INFORMATION TO USERS

This reproduction was made from a copy of a document sent to us for microfilming. While the most advanced technology has been used to photograph and reproduce this document, the quality of the reproduction is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help clarify markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure complete continuity.

2. When an image on the film is obliterated with a round black mark, it is an indication of either blurred copy because of movement during exposure, duplicate copy, or copyrighted materials that should not have been filmed. For blurred pages, a good image of the page can be found in the adjacent frame. If copyrighted materials were deleted, a target note will appear listing the pages in the adjacent frame.

3. When a map, drawing or chart, etc., is part of the material being photographed, a definite method of "sectioning" the material has been followed. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.

4. For illustrations that cannot be satisfactorily reproduced by xerographic means, photographic prints can be purchased at additional cost and inserted into your xerographic copy. These prints are available upon request from the Dissertations Customer Services Department.

5. Some pages in any document may have indistinct print. In all cases the best available copy has been filmed.

University
Microfilms
International

300 N. Zeeb Road
Ann Arbor, MI 48106

8421231

Spain, Edward Huland

A PSYCHOPHYSICAL INVESTIGATION OF THE PERCEPTION OF DEPTH WITH STEREOSCOPIC TELEVISION DISPLAYS

University of Hawaii PH.D. 1984

University
Microfilms
International 300 N. Zeeb Road, Ann Arbor, MI 48106

A Psychophysical Investigation of the Perception of Depth With Stereoscopic Television Displays

A DISSERTATION SUBMITTED TO THE GRADUATE DIVISION OF THE
UNIVERSITY OF HAWAII IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

IN PSYCHOLOGY

May 1984

by

Edward Huland Spain

Dissertation Committee:

Robert E. Cole, Chairman
Anthony J. Marsella
Ross L. Pepper
Joseph P. O'Reilly
Edward J. Weldon, Jr.

ACKNOWLEDGEMENTS

This dissertation could have never been completed without the support of many talented, hard-working, and generous friends. For expert technical assistance in designing, building, and maintaining the experimental apparatus I am indebted to David C. Smith, Alan Umeda, and Ruth Croskrey -- all of the Naval Ocean Systems Center, Hawaii Laboratory. For invaluable scientific advice and encouragement I am greatly indebted to Dr. John E. Sigurdson of the Naval Ocean Systems Center, Dr. William R. Uttal of the Institute for Social Research, University of Michigan, and Mr. John O. Merritt of Perceptronics in Woodland Hills, CA. None of this work would have been possible without continuing administrative support from Steven Nicinski and Larry Hallanger of SEACO Inc. and Jim Katayama and Dan Hightower of the Naval Ocean Systems Center. I am deeply indebted to Karen DeMello, Scotti Fujisaka, Janet Beauparlant, and Jim Robinson -- an outstanding group who "lent me their eyes and hands" for one hour each working day over a period of two months to serve as experimental observers. Jim Robinson also deserves special recognition for the fine job he did as my laboratory assistant.

ABSTRACT

A series of four experiments was conducted to investigate the influence of three video system parameters on the scaling of depth intervals with a stereoscopic (stereo) television display. A geometrical model of TV stereoscopy is presented which describes the influence of variations of the three video system parameters on retinal disparities. Experiment One investigated the independent and interactive effects of camera interaxial separation and lens magnification on depth interval scaling. Experiment Two investigated the effects of camera convergence angle on depth interval scaling. Experiments Three and Four partially replicated the video system parameters used in Experiment One under more complex scene conditions. For all experiments, ocular fatigue induced by various combinations of video system parameters was also measured.

Four trained observers participated in Experiments One and Two. An additional observer participated in Experiments Three and Four. The apparatus used to produce depth intervals in the televised scene was a Howard-Dolman two-rod device. Rods were set to a pre-selected depth interval and observers were required to verbally report perceived depth interval and match the depth interval haptically by means of a sliding peg device. Stereoscopic TV imagery was provided by means of a beamsplitter camera station and a polarizer display station. All experiments included monoscopic (2-D) and direct view control conditions. Ocular fatigue tests which were administered included a questionnaire, flicker fusion threshold adjustments, and a near-far test of oculomotor adjustment time.

Multifactorial repeated-measures analyses of covariance were performed on data derived from all experiments with a .05 level set for statistical significance. For Experiments One, Two, and Three stereoscopic imagery produced depth interval estimates which were superior to those found under monoscopic viewing conditions. In addition, increasing camera separation and thereby increasing disparities beyond "natural stereo" values produced improvements in depth interval estimation. Camera convergence exerted a significant effect on performance with camera convergence in front of objects to be compared in depth providing highest accuracy. Lens magnification, which affected retinal disparities, was not found to exert a significant influence on depth interval estimation. For all experiments, no evidence of ocular fatigue was found under any conditions tested.

Results are discussed in light of previous studies of depth resolution with stereo TV displays, geometrical models

of retinal disparities, and models to account for the discrepancies in depth perception observed between stereo TV and direct viewing conditions.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

APPENDICES

LIST OF TABLES

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF TABLES
(Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS
(Continued)

LIST OF SYMBOLS AND ABBREVIATIONS

Linear Distances and Reference Points

A = Fixation point, also linear distance from cameras (or observer) to the fixation point

CMA = Camera lateral midline axis

η_s = Screen parallax - image disparity for corresponding points in the plane of the display screen

F = Target location for a target beyond the fixation point, also distance from the camera (or observer) to that point

I_c = Camera interaxial separation

I_o = Observer's momentary interocular distance - varies with convergence angle

L = Eye to display viewing distance

M = Display horizontal width

MSP = Observer's mid-saggital plane

N = Target location for a target nearer the cameras (or direct observer) than the fixation point

ΔR = Depth increment/decrement from the fixation point to some other point of interest (e.g., N or F)

Angular Measures Expressed in Degrees

α_c = Camera convergence angle

α_o = Convergence angle to the observer's fixation point for direct view, i.e. ocular convergence angle

LIST OF SYMBOLS AND ABBREVIATIONS

(Continued)

α_s = Convergence angle to the observer's fixation point in a display screen

γ = Display screen horizontal field of view

η_o = Retinal disparity between two objects seen in depth

ϕ = Convergence angle to N

θ = Convergence angle to F

Ω = Camera horizontal field of view (FOV)

Scaling Factors

K = $M / (2 * \tan \Omega/2)$, lens magnification

M_v = Video system magnification, that is, γ/Ω

INTRODUCTION

Stereopsis is a perceptual phenomenon of binocular vision for which the necessary and sufficient proximal cue is inherent in slight differences between patterns of light falling on an observer's two retinas (Julesz, 1971). As such, it involves simultaneously viewing some aspect of the external world from two slightly separated viewpoints and perceptually blending these two separate, but distinct, perspectives into a unitary mental representation of external space. Though not a prerequisite to adequate spatial perception in many real-world situations, stereopsis is frequently a powerful adjunct to other visual spatial cues, particularly with regard to precise localization of objects in relative depth (Kaufman, 1974). Stereopsis provides an immediate and compelling perceptual solution to the problem of mentally representing three-dimensional space when the only available visual information regarding the layout of that space is derived from essentially two-dimensional retinal images. When visibility is reduced (i.e., monocular cues to distance and depth are degraded or absent) or surroundings are unfamiliar, stereopsis aids in clarifying the location, size, shape, and orientation of objects. Several prominent authors (Gregory, 1970; Frisby, 1980) have suggested that the primary adaptive significance of stereopsis lies in the ability to effortlessly differentiate objects from ambiguous surroundings. In this sense, stereopsis may be thought of as a powerful anti-camouflage mechanism requiring only low-level preconscious processing, freeing cognitive resources for higher level tasks.

The value of stereopsis is not, however, limited to its well-documented functional advantages. Numerous reports in the literature of amateur photography suggest that human observers derive a compelling sense of solidity, realism, and aesthetic pleasure from viewing stereoscopic images[1]. Indeed, every technological revolution in the collection and communication of visual imagery since Wheatstone's invention of the mirror stereoscope and his publication of a theory of stereopsis with artificial imagery (1838) has been attended by advancements in *stereoscopy* - techniques for providing human viewers with artificially-constructed three-dimensional images.

---

[1] The interested reader may wish to consult the literature of stereoscopic photography. Leading periodicals in this area are Stereo World, a monthly journal of the National Stereoscopic Association and Stereoscopy, a quarterly journal of the International Stereoscopic Union. Morgan and Symmes (1982) Amazing 3-D is an amusing manifestation of the recent resurgence of public interest in stereoscopic imagery.

Today, the technical field of stereoscopy is practiced across a wide variety of media forms including still photography, motion picture photography, aerial photography, photomicroscopy, animation, tomography, computer generated imagery, and stereoscopic television (stereo TV).

Stereo TV is a particularly powerful media form which is simple in basic conception and easily implemented with existing video hardware, but it is quite complex in actual application and presents several interesting perceptual problems to be resolved by perceptual science. Stereo TV provides an observer with detailed, real-time visual information about a remote scene. Use of stereo TV in this way requires perceptual judgments of the spatial relationships conveyed by iconic images, process control, and active observation or even manipulation of objects in the remotely-viewed scene. Stereo TV, as it will be discussed within the confines of this monograph, involves the sensing, transmittance, and display of pairs of images. This narrow definition intentionally excludes several important three dimensional display techniques such as holography, volumetric displays, three-dimensional animation, computer generated three-dimensional imagery, three-dimensional machine "vision", and advanced monoscopic display techniques which capitalize on motion parallax cues to depth (e.g., see Dennis, 1983).

Despite the wide range of specific techniques for producing stereo TV images[2], all stereo TV systems share two defining characteristics: 1) imagery taken from a scene is simultaneously recorded from two vantage points, and 2) such imagery is channeled into the eyes of an observer. Stereo TV is considered to be an important feature of remotely operated systems which are designed to interact intelligently with their environments in performing such complex tasks as sight navigation, active surveillance, and remote manipulation. The advantages of extending man's perceptual and cognitive skills into hostile or remote environments such as the deep oceans or space are considerable in terms of increased safety and reductions in cost and development time.

Within the present context the remote environment, or remote scene, is not necessarily remote in the common sense of the term. Rather, a *remote* environment is not directly observable because of distance (the common meaning), occlusion, or differences in scale between the human eye and the scene of interest. Unlike direct viewing conditions, in

---

[2] Literally hundreds of techniques exist for recording and displaying stereo TV imagery. The reader desiring a detailed review of history and recent technical progress in TV stereoscopy may consult Okoshi (1976), Butterfield (1979), or Lipton (1982).

which an observer is physically present in and visually stimulated by his environment, the remote environment may be removed from the observer by any amount of distance which remote sensors and lines of commmunication can be extended. The only fundamental impediment to providing an operator with an immediate view of a remote environment is electromagnetic transmission speed. While it is theoretically possible to reproduce the pattern of stimulation available at a remote site at a level of detail resolution exceeding the human eye's resolving power, technical limitations of video systems have thus far prevented the achievement of such high levels of fidelity. Efforts are underway to a)improve video hardware as well as to b) systematically vary the perceptual information in imagery from remote environments in order to enhance an observer's perception and ultimately the man-machine system's performance. This monograph reports the results of a series of experiments of the latter type.

Given worldwide interest in stereoscopy for well over a century, and the phenomenal growth of video technology over the past four decades, it is surprising that the available scientific/technical literature of visual performance with stereo TV displays remains small and poorly developed from the standpoint of perceptual science. Recent critical reviews (Pepper & Cole, 1978; Smith, Cole, Merritt, and

Pepper, 1979) have found conclusions and technical guidelines in many of the available reports to be based on faulty methodologies as well as untested and questionable assumptions regarding the perception of spatial relationships in remote scenes. Perhaps the primary reason for the lack of a sound perceptual database is that the great majority of stereoscopic applications to date have been purely recreational. It is obvious that stereoscopic imagery used solely for entertainment purposes need not convey a highly accurate mental representation of spatial relationships within a remote scene to an observer. It need only amuse him with an immediate and compelling sense of realism, depth, and solidity. A second obstacle to development of a general theoretical model of visual performance with stereo TV displays is largely cost based. Perceptual testing of sophisticated video systems usually requires a concerted effort on the part of display engineers and perceptual scientists and is usually both time consuming and expensive. When such research *has* been undertaken, it has usually been performed under considerable time pressure and with specific operational goals in mind. Consequently, only passing consideration has been accorded to fundamental theoretical issues. A third factor obstructing progress toward a general theoretical model involves a lack of understanding on the part of many display designers for the experimental controls required for visual performance testing. On the basis of the available literature, one must assume that many designers of stereo TV systems have relied on their own immediate subjective impressions as the sole means of assessing the perceived spatial characteristics of remote scenes. This overly simplistic and frequently biased approach often confuses functional and aesthetic aspects of image quality. It fails to provide a sound basis for generalization of findings from the laboratory to the operational environment, and provides no useful information regarding the nature of the perceptual processes involved, and their relationship to hardware parameters of the viewing system.

With the growth of remote control and teleoperator technologies in the 1950's and 1960's (chronicled in Johnsen & Corliss, 1971), the need to assess visual performance with stereo TV systems provided a practical impetus for investigating the intimate and complex man-machine interface that characterizes these systems. Recent years have witnessed an increased awareness of the human factors issues involved in implementing efficient stereo TV displays. Full maturity of stereo TV technology can only be achieved through a better understanding of how varying stereo TV geometrical configurations influence the perception of the spatial characteristics of remote environments. Such understanding can only be attained by means of experimentally controlled studies of visual performance with various stereo TV configurations. In addition, systematic assessment of the visual fatigue resulting from use of various stereo TV configurations is needed.

Geometrical Models of Stereopsis

This section is based primarily on Graham's (1965) chapter on visual space perception under direct viewing conditions and on Grant, Meirick, Polhemus, Spencer, Swain, and Tewell's (1973) discussion of retinal disparities with stereo TV viewing systems. First, a geometrical model for retinal disparities is presented for the simple case of direct viewing and then the geometrical model is extended to the situation that occurs when an observer views a remote three-dimensional scene through a stereo TV system.

When binocularly fixating an object in space (e.g., an object at position *A* in Figure 1), an observer's eyes are converged and accommodated such that the images of the fixated point are optically projected onto corresponding retinal elements (i.e., the foveas) in the two eyes. The angle formed by the lines of sight of the eyes is called the ocular convergence angle (α_o). This angle seldom exceeds 15 degrees under normal direct viewing conditions. Other reference objects lying in front of or behind the fixated object (i.e., at positions *N* and *F*, respectively) project images to non-corresponding, or disparate, locations on the retinas. These disparities are determined by three parameters in the direct viewing situation diagrammed in Figure 1: (1) I_o, the observer's interocular separation, (2) *A*, distance from the observer to the fixation point, and (3) *F* (or *N*), distance from the observer to a reference object. The second parameter is also frequently expressed in terms of ocular convergence angle since:

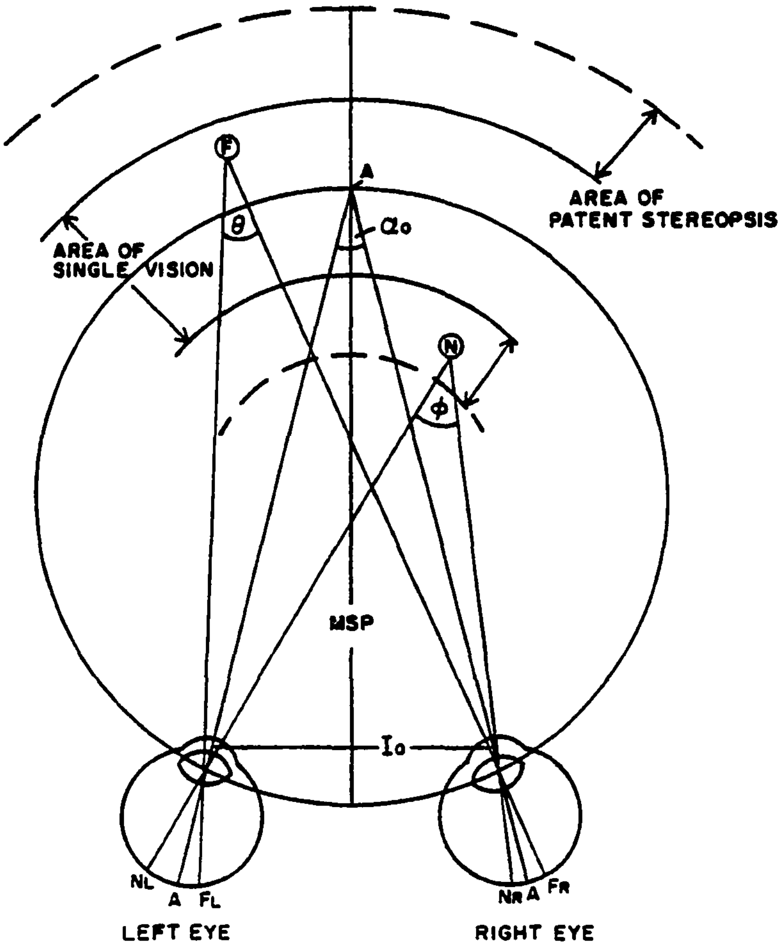
$$\alpha_o = 2 * (\arctan ((I_o/2)/A).$$

Given these three parameters for the simplest case in which the observer's eyes are symmetrically converged and reference objects fall on the observer's mid-saggital plane (*MSP*), the amount of retinal disparity (η_o) associated with a particular reference object may be determined with the following formula:

$$\eta_o = (I_o * (A - F)) / (A * F) \qquad EQ.\ 1.$$

In this case, the reference object located at *F*, beyond the fixation point, produces a positive, or uncrossed retinal disparity. A reference object lying nearer than the fixation point (as *N* does) produces a negative, or crossed disparity. More elaborate equations are required when an

FIGURE I. GEOMETRY OF THE DIRECT VIEWING SITUATION



reference objects are located off the observer's *MSP*. Equation 1 provides a reasonable approximation in cases where convergence asymmetry is less than 2 degrees and reference objects deviate from the *MSP* less than 5 degrees. The main point of this discussion is that binocular fixation of an object in external space establishes a lawful set of relationships between the relative depth of the object and the magnitude and direction of the disparity of its images in the eyes of a binocular observer. A theoretical construct used to integrate this lawful set of geometrical relationships is the horopter, a curved imaginary plane which passes through the point of fixation in external space as well as the centers of rotation of an observer's two eyes. The horopter is depicted in Figure 1 as a perfect circle though empirical research (e.g., see Ogle, 1962) suggests that it does not have such a simple shape. Controversy persists as to the precise shape of the horopter and the interested reader may wish to consult Shipley & Rawlings (1970) or Chapter 3 of Gulick & Lawson (1976) for the details of this debate. By definition, all objects located on the horopter are projected to geometrically corresponding points on an observer's two retinas and, as a result, are seen as single in binocular vision. An object not located on the horopter projects images to non-corresponding points on the retinas.

As Equation 1. implies, the degree of disparity between the object's retinal images is directly related to its distance from the horopter.

It can be proven geometrically (see Graham, 1965, pp. 522-525) that a depth interval between two objects in the visual field can be expressed as the difference between the angles formed by the lines of sight to the two objects as follows:

$$\eta_o = \phi - \theta$$

Thus, the retinal disparity between *N* and *F* in Figure 1 can be determined by simple subtraction. Depth resolution, or stereoacuity, under a given set of viewing conditions is the angular difference determined by the smallest depth interval between two objects or depth planes which can be distinguished from a null depth interval. It is the measure of stereopsis efficiency most thoroughly investigated under both direct and stereo TV viewing conditions. The measurement of depth resolution has typically involved use of the method of constant stimuli in which an observer is presented with a series of disparities between standard and reference vertical rods and required to discriminate whether the reference is nearer or further than the standard rod. A more efficient method of measuring depth resolution, the Howard-Dolman task, is an adjustment procedure in which two opaque vertical rods are presented against a luminous background. The observer adjusts the depth of one of the rods until it appears equidistant with the other. Considerable experimentation has been performed to determine all of the major parameters affecting performance of this task. Under optimal laboratory conditions with selected observers, depth resolution (at the 75% discrimination level) of up to 2 arcseconds visual angle has been reported consistently (e.g., Howard, 1919; Woodburne, 1934). A depth resolution threshold of 2 arcseconds is rather unexpected in light of the fact that the lower limit for resolution acuity for dark lines under similar viewing conditions is more than 10 times larger (Hecht and Mintz, 1939). Foveal cones, the most densely packed receptor cells in the retina, are on an order of 18 arcseconds in diameter, nearly 10 times the diameter of the image difference which must be detected for a 2 arcsecond threshold. The available evidence rather strongly suggests that there is no simple one-to-one conduction of visual information from retinal receptor cells and disparity comparitor cells in the visual cortex. Stereopsis on the basis of even the simplest visual scenes featuring retinal disparities is inherently probabilistic, involving the combined activity of large arrays of cells at each level in the visual pathways.

Depth resolution varies widely between observers (Howard, 1919), with scene illumination (Mueller & Lloyd, 1948), object-background contrast (Smith, Cole, Merritt, & Pepper, 1979), exposure time (Gassovskii & Nikol'skaya, 1934), object motion (Hirsch & Weymouth, 1947), observer head motion (Spain & Cole, 1982), observer adaptation to retinal disparity (Wallach, Moore, and Davidson, 1963), and angular position of targets relative to the fixation point (Graham, Riggs, Mueller, and Solomon, 1949). For nearly all practical applications, depth resolution is considerably poorer than the 2 arcsecond threshold cited above. Under favorable naturalistic viewing conditions it is on the order of 10 to 15 arcseconds visual angle. A more conservative estimate of the lower limit for usable disparities across a variety of natural viewing conditions is on the order of 30 arcseconds (Valyus, 1966).

The upper limit for stereopsis (approximately 20 arcminutes of disparity at the fovea) is well beyond the limits of binocular fusion. In fact, as Figure 1 illustrates, there is as wide a region of stereopsis for which objects are seen as double images as when they are seen as fused (Ogle, 1953). For central (foveal) vision, the binocular fusional areas extend approximately 15 arcminutes along the horizontal meridian with rapid increases in lateral extent of the fusional area for more peripheral locations (Ogle,1962). Depth resolution decreases rapidly as disparate images are moved out from the fovea. It is considered to be poor for retinal locations beyond 20 degrees eccentricity (Tyler, 1977). Although nonfusable disparate images in the retinal periphery convey useful information about depth, they are generally regarded as distracting and annoying when associated with objects an observer is consciously attempting to fixate and scan in detail. Under normal viewing conditions, double images for fixated objects are the result of pathological states such as strabismus, or under unusual circumstances such as extreme fatigue, or severe alcohol/drug intoxication. As will be explained below, double images are more likely to be reported by observers of stereo TV displays when scene magnification or increased camera base are used to enhance disparities.

Visual performance with stereo views of three-dimensional scenes is generally regarded as superior to performance observed with monocular views (i.e., one-eyed views) or monoscopic views (both eyes viewing a flat picture such as a photograph, a drawing, or a single TV screen). Reports of depth resolution thresholds that are substantially greater for monocular views than for stereo views are found throughout the research literature (e.g., Woodburne, 1934). Because the patterns of retinal stimulation in the two eyes are very similar there is obviously much pattern redundancy in the visual information available to both eyes that is absent in monocular views in which one eye is typically occluded with an eyepatch. Jones and Lee's (1981) experimental findings suggest that the pattern redundancy available in monoscopic views is sufficient to produce substantial improvements in visual recognition and perceptual-motor performance over levels observed under monocular viewing conditions. Part of this difference is attributable to binocular rivalry which occurs when the two eyes are presented with markedly different patterns of visual information. Binocular rivalry can be disruptive of visual performance on many perceptual and perceptual-motor tasks. Rivalry is generally not a problem under direct stereo viewing conditions because of the high pattern redundancy of the two retinal images, but may degrade performance when disparities are magnified beyond fusional limits.

A Geometrical Model of TV Stereoscopy

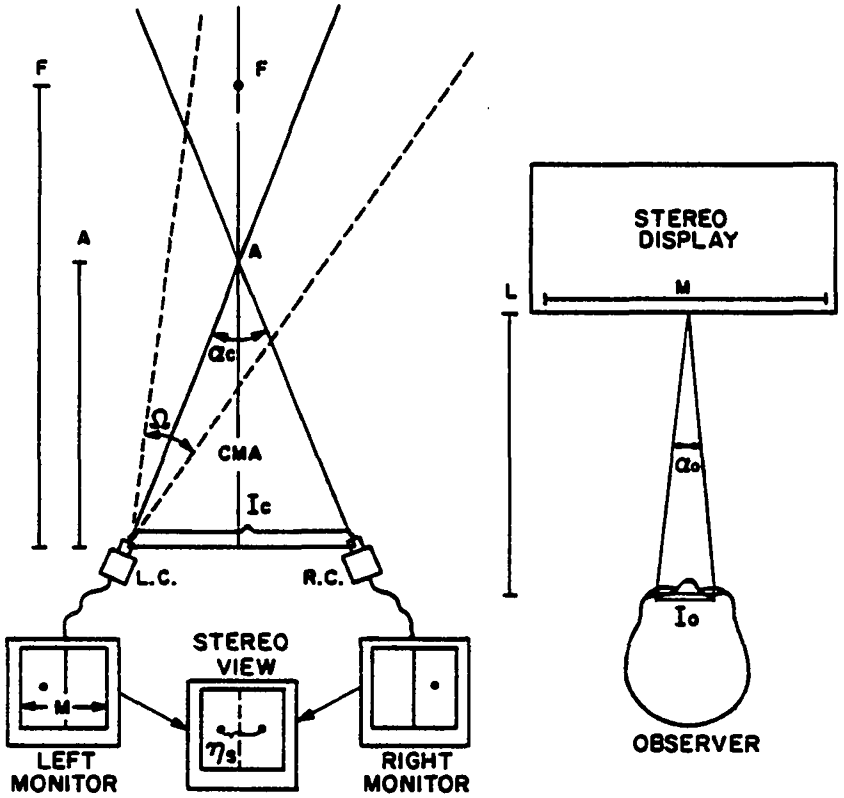
Stereopsis under stereo TV viewing conditions is similar to stereopsis under direct viewing conditions insofar as retinal disparities are a potent cue to depth perception. However, there are several important differences between direct and TV viewing conditions. These differences can exert strong effects on the perception of depth with video displays and involve the number of geometrical parameters determining disparities, information carrying capacities of present-day video systems, and perceptual cue conflicts inherent in all stereo TV viewing situations. (Pepper, Cole, and Spain, 1983).

For stereo TV displays, retinal disparities are determined by six sensor/display parameters in addition to the three parameters (i.e., α_o, A, and F) that determine retinal disparities under direct viewing conditions. Figure 2 diagrams the geometrical relationships that hold between objects in remote scenes, remote sensors, display screen images, and the observer's retinas. When an observer fixates at the depth plane of the display screen, retinal disparities may be calculated by the following equation:

$$\eta_o = \eta_s / L \qquad EQ.\ 2$$

Thus, lateral separation for corresponding points of the left and right channel images of an object at the surface of the display screen (i.e., screen parallax, or η_s) produces disparities which are inversely proportional to an observer's distance from the display screen. Thus, it is a matter of elementary geometry to derive retinal disparities from measures of screen parallax and viewing distance.

FIGURE 2. GEOMETRY OF THE STEREO TV VIEWING SITUATION



A. Parameters of the remote camera station affecting disparities.

B. Parameters of the observer station affecting disparities.

While there is a great deal of variation in eye-to-screen distances for some recreational applications of stereoscopy such as the 3-D cinema, most scientific/technical applications have assumed relatively little variability in this parameter. That is, the operator of a remote viewing system has typically been required to maintain his head at a fixed position and distance relative to the display in order to maintain proper positioning of the eyes and adequate stereo channel separation.

Basic vision research has revealed practical limits for retinal disparities in stereo TV displays. Lateral disparities of 10 to 15 arcseconds visual angle are required to produce a just noticeable perception of stereoscopic depth under favorable direct viewing conditions (e.g., Graham, et al, 1949; Ogle, 1950). To be fusable into a single object by the typical observer, disparities must not exceed 15 arcminutes for central foveal vision. This fusional limit increases monotonically as disparities are projected further into the periphery of the visual field (Ogle, 1950). Under direct viewing conditions, double images for central foveal vision are not usually a problem because the observer automatically adjusts the optical axes of his eyes to bring objects of interest into register. In this fashion, a typical young observer with no ocular abnormalities can readily converge his eyes to fuse objects from 6 inches out to infinity. When viewing a stereo TV display, he is likewise capable of converging or paralleling his eyes to various depth planes. However, it is also quite possible to provide the observer with display screen disparities that exceed the limit for binocular fusion. This is most likely when large camera interaxial separations or large lens magnifications are used. If lateral screen disparity exceeds the distance between the pupils of an observer's paralleled eyes, he must diverge his eyes in order to produce fusion. Divergence of the eyes is limited in most observers to a total of only 1 degree off-parallel (.5 degree for each eye) and frequently results in complaints of eyestrain and general discomfort (Farrell and Booth, 1975; Lipton, 1982). Following this line of reasoning, one might conclude that stereo TV systems should always be designed to provide only fusable images. On the other hand, experimental evidence cited above suggests that fusion is not a prerequisite to stereopsis and comfortable viewing so that if the observer does not strain his eye muscles in attempting to fuse images, he might still derive an accurate sense of depth. Objective measures are needed to resolve this conflict in the literature.

Because an observer is free to direct his visual attention not only horizontally and vertically but also in depth, any stereo display produces different degrees of disparity for depicted objects depending on where in the stereo imagery the observer fixates his eyes. As the observer decreases the convergence of his eyes to fixate objects beyond the plane of the display screen, disparities for objects with positive screen parallax will increase, while disparities for objects with negative screen parallax that are closer to the cameras than the fixated object will produce positive retinal disparities. Just as the observer is free to change the shape of the horopter by oculomotor adjustments under direct viewing conditions, he is also free to do so under stereo TV viewing conditions. This suggests that rather than choosing a stereo TV configuration that produces a fuseable range of retinal disparities for the simplest case in which the observer fixates the display screen, consideration should also be given to the operator's most likely range of convergence while viewing the display.

For the simplest case in which cameras are symmetrically converged and reference objects are located along the lateral midline axis of the cameras (*CMA* in Figure 2), screen parallax for an object at the remote site is determined by five additional sensor/display hardware parameters.

