An Analysis of Perceptual Errors in Perspective Displays

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Abstract

Display dimensionality is one of the most debated issues in the design of cockpit-based displays of air traffic information. Many practitioners agree that presenting air traffic information on an integrated 3D display is preferable, when compared to presenting it on a 2D planar or co-planar display. However, research has shown that operators make errors in estimating the location of objects in 3D displays. This may be because of perceptual distortions caused by the geometric parameters used to generate the image. However, despite the issues identified regarding the locating of objects, some studies have found other performance advantages associated with these 3D displays. Therefore, it seems that attempts should be made to minimise perceptual biases so that these displays can be utilised to present integrated information in 3D environments. The aim of this thesis was to develop a model of distance estimation errors in perspective displays. It was hypothesised that many of the perceptual errors observed in perspective displays, such as azimuth and inter-object distance estimation errors, were related to observers wrongly estimating the distance between themselves and objects in the virtual world. Four experiments examining inter-object distance estimation were conducted. Participants were required to set a perspective image of a box to represent a perfect cube (requiring them to make a distance estimation scaled relative to the frontoparallel plane). Results showed that participants made inter-object distance estimation errors that increased as the distance between the observer and the objects in the display increased. Based on these results, two models explaining inter-object distance estimation errors were developed. The first model postulated that participants underestimated the distance between themselves and objects in the display. The second model suggested that participants used 2D (on-screen) cues to set the box to a cube. These models were applied to azimuth estimation errors observed in studies of perspective displays. It was found that while azimuth estimation error could only be partially modelled as a distance perception error, it could be explained to a greater extent by applying a strategy based on the 2D (on-screen) image. The findings of this study indicated that either distance estimation errors or 2D strategies could account for inter-object distance estimation errors in perspective displays.

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Introduction

This thesis serves two main purposes; firstly, it contributes to the development of perspective display technology by providing a model by which some of the distortions that affect visual processing of these displays can be understood and predicted. This study focused particularly on cockpit-based displays of air traffic information (CDTIs) as the optimisation of these displays is likely to become increasingly important if pilots are required to assume more responsibility for conflict detection and avoidance (as has been proposed under a new air traffic management system called free flight).

Secondly, within this thesis issues relating to human space perception in general, and image/picture perception in particular, were examined. Though these issues have been extensively studied in the past, this study employed an alternative methodology for examining the nature of visual space.

The literature pertaining to the thesis spans three distinct areas: the applied problem (designing a CDTI for use in a free flight environment); current research on perspective displays, and; general research on space perception, both real world and picture perception. Each of these domains is presented in the following three chapters. The current chapter examines the concept of free flight and its impact on the role of the pilot. An outline of the development of the free flight concept and a definition of free flight is provided, as is a description of the modern cockpit environment. Additionally, a review of studies on CDTI displays is presented that focuses particularly on studies comparing pilot performance when using 2D planar/co-planar and perspective CDTIs. It is intended to provide the reader with an understanding of the environment within which the CDTI display will be integrated and an overview of the issues associated with CDTI design. The following chapter reviews issues related to the dimensionality of CDTI displays. As such, a review of studies that explore visual distortions in perspective displays was undertaken. Proposed models of these distortions are outlined and discussed. Finally, the third chapter provides a review of literature relating to visual space perception, and in particular, picture perception.

Air Traffic Management and the Origins of Free Flight

Initial attempts at regulating the movement of air traffic began as early as 1926. However, it was not until after the introduction of commercial jet airliners in the late 1950's, and a series of serious midair collisions, that attempts at managing air traffic began in earnest. The system of air traffic control that was subsequently developed made pilots responsible for operating their aircraft and air traffic controllers (ATCs) responsible for aircraft movements (Billings & Woods, 1995). Though technological changes over time have fundamentally altered the jobs of both controllers and pilots, the basic allocation of tasks has remained the same.

As a result, responsibility for the direction of all air traffic flying under instrument flight rules (IFR) currently resides with ATCs. Controllers make use of a variety of information sources including flight plans, radar, and radio to monitor and communicate with aircraft. They apply basic separation principles to ensure that adequate distances are maintained between aircraft (e.g. 1000 feet of vertical separation). Individual aircraft communicate with controllers primarily through voice communications, while overall system surveillance relies on radar and, more recently, airborne collision avoidance equipment (Billings & Woods, 1995). Despite the fact that aircraft now carry highly sophisticated automated equipment, the ATC system has changed little in response to technological advances.

In recent decades, ATC inefficiency has become a major concern for airlines. Deviations from the most efficient routing for individual aircraft often occur because controllers must maintain specified minimum separations between aircraft (Green, Goka, & Williams, 1997). Therefore, airlines have lobbied extensively for more fuel-efficient routing, and fewer delays resulting from ATC regulations, arguing that improvements in aircraft design and technology have not achieved their potential because ATC equipment, processes, and procedures have fallen behind rapidly developing cockpit-based technologies (Planzer & Hofmann, 1995). The airline industry regards the current ATC system as inflexible, outdated, and unable to provide the air traffic capacity required (Billings & Woods, 1995). One major American carrier estimates that ATC inefficiencies cost carriers approximately 3.5 billon dollars annually (Planzer & Hofmann, 1995). Pressure from airlines has also placed controllers under increasing strain, as they are required to handle rapidly growing numbers of aircraft.

In addition to efficiency concerns, the worldwide increase in the density of aircraft over the past decade has highlighted safety concerns with the existing ATC system. While air travel currently maintains an adequate safety record, projected traffic increases of 100% or more before 2010 may severely threaten the capacity and safety of the ATC system (Parasuraman, 1998). European and Asian air traffic is growing faster than the United States, as a result, it is expected that air traffic congestion will become a worldwide problem in the near future (Kahne, 2000). As traffic volume grows, the ATC system and personnel will have to become increasingly productive in order to effectively manage increased traffic volumes. It is clear that such increases would be impossible without improvements in supporting technology (Planzer & Hofmann, 1995).

In response to concerns about the efficiency and safety of the current ATC system, a proposal for a new system for regulating air traffic named 'free flight' has been developed. An FAA committee on advancing free flight through human factors defined free flight as:

> *"A safe and efficient flight operating capability under instrument flight rules (IFR) in which operators have the freedom to select their path and speed in real time. Air traffic restrictions are only imposed to ensure separation, to preclude exceeding airport capacity, to prevent unauthorized flight through special use airspace, and to ensure safety of flight. Restrictions are limited in the extent and duration to correct the identified problem."* (Planzer & Hofmann, 1995)

Fundamental to free flight is the concept that under most circumstances, aircraft flying within the system should be free to adopt any desired trajectory between origin and destination. Pilots would inform air traffic controllers of intended trajectories but 'flight plan contracts' between aircraft and ATC would no longer govern these movements. Controllers, or movement coordinators, would intervene only if ATC computers detected a potential conflict (Billings & Woods, 1995). Current systems of ATC would be replaced by computer-based conflict detection systems. These would provide the controller with information about imminent collisions and resolution advice. The information necessary for conflict detection would be provided by airborne collision equipment. Under this system, the role of controllers would be reduced to monitoring traffic for potential conflicts (Billings & Woods, 1995). Pilots, however,

would be required to accept greater responsibility for air traffic surveillance since they would be permitted to initiate flight path changes without advance notice. Under some circumstances full responsibility for separation assurance might rest with the pilot. While flight trajectory estimation is a three dimensional task during stable cruise flight, it becomes a four dimensional task during climbs and descents, and this is assuming a stable trajectory for other air traffic. As a consequence, Billings and Woods (1995) consider it likely that overall, operator workload will be transferred from the controller to the pilot rather than mitigated.

While current tools for conflict avoidance and resolution are certainly useful, they are not fully adequate, even in today's system. For example, information presentation needs considerable improvement to provide adequate information to pilots who would be required to evaluate any trajectory changes as well as perform other flying tasks. Therefore, most major ATC and airways organisations are currently conducting research on how free flight could best be implemented. Free flight itself necessitates a fundamental change in the way IFR flights operate at a worldwide level. Therefore, this new method of managing air traffic would have a substantial impact on the New Zealand ATC system and air carriers.

Free Flight and the Modern Cockpit Task Environment

The changes to the role of the pilot required by free flight cannot be considered in isolation from the existing task environment in the modern cockpit. In recent decades the role of the pilot has changed dramatically, moving from manually flying the aircraft towards managing a highly complex array of automated systems. Glass cockpits (where the pilot monitors aircraft performance from just a few multifunction displays) have been widely introduced into modern jet airliners (see Figure 1).

Due to the increasing sophistication of cockpit technology with its resulting reduction in the number of displays and increases in automated functions, it could be assumed that the memory and cognitive effort required for distributing attention around the cockpit would be significantly reduced. Under these circumstances any extra tasks necessitated by free flight should not significantly impact on pilot workload. However, research has shown that the technological changes described above have not resulted in the expected reductions in pilot workload.

Figure 1. Cockpit design in a Boeing 767.

In the older style traditional cockpit pilots were required to monitor the information presented on several hundred separate instruments and gauges. The main tasks of the pilot could be summed up by three terms: *aviate* (fly the aircraft); *navigate* (direct the aircraft towards its destination); and *communicate* (provide data, make requests, and receive instructions and information), (Jonsson & Ricks, 1995, cited in Baillie, 1999). By comparison, in a glass cockpit the pilot monitors a more centralised system with fewer displays. The system supports the pilot by providing automated flight-path control (autopilots). In a glass cockpit the pilots' tasks still include those mentioned above, however, the nature of the automation means that pilots are also required to *manage* systems. While cockpit automation has certainly reduced pilot workload with regard to flying the aircraft, the task of system management has placed a significant new demand on pilots. During a transition course for a new model Boeing aircraft one pilot commented that the flight management system tasks were the most complicated he had ever experienced (Baillie, 1999).

Research has shown that glass cockpits do not reduce pilot workload as much as redistribute it (Sarter, 1996). Glass cockpits appear to have shifted the emphasis from having to perform many physical actions to requiring more mental discipline and thought to oversee automated functions (Adams, Tenney, & Pew, 1995). Pilots must continually monitor the flight computers to maintain awareness of which mode the

flight computers are in. Sarter and Woods (1992, 1994) undertook a comprehensive review of workload and situation awareness (SA) issues related to glass cockpits. Their findings showed that pilots have to work hard and allocate a significant amount of visual attention to maintain an adequate level of SA about the state of the flight computers. In addition, despite the advanced technology in glass cockpits much of the decision-making task still falls to the pilot. Therefore, as well as monitoring the automation pilots must also make ongoing decisions about the mode of flight that is appropriate for any given situation. This task requires that they integrate data from a variety of sources in the cockpit (Sarter & Woods, 1992). Good SA is vital to ensure that any decisions or inputs are appropriate to the current mode of flight.

Existing research clearly shows that even when flying in glass cockpit aircraft, pilots can experience a substantial degree of mental workload (especially visual workload), particularly in novel situations or in time critical phases of flight (Sarter & Woods, 1995). It is possible that the introduction of a traffic monitoring task may have a significant impact on pilot workload, situation awareness and, performance. Therefore, it is important that any potential negative impacts resulting from the introduction of free flight systems and equipment on overall pilot performance are minimised. Systems and displays relating to traffic monitoring must be designed so that pilots can assess and integrate air traffic information quickly and accurately.

The Cockpit Display of Traffic Information

Perhaps the most important tool for cockpit traffic monitoring and navigation under the proposed free flight system will be the CDTI. CDTIs will provide pilots with information about other aircraft, including their position (in relation to the pilot's own aircraft) and possibly their expected trajectory. Shelden and Belcher (1999) state that the operational goals of the CDTI are:

- Airborne self separation and threat detection;
- Improved visual confirmation of traffic;
- Conflict resolution planning;
- Increased airspace capacity;
- Improved situational awareness;
- Improved safety during visual approaches;
- More efficient altitudes and tracks for aircraft in oceanic and non-radar airspace; and
- Delayed imposition of airport capacity restrictions when weather conditions deteriorate from visual flight rules.

The possibility of a cockpit display of air traffic was first explored in the late 1970's when researchers at NASA's Ames and Langley Research centres examined cockpit displays in relation to en-route conflict detection and maintenance of self-separation (Shelden & Belcher, 1999). This body of research resulted in the development of the Traffic Alert and Collision Avoidance System (TCAS) in 1981. TCAS is now widely used by commercial passenger airlines. However, while TCAS was only intended to provide airborne collision warnings, the CDTI envisioned for free flight would perform a much broader range of tasks.

Clearly, if the operational goals described above are to be met, CDTIs will be complex, possibly involving a range of symbols, multiple colours, and multiple screens or settings. Therefore, monitoring and interacting with the CDTI is likely to absorb a substantial proportion of pilots' attentional capacity at various stages of flight. As a result, a considerable volume of research has been devoted to developing a display from which information can be rapidly and accurately extracted. This body of research includes studies on the integration of CDTIs and free flight protocols into the Air Traffic Management (ATM) system (Kerns & Hahn, 1996; Billings & Woods, 1995); examinations of the impact of traffic monitoring on the performance of other flight tasks such as maintaining airspeed and height (Morphew & Wickens, 1998; Alexander & Wickens, 2001), and; the design and content of the CDTI itself (Palmer, Jago, Baty, & O'Conner, 1980; Hart & Loomis, 1979; Ellis, McGreevy, & Hitchcock, 1987; Haskell & Wickens, 1993; Merwin, 1997). One of the most widely studied and debated design issues surrounding CDTIs is how many dimensions should be represented on the display.

Planar and Perspective CDTIs

It is possible to present the CDTI as either a two-dimensional (2D) planar/co-planar display or an integrated three-dimensional (3D) perspective display. A 2D planar display typically represents the horizontal location of aircraft spatially and the vertical location of aircraft numerically or with symbolic icons. Two-dimensional co-planar displays have two windows, one represents the horizontal location of the aircraft, and the other represents the vertical location of the aircraft. By comparison, perspective displays utilise linear perspective to create a 3D projection of a scene onto the display screen. Using this type of display all three dimensions of space can be represented in one spatial format. Perspective displays can be presented in either an egocentric or exocentric format. In an egocentric (or pilot's eye display) the symbol representing the

pilot's aircraft remains stationary while the flight environment moves around it. In an exocentric (or god's eye display) the symbol representing the pilot's aircraft moves while the flight environment remains stationary (Naikar, 1998). Research has shown that for spatial awareness tasks (e.g. traffic monitoring) an exocentric display is more effective in terms of manoeuvre choice and avoidance of other air traffic (Olmos, Liang, & Wickens, 1997, cited in Naikar, 1998). New technology that enhances depth (for example, where two LCD screens are superimposed over each other) may open new opportunities to present images with a depth dimension and therefore enhance perspective display possibilities.

The choice between planar and perspective displays is important because, as Ellis et al. (1987) showed, the dimensionality of the CDTI can significantly affect pilot manoeuvre choice. These researchers found that pilots were more likely to make vertical manoeuvres when the display depicted altitude.

A Theoretical Model to Assess CDTI Dimensionality

The main theoretical model with regard to the impact of display dimensionality on performance of tasks is the proximity compatibility principle (PCP) proposed by Haskell and Wickens (1993). This model focuses on the characteristics of the task that will be performed using the display. In applying the PCP task types are divided into those requiring the integration of information across several sources and those requiring the focusing of attention onto information from a single source. The PCP predicts that tasks requiring information integration will benefit from an integrated display and that this benefit will not be seen for tasks that require attention to be focussed on a single dimension/source. According to the PCP operator performance on traffic monitoring tasks will be poorer when 2D displays are used because under these circumstances operators are forced to integrate textual and spatial information from several displays and mentally reconstruct the 3D nature of the visual scene.

Several researchers have supported the view that integrated (3D) CDTIs should promote superior task performance and situation awareness for traffic monitoring tasks. Delucia (1995) stated that perspective CDTIs should result in improved performance primarily because the displays appear more natural and provide depth along the line of sight. Flohr & Huisman (1997) further commented that because of the higher compatibility between perspective displays and the physical system, operators should be able to form a more accurate mental model of their environment and would therefore

use more effective visual sampling strategies. Smallman, Schiller, and Mitchell (2000) added that perspective CDTIs should promote better performance because of the similarity between human retinal images (which are perspective projections) and the format of the display. All these researchers consider that 3D CDTIs should appear more plausible to the user. However, while researchers have theorised that perspective displays should promote better traffic monitoring performance than planar displays, the empirical research surrounding this issue has shown mixed results.

A sizeable body of research now exists that draws comparisons between various types of planar and perspective displays. However, the studies most relevant to this thesis are those that address the specific types of displays and tasks that are envisioned for CDTIs in free flight. Therefore, the following review will focus on the comparison of studies that compare planar/co-planar traffic displays and exocentric perspective displays for tasks such as conflict identification (spatial/hazard awareness) and flight path planning (navigation). Studies of this type have mainly been conducted for air traffic control and cockpit-based tasks.

Perspective versus Planar Traffic Displays for Air Traffic Control Tasks

During the mid 1990s Wickens and his colleagues completed a series of studies examining the effects of display dimensionality on ATC tasks (Tham, Wickens, Liang, Long, & Carbonari, 1993; Boyer, Campbell, May, Merwin, & Wickens, 1995; Campbell, May, & Wickens, 1995). Their research compared conventional planar displays with various types of perspective displays (including stereoscopic displays). The main task that these studies investigated was conflict detection. Generally participants were required to make predictions about whether an aircraft would conflict with other air traffic, terrain, or prohibited airspace. In some studies (e.g. Boyer et al., 1995) participants were also required to issue vectors around various hazards. Merwin (1997) commented that when these studies are viewed collectively little difference in performance is observed between the planar and perspective formats and that where there were differences they tended to favour the planar format. He also observed that these differences tended to be related to time to complete a task rather than accuracy. He noted that when ATCs were required to issue vectors the perspective displays tended to foster wider vectors around obstacles. Merwin speculated that this might result from a more conservative strategy due to ambiguity of depth judgements along the line of sight.

Several other researchers, including Bemis, Leads, and Weiner (1988), have also examined the impact of display dimensionality on ATC task performance. Bemis et al. looked at the impact of display dimensionality on the performance of ATCs operating from naval vessels. They evaluated perspective and planar displays for an air intercept detection task. Participants were required to identify airborne threats and to determine which 'friendly' aircraft was nearest to the detected threat both horizontally and vertically. The displays consisted of a series of range rings with the aircraft presented on them. In the planar condition an overhead view of the range rings was presented with the participants ownship (an aircraft carrier) centred on the display and the horizontal location of other ships indicated. Vertical information could be gained by selecting an individual aircraft. In the perspective condition the same display was fixed at a 41-degree angle to the viewer. Aircraft icons were fixed to the horizontal plane using reference lines to aid in the perception of their horizontal location. The results of this experiment showed that when using the perspective display participants were significantly faster and more accurate in identifying threats and picking the closest interceptor to the threat.

Jasek, Pioch, & Zelter (1995, cited in Merwin, 1997) also compared planar, co-planar, and perspective displays for conflict detection in a simplified ATC task. They found that the co-planar display resulted in better conflict detection than the perspective display or the planar display. However, Merwin (1997) notes that the perspective display lacked grid lines which would have provided linear perspective and helped to disambiguate the horizontal location of aircraft.

Perspective versus Planar Traffic Displays for Flight Tasks

Ellis et al. (1987) conducted one of the earliest and most influential studies on the impact of display dimensionality on pilot manoeuvre choice. Ten airline pilots monitored a simulated traffic situation using either a planar display or a perspective display. Pilots were required to select a manoeuvre to avoid conflicting traffic if they felt that one was necessary. In the perspective display condition pilots manoeuvred earlier to avoid potential conflicts and were more likely to achieve the required separation with manoeuvres (with the exception of head-on traffic conditions). Pilots using the perspective display also initiated fewer unnecessary manoeuvres, fewer manoeuvres that resulted in conflicts, and were more likely to choose a manoeuvre with a vertical component when using the perspective display

Several other researchers have also examined these issues. Wise, Garland, and Guide (1993) looked at the impact of a perspective display of airspace restrictions on the quality and types of decisions made by aviation pilots when trying to manoeuvre through controlled airspace. Thirty-four pilots completed a simulated flight. Whilst flying they were required to locate their aircraft on a map periodically and if necessary, to select an appropriate avoidance manoeuvre. The results showed that the perspective display resulted in significantly fewer unnecessary avoidance manoeuvres and (like Ellis et al., 1987), yielded more manoeuvres with vertical components.

Van Breda and Veltman (1998) examined the benefits of perspective radar displays for fighter pilots by requiring them to locate and intercept a target. The display was presented as either a plan view (2D planar) display or one of two different exocentric perspective displays with either outside in or inside out motion reference. Target acquisition time, tracking accuracy, and pilot workload were measured. The results indicated that pilots were able to perform the target acquisition task faster with the perspective displays (regardless of the initial target position).

Finally, Wickens and his colleagues conducted a series of experiments comparing the impact of perspective and planar displays on pilot performance. O'Brien and Wickens (1997) compared perspective and co-planar CDTI displays in order to address the issues of dimensionality and database integration (e.g. integration of weather and traffic information). Seventeen pilots were required to fly a series of en-route trials in a flight simulator using one of four different CDTIs (perspective with or without database integration and 2D co-planar with or without database integration). The results showed that the co-planar displays with traffic and weather hazards integrated resulted in a smaller percentage of conflicts.

Wickens, Olmos, Chudy, and Davenport (1997) contrasted three displays for aircraft navigation and hazard awareness tasks. The displays consisted of a conventional co-planar display, an exocentric 'gods eye' perspective display, and an egocentric 'pilots eye' perspective display. Pilots were required to fly to various waypoints navigating around hazards. Results showed that the co-planar display supported superior performance. However, when all three displays were given cognitive engineering enhancements including auditory warnings of new targets and flight path predictor lines performance was similar.

Merwin (1997) compared the influence of co-planar and perspective displays on the ability of pilots to detect and avoid air traffic conflicts in a part-task simulation paradigm. He found that the co-planar format generally supported better conflict detection and avoidance than the perspective display.

Finally, Alexander and Wickens (2001) examined the design of CDTI displays by presenting pilots with either an exocentric perspective display or one of two co-planar displays that showed a horizontal view (top down) and either a vertical forward looking rear view or a vertical side looking view. Pilots flew a set of scenarios to compare the effects of traffic load, display dimensionality, and vertical profile orientation on manoeuvre frequency, safety, and efficiency. Their findings suggested that a rear view co-planar display promoted the best performance (in terms of efficiency and safety).

Summary of Research Findings

The body of research outlined above does not provide any clear indication as to which display dimensionality should promote better performance for the type of traffic monitoring tasks envisioned for free flight. It is notable that predicted superiority for perspective displays has not been conclusively borne out by the data. However, as Wickens et al. (1997) commented, the differences between planar/co-planar and perspective displays are quite subtle because they depend on a trade-off between two information-processing mechanisms. On the one hand, the planar/co-planar format imposes a visual scanning requirement on the pilot in order to fixate the two views and an added cognitive load required to mentally integrate them. However, the perspective format suffers from perceptual ambiguities because the 3D location of objects is projected onto a 2D viewing surface. Location of objects within the virtual environment is imprecisely determined along the line of sight and the perceived orientation and length of the vector connecting the two will be degraded by the imprecise estimates of both endpoints of the vector (McGreevy & Ellis, 1986). Several researchers have commented that the failure of perspective displays to support superior performance may be caused by these perceptual ambiguities and by perceptual biases induced by the geometric parameters used to generate the projection (McGreevy & Ellis, 1986; Barfield & Rosenberg, 1995). These distortions may cause varying degrees of difficulty depending on the display configurations and task requirements, hence the variability in performance in experiments involving perspective displays.

While these distortions are difficult to characterise and eliminate the argument made by Haskell and Wickens (1993) and others regarding the potential efficacy of integrating traffic information into one display with regard to pilot performance and situation awareness is compelling. Three-dimensional displays are also particularly appealing from the perspective of lowering operators' visual workload during traffic-monitoring tasks and therefore leaving them free to complete their primary flight tasks. Naikar (1998) commented that several studies have demonstrated performance advantages associated with perspective displays and that these results provide an incentive for continuing research in this area. She further stated that particular effort should be directed towards understanding and characterising the distorting effects of representing perspective information on a 2D surface. Therefore, the goal of the present research is to explore these distortions by examining their impact on the ability of users to effectively extract information from perspective displays and to suggest actions that may potentially limit the impact of the distortions. In order to provide a basis for the present research, a review of available research on perceptual distortions in perspective displays that are comparable to CDTIs was conducted. This review is outlined in the following chapter.

Distortions in Perspective Images

The aim of the following chapter is to provide an outline of geometric and perceptual distortions that occur when viewing perspective displays similar to proposed CDTIs. Before discussing the research on distortions in perspective displays in more detail, a brief outline of the geometric principles involved in creating a perspective display is provided.

Stimulus Geometry of Perspective Images

The following description provides a general outline of the geometric principles that allow a 3D object (such as a cube) to be projected onto a 2D surface (such as a computer screen). The projection of 3D positional information onto two dimensions is known as central or point projection (Merwin, 1997). Using this technique, a 2D image is created as a result of projecting each point from the 3D scene to the station point (centre of projection) (see Figure 2).

A plane (termed the picture plane) is placed between the 3D image and the station point. The 2D image is formed where the projected lines intersect the picture plane. The edges of the picture plane are defined by the location of the station point and the geometric field of view (the angle from the centre of the projection to the edge of the picture plane) (McGreevy & Ellis, 1986). By using this method both the 3D and 2D coordinates of a stimulus can be identified and various viewing transformations (such as altering the geometric field of view, GFOV) can be accurately manipulated. Reference coordinates are specified by the following conventions: the horizontal axis is specified by x, with positive x indicating distances to the right; the vertical axis is specified by y; and z specifies the depth axis moving into the picture plane.

Mulder (1994, cited in Merwin, 1997) stated that there are two ways that the geometric information contained in perspective images can be incorrectly interpreted. The first is due to the inherent characteristics of the geometric projection and the positioning of the viewer in relation to the geometrically correct station point. The second involves biases that the human visual system introduces when interpreting perspective images. Therefore, the following two sections will outline the main geometric and perceptual distortions that have been identified in research on perspective displays.
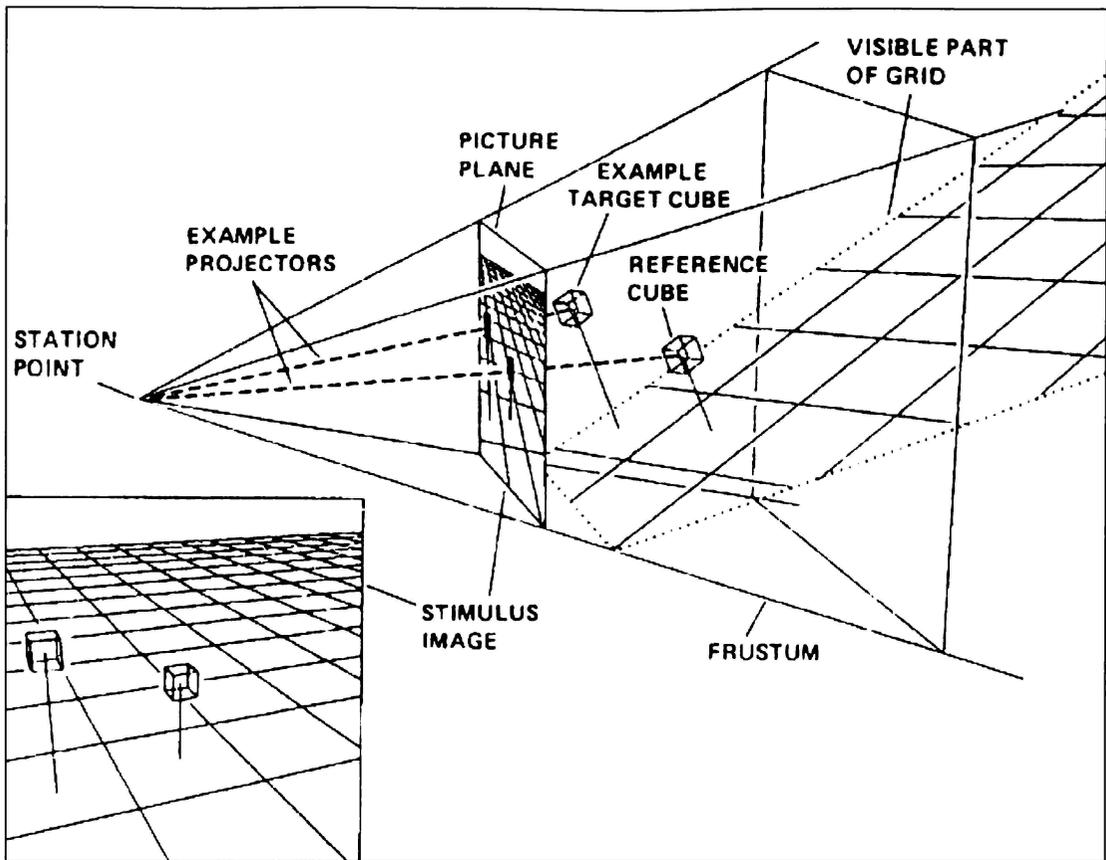
Figure 2. Example of stimulus perspective geometry, showing relationships between the 3D stimulus and its 2D projection (McGreevy & Ellis, 1986, p.443).

Geometric Distortions in Perspective Displays

A number of researchers have attempted to characterise the effects of altering various geometric parameters (including the position of the viewer) on the appearance of perspective projections (both photographs and pictures).   La Gournerie (1859) cited in Cutting (1988) was one of the first to reason that viewing a perspective image from a point other than its station point should create systematic distortions in pictorial space. The viewpoint can be dislocated along any of the primary geometric axes; along the x-axis which rotates the image horizontally; along the y-axis which rotates the image vertically, and; along the z-axis which alters the proximity to the image.   Figure 3 shows an image viewpoint (eye) and station point (Centre of Projection, COP), in this figure the viewpoint has been dislocated from the COP along the z-axis.

15
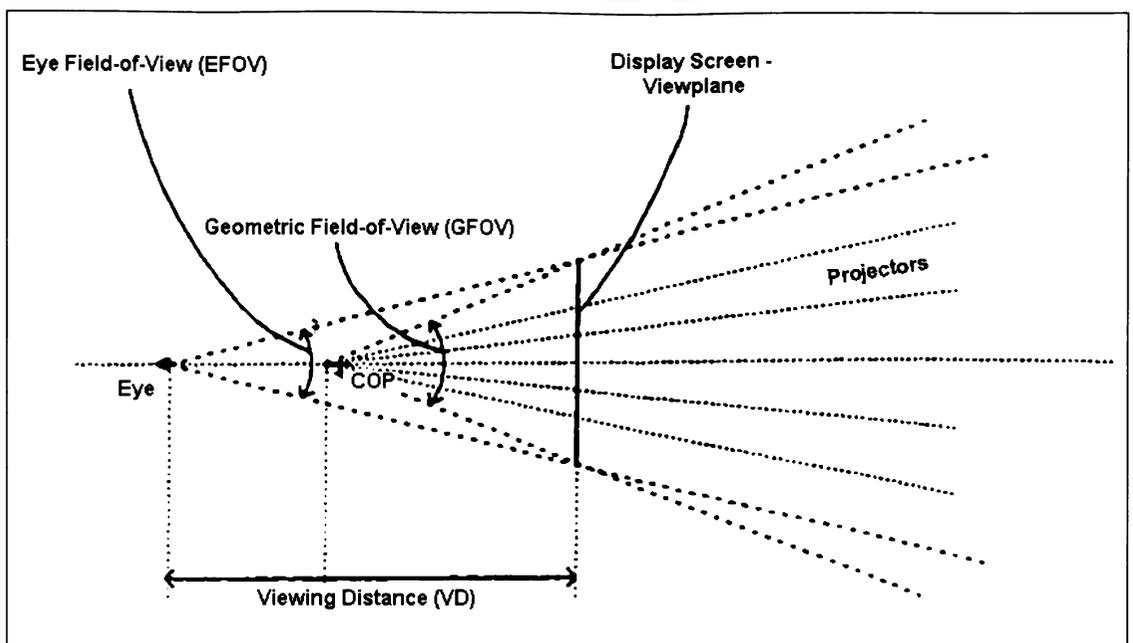
Figure 3. A diagram of perspective display parameters (Mulder, 1994; reproduced from Merwin, 1997, p.15).

Cutting (1988) went on to describe the effects of these transformations on the appearance of the perspective image. He states that when the viewpoint is moved to one side (along the x-axis) the result is an affine transformation (a mathematical process of transforming images by scaling, translating and rotating them) of the layout of pictorial space from a grid of squares to a grid of parallelograms (termed shearing). When the viewpoint is moved along the z-axis another affine transformation results (compressing or dilating the z-axis compared to the x-axis and y-axis).

Figure 4 illustrates the effects that these transformations would have on a perspective image. The left image shows the original picture and the middle image shows the same picture with the viewpoint moved to the side causing an affine shear. The right image shows an affine compression related to moving the viewpoint closer to the image (or enlarging the image with a long lens).
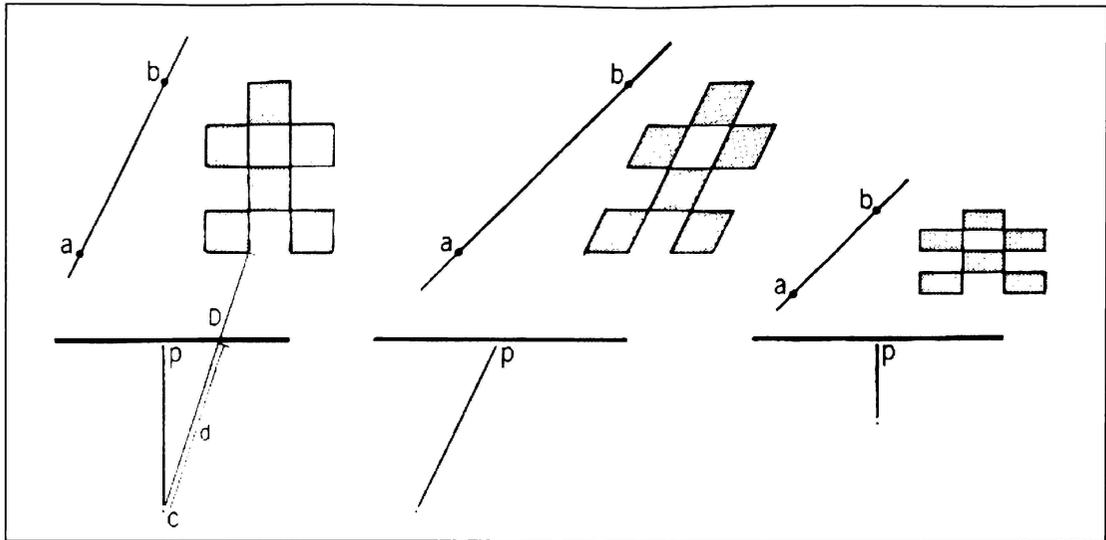
Figure 4. Distortions of pictorial space (Cutting, 1988, p.307).

Other researchers have examined the effects of moving the station point itself. Barfield, Hendrix, and Bjorneseth (1995) stated that when the station point is raised spatial information along the vertical dimension is compressed. For example, if the station point were set to 90 deg (0 deg being straight ahead), a vertical pole orthogonal to the image surface would appear as a dot. However, when the station point is lowered the depth dimension in a scene becomes compressed (i.e. foreshortening). Figure 5 shows two poles with the station point placed at various locations (from 0 deg, straight ahead, to 90 deg).
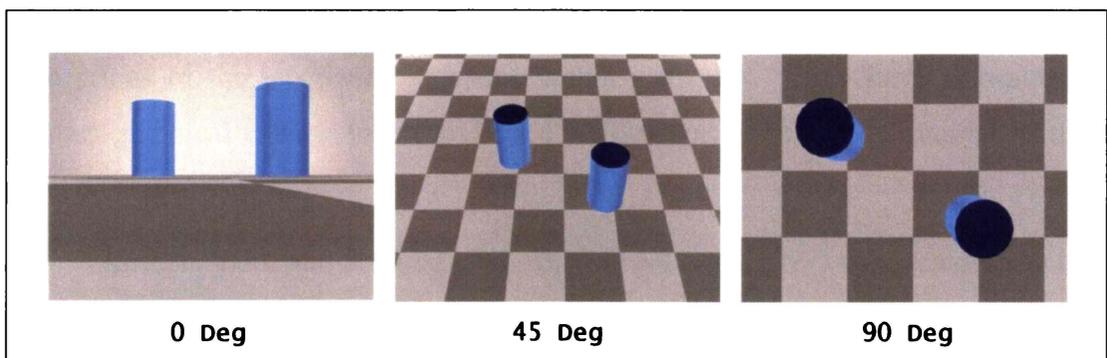
Figure 5. Distortions of pictorial space related to station point position.

Theunissen (1993, cited in Merwin, 1997) also described a distortion that is induced by rotating the station point so that an object in an image moves from the centre of the display to the edge of the display while the viewing distance is kept constant. He noted that this transformation results in the apparent magnification of the object as it moves towards the edge of the display (see Figure 6).
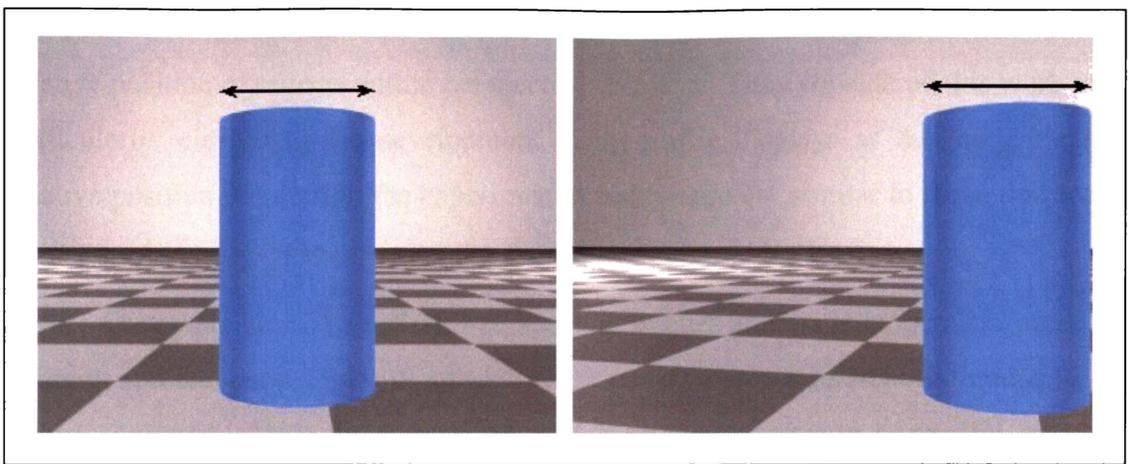
Figure 6. Distortions of pictorial space related to rotating the station point.

The research described above demonstrates that an image can be substantially altered by manipulating the geometric parameters that define the projection. As a result, the correct positioning of the viewer at the station point and the elevation and azimuth at which the image is presented are important considerations when designing perspective displays.

Perceptual Distortions in Perspective Displays

In addition to examining geometric distortions that can be created by varying the parameters used to generate perspective displays researchers have also focused on errors made during the process of perceiving displays. They have considered how various perspective parameters (such as GFOV and viewing distance) affect observers' perceptions of the locations of objects within a display. They have also attempted various graphical enhancements and used stereoscopic views in an attempt to reduce perceptual errors.

Roscoe, Corl, and Jensen (1981, cited in Merwin, 1997) conducted some of the earlier research on the perception of perspective displays. They found that displays depicting a forward view resulted in perceptual minification of the elements presented in the display. Objects appeared to observers to be closer together and/or smaller than they actually were in simulated space. The authors contended that this bias led observers to believe that objects were further away than they actually were. They argued for magnifying perspective displays to counter this effect.

One of the most comprehensive bodies of research on perceptual distortions in perspective displays was conducted by researchers at the NASA Ames Research Centre during the 1980s (e.g. McGreevy & Ellis, 1986). This group measured and modelled

the visual perceptions of observers who were required to make judgements about the relative position of objects within perspective displays. They considered this work to be particularly relevant to the development of air traffic displays as the judgements of relative position required in the experimental task were very similar to those that would be required of pilots when judging the position of other air traffic.

Observers viewed a series of perspective images and made judgements about the azimuth and elevation angles of a target stimulus relative to a reference stimulus. Each image consisted of two cubes (a target and a reference cube), a horizontal grid, and metric lines connecting the cubes to the grid (see Figure 7). The display was presented from an azimuth of −158 degrees relative to the reference cube heading of zero degrees, and from an elevation of 22 degrees above the reference cube. Participants were required to adjust the pointers in two round dials to indicate the judged azimuth and elevation angles of the target cube relative to the reference cube (See Figure 7).

