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Three-Dimensional Displays
Perceptual Research
and
Applications to Military Systems

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January 29, 1982

Edited by:

David J. Getty
Bolt Beranek and Newman Inc.
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report contains the edited proceedings of a symposium on the design and applications of three-dimensional displays. The symposium was held at the National Academy of Sciences Building in Washington, D.C. on January 29,1982.

The symposium contained three parts. The first consisted of a series of five papers that discussed basic perceptual research on, and relating to, the design and use of three-dimensional displays. The second part of the symposium was a panel discussion on the topic: "Critical Research Issues in

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3-D Displays." The third and final part of the symposium was a discussion by a second panel of the topic: "The Applicability of 3-D Display Research to Military Operational Needs."

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Preface

This report contains the edited proceedings of a symposium on three-dimensional displays held at the National Academy of Sciences Building in Washington, D. C. on January 29, 1982. The meeting was sponsored jointly by the National Academy of Sciences-National Research Council's Committee on Human Factors and the Naval Air Systems Command (Code 310C).

Technological developments in recent years have brought us to the threshold of practical three-dimensional (3-D) display systems. However, the imminent realization of such systems raises a number of perceptual, human factors, and operational issues that must be answered before these displays can be employed to best advantage in applications. The goals of this symposium were (1) to determine what we know presently about visual perception and human factors of 3-D displays, (2) to identify critical issues requiring research, and (3) to identify and explore some of the likely or possible areas of application, particularly with regard to military operational needs.

The symposium was organized in three parts, corresponding to the three goals just stated. In the first part, five researchers described basic research findings on 3-D display systems, or issues related to 3-D perception. In the second part, four panelists involved in applied research related to 3-D displays discussed the topic: "Critical Research Issues in 3-D Displays." Finally, in the third part of the symposium, a panel of three military program managers (a fourth was unable to attend the meeting) discussed the topic: "The Applicability of 3-D Display Research to Military Operational Needs."

The successful realization of this symposium was possible because of the efforts of several people whom I wish to acknowledge. First, the conception--and much of the early planning--for the symposium were the result of the enthusiastic efforts of John O'Hare of ONR. I thank also Mildred Webster for her help in the preparation of these proceedings. My deep appreciation and thanks go to Bob Hennessy, Study Director for the NAS-NRC Committee on Human Factors who shared over the months the burden of organizing the conference. Finally, I thank the symposium participants for their contributions, all of which resulted in an engaging and valuable meeting.

David J. Getty
Chairman

INTRODUCTION: THREE-DIMENSIONAL DISPLAYS

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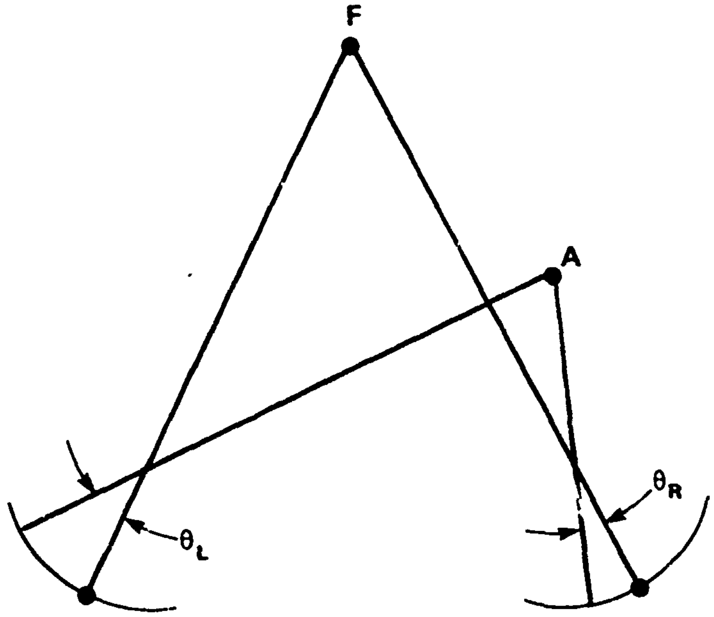
The research discussed in this symposium focuses on visual perception and human factors relating to three-dimensional displays. In this introduction, I consider what we mean by a three-dimensional display and discuss a distinction between two classes: stereo-pair displays and volumetric displays.

In a very general sense, three-dimensional displays include all systems that provide sufficient information to an observer--in whatever form--to permit the relative localization of displayed objects in three-dimensional space. This definition is too broad for our purposes. For example, it would include flat displays that present depth information to an observer through coding techniques. Illustrations of such techniques are the coding of depth through variations in the brightness or size of displayed objects. It would also include other displays that provide depth information solely through monocular cues. There are, of course, many such cues: linear perspective, size of familiar objects, interposition of objects, shadows, and texture gradients, to name some of the more important ones. We use these cues constantly in interpreting the relative depth of objects in flat, two-dimensional displays (e.g. photographs, paintings, movies and TV). These are complex cues that require a considerable amount of cognitive image processing in their application. Furthermore, the effectiveness of many of them is dependent upon familiarity with the objects being displayed.

All of the types of display described above have in common that the same information--contained in a flat, two-dimensional image--is presented to each of the observer's two eyes. From this single image, the observer extracts available monocular and coding cues to depth in order to form a perception of the relative depths of displayed objects, to whatever degree possible. We will exclude this class of displays from our consideration.

The classes of displays that we do wish to include have in common that different information is presented to each of the observer's two eyes, different in particular in that binocular disparity is present. Binocular disparity is also referred to commonly as retinal disparity, binocular parallax; or horizontal parallax. In natural viewing of a three-dimensional scene, binocular disparity is a straightforward geometrical consequence of the fact that each eye is viewing the scene from a slightly different vantage point. Because of the horizontal separation of our eyes, the visual angle subtended between any two objects located at different depths will necessarily be different in the two eyes. This geometry is illustrated in the diagram below. With both eyes fixated on object F, the angle subtended from the fovea by another object A, located at a different depth than F, is larger in the left eye than in the right. The difference in these angles is a measure of the amount of binocular disparity.



DISPARITY= $\theta_L - \theta_R$

As early as 1838, Charles Wheatstone had demonstrated that binocular disparity is sufficient to yield a strong perception of depth. Using a mirror stereoscope, which he invented, he drew two different pictures of a solid object, representing the slightly different views of th object as would be seen by the two eyes at arm's length. When the images were viewed in the stereoscope with each image channeled to the appropriate eye, he found that the object appeared in depth and occupied a volume of space just as did its real counterpart. The perception of depth resulting from binocular disparity is called <u>stereopsis</u>, and is believed to be the single most potent of the visual cues to depth.

There are two distinct classes of stereopsis-based displays. The first class, which we may call stereo-pair displays, is exemplified nicely by Wheatstone's original stereoscope. For these displays, a pair of images is constructed containing horizontal disparity appropriate for the relative depth of each object to be displayed. The image construction process may be as simple as taking two photographs of a scene, moving the camera sideways by several inches between pictures to create the two disparate views, or as complex as using a computer to do geometric modeling of a three-dimensional scene or process. Having constructed a pair of two-dimensional images, each is then transmitted independently to the appropriate eye. Since Wheatstone's invention of the mirror stereoscope, many other stereo-pair displays have been developed, differing primarily in the methodology for independent delivery of the two images, one to each of the two eyes. The techniques employed have included mirrors, prisms, crossed-polarizer glasses, red and green filter glasses, lenticular screens, and alternating shutter glasses. Some of these methods are discussed in more detail by Fox in Chapter 1, Piantanida in Chapter 3, and Uttal et al in Chapter 5.

The second class of stereopsis-based displays may be called volumetric or space-filling displays. As suggested by the name, these displays are based on a single real or virtual image which quite literally fills a three-dimensional volume of space. Over the past 40 years several volumetric displays have been developed, based on different techniques. Examples are displays produced by rapid rotation of a flat, dense matrix of LEDS through a volume, holograms, and displays produced by oscillation movement of a flexible, vari-focal mirror. Research using a particular realization of this last technique is discussed by Huggins and Getty in Chapter 2.

While both stereo-pair displays and volumetric displays are similar in that they activate human stereopsis, they differ in several significant ways. These differences, listed in the table below, have strong implications for the types of application for which each class of display is suited.

Stereopsis-Based Displays

Stereo-Pair Displays	Volumetric Displays
. Two 2-D images	. One space-filling image
. Binocular disparity produced by image generation process	. Binocular disparity produced by natural separation of observer's eyes
. Depth coordinates are not necessarily required for image generation	. Depth coordinates are required for image generation
. Single point of view, controlled by display	. Multiple points of view, controlled by viewer

The first difference concerns binocular disparity. In a stereo-pair display, the amount of binocular disparity present is determined by the process used to generate the pair of images. Whether generated by two cameras or by a computer, the horizontal separation between the two points-of-view is arbitrary and can be varied to magnify or minify perceived depth. In a volumetric display, the amount of binocular disparity present is fixed by the natural separation between the observer's two eyes. The ability to manipulate and exaggerate depth in stereo-pair displays make them of particular interest in applications where objects and background are difficult to discriminate because of minimal actual depth differences, or camouflage or both.

A second difference concerns knowledge of the three-dimensional coordinates of each object to be displayed. In stereo-pair displays, the image generation process does not necessarily require any explicit knowledge about the locations of displayed objects in three-dimensional space. For example, a stereo pair of television cameras generates images in which the geometry of the imaging system and the three-dimensional scene is sufficient to place each object at the appropriate location within each image. On the other hand, volumetric displays require the three-dimensional coordinates of each object to be displayed in order to place each one at the appropriate location within the display volume.

These differences between stereo-pair and volumetric displays have significant implications for applications. Clearly, stereo-pair displays are well-suited to situations requiring remote viewing of natural three-dimensional scenes. These scenes can be reconstructed in depth for the observer without any system knowledge of object location or depth. On the other hand, in simulation or modeling applications where coordinate information is available, volumetric displays offer a distinct advantage owing to the following difference. For a given static stereo-pair of images, the observer receives a view of a three-dimensional scene dictated by the location of the "eyes" of the imaging system. As discussed by Rosinski in Chapter 4 the observer is then constrained to view the stereo-pair with his eyes in the same positions relative to the images or suffer visual distortions of several types. Furthermore, for systems in which the display surfaces are not held in a fixed relationship to the observer's eyes, as in stereo TV, the observer is constrained to keep his head horizontal to match the direction of binocular disparity in the images. Volumetric displays, on the other hand, permit the observer to freely translate or rotate his head and body (within the viewing limits of the display), obtaining continuously changing perspectives of the scene correlated with movement, just as we do in natural viewing of the real world. The ability to look around inside, over, and under displayed objects is clearly an important property of volumetric displays for many applications, especially those involving complex three-dimensional shapes or spatial relationships among many objects.

Part I: Basic Perceptual Research

THE EFFECT OF DEPTH POSITION ON STIMULUS INTERACTION

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This paper summarizes some of the conclusions that have emerged from a program of research that my colleagues and I have underway that is concerned broadly with the processing of visual information from three-dimensional displays. One specific interest, and the one explained in the paper, concerns the effect of depth position on the interaction among stimuli. It will be helpful to begin by explaining what is meant by those phrases, depth position, and interaction among stimuli.

I'm using stimulus interaction to apply collectively to a wide range of visual phenomena that have in common changes in the perceived attributes of a stimulus that are caused by the contextual stimulation surrounding that stimulus. The change can be destructive or inhibitory in the sense that the perceptibility of the stimulus is impaired. Or, an apparent distortion of one of the dimensions of the stimulus can occur. For example, in Figure 1 the well-known phenomenon of simultaneous contrast is illustrated. Here the apparent brightness of the inner gray circles, which have the same objective reflectance, is altered by the brightness of the contextual squares in which they are embedded. In Figure 2, conditions for the phenomenon of lateral interference are illustrated. Lateral interference, which is also called "crowding" in the ophthalmic literature, refers to the impaired perceptibility of a form when it is surrounded or flanked by other forms, relative to when it is seen as isolation. Finally, Figure 3 illustrates the stimulus configuration, which is sometimes referred to as the Ponzo illusion, that produces a distortive interaction such that the apparent length of the parallel lines is altered by the linear perspective cue formed by the railroad tracks.

These examples serve to define what is meant by stimulus interaction. Consider now depth position. This refers to the position of the interacting stimulus elements along the Z axis. Almost all of the considerable research on various kinds of stimulus interaction have dealt only with the two-dimensional case, where the X and Y positions of the elements are varied while the Z axis value remains constant. The question that arises naturally from a consideration of three-dimensional space is whether stimulus interactions would be modified if the interacting elements occupied different perceived depth planes. At the most general theoretical level the answer bears upon which of two general theories of visual space perception is more nearly correct. At a more specific level it bears on the adequacy of models developed for specific interactive phenomena, which, in general, have invoked the assumption that perceived depth position is irrelevant to the occurrence of interactions. Because these theoretical issues have been treated elsewhere, there is no compelling need to consider them today. For, independent of theory, the answer to the question of depth separation is of general empirical interest.

Yet only a small number of experiments have explored the effect of perceived depth position on stimulus interaction because it is

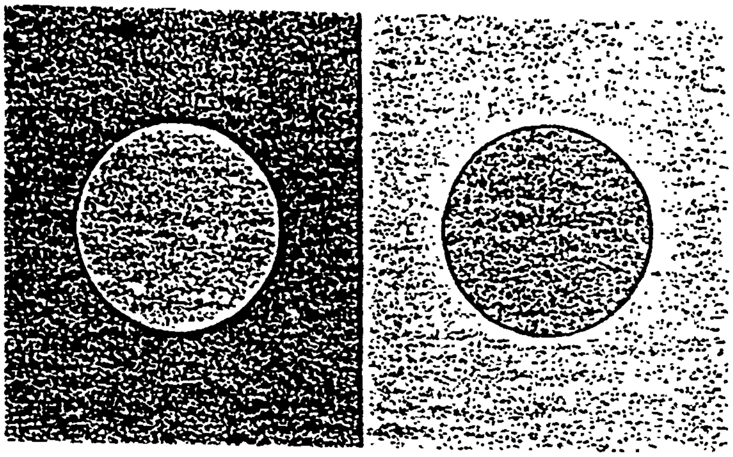

Figure 1. An illustration of simultaneous contrast. Although the two circles are physically equal in brightness, the circle on the dark field appears brighter than the circle on the light field (after Dember & Warm, 1979).

A X M B S Z O

X B Z

LATERAL INTERFERENCE

Figure 2. An illustration of the conditions that produce lateral interference. When the figures X, B, and Z are embedded within the row of other figures they are more difficult to resolve relative to when they are seen in isolation.

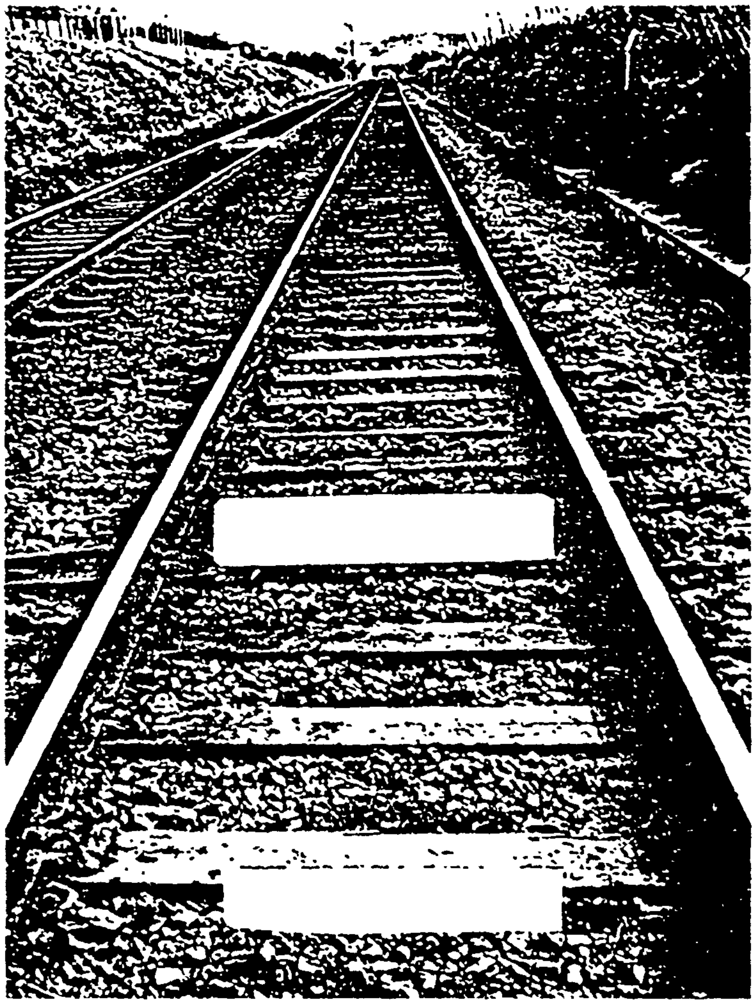

Figure 3. The Ponzo configuration embedded within a context of enhanced linear perspective.

technically quite difficult to produce changes in depth without, at the same time, introducing confounding changes in proximal stimulation. Nevertheless, it has been possible to implement successfully some experiments. In this regard, the research program of Walter Gogel (e.g., Gogel, 1978) is particularly noteworthy. In his research on space perception, Gogel has been led to develop an hypothesis known as the adjacency principle, which says, in effect, that the interaction among stimuli in visual space is inversely related to the X, Y, and Z distance separating them. To test the adjacency principle, Gogel has devised various optical methods that produce changes in perceived depth through the manipulation of different kinds of depth cues. For example, in one experiment Gogel and Newton (1975) used such cues to produce an apparent depth separation between the rod and the frame that comprise the well-known rod and frame illusion. Figure 4 illustrates schematically the general arrangement. When a vertically oriented rod is enclosed within a tilted frame, the frame acts to induce an apparent tilt in the rod. In Gogel and Newton's experiment, when both rod and frame were in the same depth plane the expected tilt of the rod was obtained. But when the rod and frame were in different perceived depth planes, such that the rod appeared closer to the observer than the frame, the effect of the frame was significantly reduced.

Another example of the effect of perceived depth position is provided by Allan Gilchrist (1977), who has been working within a theoretical framework different from that of Gogel. Gilchrist's basic experimental situation is illustrated in Figure 5. It is well established that the perceived brightness of a particular surface is controlled by the relative amounts of light reflected from adjacent surfaces. Gilchrist used the depth cue of interposition to make the target, which remained at a constant physical luminance, appear at a far depth plane adjacent to a highly illuminated surface or at a near depth plane adjacent to a more dimly illuminated surface. The perceived change in depth position produced a large change in the perceived brightness of the target. As shown in the panel at the bottom of Figure 5, the target appeared quite bright, with a Munsell value of 9 on a 10-point scale when seen next to the dimmer surface at the near position. Yet when seen against a brighter surface at the far position, the target appeared much dimmer with a Munsell value of 3.5. This result indicates that perceived depth plays a much more significant role in determining the final percept than does the actual luminances that are impinging on the retina.

As I mentioned earlier, experiments on the effect of depth separation are difficult to implement because perceived depth must be induced in a convincing way without, at the same time, introducing confounding changes in proximal stimulation. This has severely restricted the kinds of perceptual actions that can be examined and the magnitude of the variables that can be manipulated. For example, in the Gilchrist situation, it is not possible to systematically vary the

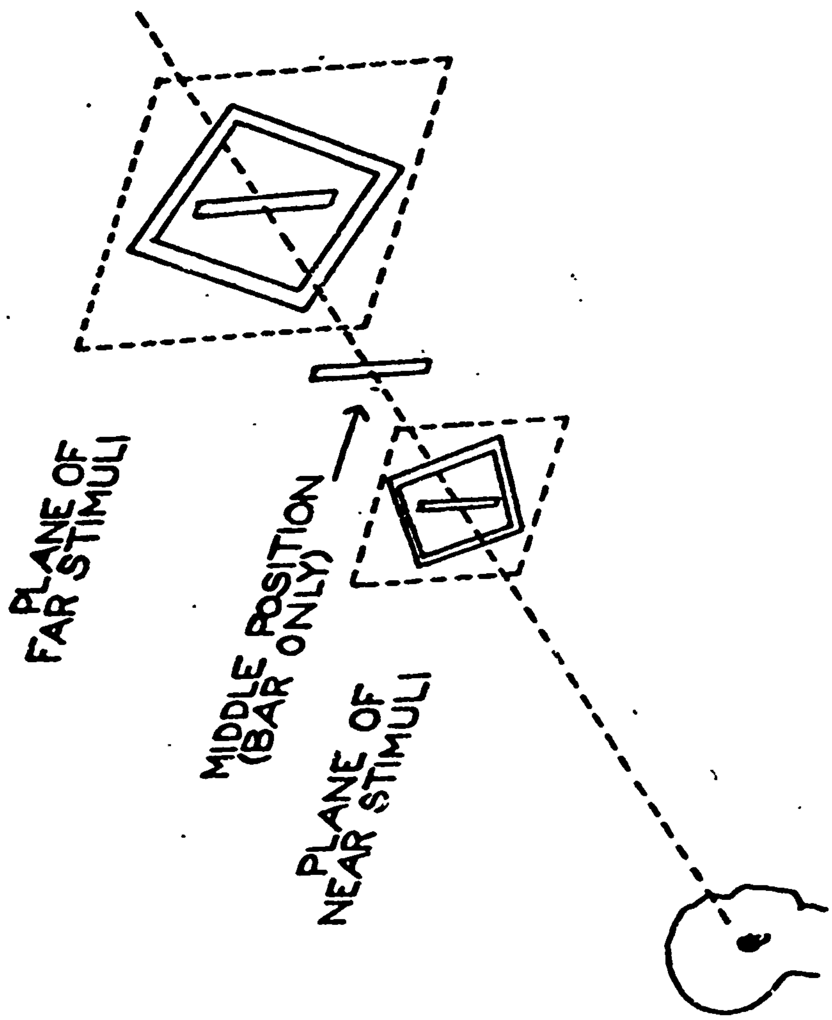

Figure 4. Displacement in depth of the rod relative to the frame (from Gogel & Newton, 1975).

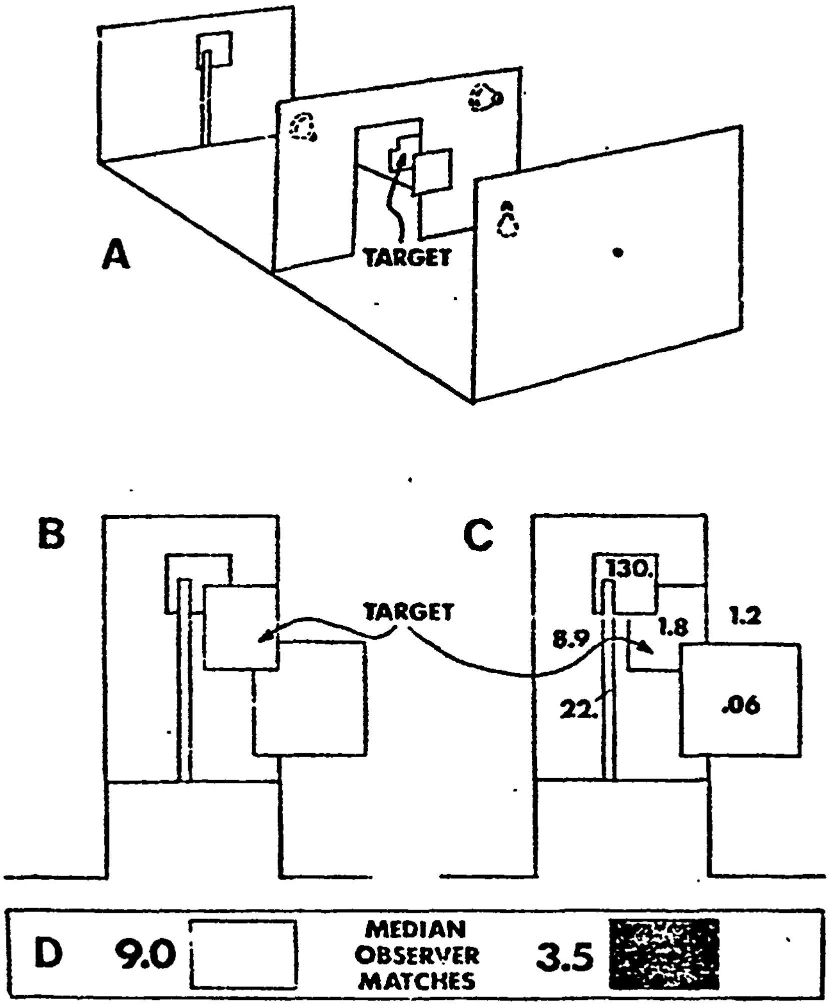

Figure 5. (A) View of stimulus display. (B) The display in which the target appeared in the rear plane. (C) The display in which the target appear in the far plane. (D) Average match from a Munsell chart for the two displays (from Gilchrist, 1980).

perceived depth position of a target over a series of values.

These considerations motivated my colleagues and me to develop a more flexible method of pursuing the question of the effect of perceived depth on stimulus interactions. The approach we have taken employs stimuli constructed from random element stereograms. As shown in Figure 6, random element stereograms, which were developed by Julesz (1960, 1971) consist of large arrays of randomly organized dots or elements. Neither the left-eye view nor the right-eye view contain any recognizable shape or contour. But retinal disparity that induces stereoscopic depth can be introduced by displacing a subset of elements within a matrix viewed by one eye. This displacement is camouflaged, however, by the myriad of surrounding dots and cannot be seen. But when an observer who possesses stereopsis views the left- and right-eye views under stereoscopic conditions, the disparity is detected by the visual system and this results in the perception of a palpable, clear-cut stereoscopic form standing out in depth. These forms originate from some central stage of the visual system where inputs from both eyes are combined and, in that sense, they bypass the retina or other peripheral stages. Nevertheless, the stereoscopic or cyclopean contours have been shown to possess many of the functional characteristics of physical contours. That is, they can induce aftereffects, eye movements, and interact in much the same manner as their physical counterparts. Our approach has been to replicate the interactions that occur among physical stimuli in stereoscopic space with stereoscopic stimuli. This allows perceived depth to be changed very easily and eliminates entirely the problem of confounding changes in proximal stimulation.

Our efforts have been greatly facilitated by the development, at Vanderbilt, of a system for generating, in real time, dynamic random element stereograms. The major components of the system are illustrated in Figure 7. The display device can be any one of several kinds of slightly modified color video receivers. By directly modulating the red and green electron guns, thousands of red and green dots are continuously generated many times a second. When an observer views the display with appropriate red and green filters before the eyes, the red and green dots are physically segregated to separate eyes, thereby fulfilling the conditions of stereoscopic viewing (i.e., the well-known anaglyph method of stereoscopic presentation). All parameters of the stereoscopic displays, such as depth magnitude and direction, are controlled by a hardwired electronic unit composed of integrated circuits. This is represented by the box marked "Stereogram Generator". The box marked "Optical Scanner" consists of modified TV cameras that operate as flying spot scanners. Any two-dimensional form that is seen or scanned by the cameras is immediately converted into its stereoscopic equivalent. Even complex shapes undergoing continuous motion can be presented as stereoscopic or cyclopean configurations. This system is quite flexible, and is being used in a variety of investigations concerned with perception of space and stereoscopic depth perception.

Figure 6. The two monocular patterns of a typical static random-element stereogram. When each pattern stimulates a separate eye, a stereoscopic form can be perceived (after Julesz, 1971).

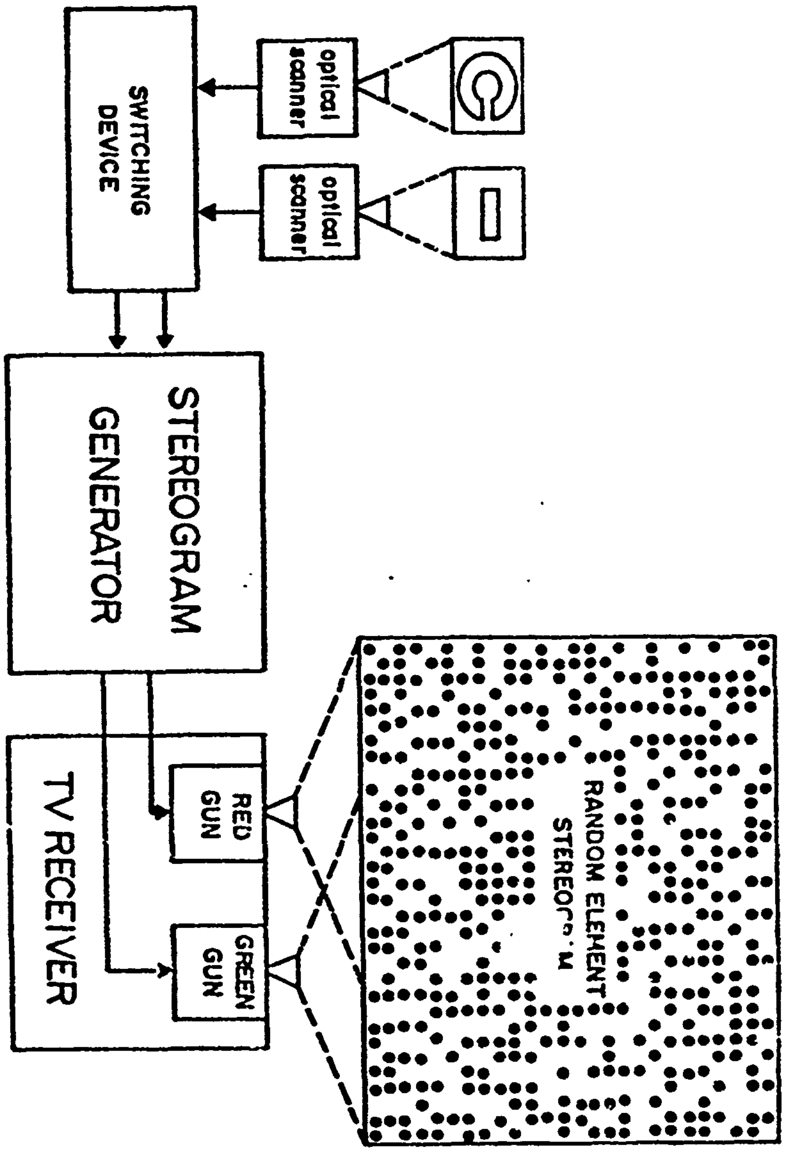

Figure 7. Display, programming, and logic units of the stereogram generation system.

With the aid of this system we have pursued investigations of the effect of perceived depth position on those stimulus interactions that involve the elevation of threshold, and those that involve distortive interactions at the suprathreshold level. In all cases we have found that perceived depth position exerts a strong effect on the magnitude of the interaction. In one study my colleague, Bob Patterson and I (Fox and Patterson, 1981b) chose the Ponzo illusion as an example of a suprathreshold distortive interaction. This illusion was mentioned at the beginning of this paper and shown in Figure 8. We investigated the effect of the perceived depth position of the inducing angle on the test lines using stereoscopic contours formed from the random element stereogram display. The essentials of our method are illustrated in Figure 9. The stimuli always appeared in front depth (with crossed disparity) in the visual space between the display and the observer. The test lines remained at the same depth position while, in different experimental conditions, the inducing angle was located at perceived depth positions in front of, and behind the test lines, as well as in a depth position equal to that of the test lines. The perceived width of the angle was kept constant, at all depth positions, to compensate for the perceived change in width produced by size constancy. The magnitude of the illusion, which is the perceived difference in length between the top and bottom lines, was assessed by the method of magnitude estimation.

The results are given in Figure 10. When both angle and test lines were in the same depth plane, a significant illusion was obtained relative to that observed under the control condition, where illusion magnitude is measured in the absence of the inducing angle. Yet, for the positions marked "back", which refers to the case where the inducing angle is in back of the test lines and closer to the display screen, that is, the test lines are in front of the angle, illusion magnitude declined significantly. But for the positions marked "front", which refers to the angle being in front of the test lines, illusion magnitude did not decline. These data indicate that perceived depth position plays a significant role in determining illusion magnitude. Moreover, the effect is asymmetrical in that the stimulus interaction declines only when the target, the acted-upon stimulus, is in a depth plane in front of the inducing stimulus and closer in space to the observer.

This same asymmetry was also found in an investigation of lateral interference (Fox & Patterson, 1981a). Recall, from the introduction, that lateral interference refers to the impaired perceptibility of a stimulus produced by spatially adjacent stimuli that are continuously present in the visual field. To investigate lateral interference we used stereoscopic contours as stimuli. Their configuration, and the general experimental arrangement, is shown in Figure 11. The target is a Landolt C, in which the gap position can be varied on a random basis to any one of two positions--3:00 and 9:00 o'clock. Interference is produced by the continuously present annulus

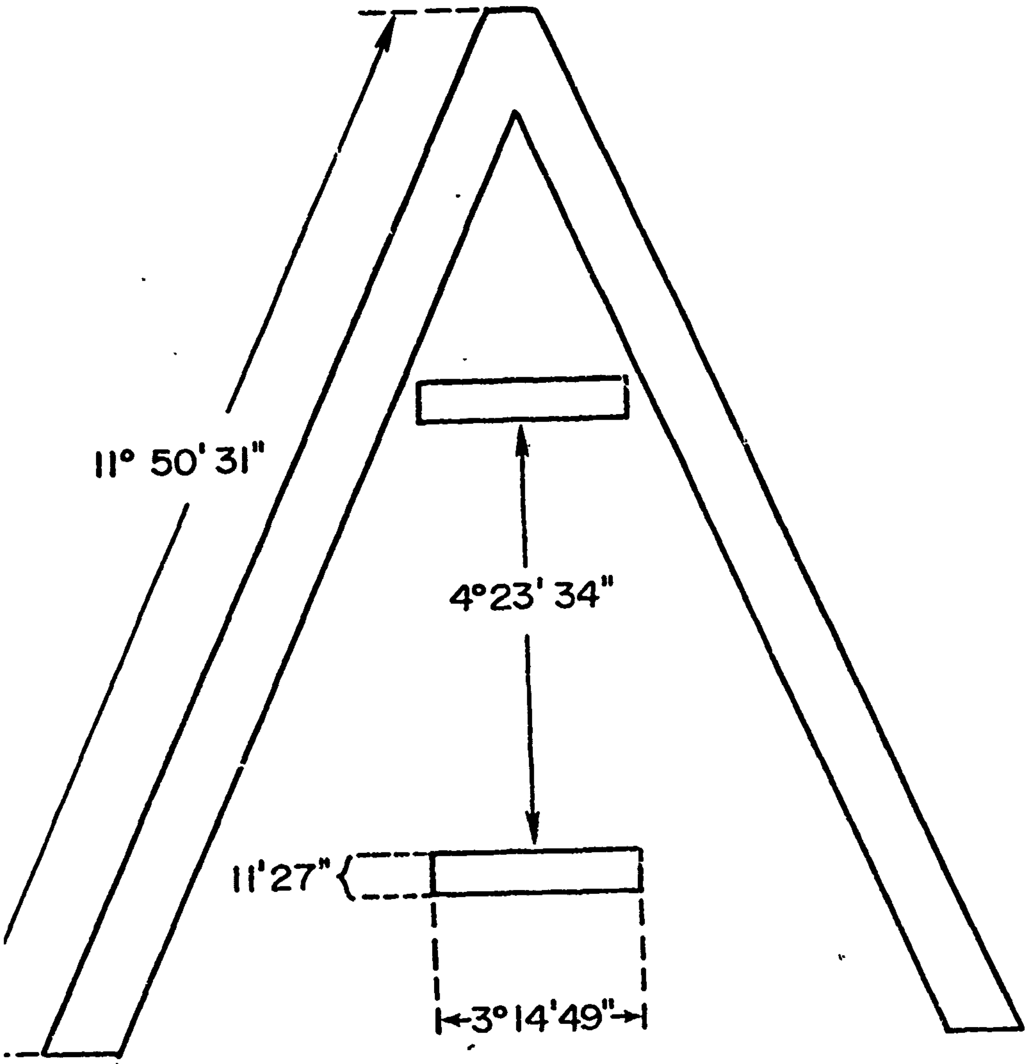

Figure 8. Configuration and dimensions of stereoscopic stimuli employed in the experiment on the Ponzo illusion (from Fox & Patterson, 1981).

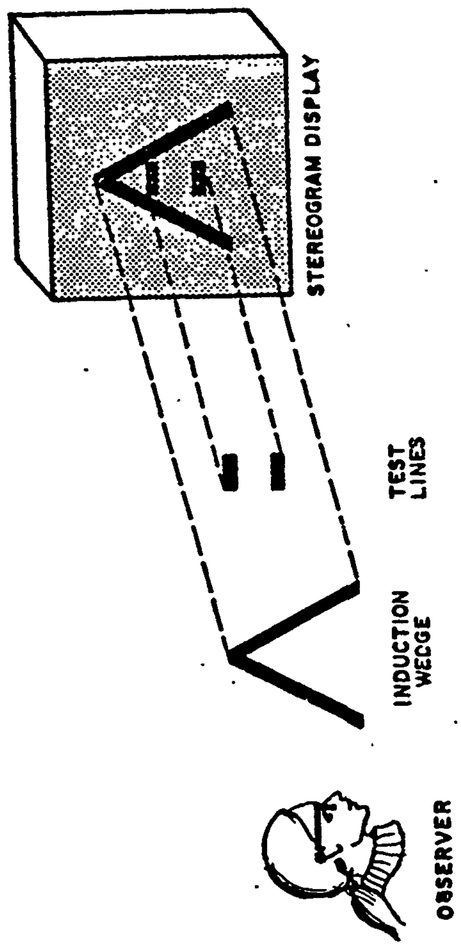

Figure 9. Stimulus arrangement showing relative depth of test lines (in front) and inducing angle. Note that the term "inducing angle" is synonymous with induction wedge in the figure (from Fox & Patterson, 1981).

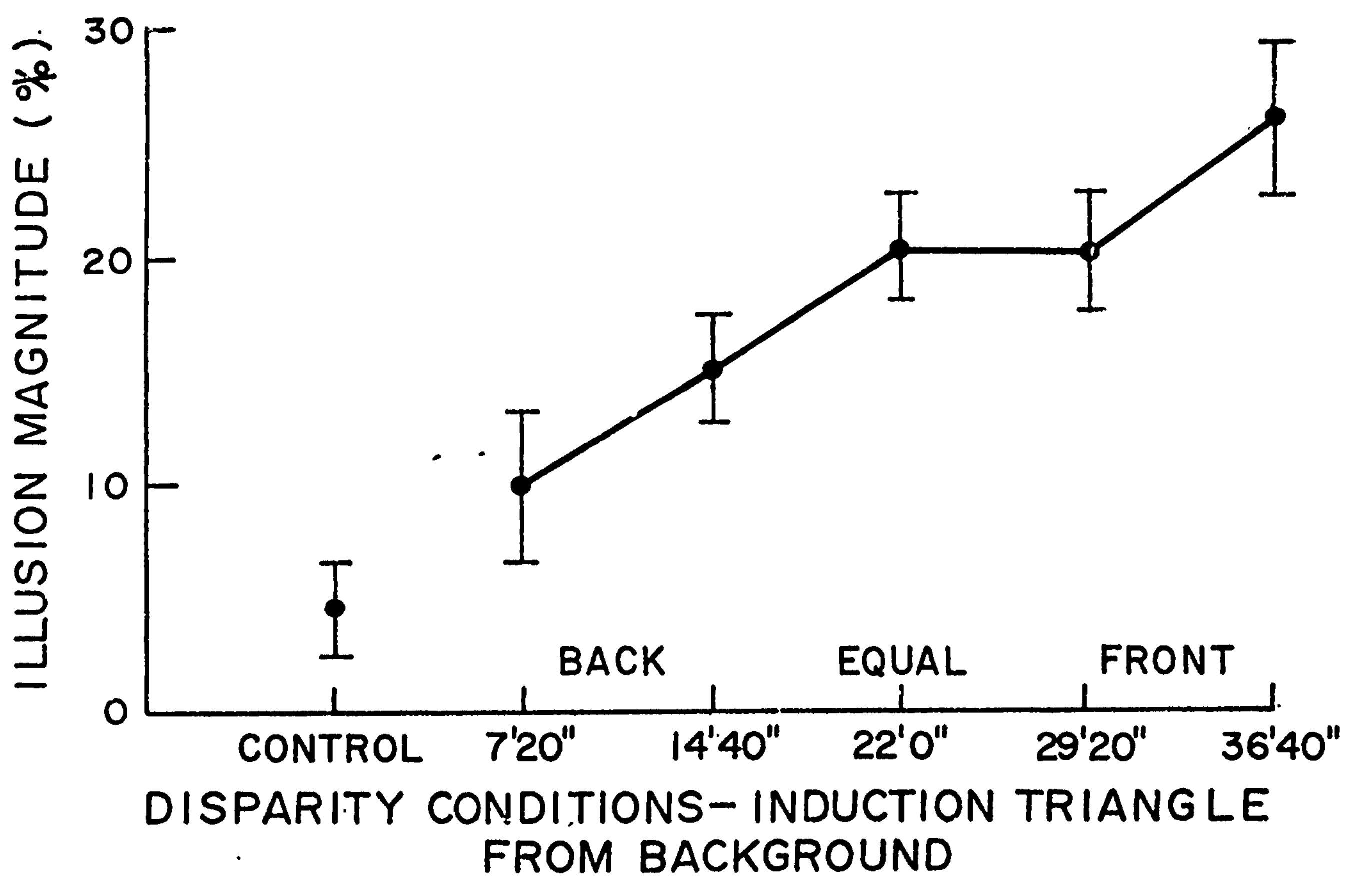

Figure 10. Illusion magnitude as a function of the separation in depth of test lines and inducing angle (from Fox & Patterson, 1981).

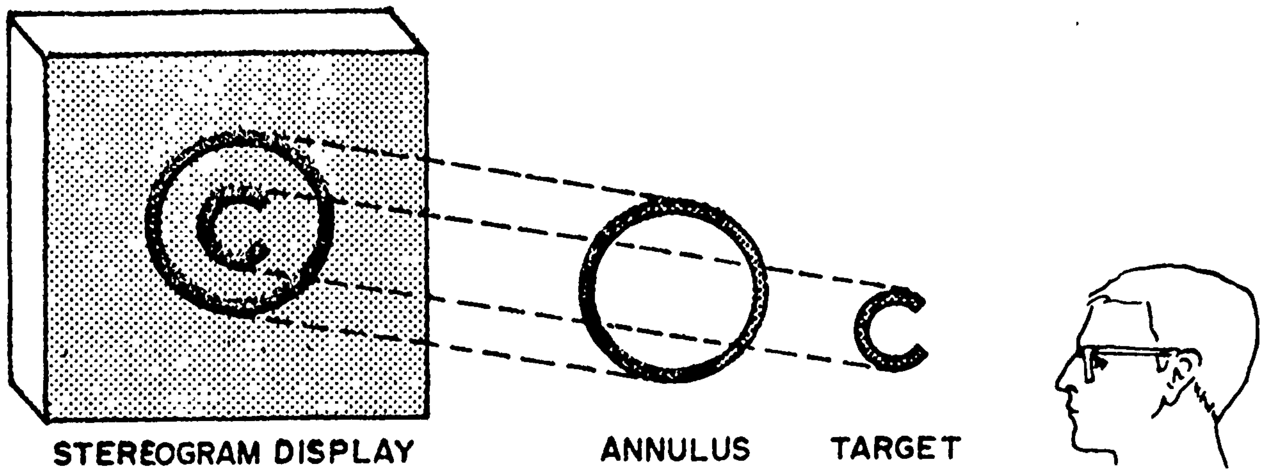

Figure 11. Stimulus arrangement showing relative depth of target (in front) and annulus.

which surrounds the target. The target remained in the same perceived depth position, while over the experimental conditions the annulus was located in front, back, and equal perceived depth positions with respect to the target. As in the previous experiment, compensation was made for perceived changes in the width of the annulus produced by size constancy. To assess interference, in one experiment, we obtained forced-choice recognition thresholds for the target as a function of perceived depth position of the annulus. The target was briefly presented, for durations on the order of 60-80 millsec, and observers were required to make forced-choice judgments about gap location, which varied randomly over trials. In a separate experiment, interference was assessed by presenting continuously the target and obtaining ratings of its clarity, as a function of the perceived depth position of the annulus.

