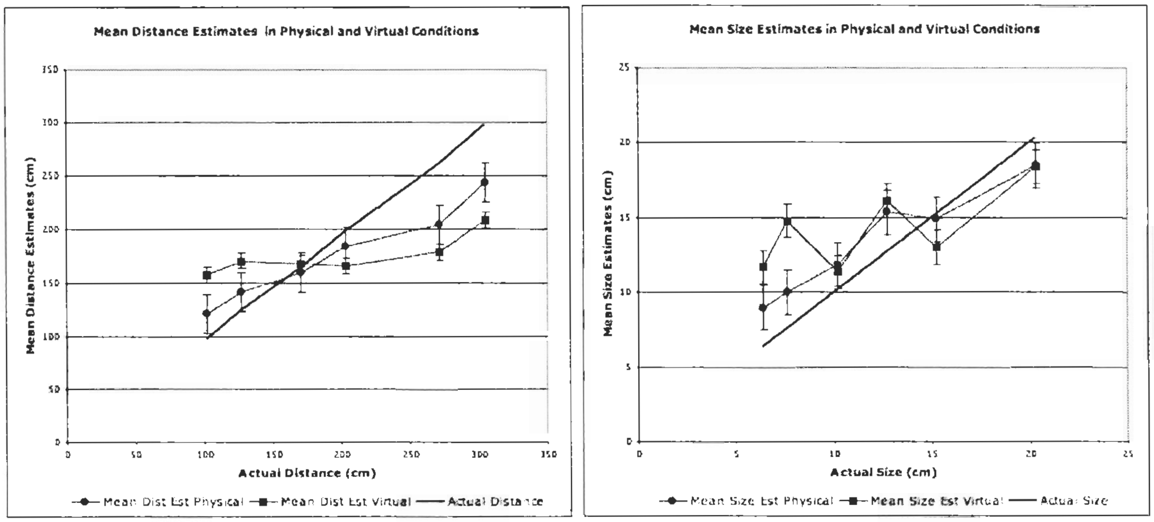


Figure 3.2: (a) Mean distance estimates with standard error in physical and virtual conditions. (b) Mean size estimates with standard error in physical and virtual conditions. Solid bar is perfect performance.

covariate. Results from the multivariate test showed showed a main effect of target distance using Roy's Largest Root ($F(2,86) = 4.23, p < .02$). A post-hoc univariate test showed that the effect of distance was on the distance estimate ($F(2,86) = 4.2, p < .02$) but not the size estimate. The data did not pass Box's test of equality, which suggests that the assumption of homogeneity of covariance matrices was not met. Though not statistically significant, Figure 3.2 shows that average distance estimates were somewhat more accurate for the physical compared to virtual conditions, while size estimates show greater variability in the virtual condition, particularly with smaller sizes. Figure 3.3 shows average individual distance estimates for the physical and virtual conditions. While Figure 3.4 shows individual size estimates for the physical and virtual conditions. High variability can be seen in both conditions, but performance is more accurate and less variable in the physical condition for both size and distance estimates.

No significant difference was found between the normal and the eccentric gazes. Biasing extraretinal inflow by using an eccentric gaze produced a slight effect similar to that of the virtual condition, though at a lower (and not significant) level. Though extraretinal gaze may be a contributing factor to individual difference in depth perception, further study is required before we can know for certain. No effect was found for visual angle on size or distance estimates.

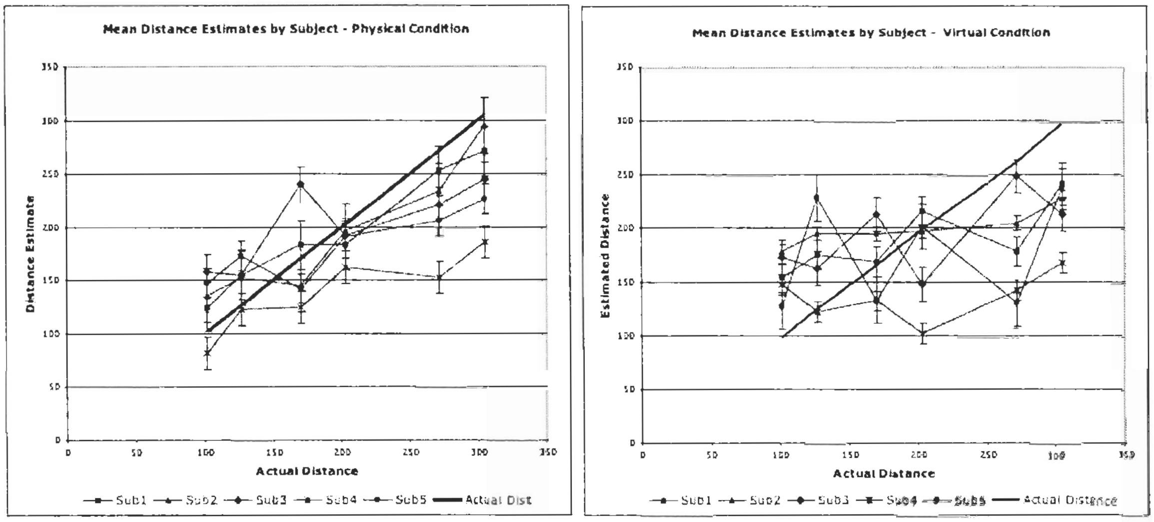


Figure 3.3: Left: Mean distance estimates in physical conditions by subject. Right: Mean distance estimates in virtual conditions by subject. Solid bar is perfect performance.

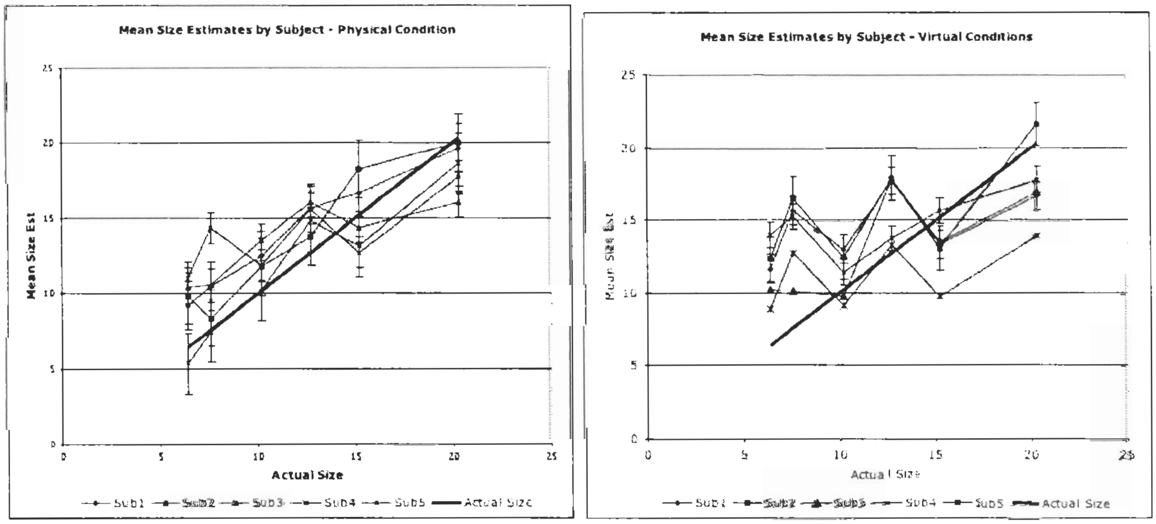


Figure 3.4: Mean size estimates in physical (left) and virtual (right) conditions by subject. Solid bar is perfect performance.

3.3.4 Discussion

The failure of the data to meet the assumption of homogeneity of variance may be partially due to the difficulty of the absolute size and distance judgment task. Estimates of absolute distance and size are difficult in the real world, and are even more so in a reduced-cue environment. It should also be noted that we were not able to control for Interpupillary distance (IPD) due to constraints with the VisualEyes software. Our reporting mechanism may also have added to the variability, since three of the subjects used Metric and three Imperial units. We noted that those who used the scale of feet and inches had a greater tendency to round estimates to upwards to whole feet than those whose used a scale in cm, (although metric users also tended towards round numbers, e.g. 200 cm, vs. 214 cm).

While real-world performance was poor, performance in the virtual condition was poorer. This was particularly true of size judgments which did not show a linear increase in estimates as size increased but showed significant overestimation at the smallest size and underestimation at the largest size. This may have been caused by requiring the subjects to look through the tube, which provided a strong frame around the spheres, making closer spheres look bigger and farther spheres look smaller. It is interesting to note the relatively low variability of responses by a given subject– although some subjects were confused about the location and size of targets they were relatively consistent. While our experiment did not show a large effect for eccentric gaze, this does not rule out a role for extraretinal inflow that may have been masked by high variability of subject response, especially in the virtual conditions.

3.4 Experiment 2

The first experiment taught us the necessity of choosing a metric that would eliminate some of the variability in our results. The second study built on the first by using a forced choice discrimination task. The task asked subjects to choose whether one of two visible virtual spheres was closer or farther and larger or smaller than the second. This allowed us to examine how the perception of depth and size scaled with distance regardless of whether or not the subject was capable of accurately reporting absolute distance.

Previous observations by GM researchers suggested that some subjects responded to stimuli in VR in terms of retinal angle, i.e. they responded to the image characteristics rather than the projected object (Kenyon, Sandin, Smith, Pawlicki, & Defanti, 2007). Given this observation we predicted that most subjects would be fairly accurate in judging the relative distance of the two spheres, but expected many would have more difficulty determining the relative size of the spheres (i.e. that size constancy might fail in the stereo display environment). In order to determine whether this was true, we tested a range of sizes and distances. Our first question was: at what size/distance combinations (if any) will individual subjects fail to scale apparent size with distance (i.e. fail to maintain size constancy)? Secondarily, if size constancy does fail, do some subjects revert to judging the real size of object by the retinal angle they subtend?

3.4.1 Materials and Methods

Participants

Ten adults between the ages of 24 and 45 years participated in the experiment. Seven of the subjects were men and three were women. Seven of the subjects were naive to the experiment goals, and three of the subjects were familiar with the experimental design. Seven of the participants were paid $15 for their participation. All participants had normal or corrected to normal vision. All subjects had their stereoacuity tested using the Titmus Stereo Fly test prior to taking part in the experiment. Only three of the subjects had any experience in virtual environments.

Apparatus

This experiment used only virtual stimuli projected in a Rave FakeSpace projection active stereo display. Stimuli consisted of white spheres ranging in size from 7.6-20.3cm set at distances ranging from 101.6-304.8cm. There were 5 different sizes and 5 different distances used in various combinations as listed in Table 1. As in the first experiment, subjects were seated 200 cm in front of the screen and wore CrystalEyes Shutterglasses throughout the experiment. GM's VisualEyes software was again used to set the proper distances and sizes of the spheres but did not allow individual IPD's to be set.

3.4.2 Procedure

For each trial two white textureless spheres were presented on the screen. Subjects were asked to tell the experimenters verbally whether the sphere shown on the right side was bigger or smaller, and farther or closer than the sphere on the left side. The experimenter entered the two responses per trial into a computer program that recorded the trial number, the size and distance of each sphere, and the correct answer. The trials consisted of 15 size/distance combinations with 8 repetitions of each, for a total of 120 trials. No chin rest was used, but subjects were asked to keep their heads still. Subjects were given the option of taking a break halfway through the trials, but many refused it since the entire experiment only took an average of 40 minutes per subject. There was no additional room illumination, so the only visible light came from the screen.

Because the stimuli were presented with minimal context, subjects had to rely on binocular disparity and visual angle as their cues to distance and size. In this situation relative binocular disparity should make closer/farther estimates fairly straightforward. However, when it came to determining sphere size, a much more precise estimate of the distance of each sphere would be needed to evaluate the two images in accordance with Emmert's law, and to make the correct judgment.

3.4.3 Results

As with the previous experiment, large individual differences between subjects were found in overall accuracy of estimating the relative size and distance of the two spheres. Accuracy was calculated based on correct responses for both size and distance and ranged from 38%-92.5%, with five of the subjects achieving accuracy of at least 80% and three subjects achieving less than 60% accuracy (see Figure 3.5). Mean accuracy between all the subjects was 72%.

The types of errors made varied, but size errors accounted for approximately 73% of the errors (see Figure 3.6). As expected, different stimulus pair combinations produced different levels of accuracy. The combination of a sphere of 15.2 cm set at a distance of 170.2 cm on the left, with a sphere of 12.7 cm at a distance of 271.8 cm on the right, had the highest percentage of error at 45%, where 50% would be chance performance. Given the small size difference and large distance from the observer ($>$ 2 m) this is unsurprising, and it gives us a reasonable estimate of the threshold for discrimination in this task and situation. Another combination of a sphere of 7.6 cm set at a distance of 203.2 cm on the left, with a sphere of 10.2 cm at a distance of 101.6 cm on the right, also had an error rate of over 41%. Again the distance between the two spheres was approximately 1m, with one of the spheres set at a distance of more than 2m and the difference in size between the spheres was relatively small (see Table 3.4.3).

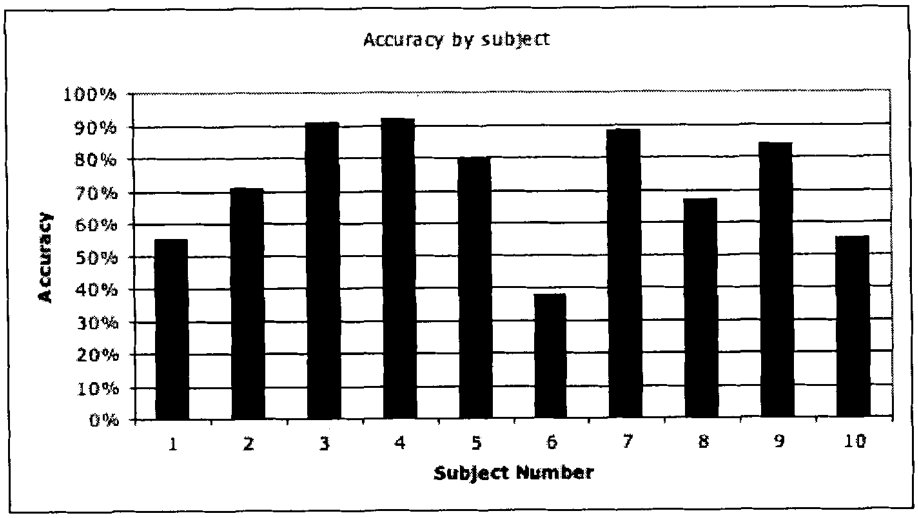


Figure 3.5: Accuracy by subject for Experiment 2.

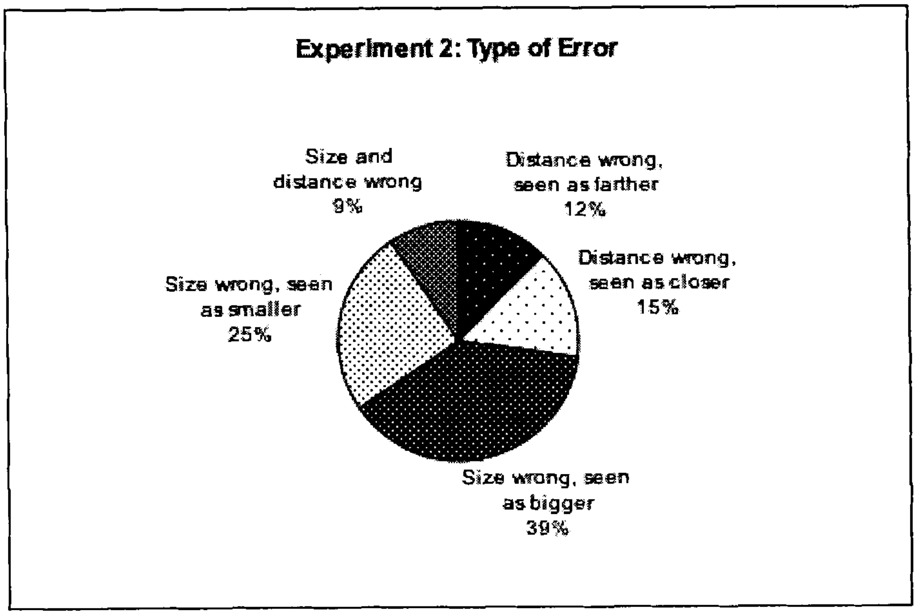


Figure 3.6: Frequency of types of errors made by subjects in experiment 2.

$Size_L$	$Dist_L$	$Size_R$	$Dist_R$	$\%TotalErr$	$\%DistErr$	$\%SizeErr$
7.6	203.2	10.2	101.6	9.97%	18%	82%
7.6	271.8	12.7	170.2	6.04%	50%	50%
7.6	271.8	15.2	304.8	6.04%	95%	5%
10.2	203.2	7.6	101.6	5.14%	0	100%
10.2	304.8	15.2	170.2	6.65%	27%	73%
10.2	170.2	20.3	203.2	6.65%	96%	4%
12.7	304.8	7.6	101.6	4.83%	44%	100%
12.7	170.2	10.2	203.2	7.25%	4%	96%
12.7	101.6	20.3	304.8	8.16%	0	100%
15.2	101.6	7.6	304.8	3.93%	15%	85%
15.2	170.2	12.7	271.8	10.88%	8%	92%
15.2	203.2	20.3	271.8	2.42%	75%	88%
20.3	271.8	10.2	203.2	6.95%	100%	17%
20.3	304.8	12.7	170.2	6.95%	57%	100%
20.3	101.6	15.2	271.8	8.16%	11%	92%

Table 3.1: Distance/Size combinations used in Experiment 2 and the number of errors for each. Total error is the percentage of error for that condition compared to total error. The distance and size errors are the percentage of those errors for that condition. The total of the two can be greater than 100% because errors could be either size or distance errors or both.

3.4.4 Discussion

It was interesting to see that half of the subjects tested performed very well (accuracy above 80%) despite the paucity of visual cues to depth, while three of the subjects performed near or below the level of chance. One subject (subject 6) had an accuracy of only 38%. While the errors made by the subject varied, it was clear that there was a pattern to the errors being made. The subject was clearly misinterpreting the cues that were given in the virtual environment, as they consistently made the same errors when viewing repetitions of the same trials. This suggests that they were aware of the cues but were misinterpreting them, often opposite of what they should be.

In general, subjects with high accuracy overall tended to make size errors predominantly, while those subjects with low overall accuracy made errors on both size and distance. However, the overall number of distance errors was higher than we had expected. Because distance judgments in this task were relative, we predicted a high level of accuracy for all subjects, however more than 27% of the errors made were in the relative distance of the two spheres from the subject. These results suggest that size constancy is not upheld for most subjects in this type of task, and the high number of distance errors found is likely an interaction between the subjects' use of visual angle to determine size which would give them an incorrect perception of distance.