As described in the previous section, there are several geometric parameters that directly affect the appearance of a perspective display. These parameters include GFOV and the position of the station point. Another issue that may potentially affect perceptions of the display is eye point elevation and offset because these parameters define how far the viewer is dislocated from the station point of the image. The NASA Ames research group examined the impact of several of these parameters. The following section will summarize the more salient findings from this series of studies.

McGreevy and Ellis (1986) conducted an experiment to determine whether the differences in display appearance (resulting from changes in GFOV and the placement of objects in the display) would affect observers' judgements of azimuth and elevation. The authors hypothesised that direction judgement error (azimuth and elevation estimation error) would vary as a function of the geometric parameters of perspective. Eight participants viewed 640 perspective stimuli. These consisted of 16 perspective conditions (four GFOV conditions crossed with four distances between the reference cube and the viewer) and 40 direction conditions between the reference cube and the target cube (within which azimuth and elevation conditions were crossed). The participants' eye position was 61 cm from the 19 x 19 cm image. It should be noted that the eye position did not match the station point in any condition so distortions due to dislocation from the station point were not controlled for.
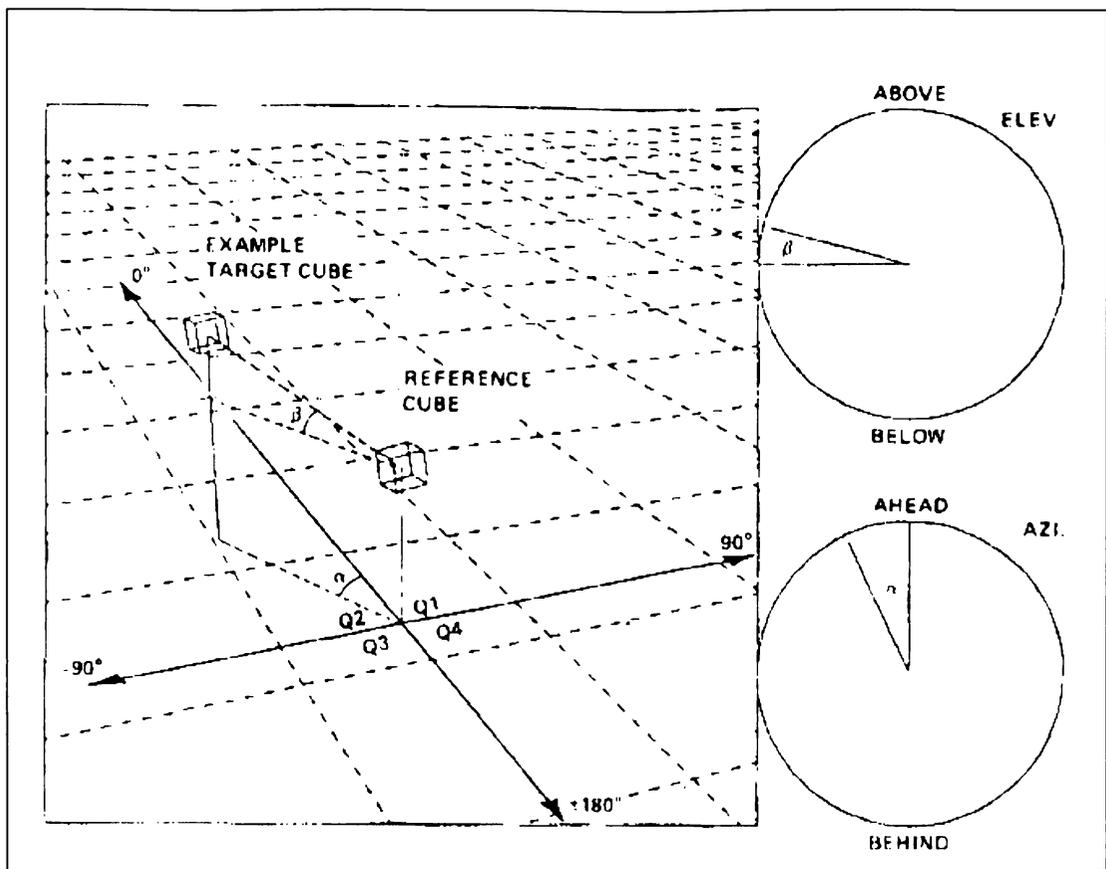
Figure 7. Experimental display used in the NASA Ames experiments (McGreevy & Ellis, 1986)[1].

Analyses between GFOV conditions showed clear differences in inter-object direction judgement error (McGreevy and Ellis, 1986). Results showed that elevation was consistently overestimated, particularly in 'telephoto' images (small GFOV). In addition, the results showed a statistically significant interaction between GFOV and azimuth. Analyses of the data showed that they were best represented by sinusoidal curves (fitted by a sixth order polynomial). McGreevy and Ellis showed that when plotted together the four curves varied systematically as GFOV changed (see Figure 8). The direction of the inter-object azimuth judgement error was gradually reversed, alternating between clockwise and counter clockwise error from one direction quadrant to the next. For example, McGreevy and Ellis state that "by varying the field of view, targets at azimuth directions of –135 deg will be seen as about 5 deg clockwise of the true direction for a 30-deg field of view, which will gradually change to about 13 deg counter clockwise for 120-deg field of view" (1986, p.450).

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[1] Note that the crossing axis and associated numbers were not presented in the experimental stimuli.
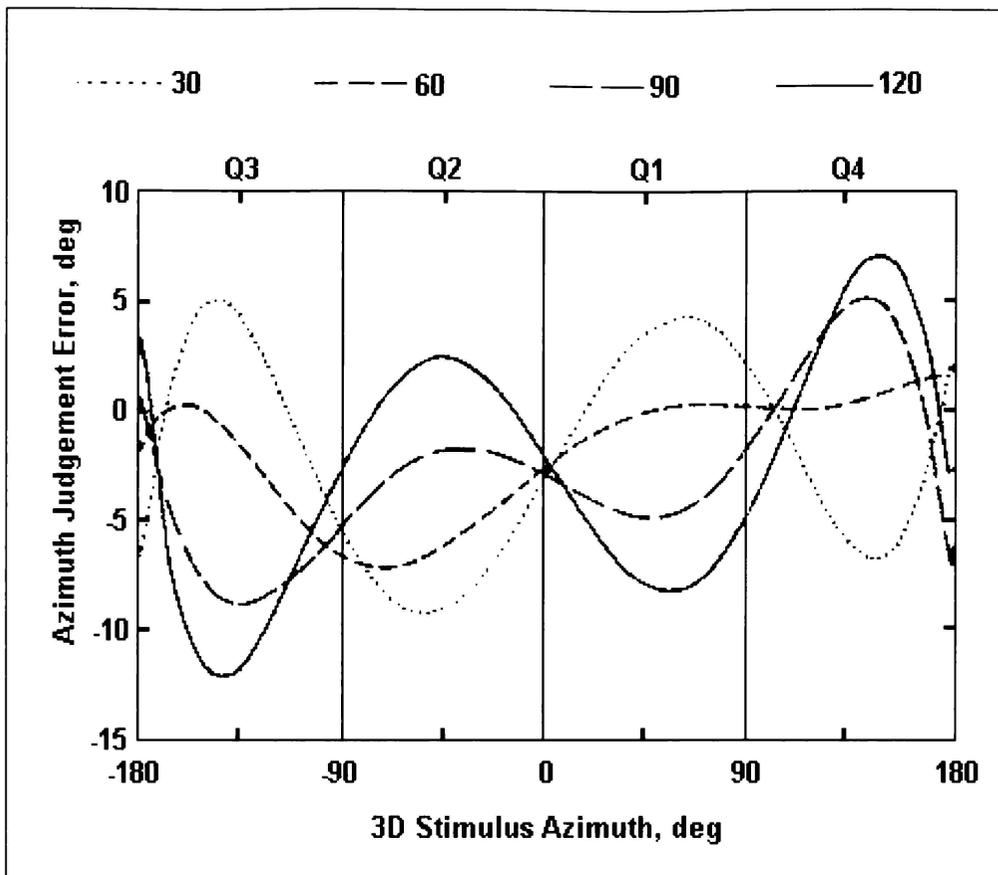
Figure 8. Azimuth estimation error polynomials (sixth-order) for each GFOV (McGreevy & Ellis, 1986, p. 452).

These results indicated that participants could not accurately estimate the relative position of objects within the perspective display and that manipulations of the geometric parameters of the display caused substantial changes in direction judgement error. It was also notable that under each GFOV condition the type of errors that were made changed depending upon where the target and reference cubes appeared in the display space. Clearly the inability of the participants in this study to accurately estimate the relative positions of two objects in the perspective display has important implications for the use of perspective displays in cockpits. Therefore, Ellis and colleagues attempted to develop a model of this error in order to better understand it and to assess the implications for display design.

A Model of Azimuth Estimation Error in Perspective Displays

In order to account for the sinusoidal changes observed when azimuth estimation error was examined in relation to GFOV the authors proposed a model that predicted an interaction between two effects; the virtual space effect and the 3D-to-2D projection effect. McGreevy and Ellis (1986) described the virtual space effect as a

mismatch between the observers' eye point and the station point of the projection. The authors stated that observers make an assumption about the structure of the projected space that they called a window assumption. When making the window assumption the observer assumes that they are at the correct station point (as they would be if they were looking out a window) and therefore assumes that the projectors from the image to their point of observation are straight, when in fact they are not. To compensate for this discrepancy between the expected straight projectors and the observed bent projectors McGreevy and Ellis stated that observers use an interpretive behaviour. They argue that the observer introduces a systematic bias into the perceived 3D space in an effort to maintain compatibility between it and the window assumption. They do this by re-projecting points on the screen back into 3D space along straight lines which all emanate from a point at the observers eye position. It should be noted that this theory predicts that there should be no error when the observer is at the correct station point.

The 3D-to-2D projection effect is hypothesised to bias 3D angular judgements towards their 2D projected angles on the display (Merwin, 1997). McGreevy and Ellis (1986) stated that the magnitude of the effect for a given angle is equal to the difference between the 2D angle on the image plane and the 3D angle it represents. The sinusoidal effect is caused by the changes in the azimuth of the target from the reference point.

The virtual space effect and the 3D to 2D projection effect could potentially bias observers' judgements about the location of objects in a perspective scene. As the observer views a display and attempts to judge distance relations between objects the judged relationships may be affected by the fact that the angle is represented by a 2D projection and that the projectors may be bent due to the observer viewing the display from an incorrect station point (McGreevy and Ellis, 1986). McGreevy and Ellis noted that while the magnitude of the virtual space effect increases as GFOV increases, the impact of the 3D-to-2D project effect decreases as GFOV increases. Thus, they proposed that the virtual space effect dominates judgements of wide fields of view, and the 3D-to-2D effect dominates at narrow fields of view (hence the reason that the sinusoids change direction at different GFOVs). McGreevy and Ellis note that their observed data (Figure 8) closely matched their predicted data (Figure 9).
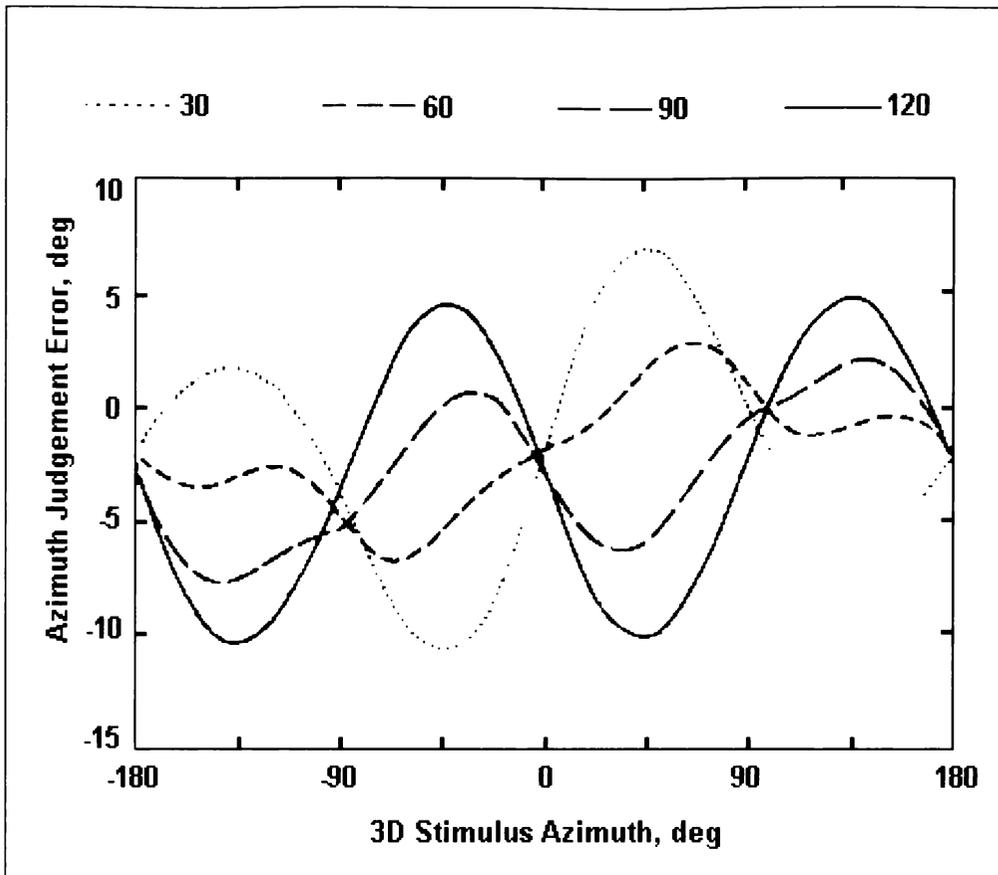
Figure 9. Predicted data from the combined virtual space effect and 3D-to-2D projection effect, which model azimuth error as a function of stimulus azimuth for each GFOV (McGreevy & Ellis, 1986, p.455).

In developing the model described above, McGreevy, Ratzlaff, and Ellis (1985) also conducted an experiment to further examine the impact of both perspective geometry (GFOV) and viewer' eye position (eye FOV) relative to the image station point. In this study 384 perspective images (using the display described at the beginning of this section) were presented to 12 observers. However, in contrast to earlier experiments, the images were presented as slides of computer generated perspective scenes and were rear-projected on to a large screen (104 cm sq). This allowed the experimenters to move the projection screen so that it was positioned at various distances from the observer. Therefore, the observer was presented with images from four different distances relative to the geometrically correct station point. On all GFOV conditions the observers' eye was at the correct station point for one of the distances presented.

The results of this study showed a significant three-way interaction between stimulus azimuth, GFOV, and eye FOV. The sinusoidal functions found by McGreevy and Ellis (1986) again appeared in this experiment (these showed an interaction between GFOV and stimulus azimuth). Eye FOV affected the interaction between these two variables in that when the viewer was placed at the correct station point error was reduced (the virtual space effect was eliminated). These results also showed that azimuth estimation error was least at the widest GFOV (120 deg) and when the observer viewed the image from the correct station point (eye FOV 120 deg). Their model states that this is because the 3D-to-2D effect is minimised at wide GFOVs, while the virtual space effect only occurs when the eye is not at the correct station point.

As a result of continued study of these effects, Ellis, Smith, McGreevy, and Grunwald (1989) extended their theory by showing that azimuth estimation errors could be modelled by assuming that the observer has misperceived their viewing orientation (azimuth and elevation angle of the viewing vector to the centre of the display). This misperception affects perception of the relationship between objects in the display causing the observer to misperceive azimuth angles. They completed an experiment within which the experimental conditions described in previous studies were replicated. However, in this study, in order to examine the impact of the competing 2D cues (hypothesised to cause the 3D-to-2D effect), an experiment was also conducted within which the reference and target cubes were recreated using PVC piping and positioned in a parking lot. Participants viewed the stimuli binocularly, behind and centred in viewing windows. They made the same azimuth judgements described above for previous experiments. Their results showed that the previously reported 'equidistance tendency' in azimuth error (where participants judged the target cubes to be closer to the axis crossing the reference axis than they actually were) was eliminated when participants viewed a similar stimulus in a real world setting. This confirmed to Ellis and his colleagues that the conflict between 3D cues and 2D projections was the cause of some of the errors observed in the original experiments.

The research group therefore extended their original model so that it assumed that observers have an internal look-up table to transform observed 2D angles into 3D angles. This look-up table could only be accurate if the observer was able to correctly estimate their viewing orientation. Ellis et al. (1989) speculated that viewing orientation might be misperceived due to opposition between the properties of the inferred virtual space and the properties of the 2D picture surface. The picture surface

was of course flat and therefore provided fixed accommodative and vergence demands as well as disparity and motion parallax cues to its physical distance. Therefore, the picture surface cues (accommodation, surface texture, etc) indicate to the observer that all the objects are at an approximately equal distance which is at odds with the monocular depth cues present in the image (e.g. the changes in cube size with distance). The authors speculate that these competing cues cause observers to make errors in the estimation of their viewing orientation. However, Ellis, Smith, Grunwald and McGreevy (1991) also acknowledge that the errors observed in their virtual display also resemble a spatial compression in depth. They also note that the azimuth errors can be modelled by a generalization of classic slant overestimation (see Perrone, 1980,1982) in which the viewer is assumed to overestimate both the pitch and the yaw of the viewing direction.

These results of this body of work have important implications for display design as they explain to some degree why the expected predicted improvements in performance resulting from an integrated display have not always been realised. In addition, the model developed by Ellis and colleagues has the potential to provide assistance to display designers. However, this research group did not attempt to enhance their displays to assess whether the observed errors could be reduced. The challenge of enhancing perspective displays to reduce known errors was taken up in the early to mid 1990s by Barfield and colleagues (Barfield, Lim, & Rosenberg, 1990; Barfield & Kim, 1991; Barfield et al., 1995). They used an experimental paradigm that was essentially a replication of that used by the NASA Ames researchers (see description above) and conducted a series of experiments to further examine perceptual distortions and to attempt to reduce them using various visual enhancements including stereoscopic presentations. While Barfield and his colleagues gathered a significant amount of information about these issues they did not develop any specific models to account for their data. The following review will outline the most significant findings by this group.

Enhancements to Perspective Displays

Barfield et al. (1990) attempted several visual enhancements to their perspective displays that had become possible through advancements in technology subsequent to the completion of the NASA Ames experiments. They used the same basic display as the NASA Ames group, but added a rotation condition (where the observer was able to

rotate the scene around the x axis while maintaining the same radial distance and angular eye point position relative to the reference cube) and the presentation of shadows associated with objects in the scene. Their results generally supported the findings of the NASA Ames group. The visual enhancement through shading condition did not significantly improve azimuth or elevation estimation accuracy. However, the rotation condition significantly improved elevation estimation (but not azimuth estimation).

In addition to adding features to the perspective display itself, Barfield and colleagues also introduced stereoscopic displays in an attempt to improve azimuth and elevation estimations. Barfield and Rosenberg (1995) compared stereoscopic and perspective displays for judgements of spatial information. Again, they used the same display design as the NASA Ames researchers. The experiment examined azimuth and elevation estimations across eight GFOV conditions and six elevation conditions (including three negative elevation conditions). Their results showed that the stereoscopic display improved estimates of elevation indicating that monocular depth cues were less effective in allowing participants to recover vertical information than stereopsis. However, the stereoscopic display did not improve estimates of relative azimuth direction. This finding is somewhat at variance with Yeh and Silverstein (1992) who found that depth judgements were more accurate using a stereoscopic display. These authors state that this difference may be due to differences in display design since this study used drop lines to anchor the cubes to the grids surface whereas Yeh and Silverstein did not.

Conclusions

A large body of work has accumulated that documents both geometric distortions resulting from the parameters used to generate perspective displays, and perceptual distortions that occur when viewing perspective displays. These studies have shown that geometric parameters such as GFOV and the position of the viewer relative to the station point do appear to impact on the degree of perceptual distortion. They have also shown that while display enhancements such as rotation and stereoscopic presentation can improve elevation estimations, to date, no set of optimal geometric parameters or display enhancements has been found to reduce errors in azimuth estimations. Though the work by Ellis and his colleagues does suggest that a wide GFOV with the viewer positioned at the correct station point may minimise error.

To a large extent the studies described above (in particular those conducted by Barfield and colleagues) have provided information about the types of perceptual distortions observed in perspective displays but have not attempted to develop any models by which perceptual distortions can be predicted. The obvious exception is the NASA Ames research group who have developed a comprehensive theory of azimuth judgement error. However, this model is complicated by the interaction of the two competing theories. Also, it does not provide any means of accurately predicting the degree to which perceptual errors may occur when viewing a display and does not suggest any enhancements that may reduce the observed errors. It is therefore of limited utility to display designers.

While Ellis and colleagues have presented one possible reason for the observed azimuth estimation errors, they have not addressed the possibility of other explanations. For example, while the research group attributes azimuth estimation error to the observer wrongly estimating their viewing position in terms of elevation and azimuth offset, it is also possible that the distortions occurred because the observer incorrectly estimated their proximity to the objects within the display (affecting their perception of depth and therefore, their estimation of angles). In fact, Ellis et al. (1991) acknowledge that their results resemble a spatial compression in depth relative to the frontoparallel plane.

It is clear that there is still considerable research needed to fully understand perceptual errors in perspective displays. It is also interesting to note that many of the errors observed in the perspective display studies described above are similar to those that have been observed in visual space perception research in general (both real world space perception and picture perception). Therefore the following chapter will review the findings in these areas to determine whether any of the models or theories developed in these studies can provide any insights into perceptual errors, particularly azimuth estimation errors in perspective displays.

Visual Space Perception

The existing body of research on the perception of visual space shows that while there is clearly some relationship between environmental stimuli and visual perception, most researchers seem to consider that there is not a one-to-one correspondence (Hardy, Rand, & Rittler, 1951). Therefore, much study has been devoted to attempting to define the relationship between the physical world and visual perception.

Visual space has been studied within two somewhat separate frameworks. The first realm of study examines the relationship between physical and visual space. In this domain it is often theorised that perceived space is a uniform distortion of physical space and that a specific transformation can be found that accurately describes the relationship between the two domains. The second field of study examines artificially constructed representations of physical space (e.g. perspective pictorial renditions) and is concerned with distortions that arise in the process of representing and viewing these images (e.g. Hecht, van Doorn, & Koenderink, 1999). These two fields are related in that some of the perceptual distortions observed in studies of physical space have also been found in studies of pictorial renditions. However, several perceptual distortions particular to pictorial renditions have also been observed. Therefore, it is important to consider findings from both of these fields of study when attempting to understand the perceptual distortions found CDTI-like perspective displays (described in the previous chapter). The following chapter will outline the main findings in both these fields and compare and contrast the theories and models that have been developed. Issues that relate to the perceptual errors found in CDTI-type perspective display research will be highlighted.

Real World Visual Space Perception

The physical world is defined using geometric measurements. Measuring instruments are used to provide the measurer with information about the structure of physical space. Visual space, by comparison, is defined by the judgements of human observers depending solely on eye measure (Koenderink, van Doorn, Kappers, & Todd, 2002). Indow (1991) provides a more detailed description of visual space. He states that it is the final product of the long series of processes from retina to brain. He reasons that visual space is a "comprehensive percept that includes all individual objects appearing in front of the perceived self. Under ordinary conditions, in every direction

we see some percept at a finite distance from the self, which means that visual space is bounded in all directions" (Indow, 1991, p.430).

Three-dimensional Euclidean geometry provides an accurate description of physical space at a local level (Coxeter, 1961, cited in Koenderink et al., 2002). However, while most people are unaware of any discrepancies between the visually perceived environment and the physical environment, experimental data have indicated that (under some circumstances) visual space diverges notably from physical space.

Helmholtz (1867, cited in Hecht, et al., 1999) was one of the first researchers to suggest a non-Euclidean account of visual space. In his classic experiment, he used three threads, two in equidistant fixed positions and a centre thread that was adjustable in depth. Participants were required to make adjustments so that the threads appeared to lie in the frontoparallel plane. Observers did not manage to produce results that represented true coplanarity. The centre thread was adjusted too close for large viewing distances and too far for short viewing distances. As a result of these findings Helmholtz suggested that a Riemannian geometry (geometry of curved space) might best describe perceived visual space.

Parallel alley studies by Hillebrand (1902, cited in Hardy et al., 1951) and Blumenfeld (1913, cited in Hecht et al., 1999) provided further evidence that visual space is distorted with respect to physical space. Hillebrand demonstrated that alley walls (outlined by black threads against a white background) which appeared to the observer to be parallel, actually converged towards the eyes and were not straight but slightly curved. Similarly, Blumenfeld found that when participants were instructed to set parallel alleys of lights so that they were evenly spaced, the participant set the lights so that the distance between the closest lights on opposite sides was smaller than those between two corresponding lights further away.

Luneburg (1947) built on these studies to provide the first comprehensive theory of the structure of visual space. His theoretical model proposed that visual space is a constantly curved Riemannian space. For example, the surface of a sphere is a 2D Riemannian space with a constant positive curvature (Cuijpers, Kappers, & Koenderink, 2000). While his model was based (in part) on experimental data, Luneburg was led mainly by theoretical considerations. As a result he made several assumptions about the nature of visual space. For example, he considered the Riemannian structure of visual

space to be self-evident and he assumed that the geometry of visual space is independent of its contents (Schoumans, Koenderink, & Kappers, 2000).

Several subsequent researchers conducted work that aimed to either explore or further refine the theories developed by Luneburg. Hardy et al., (1951) conducted experiments to test Luneburg's model. They concluded that while some of their results were in agreement with Luneburg's model, their participants experienced difficulty following the experimental instructions. Therefore, they concluded that alley experiments presented too many difficulties for practical application. Indow, Inoue, and Matsushima (1962) also conducted research examining Luneburg's model using parallel and distance alleys. They indicated that their results provided support for Luneburg's model.

Luneburg's model was further refined by Blank (1961). He also assumed that visual space had a Riemannian structure and set out to test whether visual space is curved hyperbolically or elliptically. In order to do this he created experiments in which observers were presented with three star-like lights that formed an isosceles triangle, two points were located 71 cm from the observer and the third was located at 274 cm. The observer was required to place a fourth light where it appeared to bisect the left or right side of the triangle. The points were, on average, moved inside the triangle which would indicate hyperbolic curvature of visual space (Hecht et al., 1999). Subsequently however, several researchers have suggested that visual space doesn't have a constant curvature (Indow, 1991).

The theory of visual space developed by Luneburg and refined by later researchers has greatly influenced visual space research. Post-Luneburg theories of visual space often reference themselves either in support or opposition to his metric. Wagner (1985) provides a brief overview of attempts to establish an alternative metric for visual space since the work of Luneburg. He states that several researchers have suggested that visual space is spherical (Angell, 1974; and Daniels, 1974; both cited in Wagner 1985). By comparison, other researchers such as Indow (1967,1974,1979, all cited in Wagner, 1985) agreed with Luneburg (1947) that visual space is hyperbolic. However, some researchers have suggested that it reflects a Lie algebra group (Hoffman, 1981). Koenderink and his colleagues have also explored several possible metrics including an affine structure, which is a generalisation of Euclidean geometry (Todd, Oomes, Koenderink, & Kappers, 2001). Koenderink et al. (2002) comment that

despite considerable efforts to provide a metric of visual space to date, they believe that the structure of human optical space remains effectively open.

More recent evidence has suggested that, while Luneburg's metric adequately explains much of the data gathered in reduced cue environments, in many cases it does not explain data gathered in full cue environments (e.g. Battro, di Pierro Netto, & Rozestraten, 1976). As a result, many researchers have questioned whether his theory can be generalised to full cue (e.g. real world) environments. The lack of consistent findings in this area have also led researchers to question the assumption that visual space can even be described by a homogeneous metric. Indow (1991) observed that our constructed visual space is our means of guiding our bodies through physical space. Therefore, there must be some correspondence between the structures of visual and physical space at least within close proximity to the self. However, accurate correspondence of this kind is not necessary over the entire visual field. In fact, Indow (1991) comments that there is no reason to assume that visual space as a whole can be described by any conventional geometry.

Koenderink and his colleagues provide support for these comments with their explorations of the role of context in visual space. They concluded that, in contradiction to previous theories, the geometry of visual space is not independent of its contents (Schoumans et al., 2000). They consider that it should be a point of debate whether optical space has a fixed relation to physical space independent of its contents at all. Questions and ideas such as those described above have driven post-Luneburg visual space research. Some of the research conducted on these issues will be briefly outlined below.

Visual Space in a Full Cue Environment

In recent years a growing body of visual space research conducted in full cue environments has emerged (Battro et al., 1976; Wagner, 1985; Hecht et al., 1999). These studies tend to suggest that Luneburg's results cannot be transferred to full cue (real world) environments. Cuijpers et al. (2000) further comments that the structure of visual space appears to depend on the environment within which it is measured. There are two aspects of visual space that are often considered in full cue space perception studies. The first is egocentric space perception (the perceived relationship between the observer and an object in the environment), the second is exocentric space perception (the perceived relationship between two objects in the environment).

Battro et al. (1976) conducted experiments to test Luneburg's model of visual space in a full cue environment. They required observers to instruct the experimenter regarding the arrangement of thick stakes on flat grassy terrains. Several classical laboratory based experimental methods were replicated, including visual alleys, Helmholtz horopters, Ogle horopters, and Blank's visual triangles. One of the main results of this study was that visual space is scale dependent. Distortions increased with distance between the stimuli and the observer. The researchers also found that very large objects such as roads or hills were able to fool participants quite dramatically and appeared to belong to a different class of phenomena (as compared with the relatively small objects of a laboratory display). Objects that are too large to be manipulated directly or with hand held tools appeared to be treated differently by the visual system. Likewise, objects that were far away appeared to be subject to some rather strong visual distortions (Hecht et al., 1999).

Wagner (1985) conducted a systematic investigation of judgements of distances, angles, and areas in open space using a similar method to that of Battro et al. (1976) (described above). Wagner's premise for conducting the experiment was that by knowing the metric properties of visual space and their interrelations, one can define the geometry of visual space analytically without recourse to synthetic geometry. One of the main findings from this study was that visual space was notably compressed in depth relative to physical space. In this study stimuli oriented in depth were judged to be half as large as the same stimuli oriented on the frontal plane. Angles facing either directly toward or directly away from the observer were seen as approximately twice as large as those seen on their sides. Wagner commented that two models produce a reasonable description of the visual space suggested by the results of this study. The first is an affine-transformed version of Euclidean space. In the second model, distances are viewed as vectors that can be broken down into in-depth and frontal components relative to the observer. It should be noted that the angular judgement results of this study are relatively similar to the azimuth estimation error found by Ellis and colleagues. However, Wagner attributes the effect to a compression of visual space; this compression could result from misperceptions of distance between the observer and objects in the environment.

Loomis, Da Silva, Fujita, and Fukusima (1992) and Loomis, Da Silva, Philbeck, and Fukusima (1996) conducted experiments that measured perceived egocentric and exocentric distances within both full cue and reduced cue environments. Participants' performance was measured both by distance estimations and also by visually directed action. In the visually directed action task the observer viewed a target within the immediate environment and then, with eyes closed, attempted to demonstrate knowledge of the object through some sort of action. In this experiment there were three tasks relating to visually directed action: visually directed walking, triangulation by pointing, and triangulation by walking. Results showed that in a full cue environment participants were able to perform the visually directed tasks with reasonable accuracy. However, under a reduced cue environment large systematic errors were apparent. Distances shorter than 2m were overestimated and distances further than 3m were underestimated.

Participants in this study were also required to complete tasks requiring distance estimations. Results for these tasks showed substantial errors in the perception of exocentric distance. By instructing the experimenter, each participant was required to adjust the exocentric distance between the two targets in the sagittal plane until they felt that the distance was objectively equal to exocentric distance between the two targets on the frontoparallel plane (thus creating a square). In performing the match observers consistently made the sagittal interval 50-90% larger than the frontoparallel interval. The degree of perceptual distortion increased with distance in that increasingly larger sagittal intervals were needed to create figures that were perceived as squares. Loomis et al. (1992,1996) considered that these results provide evidence for dissociation between perceived location and perceived exocentric distance. They further state that this makes intelligible the accuracy with which people can act despite systematic distortions of exocentric distance.

The findings of Wagner (1985) and Loomis et al. (1992,1996) were also supported by Toye (1986). In this study observers judged the location of objects in an open field by drawing a map of the scene. Observers were divided into two groups; one group was required to make two sets of judgements from the same position, the second group was shifted 90 deg for their second set of judgments. Results showed that judgements changed significantly as a function of observer position. Toye states that the variation was due to differences in the way observers perceive horizontal and radial distances (cf Wagner, 1985).

A more recent study by Hecht et al. (1999) examined compression of visual space in real world objects and compared them with photographic depictions of the same objects. Participants were required to make a verbal judgement of the distance to a corner on a building. They were then asked to judge how obtuse or pointed the angle of the building appeared to be. The results of this study showed that across all conditions (real world and photographic) an effect of distance was found. Building corners appeared to flatten out with distance. In addition, photographs of corners produced similar results to real world scenes. Hecht et al. (1999) suggested that visual space is distorted in a local fashion. They further stated that visual space appeared to be represented as accurately as necessary in personal and close action space. However, where accuracy is not crucial (for example in the far distance where the viewer cannot interact with the stimuli) errors enter. Again, this study found angular estimation errors not dissimilar to those found by Ellis and colleagues.

Finally, Koenderink, van Doorn, and Lappin (2000) conducted a study that tested observers angular estimations in an exocentric pointing task in an outdoor environment. One of the main aims of this study was to test the hypothesis that visual space has a constant curvature. Observers were positioned at the barycentre of an equilateral triangle so that they effectively formed one vertex of the triangle. The observer was required to use a radio transmitter to point an arrow (stationed at another vertex of the triangle) at a target that formed the final vertex of the triangle. The edge lengths of the triangle were varied. Interestingly, these authors comment that the study that perhaps best approximated what they were attempting to measure was the study by Ellis et al. (1991). Koenderink et al. (2000) showed that curvature of visual space changes from elliptic in near space to hyperbolic in far space. These results do not support Luneburg's assertion that visual space has to be one of the classical spaces of constant curvature; rather they support the comments of Indow (1991) that the curvature of visual space is not constant.

Conclusions

Hecht et al. (1999) commented that the research on subjective visual space in the last 100 years is best understood as a vast set of data that varies dramatically as a function of the experimental methodology employed. However, most of the data gathered does point to a non-Euclidean structure for visual space. In addition, more

recent data also suggests that visual space is not uniformly distorted and that traditional metrics of visual space may not be applicable in full cue environments.

The results of this body of work that are of particular interest when examining azimuth estimation errors in CDTI displays are those that examine visual space from an exocentric perspective. That is, those that examine perceptions of the relationship between objects in an environment. Several of the studies described above address this issue. One of the most consistent findings across these studies is a substantial compression of depth (in particular see, Wagner, 1985; Loomis et al., 1992,1996; and Hecht et al., 1999). These findings are particularly relevant as misperceptions of depth or distance can also affect judgements of angles and slants (as shown in Wagner, 1985 and Hecht et al., 1999).

The finding of systematic error in depth perception is also of interest because depth is often misperceived in rendered scenes as well, perhaps indicating that a common error exists in both realms (Hecht et al., 1999). Schoumans and Denier van der Gon (1999) comment that existing theories of real world visual space perception often assume that the difference between visual space and physical space exists because of a systematic misperception of the distance between the subject and any point in space as a function of that distance (in other words a distance misperception). However, distance misperception theories have not often been systematically applied when examining errors in perspective renderings. The following section will outline studies of pictorial perception, comparing theories and models of pictorial and real world perception and considering how they may be applied to the perceptual distortions identified in CDTI displays.

Visual Space Perception in Pictorial Images

Unlike real world space, no general metric of pictorial space has yet been attempted despite a growing body of work examining picture perception. It is possible that this is because any model of picture perception is complicated by the fact that it would have to account for the projective distortions that occur when pictures are viewed from a position other than the station point[2], as they most often are. In fact, Hecht et al. (1999) has noted that one of the most striking features of pictorial space is its robustness

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[2] An outline of typical distortions of pictorial space when an image is viewed at a position other than the station point is provided in Chapter Two.

despite the dramatic projective distortions that often occur due to viewing position. Understanding how the visual system extracts information from pictures despite these distortions has been the focus of a large number of studies.

Broadly, there are two possible approaches to examining picture perception. The first is to examine perception when the viewer is placed at the correct viewing point for the pictorial array thus eliminating projective distortions. The second is to examine perception when the viewer is placed at an incorrect viewing point for the array (resulting in distortions of the represented space). Both perspectives are of interest when considering azimuth estimation errors in CDTIs, as it is likely (based on current display designs) that pilots will use these displays from the incorrect station point. Current research provides some indication of the potential issues resulting from this and also provides some insights into the possible efficacy of introducing a system whereby pilots must view the display from the correct station point.

Studies of the Perception of Pictorial Space from the Correct Viewpoint

Rogers (1995) commented that the goal of research on picture perception has, to some extent, been to assess the degree to which pictures succeed in representing reality. She states that under ideal circumstances pictures could capture information for the layout of objects and surfaces in the scene such that an observer's judgements about the depicted scene match those made when the real thing is presented. She further points out that veridicality would mean the ability to match perceptions of spatial layout in pictures and perceptions of spatial layout in real scenes, taking into account that depth and distance in real scenes is systematically underestimated.

Research shows however, that even when observers are placed at the geometrically correct station point pictorial depth is often underestimated relative to perceived real world depth (Yonas & Hagen, 1973; Hagen, Jones, & Reed, 1978; Wilcox & Teghtsoonian, 1971). Hagen et al. (1978) measured the perceived distance between objects standing on a chequered ground. They found that depicted distances of between 10–50 inches were underestimated by an average of 50%. In another study, Kraft, Patterson, and Mitchell (1986) also reported systematic distortions in depth judgements made when viewing photographs of natural scenes. Typically, sagittal depth was foreshortened whereas lateral width was not. This effect was greater for narrow-angle lenses and smaller with wide-angle lenses. In another study, Drosler and Konstanty (1987, cited in Hecht et al., 1999) investigated the geometry of pictorial

monocular space. They used pictures of natural backgrounds and superimposed point lights and lines on them. Observers had to answer questions about geometric relations between the lights with respect to the frontoparallel plane. The authors concluded that monocular visual space is characterised by non-metric projections.

Rogers (1995) states that the additional compression of pictorial depth may be attributable to the conflict between the visual information that specifies a picture's surface and the pictorial information that specifies its 3D layout. Surface texture, binocular and monocular parallax, and other cues all specify the picture surface as flat. However, monocular distance cues of size, linear perspective, and texture perspective all specify a surface layout extended in depth (Hagen et al., 1978). Other researchers have also suggested that the truncation of the visual field may be a cause of compression of pictorial depth (Hagen et al., 1978). However, findings on this issue have been mixed. Rogers (1995) commented that a peephole can also be used to obscure the frame of an object and that the loss of the visible frame and discontinuous surrounding surfaces reduces information for the picture as a flat object which should increase its perceived depth. However, she further commented that the loss of foreground results in a truncation of the visual field (see below). This truncation may serve to diminish perceived depth.

Several studies have found that pictures provide a stronger impression of 3D space when they are viewed monocularly or through a peephole (thereby eliminating some of the cues that specify the picture surface). For example, Koenderink, van Doorn, and Kappers (1995) examined participants' ability to adjust a gauge figure so that it appeared to be painted on the surface of a photographed 3D sculpture. Comparisons were made between monocular and binocular and synoptical viewing (eyes optically superimposed). Results showed that relief was deepest for binocular vision, flatter for monocular vision, and flatter still for synoptical vision. Rogers (1995) comments that this study provides a good indication of the impact of stereo cues on perceived pictorial depth.

Schlosberg (1941, cited in Rogers, 1995) also found that presenting a photograph through a peephole produced a very strong illusion of a real 3D scene. In addition, Smith and Smith (1961) found that the perception of depth resulted in an accurate perception of spatial layout in that participants were able to accurately toss a ball at a target in a room viewed through a peephole (cited in Rogers, 1995). However,

Adams (1972, cited in Rogers, 1995) was unable to find a significant difference between peephole viewing and unrestricted binocular viewing. Because of the mixed results in this area researchers have also examined the impact of truncation of the visual field.