Screen parallax is calculated by the following equation:

EQ. 3.

$$\eta_s = (M/(2N * \tan(\Omega/2)) * ((N * \alpha_c) - Ic)$$

The term on the left represents the lens magnification scaling factor of the remote sensors relative to display screen size while the term on the right represents lateral differences due to the geometrical relationships between the cameras and objects in the remote scene.

Combining Equations 2 and 3, retinal disparities for the viewer of a stereo TV system may be determined as follows:

EQ. 4.

$$\eta_o = (((N * \alpha_c) - I_c) * (M/2N * \tan(\Omega/2)))/L$$

Equation 4 provides a precise mathematical model for estimating retinal disparities from objective linear and angular measurements of the observer, the viewing station, the TV hardware configuration, and distances between sensors and objects in the remote environment. The model is limited to describing only static relationships, and assumes symmetrical convergence for the observer's eyes and the remote cameras. It does not directly predict the perception of depth in remotely televised scenes. Nevertheless, it does serve as a relatively simple but powerful heuristic device for investigating the effects of variations in geometrical parameters on retinal disparities, and consequently the perception of depth with stereo TV displays.

Limits to the information carrying capacity of video systems impose limits on the degree of image detail that must be attained in order to exactly reproduce the retinal light patterns that occur under direct viewing conditions. Although optical magnification of the video image by zooming may overcome these image resolving limitations in certain instances such as inspection of fine detail from a distance (see Farrell and Booth, 1975, Section 3.3), this technique constricts an observer's field of view (FOV) and detracts from the performance of other important tasks such as orientation, surveillance, navigation, and initial inspection of a remote site. Limiting an observer's peripheral FOV has also been demonstrated to diminish depth resolution in direct view experiments (Luria, 1968). Zooming out also increases the angular separation of objects at the display screen and foreshortens the apparent depth in a scene by diminishing linear perspective cues.

Under direct viewing conditions there is usually a close correspondence between oculomotor depth cues of convergence and accommodation. That is, an observer's eyes are generally converged and focused to the same depth plane. Anatomical and neurophysiological evidence suggests that excitation in contiguous nervous pathways may underlie this close linkage of oculomotor adjustments (Westheimer, 1976). Unlike direct viewing conditions, convergence and accommodation are frequently set into perceptual conflict when an observer views a stereo TV display. To clearly focus screen images on the retinas, an observer's eyes will accommodate for the optical distance of the display screen. However, as noted above, the observer's eyes are free to converge at various depth planes within the stereo imagery. Because of the strong association of convergence and accomodation in normal viewing, both convergence and accommodation are frequently quantified in terms of diopters (i.e., the reciprocal of distance in meters). Thus, an object at one meter will normally elicit one diopter of accommodation and one diopter of convergence. Performance of a depth resolution task is significantly impaired when there is a mismatch of .75 diopters between convergence and accommodation (Farrell and Booth, 1975, p. 3.7-11). How such mismatches affect the perception of scale in remote space and visual fatigue resulting from prolonged usage remains an open topic for experimental investigation. On those relatively rare occasions when accomodation-convergence mismatches occur under direct viewing conditions, the result is typically a perceptual compromise (Swensen, 1932; Ono, Mitson, and Seabrook, 1971). That is, an object is perceived to be located at a depth somewhere in between the depths indicated by accommodation and convergence when other strong cues to depth are deficient. If such perceptual compromise occurs while viewing stereo TV, depth judgments for objects with both crossed and uncrossed disparities will be biased toward the accommodative depth of the display screen surface. Apparent depths between objects in the scene will be reduced, giving the imagery a flattened appearance.

A useful, but conservative, approach to configuring a pair of remote stereo cameras has been termed *orthostereoscopy* (or more colloquially, natural viewing or natural stereo). Orthostereoscopy is based on the simple notion that the disparities which one would encounter under direct viewing conditions should be exactly duplicated by a stereo display. According to Spottiswoode, Spottiswoode, and Smith (1953), three conditions must be fulfilled for orthostereoscopy; 1) an imaged object must subtend the same retinal area as it would in direct viewing, 2) camera interaxial distance must equal an observer's interocular distance ($I_c = I_o$), and 3) maximum screen parallax must be no greater than an observer's interocular distance

($\eta_o = I_o$). With variable focal length lenses, variable camera convergence, and variable interaxial separation between cameras, it is possible to meet conditions 1 and 3 and produce views which preserve an object's size and disparity characteristics while distorting sizes and disparities associated with objects in its surroundings. The fundamental flaw of the orthostereo approach and all other purely geometrical models of stereopsis with stereo TV displays is its overemphasis on retinal disparities as the dominant cue to accurate depth perception and its tacit disregard for other powerful spatial cues. Depending on the combination and distribution of non-stereoscopic spatial cues within a remote scene, they may reinforce, mitigate, or override perceptual information provided by retinal disparities alone.

A strong professional preference for analytical/quantitative approaches to problem solving over empirical approaches (e.g., see Machover's comments in Sherr, 1970) may have influenced many stereo TV designers to prematurely conclude that visual performance with stereo TV displays is readily predictable on the basis of information theory and geometrical theories of retinal disparity. If such a belief were true, the designer would only need to refer to a set of simple formulas to provide a mathematical solution for the problem of how to configure his sensors and displays to provide an optimal range of disparities. Unfortunately, this approach typically ignores the fact that there are several alternative geometrical models for stereoscopy (e.g., Kurtz, 1937; Rule, 1941; Hill, 1953), and that their predictive validities for visual performance have not yet been empirically assessed and compared in a systematic fashion. A "good" geometric model of stereoscopy merely describes the precise nature of the disparities in optical images falling on an observer's retinas. Evidence from several lines of human psychophysical research strongly suggests that no purely geometrical model of stereoscopy will ever provide a scientifically satisfying account of human visual perception and performance under even the simplest direct viewing conditions, much less with stereo TV systems.

While refinements continue to be made on theoretical models which address the purely geometrical aspects of retinal disparities (e.g., see Gulick & Lawson, 1976, Chpt. 3) much of the past 20 years of stereopsis research has concentrated on the perceptual aspects of visual space perception. Retinal disparity of an object codes relative depth quantitatively. It is generally true that the greater the depth interval between two objects (ΔR), the greater the retinal disparity (η_0) of their images, and within the upper and lower limits of stereopsis, the greater the perceived depth interval between them will be. However, just as perceived size does not depend solely on the retinal size of an object's images (Holway and Boring, 1942), the perceived depth interval between two objects does not depend exclusively on their retinal disparities. If the visual system is to form veridical percepts of the depth intervals between objects in the environment, apparent distance of the objects from the observer must be taken into account. Furthermore, the perceived size of an object may also affect its apparent distance from the eyes which may, in turn, affect its apparent depth relative to other objects.

The phenomenon of stereoscopic depth constancy (*SDC*) is a clear contradiction to purely disparity based theories of depth perception. Equation 1 implies that retinal disparity is inversely proportional to the square of the distance from the eyes to an object. Were the perception of depth intervals between objects to be based directly and solely on disparities, perceived depth would fall off precipitously with object distance. Whether or not depth constancy exists, its effects on perception, and what visual features influence it are all addressed by a small body of experimental evidence reviewed by Ono and Comerford (1977). Most of the studies of stereo depth constancy to date have been conducted under highly controlled and cue-diminished laboratory conditions where the only available cues to the absolute distance of objects are convergence and accommodation. Both accommodation and convergence are considered to be effective cues to depth only over a relatively restricted range of distances (i.e., less than 2 meters). Recent findings of a study by Cormack (1982) suggest that under more natural viewing conditions depth constancy may operate over a much larger range of viewing distances. Cormack held retinal disparities constant for his observers by inducing disparate afterimages. He then had observers assess the apparent depth difference as the images were projected onto surfaces which varied in distance. He found constancy to be essentially perfect for viewing distances up to at least 27 meters, the largest distance tested.

Another body of evidence which contradicts purely geometrical models of stereopsis involves demonstrations of stereoscopic adaptation. Wallach, _et_ _al_ (1963) found that viewing three-dimensional wire forms through a telestereoscope (i.e., a mirror device which increases interocular distance) enhances retinal disparities and alters the relationship between disparities and perceived depth. Following ten minutes exposure to forms using the telestereoscope, the apparent depth of directly viewed objects was reduced. Conversely, ten minutes exposure to reduced disparities enhanced the apparent depth for directly viewed objects. The generality of the aftereffect is suggested by the fact that training transferred between different geometrical forms. Stereoscopic adaptation has an essentially continuous function, but most adaptation occurs within the first several minutes of exposure to altered disparities. Dissipation of the effect is apparently not so rapid as acquisition. Even after 10 minutes of sitting in the dark or directly viewing an object, adaptation aftereffects persist. Wallach, Frey, and Bode (1972) had their observers wear special eyeglasses which altered the normal cues for convergence and accommodation by means of refractive and prismatic lenses. They found that alterations in stereo depth could be obtained after adaptation periods which had provided no opportunity for use of disparity cues to depth. This finding suggests that disparity cues are influenced by convergence, accommodation, and size cues.

Thus, geometrical accounts of retinal disparities do not, in and of themselves, constitute an adequate theoretical explanation of many of the phenomena of binocular space perception. This is particularly true for situations in which many possible cues to depth are present in the scene to be viewed. What emerges from more recent accounts of depth perception (i.e., Foley, 1976; Gogel, 1977) is the idea that perceived size, shape, distance, and depth are the outcome of perceptual processes which are differentially influenced by a wide range of available visual information. Stereo TV viewing conditions constitute a special case of space perception, a case in which the pool of cues may be substantially different from those available under direct viewing conditions in physically subtle but perceptually powerful ways. Because of this one cannot assume that findings reported in the traditional psychophysical literature are applicable to stereo TV viewing. Carefully controlled empirical investigations are necessary.

Visual Performance With Stereo TV Systems

Because of the wide range of situations encountered, the extremely high costs of serious mistakes in most of these applications, and the vagaries of human performance with complex man-machine systems, designers of stereo TV systems have conducted experiments to measure the effects of specific hardware configurations, task factors, and extended practice on visual performance. Testing procedures, observer skills, perceptual/manipulative tasks, and sensor/display parameters have varied so greatly across these experiments that it is difficult to draw any conclusions beyond the general conclusion that direct viewing is superior to TV viewing and that stereo views produce consistently superior performance over monocular or monoscopic views. Not surprisingly, there is considerable confusion within this limited literature as to what set of hardware parameters optimizes visual performance. Only a handful of researchers have even attempted the more arduous but important task of clarifying the general nature of the perception of remote scenes through stereo TV viewing systems.

The earliest comparisons of stereo and monoscopic viewing systems were performed by members of the radioactive materials handling industry in the late 1940's and throughout the 1950's. Unfortunately, most of the technical reports written at this time were not widely distributed, and the few reports which did reach a wider readership (e.g., Johnston, Hermanson, and Hull, 1950) presented only subjective impressions of the usefulness of stereo TV systems. This situation led predictably to a great deal of controversy over the usefulness of stereo TV systems for any tasks involving remote surveillance or manipulation. In the 1960's and 1970's the utility of stereo displays for various applications was repeatedly rediscovered.

Chubb (1964) reports that Kama & DuMars (1964) compared remote manipulation through a master-slave manipulator with monoscopic and stereo TV viewing systems. They found no significant differences in task performance times. In fact, performance under monoscopic viewing conditions was superior to that under stereo viewing conditions. Chubb (1964) undertook a simple, but elegant, experiment as a check on the validity of their conclusions. Chubb's observers viewed the manipulator work site directly through a plate of radiation shielding glass with (i.e., monocular) or without (binocular) an eyepatch. Performance times were significantly faster under binocular viewing conditions. On the basis of this finding, Chubb concluded that the discrepancy between his results and those of Kama & DuMars could be attributed to the distortion and loss of visual information by the video system. In other words, Kama & DuMars may have simply failed to provide their observers with a properly balanced and aligned stereo TV viewing system. Perceptual distortions and visual fatigue resulting from such misalignments could have masked any stereo TV advantage. However, Chubb's monocular viewing condition is not directly analogous to a monoscopic TV viewing situation. Aside from the physical discomfort of wearing an eyepatch, a substantial portion of the binocular visual field is occluded, and a weak form of binocular rivalry may result. Recent studies comparing monocular and monoscopic viewing conditions (Jones & Lee, 1981) suggest that at least some of Chubb's stereo advantage may be attributable to the inferiority of the monocular condition rather than the superiority of the binocular condition. Nevertheless, Chubb's study points out the importance of including, whenever feasible, monoscopic and binocular direct view control conditions. His criticisms also call attention to the importance of properly calibrating stereo TV displays. Any detailed account of a stereo display system is incomplete without a description of the procedures and tools used to insure balance, linearity, and alignment of sensors and displays.

In a study of the relative efficiencies of various manipulator control strategies, Pesch (1967) compared manipulative performance between monoscopic and stereo displays on two tasks common to many undersea salvage operations, cable handling and precise positioning of an end effector. No significant performance differences were found for the simpler end effector positioning task. For the cable handling task, a significant advantage for stereo over monoscopic performance observed on the first day of testing "washed out" during the second day of testing. Pesch interpreted this finding as implying that the stereo advantage is ephemeral and of only minor practical significance. However, as Smith _et al_ (1979) have noted, the stereo advantage observed on the first day of testing might have substantial practical significance, especially when one considers the improbability that a remotely operated vehicle performing a real-life mission would have two days of practice with precisely the same relatively simple remote manipulation task. Versatility and efficiency are important characteristics of all remotely operated systems. Under degraded visibility conditions, the sort of viewing conditions most likely to be encountered in undersea environments, Pesch found stereo viewing conditions to be superior to monoscopic viewing conditions. He concluded that any performance advantages for stereo displays are task dependent, influenced by visibility conditions in the remote environment, and may be sensitive to practice or perceptual adaptation effects.

To determine the usefulness of stereo TV for remote control of an extraterrestrial roving vehicle, Hudson & Cupit (1968) required their observers to make written estimates of the size and distance of simple cone-shaped objects stereoscopically photographed in a naturalistic setting. The natural setting which they chose, the floor of a gravel pit, was rich with monocular depth cues. Given the abundant depth information available under such viewing conditions, it is not surprising that they reported no significant stereo advantage for estimates of the sizes and distances of objects positioned 20 to 200 feet from their cameras.

Upton and Strother (1972) devised a helmet mounted stereo display consisting of two miniature CRT's and collimating optics attached to a flight helmet. The operational mission of this system was real-time aerial surveillance and detection of camouflaged ground targets from low-flying helicopters. Observers were required to verbally report presence or absence of perceived depth (ΔR) between two stationary poles of equal diameter located at a distance of 106.7 meters (350 feet) from a pair of remote cameras. Cameras were precisely converged to the distance of one of the targets at 106.7 meters. The poles were separated in depth so as to produce disparities of 1,2,4, and 8 seconds of arc for a 7.62 centimeter (3 inch) camera interaxial separation. Other camera separations tested were 30.48, 60.96, and 121.9 centimeters (12, 24, and 48 inches) which, according to Equation 4 magnified the disparities listed above by 4,8, and 12 times. In general, Upton and Strother found that increasing camera separation to yield disparities of at least 16 arcseconds produced nearly errorless depth interval discrimination. A series of helicopter flight tests was conducted with camera separation varied between 10.16 and 121.9 centimeters (4 and 48 inches). On the basis of these flight tests, Upton and Strother concluded that wider camera separations extended the perception of depth far beyond the range of unaided vision and that this extension of depth perception could improve ability to detect camouflaged targets on the ground. Although quantitative results of the flight tests were not presented in their report, Upton and Strother concluded that stereo TV was substantially superior to monocular TV viewing and was strongly preferred by flight crewmen.

Fugitt and Uhrich (1973) employed a single high-resolution TV camera with a stereo adapter which provided two separate perspectives on a remote underwater scene by means of a mirror arrangement. Their stereo display provided a 17 degree horizontal field of view for a fixed 11.94 centimeter (4.7 inch) camera interaxial separation. A submersible 2 degree-of-freedom release mechanism was built which allowed an observer to remotely adjust the depth of an object. The observer's task was to position the object directly over a cup and release the object so that it fell into the cup. Five tests were run comparing stereo and monoscopic TV performance with a 1.07 meter (3.5 foot) camera-to-object distance. On all tasks, stereo views produced significantly fewer errors and faster performance times than monoscopic views. Fugitt & Uhrich speculated that further improvements in visual performance with underwater viewing systems could be made by providing a helmet-mounted, head motion coupled viewing system which incorporated color and expanded the observer's field of view. A prototype of their innovative helmet mounted display was apparently built and tested, but no performance data were published.

Martin Marietta Corporation undertook a major development effort in the early 1970's to produce free-flying orbital teleoperator systems for NASA. Out of this large-scale and well-funded effort, several studies of visual performance with stereo TV systems were conducted. A conceptual design study (Adams, Grant, Johnson, Meirick, Polhemus, Ray, Rittenhouse, and Skidmore, 1972) identified eight potential viewing systems to be compared: direct viewing of the work site, a monoscopic TV system, and six stereo TV techniques including polarized, anaglyphic, helmet-mounted, fresnel, lenticular, and foveal-peripheral systems. Based upon subjective reports of operator comfort, engineering feasibility, cost, and preliminary bench test evaluations of the more promising systems, the fresnel system was chosen as the preferred stereo display and was used in all subsequent tests of visual performance undertaken by this group. The system consisted of two monochrome cameras with remotely controllable zoom, focus, and iris control, two 7.62 centimeter-wide (3 inch) monitors, and a specially designed 25.4 centimeter-wide (10 inch) fresnel lens which optically superimposed images from the two displays and provided for considerable head movement during stereo viewing without the need of special eyeglasses or other viewing aids. Grant et al (1973) investigated performance time on a simple manipulation task across a range of camera interaxial separations, camera convergence angles, and camera fields of view. Unfortunately, they did not include any non-stereo viewing conditions in their study for comparison. Reasoning that exaggerated disparities might be beneficial in tasks where depth range is small and realism is not of primary importance, their initial experiments involved variations in camera interaxial separations by 15.24 centimeter (6 inch) increments from 15.24 to 60.96 centimeters (6 to 24 inches) with corresponding convergence angles of 4.8 degrees to 19 degrees (i.e., camera to convergence point distance was 1.83 meters (6 feet)). Their task involved using a sophisticated remote manipulator to place a peg into a hole. Task execution times remained nearly constant across the 15.24, 30.48, and 45.72 centimeter (6, 12, and 18 inch) camera separations with a marked increase in time for the 60.96 centimeter (24 inch) separation. The second phase of their experimentation involved variations in camera field of view from 30 degrees to 5 degrees with a constant camera separation of 15.24 centimeters (6 inches). Variations in field of view correspond to magnifications of .9X to 5.4X.

Most efficient performance was recorded for Ω values between 10 degrees and 17 degrees (i.e., magnifications of 2.7X and 1.6X, respectively). Despite the absence of any measurements with camera separations less than 15.24 centimeters (6 inches), the authors recommend a 6.35 centimeter (2.5 inch) camera separation, 6.8 degree convergence angle, and zoom settings variable from 9 degrees to 54 degrees (i.e., magnifications from 2.7X to .2X, respectively).

A second group of Martin Marietta researchers (i.e., Tewell, Ray, Meirick, and Polhemus, 1974) compared performance of four complex manipulator tasks using four different TV viewing systems: black and white and color mono systems, an orthogonal monoscopic display, and an anaglyphic stereo display. The orthogonal monoscopic and stereo displays proved generally superior to the other two systems, with the orthogonal display giving the most accurate performance. Monoscopic color did not appear to provide for any advantage over monoscopic black and white.

Shields, Kirkpatrick, Malone, and Huggins (1975) utilized a Howard-Dolman type apparatus to determine the minimum detectable separation between two objects for a given distance from their cameras. The cameras were located 2.74 meters (9 feet) from the standard rod and the observer was given control over the position of the comparison rod. Camera interaxial separation was set at 15.24 centimeters (6 inches) with a 35 degree horizontal field of view for each camera. Shields _et al_ argued in favor of orthostereoscopic views but their experimental camera setup did not fulfill all conditions necessary for orthostereo. Nevertheless, they found errors to be smallest when cameras were converged behind the standard rod and largest when cameras were converged in front of the standard rod. This finding contradicts the frequently cited rule of stereo photography that cameras should be converged to a depth plane nearer than an area of interest so that objects will not appear to hover out in open space in front of the display screen frame (Grant, _et al_, 1973).

More recent research efforts at the Hawaii Laboratory of the Naval Ocean Systems Center (NOSC) have been directed toward improving viewing systems to enhance teleoperator performance. The first studies undertaken (Pepper and Cole, 1978) simply demonstrated that depth resolution as well as remote manipulation was better under stereo TV viewing than under monoscopic TV viewing. Results of a later study by Smith, _et al_ (1979) suggest that teleoperator performance is determined by a complex interaction of numerous factors including the information available at the remote site, its transmission and display to the operator, manipulator capability, task demands, and human observer capabilities including perceptual and perceptual-motor learning skills. This led to the development of a systematic approach to the analysis of the many variables involved in teleoperator performance. As a conceptual aid, Cole and Uttal (1981) attempted to define *remote presence* or *telepresence* in objective terms. While this concept has been closely associated with a global subjective feeling on the part of the operator that he is actually physically present at a remote work site (Akin, Minski, Thiel, & Kurtzman, 1983; Hightower and Smith, 1983), it is objectively specified by recourse to the display-performance transform. The display-performance transform simply involves controlling the information content of displays and noting the effects of systematic variations of the displayed information on overall teleoperator performance.

Cole, Pepper, and Pinz (1981) investigated the possible advantages of using head movement in conjunction with bench-mounted stereo displays in order to enhance depth resolution. In their experiment, depth resolution was measured with a modified Howard-Dolman apparatus which employed standard and comparison rods of different-sized diameters. Since their TV cameras remained in a stationary position throughout testing, the stereo display did not produce true motion parallax cues to depth when the observer moved his head relative to the display. Nevertheless, there is an interesting illusory movement that occurs when moving the head from side-to-side in the horizontal plane while viewing a stationary stereo TV display. The apparent motion of objects in the scene is, like true motion parallax, proportional to their distance from the convergence plane of the remote cameras, but in the opposite direction of that encountered with true motion parallax. Despite the illusory nature of this effect, it seemed reasonable to suppose that the relationship between the apparent distance of cameras and the degree of *pseudo-motion parallax* of those objects could be utilized by the observer's visual system in much the same way that true motion parallax is utilized. Results of the experiment, however, did not confirm this hypothesis. Pseudo-motion parallax cues were found to neither enhance nor degrade depth resolution relative to the level of performance associated with the use of stereo viewing conditions alone.

In more recent studies, Spain and Cole (1982) used a helmet-mounted stereo TV display (HMSD) and an isomorphic head motion tracking system developed by NOSC engineers which provided true head motion parallax cues when an observer moved his head. Preliminary results with this system were very encouraging. Though not a statistically significant effect, stereoacuity for both simple and complex perceptual tasks was superior with head motion camera coupling under both stereoscopic and monoscopic viewing conditions. The complexities of the particular head-motion camera-coupling system that was used were considerable in terms of development and maintenance. The HMSD may have also placed additional burdens on the observer which may or may not have been offset by performance gains associated with the added degree of complexity and sophistication. With improvements in system comfort, tracking, and reliability, head-motion camera coupling will undoubtedly become a very valuable means of enhancing an operator's perception of a remote site and thereby improving perceptual and manipulative performance.

Another area of interest in the NOSC-Hawaii studies has been camera interaxial separation. Over a wide range of studies using different sensor/display systems, tasks, and operators, an approximate two-fold gain in stereoacuity in the transition from monoscopic to stereoscopic TV viewing conditions was found. For each study involving comparisons of stereo and monoscopic TV systems, stereo viewing always produced superior performance, even when camera separation was set to only half the normal human interocular distance (Cole, et al, 1981). Furthermore, performance advantages associated with stereo displays were more pronounced under visually degraded viewing conditions

(Smith, et al, 1979). As camera separation was increased to the normal interocular distance and beyond into the region of hyperstereopsis, a gradual but diminishing gain in stereoacuity to a level approximating that found under direct viewing conditions was observed. This same pattern of results was found for three viewing distances (2 meters, 4 meters, and 6 meters) with a trend in the data suggesting that camera separation was more effective for larger viewing distances (Spain and Cole, 1982).

Visual Fatigue With Stereo TV Displays

One practical problem which has detracted from the use of stereo TV systems since their inception is eyestrain, or visual fatigue. The term *fatigue* generally refers to weariness from exertion or temporary loss of power to respond induced in a sensory receptor or motor end organ by continued stimulation. A universal feature of fatigue, observed in all functions accessible to precise measurement is a decrease of excitability. Visual fatigue appears to be mainly of the acute or task induced types (Smith, 1979). Acute fatigue is produced by brief but tiring activity with its primary effects in the muscles. It is relieved by rest. Task induced fatigue occurs when a person performs a monotonous task. It can be quickly reduced by rest, by changing tasks, or by reducing the monotony of a task by making it more varied.

There are three general methods by which fatigue has been assessed experimentally. The first and most frequently used method is introspective analysis. An observer is simply required to subjectively report his sensations or feelings. Introspective assessments of fatigue are considered much less reliable than they were once thought. Many studies correlating subjective reports with visual performance have failed to find substantial correlations (see Smith, 1979). The second method of fatigue assessment involves examining work output for degradation over an extended period of time. The problem with this approach is that many studies have demonstrated that performance can be maintained or even improved under what appear to be fatiguing conditions. The first two methods of assessing fatigue have been shown to be susceptible to high levels of measurement error. The third method measures physiological and neurosensory responses from an observer and correlates them with objective measures of performance. This approach is based on the assumption that observers show a consistent and measurable change in body reactions related to their present state of alertness or fatigue. Measures of this type include heart rate, respiration rate, muscle tonus, galvanic skin response, eyeblink rate, pupillary responses to light and patterned stimulation, binocular fusion times, critical flicker fusion frequency (FF), and visual accommodation time to near and far targets.

Informal reports of visual fatigue with stereo TV displays are commonplace (e.g., see Valyus, 1966; Lipton, 1982). The symptoms of visual fatigue include pain or feelings of heaviness and tension in the eyes, head, or upper body, temporary loss of acuity due to an inability to maintain focus and fixation, blurred vision, double vision, and feelings of general weariness. Any of these symptoms could conceivably result from fatigue in one or both of two different types of perceptual mechanisms, peripheral or central. For example, peripheral fatigue could be brought about by unusual use of the oculomotor muscles. An obvious candidate for this type of fatigue with stereo TV is the reported discomfort that results when observers are required to diverge their eyes for extended periods to fuse widely disparate uncrossed images. Central fatigue could result from overstimulation or an imbalance in stimulation of the cortical mechanism or mechanisms responsible for stereopsis. A possible candidate for this type of fatigue is the reported eyestrain that results from use of the anaglyphic (colored filter) technique for channel separation or the fatigue that results when a pronounced brightness difference exists between the eyes. Only one of the stereo TV studies cited above (Zamarin, 1976b) systematically investigated the effects of varying stereo TV viewing systems on subjective reports of visual fatigue. About 30% of Zamarin's 60 subjects reported eye fatigue and visual discomfort after being tested on a polarizing stereo TV system. Although he noted a trend toward difficulties in maintaining image fusion with larger camera separations (i.e., 35.6 and 43.2 centimeters), there is no indication of any correlation of these reports with subjective reports of eyestrain. Apparently, no attempt was made to assess individual differences in eyestrain or the effects of varying combinations of camera separation, lens magnification, and convergence which he tested.

Ferguson, Major, and Keldoulis (1974) in their review of the literature note that one of the visual mechanisms which appears most susceptible to fatigue is the focusing system of the eye. This system relies on both the extraocular and intraocular muscles which must be precisely coordinated in order to provide adequate convergence and accommodation for the performance of demanding visual tasks. Several experimenters (e.g., Robertson, 1936; Collins and Pruen, 1962) have attempted to measure fatigue in the eye muscles by means of timed acuity tests which require an individual to alternate accommodation and convergence between a near visual target and one located at optical infinity. Both experiments using the near-far acuity task (NF) were successful in showing significant increases in the amount of time required to perform this task following a period of visually fatiguing activity, typically two or more hours in duration.

A second neurosensory task by which researchers have attempted to assess central, cortical fatigue is flicker fusion threshold (FF). FF is related to the time parameters of cortical excitability - to the latent period, activation time, and the refractory period. It is affected by a number of bodily conditions so that a decrease in FF is not necessarily specific to fatigue of the visual system, but it has been frequently employed as an index of central visual fatigue in numerous experiments (i.e., Simonson & Enzer, 1941; Berger & Mahneke, 1954; Baschera & Grandjean, 1979; Saito, Tanaka, & Oshima, 1981).

By systematic application of simple tests of visual efficiency such as the NF and FF tasks across a variety of stereo TV viewing conditions for the same set of trained observers, it may be possible to determine which combinations of viewing system parameters have the greatest impact on fatigue and whether they primarily fatigue central or peripheral perceptual mechanisms. Such information would have obvious implications for design of practical stereo TV viewing systems. It would also provide valuable input to a theoretical area for which available empirical evidence is often methodologically unsound and inadequately reported (see Merritt, 1983).

Research Plan

The stereo TV literature strongly suggests that stereoscopic vision is an important aspect of remote viewing for many tasks under a wide variety of conditions. This is particularly true under unfamiliar or degraded viewing conditions which are frequently encountered in field applications of remote viewing systems. Unlike the human eyes, which are relatively fixed in the head with respect to directly viewed objects, stereo camera systems are variable in terms of sensor separation and image scale. Like the eyes, stereo TV camera systems can be variably converged to different distances or diverged, but the range of values within which they can be converged and diverged is obviously much greater than that of the eyes. Thus, there are many more possible combinations of retinal disparities, object sizes, and textural gradients under stereo TV viewing conditions than are possible under direct viewing conditions. The effects of camera interaxial separation, convergence angle, and magnification have all been previously studied, but always in a limited fashion. No study to date has investigated the main and interactive effects of camera interaxial separation, camera convergence angle, and image magnification on perceived depth intervals in remotely televised environments. Though there are frequent comments about increased visual discomfort and fatigue with stereo TV displays, no studies have objectively assessed visual fatigue as stereo TV viewing system parameters and visual information in the remote scene are systematically varied.