3.5 Experiment 3

Our third experiment was meant to reflect the natural use of CAVE-like environments, where it is possible to use physical props in the scene. For instance, in some car design scenarios, a real car seat is brought into the cave, as is a steering wheel control device (Brooks, 1999). This experiment attempts to better characterize how well a user is able to incorporate and resolve the different sources of information about depth from real and virtual stimuli. For this experiment we used a method of adjustment task that required the user to place the virtual sphere at the same depth plane as the real sphere. Both objects were visible in the same field of view, but were separated by 50 cm so that they could not be focused on simultaneously.

3.5.1 Materials and Methods

Participants

Four adults between the ages of 23 and 40 years participated in the experiment. Three of the subjects were male and one was a female. All participants had normal or corrected to normal vision and normal stereoacuity.

Apparatus

Subjects matched the distance of a virtual sphere to that of a physical sphere. The virtual spheres were presented in a RAVE FakeSpace active stereo projection display. Stimuli consisted of virtual white spheres sampled from a uniform size distribution between 7.6 cm and 20.3 cm, set at starting distances randomly sampled from a uniform distribution ranging from 100-300 cm. For the physical setup, a white 15 cm sphere was set at one of 9 distances ranging from 100-300 cm in 25 cm increments directly next to the Fakespace screen. The background for both the physical and real conditions was black, although the virtual condition had green intersecting lines on the floor extending 10 metres into the scene.

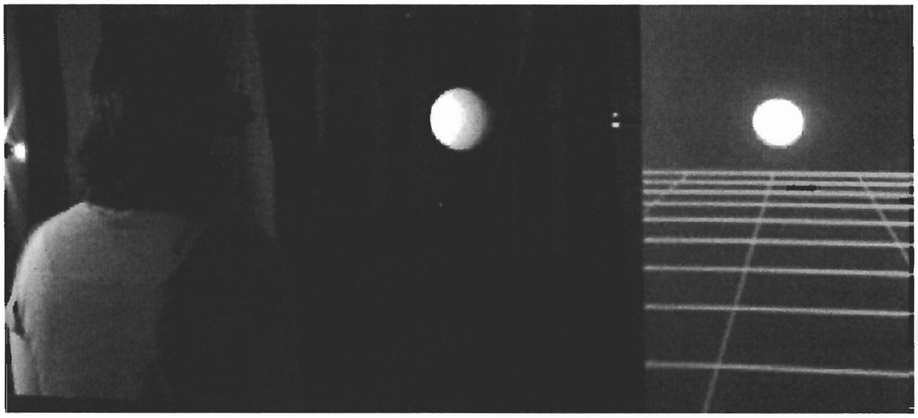


Figure 3.7: Experimental setup for the second GM experiment which used a method of adjustment to match the distance of a virtual sphere to that of a real sphere. Image credit: C. Akai.

The lines on the floor did not meet the virtual sphere during the experiment (see Figure 3.7).

Subjects were seated 200 cm in front of the screen and 20 cm from the left edge of the screen. They were able to see both the physical and virtual sphere at the same time in the same field of view. Subjects wore CrystalEyes Shutterglasses throughout the experiment. The application 'VR Juggler' (an open source virtual reality tool) was used to project the stimuli in the virtual display. The vertical position of the virtual sphere was adjusted to the height of the subject in their chair, and interpupillary distance was measured and adjusted for each subject. Subjects were not headtracked and no chinrest was used.

3.5.2 Procedure

The experiment was broken into two sessions of 135 trials per subject. Each session used the same task and range of sizes and distance but with random ordering. Sessions consisted of a series of 9 blocks. Each block used one distance setting for the physical sphere combined with three 3 different uniformly-random sizes and distances for the virtual sphere, with 5 repetitions, for a total of 15 trials per block. The 9 physical distances were randomly repeated twice, giving 18 blocks, and a total of 270 trials. During the trials, the subject used the keyboard to adjust the distance of the virtual sphere to match that of the real. Because retinal size has been shown to have a significant effect on size and distance judgments (Poupyrev, Weghorst, Billinghurst, & Ichikawa, 1998; Howard, 2002b), we randomized the size of the virtual sphere for each trial. Before the start of the experiment, the subjects were encouraged to familiarize themselves with the test procedures by doing practice trials. These trials were the same as a normal trial, except that the subject was given feedback on the correct distance. After a subject entered a distance, the virtual sphere would move slowly to the same distance of the physical, stay there for 0.75 s., before it disappeared. This gave the subjects a chance to familiarize themselves with the metric of adjustment. No feedback was given once the actual experiment started. Our subjects typically completed approximately 15 practice trials before feeling comfortable enough to start the main experiment. Subjects had access to a number of distance and depth cues to make their judgments. In the physical setting, they had some notion of the background and surroundings from the lights used to illuminate the physical sphere, and could also see the edge of the VR screen. In the virtual, they had linear perspective cues from floor, retinal size changed as the sphere changed distance, motion cues from movement of the virtual sphere, and of course binocular disparity between the real and the virtual ball.

3.5.3 Results

Distance estimates were analyzed with a General Linear Model ANOVA conducted with SPSS version 11 for Mac. Analysis showed a main effect of real distance ($F(5, 108) = 48.02, p < .001$). As expected, error increased as the distance increased (Figure 3.8). Error also varied considerably by individual (Figure 3.9).

Figure 3.8 shows individual averages of distance estimates over the two sessions. Subjects 1, 3, and 4 tended to underestimate distance while subject 2 overestimated. Figure 3.9 shows the amount of absolute error for each subject, as predicted by Weber's law there is a weighted increase of error with distance. However, at distances behind the screen (i.e. greater than 200cm), error increases markedly in several subjects. It is very interesting to note that despite a large disparity (distance was 1 metre in front of screen), all subjects were highly accurate at the closest distance. The amount of variability at the farthest distance is quite striking in that distance-matched targets varied up to a metre from each other. This is an unusually high amount of error, one that would not likely to be replicated in a real world matching task across this range of distances.

Despite accurate performance at near distances there are still noticeable individual differences. Subject 4 was the most accurate with the least variability, but still shows a slight steady increase in error as distance increases, while subject 3 had a low average error at the

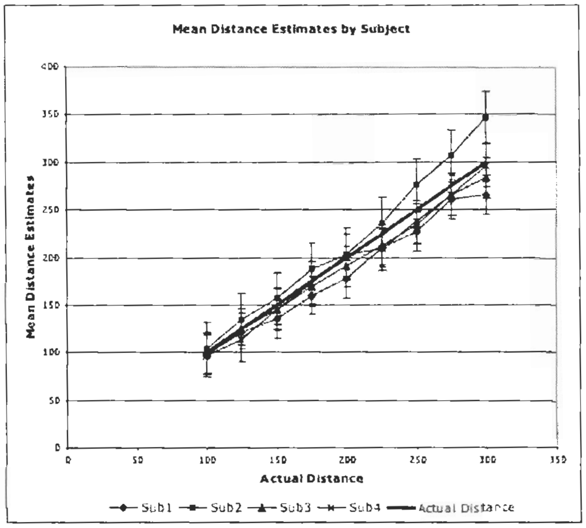


Figure 3.8: Mean distance match of virtual sphere to real-world sphere by subjects for experiment 2.

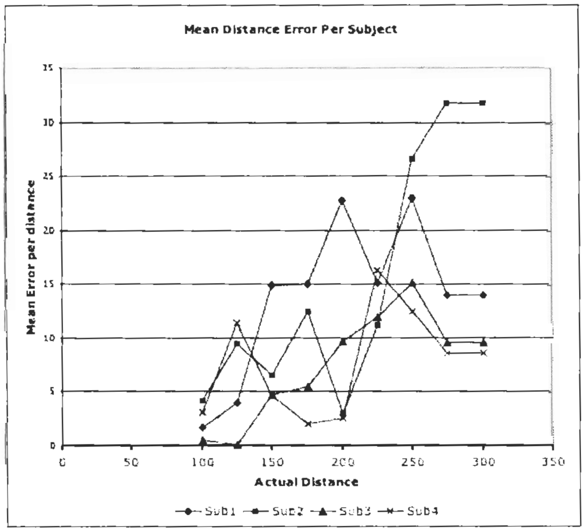


Figure 3.9: Mean absolute error for real-virtual distance match by subjects for experiment 2.

farthest distance but also the highest amount of variability.

3.5.4 Discussion

In this experiment, we tested subjects' ability to make a relative judgment with a real and virtual object in the same scene. The results show that all subjects were able to position the virtual sphere to match that of a real sphere with a high degree of accuracy. There is a trend of increased variability at larger distances, which is to be expected as the accuracy of distance estimations decrease when distance increases.

The relatively high levels of accuracy we have found at the closer distances may be caused by a number of factors, the most likely being that subjects are often able to do arbitrary matching tasks by using whichever cue supports that discrimination. Whether or not the apparent depth of real and virtual targets matched, subjects could may have noticed that stereo disparity varied directly with their manipulation of the sphere, and set the comparison sphere such that it's binocular disparity matched that of the control stimulus. The method of adjustment used for the virtual object may also have led subjects to overcome any perception of depth compression because of the motion parallax cue. Rogers & Graham (Rogers & Graham, 1979) found that motion parallax is a very strong and unambiguous cue to depth when no other depth cues are present. It may also be that having the real object in the scene 'grounded' the rest of the virtual scene, by providing a frame for which to evaluate it. While this may seem counterintuitive, it is possible that display errors and shortcomings such as lack of dynamic range, resolution and field of view limitations, accommodation/vergence mismatch, etc. act to increase uncertainty of depth judgments (perhaps through perceptual recalibration, see (Epstein, 1975)). The presence of a real object that allows users to recalibrate depth cues may support the use of any of those cues in isolation, including stereo disparity. This last explanation would imply that displays that occlude the real world, such as HMDs, may suffer from greater difficulty in depth judgment, something that should be explored in future work.

Chapter 4

Final Experiment

Individual differences are an inevitable part of perception, as each individual perceives the world slightly differently based on their experiences and their interpretation of the information they receive from their senses. However, the individual differences found by General Motors suggest that there are other factors at play. The GM study by Baitch and Smith (2000) showed that the impact of individual differences in VR was not attributable solely to variations in an individual's stereoacuity or other easily measurable visual characteristics, but must stem from other sources of perception, though it was not clear what those were. In the time we have been conducting research on depth perception in virtual reality, we have repeatedly found significant individual differences in performance. However, to date, we have also been unable to isolate the causes of these individual differences. For this final experiment, I decided to take a broader view of the perceptual process and examine individual differences from a new angle.

Using a psychophysical approach to understand perception requires low-cue stimuli in order to isolate the number of cues being studied. A difficulty of this approach is that the world rarely provides so few cues for perception, therefore, humans are not adapted to perceiving in such austere environments. In the second experiment a forced choice task was used, and it was noted that some subjects were extremely accurate and quick with their perceptual judgments even if it was their first exposure to a virtual environment, while others tended to take considerably longer to make judgments and were often less accurate. Those who hesitated were very uncertain and often asked repeatedly whether there was a difference between two stimuli in the task. It was clear that the stimuli appeared very ambiguous to them, and this seemed to perturb them. Based on this observation, it was decided to run an exploratory study to examine whether the personality trait of tolerance of ambiguity was related to performance in a depth perception task in a virtual environment. It was hypothesized that those who seemed more comfortable in the low-cue ambiguous environment were more tolerant of ambiguity in general while those who showed more difficulty in the low cue environment were generally less tolerant of ambiguity. It was also hypothesized that virtual reality environments could be perceived as more ambiguous than the real world and viewers who were less tolerant of ambiguity would be more affected by the virtual condition and show poorer performance.

A second observation made during the previous experiments was that those who performed well often had considerable experience with computers and video games. Based on this observation, it was speculated that not only would those with experience in video games show superior performance, but those who had trained themselves perceptually in sports might also show higher performance because they had trained their perception to re-calibrate under certain conditions. It was hypothesized that previous training and experience in sports or video games could allow a viewer to adapt their perception to a virtual environment more quickly than someone who has not had similar experiences.

4.1 Tolerance of Ambiguity

The idea of Tolerance of ambiguity as a personality variable is first found in work by Frenkel-Brunswick (Frenkel-Brunswick, 1949; Frenkel-Brunswick, 1951) in her work on authoritarian syndrome. Since then, the idea of tolerance or intolerance of ambiguity has been explored in conjunction with ethnocentrism (Block & Block, 1951), management (Clampitt & Williams, 2006) and perceptual closure (Smock, 1957). Budner (1962) describes tolerance of ambiguity as "the tendency to perceive ambiguous situations as desirable" and intolerance of ambiguity as "the tendency to perceive ambiguous situations as sources of threat" (Budner, 1962, p.29). He describes an ambiguous situation as one which "cannot be adequately structured or categorized by the individual because of a lack of sufficient cues" (p.30, Ibid). More recently, Furnham (1994) described tolerance of ambiguity as:

> "the way an individual (or group) perceives and processes information about ambiguous situations when they are confronted by an array of unfamiliar, complex or incongruent cues...the person with low tolerance of ambiguity supposedly experiences stress, reacts prematurely and avoids ambiguous stimuli...a person

> with high tolerance for ambiguity perceives ambiguous situations as desirable, challenging, and interesting, and neither denies nor distorts their complexity or incongruity" (p.403)

Frenkel-Brunswick maintained that Tolerance of Ambiguity "generalized to the entire emotional and cognitive functioning of the individual, characterizing cognitive style, belief and attitude systems, interpersonal and social functioning and problem solving behaviour" (Frenkel-Brunswick, 1949, p.109).

Several questionnaires have been established to measure tolerance of ambiguity as a personality variable (Budner, 1962; Rydell & Rosen, 1966; Norton, 1975). Based on a content, correlational and factor analysis of the Rydell and Rosen questionnaires (Rydell & Rosen, 1966) and MacDonald's subsequent revision of that questionnaire (MacDonald, 1970), it was found that the Rydell and Rosen questionnaire had an internal reliability of 0.78, but factor analysis showed that it contained several different factors (Furnham, 1994). Earlier work by Kirton (1981) performed an item analysis on the questionnaire and suggested a revised questionnaire that removed 9 of the original questions for failing to distribute or relate well to the other questions. The shortened questionnaire had an internal reliability of 0.71 (compared to Kirton's initial finding of internal reliability of 0.62). Because of these issues it was decided to use the Macdonald questionnaire. However, in the end the revised version by Kirton (1981), which contained eleven questions, was scored because significant differences between scores with the 20 question version and the 11 question version were found (see Appendix E for questionnaire).

4.2 Adaptation and Previous Experience

The research on adaptation in virtual environments is still fairly young, but there have been several studies that looked at the effects of adaptation on cybersickness. Regan (1995) found that cybersickness symptoms (e.g. nausea, disorientation and oculomotor disturbances) were greatly reduced for the majority of viewers even after one exposure to virtual reality on head mounted displays (HMDs), and symptoms were further reduced after 4 sessions. Fowlkes, Ken, Hettinger, and Harm (1993) found that differing patterns in subjects' dark focus points were correlated with incidence of cybersickness. Individuals who were able to adapt their dark focal points were less prone to sickness.

Robert Welch is one of the few researchers looking specifically at visual adaptation in virtual environments. He has modified the Dual Adaptation theory, which was first explored using prism adaptation, to virtual reality (Welch, 1978; Welch, Bridgeman, Anand, & Browman, 1993; Welch, Bridgeman, Williams, & Semmler, 1998). This hypothesis suggests that individuals can adapt to more than one mutually conflicting sensory environment. With experience in each environment, switching between the different environments becomes easier. However, adaptation to each environment requires a discriminative cue that is specific to that environment. While in different environments, individuals do not remain adapted to the other environments, but maintain a readiness to adapt to those environments (Welch, 1978). It was found that adaptation training must be alternated with re-adaptation for it to be successful. To encourage re-adaptation viewers must be exposed to the non-arranged sensory environment under the same conditions in which they saw the arranged environment. The most common example of this is in people who wear glasses, who can instantly adapt to seeing the world with and without glasses, though there is an adaptation period when they first start wearing glasses or when they get a significantly stronger prescription. If this hypothesis is true, then adaptation and training may yield results in improving perception in virtual environments. Welch (2002) also suggests that individual differences in virtual environment perception can be caused by 1) whether the viewer detects a given sensory conflict, 2) how much a problem this conflict is for them and 3) how adaptable they are to the conflict. The requirements necessary for adaptation (Welch, 2002), include: a stable arrangement of cues, active interaction, error corrective feedback, immediate sensory feedback, incremental exposure, and distributed practice (over time). Two types of activities that provide most of these requirements are sports and video game playing.

Perceptual learning is common in sports and video game playing. While there has been concrete evidence that sports can result in visual perception learning (Stine, Arterburn, & Stern, 1982), it is not clear whether perceptual training results in improved performance in sports (Hitzeman & Beckerman, 1993). Studies on video game players have found that players do show visual adaptation and attention effects that non-video game players do not (Green & Bavelier, 2003; Green & Bavelier, 2006). What is not clear is to what extent one's experience with perceptual learning will transfer to new environments. I hypothesized that it is possible that those with previous training in sports and video games will show better performance than those who do not, however, this will be purely exploratory, because due to serious time constraints, it was not be possible to get an adequate number of subjects to test this with any certainty.

4.3 Research Questions and Hypotheses

The main research questions guiding this work were:

- How does distance perception based on binocular depth cues in virtual stereo environments differ from depth perception of binocular cues in the real world?
- Can we isolate some of the causes of individual differences observed in virtual reality displays?

The experiment was designed to test the following hypotheses:

- Significant differences in subject accuracy will be observed in a distance discrimination task using virtual stimuli compared to a task that discriminates distance between real and virtual stimuli.
- The presence of a real stimulus will increase accuracy of distance discrimination in virtual environments.
- There is a correlation between a subject's previous experience with tasks that allow for perceptual training and their ability to discriminate distance in virtual environments.
- There is a correlation between a subject's Tolerance of Ambiguity score and their ability to discriminate distance in virtual environments.