The results for the recognition threshold experiment are given in Figure 12. The pre- and post-session control conditions refer to thresholds obtained in the absence of the annulus. "Equal" refers to the case where both annulus and test were in the same depth plane. The addition of the annulus reduced recognition performance significantly. The back depth positions refer to the case where the annulus is positioned in back of the test line. This produced a significant increase in performance relative to the equal depth condition. In the front depth positions, the annulus is in front of the target. This produced a significant decrease in performance. This same pattern of results was obtained when the target was continuously present and ratings of its clarity were made.

As Figure 12 indicates, while perceived depth position exerts a strong effect on lateral interference, the effect is asymmetrical. After observing this asymmetry in a number of experiments, we have dubbed it the "front effect". That is because the stimulus in front of its partner and closest to the observer seems to have a perceptual advantage.

What might be the origin of the front effect? We have speculated that it might represent an intrinsic preference of the visual system for the closer stimulus--not unlike the dominance of figure over ground. This preference would be involved whenever there are spatially adjacent stimuli, i.e., close to one another in the X and Y plane, which could compete for attention. It would be adaptive to give the greatest weight to the closest stimulus since it would demand the most immediate action.

Consistent with this view, interaction among stimuli declines with increasing separation in the X and Y planes. Further, this view would suggest that the asymmetry of the front effect would not occur if the interacting stimuli were not present simultaneously in the visual field.

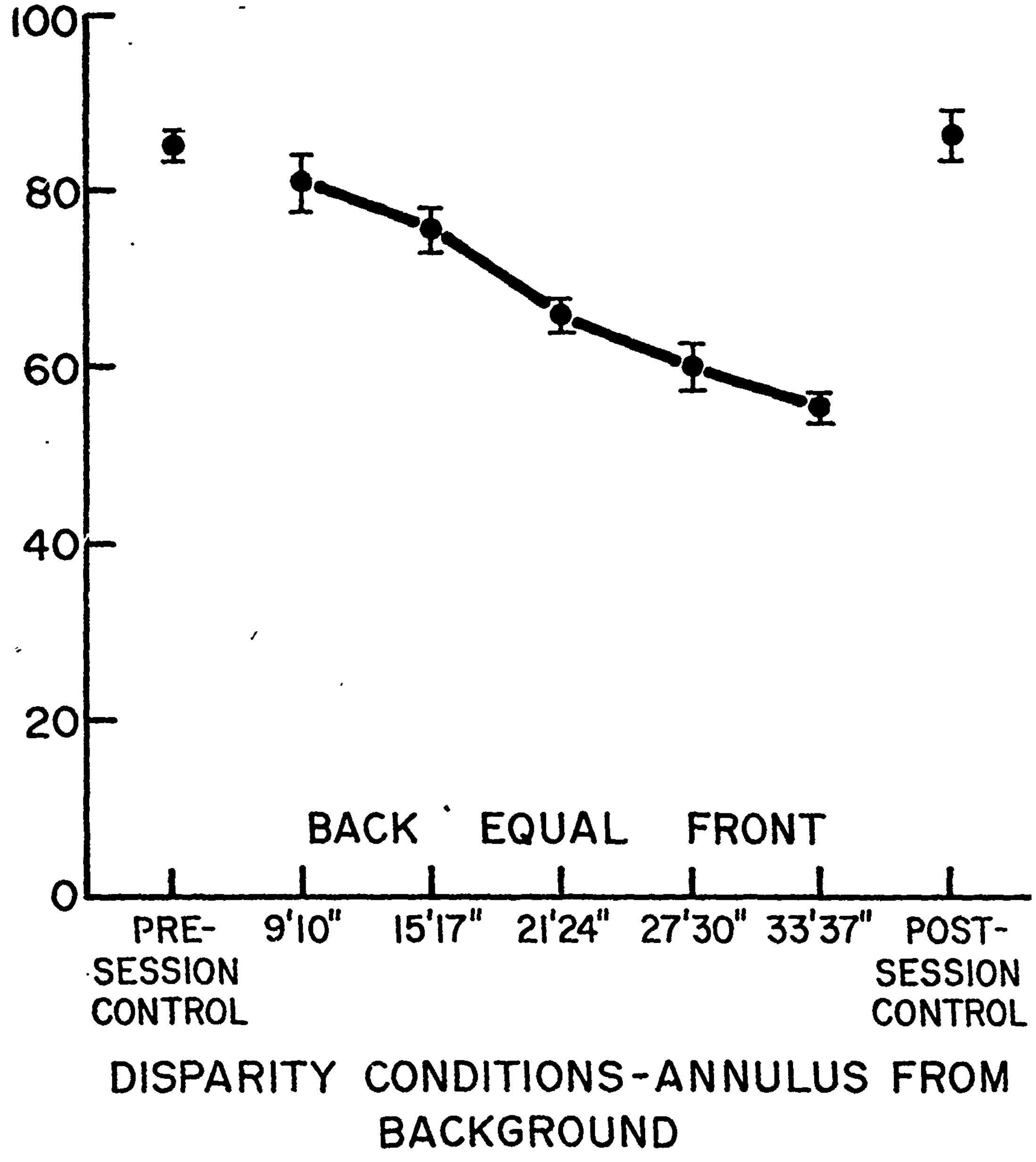

Figure 12. Recognition performance as a function of the separation in depth of the Landolt C test figure and annulus (from Fox & Patterson, 1981).

In the interactions considered so far, all stimulus elements have been present simultaneously in the field. There are, however, what might be termed successive interactive phenomena in which the aftereffects of stimulation by one stimulus alters the characteristics of the stimulus subsequently presented. Yet neither stimulus is simultaneously present. Therefore, during successive interaction the front effect should not occur.

To explore that possibility, we used the classic waterfall illusion, or motion aftereffect, as the successive interactive phenomenon (Fox, Patterson, & Lehmkuhle, 1982). The motion aftereffect occurs when one views for some seconds contours moving continuously in one direction. When that motion stops, the stopped contours now appear to move in the opposite direction. We used the stereogram generation system to generate an array of stereoscopic moving contours. Observers viewed the array for 90 seconds. Then the motion stopped and the stationary contours were viewed. The moving contours remained in one perceived depth position, and the stationary contours were placed in different perceived depth positions. A fixation stimulus in the depth plane of the moving contours kept the eyes aligned in the same depth plane for all experimental conditions. The main results are illustrated in Figure 13. The motion aftereffect was strongest when both test and inducing stimuli were in the same depth plane. But as the depth separation between test and inducing stimuli increased, the magnitude of the aftereffect decreased significantly. But in this instance, the decrease is symmetrical in that both front and back depth positions show an equivalent decrease. These data suggest, then, that the asymmetry of the front effect occurs only when adjacent stimuli are simultaneously present. Nevertheless, they do show that depth position per se plays a significant role in governing this interaction.

Indeed, the Z axis or depth position of stimuli seem to be an influential variable in determining the ease with which information can be processed in three-dimensional displays. This is, of course, not the only such variable.

I would like to briefly describe three other variables, or effects, that my colleagues and I are investigating that can also influence information processing. The first concerns an asymmetry in the perceptibility of stereoscopic stimuli between the top half and bottom half of the display that is brought about by the geometry of stereoscopic space. Consistent with a conjecture by Helmholtz, it has been recently demonstrated by Nakayama (1977) and by Cogan (1979) that the vertical horopter, which is that line or axis extending vertically in space where binocular targets are seen as single, is tilted away from the observer. Such a tilt can alter the relative perceptibility of stimuli falling in the upper and lower visual fields, depending upon the sign or depth direction of the stimuli. Indeed, Julesz, Breitmeyer, and Kropfl (1976) have reported such an asymmetry

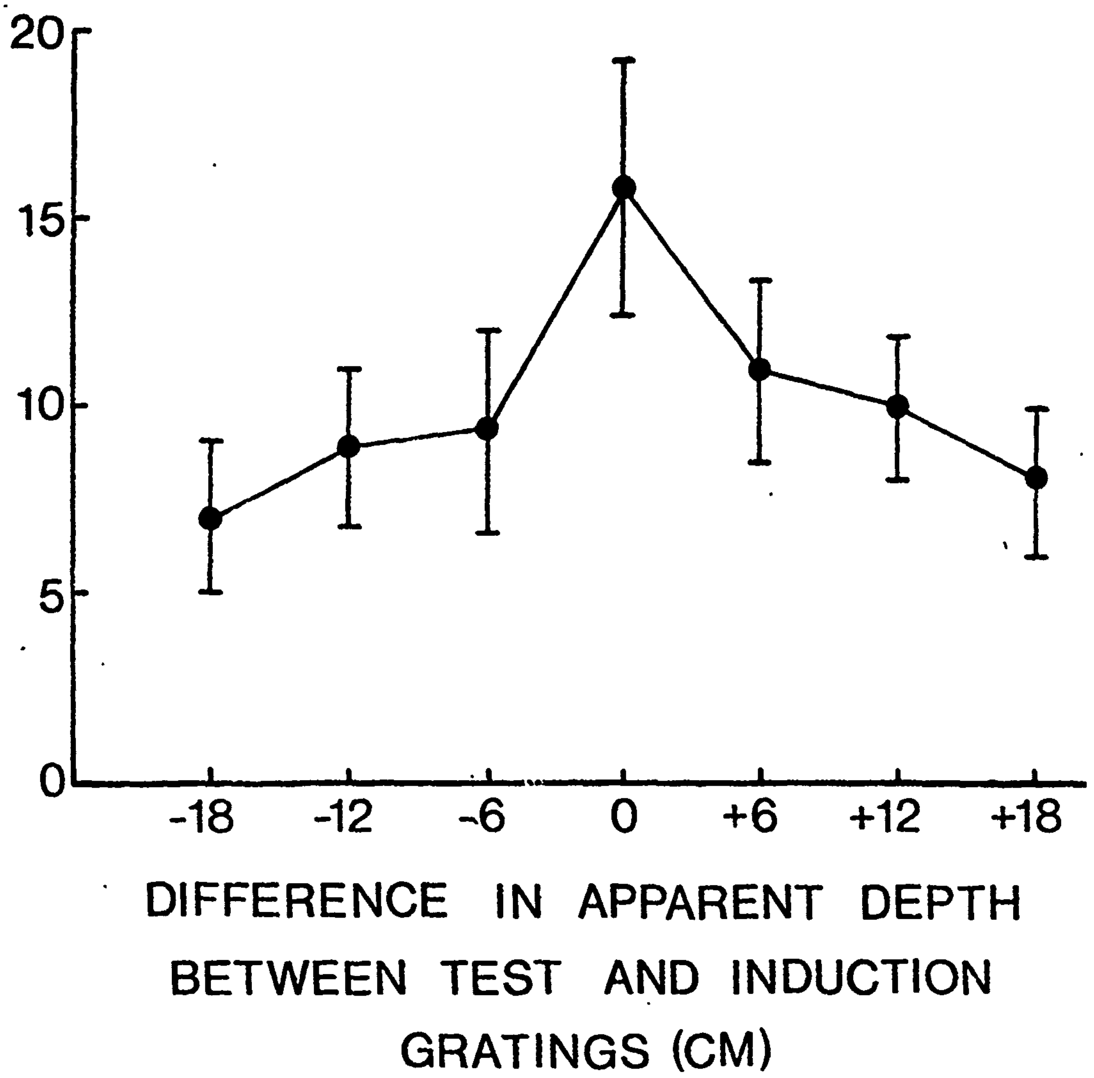

Figure 13. Aftereffect duration as a function of the separation in depth of the test and induction gratings (from Fox & Patterson, 1982).

and we have also found it. We have also found that the inherent asymmetry of stereoscopic space can be modified by physically tilting the display (Fox & Patterson, 1981c).

Second, the perceived size of stereoscopic stimuli change according to their perceived depth position. As I mentioned earlier, this is due to size constancy and is quite analogous to changes in the size of afterimages that occur as projection distance varies. We have some data which suggests that the apparent reduction in size of a stereoscopic form also reduces the discriminability of details embedded within it.

Finally, the perceived depth of any stereoscopic form, that is, how far it appears to stand out in depth in terms of some absolute metric such as centimeters, is only partially determined by retinal disparity. Due to depth constancy and related perceptual processes, perceived depth can be strongly influenced by the perceived distance between observer and display, and by the presence of other stimuli in the field that appear at different depth position.

Information on these phenomena is not complete, however, and research continues. As the data accrue they will contribute to the growing base of information that can be used to optimize the design of three-dimensional displays. Indeed, at present that data base is sufficient to support the formulation of at least some general recommendations about design. For instance, research on depth position would seem to speak directly to the question of where, in depth, critical signals should be located.

Yet one cautionary note should be registered with respect to the wholesale, literal application of that information. Almost all of the research on three-dimensional space and on stereoscopic depth perception is based on results obtained from a small number of elite observers who have received extensive training. Relatively little is known about the binocular visual capacities of the general population. It is known, however, that individuals vary widely in their visual capacities with respect to space perception, and that training can have considerable impact on these capacities. It would seem worthwhile to learn more about the abilities of the normal observer, so that we don't build displays that only the elitist can use.

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DISPLAY-CONTROL COMPATIBILITY IN 3-D DISPLAYS

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ABSTRACT

We explore some problems of display-control compatibility that confront the human operator of a true volumetric 3-D display. We measured the speed and accuracy with which an operator can make decisions about directions in displayed object-space (up, down, left, right..), when an object is presented in unpredictable orientations. Operators employ three strategies in this task. In order of decreasing speed and accuracy, they are: (1) a spatial strategy, which can be applied only when the display object and the control object are in the same orientation; (2) a relational strategy, in which the choice is made on the basis of the spatial relationship between the cued direction and the orientation cue provided in the icon; and (3) a rotational strategy, in which the operator mentally rotates his body position so as to make the orientation of the displayed object equivalent to that of the control object. In the third strategy, response times increase progressively with the amount of rotation required. In the final experiments, we show that use of the third strategy can be avoided by appropriate coding of the display icon.

Introduction

The purpose of the work described is to explore some of the difficulties human operators are likely to encounter in viewing and using abstract, volumetric, three-dimensional displays in practical applications. By an abstract display, we mean one in which the image is constructed, as opposed to reproduced veridically, e.g. a TV image. Stereoscopic 3-D displays, consisting of a pair of 2-D images, can be either abstract or veridical in this sense. Although there are several areas in which abstract 3-D displays offer obvious advantages, either in economy or clarity of the displayed data, it is not obvious how various types of data should best be displayed in order to minimize operator errors and confusion. Furthermore, although some of the relevant questions have been asked before, the answers provided by earlier research have almost invariably concerned flat, 2-dimensional displays, and their applicability to 3-D displays is not always obvious.

The approach taken in the initial experiments described here has been to study how the speed and accuracy of responses in a choice reaction task are degraded as the orientation of the stimulus image (presented in a true volumetric display) is varied relative to that of a fixed response array.

SpaceGraph

The display used in the studies is a true space-filling display called SpaceGraph. It differs from stereoscopic displays in that the image viewed by the observer is truly three-dimensional: the luminous points from which the image is composed actually exist at different depths from the observer. This contrasts with stereoscopic displays, which attempt to recreate with two flat displays what the observer's left and right eyes would see if they were looking at a three-dimensional image.

It is appropriate to describe briefly here how the display works, because this will make it easier to understand the experiments described below. [Since the display was demonstrated at the conference, anyone interested could view the display and thus experience at first hand the salience of the 3-D percept, which made detailed description unnecessary.] It is also important to stress, for readers of this report, that it is impossible to convey the immediacy and the conviction of the 3-D image except by viewing the live image: flat photographs of the images, such as appear in this paper as illustrations, are highly ambiguous with respect to depth, because they incorporate none of the cues that can be used to perceive depth.

Figure 1 shows a schematic view of the experimental apparatus, including SpaceGraph. The observer views the face of a CRT, reflected in a circular flexible mirror. The mirror is mounted on the front of a low-frequency loudspeaker. When the loudspeaker is excited by a 30 Hz

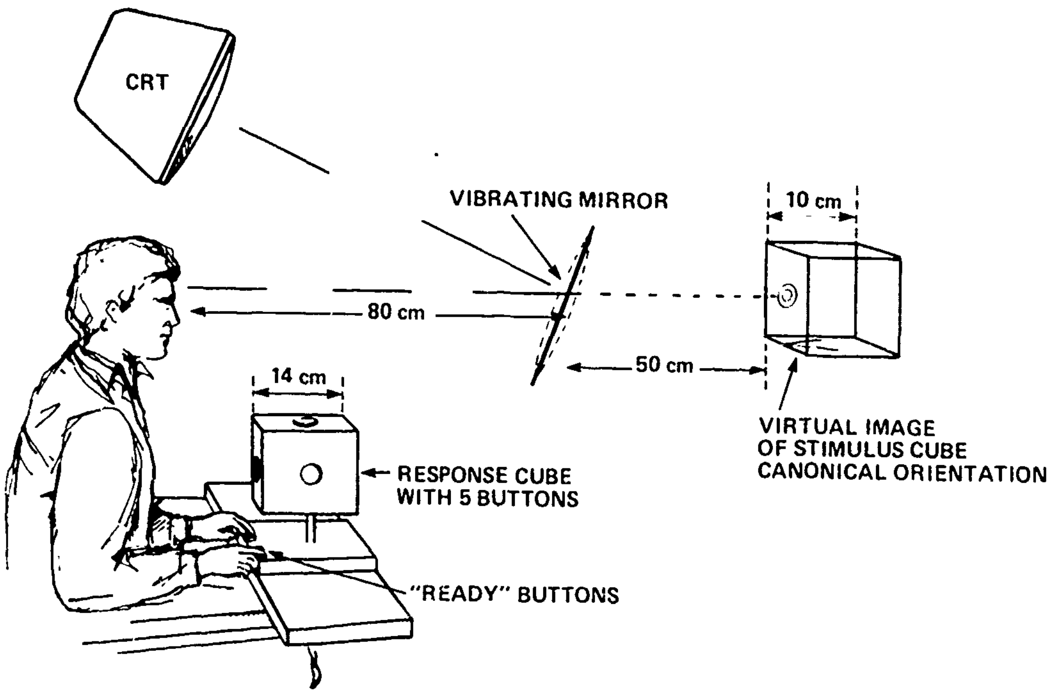

Figure 1: Sketch of observer with response box and SpaceGraph display. The observer viewed the CRT in a vibrating mirror, which generated a virtual image of the stimulus cube behind the mirror.

sine wave, the mirror flexes, approximately spherically, cycling successively through flat, concave, flat, and convex shapes 30 times per second. As it does so, the virtual image of the face of the CRT, which appears to the observer to be behind the mirror, sweeps cyclically through a depth of about 30 cm. If a point on the face of the CRT is momentarily brightened, at the same instant in every mirror cycle, the observer will see a luminous point suspended at a specific depth in the dark void behind the mirror. The depth of the point can be varied by changing the instant in the mirror cycle at which the CRT beam is unblanked. Thus the depth dimension is specified by the <u>time</u> in each mirror cycle that a point is displayed. The lateral and vertical positions of the point correspond to where on the face of the CRT the bright point is produced.

Images are built of points and linear arrays of points. In the prototype model on which we did our experiments, about 5000 points are available for drawing an image, corresponding to 500 cm of lines at 10 points per cm. This is sufficient for a fairly complex image.

Properties of SpaceGraph Images. SpaceGraph images have several properties that make them unique. First, since the points comprising the image are truly at different depths from the observer, the image shows perspective distortion identical with that of a physical 3-D object. The binocular parallax effect, and the movement parallax effects that occur when the observer moves his/her head, are not simulated, they are real. In this respect, the image has some of the properties of a hologram. The observer can move his head laterally or vertically, or rotate it about the line of sight, and indeed enhances the 3-D percept by doing so. The amount of movement possible is constrained only by the requirement that the viewer not lose sight of the CRT face reflected in the mirror.

Second, it is not possible to hide things in the image. Since the image consists of bright points floating in a dark void, displayed objects are transparent. It is not obvious whether transparency is an advantage or a disadvantage. If a large object is being maneuvered towards a smaller target, it may be helpful to be able to see the target through the interposed object being moved. On the other hand, if the background can be seen through the figure, this may make it more difficult to see the figure. These problems have not been studied previously, because volumetric displays, in which they become an issue, have not been available before SpaceGraph.

The third property (not unique to SpaceGraph) reflects the abstractness of the displayed data: all the data must be represented within the computer that drives the display. This means that very simple transformations can be applied to the data to change the viewpoint from which it is seen, or its scale, and these types of transformations can also be applied independently to any specified subset of the data as well. Thus, although the observer cannot walk around the displayed object to view it from behind, he can have the computer rotate the contents of the display, or part of it, thus achieving the same effect.

Experiments on Orientation

One of the primary application areas for displays such as SpaceGraph will be to present to an operator information about the relative position, orientation, and movement of vehicles under his control -- such as an integrated plan position indicator and vertical situation display for an Air Traffic Controller. On the basis of information gleaned from the display, the operator will make decisions relating to the control of the vehicles. It is important to know how quickly such information can be obtained from the display, what sorts of confusions are likely to occur, and how best to present the information so as to minimize control errors. The area we have chosen to address first concerns the identification of direction (up, down, left, right, etc.) for an object presented in an arbitrary orientation.

The control movements and stimulus images used are sketched in

Figure 1. The stimulus image consisted of an outline cube with sides about 12 cm long. An orientation cue was drawn on its bottom face, consisting of a capital letter V with its apex almost touching the front edge. One of the other five sides, chosen randomly on each trial of an experiment, was marked with a "stimulus button" consisting of two concentric circles. The observer's task was to decide which face was so marked.

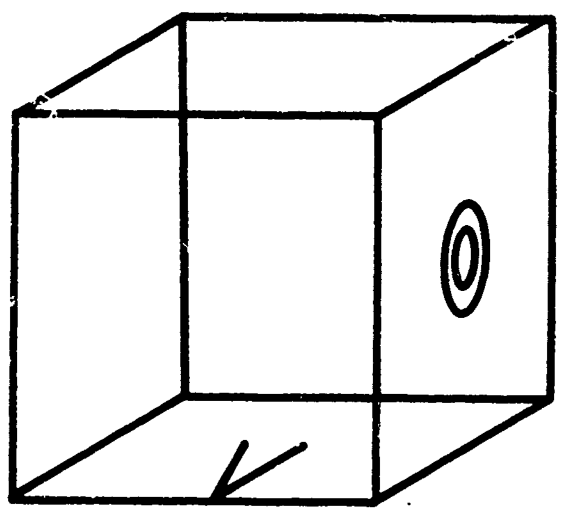

Figure 2: Schematic illustration of the appearance of the stimulus cube on a typical trial.

Figure 2 presents a schematic illustration of what the observer saw on a typical trial: the correct response here is the right button. The first four experiments studied the effects of varying the orientation in which the stimulus cube was presented. In each of the first three experiments, all the cube orientations seen by the observer were obtained by rotating the cube about one of its major axes: about the vertical Y-axis in Experiment 1, about the depth or Z-axis in Experiment 2, and about the lateral X-axis in Experiment 3. In Experiment 4, rotations about any one of the three axes occurred. Only the first experiment will be described in any detail here. A more extended description can be found in a recent report (Huggins & Getty, 1981).

Experiment 1

In the first experiment, the cube could appear in any one of 24 different orientations, which together comprise a complete rotation of the cube image about its vertical Y-axis in 15 degree steps, starting at a "canonical" orientation, which was rotated 10 degrees from the head-on orientation, to avoid a problem inherent in SpaceGraph with drawing lines strictly parallel to the virtual image of the CRT face.

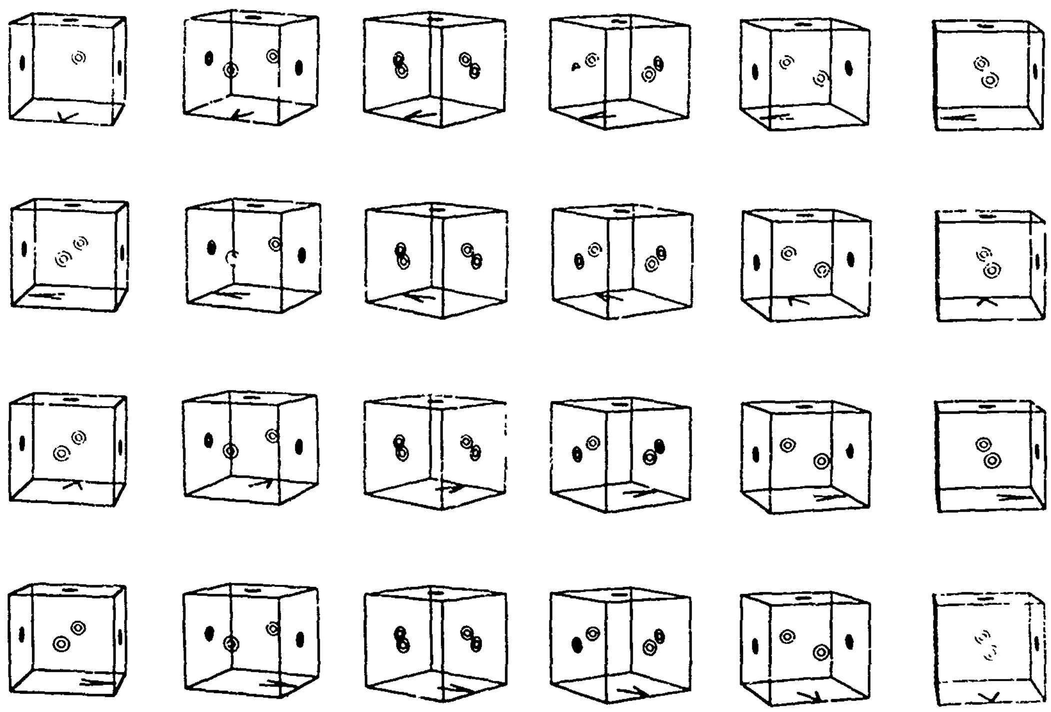

Figure 3: The 24 orientations of the stimulus cube used in Experiment 1, in which rotation was around the cube's vertical or Y-axis. All five stimulus "keys" are shown in each view, to save space. On each trial, the observer saw only one of the five stimulus keys.

On a single trial, the observer might see the cube in any of the 24 orientations, and any one of the five buttons might be showing, yielding a total of 120 distinct trials. The 24 orientations are shown in Figure 3, which is a paste-up made from photographs of the actual images. The images shown in the figure differ in two respects from those seen by the observers:

- All five buttons appear in each illustrated image, for economy, whereas observers never saw more than one button on a single trial.
- The photographs are flat, 2-D representations of the 3-D

images, and are quite hard to interpret in depth because they contain none of the usual cues to depth. When the corresponding 3-D images were presented on SpaceGraph, their depth was immediately and unambiguously apprehended.

Procedure. The same three observers[1] served in all experiments. To begin a trial, the observer pressed two "Ready" buttons, one with each hand. Two seconds later the stimulus cube appeared, with a button showing on one of its five faces excluding the bottom (which bore the V). The observer held down the ready buttons until he had decided which face of the stimulus cube was marked with a button, and then pressed the physical button on the corresponding face of the response cube as fast as possible, while minimizing errors. Each observer served for six sessions, with a maximum of two experimental sessions in a day, and a rest of at least 30 minutes between sessions. Each session lasted 30-40 minutes. The data from the first of the six sessions was discarded, to reduce familiarization effects.

Two times were recorded for each trial: the "reaction" time, from the presentation of the stimulus cube to the release of the ready key by the hand that then made the response, and the "movement" time, from the release of the ready key to the depression of the response key. After the subjects had become familiar with the procedure, movement times were virtually unaffected by the orientation in which the stimulus cube appeared, although they varied slightly for the five different responses. Error rates, also, were very low: about 2% of trials in the initial sessions, and falling to about 0.5% thereafter.

Results. Mean reaction times pooled across observers are plotted for each of the five responses as a function of stimulus cube orientation in Figure 4. In all the plots, the abscissa values represent rotations away from the head-on orientation. Thus, the canonical orientation is represented by the data points immediately to the right of the vertical dotted lines at zero rotation. Data points for up to one quarter revolution in each direction from the head-on

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[1]During the Symposium, the generality of 3-D display results obtained from small numbers of subjects was questioned. A range of figures was quoted, some quite low, for the proportion of the population who have stereopsis (but see (Newhouse & Uttal, 1982) for conflicting evidence). These may be valid objections. On the other hand, we have never heard of any viewer of the SpaceGraph display (of the hundreds who have seen it, including some who were known not to have stereopsis), who did not immediately and effortlessly perceive the image in 3-D. This should not be surprising, since the image itself was truly volumetric. However, since this evidence is only anecdotal and informal, it may be appropriate to support it more formally.

view are duplicated at the left and right sides of the plot, to make the symmetry of the minimum at zero rotation more apparent. To reduce the noise in the plotted data, we applied boxcar smoothing[2] to each point before plotting it.

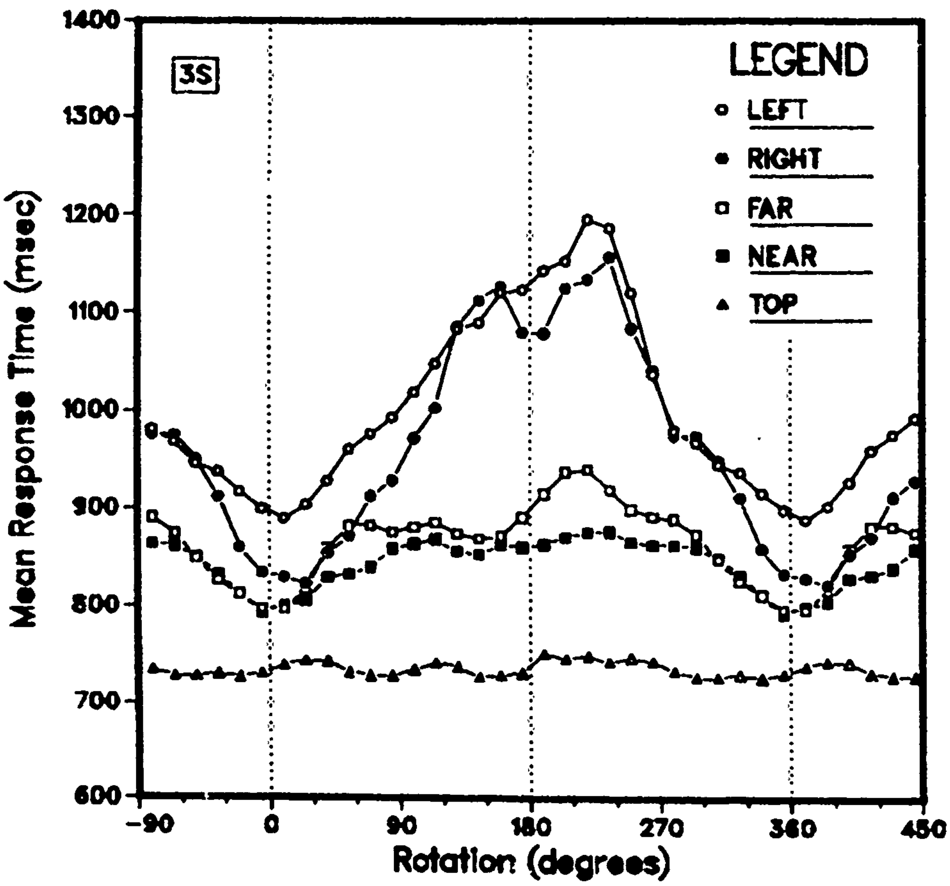

Figure 4: Mean reaction times in the Y-axis task for each of the five response buttons, as a function of the orientation of the stimulus cube.

The functions shown in Figure 4 fall into three groups: that for

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[2]In boxcar smoothing, a plotted point represents the average of the true data point for that abscissa value with the two immediately adjacent values.

the TOP responses; those for the NEAR and FAR responses; and those for the LEFT and RIGHT responses. (1) The function for the TOP responses is essentially flat at about 740 ms, showing that this reaction was not affected by the orientation of the stimulus cube. (2) The functions for the NEAR and FAR responses exhibit plateaus. The reaction time is lowest (about 800 ms) at the head-on orientation, and rises roughly linearly with rotation away from the head-on orientation until the plateau is reached for rotations more than about a quarter revolution from the head-on orientation. The plateau is at about 860 ms for the NEAR reaction and 890 ms for the FAR reaction. (3) The third group of functions, the LEFT and RIGHT responses, exhibit much more dramatic effects of orientation. The LEFT and RIGHT reactions, like the NEAR and FAR, show minima of about 830 and 890 ms, respectively, near to the head-on orientation. (The elevated minimum for the LEFT response is probably due to the different response expectancies for this response: for all three observers it was the only response made with the left hand.) For both the LEFT and RIGHT responses, reaction time increased rapidly and roughly linearly with rotation away from the head-on position, reaching ragged peaks of about 1150 ms at one-half revolution from the head-on orientation.

Discussion. We suggest the following explanations for the shapes of the three types of function. Observers use several different strategies for determining which face of the cube is marked. The strategies differ both in their efficiency, and in the conditions under which they can be applied. In conditions under which more than one strategy can be applied, observers apparently follow both strategies in parallel, and accept whichever result becomes available first.

Three main strategies were used, as follows:

The Spatial Strategy: Consider first the TOP stimulus key. With rotation about the vertical axis, neither the position within the retinal image nor the retinal shape of the TOP key changed as the orientation of the stimulus cube was altered. Furthermore, the spatial loci of all the other stimulus keys in the retinal image, in all orientations used in the experiment, were well separated from that of the TOP key. Therefore, observers were able to use a highly efficient and compatible spatial mapping strategy for selecting the TOP response, independent of cube orientation, and this resulted in the fast flat reaction time function.

The Rotational Strategy: As can be seen from Figure 3, the 24 stimulus cube orientations fall into four groups (corresponding to the four rows of the figure), with the same six images appearing in each group. The only difference between the four images in a single column of the figure lies in the different orientation of the V on the cube's bottom face. Thus, for the four keys on the vertical sides of the cube, the only information that specifies which face of the cube bears the stimulus key is the position of the V relative to the stimulus key. With respect to the V, the four stimulus keys fall into two classes, with the LEFT and RIGHT keys in one class and the NEAR and FAR keys in the other.

The V exhibits lateral symmetry, so although a stimulus key appearing to the side of the V can be quickly identified as either the LEFT or the RIGHT key, picking the correct one is not easy. The orientation of the key relative to the V must be determined in detail before the choice between them can be made. Subjective reports suggest that the observers imagined themselves looking from the apex of the V towards its points, and then deciding whether the displayed key was on the left or the right. This implies a sort of mental rotation, although it is the observer's body image that is rotated rather than the stimulus image. The possibility that observers perform some sort of mental rotation gains some credibility from the strong similarity between the shape of the reaction time functions for the LEFT and RIGHT responses and those obtained by (Cooper & Shepard, 1973) and by (Hintzman, O'Dell, & Arndt, 1981), in earlier studies of mental rotation. The slight minimum at one-half revolution from the head-on position for the RIGHT response was much more pronounced in the data of one observer, who reported that in these orientations he recognized the cube as being reversed, and chose his response on the basis of the spatial strategy, and then reversed it.

With regard to the NEAR and FAR stimulus keys, the same rotational strategy could be applied. That is, the observer could mentally rotate his/her body image into alignment with the V, and then make a NEAR or FAR response according to the near or far location of the stimulus key. This rotational strategy would account for the sloping skirts of the NEAR and FAR response functions for orientations near the head-on position. However, the flat plateaus observed in the NEAR and FAR functions over much of the range of orientations probably reflects the use of a second, non-rotational strategy.

The Relational Strategy: The V is asymmetric about its horizontal bisector, so the NEAR and FAR keys are uniquely coded by their relation to the V. The apex of the V always points towards the NEAR key, and the open end of the V always points towards the FAR key. The coding of the NEAR key is slightly more direct than that of the FAR key, because the apex of the V almost touches the NEAR face of the cube, whereas the points of the V do not reach far enough to touch the FAR face. Secondly, the V is easily interpreted symbolically as an arrow pointing towards the NEAR key, which has a high compatibility. This means that the NEAR and FAR responses can always be selected by a relational strategy: if the V is pointing towards the stimulus key, press the NEAR button; and if it is pointing away, press the FAR button. Use of this relational strategy would yield reaction times that are relatively independent of cube orientation and, except for orientations near the head-on position, apparently faster than those obtained with the rotational strategy. It is not clear whether the observer first processes cube orientation in order to choose between the rotational and the relational strategies, or pursues both strategies in parallel

(Woods, 1974). In the latter case, the response would be determined by whichever strategy first produced a decision, and the observed composite reaction time functions would reflect the fact that each strategy wins over only part of the cube's rotational cycle.

In either case, the utility of relational strategies obviously depends on the cue used to mark the orientation of the cube. In the present experiment, the symbol chosen displayed left-right symmetry but not top-bottom symmetry. Furthermore, it was placed on the bottom face of the cube, symmetrically between the left and right faces, but asymmetrically between the front and back faces (that is, the V was placed between the center of the bottom face and its NEAR edge). Thus two distinct relational strategies could be used for the NEAR and FAR responses, one based on the position of the V and the other on its shape: the V appeared on the NEAR half of the bottom face, and its apex also pointed towards the NEAR face.

A relational strategy could have been used to select the TOP response, since the TOP key always appeared on the face opposite the V. This strategy would have depended only on the _position_ of the V, and not on its shape. However, this strategy was probably not used because the spatial strategy consistently gave faster decisions. No relational strategy was possible for the LEFT or RIGHT responses, because the LEFT and RIGHT stimulus keys were placed symmetrically with respect to both the position and the shape of the V. Had a different letter been chosen, such as an E or an F, or had the cue been placed left-right asymmetrically, then a relational strategy could have been used for these responses also. On the other hand, the choice of an E, with its up-down symmetry, would have prevented a relational strategy for the NEAR and FAR responses based on the _shape_ of the letter, although one based on its position would still have been available.

Experiment 2

The second and third experiments were virtually identical with the first, except that the stimulus cube was rotated about the Z, or depth axis, in Experiment 2, and about the X, or lateral axis, in Experiment 3.

The hypotheses proposed above to explain the results obtained with rotation about the Y-axis make the following predictions when the cube is rotated about its Z-axis instead. Since the axis of rotation now passes through the NEAR and FAR stimulus keys, instead of the TOP key, these two responses should show the fast, flat response time functions associated with use of the spatial strategy, whereas the TOP function should now show a plateau, appropriate to the use of the relational strategy. The LEFT and RIGHT functions should be similar to those obtained in Experiment 1, since the same constraints apply as before. That is, the spatial strategy cannot be applied to the LEFT and RIGHT keys, since the locations of these keys vary with cube orientation, and the relational strategy is not effective either, because the lateral symmetry of the V complicates the choice between them. The rotational strategy is the only one remaining.

A second purpose of Experiments 2 and 3 was to compare the difficulty of rotation about each of the three axes: people have much more experience with rotations about the vertical, Y-axis in everyday life, and therefore one might expect rotation about this axis to be easiest. The procedure exactly repeated that in Experiment 1, except for the changed stimulus images. These are shown in Figure 5.

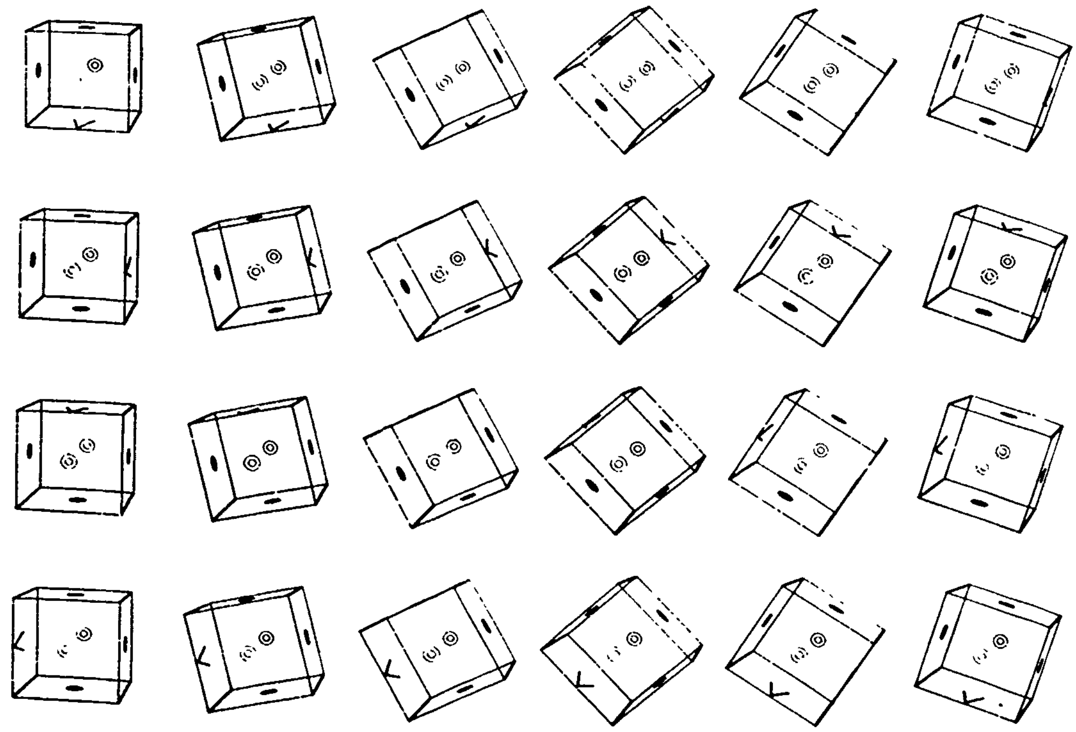

Figure 5: The 24 orientations of the stimulus cube used in the Z-axis task. On each trial, the observer saw only one of the five stimulus keys.