Hagen et al. (1978) conducted an often-cited study on this issue. They noted that truncation of the visual field; particularly the foreground, is an important characteristic of pictures that differentiates them from real world scenes. In their study, participants were required to scale five isosceles triangles at five different distances under four different viewing conditions. The conditions were, unobstructed static monocular view, peephole view, view through a rectangular frame, and view of all the stimuli photographed in a slide. The results of this study showed that truncation of the visual field, both in pictures and peepholes of the real world, caused a frontal shift in the localization of the visible field with a resultant compression of perceived size and distance.

One of the key findings of the studies quoted above in terms of CDTI design is that substantial distortion in the perception of images does occur even when they are viewed from the correct station point and are therefore presented to the eye in an undistorted fashion. Perception of depth in images seems to be particularly affected. Several studies appear to have provided some explanations for these effects, including the idea that it results from competition between visual cues that specify the picture surface and cues that specify the picture depth, and truncation of the visual field in pictures. However to date, no definitive explanation has been provided.

Studies of the Perception of Pictorial Space from an Incorrect Viewpoint

As described in Chapter Two, if an image is viewed from the centre of projection (station point) there will be a geometric match between the optic array projected from the picture and that projected from the original scene. The picture will accurately present the same array of visual angles to the observer that the original scene would have. However, when viewing an image under ordinary conditions viewers almost never position themselves at the station point. Therefore, the projective distortions discussed in Chapter Two are introduced (magnification/minification and shear). Despite these distortions, viewers rarely complain that objects in a picture appear distorted or inaccurate. As a result, questions have been raised about the robustness of this perceived space and whether the distortions impact on perception

(even though the viewer may not be aware of them). Rogers (1995) provides an excellent framework for considering studies that attempt to answer these questions. She states that there are four (not necessarily exclusive) possible explanations for the absence of perceived distortions.

1. Relying on intuition the viewer somehow corrects (or compensates for) the distortions produced by ordinary picture viewing.

2. Some pictorial information for layout is unaffected by ordinary viewing (remains invariant).

3. Distortions are minimal so are not noticed and do not matter.

4. Distortions in virtual space are perceived and do affect judgements about layout.

The first three of these explanations assume that visual distortions are not perceived despite the geometric distortions present in the visual array, the final explanation assumes that distortions are perceived and can be measured experimentally. The research available on pictorial perception when the viewer is not placed at the station point of the image will be discussed within the context of these explanations.

Viewer Compensation

Kubovy (1986) cited in Rogers (1995) stated that viewers are unaware of visual space distortions because the visual system registers both the nature of the visual space and the orientation of the surface of the picture and corrects the visual space with reference to the picture surface. This theory is termed a compensation theory. It is a perspective that has been adopted by several researchers in the field of picture perception. Farber and Rosinski (1978) also presented a similar viewpoint. They stated that determining whether compensation is necessary requires the observer to make certain assumptions about the nature of the environment or the nature of the picture. They speculate that some possible bases for these assumptions might be that objects in the pictorial array may be assumed to be symmetrical or rectangular. They also contend that a second assumption might be the assumed location of the correct viewing point relative to the picture itself. They state that some research suggests that the observer assumes that the correct viewing point is along a line normal to the centre of the picture and compensates for the dislocation of the actual viewing point from this ideal. Ellis and colleagues (1986, 1989) adopted a variation of this idea when they argued that the one of the causes of the errors in azimuth estimation in pictorial displays was that the viewer either failed to compensate or compensated incorrectly for their viewing position.

Compensation theorists all point to the role of the picture frame and surface to restore the correct view when a picture is looked at from the wrong position. However, they also posit that there may be information available in the picture itself that assists viewers in compensating. Therefore, it is important to establish whether there is information available in the picture that would enable compensation to occur. The work presented below on pictorial invariants provides some important answers to these questions.

Pictorial Invariants

If viewers are to compensate in some way for pictorial distortions as described above, it is necessary that some aspects of the picture remain invariant in order to support this behaviour. Rogers (1995) comments that there are a surprising abundance of pictorial structures that actually remain invariant under a variety of ordinary picture viewing conditions; one example she cites is that of structures available in the picture based on the horizon. Sedgwick (1980) showed that the observer can use this invariant to calculate the relative sizes of objects in a scene. The horizon ratio is: total size of the object divided by the distance from the bottom of the object to the horizon. This calculation tells the observer how much taller or smaller the object is than his eye-height (e.g. an object that has half its size above the horizon, is twice as large as the observer's eye-height. Lumsden (1980) also examined invariants in pictures and found that under magnification and minification produced by viewing the picture from the wrong station point, all angular relationships are uniformly transformed. Therefore, all angular relationships are invariant, as are relative sizes, shapes, slants, and distances.

Several researchers have tested whether observers use pictorial invariants when looking at pictures. Rogers and Costall (1983) tested Sedgwick's hypotheses to establish whether viewers used pictorial invariants. They demonstrated that horizon information could be effective in picture perception. It seems therefore, that it is possible that the visual system can compensate for geometric distortions in some way by using the frame, picture surface, and pictorial invariants to adjust for distortions. However, a few researchers have argued that the compensation hypothesis is unnecessary as geometric distortions in pictures viewed from the wrong station point are too small to be relevant to normal viewing.

Distortions may be too Small to Affect Perception

A few researchers, J.J. Gibson in particular, have contended that the distortions created by ordinary pictorial viewing are insufficient to cause major perceptual disruptions. Gibson (1979) commented that distortions themselves are not all that serious (cited in Rogers, 1995). Other researchers have also supported the viewpoint presented by Gibson. Cutting (1987) conducted several experiments to examine whether observers experienced distortions in moving objects projected at a slant. His data supported the view that local distortions in moderately slanted moving objects are sufficiently small as to be unregistered by the visual system. He further states that film and cinema (moving objects) can be viewed from a position other than the composition point because the optics of parallel projection of objects are sufficiently robust against moderate screen slants seen from moderate distances. In addition, he considered that the human visual system is inexact in its local measurements and therefore tolerates small distortions.

The three theories presented above assume that despite geometric distortions present in the optic array, viewers of pictures do not perceive any distortions. However, the research presented below seems to indicate that pictorial perception is affected by distortions under some circumstances.

Perception is Affected by Distortions

In contrast to the ideas presented above which suggest that the viewer is not affected by pictorial distortions, either because they compensate for them in some way or because the distortions are too small to affect perception, the following body of research tends to indicate that picture perception is affected by pictorial distortions. Farber and Rosinski (1978) commented that there is evidence that under some conditions, dislocation of the viewing point can affect space perception in some way consistent with the distortions of virtual space that result. In more recent years a sizeable body of evidence (outlined below) has been gathered which suggests that perceived depth (in particular) varies systematically with perpendicular displacement of viewing position such that perceived depth is compressed by magnification and stretched by minification.

Magnification and Minification Distortions

Magnification and minification have been produced in studies by varying either viewing distance relative to the station point or the type of lens used[3]. Most of these studies support the hypothesis that geometry, at least to some extent, determines depth perception. Smith and Gruber (1958) cited in Rogers (1995) found that the transformed virtual space was closely related to perceived depth. Participants viewed a corridor and a photograph of a corridor through a peephole. The photograph was positioned so that the degree of magnification/minification was varied. The participants were required to estimate distances in the photographed corridor as proportions of the same distances in the real corridor. They found a match to within 6% of predictions based on geometric transformations through magnification/minification. However not all studies have successfully obtained results such as this. Some studies have found that magnification can be more precisely predicted than minification (e.g. Smith, 1958b, cited in Rogers, 1995).

A few studies have examined distance perception using photographic lenses including Kraft et al. (1986) and Kraft and Green (1989). In both of these studies participants were required to estimate apparent distances to specified target objects in a photographic scene presented on a slide. Results showed that the shorter the focal length of the camera lens, the greater the perceived distance. However, perceived distance between objects along the lateral plane was unaffected by changes in lens focal length. In this context also, perceived depth compression has been found to be less than would be predicted by geometry. Lumsden (1983) also used photographic lenses to examine distance perception under two levels of magnification and two levels of photographic truncation. This design separated out the effects of magnification from the effects of truncation (which usually results when magnification is optically produced). Participants were required to make judgements of the radial distance between two posts presented in the photographic slides. Results showed a significant main effect of magnification. However, the reduced radial distance reported by participants was less than predicted mathematically. He also reported that the underestimation of radial distance between the distant posts was so great, even in normally truncated slides, that little more compression of space could occur due to magnification or further truncation.

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[3] For an explanation of this type of distortion see Chapter Two.

Some authors have contended that this failure to find congruence between expected and predicted results indicates some degree of compensation, however, Rogers (1995) feels that this explanation is premature. She states that one factor that may contribute to the flattening of pictorial depth is that many of these studies used relatively unrestricted viewing conditions that may have allowed information about the flatness of the picture itself to interfere with the pictorial information of the 3D scene.

Affine Shear Distortions

Rogers (1995) also commented that there are some remarkable visible distortions in pictorial space that are produced by lateral displacement. She notes the often commented upon effect of depicted objects appearing to follow the viewer as they walk past a picture. One of the most common examples of this was the recruiting poster of Uncle Sam. She further notes that most of the early work on perception of slanted pictures aimed to prove that a compensation mechanism existed by showing that distortions of shape and slant were either absent or minimal. However, more recent research has shown strong effects of vertical displacement on perceived slant and some studies have found distortions in objects and slanted surfaces in line with geometric predictions (Ellis et al., 1989). However, perceived distortion is generally less than predicted and there is some evidence that relative spatial position of objects is preserved even in pictures showing marked deformation when viewed from the side. Rogers (1995) comments that these results seem to imply that information for picture orientation comes from the frame.

Two sets of studies by Goldstein indicate that the orientation of depicted objects is systematically distorted when pictures are viewed from the side. Goldstein (1979) found that rods appeared to rotate by differing amounts as viewing angle changed. Those that were pointing directly out of the picture appeared to rotate the most, while rods parallel to the picture plane appeared to rotate least (Goldstein calls this differential rotation). In this study he also found that even virtually depthless objects appear to rotate a little with viewing angle (e.g. flat disks or arrows). Ellis et al. (1991) also found similar differential rotation effects. Cutting (1988) applied an affine geometry model (based on La Gournerie's 1850 analyses) to Goldstein's (1987) experimental stimuli in an attempt to explain the observed effects. The analysis used a model based on affine geometry to transform pictorial space behind the picture by shears, compressions, and dilations according the viewpoint of the observer in relation to the

station point. He found that this model accounted for Goldstein's differential rotation effect.

In contradiction to the above studies, however, Perkins (1973, cited in Rogers, 1995) found considerable tolerance for shape distortions when viewing from the side. Participants classified drawings as rectangular or not (when viewing at 26-deg and 42-deg) and appeared to judge the drawing as if they were seeing it from the front.

Conclusions

The available data on picture perception presents an array of conflicting results and theories. To date little consensus has been reached and, as mentioned at the beginning of this section, no model of picture perception has yet been attempted. However, across all the studies reviewed a common finding has been that visual perception of pictures is not veridical, particularly in terms of the depth dimension. Picture perception is not accurate even when viewers are positioned at the correct station point. However, it is generally not distorted to the degree that would be predicted optically when viewers are positioned away from a picture's station point. These results seem to suggest a complex interaction of visual processes. Perhaps while observers may be able to compensate for geometric distortions to some degree under some circumstances, the compensation that they make is imperfect.

Comparisons Between Real World and Pictorial Perception

The research outlined in the current chapter on both physical and pictorial space seems to indicate that some of the observed effects are common to both paradigms; the most obvious being the compression of perceived depth. However, few studies have attempted to compare perception across both paradigms using a common methodology. The studies that have compared results across the two fields have tended to examine flattening and compression effects. One often cited study was conducted by Ellis et al. (1989) and is described in detail in Chapter Two. As mentioned previously, this study compared performance in a direction judgement task between a computer-based simulation and a real world situation. Results from the computer display portion of the experiment showed a judgement bias resembling a spatial compression in depth. Ellis et al. (1991) note that the errors observed in their experiment can be modelled by a generalisation of classic slant overestimation in which the viewer is assumed to overestimate both the pitch and yaw of the viewing direction. However, these authors note that in the physical space portion of this experiment the judgement bias observed in

the display portion of the experiment was markedly reduced. It appeared that participants were better able to estimate exocentric direction in a real world environment.

Hecht et al. (1999) also compared real world objects with photographic depictions of the same objects. The study aimed to investigate to what extent distortions are introduced in the photographic medium. Observers were required to judge how obtuse or pointed the angle on the corner of a building looked to them. The angle was actually 90 deg. Across all conditions a robust effect of viewing distance was found. Observers reported that building corners appeared flatter as distance increased. Moreover, depictions of corners produced very similar results to real world scenes. The authors stated that the flattening of corners couldn't be explained by a linear distortion of the entire visual space. They suggest that for natural scenes, compression of space is local and very moderate.

The two studies described above provide some evidence that the perceptual effects observed in real world experiments do relate in some way to the effects observed in pictorial experiments. Therefore, it seems that some of the models developed in the real world paradigm may be able to contribute in some way to explaining the effects observed in the pictorial realm. However, the studies described in the above sections do clearly indicate that the act of pictorial perception is fundamentally different from real world perception in that the sources of information available to the viewer are constrained. It seems likely therefore, that while the errors made in the two realms may be similar, viewers may make more frequent and larger perceptual errors when viewing pictorial images.

Summary and Conclusions

In response to concerns about the efficiency and safety of the current air traffic management system a new structure for regulating air traffic named 'free flight' has been proposed. Under the free flight system aircraft would be able to choose any flight path that allowed them to reach their destination with maximum efficiency. Pilots would be required to inform air traffic controllers of their flight plan but they will be free to make changes to the plan without prior permission from a controller. As a result, pilots would become responsible for conflict avoidance and controllers would only intervene if conflict detection software predicted a potential conflict.

While there are currently tools available for conflict avoidance and resolution they would not provide sufficient information to be useful in a free flight situation. Therefore, most major ATC and airways organisations are currently conducting research on how free flight could best be implemented. One of the main areas of interest is the design of CDTI displays because these displays would provide pilots with information to assist with decisions about conflict detection and avoidance. One of the most prominent debates in this area has been whether CDTIs should be presented as planar or perspective displays. While many researchers feel that perspective displays are intuitively preferable, perceptual errors in locating aircraft in perspective displays have raised questions about their efficacy. However, Naikar (1998) commented that several studies have demonstrated performance advantages associated with perspective displays and that these results provide an incentive for continuing research in this area. She further states that particular effort should be directed towards understanding and characterising the distorting effects of representing perspective information on a 2D surface.

Chapter Two of this thesis outlined a range of research on the use of perspective displays with experimental tasks that were fundamentally similar to air traffic conflict detection tasks (e.g. McGreevy & Ellis, 1986; Barfield et al., 1990; Barfield & Rosenberg, 1995). Azimuth and elevation estimation errors were consistently observed in these studies. It was also found that geometric parameters (such as GFOV and the position of the viewer relative to the station point) affected the degree to which errors occurred. While Barfield and colleagues demonstrated that elevation estimation errors could be reduced with display enhancements (such as rotation and stereoscopic

presentation) no enhancements or set of display parameters has yet been found to reduce azimuth estimation errors.

The main theory put forward to explain inter-object azimuth estimation errors is a model developed by Ellis et al. (1989). These authors hypothesised that competing picture surface and pictorial depth cues cause observers to make errors in the estimation of their viewing orientation and that further errors are caused by the observer not being positioned at the correct station point for viewing the image. This explanation takes a view somewhat similar to compensation theorists who speculate that the viewer is able to use cues in the picture to extract accurate perspective information even when the image is distorted geometrically. The theory developed by Ellis et al. suggests that viewers attempt to make this compensation but do it incorrectly. However, Ellis and colleagues have failed to produce specific guidelines to assist in designing perspective displays as they did not translate their findings into a model that could be applied when designing CDTIs.

There are possible alternative explanations for azimuth estimation errors. One plausible explanation is that viewers make depth perception errors (misperceive the distance between themselves and objects in the display) resulting in distortions in the perceived angular relationships between objects. This explanation seems possible given that compression of depth has been observed across a broad range of experiments in both real world and pictorial paradigms (see Chapter Three of this thesis). In addition, several of these studies have found angular estimation errors similar to those observed by Ellis et al. (Loomis, 1992, 1996; Wagner, 1985; and Hecht et al., 1999 in particular). This would appear to imply that the general effect is not specific to studies conducted in virtual environments.

Therefore, the purpose of this research is two-fold. Firstly, it aims to contribute to the development of perspective display technology by developing a model of distance perception in perspective displays that can be used to examine azimuth estimation errors. Secondly, it aims to explore the issues related to visual space perception in general, and image/picture perception in particular. It is hypothesised that the azimuth estimation errors observed by Ellis and colleagues were caused by distance estimation errors. It is further hypothesised that distance estimation errors could also result in inter-object distance estimation errors. Therefore, the following experiments aimed to explore these hypotheses by measuring inter-object distance estimation in perspective

images. The results of the experiments were then used to develop a model of distance perception in perspective images that could tested against the azimuth estimation errors found by Ellis and colleagues. Geometric parameters (such as GFOV) and display enhancements were also tested to examine their effect on inter-object distance estimation. Four experiments were completed. Experiment 1 examined inter-object distance estimation in a reduced cue environment and the subsequent three experiments presented the same environment with various enhancements (ground planes, apertures, and stereographic presentation).

Experiment One

One of the main objectives of this thesis was to develop a model of distance perception in perspective displays that could be used to assess whether distance perception errors might be related to the azimuth estimation errors observed by Ellis and colleagues. As the literature review has shown, azimuth estimation errors (such as those made by participants in the experiments carried out by McGreevy and Ellis, 1986; and Ellis et al., 1989) could be caused by a range of factors. Ellis and colleagues theorised that the errors they observed were caused by competing picture surface and pictorial cues which could result in observers making errors in estimating their viewing orientation relative to the image surface. They theorised that this error was further compounded if the observer was positioned at an incorrect station point. While this theory does explain their results relatively well, Ellis and colleagues did not go on to build a model that predicted observer error. Therefore, their theories do not provide display designers with a basis for developing CDTI displays as they do not assist them in predicting potential visual perception issues.

Another, perhaps more parsimonious, explanation for the errors observed by Ellis et al. is that their observers made distance estimation errors, misperceiving the distance between themselves and objects in the display (which would, in turn, affect any angular estimations). While they did consider the potential effects of distance estimation errors on their experimental data they did not explicitly incorporate these ideas into their theories (Ellis et al., 1991). However, several studies (both real world and pictorial) have shown that human visual space differs significantly from Euclidean space, particularly in terms of perceived depth (Helmholtz, 1867; Todd et al., 2001; Hagen et al., 1978; Wagner, 1985; Toye, 1986; Lumsden, 1983).

Wagner (1985) found that in his real world experiment visual space was compressed by as much as 50%, so that two objects in depth would need to be set twice as far apart as two objects on the frontoparallel plane in order to appear to be the same distance apart. Loomis et al. (1992,1996) found that when participants were required to set two points in depth so that the distance between them matched two points on the frontoparallel plane they overset the points in depth by 50-90%. In this study participants also made notable errors in estimating the distance between themselves and

objects in the world. In addition, both of these researchers also found that participants made inter-object angular estimation errors similar to those observed by Ellis and colleagues despite the full cue environment and absence of any confounding 2D cues. However, it is worth noting that neither of these researchers cite Ellis in their papers and do not appear to have connected their own work to his findings.

Based on the findings of these studies it seems appropriate to examine the theory that errors in distance estimation may have contributed to the azimuth estimation errors observed by McGreevy and Ellis (1986). However, it is currently difficult to examine this hypothesis as no definitive explanation of distance estimation has been developed for either real world or pictorial environments. In order to examine the possibility that errors in distance estimation may have caused azimuth estimation errors a greater understanding of distance estimation in pictures is required. Therefore, the following experiment sought to examine inter-object distance perception in perspective images. Inter-object distance perception was of particular interest because it is possible to use inter-object distance estimates to establish the perceived distance between the observers and objects in the environment.

Within this experiment a new methodology was employed by which participants were not required to make explicit distance estimations, but rather they were required to set an image of a 3D box so that it appeared to them to be a perfect cube. They adjusted the length by moving the rear face of the box (see Figure 10). Participants were in effect required to make a depth estimate scaled relative to the frontoparallel dimension of the box.

It was hypothesised that participants would make increasingly large errors in setting the 3D box to a cube as the virtual distance between the cube and the observer increased. It was believed that this would occur because observers would fail to account for the decrease in the rate of visual angle change that occurs as distance increases.
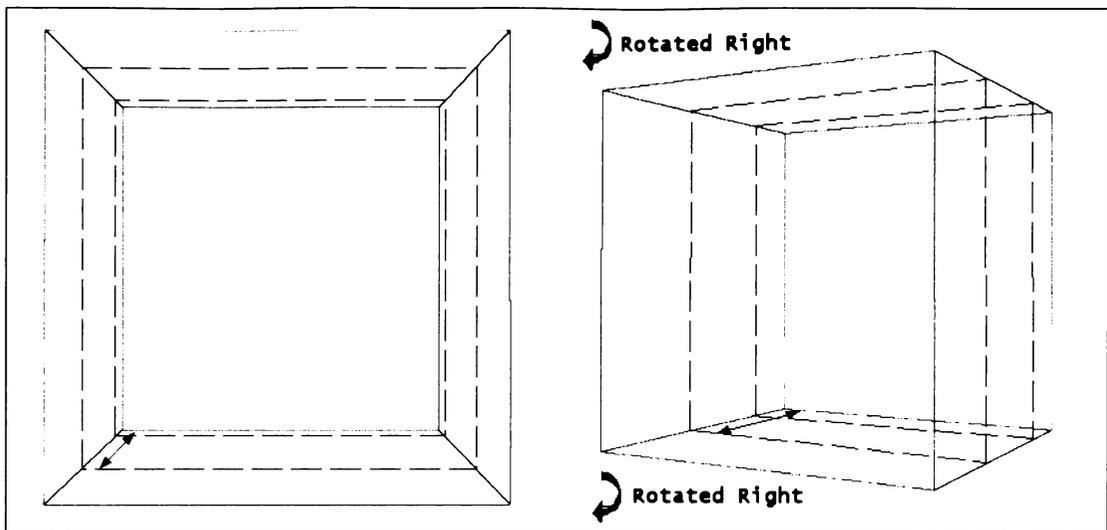
Figure 10. Three-dimensional box viewed from the front (participants' view) and then rotated to the right for clarity. The dashed lines and arrows show how the shape of the box changed as participants moved the rear face (z-axis) during the experiment.

Figure 11 provides an example of visual angle change with distance. The figure illustrates the visual angle difference between the front face and back face of two boxes set at varying distances from the observer. When the front face of Box A is positioned one metre from the observer the back face of Box A is 1.5 metres from the observer. The y-axis shows that the visual angle subtended by the front face of Box A at the observers eye is 28 degrees and the visual angle subtended the rear face of Box A is 19 degrees. By comparison, the front face of Box B is placed 5 metres from the observer (the back face is therefore 5.5 metres from the observer). In this case, the visual angle subtended by the front face of Box B is 5.5 degrees. However, the visual angle of the rear face of Box B is 5.2 degrees. It is clear from this comparison that the relative visual angles taken up by each face of the box change dramatically as the distance between the box and the observer is increased. Therefore, as the distance of the box increased observers would be required to set the front and rear faces of the box closer together (in a 2D sense) to replicate a true cube in 3D space. It was of interest to examine whether participants would be able to set the rear face of the box as a function of distance (i.e. whether they were able to take into account the highly non-linear relationship between visual angle and distance). As will be shown below, the observer's visual angle settings can be used to estimate the perceived distance of the box.
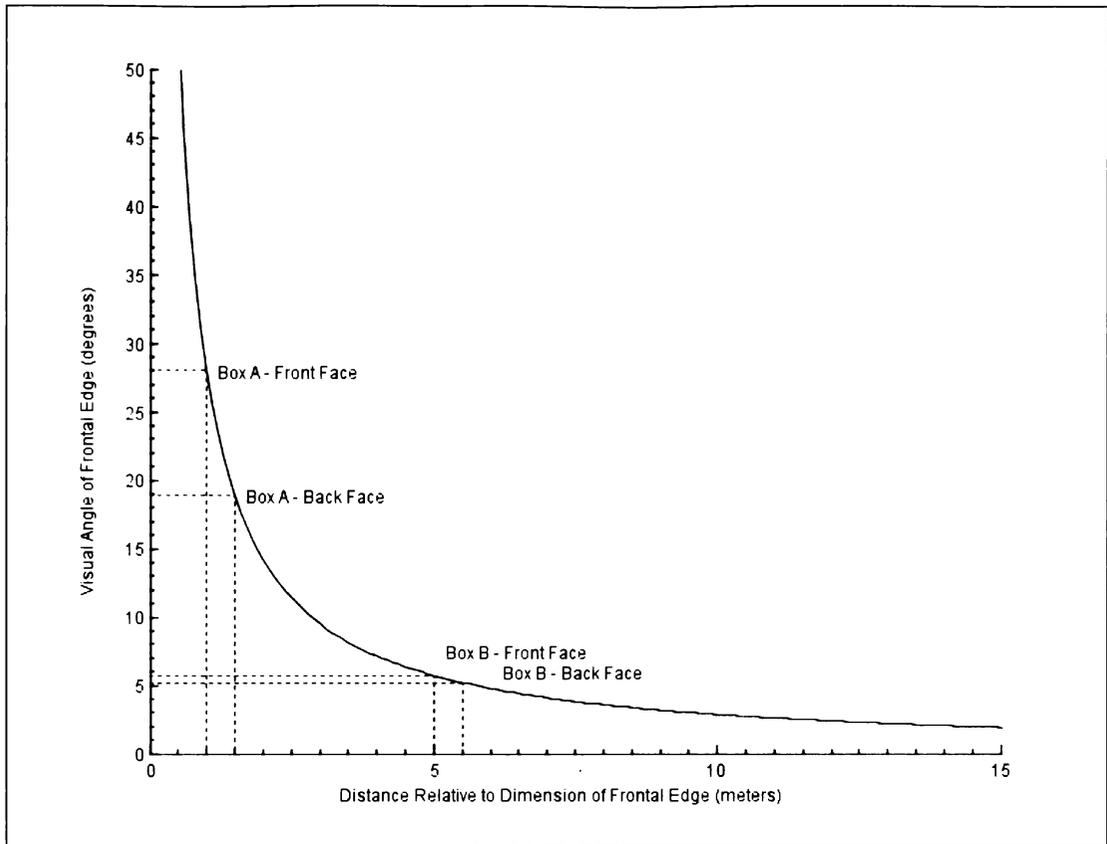
Figure 11. Projected visual angle as a function of distance of observation for two hypothetical boxes with a size of 0.5 metres.

The impact of GFOV on inter-object distance perception was also of interest because the findings of Smith and Gruber (1958) suggested that field of view could have a substantial impact on distance perception and may therefore affect inter-object distance perception.

Methodology

Participants

Four male and eight female students from first year psychology courses at the University of Waikato volunteered to take part in this experiment in return for course credit. Participants ranged in age from 18-56 years. All participants had normal or corrected to normal visual acuity. University of Waikato Psychology department ethical procedures were followed during the recruitment and running of this experiment.

Apparatus

During the experiment participants were seated at a table in front of a display monitor. The experimental room had no windows and was darkened to prevent screen glare. Experimental stimulus presented on a computer with a 19-inch screen. Screen brightness was set to 11% (to prevent 'ghosting' around the box outline). The monitor had a spatial resolution of 1280x1024 pixels. The stimulus was manipulated by the participants using mouse commands.

The stimulus was viewed binocularly. Participants' heads were positioned so that their eyes were horizontally and vertically aligned with the centre of the computer screen. A headrest was used to ensure that that their head remained in the correct position during the experiment A picture of the apparatus is provided in Figure 12 (below).

Stimuli

The stimulus presented for this experiment consisted of a three dimensional box (see Figure 12). The front face of the box measured 0.5 x 0.5 metres in virtual space. When the box appeared on the screen the rear face was set at random distances between the values of 0.031m and 3.78m (so that it was not always a cube) and participants were then required to adjust it until it looked like a cube.
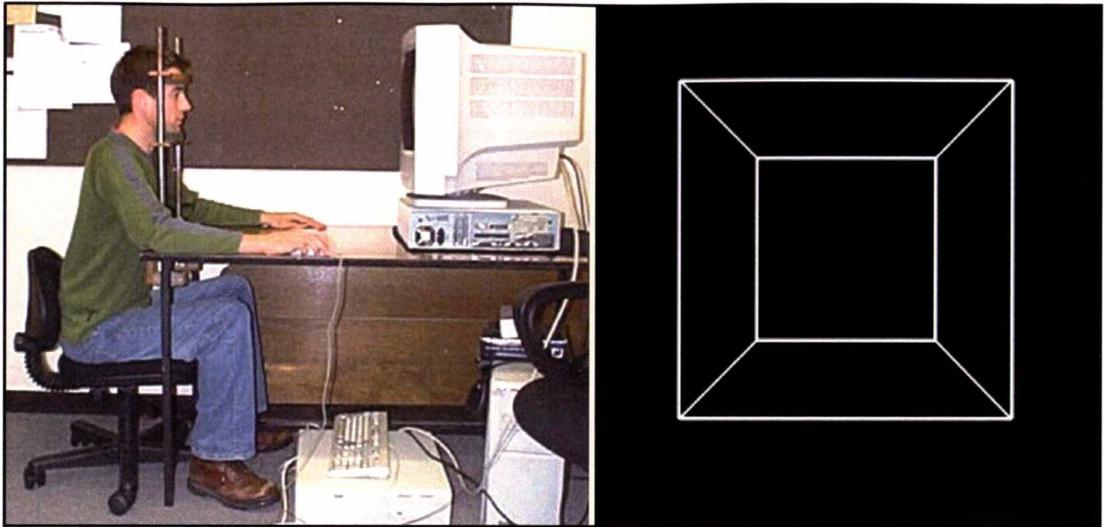
Figure 12. Experimental apparatus (left) and stimuli (right).

Experimental Design and Procedure

Design

A within-subjects repeated-measures design was used in this experiment. The experimental hypotheses were tested by systematically varying the geometry of the virtual world and the stimulus (box). The virtual world was manipulated by altering the GFOV and the stimulus was altered by placing it at varying distances from the observer within the virtual world. Each of the 12 participants viewed 112 images (four GFOV conditions crossed with seven distance conditions). Each GFOV by distance combination was repeated four times.

The four GFOV conditions were 30, 40, 60, and 80 degrees. The 30 deg GFOV condition presented a relatively narrow view of the virtual world, whereas the 80 deg GFOV condition gave a much wider view of the virtual world (see Figure 13). The vertical and horizontal GFOVs were kept the same so that the resulting image was square. Because the size of the display screen was constrained, the station points were positioned at 0.75m for the 30 deg GFOV, 0.55m for the 40 deg GFOV, 0.35m for the

60 deg GFOV, and 0.24m for the 80 deg GFOV in order to attain the appropriate eye FOV[4].
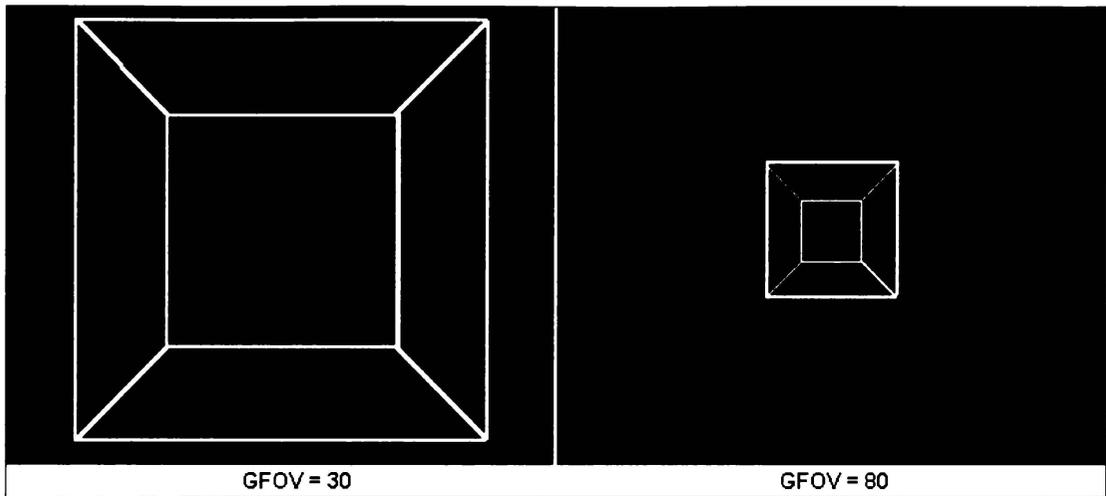
Figure 13. 3D Boxes shown at 30 and 80 Degree GFOVs from a distance of 1.25m[5].

The distances presented within each GFOV condition are shown in Table 1 (distance is the total distance from the observer to the screen). Distances between one and five virtual metres were chosen for each GFOV (the possible distance settings were dictated by the size of the viewport).

Table 1.

Distance settings presented for each field of view condition.

GFOV	Distance One (m)	Distance Two (m)	Distance Three (m)	Distance Four (m)	Distance Five (m)	Distance Six (m)	Distance Seven (m)
30	1.25	1.5	1.75	2.0	3.0	4.0	5.0
40	0.9	1.0	1.25	1.5	1.75	2.0	3.0
60	0.7	0.8	0.9	1.0	1.25	1.5	2.0
80	0.5	0.6	0.7	0.8	0.9	1.0	1.5

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[4] It should be noted that, due to an error in calculating screen width in this experiment, participants were positioned between 3-8 cm away from the correct station point. However, analysis of this and following experiments indicated that the error did not impact on participant behaviour.

[5] The boxes depicted in Figure 13 are 0.5 x 0.5 x 0.5 metres square.

Participants were presented with the stimuli grouped by GFOV. The presentation order of the GFOV conditions was pseudo-randomised to avoid order effects. In addition, the distance conditions presented within each GFOV condition were also pseudo-randomised.

Procedure

Participants were first given a full explanation of the experiment. They were told that the experiment was intended to test their perception of 3D virtual environments and that the box stimulus was an example of an object in a 3D environment. Participants were instructed that they should adjust the rear face of the 'box' until they considered that it looked like a perfect 3D cube. They were instructed that they could spend as long as they needed to adjust the box and that, when they were satisfied with their judgement, they should press the left mouse button (at which point the computer would record their response). They were further advised to go with their impression regarding where the box should be set rather than trying to use some sort of measuring strategy. Participants were then permitted to practice until they felt comfortable with the task. For most participants, four practice trials were sufficient for them to feel comfortable with the procedure. At this stage the experimenter questioned the participant to ensure that the task was fully understood, demographic information was gathered, and the participants near and far eyesight was checked using a Keystone View VSII vision screener.

As stated previously, participants received each set of images grouped by GFOV. Between each GFOV condition (approximately every 30 stimuli) the computer screen went blank. The experimenter then turned on the room light and moved the screen to the correct station point for the next GFOV condition. During this time participants were encouraged to take a break from the task if they felt they needed to. Most participants completed the experiment in approximately 25 minutes.

Results

Analyses were conducted on the errors made by participants as they attempted to set the box stimulus to a true cube. Because the front face of the box was 0.5m square, error was equal to the box length set by participants minus 0.5m. Setting the rear face of the box to greater than 0.5m resulted in a positive error score and setting it at less than 0.5m resulted in a negative error score. Participants received four trials for each condition (distance x GFOV). The results of these trials were averaged in order to arrive at an error score for each participant for each condition. The aim of this analysis was to establish whether participant error increased as virtual distance increased and to assess the effect of GFOV on error.

Analysis of the Impact of Distance on Error

In order to evaluate the hypothesis that error in setting the box to a cube would increase as the virtual distance between the box and the observer increased, participant error at various distances within each GFOV condition was examined. Figure 14 illustrates all participants mean errors for each distance presented. Data for each GFOV is presented on separate panels in the figure.

The majority of the error scores illustrated in Figure 14 were positive numbers. This indicated that participants generally set the rear face of the box further away from the front face than was required to form a true cube. Appendix A contains the mean error scores and standard deviations for each condition. The data in the graphs and in the appendix showed that mean error consistently increased with distance.

Polynomial curve fitting to the error data showed a linear fit to be significant ($p < .05$). Therefore a linear regression analysis was conducted to further evaluate the prediction of an increase in error related to increases in the distance between the box and the participant. The regression statistics are presented in Table 2 and an illustration of the fitted line resulting from the regression is shown in Figure 14
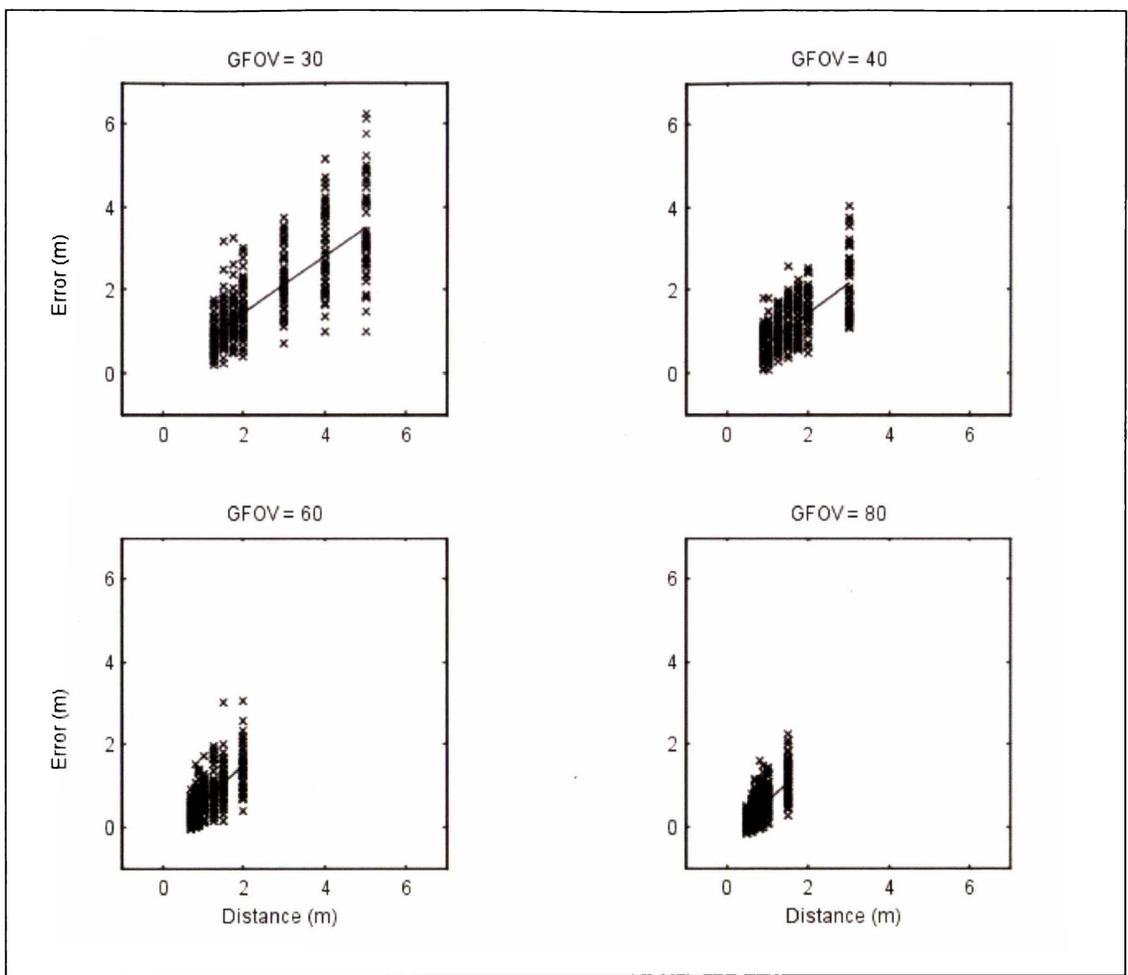
Figure 14. Errors made by participants setting the rear face of the box by GFOV and a regression line fitted to the data for each GFOV.

As mentioned previously, an error score of zero would indicate that the participants set the box to a true cube at all distances. Thus, a perfect score would result in a fitted line of y = 0. Because the confidence intervals for the slope of the regression lines (shown in Table 2) do not include zero it can be concluded that the slopes were significantly different from zero for all GFOV conditions. In other words, participant error increased with distance.

Table 2.

Slope and intercept of lines fitted using linear regression.