4.4 The Experimental design

The goal of this final experiment was to ex how difference thresholds for distance discrimination vary in a comparison of a real to a virtual stimulus and between two virtual stimuli using a staircase method (a modified method of limits task) and to explore some possible causes of individual differences with the use of qualitative questionnaires. The experiment was informed both by the literature presented in Chapter 2 and by the previous work described in Chapter 3. The choice of task was based on the experience with different metrics in the first three experiments. A metric that relied on absolute judgments was found to produce large variance in responses in the first experiment, while the third experiment showed very little variability, but was likely confounded by a cue other than the one we were hoping to measure. The second experiment had given us a range of performance among subjects and seemed likely to produce individual differences that were not purely caused by the metric, so a similar task to the second experiment was used, but only distance perception (not size perception) was measured. As in two of the previous experiments, the difference in perception between a real stimulus compared to a virtual stimulus, and two virtual stimuli were compared. Based on the results of the third experiment, it was anticipated that the real stimulus would improve performance. A transformed adaptive staircase method was used because they tend to be more efficient (require less trials than other methods because they start closer to the threshold), more flexible (can be used for various modalities) and have less restrictions than other methods (the only significant restriction is that there must be a monotonic relationship between the stimulus intensity and performance level) (Levitt, 1971). Adaptive staircases incorporate previous subject responses to determine the value of future stimuli. A transformed staircase is more robust to noise since it can incorporate various rules that will reduce the effects of noise such as mistakes in response entry, it will also set a higher performance level, for example an 80% performance level instead of the usual 50% level produced by standard staircase procedures (Ibid).

The decision to include Tolerance of Ambiguity as a potential covariate in depth perception was based on an observation in the second experiment. However, psychophysical methods are meant to address low levels of perception, and the question of whether perception is cognitively penetrable has been hotly debated. Pylyshyn (1999) suggested that early vision (in a pre-perceptual allocation stage) is not cognitively penetrable, but that later processing in a post-perceptual evaluation, selection and inference stage is. The question of where to draw the line between early and later stages is still unclear. Pylyshyn notes that "psychophysical tasks typically involve at least two stages, one of which, sometimes called 'detection' or 'stimulus evaluation' is immune from cognitive influences, while the other, sometimes called 'response selection' is not." (Pylyshyn, 1999, p.389). Recent work by Balcetis and Dunning (2006) found that people's motivations or preferences influenced their perception of ambiguous stimuli. They suggest that these motivations and preferences influence preconscious processing and help determine what the visual system presents to conscious awareness. Because the decision stage effect might prove important for a subject's ability to tolerate ambiguity the task was not a two-alternative forced choice in the traditional sense. A true psychophysical 2-alternative forced choice task requires that the stimulus presentation be varied either spatially or temporally to reduce the impact of subject bias. This was not possible in the condition that compared a real to virtual stimulus because the real sphere was always on the right side as the standard while the virtual sphere on the left was always the comparison and they were shown simultaneously. So the subject always knew where the standard was and to try to match the conditions the same was done for the virtual/virtual condition. Two-alternative forced-choice tasks are designed to be criterion (or bias) free measures that eliminate some of the bias from individual subject's responses so that the data can more easily be generalized to a population. But because individual differences were of more interest than generalized results, it was anticipated that the task would still provide interesting information, though it would be difficult to determine the exact role of bias in the results.

4.5 Materials and Methods

4.5.1 Participants

Eight participants took part in this study, 4 females and 4 males. Five of the subjects were naive to the purpose of the study, while three subjects were familiar with the study. All subjects were students or faculty of the university and signed informed consent forms. All subjects were paid $20 for their participation. Prior to the experiment, each subject was tested with the Titmus StereoFly test to ensure that they were not stereoblind. All subjects had normal or corrected to normal vision.

4.5.2 Apparatus

Two conditions were tested: a comparison of a real stimulus to a virtual stimulus (real condition) and a comparison of two virtual stimuli (virtual condition). The stimuli for the real condition included a white Styrofoam sphere mounted at the end of a hand-built stand that held an extendable pole, which could be set to different distances (see Figure 3.1). The stand was painted black to minimize its use as a relative cue. The real sphere was 20 cm in diameter and was textureless like those in the previous experiments. The virtual sphere was projected on portable screen set at 2 metres away from the subject. The virtual sphere was a white textureless OpenGl sphere with some lighting and shading to give it a sense of volume. The sphere was created using VRJuggler open-source Virtual Reality software.

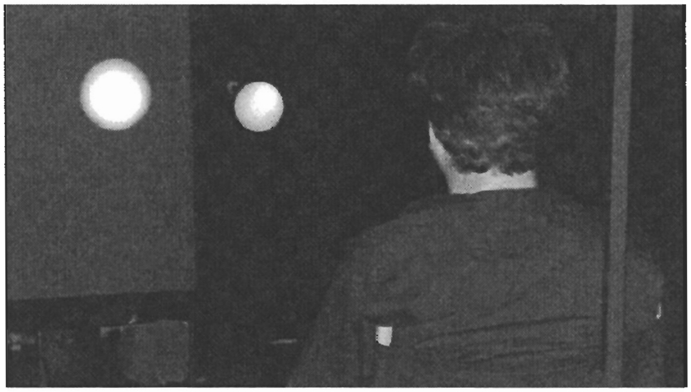


Figure 4.1: Experimental setup for experiment in the real/virtual stimulus condition. The real (standard) stimulus is set at a distance of 175cm from the subject. Image credit: C. Akai.

It was rear-projected onto the screen using a DepthQ InFocus projector with a refresh rate of 120 Hz. Both stimuli were viewed with LCD Shutterglasses. Because the shutterglasses split the field rate between two eyes, the field rate was 60 Hz per eye. The virtual sphere diameter was set at 15 cm. The real sphere was presented directly beside the screen so that a distance of approximately 10 cm separated the edges of the real from the virtual sphere (this measure is approximate because the distance varies slightly as the virtual sphere changes distance) (Figure 4.1).

For the virtual condition, two virtual spheres were shown side by side on the screen, separated by 10 cm (Figure 4.2.) The sphere on the right hand side was the standard and did not change position throughout each block of trials. The size of the standard was set at 20 cm and the size of the comparison sphere was set at 15 cm. During both conditions, the subject could easily see both spheres without moving their head. No chin rest was used, but subjects were asked to keep their heads still while making their judgments. All conditions were conducted in a darkened room, with the light from the screen, and the lighting for the real sphere (in the real condition only) as the sole sources of illumination.

4.6 Procedure

Prior to beginning the experiment, subjects completed the Titmus Stereofly test, signed consent forms and had their interpupillary distance (IPD) measured. The IPD was then input into the VRJuggler software so that the virtual images would be projected appropriately

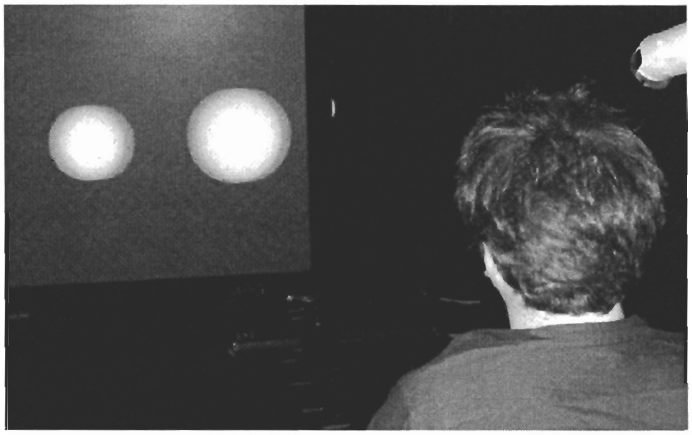


Figure 4.2: Experimental setup for virtual/virtual stimulus condition. The virtual standard is set at 175 cm from the subject. Image credit: C. Akai.

for them.

This research focused on egocentric and exocentric distance from 1-3 Metres (personal and action space) because this is the main distance range used by General Motors for models in virtual environments. It is known that depth perception becomes less accurate as distance increases, and optical infinity is generally defined as 6 Metres (Baitch & Smith, 2000; Howard, 2002a). For both the virtual and real conditions, the standard sphere was placed at three distances: 125, 175, and 250 cm from the subject. A block of 160 trials was performed for each condition/distance combination for a total of 6 blocks. There were 480 trials for each condition and 960 total trials per subject. The standard stimulus distances were chosen based on data from previous experiments which showed that accuracy went down and variability increased around the 3 m mark, while accuracy was extremely high at 175cm (sometimes higher than equal to the screen distance of 200cm). It was expected that accuracy would be high at 125cm, but would likely be slightly overestimated. Accuracy at 175cm would be high, while perception of distance at 250cm would be less accurate and underestimated.

A transformed adaptive staircase procedure was used to set the distance of the comparison sphere. The staircase code was adapted from code written by the Oxford Virtual Reality Research Group (Virtual Reality Research Group, 2005), and used four interleaved staircases. The four staircases behaved in the following manner:

1. Staircase 1: Three up, 1 down, starting from below the standard distance. The

comparison stimulus distance moves closer to the standard distance if 3 consecutive correct answers are given. One incorrect answer moves the distance of the next trial farther from the standard distance.

2. Staircase 2: 1 up, three down, below the standard distance. The comparison stimulus distance moves closer to the standard distance if one correct answer is given. Three consecutive incorrect answers move the distance of the next trial farther from the standard distance.
3. Staircase 3: Three down, 1 up, starting from above the standard distance. The comparison stimulus distance moves farther from the standard distance if one correct answer is given. Three consecutive incorrect answers move the distance of the next trial closer to the standard distance.
4. Staircase 4: 1 down, three up, above standard distance. The comparison stimulus distance moves farther from the standard distance if one correct answer is given. Three consecutive incorrect answers move the distance of the next trial closer to the standard distance.

Staircases 1 and 3 are more sensitive to noise, but converge quickly on the standard distance, while staircases 2 and 4 will take longer to reach the standard distance but are more robust against noise. The step size used was 1/24th of the range of distances tested (12 cm), making the step size 0.25cm. Based on a study by Johnston et al. (1993) step size was weighted such that the step size was increased by a factor of 6/N, where N was the number of trials already presented in that staircase. This weighted steps at the beginning of the staircase more heavily so that the comparison stimulus distance approached the standard distance more quickly. This weighting increased the first step in the staircase by a factor of 6, the second by a factor of 3, the third by a factor of 2, after this point the factor became negligable, though the factor was never allowed to be less than 1. The range of 12 cm (6 cm below and 6 cm above the comparison distance) was determined based on pilot testing, which found that most errors were made within 5 cm of the standard distance. Larger ranges of 50cm and 25 cm were tested during the pilot study but required overly large step sizes. Figure 4.3 shows an example of how the four staircases progressed for one subject in the virtual condition.

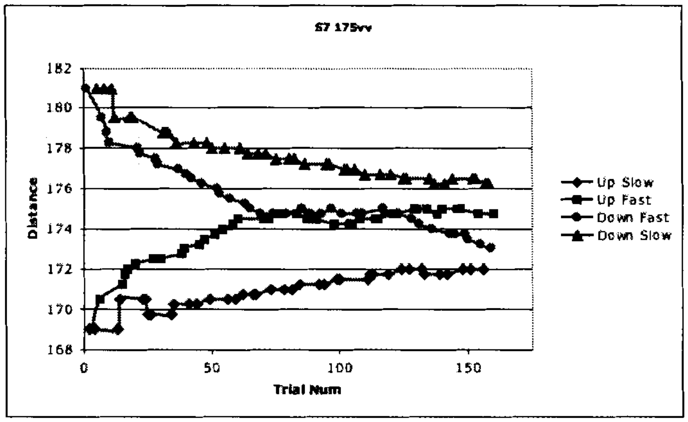


Figure 4.3: An example of how the four staircases behaved for Subject S7 in the 175 cm virtual condition. The movement of the staircases is dependent on subject performance so the exact staircase varied for each block of trials for each subject.

The task was a distance discrimination task that required a 2-alternative judgment as subjects declared whether the virtual comparison sphere on the left-hand side was closer or farther than the standard. During each trial the subject entered their response (closer or farther) by hitting the appropriate key on a keyboard. The computer tracked the subject's performance and input the data into the staircase function in order to determine future trial distances. The distance of the virtual sphere for the next trial was randomly selected from one of the 4 staircase procedures. Trials were advanced by pressing the spacebar, and the subjects were permitted to advance at their own pace. This was done so that they did not feel pressured to move more quickly through the trials than they were comfortable with, and to ensure that if necessary, they could stop running trials during a block, if they experienced any symptoms of cybersickness. However, all subjects completed every block in one sitting. Between blocks, subjects were encouraged to get up and remove the LCD shutterglasses to let their eyes rest. During breaks, the lights were turned on and they filled out the questionnaire or simply relaxed.

The questionnaire was divided into two parts, the first part asked about their previous experience playing sports and video games. It also asked about several factors that could impact their depth perception including whether they had ever had eye correction surgery, whether they had any problems with their vision that had or had not been corrected (since childhood problems can affect perception in adults), whether they could see Magic Eye images, and how much time they spend on the computer. The questions about their vision were used because it was not possible to do any sophisticated visual testing, and it was important to know of pre-existing vision issues that subjects might have. The question about Magic Eye puzzles was added to determine whether they had experience using binocular disparity as the main cue to depth. The question on computer use was to determine whether they were used to spending time with a virtual (non-stereo) display that might help them to be more comfortable in a virtual reality environment. The second part of the questionnaire was a personality test for Tolerance of Ambiguity.

4.7 Results

The data collected during each trial included the subject's response (closer, farther) which was compared to the actual distance to determine accuracy (correct, incorrect), and response time (the time from when subjects began a trial to the time when they enter their response).

Thresholds for each condition/distance combination were calculated by averaging the reversal points of the two ascending and two descending staircases separately to create an up threshold (based on ascending staircases) and a down threshold (based on the decending staircases). Graphs of the two thresholds for all subjects are shown in Appendix B. This technique for measuring thresholds has been found to give a fairly consistent threshold comparable to other methods such as averaging the stimulus intensities or using the point of subjective equality (Dallenbach, 1966). Keeping the ascending and descending staircases separate was extremely important as they were markedly different.

Psychometric functions were fitted to the data for each of the six conditions (2 conditions x 3 distances) for each subject using Psignifit, version 2.5.6 (see http://bootstrap-software.org/psignifit), an extension for Matlab that uses a maximum-likelihood method to test the quality of fit (Wichmann & Hill, 2001). The functions were fitted using a cumulative gaussian curve and predict the probility with which the subjects could correctly identify the distance difference between the comparison stimulus and the standard stimulus (see Appendix A for psychometric functions for all subjects).

Results from the tolerance of ambiguity questionnaire, which included 20 questions from the questionnaire revised by Macdonald (MacDonald, 1970), were calculated using a shortened (11 question) version of the questionnaire that removed 9 questions that were found to reduce internal validity in an item analysis (Kirton, 1981). Scores were converted to a percentage and ranged from 64%-100%.

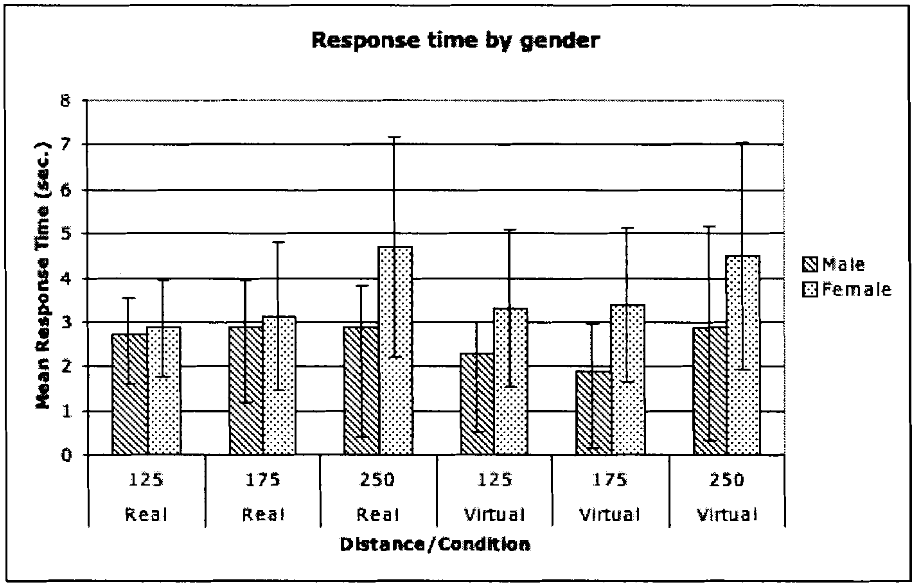


Figure 4.4: Response time by gender across all distances for both real and virtual conditions.

The up thresholds and the down thresholds were analyzed in a 2 (real vs. virtual condition) x 3 (125cm, 175cm, and 250cm distance) factorial multivariate-analysis of covariance (MANCOVA) with gender as a between-subjects factor and tolerance of ambiguity score (TOA) as a covariate using SPSS for Mac, version 11. Results showed a significant main effect for condition with Roy's Largest Root ($F(2,34) = .232, p < .03$) and for gender ($F(2,32) = .300, p < .015$). Seperate ANOVA's run on the up and down thresholds showed that there was a significant effect for the up threshold but not for the down threshold for both condition ($F(1,48) = 5.5, p < .03$) and gender ($F(1,48), p < .007$).

A separate ANCOVA was run on response time and found an effect for Tolerance of Ambiguity (TOA) ($F(1,48) = 6.85, p < .015$) and for gender ($F(1,48) = 9.101, p < .005$). The interaction between distance and gender can be seen in Figure 4.4. Females tended to take nearly twice as long to respond when the standard was set at a distance of 250 cm in both the real and virtual conditions. It is highly probable that the significant effects of TOA and gender are correlated because the males had higher average TOA scores than the females (approximately 89% for males compared to 71% for females).

Accuracy was also calculated by condition and distance for each subject and is summarized in Table 4.1.

SID	*Accur*125*r*	*Accur*125*v*	*Accur*175*r*	*Accur*175*v*	*Accur*250*r*	*Accur*250*v*
S1	66%	72%	72%	90%	85%	86%
S2	65%	52%	53%	77%	66%	68%
S3	64%	64%	63%	87%	71%	90.5%
S4	70%	67%	72%	76%	70%	68%
S5	49%	69.5%	64%	97.5%	95%	77%
S6	62%	63%	65%	94%	97%	93%
S7	97%	78%	53%	82%	63%	75%
S8	88%	75%	67%	84%	81.5%	76.5%

Table 4.1: Accuracy of each subject by condition with their previous experience.

Data from the questionnaire on previous experience and training is presented in Appendix F. Based on the questionnaire responses the subjects were categorized into groups of those who played no video games (none), occasionally played video games (low: less than 5 hours a week), regularly played video games (medium: 6-15 hours a week), and avid video game players (high: 16+ hours a week); as well as how frequently they played sports: none, low: some fitness activity (not necessarily sports), medium: regularly played sports (team, individual sports), and high: avid sports player (plays 2 or more times a week). Computer use was also coded as none, low (0-15 hours/week), medium (16-30), and high (31+hours per week). These results are summarized in Table 4.2.