Designers and users of stereo TV systems have relied heavily on purely analytical approaches or somewhat haphazard trial and error adjustments to configure the hardware components of stereo viewing systems. The shortcomings of both approaches are obvious in light of the vision research literature. Given the enormous complexity of factors affecting spatial perception in everyday life, it is obvious that no single series of studies will resolve all of the uncertainties of visual perception and performance with stereo TV displays. However, the series of four studies reported in this monograph does provide a more solid empirical foundation for configuring stereo TV systems to maximize performance while holding visual fatigue resulting from their use at tolerable levels.

The following set of experimental hypotheses will be put to test:

1. Stereo TV viewing conditions afford an observer more accurate perception of depth intervals in remotely televised environments than monoscopic TV viewing conditions.

2. Non-fusable disparities in Ogle's region of patent stereopsis can provide useful depth information under direct viewing conditions. Such large disparities should also provide useful depth information under stereo TV viewing conditions resulting in more accurate depth judgments than comparable monoscopic viewing conditions.

3. Inclusion of strong non-disparity based cues to depth and distance will produce more accurate depth perception than that found under stimulus conditions in which such cues are absent.

4. Increasing or decreasing stereo TV camera interaxial separation so that retinal disparities are enhanced or diminished will produce distortions of perceived depth intervals which are in accordance with the geometrical model of stereopsis with stereo TV displays. Diminished disparities will result in underestimates of depth intervals. Enhanced disparities will result in overestimates of depth intervals.

5. Camera convergence angle influences the magnitude and polarity of disparities. Depending on its specific effects on disparities, camera convergence will exert a significant influence on depth interval judgment accuracy.

6. Optical magnification, like camera separation, can be used to enhance or diminish disparities according to the geometrical model. When magnification enhances disparities, depth intervals will be overestimated.

7. Different TV viewing system configurations may be characterized in terms of deviation from "normal" orthostereoscopic viewing conditions. The more the deviation from normality, the greater the likelihood that eyestrain will result from viewing.

8. If present, visual fatigue will be differentiable between central and peripheral perceptual mechanisms on the basis of performance on tests known to reflect the efficiency of processes underlying these mechanisms.

METHODS

Experiment One

Observers

Because of security restrictions limiting access to the testing facilities at the Naval Ocean Systems Center, only four observers were available to participate in Experiment One. Two of the observers were the author and his male laboratory assistant (ages 33 and 18). Both were highly practiced (i.e., more than 50 hours) at viewing a variety of stereo TV displays and making depth interval judgments under controlled laboratory conditions. Both served as experimenters as well as observers and were thus generally more cognizant than other observers of contingencies operating in the testing situation. Only the author was clearly aware of the experimental hypotheses being tested. Two additional observers were female clerical workers who had no exposure to stereo TV systems prior to the five one-hour practice sessions they received before commencement of Experiment One. Unfortunately, there is an obvious confoundment of observer stereo TV viewing experience and sex in this group of observers, and this eliminates the possibility of determining the independent effects of experience and sex on performance. Observers must be considered on an individual basis for theoretically interesting effects and all other effects found statistically significant for the group as a whole.

Prior to testing, five observers were screened for ocular anomalies. They were first asked questions about previous visual difficulties, recent visits to medical eye specialists, and optical corrections. Observer JR reported a history of difficulties with his left eye. According to JR, an infection of the retina encountered at age 10 left a blurry patch for central vision which has gradually healed over the past eight years. Testing revealed that he now has 20/22 (.9) Snellen acuity for the left eye. JR also has pterigium, a wing-shaped growth on the nasal sclera of both eyes which does not affect his vision but is occasionally painful. Two observers (KD and SK) wore contact lenses which corrected their eyes for myopias. All observers were administered a battery of tests of visual efficiency with a Bausch and Lomb Armed Forces Vision Tester. This battery measured stereoacuity thresholds, phorias, and Snellen acuities for near and far distances. Interpupillary distances (I_o) were measured with a Bausch & Lomb P-D gauge. Results of the visual screening procedures are summarized below in Table 1.

TABLE 1.
Results of Visual Screening Procedures

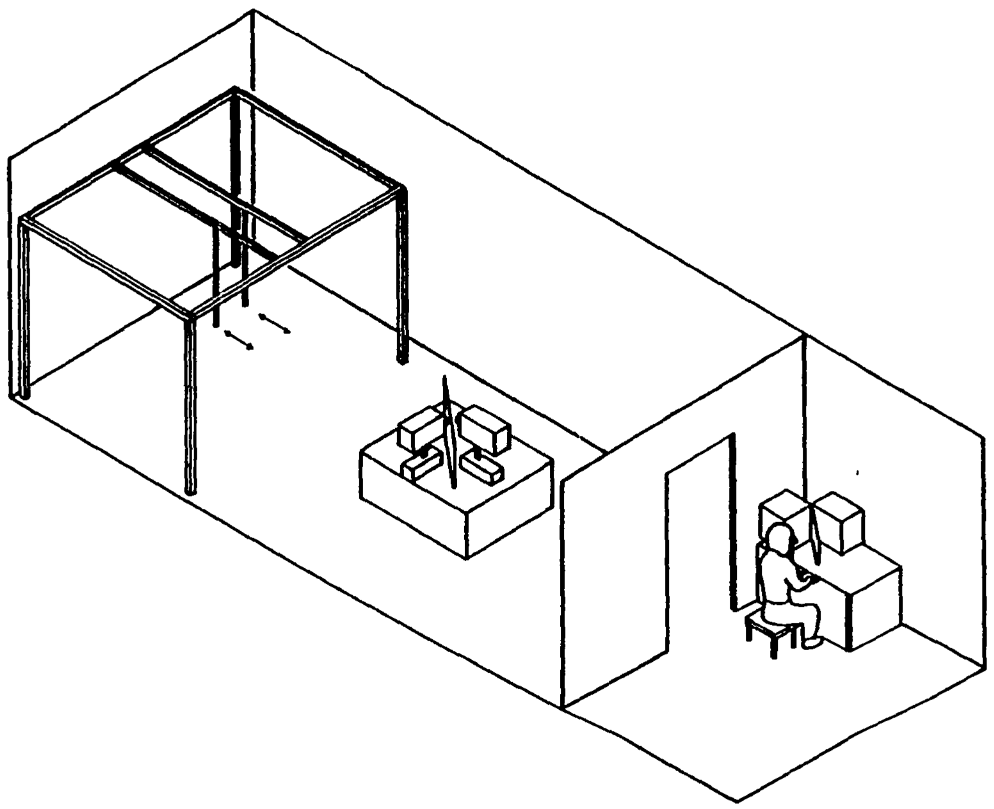
				Visual Acuity					
Obs	Sex	Age	I_o	Near Left	Near Right	Near Binoc	Far Left	Far Right	Stereo Acuity
JB*	F	>39	60	1.1	1.0	1.2	1.1	1.1	<10"
KD	F	33	60	.9	.9	1.1	.9	.9	<10"
SF	F	22	60	.9	.9	1.1	.9	.9	<10"
JR	M	18	67	.9	1.0	1.0	.9	.9	<10"
ES	M	33	67.5	1.1	1.0	1.2	1.0	1.0	<10"

* Observer JB participated in Experiments 3 & 4 only.

Facilities and Apparatus

The facility in which all experiments were conducted was the Teleoperator Performance Laboratory located at the Naval Ocean Systems Center (NOSC), Kaneohe Marine Corps Air Station, Kailua, Hawaii. This laboratory consists of a 3 meters wide by 14.5 meters long light-tight, temperature-controlled structure dedicated to visual preformance testing. It is divided into three rooms -- an 8.5 meter-long remote camera chamber, a 3 meter-long observer station, and a 3 meter-long office. Figure 3 presents a cutaway diagram of the remote camera chamber and the observer station. The remote camera station housed: 1) a microcomputer console which served as the experimenter

FIGURE 3. TEST FACILITY LAYOUT



station during the depth perception test, 2) a computer-controlled stimulus positioning apparatus, 3) the remote camera station, and 4) the Near-Far Test apparatus. The observer station contained a table-top polarizing stereo TV display and various visual screening devices. During stereo TV testing sessions the observer was isolated from the remote camera chamber and communication between the observer and the experimenter was conducted over an intercom.

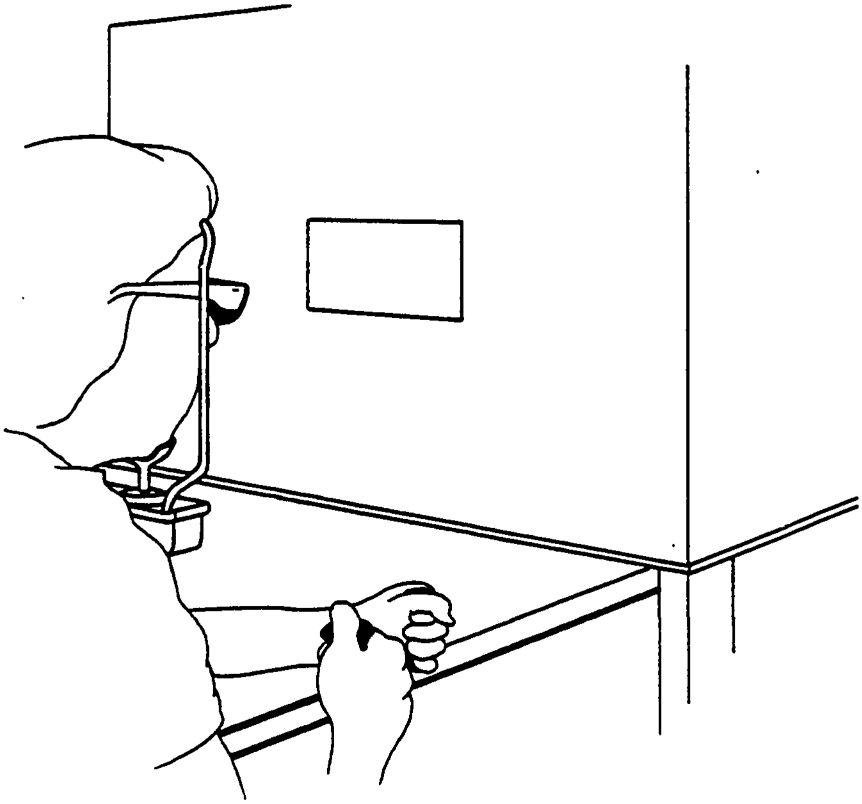
Devices used in the experimentation can be organized into three distinct groups -- a stereo TV viewing system, a microcomputer controlled stimulus positioning apparatus, and devices dedicated to measuring decrements in visual performance. The central component of the control system was the Apple II+ microcomputer which was interfaced with a 12-bit analog-to-digital converter, an Intex Talker phonemic speech synthesizer, stepper motor driving circuitry, millisecond precision timers, and four parallel 8-bit input output ports. For all experimental tests, observer's responses were collected on-line and stored to floppy disk at the conclusion of each testing session.

In order to efficiently assess the influence of specific geometrical parameters of stereo TV systems on accuracy of depth interval estimates, a versatile stereo camera bench was constructed and appears in the foreground of Figure 3. Two orthogonally positioned RCA CC002 color video cameras fitted with Canon TV (17 to 102mm) zoom lenses were optically paralleled by means of a 81 X 61 cm 70%/30% beamsplitter. A neutral density filter (.4 log unit) was placed in front of the straight view camera to equalize the beamsplitter's light passing asymmetry. F-stops (i.e., lens apertures) for both cameras were set to 5.6 for all sessions in all experiments. The beamsplitter camera arrangement allowed camera interaxial separation between the cameras to be reduced beyond the physical limit imposed by the video camera cases. The ability to move cameras very close together made it possible to measure performance under two of the three (i.e., 3.175 cm and 19.05 cm) interaxial separations tested. For all stereo TV viewing conditions tested in Experiment One, the cameras were symmetrically converged and focused for a point 2 meters distant. Scanning signals from the video camera pair were electronically synchronized.

The stereo TV display consisted of a pair of orthogonally positioned studio-quality color TV monitors (Conrac Model SNA14/C's) which were dichoptically viewed (by means of polarized filters) through a beamsplitter which optically superimposed the two monitor's display screens. See Cole, _et_ _al_ (1981) for a detailed description of a similar polarizer display. The monitors' 47 cm-wide video screens (*M* in Equation 4) were viewed from a distance (*L*) of 75 cm, providing the observer with a 17.8° horizontal field of view (Ω). Observer head position and movement were controlled with a chin rest and forehead bar (see Figure 4). An adjustable chair was used to comfortably seat observers. They rested their forearms on a shelf which was attached to an apparatus consisting of two pegs used for measuring haptic depth responses. The peg on the observer's right was 2.5 cm in diameter and was not moveable. The peg on the observer's left was 1.9 cm in diameter and could be moved to various distances out to 40 cm along the observer's depth axis. It could also be pulled back toward an observer to a position 3 cm closer than the right peg. A high precision linear potentiometer was attached to the moveable peg by means of a sprocket and chain arrangement. Voltages which were attenuated by the potentiometer depending on the position of the moveable peg were input to the controlling microcomputer's analog-to-digital converter which recorded observer's haptic depth adjustments whenever a button on top of the right peg was pressed.

The stimulus positioning apparatus consisted of a 135 X 125 cm metal beam frame to which a pair of three degree of freedom (DOF) actuators were attached. This apparatus is depicted in Figure 3. Given controlling pulses from the

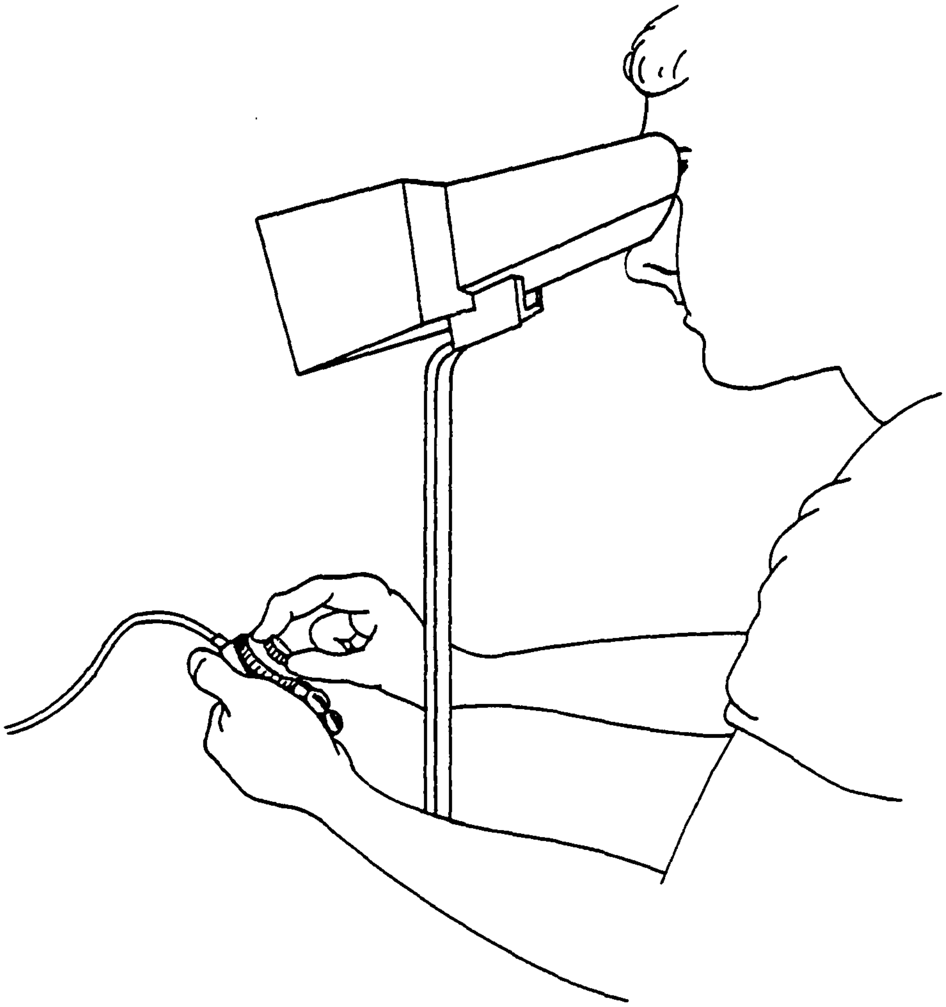
FIGURE 4. STEREO TV OBSERVER STATION



Apple II+ microcomputer, each of these stepper motor driven actuators was capable of precisely positioning a black 7.9 mm diameter stimulus rod anywhere within its lateral half of the total space in the metal frame. Rods were laterally separated by 12.7 cm and their movements were further restricted to a workspace centered in depth at the camera convergence point, 2 meters in front of the remote cameras. During testing, two rods were pre-positioned to one of six depth intervals (0, 5.1, 10.2, 15.2, 20.3, or 25.4 cm) within the workspace. An unpatterned white background was illuminated from above by a diffuse 1000 watt incandescent source (Berkey Colortran #104-171). This arrangement provided a bright and evenly illuminated background which did not produce shadows of the stimulus rods.

Two devices were specially constructed to measure visual fatigue resulting from use of stereo TV configurations. Both were used to measure a baseline of performance prior to testing with stereo TV and again immediately after. Shifts in pre-post performance would indicate visual fatigue. The first device consisted of two square wave pulsed light emitting diodes (LED's), a viewing hood, and a pair of lenses which allowed the observer to comfortably focus and fuse images of two LED's. The FF test observer station is depicted in Figure 5. Under computer synthesized voice instructions, the observer adjusted the

FIGURE 5. FLICKER FUSION TEST OBSERVER STATION

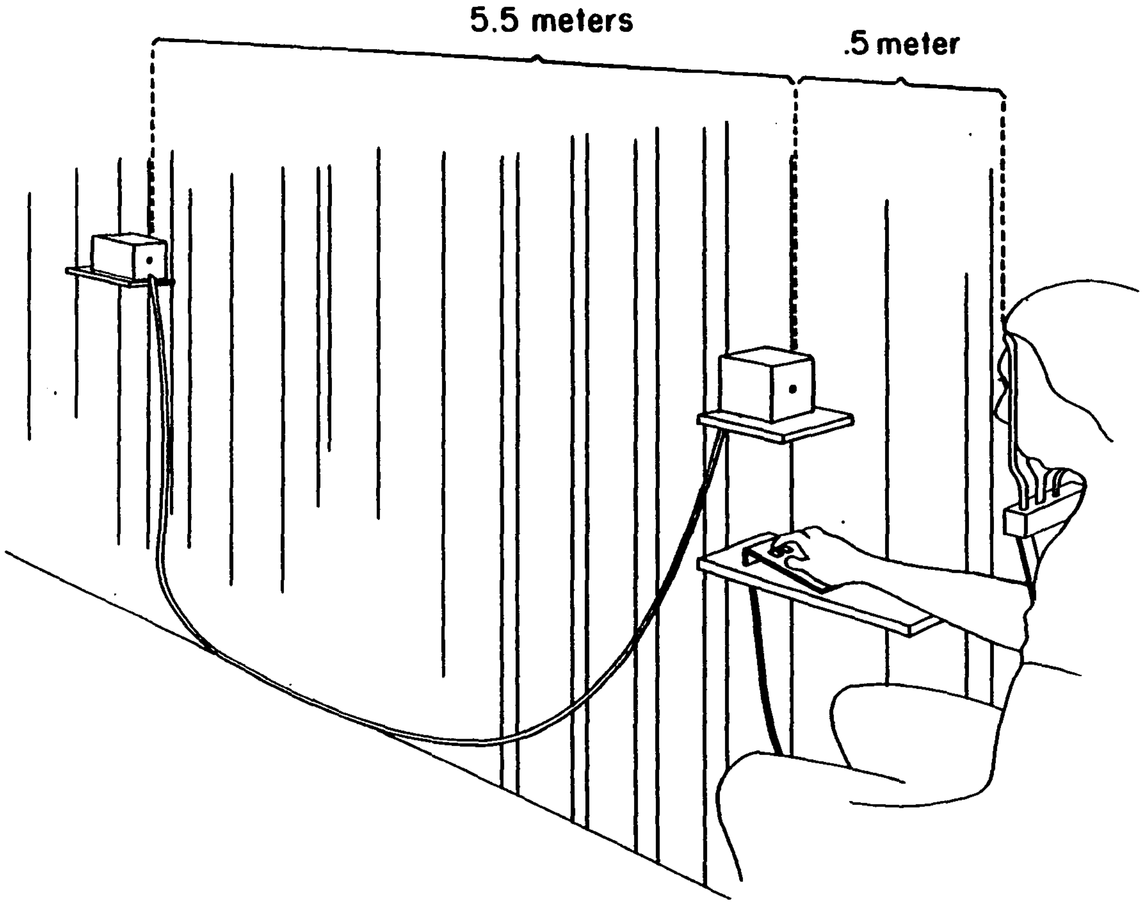


setting of a hand-held dial to his momentary flicker fusion threshold. The second device for measuring visual fatigue consisted of Landolt squares of equal angular subtense (1.5 arcminute gap) positioned directly in front of the observer at .5 and 6 meters (see Figure 6). Observer head position and movement were restrained with a chin rest and forehead bar. The Landolt squares were attached to stepper motors that were precisely positioned to one of four gap orientations by controlling pulses from the microcomputer. On each testing trial the observer indicated gap orientation by means of manual key presses as the near and far Landolt squares were alternately exposed to view. Response times from onset of stimulus exposure were automatically recorded to millisecond precision by the microcomputer.

Procedure

Experiment One was comprised of thirteen one-hour long testing sessions which were scheduled, whenever possible, at the same hour of the day for each observer. Each session measured performance for a single set of viewing conditions. Twelve of the sessions were derived from a full factorial crossing of four levels of camera interaxial separation (0 cm, 3.175 cm, 6.350 cm, and 19.05 cm) and three levels of image magnification (1X, 2X, and 3X). The thirteenth session was a direct view control condition in

FIGURE 6. NEAR-FAR TEST OBSERVER STATION



which the observer's eyes were positioned at the same location as the cameras in the 6.350 cm camera separation condition. Order of the testing sessions was randomized (see Appendix D, Table 25) so that any practice effects between testing conditions would be minimized in the analysis.

Within a single testing session, three brief measures of visual efficiency were administered before and after measurements of perceived depth. The first of these measures was a computer-administered questionnaire (see Appendix C for text). Observers responded to eleven 5-point semantic differential scales. Five of the eleven items concerned general mood state (i.e., arousal, tension, depression, enthusiasm, concentration) while the remaining six scales were derived from a survey developed by the National Institute of Occupational Safety and Health (Smith, Cohen, & Stammerjohn, 1981) to measure visual fatigue and job stress in video display terminal operators. Scale scores on the Mood and Eyestrain components were analyzed separately in a 4 (Viewing Conditions) X 3 (Magnifications) X 2 (Pretest-Posttest) repeated measures design. After completing the questionnaire, observers were given an eight-minute rest period during which they could simply relax and adapt their eyes to the low light levels used throughout the remainder of the testing session.

Following the eight-minute rest period, the near-far test of visual acuity was administered. The text of verbal instructions for this test is included in Appendix A. Each observer received 15 practice sessions on the near-far test prior to commencement of Experiment One in order to minimize the influence of practice on results. A single test of near-far acuity was comprised of two sets of five trials each. During the first set of trials, the observer shifted convergence and accommodation from a near Landolt target (.5 meter distant) to a far Landolt target (6 meters distant). During the second set of trials, she/he shifted convergence and accommodation from the far target to the near one. The observer did this in a room that was totally dark (except for the Landolt squares, when illuminated). For each trial, an observer was required to indicate (by means of pressing one of two buttons) whether gap orientations of the near and far Landolt squares matched. Observers were counterbalanced for finger of response (middle or index finger of the right hand). Each trial began with a synthesized speech "*READY*" signal. One second later, the first Landolt square was illuminated. Following another one-second delay the second Landolt square was illuminated and a response time clock was started in the computer. Observers were instructed not to redirect their eyes to the second target until it was illuminated and to make their key pressing responses as quickly and accurately as possible. Incorrect responses were immediately pronounced "*WRONG*" by the computer's voice synthesizer. No other feedback was given to observers regarding their performance of this task. Four orders of presentation for various orientations of the target pairs were generated (see Appendix D, Table 23) and one of these orders was selected at random for each administration of the near-far test. Data was analyzed in a 4 (Viewing condition) X 3 (Magnification) X 2 (Pretest-Posttest) X 2 (Refocus Direction) repeated measures design. The entire near-far test procedure (comprised of ten trials) required approximately one minute to complete.

Immediately following the near-far test, observers were seated at the observer station and administered the flicker fusion (FF) measure. Verbal instructions for the FF measure are recorded in Appendix A. Observers viewed a pair of LED's through a stereoscope viewing hood fitted with optics which allowed them to view the pair of LED's as a single fused image at optical infinity. The LED's thus appeared to the observers as a single red circle set within a darkened surround. Observers were instructed to adjust flicker frequency to fusion threshold on four successive trials, always starting adjustments from a readily apparent 25 Hz flicker rate. They were given no feedback recording performance of this test. On two trials, the LED's flickered in counter-phase and on the remaining two trials, they flickered in-phase. Four orders of presentation for these phase relationships were generated (See Appendix D, Table 24) and one of these orders was selected at random before each administration of the FF measure. Data was analyzed in a 4 (Viewing Condition) X 3 (Magnification) X 2 (Pretest-Posttest) X 2 (Flicker Phase) repeated measures design. Each administration of the flicker fusion test required approximately 30 seconds to complete.

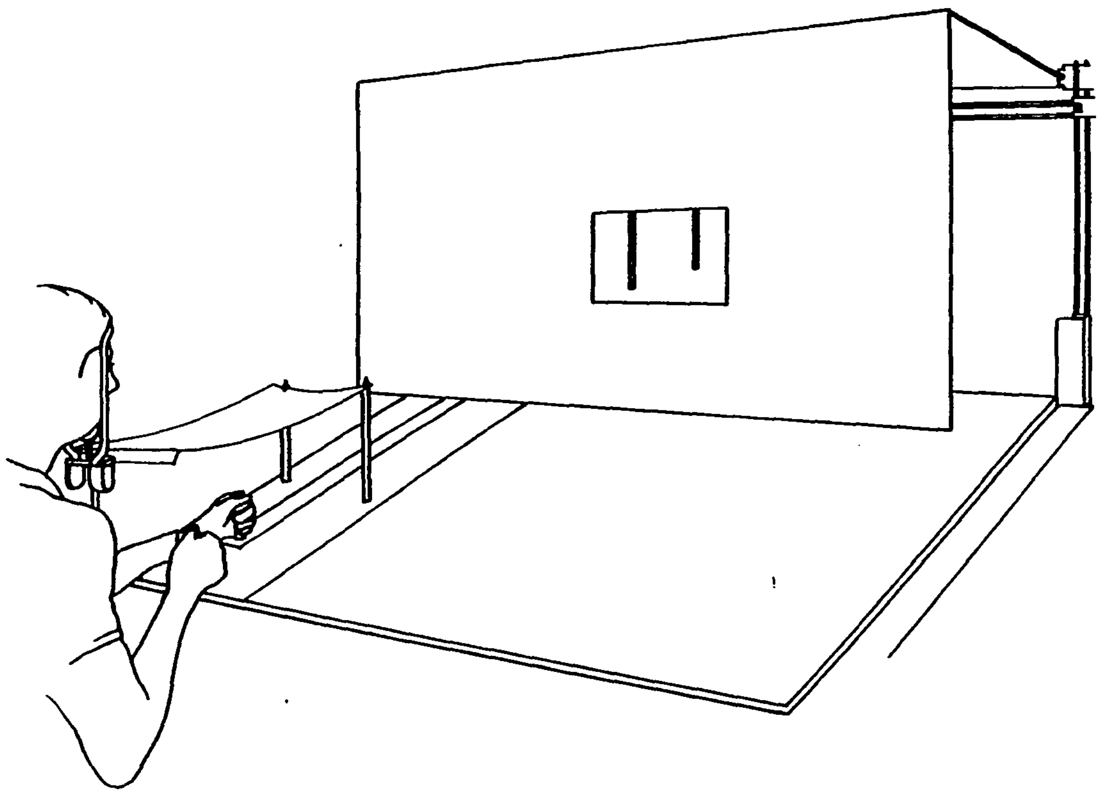
For all testing sessions (with one exception -- the direct view control condition), observers next donned a pair of polarizer eyeglasses and viewed the TV display. Each observer received no fewer than five practice sessions prior to experimental testing. Sixty trials were administered per session. Each trial began with the computer speech synthesizer announcing the trial number, blanking the video screens, and pre-positioning the stimulus rods to one of six depth intervals (0, 5.1, 10.2, 15.2, 20.3, 25.4 cm) symmetrically separated in depth around the mid-point of the workspace which was two meters directly in front of the cameras. Side of the closer rod was counterbalanced across trials for each depth interval tested so that five trials were presented for each combination of depth interval and side. Four randomized orders of presentation of depth intervals were generated (see Appendix D, Table 22) and one of these orders was selected at random for each observer at the beginning of each session. Once the rods were positioned, the video screens were turned on and the voice synthesizer asked the question *"LEFT OR RIGHT?"*. This was the observer's prompt to verbally report the side of the rod which appeared closer in depth. The speech synthesizer then informed the observer whether his/her response was *"CORRECT"* or *"WRONG"*. Next, the speech synthesizer asked the question, *"HOW FAR?"*. This was the observer's prompt to report how far (in inches) the two rods appeared to be separated in depth. The observer received no feedback on the accuracy of her/his reply to this question. Next, the synthesizer said the word *"SLIDER"* which prompted the observer to adjust te depth interval between two hand-held pegs to match the perceived depth interval between the rods in the televised scene. Once she/he had done so and pressed the response button, the speech synthesizer immediately reported the direction and error of haptic adjustment in inches. Error scores for both verbal judgments of depth and haptic adjustments were analyzed separately in 4 (Viewing Conditions) X 3 (Magnifications) X 6 (Rod Depth Intervals) repeated measures designs. Total testing time for all 60 trials was on the order of 23 minutes for Experiment One. During direct view control sessions, the observer was positioned at camera depth from the rods in the remote camera chamber (see Figure 7).