Condition	Slope	95% CI	Intercept	95% CI	R²	F	p
GFOV 30	0.686	0.62 – 0.749	0.063	-0.122 - 0.249	.58	462.102	<.01
GFOV 40	0.715	0.635 – 0.795	0.005	-0.135 - 0.146	.482	310.587	<.01
GFOV 60	0.842	0.743 – 0.940	-0.194	-0.316 - -0.073	.458	284.503	<.01
GFOV 80	0.909	0.790 – 1.027	-0.271	-0.379- -0.163	.405	226.914	<.01

Analysis of the Impact of GFOV on Error

Within this study it was also of interest to examine the impact of GFOV on error. Therefore, a three-way between subjects ANOVA was conducted to examine the effect of GFOV on overall error. The results of the ANOVA indicated that error was significantly affected by GFOV, $F_{(3,1340)} = 202.61$, $p < .001$. Post-hoc Least Significant Difference tests indicated that the GFOV conditions were significantly different from each other ($ps < .001$). They also showed that error increased linearly with GFOV with the greatest degree of error being associated with the narrowest GFOV. However, because previous analyses showed a strong distance effect a further ANOVA was conducted within which distance was entered as a covariate. The results of this analysis indicated that the effect of GFOV was attenuated by distance such that there was only a marginally significant effect of GFOV on error, $F_{(3, 1339)} = 2.42$, $p < .065$.

In addition to examining the effect of GFOV on overall error, it was also of interest to establish whether GFOV affected the rate at which error increased as distance increased (the slope of the regression line). Figure 14 illustrates the regression lines for each GFOV condition. A visual examination of the figure suggests that there is little difference in slope between GFOVs. To examine this issue further a one-way repeated measures ANOVA was conducted on the slope of the regression lines for each GFOV. The differences between GFOVs were evaluated against the multivariate criterion of Wilk's lambda (Λ). Results showed a significant difference between GFOVs (Wilks' Λ = .44, $F_{(3, 9)} = 3.76$, $p < 0.05$). As shown in Table 3, pairwise comparisons of the individual slopes associated with each GFOV condition indicated that the largest difference was obtained between the 30 and 80 degree conditions. The slope of the

regression line for the 80 degree GFOV was 0.909, which is steeper than the slope of the regression line for the 30 degree GFOV (0.686), indicating that participant error showed greater increases with distance at the 80 degree GFOV.

Table 3.

Pairwise comparisons of slopes between GFOVs.

GFOV Pair	T	P
30 and 40	0.48	0.64
30 and 60	2.81	0.02
30 and 80	3.20*	0.01
40 and 60	1.86	0.09
40 and 80	2.67	0.02
60 and 80	1.0	0.34

*t crit for Bonferroni adjusted α of 0.5 = 3.20

In summary, participant error in setting the box to represent a true cube increased linearly with distance. However the effect was attenuated to some degree by GFOV. While wider GFOVs were associated with lower overall error rates they were also associated with greater increases in error as the distance between the observer and the front face of the box increased.

Discussion

The results of this experiment supported the hypothesis that error in setting the box to a cube would increase as distance increased. Participants made substantial errors in setting the box to a cube at greater distances. For example, within the 30 deg GFOV condition when the box was placed a distance of 5 metres from the participant the rear face of the box was set (on average) at 3.36 metres from the front face (a 550% error). A correct setting would have been 0.5 metres from the front face. However, it is notable that error was relatively low at close distances. Results also showed that overall error rate was lower at wider GFOVs. However, wider GFOVs were also associated with greater increases in error as the distance between the observer and the screen increased.

One of the key aims when conducting this study was to gather information about inter-object distance estimation so that a model of distance perception in perspective displays could be developed. The results of this study provide some important information about inter-object distance estimation. They indicate that in general, to make an object appear to be the same size in depth as in width the object must be set so that it is substantially larger in depth. This indicates that the same distance is seen as much smaller when presented in depth than when it is presented in width.

These findings are consistent with existing research that also found substantial errors in inter-object distance estimation (Wagner, 1985; Loomis et al., 1992,1996; Toye, 1986). In particular, this study supports the findings of Loomis et al. who reported that when participants were required to set two targets lying in depth so that they matched (in exocentric distance) two targets lying on the frontoparallel plane (therefore creating a square) they consistently made the sagittal (orthogonal to the frontoparallel plane) interval 50-90% larger than the frontoparallel interval. Loomis et al. also found that error in setting the sagittal interval increased with distance. In addition, the results are consistent with Wagner (1985) who found that, on average, the same physical distance was seen as twice as large for frontal orientations as it was for in-depth orientations (however, the error rates found in the current study were higher). It is interesting to note that both Loomis et al. and Wagner conducted their experiments in a full cue environment suggesting that the observed errors are a pervasive effect and

not limited to laboratory or pictorially based studies. In terms of pictorial representations, several studies in this realm have also found depth is underestimated in relation to width (Hagen et al., 1978; Kraft et al., 1986).

The finding that there was a significant (but relatively small) effect of GFOV is somewhat contrary to the findings of McGreevy and Ellis (1986). These authors found that inter-object azimuth estimation error reversed as a function of GFOV. In their study error was at it's lowest at a 60 degree GFOV and increased (in opposing directions) at both 30 and 120 degree GFOVs. However, it is likely that the GFOV effect observed by McGreevy and Ellis (1986) occurred because the stimulus image was scaled in proportion to the GFOV. The radial separation and distance of the cubes above the grid were scaled so that the screen extent of the stimulus was held constant as perspective (GFOV) was varied. This type of scaling would result in changes in the 2D (on screen) angle presented to viewers. It is possible that these changes may have impacted upon their results and would explain the discrepancy between the results of this study and theirs.

One possible explanation for the inter-object distance estimation errors observed in this experiment is provided by Rogers (1995) who stated that errors in perceived distance when viewing images may be attributable to a conflict between the visual information that specifies a picture's surface and the pictorial information that specifies its 3D layout. Surface texture, binocular and monocular parallax, and other cues all specify the picture surface as flat. However, monocular distance cues of size, linear perspective, and texture perspective all specify a surface layout extended in depth (Hagen et al., 1978). Therefore, participants may have been influenced by 2D surface cues when judging the distance of the box. This explanation was adopted by McGreevy and Ellis to explain some of the error observed in azimuth estimations in CDTIs. While this explanation does not account for the fact that similar errors are observed in full cue environments, it suggests that any augmentation that serves to reduce the available 2D cues and increase the 3D cues may reduce error.

Another possible explanation for the observed error is that participants failed to account for the non-linear change in visual angle as distance increased. Figure 11 (above) shows the rate of visual angle change with distance. It is clear that there is a

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rapid change in visual angle at distances less than one metre. However, there is very little change at all for distances greater than five metres. The results of this experiment show that at close distances (e.g. when the front face of the cube was placed approximately 0.5m from the observer) participants were able to set the box to a cube with relative accuracy. However, as distance increased and the rate of visual angle change reduced, participants became increasingly inaccurate at setting the box to a cube. It is possible that participants continued to set the cube as though it were still very close to themselves (i.e. made distance perception errors). This idea will be explored further in Chapter 9.

This experiment indicated that observers make substantial inter-object distance estimation errors when viewing perspective displays. However, it should be noted that within this experiment observers were presented with relatively few distance cues. The only cue that specified distance was the relative size of the box over trials. Other cues such as accommodation and binocular disparity specified a constant distance. While participants were informed that the box remained a constant size throughout the experiment and should have therefore inferred that the smaller box was further away, it is possible that other cues specifying that the box was a constant distance overrode this instruction. Therefore, it was of interest to examine several display enhancements that provided observers with more cues as to the distance of the box to ascertain whether they might mitigate distance estimation errors. Therefore, the following experiments examined the issues raised by Rogers (1995) regarding reducing 2D cues and increasing 3D cues to limit depth perceptions errors in perspective displays. Attempts were made to augment the display so that monocular distance cues were emphasised and surface texture and binocular cues minimised.

Experiment Two

The findings of Experiment 1 were consistent with several other studies, in particular, Loomis et al. (1992,1996), and Wagner (1985). In addition, they were consistent with a number of pictorial display studies (e.g. Lumsden, 1983). However, one of the main differences between the studies listed above and experiment one is that the displays presented in the studies listed above contained more complex background stimuli. Several of the studies (Loomis et al, 1992, 1996; Wagner, 1985) were conducted in a full cue environment and the pictorially based ones presented objects against detailed backgrounds. For example, Hagen et al. (1978) presented objects on a chequered ground plane. These types of cues provide participants with more information about the 3D layout of the image. Rogers (1995) suggested that increased 3D cues (such as providing a ground plane) should reduce errors in inter-object distance perception by providing the viewer with more information about the nature of the pictorial space. Therefore, it was of interest to establish whether additional cues would assist participants in more accurately setting the 3D box to a cube. In the current experiment participants were presented with a ground plane as similar as possible to that presented by McGreevy and Ellis (1986). Horizontal lines were placed on the ground plane (as shown in Figure 15). A full grid could not be used as this would have allowed participants to count squares to assist in setting the box. It was hypothesised that the addition of the grid lines on the ground plane would reduce error in setting the box to a cube because participants would be provided with more information about the nature and extent of the virtual space.

Methodology

Participants

Three male and five female students from first year psychology courses at the University of Waikato volunteered to take part in this experiment in return for course credit. Participants ranged in age from 17-50 years. All participants had normal or corrected to normal visual acuity. University of Waikato Psychology department ethical procedures were followed during participant recruitment and running of this experiment.

Apparatus

The apparatus used in the experiment were the same as that used for Experiment 1. As with Experiment 1, the experimental stimulus was viewed binocularly and participants' heads were positioned so their eyes were centred on the computer screen. A headrest was used to ensure that their head remained in the correct position during the experiment

Stimuli

The main stimulus in this experiment was the same as that for Experiment 1, a three dimensional box was presented so that participants looked through the front face of the box towards the rear face. The box size was set at 0.5 x 0.5 x 0.5 metres in virtual space. However, in this experiment the background image on the display screen was varied. Three background conditions were presented against a ground plane that measured 8 x 8 units: background condition 1 was a plain black background (the same as Experiment 1); background condition 2 was a set of horizontal lines presented so that the ground plane was divided 30 times (Grid A); background condition 3 was a set of horizontal lines presented so that the ground plane was divided 15 times (Grid B) (see Figure 15). Therefore, the Grid A condition presented many more lines than the Grid B condition. The horizontal lines in both conditions were coloured light grey and the box was coloured white so that participants were able to easily distinguish between the ground plane and the box. The box was positioned so that it sat on the grid. Therefore, there was no distance between the grid and the base of the box.
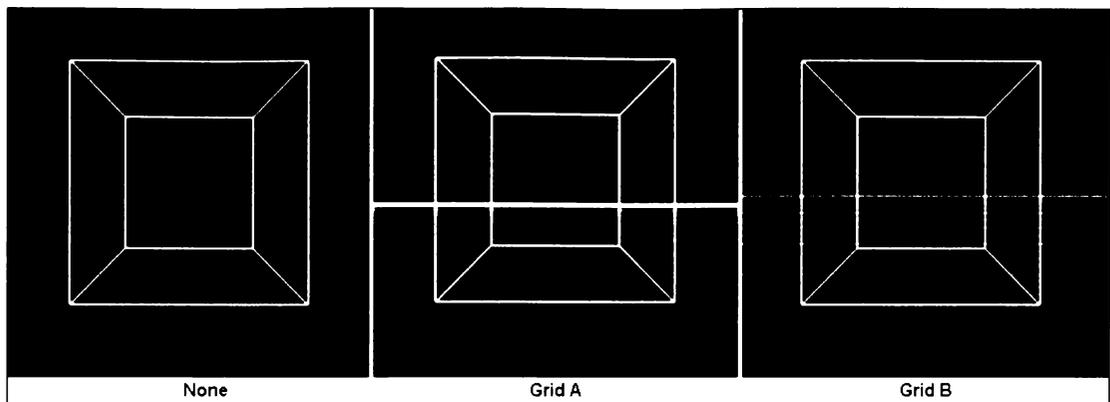
Figure 15. Experimental stimuli.

Experimental Design and Procedure

Design

As with Experiment 1, this experiment utilised a within-subjects repeated-measures design. The experimental hypotheses were tested by systematically varying the appearance of the ground plane (background conditions), the geometry of the virtual display (GFOV), and the stimulus (box). Each of the eight participants viewed 336 stimulus images which were obtained by presenting three background conditions (No grid, Grid A, and Grid B). Within each background condition four GFOV conditions (30, 40, 60, and 80 deg) and seven distance conditions were presented. The distance conditions were the same as those presented in Experiment 1 and are outlined in Table 4 for easy reference. Each condition was repeated four times to make up the 336 presentations.

Table 4.

Distance settings presented for each field of view condition.

GFOV	Distance One (m)	Distance Two (m)	Distance Three (m)	Distance Four (m)	Distance Five (m)	Distance Six (m)	Distance Seven (m)
30	1.25	1.5	1.75	2.0	3.0	4.0	5.0
40	0.9	1.0	1.25	1.5	1.75	2.0	3.0
60	0.7	0.8	0.9	1.0	1.25	1.5	2.0
80	0.5	0.6	0.7	0.8	0.9	1.0	1.5

As before, the station points were positioned at 0.67m for the 30 deg GFOV, 0.49m for the 40 deg GFOV, 0.31m for the 60 deg GFOV, and 0.21m for the 80 deg GFOV in order to attain the appropriate eye FOV.

Procedure

As with Experiment 1, participants were first given a full explanation of the experiment. They were instructed to adjust the rear face of the box until they considered that it was a perfect 3D cube and advised to go with their immediate impression rather than trying to use measuring strategies (such as setting it on the horizontal lines). Participants were then permitted to practice the task until they felt comfortable, demographic information was collected, and their near and far eyesight was checked using a Keystone View VSII vision screener.

Between background and GFOV conditions the experiment was paused to allow the experimenter to set up the new condition. During this time participants were encouraged to take a break from the task if they felt they needed to. Most participants completed the experiment in 40-50 minutes.

Results

Analyses were conducted on the errors made by participants when attempting to set the box stimulus to a cube. As with Experiment 1, error was defined as the degree to which participants deviated from setting the box to a cube. Again, participants received four trials for each condition (distance x GFOV x background condition) and the results of these trials were averaged in order to arrive at an error score for each participant for each condition.

This analysis was conducted with the aim of achieving two goals; firstly, to establish whether (as in the previous experiment) error increased as virtual distance between the participant and the box increased, and; secondly to assess the impact of background condition and GFOV on error.

Analysis of the Impact of Distance on Error

In order to evaluate the hypothesis that error in setting the box to a cube would increase as the virtual distance increased, the errors made by participants at various distance settings within each GFOV were examined. Figure 16 shows the mean error for each distance within each background condition. The data for the different GFOVs are presented on different panels in the figure. As the figure shows, mean error scores were all positive. This indicated that (on average) participants set the rear face of the box too far away to be a true cube. An inspection of the graph also indicates that (as with Experiment 1) error increased with distance. Appendix B gives the mean error scores and standard deviations for each condition. In all conditions mean error increased as virtual distance increased.

A linear regression analysis was conducted to further test the hypothesis of an increase in error related to increases in virtual distance. The regression statistics are presented in Table 5 and an illustration of the fitted lines resulting from the regression is shown in Figure 16.
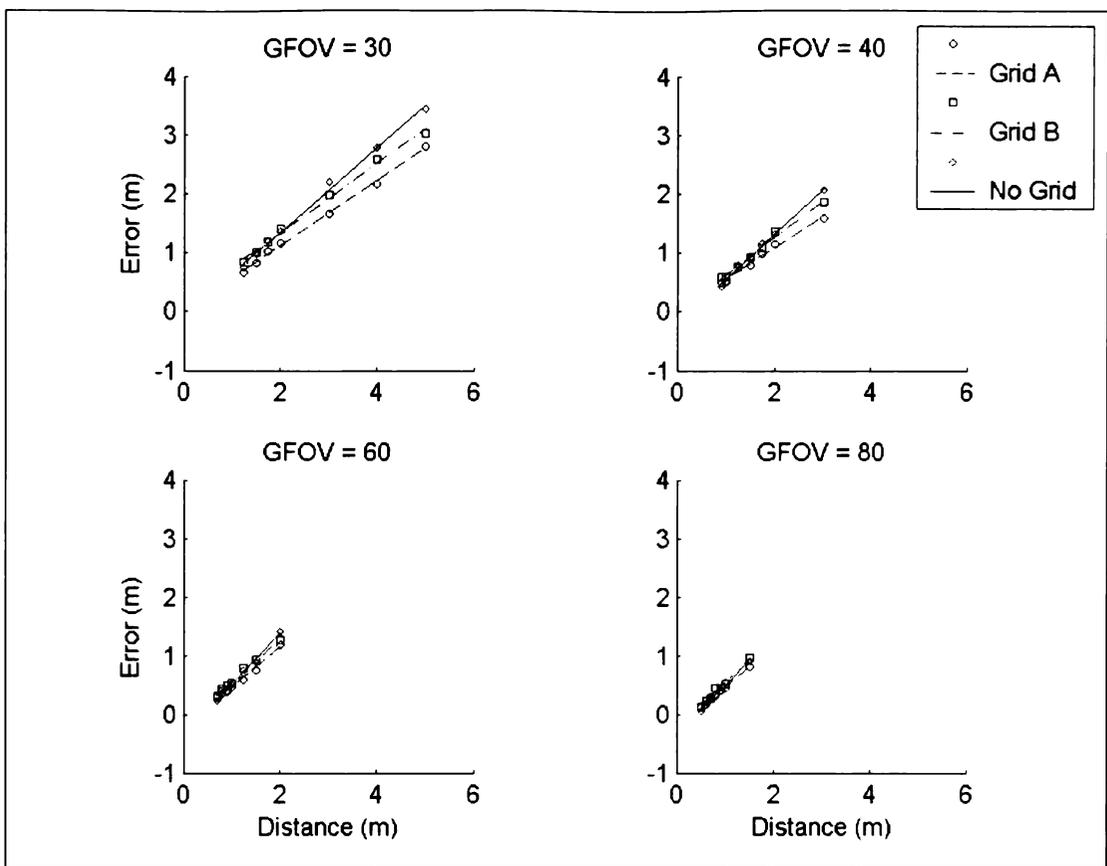
Figure 16. Mean error made by participants setting the rear face of the box by GFOV and a regression line fitted to the data for each GFOV.

As with Experiment 1, a perfect score at all distances would result in a fitted line of y = 0. Because the confidence intervals for the slopes of the regression equations do not include zero it can be concluded that the slope is significantly different from zero for all conditions. Therefore, error in setting the box to a cube increased with distance.

Table 5.

Slope and intercept of lines fitted using linear regression.

Condition	Grid	Slope	95% CI	Intercept	95% CI	R²	F	p
GFOV 30	No Grid	0.72	0.66 – 0.77	-0.08	0.25 – 0.09	0.721	572.78	<.01
	Grid A	0.55	0.50 - 0.60	0.02	-1.2 - 0.16	0.704	528.4	<.01
	Grid B	0.59	0.52 – 0.65	0.17	-0.02 – 0.35	0.607	343.60	<.01
GFOV 40	No Grid	0.77	0.68 – 0.86	-0.23	-0.38 - -0.07	0.570	296.88	<.01
	Grid A	0.53	0.47 - 0.59	0.02	-0.8 – 0.13	0.576	301.46	<.01
	Grid B	0.63	0.56 – 0.70	0.01	-0.14 – 0.11	0.583	309.91	<.01
GFOV 60	No Grid	0.89	0.78 – 0.98	-0.38	-0.49 - 0.26	0.613	351.46	<.01
	Grid A	0.69	0.59 – 0.74	-0.18	-0.28 - -0.09	0.578	303.65	<.01
	Grid B	0.73	0.64 – 0.81	-0.16	-0.27 - -0.05	0.536	258.72	<.01
GFOV 80	No Grid	0.85	0.75 – 0.95	-0.34	-0.43 - -0.25	0.546	267.42	<.01
	Grid A	0.69	0.60 – 0.78	-0.22	-0.30 - -0.14	0.518	238.44	<.01
	Grid B	0.83	0.72 – 0.93	-0.27	-0.36 - -0.17	0.512	235.37	<.01

Analysis of the Impact of GFOV and Background Condition on Error.

Within this experiment it was also of interest to examine whether changes in GFOV and background stimuli (horizontal lines) would affect error in setting the box to a cube. Therefore a two-way between subjects ANOVA was conducted to assess the effects of GFOV and background condition on overall error rates. The results of the ANOVA showed that there was a significant interaction between GFOV and background condition, $F_{(6, 2676)} = 2.84$, $p < .01$. As Figure 17 shows, the effect of background condition was minimised at wider GFOVs.
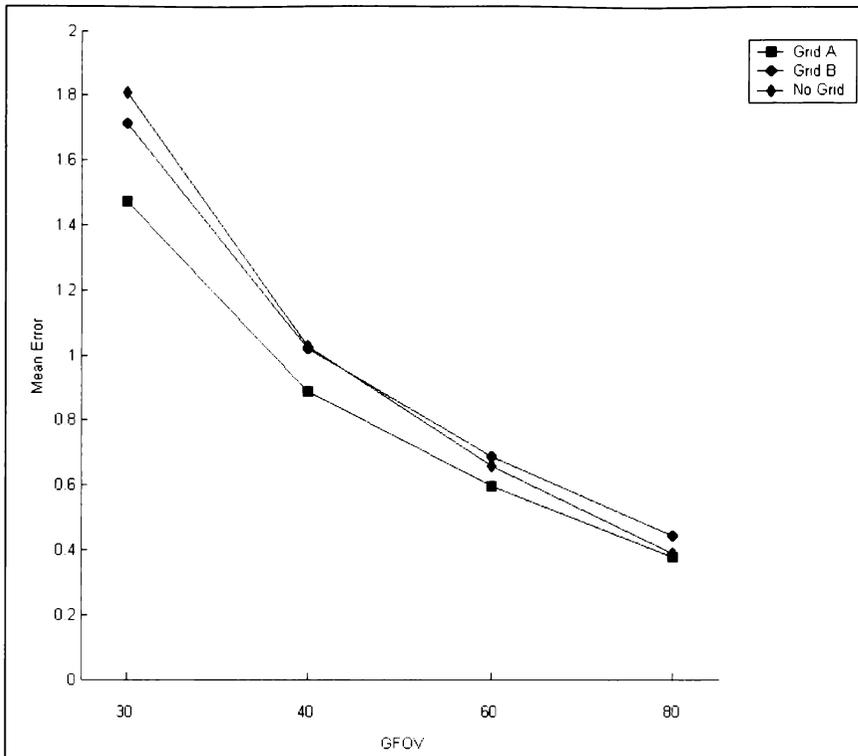
Figure 17. Interaction between GFOV and grid conditions.

Because of the strong effect of distance, a further ANOVA was conducted within which distance was entered as a covariate. The results of this analysis indicated that there was still a significant interaction between GFOV and background condition, $F_{(6, 2675)} = 7.52$, $p < .01$. In addition, there was a significant main effect of distance, $F_{(1, 2675)} = 668.47$, $p < .01$.

As well as examining the impact of GFOV and background condition on overall error rates, it was also of interest to assess the impact of these variables on the rate at which error increased as distance increased (the slope of the regression line). Figure 16 illustrates the regression lines for each background condition. A visual examination of the figure suggests small differences in slope between background conditions at the 30 and 40 degree GFOVs (with Grid A showing fewer errors than the No Grid). It also suggests that the slopes of the regression lines were steeper at the wider GFOVs. To further evaluate this issue the slopes resulting from the linear regression analysis were analysed to ascertain whether they were significantly different. A repeated-measures MANOVA contrasting the GFOV and background conditions was conducted on the slope of the regression lines obtained for each participant. The GFOV and background

condition main effects and the GFOV x background condition interaction effect were tested using the multivariate criterion of Wilk's lambda (Λ). The results of this analysis showed there was no significant interaction between GFOV and background condition ($p > .10$). However there was a statistically reliable difference for the background conditions (Wilks' $\Lambda = .26$, $F(2,6) = 8.49$, $p < .05$), and a marginal statistical difference between the four levels of GFOV (Wilks' $\Lambda = .31$, $F(3,5) = 3.64$, $p < .10$). The magnitude of the GFOV main effect was primarily due to the small number of participants tested relative to the number of cells in the experimental design. Therefore, as a further test of the effect of GFOV on slope, a Friedman's non-parametric test of the slopes ranks across GFOV was conducted. These results showed a significant GFOV effect for the Grid B condition only, with the 30 degree condition ranked first, 40 degree ranked second, 60 degree ranked third, and 80 degree ranked fourth (Chi-square = 10.14, df = 3, p <0.01). An examination of Table 5 shows that in the Grid B condition the slope of the regression lines increased as GFOV increased.

To follow up the significant main effect of background condition on slope found in the repeated measures MANOVA, paired samples t-tests were conducted. As Table 6 shows, the greatest difference was between the Grid A and No Grid conditions. An examination of Table 5 indicates that, in general, the slope of the regression lines decreased as more lines were added to the ground plane.

Table 6.

Pairwise comparisons of background conditions (slope).

Grid Pair	t	p
Grid A and Grid B	2.57	0.04
Grid A and No Grid	4.39*	0.01
Grid B and No Grid	2.66	0.03

*t crit for Bonferroni adjusted α of 0.5 = 3.8

In summary, the results outlined above showed that participant error increased linearly with distance across all conditions. However, this effect was attenuated to some degree by GFOV and background condition. Participants generally had lower overall error rates at wider GFOVs. In addition, error was typically reduced by the addition of a grid on the ground plane.

Discussion

The purpose of this experiment was to build on Experiment 1 by adding grid-type stimuli to the ground plane of the perspective image that provided extra information about the nature of the virtual space. It was hypothesised that the addition of horizontal lines would improve participant performance in setting the box to a cube because the lines would provide better cues about distance in the virtual display. However, it was also hypothesised that participant error would increase as distance between the observer and the box increased. The results of this study supported the hypothesis that participant error would increase with distance. As with Experiment 1, an effect of GFOV was observed, with wider GFOVs being associated with somewhat lower overall error rates. The addition of horizontal lines also reduced participant error particularly at narrower GFOVs.

One of the key goals of this thesis was to examine the effect of display enhancements that may reduce inter-object distance estimation errors in perspective displays. The addition of horizontal lines to the ground plane represents one such enhancement. It is clear that providing horizontal lines assisted participants in setting the box to a cube (particularly at narrower fields of view). These results provide support to the comments of Rogers (1995) that increasing the 3D monocular cues in an image should reduce distance estimation errors. In addition, the results build on Experiment 1 to provide information about the design of perspective displays. The results of Experiments 1 and 2 suggest that inter-object distance estimation error was reduced by the provision of grid lines to the ground plane, and was also reduced at wider GFOVs. However, it should be noted that while the background conditions in this experiment did increase the linear perspective cues available to participants, no attempt was made to reduce the 2D cues resulting from the screen frame, surface texture, and binocular parallax. Rogers (1995) speculates that these cues may serve to specify the picture surface as flat and cause participants to make errors in distance perception. Therefore, the following experiment attempted to reduce the 2D surface cues available to the participant.

Experiment Three

The results of the previous two experiments showed that participants consistently set the rear face of the box too far back in the virtual world to represent a true cube (i.e. in plan view they set it as a rectangle) indicating that they made significant inter-object distance estimation errors. This effect was mitigated by the addition of gridlines and reduced somewhat at wider GFOVs.

Several studies have found that viewing pictures either monocularly or through an aperture or peephole increases perception of depth. For example, Schlosberg (1941) found that using a peephole resulted in a strong illusion of real 3D space (cited in Rogers, 1995). It has been suggested that this is because the peephole obscures the frame of the object which reduces the information about the picture as a flat object and therefore increases its perceived depth. The impact of the 2D cues presented by the picture frame were of particular interest in this study because McGreevy and Ellis (1986) attributed some of the azimuth estimation error observed in their study to competition between the 2D surface cues and 3D perspective cues in their displays. Therefore, it was of interest in the following experiment to examine the impact of the picture frame (edges of the computer screen) on distance estimation errors. To test this idea an aperture was placed between the participant and the perspective image so that it prevented the participant from viewing the frame of the computer screen. It was hypothesised that the reduction of 2D cues to the picture surface would reduce distance estimation errors.

Methodology

Participants

Eight participants in total, five male and three female students from first year psychology courses at the University of Waikato volunteered to take part in this experiment in return for course credit. Participants ranged in age from 17-50 years. All participants had normal or corrected to normal visual acuity. University of Waikato Psychology department ethical procedures were followed during participant recruitment and the running of this experiment.

Apparatus

The apparatus used in the current experiment was the same as that used for Experiments 1 and 2. However, in this experiment the stimulus was viewed through an aperture placed between the viewer and the computer screen (see Figure 18).
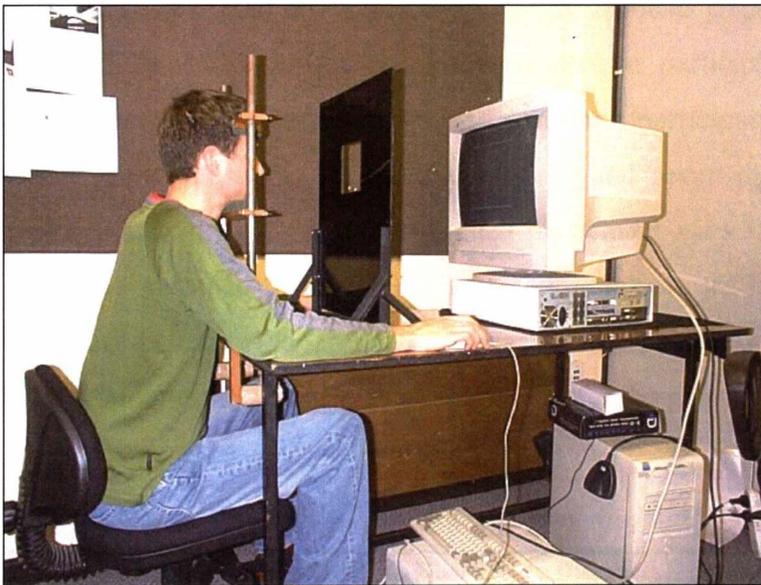
Figure 18. Experimental apparatus.

The aperture consisted of a freestanding black Perspex (Plexiglass) screen, the centre of the screen had a square cut into it that measured 12 cm by 12 cm. The screen was positioned so that the participant was able to see the contents of the computer screen but was unable to see the screen surround. As with the previous experiments, the participants' head was positioned so that the centre of their head was horizontally aligned with the centre of the computer screen and eye height was vertically aligned

with the centre of the screen. A chinrest was used to ensure that that their head remained in the correct position during the experiment

Stimuli

The stimulus presented for this experiment was the same as that presented for Experiment 2 (see Figure 15 in Chapter Five). Again, it consisted of a 3D box presented so that participants looked through the front face towards the rear face. As with the previous experiments, the centre of the box was vertically aligned with the participants' eye height. The box size was set at 0.5 metres square in virtual space. Participants were presented with three background conditions, the same as for Experiment 2 (No Grid, 30 grid lines (Grid A), and 15 grid lines (Grid B)).

Experimental Design and Procedure

Design

The design of this experiment was the same as Experiment 2. A within-subjects repeated measures design was used to present participants with three background conditions. Within each background condition participants were presented with four GFOV conditions (30, 40, 60, and 80 deg) and seven distance conditions (each was repeated four times). As a result each participant viewed 336 stimulus images. The distances presented for each GFOV condition are shown in Table 7 for easy reference. Distances between one and five 'metres' were chosen for each GFOV. The order of presentation of the stimulus was the same as for the previous experiments.

Table 7.

Distance settings presented for each field of view condition.

GFOV	Distance One (m)	Distance Two (m)	Distance Three (m)	Distance Four (m)	Distance Five (m)	Distance Six (m)	Distance Seven (m)
30	1.25	1.5	1.75	2.0	3.0	4.0	5.0
40	0.9	1.0	1.25	1.5	1.75	2.0	3.0
60	0.7	0.8	0.9	1.0	1.25	1.5	2.0
80	0.5	0.6	0.7	0.8	0.9	1.0	1.5

As before, because the size of the display screen was constrained, the station points were positioned at 0.67m for the 30 deg GFOV, 0.49m for the 40 deg GFOV, 0.31m for the 60 deg GFOV, and 0.21m for the 80 deg GFOV in order to attain the appropriate eye FOV.

Procedure

As with Experiments 1 and 2, participants were first given a full explanation of the experiment. They were instructed that they should adjust the rear face of the box until they considered that the box was a perfect 3D cube. They were then permitted to practice the task until they felt comfortable. At this stage demographic information was collected and participants near and far eyesight was checked using a Keystone View VSII vision screener. Once participants had completed the eye test they began the experiment. During the experiment participants were encouraged to take a break from the task if they needed to. The experiment took 40-50 minutes to complete.

Results

Analyses were conducted on the errors made by participants when attempting to set the box stimulus to a cube. As with Experiments 1 and 2, error was defined as the degree to which participants deviated from setting the box to a cube (error = set box length – 0.5m). Again, as with previous experiments, participant trials for each condition were averaged in order to arrive at an error score for each participant for each condition.

This analysis aimed to achieve three goals; firstly, to further assess whether (as with Experiments 1 and 2) participant error increased as virtual distance increased; secondly, to assess the impact of background condition and GFOV on error, and; finally, to compare the results of this experiment to the results of Experiment 2 in order to establish whether the addition of an aperture reduced error.

Analysis of the Impact of Distance on Error

Figure 19 shows the mean error made by participants at each distance in each background condition. The data for the various GFOVs are presented on separate graphs. An examination of the figure shows that participant error increased with distance. Appendix C provides the mean error scores and standard deviations for each condition (averaged across all participants). The data in the appendix further illustrates that in all conditions mean error increased as virtual distance increased.

To further analyse the effect illustrated in Figure 19 a linear regression analysis was conducted. The regression statistics are presented in Table 8 and an illustration of the fitted lines resulting from the regression is shown in Figure 19. Because the confidence intervals for the slopes of the regression (shown in Table 8) do not include zero, it can be concluded that the slope is significantly different from zero for all GFOV conditions. Thus, as with previous experiments, error increased with distance.
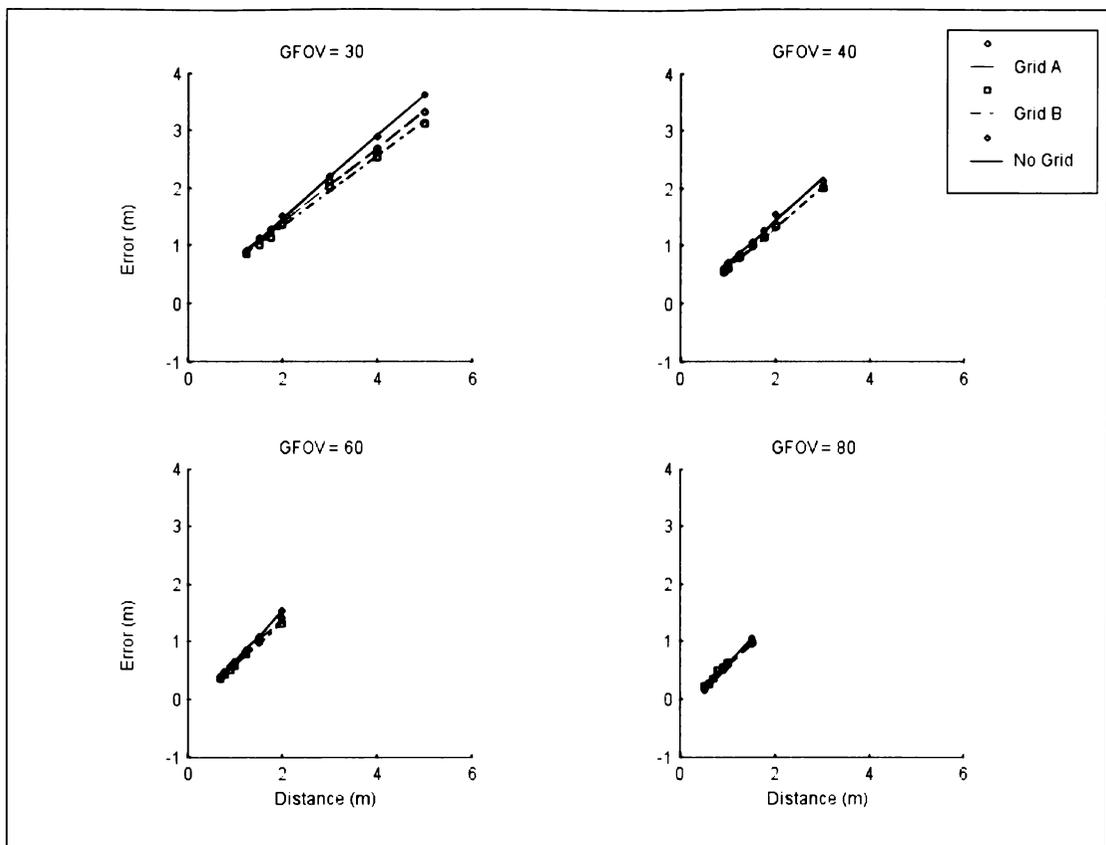
Figure 19. Mean error made by participants setting the rear face of the box by GFOV and a regression line fitted to the data for each GFOV.

Analysis of the Impact of GFOV and Background Condition on Error.

As with Experiment 2, it was again of interest to assess whether changes in GFOV and background stimuli (horizontal lines) would affect error in setting the box to a cube. Therefore, a two-way between subjects ANOVA was conducted to assess the effects of GFOV and background condition on overall error. The results of the ANOVA showed that there were significant main effects of GFOV, $F (3,2676) = 224.34$, $p < .01$, and background condition, $F (2, 2676) = 2.11$, $p < .05$. Post hoc Least Significant Difference tests indicated that the GFOV conditions were all significantly different from each other (ps $< .001$), with wider GFOVs being associated with reduced error. In addition post hoc tests indicated that the Grid B condition was different to the No Grid condition ($p < .01$), with the addition of a grid being associated with slightly reduced error. However, because of the strong effect of distance, a further ANOVA was conducted within which distance was entered as a covariate. The results of this analysis showed that there were still significant main effects of GFOV, $F (3, 2675) =$

3.06, p < .01, and background condition, F (2, 2675) = 2.11, p < .05. However, there was also a significant main effect of distance, F (1, 2675) = 2209.31, p < .001.

Table 8.

Slope and intercept of lines fitted using linear regression.

Condition	Grid	Slope	95% CI	Intercept	95% CI	R^2	F	p
GFOV 30	No Grid	0.71	0.62 – 0.81	0.05	-0.23 – 0.32	0.50	223.1	<.01
	Grid A	0.64	0.55 – 0.73	0.11	-0.16 – 0.37	0.47	196.6	<.01
	Grid B	0.60	0.51 – 0.71	0.11	-0.18 – 0.40	0.40	148.4	<.01
GFOV 40	No Grid	0.73	0.63 – 0.84	0.04	-0.23 – 0.15	0.45	179.1	<.01
	Grid A	0.71	0.61 – 0.80	-0.09	-0.26 – 0.08	0.49	215.1	<.01
	Grid B	0.70	0.59 – 0.80	0.07	-0.25 – 0.11	0.45	177.6	<.01
GFOV 60	No Grid	0.88	0.75 – 1.01	-0.22	-0.39 - -0.06	0.44	172.5	<.01
	Grid A	0.78	0.67 – 0.89	-0.16	-0.29 - -0.02	0.46	189.7	<.01
	Grid B	0.76	0.64 – 0.88	-0.18	-0.32 - -0.03	0.43	165.1	<.01
GFOV 80	No Grid	0.89	0.77 – 1.02	-0.29	-0.41 - -0.18	0.46	191.2	<.01
	Grid A	0.75	0.65 – 0.86	-0.17	-0.26 - -0.07	0.47	193.3	<.01
	Grid B	0.79	0.67 – 0.91	-0.18	-0.29 - -0.07	0.42	163.1	<.01

In addition to examining the impact of GFOV and background condition on overall error rates, it was also of interest to examine whether these variables would impact on the rate at which error increased as distance increased (the slope of the regression line). Figure 19 illustrates the regression lines for each background condition. A visual examination of the figure appears to indicate few differences between background conditions for any of the GFOVs. To further evaluate this issue the slopes resulting from the linear regression analysis were analysed to ascertain whether there were any significant differences. A repeated-measures MANOVA contrasting the GFOV and background conditions was conducted on the slope of the regression lines obtained for each participant. The GFOV and background condition

main effects and the GFOV x background condition interaction effects were tested using the multivariate criterion of Wilk's lambda (Λ). The results of this analysis indicated that there was a statistically significant main effect for GFOV (Wilks' Λ = .15, F (3, 5) = 9.5, $p < .05$). However, there was no significant effect of background condition, or a significant interaction between the GFOV and background condition (ps > 0.5). As with Experiment 2, this experiment had a small number of participants relative to the number of cells in the experimental design. Therefore, a Friedman's non-parametric test of the slopes ranks within GFOV was also conducted as a further test of the impact of background condition. These results showed no significant effect of background at any GFOV. However, Friedman's tests did show several significant differences of GFOV. Results showed a significant difference between GFOVs within the Grid B condition (Chi-squares > 10.69, p < 0.01, df =3) and the No Grid condition. (Chi-squares > 10.58, p < 0.01, df =3).