S_ID	*Gender*	*TOA*	*ExpVidGam*	*ExpSprt*	*ExpCmpt*
S1	M	100%	med	none	med
S2	F	64%	none	low	med
S3	F	64%	none	low	med
S4	M	100%	none	none	high
S5	M	73%	none	none	high
S6	F	91%	low	none	high
S7	M	82%	med	med	med
S8	F	64%	med	med	med

Table 4.2: Summary of results of questionnaire: Tolerance of ambiguity scores and previous experience for each subject.

Because subjects were volunteers and self-selected, there is not as great a range in experience and training as needed to provide any detailed information on the impact of previous experience and training on depth perception. None of the subjects devoted large amounts of time playing video games (15 hours or more/week). Few subjects had any experience

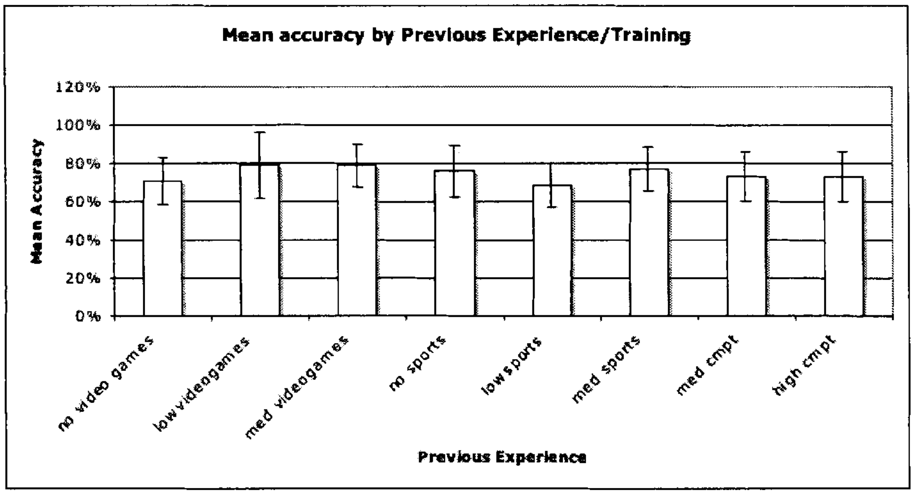


Figure 4.5: Mean accuracy for subjects grouped by distance and condition.

with sports, particularly sports that would be more likely to train depth perception (e.g. baseball, basketball), as opposed to individual fitness activities like fitness classes or swimming (which were coded as low experience with sports). Figure 4.5 shows the means for subject accuracies as grouped by their previous experience and training. There is clearly no significant difference between any of the groups, nor is there much difference in the standard deviation of each.

4.7.1 Individual Performance

As expected, considerable individual differences were observed between subjects. For most subjects, there was more variability in the real condition than in the virtual condition (see Appendix C).

Subject S1 underestimated the distance (i.e. perceived the comparison sphere as being farther than the standard) in both the real and virtual conditions for each distance. This subject had a perfect score on the Tolerance for Ambiguity test (100%) and did have experience playing video games.

Subject S2 significantly underestimated distance (by 5cm) at 125cm and 175cm in the real condition, but overestimated it just as significantly at a distance of 250cm. In the virtual condition, they consistently underestimated at each distance, with considerably more variability than in the real, with the highest variability at 175cm. This subject had the largest thresholds of the subjects tested, and also a lower score on the TOA questionnaire

(64%), no experience with video games, and little experience in sports. They were also the only subject who reported that they were unable to view Magic Eye images.

Subject S3 consistently overestimated the distance in the real condition, with a slight increase in threshold as distance increased. In the virtual condition, they underestimated at both the 125cm and 175cm distances, but showed both under and overestimation at the 250cm distance (based on the ascending and descending staircases). This subject had a lower TOA score (64%), did not play video games, but did do fitness classes.

Subject S4 consistently overestimated distance in the real condition, but showed more variability and some underestimation at 250cm. In the virtual condition, they consistently underestimated distance. They did not report playing videogames or sports, but did have a high TOA score (100%), and spent an average of 60 hours per week on the computer. They also had some experience using virtual reality displays.

Subject S5 showed a large effect for distance in the real condition, by consistently underestimating (i.e. perceiving the stimulus as closer than the standard) at 125cm, and consistently overestimating (perceiving stimulus as behind standard) at 250cm. They slightly overestimated at 175cm in the real condition. In the virtual condition, they showed the highest accuracy of all subjects, with only slight overestimation across all distances, and most variation occurring at 175cm. The subject did not play video games or sports, but did report spending an average of 60 hours on the computer, and had a medium TOA score (73%).

Subject S6 showed nearly the opposite results to Subject S5, by overestimating the distance at 125cm in the real condition, and underestimating distance at 250cm. They were also very accurate in the virtual condition, but showed a slight overestimation of distance, most significantly at 125cm. The subject did not report playing sports, but did play video games, and had a high TOA score (91%). Subject S7 showed a significant overestimation (over 3cm on average) in the real condition at the 175cm distance, and an overestimation (average of 4cm) at 250cm. They showed a very slight overestimation at 125cm. In the virtual condition, they showed consistent underestimation and large variability across all distances, with the most variation occurring at 125cm and 250cm. They had played video games in the past (but not in the last year) and cycled regularly. They had a fairly high TOA score (83%), and had some experience with virtual reality environments.

Subject S8 showed both over and underestimation in the real and virtual conditions across all distances. Though for the real condition there was high variability at 175cm while the highest variability in the virtual condition was at 250cm. The trend of underestimation of distance was much stronger in the real condition and increased with distance. The subject had played video games regularly approximately 10 years ago, but no longer did, and had participated in some sports years earlier. They had a lower TOA score of 64% and had some experience in virtual reality environment.

Chapter 5

Discussion

While the results showed substantial individual differences, it is clear that the null hypothesis can not be rejected for several of the hypotheses the experiment was designed to test. The results for each hypothesis will be discussed in relation to the results, followed by further findings and implications.

Hypothesis 1: Significant differences in subject accuracy will be observed in a distance discrimination task using virtual stimuli compared to a task that discriminates distance between real and virtual stimuli.

Strong individual differences were found, and the omnibus tests showed that there was a relationship between the up-threshold and the two conditions. Individual subject accuracy was slightly more accurate in the virtual condition than the real condition (see Figure 5.1). This was likely due to increased cue conflict in the real/virtual condition. Designing studies to compare depth perception using low cue real and virtual stimuli is quite difficult, as it is nearly impossible to match the depth cues available in the real world to those in the virtual world. Care was taken in the experiments to ensure that the virtual and physical stimuli were as closely matched as possible, but some differences in the stimuli were unavoidable. In particular, the lighting was extremely difficult to match, as both the real and virtual stimuli had to be viewed with stereoshutter glasses which darkened the scene considerably, and shading was not exactly replicated. As well, small differences in the height between the real and virtual stimuli were sometimes present, as the height of the virtual comparison sphere appears to change as the distance changes. These differences could have created cue conflicts for subjects, and biased their perception in the real condition. If this was the case, then cue conflicts may have had a stronger effect on performance than the presence

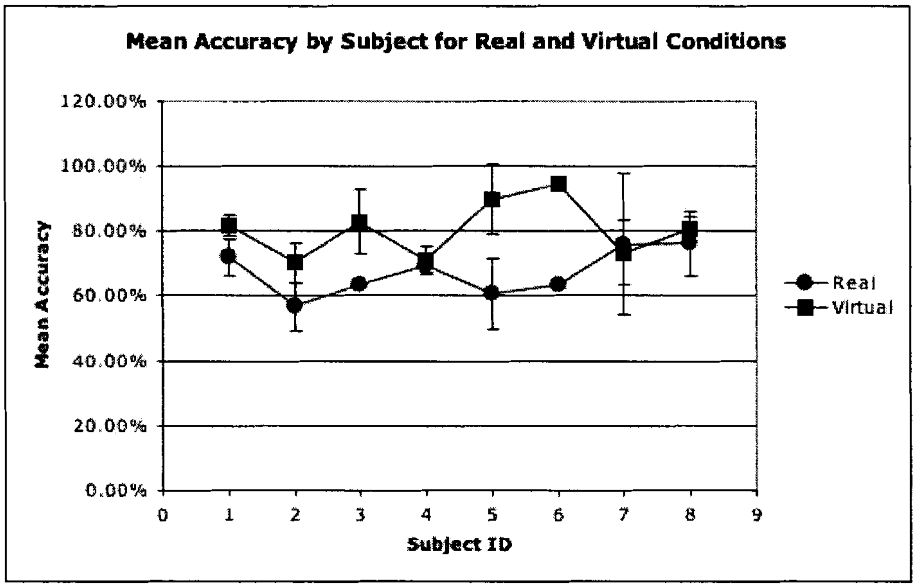


Figure 5.1: Mean accuracy for subjects grouped by condition.

of additional depth cues that were not available in the virtual condition, and should be explored further in future research.

Subjects had very different perceptions of where the stimulus appeared and they were extremely consistent in these perceptions. The thresholds seem much larger than would be expected based on average stereoacuity, with several subjects having thresholds of 4 cm and higher. The relationship between the ascending and descending threshold is also interesting because for most subjects (with the exception of subject S8) one staircase would show a threshold near zero, while the other showed a threshold of several cm. This effect may be the result of noise in the data.

There were significant interaction effects for distance on response time. Appendix C shows scatterplots of response time for each condition by subject. These are the response times for each trial. Some subjects took considerably longer to respond than others. For example, subject S1 almost always took less than 10 seconds to respond in the virtual condition, while subject S3 regularly took 20 seconds or longer in the real condition. Response times show a slight linear (though not nearly significant) increase with distance, with slightly longer response times being more common at a distance of 250 cm than at 125 cm (Figure 5.2).

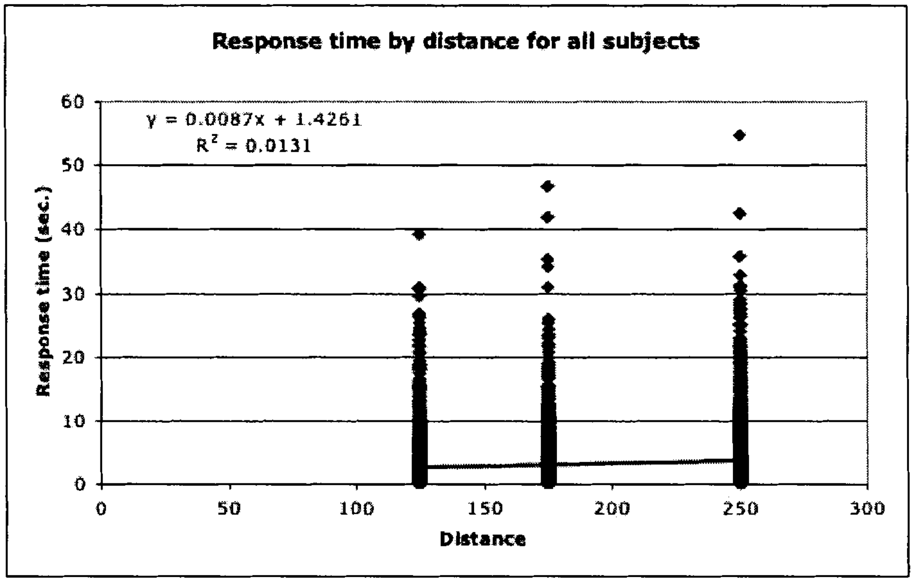


Figure 5.2: Response times for all subjects by distance.

Hypothesis 2: The presence of a real stimulus will increase accuracy of distance discrimination in virtual environments.

This hypothesis was clearly not supported by the results. In the majority of cases, subjects showed lower (i.e. smaller) thresholds and higher accuracy in the virtual/virtual condition. As discussed above, this was likely caused by conflicting cues (e.g. from the screen edge) in the real/virtual condition. Several subjects noted that it was more difficult to make the discrimination between the real and virtual stimuli, because it seemed harder to compare them. The difference between conditions was particularly noticeable in the threshold data for subject S5 (Figure 5.3). Their thresholds in the virtual condition were the lowest of any subjects (ranging between 0.375 cm to -1.75 cm) and their accuracy ranged between 77.5%-97.5%. However, their threshold increased significantly in the real condition (ranging between 3.96 to -5.7 cm) and their accuracy decreased dramatically (49%-69%). They show a strong effect for distance in the real condition with a large underestimation at 125 cm and a large overestimation at 250 cm. This result suggests that the high performance accuracy found in our previous work in experiment 2 (which used the same real stimulus) was the result of either disparity matching or more likely the strong motion cue and not the presence of a real stimulus.

Hypothesis 3: There is a correlation between a subject's previous experience

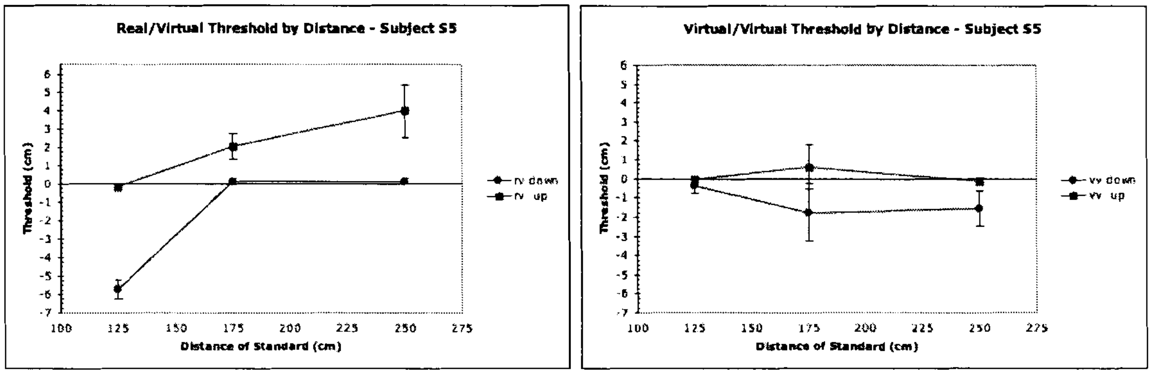


Figure 5.3: Thresholds for subject S5. Note the extremely low thresholds for the virtual condition, compared to the more extreme thresholds in the real condition.

with tasks that allow for perceptual training and their ability to discriminate distance in virtual environments.

Unfortunately, the results of the experiment did not support this hypothesis. However, it should be noted that the experiment also did not generate enough data to truly accept or reject this hypothesis. Further work in this area is still worthwhile, but a much larger subject pool categorized by experience and training will be required. As well, it became apparent as subjects filled out the questionnaires that more information is needed on how current the experience needs to be, and what level of expertise the subject had achieved in the sport or video game in question. While there is still no confirmed information on how well these skills might transfer over to a virtual reality environment, it still seems feasible that those who are comfortable moving around 2d virtual environments will have an easier time transitioning to a 3d virtual environment, than those who do not have that experience, particularly if considered from the point of view of dual adaptation.

Hypothesis 4: There is a correlation between a subject's Tolerance of Ambiguity score and their ability to discriminate distance in virtual environments.

Results did show an effect for Tolerance of Ambiguity and distance on response time, but not for threshold (see Figure 5.4). The effect on response time is not that surprising since the hypothesis was based on an observation in experiment 2 of subjects' slower response time when they were more uncertain. However, it suggests some very interesting implications for Human Computer Interaction. A strong correlation between response time and TOA suggests that analyzing user interfaces for and eliminating ambiguous elements could lead to improved response time for users with a lower tolerance of ambiguity. Response time

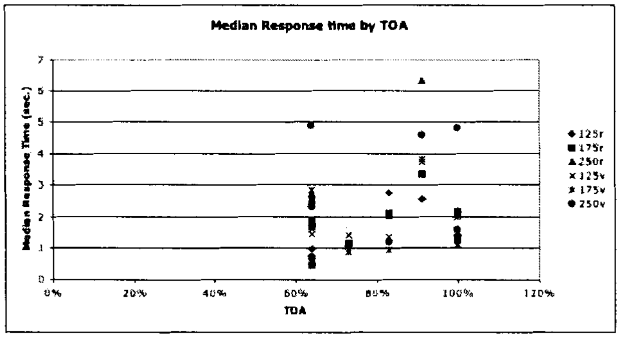


Figure 5.4: Median response time for each subject across all conditions and distances compared to TOA.

is a very common measure of performance in HCI tasks, however, more work would need to be done with an HCI task to determine whether this would show a significant effect. It would also be interesting to test whether this effect holds in a fuller cue virtual environment, such as that used by GM. The psychophysical approach used in this experiment required an extremely reduced cue environment that is rarely found in virtual environments in practice. It is possible that in fuller cue environments the correlation would no longer be significant, however, a fuller cue environment would not necessarily be less ambiguous to a viewer than a low cue environment, particularly if some of the cues conflicted (as accommodation and vergence do in VR). It is also worth noting that the subjects tested did not show a complete range of tolerance of ambiguity as the lowest score was 64%. This suggests that testing with a larger subject group would be an important follow up to ensure that the effect holds across all levels of TOA.

An interaction effect was also found between distance and gender on response time. Women took significantly longer to make their responses than men did across all conditions. However, it is likely that this is the result of varying levels of criterion between men and women and not an effect of differences in perception between genders. Further testing is warranted using signal detection theory tasks or an n-alternative forced choice task that can identify the effect of the criterion or bias to determine this.

5.1 General Discussion and Implications of results

Results from the experiment produced several unexpected outcomes. First, the thresholds were significantly larger than anticipated. It was expected that the difference thresholds would show only slight variability between the up and down thresholds because disparity thresholds are generally very small (Harris, 2004). That subjects were showing thresholds that were sometimes as high as 5 cm from the standard distance, suggests that some noise was affecting the results. The decision to use a staircase method was based on the desire to reduce some of the variability, and to try to determine how the threshold varied when comparing real and virtual stimuli to virtual stimuli. The drawback of the staircase algorithm used for this experiment was that it required a large number of trials (160 trials per block) and because 4 separate staircases were run simultaneously, only 40 trials were provided per staircase. While staircases with varying sensitivities are useful for some types of studies, it is now clear that they are not ideal for virtual tasks such as this, where exposure time to the display needs to be minimized to avoid cybersickness symptoms. For this reason, the number of trials was capped at 160 trials per block, which barely allowed the slower moving staircases to get close to the standard distance with perfect performance. This slow movement of two of the four staircases, could have caused the resulting thresholds to be larger than the subjects' true thresholds. However, the thresholds were based on many trials, and errors found were made repeatedly (often 3 or more times). Less restrictive staircases, such as those using the Parameter Estimation (PEST) method, that move more quickly to the threshold might provide better data, and be less stressful on the subjects. The lengthy running time of the experiments (nearly 2 hours per subject) was prohibitive both to the subject and to the experimenter, making it difficult to run larger numbers of subjects, and may in itself contributed to the noise in the data.