Results. Pooled reaction times are plotted for each response in Figure 6. The function for the TOP response is roughly plateau-shaped, as predicted, but there is an additional minimum at one half revolution from the head-on orientation, giving the function an M-shape. The functions for the LEFT and RIGHT responses are sharply peaked, and are very similar in shape to those of Experiment 1, again as predicted. The functions for the NEAR and FAR responses are plateau-shaped, and are very similar both in overall shape and level to the corresponding functions in Experiment 1 (Figure 4). The prediction for these

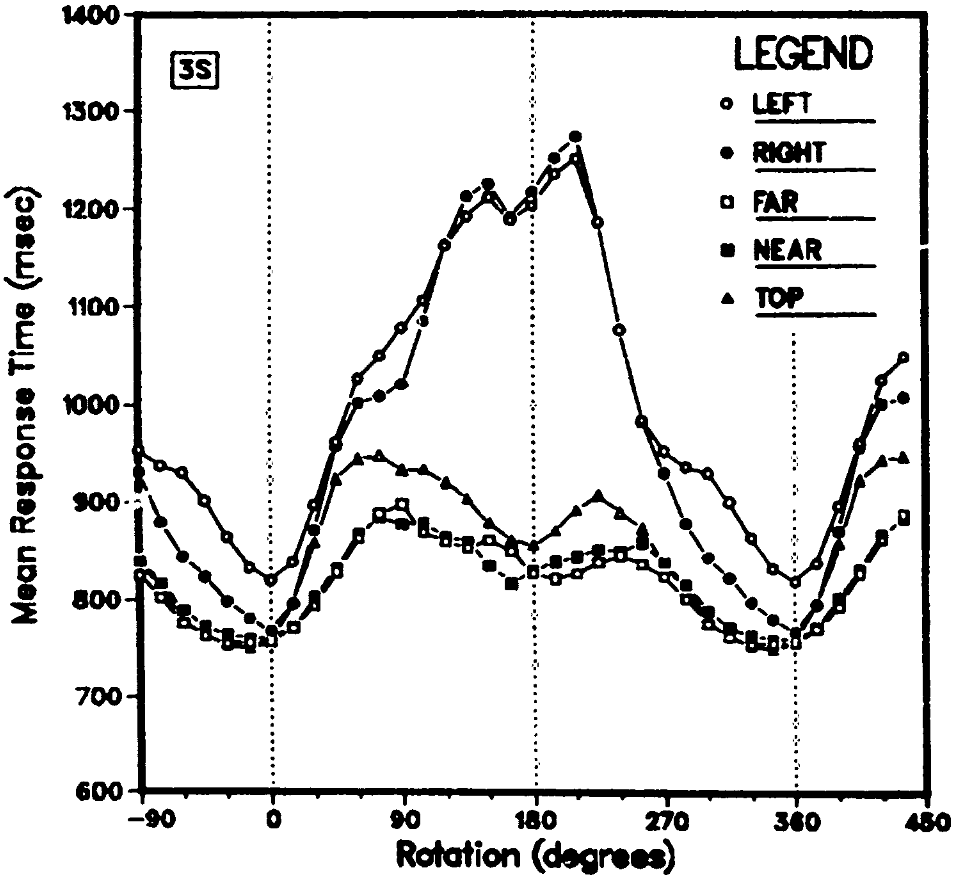

Figure 6: Mean decision times in the Z-axis task for each of the five response buttons, as a function of the orientation of the stimulus cube.

functions was not fulfilled: a fast flat function appropriate to the spatial strategy was expected.

Discussion. When the stimulus cube is rotated about its depth axis, the positions of the NEAR and FAR stimulus keys remain invariant within the image. However, observers were apparently not able to use a spatial coding strategy for the NEAR and FAR keys, because, if they had, the reaction time functions would have been flat and fast like that for the TOP response in Experiment 1.

Why could a spatial strategy not be used for the NEAR and FAR responses in the present experiment? One possibility is that the spatial strategy of Experiment 1 did not require the image to be interpreted as a 3-D object, but could be applied directly to the raw 2-D retinal image. Thus, however immediate, automatic, and salient the 3-D percept was, the TOP response in Experiment 1 could be made on the basis of a patch of light at a particular place in the retinal image. Two aspects of the image may have discouraged or prevented use of the spatial strategy in Experiment 2. First, the NEAR and FAR stimulus keys appear very close to each other within the 2-D retinal image (see Figure 5), so application of the spatial strategy to the retinal image requires a finer discrimination than was necessary to identify the TOP key in Experiment 1. Secondly, the main spatial separation between the NEAR and FAR stimulus keys was in the depth dimension, and apprehending this separation therefore required that the image be perceived in 3-D before the difference in depth between the NEAR and FAR keys became available to support response selection.

The similarity of the NEAR and FAR functions in Figure 6 to those in Figure 4 suggests that observers used the same strategy for these keys in the two experiments, and we argued above that this must be a relational strategy that relied on the V pointing towards the NEAR key and away from the FAR key. As before, we attribute the sloping skirts of both functions to the use of a rotational strategy near the head-on orientation. (Although the NEAR and FAR keys remain fixed in position, the position of the bottom face, bearing the V, varies as the cube is rotated about its Z-axis.) Thus, for small rotations of the cube, it appears to be faster to rotate one's body image mentally until the face with the V appears on the bottom of the cube, and then respond spatially, while for larger rotations it is faster to determine the relationship of the stimulus key to the V without mental rotation.

The plateau shape of the TOP function suggests that the TOP key also was identified by means of a relational strategy, except in orientations close to the upright, when a combination of a small rotation and the spatial strategy was used. The dip in the TOP function at one half revolution suggests that the spatial strategy may have been applied here also, as well as in the upright orientation. Provided that either the key or the V was on the uppermost face, and the other was on the lower face, the TOP response could be correctly chosen without deciding which was which.

The shape of the LEFT and RIGHT functions suggest that the same difficulties were encountered in choosing these responses as in Experiment 1. Because of the lateral symmetry of the V, a relational strategy was not effective, and the rotational strategy was adopted by default. As before, reaction times increased dramatically with increasing rotation away from the head-on orientation.

Experiment 3

In Experiment 3, the cube was rotated about its lateral X-axis. The spatial strategy now applies to the LEFT and RIGHT responses, since the position of these keys remains fixed in the image. On the other hand, the TOP, NEAR, and FAR keys require the use of a relational strategy, since each appears in an unambiguous spatial relationship to the V. Accordingly, the reaction time functions should be plateaus with sloping skirts near to the head-on orientation, as found earlier with the relational strategy. The procedure exactly repeated the earlier experiments, except for the stimulus images, which are shown in Figure 7.

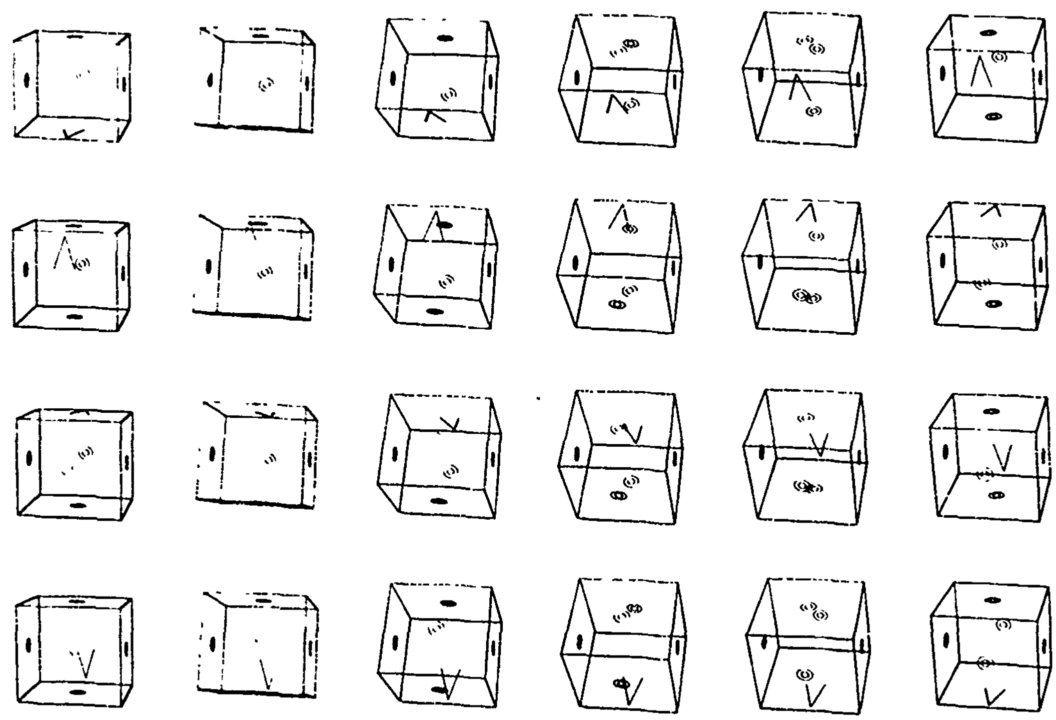

Figure 7: The 24 orientations of the stimulus cube used in the X-axis task. On each trial, the observer saw only one of the five stimulus keys.

<u>Results</u>. The pooled reaction time functions for each of the responses are plotted in Figure 8. The functions for the LEFT and RIGHT responses are fast and almost flat, showing that rotation of the cube image about its lateral axis did not have any effect on the time taken to identify these faces. The NEAR and FAR response functions have pronounced peaks at about one half revolution from the head-on orientation, where the reaction times are about 1100 ms (NEAR) and 1200 ms (FAR). In each function, there are subsidiary minima at about one quarter and three quarters of a revolution from the canonical orientation. The function for the TOP response is similar to those for the NEAR and FAR responses, except that, instead of a peak at one half

revolution from the canonical orientation, there is a minimum. This gives the function an oscillatory character, with pronounced minima at the four quarter-revolution orientations, and pronounced maxima at intervening orientations.

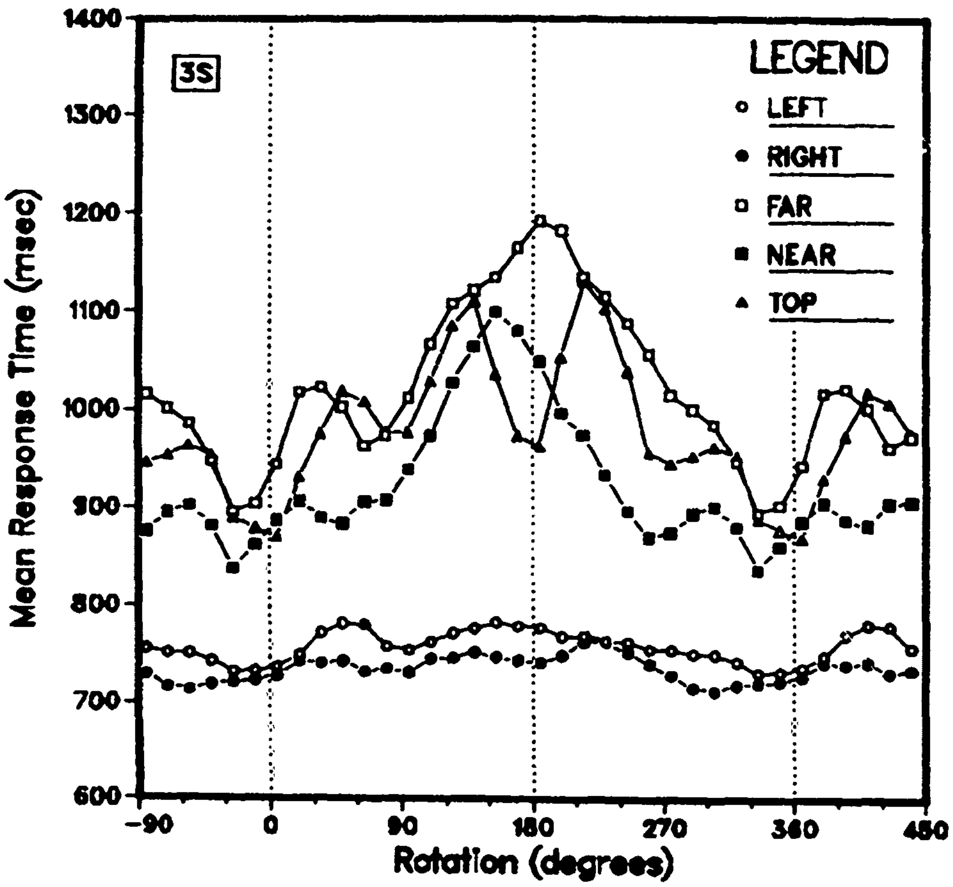

Figure 8: Mean decision times in the X-axis task for each of the five response buttons, as a function of the orientation of the stimulus cube.

Discussion. When the cube was rotated about its lateral axis, all the conditions were met for the retinal spatial strategy to apply successfully to the LEFT and RIGHT responses. The flatness of the reaction time functions for these two responses, and the similarity of these times (720 ms and 750 ms respectively) to the times for the TOP response in Experiment 1 (730 ms), support the conclusion that the spatial strategy was in fact used.

The TOP reaction time function passes through four distinct maxima and minima as the cube image completes a single revolution about its lateral axis. The minima correspond to images in which the cube is seen with its edges aligned vertically and horizontally. A sinusoidal shape similar to the shape of the TOP function is obtained by plotting the distance between the TOP key and its nearest neighbor in the retinal image. Several details in the shapes of the functions may be explainable in terms of such properties of the images involved, but the evidence is insufficient to warrant firm conclusions.

The functions for the NEAR and FAR responses are, with minor exceptions, very similar to those for the LEFT and RIGHT responses in Experiment 1 (Figure 4), which were associated with the rotational strategy. This conflicts with our expectations for the NEAR and FAR responses in the present experiment. We expected the relational strategy to be applied, since the NEAR stimulus key is always "pointed to" by the V, and the FAR key is "pointed away from." But the functions obtained are not the plateau-shaped functions we associated with use of the relational strategy. Rather, they repeat the peak-shaped functions found in Experiment 1 for the LEFT and RIGHT responses, which we ascribed to use of a rotational strategy. Comparison of Figures 3 and 7 suggests that the "pointing" aspect of the V was much easier to apprehend when the cube was rotated about its vertical axis (Figure 3) than when it was rotated about its lateral axis (Figure 7). In the former case, the V always lay in a true horizontal plane near the bottom of the image, whereas its position was much less predictable in the latter. This may have made it much harder to apply a relational strategy in the present experiment than in Experiment 1, leading to adoption of a rotational strategy instead.

Experiment 4

In typical real-life applications of a display such as SpaceGraph, objects will likely appear in arbitrary orientations. Users of the display will therefore not be able, in general, to use strategies that capitalize on properties of a particular set of orientations, such as the fact that all orientations represent rotation about a single axis. In two of the foregoing experiments, a direct spatial encoding strategy could be used to select one or two of the available responses. In the wider context, the spatial strategy will be less effective. Its use will be appropriate in only some orientations, and its applicability must be determined before it can be applied.

Procedure. Experiment 4 was similar to the earlier experiments, except that the stimulus ensemble included rotations about each of the three axes. Eight stimulus cube orientations were selected from each of the three earlier experiments, representing between them a complete rotation of the cube image about each of the three major axes of the cube by equal increments of 45 degrees. The 24 images correspond to the first and fourth columns of images that appeared in Figures 3, 5, and 7. Of these 24 images, only the 22 different ones were used in the experiment: the repetitions of the canonical orientation were omitted. The procedure was again identical to that of the first three experiments, except that there were only 110 different stimuli (5 stimulus keys x 22 orientations) in each block instead of 120.

Results. The reaction time functions for the 15 combinations of the 5 responses and the three rotation axes are shown in Figure 9. The rows of panels correspond to the 5 responses, and the columns show the effects of rotations about the Y, Z, and X axes. Two functions appear in each panel. The dashed line represents the reaction times obtained in the present experiment, with "mixed" trials (rotation about any one of the three axes), and the solid line represents the reaction times obtained for the identical stimuli in Experiment 1, 2, or 3, with "pure" trials (rotation about only one of the three axes, a different one in each experiment). Each panel is labeled with a letter to simplify reference. Boxcar averaging was not applied to the data points in Figure 9.

Three different relationships occur between the results obtained with pure rotations (solid functions) and with mixed rotations (dashed functions). In four panels (B, K, L, M) there are only minor differences between the two functions; and in six more (C, D, E, F, I, J) there are only minor differences except at the half-revolution orientations, where the mixed functions show a marked peak. In the remaining five panels (A, G, H, N, O), the reaction times are longer in the mixed condition (dashed function) than in the pure condition (solid function) at all orientations, the differences ranging from 50-100 ms at the canonical orientation to over a second at the reversed orientations. Of these latter five panels, three (A, N, and O) correspond to conditions in which the spatial strategy was applied in Experiments 1 and 3. The other two (G and H) correspond to conditions in which the spatial strategy was expected to apply in Experiment 2. Thus, the reaction times obtained in the present experiment were quite similar to those obtained in the earlier experiments, except that (a) the peaks at the reversed orientations were much more pronounced, and (b) no fast, flat reaction time functions were obtained like those associated with the spatial strategy.

Discussion. Consider first the pairs of functions for the LEFT and RIGHT responses shown in the six lower panels of Figure 9. There is a striking similarity among the skirts of 10 of the 12 functions, the exceptions being the solid functions in panels N and O where the spatial strategy was applied. There are two aspects to the similarity. First, setting aside for the moment the data points at the half-revolution orientations, in panels D, E, I, and J each solid function is similar to the dotted function in the same panel. This suggests that observers used the same strategy in the pure- and mixed-axis conditions for the LEFT and RIGHT responses. Second, (a) the solid functions in these same panels are very similar to each other, and (b) the mixed functions in the same panels (and also those in panels N and O) are also very similar to each other, again excluding the data

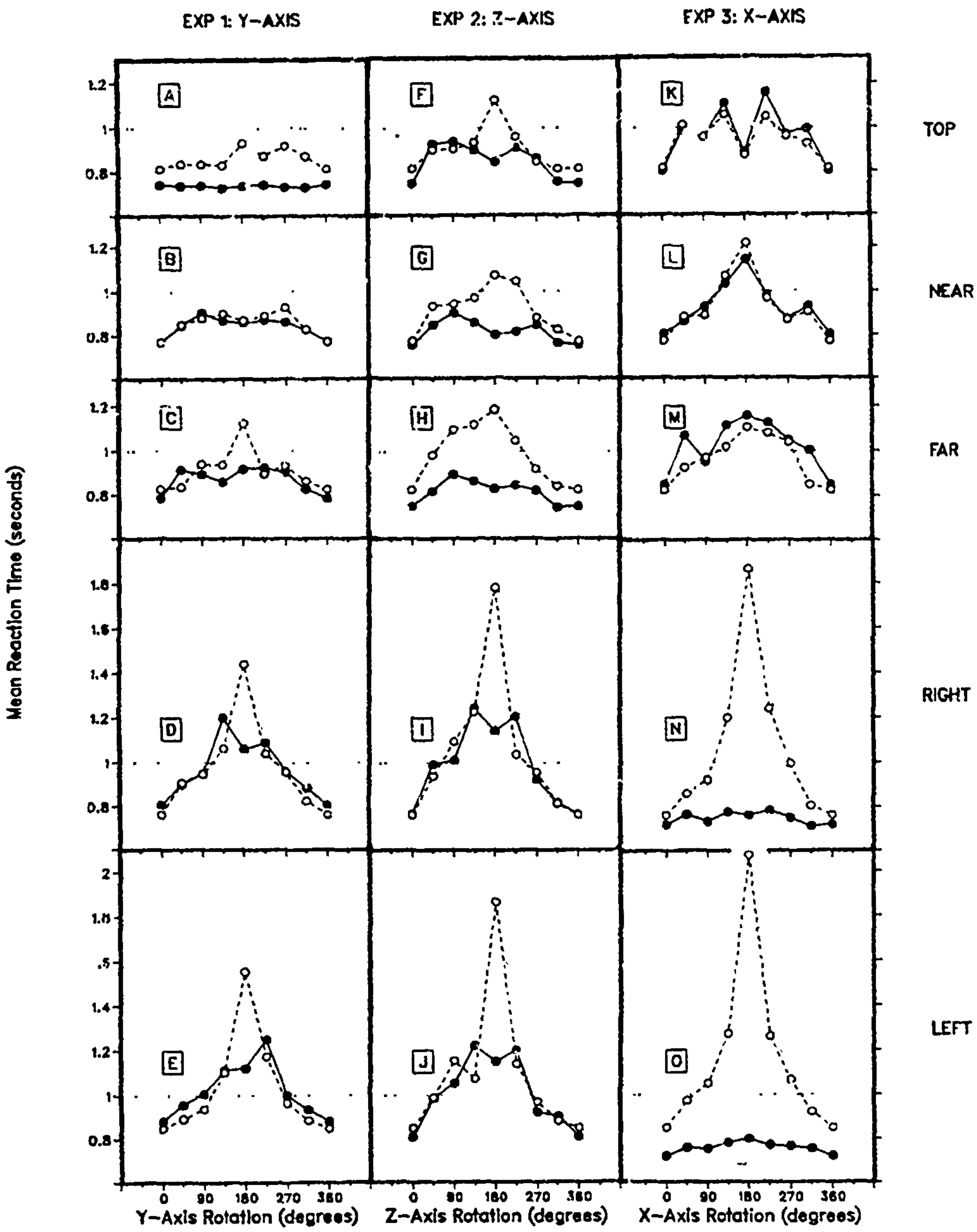

Figure 9: Mean decision times in the XYZ-task (dashed lines joining open data points) are compared with mean decision times obtained on the same stimuli in Experiment 1, 2, or 3 (solid lines joining filled data points) as a function of orientation. Functions are plotted separately for each of the five responses (rows), and for rotations about the Y, Z, and X axes (columns).

points at the peaks. This suggests that the amount of rotation was more important than which axis it was about. These observations lead to a striking conclusion: that the basic strategy for determining the LEFT and RIGHT responses was similar in all the experiments, except in Experiment 2, where the spatial strategy could be used because the rotational axis passed through the LEFT and RIGHT keys. Because of the peaked shape of all of these functions, we believe the common strategy was rotational. The effect on reaction times of rotating the cube away from the canonical orientation was very similar for all three of the rotation axes, both for the pure and the mixed conditions This result was quite unexpected.

The only orientations where major differences occurred between the present experiment and the earlier pure-axis rotations were those one half revolution away from the canonical orientation. Here, the reaction times for the LEFT and RIGHT responses were very much longer than before. There is an obvious explanation for the peaks in the Z-axis and the X-axis functions. The two images involved were the only two in which the cube image was inverted, with the V on its uppermost face. When the cube was inverted by rotation around the Z-axis, the apex of the V pointed <u>towards</u> the observer and the stimulus key on the left of the image required a RIGHT response. When the cube was inverted by rotation about the X-axis, on the other hand, the V pointed away from the observer and the stimulus key on the left of the image required a LEFT response. Furthermore, this relationship between the direction of the V and the reversal of the spatial coding was the opposite of that applying when the cube was rotated about the Y-axis. That is, when the cube was inverted, the spatial strategy could be applied directly if the V pointed away from the observer. But when the cube was upright, with the V on the under face, the spatial strategy had to be <u>reversed</u> if the V pointed away from the observer. The fact that peaks occurred also in the mixed functions in panels D and E suggests that observers were influenced by this inconsistency. Similar factors may account for the much smaller peaks that occurred in the mixed functions in panels C and F. The observer could resolve this quandary by rotating the cube mentally about the Z- or the X-axis, whichever was appropriate. The observers reported great uncertainty in choosing which axis to rotate about. This indecision, possibly accompanied by unsuccessful initial rotations about the wrong axis, may well account for the considerably lengthened reaction times to the half-rotated cubes.

<u>Experiments on Cue Ambiguity</u>

The foregoing experiments involved measuring how long an observer took to identify the marked face of the stimulus cube, using an orientation cue whose shape and location exhibited symmetries with respect to one pair of responses, but not to another. The hypotheses proposed to explain the experimental findings involve strategies that depend on these symmetries. The hypotheses can be simply tested by altering the relations between the symmetries and the pairs of responses.

Thus, the aim of Experiments 5 and 6 was to find out whether appropriate coding of the stimulus objects within the display can significantly reduce the substantial display-control incompatibility found in the earlier studies.

Experiment 5

In Experiment 5, the orientation cue was again a left-right symmetric capital letter drawn on the bottom face of the cube. The letter was an A, rather than a V, to minimize possible interference from the earlier tasks while retaining the symmetry of the V. Second, the A appeared with its base almost touching the left edge rather than the near edge of the cube image. The shape and the position of this orientation cue are asymmetric with respect to the LEFT and RIGHT stimulus keys, but symmetric with respect to the NEAR and FAR keys, reversing the relationships of Experiment 1. Figure 10 is a schematic illustration of the stimulus cube as it might appear on a typical trial.

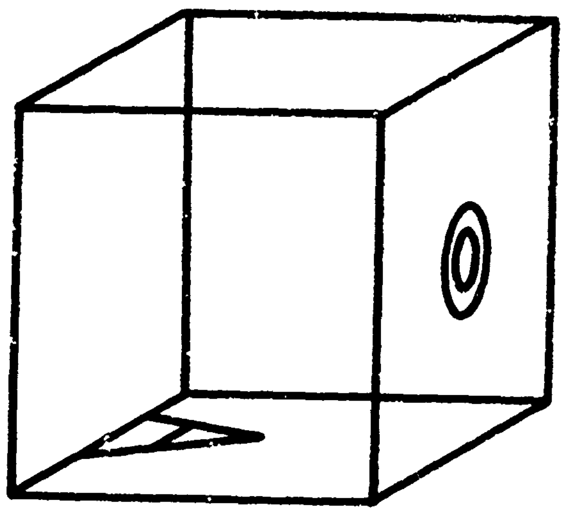

Figure 10: Schematic diagram of the stimulus cube for a typical trial in Experiment 5, which was identical with Experiment 1 except that both the shape and the orientation of the orientation cue was changed. The new orientation cue was a capital letter A with its base on the left edge of the bottom face.

The procedure used was identical to that in Experiment 1: in fact, exactly the same stimulus sequence was followed, to maximize the comparability of the results. The cube image appeared in 24 orientations constituting a complete revolution around the cube's vertical Y-axis, and the same three observers served.

Results and Discussion. The results are presented in Figure 11.

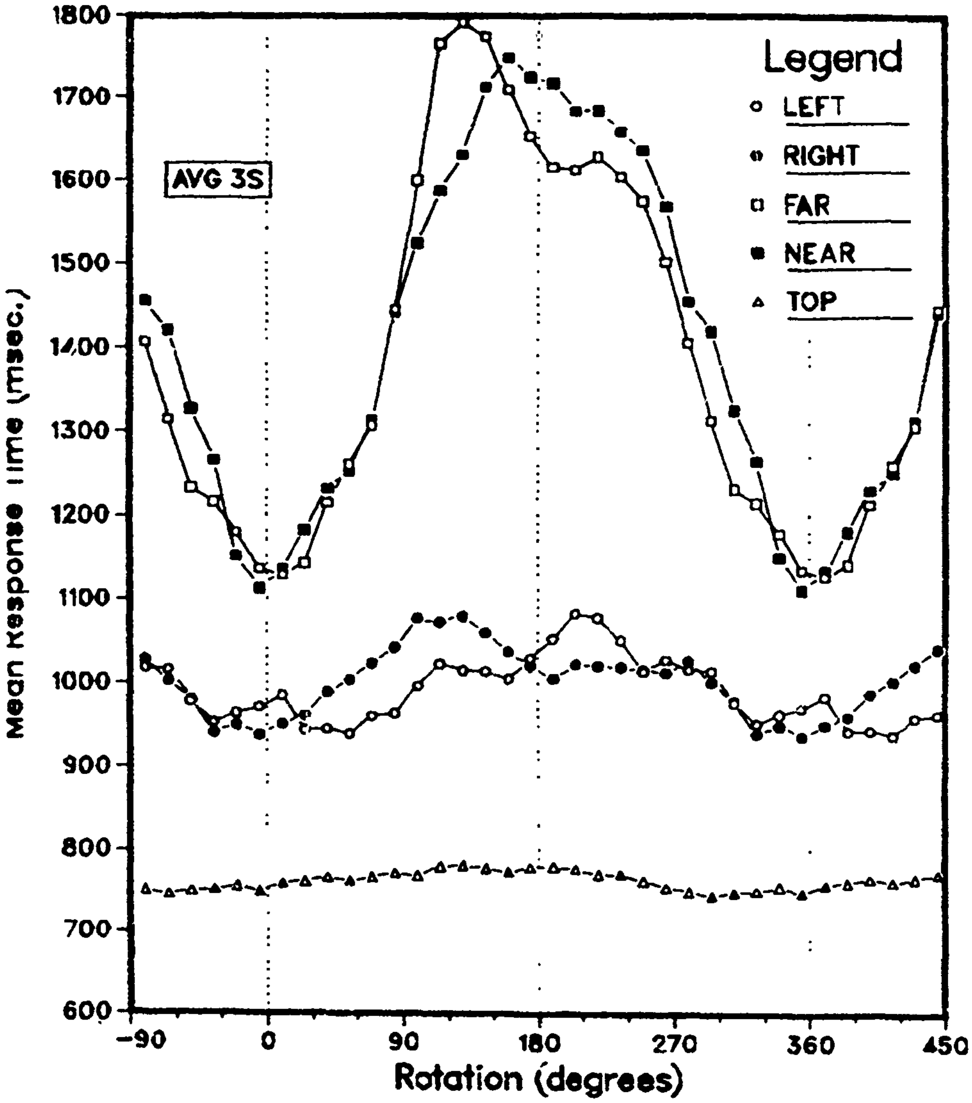

Figure 11: Mean reaction times in the Y-axis task for each of the five response buttons, as a function of the orientation of the stimulus cube, using a capital A on the left edge of the bottom face as orientation cue.

The reaction times for each of the five responses are plotted as a function of the orientation of the stimulus cube, expressed as a rotation away from the head-on orientation. As predicted, the asymmetric position and shape of the A made it easy to distinguish between LEFT and RIGHT stimulus keys, since the foot of the A almost touched the LEFT face of the stimulus cube, and its apex pointed towards the RIGHT face. Observers were able to use a relational strategy to distinguish between these responses, and the LEFT and RIGHT reaction time functions show plateaus similar to those in the NEAR and FAR functions in Experiment 1. On the other hand, the NEAR and FAR stimulus keys could not be distinguished on the basis of the asymmetry of either the position or the shape of the A. Observers were forced to adopt a rotational strategy, which resulted in reaction time functions that were sharply peaked at the half-rotation orientations. Thus changing the orientation cue from a V on the bottom face pointing at the cube's front edge into an A on the bottom face standing on the cube's left edge reversed the types of function associated with the LEFT/RIGHT and the NEAR/FAR pairs of responses.

Experiment 6

Experiment 6 also involved only a change in the orientation cue: this time, the cue was made asymmetric in shape relative to both pairs of responses. A modified letter V was used, drawn on the bottom face of the stimulus cube with its apex almost touching the front edge as before, but with an additional cross-bar or serif added at the top and to the left of the left arm of the V, as illustrated schematically in Figure 12.

The serif made the V left/right asymmetric as well as up/down asymmetric. The serif pointed towards the LEFT key and away from the RIGHT key, and as before the apex of the V pointed towards the NEAR key and away from the FAR key. The same procedure was followed, with the stimulus cube appearing in 24 orientations constituting a revolution about the vertical Y-axis, and the same three observers served.

Results and Discussion. The five reaction time functions are shown in Figure 13. All four of the confusable responses yielded plateau-shaped functions, consonant with our expectation that observers would be able to use the relatively efficient relational strategy. The large peaks associated with use of the rotational strategy have disappeared. The results demonstrate that display-control incompatibility can be reduced by appropriate coding of the orientation of objects within the display, and show that it is very important to desymmetrize any object presented in a 3-D display, to permit operators to determine orientation directly from the displayed object without having to resort to the potentially slow and inaccurate rotational strategy.

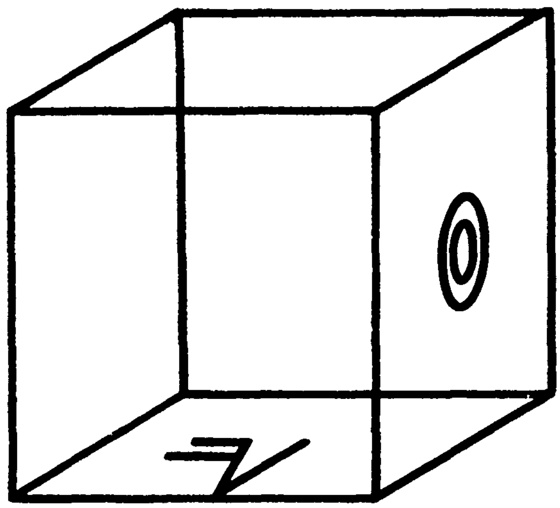

Figure 12: Schematic diagram of the stimulus cube for a typical trial in Experiment 6. The orientation cue is a capital letter V oriented as in Experiment 1, but with an extra serif attached to the top of its left upright.

Conclusions

Since the images displayed on SpaceGraph are generated from abstract data in the computer, it is up to the applications designer to choose representations or icons of the objects to be displayed. For example, two options in an Air Traffic Control application would be to display aircraft positions in an integrated plan- and vertical-situation display (1) as points, or (2) as miniature aircraft icons. In the former case, heading information might be indicated by a wake extending behind the aircraft, or might not be indicated in the display at all. Even with the wake, it would take some time before a sudden turn would be clearly visible in the wake, if the scale were small. On the other hand, if a small aircraft icon were placed at the appropriate point in the display, the attitude of the icon would show the aircraft's present heading directly, and a sudden turn would be seen immediately as a discrepancy between the attitude of the icon and the wake. The representations that are chosen will have large effects on how easy the display is to interpret and use. Our experiments have shown that, in an application where orientation of the displayed objects is important, the icon chosen should deliberately be made asymmetric on all its major axes. In a left/right symmetrical icon, such as an aircraft, the right side should be made different from the left side, for example by filling in that half of the icon, or by adding a vertical fin at the end of the right wing. This addition will

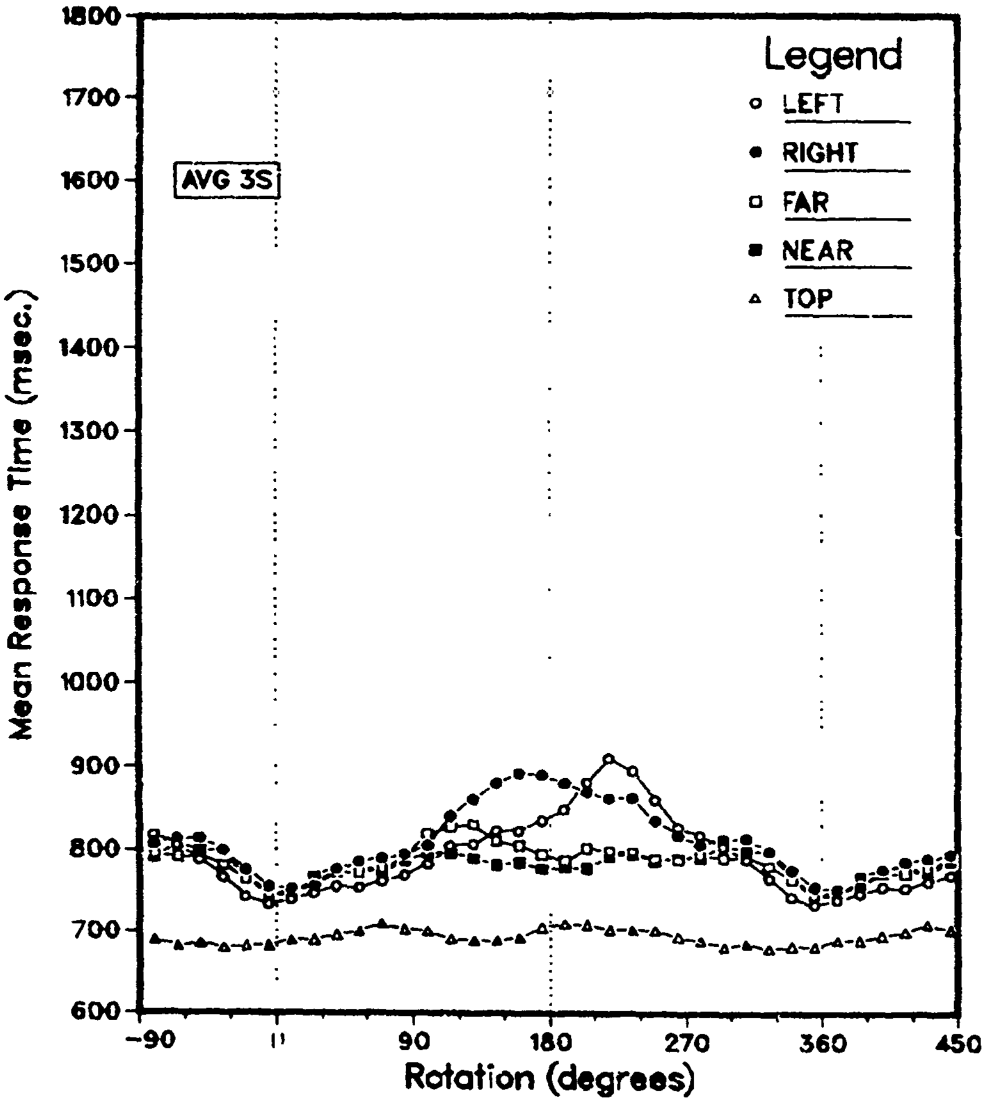

Figure 13: Mean reaction times in the Y-axis task for each of the five response buttons, as a function of the orientation of the stimulus cube, using an asymmetric capital V almost touching the front edge of the bottom face as orientation cue.

permit the operator to use a relational strategy to determine the orientation of the icon, which we have seen is much more efficient than a rotational strategy.

A second important point is that even the relatively efficient relational strategy is not as effective as a spatially-based strategy, where the conditions are appropriate for that to be applied. This suggests that it might be beneficial to give the operator controls that would allow him to rotate the display space into a preferred orientation. Unfortunately, in our present implementation of SpaceGraph, it is not possible to generate a new image from a different viewpoint fast enough to permit meaningful experiments to be run to test either this suggestion, or whether the suggestion applies to a multi-vehicle control task as well. The commercial version of SpaceGraph, of which initial deliveries have already been made, is sufficiently fast to support such experiments, however, and we hope to be able to work on them soon.

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STEREOPSIS HAS THE "EDGE" IN 3-D DISPLAYS

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ABSTRACT

This paper reports the results of studies conducted at SRI International to explore differences in image requirements for depth and form perception with 3-D displays. Monocular and binocular stabilization of retinal images was used to separate form and depth perception and to eliminate the retinal disparity input to stereopsis. Results suggest that depth perception is dependent upon illumination edges in the retinal image that may be invisible to form perception, and that the perception of motion-in-depth may be inhibited by form perception, and may be influenced by subjective factors such as ocular dominance and learning.

Piantanida

As display-system technology has advanced, we have learned how to present features to the human observer in such a way that his perceptual processing mechanisms can synthesize the desired view of the world. The methods we have chosen have not always duplicated events as they naturally occur. For example, when the dimension of motion was added to displays, we found that, although the motion of objects in the real world is usually continuous, it was not necessary to provide continuous motion of display features for the observer to see these features moving smoothly. A series of still pictures presented in rapid succession was entirely adequate for producing the perception of continuous motion. Likewise, when color was added to the displays, it was accomplished by presenting the observer with display features whose color was synthesized from a limited number of relatively narrow-band spectral elements, rather than from the continuous spectral range found in nature.

Now we are on the threshold of adding another dimension to display systems--depth. To do this, we must know which of the many stimulus variables in the real world are important to the stereopsis mechanism, and which are not. To acquire this knowledge, we sought to answer three major questions about 3-D displays: 1) What features of 3-D displays promote stereopsis? 2) Do these same features promote form perception? 3) How can stereoscopic depth perception be optimized? Ascertaining which stimulus features underlie the perception of depth and form is the essential first step toward optimizing the perception of both on visual displays.

We have approached this problem in two ways: by isolating inputs to stereopsis and by systematically reducing the effectiveness of inputs to stereopsis. This discussion will concentrate upon the isolation of inputs.

To say that we isolated inputs to stereopsis could imply that depth perception was stimulated without form perception, or that two members of the triad vergence, retinal disparity, and accommodation--were held constant while the third was manipulated. We wish to imply both these situations.

By using a technique that stabilized selected features of one or both retinal images, we were able to alter or eliminate form perception in one or both eyes. We did this to investigate whether depth perception was possible without form perception and to see if it might be possible to modify the features presented on 3-D displays so as to enhance depth perception without distorting form perception.

To stabilize the retinal image, we used an SRI eyetracker and stimulus-deflector system. Without going into details, let me say that the eyetracker can determine eye position dynamically over a 20 to 30° range of gaze angle to an accuracy on the order of 1' of arc. Horizontal and vertical eye-movement signals from the eyetracker can be used to drive the mirrors of the stimulus deflector.

The stimulus deflector, shown diagrammatically in Figure 1, requires a bit more explanation. An observer views the display screen through two unity-magnification relay lens pairs. Conceptually, each unity-magnification lens pair reimages the observer's eye without magnification. Rotation of a mirror placed in the plane of the reimaged observer's eye results in retinal-image displacements identical to those that would occur if the observer's eye were rotated about this point. By using two orthogonal rotating mirror systems, we can produce any desired retinal-image motion.

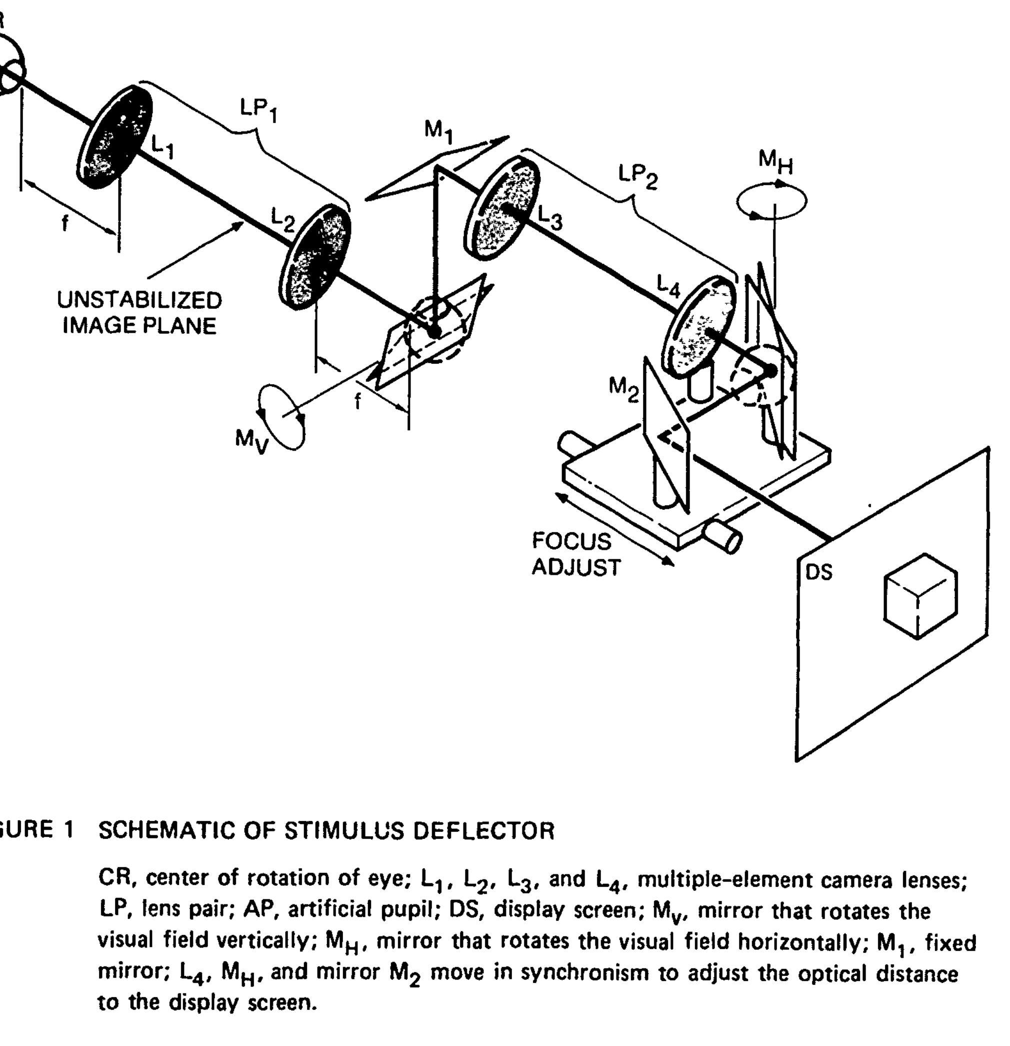


FIGURE 1 SCHEMATIC OF STIMULUS DEFLECTOR

CR, center of rotation of eye; L_1, L_2, L_3, and L_4, multiple-element camera lenses; LP, lens pair; AP, artificial pupil; DS, display screen; M_V, mirror that rotates the visual field vertically; M_H, mirror that rotates the visual field horizontally; M_1, fixed mirror; L_4, M_H, and mirror M_2 move in synchronism to adjust the optical distance to the display screen.