To follow up the significant main effect of GFOV on slope found in the repeated measures MANOVA, paired samples t-tests were conducted. As Table 9 shows, the greatest difference was between the 40 and 60 degree GFOV. However, the pairs 30 and 60 degree GFOV, 30 and 80 degree GFOV, and 40 and 80 degree GFOV all exceeded t crit. An examination of Table 9 indicates that the slope of the regression lines tended to increase as GFOV increased.

Table 9.

Pairwise comparisons of GFOV conditions (slope).

GFOV Pair	t	p
30 and 40	2.13	0.07
30 and 60	4.24*	0.004
30 and 80	3.61*	0.009
40 and 60	5.49*	0.001
40 and 80	4.50*	0.003
60 and 80	0.27	0.80

*t crit for Bonferroni adjusted α of 0.5 = 3.5

Analysis of the Impact of the Aperture on Error

Finally, the aim of this experiment was to examine the impact of the aperture on participant error. In order to do this it was necessary to compare between subjects across Experiments 2 and 3. This was possible because these experiments had the same conditions in terms of GFOV, background conditions, and distance conditions. Figure 20 provides an overview of participant error for each condition across Experiments 2 and 3. A one-way between subjects ANOVA was conducted to assess the impact of the aperture on overall error. The results of the analysis indicated that there was a significant effect resulting from the aperture, $F (1, 5374) = 16.95$, $p < .001$. The mean overall error when the aperture was present was 0.92m. By comparison, the mean error when the aperture was not present was 1.04m. This indicates that the aperture had a small but consistent effect in terms of reducing overall error.

It was also of interest to establish whether the addition of the aperture had an effect on the rate at which error increased as distance increased (the slope of the regression line). Therefore, a MANOVA was conducted on slope of the regression lines for these conditions. The within-subjects factors were GFOV and background condition, and the between-subjects factor was aperture. The dependant variable was the slope of the regression lines. These factors were tested using the multivariate criterion of Wilk's lambda (Λ). Results for analyses of the slope of the regression lines showed that the aperture did not significantly interact with either the background condition (Wilks' $\Lambda = .71$, $F (2, 13) = 2.69$, $p = .11$) or the GFOV condition (Wilks' $\Lambda = .88$, $F (3, 12) = .53$, $p = .67$). This indicates that the aperture did not have a significant effect on rate with which error increased with distance.

In summary, the results of this experiment showed that (as with previous experiments) participant error increased linearly with distance. However, this effect was attenuated somewhat by GFOV, with lower overall error being associated with wider GFOVs. The addition of an aperture had a small but significant effect on overall error rates but did not affect the degree to which error increased with distance.
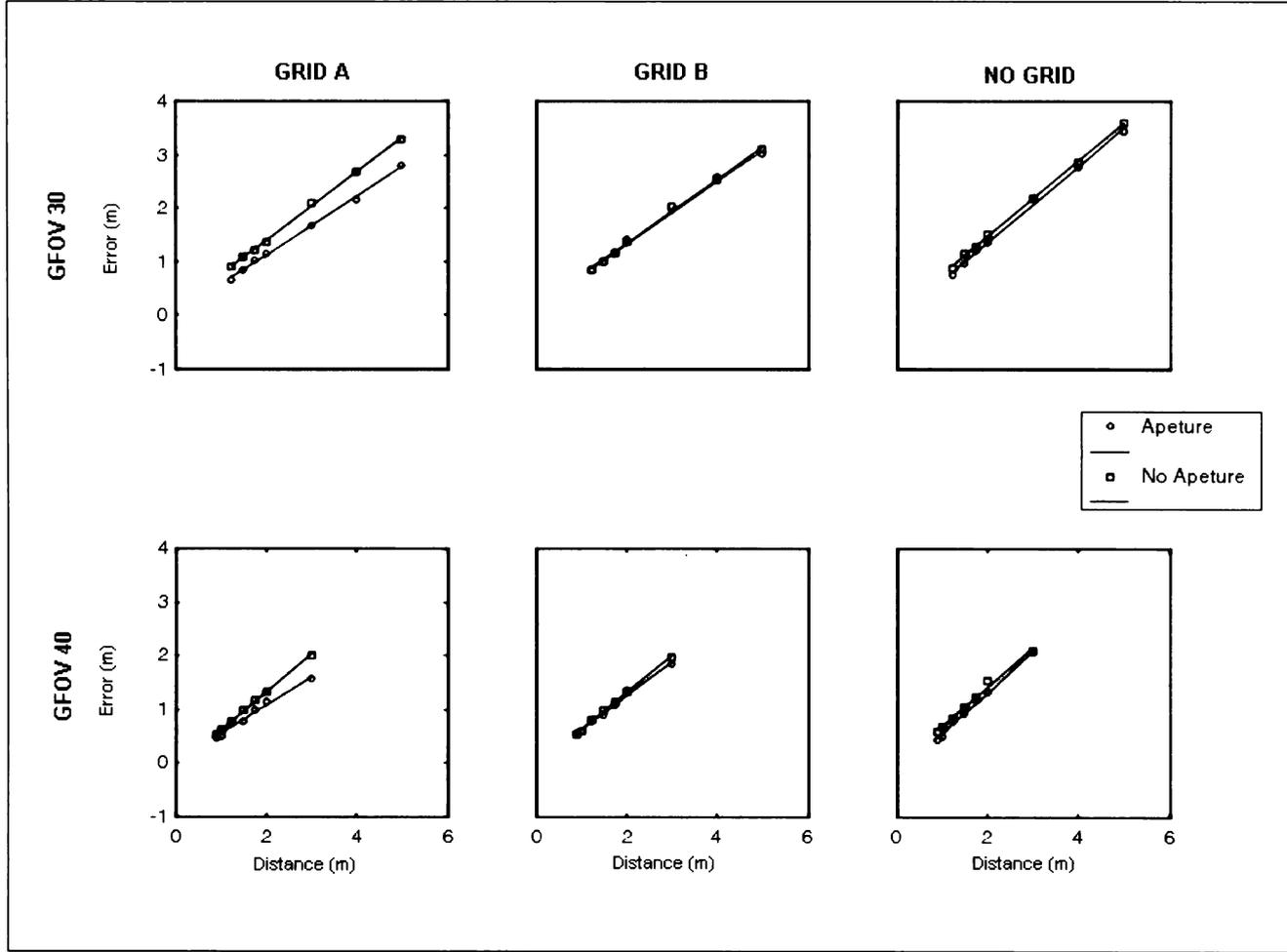
Figure 20 Mean error made by participants in Experiments 2 and 3 in setting the rear face of the box by GFOV, along with fitted regression lines.
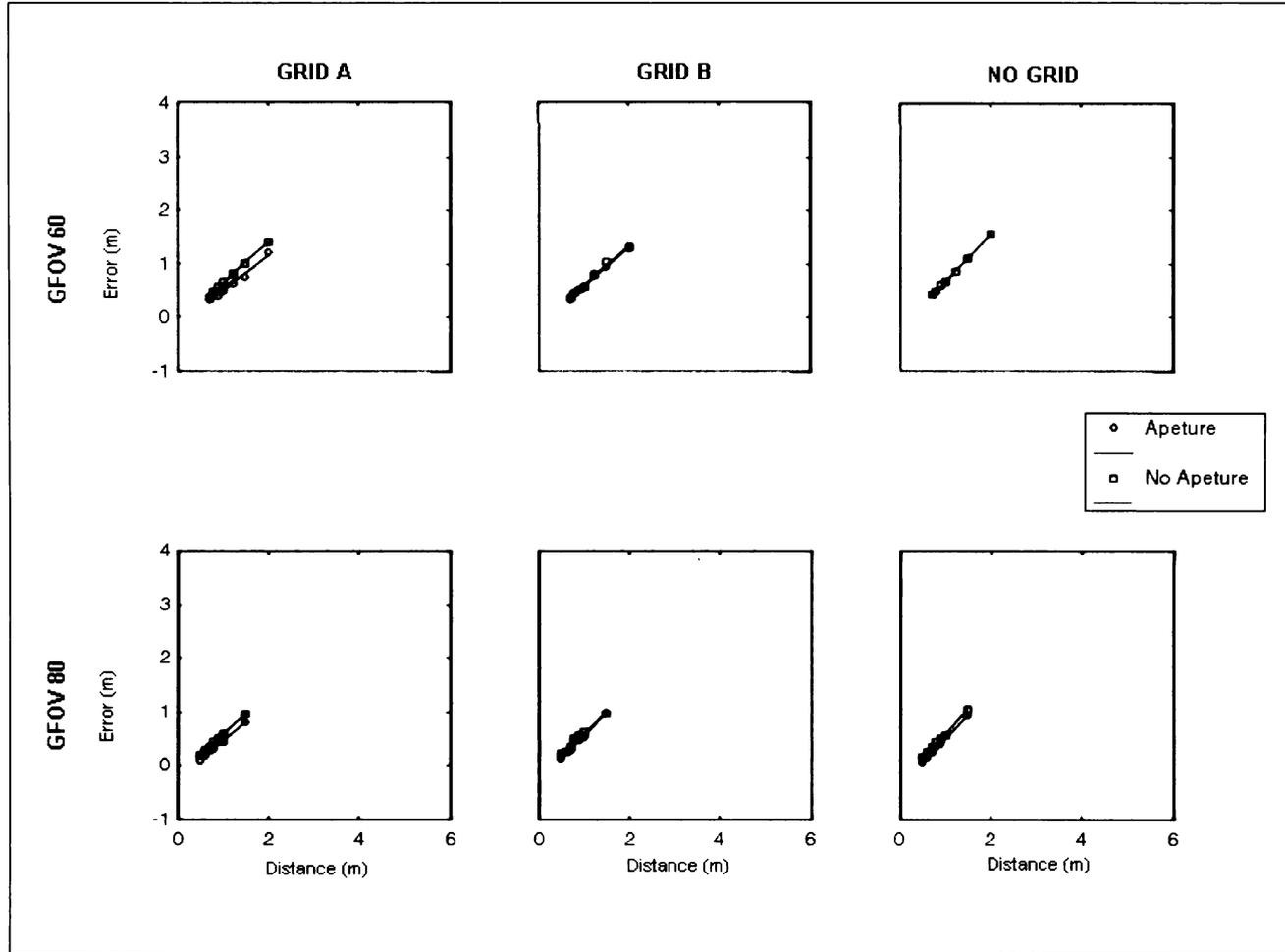
Figure 20 (contd). Mean error made by participants in Experiments 2 and 3 in setting the rear face of the box by GFOV, along with fitted regression lines.

Discussion

The purpose of this experiment was to further examine the impact of various display augmentations on inter-object distance estimation error. This experiment built on Experiment 2 by not only enhancing the 3D cues available to participants, but also reducing some of the 2D cues that specified the image surface by obscuring the frame of the computer screen with an aperture. It was hypothesised that obscuring the frame would reduce participant error by eliminating some of the 2D cues available to the participant.

As with Experiments 1 and 2, the results of this experiment showed that participants made significant inter-object distance estimation errors when setting the box to a cube and that these errors increased as the virtual distance between the participant and the box increased. Results also showed that error was mitigated to some degree by wider GFOVs. Unlike Experiment 2, the addition of horizontal lines to the ground plane did not significantly affect error. However, a visual examination of the slopes of the regression lines indicated that the addition of horizontal lines did reduce participant error to some degree. The addition of an aperture also had a small but significant effect on overall error rates.

It is perhaps not surprising that the aperture failed to eliminate or substantially reduce error. Studies examining apertures have produced mixed results with some researchers finding that they increased depth perception and others finding that they did not. For example, Adams (1972, cited in Rogers, 1995) was unable to find a significant difference between peephole viewing and unrestricted binocular viewing. This may be because using an aperture only eliminates some sources of 2D information that the viewer may use. While using an aperture appeared to have only a small effect on participant performance, the theory that reduction of 2D cues may reduce distance estimation error can be further explored by the elimination of other cues such as binocular disparity. Therefore, the following experiment attempted to eliminate other 2D cues to the picture surface so that their effect on distance estimation error could be examined.

Experiment Four

The results of the previous three experiments showed that participants consistently made inter-object distance estimation errors when setting the box to a cube. In addition, error increased as the distance between the box and the observer increased in virtual space. This was minimised to some degree by the addition of gridlines to the ground plane and by wider GFOVs. However, the addition of an aperture only reduced participant error by a small degree (despite obscuring the frame of the computer screen and therefore reducing cues available to participants about the 2D nature of the image).

As mentioned previously, adding an aperture does reduce the 2D cues presented to participants by eliminating the picture frame. However, an aperture can also truncate the visual field, eliminating some of the picture, which can affect the observers ability to locate themselves in relation to the object. In addition, it does not reduce other 2D cues such as binocular disparity. Presenting the stimulus stereoscopically eliminates 2D cues such as binocular disparity and does not have any associated problems with truncation. The elimination of these cues should remove the conflict between the 2D cues regarding the picture surface and 3D monocular cues about the image (such as perspective). Because one of the main goals of this study was to investigate the effects of display augmentations on depth perception, it was of interest to establish whether presenting the stimulus stereoscopically (and thereby eliminating 2D cues) would impact upon error in setting the box to a cube. Therefore, in the following experiment participants were presented with a stimulus similar to the previous three experiments. However, two conditions were presented stereoscopically. It was hypothesised that under stereoscopic conditions error would be reduced.

Methodology

Participants

Eight participants in total, four male and four female students from first year psychology courses at the University of Waikato, volunteered to take part in this experiment in return for course credit. Participants ranged in age from 20-60 years. All participants had normal or corrected to normal visual acuity. University of Waikato Psychology department ethical procedures were followed during participant recruitment and running of this experiment.

Apparatus

The general apparatus used in the current experiment was the same as that used for Experiments 1, 2, and 3. However, within two conditions in the current experiment the stimulus was presented in stereo (see Figure 21). E-D stereo shutter glasses were used to present a stereoscopic image to participants. The E-D system produces the stereoscopic image by alternating left eye and right eye views of the image. During use a left eye image is first displayed on the screen and the right eye of the stereo glasses is darkened. The image in the glasses is then switched to the right eye view and the left eye of the glasses is darkened. Zero disparity was set at the plane of the screen. The stereo refresh rate was set at 70 Hertz.

Stimuli

The stimulus presented for this experiment was similar to those presented for Experiments 2 and 3. Again, it consisted of a 3D box presented so that participants looked through the front face towards the rear face. The box size was set at 0.5 x 0.5 metres square in virtual space (see Figure 22). In addition, in some conditions a background condition was added that divided the ground plane into 30 horizontal grid lines (equivalent to the Grid A condition in previous experiments).
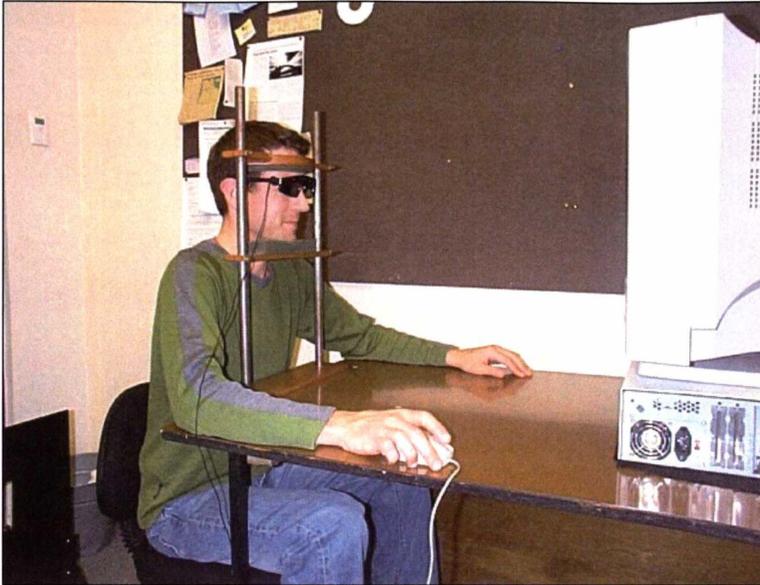
Figure 21. Experimental apparatus including stereo glasses.

Experimental Design and Procedure

Design

This experiment used a within-subjects repeated-measures design. Key conditions from previous experiments were chosen. Participants were presented with two stereo conditions (Stereo/No Stereo). Within each stereo condition, two grid conditions (No Grid, and Grid A) and two GFOV conditions (30 and 60 deg) were presented. Each of the above conditions was presented to the participant from seven distance conditions (see Table 10). The distances presented were changed from previous experiments. Close distances were eliminated because in initial pilot trials some participants experienced difficulties fusing the left and right eye images. Each condition was repeated four times. Therefore, participants viewed 224 stimulus images.

Because the size of the display screen was constrained, the station points were positioned at 0.67m for the 30 deg GFOV, and 0.31m for the 60 deg GFOV in order to attain the appropriate eye FOV. The stimulus was presented grouped by Stereo/No Stereo condition.
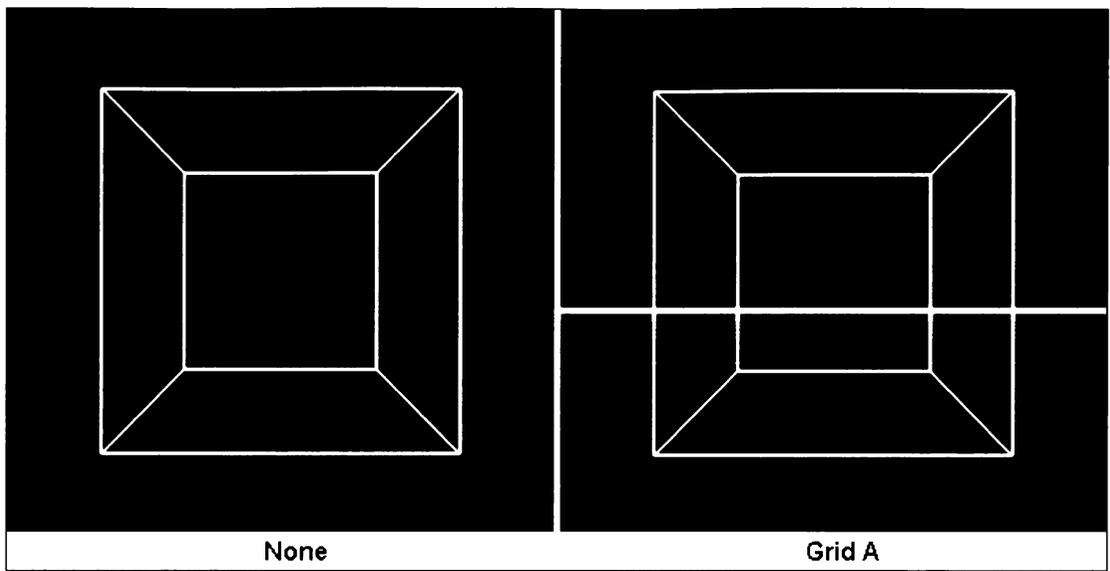
Figure 22. Experimental stimuli.

Table 10.

Distance settings presented for each field of view condition.

GFOV	Distance One (m)	Distance Two (m)	Distance Three (m)	Distance Four (m)	Distance Five (m)	Distance Six (m)	Distance Seven (m)
30	1.75	2.0	2.25	2.5	2.75	3.0	4.0
60	1.75	2.0	3.0	4.0	5.0	6.0	7.0

Procedure

As with previous experiments, participants were first given a full explanation of the study. They were instructed that they should adjust the rear face of the box until they considered that the box was a perfect 3D cube. They were then permitted to practice the task until they felt comfortable. At this stage demographic information was collected. Participants near, far, and stereo eyesight was also checked using a Keystone View VSII vision screener. All participants had normal or corrected to normal vision and normal stereo vision. Participants were then positioned in front of the experimental apparatus and their seat was adjusted so that they could rest their chin comfortably in the chin rest. The stereo glasses were then put on the participants (these remained on for all conditions but the stimulus was presented at zero disparity during the no stereo condition). During the experiment participants were encouraged to take a break from the task if they needed to.

Results

Analyses were conducted on the errors made by participants when attempting to set the box stimulus to a cube. As with previous experiments, error was defined as the degree to which participants deviated from setting the box to a cube (set box length − 0.5m). Participants results were averaged across four trials to provide an error score for each participant for each condition.

This analysis aimed to achieve several objectives; firstly, to test whether error increased with distance; secondly, to establish whether there was any effect of GFOV, background condition, or stereo condition on error, and; thirdly, to compare errors made when viewing the stimulus through an aperture to errors made when viewing the stimulus stereoscopically.

Analysis of the Impact of Distance on Error

Figure 23 shows the mean error made by participants at each distance. As the figure shows, the mean error scores for each condition were all positive and appeared to increase with distance. A visual inspection of the graph seems to indicate that participants made more errors on the No Grid/No Stereo condition than they did on the Grid A/Stereo condition. Appendix D provides the mean error scores and standard deviations for each condition across all participants. The data in this appendix further supports the observation that participants generally performed best on the Grid A/Stereo condition.

A linear regression analysis was conducted to further test the hypothesis of an increase in error related to increases in virtual distance. The regression statistics are presented in Table 11 and an illustration of the fitted lines resulting from the regression is shown in Figure 23. Because the confidence intervals for the slope of the regression equations (shown in Table 11) do not include zero, it can be concluded that the slope is significantly different from zero for all conditions. This indicates that error increased with distance.
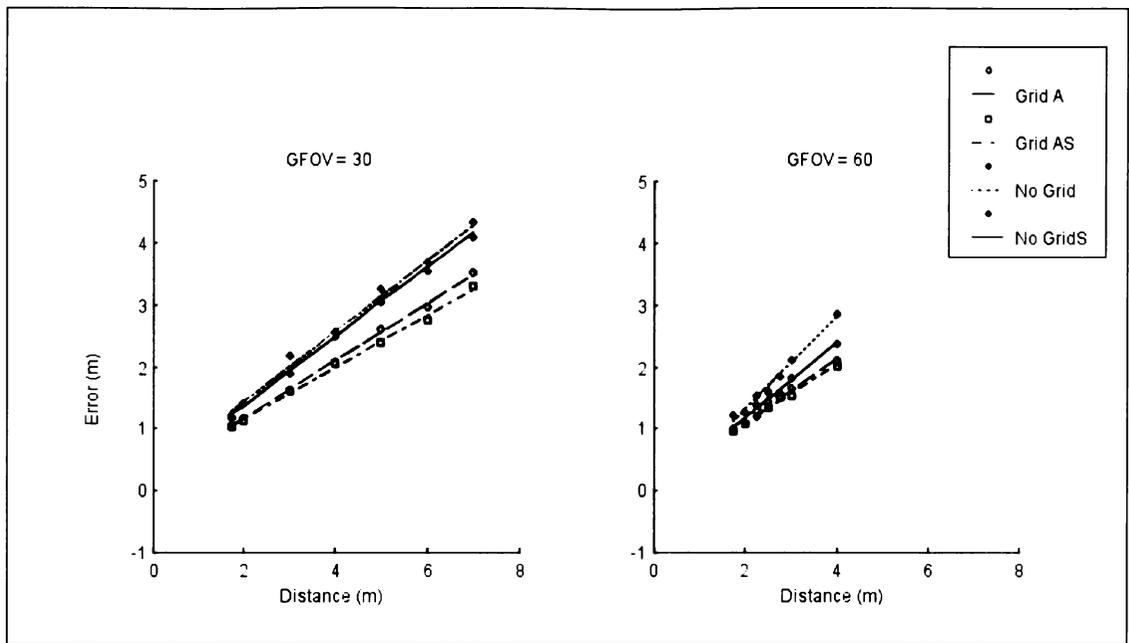
Figure 23. Mean error made by participants setting the rear face of the box by GFOV and a regression line fitted to the data for each GFOV[6].

Table 11.

Slope and intercept of lines fitted using linear regression.

Condition	Grid	Slope	95% CI	Intercept	95% CI	R²	F	p
GFOV 30	No Grid	0.57	0.50 – 0.63	0.30	0.01 – 0.59	0.57	294.9	<.01
	No Grid – Stereo	0.56	0.50 – 0.62	0.26	-0.16 – 0.53	0.60	333.2	<.01
	Grid A	0.46	0.41 – 0.51	0.25	0.34 – 0.47	0.61	351.4	<.01
	Grid A - Stereo	0.42	0.37 – 0.47	0.30	0.09 – 0.53	0.57	293.2	<.01
GFOV 60	No Grid	0.76	0.66 – 0.85	-0.20	-0.46 – 0.65	0.52	238.0	<.01
	No Grid – Stereo	0.60	0.51 – 0.70	-0.02	-0.26 – 0.22	0.44	173.3	<.01
	Grid A	0.51	0.41 – 0.59	0.10	-0.13 – 0.34	0.37	131.3	<.01
	Grid A - Stereo	0.46	0.37 – 0.55	0.20	-0.05 – 0.45	0.30	96.44	<.01

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[6] The 'S' notation on the legend of this figure stands for Stereo. Therefore, Grid A S is the Grid A stereo condition and the No Grid S is the No Grid Stereo condition.

Analysis of the Impact of GFOV, Background, and Stereo Condition on Error.

Within this experiment it was also of interest to examine the impact of GFOV, background condition, and stereo condition on error. Therefore, a three-way between subjects ANOVA was conducted to assess the impact of these variables on overall error. The results of the ANOVA showed a significant interaction between GFOV and background condition, $F_{(1,1784)} = 6.96$, $p < .01$. Figure 24 illustrates the interaction between these two variables. As the figure shows, the effect of GFOV is minimised when a grid was present. In addition, there was a significant main effect of stereo condition, $F_{(1,1784)} = 5.86$, $p < .05$. However, as with previous experiments, this study showed a strong effect of distance on error. Therefore, a further ANOVA was conducted within which distance was entered as a covariate. The results of this analysis still showed a significant interaction between GFOV and background condition, $F = (1,1783) = 15.16$, $p < .001$. In addition there were also significant main effects of stereo condition, $F = (1, 1783) = 12.77$, $p < .001$, and distance, $F = (1, 1783) = 2102.7$, $p < .001$.
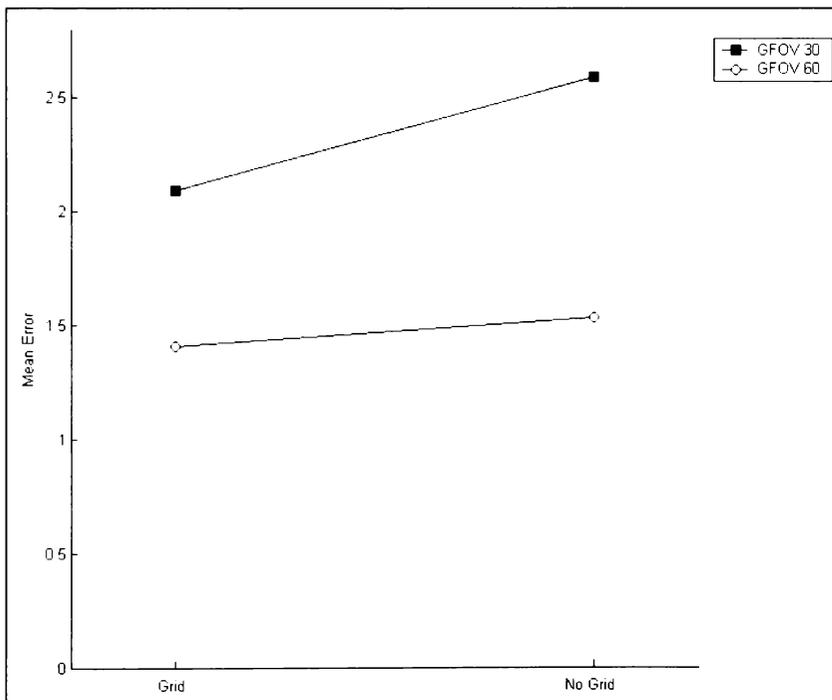
Figure 24. Interaction between GFOV and background conditions.

In addition to examining the effect of GFOV, background condition, and stereo on overall error, it was also of interest to consider the effect of these variables on the rate of increase in error as distance increased (the slope of the regression lines). Therefore, the slopes of the regression lines were compared using a three-way repeated-measures MANOVA. The GFOV, background, and stereo condition main and interaction effects were tested using the multivariate criterion of Wilk's lambda (Λ). Results for analyses of the slope of the regression line showed no significant higher order interactions (ps > .10). Likewise there was no significant GFOV x stereo condition interaction or background condition x stereo condition interaction (ps > .10). However, there was a significant interaction between GFOV and background condition (Wilks' Λ = .47, $F(1, 7)$ = 7.79, $p < .05$), and a marginally significant effect of stereo (Wilks' Λ = .60, $F(1, 7)$ = 4.7, $p = .067$). Figure 25 illustrates the interaction observed between GFOV and background condition. The figure shows that, as with overall error, the effect of GFOV was minimised where a grid was present.
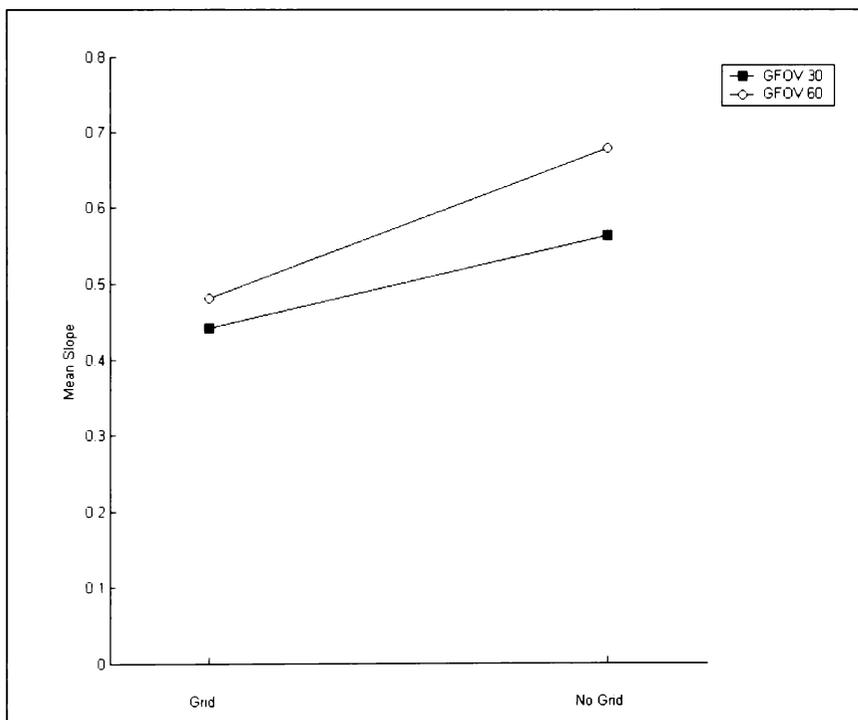
Figure 25. Interaction between GFOV and background conditions.

The results of the three way MANOVA on the slopes of the regression lines also showed a marginally significant main effect of stereo condition. Because the sample sizes used for this experiment were small, Wilcoxon Signed Ranks test of the slopes

ranks within GFOV were also conducted as a further test of the impact of the stereo condition. Results showed a marginally significant difference between the stereo conditions at the 60 GFOV, No Grid condition (Z = -1.82, p = .069). An examination of the mean slope of the regression line for each condition shows that when stereo was not present the mean slope (0.57) was slightly steeper than when it was present (0.51). This indicates that error showed slightly greater increases with distance when no stereo was present.

Comparisons of the Impact of Aperture and Stereo Conditions on Error

Finally, it was also of interest to compare the impact of the two display augmentations designed to limit the 2D surface cues presented to participants. Therefore, the aperture and stereo conditions from Experiments 3 and 4 were compared. This resulted in the following conditions being compared for both 30 and 60 degree GFOVs:

- No Grid Aperture
- Grid A Aperture
- No Grid Stereo
- Grid A Stereo

Figure 26 shows the regression lines for each of the conditions (GFOV plotted separately). An examination of the graph indicates that visually there are clear differences between the aperture and stereo conditions. It appears that participants made fewer errors in setting the box to a cube under the stereo conditions.
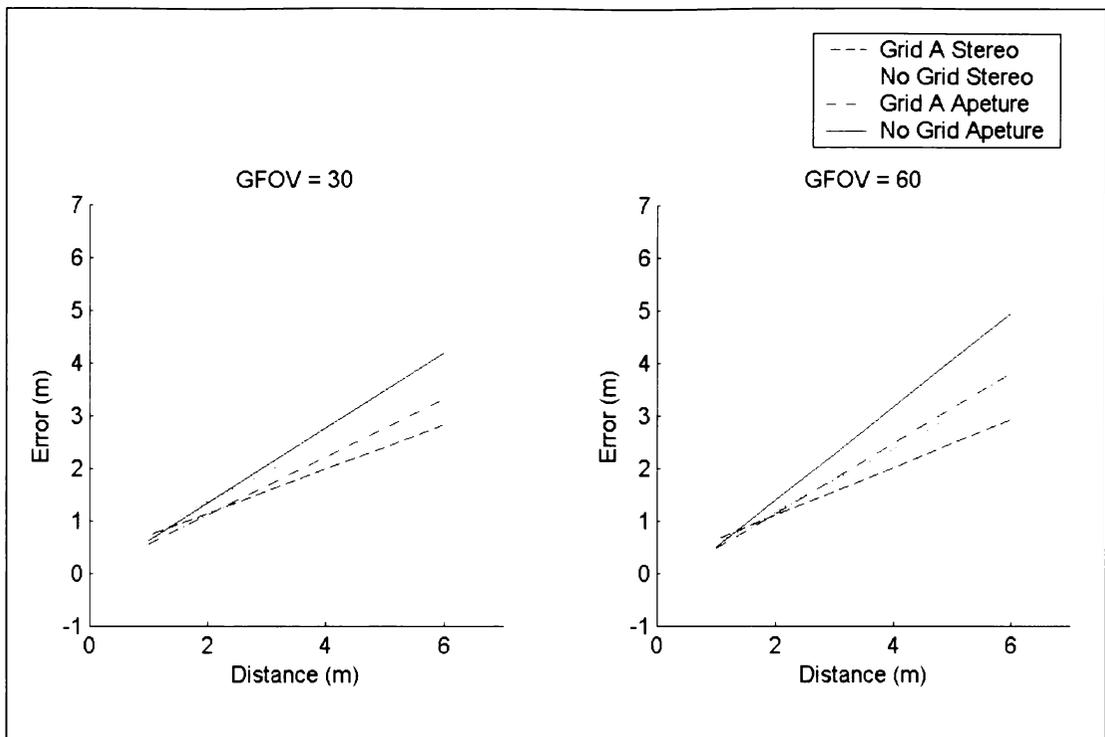
Figure 26. Fitted regression line for error in setting the rear face of the box in Experiments 3 and 4 by GFOV.

To further examine this issue a one-way between subjects ANOVA was conducted to assess the impact of the aperture and stereo conditions on overall error. The results of the analysis indicated that there was a significant difference between conditions, $F (1, 1790) = 121.07$, $p < .001$. An examination of the means for each condition showed that the mean overall error under the aperture conditions was 1.32m and the mean overall error under the stereo conditions was 1.88m. However, because these conditions were tested at different distances, a further ANOVA was conducted where distance was entered as a covariate. The results of this ANOVA again indicated that there was a significant difference between stereo and aperture conditions $F (1, 1789) = 28.37$, $p < .001$. However, there was also a significant effect of distance $F (1, 1789) = 1219.6$, $p < .001$. When the estimated marginal means for stereo and aperture were examined it was noticed that the mean overall error had changed notably such that the mean error for the aperture condition (1.74m) was greater than the mean error for the stereo condition (1.46m).

To further compare the impact of the aperture versus stereo on participant error a between-subjects ANOVA was conducted on the slopes of the regression lines which provided information about the rate of increase in error as distance increased. The between subjects factors were GFOV, background condition, and aperture/stereo condition. The dependant variable was the slope of the regression lines. Results for analyses of the slopes of the regression lines showed that there was no significant higher order interactions (ps > .10). In addition there was no significant two-way interactions between GFOV x stereo/aperture, grid x stereo/aperture, or grid x GFOV (ps > .05). There was however, a significant main effect of stereo/aperture ($F_{(1,7)}$ = 11.59, $p <$ .01). An examination of the mean slope of the regression lines for aperture conditions showed that it was .75 compared to a mean slope of the regression lines for stereo conditions of .51. This indicated error increased less with distance under the stereo conditions.

In summary, the results of this experiment showed that (as with previous experiments) participant error increased linearly with distance. However, this effect was attenuated somewhat by wider GFOVs and the addition of gridlines on the ground plane. In addition, presenting the images stereoscopically reduced participant error.

Discussion

The purpose of the current experiment was to further assess the impact of removing 2D cues to the image surface on error in setting the box to a cube. This experiment built on Experiment 3 where the 2D cues provided by the picture frame were eliminated. The results of Experiment 3 showed that removal of the picture frame only slightly reduced error. Therefore, in this experiment the image was presented stereoscopically because stereo images reduce other cues pointing to a flat image surface such as binocular disparity. It was hypothesised that removing these cues would reduce error in setting the box to a cube. This hypothesis was supported by results that showed an effect of stereographic presentation on error. Analyses also showed that stimulus presented stereoscopically showed significantly reduced error when compared to stimulus presented using an aperture.

These results are supported by the findings of Koenderink et al. (1995) who found that providing stereo cues increased perceived depth. In addition, Yeh and Silverstein (1992) also found that depth judgements were more accurate using a stereoscopic display. However, in the current study while error was reduced, it was not eliminated. As Rogers (1995) noted, depth perception errors are found even in real world studies. Therefore, it could only be expected that display enhancements (such as stereo presentation) will only reduce depth perception error to the same level noted in real world studies.

The findings also provide support to the theories developed by McGreevy and Ellis (1986) who theorised that the competition between 2D surface cues and 3D monocular cues was the partial cause of azimuth estimation errors observed in their study. This thesis proposes that azimuth estimation errors are caused by distance perception errors that impact on perceptions of the angular relationships between objects. It seems that 2D cues do impact on depth perception and may therefore impact on angular estimation.

Summary of Experimental Findings

The purpose of this study was to develop a model of distance perception in perspective displays and to apply this model to the azimuth estimation errors made by users of perspective displays in studies by McGreevy and Ellis (1986) and Ellis et al. (1989). Therefore, four experiments were conducted examining inter-object distance estimation in perspective displays. The main experimental stimulus in all experiments was a three-dimensional box. Participants were required to adjust the rear face of the box until they felt that it appeared to be a perfect cube. Within these four experiments the effects of various enhancements on inter-object distance estimation were also examined. These included GFOV, adding gridlines to the ground plane, adding a viewing aperture, and presenting the stimulus in stereo.

The key finding across all four experiments was that participants made substantial errors in setting the box stimulus to a cube. Generally speaking, participants underestimated the depth dimension of the box (sagittal plane) relative to the frontal dimension of the box (frontoparallel plane) and therefore set the rear face of the box further away than necessary to form a cube. This effect increased substantially as the distance between the participant and the box increased. This indicated that participants failed to account for changes in visual angle between the projected front and back faces as the distance between themselves and the box increased. As outlined in previous sections, this finding was supported by a number of studies which have found similar depth perception errors (Loomis et al., 1992,1996; Wagner, 1985).

In terms of the impact of the various display enhancements on participant error, the results of these experiments showed a small but consistent effect of GFOV such that overall error was reduced somewhat at wider GFOVs. Interestingly, these results are in contradiction to the findings of McGreevy and Ellis (1986) who found that azimuth estimation error was gradually reversed as GFOV was altered. Targets at azimuth directions of −135 degrees were seen as about 5 deg clockwise of true directions for a 30-deg field of view, through to approximately 13 deg counter clockwise for a 120-deg field of view. They also found that error was minimised at a 60 degree GFOV. This study showed no such reversal in error due to GFOV. However, it should be noted that the images presented by Ellis and colleagues were scaled so that screen extent of the

stimulus was held constant as perspective (GFOV) was varied. This type of scaling may have influenced the GFOV effects observed by Ellis et al.