The goal of the experiment was not to eliminate all decision-stage influences, since this was where the effect of tolerance of ambiguity would most likely be seen (since according to Pylyshyn (1999), it is the decision stage and not the detection stage that is cognitively penetrable). But the results suggest that either there were confounding factors at play or the decision-stage factors of the subjects' criterions were more pronounced than expected.

Throughout the experiment, several subjects commented on the difficulty of the task, and some spent considerable time making their decisions. If the decision stage was producing significant bias in subjects' thresholds, a possible alternative metric could be used to adapt the task to include a third response of 'I don't know', to allow for an 'unforced choice' task (Kaernbach, 2001). This would be a particularly useful tool for studying the impact of ambiguity as it might help to determine not just where subjects are having difficulties perceptually but at what distance their cognition is most affected by the ambiguity of depth cues.

Effects of distance were also different than expected. No significant effects were found for distance. Unlike earlier experiments, accuracy was not necessarily highest at 125 cm, it varied for each subject. Three subjects underestimated at 125 cm in the real condition, and 5 overestimated. In the virtual condition, 2 subjects overestimated distance, and 5 undererestimated, while one (subject S8) showed both over (down threshold) and underestimation (up threshold). For the most part the distance of 175cm was no less accurate than the other distances, but it did show much less variability in the real condition for all but two subjects. This effect did not occur in the virtual condition, where variability was very high at 175cm for 5 of the subjects. The reduction of variability in the 175cm real condition was likely caused by the presence of the screen edge between the real and virtual stimuli, which provided a strong relative cue to distance for the real sphere. The distance of 250cm was expected to be the least accurate, since accuracy of distance estimation typically degrades as distance increases. In the real condition, distance was underestimated at 250cm for all but two subjects. In the virtual condition, 5 subjects underestimated distance at 250cm. Previous studies of distance perception in virtual environments using Head Mounted Displays commonly report a consistent pattern of distance compression, (Thompson et al., 2004; Loomis et al., 1996; Loomis & Knapp, 2003; Sahm et al., 2005). While this study was not specifically designed to test this hypothesis, no such effect was observed, which suggests that previous findings of compression may be a factor either of that type of display or of the metrics being used to measure distance estimation, as opposed to a human depth perception error resulting from VR.

The use of qualitative questionnaires provided some interesting possibilities to examine the causes of individual differences. However, the small sample size used in this study makes it impossible to make any strong claims on the possible effects of previous training and experience and Tolerance of Ambiguity on depth perception in VR. It is important to note that some interaction effects were found for Tolerance of Ambiguity, so that it would be worthwhile to continue examining these issues in more depth. Also the subject with the highest (i.e. largest) threshold had little experience in sports or video games, and had a moderately low TOA score. Further studies are needed to reduce the effect of bias to determine the true impact of individual differences. Future experiments would require a large number of participants to complete the Tolerance of Ambiguity questionnaire (at least 100 participants) and ask participants scoring on the highest and lowest TOA scale to complete further testing in a virtual distance perception task to determine whether it is possible to generalize the results of this study.

Other variables that could have confounded the results include subject age and apparent motion. Due to time constraints, subjects were self-selected from the graduate student population at SFU's School of Interactive Arts and Technology, and as such, it was difficult to find a range of ages to test. Because this variable was not controlled, it is possible that some of the variation was caused by this, however, Baitch and Smith (2000) did not find any correlation with age in their work, despite the fact that accommodation degenerates significantly with age (Heron et al., 2001). Future work will need to examine the impact of age on depth perception in virtual environments, but it is doubtful that it will account for a significant amount of the observed individual difference. A second possible confounding variable was observed during the experiment. During the experiment subjects were allowed to control the pace of the stimulus presentation to give them a chance to stop if they felt any cybersickness symptoms or grew tired. However, no masking was used between the time the last stimulus was viewed and when the next stimulus was presented, which allowed users who moved quickly through the trials to see a brief afterimage of the previous comparison stimulus. This meant that they could base their judgment on the previous comparison stimulus as well as the standard. This should have improved performance for those with shorter response time, however, this was not the case (see Figure 5.5). The majority of response times were less than 3 seconds, with a few outliers with higher response time at various levels of accuracy. All of the highest response times were associated with a distance of 250cm in both the real and virtual conditions.

5.2 Applying the results to perceptual problems in virtual reality

The experiments conducted to date comparing distance perception of real and virtual stimuli have provided several important observations on individual behaviour of depth perception in virtual environments, but for companies like GM that need to convert these findings into guidelines that can be applied to improve virtual environments, there is still much work to be done. Significant technological advances, such as improved resolution, frame rates and blur characteristics, will likely be required before design tasks such as those used by GM are feasible for a large number of individuals. But this does not mean that VR cannot be

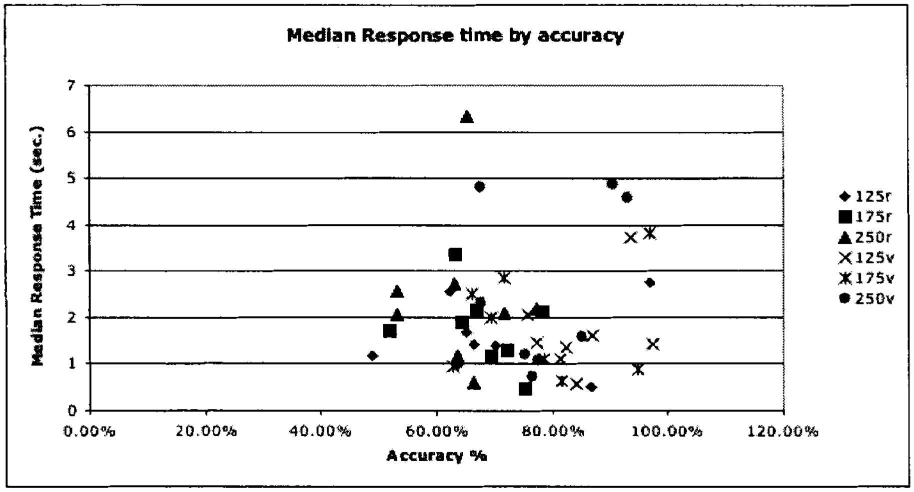


Figure 5.5: Accuracy by median time for all conditions and distances for each subject. There does not appear to be any time-accuracy trade-off.

a beneficial addition to the industrial design process today. The types of tasks that virtual environments are used for may need to become more constrained, so that they are used less for tasks requiring high realism and detail. VR can still be used to examine issues such as colour and sparingly to evaluate form and shape, however, designs that require accurate perceptions of distance, may need to be minimized until more information on what causes individual differences in depth perception becomes available.

Due to the reduced cue nature of psychophysical experiments, these findings cannot be applied directly to industrial design tasks without further testing. The act of isolating a cue can change its effect, making it difficult to generalize results to more ecologically valid full-cue environments (Harris, 2004). Several studies have found that depth cues are perceived differently when isolated than when seen in a full cue environment. For example, the ability to integrate cues was a strong correlate of depth perception when multiple cues present, and was more important than individual cues (Westerman & Cribbin, 1999). Some cues, like accommodation and vergence, are perceived differently under darker conditions than in full light. In a study that used a reaching task in a dark environment, Bingham and Pagano (1998) found that subjects under-reached to targets, while Johnston (1991) found that cylindrical objects viewed in dark were perceived as being expanded or compressed depending on viewing distance. Using verbal reports and walking metrics, Philbeck and Loomis (1997) found that distance perception in reduced cue (e.g. dark compared to bright) real world conditions consistently showed systematic error, while perception was essentially accurate with full cues. Loomis et al. (1996) found that in reduced cue conditions subjects overestimated target distances of less than 2 metres, but underestimated targets over 3 metres away.

Another issue is that psychophysics generally uses small numbers of subjects with extremely high number of trials, and the research is primarily conducted at universities on a 'relatively' young student population, so the results may not generalize to the population of employees in industrial manufacturing companies. Though this research was a follow up to research conducted in-house at GM, further studies in the actual environment with the employees who will be using the display are also necessary. Following the idea of interaction science, grounding this perceptual research in 'actual use' with the industrial design company facilities would be an ideal way to continue to build on the results. This combined with the Human-Computer Interaction approach of examining the task being performed is essential to understanding individual difference, and will allow us to 'seek robust cognitive and psychopysiological constructs on which to categorize users.'(Dillon & Watson, 1996, p.624).

Chapter 6

Conclusion

Although a tremendous amount of information on depth perception in virtual environments has been uncovered through research, the cause of perceptual distortions in virtual reality and possible solutions remain poorly understood. In order to explore the causes of individual differences in perceiving depth in virtual reality displays, our research has focused on the question of how depth perception varies in real and virtual environments by comparing perception of real and virtual stimuli. The comparison of real to virtual objects, while difficult to accomplish, has provided interesting observations. However, further work needs to be done on a larger subject pool, in order to determine the effect of individual cues in the virtual environment and to ascertain whether stronger cues in the real setting will improve depth estimation at greater distances. While results show some promise, particularly for the personality variable of Tolerance of Ambiguity on response time, there is still no clear indication of the exact causes of individual difference, as there appear to be a complex interaction of variables that contribute to the problems.

To summarize, the final experiment compared perception of real and virtual stimuli to two virtual stimuli and results showed significant individual differences in thresholds among individuals, with decreased performance in the comparison of real and virtual stimuli. Significant effects were found with Tolerance of Ambiguity and gender on the dependent variable of response time. However, it was noted that the experimental design was not ideal for comparing qualitative and quantitative data.

6.1 Future Directions

Future depth perception research in virtual reality environments should expand its current focus to include more research on complex conditions including multiple cues. While research conducted in complex environments can obscure the exact cause of effects, reduced cue conditions are not equivalent to the typical environment encountered by virtual reality users. The use of Virtual Environments in industrial design applications are highly task dependent, and while using psychophysics to isolate specific depth cues can provide critical information to how depth perception behaves in reduced cue conditions, this information does not necessarily transfer to the complex environments used by companies like GM to evaluate designs of CAD models. It is recognized that distance perception is only a single component of the task of evaluating designs in virtual reality, so future work will explore the addition of other depth cues to provide more structured visual physical and virtual environments to see how depth perception might fare in a more ecological setting.

Future research will also focus on the interaction of visual and non-visual cues in virtual environments. Research has already begun to look more closely at haptic and auditory cues as feedback. The use of tactile augmentation (using real objects for haptic feedback with virtual visual feedback) has been shown to increase the perception of weight and realism of objects viewed in VR (Hoffman, 1998). Applications for haptic feedback in VR include distractions for burn victims during wound cleaning, and treatment of phobias like arachnophobia (refs).

Though no significant effect was found for previous experience and training in this experiment, the role of adaptation in virtual environments to increase user comfort and reduce the incidence of cybersickness and eyestrain will also require further work (Welch, 2002). Accommodation and vergence show signs of adaptation after time spent in virtual environments, which may lead to solutions for the accommodation-vergence conflict (Jansen-Osmann & Berendt, 2002). If the dual-adaptation theory is correct, it may one day be possible to develop personalized training programs for viewers to improve their depth perception in virtual displays.

6.2 Suggestions for improving depth perception in virtual environments

Based on the literature surveyed and the results of the experiments conducted the following are suggestions for the use of virtual reality displays and areas for future research on depth perception in virtual environments that might be useful for companies interested in using virtual displays for industrial design.

- Since stereopsis is such as important cue in virtual environments, more research should be done on the correlation of stereoanomalies to depth perception in virtual environments (Patterson & Fox, 1984).
- To reduce distortion, reducing interpupillary distance in virtual displays has been found to help, (as part of training program, first reducing, then eventually increasing to normal), and keeping field of view as large as possible is also critical (Psotka et al., 1998).
- Include as many non-conflicting monocular cues as possible, in particular, linear perspective has been found to be an important cue in distance perception in virtual environments (Surdick et al., 1997).
- Exposure to VR should be controlled and repeated, so that viewers can adapt their perception to the new environments over time. While some may be able to perceive veridically immediately, others will require more time to adjust (van Ee & Richards, 2002).
- Training programs for those who have initial difficulty may be helpful in improving depth perception, humans did not adapt for these environments and many will require training to adapt to the new environments. The exact nature of the training requires further research.
- Include interaction, which provides feedback and is a necessary component of most tasks. It has been suggested that studies that do not use interaction are not applicable to understanding how interactive displays work (Westerman & Cribbin, 1999)
- To reduce the ambiguity in the scene, feedback should be frequent and multimodal.

- More work is needed on the impact of age and depth perception in virtual reality environments, since it has been found that vergence does not change with age, but accommodation does and is degrades significantly after age 40 (Heron et al., 2001).

Appendix A

Psychometric Functions

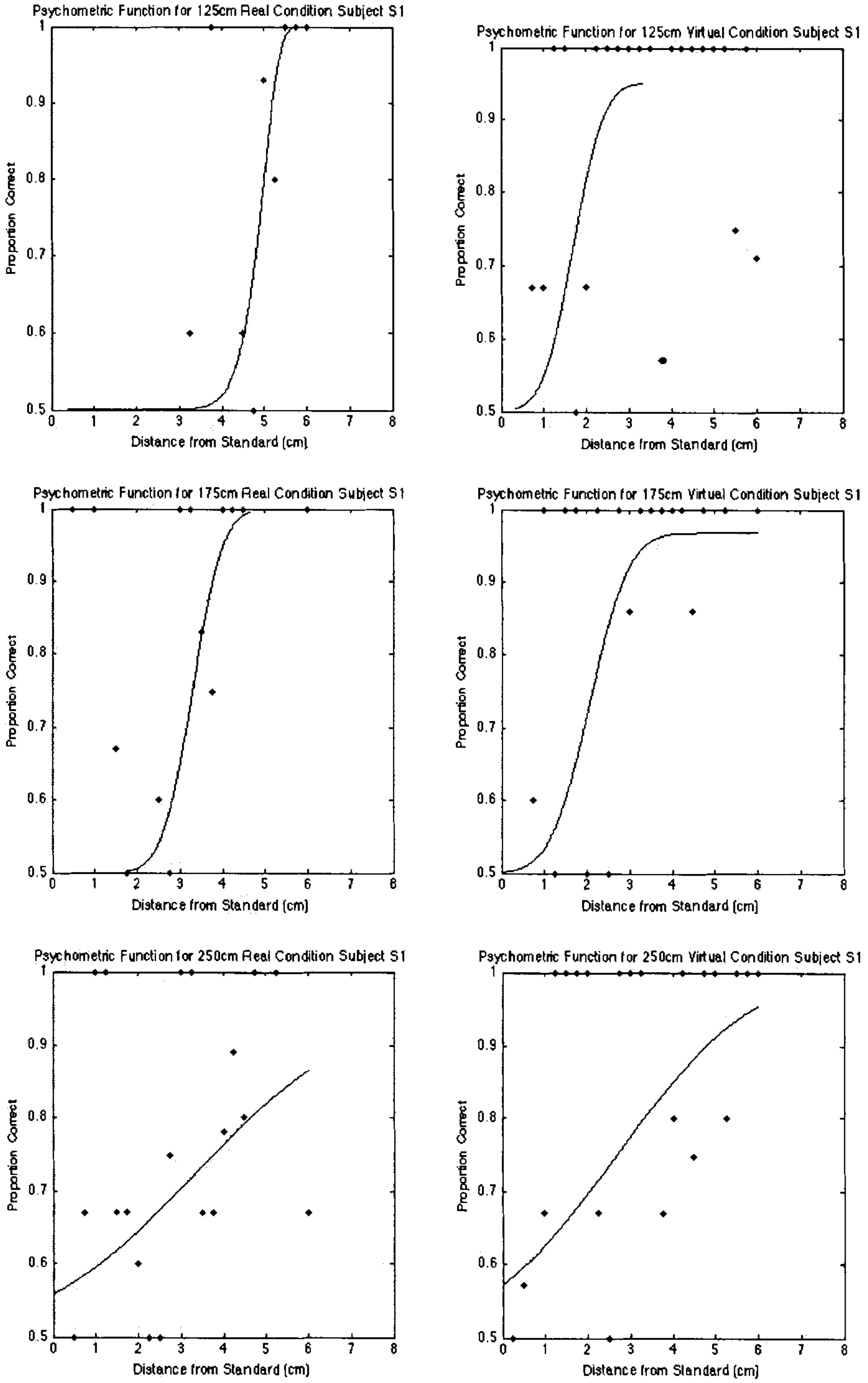


Figure A.1: Psychometric Functions for Subject S1 of the three distances tested: 125cm, 175cm and 250cm for both the Real/Virtual (left) and Virtual/Virtual (right) conditions.