To stabilize the retinal image of any display feature viewed through the stimulus deflector system, we use the horizontal and vertical eye-rotation signals from the eyetracker to drive the corresponding mirrors in the stimulus-deflector system. When the gain between the two instruments is set precisely, any rotation of the observer's eye is exactly compensated by a rotation of the stimulus-deflector mirrors, resulting in the elimination of motion of the retinal image. In addition, there is a plane conjugate to the observer's retina between the lenses of the first relay pair. Because this image plane is proximal to either movable mirror, stimuli placed in this image plane will remain unstabilized (i.e., normal). Typically, fixation points and sharply focused vertical field stops, which I'll refer to as occluders, are placed in this unstabilized image plane.

The stimulus-deflector mirrors can also be driven by sources other than the eyetracker. For example, in most of our studies of the perception of motion-in-depth, we presented the observer with stereo image pairs that oscillated horizontally in sinusoidal antiphase, i.e., alternately toward and away from one another. This motion was imparted to the stimuli by driving the stimulus deflector mirrors with sinewave generators.

One of the display systems we used is shown in Figure 2. It is a rear projection system that can present either a monocular image or binocular mirror images of slides inserted in the projector. The system can also be used simply to illuminate the rear projection screen.

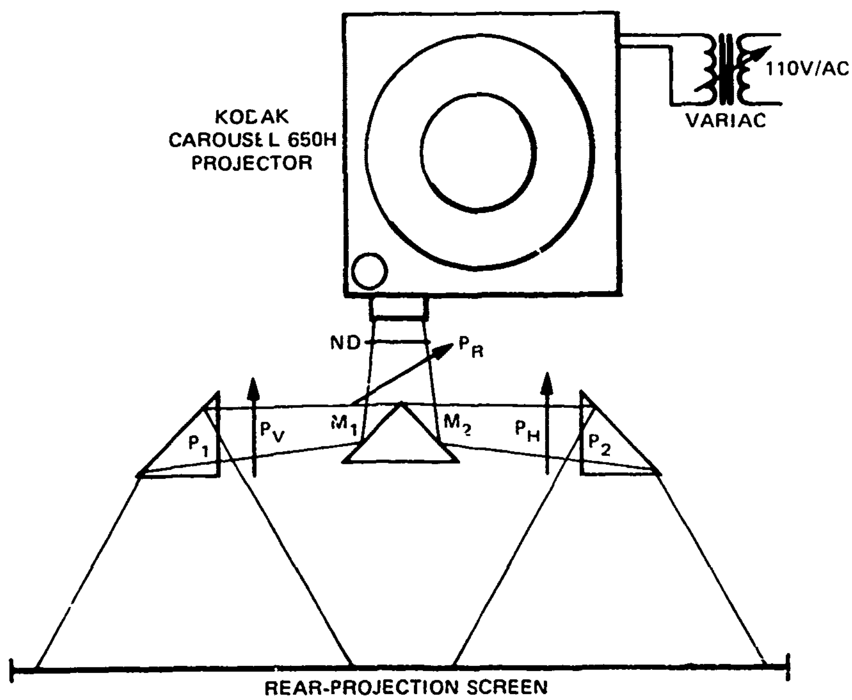


FIGURE 2 SCHEMATIC OF DISPLAY SYSTEM

ND, neutral density filter; P_R, rotatable plane polarizer; P_V, vertical plane polarizer; P_H, horizontal plane polarizer; M_1 and M_2, front surface mirrors; P_1 and P_2, prisms.

In this illumination configuration, transparent gelatin filters or opaque figures can be affixed to the screen, presenting the observer with sharply defined luminance or chrominance patterns.

During the course of our investigations, several response modes were used to indicate perceptual changes. Our earliest studies were phenomenological in nature; observers made verbal reports of their perception of the stimuli. Later we began to quantify our results, having the observers respond by changing the positions of switches to indicate changes in perceptual state. Eye movements were monitored by the eyetracker during all these studies, and the eyetracker signals were frequently recorded on a four-channel recorder. An example of eye-movement records and subject responses will be presented later.

Now let me tell you some of our observations. From the very first observations of stabilized images, it was apparent that filling-in was occurring across the stabilized areas. Filling-in is a very common phenomenon that seems to occur whenever an insensitive patch of retina is contiguous with a sensitive patch. For example, perception is filled in across your blind spot and across small scotomas. To the extent that the disappearance of stabilized images mimics suppression, we may assume that filling-in also occurs across suppressed areas of the visual field. Knowledge of the origin of the percepts seen in suppressed areas may be beneficial in deciding which features to present in 3-D display systems and how best to present them. The sequence of results that I will present next will show the development of our understanding of the phenomenon of filling-in and of the effects of edges, both perceived and invisible, on this process. I will then discuss how these edges affect form and depth perception.

One of our earliest observations involved the simple stimulus shown in Figure 3. It was a vertical black stripe on a white background, which the observer viewed monocularly. This figure and subsequent figures do not accurately portray the observer's field of view. The circular field of view subtended approximately 25° and the outer edges were very blurred, being formed by the circular lens holder that was located well within the observer's near point. Also, the horizontal-line pair drawn across the edge was not on the stimulus. They are the symbols we've adopted to indicate that that edge is stabilized. Edges in the field of view that do not show the horizontal-line pair are unstabilized edges.

After viewing the black bar shown here for a few seconds, the observer found that it disappeared because it was stabilized, and the observer then saw a uniform gray field. However, if the stabilized black bar was flanked by a pair of unstabilized occluders such as those shown in Figure 4, then the observer saw a white field when the stabilized black bar disappeared, rather than the gray field seen in the previous experiment. We interpret these results to mean that the lightness of the stabilized field of view is determined by the

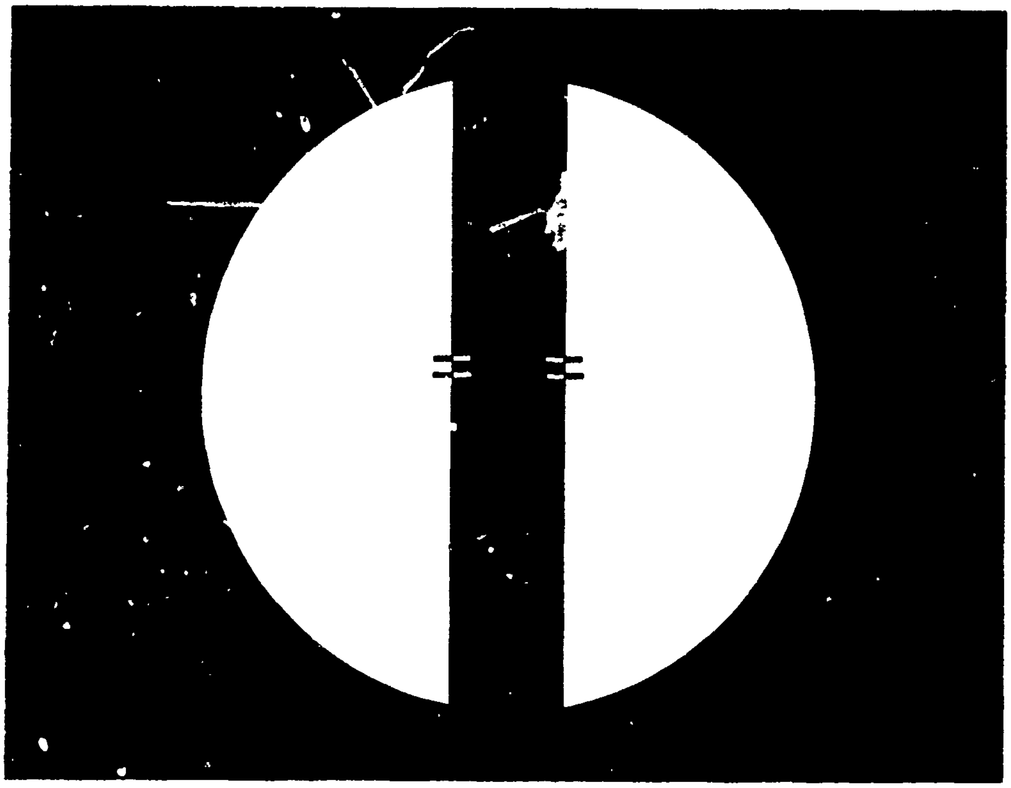


FIGURE 3 A STABILIZED BLACK BAR ON A WHITE BACKGROUND

luminance contrast at the edges bounding the uniform field. In the absence of the occluders, the contrast gradient at the edge of the field was shallower and further in the periphery, resulting in the perception of the uniform gray field. When the occluders were introduced, a much steeper luminance-contrast gradient was present in the near periphery. The high-contrast edges made the field appear white.

We then turned our attention to chromatic stimuli. Initially, we created stimuli without controlling the luminous component; Figure 5 shows one of our early chromatic stimulus configurations. It consisted of a stabilized green disk on a red background whose angular subtense was limited to 12° by a circular unstabilized black mask. When the stabilized green disk disappeared, the observer reported seeing a uniform circular red field. We next presented the observer with stimuli such as those shown in Figure 6, consisting of the same stabilized green disk on a red background, but now with the red background extending to the limits of the viewing field and having diffuse edges. In the center of the stabilized green disk, we positioned a circular unstabilized black mask. Under these conditions, when the stabilized red/green boundary disappeared, the observer reported seeing the central black mask on a uniform green field. In both of the preceding

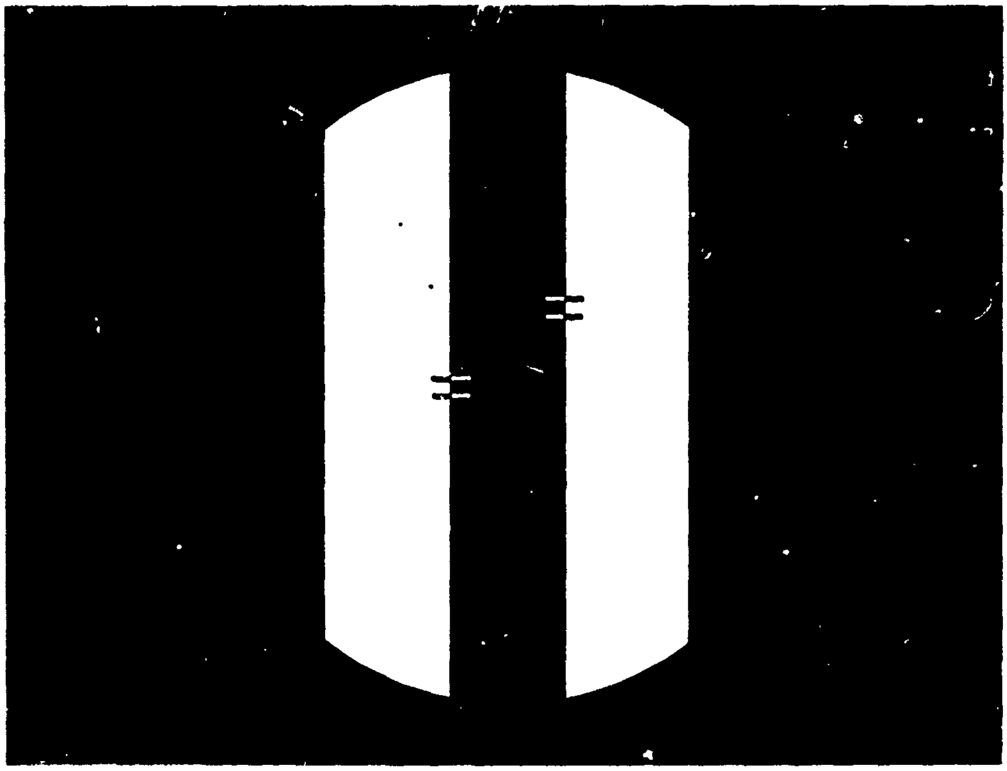


FIGURE 4 A STABILIZED BLACK BAR ON A WHITE BACKGROUND WITH FLANKING UNSTABILIZED OCCLUDERS

chromatic experiments, the chromatic appearance of the field was in agreement with the chromatic contrast at the only perceptible edge in the field.

One of our most interesting chromatic studies involved a stimulus configuration whose only perceptible edges contained conflicting chromatic information. The stimulus configuration is similar to that shown in Figure 7. It consisted of a vertically divided bipartite field, green on the left and red on the right, framed by a pair of vertical unstabilized black occluders. The boundary between the red and green halves of the field was stabilized. From the results of our previous stabilized chromatic experiments we predicted that the chromatic contrast at the left unstabilized occluder would make the field appear uniformly green, and simultaneously the chromatic contrast present at the right unstabilized occluder would make the field appear uniformly red. It is impossible to produce a slide showing the observer's perceptions of this stimulus. Numerous observers reported the field as reddish-green, greenish-red, or something that they recognized as a color but had never seen before and for which they had no name. The anticipated conflict was evident indeed.

Back in the world of black and white, we conducted several quantitative experiments to investigate the effects of perceptible edges

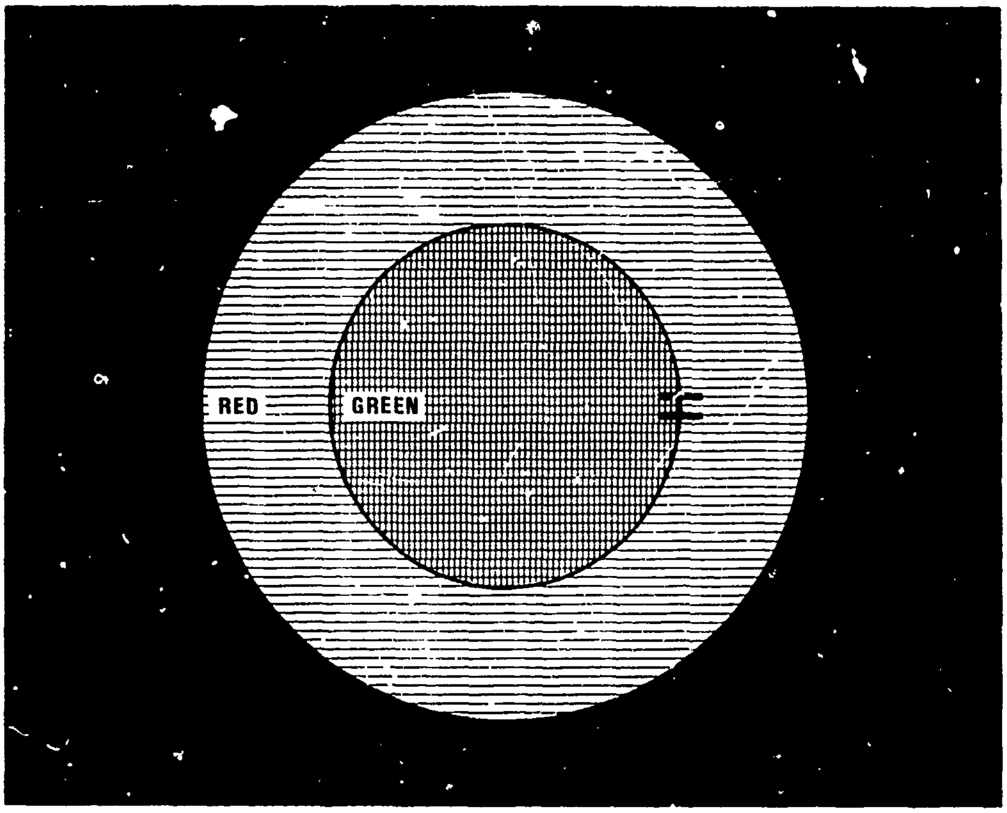


FIGURE 5 A STABILIZED GREEN DISC ON A RED BACKGROUND

on lightness perception. The stimulus configuration we used is shown in Figure 8. It consisted of stabilized black and white backgrounds, each showing a single unstabilized gray target square. The black and white backgrounds were surrounded by a uniform unstabilized gray surround of the same luminance as the two target squares. As long as the black and white backgrounds were visible as such, the lightness of the two target squares appeared to be the same. After disappearance of the stabilized black and white backgrounds, the observer perceived a uniform gray field upon which were positioned a black target square and a white target square. The results consistently indicated that the lightness of the unstabilized target squares changed when the perception of the background changed from black and white to gray. The point here is that there is no change in retinal illumination, but there is a change in lightness. Perceived lightness of the target squares varied with the perceived brightness contrast of these target squares with their background, not with the retinal illuminance contrast of these target squares with their background.

The chromatic analogues of these experiments yielded equally dramatic results. They indicated that perceived color contrasts rather

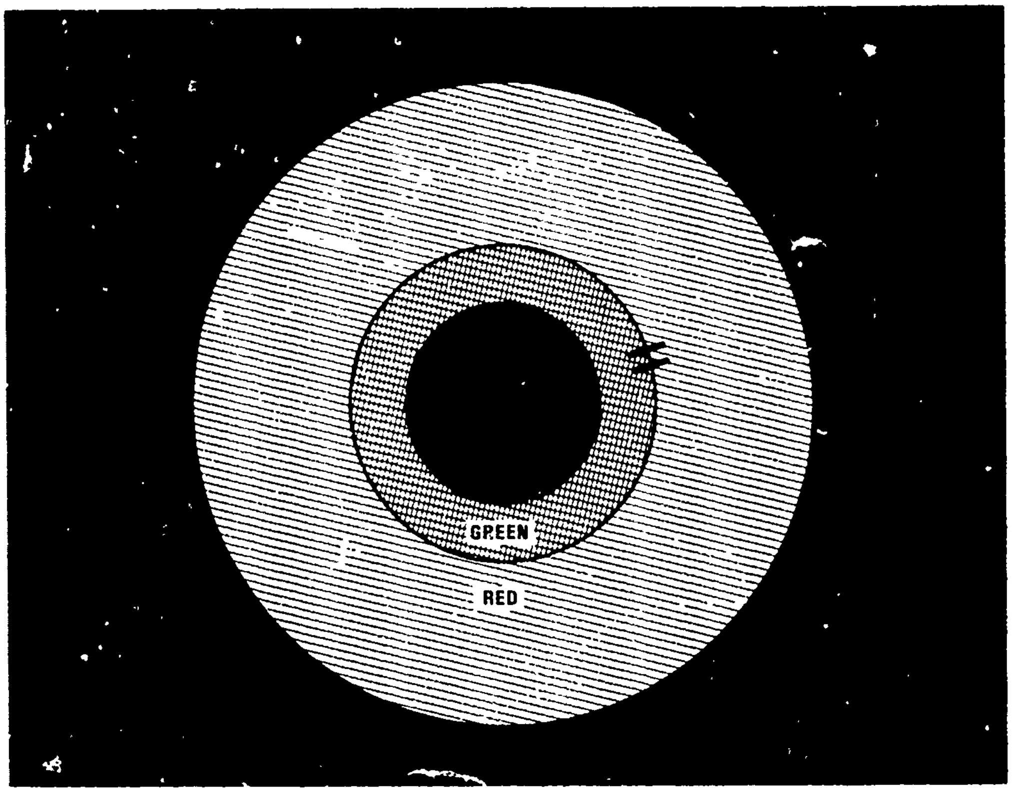


FIGURE 6 A STABILIZED GREEN DISC ON A RED BACKGROUND WITH AN UNSTABILIZED CENTRAL BLACK MASK

than retinal wavelength contrasts determine the color of unstabilized target squares seen against stabilized chromatic backgrounds.

We conclude from the foregoing that the color and lightness of objects is determined by the chrominance and luminance contrast at the perceived edges of these objects, not by the contrast at the retinal-image edges of the objects.

Although the visual system frequently suppresses information about edges imaged on one or the other retina, for example, to obtain a single binocular image, it is nonetheless capable of using that suppressed retinal-edge information to produce depth perception. Therefore, we naturally asked whether stabilized edges, like suppressed edges, might also be capable of supporting depth perception. If this were the case, then it might be appropriate to reconsider what information should be displayed on three-dimensional display systems.

Because of suggestions in the literature about the different effects of chromatic and achromatic information on depth perception, we produced our stimuli very carefully to eliminate chromatic gradients from our luminance experiments and luminance gradients from our chromatic experiments. One of the simpler stimuli we used consisted of a

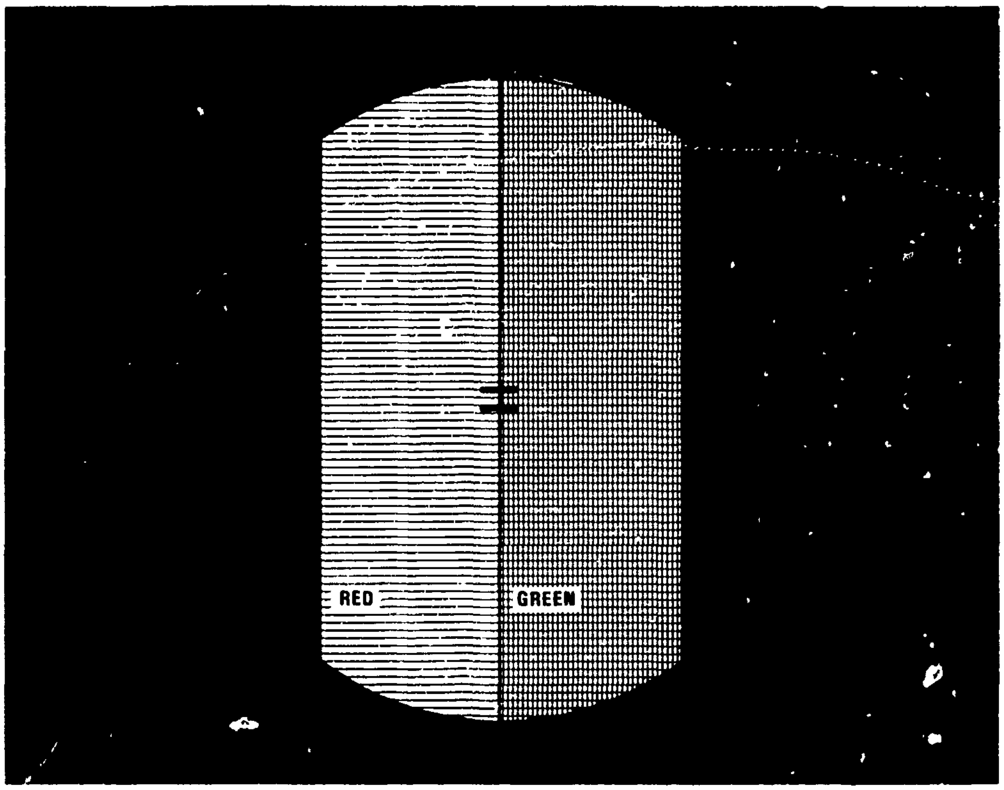


FIGURE 7 A STABILIZED RED/GREEN BOUNDARY

vertical black bar on a white background, which the observer viewed with both eyes. The image of the black bar was stabilized on one retina and unstabilized on the other. The image of the unstabilized bar could move laterally back and forth. Before stabilizing the stationary bar, the observer positioned the two bars so that they appeared as a single fused bar in the center of his field of view. We then moved the image of one of the bars laterally back and forth, and the observer saw a single fused bar moving in depth along a diagonal path. Next, we stabilized the image of the stationary bar to disappearance and moved the image of the other bar laterally as before. Under these conditions, the observer still saw the black bar moving in depth along a diagonal pathway even though there was no bar perceptible to one of his eyes. Depth was maintained in the absence of binocular form perception.

When we performed the chromatic analogue of this experiment, using isoluminant chromatic stimuli, we found that only a weak motion-in-depth percept was generated when both stimuli were unstabilized, and that when one stimulus was stabilized, no motion-in-depth percept was produced. Isoluminant chromatic stimuli gave only weak depth information at best.

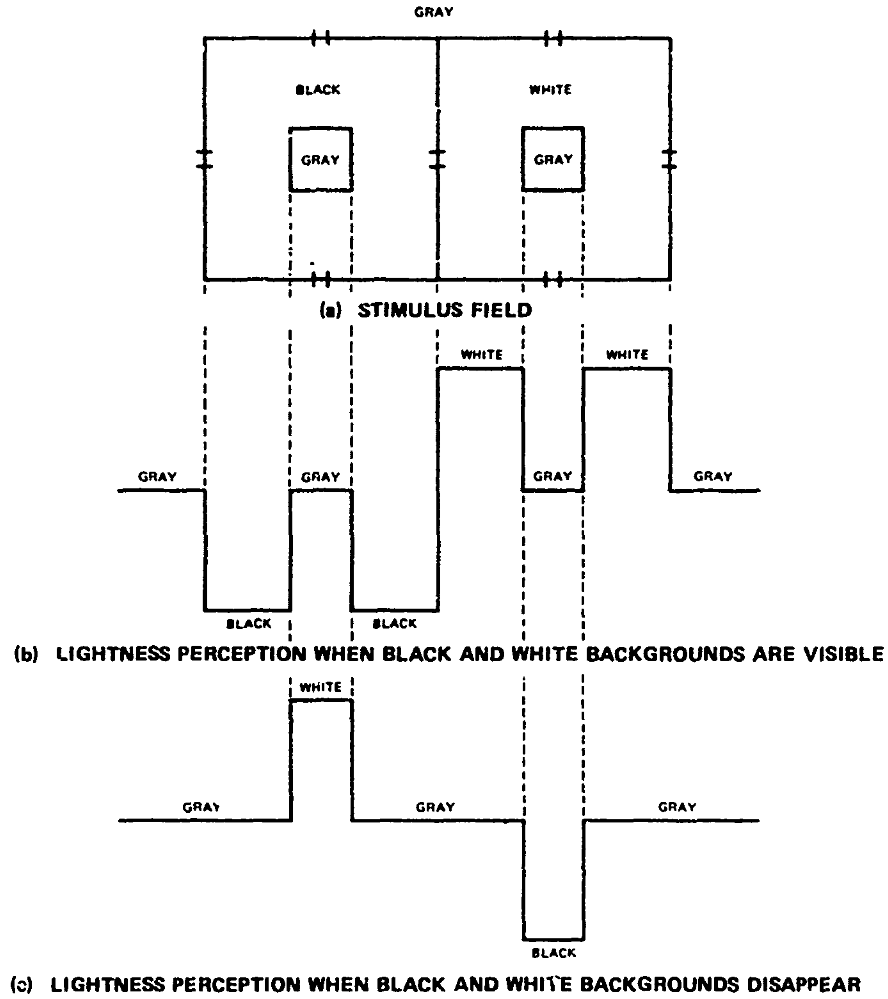


FIGURE 8 UNSTABILIZED GRAY SQUARES ON STABILIZED BLACK AND WHITE BACKGROUNDS

We proceeded to try to quantify the depth percept obtained with the achromatic stabilized stimulus. In the experiment, each of the observer's eyes viewed a vertical luminance sine-wave grating similar to that shown in Figure 9. The grating might be any one of nine spatial frequencies, but the observer was always presented with two gratings of the same spatial frequency. One of the gratings was stationary and of fixed contrast, and the other moved laterally back and forth and was of variable contrast. When the contrast of the movable grating was high enough, the observer saw a single fused grating moving in depth along a diagonal path When the contrast of the moving grating was too low to support stereopsis, the observer saw either the variable grating moving laterally, or, at very low contrasts, just the stationary grating. We measured the contrast-sensitivity function for the perception of lateral motion and of motion-in-depth for the grating as a function of the spatial frequency of the grating under unstabilized

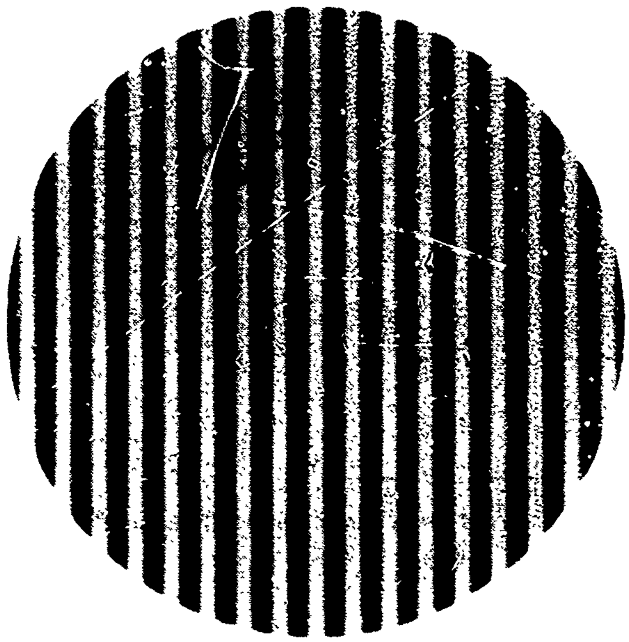


FIGURE 9 A SINE WAVE GRATING

and stabilized conditions. Figure 10(a) shows data from one of our observers under unstabilized conditions. As you might expect, the contrast required for detecting motion-in-depth is higher than the contrast required for detecting the lateral motion of the grating. In Figure 10(b) we see the data from the same subject under conditions where the stationary grating was stabilized to disappearance. Under this stabilized-image condition, the observer required less contrast in the moving grating to see it moving either laterally or in depth. To our knowledge, this is the first quantitative evaluation of the sensitivity of the stereopsis mechanism to stabilized images. The data suggest that the sensitivity of the motion-in-depth perception mechanism increases when form perception is eliminated in one of the observer's eyes.

These results imply that stereopsis (at least the motion-in-depth system) can compare the locations of corresponding edges on the two retinas even if only one of these edges reaches perceptual awareness. Furthermore, it is the luminance component, rather than the chromatic component, of these edges that supports stereopsis.

These observations raised some interesting questions relative to three-dimensional display systems. For example, if binocular form

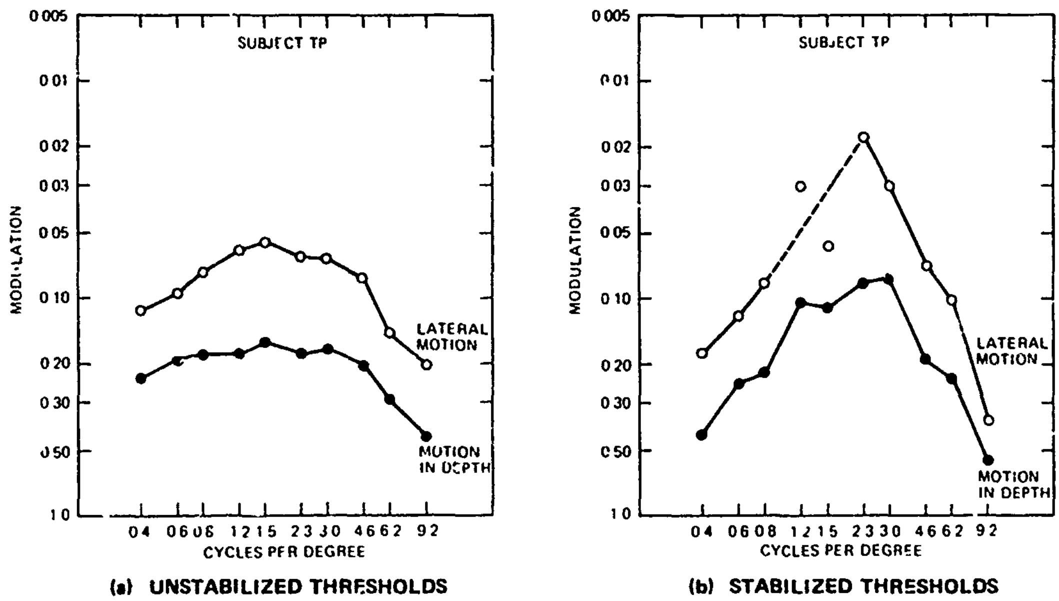


FIGURE 10 COMPARISON OF STABILIZED AND UNSTABILIZED THRESHOLDS

perception is not essential to stereopsis, is it necessary for three-dimensional displays to present two complete stereo images to an observer? Also, if chromatic edges do not convey depth information, is it necessary for both stereograms to be chromatic?

The results of our monocular stabilization studies prompted us to ask whether depth perception might remain when form perception had been eliminated in both eyes. To test this, we used a binocular pair of eyetrackers and stimulus deflectors such as those shown in Figure 11. With this apparatus, it was possible for us to stabilize both retinal images. We presented the observer's left eye with an image similar to that shown in Figure 12(a), consisting of an unstabilized black fixation point and unstabilized black occluders framing a white field upon which was presented a stabilized black bar. We presented a mirror image of this stimulus to the observer's right eye [Figure 12(b)]. Before disappearance of the stabilized black bar, the observer's perception of the stimulus was as shown in Figure 13(a). He saw a single fixation point centered in an aperture that was produced by a fused pair of occluders, and behind the aperture at some distance, he saw a single fused black bar. Upon disappearance of the stabilized black bar, the observer's view consisted of the fixation point and occluders lying in one plane and a uniform empty white plane at some distance behind the occluders, as shown in Figure 13(b). Thus, the depth plane specified by the retinal disparity of the black bar imaged in each eye remained, even though form perception of both black bars was eliminated.

Next, we provided observers with a comparison stimulus consisting of a movable unstabilized black bar. The experimenter adjusted the

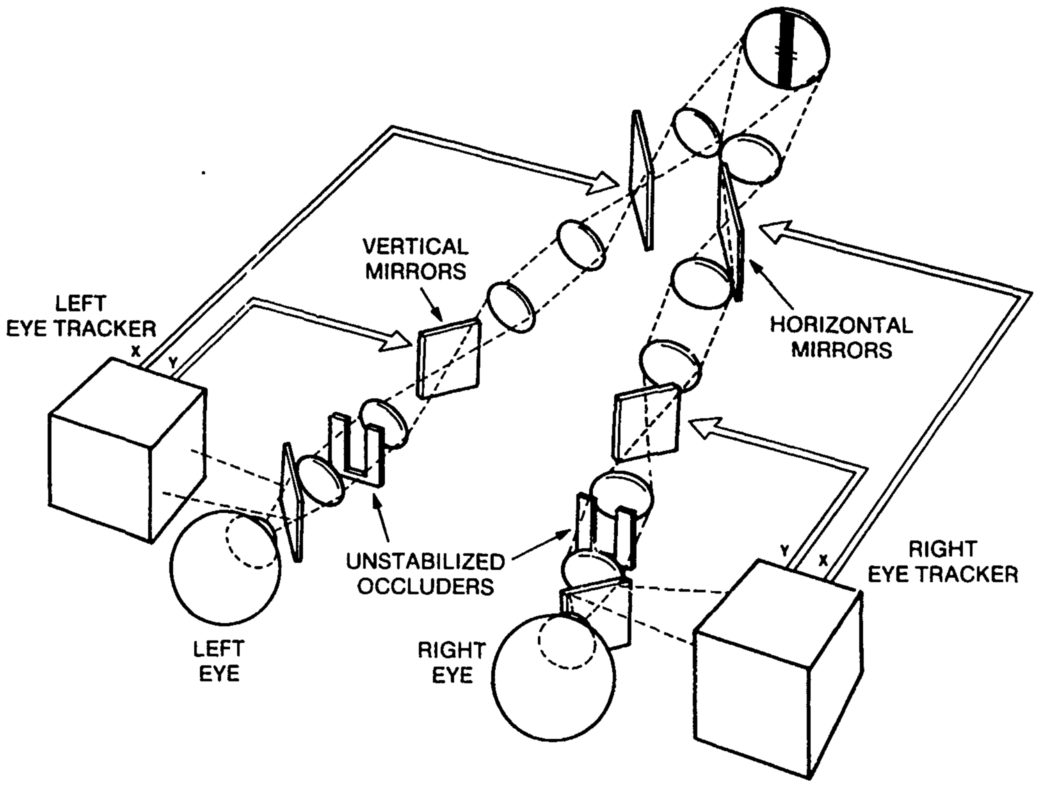
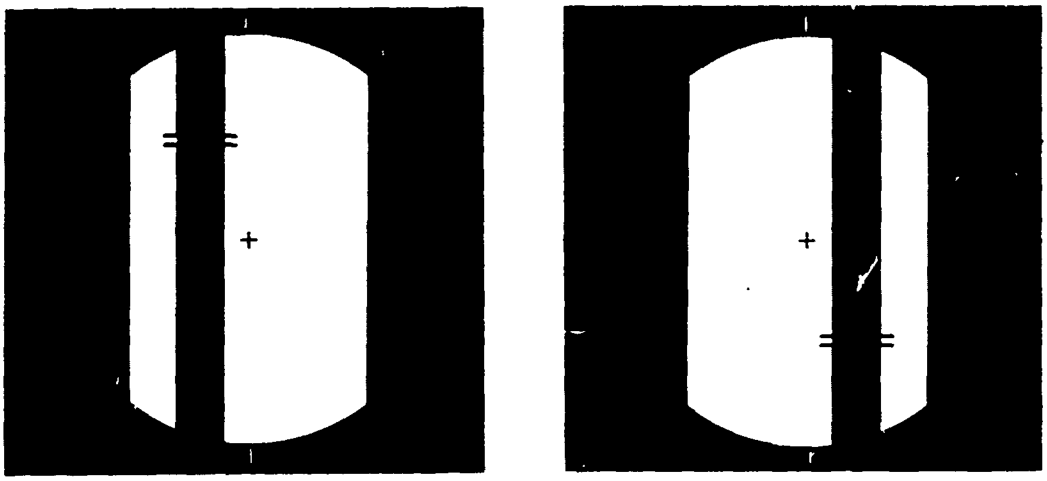


FIGURE 11 BINOCULAR IMAGE STABILIZER

position of the comparison bar until the observer indicated that it was in the plane occupied by the fixation point or the plane occupied by the fused black bar. Two sets of measurements were made, one when the stabilized black bar was visible, and the other when it was invisible to both eyes. Figure 14 shows that the observer perceived two planes separated by about 25 cm whether the black bar was visible or invisible. The observers saw depth without form.

What we have learned from these experiments is that stereopsis, which includes both stereoscopic depth perception and the perception of motion in depth, does not require form perception. However, it does require luminance edges in both retinal images; chrominance edges are not sufficient.

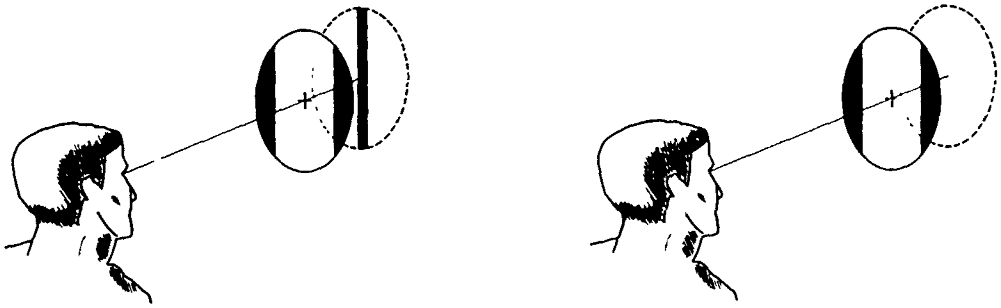
When we began our binocular stabilization studies, we observed an interesting phenomenon resulting from our ability to eliminate retinal disparity signals to stereopsis, which allowed us to assess the effects of vergence alone. When we first presented an observer with binocularly stabilized black bars, the field of view did not include any fixation points or unstabilized occluders. Under these conditions, there were no anchoring stimuli to align the observer's eyes. Consequently, when the observer's eyes converged spontaneously, he saw the black bar



(a) LEFT EYE VIEW OF THE STABILIZED AND UNSTABILIZED STIMULUS ELEMENTS

(b) RIGHT EYE VIEW OF THE STABILIZED AND UNSTABILIZED STIMULUS ELEMENTS

FIGURE 12 OBSERVER'S VIEW OF STIMULUS ELEMENTS



(a) BEFORE DISAPPEARANCE OF THE BLACK BAR

(b) AFTER DISAPPEARANCE OF THE BLACK BAR

FIGURE 13 OBSERVER'S VIEW OF THE STIMULUS ELEMENTS

advancing, and when they diverged, he saw the black bar receding. This perceptual motion-in-depth must have resulted from vergence inputs to stereopsis, because changes in retinal disparity were eliminated by stabilizing both retinal images. We also found that the magnitude of the perceived motion-in-depth was much greater when the binocularly stabilized images of the black bar were shifted on each retina, to be imaged with static crossed retinal disparity, than when they were each imaged across the fovea, so as to have no static retinal disparity.

In our binocular experiments, we also observed some size distortion accompanying the motion-in-depth distortion. When an object appeared to approach, it also appeared to get smaller, because the size of its retinal image did not change. These results show us that

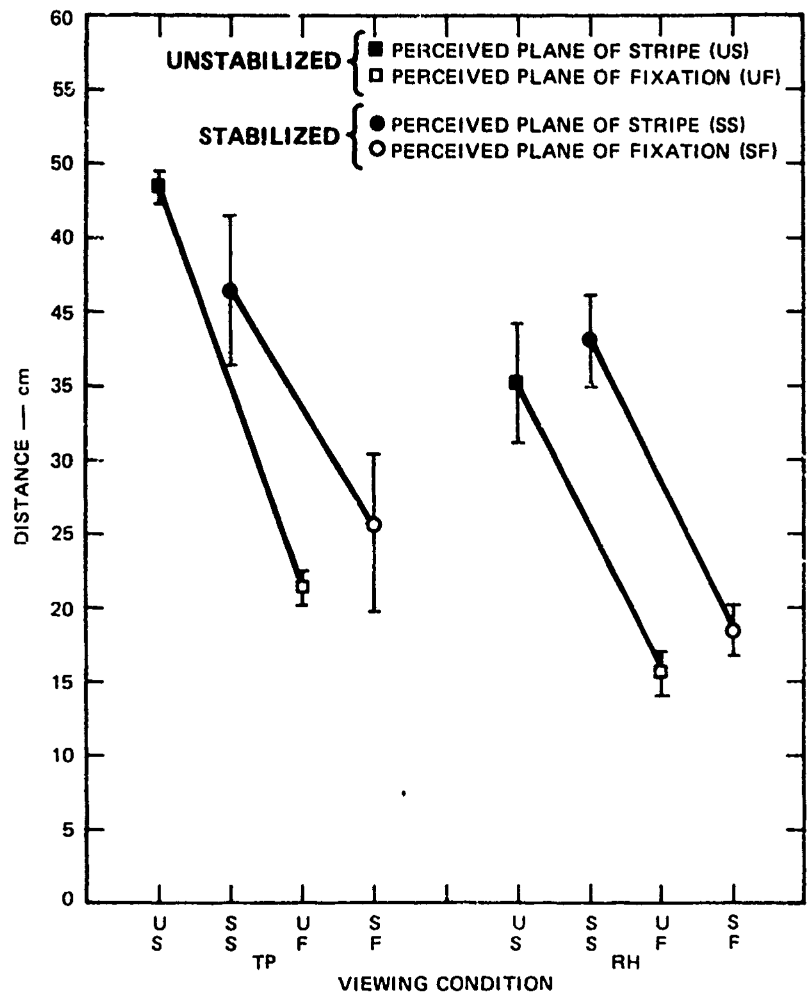


FIGURE 14 PERCEIVED DISTANCE TO FIXATION POINT AND PLANE OF STRIPE

the position of edges in the retinal image affect such factors as the efficacy of vergence signals to stereopsis and size constancy. It is important that we understand these edge-position effects when producing three-dimensional displays, particularly because we do not know where the observer will be looking at any given instant.