A key aim of this study was to examine the effect of display enhancements that provided cues to the 3D nature of the perspective image and minimised cues about the 2D nature of the image surface. The 3D enhancement used was a set of gridlines (horizontal lines) presented as a part of the perspective display. These lines were intended to provide the participant with information about the scaling of the visual space. Results showed that the addition of the gridlines almost always reduced error. The addition of both the aperture and stereo enhancements was intended to reduce the 2D cues about the picture surface available to the participants. Results showed that that the aperture reduced error to a small degree. The presentation of the stimulus in stereo also reduced error. These results indicated that enhancing the 3D cues and minimising the 2D cues regarding the image reduces error. These results suggest that the theory developed by McGreevy and Ellis (1986) that observers use 2D on-screen images to establish geometric relations in the 3D image is possibly correct. However, it should be noted that within these experiments no set of display configurations or enhancements managed to eliminate error completely. Though this is not surprising given that depth perception errors have been observed in full cue environments.

Overall, the results of these experiments showed a clear and consistent inter-object distance estimation error. In the following sections the data collected in these experiments were used to develop a model of distance perception in perspective displays. The predictions of this model in terms of azimuth estimation error will then be compared to the findings of McGreevy and Ellis (1986) and Ellis et al. (1989).

Model of Distance Perception in Perspective Displays

One of the main goals of this thesis was to develop a model of distance perception in perspective displays. The data gathered in Experiments 1 to 4 provided information about inter-object distance estimation. These data were used to formulate and examine possible models.

During the model development process two main ideas were explored. Firstly, the relationship between the visual angle subtended by an object and the distance between the object and the observer (see Figure 27) was examined as a means of studying perceived distance. An appreciation of the degree to which visual angle decreases (non-linearly) with distance is necessary in order to accurately locate an object in relation to oneself and/or other objects in a scene (both real world and pictorial). By using participants' visual angle settings and the known relationship between visual angle and distance (Figure 27), it is possible to probe the perceived box distance, i.e., it can be inferred whether or not the observer misperceived the distance of the box in any systematic way. Misperceptions of the distance between an observer and an object in a scene could also lead to errors in inter-object distance estimation. In addition, they could also lead to errors in estimating angular relationships (leading to azimuth estimation errors such as those observed by McGreevy and Ellis, 1986). For example, if the distance between the reference and target cubes in Figure 7 (Chapter 2) is misperceived as less than the true distance, but the frontal dimensions are seen as veridical, then the azimuth angle will be overestimated.

The second idea considered during the model development process was whether participants had simply used a 2D strategy based on the lines that made up the box when attempting to set the box to a cube (e.g. some kind of ratio between the horizontal and vertical lines that make up the box). Therefore, two possible models explaining inter-object distance estimation errors will be outlined.
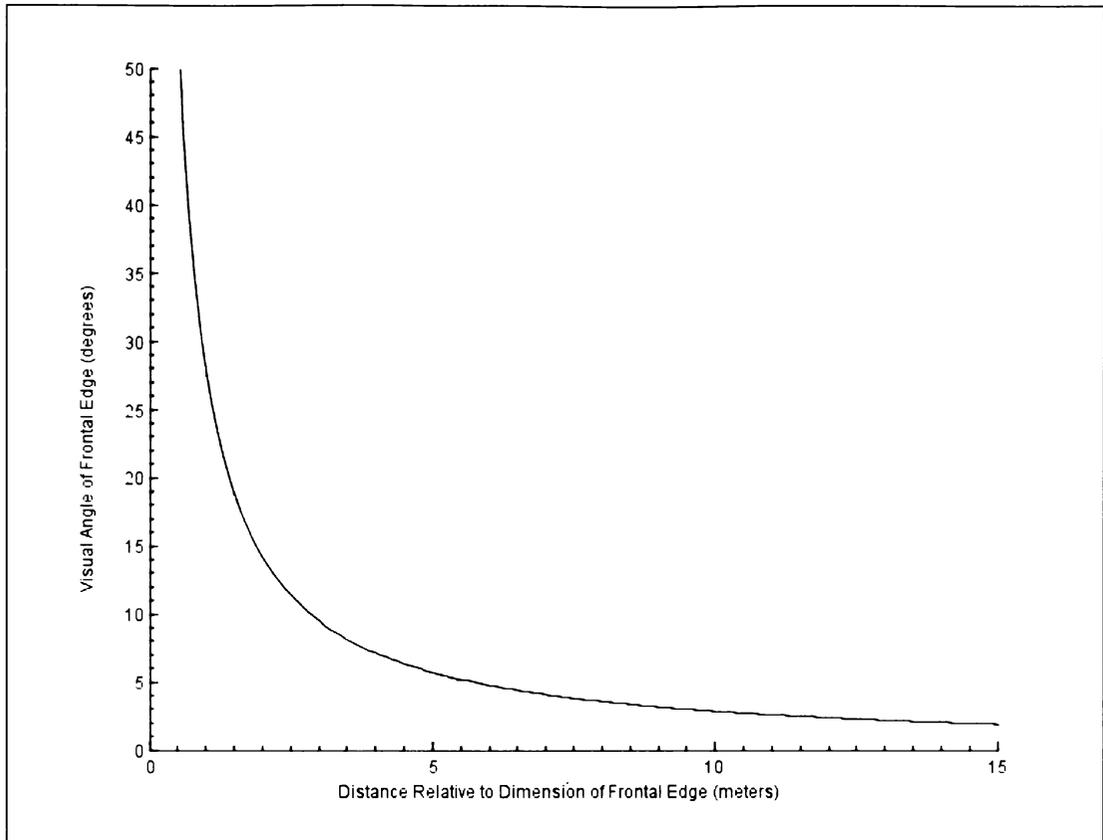
Figure 27. Projected visual angle as a function of distance of observation for an object of 0.5 metres high.

Distance Misperception Model

Figure 27 illustrates the relationship between the visual angle subtended by an object 0.5 metres high and its distance from the observer. It is clear from an examination of the figure that two objects of the same height placed very close to the observer (such as the front and rear face of a cube) would differ markedly in their relative visual angles when compared to the same two objects placed at a greater distance (e.g. 10 metres)[7]. Therefore, it is essential that an observer is able to estimate the distance between themselves and an object in a perspective display in order to accurately estimate inter-object distances.

Figure 28 (below) illustrates the visual angle ratio subtended by two objects (0.5 metres high and 0.5 metres apart) as the distance between the observer and the objects is

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[7] For further discussion of this issue see Chapter Four

increased. As the figure shows, the visual angle ratio follows a non-linear diminishing function. For the experiments described in this thesis, participants were required to follow this function in order to successfully set the box to a cube. As the box was moved away from them in virtual space to a new distance (D), they needed to set the rear face of the box at a position that produced a visual angle ratio consistent with that distance. The results of Experiments 1 to 4 show that participants failed to do this, becoming more inaccurate as distance increased.
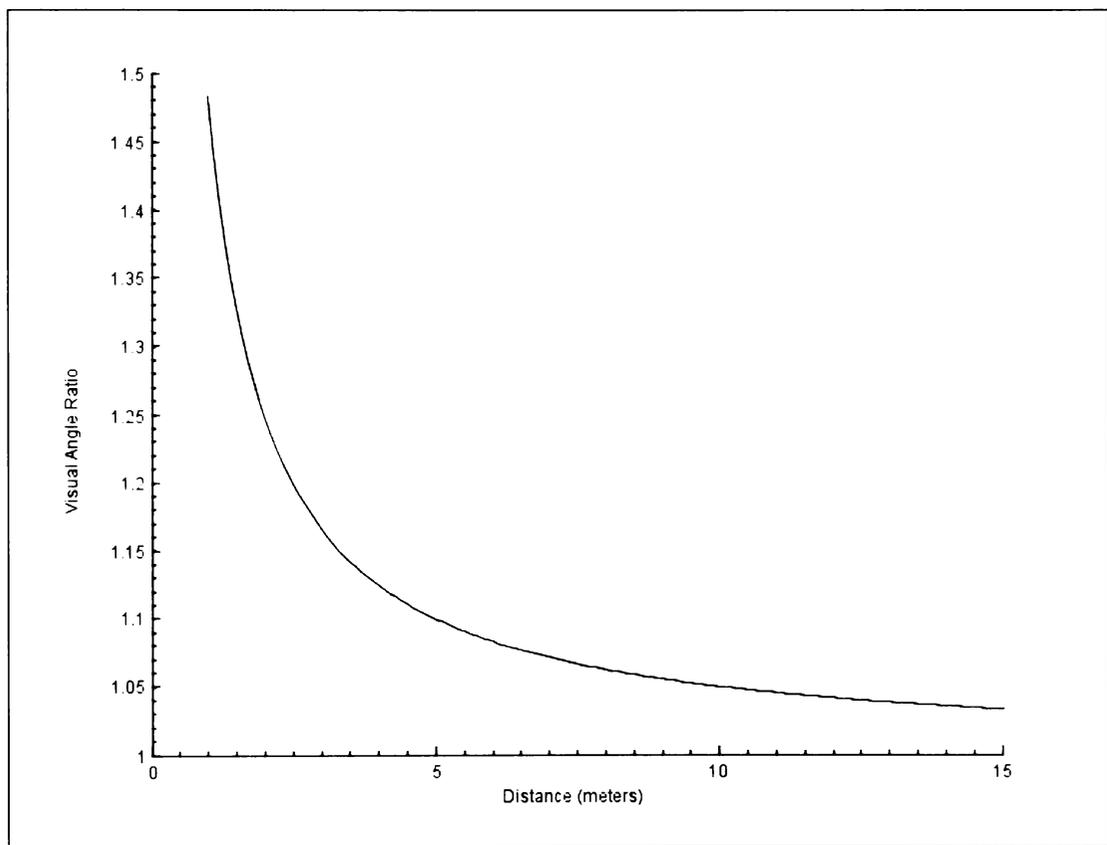
Figure 28. Visual angle ratio for two objects 0.5 metres high and 0.5 metres apart, as a function of the distance of the object closest to the observer.

While participants failed to follow the visual angle ratio function specified in Figure 28, their errors did show a consistent trend. Across all experiments there was a linear increase in error as distance increased. Therefore, it was of interest to examine the ratios set by participants to discern any patterns in their responses. As mentioned above, one possible reason that participants failed to correctly follow the function in Figure 28 may be that they incorrectly estimated the distance between themselves and the objects in the display. If this were the case participants may have set a visual angle

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ratio that was correct for the distance they perceived the objects to be from themselves even though this ratio was incorrect for the actual distance of the objects. Therefore, analyses were conducted to ascertain whether the visual angle ratios set by participants provided any information as to their perception of distance. An estimate of the perceived distance between an observer and the objects in a scene (D' prime), based on the visual angle ratio set, can be derived as follows:

From the perspective geometry of the box and the eye (Figure 29), triangle OF_1F_2 is similar to triangle OY_0Y_1 and OB_1B_2 is similar to OY_0Y_2. Also $F_1F_2 = B_1B_2 = (0.5/2) = 0.25$m. Let $Y_0Y_1 = Y_f$ and $Y_0Y_2 = Y_b$, therefore:

$Y_f / f = 0.25 / D$ and $Y_b / f = 0.25 /(D + 0.5)$

and so

$Y_f / Y_b = f (0.25 / D) / f (0.25 / D + 0.5)$

Rearranging terms gives:

$D = 0.5 / ((Y_f / Y_b) - 1)$

The above equation links distance of the cube (specifically the distance of the front face) to the ratio of the projected heights of the front and back faces. In order to calculate perceived distance, let $R = (Y_f/Y_b)'$ which is the ratio of the front face to back face set by the observer,

therefore:

$D' = 0.5 /(R - 1)$ (Equation 1)

Assuming that everything else remains constant (e.g. perceived height of the box), this equation enables us to infer the distance of the box perceived by the observers from the front face/back face ratio (R) they set when adjusting the box to look like a cube.

Figure 29. Geometric parameters for equation derivation.

Appendix E provides graphical representations of D' for each experiment. However, in order to provide sufficient data to examine the issue of perceived distance in detail, the results from experiments 1 to 3 were combined into two data sets. Data set one included all experimental conditions without any background grid, data set two included all experimental conditions with a background grid (either Grid A or Grid B). Collapsing of the background conditions was done because there were no significant differences between the background conditions (Grid A and Grid B) in any of the experiments. An examination of Appendix E indicates that were relatively few differences in D' between experiments thereby justifying combining the data sets.

As the data in Appendix E shows, perceived distance followed a broadly curvilinear function in all experiments. Therefore, a curve-fitting tool was used to establish what the best fit to the combined data sets would be and to provide predictive power to the model beyond the range of distances tested in the experiments. The resultant fitted curves for the combined data sets are shown in Figures 30 and 31 and the equations for the fitted lines and relevant statistics are shown in Table 12. The general equation for these lines was $y = a x^b$.
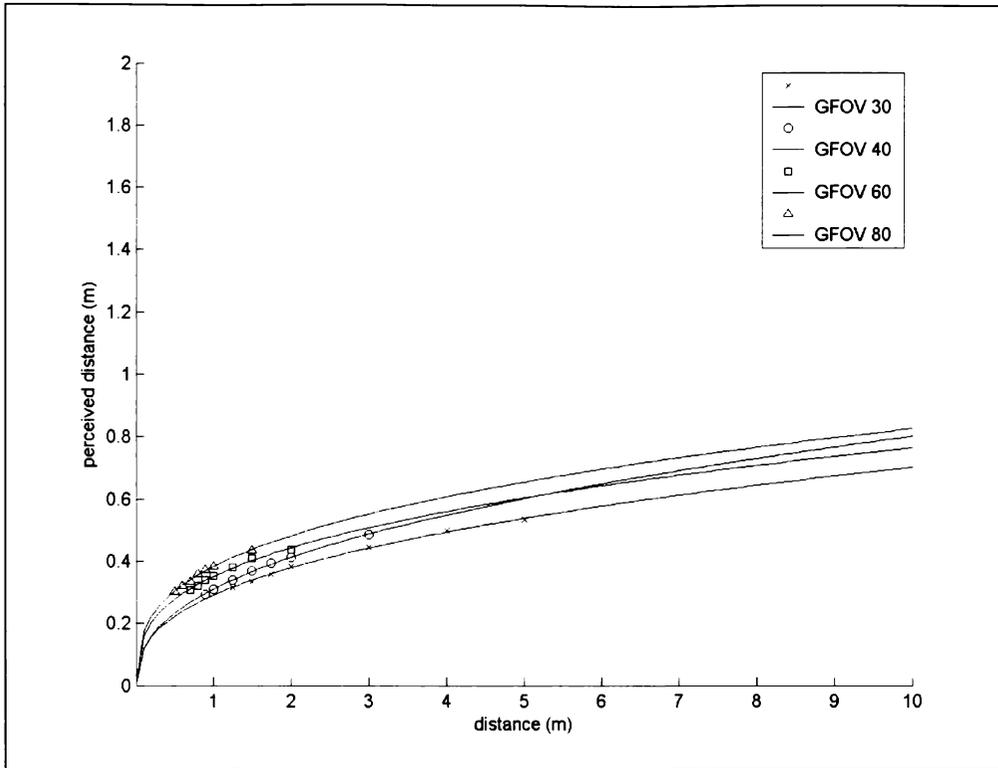
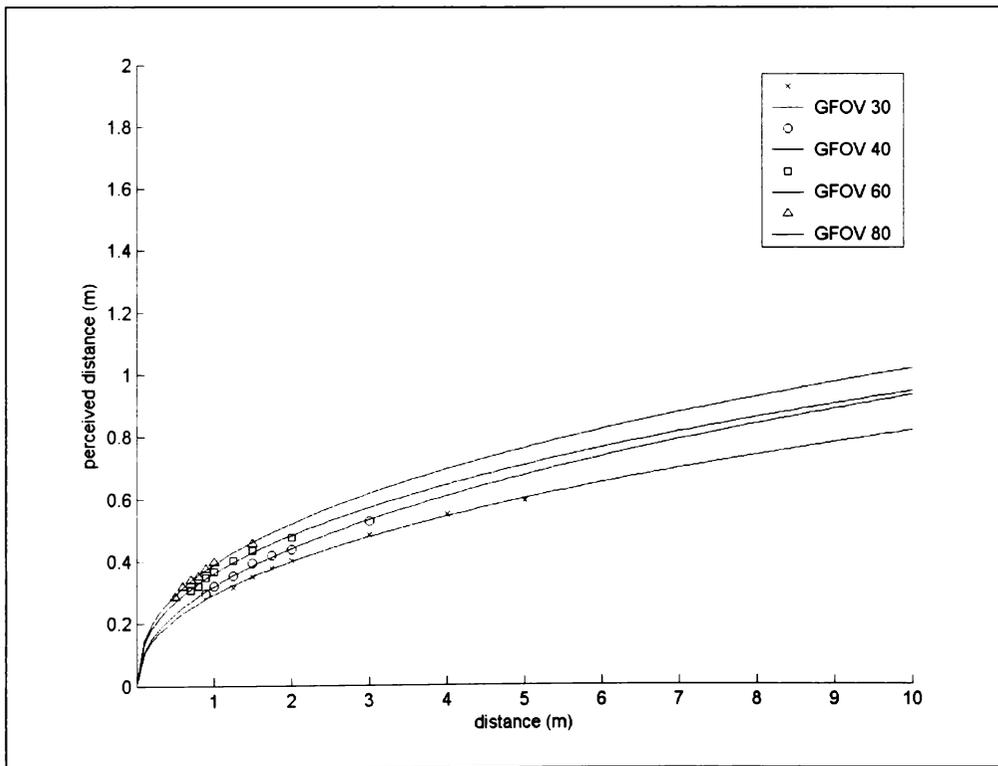*Figure 30.* Perceived distance for combined data (no background grid).

Figure 31. Perceived distance for combined data (with background grid).

Table 12.

Equation for fitted curve.

Condition	a	95% CI	b	95% CI	R²
GFOV 30 – No Grid	0.29	0.28 – 0.3	0.38	0.37 – 0.40	0.997
GFOV 40 – No Grid	0.31	0.31 – 0.43	0.41	0.40 – 0.43	0.998
GFOV 60 – No Grid	0.35	0.35 – 0.36	0.34	0.30 – 0.38	0.986
GFOV 80 – No Grid	0.38	0.38 – 0.39	0.34	0.31 – 0.36	0.995
GFOV 30 – Grid	0.29	0.28 – 0.30	0.45	0.42 – 0.48	0.996
GFOV 40 – Grid	0.32	0.31 – 0.33	0.47	0.43 – 0.50	0.995
GFOV 60 – Grid	0.36	0.35 – 0.37	0.42	0.37 – 0.47	0.987
GFOV 80 – Grid	0.39	0.38 – 0.40	0.42	0.38 – 0.46	0.990

Table 12 provides values for the functions that predict D' when viewing objects in a perspective display. The fits of the function to the data are all excellent ($R^2 > .98$). The equation for the fits represents a power function with an exponent of less than one and is similar to the classical Stevens Power law (Levine & Shefner, 1991). It should be noted that the equations specified in Table 12 are all relatively similar. Therefore, these equations were combined to provide one equation that would predict perceived distance across all GFOVs and background conditions. This equation, provided below, gives a general (averaged) prediction of perceived distance in perspective displays (where D is the actual distance in virtual space).

$$D' = .34D^{0.4} \hspace{4cm} \text{(Equation Two)}$$

The model proposes that observers' see objects in perspective displays as being much closer to themselves than the true depicted distances. This means that their concept of how visual angles and relative distances should change with distance is greatly distorted. They are basing their relative distance estimates on 2D screen values that are appropriate for much nearer objects. According to this model, when the box is actually placed at 5m from the eye it is perceived at about 0.6m and thus needs to be stretched out much larger than 0.5m in depth in order to be seen as a cube (see Figure 11, Chapter

4). The depth relationship between the front and back faces looks highly compressed (much less than 0.5m) when the box is seen to be at 0.6m rather that its true 5m distance. The observers are basing their estimates on a section of the visual angle/distance curve that is appropriate for near distances, not far ones (Figure 11). Therefore equation two predicts a compression of visual space that gets worse the further out the box moves from the observer. As Figures 30 and 31 show, the perceived distances predicted by the equations in Table 12 are very low. The equations predict that even at distances in the virtual world of approximately 10 metres the observer will perceive the distance to be approximately one metre. According to this model, at relatively close distances observers underestimate distance by a factor of approximately 10. However, it should be noted that the model assumes that observers perceive the size of the box to remain a constant size during a series of trials. Since size and distance are inversely related, the actual size and distance of the cube is ambiguous. The model assumes that perceived size is fixed at some value (0.5m) in order to study the relationship between perceived and actual distance. Attempts were made to confirm this constant size assumption during experimental testing and to determine the perceived size of the box. However, it was apparent that when questioned about the box size observers had difficulty in confidently making estimates. While most estimates were between 0.3 and 1.5 metres, it was decided that further study would be required to investigate this issue fully.

There are several possible reasons why perceived distance may be so low. Firstly, it is possible that participants may have been influenced by the screen distance when judging the distance of the box. Accommodation cues would have indicated that there was something close to the eye (the screen). However, because of the minimal differences in perceived distance between GFOVs it seems probable that participants were not relying entirely upon screen distance. Screen distance was varied for different GFOVs because the screen was moved to ensure that participants were placed at the correct station point for the image. For example, for the 30 degree GFOV, participants were placed at .67m from the screen. However, at the 80 degree GFOV participants were placed at .21m from the screen. If participants were basing their distance estimates solely on screen distance one would have expected participant performance to

be slightly worse at wider GFOVs. However, the results show that participants actually performed slightly better at the 80 degree GFOV.

Another cue that may have caused participants to perceive the box to be close is that they manipulated the box using a mouse positioned approximately 50 cm from themselves. Interacting with the mouse could have further cued participants that the box was extremely close.

Another explanation as to why participants may have perceived the box to be close is provided by Previc (1998) who developed a model of human visual perception in 3D space. In his model, space is divided up into four distinct zones (shown in Figure 32). The zones are the peripersonal, the focal extrapersonal, the action extrapersonal, and the ambient extrapersonal.
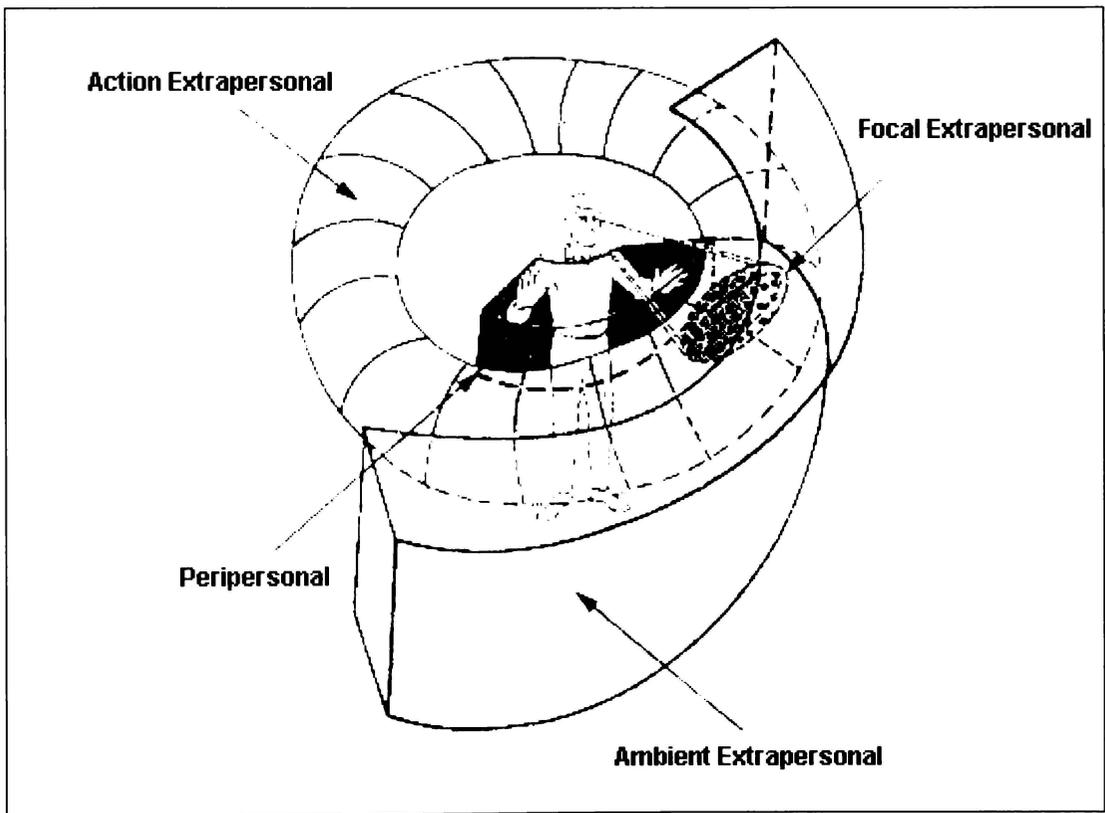

Figure 32. Model of 3D spatial interactions (Previc, 1998, p. 126).

Previc states that the peripersonal zone extends approximately one metre from the body and is primarily associated with reaching for and grasping objects. As such, the perceptual mechanisms in this part of visual space are specialised for global form,

depth, and motion processing. The focal extrapersonal system is located in a relatively small region of central vision anchored in the plane of fixation and therefore does not occupy a static position in terms of distance from the observer (being located instead where the observer's eyes are fixated up to a distance of approximately 6 metres). The major function of this system is to search for and recognise objects. Therefore, the main visual processing that occurs in this realm is colour processing, high-resolution contour analysis, and feature integration. The action extrapersonal system occupies a zone between approximately 2 metres and 30 metres from the observer. The main function of this system is to orient and navigate in relation to places and objects. Therefore, Previc states that the visual processing performed in this realm is probably not closely linked to detailed motion, depth, or form perception. He states as evidence for this, the lack of general stimulus selectivity in the hippocampus and other brain regions associated with this form of visual processing. Rather, he states that this system provides the human observer with a presence in the world. "... a crude topographical representation that is useful in navigation and in orienting to salient stimuli" (Previc, 1998, pp. 132). The final realm in Previc's system is the ambient extrapersonal. This system is located beyond 30 metres from the observer and is predominantly concerned with location in overall space. Previc postulates that these four systems are controlled through quite different parts of the brain.

In terms of the distance misperception model described above, Previc's model of visual space has several interesting implications. The perceived distances derived from the model show that participants set the cube as if it were in the realm of the peripersonal. This is the realm in which detailed depth perception related to grasping and reaching occurs. However, in the virtual world the cube was actually located in the action extrapersonal realm. Previc notes that the action extrapersonal realm lacks detailed depth processing mechanisms. Therefore, it seems possible that (lacking the ability to set the box to a cube in the space in which it was located) participants reverted to setting it as if it were in an area of space within which they were able to process detailed depth information. In addition, it is possible that the presence of the computer screen in near space may have also cued participants to work in the peripersonal zone. Finally, Previc notes that the peripersonal zone is associated with reaching and grasping (i.e. the actions that participants engaged in with the mouse). Therefore, interacting

with the mouse may have further biased participants towards working in the peripersonal zone.

While the distance misperception model described above adequately accounts for the errors made by participants in setting the box to a cube, there is always a possibility in these types of experiments that observers used a purely 2D strategy (i.e. they do not consider the depth dimension of the display). Therefore, the following section analyses possible 2D based strategies that can be used to account for inter-object distance estimation errors in perspective displays.

2D Strategy Model

The Distance Misperception model described above provides a model of participant error in setting the box to a cube in terms of the 3D perspective image. However, it is also possible that observers may have reacted to the task of setting the box to a cube solely in terms of the 2D image presented on the display screen and ignored the depicted 3D dimension. If this was the case, then it could be expected that they did not perceive the box as a 3D object, rather they saw it as a collection of lines on a screen that had no depth in 3D space. In this instance it might be expected that participants would set the box based on the proportions (heights and widths) of the lines. During the process of conducting the experiments described in this thesis participants were casually questioned about whether they had used any particular strategies to set the box to a cube. Comments from some participants implied that they may have used a strategy involving the height of the lines representing the front face of the box and the distance between these lines and the lines representing the back face of the box (see Figure 33). Therefore, the following analysis was intended to assess whether or not participants set distance B so that it was a constant proportion of height A (see Figure 33).
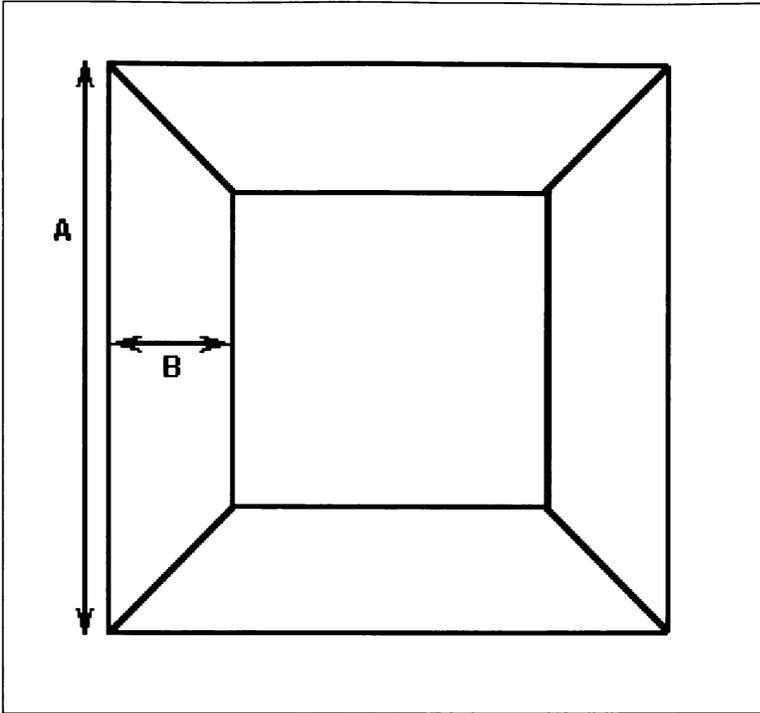
Figure 33. Possible 2D strategy used by participants to set the box to a cube.

Figures 34 and 35 (below) illustrate height A/distance B for all conditions. An examination of these figures indicates that participants consistently set the cube so that distance B was approximately 25% of the height A. It should be noted that the ratios set are quite different from the ideal ratio function for an actual cube, as shown on the figures. Appendix F provides the ratios set for each distance within each GFOV. As the appendix shows, in general the ratios begin at slightly higher than 25% and reduce slightly as distance increases. Figure 36 (below) provides a pictorial representation of a box where the ratio (height A/distance B) is set to 25%. This figure represents the ratio set, on average, by participants.
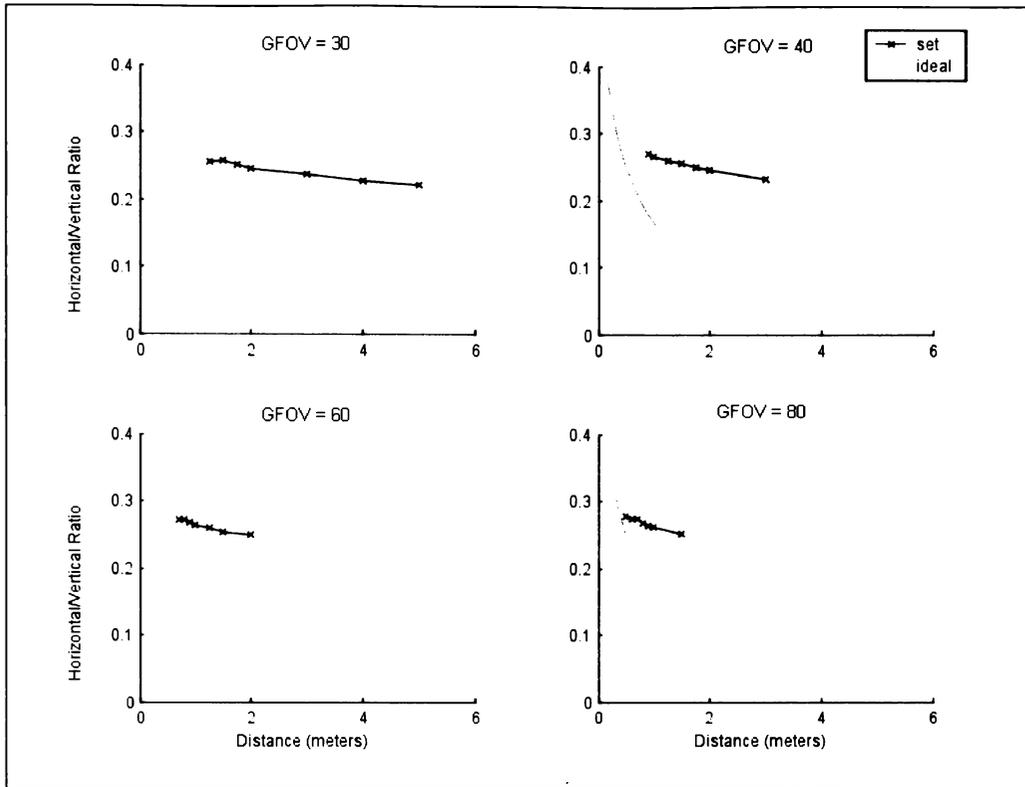
Figure 34. Ratio set for height A/distance B for combined data (with no background grid).
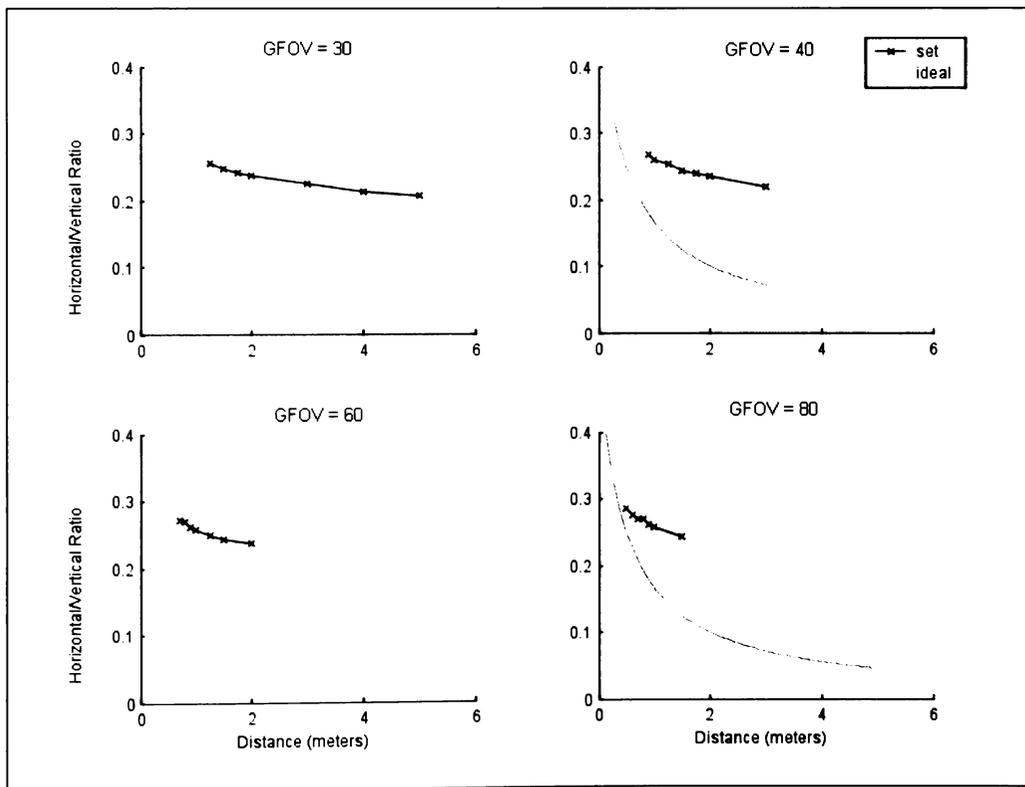

Figure 35. Ratio set for height A/distance B for combined data (with background grid).
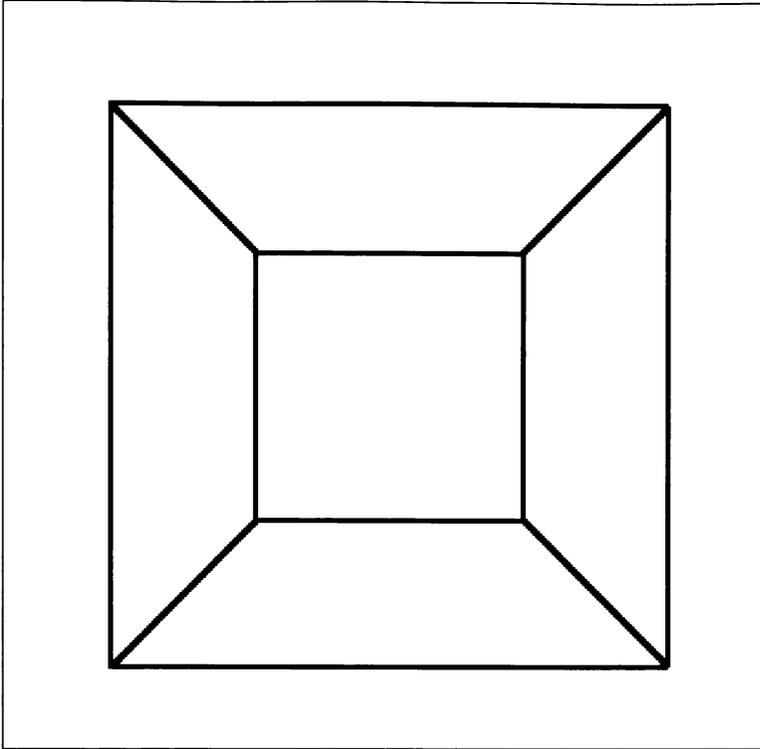
Figure 36. Mean box proportion set by participants.

A linear regression analysis was conducted to further evaluate the prediction that participants used a constant ratio of height A/distance B when setting the box to a cube. The regression statistics are presented in Table 13 (below). Because the confidence intervals for the slopes of the regression lines do not include zero it can be concluded that the slopes of the regression lines are significantly different from zero for all conditions. If participants had used a 2D strategy for setting the box to a cube it would be expected that they would apply the strategy consistently to all the boxes presented (resulting in a line with a slope of zero). However, because the slopes of the lines are so close to zero the hypothesis that some participants were using a 2D strategy to carry out the cube setting task cannot be discounted.

Table 13.

Slope and intercept of lines fitted using linear regression.

Condition	Slope	95% CI	Intercept	95% CI	R²	F	p
No Background Grid							
GFOV 30	-0.01	-0.12 - - 0.01	0.27	0.26 – 0.27	.97	185.07	<.001
GFOV 40	-0.02	-0.02 - - 0.01	0.28	0.28 – 0.29	.97	166.98	<.001
GFOV 60	-0.02	-0.02 - -0.01	0.28	0.28 – 0.29	.94	83.55	<.001
GFOV 80	-0.03	-0.03 - -0.02	0.29	0.29 – 0.29	.97	171.18	<.001
Background Grid							
GFOV 30	-0.01	-0.02 - -0.01	0.27	0.26 – 0.28	.95	104.42	<.001
GFOV 40	-0.02	-0.03 - -0.02	0.28	0.27 – 0.29	.94	77.49	<.001
GFOV 60	-0.03	-0.04 - -0.02	0.29	0.28 – 0.30	.93	66.70	<.001
GFOV 80	-0.04	-0.05 - -0.03	0.30	0.29 – 0.31	.94	71.68	<.001

Conclusions

This chapter presented two possible models to account for inter-object distance perception errors made by participants when setting the box to a cube in Experiments 1 to 4. The first model (Distance Misperception model) shows that inter-object distance estimation errors can be explained in terms of an error in perceiving the distance between the observer and objects in the perspective display. This model shows that participants may have been acting as if the box was much closer to themselves than it actually was when setting the box to a cube. It is hypothesised that this may be because the visual system is best able to cope with depth judgements at distances close to the observer (peripersonal zone). Therefore, participants may have reverted to using this zone when making judgements about setting the box to a cube. In addition, the presence of the computer screen in near space and the behaviour of grasping and manipulating the mouse may have further biased participants towards working in the peripersonal zone. However, it should be noted that this model assumes that observers estimates of the size of the box were constant and accurate.

The 2D Strategy model examines participant responses in terms of whether they used a simple strategy to set the box to a cube based on the lines presented on the computer screen to represent the box. The results of these analyses showed that while

participants did not apply a totally consistent strategy to setting the box in a 2D sense, they generally set it so that the ratio of height A/distance B was approximately 25%. However, this model does not account for the effects of background condition, GFOV, and stereoscopic presentation. It should also be noted that there is some overlap between these models. Because the distances predicted by the Distance Misperception model are so compressed, it would be expected that participants would set the box to a relatively consistent 2D ratio.