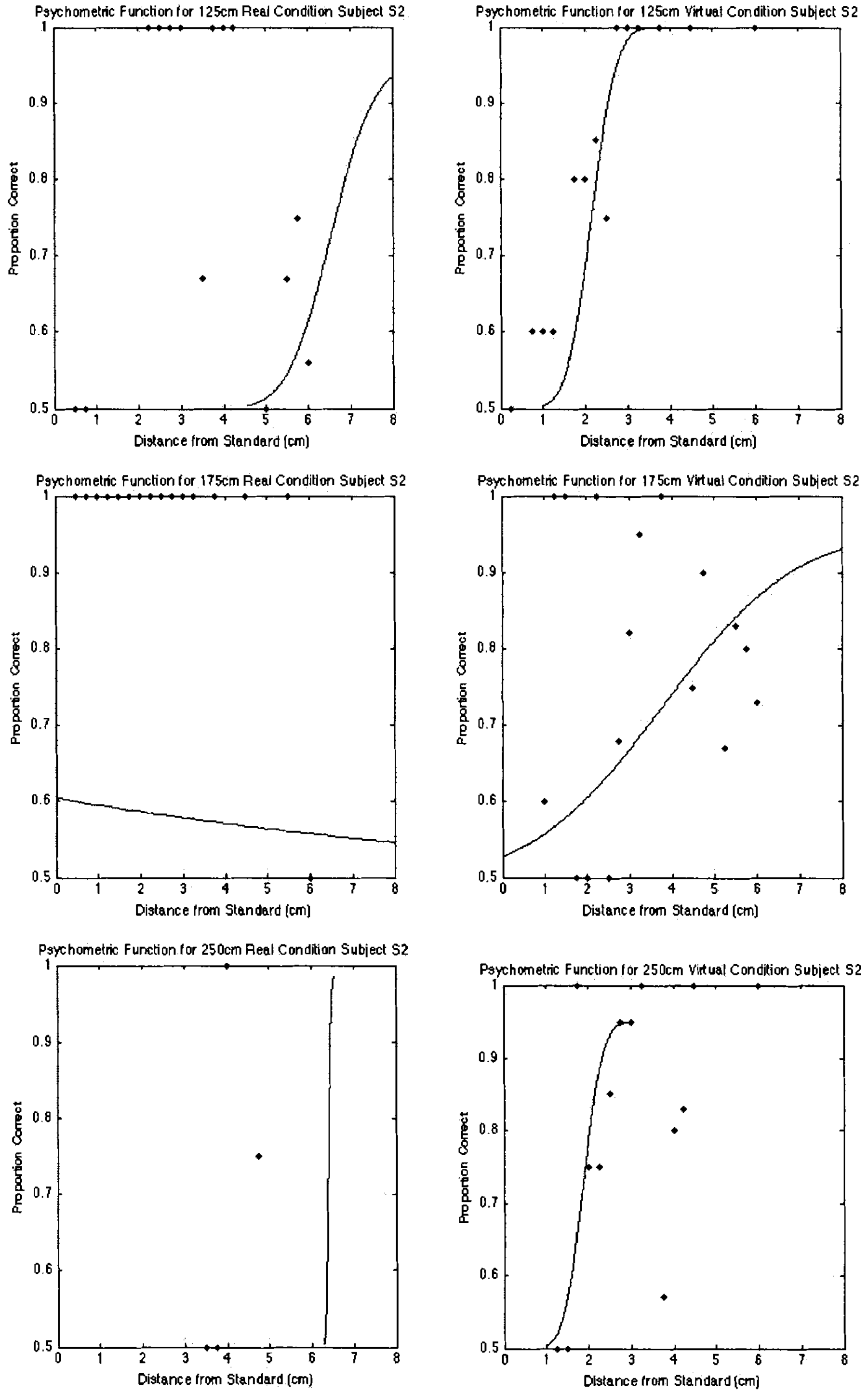


Figure A.2: Psychometric Functions for Subject S2 of the three distances tested: 125cm, 175cm and 250cm for both the Real/Virtual (left) and Virtual/Virtual (right) conditions.

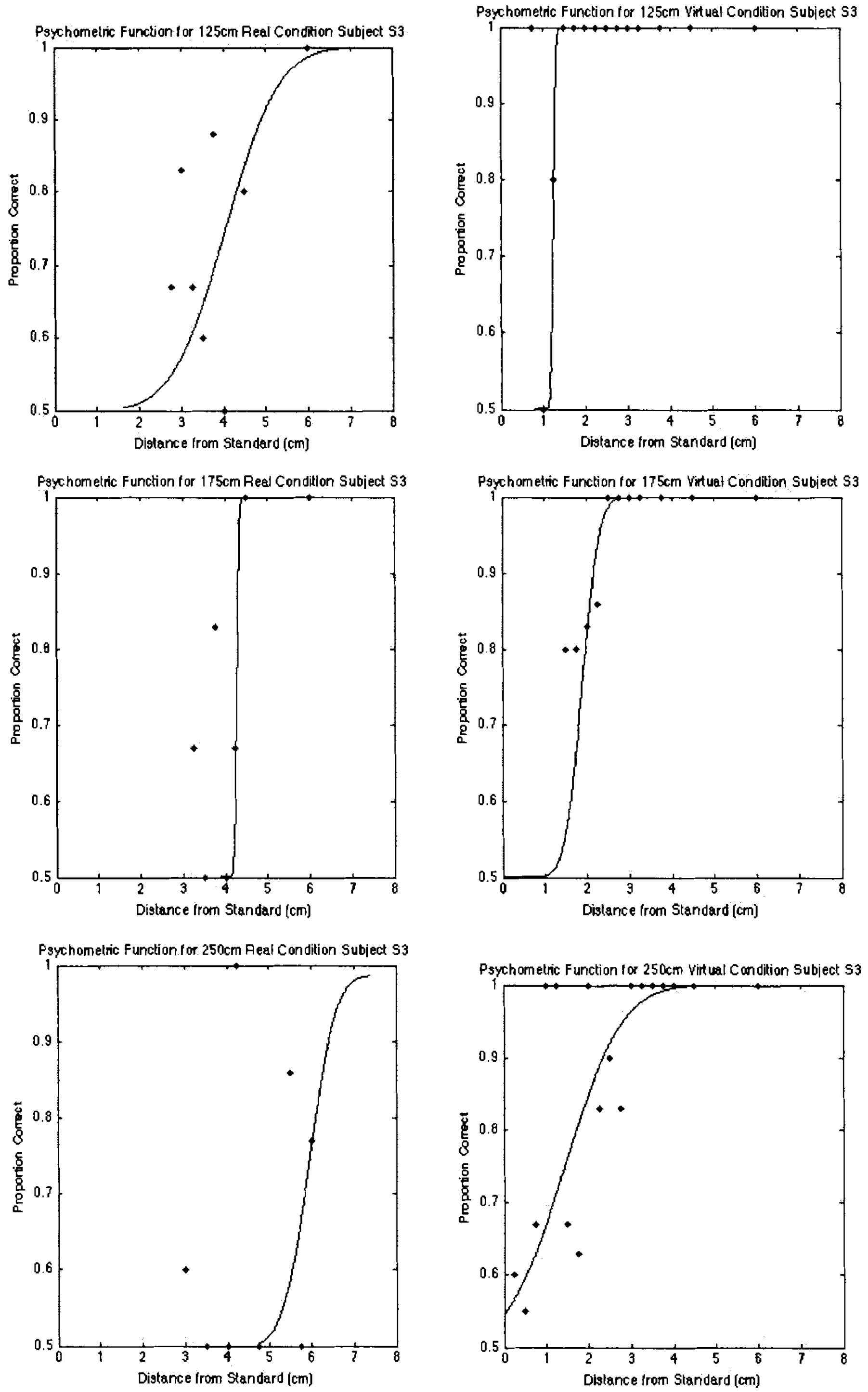


Figure A.3: Psychometric Functions for Subject S3 of the three distances tested: 125cm, 175cm and 250cm for both the Real/Virtual (left) and Virtual/Virtual (right) conditions.

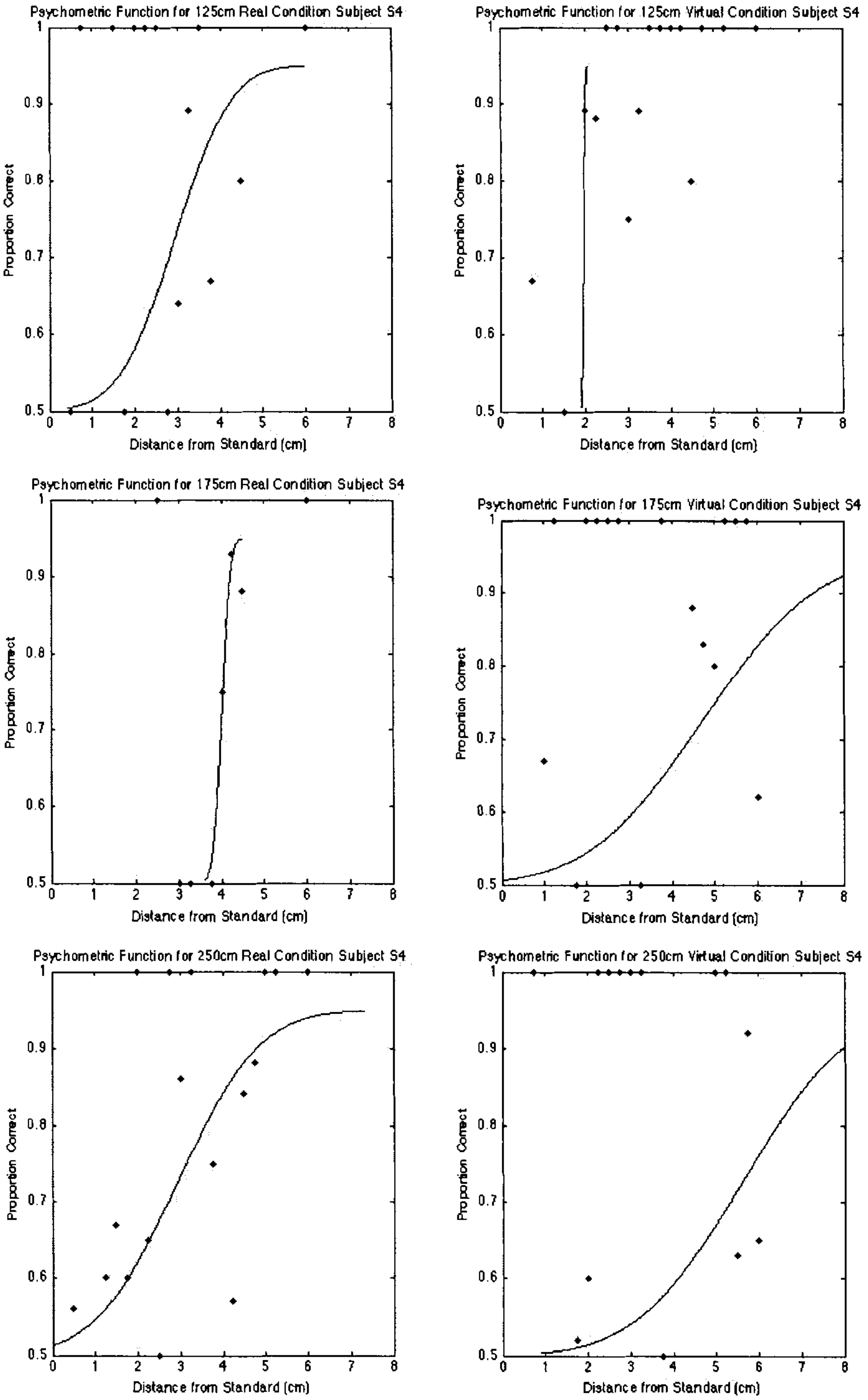


Figure A.4: Psychometric Functions for Subject S4 of the three distances tested: 125cm, 175cm and 250cm for both the Real/Virtual (left) and Virtual/Virtual (right) conditions.

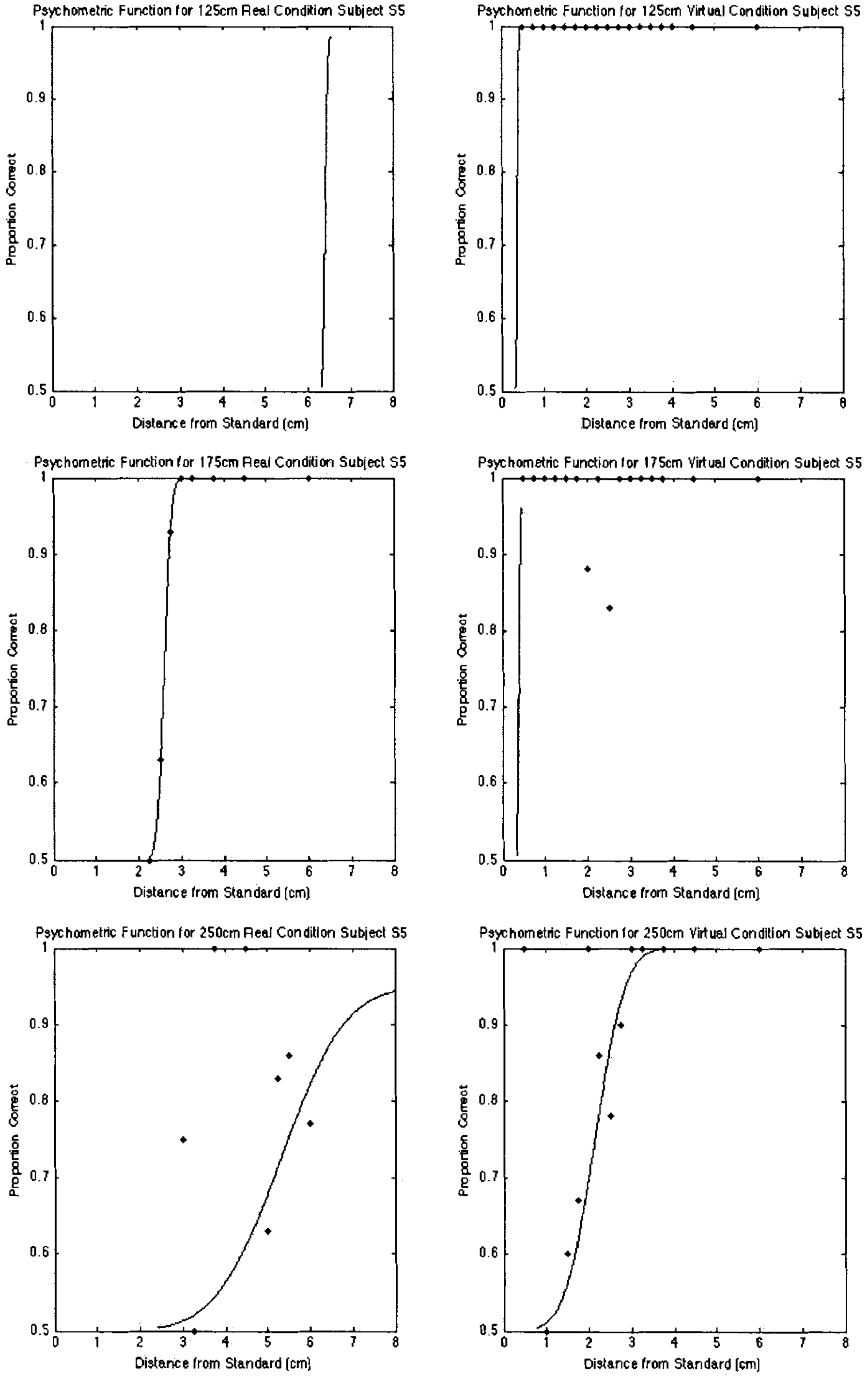


Figure A.5: Psychometric Functions for Subject S5 of the three distances tested: 125cm, 175cm and 250cm for both the Real/Virtual (left) and Virtual/Virtual (right) conditions.

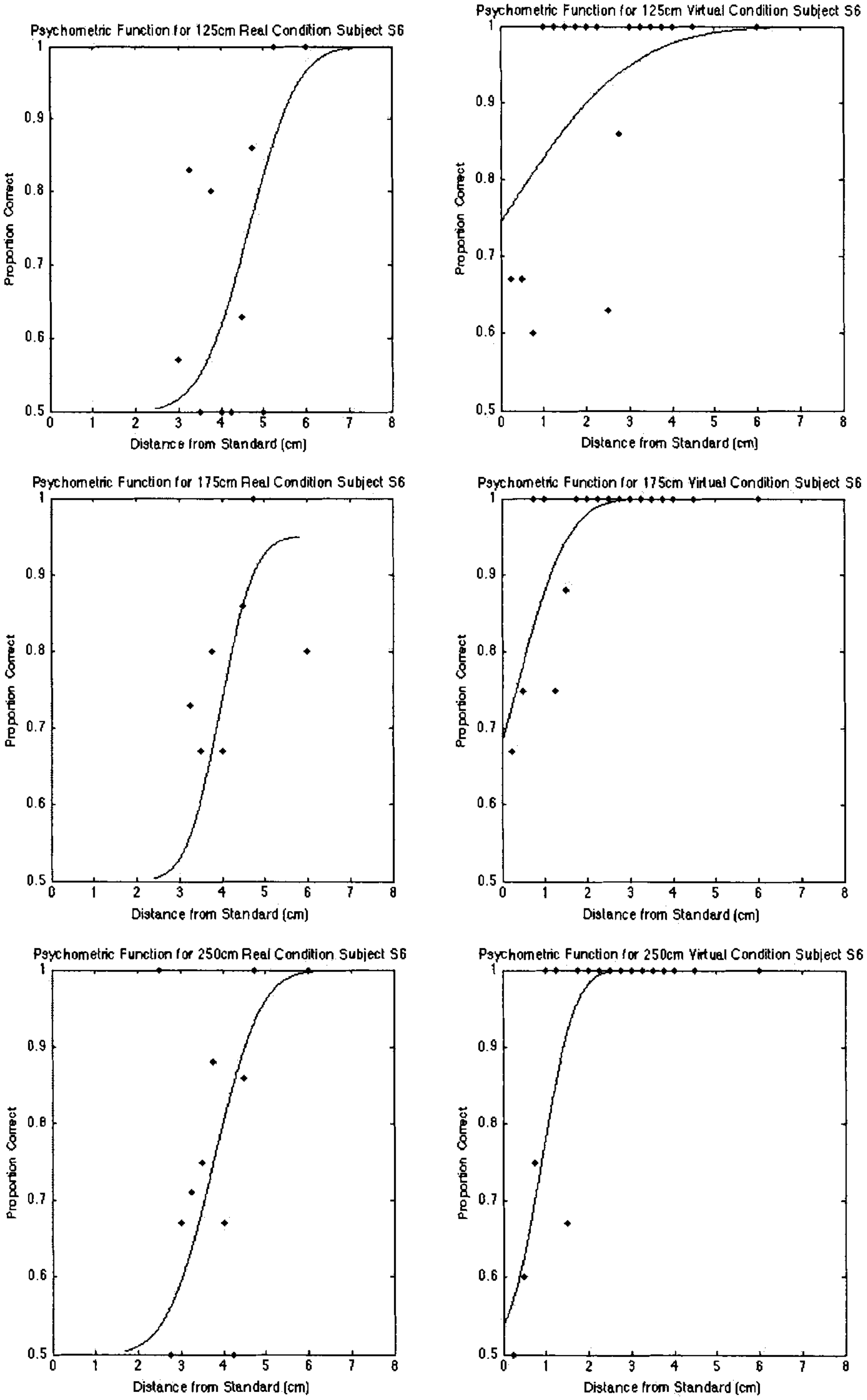
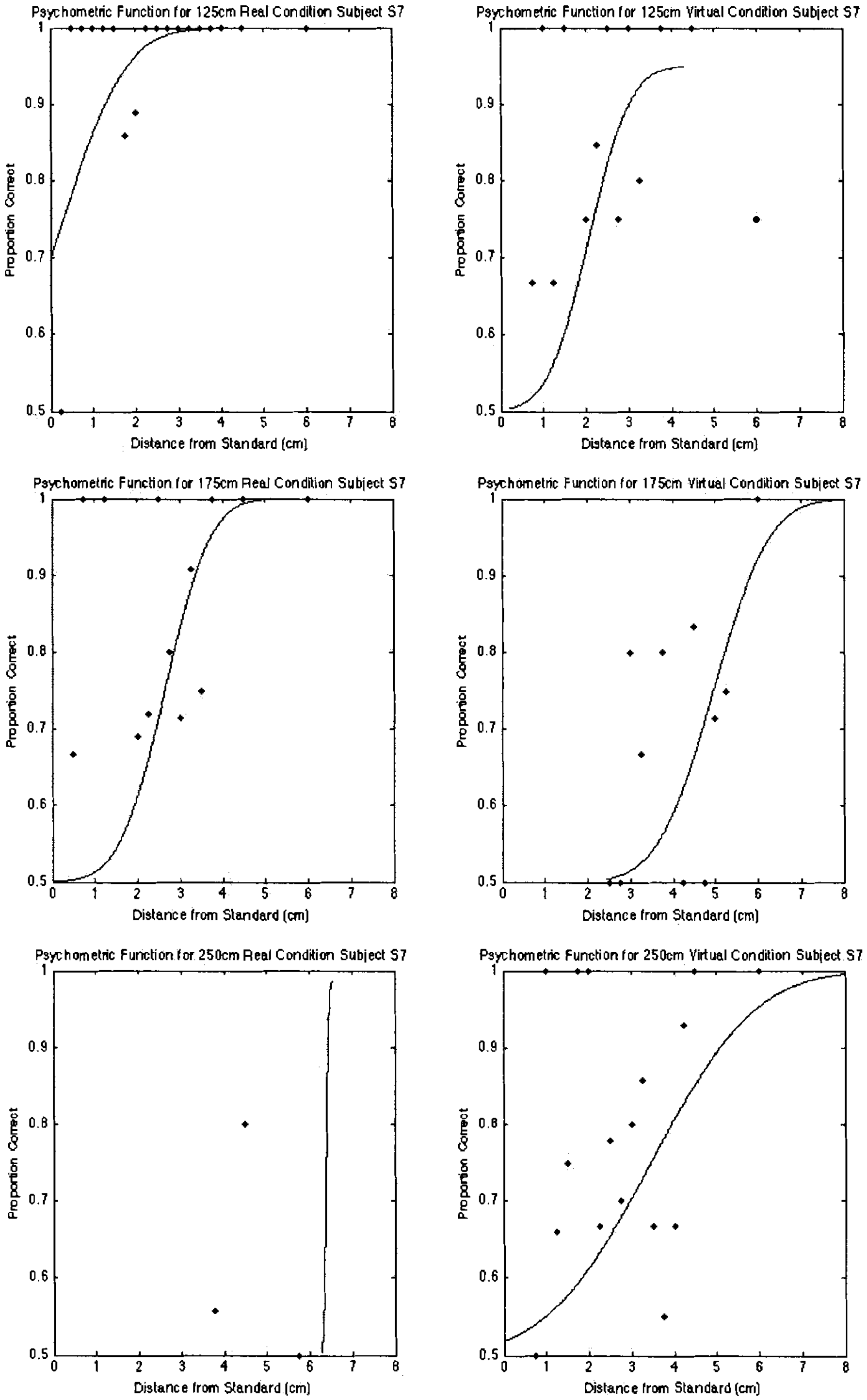