Let us now leave the selectively stabilized image technique and examine some changes in the perception of motion-in-depth that occur when the stimulus parameters of three-dimensional displays are varied. Using the psychophysical method of limits, we asked how much corresponding edges in three-dimensional display systems can be changed along various display dimensions before stereopsis suffers.

In the technique we used to address this question, observers viewed mirror images of geometric targets through the binocular stimulus-deflector system. The horizontal deflection mirrors of the two stimulus-deflector systems oscillated sinusoidally in antiphase. This moved the two retinal images alternately nasally and temporally, producing a compelling illusion of motion-in-depth of the single fused target. The observer's task was to decide when the target appeared to move exclusively in-depth, ambiguously, or exclusively laterally. We recorded the observer's subjective response to the motion of the stimulus along with a record of the motion of the stimulus and a record of the observer's eye movements.

Some of the parameters we varied were the luminance contrast between the target and its background, the luminance level of the target, and interocular contrast. Conceptually, interocular contrast is the ratio between the luminances of the two monocularly perceived targets of the stereogram. Interocular contrast has been shown to be associated with perceptual distortions, such as the Pulfrich phenomenon. In a typical experiment, observers were seated before the binocular eyetracker/stimulus-deflector system and viewed targets having a mean luminance of, say, 3.0 foot lamberts, and having a contrast with their surround of, say, 60 percent. Starting from a condition in which the luminance of the left and right targets was the same, and the observer saw the single fused target moving in depth, we varied the luminance of the left and right targets inversely, so that as one got brighter the other got dimmer. Eventually the luminance difference between the two targets was great enough that at times the observer did not see the single fused target simply moving unambiguously in depth, but rather he saw a combination of lateral motion and motion-in-depth. As the interocular contrast ratio between the two targets continued to increase, the observer saw only lateral motion of the targets. During the experiment, the observer indicated the type of motion he was seeing, motion-in-depth, ambiguous (both lateral and depth), or lateral motion only. An example of data collected in these experiments is shown in Figure 15. During periods of versional eye movements the observer tended to see the target moving laterally, whereas during periods when he made large-amplitude vergence movements, he reported seeing the target moving in depth.

Several interesting results were obtained from this study. The first was that for contrasts greater than 20 percent, the contrast of the stimuli was not a primary factor in determining an observer's perception of motion-in-depth. Target luminance in the range 1.5 to 3.0 foot lamberts was also not a primary factor. Three factors were found that substantially influenced the observer's perception of motion in depth. These were the interocular contrast of the target, the ocular dominance of the observer, and the previous experiences of the observer with three-dimensional displays.

Figure 16 shows the interocular contrast ratios at which trained and naive observers saw the stimulus target moving exclusively in depth, ambiguously, or laterally when the stimulus target had a mean luminance of 1.5 foot lamberts. The data points in this and the

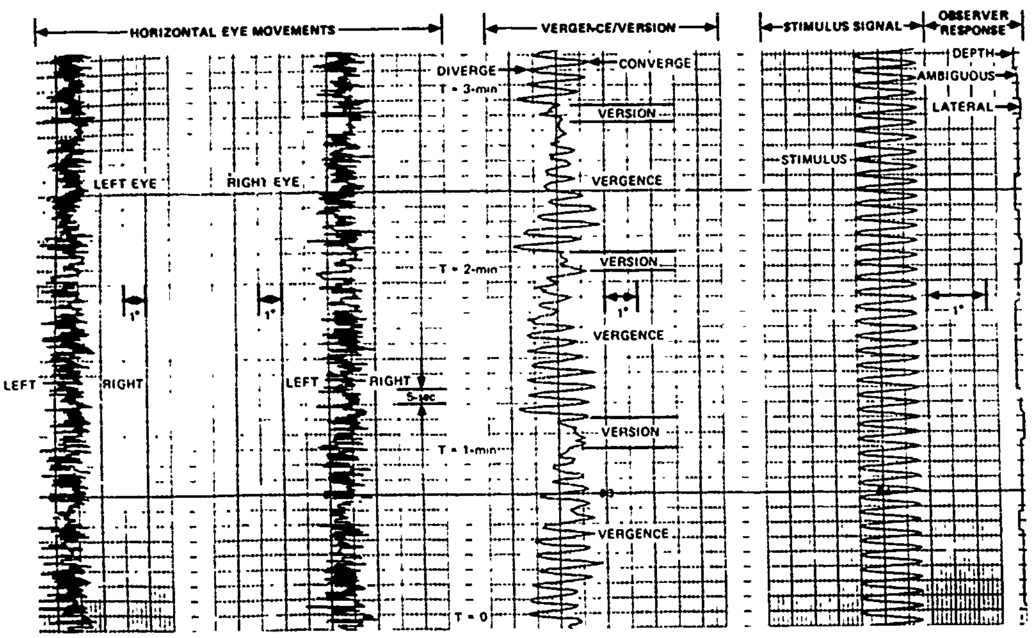


FIGURE 15 PHYSIOLOGICAL AND SUBJECTIVE MEASURES OF OBSERVER RESPONSES

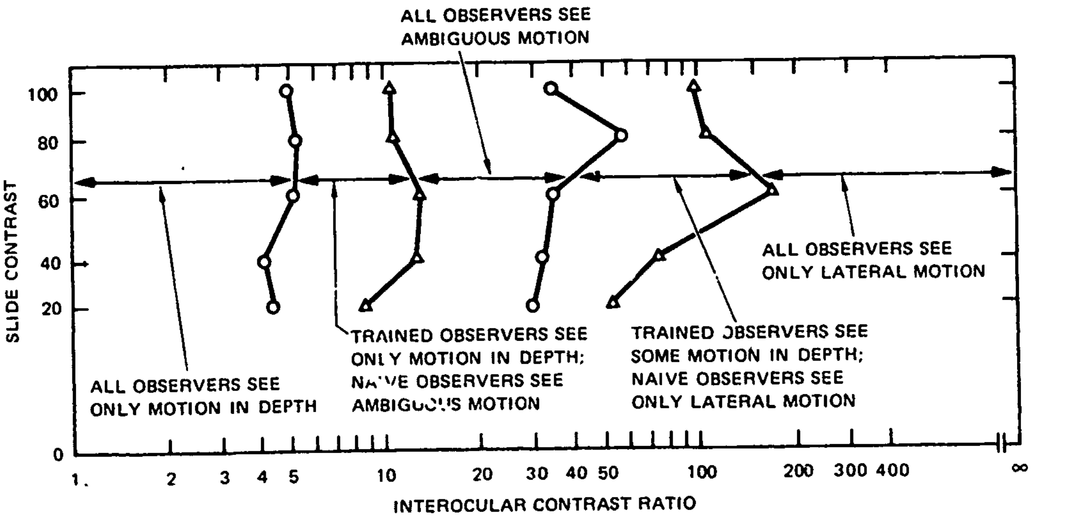


FIGURE 16 TRANSITION INTEROCULAR CONTRAST RATIOS OF TRAINED AND NAIVE OBSERVERS FOR THE PERCEPTION OF MOTION IN DEPTH, AMBIGUOUS MOTION, AND LATERAL MOTION OF A 1.5-fL STIMULUS

following figure are the mean interocular contrast ratios at which, for a given contrast of the stimulus, an observer's perception of object motion changed, for example from motion-in-depth to ambiguous motion. The connecting lines are the limits of one type of motion perception, for example ambiguous motion. Notice on the right-hand side of the figure that at very high interocular contrast ratios all observers saw the target moving only laterally. Moving leftward, we find a region of interocular contrast ratios within which naive observers saw the target moving laterally but trained observers continued to see the target moving with some motion-in-depth. Moving further to the left is a region of interocular contrast ratios at which all observers saw the targets moving ambiguously. Another step to the left and we find a region where naive observers continued to see the target moving ambiguously but trained observers saw the target moving only in depth. Finally we come to the lowest interocular contrast ratios wherein all observers saw the targets moving in depth.

Figure 17 shows the effect of ocular dominance on the perception of motion-in-depth. Starting from the right side once again, there is a region of interocular contrast ratios at which a right-eye-dominant observer saw only lateral motion, irrespective of whether the luminance of the left or the right target is greater. Moving to the left, we find a region of interocular contrast ratios at which this right-eye-dominant observer continued to see the target moving in depth when the luminance was reduced in his right--that is, his dominant--eye, but saw only lateral motion when the luminance was reduced in his left eye. Moving to the left once again, there is a region of interocular contrast ratios where the observer saw the target moving ambiguously irrespective of whether his left eye or his right eye viewed the target of greater luminance. The next region to the left is a region in which the observer saw only motion-in-depth when luminance was reduced in his dominant eye

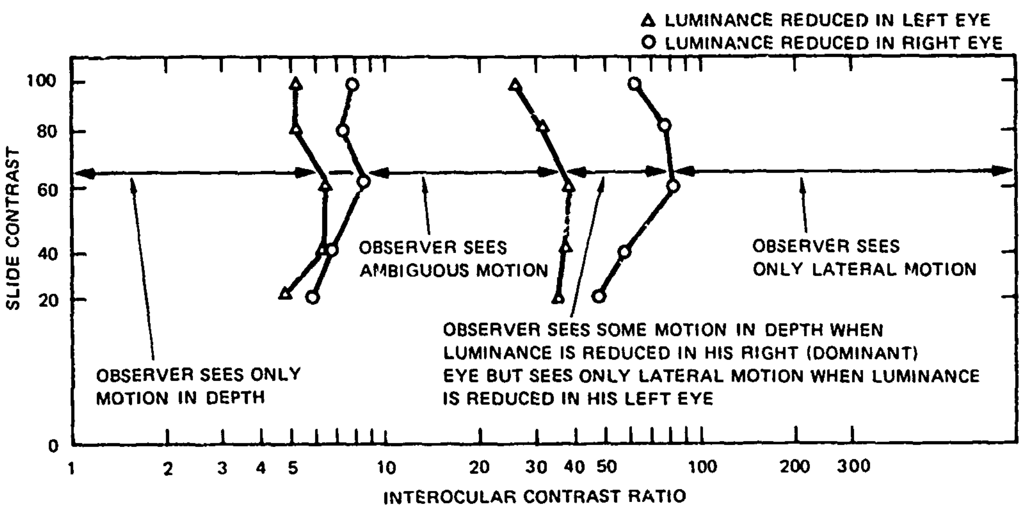


FIGURE 17 TRANSITION INTEROCULAR CONTRAST RATIOS OF THE DOMINANT AND NONDOMINANT EYES OF A RIGHT-EYE-DOMINANT OBSERVER FOR THE PERCEPTION OF MOTION IN DEPTH, AMBIGUOUS MOTION, AND LATERAL MOTION OF A 1.5-fL STIMULUS

but ambiguous motion when the luminance was reduced in his nondominant eye. Finally, at the lowest interocular contrast ratios is a region where an observer saw the target moving only in depth irrespective of which eye saw the higher-luminance target.

It is important to note that under conditions where observers first saw the target moving only laterally, this was not because the lower-luminance target was too dim to be perceived. Most often, the observer could see both targets, but they both appeared to be moving laterally. This may indicate that the form-perception threshold--that is, the threshold for the perception of a target edge--is lower than the depth perception threshold for that same target edge.

The observation that ocular dominance also appears to affect the threshold for the perception of motion-in-depth is particularly interesting. We usually assume that ocular dominance is a phenomenon that affects only form perception. However, these data indicate that the sensitivity of both the form-perception mechanism and the depth-perception mechanism may be affected by ocular dominance.

Finally, it is interesting to note that familiarity with three-dimensional display systems appears to alter the threshold for the perception of depth, but not for the perception of form. One reason may be that depth cues presented in three-dimensional displays are different from those normally used by the stereopsis mechanism. This mechanism may require some retraining to use these unusual depth cues adequately.

To summarize the results I have presented here, I should like to return to the analogy I drew at the beginning of this discussion. The color and motion of images on two-dimensional displays are perceptions generated by unnatural inputs to the visual system. By understanding the processes by which the visual system arrives at the perception of motion and color, we have been able to reproduce these percepts by artificial means.

We do not yet have adequate information about how the visual system synthesizes the third dimension to allow us artificially to manipulate the input to the stereopsis mechanism. Our studie strongly suggest that form perception and depth perception have different image requirements. In our ongoing research program we are studying means by which we may exploit the different requirements for form perception and depth perception to efficiently produce a realistic impression of both form and depth on 3-D displays.

EFFECTS OF PROJECTIVE DISTORTION ON PERCEPTION OF GRAPHIC DISPLAYS

Richard R. Rosinski

University of Pittsburgh

ABSTRACT

Graphic displays can provide accurate representations of three-dimensional space only if they are viewed from the geometric center of projection. Other viewing conditions result in distortions of virtual space. A current paradox of graphic display perception is that such distortions are not always evident in perception of depicted space.

This paper presents an analysis of the geometric basis for distortions of the virtual space depicted in pictorial displays. Recent experiments are summarized which define the conditions under which geometric distortions affect perceived space. Under some conditions, an active perceptual compensation process exists which discounts the compression and expansion of virtual space. In addition, regularity or familiarity of the viewed object greatly reduce the sensitivity to distortion of spatial information.

EFFECTS OF PROJECTIVE DISTORTION ON PERCEPTION OF GRAPHIC DISPLAYS

Richard R. Rosinski

University of Pittsburgh

Introduction

The work that I will discuss today is directed toward a fundamental issue in the study of Visual Perception, and in the application of perceptual studies to the design of graphic displays. Specifically, what is the relationship between visual stimulation or visual information, on the one hand, and perceptual experience on the other. This is a fundamental question, that one would have hoped could have been settled long ago, but this is not the case. In the area of space perception, for example, there is little agreement regarding the extent to which the characteristics of the visual array projected to the eye determine the nature of perceived experience.

When one considers the perception of space represented in pictures, these issues are relevant to both a theoretical psychological and an applied engineering perspective. From the standpoint of perceptual theory, the basic nature of picture perception has been ambiguous. Originally, Gibson (1951) and many of his colleagues interpreted the phenomena of picture perception as evidence for a direct theory of perception. Individuals were able to make accurate judgments of depth represented in pictures; and there was a suggestion that under the right conditions, observers were unaware that they had been viewing pictures. The interpretation for such results was that the array projected to the eye from the picture was identical to the array from the real world. Geometrically, the information was the same in the two cases. Therefore, the same processes which were involved in the pick-up of information from the real world could be used to pick up the information projected from a photograph. Pictures acted as informational surrogates for actual spatial layouts. Considerable evidence was accumulated regarding the equivalence of pictures and real scenes, and this surrogate theory of picture perception was perhaps the most influential over the last two decades.

There are substantial problems with such a view that are fairly easy to point out. There is a geometric isomorphism between the pictorial and environmental arrays only when a picture is viewed from the geometrically correct center of projection. When a picture is viewed from some other place, the geometric relations are changed; the space specified by the picture is distorted in the sense that it does not correspond to the actual scene that was depicted. Now, if space perception in pictures were simply and directly based on the information projected to the eye, such distortions should be evident in perceived space. Our impressions and judgments of space should be similarly distorted. But this does not occur. Pictured space does not seem to distort when we walk past a picture; we are usually unaware of the distortions present in studio photography; and artists and photographers have long known that it is often necessary to distort perspective to make a scene "look right".

In response to such difficulties with the surrogate theory, Gibson (1979) later argued that picture perception was very different from normal space perception in that it was indirect and mediated by some interpretive mechanism. Hagen (1974) proposed that picture perception involved an entirely different "mode" of perception, although the nature of this mode was not specified. Others such as Pirenne (1970) suggested that there was a compensation process which, in some way, was able to discount the effects of geometric distortions on perception.

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From an applied perspective, the role of non-visual processes in the perception of space can play an important role in graphics design. There has been increased use of two-dimensional displays of three-dimensional space in such areas as simulation, master-slave robotics, remote piloting of vehicles, and in multi-variable integrated displays. In each of these applications it is necessary that an operator respond to perceived space from a two dimensional display. Geometric accuracy (although not necessarily realism) has been an important aspect of display design. The non-visual factors that affect the way that spatial information is used would be important variables in design of spatial displays.

The general questions that have been at the focus of the research that I will discuss concern the determination of spatial perception by the geometry of the visual array, and the nature of non-visual compensation processes that affect perception of space based on graphic displays. That is, processes which can discount the effects of projective distortions of the visual array. I will simply assert here that there is no optical information available from a picture or graphic display for the presence, absence, or extent of any projective distortion. Ideally, a compensation phenomena, were it to exist, would operate primarily when distortions existed; but if no optical information for distortion is present, how is the presence of a distortion detected?

Early evidence for a spatial compensation process is rather sparse, and many including myself doubted its existence. One investigator (Perkins, 1973) showed that shape distortions were not perceived until the projective distortion was quite extreme; yet these data might not indicate a perceptual compensation as much as a failure of discrimination of shape categories. A second investigator (Hagan, 1974) found no perceptual effect of distortions on relative depth, but information for relative depth is not affected by such distortions. Occasionally the magnitude of the geometric distortion has been miscalculated, so conclusions about compensation were moot. Finally, many arguments, and the data used to support them have been intuitive and phenomenological. One's intuition or awareness is not relevant here since the empirical question is whether perception is in greater correspondence with the distorted projection or with the environment that the picture is supposed to represent.

Preliminary studies that were conducted in my lab (Rosinski, Mulholland, Degelman, & Farber, 1980), however, provided evidence for some form of pictorial compensation. In a task requiring judgments of surface orientation represented in pictures, one arrangement showed a close correspondence between perceived slant and the distorted projection, a second showed no effects at all of the projective distortion. This particular pattern of results could only be reconciled in terms of some compensation mechanism.

An initial issue was to assess the degree to which perceived space corresponded to distorted space. To accomplish this, Farber and I (Farber and Rosinski, 1978; Rosinski and Farber, 1980) developed a geometrical analysis that could be used to quantitatively determine the effects of projective distortions on depicted space. We reanalyzed a number of early studies to determine the extent of the effects of distortion. Based on these findings, a research program was initiated under the sponsorship of the Office of Naval Research to specifically test the correspondence between perceived and geometrically specified space.

The essential nature of this analysis can be seen in Figure 1. This drawing represents a square-tiled surface lying at an angle on another square-tiled surface. The same perspectival rules used to create such a drawing can be used to analyze distortion. For either a real scene viewed directly, or for a picture viewed from the geometrically correct center of projection a number of geometric relations obtain. For any surface, a line from the eye to the primary vanishing point has the same orientation as the slant of the surface. The angle between the lines from the eye to the primary vanishing point of one surface, and the line from the eye to the primary vanishing point of the second surface corresponds to the angle between the two surfaces. The angle between the eye and the two vanishing points for the tiles diagonals should be 90 degrees.

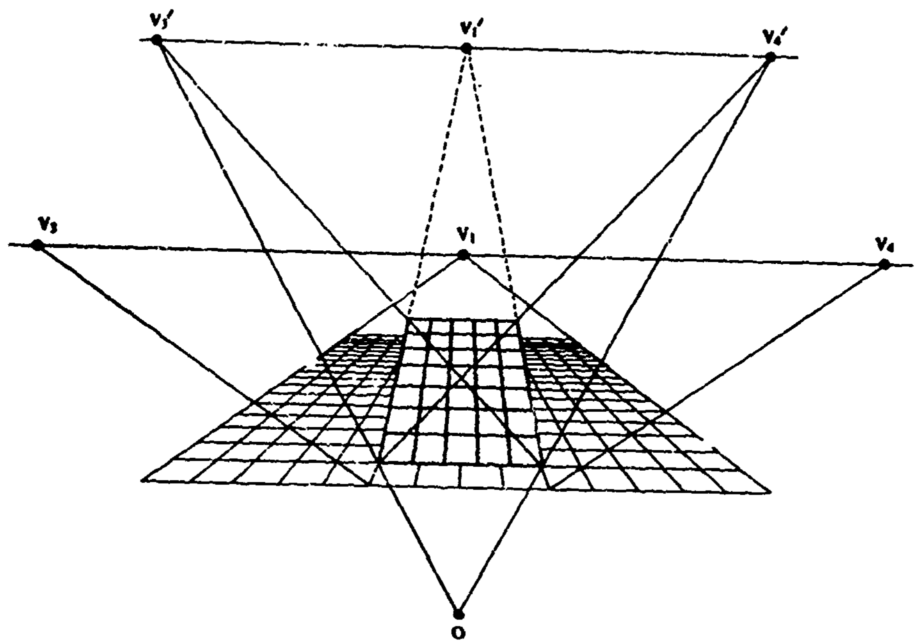

Figure 1. Geometry of Surface Layout.

It follows from this sort of analysis that if the eye is positioned at the correct center of projection, the visual array from the display specifies the location of objects and surfaces in the world. That is, when the eye is at the center of projection, the environmental and pictorial arrays are identical, and the displayed space corresponds to the real scene. This is the simple geometry that is the basis for linear perspective in drawings and in computer graphic representations of three-dimensional space.

How can we characterize the distortions of space that result when the viewing point is changed? We adopt a simple convention. For any new viewing point, we could describe the new virtual space which would have generated the new array. A comparison of the new virtual space with the the original virtual space gives a quantitative index of the distortion. Magnification is obtained if the viewing point is closer to the display that is the center of projection. Magnification, implies a compression of internal depth, with slanted surfaces becoming more frontal. We represent magnification and minification as the ratio of correct to actual viewing points. Thus, if one views from one-half the correct distance the magnification ratio is 2.0; if one views from twice the correct distance, the magnification ratio is 0.5. The changes in internal depth of objects in the virtual space corresponds to the reciprocal of the magnification ratio. Similar descriptions of virtual space can be generated for lateral displacements of the viewing point. Lateral displacements of the viewing point result in an additive combination of shear and magnification. The point to be stressed here is that these distortions are not due to any particular viewing point, but rather the relation between the actual and the correct viewing point.

Since we can define the real space, can calculate the virtual space, and can record judgments indicating perceived space, the psychological question becomes quite simple. When does the perception of space in graphic displays correspond to the geometrically specified space? Does compensation for distortion occur? Psychophysically, these become relatively easy questions to answer.

Before reviewing some of our results, let us consider how such a compensation mechanism might operate. As I asserted earlier, there is no optical information for distortion, and the nature or extent of any distortion is not given in the display. On what might a pictorial compensation be based? One alternative is that one recognizes the objects depicted, and the pattern match criteria are extremely broad. Thus one might recognize horizontal surfaces or right angles even if the geometry of the projection did not correspond to these spatial details. A second alternative is a much more active compensation process. What we have proposed, and what our results indicate is happening, is that the discrepancy between an actual viewing point and an assumed correct viewing point is evaluated, and is used to discount the effects of the geometric distortion caused by the dislocation of the viewing point.

I will review the results of a series of studies which support this proposal. This review is selected from several studies in which we have examined all possible distortions of displays of static objects and spatial layout, and their effects on perceived slant, depth, internal depth, height, width. In addition, we have explored the effects of geometric distortions of these dimensions of space on moving objects and layouts, and in all cases a single pattern of results emerges.

Distortions of Unfamiliar Objects

One set of studies have dealt with the effects of geometrical distortions on perceived depth of unfamiliar objects. Magnification or minification induced by viewing a display from too close or too far away (relative to the correct center of projection) causes a compression or expansion of virtual space. We asked people to make magnitude estimates of the internal depth of objects depicted on a CRT screen. The procedure that was used was to project concentric irregular five-sided shapes. The corresponding vertices of the shapes were connected by lines to increase linear perspective information. The overall impression was of looking into an irregularly shaped tunnel which receded into the distance. The participants were asked to judge the objects' internal depth. The objects were computer drawn, and displayed on a CRT screen which the observers viewed while in a chin rest to assure appropriate viewing distances. In the first experiment the viewing point for all conditions was constant at 112 cm. while the center of projection was varied to result in a range of distortions of virtual space equivalent to magnifications of 0.25 to 3.0.

If perception of the displayed space were determined by the projection, we should expect a correspondence between perceived space and the distortion virtual space specified by the display. In fact, as can be seen in Table 1, there was an extremely close correspondence between the actual judgments and those expected on the basis of the geometric distortion. In general, internal depth was accurately perceived when the CRT screen was viewed from the correct center of projection.

Table 1
Power Functions for Magnification
Viewing Distance Constant

Magnification	Coefficient	Exponent
0.25	4.67	0.58
0.50	1.86	0.69
1.00	1.32	0.72
2.00	0.60	0.73
3.00	0.61	0.70

A 4X minification resulted in an expansion of perceived space by a factor of approximately 4. Similarly, magnifications resulted in compressions of perceived space as expected from the induced distortions of geometric information.

It is clear from these results, that there is a close relationship between the perception of internal depth represented in graphic displays, and the nature of the geometric information provided by the display. Inducing distortions in the display projections results in regular and predictable errors in perception. If distortions are introduced by projecting the display to a point other than the normal viewing point, corresponding distortions in perception result. Appropriate choice of a center of projection in designing graphic displays is crucial for perceptual judgments, at least under certain circumstances.

It is to be expected that there would be a close relationship between judged depth and distortion. Since there is no optical information for distortion, judgments correspond to that specified by available information. The projective distortions of magnification and minification can be generated in two ways: moving the center of projection while maintaining a constant viewing position as was done above, and by moving the viewing point while maintaining a constant location for the center of projection. In this latter case, the degree of magnification (and of the expansion or contraction of perceived space) is perfectly related to viewing distance. Under such conditions, a non-optical basis for compensation exists, and individuals could, in principle, discount the effects of variation in viewing point.

To determine whether such discounting of distortion occurs within the context of the perception of unfamiliar objects, magnifications ranging from 0.33 to 4.0 were created by projecting the display to a point 112 cm away from the screen while the display was viewed from points between 28 cm and 337 cm away. Since magnifications are related to the ratio of actual to correct viewing distance, these viewing conditions result in projective distortions equivalent to those used in the preceding experiment. Equivalent distortions of perceived depth are expected in perception, in this case, if only the projection affects judgment.

Subjects' judgments however, showed no effect of the geometric distortions in this case. As shown in Table 2, in spite of a twelve-fold distortion

Table 2
Power Functions for Magnification
Viewing Distance Varied

Magnification	Coefficient	Exponent
0.33	1.02	0.77
0.50	1.12	0.74
1.00	1.09	0.76
2.00	1.04	0.78
4.00	1.17	0.72

of virtual space induced by the geometric distortion, there is no effect demonstrated in perceived depth; power function coefficients are constant. These data conclusively demonstrate that compensation for the distorting effects of magnification occurs when the distortions are caused by moving the viewing point, but not when equivalent distortions are caused by moving the center of projection. Since the distortions are discounted only when the distortions are correlated with viewing distance, we have suggested that a comparison between the actual distance and some assumed correct or standard distance froms the basis for compensation.

Effects of Familiarity

It is clear that individuals can actively discount the distorting effects of projective transformations of displayed objects. The commonly reported inability of individuals to notice such distortion seems to be due to some additional factor. Under some conditions people do not appear to notice that a distortion is present. We distinguish this from a more active compensation because some failure to discriminate or loss of sensitivity seems to occur.

Perceptual judgments of spatial layouts can involve two different activities. One is the registration and processing of projective geometric information. A second may simply involve a perceptual categorization of an object. If something is categorized as a cube, judgments of its relative dimensions may be influenced by assumptions concerning known qualities of the object.

To explore such an effect, further experiments were conducted that were analogous to the ones discussed above. A series of rectangular solids with equal length and width were created. The stimulus objects were subjected to two Euhler transforms so that the two sides were at a 45 degree angle to the screen, and the top was at 10 degrees relative to the screen. Such an arrangement gives good 3-point perspective. In one experiment, the subjects viewed the screen from a distance of 112 cm. while the objects were displayed with centers of projection ranging from 28 cm to 450 cm. These relations give magnifications which result in distortions of virtual space of from 0.25 to 4.0. The observation conditions were identical to those described in the first experiment above which resulted in large distortions of judgment.

In contrast, judgments of the internal depth of the regular parallelopipeds showed little effects of the distortion of virtual space. Although there are visible, significant effects of the effects of the distortion of virtual space, their size was an order of magnitude less than expected from the distortion. Thus is appears that the perceptual effects of an expansion of compression of virtual space is severely restricted when a familiar, regular target object is used.

In a further experiment using the rectangular solids, the displays were projected to a constant distance 112 cm from the screen, But the displays were viewed from various distances that resulted in expansion or contraction of virtual space by factors ranging from 0.25 to 4.0. In this study the degree of distortion was directly related to the distance from the subject to he display screen. The range of the effect of the geometric distortions is reduced relative to the preceding experiment, and statistically, the perceptual effects of distortions of virtual space are reduced when the degree of distortion is caused by moving the observer's viewing point. However, the absolute magnitude of this compensation is extremely small. The familiarity or regularity of the objects renders the perceptual system quite insensitive to projective distortions.

Insensitivity To Distortions

The results of the preceding experiments show that for regular objects, it is virtually impossible for observers to detect projective distortions of their virtual dimensions. The extent of this insensitivity is revealed by a series of signal detection experiments undertaken to assess the sensitivity to geometric distortion. The method used was a modified stair-case scaling procedure. The rectangular solid described above under 10 different degrees of distortion were projected on a CRT screen. Subjects were asked to simply indicate whether the depicted object appeared distorted (under various criteria). If the subject responded no, the experimental program increased the degree of projective distortion. If the subject responded yes they saw some distortion on two successive trials, the amount of distortion was decreased. This procedure effectively tracks the $d' = 0.707$ point. The intent was to compare different distortions that corresponded to a constant value of d'.

In three initial experiments, using different definitions of distortion, it was impossible to obtain any measure of d'. Magnifications resulting in a thirty-fold compression of virtual space were not reported as distorting the objects.

To simplify the task, the procedure was changed to a two-alternative forced choice paradigm, and only one object (a cube) was used in place of the series of rectangular solids. Pairs of cubes were presented successively. One was undistorted (i.e. was projected to the viewing point), the other was determined to the extent determined by the staircase procedure. Using this procedure is was possible to make a crude estimate of sensitivity. The average value of distortion which corresponded to a d' of 0.707 was magnification equal to 2.8 for compression of space, and magnification of 0.33 for expansion. Thus, virtual space had to be compressed or expanded by a factor of three in order for observers to discriminate a shape distortion at this low level of sensitivity. In addition, there was a great deal of intra-subject variability. There appears to be no fixed separation of the underlying signal and noise distributions, rather sensitivity changes greatly from trial to trial. The processes that are involved in recognition of regular objects appear to greatly interfere with the ability to judge displayed space simply on the basis of projected information.

Implications

The theoretical conclusions to be drawn from this work seem to be clear-cut. With irregular or unfamiliar targets, and novel visual display systems, the geometric projection is the major, if not sole, determiner of space perception based on graphic displays. For display applications intended for unusual environments, work must concentrate on increasing display fidelity. Discovery of basic processes in perception, especially in terms of the integration of several different sources of visual information (eg. binocular, monocular, motion-carried) is critical. In addition, I would like to see the growth of exploratory studies. We need to relate the kinds of results that I have reported to actual control activities. A pressing question concerns the relationship between perception based on graphic displays, and remote piloting and video maneuvering.

With familiar display systems, our results suggest that geometric distortions can be discounted by the perceptual system. The discrepancy between the actual viewing point for a display and some assumed correct viewing point is used to eliminate the effects of distortion in space perception. An obvious, but important question concerns the nature and amount of experience that maximizes this effect. How can we train display operators and users to make them maintain perceptual accuracy in spite of geometric distortions?

For regular, familiar target objects, the categorization of these objects may reduce or eliminate sensitivity to spatial information. This raises important questions. What is the interaction between training and sophistication, and the ability to accurately use spatial information? Can we, for certain applications, degrade the fidelity of a display effectively. If details of spatial information are unimportant in some instances, can we save display and computing costs by using symbols rather than accurate graphic representations. In a related vein, if sensitivity to distortion is low in some cases, can we more effectively use bandwidth by updating displays only when the displays are *perceptually* different.

Future challenges lie in exploratory developments making use of, and further driving additional basic research.

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DOT AND LINE DETECTION IN STEREOSCOPIC SPACE[1, 2]

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ABSTRACT

This report presents the results of a series of five experiments in which we sought to determine the effect of the spatial and temporal attributes of a dotted stimulus form on its detectability when masked by random dotted visual noise. The stimulus consisted either of a single dot that was repetitively flashed or of a straight line of seven dots. The number of noise dots, the interval between stimulus dots, dot position, trajectory direction, and regularity of the spatial and temporal intervals were examined to determine what, if any, influence these stimulus properties exerted on stimulus detectability. Among the more surprising results of our study was the discovery of a remarkable insensitivity to the temporal irregularity of either a flashing single dot or a sequentially plotted line of dots. In addition, an equivalent insensitivity to spatial position irregularity in a line of dots was also discovered for the conditions used in this experiment. The significance of these findings to our understanding of visual image processing is discussed as well as possible applications of the methods and findings emerging from these experiments. Some suggestions for future research are also presented.

INTRODUCTION

The explanation, analysis, and understanding of visual form perception has been a major goal of experimental psychology throughout its history. This problem area is of central concern for the simple reason that our relationship to the external world is so dependent upon our ability to detect, recognize and classify stimuli as well as to choose an appropriate response to them. The history of the problem of form perception contains such illustrious names (sometimes extremely unexpectedly and sometimes quite expectedly) as Plato, Aristotle, Democritus, Alhazen, Seneca, Galen, Avicenna, Grossteste, Descartes, Da Vinci, Vesalius, Berkeley, Hobbes, Goethe, Muller, Hemholtz, Mach, James, Koffka, Wertheimer, and Gibson. There is also a large company of other historical figures, as well as a growing army of our contemporaries who have all been concerned with various aspects of the form perception problem.

In spite of this broad and long history of interest in the problem it is startling to realize how infrequently form perceptionists of the past or present have asked what is perhaps the fundamental question in studies of this genre. That question, whose neglect a number of our contemporaries (e.g., Zusne, 1970; Sutherland, 1967) have also noted, is -- What are the specific attributes or characteristics of a form that regulate its detectability or recognizability? Since the heydey of the Gestalt tradition, only a few psychologists have approached the study of visual form perception from this perspective (e.g. Rock, 1973; Brown and Owen, 1967), and then usually in a manner that emphasized some simple transformation (e.g. orientation), some general feature (e.g. compactness), or memory rather than the specific geometry of the stimulus form itself.

We believe that there are three main reasons for the neglect of this fundamental question. First, there is as yet no adequate means of quantifying what exactly we mean by the word "form". While some authors have suggested statistical families of forms that are alike in some general way, there is not yet any satisfactory single dimension along which form may be continuously measured comparable to electromagnetic frequency in color research or acoustic frequency in pitch research. Furthermore, neither the algebra of form suggested by Leeuwenberg (1969, 1971) nor the statistical algorithms for generating individual samples of broad classes of form (Attneave and Arnoult, 1956; Fitts and Leonard, 1957) have yet proved to be a satisfactory and acceptable means of quantification of form as an experimental variable. Forms, therefore, are usually generated in a more or less arbitrary manner and are often defined as experimental stimuli on the basis of some vaguely articulated ad hoc rule. This difficulty remains; our group has done no better than our predecessors in resolving this problem. As reported in a later section, our stimuli are also more or less arbitrary, although in some cases a natural measure (e.g., variance) does satisfy the immediate needs of a particular experiment.

The second reason that the specific attribute problem has been ignored is that heretofore there has been no easy way to manipulate even arbitrarily defined forms in stimulus displays. The advent of the laboratory computer, however, has ameliorated this difficulty and forms of great variety and complexity in two, three, and even four dimensions (i.e., X,Y,Z,t) are easily generated in many laboratories about the world today.

The third reason that the attribute problem has been neglected is that the manipulation of the form of continuous figures usually leads to a confounded outcome. That is, changing the global arrangement of the form also often covaries other local features or attributes (e.g., number of elements in a continuous line, angles, etc.) in a way that makes the actual causal relationship between a particular attribute of the form and a measure of the perceptual response uncertain. The use of dot patterns at least partially overcomes this problem. There are no local attributes other than "arrangement" when one is dealing with dot patterns; as long as the number of dots remain constant, all of the other aspects of the stimulus can be subsumed under the single factor. On the other hand, "arrangement", however singular, is not itself a simple term; it is at least as complicated as "form" and it may involve multidimensional variation when a single attribute is changed. Nevertheless, dot patterns can be manipulated in a reasonably straightforward manner.

At present our laboratory is carrying out a program of research aimed at elucidation of the factors influencing the detection of dotted forms in a dynamic stereoscopic space. Our observers perceive what appears to them to be a three dimensional (cartesian) volume in which some of the stimuli may be moving or flickering. This temporal property makes our experiments four dimensional, but in an "Einsteinian" rather than a "hyperspace" context. That is, our "space" is one defined by three spatial coordinates and one temporal one, and not four spatial ones. Our current four dimensional studies are an outgrowth of studies carried out earlier on analogous detection tasks in two dimensional space (as summed up in Uttal, 1975) and others (Uttal, Fitzgerald and Eskin 1975, A; B) in which we examined some of the fundamental properties of stereoscopic space itself using random dot stereograms in the tradition established by Julesz (1960; 1971).

One of the most important aspects of both the earlier and the present work is that we conceive of it as being quite limited in scope. That is, we are not studying all stages of form perception in these experiments. As will become evident when we discuss our experimental paradigm, our concern is only with what is a putatively "primitive" stage of form detection and the stimulus attributes that affect that stage. It is also important to appreciate that our goal is to study form perception and not short term memory or stereopsis themselves. Others such as Hogben (1972), Di Lollo (1980), and Jonides, Irwin, and Yantis (1982) share with us an enthusiasm for the dot as a research tool. However, our goal here is to use persistance, masking, and binocular disparity as vehicles to explore the perception of form rather than short term visual memory, the target of their studies. This is a goal we share with Lappin and his colleagues (Lappin, Doner, and Kottas, 1980; Falzett and

Lappin, 1981) and Johansson (e.g., 1978) who also use dot patterns as a means of studying form perception.

More specifically, the long term goal of our project is to determine how we detect dotted forms in a volume and to infer from these data, how we see forms in general. We plan to achieve this goal by examining the detectability of static and dynamic single dots, dotted lines, dotted surfaces, and dotted solids in a variety of masking environments. In particular, we are attempting to determine what aspects of the spatial and temporal arrangement of these dots influence their detectability when they are embedded in camouflaging visual noise made up of randomly positioned dots or dot arrays. Our hope is that the results obtained in this highly abstract stimulus situation will generalize to other kinds of visual stimuli, and that what we learn here will tell us something about how we see all kinds of forms. In the particular studies that are presented in this report we are specifically concerned with determining the effects of the spatial and temporal characteristics of single dots and dotted lines on their detection in noise that consists of briefly presented, randomly placed, single dots. Our experimental paradigm is thus a masking experiment, however, it is not intended to be a study of masking per se. Masking in this case is but the vehicle we use to study form detection.

In the earlier work (Uttal, 1975), the two dimensional analog of the present stereoscopic experiments, we were successful at proposing a mathematical model based on the autocorrelation function that was capable of predicting the rank order detectability of sets of targets. We also hope to extend that model, or some modification of it, to the multidimensional case embodied in the dynamic stereoscopic stimulus space in which our observers now operate. However, these initial experiments have only begun to provide the information required for such modeling and, therefore, this report will not speak to that theoretical part of our task.

We report here the results of five experiments concerned with the detection of dots and dotted lines. In Experiment I, we consider the detectability of evenly spaced dotted lines as a function of their direction and the magnitude of regular (equal) temporal intervals between the plotting of the sequence of stimulus dots in successive equally spaced locations. This is the master experiment for the dotted line study. It provides the basic parametric data against which the results of the other experiments will be referenced. Experiment II explores the effects on detectability of introducing irregularity into the temporal intervals between the successive dots of a dotted line. Experiment III determines the effect of introducing irregularity into the spatial separations between the successive dots of similar dotted lines.

Experiments IV and V deal with the detectability of repetitively flashing dots positioned at a single point in space. Experiment IV, like Experiment I is the master experiment that provides the basic parametric data for flashing dots. Experiment V, like Experiment II, investigates the effect of irregular temporal intervals but in this case also for only a single dot. In both Experiment I and IV we have also parametrically varied the density of the masking noise to determine the effect of this very important variable and to determine if there are any discontinuities in the detectability functions over the range of noise densities used in these experiments.

METHOD

Observers. In each of the experiments we report here, at least three and usually four undergraduate students at the University of Michigan were used as paid observers for at least one academic term. Each was tested for normal stereoscopic vision with an anaglyphic screening procedure (Figure 8.1-2* from Julesz, 1971) and self reported normal or corrected refraction. One observer, however, was dissociated from the project after demonstrating adequate stereopsis with anaglyphs, but failing to display discrimination in the computer controlled task.[3] The data reported here are from several groups of observers in two sets of experiments carried out several years apart. Adequate replication of all of the older work has been carried out to assure that no significant difference in results occurred as a result of new procedures or equipment. (In the present report we describe only a new version of the instrumentation.) All observers were pretrained with unmasked versions of the stimulus forms used in each experiment for several days prior to the actual data collection sessions.

General Procedure. All of the experiments reported here were carried out using a two alternative, forced choice, dot-masking paradigm in which the percentage of the total number of trials in which the stimulus forms were correctly detected was the criterion of performance. Stimulus forms to be detected were constructed of one or seven prearranged dots. These stimulus forms are presented hidden in varying numbers of randomly placed masking dots - subsequently referred to as visual noise. The organized stimulus forms (e.g., a single repetitively flashing dot or sequentially presented straight line of seven dots) are thus interspersed both temporally and spatially among the random masking dots. The masking dots are always presented at constant interdot temporal intervals; the temporal and spatial regularity of the stimulus dots are both experimental variables in the present study.