Observers proceeded through the following sequence of events during a single testing session: 1) preliminary mood and eyestrain questionnaire, 2) 8 minutes of rest in a darkened room, 3) near-far acuity test, 4) flicker fusion test, 5) 60 perceived depth interval trials, 6) flicker fusion test, 7) near-far test, 8) concluding mood and eyestrain questionnaire. An entire session reequired approximately 50 minutes to one-hour to complete.

Experiment Two

Observers, facilities and testing procedures used in Experiment two were identical to those used in Experiment one with the following exceptions. Camera interaxial separation and lens magnification parameters which according to preliminary analysis produced the best overall performance in Experiment One (M=2X, Ic=19.05 cm) were held constant while camera convergence angle was varied in Experiment Two. Three camera convergence settings were tested. For the first, cameras were symmetrically converged to the mid-point of the workspace depth interval (at 2 meters) as they were throughout Experiment One. This setting produced both crossed and uncrossed screen disparities for the rods. For the second convergence

FIGURE 7. DIRECT VIEW OBSERVER STATION



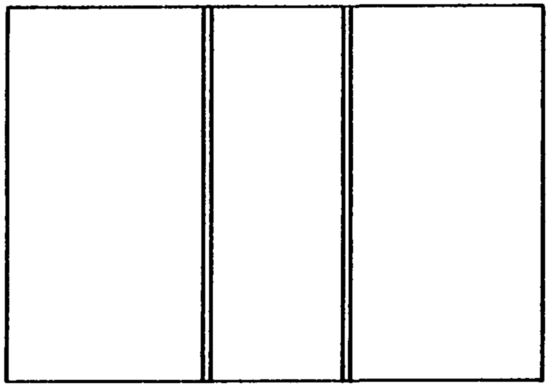
condition, cameras were converged at a distance of 1.6 meters in front of the cameras. This convergence point produced only uncrossed disparities for the rods. For the third convergence condition, camera axes were paralleled and produced only crossed screen disparities for the rods. Performance under direct view and monoscopic control conditions was also measured making a total of five experimental sessions per observer. The randomized order of presentation of these testing sessions is reported in Appendix D, Table 26. Total session testing time was approximately one hour.

Experiment Three

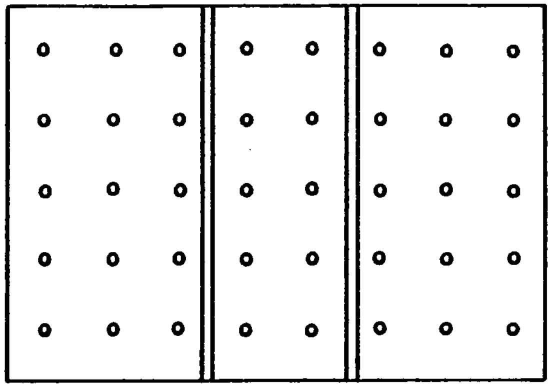
Observers, facilities, and procedures were identical to those of Experiment Two except for the following changes. An additional observer (JB) was available to participate in Experiment Three. Visual screening procedures revealed that she had no history of problems with vision and exceptionally high visual acuity for both near and far distances (see Table 1). JB received no training sessions for stereo TV viewing prior to participating in Experiment Three. Her performance may be viewed as that of a naive observer and contrasted with performance of the four experienced stereo TV observers to assess effects of prior practice.

Since the eyestrain measures used in Experiments One and Two produced no evidence of eyestrain on either flicker fusion on near-far tests, both were eliminated from the testing protocol of Experiment Three and more trials of rod depth interval judgments were substituted in their place. As a result of this change the testing protocol for Experiment Three consisted of the following sequence of events: 1) preliminary mood and eyestrain questionnaire, 2) 96 perceived depth interval trials, and 3) the concluding mood and eyestrain questionnaire. As Figure 8 illustrates, stimulus conditions used in Experiment Three were different from those used in Experiments One and Two. Rods were presented against a regularly patterned background plane which was 62 cm behind the depth mid-point of the rod workspace (262 cm from the cameras). TV cameras were separated 19.05 cm symmetrically converged on a point 1.6 meters distant, and their lenses were set for 2X magnification. The patterned background produced uncrossed disparities at the stereo display screen. Patterning on the background plane consisted of a matrix of dots (each 1.9 cm in diameter) which were equally spaced at 12.7 cm intervals in an upright grid pattern (See Figure 8). Three camera interaxial separations were tested (3.175, 6.350, and 19.05 cm) in addition to the monoscopic and direct view control conditions. Order of sessions was randomized

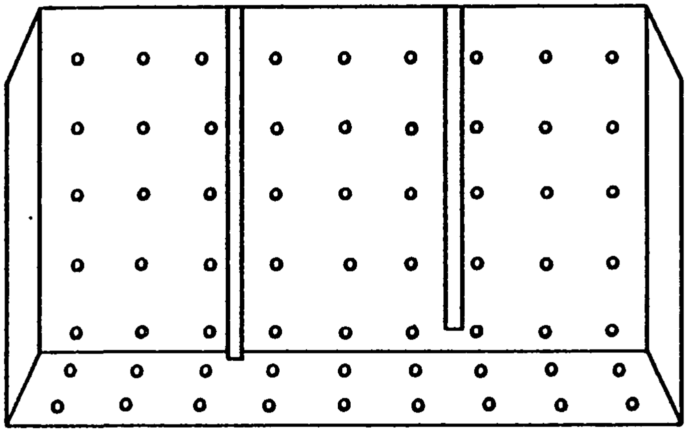
FIGURE 8. REMOTE STIMULUS CONFIGURATION



EXPERIMENT ONE & TWO
STIMULUS CONFIGURATION



EXPERIMENT THREE
STIMULUS CONFIGURATION



EXPERIMENT FOUR
STIMULUS CONFIGURATION

(see Appendix D, Table 27). Total session testing time was approximately one hour.

Experiment Four

Experiment Four was identical to Experiment Three except for the following changes. The beamsplitter camera station was tilted so that cameras were aimed down 15° off-level. Rods were presented against a clearly patterned three-dimensional background which consisted of the same dotted backplane used in Experiment Three with the addition of a similarly dotted floor plane which provided clear perspective and interposition depth cues (see Figure 8). The lower ends of the rods were clearly visible and also provided relative height cues to depth. Five testing sessions identical (except for stimulus conditions) to those used in Experiment Three were run. Randomized order of presentation for these sessions is reported in Appendix D, Table 28.

RESULTS

Experiments One through Four each produced multiple sets of visual performance measures for analysis. Scores on each measure were compiled for analysis from each testing session. Given the full factorial structure of the designs utilized in the experiments and the availability of appropriate covariate measures, it was possible to analyze each of the dependent variables with a repeated measures analysis of covariance (ANCOVA). In all cases analysis was performed with BMDP Program 2V -- analysis of variance and covariance including repeated measures (Dixon, Brown, Engleman, Frane, Hill, Jennrich, & Toporek, 1981). For each analysis, a single covariate was selected to statistically level observers on an uncontrolled factor operating in the testing situation which was previously demonstrated to be linearly related to the dependent measure. The statistical assumption of symmetry for the orthogonal polynomials in each analysis was tested with Anderson's (1958, p. 259) sphericity procedure. Whenever the symmetry hypothesis was rejected, an adjustment to the degrees of freedom of the F test (Greenhouse & Geisser, 1959; Winer, 1971, p. 523) was performed which protects for Type I errors when symmetry assumptions are violated. Analyses subsequent to ANCOVAs consisted of inspections of by observer plots for theoretically or statistically significant effects in order to determine the consistency of those effects across observers. Multiple comparisons of cell means within statistically significant effects were conducted with conservative procedures (i.e., Duncan's New Multiple Range Test reviewed in Kirk (1968), pp 93-944) which protected against Type I errors. A minimum significance criterion of $p < .05$ was set for all statistical hypotheses tested.

Experiment One

Experiment One produced six sets of dependent measures for statistical analysis, 1) haptic adjustment error scores, 2) verbal depth judgment errors, 3) near-far acuity test response times, 4) flicker fusion thresholds, 5) eyestrain questionnaire scale scores, and 6) mood state questionnaire scale scores. Data points from each of these sets of scores were collapsed across repeated trials of identical test conditions and subjected to a repeated measures analysis of covariance. The covariate used in analyses of eyestrain scores (items 1-4 above) was depth judgment testing time in minutes, while the covariate used in analyses of perceived depth measures (items 5 and 6) was observer interpupillary distance.

Haptic Adjustments of Perceived Depth Intervals

For each testing session, error scores (in inches) from 10 repeated measures for each of the six objective depth intervals were absolutized and transformed to centimeters prior to being averaged and subjected to a 4 (Viewing Condition) X 3 (Magnification) X 6 (Rod Depth Intervals) ANCOVA with observer interpupillary distance (I_o) serving as covariate. I_o was employed as a covariate in this analysis because of its simple geometrical relationship to retinal disparities. Results of this analysis are reported in Table 2.

I_o accounted for a significant proportion of variation in haptic adjustment errors (F(1,2)=140.92, p=.007) because of the very small amount of error variation associated with its effect. In my opinion, this is not likely to be due to the effect of I_o *per se*. It is more likely to be a reflection of either a sex or experience effect. Males had more experience, larger I_o's (67 and 67.5 mm), and were more accurate than the less experienced, less accurate females, both of whom had Io's of 60 mm.

Viewing condition also exerted a strong main effect (F=72.13, df=(3,9), p < .001) on the results of the analysis. Cell means for this effect are plotted for each

Table 2.
Source Table of the Analysis of Covariance for Haptic Adjustments of Depth. Data from Experiment One.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARES	F	TAIL PROB.
COVARIATE (I_o)	15.528	1	15.528	140.92	.007
ERROR	0.220	2	0.110		
VIEWING CONDITION (V)	103.447	3	34.482	72.13	<.001
ERROR	4.302	9	0.478		
FOV (Ω)	1.432	2	0.716	0.60	ns
ERROR	7.168	6	1.195		
V X Ω INT.	28.356	6	4.726	8.43	0.018 ^{g}
ERROR	10.096	18	0.561		
DEPTH (ΔR)	77.126	5	15.425	5.08	ns ^{g}
ERROR	45.508	15	3.034		
V X ΔR INT.	23.944	15	1.596	2.45	ns ^{g}
ERROR	29.342	45	0.652		
Ω X ΔR INT.	6.709	10	0.671	1.43	ns ^{g}
ERROR	14.036	30	0.468		
V X Ω X ΔR INT.	23.456	30	0.782	2.89	ns ^{g}
ERROR	23.267	90	0.271		

^{g} Significance based on Greenhouse-Geisser corrected probability.

FIGURE 9.
VIEWING CONDITION MAIN EFFECT
FOR HAPTIC DEPTH ADJUSTMENTS.
DATA FROM EXPERIMENT ONE.

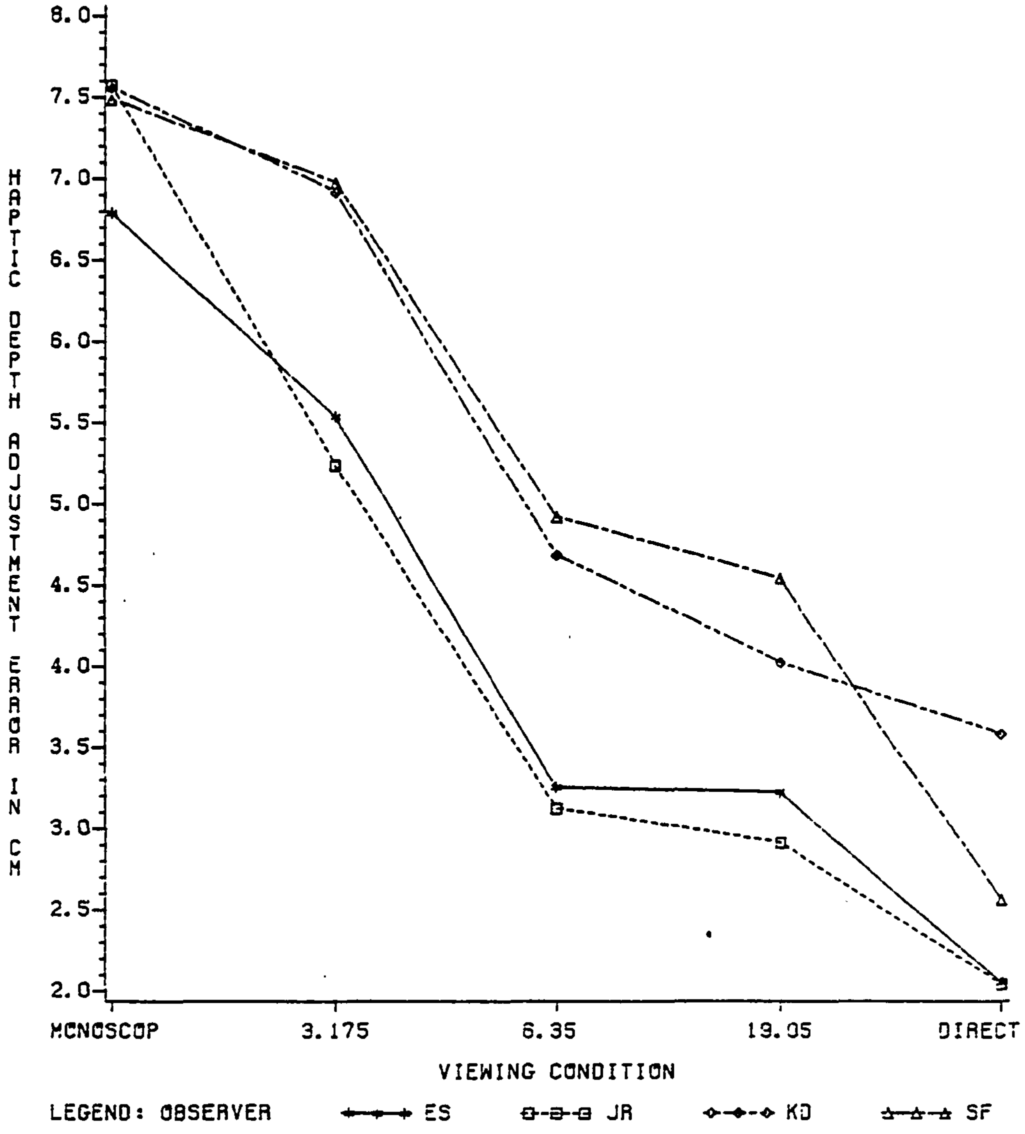


Table 3.
Duncan New Multiple Range Statistic.
Mean Scores for Haptic Adjustment Errors
on the Viewing Condition Main Effect.
Data from Experiment One.

	MONO-SCOPIC	3.175 CM	6.35 CM	19.05 CM
MEAN SCORE	7.35	6.17	3.99	3.68
MONOSCOPIC		*	**	**
3.175 CM			**	**
6.350 CM				--
19.05 CM				

* p < .05

** p < .01

observer in Figure 9, and tests of specific cell mean differences are reported in Table 3. Although they were not included in the factorial design of the experiment, means for the direct view control condition are included in Figure 9 for comparison. Inspection of Figure 9 reveals that accuracy of haptic adjustments under stereo TV conditions was superior to that under monoscopic viewing conditions. Comparisons of cell means revealed that depth interval estimation under monoscopic and reduced camera base viewing conditions (3.175 cm) was significantly poorer than estimation under orthostereoscopic (6.35 cm) and hyperstereoscopic (19.05 cm) viewing conditions. No statistically significant difference was found between orthostereoscopic and hyperstereoscopic viewing conditions. As camera interaxial separation increased, the accuracy of haptic adjustments increased. These results are consistent with previous experimental findings with stereo TV systems (i.e., Cole, Pepper, & Pinz, 1981; Pepper, Cole, & Spain, 1983; Spain & Cole, 1982) which used depth resolution as the dependent measure of depth perception. There is also a rather apparent difference in overall accuracy between more experienced male observers (JR and ES) and less experienced females (KD and SF).

A significant interaction was also found between viewing condition and camera field of view (F(6,18)=8.43, corrected p=.018). This interaction is plotted individually for each observer in Figure 10, and tests of specific cell mean differences are reported in Table 4. For both 1X and 2X magnifications, all observers showed increases in performance as camera separation increased. For the 1X and 2X magnifications, the more experienced male observers (JR and ES) showed large improvements between monoscopic and the 3.175 cm separation, and between 3.175 and 6.35 cm separations while the transition from 6.35 to 19.05 cm camera separation yielded only slight improvements in performance. The less experienced female observers (KD and SF) showed more gradual increases in performance with increases in camera separation, with considerably greater improvement in the transition from 6.35 to 19.05 cm camera separation. The pattern of results for the 3X magnification condition was consistent for all subjects in differing from the other two magnifications. Three out of four observers showed moderate (.5 to 1 cm) decreases in haptic adjustment accuracy in the transition from monoscopic to 3.175 cm camera separations. All show moderate to substantial increases in accuracy for the transition from 3.175 cm to 6.35 cm camera separations. Under 3X magnification, all observers showed decreases in accuracy in the transition from 6.35 cm to 19.05 cm camera separation with less experienced, female observers showing larger (approximately

FIGURE 10.
CAMERA SEPARATION X MAGNIFICATION INTERACTION
FOR HAPTIC DEPTH ADJUSTMENTS
DATA FROM EXPERIMENT ONE.

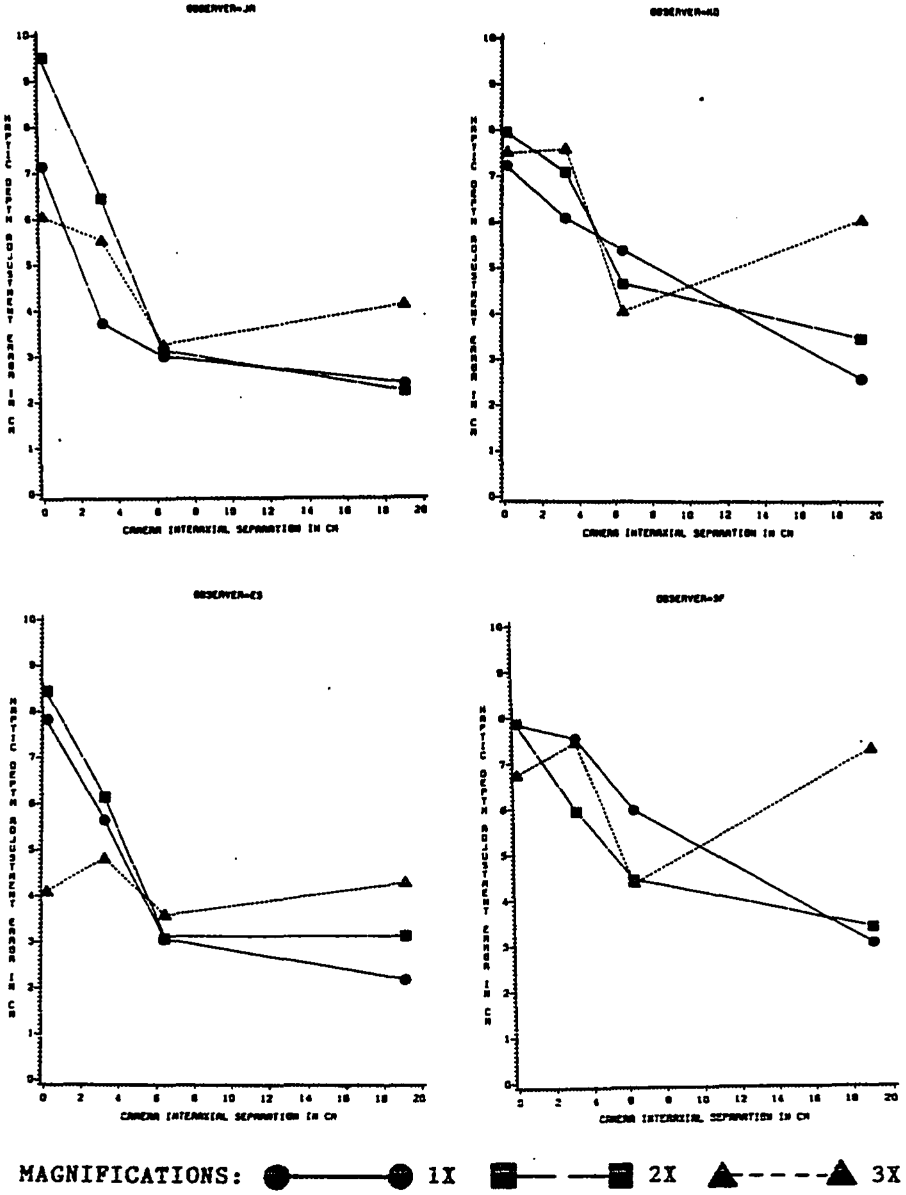


Table 4.
Duncan New Multiple Range Statistic.
Mean Scores for Haptic Adjustment Errors
on the Viewing Condition X Rod Depth Interval Interaction.
Data From Experiment One. * p < .05 ** p < .01

	Monos 1X	Monos 2X	Monos 3X	3.175 1X	3.175 2X	3.175 3X	6.35 1X	6.35 2X	6.35 3X	19.05 1X	19.05 2X	19.05 3X
MEANS	2.56	3.05	3.81	3.83	4.36	5.43	6.08	6.35	6.40	6.40	7.52	8.44
Monoscopic 1X		--	*	*	**	**	**	**	**	**	**	**
Monoscopic 2X			--	--	*	**	**	**	**	**	**	**
Monoscopic 3X				--	--	*	**	**	**	**	**	**
3.175 CM 1X					--	*	**	**	**	**	**	**
3.175 CM 2X						--	**	**	**	**	**	**
3.175 CM 3X							--	--	--	--	**	**
6.350 CM 1X								--	--	--	*	**
6.350 CM 2X									--	--	--	**
6.350 CM 3X										--	--	**
19.05 CM 1X											**	**
19.05 CM 2X												--

2 to 3 cm) decreases than the more experienced males (appoximately 1 cm). Whatever the disadvantages of using large camera separation with higher magnifications may be, they appear to be less disruptive of performance with the more highly practiced male subjects. No other statistically significant effects emerged from the analysis.

Verbal Judgments of Perceived Depth Intervals

For each testing session, error scores (in inches) from 10 repeated measures for each of the 6 rod depth intervals were absolutized and transformed to centimeters prior to being averaged and input to a 4 (Viewing Condition) X 3 (Magnification) X 6 (Rod Depth Interval) ANCOVA with observer I_o serving as the covariate. Results are reported in Table 5. The only significant effect to emerge from the analysis was that of viewing condition ($F(3,9)=23.63$, $p < .001$). Cell means for this effect are plotted for each observer in Figure 11, and tests of specific cell mean differences are reported in Table 6. Cell means for the direct view control condition were not included in the analysis, but are plotted in Figure 11 for comparison. Stereo TV viewing conditions produced greater accuracy in depth interval estimates than monoscopic viewing conditions, although this effect was not as pronounced as the corresponding effect found for haptic adjustments.

Table 5.
Source Table of the Analysis of Covariance for Verbal Judgements of Depth. Data from Experiment One.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARES	F	TAIL PROB.
COVARIATE (I_o)	21.605	1	21.605	7.90	ns
ERROR	5.477	2	2.735		
VIEWING CONDITION (V)	58.831	3	19.610	23.63	<.001
ERROR	7.468	9	0.830		
FOV (Ω)	1.602	2	0.801	0.49	ns
ERROR	9.789	6	1.632		
V X Ω INT.	11.481	6	1.914	1.6	ns [g]
ERROR	21.488	18	1.194		
DEPTH (ΔR)	35.597	5	7.119	0.79	ns [g]
ERROR	135.318	15	9.021		
V X ΔR INT.	11.252	15	0.750	1.78	ns [g]
ERROR	18.954	45	0.421		
Ω X ΔR INT.	12.646	10	1.265	2.36	ns [g]
ERROR	16.105	30	0.537		
V X Ω X ΔR INT.	30.260	30	1.009	3.35	ns [g]
ERROR	27.096	90	0.301		

[g] Significance based on Greenhouse-Geisser corrected probability.

FIGURE 11.
VIEWING CONDITION MAIN EFFECT FOR VERBAL DEPTH JUDGMENTS. DATA FROM EXPERIMENT ONE.

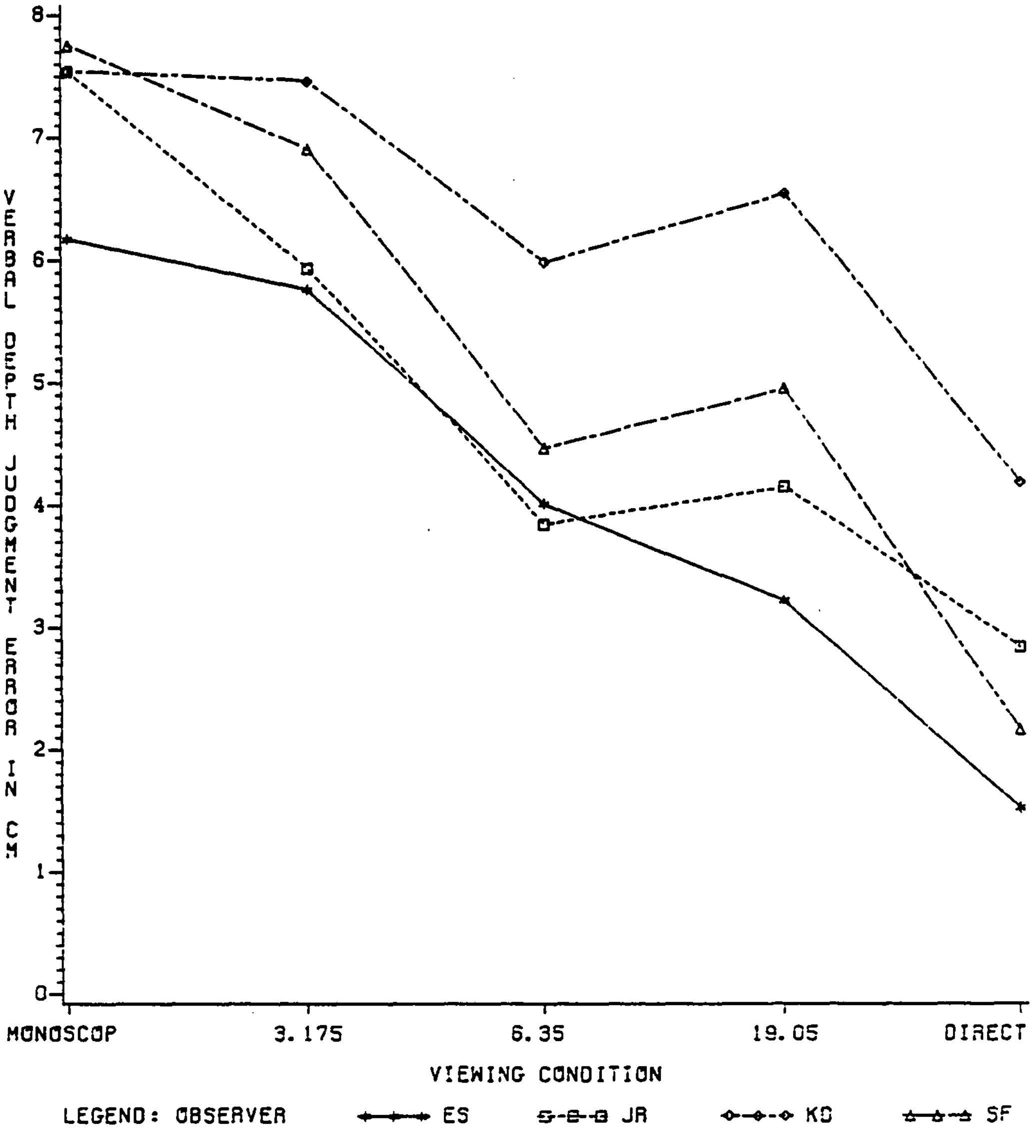


Table 6.
Duncan New Multiple Range Statistic.
Mean Scores for Verbal Judgment Errors
on the Viewing Condition Main Effect.
Data from Experiment One.

		:-- CAMERA SEPARATIONS	--:	
	MONO-SCOPIC	3.175 CM	6.35 CM	19.05 CM
MEAN SCORE	7.25	6.51	4.57	4.72
MONOSCOPIC		--	**	**
3.175 CM			--	*
6.350 CM				--
19.05 CM				

* p < .05

** p < .01

Inspection of Figure 11 suggests that experienced males produced more accurate judgments than inexperienced females. Greatest improvements in accuracy under stereo viewing conditions occurred in the transition from 3.175 to 6.35 cm camera separation. Unlike the haptic adjustments, however, there was a decrement in performance in the transition from 6.35 to 19.05 cm separations for three of the four observers. While these decrements are not large, they may suggest that "natural stereo" imagery produces more accurate perception of depth than hyperstereo does -- a suggestion which is at variance with results of the analysis of haptic adjustments.