Figure A.6: Psychometric Functions for Subject S6 of the three distances tested: 125cm, 175cm and 250cm for both the Real/Virtual (left) and Virtual/Virtual (right) conditions.



Psychometric Function for 125cm Real Condition Subject S7

Psychometric Function for 125cm Virtual Condition Subject S7

Psychometric Function for 175cm Real Condition Subject S7

Psychometric Function for 175cm Virtual Condition Subject S7

Psychometric Function for 250cm Real Condition Subject S7

Psychometric Function for 250cm Virtual Condition Subject S7

Figure A.7: Psychometric Functions for Subject S7 of the three distances tested: 125cm, 175cm and 250cm for both the Real/Virtual (left) and Virtual/Virtual (right) conditions.

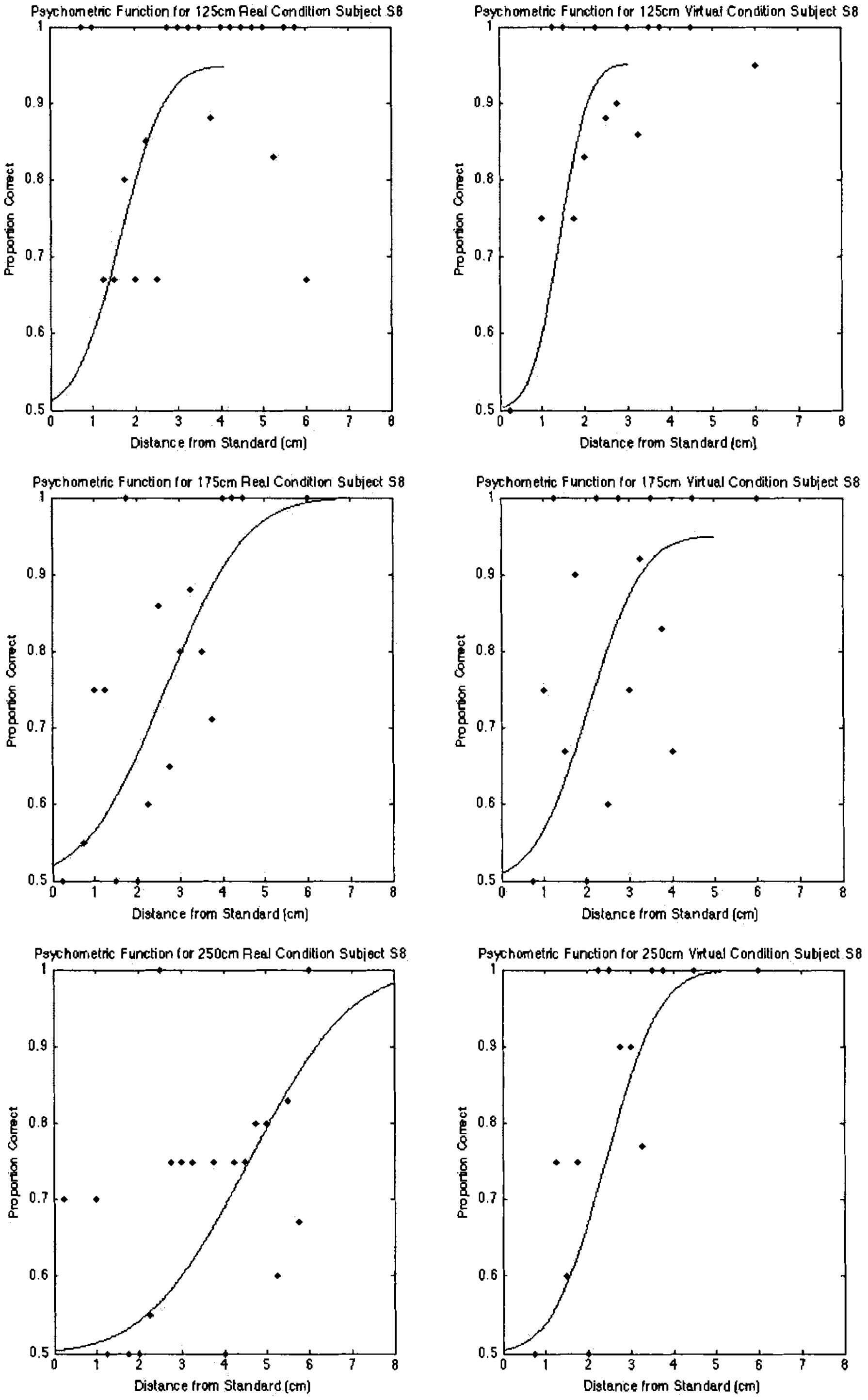


Figure A.8: Psychometric Functions for Subject S8 of the three distances tested: 125cm, 175cm and 250cm for both the Real/Virtual (left) and Virtual/Virtual (right) conditions.

Appendix B

Threshold Graphs

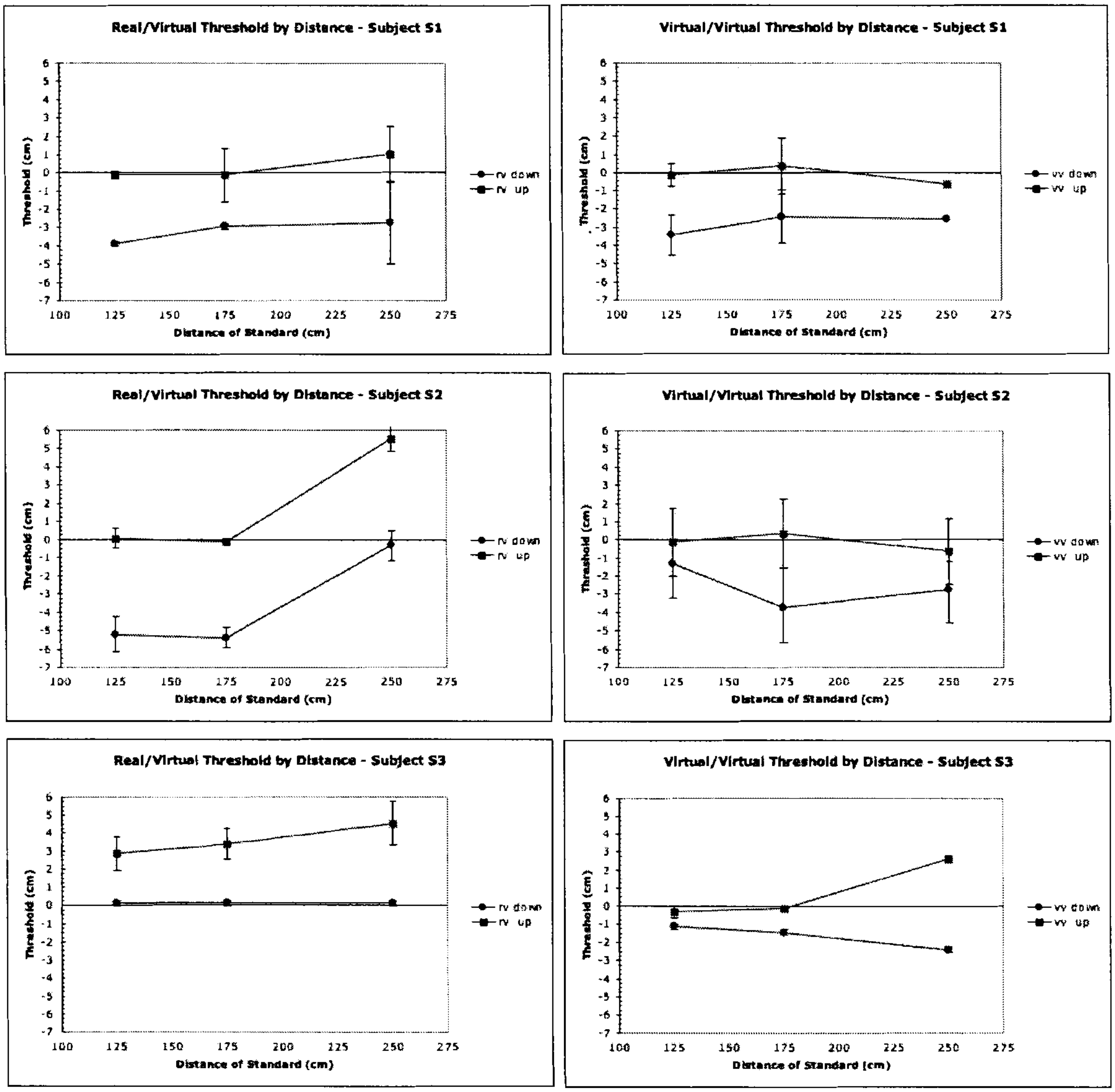


Figure B.1: Up and Down thresholds for the three distances tested: 125cm, 175cm and 250cm for the Real/Virtual (left) and Virtual/Virtual (right) conditions for Subjects 1, 2, and 3.

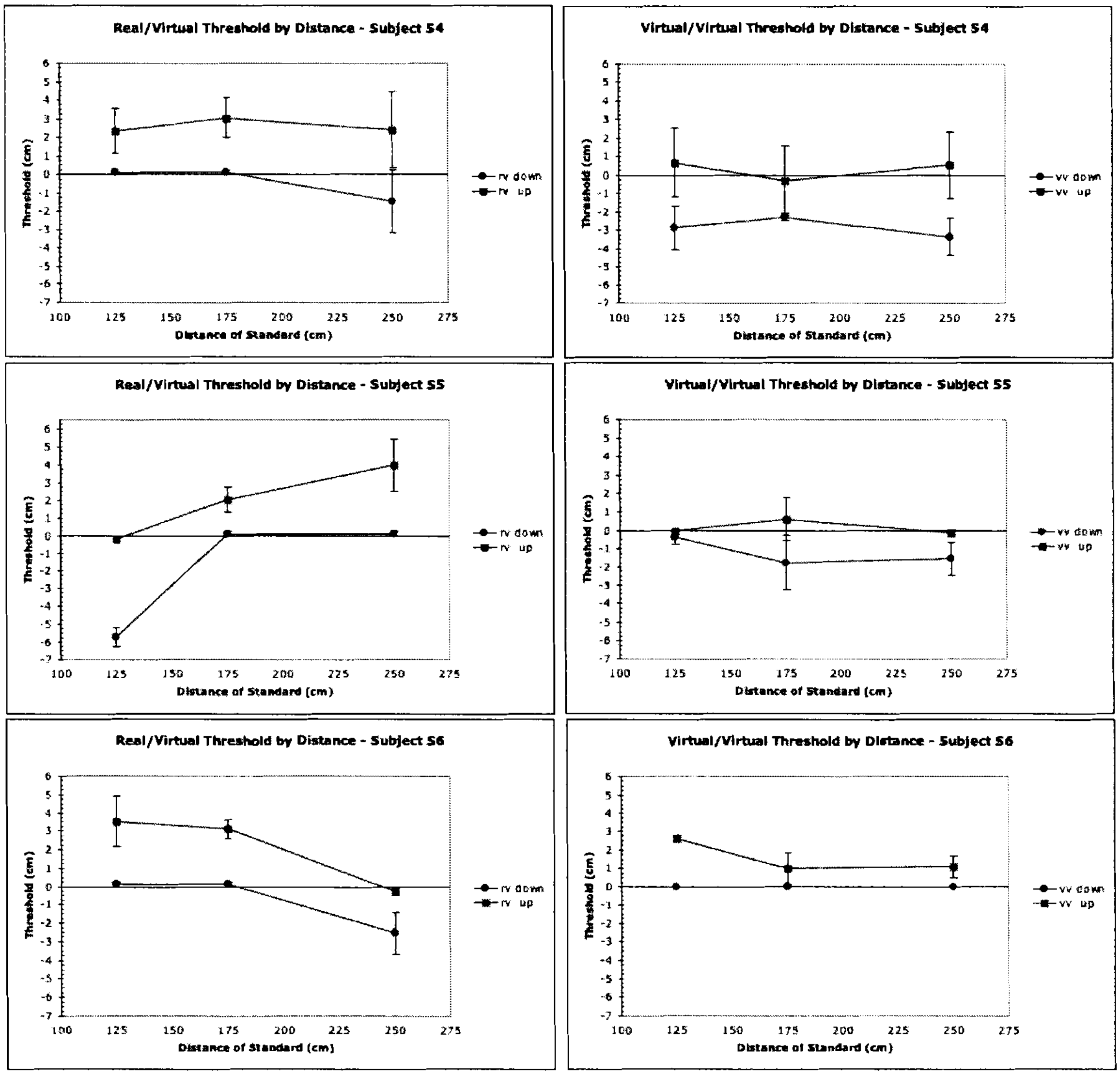


Figure B.2: Up and down thresholds for the three distances tested: 125cm, 175cm and 250cm for the Real/Virtual (left) and Virtual/Virtual (right) conditions for Subjects 4, 5, and 6.

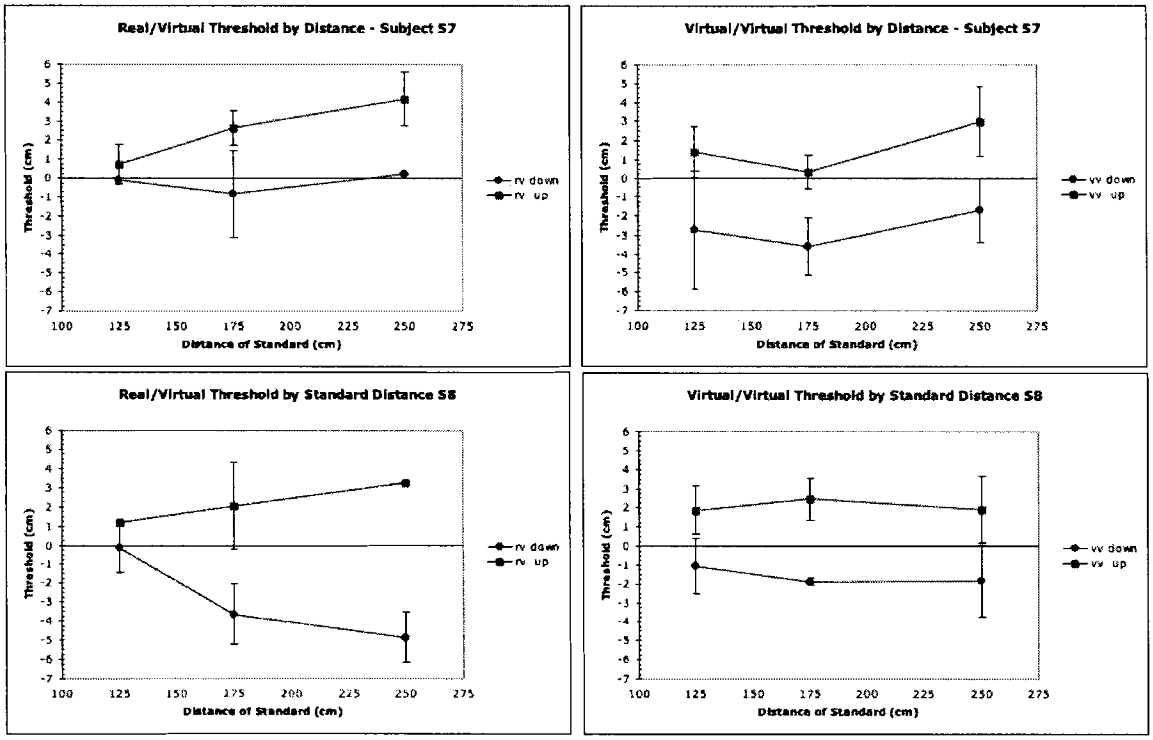


Figure B.3: Up and down thresholds for the three distances tested: 125cm, 175cm and 250cm for the Real/Virtual (left) and Virtual/Virtual (right) conditions for Subjects 7 and 8.