Figure 1 shows a typical dotted line stimulus form consisting of seven dots presented in four stereoscopic displays in successively higher levels of visual noise. The observer's task in each case is to report in which of two sequential stereoscopic presentations the stimulus form is located. Each presentation is presented as a dichoptic pair of images that, when perceptually fused, creates the impression of a cubical volume in which the dots constituting the stimulus forms and the random dotted visual noise appear at times and positions depending upon the design of the particular experiment. The right and left-eyed images are presented on horizontal halves of a split screen oscilloscope coated with a high speed P-15 phosphor. The observer views the two images through prism lenses that are individually adjusted for comfortable convergence for each session. A septum divides the two halves of the screen so that neither eye sees the field of view of the other eye.

A trial consists of two presentations; either the first or the second presentation contains a stimulus form (a repetitively flashing dot or a line of seven dots) plus visual noise, in which case the other presentation contains exactly the same noise pattern plus an additional number of randomly placed "dummy" dots. The number of dummy dots is equal to the number of dots in the stimulus form and limited in spatial extent to the maximum and minimum values of the dots of the stimulus form. Dummy dots are presented at the same time as the stimulus form dots would have occurred -- timing information being transposed from the stimulus dot file to the dummy dot file without change during the course of a single trial. In this manner, both presentations contain the same number of dots and temporal patterns. Stimulus form alone constitutes the sole difference between the two alternative presentations. The observer's task is to specify in which of the two presentations the organized (as opposed to the dummy) stimulus form occurred.

The sequence of visible events in each trial is presented in a precise order. First, a single fixation-convergence dot located at the mathematical and stereoscopic center of the apparent cube is illuminated for one second. The purpose of this dot is to assist the observer to align his eyes so that the subsequent stimulus information is properly registered for stereoscopic viewing. The strong perception of a dot filled cube obtained in this experiment indicates that this was a successful strategy in spite of the very brief exposure of the individual dots: Only 50 microseconds elapse before the image fades to less than 1% of its initial luminance on the P15 phosphor according to the manufacturer's specifications. Immediately following the display of the fixation-convergence dot, the first of the two presentations occurs. Each presentation lasts for 1 second during which masking noise dots are continuously presented at equal intervals. Because of the persistance of the visual system's response the apparent cube appears to be filled with a varying number of dots in random position, an illusion not unlike a flurry of snowflakes. The particular stimulus form chosen determines when, as well as where, its constituent dots are plotted within this flurry of masking dots. The first presentation is then followed by a one second period in which the solitary fixation-convergence dot is again presented. The second of the two presentations then occurs. Following the second presentation the screen remains dark until the observer responds by depressing one of two hand held pushbuttons indicating that he believes the stimulus form is in the first or second presentation respectively. At that point, a "plus" or a "minus" indicating either a correct or incorrect choice is briefly flashed on the oscilloscope. The cycle then repeats.

The entire experimental procedure is run totally automatically. After the control program has been initially loaded from disc memory into the working memory of the computer at the beginning of each day, the observer signs on at the computer terminal and begins the experimental session by depressing either one of the two response buttons. At the end of fifty minutes the observer terminates the session and the resulting data are immediately analyzed by the computer and printed. Pooled data from several observers and/or conditions are subsequently analyzed by another more comprehensive data analysis program.

Apparatus. The stereoscopic stimuli used in this experiment are generated by a hybrid computer system consisting of a Cromemco System 3 digital microcomputer and a subsystem of Optical Electronics, Inc. analog computer components. This hybrid computer approach circumvents one of the most difficult problems in the presentation of this kind of haploscopic stimuli. While it is not particularly time consuming to generate the tabular representation for any single dot or group of dots in a digital computer (X,Y,Z, and t coordinates can be generated by simple algorithms or prestored information) the construction of the actual real time analog representations of such mathematical abstractions is a much more difficult programming task. This difficulty is exascerbated in the highly demanding sub-millisecond real time environment we sought to achieve in the present study. The X,Y,Z and t coordinates for each dot internally represented in the computer must be transformed into two sets of two-dimensional coordinates (X_L,Y_L,t and X_R,Y_R,t) with the proper disparity, perspective, and separation to project a haploscopic pair of images at the proper locations on the two halves of the oscilloscope. Each pair of dots in these images must be capable of being processed by the visual system into an illusion of three dimensional space.[4] The transformation from X,Y,Z, t to X_L,Y_L,t and X_R,Y_R,t involves extensive trigonometric calculations that would quickly overload the capacity of all but the largest computers if attempts were made to carry them out in real time.

The analog subsystem (shown in Fig. 2) provides a means of finessing this digital processing overload difficulty. The trigonometric problem is solved by means of analog circuitry in real time whenever the signals to plot a haploscopic pair of dots on the oscilloscope are required. It is only necessary to provide this subsystem with the analog voltages representing the three-space coordinates X,Y,Z at the appropriate time. These analog voltages are easily and quickly obtained from the internal digital representation by means of high speed digital to analog converters. In our hybrid computer the digital to analog converter used is the California Data Corporation DA-100, a four channel system. Each channel is capable of converting any single dimension of the digital representation into the equivalent analog voltage in approximately three microseconds.[5] Three channels of the system are used to convert the X,Y,Z dimensions and one to regulate the spatial separation between the left and right eye oscilloscopic images. The Optical Electronics Inc. components carry out this conversion in what is easily "real time". Disparity and perspective were adjusted with external regulating potentometers and kept constant throughout the experiments.

The band pass (DC to 500k Hz) for the analog Optical Electronics Inc. units is such that the entire set of trigonometric computations is carried out in a few microseconds, a duration comparable to the settling time of the entire electronic system used in the study and to one or two average digital computing instruction execution times. One thus has only to wait for one or two computer instructions before sending an intensify signal (obtained from one bit of a parallel output port) to the oscilloscope to maintain good dot quality. The speed of generation of haploscopic pairs of left and right eye images is thus constrained only by the minimal digital computer programming required to read information from an internally stored table of X,Y,Z,t values (all of which had either been computed or arbitrarily generated prior to the trial) to the digital to analog converters.

The times at which the stimulus form and visual noise dots in each trial are presented are controlled by a system of three real time clocks located in the digital computer. The first clock regulates the times at which dots comprising the stimulus forms will be plotted. Each dot of the stimulus is represented, as we have noted by four coordinates (X,Y,Z,t). The t value is used to set this first clock so that the computer will be interrupted at the appropriate time from a waiting routine to plot the left and right eye images (X_L,Y_L, and X_R,Y_R) of X,Y,Z,t. The second clock is set to interrupt the computer at regular intervals -- defined at load time by the experimenter. This is the interval between the regularly spaced (in time) noise dots. These randomly (in space) positioned dots are plotted continuously during the entire period of each stimulus presentation -- one second as controlled by the third clock.

The field of view presented to each eye on the oscilloscope screen is shielded by a black paper through which a pair of 5.4 deg x 5.4 deg apertures had been cut for the left and right image respectively. The viewing distance from the observer's cornea to the oscilloscope surface is 31.75 cm. The screen is far enough from the observer and the persistance of the oscilloscope is short enough that each dot appeared to be virtually point-like in both time and space. Luminosity was adjusted initially with a Salford S.E.I. photometer to approximately 0.1 candles/m^2.

The two pushbuttons used by the observer to respond are connected to Schmitt triggers designed to smooth switch contact "bounce." The outputs of the Schmitt triggers are fed to the input of a parallel bit input port of the computer for acquisition and processing.

<u>The Perceived Cubical Space</u>. Stereoscopic depth is defined by the disparities between X_L,Y_L and X_R,Y_R for each dot. Retinal disparity, however, does not define absolute depths but rather cues the observer to relative depths; i.e., a dot may be perceived in front of or in back of the reference depth (the point in depth at which the lines of sight converge). Furthermore, in the hybrid computer system utilized in the present study, the electronic disparity adjustment is uncalibrated and arbitrary. It is, therefore, necessary to calibrate the actual disparity of dot pairs by direct measurements from photographs of special test patterns on the display screen and from measurements of the distance from the observer's eye to the display screen. These angular measurements are then related to the Z axis values stored within the computer. It should be noted that this relationship between disparity and internally represented Z values is accurate only for our system and as it is adjusted for these experiments. Within this constraint, we determined that if the observer fixated on the fixation-convergence dot centered in the cube, then the maximum crossed relative disparity for a dot positioned on the front surface of the apparent cube was 14 min. of visual

angle and the maximum uncrossed disparity for a dot positioned on the rear surface of the apparent cube was also 14 min. of visual angle. These maximum crossed and uncrossed disparity values were arbitrarily chosen so that the perceived space appeared as close to an apparent cube as possible. Because of the several stages of transformation involved, all disparity values should be considered to be approximate. Furthermore, in some of the experiments reported here less than this full range of disparity was utilized.

EXPERIMENTAL DESIGN AND RESULTS

Experiment I.

Design and rationale: Experiment I is the foundation study for all experiments involving straight lines. In particular, this first experiment was designed to examine the detection of regular dotted lines in a visual noise filled stereoscopic space. Regular dotted lines, for the purpose of this experiment, are defined as those in which the dots are separated by equal intervals in both time and space. Fig. 3 displays in a graphic manner the four different diagonally oriented dotted line stimuli that were used in this experiment superimposed in a single drawing. However, it must be remembered that only one of these lines is used in any one stimulus trial. It always consists of seven dots. The outer outline cube in Fig. 3 represents the total extent of the volume in which the dotted visual noise is evenly distributed. This apparent cubicle volume is defined by the 5.4 deg by 5.4 deg areas presented to each eye in the X-Y plane and by disparities ranging from 14 minutes (crossed) to 14 minutes (uncrossed). Stimulus forms are presented in the slightly smaller volume indicated by the inner outline cube. The X and Y dimensions of the smaller cube are both limited to 3.25 deg. The apparent depth of the first and last dots of each diagonal line is set by disparity values of 12.25 min uncrossed and 12.25 min crossed respectively. The dots of each stimulus line are sequentially plotted from the back plane of the inner cube to the front plane as indicated by the arrow heads in Fig. 3. Neither the inner nor outer outline cubes are ever visible to the observer.

The direction of the dotted stimulus line is one of the parameters manipulated in this experiment. We explored this variable to determine if visual space is isotropic for this kind of visual information processing. Three other parameters influencing line detection, however, were the main targets of our research in this experiment. These three were plotting interval, noise density, and viewing condition. To examine the effect of interval, the seven dots composing each stimulus line are plotted in sequential order with the delays between successive dots varying from trial to trial. The intervals used in this experiment include 10, 20, 30, 40, 50, 60, and 70 msec respectively. The middle dot -- the fourth -- is always plotted at the temporal midpoint (t=500 msec) of the presentation interval. At the shortest interval, the entire line of dots appears to the observer to be plotted simultaneously. At longer intervals, the dots appears to be successively plotted giving rise to an increasingly strong impression of a single dot in apparent movement, but at a progressively slower velocity as the selected interdot interval increased.

A major reason for studying the effects of interval is to compare what a priori might have been hypothesized to be compensatory effects of apparent motion on non simultaneous dot plotting. We know that simultaneously appearing lines of dots are easily detected, and it is obvious that there should be some degredation of line detectability at very long intervals. There was, however, the possibility that an increase in apparent motion might compensate for the loss in simultaneity. It was not possible, therefore, to predict at the outset with any certainty what the effect of interval would be.

All of the four directions and the seven intervals used in this experiment are presented in each daily session. On seperate daily sessions, however, the two other parameters -- viewing condition and noise density -- are varied. To determine the effects of viewing condition, each daily session was repeated six times at each noise density -- twice using dichoptoptic viewing (in which stereopsis was possible) and twice using an eye patch over each eye so that only monocular cues were available. Our purpose here was to determine what advantage, if any, was gained from stereopsis. Five different noise densities were chosen such that the stimulus line was embedded in 125, 166, 250, 500, and 1000 dots per second respectively in this order. Following the descending series, the entire experiment was repeated in reverse order. Thirty sessions (3 viewing conditions x 5 noise levels x 2 series) were thus required to complete this experiment.

Results: The major results of Experiment 1 are plotted in Figs. 4, 5, 6, 7, and 8 in order for masking noise densities of 125, 166, 250, 500, and 1000 dots respectively. On each of these graphs, the abscissa represents the temporal interval between plotting each of the dots making up the stimulus line. The ordinate represents the proportion of trials in which the observer selected the correct presentation; i.e., the one in which the stimulus line rather than the dummy noise, was present. The three parametric curves in each of these figures represent the data obtained for the three viewing conditions on three successive days. The data obtained from all four line directions have been pooled to produce these graphs.

Three main results are to be noted in this set of figures. First, the general trend produced by varying noise density is evident. The overall performance of the observers decreases as the noise density increases. Under optimum conditions of minimal noise, binocular viewing, and the briefest interdot intervals, (data typified by the left hand portion of Fig. 4) observers perform at the 95% correct detection level, a score that is about the best that can be expected in experiments of this kind. On the other hand, when the visual noise is the densest, the temporal intervals between the dots of the stimulus line are long, and only monocular viewing is allowed (as exemplified by the right hand side of Fig. 8), observers perform at virtually chance levels (50% for the two alternative forced choice design used here).

Second, the effect of viewing condition is also clear. For virtually all experimental conditions, there is a clear advantage obtained by stereoscopic viewing in this detection task. This effect is modulated by ceiling effects for low noise densities and floor effects for high noise densities, but the stereoscopic advantage is pervasive throughout all five graphs. This advantage is substantial: in some conditions it is greater than 12 percentage points, a value which is over a quarter of the range of responses obtainable in this type of experiment. On the other hand, differences between the two monocular viewing conditions are small.

Third, and most important for the purposes of this study, there is also an unequivocal and major effect of dot plotting interval evidenced in this experiment. Any hypothetical compensation effect of apparent motion is obviously swamped out by the loss of the much stronger influence of simultaneous plotting. Dotted stimulus lines become progressively less detectable as the interval between them increases. Indeed, the slope of the function relating detectability and interdot interval is virtually constant. There is not the slightest suggestion of even a slowing of the diminution in detectability at long intervals -- a phenomenon that would have been expected if apparent motion had any significant influence on detectability. Whatever detection mechanism is at work here, apparent motion can not substitute for simultaneity. As we shall see later, however, irregularities in time and space do seem to be smoothed over by stimulus conditions that produce apparent motion.

Figure 9 displays the results of the other major parameter of this experiment -- track direction. Only data from the 166 noise dot/sec condition have been presented here, but all other dot densities produce similar results. These data strongly suggest that visual space is isotropic -- there is no advantage accruing to any of the four track directions for the perceptual mechanisms underlying dotted line detection. This insensitivity to orientation and direction in three dimensions is in accord with our earlier findings (Uttal, 1975) for two dimensional stimuli.

Experiment II.

Design and Rationale: Experiment II investigates the effect of temporal irregularity on the detectability of a dotted stimulus line. The main independent variable in this experiment is variability of the intervals of time between the successively plotted dots of the line. The mean interval is arbitrarily set at 50 msec. This value gives a moderately high average detection score of approximately 85% for the group of observers used in this experiment. Interval irregularity is measured in terms of standard deviation from the mean 50 msec value. Standard deviations of 0, 2.9, 6.45, 10.4, 14.4, 16.8, and 20.4 msec. are utilized. A standard deviation of 16.8, for example, corresponds to an interval sequence of 75, 35, 25, 50, 65, and 50 msec respectively. The masking noise density is kept constant throughout Experiment II at 250 dots/sec and only the dichoptic viewing condition is used to test the detectability of straight lines of seven evenly spaced colinear data. Each observer was run twice under these conditions.

Results: Figure 10 depicts the results of this examination of the effects of temporal interval irregularity on dotted line detection. Surprisingly, there is virtually no observable effect of irregularity measured in this experiment. The visual system, however sensitive it may be to mean interval, appears to be totally insensitive to even the most extreme temporal interval irregularities when measured by this dotted form detection paradigm at a 50 msec mean interval.

Experiment III.

Design and Rationale: In our earlier work (Uttal 1975) spatial irregularity had been shown to be a powerful determinant of the detectability of straight lines in two dimensional space. We had initially assumed, therefore, that spatial irregularity would also be a powerful influence on detectability and had not planned to attempt to confirm this presupposition. However, the surprising results of Experiment II suggested that this hypothesis should indeed be verified and measured. Therefore, Experiment III was designed utilizing dotted line stimuli consisting of seven dots with regular temporal intervals, but irregular dot spacing. In this experiment, the standard deviation of the spacing is used as the independent variable; specifically, the spatial coordinates of an evenly spaced dotted line are changed to create irregular intervals proportionately equivalent to the values of temporal irregularity used in Experiment II. That is, where there was a 10% increase in one temporal interval and a compensating 10% decrease in another temporal interval (designated as ±10%) in Experiment II, we introduced an equivalent 10% change in two spatial separations in Experiment III. Seven combinations of separation changes were used in this experiment defining progressively increasing spatial irregularity values. These combinations are ±0; ±10%; ±10% and ±20%; ±20% and ±30%; ±50%; ±30% and ±50%; and finally, ±50% and ±50%. Because of the arbitrary value of the Z-axis, no particular units can be associated with the actual Euclidean distances corresponding to these irregularity values (i.e., to add degrees of visual angle subtended in the X-Y plane to seconds of stereodisparity would be meaningless.) Therefore, we have simply designated the seven irregularity values as 0, 1, 2, 3, 4, 5, and 6 on Fig. 11. A single regular temporal interval value of 50 msec and a single noise level of 250 dots/sec were used in this experiment. Only the dichoptic viewing condition was used and each of four observers was run twice under these conditions.

Results: The results of Experiment III are plotted in Fig. 11. The outcome is even more surprising than that of Experiment II. These data indicate that there is virtually no effect of spacing irregularity when the dots in the line are separated by a period of time that is long enough to produce a substantial apparent motion! This is a remarkable result in light of the fact that the detectability of dotted lines in the two dimensional case in which all of the dots are presented simultaneously is extremely sensitive to spacing irregularity. Yet, in this dynamic three-dimensional case there is but the slightest suggestion (2 or 3%) of a diminution of the response accuracy at the greater irregularity values. In the two dimensional simultaneous dot presentation case, the difference obtained for comparable conditions was 12 to 14% (See Fig. 2-13 in Uttal, 1975).

Experiment IV.

Design and Rationale: Experiment IV is the foundation experiment for the study of the detectability of repetitively flashing single dots embedded within a volume of randomly placed visual noise dots (each of which flashes only once). Three independent variables are manipulated in this experiment. First, the interflash interval between successive flashes of the stimulus dot is varied. It must be remembered that the stimulus dot is distinguished from any of the random noise dots only by the fact that it is flashed 4 times in a single position rather than only once. The three regular temporal intervals between successive flashes are set at one of the values 50, 100, 150, and 200 msec for each trial. Stimuli with these four interval values are presented in random order during each daily session. The stimulus dot in each presentation is always timed such that the stream of repetitive flashes is centered at the temporal midpoint (500 msec). The same time pattern was used in the dummy position presentation, but no dot position was repetitively flashed in this case.

The second independent variable is the position of the dot. The flashing dot occupied any one of the seven possible positions shown in Fig. 12 in each trial. The outer cube shown in this drawing delimits the 5.4 deg x 5.4 deg x 28 min. disparity) cube perceived by the observer. The inner outline cube depicts the seven possible locations of the flashing dot in each trial, but it, like the outer outline cube, is not visible to the observer. For example, position 1 is situated at the perceived center of the apparent cube, i.e., the location of the fixation-convergence point. As another example, location 5 is centered on the right hand side of the inner outline cube. Which of the seven positions is used in each trial is chosen randomly prior to each trial.

The third parameter varied in this experiment is the masking noise density. Densities of 10, 14, 20, 33, and 100 dots/sec were utilized. Since no differences were observed in left and right eye monocular viewing, and to provide a check that monocularity per se was not accounting for the difference obtained in other experiments, our control for stereopsis in this case was binocular viewing. Thus, only two viewing conditions are used in this experiment, the standard dichoptic one which allowed stereoscopic perception and the binocular one in which both of the observer's eyes viewed the left eye image of the stereoscopic pair. In the binocular condition, therefore, no disparity, and thus no perceived depth, is present.

The experiment was designed so that each daily session included all possible combinations of the 7 positions and 4 flashing rates presented in random order, but viewing condition and noise density were held constant each day. The experiment was performed dichoptically and then binocularly on alternative days. On successive pairs of days, the noise density was varied starting from the minimum value of 10 dots and ending on the 9th and 10th days with the maximum values of 100 dots/sec. The entire experiment was then repeated varying masking noise dot densities in the descending order.

Results: The results of this foundation experiment for flashing single dots are plotted in three separate graphs. Figure 13 displays the effect on detection of varying the masking noise density. As expected, there is a progressive decline in detectability of the flashing dot as the noise density increases. Nevertheless, it is somewhat surprising to note that a single dot flashing only 4 times is still partially detectable (i.e, at better than chance levels) even though it is camouflaged by the frenetic blinking of 100 random dots. The distinct advantage of the stereoscopic view over the binocular one is also clearly evidenced here just as stereoscopic viewing proved to be superior to the monocular viewing conditions in Experiment I. However, the disadvantage obtained with binocular viewing in Experiment IV is only half of that obtained in the earlier experiments when monocular viewing was used on the central condition.

The influence of the position of the flashing dot stimulus is plotted in Fig. 14. The only dot position that appears to have any substantial advantage over the others is position 1 -- the one located at the very center of the inner cube. The only dot that appears to have any substantial disadvantage is the one located in the bottom rear lower corner of the inner cube. Other than that, all dot locations appear to have roughly equal probability of detection. However, once again the stereoscopic advantage is clear -- only position 4 seemed to not display this advantage and we believe this to be a spurious fluctuation rather than a true nondifference.

Finally, Fig. 15 plots detectability for all data collected at all noise levels plotted as function of the interflash interval. Most interestingly, the resulting curve is non monotonic. Peak detectability occurs at an interval of 100 msec and thus there is a sharp decline in detectability for longer interflash intervals and a less sharp decline for shorter ones.

Experiment V.

Design and Rationale: Experiment V is the analog of Experiment II in that it is concerned with temporal irregularity. In this experiment, however, the regularity of the temporal intervals between successive flashes of a dot stimulus positioned at a single point in space (rather than along a dotted line) is varied as the independent variable. The temporal irregularity is measured in units of standard deviation, about a mean flicker interval of 100 msec. Six values of this measure are used including 0, 4.1, 8.2, 12.2, 16.3, and 20.4, msec. The combinations used here, therefore, are $\pm$0%; $\pm$5%; $\pm$10%; $\pm$15%; $\pm$20%; and finally $\pm$25%. In order to use this full range of six irregularity values, the number of dot positions utilized in each daily session in Experiment V had to be reduced from the seven locations used in Experiment IV to four. The four positions utilized are those numbered 1, 4, 5, and 6 in Fig. 12.

Results: Figure 16 displays the results of Experiment V. Once again, as in Experiment II there is a remarkable and surprising insensitivity to wide variations in the regularity of temporal intervals between successive flashes of a single dot. The curve is virtually flat over the full range of of interval irregularity values.

DISCUSSION

These then are the findings that we have obtained in our study of the influence of stimulus form on the detectability of dotted patterns in stereoscopic space. The discussion now presented is divided into two parts. First we will consider the significance of our work in helping to understand the nature of vision in general and dotted form detection in particular. We will then consider some practical matters upon which we believe our data impinges and make some suggestions concerning possible future research efforts.

Perceptual Significance. It is important to remind the reader that all of the experiments reported here are confounded by the presence of monocular cues. Both flashing dots and dotted straight lines are detectable to a certain degree in monocular viewing conditions. However, one of the major findings that has emerged from this study is our confirmation of earlier work (e.g., Smith, Cole, Merritt, and Pepper, 1976; Pepper, Cole, Merritt, and Smith, 1978) that this confounding is not total and that there is a substantial advantage in detecting orderly (in time or space) dots in a volume filled with masking dots. This result seems to be ubiquitous and uniform within the limits of statistical fluctuation of the kinds of experiments carried out in our laboratory. One has only to compare the last frame of Fig. 1 when viewed stereoscopically and when viewed monocularly to appreciate the advantage of stereoscopic viewing for complex stimuli of this kind.

How does one account for the advantage of stereoscopic viewing in the masking paradigm? The answer to this question is probably closely related to one that may be suggested to account for the data obtained by Fox and his colleagues (Fox, 1980; 1981: Lehmkuhle and Fox, 1980) for metacontrast and contour interaction and by Ogle and Mershon (1969) and Mershon (1972) for simultaneous contrast as a function of the apparent depth between the inducing and induced stimuli. The central idea in this speculative suggestion is that any explanation of these phenomena based upon peripheral lateral inhibitory interactions is incapable of accounting for the associated decline in the interactive effects and, therefore, the responsible process must be a function of the central nervous system. In these experiments the two dimensional attributes of the image projected on either retina remain constant as disparity changes; i.e., the horizontal spatial separation between the foreground and background elements of the stimuli remain nearly constant. Thus any putative peripheral interaction should remain constant. Nevertheless, there is a progressive reduction of the magnitude of both simultaneous and meta-type contrast as the apparent depth difference increases. Thus, the "distance" between the two interacting stimulus elements that seems to be significant is not the distance projected onto the 2-dimensional physical plane of the retina, but rather the "true" volumetric distances in the perceptually constructed X,Y,Z volume.

In our experiments, the same sort of explanation seems to hold. That is, the effect of the masking noise is not a function of its density in the physically projected retinal plane, but rather of its density in the apparent three dimensional space. Therefore, spreading the dots further apart in the perceptually constructed depth dimension is the equivalent of spreading them further apart in the projected plane. Since volumes have more constituent unit elements than planes, the average density of the masking noise must decrease when a plane is extruded into a volume even though there is no change in the number of visual masking dots present.

In a more philosophical vein, we should note that the results obtained by Fox and his associates, Gogel, Mershon, as well as those from both this present study and earlier studies from our laboratory (Uttal, Fitzgerald and Tucker, 1975b) supporting the perceptual equivalence of the X, Y, and Z axes represent an extraordinary outcome. These data jointly suggest that Z axis distances, constructed from indirect and nonisomorphic aspects (disparity) of the stimulus, are just as "real" in a perceptual sense as are the X and Y distances that do have a more direct and isomorphic physical counterpart (retinal distance). Considering that stereoscopic depth is the indirect result of invariance computations based on the magnitude of minute retinal disparities, the unavoidable conclusion to which we are compelled is that the X and Y distances may themselves also be "constructs" calculated on the basis of some equally indirect relationship between the retinal image and the perceived plane. It is, according to this point of view, only fortuitous that the perceived space appears to be isomorphic to the stimulus space in the X and Y dimensions. Thus, this line of thought suggests that there is nothing especially direct or real about X and Y, but, rather, they are as indirect as the Z dimension.

Pursuing this line of thought, the totality of our visual experience can thus be considered to be indirect, not only the obviously constructed dimensions that are computed from invariant coding relationships among alternative representations of the stimulus object. While this logic leads to a model of a perceptual world that is in practical terms no different than the classic deterministic stimulus-response point of view, it is substantially different in terms of the epistemological model that must be invoked to explain how we actually perceive.

Another less weighty aspect of our study concerns the different results that are obtained with binocular viewing (in which both of the observers' eyes see a same nondisparate stimulus) and with monocular viewing (in which one eye is covered with an eye patch). In general, binocular viewing is superior to monocular viewing (compare Figs. 4-8 and Fig. 13) by a factor of at least two. Theoretically, however, the information available in the two viewing conditions is identical since there is no disparity in the binocular viewing condition -- the two eyes are seeing exactly the same thing. The simple fact of binocularity of non disparate images, therefore, offers nothing in the way of additional stimulus information to the observer that is not in the single monocular image. Nevertheless, we have determined that the binocular viewing condition does have an advantage over the monocular one. This may be due to some subtle advantage in central nervous system processing that is gained when the images from the two eyes are identical. In other words, redundancy itself may be of value. However, the binocular advantage may also arise from artifacts of far less theoretical significance. Such uninteresting factors as simple distraction resulting from the very fact of the occlusion of vision to one eye or even the presence of the eye patch itself may be involved. The resolution of this matter is left to others. It is important to us only to note that, for our observers and in this kind of experiment, the substantial advantage of binocular (as opposed to dichoptic) over monocular viewing is an empirical fact.

Another outcome of the experiments reported here of interest in our search for an understanding of visual perception is the isotropic nature of visual space obtained in these experiments. There is no difference in the detection scores in Experiment I as a function of the orientation of a line of simultaneously presented dots nor of the direction of the trajectory of a sequence of dots traced out so slowly as to produce apparent movement. This insensitivity to orientation and direction in these three dimensional experiments is consistent with what we have observed in two dimensional space for similar dotted patterns (Uttal, 1975), but inconsistent with what many other students of vision had previously observed for continuous stimuli (as summarized in Appelle, 1972). It is, therefore, possible that the lack of continuity of the dotted stimulus forms we use is a special property and the extrapolation of this concept of isotropic visual space to continuous stimuli would be inappropriate.

One can speculate why this difference between dotted and continuous forms exists. One speculation leads to the suggestion that the very same attributes that produce to the advantages of dotted patterns also give rise to the observed differences in orientation sensitivity. Dots are isolated entities both in the mathematical and the neurophysiological senses; they are not "connected" to other dots in other locations in the field of view in the same way as are the elements of a continuous form. Rather, we see dotted forms because of their global arrangement. Thus each dot in the physical stimulus, in the projection on the retina, and perhaps even in the neural networks representing that dot, functions discretely and independently. These discrete points have no direction or orientation of their own. Only the global pattern, a property that is properly denoted as an abstraction, has direction and/or orientation. But, that abstraction has no physical reality, it only possesses an intangible organizational reality. Presumably this kind of form is so intangible that it does not activate the same mechanisms as do physically continuous stimuli. It is for this reason that the perception of dotted patterns may be insensitive to direction and orientation, in a manner quite different from the sensitivity exhibited in the perception of continuous lines and contours.

The next point in our findings to be considered concerns the difference in detectability of dotted lines with small interstimulus dot intervals (perceptually simultaneous) and lines with such long intervals that the sequential nature of the patterns becomes clear and apparent motion may even be experienced. As suggested earlier, one a priori hypothesis would have suggested that the apparent motion attributes of a stimulus might at least partially compensate for the reduction in apparent simultaneity. However, our data provide no evidence of such a compensatory effect. The greater the interval between the dots of the stimulus form, the less detectable the forms are, regardless of how strong the perception of a moving trajectory reported by the observer. The mechanism that detects coherent forms among dot patterns is better able to process information when it is presented simultaneously than when it is distributed in time. The strong effect of interval has also been confirmed in two dimensional space by Falzett and Lappin (1981).

It was, therefore, a somewhat unexpected outcome, in the context of the extreme sensitivity to average temporal interval between the dots just mentioned, to observe that the mechanism integrating dots into forms is virtually insensitive to the temporal regularity of the sequence of dots. Stimulus lines with evenly spaced 50 msec. intervals are detected only slightly better than lines with highly irregular intervals. This insensitivity to temporal irregularity exhibited in this detection task is also surprising in the context of the visual system's ability to detect brief gaps in a train of otherwise regular flashing dots (Uttal and Hieronymus, 1970).

Even more surprising was our subsequent discovery that spatial irregularity also produced only a minimal effect on detection scores for lines of dots plotted at intervals that would be expected to produce apparent movement. In some manner the visual system seems to smooth over both the spatial position and temporal interval irregularities programmed into the stimulus lines. We can speculate that this is accomplished by the same kind of mechanisms that are well known to account for path smoothing in apparent motion itself. Classic and modern studies of apparent motion have indicated that the apparent trajectory tends to be smoothed in such a way that the perceived pathway is more likely to reflect a good form (in the Gestalt sense) than the actual spatio-temporal form of the physical stimulus. This phenomenon has been formalized by Foster (1978) into a theory of apparent motion analogous to the calculus of variations used in mechanics. In his theory "perceptual forces" are minimized just as are physical forces in the physicist's calculus of variations. Obviously there is a considerable amount of future research that has to be done to substantiate and understand this surprising result. It seems to us particularly important that the experiment be repeated at other shorter inter-target dot intervals to see if the insensitivity to spatial irregularity disappears at shorter intervals where the apparent motion phenomenon is no longer involved.

One of the major hypotheses initially motivating this study was our expectation that since spatial regularity was such a powerful determinant of detectability in two dimensional space, so, too, should be spatial and temporal irregularity in three dimensional space. It was on this basis that we anticipated that any future three or four dimensional mathematical model of the processes we are studying here that is similar in concept to the two dimensional autocorrelation theory would be extremely demanding of computer time for its evaluation. However, if this initial finding of insensitivity to both spatial and temporal irregularity is generalizable to other conditions the model towards which we are working may be considerably simpler than we had anticipated.

In summary, our experiments describe a visual mechanism that has some extraordinary powers. The system seems to be extremely sensitive to mean spatial and temporal intervals. However, both spatial and temporal interval irregularity seem not to influence the kind of detection task we are using here when dot intervals are large enough to create apparent motion. This surprising outcome may be explained by the same sort of mechanisms that account for apparent motion, a phenomenon in which discrete and intermittent stimuli are perceived as smooth and continuous under the control of constructive mental process whose origins and mechanisms remain almost totally unknown.

Possible Applications.

Above and beyond whatever contribution our study makes to understanding the fundamental nature of visual perception, we believe that it may also have some useful and practical applications to other display-related problems. These potential applications emerge both from the technology that we have used to instrument these excursions in basic perceptual science and from the results we have obtained in these studies. In general, the three dimensional display methodology offers a means by which the computer can preprocess and integrate multidimensional visual information rather than imposing this processing load on the observer. The use of the computer to graphically display the three dimensions of spatial information in this manner makes for a much more realistic, direct, and compatible relationship than that obtainable with a plan position indicator (PPI) display. Not only is the relationship between the real environment and the display improved, but also the directness of the relationship between the observer's percept and the environment. To do otherwise loads the observer with an information processing task much better accomplished by the computer. The end result of using a two dimensional representation of the three dimensional world is to distract the observer's attention from the tasks he can perform better than the computer.

Perhaps there is no clearer instance of the urgent need for a three dimensional (rather than a two dimensional) presentation of spatial information than in the volumetric environment exemplified by either the air or undersea traffic control situations. Merging polar coordinate height (or vertical depth) information and plan position information from two RADAR systems is a relatively easy computational excercise. The techniques used in our experiments suggest that it would be no great technological feat to present that information stereoscopically. We are convinced that there are no computational or instrumentation difficulties in implementating such a device. The question then is, would such a device provide enough advantages to warrant the cost and effort of its development? While a full answer to this question can only be found in the laboratory, it seems clear that the possible reduction in information processing load required of the observer in these traffic control situations would be significant.

We should also mention that the particular technique we use here to construct three dimensional experiences is not unique. Our strategy is only one possible alternative approach. Others have been offered including Bolt Beranek and Newman's SpaceGraph (Sher, 1979; Huggins and Getty, 1981), hologram type devices, and Shetty, Brodersen, and Fox's (1979) anaglyphic method. Of course, certain advantages and disadvantages are characteristic of each device; each may fill some need better than the others.

As noted, the general advantage that all such three dimensional systems possess is that they drastically reduce the information processing load on the observer. Rather than observing displays with altitudes marked in numeric codes near two dimensionally located targets, the observer would be confronted with an apparent three dimensional display in which accessory numeric information representing height need not be separately processed. Furthermore, proximity would be much more directly evident, less dimensional recoding would be required, and the task would, therefore, be less stressful, less demanding, and require much less operator training to achieve a given level of competence than would the conventional two dimensional displays now in use. We believe that the advantages of such a system would be profound. In sum, these advantages include:

(1) Improved observer reaction times.
(2) Reduced observer information processing load.
(3) Enlarged traffic capacity.
(4) Reduced observer training requirements.
(5) Increased conspicuity of hazardous conditions.

Using modern computer graphic devices, other useful attributes can also easily be designed into such a display system. For example, proximity could be coded by color in a way that would very conspicuously indicate the imminence of dangerous traffic conditions. Trajectory extrapolation information could also easily be added to the stereoscopic display to indicate where future difficulties may be developing. In addition, a joystick controlled cursor could be added so that individual targets could be located in the three dimensional space of the stereoscopic display; the three spatial coordinates so targeted could then be displayed on digital readouts. Alphanumeric information could be plotted on the display as well. Figure 17 is a two dimensional projection of a hypothetical three dimensional display presented to give a more graphic idea of the sort of device we imagine would be useful in the traffic control situation.

It is our expectation that such a three dimensional device would be easy to use, would require less training, and would provide higher margins of safety in critical control situations. However, a considerable amount of empirical research is necessary to validate these presuppositions. In particular it seems necessary and appropriate to determine the limits of depth discrimination that are achievable with this type of display as well as the precision with which the three dimensional cursor can be used to determine the position of objects in the stereoscopically generated space. Determining the conspicuity of color and the ability of the observer to use three dimensional trajectory extrapolation are among the many other perceptual experiments that would have to be carried out to fully evaluate the advantages and disadvantages of these devices.

A second area of application has been suggested to us by T. Uttal (1982). Three dimensional displays of the kind we propose here would be of enormous help, she suggests, in reducing the complex data now obtained in studies of atmospheric physics. At present, inadequate attention has been paid to the use of dynamic, three dimensional graphic displays in this important area of science. Since time plays a particularly important role in this application, the possibility of animated displays, perhaps recalling previous sequences of atmospheric activity, is an exciting concept. Stereoscopic displays may provide a way to reduce the large scale computing requirements in atmospheric physics by substituting the powerful integrative abilities of the human mind for the ponderous parallel numerical calculations required in complex fluid dynamics problems. The idea of some future meteorologist studying a recurrently recalled record of the spatial and temporal history of a storm is an intriguing idea.

A third area of application of our findings may lie in two dimensional dynamic graphics. We also believe that the insensitivity to temporal and spatial irregularity that we have discovered for moving dots may have important implications for the design of future video displays. Future digital displays are likely to exhibit some of these characteristic distortions. Since it seems likely that these irregularities may be undetectable in the trajectories of moving objects, vast savings in engineering time and costs are likely if we determine the thresholds of visibility of those distortions.

To conclude this brief note on future applications, we should note that there have already been many developments comparable to the ones proposed here outside of traffic control, atmospheric physics, and video displays. Chemists routinely look at the three dimensional shapes of molecules and neuroanatomists have applied similar techniques to study brain structure. It is somewhat surprising that the potential applications we have noted here have not yet been the targets of similarly intense implementation efforts.

FOOTNOTES

1. This project is supported by Contract #N00014-81-C-0266 from the office of Naval Research, Alexandria, Virginia. We are especially appreciative of the cooperative support of the science officer Dr. John O'Hara.

2. We express our appreciation to Cheryl Slay whose editorial and typing skills made this a far better document than it would otherwise have been.

3. Earlier studies in our laboratory had suggested that a large proportion of possible observers were stereoanomalous. This anecdotal evidence was supported by Richards' (1970) contention that approximately 30% of the population may be deficient to at least some degree. A follow-up study, carried out in our lab by Millicent Newhouse -- our laboratory's ONR science apprentice -- has shown, however, that only 1 in 100 randomly sampled Ss was actually stereodeficient when carefully tested with an anaglyphic screening procedure. Patterson and Fox (1981) have also recently reported the same low level of stereoanomaly in the general population.

4. It is interesting to note that the transformation of the X,Y,Z,t internal representation in the computer to the X_L,Y_L,t and X_R,Y_R,t representation on the face of the oscilloscope is the inverse of what the visual system does when it coverts the haploscopic images (X_L,Y_L,t and X_R,Y_R,t) into an illusion of solidity. In neither case does a solid actually exist in three space, however. Certainly in the computer and probably in the "mind", volumes are "represented" in what is best described as a symbolic code.

5. To achieve this high speed conversion, we had to modify the delivered system by removing capicitors C10, C13, C16, C19 from the four digital to analog converter output stages.

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A

B

C

D

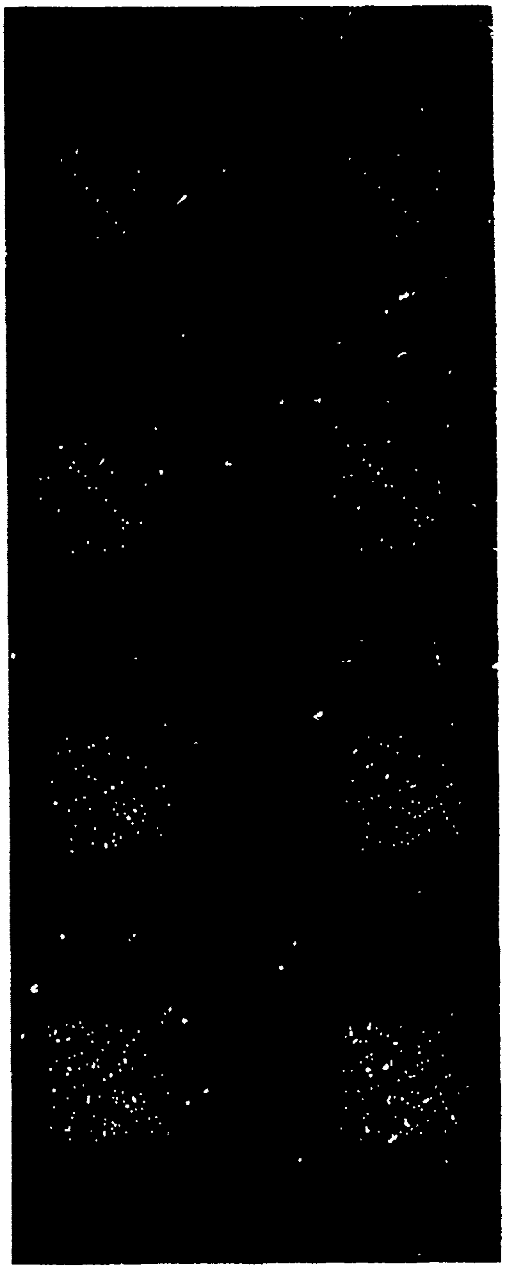

Figure 1. Four sample dotted line stimulus forms in different levels of dotted visual noise. (A) 3 noise dots/sec; (B) 20 noise dots/ sec; (C) 50 noise dots/sec; (D) 100 noise dots/sec. The noise dots and the stimulus form dots in the actual stimulus display may be distributed anywhere within the one second presentation duration. These still photographs obscure the dynamic quality of the display.