Near-Far Test

During each experimental session, 20 NF test response times were measured -- 10 prior to making depth judgments through the TV system, 10 after. Within a single administration of the NF test, the first five trials reflected refocus time from near-to-far distances while trials 6 through 10 reflected refocus times from far-to-near distances. Alpha reliabilities for pre-test administrations of this test were found to be .92 for near-to-far trials and .98 for far-to-near trials. Overall alpha was .97. Averaging the five measures within each of these Pretest-Posttest X Refocus Direction combinations yielded

Table 7.
Source Table of the Analysis of Covariance
for Near-Far Test Response Times.
Data From Experiment One.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
ELAPSED TIME (COVARIATE)	0.338	1	0.338	0.00	ns
ERROR	66.318	2	33.159		
VIEWING CONDITION (V)	0.295	3	0.983	0.26	ns
ELAPSED TIME	2.347	1	2.347	6.18	.04
ERROR	3.037	8	0.380		
FOV (Ω)	0.583	2	0.269	0.62	ns
ELAPSED TIME	0.030	1	0.030	0.07	ns
ERROR	2.167	5	0.433		
V X Ω INT.	4.520	6	0.753	1.26	ns [g]
ELAPSED TIME	0.460	1	0.460	0.77	ns
ERROR	10.138	17	0.596		
REFOCUS DIRECTION (R)	0.257	1	0.257	3.23	ns
ERROR	0.239	3	0.080		
V X R INT.	0.136	3	0.045	0.94	ns
ERROR	0.433	9	0.048		
Ω X R INT.	0.066	2	0.033	1.02	ns [g]
ERROR	0.193	6	0.032		
V X Ω X R INT.	0.738	6	0.123	1.64	ns [g]
ERROR	1.351	18	0.075		
PRETEST-POSTTEST (P)	0.252	1	0.252	0.10	ns
ERROR	12.126	3	4.042		
V X P INT.	0.371	3	0.124	1.26	ns
ERROR	0.881	9	0.098		
Ω X P INT.	0.034	2	0.017	2.00	ns
ERROR	0.051	6	0.008		
V X Ω X P INT.	1.213	6	0.202	1.56	ns [g]
ERROR	2.335	18	0.130		

Table 7.
Source Table of the Analysis of Covariance for Near-Far Test Response Times. Data From Experiment One. (Continued)

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
R X P INT.	0.218	1	0.218	4.22	ns
ERROR	0.155	3	0.052		
V X R X P INT.	0.068	3	0.023	0.38	ns
ERROR	0.533	9	0.059		
Ω X R X P INT.	0.201	2	0.101	0.59	ns [g]
ERROR	1.016	6	0.170		
V X Ω X R X P	1.296	6	0.216	3.20	ns [g]
ERROR	1.217	18	0.068		

[g] Significance based on Greenhouse-Geisser corrected probability.

four scores per session which served as input to a 4 (Viewing Conditions) X 3 (Magnification) X 2 (Pre-Post) X 2 (Refocus Direction) ANCOVA with TV depth judgment test time as covariate. The source table for this analysis is reported in Table 7. No main or interactive effects were found for any of the factors investigated. Again, the main variable of interest was the Pre-Post contrast which would have indicated eyestrain had there been a substantial slowing of response time following TV testing. No such effects nor any interaction was found with this factor, so it must once again be concluded that substantial deviations from natural stereo TV imagery do not produce eyestrain under the testing conditions utilized in Experiment One.

Flicker Fusion Test

Each observer made eight judgments to FF threshold per session -- four prior to stereo TV trials and four after. Two in-phase and two counter-phase trials were given within a single administration of the test. Alpha reliabilities for in-phase and counter-phase flicker trials were Overall alpha was .95. Averaging the two measures within each of the Pre-Post X Flicker Phase combinations tested yielded four scores per session for analysis. Scores from 12 sessions were subjected to a 4 (Viewing Condition) X 3 (Magnification) X 2 (Pre-Post) X 2 (Flicker Phase) ANCOVA

Table 8.
Source Table of the Analysis of Covariance
for Flicker Fusion Thresholds.
Data From Experiment One.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
ELAPSED TIME	112.317	1	112.317	1.31	ns
ERROR	171.054	2	85.527		
VIEWING CONDITION (V)	11.949	3	3.983	0.56	ns
ELAPSED TIME	2.197	1	2.197	0.31	ns
ERROR	56.878	8	7.110		
FOV (Ω)	8.096	2	4.048	3.76	ns
ELAPSED TIME	0.406	1	0.406	0.38	ns
ERROR	5.379	5	1.076		
V X Ω INT.	4.209	6	0.702	0.21	ns[g]
ELAPSED TIME	7.870	1	7.870	2.37	ns
ERROR	56.500	17	3.324		
PRETEST-POSTTEST (PP)	0.943	1	0.943	0.08	ns
ERROR	35.303	3	11.767		
V X PP INT.	2.143	3	0.714	0.39	ns
ERROR	16.615	9	1.846		
Ω X PP INT.	1.458	2	0.729	0.09	ns
ERROR	47.468	6	7.911		
V X Ω X PP INT.	18.259	6	3.043	1.34	ns[g]
ERROR	40.955	18	2.275		
PHASE (PH)	0.252	1	0.252	0.10	ns
ERROR	7.666	3	2.555		
V X PH INT.	3.772	3	1.257	0.71	ns[g]
ERROR	15.853	9	1.762		
Ω X PH INT.	9.141	2	4.571	1.56	ns
ERROR	17.523	6	2.921		
V X Ω X PH INT	20.484	6	3.414	0.60	ns[g]
ERROR	102.173	18	5.676		
PP X PH INT.	1.283	1	1.283	1.70	ns
ERROR	2.262	3	0.754		

Table 8.
Source Table of the Analysis of Covariance for Flicker Fusion Thresholds.
Data From Experiment One.
(Continued)

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
V X PP X PH INT	10.543	3	3.514	1.38	ns
ERROR	22.921	9	2.547		
Ω X PP X PH INT	4.109	2	2.054	2.57	ns
ERROR	4.796	6	0.799		
V X Ω X PP X PH	8.682	6	1.447	0.97	ns
ERROR	26.731	18	1.485		

[g] Significance based on Greenhouse-Geisser corrected probabilities.

with stereo TV test time as covariate. The source table for the analysis is found in Table 8. Again, no main or interactive effects were found for any of the factors included in the analysis. Once again, the hypothesis that no changes in eyestrain resulted from various combinations of viewing conditions utilized in this environment could not be rejected.

Questionnaire

The preliminary and concluding questionnaires were divided into mood and eyestrain scales for analysis. The mood scale was composed of screen frames 1 through 5; whereas, the eyestrain scale was composed of items 6 through 11 (see Appendix C). Since polarity of two of the mood items (i.e., screen frames 2 and 6) and three of the eyestrain items (i.e., screen frames 6, 8, and 10) was reversed during administration, these items were positively rescaled prior to summing with responses on the remaining items to yield the scale scores which were analyzed. Higher scores on the mood scale indicated that the observer was more comfortable and more motivated. Higher scores on the eyestrain scale indicated an absence of common eyestrain symptoms. Since mood and eyestrain scales employed in Experiment One were newly constructed, alpha reliabilities were calculated to determine the internal consistency of scores on the pre-test administrations across all 13 testing sessions. Alpha was found to be .98 for the mood scale and .43 for the eyestrain scale. Scores from mood and eyestrain scales were subjected to a 4 (Viewing Condition) X 3 (Magnification) X 2 (Pretest-Posttest) ANCOVA with depth judgment test time as the single covariate in both analyses. The factor of greatest interest in both ANCOVAs, the pretest-posttest contrast would interact with viewing conditions or magnification should the various levels of these factors exert differential effects on mood and eyestrain.

ANCOVA source tables for mood and eyestrain scale scores are reported in Tables 9 and 10, respectively. No main or interactive effects were found to be significant in either analysis. On the basis of these results the null hypothesis that test conditions would not influence reports of mood and eyestrain could not be rejected. More importantly, no evidence was found to support the hypothesis that variations in camera interaxial separation or lens magnification exerted differential effects on observer mood and eyestrain.

In addition, no support was found for the hypothesis that substantial variation in camera interaxial separation or lens magnification exerted substantial effects on

Table 9.
Source Table of the Analysis of Covariance
for Eyestrain Scale Scores.
Data From Experiment One.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
COVARIATE (ELAPSED TIME)	0.981	1	0.981	0.04	ns
ERROR	48.852	2	24.426		
VIEWING CONDITION (V)	16.450	3	5.483	0.65	ns
COVARIATE	3.041	1	3.041	0.36	ns
ERROR	67.709	8	8.464		
FOV (Ω)	7.475	2	3.738	0.81	ns
COVARIATE	0.773	1	0.773	0.17	ns
ERROR	23.143	5	4.629		
V X Ω INT.	35.605	6	5.934	1.31	ns [g]
COVARIATE	2.476	1	2.476	0.55	ns
ERROR	77.024	17	4.531		
PRETEST-POSTTEST (PP)	7.042	1	7.042	7.04	ns
ERROR	31.458	3	10.486		
V X PP INT.	1.708	4	0.569	0.35	ns
ERROR	14.458	9	1.606		
Ω X PP INT.	3.083	2	1.542	1.25	ns
ERROR	7.417	6	1.236		
V X Ω X PP INT.	11.667	6	1.944	0.94	ns [g]
ERROR	37.167	18	2.065		

[g] Significance based on Greenhouse-Geisser corrected probability.

Table 10.
Source Table of the Analysis of Covariance
for Mood State Scale Scores.
Data From Experiment One.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
COVARIATE (ELAPSED TIME)	431.091	1	431.091	3.06	ns
ERROR	281.450	2	0.912		
VIEWING CONDITION (V)	7.852	3	2.617	0.32	ns
COVARIATE	0.153	1	0.153	0.02	ns
ERROR	65.888	8	0.236		
FOV (Ω)	6.894	2	3.448	0.89	ns
COVARIATE	1.012	1	1.012	0.26	ns
ERROR	19.322	5	3.864		
V X Ω INT.	44.410	6	7.402	0.75	ns [g]
COVARIATE	3.942	1	3.942	0.40	ns
ERROR	166.892	17	9.817		
PRETEST-POSTTEST (PP)	9.375	1	9.375	0.86	ns
ERROR	32.875	3	10.958		
V X PP INT.	2.208	4	0.736	0.30	ns
ERROR	22.208	9	2.468		
Ω X PP INT.	6.750	2	3.375	3.12	ns
ERROR	6.500	6	1.083		
V X Ω X PP INT.	2.917	6	0.486	0.26	ns
ERROR	34.167	18	1.898		

[g] Significance based on Greenhouse-Geisser corrected probability.

observer mood and eyestrain.

Experiment Two

Six sets of data were obtained for analysis in Experiment Two. They were the same dependent measures obtained in Experiment One, and each was transformed and/or averaged in the same fashion as its Experiment One counterpart prior to analysis. Five sessions were run in which camera separation was fixed at 19.05 cm and magnification was fixed at 2X. Camera convergence was varied at three levels (1.6 meters (Fore), 2 meters (Middle), and ∞ (Parallel), and monoscopic and direct view sessions were also administered.

Haptic Adjustments of Perceived Depth Intervals

Average absolutized errors for haptic adjustment were subjected to a 5 (Viewing Conditions) X 6 (Depth Intervals) repeated measures ANCOVA with observer I_o serving as covariate. Results of this analysis are reported in Table 11. Both Viewing Condition (F(4,12)=33.26, p=.002) and Rod Depth Interval (F(5,15)=8.66, corrected p=.014) emerged as significant factors in the analysis.

The Viewing Condition main effect is plotted in Figure 12, and tests of specific mean differences are reported in

Table 11.
Source Table of the Analysis of Covariance
for Haptic Adjustments of Depth.
Data from Experiment Two.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARES	F	TAIL PROB.
COVARIATE (I_o)	5.140	1	5.140	1.25	ns
ERROR	8.227	2	4.114		
VIEWING CONDITION (V)	449.510	4	112.378	33.26	.002
ERROR	40.550	12	3.379		
DEPTH (D)	75.829	5	15.166	8.66	.014 [g]
ERROR	26.280	15	1.752		
V X D INT.	117.332	20	5.867	3.32	ns [g]
ERROR	105.991	60	1.767		

[g] Significances based on Greenhouse-Geisser corrected probability.

FIGURE 12.
VIEWING CONDITION MAIN EFFECT FOR HAPTIC DEPTH ADJUSTMENTS. DATA FROM EXPERIMENT TWO.

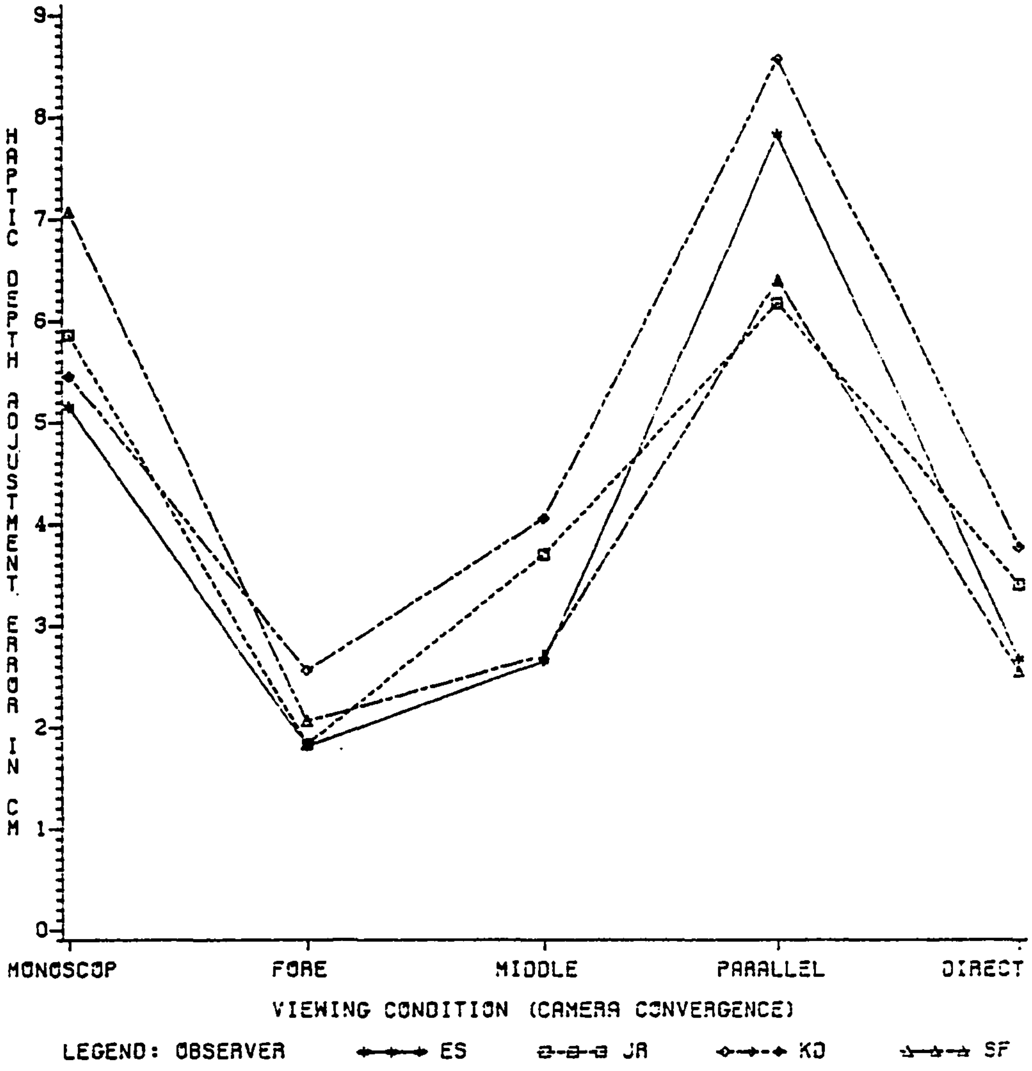


Table 12.
Duncan New Multiple Range Statistic.
Mean Scores for Haptic Adjustment Errors
on the Viewing Condition Main Effect.
Data from Experiment Two.

		:- CAMERA	CONVERGENCE	-:	
	MONO-SCOPIC	FORE	MIDDLE	PARALLEL	DIRECT VIEW
MEAN SCORE	5.89	2.06	3.10	7.25	3.28
MONOSCOPIC		*	--	--	--
FORE			--	**	--
MIDDLE				--	--
PARALLEL					*
DIRECT VIEW					

* $p < .05$

** $p < .01$

Table 12. All observers produced similar patterns of response for the five viewing conditions tested. Monoscopic viewing conditions produced haptic error comparable to those found in Experiment One. When cameras were converged in front of the rods at a distance 1.6 meters, haptic accuracy was greatest. When cameras were converged to the middle of the rod workspace, 2 meters distant, accuracy was approximately 25% lower than under the "Fore" convergence condition, but also closely comparable to accuracy under direct viewing conditions. Paralleling the cameras produced screen disparities which were so large that they could not be fused and produced poorer accuracy than was found under monoscopic viewing conditions.

The depth interval main effect is plotted in Figure 13, and tests of specific cell mean differences are reported in Table 13. The general trend apparent in Figure 13 is that haptic adjustment accuracy declines as size of the depth interval is increased from 55.12 to 25.4 cm. The most accurately estimated interval was 5.12 cm with poorer accuracy found for the null interval.

Verbal Judgments of Perceived Depth Intervals

Average absolutized errors for verbal judgments were subjected to a 5 (Viewing Condition) X 6 (Depth Intervals)

FIGURE 13.
ROD DEPTH INTERVAL MAIN EFFECT FOR HAPTIC DEPTH ADJUSTMENTS. DATA FROM EXPERIMENT TWO.

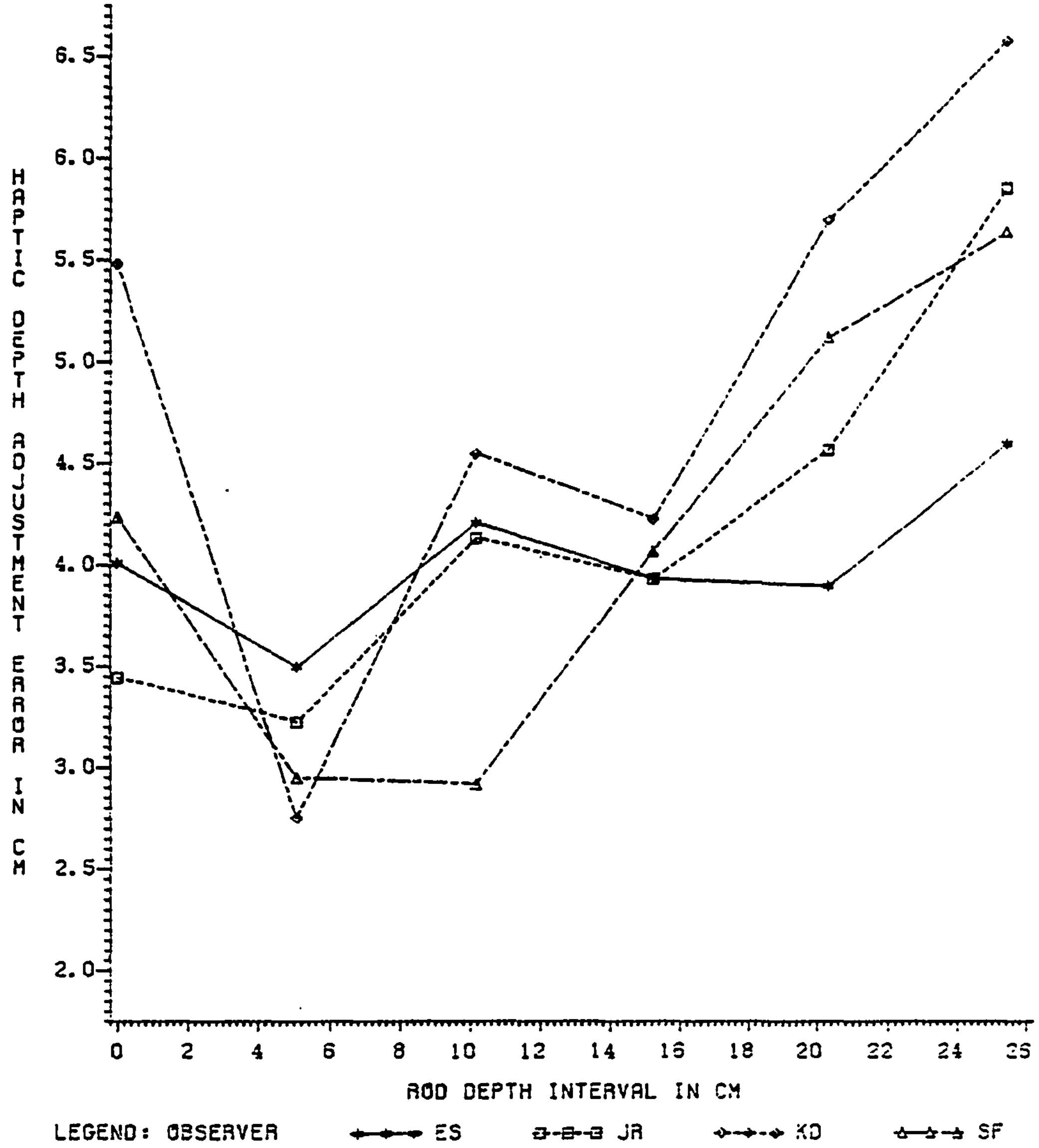


Table 13.
Duncan New Multiple Range Statistic.
Mean Scores for Haptic Adjustment Errors
on the Rod Depth Interval Main Effect.
Data from Experiment Two.

	ROD DEPTH INTERVALS					
	0.00 CM	5.08 CM	10.16 CM	15.24 CM	20.32 CM	25.40 CM
MEAN SCORE	4.29	3.10	3.95	4.04	4.83	5.68
0.00 CM		--	--	--	--	--
5.08 CM			--	--	--	*
10.16 CM				--	--	--
15.24 CM					--	--
20.32 CM						--
25.40 CM						

* $p < .05$

** $p < .01$

repeated measures ANCOVA with observer I_o serving as covariate. Results of this analysis are reported in Table 14. The Viewing Condition main effect (F(4,12)=10.23, p=.019) was found significant, and is plotted in Figure 14. Tests of specific cell mean differences are reported in Table 15. Inspection of Figure 14 reveals a pattern of results similar but less clear because of greater interobserver variability than those found for haptic adjustments. Verbal judgments for both control conditions (i.e., monoscopic and direct view) were comparable to levels found in Experiment One. For stereo viewing conditions, verbal judgments were most accurate when cameras were converged in front of the rods and least accurate when paralleled. Converging the cameras in front of the rods produced greater accuracy than was found under direct viewing conditions. Converging cameras to the midpoint of the rod workspace produced accuracy closely approximating direct viewing conditions, and paralleling the cameras produced poorer accuracy than monoscopic viewing conditions.

Near-Far Test

Average response times from the near-far test were subjected to a 5 (Viewing Condition) X 2 (Pretest-Posttest) X 2 (Refocus Direction) repeated measures ANCOVA with depth

Table 14.
Source Table of the Analysis of Covariance
for Verbal Judgments of Depth.
Data from Experiment Two.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARES	F	TAIL PROB.
COVARIATE (I_o)	1.182	1	1.182	0.03	ns
ERROR	122.229	2	61.114		
VIEWING CONDITION (V)	273.288	4	68.322	10.23	.019
ERROR	80.160	12	6.680		
DEPTH (D)	142.726	5	28.545	1.14	ns [g]
ERROR	374.729	15	24.982		
V X D INT.	89.803	20	4.490	3.54	ns [g]
ERROR	76.087	60	1.269		

[g] Significance based on Greenhouse-Geisser corrected probability.

FIGURE 14
VIEWING CONDITION MAIN EFFECT
FOR VERBAL DEPTH JUDGMENTS.
DATA FROM EXPERIMENT TWO.

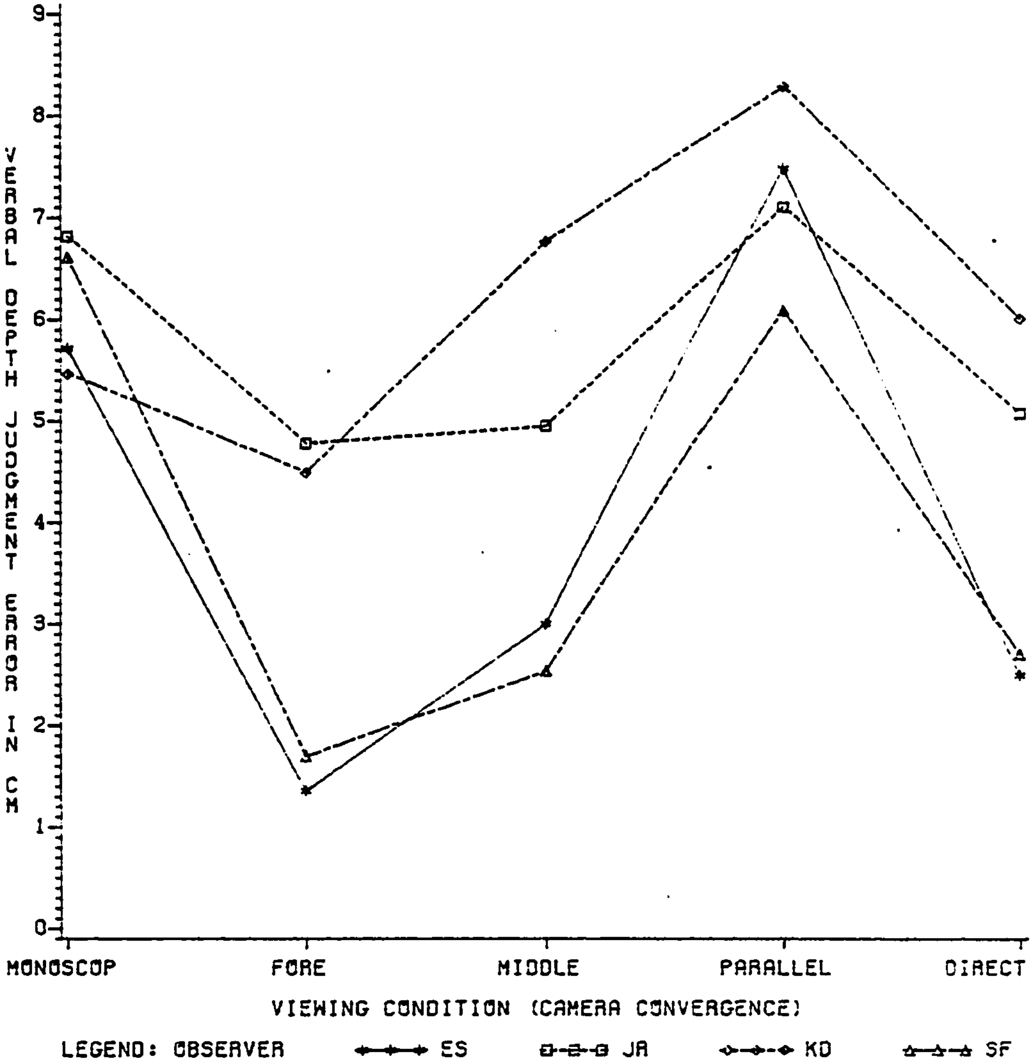


Table 15.
Duncan New Multiple Range Statistic.
Mean Scores for Verbal Judgment Errors
on the Viewing Condition Main Effect.
Data from Experiment Two.

		:- CONVERGENCE POINTS -:			
	MONO- SCOPIC	FORE	MIDDLE	PARALLEL	DIRECT VIEW
MEAN SCORE	6.15	3.08	4.07	7.25	4.32
MONOSCOPIC		--	--	--	--
3.175 CM			--	*	--
6.350 CM				--	--
19.05 CM					--
DIRECT VIEW					

* $p < .05$

** $p < .01$

judgment test administration time serving as the covariate. Results of this analysis are reported in Table 16. No significant main effects or interactions emerged from this analysis. Apparently, performance was stable for all viewing conditions tested for both near-to-far and far-to-near refocus adjustments and there was no slowing of response times in the transition from pretest to posttest measures.

Flicker Test

Average flicker fusion thresholds were computed and subjected to a 5 (Viewing Condition) X 2 (Pretest-Posttest) X 2 (Flicker Phase) ANCOVA with depth judgment test time as the covariate. Results of this analysis are reported in Table 17. No significant main effects or interactions emerged from this analysis, once again suggesting stable performance and no support for rejection of the null hypothesis for eyestrain.

Questionnaire

No significant main or interactive effects emerged from a 5 (Viewing Conditions) X 2 (Pretest-Posttest) ANCOVA (with depth judgment test time as covariate) which was performed on the mood scale scores from Experiment Two. The results

Table 16.
Source Table of the Analysis of Covariance for Near-Far Test Response Times. Data from Experiment Two.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
COVARIATE (ELAPSED TIME)	0.906	1	0.909	0.99	ns
ERROR	1.832	2	0.912		
VIEWING CONDITION (V)	1.821	4	0.455	2.48	ns [g]
COVARIATE	0.627	1	0.627	3.42	ns
ERROR	2.016	11	0.183		
PRETEST-POSTTEST (PP)	0.234	1	0.234	2.61	ns
ERROR	0.269	3	0.090		
V X PP INT.	0.670	4	0.168	0.97	ns [g]
ERROR	2.080	12	0.173		
REFOCUS DIRECTION (R)	1.815	1	1.815	3.10	ns
ERROR	1.754	3	0.585		
V X R INT.	0.662	4	0.166	0.86	ns [g]
ERROR	2.320	12	0.193		
PP X R INT.	0.413	1	0.413	2.10	ns
ERROR	0.590	3	0.197		
V X PP X R	0.662	4	0.166	1.05	ns [g]
ERROR	1.893	12	0.158		

[g] Significance based on Greenhouse-Geisser corrected probability.

Table 17.
Source Table of the Analysis of Covariance for Flicker Fusion Thresholds. Data from Experiment Two.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
COVARIATE (ELAPSED TIME)	288.803	1	288.803	5.78	ns
ERROR	99.871	2	49.935		
VIEWING CONDITION (V)	20.061	4	5.015	0.79	ns [g]
COVARIATE	0.179	1	0.179	0.03	ns
ERROR	69.520	11	6.320		
PRETEST-POSTTEST (PP)	6.938	1	6.938	2.96	ns
ERROR	7.032	3	2.344		
V X PP INT.	10.017	4	2.504	0.67	ns [g]
ERROR	44.651	12	3.721		
PHASE (PH)	0.872	1	0.872	1.46	ns
ERROR	1.787	3	0.596		
V X PH INT.	4.477	4	1.119	1.13	ns [g]
ERROR	11.937	12	0.995		
PP X PH INT.	0.146	1	0.146	0.13	ns
ERROR	3.472	3	1.157		
V X PP X PH	9.086	4	2.272	1.11	ns [g]
ERROR	24.456	12	2.038		

[g] Significance based on Greenhouse-Geisser corrected probability.

of this analysis are reported in Table 18. No significant effects were found on the eyestrain scale (see Table 19), although there was a trend in the Viewing Condition X Pretest-Posttest interaction (F(4,12)=4.89, corrected p=.06) which merits comment. The interaction is plotted in Figure 15. If one considers posttest scores only, each observer appears to experience more discomfort and eyestrain for the parallel camera viewing condition than for any of the other viewing conditions tested. This contention is supported by spontaneous verbal reports from three observers that this condition produced considerably more discomfort than any of the other conditions tested to date. The effect is possibly mitigated by the fact that three of four observers also reported lowest levels of eyestrain on the pretest for that session.