Both models have some implications for the angular estimation errors observed in the data gathered by McGreevy and Ellis (1986) and Ellis et al. (1989). A misperception of the distance between the observer and the objects in the scene may have caused a misestimation of the angular relationship between the objects in the scene. However, the 2D model also shows that when they lack sufficient information about the 3D nature of an object observers could resort to using 2D strategies to ascertain the relationship between objects in a perspective display. Therefore, the following chapter will explore these models and assess whether they can predict the angular estimation errors observed by Ellis and colleagues.

Application of Models to Azimuth Estimation Errors

One of the main goals in developing a model that explained inter-object distance perception in perspective displays was to examine whether the model predictions in terms of azimuth estimation errors matched the errors found by McGreevy and Ellis (1986) and Ellis et. al (1989). In the previous chapter two models were proposed that both explained the inter-object distance estimation errors observed in Experiments 1 to 3. In this chapter each model will be applied to the azimuth estimation errors observed by Ellis and colleagues to assess whether the predictions of the model can account for the errors observed in their data.

Application of the Distance Misperception Model to Azimuth Estimation Errors

The Distance Misperception model is based upon the idea that observers underestimate the distance between themselves and objects in a scene when viewing perspective displays. If distance is incorrectly estimated it could have a substantial impact on angular estimations. When viewing a perspective display one of the main cues regarding the angular separation of two objects is the distance between the observer and the objects. Once distance is known the visual system is able to translate the 2D angles presented on the display screen into 3D angles in virtual space. However, if distance is incorrectly estimated the visual system could incorrectly translate the 2D (on-screen) angles. Figure 37 (below) provides some examples of the relationship between 2D screen angles and 3D perspective angles at various distances. Each curve shows the values of α in Figure 7, plotted against the 2D screen angle (the projection of α). The figure clearly illustrates that distance has a substantial impact upon this relationship.

The Distance Misperception model predicts that observers will underestimate distance by a factor of approximately 10 (at distances of around 10 metres). Therefore, the model predicts that participants in the experiments conducted by Ellis and colleagues would have assumed that the objects in the display were much closer to themselves than they were actually depicted to be. In the experiments of Ellis et al., the mean distance at which objects were presented was approximately 28 m. However, it should be noted that 28m represents an estimate of the mean distance as the distances for these experiments are given in display units (the mean distance was 10,500 display

space units). In addition, the stimulus was presented across a wide range of distances (1000 to 20,000 units). However, if the mean distance at which stimulus was presented was 28m and participants were to underestimate the distance between themselves and the objects in the display by a factor of 10 then they would perceive the objects to be approximately 2.8 metres from themselves.
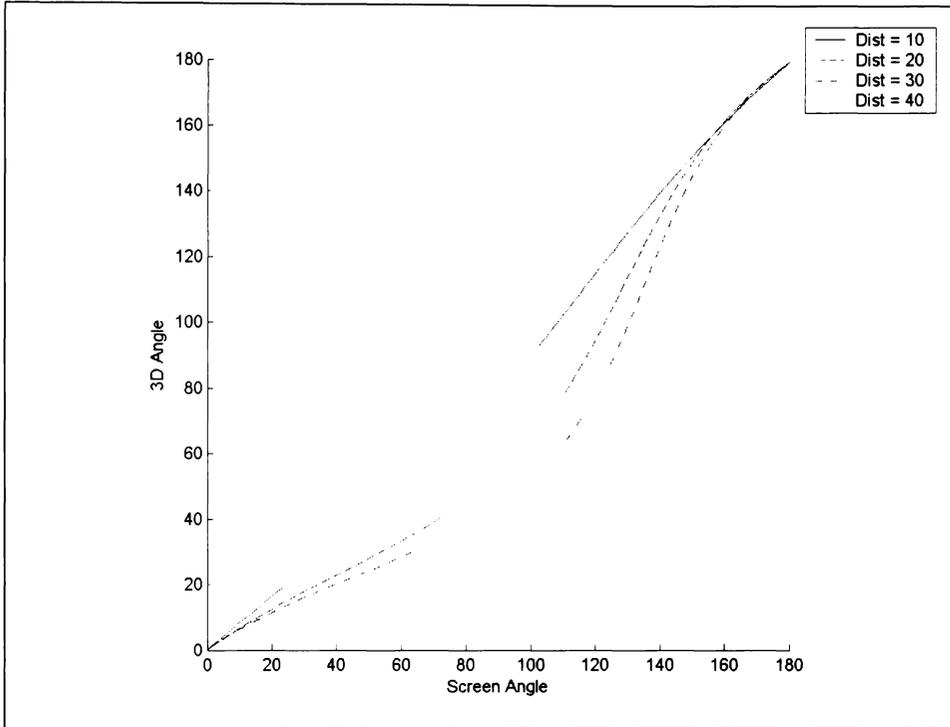
Figure 37. Examples of the translation between 2D screen angles and 3D perspective angles at various distances.

Based on these suppositions, it is possible that the error observed by Ellis and colleagues resulted from the discrepancy between the 2D on-screen angles being translated to 3D angles as if the observer were at 2.8m instead of 28m (i.e. a type of look-up table error). Figure 38, below, illustrates predicted observer error based on this premise.

Figure 38. Differences between 3D angles at 2.8 m and 28 m. Q indicates which quadrant the target is positioned in (see Figure 7, Chapter Two).

It is clear from an examination of Figure 38 that the error predicted by assuming that the observer perceives their distance to be 2.8 m from objects in the display is different to the errors observed by Ellis and colleagues (see Figure 39 below). While the predicted error does show a curvilinear relationship, it does not predict error in the correct direction within quadrants two and four. In addition, the error fails to reverse within the 120 degree GFOV. Therefore, it is clear that the azimuth estimation errors observed by Ellis et al. cannot be easily accounted for by the Distance Misperception model.
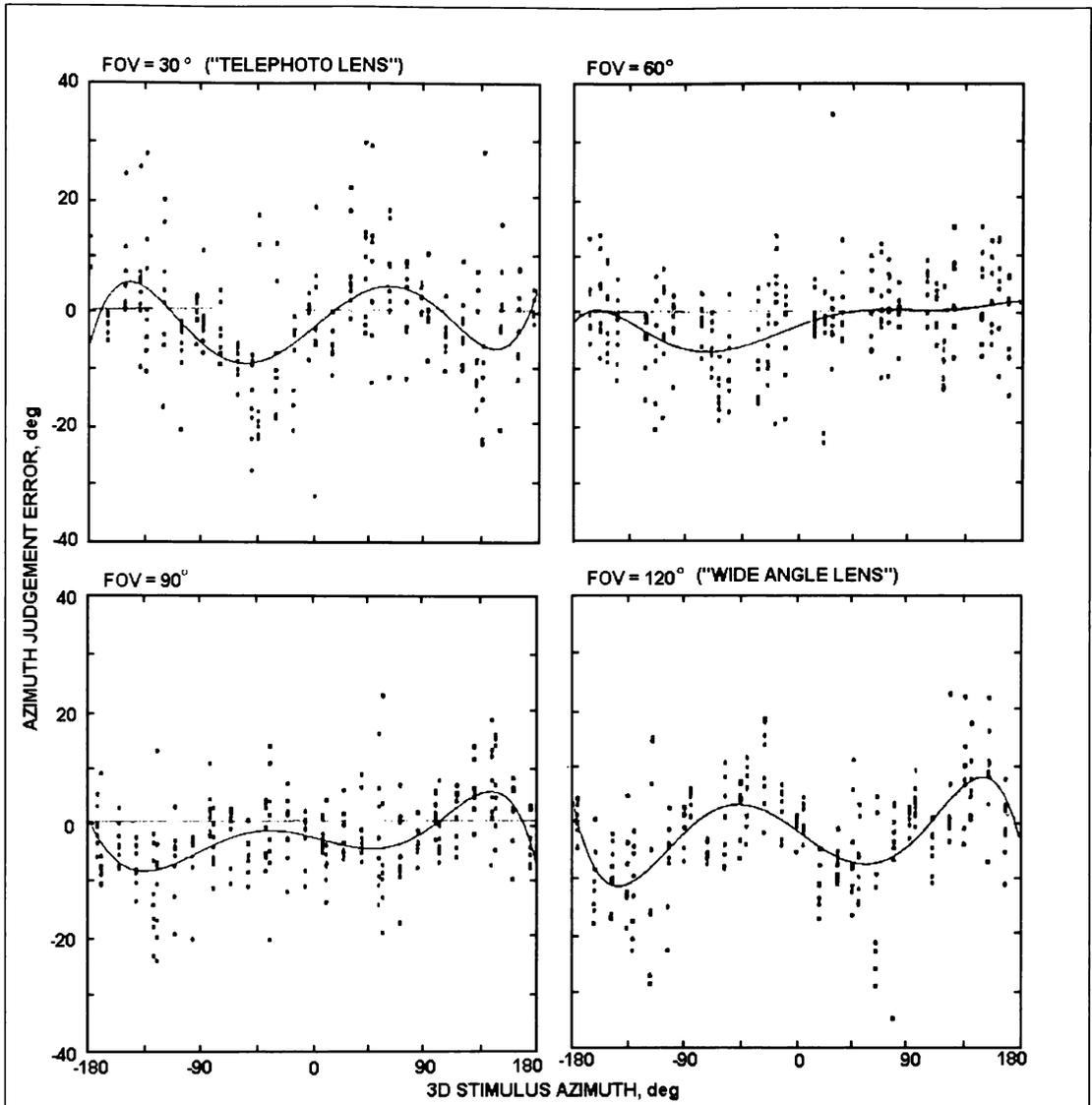
Figure 39. Azimuth estimation error and azimuth estimation error polynomials (sixth-order) for each GFOV (McGreevy & Ellis, 1986, p. 451).

While the Distance Estimation model failed to predict the azimuth estimation errors observed by Ellis et al. at a distance of 2.8m, it should be noted that several features of the displays presented in these experiments might have impacted upon participants perceptions of distance. Firstly, they were presented with an elevated view of the stimulus so that the participant was looking down on the display space from an angle of 22 deg. Secondly, participants were presented with an offset view of the display space (22 deg left). In addition, the images presented to participants were scaled so that the screen extent of the stimulus was held constant. These display parameters may have served to increase perceived distance. Therefore, analyses were

also conducted assuming that participants perceived the distance between themselves and the objects in the display to be approximately 14 metres (half the mean distance presented by Ellis and colleagues). Figure 40 illustrates the error predicted by the model at 14 metres.
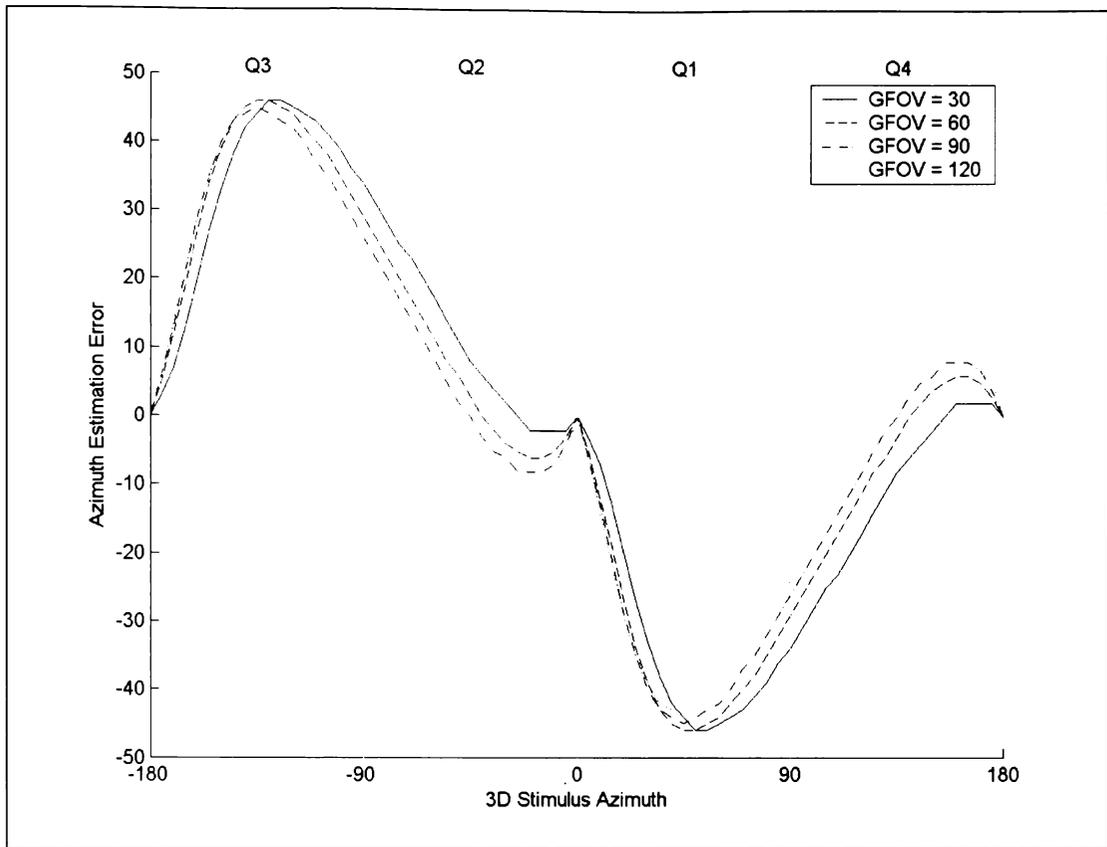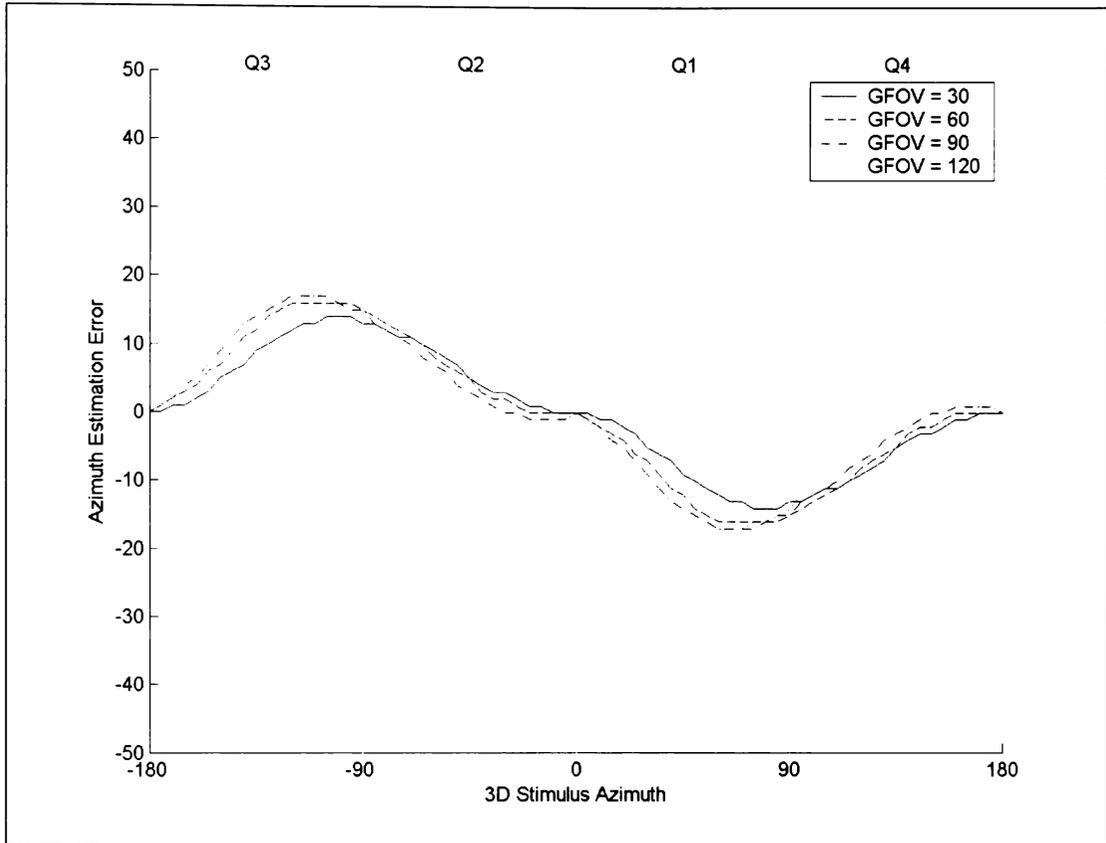

Figure 40. Differences between 3D angles at 14 m and 28 m. Q indicates which quadrant the target is positioned in (see Figure 7, Chapter Two).

Again, it is clear that the error predicted by the model (Figure 40) does not match the error observed by Ellis and colleagues. Therefore, the azimuth estimation errors observed in these studies do not appear to be a direct result of underestimations of the distance between the observer and objects in the display. However, it is interesting that the general curvilinear relationship is somewhat similar to their observed results, suggesting that distance estimation errors may have influenced participants to some degree. In addition, these analyses have only attempted one possible way of linking distance misperception to azimuth estimation errors. It is possible that with further analysis the fit of the model may be improved.

Application of the 2D Strategy Model to Azimuth Estimation Errors

The second model developed in Chapter Nine assumed that observers used the 2D information available on the display screen to make estimations about the nature of the display without making any specific use of the perspective information presented in the image. In other words, they treated the image as if it were a collection of lines on a screen and did not consider it to be a cube with depth. When testing the data collected by Ellis et al. against the depth perception model it became apparent, through comments made by naive viewers of a version of their stimulus, that a simpler 2D strategy may also have been used by their participants. Therefore, one particular 2D strategy was considered to ascertain whether it could predict the errors shown in their data. This strategy was decided upon after the display used by Ellis et al. was shown to several observers and they were questioned regarding the strategies they might use to estimate the azimuth angles.

The 2D strategy presented in this section presumed that observers used the 2D angles specified by the gridlines in the display as a reference for making estimations about the 3D angular relationship between the target and reference cubes. Specifically, it was hypothesised that they used both the 2D (on-screen) angle specified at the intersections of the gridlines in the display and the 2D angle (on screen) angle formed by the reference and target cubes to estimate the 3D angle formed by the reference and target cubes. The proposal is that, because observers knew that the gridlines formed squares in 3D space, they used the 2D angle specified by the gridlines as assumed 90 degree corner 'standards' against which the 3D azimuth angle of the reference/target cube could be established (by comparing the 2D angle of the gridline and the 2D reference/target cube angle). For example, if the 2D angle of the gridline intersection was 110 degrees, and the 2D angle of the reference/target cube angle was 55 degrees, observers would know that that the reference/target cube was half the angle of the gridline intersection. Because they knew that the gridlines were squares and the corners were 90 degrees in a 3D sense they would then assume that half of this, 45 degrees, was the 3D angle taken up by the target/reference cubes. However, the gridline intersections are rarely 90 degrees in a 2D sense as their angular size varies as a function of distance

and GFOV (see Figure 41). Therefore, if observers used this as a standard with which to make estimations they would make errors.

Figure 41 provides an illustrated example of this 2D strategy. Let angle GOT = A and angle $S_1S_2S_3$ = B The projected (2D) size of onscreen A is 24 degrees and the projected (2D) size of B is 88 degrees (therefore A is 21 % of B). The model predicts that the observer would then state that the 3D angle is 21% of 90 degrees, or 19 degrees. The true 3D angle is 22 degrees. Therefore, under this schema, observers would make an error of 3 degrees. This is a similar level of error to that observed by Ellis and colleagues for this angle.
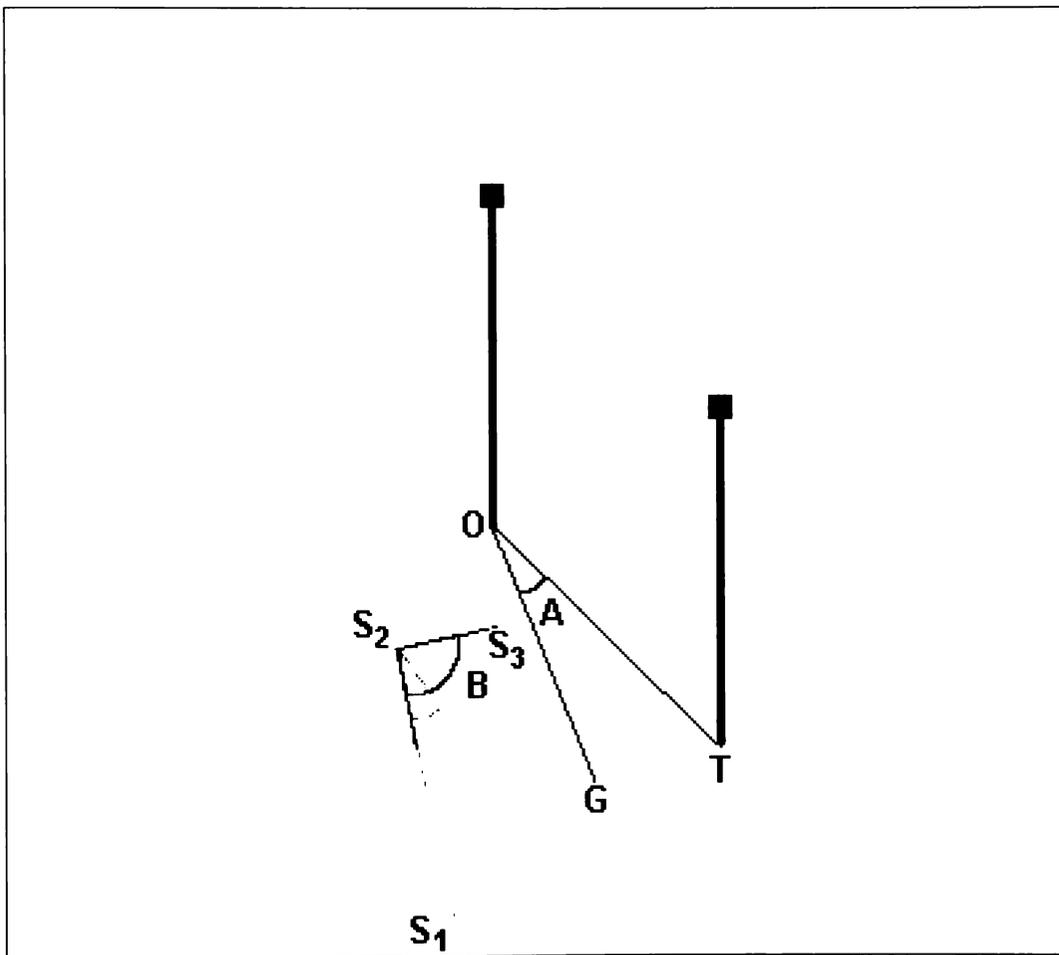

Figure 41. Illustration of the 2D strategy that observers may have used when viewing the stimulus presented by McGreevy & Ellis (1986) and Ellis et al. (1989).

The theory described above was tested by developing some code with Matlab™ that enabled the testing of the model at different fields of view. To test the theory grid crossings that it was thought that participants might use when employing the 2D strategy were chosen. The criterion for selection relied predominantly on the visibility of the grid crossing. As shown in Figure 42 below, GFOV impacts which grid crossings are visually salient. Therefore, at the 30 degree GFOV, grid crossings A and B were identified as likely candidates (as C is partly obscured and D is not visible). For the 60 degree GFOV it was determined that all grid crossings (A, B, C, and D) were likely candidates, as was the case in the 90 degree GFOV sample. In the 120 degree GFOV sample it was determined that grid crossings C and D were the likely candidates, as both A and B are too distant and small to be practically useful in terms of the strategy.

The code developed for this analysis took the grids crossings identified for each GFOV and identified the 2D angles. The 2D angles of the reference and target cube were also established as they were incremented from 0 to 360 degrees. The error was then identified by averaging the 2D angles at the grid crossings to provide the average 2D grid crossing that the participants may have used to compare against the 2D angle specified by the reference and target cubes. The averaged angle for the grid intersections and the 2D angle subtended by the stimuli were then used to calculate the error as described in the model.
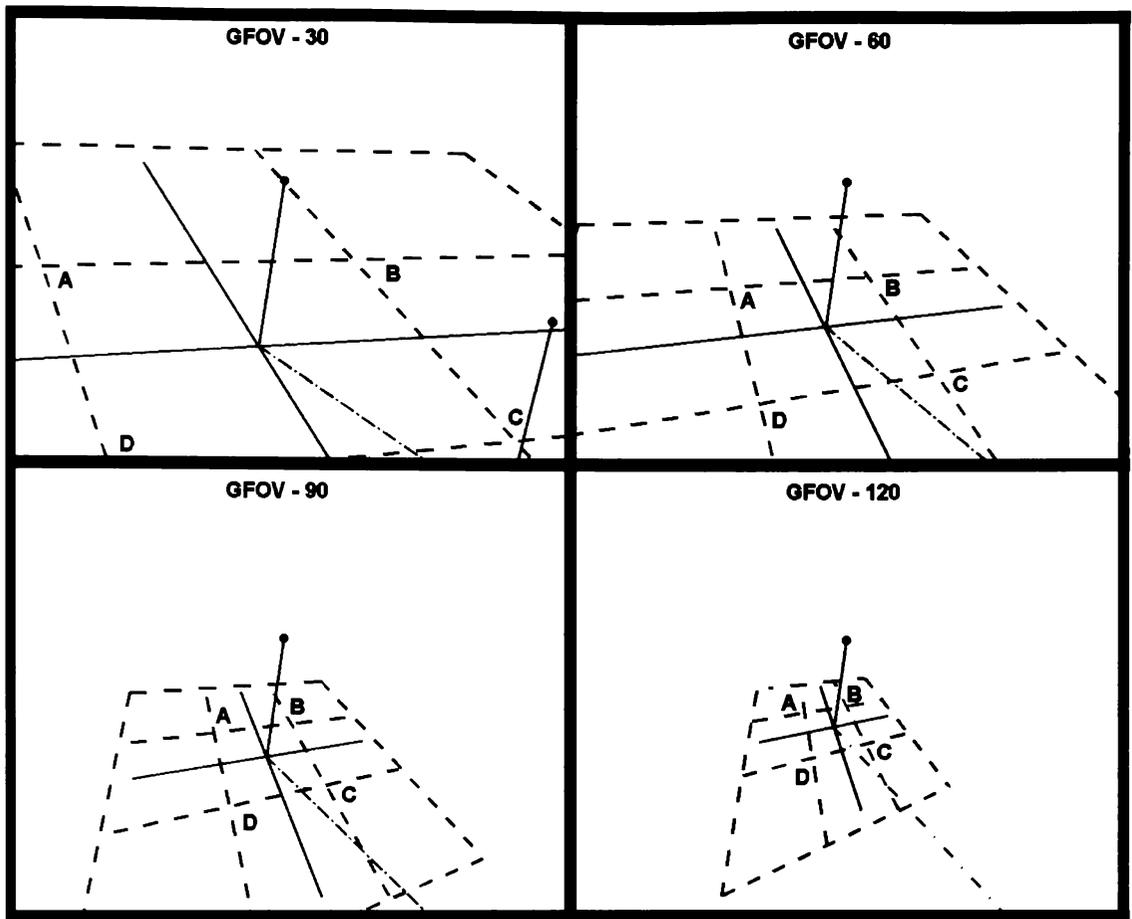
Figure 42. Grid crossings used for analysis at each GFOV.

This 2D strategy was tested across a range of distances, since Ellis et al., presented their stimulus at a range of distances. Figure 43 (below) illustrates the predicted azimuth estimation error when this 2D model is applied to a range of azimuth angles at a distance of 20 metres. An examination of Figure 43 shows that the 2D strategy predicts the error observed by Ellis et al. relatively well (cf, Figure 39). The curvilinear relationship is correctly predicted for the 30 and 60 GFOVs, and the error does reverse at the 120 GFOV. However, the positive errors are slightly over predicted and the negative errors slightly under predicted. Therefore, this model was further tested at other distances. Figure 44 shows the predicted error when the stimulus is presented at a distance of 15 metres. Again, the figure shows that the model predicts Ellis et al's error data, accurately predicting the direction of the error in all quadrants for all GFOVs. In addition, the magnitudes of the predicted errors are more accurate than

those predicted by McGreevy et al (1985). Their model predicts errors of up to 60 degrees (see Appendix G). Errors this large are not observed in the data.

It should be noted, however, that while the data presented in Figures 43 and 44 is suggestive, the theory presented in this section has only been subjected to preliminary analysis. Further analysis and experimentation is required before it could be confidently stated that this model provides an explanation for azimuth estimation errors.
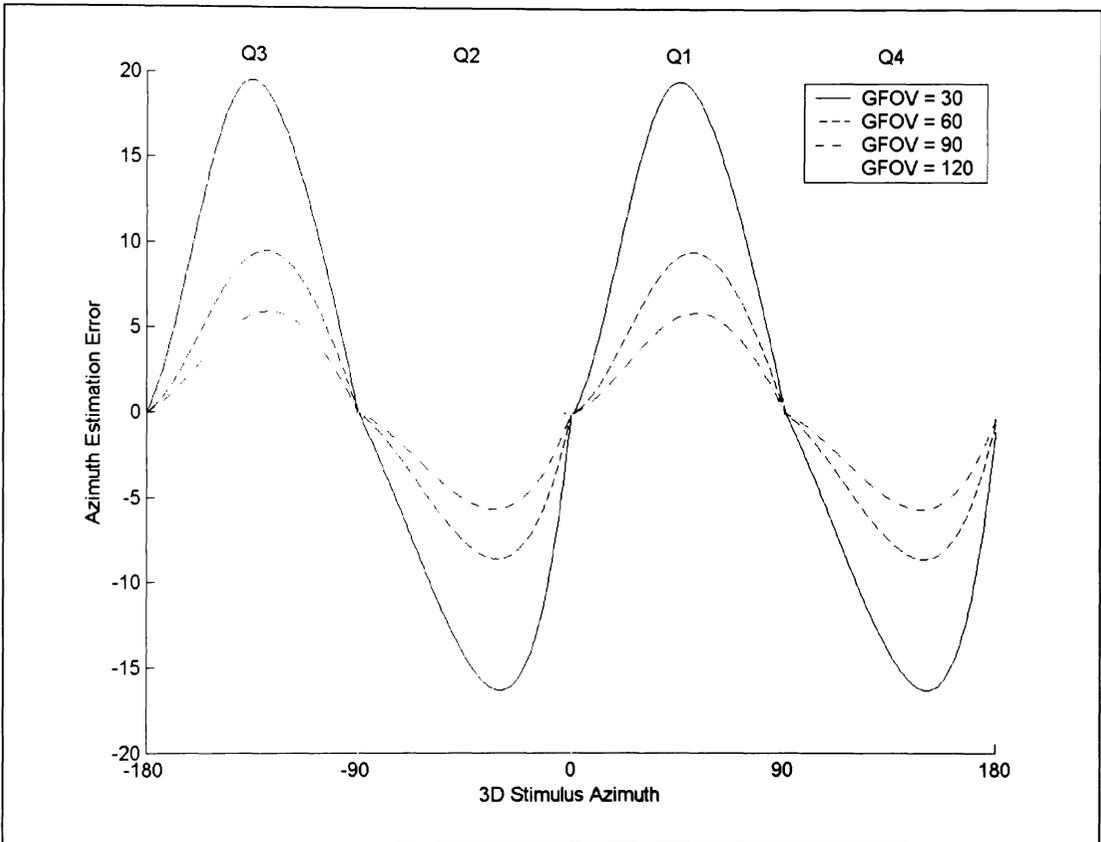
Figure 43. Predicted error based on the 2D strategy at 20 metres.
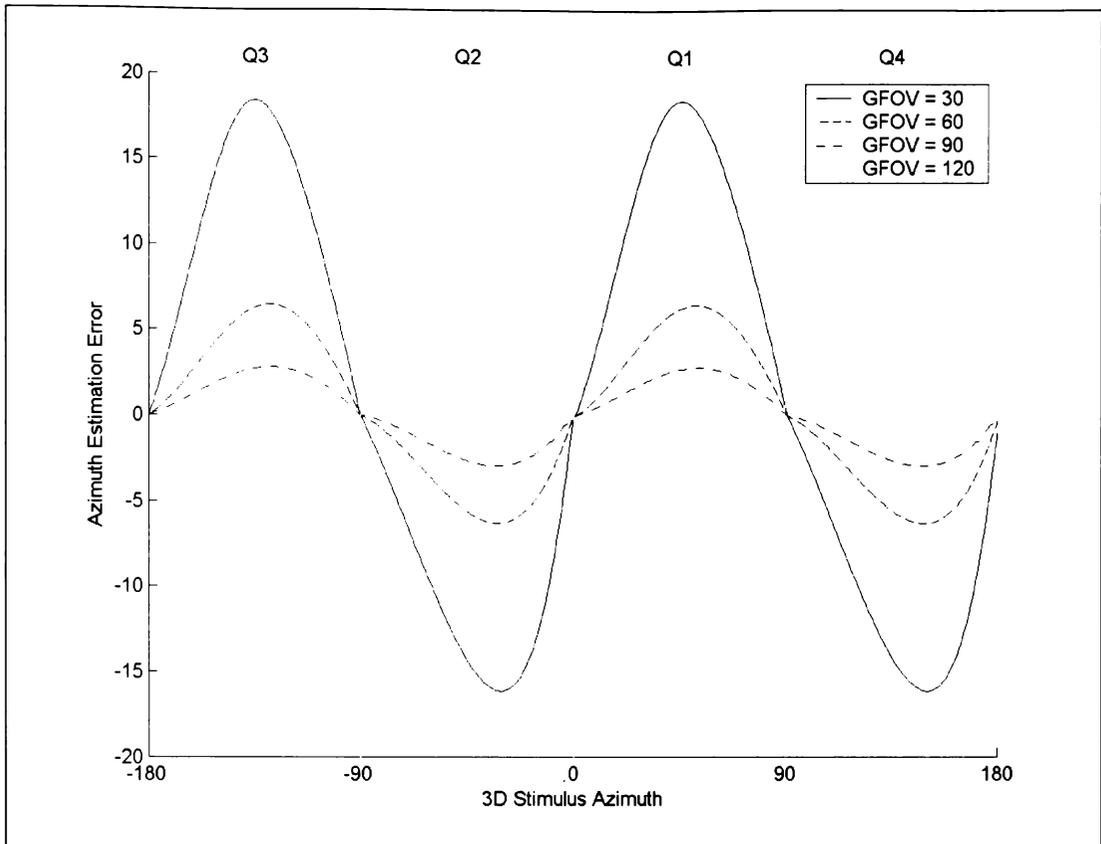
Figure 44. Predicted error based on the 2D strategy at 15 metres.

Conclusions

Within this chapter the two models developed to explain inter-object distance estimation errors in perspective displays were applied to the azimuth estimation errors observed by McGreevy and Ellis (1986) and Ellis et al. (1989). Firstly, the predictions of the Distance Misperception model were compared to the errors observed by Ellis and colleagues. The model posited that observers made errors in estimating the distance between themselves and objects in the display. It was theorised that these distance estimation errors might result in the observer incorrectly translating the 2D (on-screen) angles into 3D perspective angles. However, analyses revealed that the errors found by Ellis and colleagues could not be modelled as simple distance misperception errors. Though it should be noted that the predictions of the distance misperception model did show a similar curvilinear function to the errors observed by Ellis et al. suggesting that a distance perception error may play some part in the errors observed in their data and that further explorations of distance misperception may result in a better fit of the model

to the data. Analyses were also conducted based on a 2D-based strategy that hypothesised that observers made use of the projected 2D angles within the grid lines and the 2D angle between the reference and target cubes. Results showed that this model predicted azimuth estimation error quite closely. In fact, the models predictions were somewhat closer to the data than those presented by Ellis and colleagues own model (presented in Appendix G).

The results of the analyses of the two models presented in this chapter suggest that observers may have used a 2D based strategy to estimate the 3D relationship between the target and reference cubes in the NASA-Ames stimulus. However, it should be noted that the 2D strategy model was only applied to a limited range of gridline positions (they vary throughout the image). Also, it was difficult to ascertain the exact distances at which the images were presented in these studies. As a result, the distances chosen represent estimations of distances that were within the range tested by Ellis and colleagues. In addition, the current analysis could only approximate the scaling that was conducted on the images presented in the original experiments. Therefore, with further work it is possible that the 2D model might be refined so that it better approximates the azimuth estimation errors observed by Ellis et al.

General Summary and Conclusions

One of the main areas of interest in research on free flight is the design of CDTI displays. Under free flight these displays would be added to aircraft cockpits to assist pilots when navigating, particularly in terms of avoiding conflicts with other aircraft. While researchers have stated that presenting CDTIs as perspective displays is intuitively preferable (as the user is not required to integrate information from several sources) studies have also shown that operators can experience difficulties in accurately identifying and avoiding conflicts. It has been suggested that this is because of perceptual ambiguities and biases caused by the geometric parameters used to generate the projection (McGreevy & Ellis, 1986). However, because of the potential advantages in integrating CDTIs researchers have urged continued efforts in characterising and eliminating these perceptual distortions.

The main goal of this thesis was to develop a model of distance estimation in perspective displays and to test the model against the azimuth estimation errors observed by McGreevy and Ellis (1986), and Ellis et al. (1989). It was hoped that this study would contribute both in terms of assisting in display design and also in terms of adding to general understanding of picture perception. It was hypothesised that azimuth estimation errors resulted from observers misperceiving the distance between themselves and objects in the virtual world. This explanation was based on previous studies which found compression of perceived depth in both real world and pictorial paradigms. It was notable that several of these studies also found angular estimation errors similar to those observed by Ellis and colleagues (e.g. Wagner, 1985).

In order to develop a model of distance estimation, experiments were conducted that measured inter-object distance estimations (see Experiments 1 to 4). The main finding of these studies was that participants made substantial inter-object distance estimation errors. They tended to underestimate the depth relative to width. This effect increased substantially as the distance between the participant and objects in the scene increased, indicating that they failed to follow the function that specified the relationship between visual angle and distance. Results showed a small but consistent effect of GFOV such that overall error was reduced somewhat at wider GFOVs. The presentation of gridlines on the ground plane also almost always reduced error. Finally,

the addition of both aperture and stereo enhancements (intended to reduce the 2D cues to the picture surface available to participants) reduced error to a small extent. However, the main finding of inter-object distance estimation errors remained consistent across all experimental conditions.

Based on these findings, two models were developed. The Distance Misperception model predicted inter-object distance estimation error by assuming that observers were acting as if objects in the perspective display were much closer to themselves than they actually were. The relationship between perceived and actual distance was found to be well modelled using a power function of the form $D' = 0.34/D^{0.4}$. This model could potentially explain many aspects of picture perception in which visual space is compressed. However, it needs to be tested more systematically against the results of other studies involving relative depth estimation (e.g. slant estimations, Perrone 1980, 1982). While this model appears to provide a good account of the distortions in perceived pictorial space that occur in 'simple' displays with the line of sight aligned with the horizontal, it does not seem to be easily applied to cases in which azimuth and elevation of the viewport are utilised (e.g. Ellis et al, 1989). Though it should be noted that only one possible type of distance estimation error was tested against azimuth estimation errors, it is possible that with further work a distance estimation model might be developed that better predicts these errors. However, while testing Ellis et al's data against the depth misperception model it was noticed that participants in this study could also have used a simple 2D strategy.

The 2D Strategy model showed that it was possible to model inter-object distance estimation errors by assuming that observers used a 2D strategy based solely on the image projected onto the computer screen with no assumptions about the perceived distance of objects in the scene. Therefore, the possibility of a 2D strategy that may explain azimuth estimation errors was also considered. It was found that a strategy based upon observers using the 2D on-screen projections of both the gridlines and the target/reference cube angle predicted errors that fitted well with the azimuth estimation errors observed by Ellis and colleagues. The 2D model provides a relatively simple explanation of the observed errors and also seems to predict the errors more accurately than the model developed by McGreevy et al. (1985).

It should be noted that assessing the two models developed in this study against the data described by Ellis and colleagues presented several issues. Because the distances at which stimulus was presented in these studies were given in arbitrary units it was not possible to be absolutely sure that the correct distances were being compared. In addition, information about the scaling conducted on the perspective images in the NASA-Ames studies was not sufficient to be certain that the parameters had been completely replicated in the current studies. Therefore, the parameters provided to the models were (to a certain extent) estimates. It seems likely that with further testing, and clarification of the original display parameters, the model may be fitted even more accurately to the azimuth estimation data collected by Ellis and colleagues.