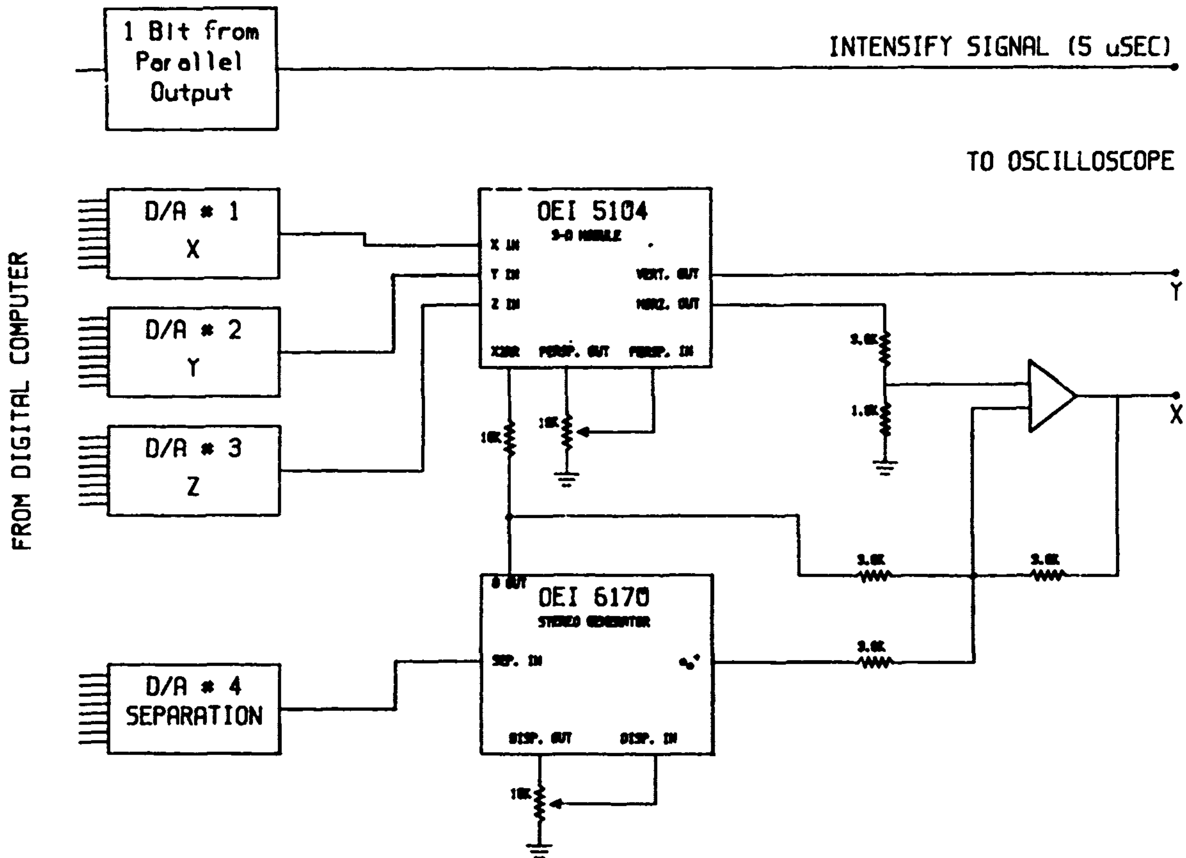

Figure 2. The analog subsystem of the hybrid computer. These components generate the stereoscopic displays. The OEI units (Mfd. by Optical Electronics Inc., Tuscon, Arizona) are interconnected by a passive network designed by the manufacturer. This system transforms the digital signals from the Cromemco System III microcomputer into analog voltages to control the plotting of the dichoptic images in real time without a prolonged period of digital computation. (Abbreviations on the OEI modules are designated in the manufacturer's manual.)

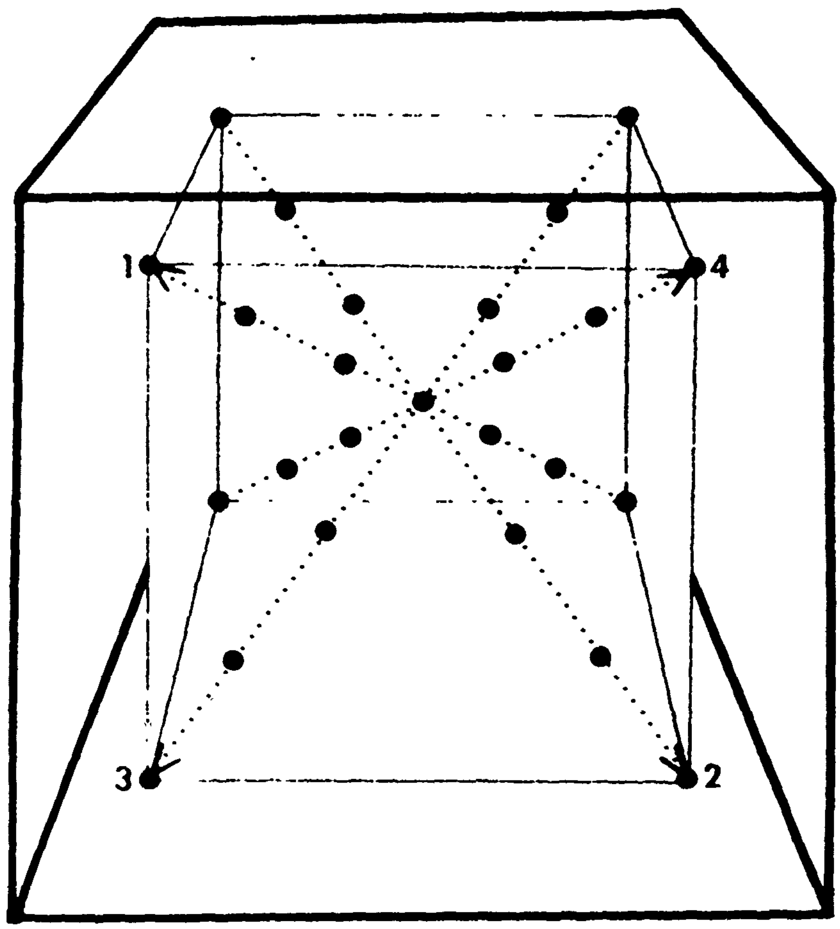

Figure 3. A graphic depiction of the four diagonal lines of dots used in Experiments I and II. Only one line was presented in each trial. The temporal interval between the dots of each line varied from values so small that the seven dots appeared to be simultaneous to values large enough to give the impression of apparent motion.

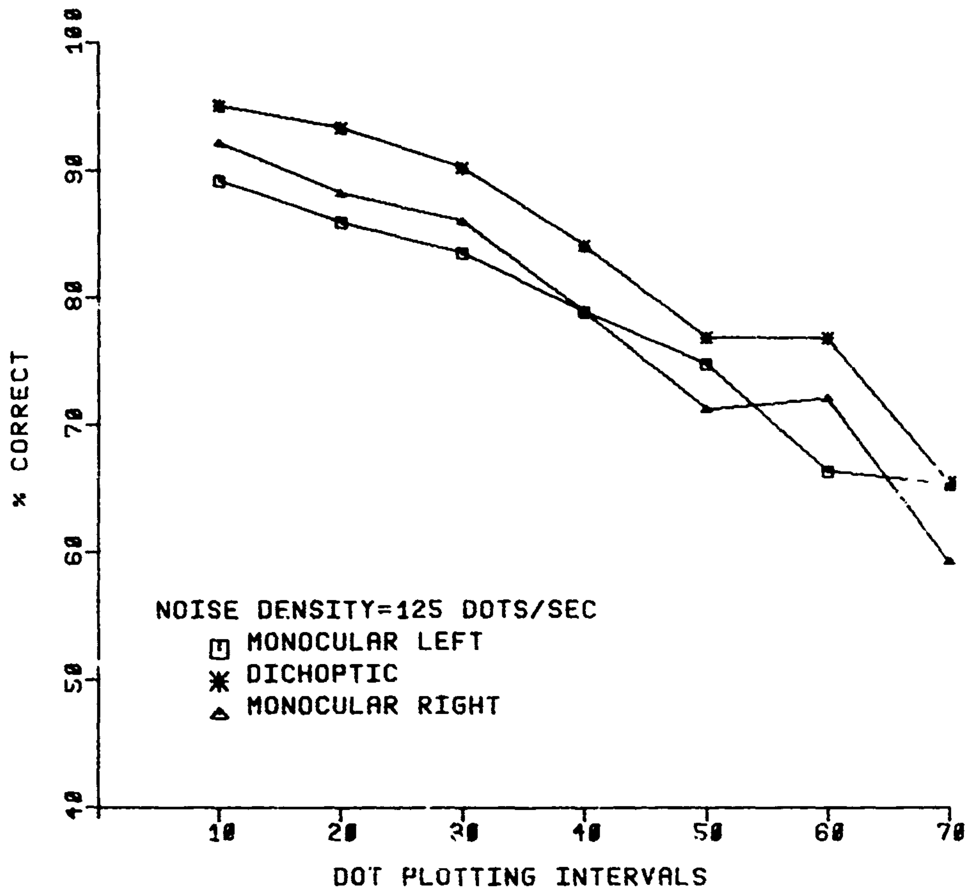

Figure 4. The results of Experiment I for noise densities of 125 dots/sec. The horizontal axis indicates the duration of each of the equal intervals between successive dots. The three curves are for dichoptic and left and right eye monocular viewing respectively. The vertical axis indicates the pooled average of all observers' scores for this condition.

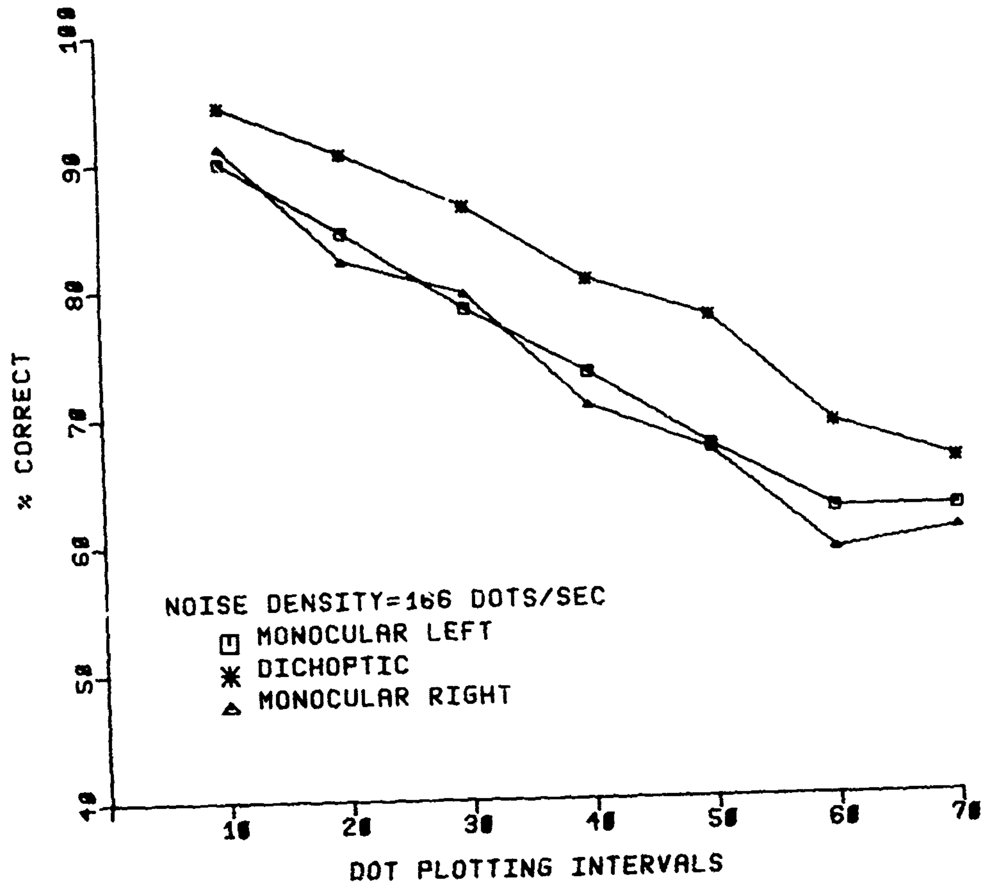

Figure 5. The results of Experiment I for noise densities of 166 dots/sec.

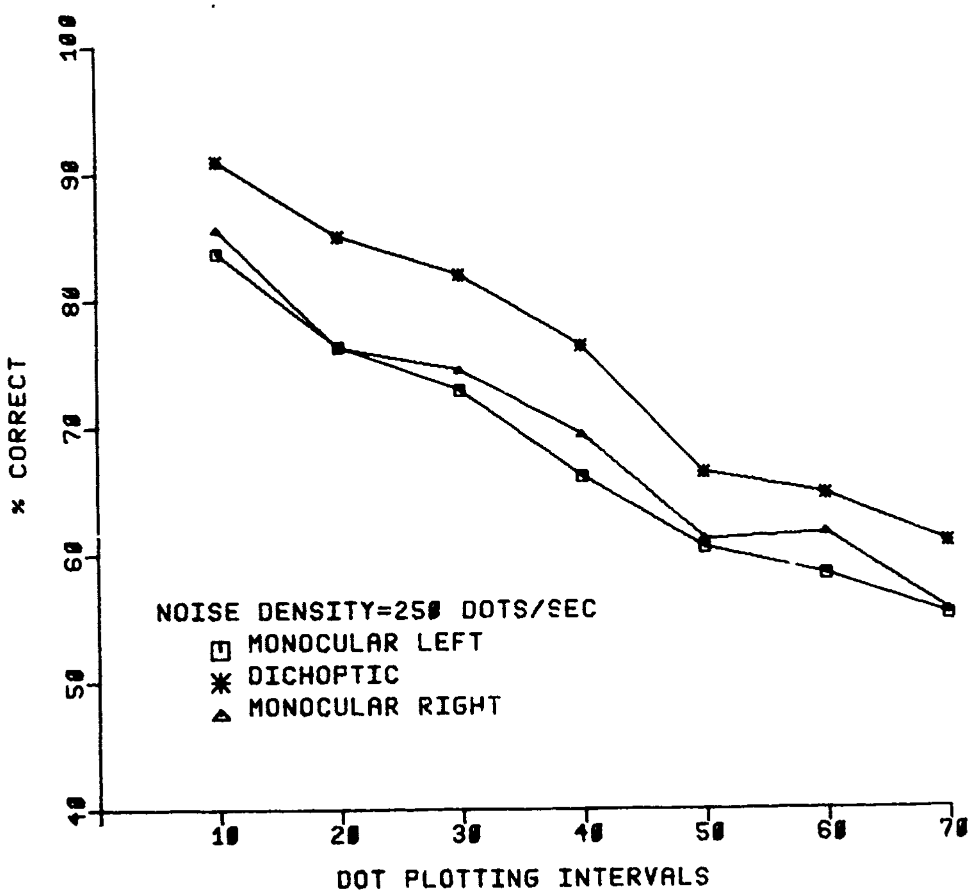

Figure 6. The results of Experiment I for noise densities of 250 dots/sec.

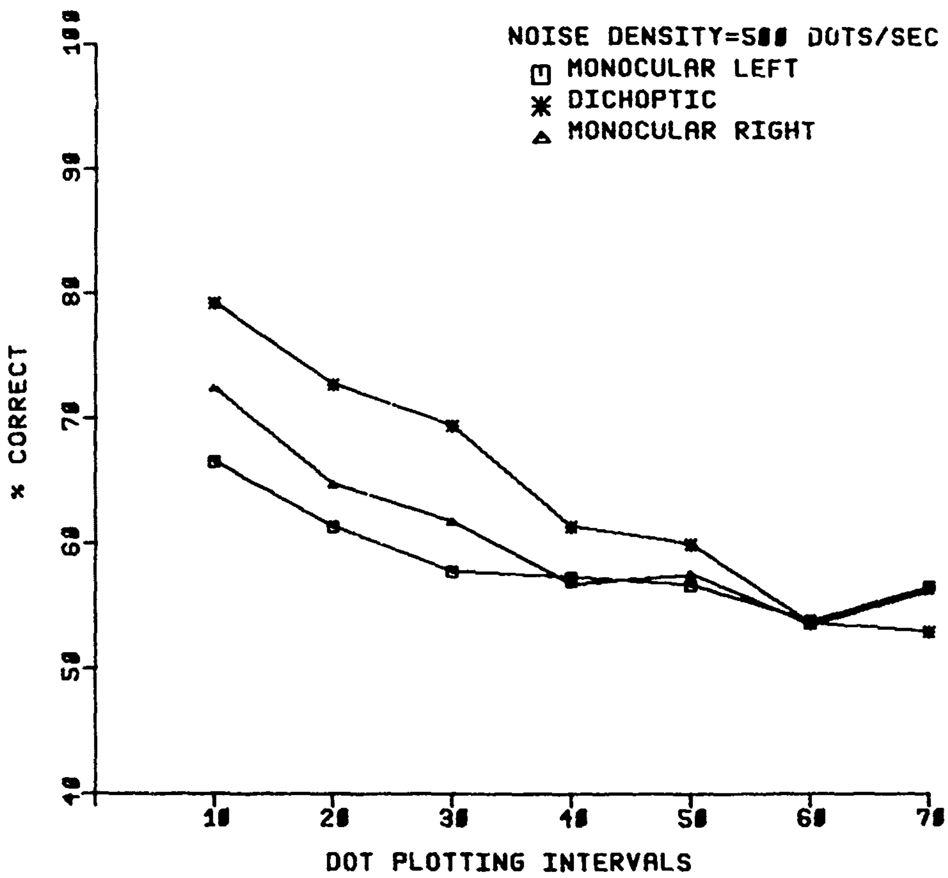

Figure 7. The results of Experiment I for noise densities of 500 dots/sec.

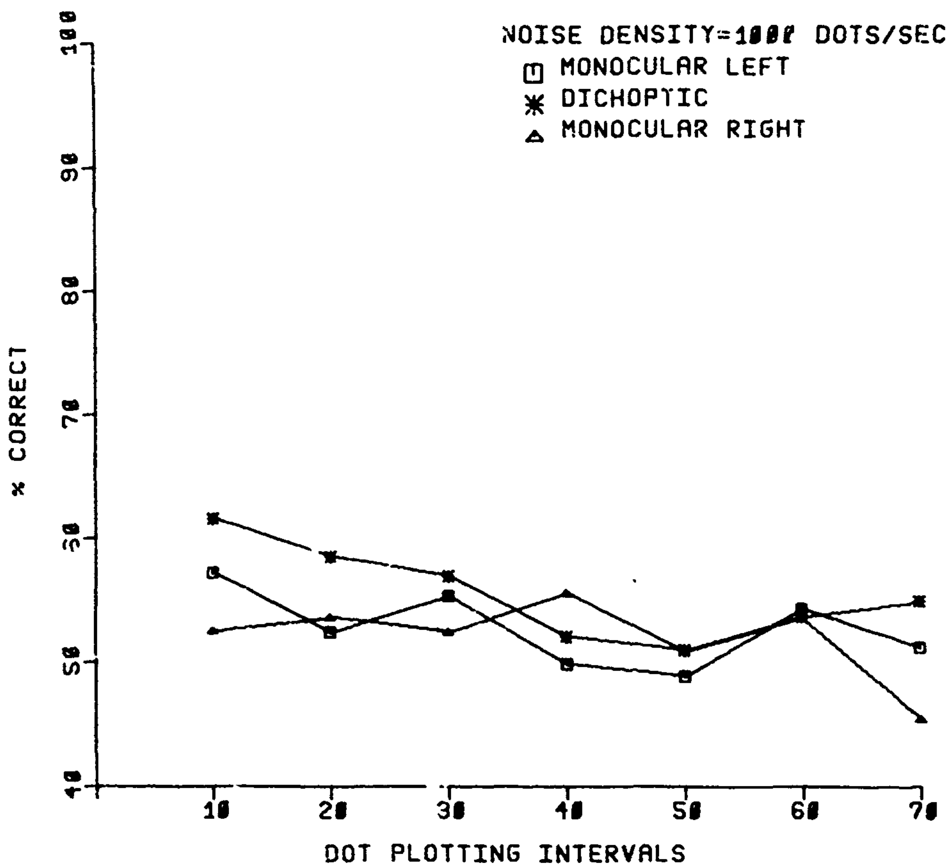

Figure 8. The results of Experiment I for noise densities of 1000 dots/sec.

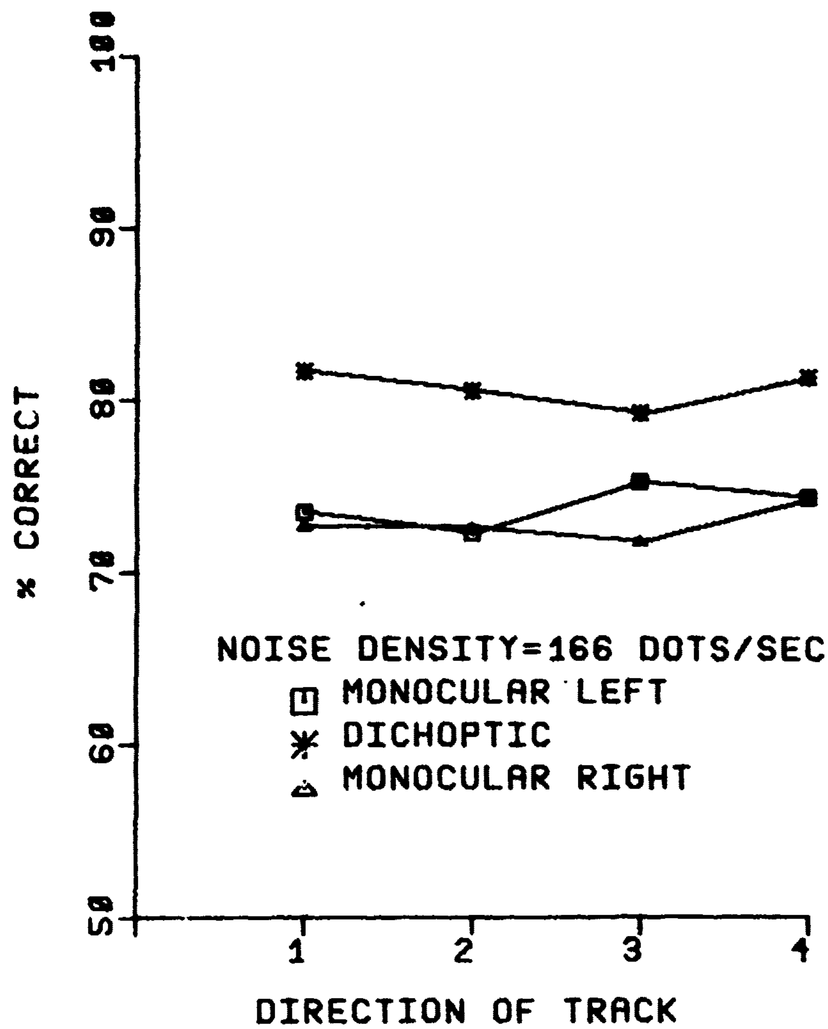

Figure 9. The results of Experiment I reanalyzed to display the negligible effect of track direction (for noise dot densities of 166 dots/sec.)

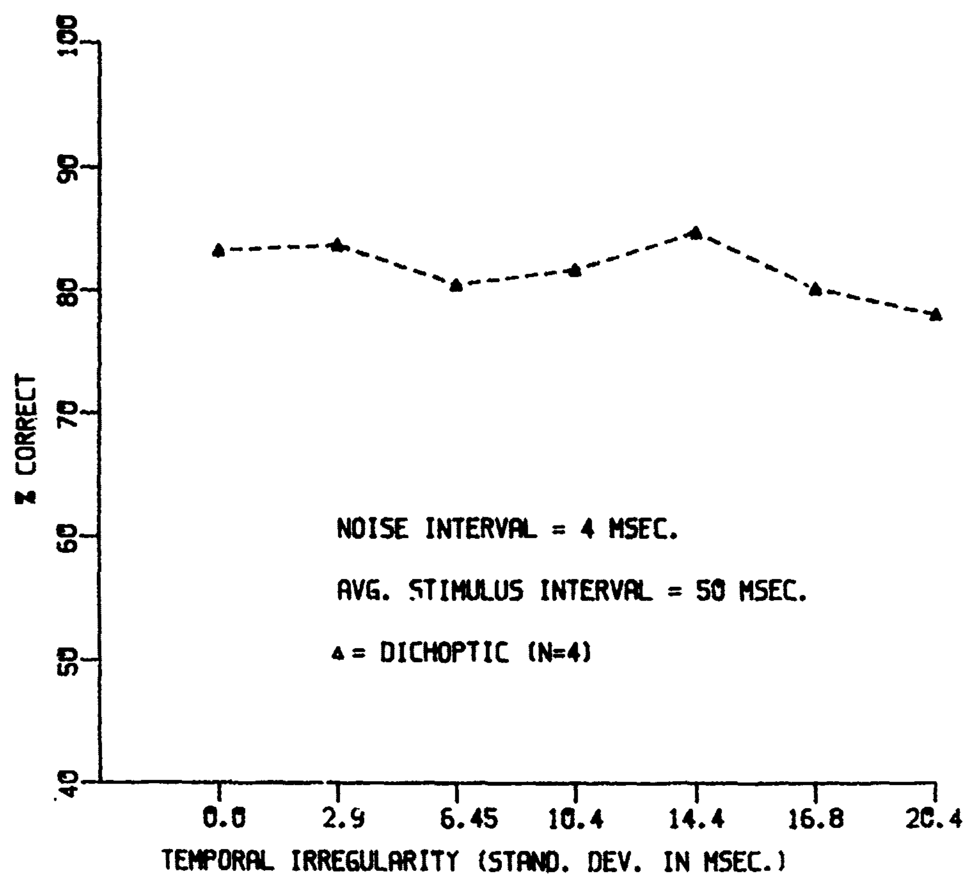

Figure 10. The results of Experiment II in which the temporal intervals between successive dots of the straight line stimulus were made progressively more irregular. There is but the slightest effect of interval irregularity, if any, on detectability. Only the dichoptic condition was run in this experiment.

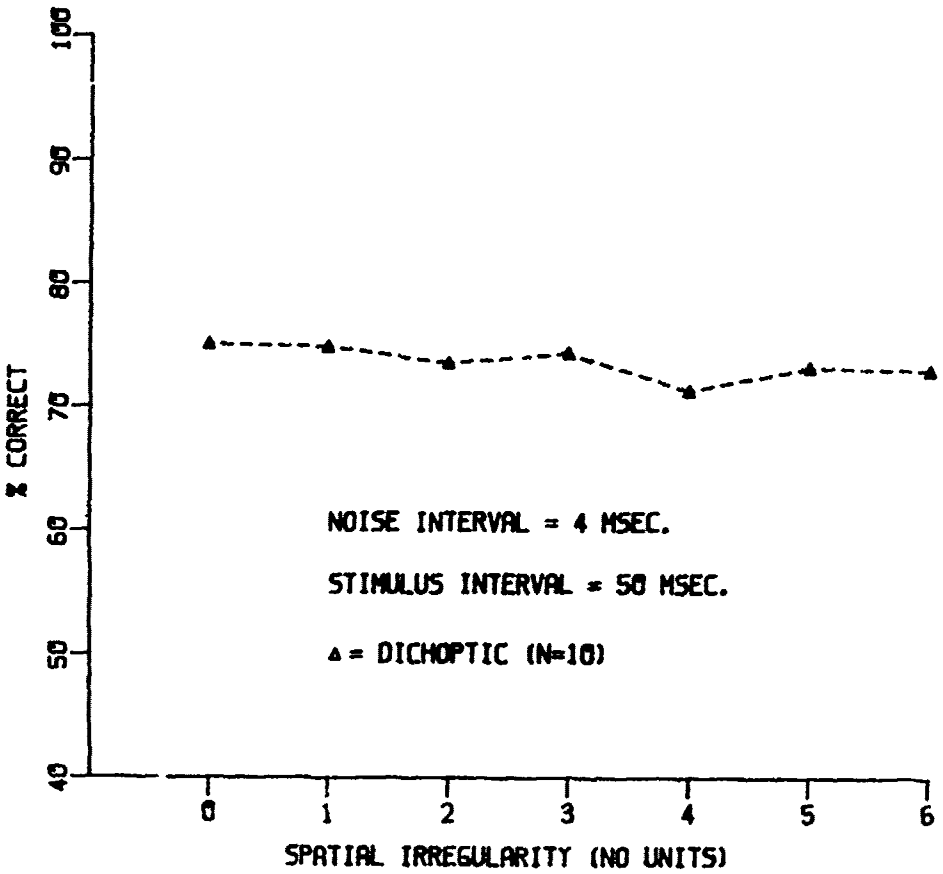

Figure 11. The result of Experiment III in which the spatial intervals between successive dots were made progressively more irregular. These data indicate virtually no sensitivity to spatial irregularity when there is a 50 msec interval between dots. As discussed in the text, no meaningful units can be attached to the values of the horizontal coordinate.

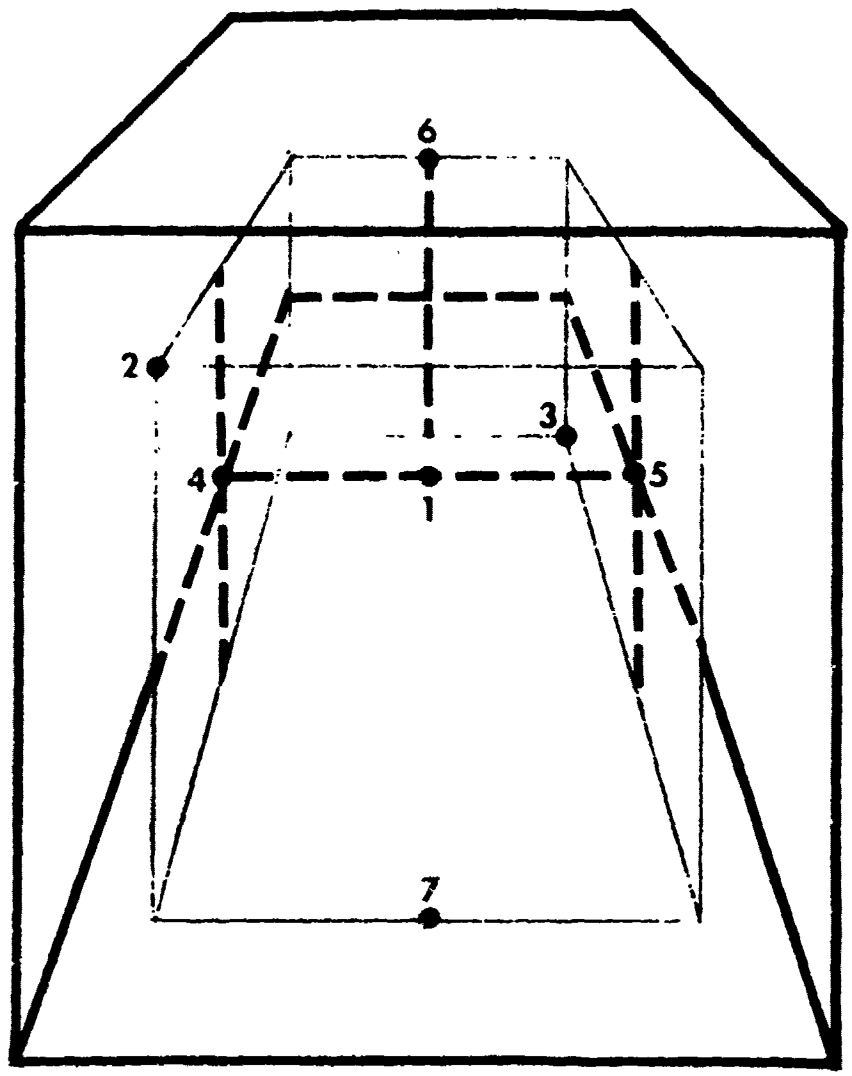

Figure 12. A graphic depiction of the seven positions in which the flashing dot used in Experiment IV might be located in any trial. The flashing dot stimulus was placed in only one of these dot positions in each trial.

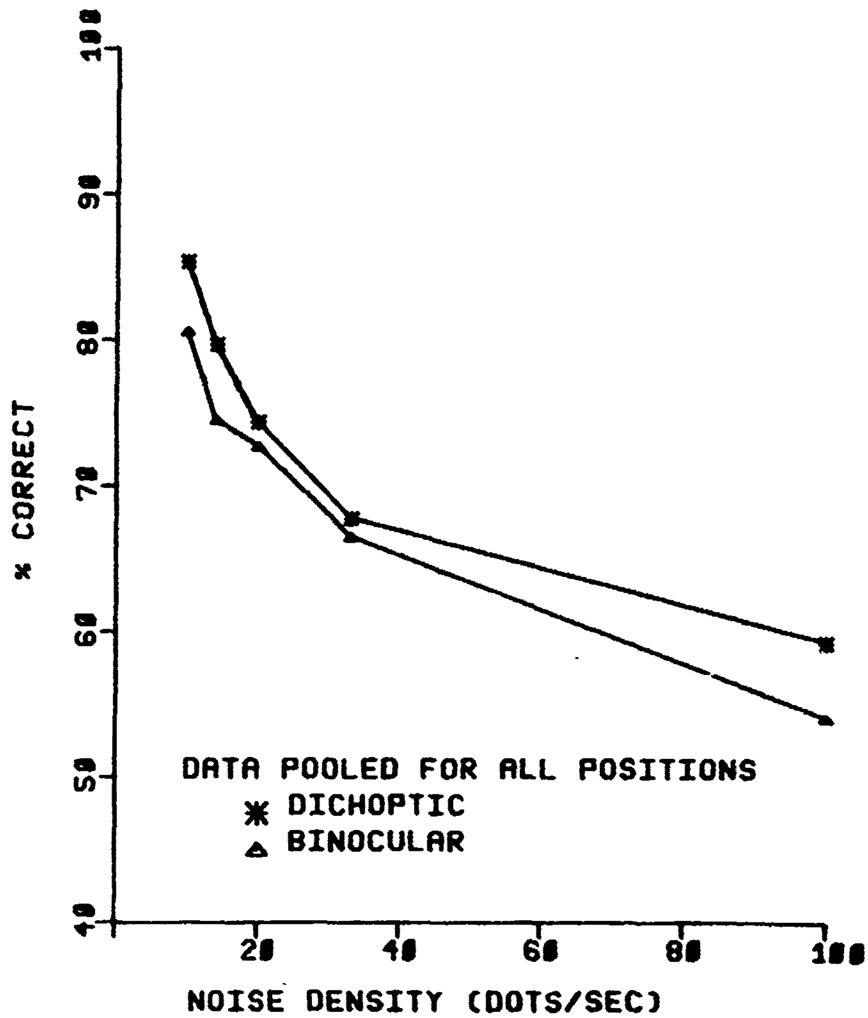

Figure 13. The results of Experiment IV plotted as a function of the density of the noise dots. The two curves are for the dichoptic and binocular viewing conditions respectively.

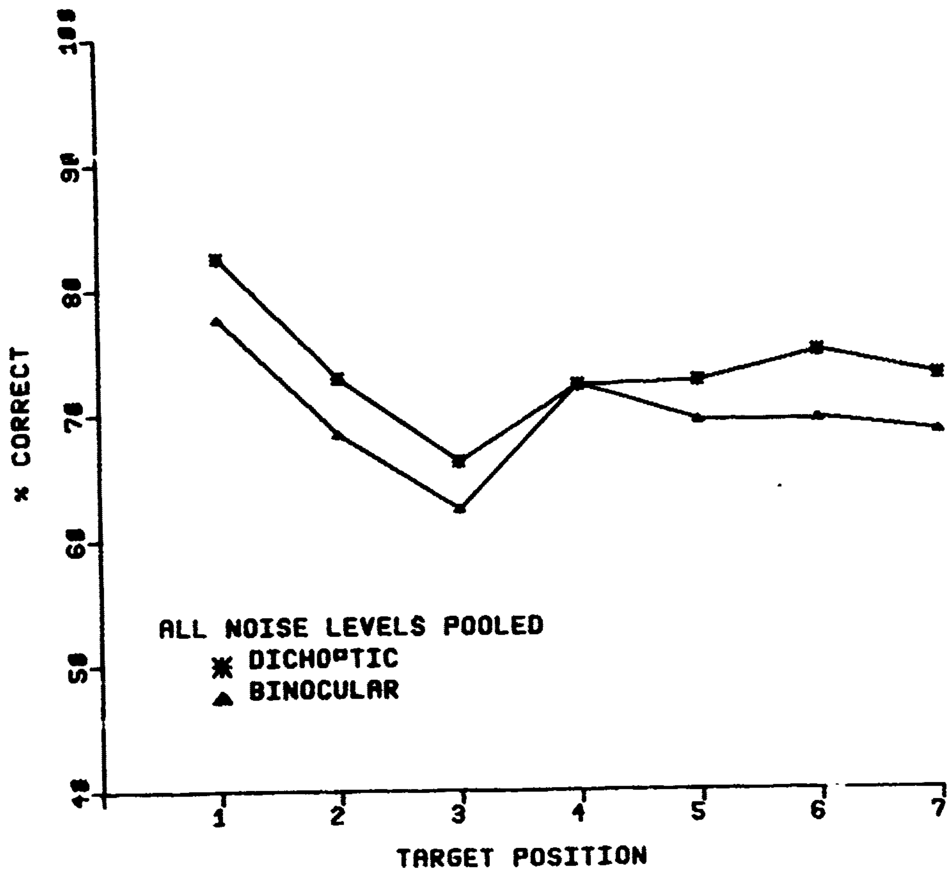

Figure 14. The results of Experiment IV plotted as a function of the position of the flashing dot. The numbers on the horizontal axes are keyed to the positions shown in Fig. 12.

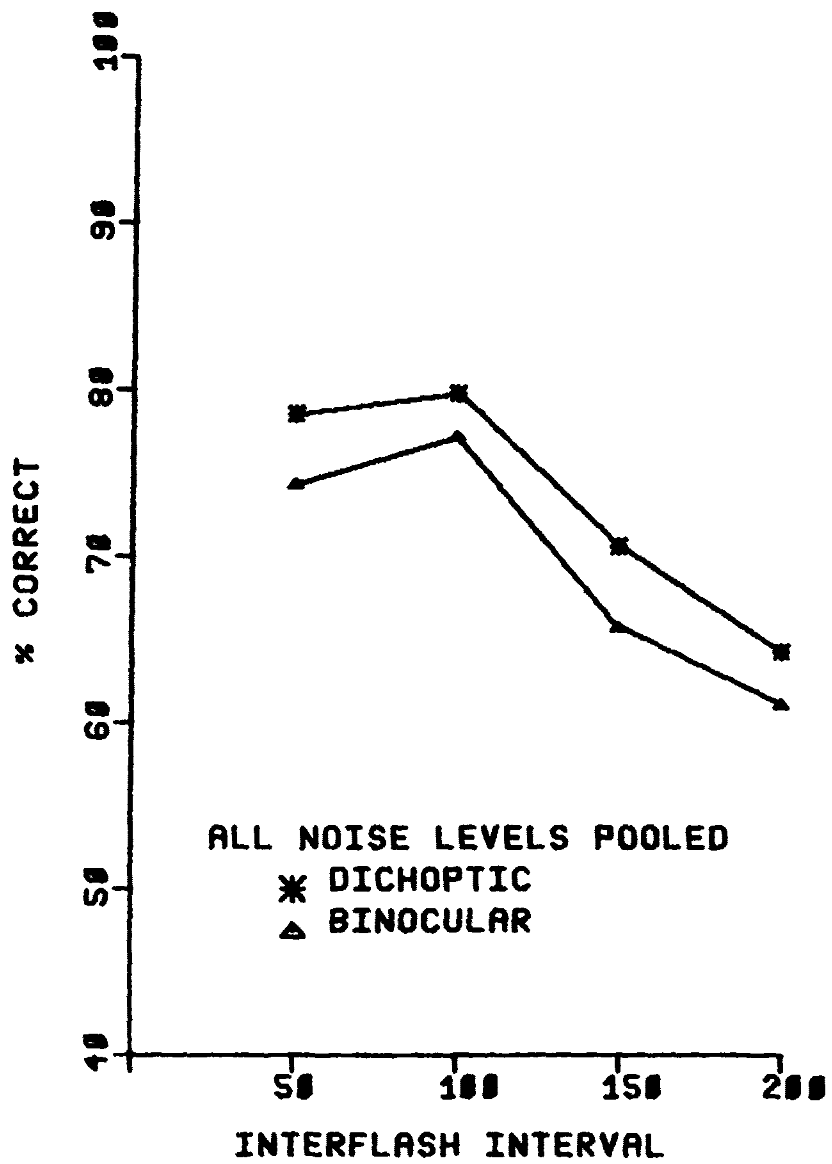

Figure 15. The results of Experiment IV plotted as a function of the length of the interval between flashes with data pooled from all noise levels. Only the dichoptic condition was run in this experiment.

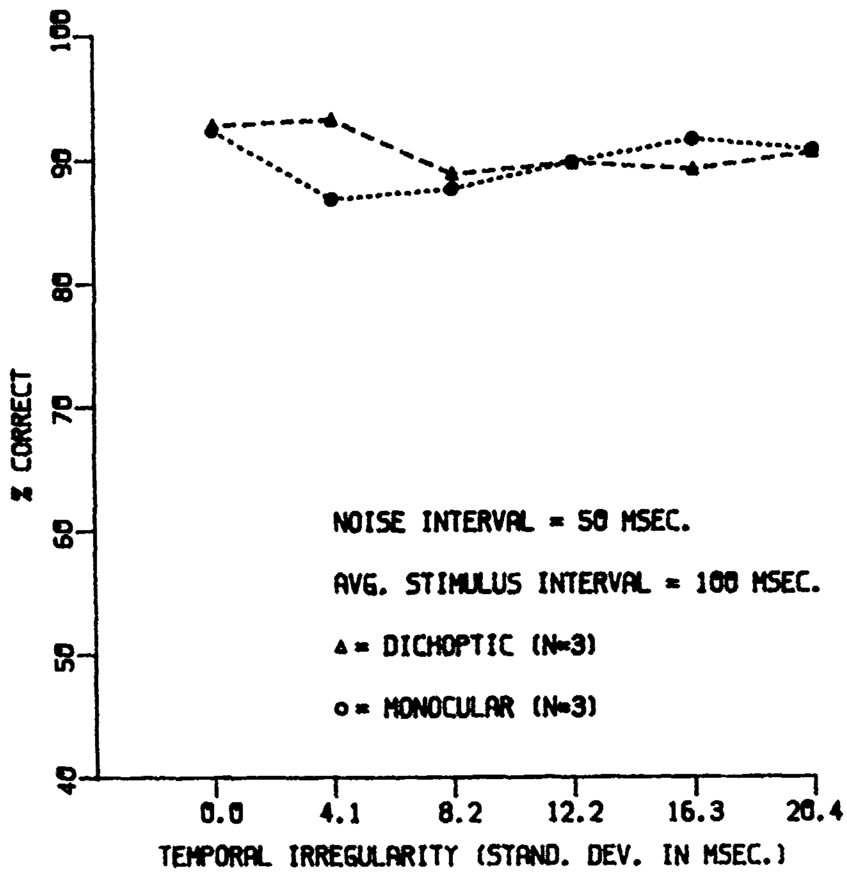

Figure 16. The results of Experiment V in which the interval between flashing dots was made irregular. Data are plotted for both the dichoptic and monocular viewing conditions.