Experiment Three

Since the near-far test and the flicker test were not included in Experiment Three, measures on four dependent variables were obtained for analysis: 1) the mood scale, 2) the eyestrain scale, 3) haptic adjustments, and 4) verbal judgments of depth. Data were transformed and/or averaged in the same manner as their counterparts in Experiment One and subjected to repeated measures ANCOVAs. Analyses were of the same form as was used in Experiment Two with three

Table 18.
Source Table of the Analysis of Covariance
for Eyestrain Scale Scores.
Data From Experiment Two.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
COVARIATE (ELAPSED TIME)	2.238	1	2.138	0.34	ns
ERROR	142.397	2	71.199		
VIEWING CONDITION (V)	65.923	4	16.481	5.00	ns [g]
COVARIATE	1.918	1	1.918	0.58	ns
ERROR	36.232	11	3.294		
PRETEST-POSTTEST (PP)	0.625	1	0.625	0.27	ns
ERROR	6.875	3	2.292		
V X PP INT.	14.250	4	3.563	4.89	ns [g]
ERROR	8.750	12	0.729		

[g] Significance based on Greenhouse-Geisser corrected probability.

FIGURE 15.
VIEWING CONDITION X PRE-POST INTERACTION FOR EYESTRAIN SCALE SCORES DATA FROM EXPERIMENT TWO

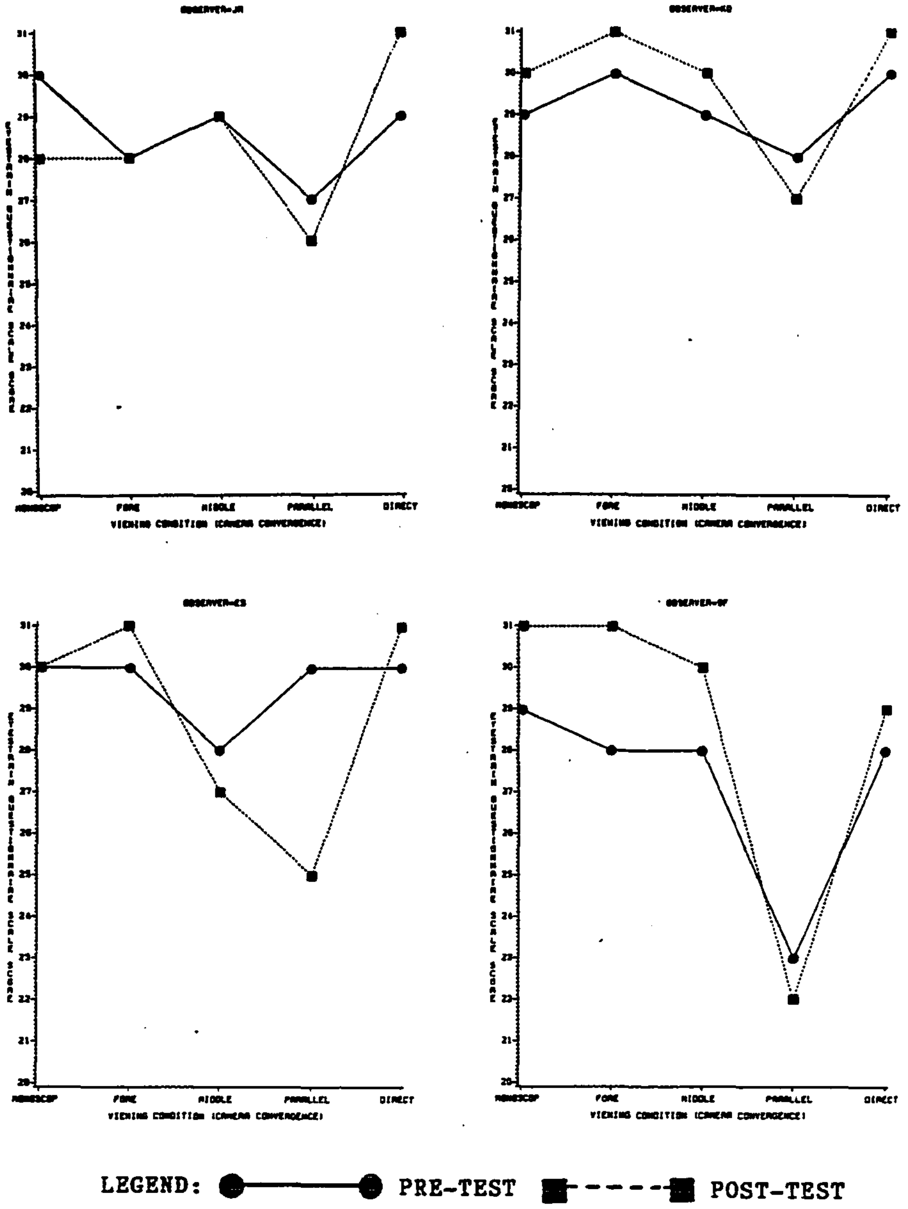


Table 19.
Source Table of the Analysis of Covariance
for Mood State Scale Scores.
Data From Experiment Two.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
COVARIATE (ELAPSED TIME)	90.678	1	90.678	1.27	ns
ERROR	142.397	2	71.199		
VIEWING CONDITION (V)	44.792	4	11.197	2.50	ns [g]
COVARIATE	0.181	1	0.181	0.04	ns
ERROR	49.369	11	4.488		
PRETEST-POSTTEST (PP)	7.225	1	7.225	1.63	ns
ERROR	13.275	3	4.425		
V X PP INT.	17.650	4	4.413	2.89	ns [g]
ERROR	18.350	12	1.529		

[g] Significance based on Greenhouse-Geisser corrected probability.

levels of camera separation (3.175 cm, 6.35 cm, and 19.05 cm) substituted for the convergence conditions employed in Experiment Two.

Haptic Adjustments of Perceived Depth Intervals

The ANCOVA for haptic adjustments (reported in Table 20) revealed significant main effects for Viewing Condition (F(4,16)=19.78, corrected p=.002) and for rod depth interval (F(5,20)=7.99, corrected p=.020). The Viewing Condition main effect is plotted in Figure 16, and tests of specific cell mean differences are reported in Table 21. Inspection of Figure 16 reveals the same basic pattern of results that was found for the viewing condition main effect in Experiment One. Stereo TV viewing conditions were superior monoscopic ones. Two observers (KD and JB) produced data points for the 3.175 cm camera separation which contradict this general trend. Since JB was an inexperienced observer, her data were generally the least accurate in Experiment Three for all TV viewing conditions. She did, however, produce data closely comparable to that of the other experienced observers. There was no obvious difference in overall accuracy for the more experieced males versus the less experienced females (KD and SF). Largest deviations from the group mean for experienced observers (all except JB) occurred for KD at the 3.175 cm separation and for SF at

Table 20.
Source Table of the Analysis of Covariance
for Haptic Adjustments of Depth.
Data from Experiment Three.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARES	F	TAIL PROB.
COVARIATE (I_o)	84.039	1	84.390	1.75	ns
ERROR	144.190	3	48.063		
VIEWING CONDITION (V)	1304.991	4	326.248	19.78	.002 [g]
ERROR	263.864	16	16.492		
DEPTH (ΔR)	249.588	5	49.918	7.99	.020 [g]
ERROR	124.997	20	6.250		
V X ΔR INT.	202.654	20	10.132	2.80	ns [g]
ERROR	289.939	80	3.624		

[g] Significance based on Greenhouse-Geisser corrected probability.

FIGURE 16.
VIEWING CONDITION MAIN EFFECT FOR HAPTIC DEPTH ADJUSTMENTS. DATA FROM EXPERIMENT THREE.

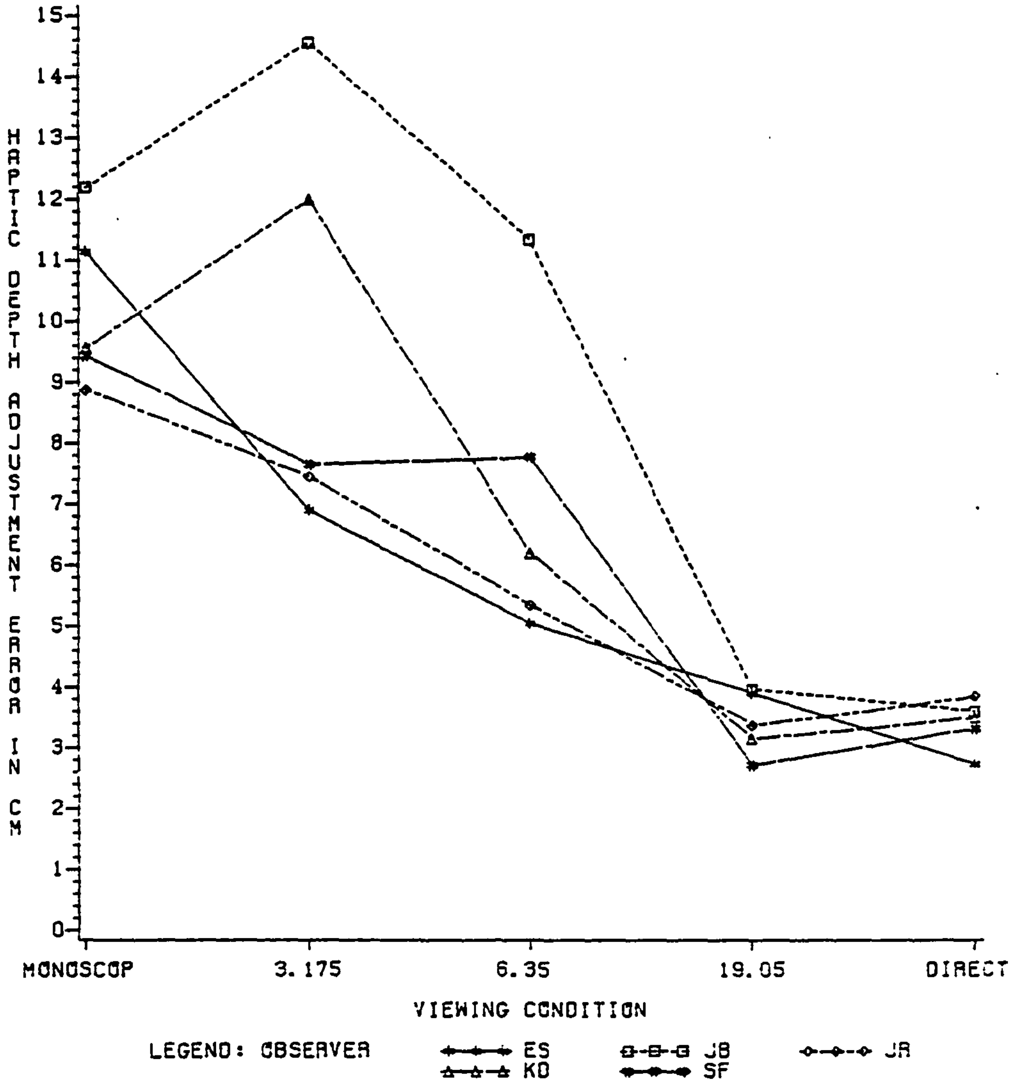


Table 21.
Duncan New Multiple Range Statistic.
Mean Scores for Haptic Adjustment Errors
on the Viewing Condition Main Effect.
Data from Experiment Three.

	MONO-SCOPIC	3.175 CM	6.35 CM	19.05 CM	DIRECT VIEW
MEAN SCORE	10.23	9.70	7.12	3.40	3.38
MONOSCOPIC		--	--	*	*
3.175 CM			--	*	*
6.350 CM				--	--
19.05 CM					--
DIRECT VIEW					

* $p < .05$

** $p < .01$

the 6.350 cm separation.

The rod depth interval main effect is plotted in Figure 17 and reveals a trend very similar to that found in Experiment Two. Tests of specific cell mean differences within this effect are reported in Table 22. Greatest accuracy was obtained for the 5.08 cm rod depth interval with gradual decreases in accuracy for longer depth intervals out to the largest interval tested (25.4 cm).

Accuracy for the null depth interval was substantially poorer and more variable than that observed with the 5.08 cm depth interval. The inexperienced observer, JB, produced a similar pattern of data at a lower level of accuracy.

Verbal Judgments of Perceived Depth Intervals

An ANCOVA of absolutized verbal judgments also produced a pattern of results similar to those found in Experiment One. Results of this analysis are reported in Table 23. Both the Viewing Condition and the Viewing Condition ($F(4,16)=8.05$, $p < .001$) by Depth Interval interactions ($F(20,80)=3.81$, corrected $p=.042$) emerged as significant factors in the analysis. The Viewing Condition main effect for verbal depth judgments is plotted in Figure 18. Tests of specific cell mean differences wiithin this effect are reported in Table 24. Interobserver differences are greater

FIGURE 17.
ROD DEPTH INTERVAL MAIN EFFECT FOR HAPTIC DEPTH ADJUSTMENTS. DATA FROM EXPERIMENT THREE.

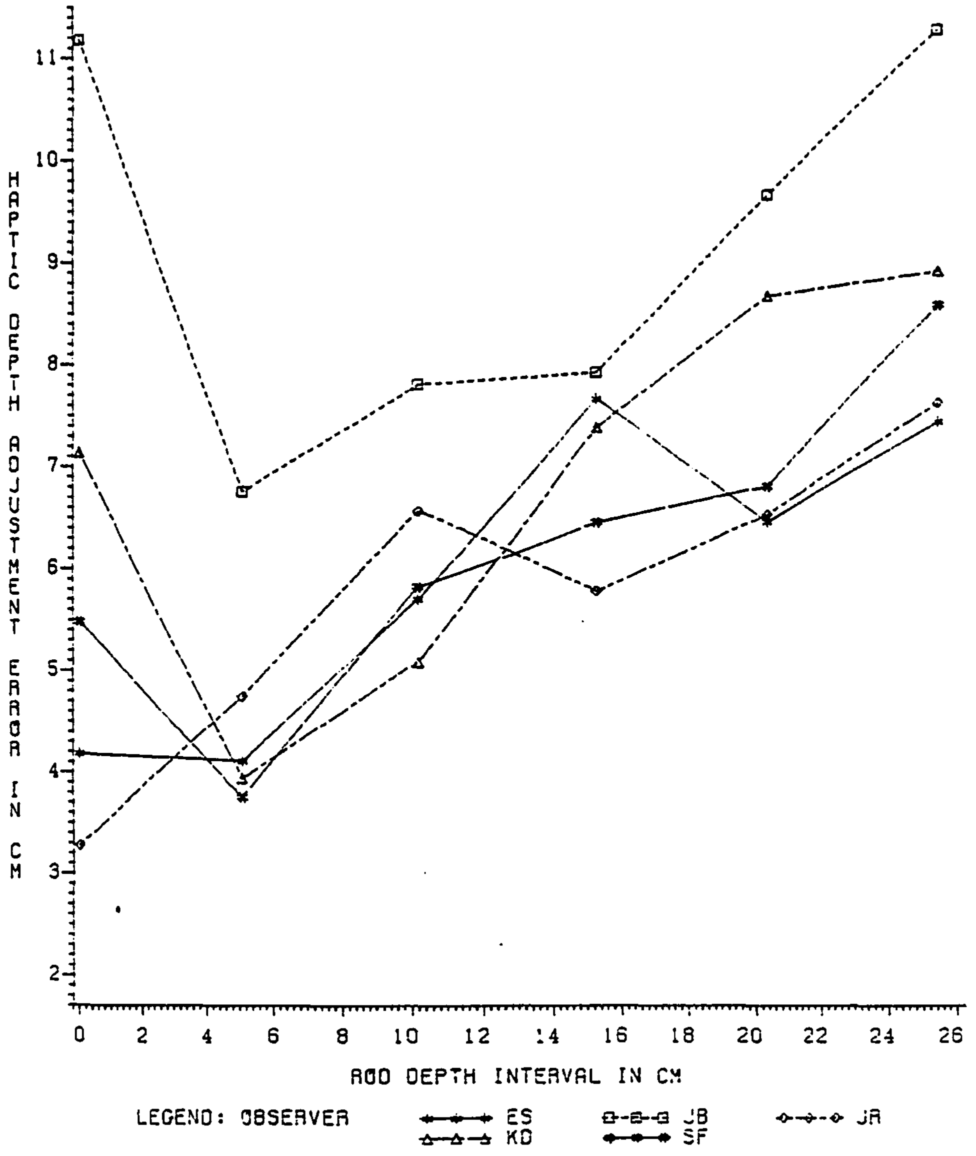


Table 22.
Duncan New Multiple Range Statistic
Mean Scores for Haptic Adjustment Errors
on the Rod Depth Interval Main Effect.
Data from Experiment Three.

	ROD DEPTH INTERVALS					
	0.00 CM	5.08 CM	10.16 CM	15.24 CM	20.32 CM	25.40 CM
MEAN SCORE	6.25	4.66	6.21	7.05	7.64	8.80
0.00 CM		--	--	--	--	--
5.08 CM			--	--	--	*
10.16 CM				--	--	--
15.24 CM					--	--
20.32 CM						--
25.40 CM						

* $p < .05$

** $p < .01$

Table 23.
Source Table of the Analysis of Covariance
for Verbal Judgments of Depth.
Data from Experiment Three.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARES	F	TAIL PROB.
COVARIATE (I_o)	61.852	1	61.852	0.37	ns
ERROR	495.563	3	165.188		
VIEWING CONDITION (V)	829.065	4	207.266	8.05	<.001
ERROR	411.885	16	25.743		
DEPTH (ΔR)	169.658	5	33.932	0.54	ns [g]
ERROR	1256.844	20	62.842		
V X ΔR INT.	293.808	20	14.690	3.81	.042 [g]
ERROR	308.482	80	3.856		

[g] Significance based on Greenhouse-Geisser corrected probability.

FIGURE 18.
VIEWING CONDITION MAIN EFFECT FOR VERBAL DEPTH JUDGMENTS DATA FROM EXPERIMENT THREE.

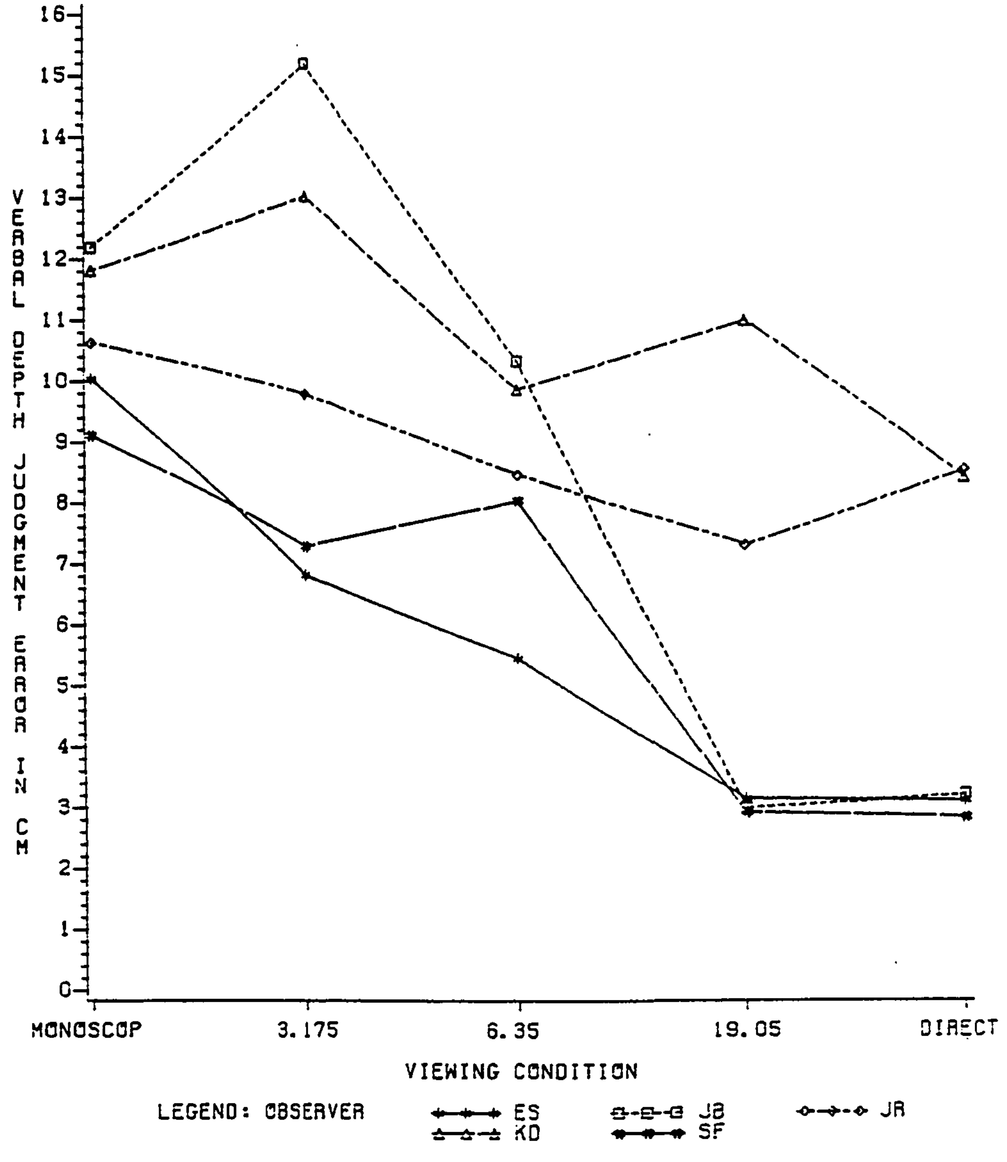


Table 24.
Duncan New Multiple Range Statistic.
Mean Scores for Verbal Judgment Errors
on the Viewing Condition Main Effect.
Data from Experiment Three.

		:- CAMERA	SEPARATION	-:	
	MONO-SCOPIC	3.175 CM	6.35 CM	19.05 CM	DIRECT VIEW
MEAN SCORE	10.75	10.42	8.43	5.48	5.22
MONOSCOPIC		--	--	--	--
3.175 CM			--	--	--
6.350 CM				--	--
19.05 CM					--
DIRECT VIEW					

* $p < .05$

** $p < .01$

than with haptic judgments but the same general trend appears in the plot. Stereo TV views produce more accurate reports than monoscopic views (with the exception of KD and JB for the 3.175 cm camera separation) and there is a trend toward greater accuracy for wider interaxial camera separations. Accuracy for the 19.05 cm camera separation is comparable to that found under direct view control conditions. The Viewing Condition by Depth Interval interaction was plotted for each observer in Figure 19. So much heterogeneity of patterning across observers exists for this effect that there seems little justification for considering the effect to reflect anything more than a statistical artifact.

Questionnaire

ANCOVAs for the mood scale and eyestrain scale scores found no significant F-ratios for any main or interactive effects. Source tables for eyestrain scale and mood scale scores are reported in Tables 25 and 26, respectively.

Experiment Four

Data obtained in Experiment Four were analysed in the same way as data analysed in Experiment Three. The only difference between the two experiments was in perceptual information available in imagery from the remote

Table 25.
Source Table of the Analysis of Covariance
for Eyestrain Scale Scores.
Data From Experiment Three.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
COVARIATE (ELAPSED TIME)	22.858	1	22.858	1.26	ns
ERROR	54.622	3	18.207		
VIEWING CONDITION (V)	30.979	4	7.745	2.72	ns
COVARIATE	1.026	1	1.026	0.36	ns
ERROR	42.694	15	2.846		
PRETEST-POSTTEST (PP)	10.580	1	10.580	3.61	ns
ERROR	11.720	4	2.930		
V X PP INT.	5.320	4	1.330	0.89	ns
ERROR	23.880	12	1.493		

Table 26.
Source Table of the Analysis of Covariance
for Mood State Scale Scores.
Data From Experiment Three.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
COVARIATE (ELAPSED TIME)	114.438	1	114.438	0.92	ns
ERROR	373.442	3	124.481		
VIEWING CONDITION (V)	12.580	4	3.145	0.73	ns [g]
COVARIATE	5.002	1	5.002	1.16	ns
ERROR	64.518	15	4.301		
PRETEST-POSTTEST (PP)	0.320	1	0.320	1.19	ns
ERROR	1.080	4	0.270		
V X PP INT.	21.080	4	5.270	3.92	.02
ERROR	21.520	16	1.345		

[g] Significance based on Greenhouse-Geisser corrected probability.

environment.

Haptic Adjustments of Perceived Depth Intervals

The ANCOVA for haptic adjustments (see Table 27) revealed only one significant source of variation, the depth interval main effect (F(5,20) = 12.58, corrected p = .001). This effect is plotted in Figure 20. and tests for specific cell mean differences are reported in Table 28. As with the results of Experiments Two and Three, there was a general trend toward increased error for the longer depth intervals. Unlike results from earlier studies, the null depth interval produced more accurate responses than any of the other depth intervals tested.

Verbal Judgments of Perceived Depth Intervals

An ANCOVA for verbal judgments failed to reveal any statistically significant effects. Results of this analysis are reported in Table 29.

Questionnaire

ANCOVA's for the mood and eyestrain scales failed to provide any evidence of change as a result of exposure to the various viewing conditions tested in this study. Results of the analysis of eyestrain and mood scales are reported in Tables 30 and 31, respectively.

Table 27.
Source Table of the Analysis of Covariance for Haptic Adjustments of Depth. Data from Experiment Four.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARES	F	TAIL PROB.
COVARIATE (I_o)	0.120	1	0.120	0.05	ns
ERROR	7.825	3	2.608		
VIEWING CONDITION (V)	9.120	4	2.300	1.24	ns
ERROR	29.644	16	1.853		
DEPTH (ΔR)	187.542	5	37.508	12.58	.001 [g]
ERROR	59.613	20	2.981		
V X ΔR INT.	25.626	20	1.281	0.95	ns [g]
ERROR	107.627	80	1.345		

[g] Significance based on Greenhouse-Geisser corrected probability.

FIGURE 19.
ROD DEPTH INTERVAL MAIN EFFECT FOR HAPTIC DEPTH ADJUSTMENTS. DATA FROM EXPERIMENT FOUR.

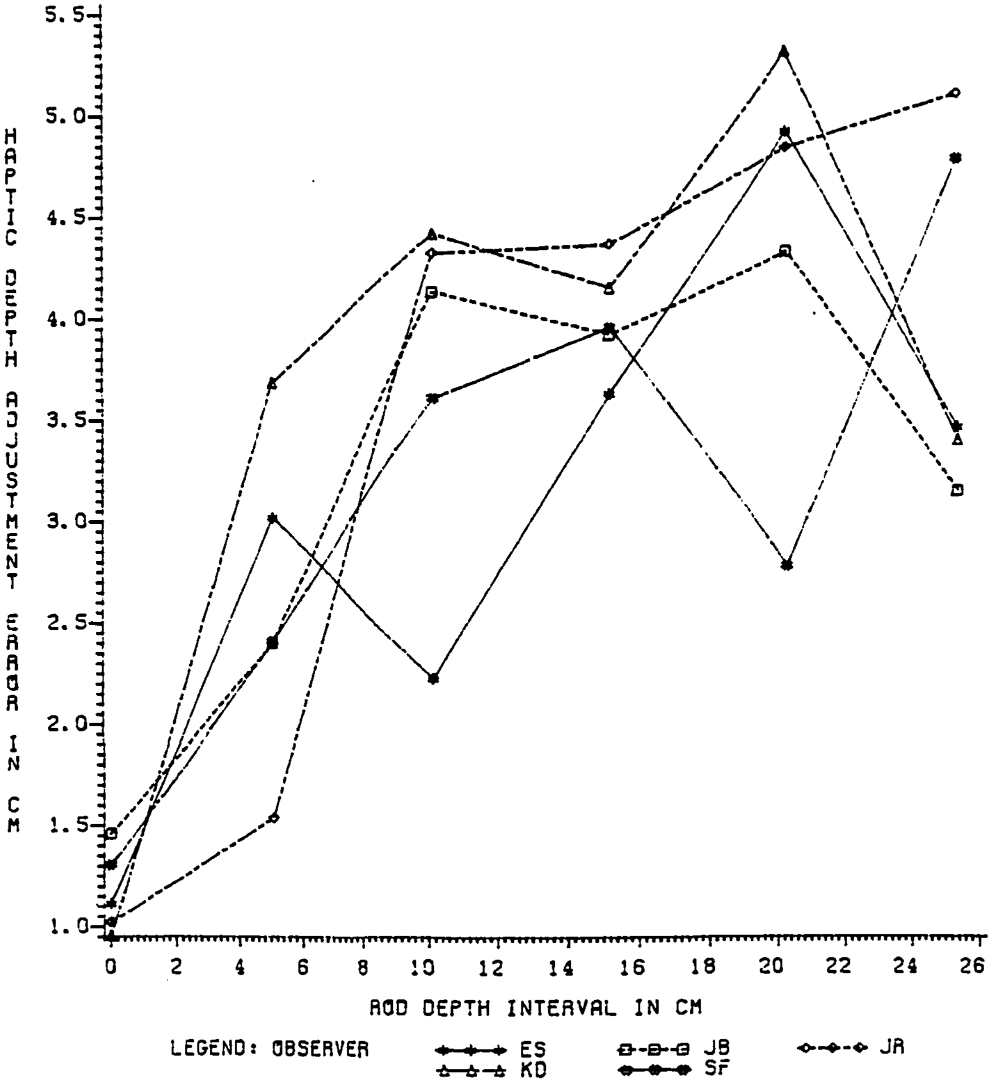


Table 28.
Duncan New Multiple Range Statistic.
Mean Scores for Haptic Adjustment Errors
on the Rod Depth Interval Main Effect.
Data from Experiment Four.

	ROD DEPTH INTERVALS					
	0.00 CM	5.08 CM	10.16 CM	15.24 CM	20.32 CM	25.40 CM
MEAN SCORE	1.17	2.61	3.75	4.02	4.45	3.99
0.00 CM		--	--	*	*	--
5.08 CM			--	--	--	--
10.16 CM				--	--	--
15.24 CM					--	--
20.32 CM						--
25.40 CM						

* $p < .05$

** $p < .01$

Table 29.
Source Table of the Analysis of Covariance for Verbal Judgments of Depth. Data from Experiment Four.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARES	F	TAIL PROB.
COVARIATE (I_o)	21.525	1	21.525	0.11	ns
ERROR	582.932	3	194.311		
VIEWING CONDITION (V)	43.627	4	10.907	0.83	ns [g]
ERROR	210.705	16	13.169		
DEPTH (ΔR)	574.526	5	114.905	4.30	ns [g]
ERROR	535.054	20	26.753		
V X ΔR INT.	54.725	20	2.736	1.71	ns [g]
ERROR	127.988	80	1.600		

[g] Significance based on Greenhouse-Geisser corrected probability.