As noted above, this study was designed to provide information that might assist display designers in developing perspective displays (particularly CDTIs) that reduce perceptual errors. The results of this study provide some clear indications with regard to display design. Firstly, it appears that observers are prone to using the 2D information available on the display screen to make judgements about the relationship between objects in 3D space. It seems possible that they do this because the visual system is not equipped to derive detailed spatial information from the impoverished perspective images used in these displays. Therefore, one method of reducing perceptual errors (such as azimuth estimation errors) may be to present the display so that the 2D projections on the display screen match the 3D relationships in virtual space as closely as possible. While this may be difficult in many instances, it is possible to use GFOVs, elevated views, and distances (observer to objects in the display) that will achieve this goal. Perhaps the more difficult issue to overcome in terms of display design is the large inter-object distance estimation errors that were made by participants in the experiments conducted in this thesis. It is hard to envisage how the viewers' lack of understanding of fundamental principles of perspective geometry (such as the relationship between visual angle and distance) could be overcome.

In reference to comparing perspective displays with conventional co-planar displays, Wickens et al. (1997) stated that the performance differences between planar/co-planar and perspective displays were relatively subtle because of the trade-off between two information-processing mechanisms. The planar/co-planar format requires

pilots to visually scan several displays and to mentally integrate them. However, the perspective format results in perceptual ambiguities which the pilot may not even be aware of. Therefore, any decision regarding the efficacy of perspective displays must be made in light of the alternative, 2D co-planar displays. While the co-planar format would likely impose a higher workload on pilots particularly because they must integrate two 2D projections into an integrated 3D space, misperceiving the relationship between objects in the display space would have a substantial impact on pilot SA and performance. Therefore, it must be concluded that a co-planar display is preferable until the perceptual errors inherent in perspective displays are fully understood and eliminated. The results of this thesis suggest some avenues for further research towards achieving this goal. In particular, future research should explore the impact of 2D information on viewers perceptions of 3D virtual space.

Another goal of this study was to examine issues related to picture perception in general, and also to test an alternative methodology for examining the nature of visual space. The study provided a new method for testing both distance perception and inter-object distance perception. The method (adjusting a 3D box until it appeared to be a cube) required participants to make a depth estimate scaled relative to the frontoparallel plane. However, it did not require them to make any explicit distance estimations. The findings of this study were relatively similar to other studies of distance estimation providing support for this new methodology. In addition, participants found adjusting the box to be relatively easy and intuitive. Therefore this thesis provided a new tool with which space perception could be examined.

As mentioned above, the results of this study were similar to several other studies that have examined depth perception (both real world and pictorial). Several other researchers have also found that inter-object depth is misperceived, in particular Wagner (1985). However, within his study observers were generally required to estimate the distance between two objects, in the current study participants were required to scale one object relative to another. Therefore, they were required to interact with objects in the display rather than merely view them. Given the fundamental differences between these types of tasks it is notable that the results were

similar. However, the differences between the tasks may account for the larger errors observed in the current study.

In addition to examining space perception and picture perception in general, this study investigated whether the observed perceptual errors were affected by various display parameters. The impact of GFOV was of particular interest as was the effect of enhancing 3D monocular cues to the virtual space and limiting 2D cues to the image surface (screen frame, binocular disparity, etc). Therefore, across all experiments stimulus was presented at a range of GFOVs. Several researchers have found that GFOV impacts on perceived distance to a substantial degree. For example, Kraft et al. (1986) and Kraft and Green (1989) both found that the shorter the focal length of the camera lens the greater the perceived distance of objects in the scene. Also, Lumsden (1983) used photographic lenses to examine distance perception under two levels of magnification and two levels of photographic truncation. Participants were required to make judgements of the radial distance between two posts presented in the photographic slides (a very similar task to setting the 2D box to a cube). Results showed a significant main effect of magnification. Interestingly, he also reported that the underestimation of radial distance between the distant posts was so great, even in normally truncated slides, that little more compression of space could occur due to magnification or further truncation. These observations seem to relate well to the substantial errors in setting the box to a cube at distance observed in these experiments. However, within this study the effect of GFOV, while significant, was relatively small. This may be because (as Lumsden observed) perceptions of distance were so distorted that there was relatively little room for them to be affected by field of view.

One suggested hypothesis for depth estimation errors in pictures is that cues that specify the picture surface conflict with the cues that specify depth causing the observer to underestimate the distance to objects in the scene. Rogers (1995) commented that obscuring the frame of an object reduces information for the picture as a flat object and should, theoretically, increase its perceived depth. Several studies have found that viewers have a stronger impression of 3D space when pictures are viewed so that the frame is obscured (e.g. Koenderink et al., 1995). Therefore, one experiment in this thesis eliminated the frame using an aperture. However, in this study obscuring the

picture frame had a relatively minor effect on error. It was thought that this was most likely because only one source of information about the 2D nature of the image was eliminated. Other, perhaps more important, sources such as binocular disparity were retained. Therefore, a further study was conducted that eliminated binocular disparity by presenting the stimulus stereoscopically. However, it was found that this enhancement had only a marginal impact on error. While error was reduced under these conditions, participants still continued to set the front face of the box too far away to represent a true cube. This result is of interest because it suggests that, contrary to the comments of Rogers (1995), errors in perceiving depth in perspective images cannot be attributed to a conflict between the visual information that specifies the pictures surface and the pictorial information that specifies its 3D layout. The Distance Misperception model developed in this thesis provides a possible alternative explanation for depth perception errors when viewing pictures. However, while the model adequately predicted the data within this experimental task, it is essential that the predictions of the model be tested against other experimental tasks (e.g. slant perception). It is important to note that the virtual environment presented to participants within these experiments was relatively impoverished. Therefore, it seems likely that in less sparse environments distance perception errors may well be less severe.

This thesis examined a range of issues in picture perception; in particular, it highlighted the effect of distance perception errors on the ability of the observer to extract accurate information about the relationship between objects in an image and provided a model to predict distance estimation errors in perspective displays. In addition, the use of 2D strategies to extract information about the 3D nature of visual space was also explored. It was found that a 2D strategy could account for azimuth estimation errors. Designers and researchers need to be aware that some observers perceive and respond to '3D' perspective displays as though they are flat 2D pictures! The information gathered in this thesis is of interest both at a theoretical and a practical level and, with further work, could assist display designers in producing CDTIs that reduce perceptual errors.

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APPENDIX A - Mean Error and SD (Experiment 1)

GFOV 30	Dist One 1.25 (m)	Dist Two 1.5 (m)	Dist Three 1.75 (m)	Dist Four 2.0 (m)	Dist Five 3.0 (m)	Dist Six 4.0 (m)	Dist Seven 5.0 (m)
Mean Error (m)	0.80	1.12	1.3	1.45	2.19	2.19	2.86
Std. Dev (m)	0.41	0.54	0.53	0.67	0.98	0.71	0.98
GFOV 40	**Dist One 0.9 (m)**	**Dist Two 1.0 (m)**	**Dist Three 1.25 (m)**	**Dist Four 1.5 (m)**	**Dist Five 1.75 (m)**	**Dist Six 2.0 (m)**	**Dist Seven 3.0 (m)**
Mean Error (m)	0.61	0.69	0.91	1.14	1.27	1.46	2.12
Std. Dev (m)	0.36	0.37	0.37	0.49	0.46	0.50	0.78
GFOV 60	**Dist One 0.7 (m)**	**Dist Two 0.8 (m)**	**Dist Three 0.9 (m)**	**Dist Four 1.0 (m)**	**Dist Five 1.25 (m)**	**Dist Six 1.5 (m)**	**Dist Seven 2.0 (m)**
Mean Error (m)	0.35	0.49	0.57	0.65	0.89	1.1	1.5
Std. Dev (m)	0.23	0.30	0.34	0.31	0.44	0.45	0.54
GFOV 80	**Dist One 0.5 (m)**	**Dist Two 0.6 (m)**	**Dist Three 0.7 (m)**	**Dist Four 0.8 (m)**	**Dist Five 0.9 (m)**	**Dist Six 1.0 (m)**	**Dist Seven 1.5 (m)**
Mean Error (m)	0.13	0.26	0.40	0.46	0.59	0.66	1.1
Std. Dev (m)	0.20	0.24	0.30	0.32	0.36	0.38	0.05

APPENDIX B - Mean error and SD (Experiment 2)

GFOV 30	Dist One 1.25 (m)	Dist Two 1.5 (m)	Dist Three 1.75 (m)	Dist Four 2.0 (m)	Dist Five 3.0 (m)	Dist Six 4.0 (m)	Dist Seven 5.0 (m)
No Grid							
Mean Error (m)	0.74	0.97	1.20	1.35	2.20	2.76	3.44
Std. Dev (m)	0.30	0.33	0.35	0.45	0.54	0.84	0.95
Grid A							
Mean Error (m)	0.67	0.83	1.02	1.16	1.67	2.17	2.80
Std. Dev (m)	0.31	0.28	0.38	0.37	0.42	0.59	0.77
Grid B							
Mean Error (m)	0.85	1.0	1.19	1.41	1.98	2.58	3.01
Std. Dev (m)	0.22	0.32	0.38	0.37	0.59	0.85	1.10
GFOV 40	Dist One 0.9 (m)	Dist Two 1.0 (m)	Dist Three 1.25 (m)	Dist Four 1.5 (m)	Dist Five 1.75 (m)	Dist Six 2.0 (m)	Dist Seven 3.0 (m)
No Grid							
Mean Error (m)	0.43	0.50	0.78	0.92	1.17	1.32	2.06
Std. Dev (m)	0.26	0.26	0.35	0.45	0.38	0.49	0.76
Grid A							
Mean Error (m)	0.48	0.50	0.75	0.79	0.99	1.15	1.57
Std. Dev (m)	0.20	0.17	0.27	0.28	0.31	0.35	0.46
Grid B							
Mean Error (m)	0.58	0.59	0.77	0.91	1.09	1.35	1.85
Std. Dev (m)	0.30	0.23	0.19	0.29	0.38	0.43	0.56
GFOV 60	Dist One 0.7 (m)	Dist Two 0.8 (m)	Dist Three 0.9 (m)	Dist Four 1.0 (m)	Dist Five 1.25 (m)	Dist Six 1.5 (m)	Dist Seven 2.0 (m)
No Grid							
Mean Error (m)	0.25	0.35	0.41	0.52	0.76	0.90	1.42
Std. Dev (m)	0.21	0.24	0.23	0.21	0.24	0.34	0.52
Grid A							
Mean Error (m)	0.31	0.40	0.40	0.48	0.61	0.76	1.21
Std. Dev (m)	0.17	0.19	0.19	0.20	0.22	0.28	0.39

GFOV 60	Dist One 0.7 (m)	Dist Two 0.8 (m)	Dist Three 0.9 (m)	Dist Four 1.0 (m)	Dist Five 1.25 (m)	Dist Six 1.5 (m)	Dist Seven 2.0 (m)
Grid B							
Mean Error (m)	0.32	0.44	0.50	0.53	0.80	0.93	1.27
Std. Dev (m)	0.19	0.21	0.24	0.25	0.35	0.44	0.37
GFOV 80	Dist One 0.5 (m)	Dist Two 0.6 (m)	Dist Three 0.7 (m)	Dist Four 0.8 (m)	Dist Five 0.9 (m)	Dist Six 1.0 (m)	Dist Seven 1.5 (m)
No Grid							
Mean Error (m)	0.07	0.18	0.26	0.34	0.41	0.55	0.92
Std. Dev (m)	0.18	0.18	0.20	0.20	0.22	0.25	0.38
Grid A							
Mean Error (m)	0.12	0.18	0.30	0.33	0.43	0.46	0.82
Std. Dev (m)	0.19	0.13	0.22	0.21	0.20	0.20	0.29
Grid B							
Mean Error (m)	0.14	0.24	0.28	0.46	0.46	0.53	0.98
Std. Dev (m)	0.18	0.14	0.18	0.26	0.23	0.25	0.40

# APPENDIX C - Mean error and SD (Experiment 3)

GFOV 30	Dist One 1.25 (m)	Dist Two 1.5 (m)	Dist Three 1.75 (m)	Dist Four 2.0 (m)	Dist Five 3.0 (m)	Dist Six 4.0 (m)	Dist Seven 5.0 (m)
No Grid							
Mean Error (m)	0.89	1.14	1.28	1.51	2.20	2.88	3.61
Std. Dev (m)	0.33	0.43	0.52	0.63	0.89	1.30	1.68
Grid A							
Mean Error (m)	0.90	1.10	1.22	1.36	2.11	2.67	3.30
Std. Dev (m)	0.37	0.42	0.54	0.53	0.92	1.23	1.58
Grid B							
Mean Error (m)	0.85	1.0	1.14	1.36	2.02	2.53	3.11
Std. Dev (m)	0.37	0.45	0.51	0.61	1.0	1.25	1.80
GFOV 40	**Dist One 0.9 (m)**	**Dist Two 1.0 (m)**	**Dist Three 1.25 (m)**	**Dist Four 1.5 (m)**	**Dist Five 1.75 (m)**	**Dist Six 2.0 (m)**	**Dist Seven 3.0 (m)**
No Grid							
Mean Error (m)	0.59	0.69	0.85	1.07	1.25	1.54	2.11
Std. Dev (m)	0.25	0.31	0.43	0.45	0.54	0.65	0.93
Grid A							
Mean Error (m)	0.52	0.62	0.78	0.99	1.19	1.32	2.0
Std. Dev (m)	0.20	0.22	0.31	0.38	0.49	0.53	0.90
Grid B							
Mean Error (m)	0.54	0.59	0.80	1.0	1.15	1.34	1.99
Std. Dev (m)	0.20	0.24	0.32	0.39	0.49	0.56	1.02
GFOV 60	**Dist One 0.7 (m)**	**Dist Two 0.8 (m)**	**Dist Three 0.9 (m)**	**Dist Four 1.0 (m)**	**Dist Five 1.25 (m)**	**Dist Six 1.5 (m)**	**Dist Seven 2.0 (m)**
No Grid							
Mean Error (m)	0.40	0.48	0.58	0.64	0.85	1.08	1.55
Std. Dev (m)	0.25	0.24	0.30	0.34	0.39	0.56	0.70
Grid A							
Mean Error (m)	0.35	0.48	0.56	0.65	0.81	0.99	1.40
Std. Dev (m)	0.15	0.21	0.23	0.27	0.37	0.39	0.66

| GFOV 60	Dist One 0.7 (m)	Dist Two 0.8 (m)	Dist Three 0.9 (m)	Dist Four 1.0 (m)	Dist Five 1.25 (m)	Dist Six 1.5 (m)	Dist Seven 2.0 (m)
Grid B							
Mean Error (m)	0.35	0.43	0.50	0.57	0.77	1.01	1.31
Std. Dev (m)	0.19	0.20	0.23	0.27	0.37	0.51	0.64
GFOV 80	Dist One 0.5 (m)	Dist Two 0.6 (m)	Dist Three 0.7 (m)	Dist Four 0.8 (m)	Dist Five 0.9 (m)	Dist Six 1.0 (m)	Dist Seven 1.5 (m)
No Grid							
Mean Error (m)	0.16	0.24	0.35	0.44	0.50	0.57	1.06
Std. Dev (m)	0.15	0.14	0.22	0.25	0.27	0.31	0.55
Grid A							
Mean Error (m)	0.20	0.28	0.35	0.44	0.50	0.60	0.95
Std. Dev (m)	0.10	0.14	0.16	0.19	0.20	0.27	0.48
Grid B							
Mean Error (m)	0.21	0.24	0.36	0.50	0.57	0.63	0.98
Std. Dev (m)	0.16	0.17	0.20	0.28	0.25	0.29	0.50

APPENDIX D - Mean error and SD (Experiment 4)

| GFOV 30	Dist One 1.75 (m)	Dist Two 2.0 (m)	Dist Three 3.0 (m)	Dist Four 4.0 (m)	Dist Five 5.0 (m)	Dist Six 6.0 (m)	Dist Seven 7.0 (m)
No Grid - Normal							
Mean Error (m)	1.21	1.42	2.18	2.50	3.26	3.55	4.33
Std. Dev (m)	0.35	0.46	0.56	0.77	0.96	1.30	1.45
No Grid – Stereo							
Mean Error (m)	1.18	1.43	1.88	2.57	3.03	3.69	4.10
Std. Dev (m)	0.47	0.45	0.65	0.67	0.97	1.18	1.23
Grid A- Normal							
Mean Error (m)	1.06	1.18	1.63	2.09	2.61	2.96	3.52
Std. Dev (m)	0.36	0.42	0.46	0.63	0.72	0.74	1.15
Grid A- Stereo							
Mean Error (m)	1.03	1.12	1.61	2.06	2.38	2.74	3.31
Std. Dev (m)	0.43	0.50	0.50	0.67	0.80	0.74	0.99
GFOV 60	**Dist One 1.75 (m)**	**Dist Two 2.0 (m)**	**Dist Three 2.25 (m)**	**Dist Four 2.5 (m)**	**Dist Five 2.75 (m)**	**Dist Six 3.0 (m)**	**Dist Seven 4.0 (m)**
No Grid – Normal							
Mean Error (m)	1.21	1.26	1.53	1.61	1.85	2.11	2.85
Std. Dev (m)	0.57	0.34	0.41	0.48	0.54	0.46	0.70
No Grid – Stereo							
Mean Error (m)	1.0	1.11	1.40	1.59	1.59	1.83	2.35
Std. Dev (m)	0.33	0.43	0.43	0.52	0.48	0.50	0.60
Grid A - Normal							
Mean Error (m)	1.19	1.43	1.52	1.65	1.51	1.65	2.09
Std. Dev (m)	0.38	0.46	0.47	0.49	0.47	0.49	0.49
Grid A - Stereo							
Mean Error (m)	0.96	1.07	1.29	1.34	1.50	1.53	2.01
Std. Dev (m)	0.38	0.43	0.64	0.36	0.49	0.47	0.55

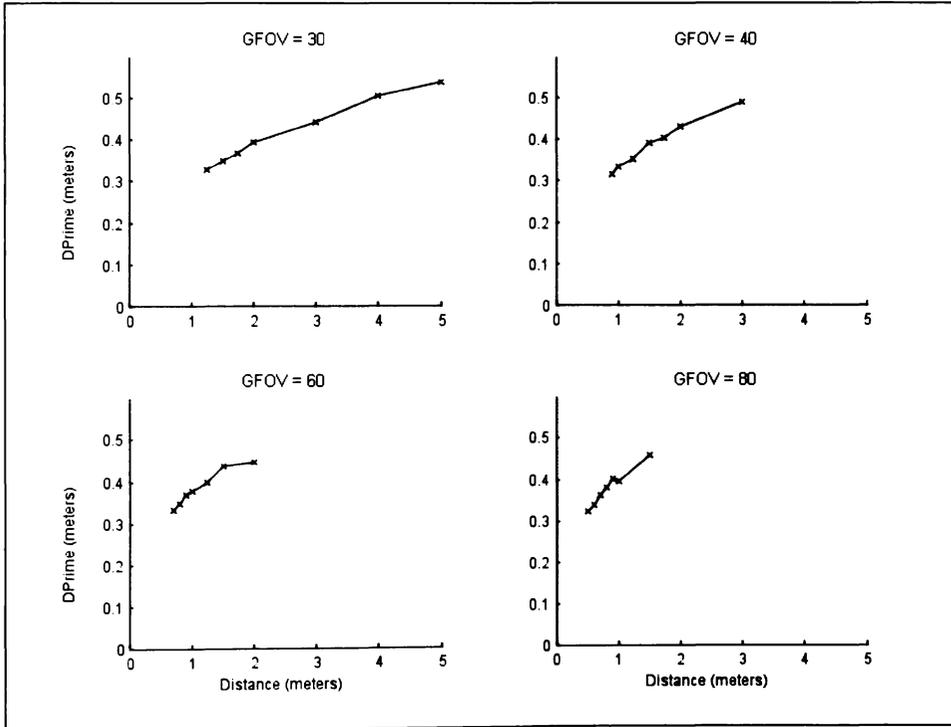# APPENDIX E – Perceived Distance (Experiments 1 thru 3)
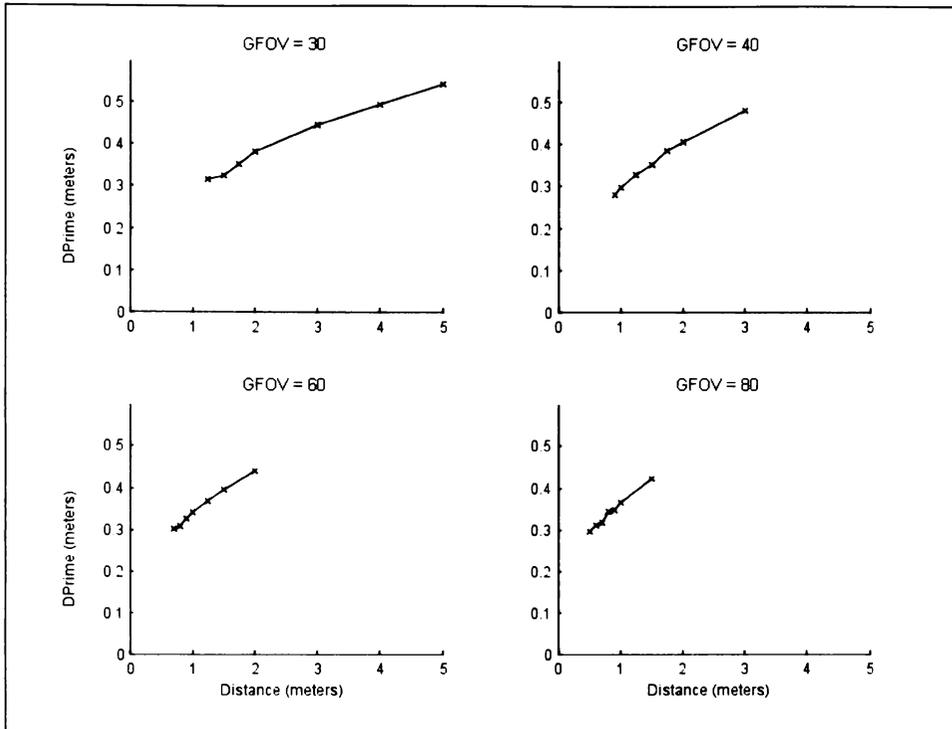
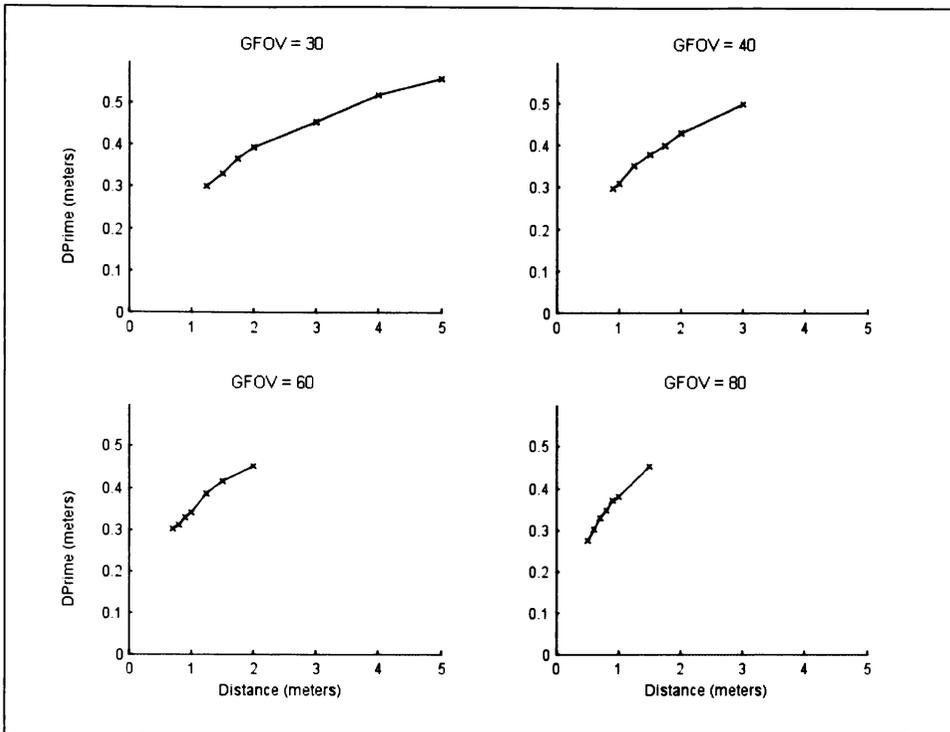Perceived distance to front face of box (Experiment 1).
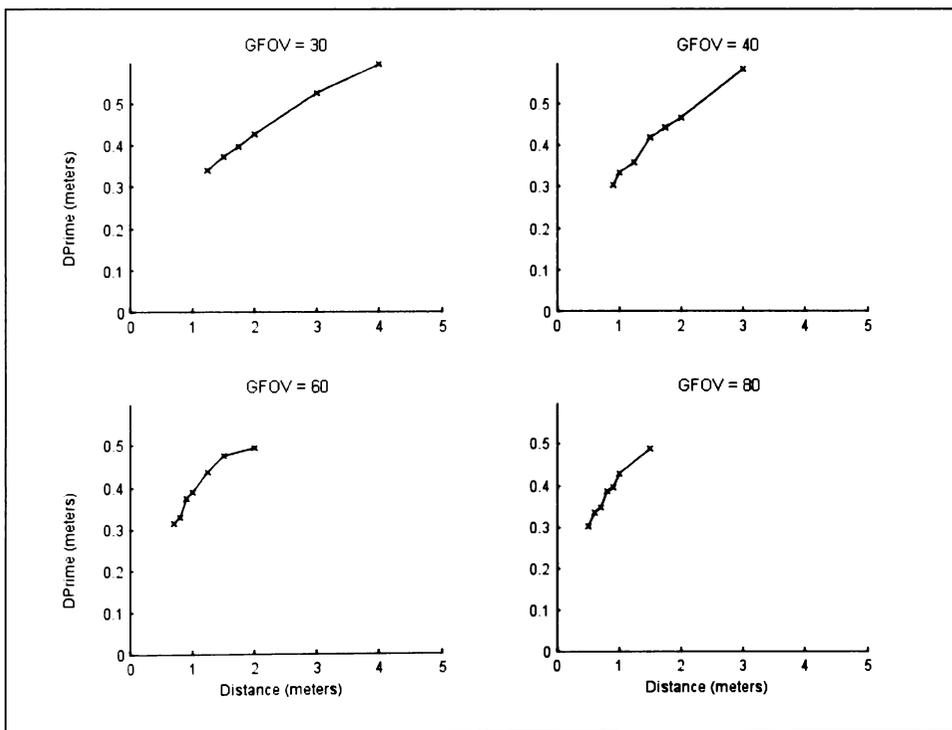
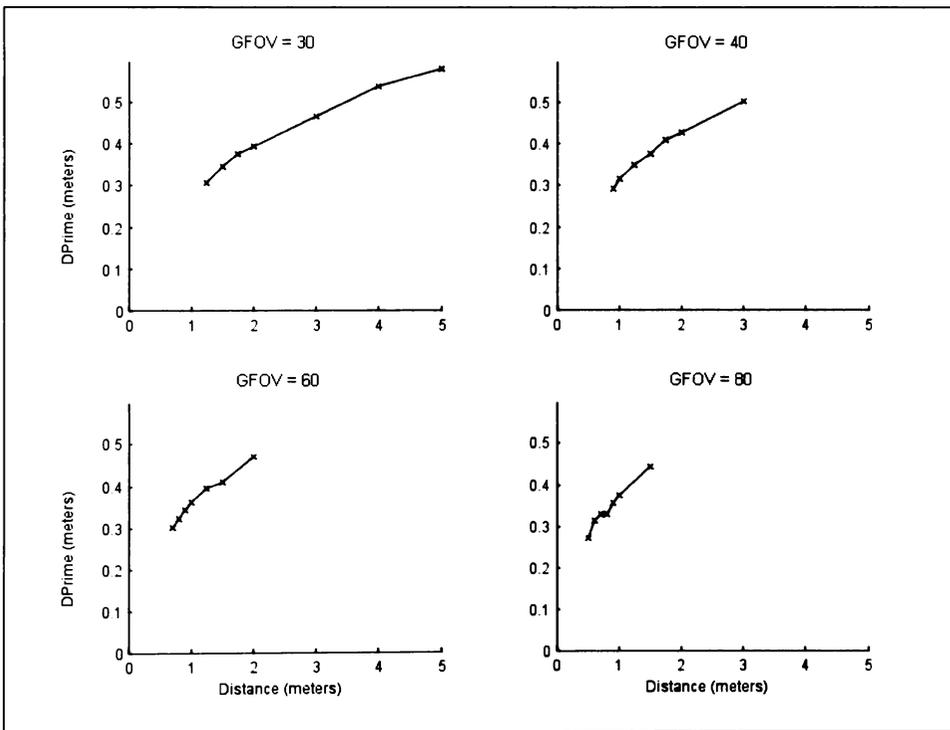Perceived distance to front face of box (Experiment 2, no grid condition).
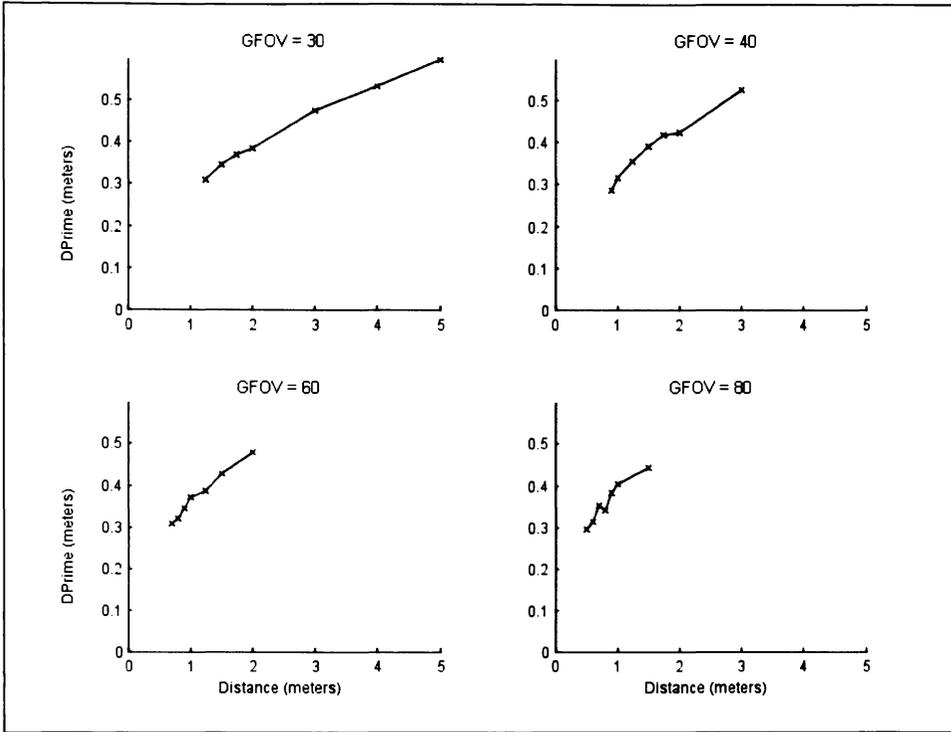
Perceived distance to front face of box (Experiment 2, grid A condition).
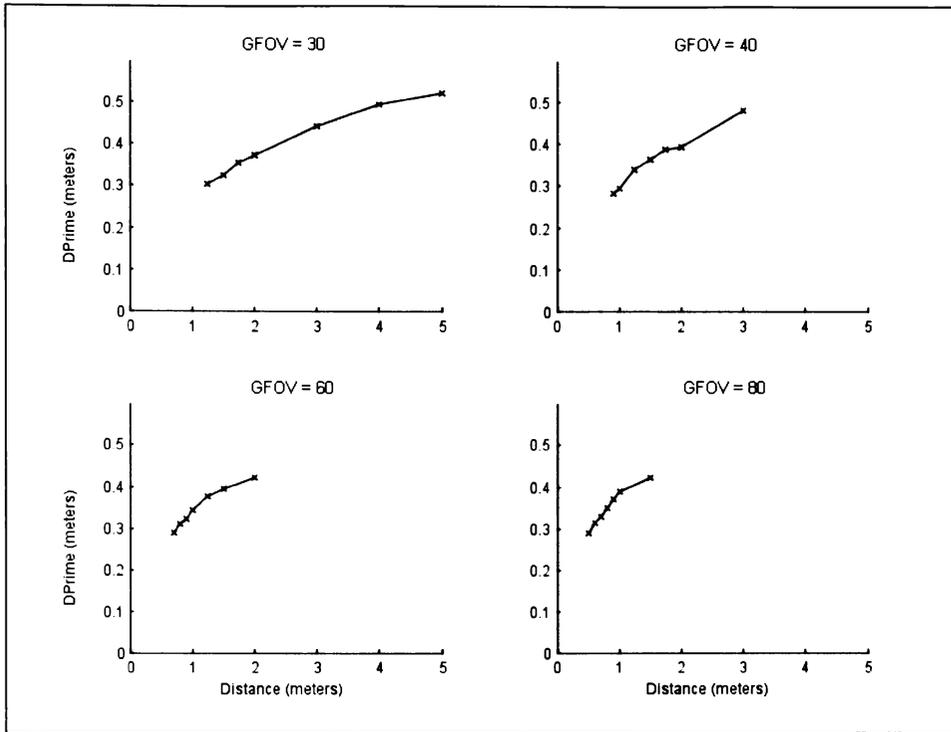

Perceived distance to front face of box (Experiment 2, grid B condition).

Perceived distance to front face of box (Experiment 3, no grid condition).

Perceived distance to front face of box (Experiment 3, grid A condition).

Perceived distance to front face of box (Experiment 3, grid B condition).

APPENDIX F – Ratio Set (Front Face Height/Width)

NO GRID							
GFOV 30	**Dist One 1.25 (m)**	**Dist Two 1.5 (m)**	**Dist Three 1.75 (m)**	**Dist Four 2.0 (m)**	**Dist Five 3.0 (m)**	**Dist Six 4.0 (m)**	**Dist Seven 5.0 (m)**
Percentage Set (%)	26	26	25	25	24	23	22
GFOV 40	**Dist One 0.9 (m)**	**Dist Two 1.0 (m)**	**Dist Three 1.25 (m)**	**Dist Four 1.5 (m)**	**Dist Five 1.75 (m)**	**Dist Six 2.0 (m)**	**Dist Seven 3.0 (m)**
Percentage Set (%)	27	27	26	25	25	25	23
GFOV 60	**Dist One 0.7 (m)**	**Dist Two 0.8 (m)**	**Dist Three 0.9 (m)**	**Dist Four 1.0 (m)**	**Dist Five 1.25 (m)**	**Dist Six 1.5 (m)**	**Dist Seven 2.0 (m)**
Percentage (%)	27	27	27	26	26	25	25
GFOV 80	**Dist One 0.5 (m)**	**Dist Two 0.6 (m)**	**Dist Three 0.7 (m)**	**Dist Four 0.8 (m)**	**Dist Five 0.9 (m)**	**Dist Six 1.0 (m)**	**Dist Seven 1.5 (m)**
Percentage (%)	28	27	27	27	26	26	25
GRID							
GFOV 30	**Dist One 1.25 (m)**	**Dist Two 1.5 (m)**	**Dist Three 1.75 (m)**	**Dist Four 2.0 (m)**	**Dist Five 3.0 (m)**	**Dist Six 4.0 (m)**	**Dist Seven 5.0 (m)**
Percentage (%)	26	25	24	24	22	21	21
GFOV 40	**Dist One 0.9 (m)**	**Dist Two 1.0 (m)**	**Dist Three 1.25 (m)**	**Dist Four 1.5 (m)**	**Dist Five 1.75 (m)**	**Dist Six 2.0 (m)**	**Dist Seven 3.0 (m)**
Percentage (%)	27	26	25	24	24	24	22
GFOV 60	**Dist One 0.7 (m)**	**Dist Two 0.8 (m)**	**Dist Three 0.9 (m)**	**Dist Four 1.0 (m)**	**Dist Five 1.25 (m)**	**Dist Six 1.5 (m)**	**Dist Seven 2.0 (m)**
Percentage (%)	27	27	26	26	25	24	24
GFOV 80	**Dist One 0.5 (m)**	**Dist Two 0.6 (m)**	**Dist Three 0.7 (m)**	**Dist Four 0.8 (m)**	**Dist Five 0.9 (m)**	**Dist Six 1.0 (m)**	**Dist Seven 1.5 (m)**
Percentage (%)	29	28	27	27	26	26	24

APPENDIX G – Azimuth Estimation Errors and Predictions based on Model (McGreevy et al., 1985).
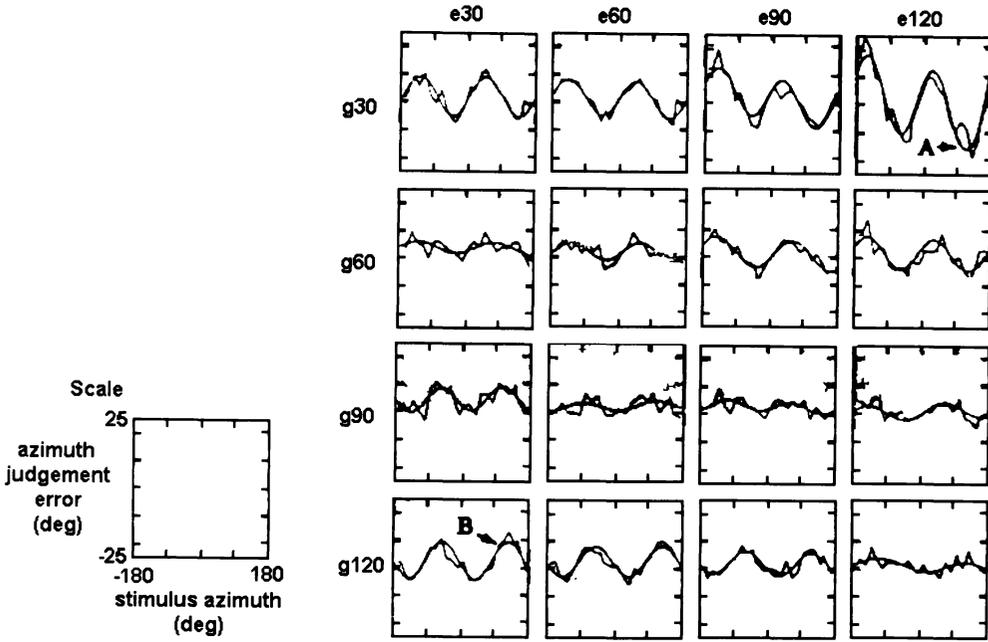
Mean azimuth error and fitted lines (note that errors at A and B differ by about 25 degrees)
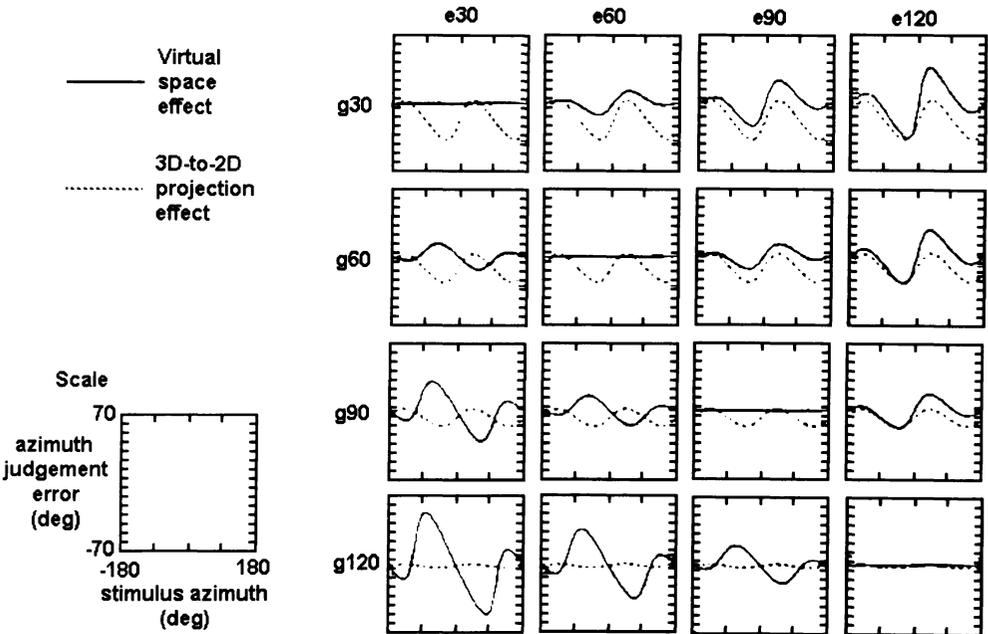
Virtual space effect and 3D-to-2D projection effect difference functions for conditions of the experiment