Appendix C

Accuracy Graphs

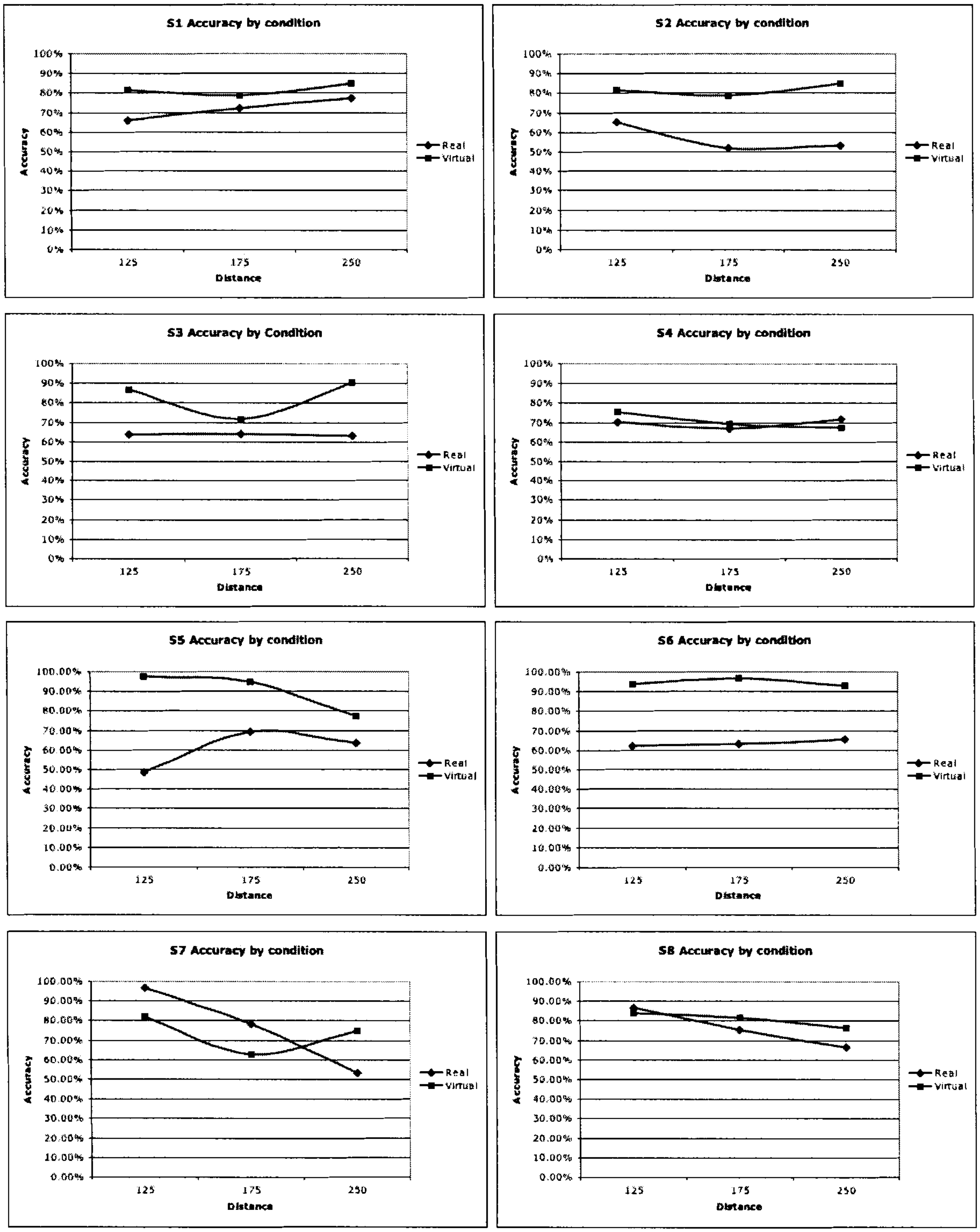


Figure C.1: Accuracy for real/virtual and virtual/virtual conditions by distance for each subject.

Appendix D

Response Time Graphs

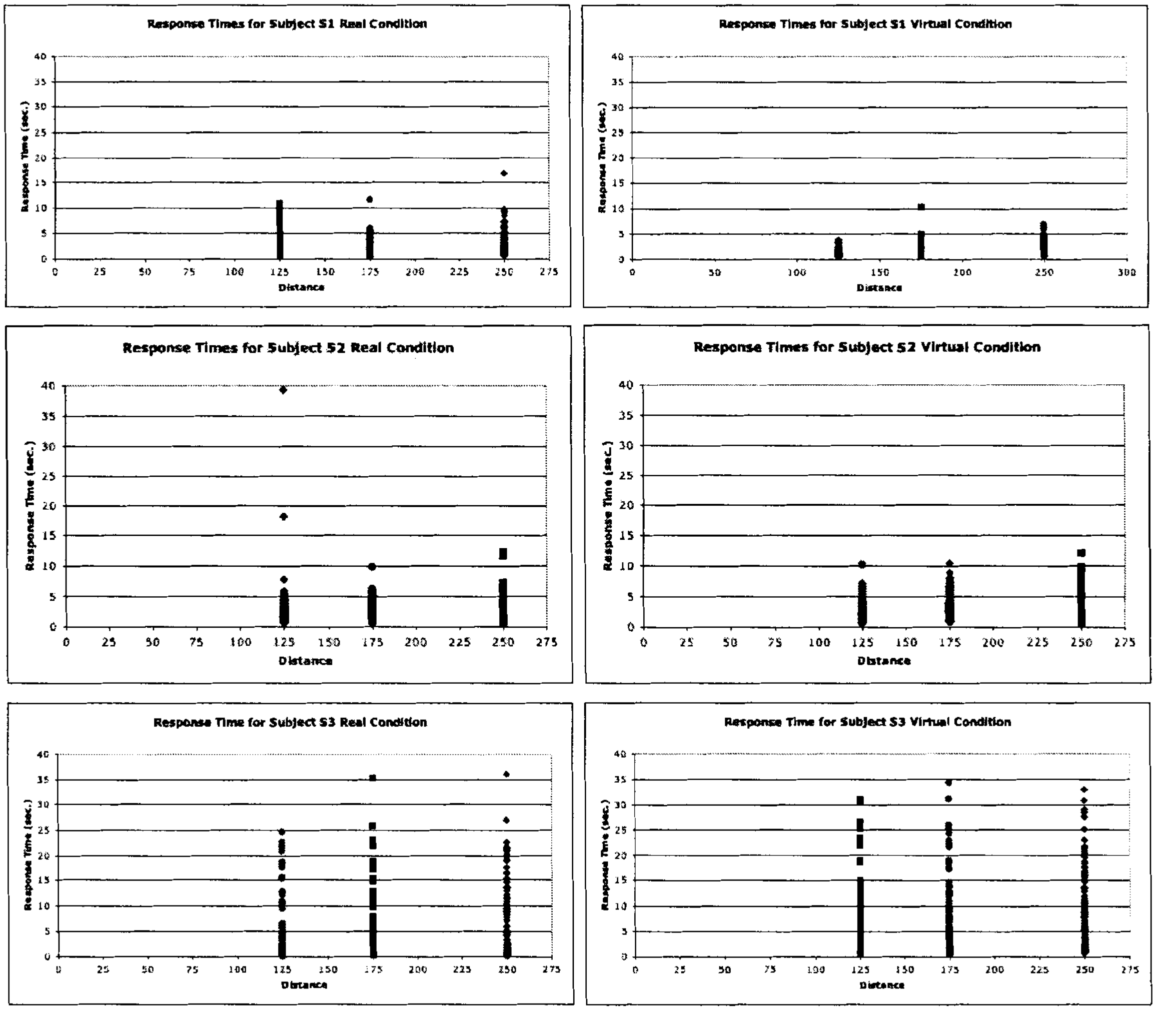
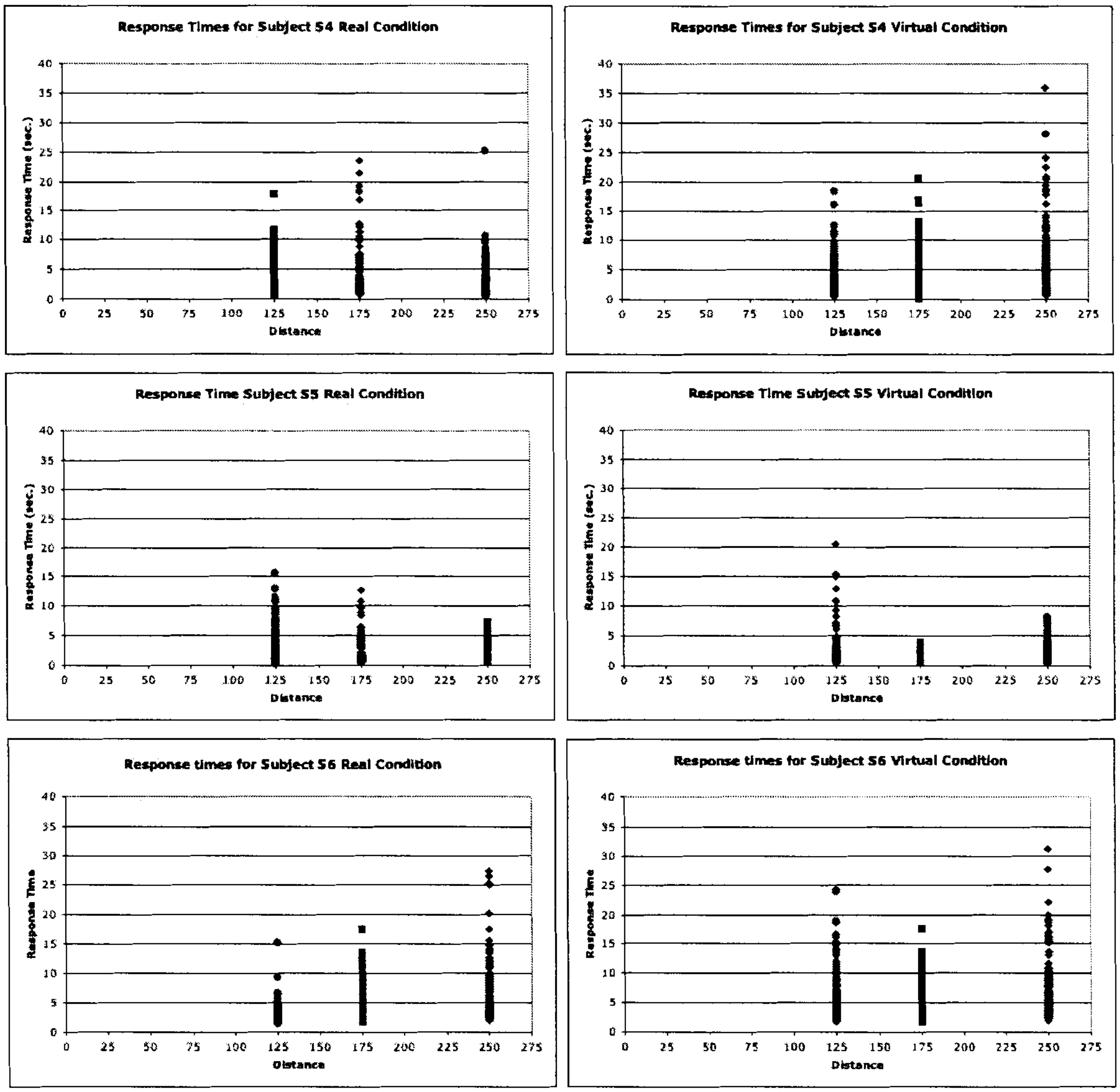


Figure D.1: Scatterplots of response time for subjects S1-S3 by condition and distance.


Response Times for Subject S4 Real Condition

Response Times for Subject S4 Virtual Condition

Response Time Subject S5 Real Condition

Response Time Subject S5 Virtual Condition

Response times for Subject S6 Real Condition

Response times for Subject S6 Virtual Condition

Figure D.2: Scatterplots of response time for subjects S4-S6 by condition and distance.

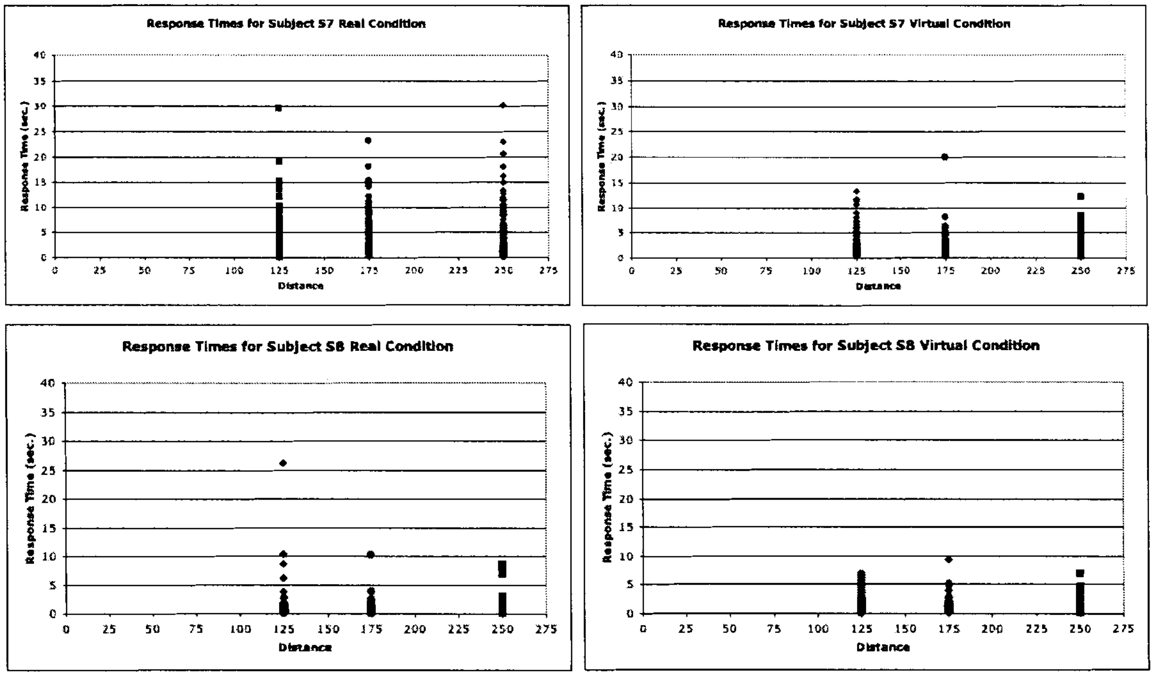


Figure D.3: Scatterplots of response time for subjects S7 and S8 by condition and distance.

Appendix E

Experiment Questionnaire

E.1 Background Questionnaire

1. Do you play any computer or video games? (Please circle one)

Yes No

If no, please skip to question 2.

b. If yes, how many hours a week do you usually spend playing video/computer games? Hours per week:

c. Please list the three video games and the video game system (e.g. computer, Xbox, etc) you play most often:

Game: System:

2. In the last two years, have you regularly played any sports (team or individual)?

Yes No

If no, please skip to question 3.

b. Please list the three sports you played most often and the length of time you have been playing each of them:

Sport: Time playing:

3. Have you ever had corrective eye surgery (e.g. Lasik)?

Yes No

If no, please skip to question 4.

If yes, when?

Do you have any recurring side effects from the surgery? Yes No

If yes, what side effects do you have?

4. Do you wear glasses/contacts?

Yes No

If yes, are you nearsighted or farsighted ? (Please check one or both)

5. Other than needing glasses, have you ever been diagnosed with any vision problems that required treatment?

Yes No If no, please skip to question 6.

If yes, what was the problem?

Was it successfully treated? Yes No

If yes, when was it treated?

If no, please describe how the problem currently affects your vision:

6. Are you able to see the hidden images in MagicEye puzzles?

Yes No

7. In the last three months, how many hours a week, on average, did you spend using the computer?

hrs/week

E.2 Personality Questionnaire

(Questions with ** were scored)

Please answer True (T) or False (F) to each of the following questions

1. A problem has little attraction for me if I don't think it has a solution.
2. I am just a little uncomfortable with people unless I feel that I can understand their behaviour.
3. **There's a right way and a wrong way to do almost everything.
4. I would rather bet 1 to 6 on a long shot than 3 to 1 on a probable winner.
5. The way to understand complex problems is to be concerned with their larger aspects instead of breaking them into smaller pieces.
6. I get pretty anxious when I'm in a social situation over which I have no control.
7. **Practically every problem has a solution.

8. It bothers me when I am unable to follow another person's train of thought.
9. **I have always felt that there is a clear difference between right and wrong.
10. It bothers me when I don't know how other people react to me.
11. **Nothing gets accomplished in this world unless you stick to some basic rules.
12. **Vague and impressionistic pictures really have little appeal for me.
13. **Before an examination I feel much less anxious if I know how many questions there will be.
14. Sometimes I rather enjoy going against the rules and doing things I'm not supposed to do.
15. **I like to fool around with new ideas, even if they turn out later to be a total waste of time.
16. **Perfect balance is the essence of all good composition.
17. **If I were a doctor I would prefer the uncertainties of a psychiatrist to the clear and definite work of someone like a surgeon or X-ray specialist.
18. If I were a scientist, I might become frustrated because my work would never be completed (science will always make new discoveries).
19. **I don't like to work on a problem unless there is a possibility of coming out with a clear-cut and unambiguous answer.
20. **The best part of working a jigsaw puzzle is putting in that last piece.

Appendix F

Questionnaire Data

ID	*Vgame*	*Hrs*	*Game*	*Sprts*	*Type*	*Surg*	*Glasses*	*VisProb*	*MgEye*	*HrCpt*	*TOA%*
S1	Yes	10-15	WoW,Eve,MoH	No		No	No	No	Yes	30	100
S2	No			Yes	Swim	No	Yes,near	No	No	30	64
S3	No			Yes	Fitness	No	No	No	Yes	35	64
S4	No			No		No	Yes,near	No	Yes	60	100
S5	No			No		No	No	Yes(child)	Yes	60	73
S6	Yes	3	Strcrft,WoW	No		No	No	No	Yes	35	91
S7	Yes	12	WoW	Yes	Cycling	No	No	No	Yes	30	82
S8	Yes	10	MarioBro,Sierra	Yes	Curl,Snwbd	No	Yes,near	No	Yes	25	64

Table F.1: Questionnaire data on previous experience and tolerance for ambiguity (TOA).

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