FIGURE 20.
VIEWING CONDITION X DEPTH INTERVAL INTERACTION FOR VERBAL JUDGMENTS OF DEPTH DATA FROM EXPERIMENT THREE.

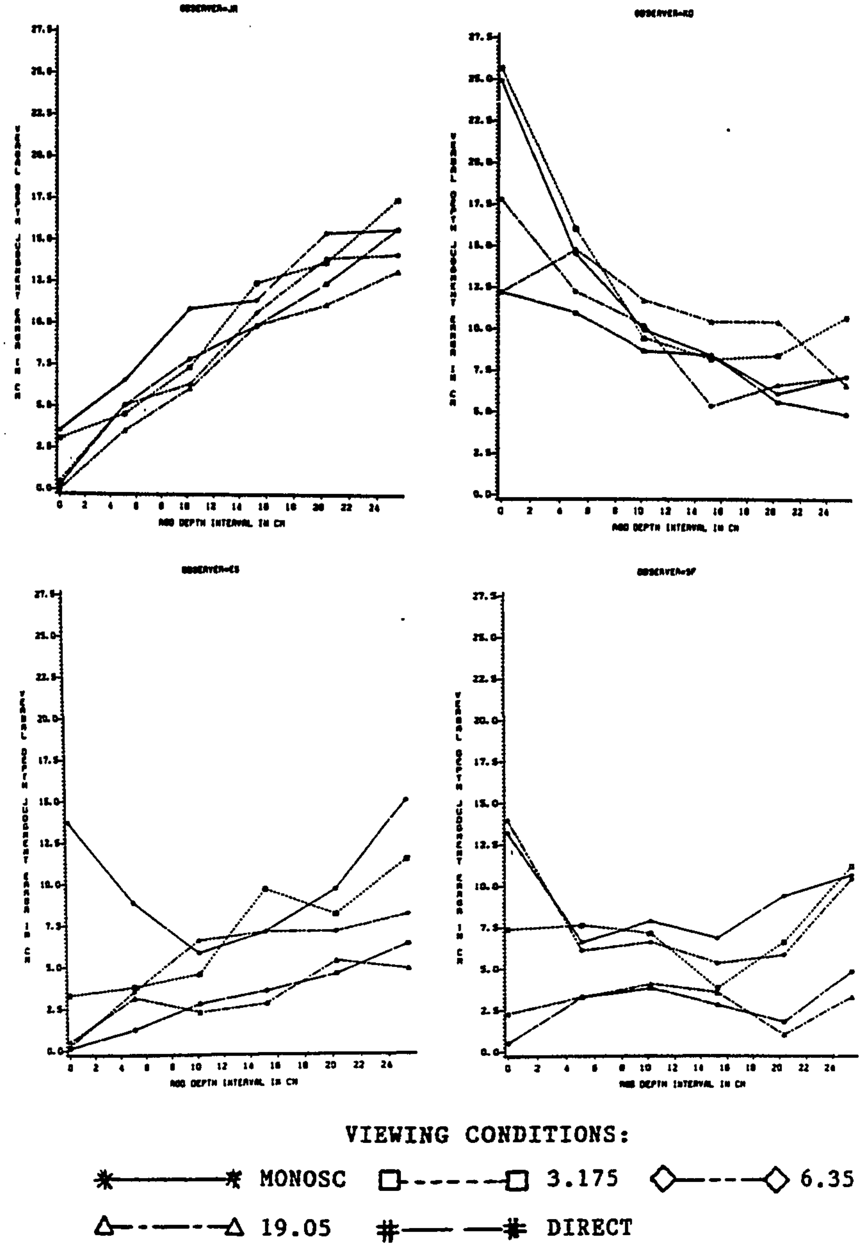


Table 30.
Source Table of the Analysis of Covariance
for Eyestrain Scale Scores.
Data From Experiment Four.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
COVARIATE (ELAPSED TIME)	20.613	1	20.613	2.34	ns
ERROR	26.387	3	8.796		
VIEWING CONDITION (V)	9.444	4	2.361	1.82	ns
COVARIATE	0.107	1	0.107	0.08	ns
ERROR	19.493	15	1.300		
PRETEST-POSTTEST (PP)	1.280	1	1.280	3.88	ns
ERROR	1.320	4	0.330		
V X PP INT.	9.320	4	2.330	2.65	ns [g]
ERROR	14.080	12	0.880		

[g] Denotes Greenhouse-Geisser corrected probabilities.

Table 31.
Source Table of the Analysis of Covariance
for Mood State Scale Scores.
Data From Experiment Four.

SOURCE	SUM OF SQUARES	DF	MEAN SQUARE	F	TAIL PROB.
COVARIATE (ELAPSED TIME)	0.003	1	0.003	0.0	ns
ERROR	367.716	3	122.572		
VIEWING CONDITION (V)	45.593	4	11.398	0.66	ns
COVARIATE	0.347	1	0.347	0.02	ns
ERROR	258.133	15	17.209		
PRETEST-POSTTEST (PP)	11.520	1	11.520	1.45	ns
ERROR	31.880	4	7.970		
V X PP INT.	6.480	4	1.620	0.40	ns [g]
ERROR	65.120	16	4.070		

[g] Significance based on Greenhouse-Geisser corrected probability.

DISCUSSION

Experiment One

Results of Experiment One support the hypothesis that stereo TV provides valuable perceptual information which significantly enhances an observer's ability to perceive three-dimensional spatial relationships (i.e., depth intervals) in remote environments. This finding is supported by a substantial body of evidence demonstrating increased depth resolution with stereo displays (Upton and Strother, 1972; Fugitt and Uhrich, 1973; Shields *et al*, 1975; Zamarin, 1976; Pepper and Cole, 1978; Pepper, Cole, and Pinz, 1981; Spain and Cole, 1982). However, these previous studies provided no evidence which inevitably leads to the conclusion that results on a depth resolution task will predict those of a depth scaling task. If disparities alone were a completely dominant cue for the perception of depth relationships as the simple geometrical model of stereopsis assumes, it would be reasonable to predict enhancements in depth resolution since a constant physical depth interval would produce greater disparities at higher lens magnifications and/or camera separations. While human stereoacuity thresholds remain relatively constant over repeated measurements, the physical depth interval necessary to provide threshold disparity would vary as a direct function of camera parameters of I_c and M (as implied by Equation 4). When a scaling of space in the remote environment is involved, one would expect to see over- or under-estimates of depth extent depending on the magnification or minification of disparities with respect to their orthostereoscopic values. Thus, if disparities were doubled by manipulation of viewing system parameters, one would expect an observer to experience twice as much depth sensation in a given scene. Put most simply, an object of unit depth would be perceived as having two units of depth. Such a pattern of results was not found in Experiment One. The series of experiments reported herein was an initial effort toward understanding an as yet little explored aspect of remote presence, an aspect intermediate between simple depth resolution and active manipulation in the remote environment. Rather than asking the observer whether depth intervals between stimulus objects were present or absent or requiring him to perform a complex manipulation in the remote environment, the approach taken was to measure how large or small objective depth intervals appeared to be under the range of viewing conditions investigated.

Whereas earlier applied studies with stereo TV systems (e.g., Pesch, 1968; Tewell, et al, 1974; Smith, et al, 1979) provided substantial evidence of stereo TV's advantages for remote manipulation, the level of complexity associated with control dynamics of manipulators and the interactive nature of manipulator tasks have unfortunately confounded efforts to understand *perception* of remote environments through stereo TV systems. An orthostereoscopic condition in which retinal disparities were matched to those occuring under direct-view conditions produced less accurate performance than the direct view condition. Though not statistically significant, performance under orthostereoscopic TV views was consistently less accurate across all observers. Similar results have been found in several studies of depth resolution which included a direct view control condition (e.g., Zamarin, 1976b; Pepper, Cole, and Pinz, 1981; Pepper, Cole, and Spain, 1983).

As disparities were increased in the present experiment by widening camera separation, there was a resulting increase in each observer's accuracy in gauging depth intervals within the remotely imaged scene. Following testing sessions, observers spontaneously reported that the largest camera separation tested (19.05 cm) provided the most "natural appearing" views of the remote scene. Smaller (i.e., 3.175 and 6.35 cm) camera separations produced imagery which observers reported to appear flattened in depth. Results for both the haptic adjustments and verbal judgments of perceived depth measured in Experiment One demonstrated that increasing disparities beyond their orthostereoscopic values by an enhancement ratio of 3.0 produced by a combination of 1X magnification and 19.05 cm camera separation resulted in depth estimates which most closely approximated those found under direct viewing conditions. Studies by Grant, et al, 1973, Tewell, et al, 1974, and Shields, et al, 1975 utilized camera separations of 15.24 cm. Of these early studies only Grant, et al varied camera separation while holding magnification constant at 1.02x finding a very slight improvement in performance (task times) in the transition from 15.24 cm to 20.32 cm camera separations and shortest task times when cameras were separated by 45.72 cm (18 inches). This is not surprising when one considers that cameras were converged to the distance of one of the rods at all times. Zamarin (1976b), however, in the largest and most complete investigation to date of the impact of viewing system parameters on depth resolution, found that a 17.8 cm camera separation across a range of camera convergence conditions similar to that tested in the present study produced faster and more accurate adjustments than any of the other camera separations measured. Although the largest camera separation tested was 12.7 cm, results of Cole et al's (1981) study are in accordance with those found by Zamarin. Spain and Cole's (1982) study of depth resolution with a helmet mounted stereo TV display also suggested that depth resolution is more acute under 1X magnification and 19.05 cm camera separation than under smaller camera separations.

Two of the conditions tested in Experiment One (3X magnification with 6.35 cm camera separation and 1X magnification with 19.05 cm camera separation) provided stereo imagery with a 3.0 disparity exaggeration ratio, but the former produced greater depth matching accuracy for all four observers tested. Why this occurred is as yet unclear, but the answer must lie in the patterning of cues inherent in the televised scene, and in the rules by which the human visual system weights various sensory inputs prior to deriving depth percepts. It should be noted that the effect of camera separation would have been even more pronounced in the analysis of Experiment One's results if the 3X magnification condition had been excluded. The combination of 3X magnification and 19.05 cm camera separation produced disparities which were nine times their orthostereoscopic values. For the largest depth interval tested (i.e., 25.4 cm) this produced a disparity difference between the two rods which was on the order of 64 arcminutes making it extremely difficult, if not impossible, for observers to fuse the disparate images of both rods simultaneously. Following the session in which these viewing conditions were tested, the two inexperienced female observers spontaneously commented on their difficulties in maintaining fusion on some testing trials. Even in light of this evidence suggesting that difficulties in fusion brought about a decline in accuracy, one might possibly argue that it was not the extreme exaggeration of disparities which degraded performance, but the widening angular separation between screen images of the targets to be judged in depth. Clearly, increasing lateral angular separation between targets in a Howard-Dolman type task does degrade depth resolution under direct viewing conditions (Matsubayashi, 1937; Graham, _et al_, 1949). However, if this were the sole or primary contributory factor to the effect apparent in the 3X magnification with 19.05 cm camera separation viewing condition, one would expect to see similar decreases in performance for other conditions in which 3X magnification was utilized (i.e., monoscopic, 3.175 cm, and 6.35 cm camera separations). Such was clearly not the case as a review of Figure 10 (p. 85) reveals. In fact, three of the four observers tested were most accurate under 3X magnification with its attendant wide angle of screen separation between rods under the monoscopic viewing condition. Obviously, there is a factor (or factors) other than angular separation of targets to be compared which is responsible for producing these differences in depth estimation accuracy. This conclusion is supported by the finding of no significant effect for magnification for haptic adjustments and verbal judgments of depth. It is further supported by Zamarin's finding of no significant effect for camera magnification on a depth resolution task under similar stimulus conditions.

Average administration time for 60 depth judgement trials across all 13 sessions was 23.3 minutes (standard error = 2.43 minutes). This was barely one-fifth the total amount of time required to produce statistically significant evidence of visual fatigue with NF and FF measures in previous studies employing these measures (e.g., Collins and Pruen, 1959; Simonson and Enzer, 1941). Due to the unusual viewing conditions (enhanced or diminished disparities, distortions of normal perspective, mismatches between convergence and accommodation) which occurred during stereo TV viewing and subjective reports of discomfort and eyestrain from stereo TV users following brief (i.e., less than 30 minute) exposure (Liebowitz and Sulzer, 1965), it was hypothesized that substantial shifts in visual performance on the NF and FF tests could be induced with relatively brief exposure to stereo TV displays. To the contrary, no evidence was found on either the NF or the FF tests to support the hypothesis that stereo TV viewing under any of the viewing conditions tested in Experiment One caused or contributed to observer eyestrain. Consequently, no differentiation between fatigue in central or peripheral sensory mechanisms was possible on the basis of the results of Experiment One. Informal discussions with observers subsequent to testing sessions supported the conclusion that no appreciable eyestrain was produced under the viewing conditions tested. The two less experienced, female observers reported that the hour spent in a typical testing session was less strenuous for their eyes than an hour spent working at their normal jobs. They also, on occasion, spontaneously reported that they were returning to their jobs feeling more relaxed than they felt at the beginning of testing sessions. Liebowitz and Sulzer suggested that slight misalignments of retinal images due to ocular phorias and aniseikonia contributed to visual fatigue in observers of stereo displays though this proposition has never been put to test. In future experiments, individuals with slight, but measurable, eye muscle imbalances or aniseikonia should be compared with normals across various viewing system configurations for evidence of visual fatigue.

In summary, results of Experiment One supported previous findings of practical advantages for using stereo TV to perform tasks which require accurate scaling of depth dimensions in a remotely televised environment. They also supported the practice of using increased camera separation to enhance the accuracy of depth perception, a finding which contradicts the orthostereoscopic strategy for configuring a stereo TV camera system to provide natural-appearing imagery. Magnification was not found to exert a statistically significant effect on depth estimation accuracy. This finding contradicts the simple geometrical model of depth perception with stereo TV displays because, like camera separation, disparities are directly varied by lens magnification. In addition to increasing disparities, however, magnification narrows an observer's effective field of view of the remote scene and increases the angular separation between objects in the televised scene. Though not statistically significant, the pattern of results found in Experiment One suggests that magnification contributed to a decrease in accuracy when high magnification was used in conjunction with wide camera separation. Under some stimulus conditions the combination of wide camera separation and lens magnification produced disparities which were very difficult if not impossible for observers to fuse. No evidence was found to suggest that the range of stereo TV parameters tested contributed to observer eyestrain over an average 23.3 minute exposure time.

Experiment Two

Results of Experiment Two conclusively demonstrated that camera convergence angle exerted a statistically significant effect on the accuracy of observer's judgments of relative depth, both haptic and verbal. Most accurate perception of depth intervals was produced when the cameras were converged in front of the workspace within which the stimuli to be compared in depth were positioned. This camera convergence condition produced uncrossed disparities for the stimulus rods which the visual system interpreted as appearing to be located in "screen space", that is, behind the frame of the "stereo window" (i.e., the border of the optically superimposed monitor screens). This viewing condition is "natural" in the sense that it occurs frequently in everyday experience -- whenever one looks out of a window onto a scene. Less accurate depth interval estimation was found when cameras were converged to the center of the workspace within which stimulus rods were positioned. This convergence condition produced uncrossed disparities for rods located beyond the convergence point and crossed disparities for rods located nearer than the convergence point. It was identical to the 2X magnification with 19.05 cm camera separation viewing condition tested in Experiment One and produced very similar levels of performance. Video images of the stimulus rods extended across the entire vertical length of the display screens, their upper and lower ends being contiguous with the upper and lower borders of the stereo window. Whenever rods with crossed disparities were displayed in this way a perceptual conflict occurred. The stereo window clearly overlapped screen images of the rods. This provided the observer with a paradoxical viewing situation in which disparities signaled that the rods were nearer than the depth plane of the stereo window while interposition cues signaled that the rods were overlapped by the screen. Studies performed under direct viewing conditions (i.e., Gregory, 1970) suggest that when conflict between interposition and disparities occurs, interposition cues tend to dominate in perception, particularly in the region immediately adjacent to the overlap. This situation would, of course, detract from accurate perception of the remote scene by altering the perceived depth of objects having crossed disparities. In any event, the above discussion is largely speculative and remains to be confirmed by future studies in which objects having boundaries contiguous and non-contiguous with the screen frame are compared and sharp contours of the stereo window are effectively eliminated either by blurring or by expanding the display field of view and thereby projecting boundaries of the stereo window onto more peripheral retinal regions.

By far, the least accurate depth estimates were found in Experiment Two under the paralleled camera viewing condition. Since 2X magnification and the 19.05 cm camera separation were employed throughout all testing sessions in Experiment Two, paralleling the camera axes not only produced crossed disparities for the rods, but also produced disparities so large that they were impossible for observers to fuse simultaneously for even the smallest rod depth interval tested (5.08 cm). The paralleled camera viewing condition produced spontaneous complaints from observers about the great difficulty and stress involved in performing the depth estimation task. Though not a statistically significant effect, performance for 3 of the 4 observers tested was found to be poorer under the paralleled camera stereo condition than under the monoscopic viewing condition. Thus, even though disparities within Ogle's range of patent stereopsis were present in the imagery, they may have provided only distracting information for performance of the depth estimation tasks. One obvious implication for the design of practical stereo TV systems is to configure the cameras so that objects of interest at various distances from the cameras do not provide such large disparities that they cannot be fused by an observer. In the case where objects may occasionally intrude between cameras and objects of interest and produce unfusable crossed disparities, it would be advisable to provide a "stereo kill" function that switches the stereo display to a monoscopic view. So long as stereo TV displays continue to have high contrast screen borders, providing observers with a sharply defined stereo window, it also appears advisable to provide the observer with a means of remotely adjusting camera convergence from 20° to parallel so that objects of interest produce uncrossed screen disparities.

Even with three of four observers spontaneously complaining about the difficulty of performing the depth perception task under the parallel camera viewing conditions, no evidence of eyestrain was found on any of the three measures administered immediately prior to and following depth perception trials. Average depth perception test time in Experiment Two was 20.0 minutes.

Experiment Three

Experiment Three was designed to determine whether the relationships that were found in Experiment One between camera separation and accuracy of depth estimation would hold for a slightly more complex remote scene. The only difference between stimulus conditions used in Experiment One and those used in Experiment Three was the presence of a patterned plane behind the null point for the rods. In general, results of Experiment Three were quite similar to those found for Experiment One. Stereo TV viewing conditions produced more accurate depth estimates than the monoscopic control condition and larger values of camera separation also produced increases in accuracy for both haptic adjustments and verbal estimates of depth. More between-observer variability is evident for the verbal report measure than on the haptic adjustment measure, a pattern not readily discernable in Experiment One most likely because of differences between experienced males and relatively inexperienced females on the haptic measure, but quite apparent in the results of Experiment Two.

The reasoning behind assessing depth perception with the clearly defined repetitive background pattern was not to introduce additional cues to depth and measure the amount by which they promoted accuracy. Rather, repetitive patterning was introduced to determine whether the introduction of ambiguous cues to depth in the background plane would result in less accurate depth estimates. It has long been known (e.g., see Helmholtz, 1962, p. 316) that horizontally repeating patterns frequently give rise to false fusions (convergence not appropriate to the true distance of the repeating pattern such that images from different features are projected onto corresponding parts of the eyes) and distorted perceptions of depth intervals (Ono, Seabrook, & Mitson, 1973) under direct viewing conditions. Whether this was an important determinant of performance under stereo TV viewing conditions required empirical study. Another possible source of degraded performance with stereo TV displays was an optical distortion that occurs when cameras are widely separated and converged to near distances (as they were in Experiment Three). This effect, commonly known as "keystoning" among stereophotographers, produced vertical disparities for objects in the lateral periphery of stereo imagery. The interested reader may consult Ferwerda (1982) for a clear description of keystoning and arguments against converging stereo cameras. Keystoning was not present to any appreciable extent in either Experiments One or Two because of the vertical orientation of the rods and the absence of pattern in the background plane. It is argued by stereophotographers, primarily on an aesthetic basis, that keystoning produces unappealingly distorted imagery and contributes to eyestrain. One oft-quoted rule-of-thumb in stereophotography states that if one must converge cameras, the distance of the convergence point from the cameras should be no less than thirty times greater than the interaxial separation between the cameras (Ferwerda, 1982; Valyus, 1966). This "one-in-thirty" rule was clearly violated by the camera convergence angle utilized in Experiment Three. Since the camera convergence point was 1.6 meters distant and cameras were separated by approximately .2 meter, the ratio of separation to convergence distance was only one-to-eight. There was, however, no evidence produced by Experiment Three which suggested that keystoning brought about any substantial decrements in depth interval estimation when the results of Experiment Three are compared to those of Experiment One.

While accuracy was generally lower under Experiment Three testing conditions than it was under comparable conditions employed in Experiment One (2X magnification with 19.05 cm camera separation), this general decrement in performance was probably not due to keystoning because similarly proportioned decrements occurred for the monoscopic and direct viewing conditions, neither of which were influenced by keystoning. It is more likely that the decrements which appear to have occurred in the transition from Experiment One to Experiment Three occurred as a result of false fusions of the repetitive background and subsequent distortions. Comparisons of the patterns of results for Experiments One and Three do not suggest an interactive influence on remote depth perception for repetitive background patterns and the range of stereo camera separations tested.

The depth interval main effect for haptic adjustments was similar to that found under different viewing conditions investigated in Experiment Two. As with the results of Experiment Two, the explanation for this effect lies in the complex set of factors that intervene between visual perception, haptic matching procedures, and strategies utilized by the observers to optimize their success in the face of uncertainty.

No evidence was found with the questionnaire, NF, or FF tests to support the hypothesis that eyestrain resulted from the stimulus conditions tested in Experiment Three.

Experiment Four

Experiment Four was designed to determine whether the influence of camera separation on depth estimation accuracy found in Experiments One and Three would hold for a complex scene in which "strong" cues to depth perception other than retinal disparities were present in the visual imagery. Results from analysis of both dependent measures of depth perception revealed no significant differences for any of the viewing conditions tested -- the same viewing conditions which produced significantly different levels of accuracy of depth estimates in Experiments One and Three. Overall level of depth estimation accuracy for Experiment Four was superior to levels of accuracy found in Experiments One through Three owing to the addition of linear perspective, relative height in field, and interposition cues to depth.

A significant rod depth interval main effect was found for the haptic adjustment measure which took the same general form revealed in analyses of Experiments Two and Three. Overall accuracy for the haptic measure was greater than that found in Experiments One, Two, and Three. This was, of course, an expected difference. Having access to more perceptual information about the spatial layout of a remote scene allows an observer to form more accurate spatial percepts of that scene and to respond more accurately. Thus, it appears that stereo TV neither enhances nor degrades depth perception of scenes which are rich with unambiguous non-disparity cues to depth such as interposition, relative height in the field of view, and linear perspective.

Analysis of eyestrain scale scores revealed no evidence of eyestrain for any of the viewing conditions investigated in Experiment Four. Again, keystoning appears to have produced no eyestrain over the average 19 minute exposure period in which the ratio of camera separation to convergence distance was .125, much larger than the maximum .033 recommended by stereophotographers.

General Conclusions and Implications for Future Research

Depth interval estimation under the stimulus conditions employed in Experiments One, Two, and Three was significantly improved over monoscopic levels when observers were provided with retinal disparity cues to depth. This finding is in accordance with a substantial body of evidence collected under both direct and TV viewing conditions. Thus, the retinal disparities produced by stereo TV displays are not only useful in enabling an observer to detect depth when it exists in the remote environment, they also increase the accuracy of estimates of depth magnitude, though not necessarily in a linear fashion. This is not surprising when one considers everyday experience or the literature of remote manipulation literature with stereo TV displays, but results presented herein are reflective of more purely perceptual responses than are possible in remote manipulation studies.

Unlike direct viewing conditions in which large, non-fusable disparities can give rise to sensations of depth and enable observers to scale depth intervals more accurately than they can under monocular viewing conditions, it was found that increasing disparities beyond the limits of fusability and into Ogle's area of patent stereopsis resulted in subjective complaints and produced consistently (but not significantly) less accurate depth interval estimates than monoscopic viewing conditions. One obvious implication of this finding for stereo TV applications is that non-fusable images for objects to be compared in depth should be avoided. Apparently, the upper limit of useful disparities with stereo TV displays is somewhat more restricted than the upper limit under direct viewing conditions. It must be pointed out that this statement is made only tentatively on the basis of a single experiment's results and should be replicated. Just what the upper limit is for useful retinal disparities under stereo TV viewing conditions can be determined by replication of Ogle's (1953) original design with televised orthostereoscopic imagery. Whether non-fusable objects which are not of interest in performing a particular task influence the perception of depth between fusable objects is a question which will require further investigation to answer.

Experiment Four was the only experiment involving stereo TV undertaken in NOSC's Teleoperator Performance Laboratory which did not demonstrate a significant advantage for stereo TV viewing conditions relative to monoscopic TV viewing conditions. The reason for this difference in findings is attributable to the presence of several sources of perceptual information in the remote scene regarding the relative depths of the stimulus rods which was not present in earlier studies. Relative height in the field of view, a pronounced texture gradient, and the interposition of the stimulus rods with the texture gradient provided powerful monocular depth information which increased accuracy overall while washing out the performance advantages found for stereoscopic viewing conditions in earlier studies. Disparities appear to have merely provided redundant depth information that did not improve performance in situations where monocular depth cues were present in abundance. It is important to perform a more exacting analysis of the stimulus information inherent in natural scenery to determine precisely when retinal disparities do provide useful depth information and when they are redundant to other cues. Such knowledge would allow for design and construction of remote spaces (e.g., high-radiation fuel processing cells) which would not require stereo TV displays for adequate telepresence to perform remote manipulations at tolerable levels of safety and efficiency.

Camera interaxial separation was not found to influence perceived depth in the manner predicted by the geometrical model of depth perception with stereo TV displays. That is, observers were not found to over-estimate or under-estimate objective depth as a direct function of disparity exaggeration ratios. Depth intervals under reduced camera separation conditions appeared flattened, but they also appeared flattened to a lesser degree under orthostereoscopic viewing conditions. According to observers' subjective reports, it was only under viewing conditions in which retinal disparities were exaggerated to three times their normal magnitude by means of camera separation that perceived depth intervals between the rods began to take on their "natural" appearances. These results are in obvious conflict with the geometrical model. They suggest that once observers are practiced and adapted to stereo TV viewing conditions, they interpret the disparity cues present in a scene in light of feedback provided regarding depth scale in that scene. The greater the range of disparities (within fusional limits) corresponding to a given set of depth intervals in the scene, the more accurate observers judgments appear to be. It is now necessary to investigate the course of adaptation within viewing conditions for both experienced and inexperienced stereo TV observers. Also, feedback regarding depth estimation in the remote environment under varying degrees of hyperstereopsis should be investigated.

Alternatives to the geometrical model of depth perception with stereo TV displays must be constructed and tested under controlled conditions. On the basis of experimental results reported herein, these theoretical models will need to incorporate not only disparities, but also the effects of perceptual cues such accommodation, convergence, relative size, textural gradients, interposition, and other higher-order effects such as perceptual adaptation.

REFERENCES

Adams, D., Grant, C., Johnson, C., Meirick, R., Polhemus, C., Ray, A., Rittenhouse, D., Skidmore, R. Conceptual design study for a teleoperator visual system. Denver, CO: Martin Marietta Corporation Phase I Final Report for Contract NAS8-29024, December 1972.

Akin, D.L., Minsky, M.L., Thiel, E.D., and Kurtzman, C.R. Space applications of automation robotics and machine intelligence systems (ARAMIS) -- Phase II, Volume III: Executive Summary. Huntsville, AL: Marshall Space Flight Center, NASA Contractor Report 3736, 1983.

Anderson, T.W. Introduction to multivariate statistical analysis. New York: John Wiley & Sons, 1958.

Butterfield, J.F. Survey of three-dimensional television. In Optics and photonics applications to three-dimensional imagery, SPIE Proceedings, Vol 212, 1979, pp. 40-47.

Baschera, P. and Grandjean, E. Effects of repetitive tasks with different degrees of difficulty on critical flicker fusion (CFF) and subjective state. Ergonomics, 1979, 22, 377-385.

Berger, C. and Mahneke, A. Fatigue in two simple visual tasks. The American Journal of Psychology, 1954, 67, 509-512.

Chubb, G.P. A comparison of performance in operating the CRL-8 master slave manipulator under monocular and binocular viewing conditions. Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, OH, MRLD-TDR-64-68 (AD 608791), 1964.

Cole, R.E., Pepper, R.L., and Pinz, B.L. The influence of head movement parallax on perceptual performance under direct- and TV- displayed conditions. San Diego, CA: Naval Ocean Systems Center Technical Report 678, May 1981.

Cole, R.E. and Uttal, W.R. The display-performance transform as a measure of teleoperator presence: A research program proposal. Honolulu, HI: TIBS Monthly Progress Report #4, April 1981.

Collins, J.B. and Pruen, B. Perception time and visual fatigue. Ergonomics, 1962, 5, 533-538.

Cormack, R.H. The constancy of stereoscopic depth perception (Technical Report N00014-82-C-01). Arlington, VA: Engineering Psychology Programs, Office of Naval Research, March 1982.

Dennis, J. VISIDEP - One-eyed 3-D? Stereo World, 1983, 10, 25 & 29.

Dixon, W., Brown, M.B., Engelman, L., Frane, J.W., Hill, M.A., Jennrich, R.I., and Toporek, J.D. BMDP statistical software 1981, Berkeley, CA: University of California Press, 1981.

Farrell, J.M. and Booth, J.M. Design handbook for imagery interpretation. Seattle, WA: Boeing Aerospace Corporation Document No.. D180-19063-1, December 1975.

Ferguson, D.A., Major, D.A., and Keldoulis, T. Vision at work: Visual defect and the visual demand of tasks. Applied Ergonomics, 1974, 5, 84-93.

Ferwerda, J.G. The world of 3-D: A practical guide to stereo photography. Borger, The Netherlands: Netherlands Society for Stereo Photography, 1982.

Foley, J.M. Binocular depth mixture. Vision Research, 1976, 16, 1263-1267.

Frisby, J.P. Seeing: Illusion, brain, and mind. New York: Oxford University Press, 1980.

Fugitt, R.B. and Uhrich, R.W. Underwater stereoscopic television and display realism. San Diego, CA: Naval Undersea Center Technical Paper 358, July 1973.

Gassovskii, L.N. and Nikol'skaya, N.A. Data republished in N.A. Valyus. Stereoscopy. New York: Focal Press, 1966, pp. 42-43.

Gogel, W. The effect of convergence on perceived size and distance. The Journal of Psychology, 1962, 53, 475-489.

Gogel, W. The metric of visual space. In Epstein, W. (Ed.) Stability and constancy in visual perception: Mechanisms and processes. New York: John Wiley & Sons, 1977, pp. 129-181.

Graham, C.H. Visual space perception. In. C.H. Graham (Ed.) Vision and visual perception. New York: John Wiley & Sons, 1965, pp. 504-547.

Graham, C.H., Riggs, L.A., Mueller, C.G., and Solomon, R.L. Precision of stereoscopic settings as influenced by distance of target from a fiducial line. Journal of Psychology, 1949, 27, 203-207.

Grant, C., Meirick, R., Polhemus, C., Spencer, R., Swain, D., and Tewell, R. Conceptual design study for a teleoperator visual system report. Denver, CO: Martin Marietta Corporation Report NASA CR-124273, April 1973.

Greenhouse, S.W. and Geisser, S. On methods in the analysis of profile data. Psychometrika, 1959, 24, 92-112.

Gregory, R.L. The intelligent eye. New York: McGraw Hill, 1970.

Gulick, W.L. and Lawson, R.B. Human stereopsis: A psychophysical approach. New York: Oxford University Press, 1976.

Hecht, S. and Mintz, E.U. The visibility of single lines at various illuminations and the retinal basis of visual resolution. Journal of General Physiology, 1939, 22, 593-612.

Helmholtz, H. v. Treatise on physiological optics. Volume III. J.P.C. Southall (Ed.), New York: Dover Publications, Inc., 1962.

Hightower, J.D. & Smith, D.C. Teleoperator technology development. Paper presented at the 12th US-Japan National Resources Committee Meeting, San Francisco, August 1983.

Hill, A.J. A mathematical and experimental foundation for stereoscopic photography. Journal of the Society of Motion Picture and Television Engineers, 1953, 61, 461-486.

Hirsch, M.J. and Weymouth, F.W. Distance discrimination V. Effect of motion and distance of targets on monocular and binocular distance discrimination. Journal of Aviation Medicine, 1947, 18, 594-600.

Holway, A.H. and Boring, E.G. Determinants of apparent visual size with distance variant. _The American Journal of Psychology_, 1941, _54_, 21-37.

Howard, H.J. A test for the judgment of depth. _American Journal of Ophthalmology_, 1919, _2_, 656-675.

Hudson, D.E. and Cupit, G. Stereo TV enhancement study. Final technical report prepared for NASA. Syosset, NY: Kollsman Instrument Corporation, Electro-Optics Division, February 1968.

Johnsen, E.G. and Corliss, W.R. _Human factors applications in teleoperator design and operations_. New York: John Wiley & Sons, 1971.

Johnston, H.R., Hermanson, C.A., and Hull, H.L. Stereo television in remote control. _Electrical Engineering_, 1950, _69_, 1058-1062.

Jones, R.K. and Lee, D.N. Why two eyes are better than one: The two views of binocular vision. _Journal of Experimental Psychology: Human Perception and Performance_, 1981, _7_, 30-40.

Julesz, B. _Foundations of cyclopean perception_. Chicago: University of Chicago Press, 1971.

Kama, W.N. and DuMars, R.C. Remote viewing: A comparison of direct viewing, 2-D and 3-D television. Report AMRL-TDR-64-15, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, OH, February 1964.

Kaufman, L. _Sight and mind: An introduction to visual perception_. New York: Oxford University Press, 1974.

Kirk, Roger E. _Experimental design: Procedures for the Behavioral Sciences._ Belmont, CA: Brooks-Cole Publishing Co., 1968.

Kurtz, H.F. Orthostereoscopy. _Journal of the Optical Society of America_, 1937, _27_, 323-339.

Laycock, J. A review of the literature appertaining to binocular rivalry and helmet mounted displays. British Royal Aircraft Establishment Technical Report 76101, July 1976.

Lipton, L. Foundations of the stereoscopic cinema: A study in depth. New York: Van Nostrand Reinhold, 1982.

Luria, S.M. Stereoscopic and resolution acuity with varying field of view. Groton, CT: Naval Submarine Medical Center Report No. 557, December 1968.

Merritt, J.O. A review of methodology in studies of visual functions during VDT tasks. In Video Displays, Work, and Vision, a report prepared by the National Academy of Science's Panel on the Impact of Video Viewing on Vision of Workers. Washington, D.C.: National Academy Press, 1983, pp. 219-226.

McAdam, D.L. Stereoscopic perceptions of size, shape, distance, and direction. Journal of the Society of Motion Picture and Television Engineers, 1954, 62, 271-293.

Mueller, C.G. and Lloyd, V.V. Stereoscopic acuity for various levels of illumination. Proceedings of the National Academy of Science, 1948, 34, 223-227.

Ogle, K.N. Researches in binocular vision. Philadelphia: W.B. Saunders Co., 1950.

Ogle, K.N. Precision and validity of stereoscopic depth perception from double images. Journal of the Optical Society of America, 1953, 43, 906-913.

Ogle, K.N. The optical space sense. In H. Davson (Ed.) The eye: Volume 4. New York: Academic Press, 1962, pp. 211-432.

Okoshi, T. Three dimensional imaging techniques. New York: Academic Press, 1976.

Ono, H. and Comerford, J. Stereoscopic depth constancy. In Epstein, W. (Ed.) Stability and constancy in visual perception: Mechanisms and processes. New York: John Wiley & Sons, 1977, pp. 91-128.

Ono, H., Mitson, L. and Seabrook, K. Change in convergence and retinal disparities as an explanation for the wallpaper phenomenon. Journal of Experimental Psychology, 1971, 91, 1-10.

Pepper, R.L. and Cole, R.E. Display system variables affecting operator performance in undersea vehicles and work systems. San Diego, CA: Naval Ocean Systems Center Technical Report 269, June 1978.

Pepper, R.L., Cole, R.E., and Spain, E.H. The influence of camera separation and head movement on perceptual performance under direct and TV-displayed conditions. Proceedings of the Society for Information Display, 1983, 24, 73-80.

Pesch. A.J. Behavioral cybernetic theory applied to ship/manipulator control in small submarines. Journal of Hydronautics, 1967, 1, 35-40.

Robertson, C.J. Measurement of speed of adjustment of eye to near and far vision. Archives of Ophthalmology, 1936, 15, 423-434.

Rule, J.T. The shape of stereoscopic images. Journal of the Optical Society of America, 1941, 31, 124-129.

Saito, M., Tanaka, T., and Oshima, O. Eyestrain in inspection and clerical workers. Ergonomics, 1981, 24, 161-173.

Sherr, S. Fundamentals of information display. New York: McGraw Hill, 1970.

Shields, N.L., Kirkpatrick, M., Malone, T.B., and Huggins, C.T. Design parameters for a stereoptic television system based on direct depth perception cues. Washington, D.C.: Proceedings of the Human Factors Society 19th Annual Meeting, 1975, pp. 423-427.

Shipley, T. and Rawlings, S.C. The Nonius horopter - I. History and theory. Vision Research, 1970, 10, 1225-1262.

Simonson, E. The fusion frequency of flicker as a criterion of central nervous system fatigue. American Journal of Ophthalmology, 1959, 47, 556-565.

Simonson, E. and Enzer, N. Measurement of fusion frequency of flicker as a test for fatigue of the central nervous system. Journal of Industrial Hygiene and Toxicology, 1941, 23, 83-89.

Smith, D.C., Cole, R.E., Merritt, J.O., and Pepper, R.L. Remote operator performance comparing mono and stereo TV displays: The effects of visibility, learning and task factors. San Diego, CA: Naval Ocean Systems Center Technical Report 380, February 1979.

Smith, M.J., Cohen, B.G.F., and Stammerjohn, L.W. An investigation of health complaints and job stress in video display operators. *Human Factors*, 1981, *23*, 387-400.

Smith, W. A review of the literature relating to visual fatigue. Boston, MA:*Proceedings of the Human Factors Society 23rd Annual Meeting*, 1979, pp. 362-366.

Spain, E.H. and Cole, R.E. Camera separation, head motion camera coupling, and perceptual performance with a helmet-mounted stereo TV display. Kailua, HI: SEACO, Inc. Report No. 82-11-03, November 1982.

Spain, E.H., Cole, R.E., and Hoban, E. The effects of visual target distance and camera separation on perceptual performance under direct and TV-displayed conditions. Kailua, HI: SEACO, Inc. Report No. 82-03-01, March 1982.

Spottiswoode, R., Spottiswoode, N.L., and Smith, C. Basic principles of the three-dimensional film. *Journal of the Society of Motion Picture and Television Engineers*, 1952, *59*, 249-285.

Swensen, H.A. The relative influence of accommodation and convergence in the judgment of distance. *Journal of General Psychology*, 1932, *7*, 360-380.

Tewell, J.R., Ray, A.M., Meirick, R.P., and Polhemus, C.E. Teleoperator visual system simulations. *Journal of Spacecraft*, 1974, *11*, 418-423.

Tyler, C.W. Spatial limitations of human stereoscopic vision. In S.F. Benton (Ed.) *Three-dimensional imaging, SPIE Proceedings, 120*, 1977, pp. 36-42.

Upton, H.W. and Strother, D.D. Design and flight evaluation of a helmet-mounted display and control system. In Birt, J.A. & Task, H.L. (Eds.) A symposium on visually coupled systems: Development and application (AMD-TR-73-1). Brooks Air Force Base, TX, September 1973.

Valyus, N.A. Stereoscopy. New York: Focal Press, 1966.

Wallach, H., Frey, K.J., and Bode, K.A. The nature of adaptation in distance perception based on oculomotor cues. Perception and Psychophysics, 1972, 11, 110-116.

Wallach, H, Moore, M.E., and Davidson, L. Modification of stereoscopic depth perception. The American Journal of Psychology, 1963, 76, 191-204.

Westheimer, G. Oculomotor control: The vergence system. In Monty, R.A. and Senders, J.W Eye movements and psychological processes. Hillsdale, NJ: LEA Books, 1976, pp. 55-64.

Wheatstone, C. Contributions to the physiology of vision: On some remarkable and hitherto unobserved phenomena of binocular vision. Philosophical Transactions of the Royal Society of London, 1838. Reprinted in Herrnstein, R.J. and Boring, E.G. (Eds.). A source book in the history of psychology. Cambridge, MA: Harvard University Press, 1965, pp. 125-131.

Winer, B.J. Statistical principles in experimental design: Second edition. New York: McGraw-Hill, 1971.

Woodburne, L.S. The effect of constant visual angle upon the binocular discrimination of depth differences. The American Journal of Psychology, 1934, 46, 273-286.

Zamarin, D.M. Use of stereopsis in electronic displays: Part I - Review of stereoscopic characteristics and applications of stereo viewing systems. Douglas Aircraft Company Report MDC J7084, December 1976a.

Zamarin, D.M. Use of stereopsis in electronic displays: Part II - Stereoscopic threshold performance as a function of system characteristics. Douglas Aircraft Company Report MDC J7410, December 1976b.

APPENDIX A

INSTRUCTIONS TO OBSERVERS

Verbal Instructions for the Near-Far Test

This is a measure of how quickly you can refocus your eyes from near to far distances. The near and far objects which you will be looking for are small squares which have a gap in one of their sides. This is what the small squares look like. << *The experimenter points to the near Landolt square which is illuminated and visible through an aperture 50 cm in front of the observer's eyes* >>. Notice that there is another square just like this one at the far end of the room. << *The experimenter points to the Landolt square 6 meters distant and asks the observer whether she/he can see it clearly* >>. Notice also that gaps in the two squares are on top. When the gaps are in the same position, whether it be up, down, left, or right - they match. Whenever the gaps are in different positions, they do not match.

When we begin testing, you will indicate whether the gaps match or do not match by pressing one of these two buttons. << *The experimenter points to the response keypad which rests on a ledge approximately 50 cm in front of the* *observer* >>. Whenever the gaps match you will press the (right/left) button. When they do not match, you will press the (left/right) button.

During actual testing, the room will be totally dark and you will only be able to see the squares when they are lighted. We will take ten measures of refocus time each time you are tested. For the first set of five measures, the near square will light up first and remain lighted for one second before the far square lights up. While the near square is the only square lighted, you should look only at it. Do not redirect your eyes until the far square is lighted. Once the far square is lighted, look for its gap and press the appropriate button on the keypad as quickly as possible, indicating whether or not the near and far squares match.

For the second set of five measures, the far square will light up first and remain lighted for a second before the near square is lighted. Again, do not redirect your eyes to the near square until it is lighted and press the appropriate button as quickly as possible.

The computer will help you. Before each set of five trials, it will tell you which square will be lighted first and which keypad button (left or right) should be pushed to indicate a match. Also, before each measure the computer will say *"READY"* and there will be a one second delay before the first square is lighted. Once you've pressed the button, the computer will tell you if you were wrong. If the computer says nothing, your response was correct.

All this sounds a bit complicated, but it is really very simple and you will be allowed enough practice to feel comfortable with this test before we begin the actual experiment.

Do you have any questions?

Verbal Instructions for the Flicker Fusion Measure

This is a measure of your ability to detect flickering light. << *The experimenter points to the viewing hood depicted in Figure 6.* >>. Look into this viewing hood with both eyes open and you will see a flickering red dot of light set within a dark background. Using this hand-held dial, you will adjust the flickering of the light until it no longer appears to be flickering. That is, across the entire area of the dot, you see no flickering at all. This is how that looks. << *The experimenter adjusts the flicker rate to the maximum of 50 Hz.* >>. Can you see the dot flickering now. << *None of the observers answered in the affirmative* >>.

We will take four measures of flicker sensitivity each time you are tested. The computer will instruct you. At the beginning of each measure, the computer will say *"COUNTER-CLOCKWISE"*. This is a reminder for you to turn the dial all the way to the stop in the counter-clockwise direction. After you have done so, the flickering should be clearly apparent as it is now << *at 25 Hz* >> and the computer will say *"START"*. At this point, slowly turn the dial in the clockwise direction until the dot no longer appears to flicker. It is important that you adjust the dial to the point where the flickering just barely disappears. If you overshoot the mark a little, it is OK to turn the dial back in the counter-clockwise direction. When you have adjusted the dial so that the dot no longer flickers, press this button. << *The experimenter points out the response button on the side of the dial* >>. Be careful not to push this button inadvertently. If you do, inform the experimenter.

Do you have any questions? << *The experimenter answers questions.* >>

Remember to keep both eyes open and to adjust the dial to the point at which flicker just barely disappears completely.

Verbal Instructions for Stereo and Monoscopic TV

This is a measure of your ability to accurately judge the distances between two rods which you will see on the TV screen in front of you. During the experiment you will wear these special glasses while looking at the screen. << *The experimenter hands the observer a pair of polarizer glasses.* >> Keep both eyes open at all times and keep your eyes level with the bottom and top of the screen. Rest your chin in the chin cup and do not allow your head to tilt to one side or the other. This will help you to see the rods clearly in depth.

The test consists of sixty trials << *ninty-six trials for Experiments Three and Four* >>. At the beginning of each trial the screen will go blank and you will not be able to see the rods. Next, the computer will announce the trial number and two vertical rods will appear on the screen. Your task will be to describe the distance between the two rods in depth. << *Experimenter demonstrates the depth dimension to the observer with his hands and insures that she/he understands that it is the depth interval between rods which is to be measured.* >> First, the computer will ask the question, "*LEFT OR RIGHT?*". Look at the rods carefully and decide whether the left rod or the right rod appears to be closer to you, then speak your answer out loud. The computer will immediately tell you whether you were correct or wrong. Next, the computer will ask, *"HOW FAR?"*. Look at the rods carefully again and decide how many inches they appear to be separated in depth, then speak your answer. It is OK to use fractional numbers when making your reply. For example, three and one-half inches is an acceptable reply.

Notice that on the shelf top in front of you there are two pegs. The peg on the left is attached to a sliding device which can be moved in and out in depth. The right peg does not move and has a cushion grip with a red pushbutton on top of it. You will use the distance between these two pegs to indicate the distance that the rods appear to be separated in the televised scene. When the computer says *"SLIDER"*, move the left peg to a distance from the right peg that is equivalent to the distance the two rods are separated in depth. When you have done so, press the button on top of the right peg. The computer will immediately tell you how accurately you positioned the peg. For example, if the rods were separated by seven inches and you separated the pegs by five inches before pushing the button, the computer will say *"SHORT TWO POINT ZERO"*. If the rods were separated by two inches and you moved the pegs two and one-half inches apart, the computer will say *"LONG POINT FIVE"*. The rods may be separated from zero to twelve inches in depth. Moving the pegs to a side-by-side position like this will indicate that the two rods appear to have no depth between them. Notice that moving the left peg all the way back into the near stop does not set it equal in depth with the right peg, so do not pull the left peg back into the stop when the rods do not appear to be separated in depth.

Do your best, but do not be overly concerned with your accuracy at first You will be allowed enough practice to feel comfortable with this test before we begin the actual experiment.

Do you have any questions?

APPENDIX B

Hardware Calibration Procedures

Prior to each day's experimental testing, the following set of calibration procedures were carried out on the video equipment:

1) Cameras and monitors were turned on and allowed to warm up for at least 15 minutes.

2) Camera lenses were adjusted to pre-selected magnification values (i.e., 1X, 2X, or 3X) and focused for the distance of the camera convergence point. Lens aperture was checked to insure an f-stop setting of 5.6.

3) Cameras were separated and converged to pre-selected distances. This also involved centering the camera baseline with respect to the lateral midpoint between the two stimulus rods. Cameras were thus symmetrically converged regardless of camera separation.

4) Brightness and contrast of displayed targets were matched between the left and right video channels by the use of opaque masks with holes cut out to reveal a segment of one of the rods. With both rods displayed on both channels, masks were placed in front of the left and right channel monitors and adjustments were made to

brightness and contrast knobs on the front of the monitors.

Prior to testing each experimental observer, an additional procedure was performed to finely align the cameras. An opaque, star-shaped target was positioned at the convergence point of the cameras and used as test pattern for finely adjusting the tilt and roll of the cameras such that screen images of the star were precisely aligned. Following a testing session, the star was repositioned at the convergence point to determine whether cameras had drifted out of alignment during testing.

APPENDIX C

Text of the Computer-Administered Preliminary Mood and Eyestrain Questionnaire

NOTE: Screen frames 12 through 16 were excluded from the concluding version of this questionnaire.

SCREEN FRAME 1

```
===============================================
       INDICATE HOW YOU FEEL RIGHT NOW
     BY ENTERING THE APPROPRIATE NUMBER
        FOR EACH OF THE SCALES BELOW

     TIRED  : 1 : 2 : 3 : 4 : 5 :  ALERT

             YOUR RESPONSE? =>

===============================================
```

SCREEN FRAME 2

```
===============================================
       INDICATE HOW YOU FEEL RIGHT NOW
     BY ENTERING THE APPROPRIATE NUMBER
        FOR EACH OF THE SCALES BELOW

    RELAXED  : 1 : 2 : 3 : 4 : 5 :  TENSE

             YOUR RESPONSE? =>

===============================================
```

SCREEN FRAME 3

```
===============================================
       INDICATE HOW YOU FEEL RIGHT NOW
     BY ENTERING THE APPROPRIATE NUMBER
        FOR EACH OF THE SCALES BELOW

 DISTRACTED  : 1 : 2 : 3 : 4 : 5 :  FOCUSED

             YOUR RESPONSE? =>

===============================================
```

SCREEN FRAME 4

```
===========================================
      INDICATE HOW YOU FEEL RIGHT NOW
     BY ENTERING THE APPROPRIATE NUMBER
        FOR EACH OF THE SCALES BELOW

  DEPRESSED  : 1 : 2 : 3 : 4 : 5 :  ELATED

             YOUR RESPONSE? =>

===========================================
```

SCREEN FRAME 5

```
===========================================
      INDICATE HOW YOU FEEL RIGHT NOW
     BY ENTERING THE APPROPRIATE NUMBER
        FOR EACH OF THE SCALES BELOW

 ENTHUSIASTIC  : 1 : 2 : 3 : 4 : 5 :  BORED

             YOUR RESPONSE? =>

===========================================
```

SCREEN FRAME 6

```
===========================================
      INDICATE HOW YOU FEEL RIGHT NOW
     BY ENTERING THE APPROPRIATE NUMBER
        FOR EACH OF THE SCALES BELOW

                 EYESTRAIN
NOT AT ALL  : 1 : 2 : 3 : 4 : 5 :  VERY MUCH

             YOUR RESPONSE? =>

===========================================
```

SCREEN FRAME 7

```
==========================================
      INDICATE HOW YOU FEEL RIGHT NOW
    BY ENTERING THE APPROPRIATE NUMBER
       FOR EACH OF THE SCALES BELOW

                 EYE PAIN
VERY MUCH   : 1 : 2 : 3 : 4 : 5 :  NOT AT ALL

             YOUR RESPONSE? =>

==========================================
```

SCREEN FRAME 8

```
==========================================
      INDICATE HOW YOU FEEL RIGHT NOW
    BY ENTERING THE APPROPRIATE NUMBER
       FOR EACH OF THE SCALES BELOW

                 HEADACHE
NOT AT ALL  : 1 : 2 : 3 : 4 : 5 :  VERY MUCH

             YOUR RESPONSE? =>

==========================================
```

SCREEN FRAME 9

```
==========================================
      INDICATE HOW YOU FEEL RIGHT NOW
    BY ENTERING THE APPROPRIATE NUMBER
       FOR EACH OF THE SCALES BELOW

       PAIN IN THE NECK OR SHOULDERS
VERY MUCH   : 1 : 2 : 3 : 4 : 5 :  NOT AT ALL

             YOUR RESPONSE? =>

==========================================
```

```
                SCREEN FRAME 10
=============================================
      INDICATE HOW YOU FEEL RIGHT NOW
    BY ENTERING THE APPROPRIATE NUMBER
       FOR EACH OF THE SCALES BELOW

           PAIN IN THE ARMS OR LEGS
NOT AT ALL  : 1 : 2 : 3 : 4 : 5 :  VERY MUCH

               YOUR RESPONSE? =>

=============================================
```

```
                SCREEN FRAME 11
=============================================
      INDICATE HOW YOU FEEL RIGHT NOW
    BY ENTERING THE APPROPRIATE NUMBER
       FOR EACH OF THE SCALES BELOW

                BLURRED VISION
VERY MUCH  : 1 : 2 : 3 : 4 : 5 :  NOT AT ALL

               YOUR RESPONSE? =>

=============================================
```

```
                SCREEN FRAME 12
=============================================

    APPROXIMATELY HOW MANY HOURS OF SLEEP
           DID YOU GET LAST NIGHT?
               EXAMPLE: 8.5

              YOUR RESPONSE? =>

=============================================
```

SCREEN FRAME 13

```
============================================

       DO YOU FEEL WELL-RESTED? (Y/N)
             YOUR RESPONSE? =>
                WHY NOT? =>

============================================
```

SCREEN FRAME 14

```
============================================

       IS THERE ANYTHING UNUSUAL ABOUT
        YOUR VISION TODAY? (Y/N) =>

                  WHAT? =>

============================================
```

SCREEN FRAME 15

```
============================================

         HAD ANY COFFEE IN THE PAST
             TWO HOURS? (Y/N)  =>

             HOW MANY CUPS? =>

============================================
```

SCREEN FRAME 16

```
============================================

      SMOKED ANY CIGARETTES IN THE PAST
                TWO HOURS? =>

      HOW MANY AND OF WHAT BRANDS? =>

============================================
```

APPENDIX D

Table 32.
Randomized Orders for Depth Intervals (In Inches) Used in Stereo TV Testing Sessions

Trial	Order 1	Order 2	Order 3	Order 4
1	6	6	8	6
2	4	8	10	0
3	2	4	0	10
4	6	2	4	0
5	10	0	2	2
6	0	2	8	4
7	4	4	6	8
8	2	0	2	10
9	10	10	0	8
10	0	6	4	6
11	8	8	10	4
12	8	10	6	2
13	6	8	2	8
14	4	2	8	8
15	8	6	10	6
16	8	8	4	2
17	4	4	8	0
18	6	4	4	2
19	0	10	0	10
20	10	10	10	4
21	0	0	0	0
22	2	6	6	10
23	2	2	2	4
24	10	0	6	6
25	8	10	10	6
26	4	0	0	0
27	8	2	4	8
28	6	6	8	2
29	6	10	8	0
30	10	0	10	10
31	2	6	6	4
32	0	4	0	2
33	0	8	2	10
34	2	4	4	4
35	10	2	6	6
36	4	8	2	8
37	8	10	0	8
38	4	10	2	6
39	8	8	4	6
40	6	6	10	0
41	4	4	8	10
42	0	4	8	2
43	10	8	0	8
44	0	0	2	4
45	2	2	4	4
46	2	6	6	10

Table 32. Randomized Orders for Depth Intervals (Inches) Used in Stereo TV Testing Sessions (Continued)

Trial	Order 1	Order 2	Order 3	Order 4
47	6	2	10	0
48	10	0	6	2
49	2	6	10	2
50	4	0	4	6
51	6	0	4	0
52	10	8	8	4
53	0	6	8	8
54	8	10	10	6
55	8	2	2	10
56	4	8	2	4
57	10	4	6	2
58	2	4	0	0
59	0	10	6	10
60	6	2	0	8
61	8	2	6	10
62	0	8	8	2
63	4	8	6	8
64	2	2	0	10
65	0	10	2	4
66	4	10	4	0
67	6	4	8	6
68	6	4	10	4
69	2	0	0	0
70	10	0	2	2
71	8	6	4	8
72	10	6	10	6
73	0	2	2	10
74	4	0	10	6
75	2	8	2	4
76	10	2	6	0
77	6	10	10	4
78	8	6	6	0
79	4	4	4	2
80	10	10	0	6
81	8	4	8	10
82	2	8	4	8
83	6	0	0	8
84	0	6	8	2
85	6	8	2	6
86	8	10	6	4
87	2	4	0	4
88	0	8	6	2
89	10	2	10	0
90	4	6	4	10
91	4	2	4	8
92	10	6	10	10
93	2	0	8	2
94	0	4	2	8
95	6	10	8	6
96	8	0	0	0

Table 33.
Randomized Orders of Landolt Square Gap Orientations for the Near-Far Test

Where: L = Left R = Right U = Up D = Down

Order 1

Trial	Gap Orientation		Match
Near First	Near Target	Far Target	
1	L	L	Y
2	U	D	N
3	D	D	Y
4	R	R	Y
5	L	R	N
Far First	Far Target	Near Target	
6	D	U	N
7	L	L	Y
8	R	L	N
9	U	U	Y
10	L	R	N

Order 2

Trial	Gap Orientation		Match
Near First	Near Target	Far Target	
1	D	D	Y
2	R	R	Y
3	U	D	N
4	L	R	N
5	L	L	Y
Far First	Far Target	Near Target	
6	R	L	N
7	L	L	Y
8	D	U	N
9	L	R	N
10	U	U	Y

Order 3

Trial	Gap Orientation		Match
Near First	Near Target	Far Target	
1	D	U	N
2	L	L	Y
3	R	L	N
4	U	U	Y
5	L	R	N
Far First	Far Target	Near Target	
6	L	L	Y
7	U	D	N
8	D	D	Y
9	R	R	Y
10	L	R	N

Order 4

Trial	Gap Orientation		Match
Near First	Near Target	Far Target	
1	R	L	N
2	L	L	Y
3	D	U	N
4	L	R	N
5	U	U	Y
Far First	Far Target	Near Target	
6	D	D	Y
7	R	R	Y
8	U	D	N
9	L	R	N
10	L	L	Y

Table 34.
Randomized Orders of In-Phase and Counter-Phase Flicker for the Flicker Fusion Threshold (CFF) Measure

Where: IP = In-Phase Flicker CP = Counter-Phase Flicker

Trial	Order 1	Order 2	Order 3	Order 4
1	IP	CP	IP	CP
2	CP	IP	IP	CP
3	IP	CP	CP	IP
4	CP	IP	CP	IP

Table 35.
Randomized Order of Testing Sessions for Experiment One.

Date	Viewing Condition	Magnification
9/26/83	19.05 Cm Camera Separation	3X (5.9° H. FOV)
9/27/83	3.175 Cm Camera Separation	3X
9/28/83	3.175 Cm Camera Separation	1X (17.8° H. FOV)
9/29/83	Monoscopic TV	2X (11.9° H. FOV)
10/03/83	6.350 Cm Camera Separation	1X
10/04/83	Monoscopic TV	1X
10/06/83	3.175 Cm Camera Separation	2X
10/07/83	19.05 Cm Camera Separation	2X
10/11/83	Monoscopic TV	3X
10/12/83	Binocular Direct View	---
10/13/83	6.350 Cm Camera Separation	3X
10/17/83	6.350 Cm Camera Separation	2X
10/18/83	19.05 Cm Camera Separation	1X

Table 36.
Randomized Order of Testing Sessions for Experiment Two.

Date	Viewing Condition
10/20/83	Binocular Direct View
10/24/83	Cameras Converged at Middle of Workspace
10/25/83	Camera Axes Paralleled
10/26/83	Cameras Converged 20 Cm in Front of Workspace
10/27/83	Monoscopic TV

Table 37.
Randomized Order of Testing Sessions
for Experiment Three.

Date	Viewing Condition
11/01/83	3.175 Cm Camera Separation
11/02/83	19.05 Cm Camera Separation
11/03/83	Monoscopic TV
11/04/83	6.350 Cm Camera Separation
11/05/83	Binocular Direct View

Table 38.
Randomized Order of Testing Sessions
for Experiment Four.

Date	Viewing Condition
11/07/83	Monoscopic TV
11/08/83	6.350 Cm Camera Separation
11/09/83	3.175 Cm Camera Separation
11/14/83	19.05 Cm Camera Separation
11/15/83	Binocular Direct View