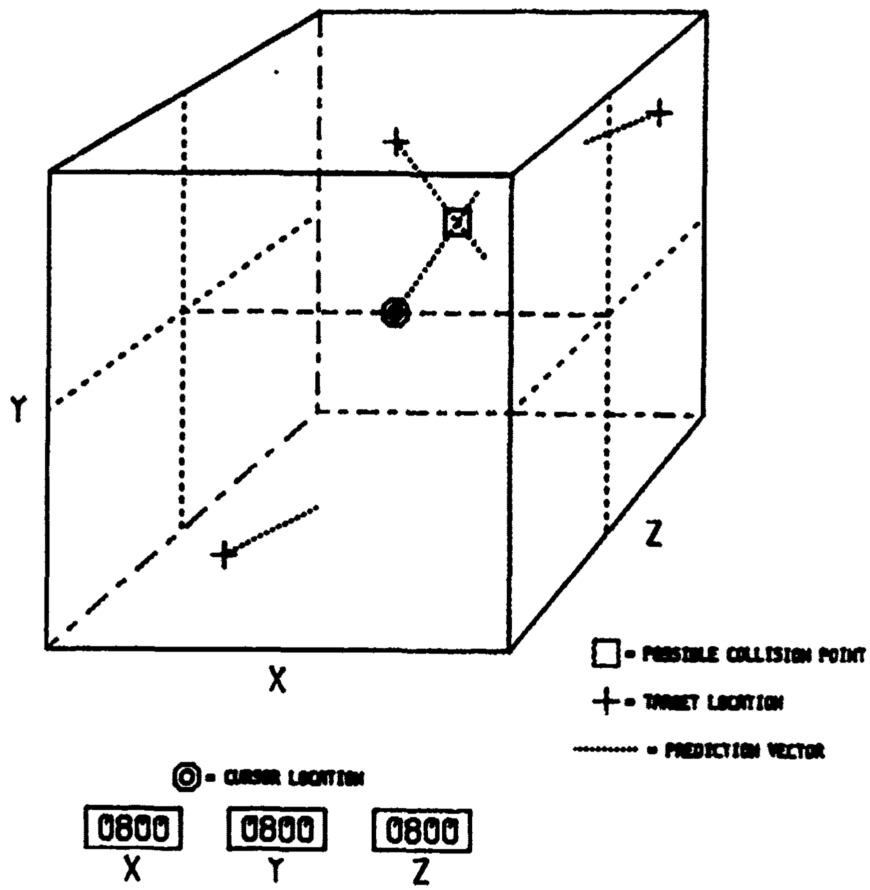

Figure 17. A two dimensional projected drawing of a proposed three dimensional traffic controller display. The apparent cube models the true air or sea space. "+" marks indicate vehicle current positions. Lines indicate extrapolated trajectory. Such a device would be easy to build and might have substantial perceptual advantages over two dimensional displays since preprocessed height and plan information is integrated by the computer prior to display. The observer's task is thus greatly reduced in complexity.

Part II: Panel Discussion -- Critical Research Issues in 3-D Displays

CRITICAL RESEARCH ISSUES ON COCKPIT APPLICATIONS OF 3-D DISPLAYS

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Introduction

Today's operational aircrews continue to experience workload saturation despite the infusion of new display and data handling technologies. Part of the reason for this lies with the overwhelming volume of displayed visual information which competes, at any given moment, for the pilot's attention. Design decisions regarding when and how (i.e., digital, symbolic or pictorial) this information should be portrayed and its spatial temporal configuration can account for a significant measure of variance with respect to the operator's ability to acquire and process task critical information.

The Human Engineering Division of the Air Force Aerospace Medical Research Laboratory (AFAMRL) is engaged in exploratory research to support development of a pilot-centered cockpit design technology. This involves the development of sound theoretical and empirical bases for matching the perceptual and psychomotor characteristics of the aircrew with the design of controls, displays and approaches for portrayal of information within the cockpit.

Applications of the three-dimensional (3-D) presentation of information which exploit the human's highly refined and well practiced sense of depth have been considered for their potential in facilitating the transfer of information in future aircrew cockpits. One application, suggested by Furness (1981) involves the use of 3-D in an integrated tactical display as a means for a) providing the aircrew with a spatial analog of objects and events occurring in real 3-D space and, b) configuring information to reduce apparent clutter. Figure 1 shows a conceptual representation of an integrated tactical display which combines information from a range of different sources into a single pictorial output. In this example, information is presented to the pilot in a full field hemispherical display. Information may be accessed along the line of sight within an instantaneous binocular field of regard that can freely search the total field of view. This display combines information from instruments, sensors, and data links from other airborne and ground-based sources. It presents these data in a hybrid literal/symbolic package to provide the aircrew with a "pathway in the sky" presentation complete with threat warning and various cues to situation awareness. However, before the three-dimensional presentation of information can be seriously considered for future implementation in integrated cockpit displays, a number of critical research issues need resolution.

Critical Research Issues

A. EFFECTIVENESS OF 3-D AS A MEDIUM FOR INFORMATION TRANSFER.

The relative effectiveness of 3-D displays as compared with encoded volumetric information in two-dimensional (2-D) presentations needs to be determined. Over the past thirty years, studies have been conducted comparing various parameters of visual performance (e.g., target acquisition, estimation of relative and absolute position or velocity of targets, etc.) and various 2-D encoding techniques versus 3-D presentations (Kennedy and LaForge, 1958; Guttman and Anderson, 1962; Bassett, Kahn, LaMay, Levy, and Page, 1965; and others).

For the most part, these studies did not find evidence to support a hypothesis of improved visual performance for various applications of 3-D displays. Careful review of these past studies suggests many methodological difficulties which raise questions as to the validity of the results. Potential problems were identified ranging from display approach, stimulus content and configuration, and the prior experience and training of subjects. Nevertheless, this line of research has continued based in part on the assumptions that a 3-D presentation should involve "less mental computation" than a coded 2-D presentation (Guttman and Anderson, 1962) and that the "natural ability" to discriminate the relative spatial orientation and range of objects in visual depth is not exploited by viewing 2-D displays (Leibowitz and Sulzer, 1965; Abbott, Higgens, Strotter, and Upton, 1971). Therefore, further research is needed to determine the specific conditions under which 3-D presentations can enhance an operator's ability to acquire and process task critical information. Any observed increments or decrements in performance need to be evaluated, in turn, with respect to the effects of depth cue conflicts resulting from artifacts of the display approach, requirements for depth cue redundancy, and effects of information complexity and clutter. Another area which needs to be empirically addressed is the information transfer effectiveness of depth codes for non-spatial information such as time (e.g., immanence) or some other assigned parameter (e.g., lethality of threat) and the extent to which depth encoded, non-spatial information may be used to organize or declutter displays (Lehmkuhle and Fox, 1980). Additionally, the effects on operator performance of co-locating depth encoded non-spatial information and spatial analog information within the same display or instrument console needs to be determined.

Research is also required to evaluate the impact, if any, of 3-D presentations on the overall processing capability of the system operator. If, on one hand, a 3-D presentation demands less processing capacity than an information equivalent 2-D encoded presentation, then whether use of 3-D displays enhances the total amount of information which the operator can perceive or attend to at any given moment needs to be determined (Miller, 1956; Leibowitz and Sulzer, 1965). On the other hand, if the ability to perceive information presented in 3-D is enhanced in terms of speed or reduced error rate without a corresponding increase in total channel capacity, then 3-D presented information of low criticality could interfere with the operator's ability to acquire or process more critical items of information (Hill and Self, 1961).

B. THREE-DIMENSIONAL DISPLAY QUALITY REQUIREMENTS FOR EFFICIENT OPERATOR INTERFACE.

For future applications, it will be necessary to establish psychophysically based criteria and specifications for the "packaging" of information in 3-D displays. More specifically, the following are of concern: absolute versus relative values (e.g., across channels in a two eye display) and required system tolerances for luminous intensity, color, disparity, distortion, etc. with respect to the operator's sensory limitations, factors leading to early fatigue or stress, and individual differences among perspective users. Most of the existing psychophysical data germane to the 3-D presentation of information bear on these issues (Ogle, 1950; Farrell and Booth, 1975).

Future consideration of an operational flight display which utilizes a 3-D presentation will require resolution of these and other unstated critical research issues. In part, some of these issues can be addressed with relatively simple stimuli and conventional methodologies. However, exploratory research in a workload constrained environment is necessary to evaluate and validate the advantages of 3-D. Investigation of these issues will take place using the AFAMRL visually coupled airborne systems simulation.

Visually Coupled Airborne Systems Simulator (VCASS)

Since 1966, the AFAMRL has been developing a new technology for coupling pilot/crew member visual input into aircraft systems. Collectively termed "visually-coupled systems", this new technology takes advantage of the precision with which a crew member can aim his head and direct his gaze. In essence, the interface between the crew member and the aircraft systems is brought about through the communication of head position (and, consequently, eye position) coordinates in order to designate targets, slew weapons or sensors, or activate switches. A feedback presentation of information is also provided within the operator's field of vision regardless of head position. The two subsystems which comprise visually-coupled systems are the helmet-mounted sight (HMS) which provides line-of-sight data and the helmet-mounted display (HMD) which provides a virtual collimated image presentation of information (Birt and Furness, 1974; Kocian, 1977; Furness, 1980; Task, Kocian, and Brindle, 1980).

In 1976, AFAMRL began the Visually-Coupled Airborne Systems Simulator (VCASS) program to exploit the advantages of the helmet-mounted sight/display for visual scene simulation. Figure 2 shows the conceptual operation of the VCASS. A helmet-mounted display, modified to provide a wide field-of-view (variable from 100-140 degrees) binocular presentation, provides an instantaneous binocular visual field of view selected from an overall computer generated scene using helmet position and attitude determined by a six-degree-of-freedom helmet-mounted sight (Fig. 3). In addition to the outside scene, head-up display information and synthesized virtual cockpit instruments can be displayed at appropriate locations in space.

The VCASS display is a complete two eye system with separate cathode ray tubes (CRTs) feeding information to each monocular. The monoculars are overlapped in angular space, permitting a continuous presentation to both eyes and allowing 3-D information to the observer in the overlapped pattern of the display. Table 1 provides detailed specifications of the Laboratory VCASS.

The VCASS display provides a vehicle for exploratory investigation of critical human factors issues in the presentation and utilization of information presented in 3-D space. Use of the helmet-mounted display in synchrony with a simulator cockpit, affords a unique capability for testing and evaluating integrated 3-D displays, such as that illustrated in Figure 1, in a flight-task loaded environment.

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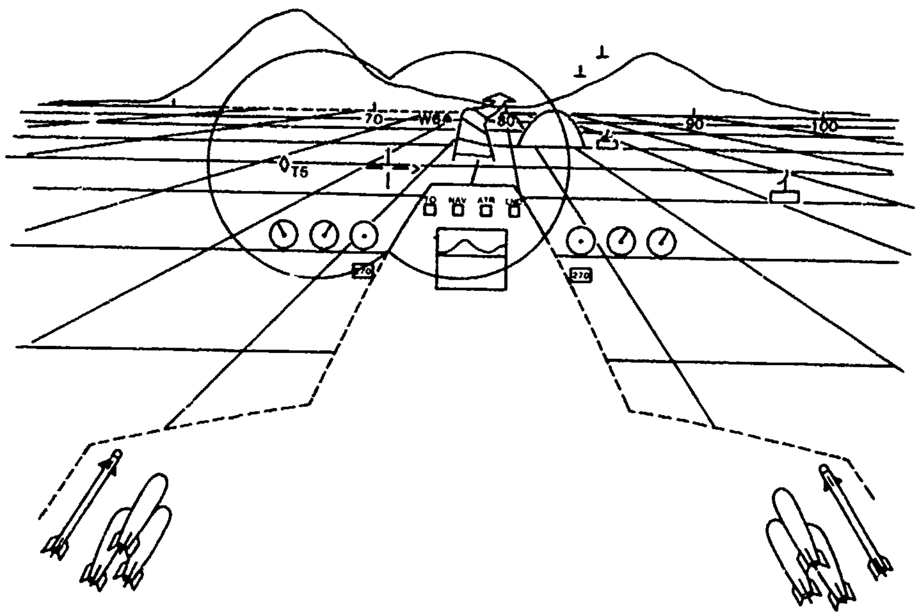

Figure 1. Conceptual representation of an integrated tactical display.

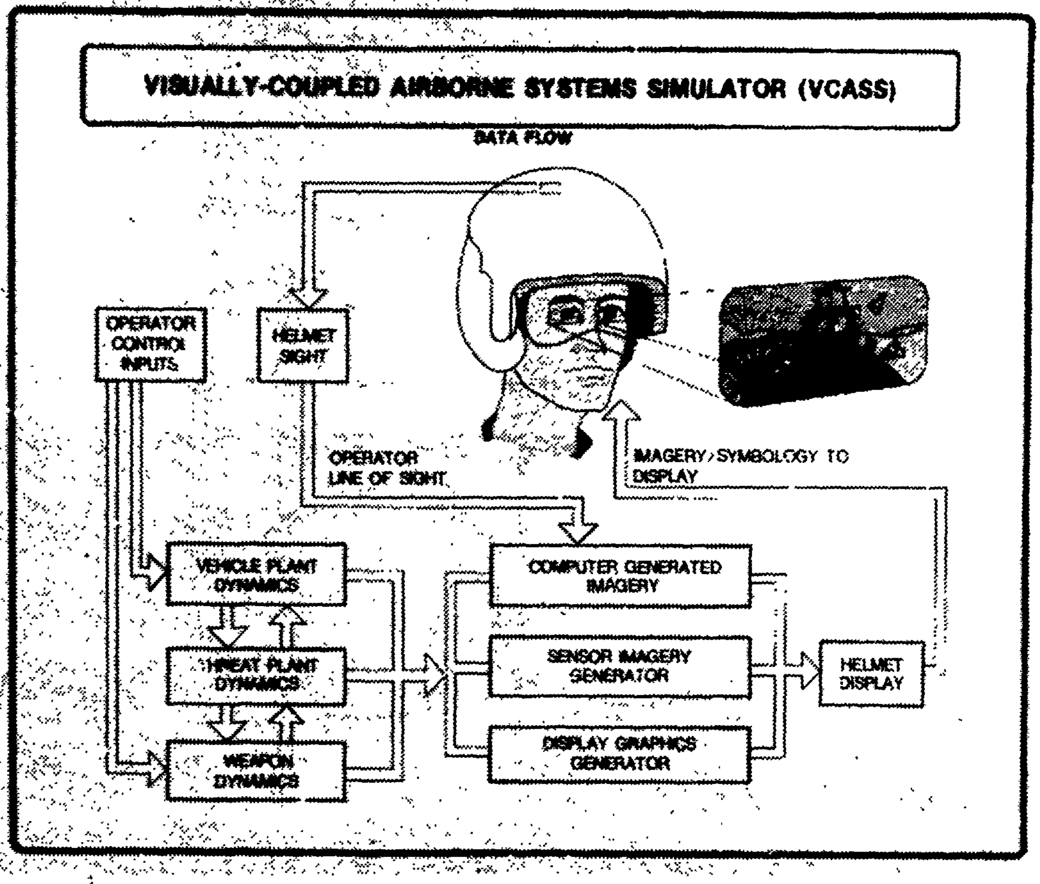

Figure 2. Conceptual operation of the Visually-Coupled Airborne System Simulator (VCASS).

VCASS HELMET MOUNTED SIGHT AND DISPLAY SYSTEM

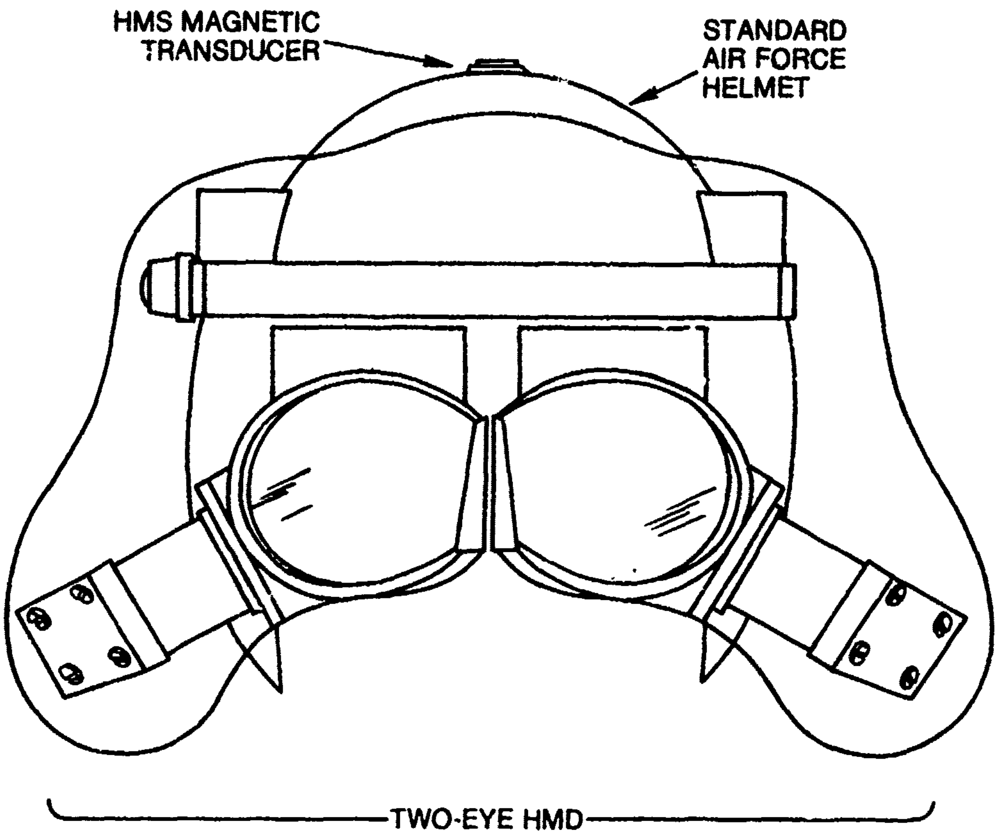

Figure 3. VCASS helmut-mounted sight and display system.

TABLE 1

Laboratory VCASS Performance

Head position sensor	
Attitude/position sensing	6 DOF
Allowable head movement	6.25 cubic feet
Accuracy	0.2° CEP
Angular resolution	0.03°
Update rate	100 HZ
Optical	
Optical design	binocular/color corrected (infinity collimated)
Field-of-view	
horizontal	100-140 degrees
vertical	60 degrees
overlap	20-60 degrees
Exit pupil	15 mm
Transmission (CRT to eye)	0.8 current
(ambient to eye)	7.0 current
Optical transfer function	60 LP/mm @94% modulation (on axis)
Distortion	.002

A STEREO-RANGEFINDER EXPERIENCE

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University of Louisville

I would like to review for you work with which I was associated in the 1950s at Fort Knox, Ky. At the time, the Army was concerned to incorporate a stereo-rangefinder in the fire control system of the tank (1). The seeming straight forward design task was almost completely dominated by tactical and engineering considerations. In the end, stereo was abandoned for a coincidence task. It would be nice to conclude that recognition of human factors early on would have saved the project. However, experience with stereo-displays has indicated that stereo-ranging is inappropriate against ground targets.

The activity in which I took part sought to answer the question: Can armored personnel of class A physical profile operate a stereo-rangefinder against ground targets to an expectation of 80% first round hits? To speak to the question, range readings were taken with one meter base, Navy, stereo-rangefinders modified to incorporate the Army "flying geese" reticle. The optics of these instruments were uncomplicated and balanced before the two eyes. The reticle to each eye was inserted independently. An internal corrector in the left eye system was used to bring the reticles into zero registry and presumably to remove operator bias. The ranging wedge was in the right eye system. The resultant asymmetrical vergence caused the path of the flying geese to be diagonal from near left to far right.

Analysis of the range readings concentrated on variability with the expectation that localization error would be handled by a one time, zero adjustment. The newly designed Army instruments were to have auto-collimation in the reticle system which would eliminate operator adjustment of the internal corrector and reduce variability by a factor of two. Operator performance with the Navy instrument seemed to indicate that the 80% criterion could be achieved easily by 90% of the Army population. However, practice ranging did not show the expected incremental increase in precision. Rather, individuals who started out doing well continued to do well and individuals who did poorly continued to do poorly. Occasionally, for no obvious reason, an individual would shift from one group to the other. It was as though stereo ability was a given and the variablitiy of ranging reflected the individual's attention to the task. Given these findings, two thousand range settings was fixed as an arbitrary requisite to qualify a range-finder operator.

In another phase of the effort, all available stereoscopic vision tests, some 30 in number, were assembled with the help of the National Research Council - Armed Forces Vision Committee. The objective was to identify an appropriate selection device. The rationale of the project called for choosing a device that loaded significantly on a stereo-factor to be defined by factor analysis with rotation to simple structure. Some tests were dynamic, requiring the subject to stop a cycling display. One such test presented a line inclined in depth which was to be stopped as it passed through vertical. Other tests required the subject to make an adjustment to equidistance as with the Howard-Dolman or a rangefinder. The largest group of tests were variations on the familiar Wheatstone stereogram. These tests variously included, in conjunction with the requisite disparity, size cue, color, realistic field of view, etc. A group of 200 or more enlisted men was processed through the vision tests.

The results of the factor analysis were disappointing. A stereo-factor if identified was minimal in its loading on the tests. Rather, the data fell into groups by the type of judgement required of the subject and the mechanics of the test device. In the absence of a test that could be characterized as uniquely "stereoscopic," the rangefinder was chosen as the selection device. Thus, selection and training of stereo operators was to be accomplished concomittantly with instruction in the detail and use of the fire control system.

With delivery of a one meter Army instrument which mounted in the nose of the tank turret, the project began to fall apart. The number of men who could operate in stereo dropped precipitously. Auto-collimation may have been a plus, but provision of alternate sighting systems to handle combat eventualities had multiplied the number of elements in the optical paths to a point that binocular vision was all but impossible. Any semblance of balance in the optical paths was gone to include a golden tint from a partial mirror which appeared in the left eye system only. A second Army instrument of one and a half meter base was designed to be mounted across the turret about midway back. The latter instrument was balanced for number of optical elements but was asymmetrical for base and though considerably simpler than the first Army instrument was still more complex than the Navy instrument. In the end, less than forty percent of the Army population could work in stereo and there was serious doubt that range readings to any selection of targets could be zeroed by a single adjustment for operator bias. In working with these instruments, the flying geese all too frequently appeared as fence posts superimposed upon the terrain, a dead give away that the operator was perceiving at least the reticles monocularly. Ultimately, all instruments were modified to a full field, superimposed image viewed monocularly. To range, one eliminated double images of the target in the presence of double images of the rest of the field of view.

The point in reviewing this effort to utilize stereoscopic vision in a seemingly straight forward application is to bring the experience gained into current time. It should be noted that tactical and engineering considerations, not human factor, guided the design process because there was little human factors information. The consequences for stereo of the various compromises necessary to production of these instruments were not known.

As part of a program to study the human factors questions evident with the rangefinders, e.g., What is the effect on performance of asymmetrical reticle movement?, What is the relation of rate of range-knob rotation to seen movement in the stereo reticle?, etc., a laboratory instrument was construcced. The stereoptometer (2) consisted of two reflex sights each of which delivered a reticle from a reflection plate to one eye of the operator. The operator's interpupillary distance was the base of the instrument. The angle between the parallel beams from the reflex sights measured the range. A circle or dot of light served as the reticle. To use the instrument, the operator adjusted the vergence of the reflex sights to place the fused reticle at the distance of a designated target in the immediate environment seen through the reflection plates.

Figure 1A and B present stereo acuities taken with the stereoptometer for two groups of enlisted men. The target, a white dowel ¼ inch in diameter was 302 cm distance from the operator. The acuities in seconds of arc are the standard deviation of twelve range settings. Most of the acuities are below a criterion of one minute of arc. One U.O.E. (12 sec. of arc) was the performance desired of trained Army range-finder operators. Figure 1B illustrates the change in distribution of acuities before and after five weeks of training or two thousand range finder settings. The effect was rather to increase the separation of the poorest from the better performers. These findings parallel the experience with the Navy instrument.

Pilot studies demonstrated that performance with the stereoptometer was insensitive to the engineering variables that had been so devastating in the production rangefinders. However, range settings did reflect the same limitation which frustrated the stereo operator when working against ground targets. The presence of stimuli in the field of view which interferred with free movement in depth of the stereo reticle distorted the measures obtained, i.e., the integrity of the reticle was lost when projected on a near background or intermediate object. The Zaroodny ballistic sight (5) illustrated this feature of stereo displays as did the study by Irvine C. Gardner of the National Bureau of Standards (4). Gardner used a stereo instrument which permitted both ortho- and pseudoscopic viewing to range on seventeen targets in the Washington skyline. The resultant mirror image of range displacements documents two points: 1) the position in depth of a stereo reticle is influenced by perceptual factors, and 2) the resultant displacement in depth of a stereo reticle is unique to the individual target and its surroundings. With the tank mounted stereo-rangefinder this was evident in gross inaccuracies of determined range to targets on a forward slope or in front of an immediate background. Range readings were short if the operator kept clearance between his reticle and the background or were long if he lost clearance and drove the reticle into the background.

To sum up the stereo-rangefinder experience, the almost universal utility of the stereoptometer relative to that of the three production rangefinders supports Harker's law - a law akin to Murphy's law - which states: An observer will see stereo as an inverse function of the num-

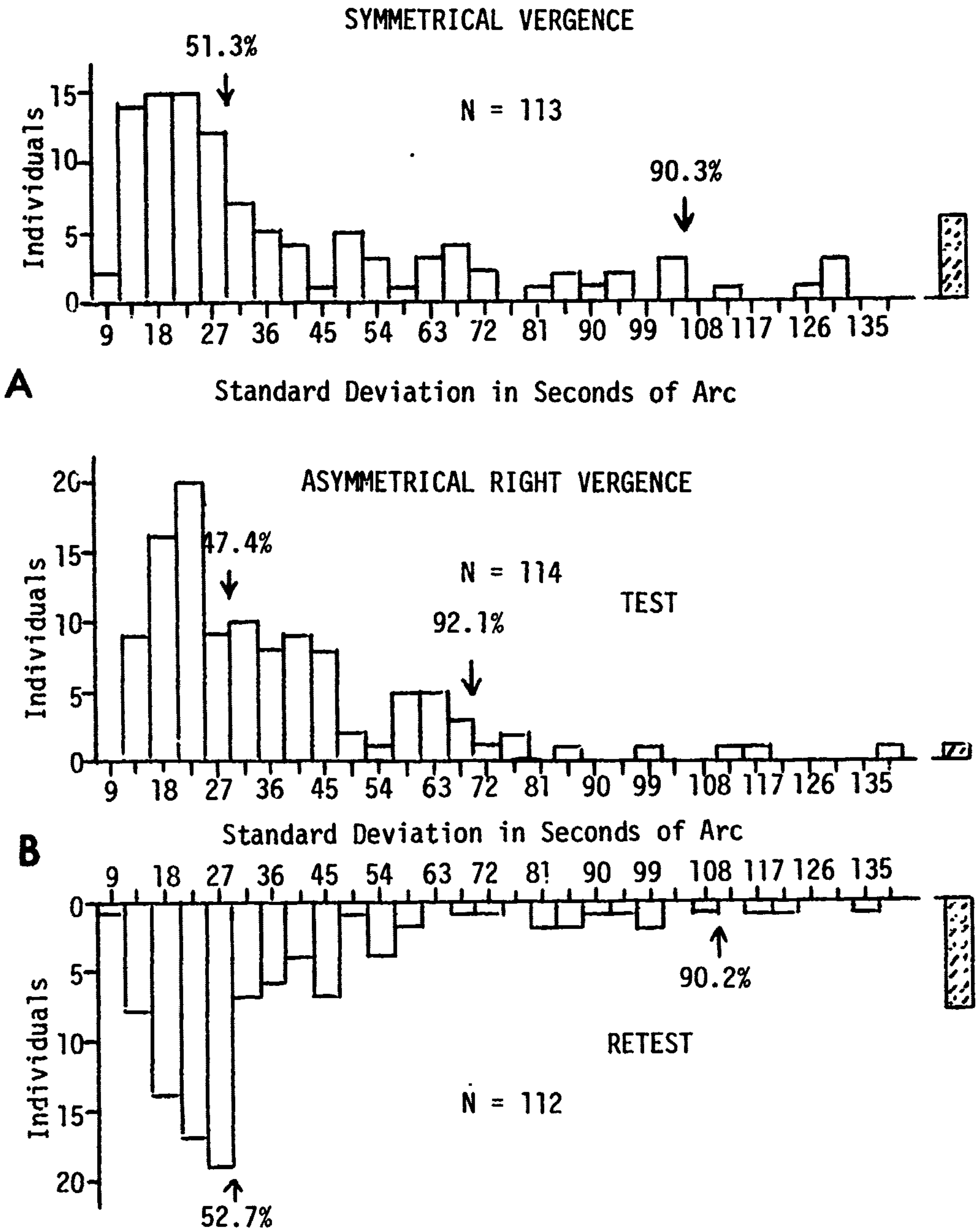

Fig. 1 Measures are standard deviation of twelve settings with random offset to a target at 302 cm distance. Extreme values are summed at the right. Five weeks of range-finder training separated test and retest.

ber of surfaces in the binocular paths. A possible explanation for this became apparent in subsequent research with the stereoptometer which demonstrated that symmetrical vergence could be diagnostic with individuals who had trouble seeing stereo but who were otherwise visually normal. With symmetrical vergence, the reported direction of reticle movement when left or right rather than in depth is referrable to the use of a specific eye. A change of vergence in the instrument to frustrate the observer's inappropriate eye use can be sufficient to elicit a full stereoscopic response or the change will confirm the initially determined eyedness. When an individual reacts with a stereo response under these circumstances, it is evident that he initially suppressed vision in one eye in response to some feature of the presentation. Thus, spontaneous suppression could account for the failure, as with the rangefinder, of an instrument or a display. In retrospect, the problems that beset the stereo-rangefinder suggest that we lack basic understanding of the stereo processes.

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ISSUES IN THE EVALUATION OF 3-D DISPLAY APPLICATIONS

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The potential benefits of 3-D or stereoscopic visual displays have not been fully appreciated in a number of important application areas. This may be due to problems in the way stereo systems have been evaluated with respect to non-stereo displays.

Only a few experimental evaluations have shown performance advantages for stereoscopic displays, whereas most comparisons have shown little or no stereo benefit. In some cases, performance with stereo was worse than with a non-stereo system.

Proper experimental evaluation of 3-D visual display systems requires attention to the following factors:

- Equal display quality in the stereo and non-stereo systems.
- Performance measurement with tasks that realistically represent the perceptual complexity of the operational environment, and the learning, time constraints, and error penalties present in the real world.
- Appreciation of the several side benefits obtained with stereoscopic visual displays, such as improved image interpretability and wider field of view, as well as better system reliability.
- Reconsidering the practicality of stereoscopic techniques in applications where stereo has previously been thought to be of little value, as in flight simulator displays.

Much of the research in stereoscopic vision is focused on how the human visual system works to derive depth information from the disparity between left and right retinal images, and on techniques for producing appropriate left and right retinal inputs to the two eyes. One neglected part of stereo research is the methodology for demonstrating the applications in which stereo can be worth the extra cost, complexity, and in some cases, the discomfort relative to non-stereo systems.

Display Quality and Test Methodology

In many comparisons between performance with stereo versus non-stereo displays, the stereo system was a poor quality experimental prototype set up just for the test, while the non-stereo system was a high-quality commercial display. In a number of laboratories, it was observed that researchers were working with the left TV camera connected to the right eye display, and vice versa; this produced reversed binocular depth, but the observers were not able to tell why the display "never looked quite right" until a visiting colleague reversed the camera cables.

Many of the comparisons between stereo and monoscopic displays have used stereo display techniques that introduced annoying flicker, coarser vertical resolution, reduced field of view, binocular misalignment, uncomfortable viewing equipment, and other extraneous factors into the experimental test. Proper design and construction of stereoscopic viewing equipment requires strict attention to alignment and congruence between the two eye channels; as in the manufacture of good quality binoculars, close tolerances must be observed in the image acquisition and display systems. The eyestrain and discomfort that can result from inattention to the special requirements of stereo systems may be responsible for test results wherein performance with a 3-D system is worse than with a 2-D system.

Certain stereo applications could not practically be evaluated in the past, due to the state of the art in display technology. Now, however, it is possible to conduct a proper comparison of performance with a stereo system that is equal in visual comfort and resolution to the non-stereo system. This would provide data on the stereo/mono factor alone, unconfounded by ease of operator use and all those other problems that have plagued stereo systems in the past.

In 1964, Kama and DuMars compared performance on a simple peg-in-hole task using a through-the-wall master-slave remote manipulator with force feedback, viewed either with stereo TV or conventional 2-D TV. There was no significant difference between performance times with 3-D as opposed to 2-D TV, although during practice sessions the average time with non-stereo TV was 81 seconds while 3-D TV required 63 seconds. Observing that in this test the stereo TV had only half the resolution of the non-stereo TV, Chubb (1964) used the same subjects and apparatus to compare performance using direct viewing through the hot-lab window, with either one eye (mono) or two eyes (stereo). Performance times for 40 performance trials (presented in blocks of 5 trials mono and stereo, balanced across subjects) were longer with monocular viewing than for binocular viewing. Both mean time and variance were greater in mono, with mono taking about 20 percent longer than stereo for these well-practiced subjects. Although the novelty of one-eyed viewing may account for some of the longer performance times, there was certainly no problem in unequal resolution or field of view between mono and stereo.

Smith, Cole, Merritt, and Pepper (1979) found a similar 20 percent increase in performance time for mono TV compared with stereo TV, using the same type of through-the-wall manipulator and a variable peg-in-hole task. Under both clear and moderately degraded visibility conditions, the average performance times for highly practiced subjects was 20 percent longer with non-stereo TV, even though the stereo TV had only half the vertical resolution of the mono system. In addition, the variance with stereo TV was considerably less than with the mono system. These results were obtained using a within-subjects design, with each subject trained to asymptotic performance. The peg task board was rotated and elevated to a new position for each trial; stereo was used first, then without changing board position, the trial was repeated using mono TV. This was done to ensure that whatever learning advantage occurred would help in the mono TV mode. The mono-stereo display factor was significant at the 0.0025 level, even for this task rich in 2-D depth cues.

A second experiment was conducted with the apparatus described above, but in this case a between-groups design was used, with unpracticed subjects (a limited amount of familiarity with the manipulator was permitted, but not with the task itself). In this test, there was no significant mono-stereo display effect, probably because the subjects were spending most of the performance time (200 to 400 percent longer than the practiced group) learning how to do the task. The variability among individual performances in approaching this task makes the between-groups design unsuitable for detecting the display effect--the mono-stereo factor was submerged in the noise.

A different task, however, showed highly significant mono-stereo TV effects even though a between-groups design was used. This task, unlike the peg-task described above, was not rich in monocular cues to depth and shape. It represented a realistic undersea situation wherein task objects are often obscured by marine growth and sediment, and the usual cues of shadow, size, interposition, and perspective may be severely limited. The average performance times were 40 to 75 percent longer with 2-D TV than with 3-D TV, despite the poorer vertical resolution and annoying flicker of the 3-D system that was then in use. The number of errors was 100 to 170 percent higher with non-stereo TV.

These three experiments in 1979, and the two in 1964, are presented as examples of how the methodology used to test the advantages of stereoscopic displays versus non-stereoscopic displays can produce either a highly significant stereo effect, or no significant effect at all.

It would seem likely that as stereo display evaluations are conducted with new technologies now becoming available (e.g., solid state cameras and displays, automated stereo alignment and image matching), and experimental evaluations are conducted with operationally realistic tasks and appropriate test procedures, there will be increased utilization of 3-D displays for data analysis and for remotely manned systems.

Extra Benefits from Stereo Displays

In addition to the improved spatial perception and visual-motor coordination obtained with stereoscopic displays, there are a number of important side-benefits that are often overlooked in considering use of a 3-D system.

Stereo display systems are usually thought of primarily as aids to seeing where things are in 3-dimensional space. Stereo also provides a tremendous advantage in seeing what things are in an unfamiliar scene or unexpected arrangement of familiar objects (e.g., a salvage situation).

Stereopsis derived from binocular retinal disparity provides an unambiguous and primary visual separation of figure and ground without, paradoxically, having to see and object before separating it from the background. As many photointerpreters have found, stereo is often essential for rapid and accurate initial perception of objects in the scene, especially when the imagery has low resolution, poor contrast, or noise that camouflages the signal. In fact, the poorer the image quality (typical of LLLTV or FLIR imagery) the more stereo can help in initial target acquisition and identification; this is because the target image signal is correlated in the left and right images, while the noise (assuming independent channels) is not. It is a property of the binocular stereopsis system that it can reject uncorrelated noise while retaining those image points that are correlated in a depth plane reasonably close to the fixation plane.

The limited resolution and gray scale typical of current systems to aid pilot vision in low levels of illumination or in poor visibility may benefit greatly from stereo display techniques, especially for nap-of-the-earth flight and low-level target acquisition. Stereo can help sort out the masses of poorly resolved terrain and foliage that are jumbled together in a conventional 2-D display (particularly because the limited gray scale gives little information from interposition cues).

Improved resolution versus field-of-view is contributed by the extra information in two image channels versus one in a non-stereo system. Just as a person can read an eye-chart better with two eyes than with one, the effective visual performance with a stereo TV display could be expected to exceed than for a comparable mono TV system by about 40 percent. This would permit either much better resolution with the same field of view, or a bigger field of view with the same resolution, as compared to a mono system comprising the same video hardware in a single channel. This means that the current state of video hardware can be purchased in duplicate to achieve significantly better seeing for the human operator. In addition, two independent channels, like two engines on an aircraft, provide a contingency mode in case one of the camera/display channels should fail.

New Applications for Stereo

One of the reasons for not properly evaluating stereo in certain applications is the belief that it would have no relevance, and thus it is never tried.

It is often said that 3-D displays are not needed in flight simulators, since binocular stereopsis in normal human vision is not a strong cue beyond several hundred feet in visual range. Certain flying tasks are now becoming increasingly common where the visual distances involved fall well within human stereo thresholds. Nap-of-the-earth flight, low-level attack missions, VSTOL take-off and landing, and other flight operations rely on binocular cues in the real world. By providing stereo cues in the flight simulator display, trainees can begin to learn these cues just as they will eventually in the real world. Other examples of close visual distances in flight are in-flight refueling and formation flying, where depth differences as little as 6 inches are resolved at a distance of 30 feet.

New types of operational requirements and new types of video display hardware suggest a re-examination of those areas where stereo benefits may be worth the extra cost and inconvenience of a dual channel display.

Whatever the application and the hardware selected for intial evaluation, the methodology for comparing 3-D versus 2-D systems is extremely critical for a proper assessment of the costs and benefits.

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VISUAL PERCEPTION RESEARCH AT NAVAL OCEAN SYSTEMS CENTER

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As many of you know, the Naval Ocean Systems Center has played a leading role in the development of a number of undersea vehicles and work systems, both manned and unmanned. For example, the family of curve vehicles, Curve 1, Curve 2, Curve 3, and RUWS, the remote underwater work system, their contemporaries, AUWS and the advanced tethered vehicle that we are working on today, are all products of NOSC's exploratory development efforts.

I have to give credit to Dr. Robert Cole of the University of Hawaii, who has been my constant colleague since I became involved in vision research. Our early work included John Merritt of HFR and David Smith, an engineer at NOSC.

When we initiated research in 3D displays at NOSC to support the undersea vehicle program, I felt that we should employ the best visual systems that were available. Initially, I encountered a lot of resistance to the idea of stereo television, even at NOSC. The prevailing attitude was that it had been tried but it doesn't work. It causes eye strain. It's too complicated and it's too costly, so we don't want it! I began to survey the literature to try to verify some of these claims. The literature indicated that there was no significant performance advantage to stereo displays compared to conventional TV displays, and in some cases the stereo systems were found to produce results that were poorer than the conventional systems. I found this hard to believe. After all the findings in perceptual research under direct experience conditions which consistently show a tremendous advantage to binocular vision with appropriate controls to eliminate motion paralax cues, stereo acuity thresholds are nearly a magnitude smaller than mono acuity thresholds when tested in an apparatus like the Howard-Dolman situation.

The results of our early work suggest that manipulator/operator performance under simulated undersea work conditions is determined by a complex interaction of several important factors. These factors are the visual information available to the operator, including the visibility conditions and the sensitivity of the display-sensor system; the manipulator capability; the task requirements imposed upon the operator;

and the operator's capacities themselves, that is, his experience, his learning abilities, and his motivation to perform.

Under controlled conditions with tasks which required the operator to position the manipulator end-effector in the Z axis or depth plane, performance was always superior when stereo systems were compared to conventional TV systems. The performance advantage with stereo was even greater under degraded visibility conditions.

Our first studies were valuable to me for a number of reasons. First, at least in my own mind, I unravelled the inconsistency in the literature regarding the meager support for stereo versus conventional TV displays. These variables that I found to account for the discrepancy were poorly conceived experiments, inferior stereo systems (which exist even today), and little or no control over learning and practice effects on the part of the operators. I acquired an appreciation for the immense human factors engineering of man-machine interface problems that exist in employing stereo displays, especially when we ultimately seek to extend this sensory capacity to the operator. This appreciation led my colleagues and I to develop a systematic approach to the analysis of the necessary and sufficient display conditions responsible for the various levels of operator or teleoperator performance. We are currently employing this display performance transform method to evaluate a variety of display features which are state-of-the-art or which show promise to extend man's capabilities.

The recognition of the human factors complexities involved in teleoperator displays became apparent during the course of our research. We discovered an interesting illusory movement that occurs when one's head is translated from side to side in a horizontal plane while viewing a stereo TV display. The apparent motion of the stereo targets which result from lateral head movements is like true motion parallax, that is, movements which are proportional to their distance from the convergence plane but in the opposite direction of true motion parallax. This illusory motion is thought to be the result of a central compensation mechanism which compares head movements with retinal image movements in order to maintain a stabilized image of the environmental objects.

Regardless of its illusory nature, it seemed reasonable to expect that the relationship which holds between the apparent distance of objects, the convergence angle of the cameras, and the degree of what we term the "pseudo-parallax" of these objects, could be used by the visual system in much the same way that true motion parallax is used. Results of our initial study of this phenomena indicated that the "pseudo-parallas" cues did not improve the performance associated with the use of stereo cues alone. While this result cast some doubt on the usefulness of head movements in conjunction with stereo displays in which camera positions are fixed during the given task, it does not detract from the idea that an isomorphic head-coupled, camera-aiming system could produce substantial benefits in teleoperator performance. Such a system would not only produce true motion parallax cues to depth but would also allow the operator to visually search the remote work site in a manner analogous to direct experience.

The second variable of interest in these studies is lateral camera separation, which results in a magnification of the retinal disparity cue to depth. In general we found that with TV displays, stereo acuity provides the most substantial gain in the transition from mono to stereo viewing conditions. In this earlier study, this two-fold increase in performance occurred with camera separations set at approximately half the interocular distance of the human eye. With camera separation increased to normal interocular distances, then beyond into the region of hyperstereopsis, we observed a gradual but diminishing increase in stereo acuity to a level approximately that found under direct viewing conditions. Thus, enhancing the retinal disparity cues to depth through increasing camera separation, teleoperator performance can be substantially improved.

In our most recent work, we elected to obtain a pure measure of hyperstereopsis by eliminating the cue conflict inherent in our previous study. A new stimulus presentation apparatus was constructed in a room which could be totally darkened. The apparatus consisted of two parallel guide ways from which light sources are suspended. This enables us to present luminous two-dimensional targets along the observer's Z-axis plane. We additionally built a camera station which is easily moveable with respect to distance from the targets. This enabled us to examine the joint effects of camera separation and distance on stereo acuity. The results of this study paralleled those of the initial effort using the Howard-Dolman apparatus. For all three conditions employed ere was a subsantial gain in performance associated with the transition from mono to stereo viewing conditions. Further increases in camera separation led to gradual but diminishing increases in stereo acuity. At the largest camera separation tested, 38 cm, performance was similar to that observed under direct view. It is important to bear in mind t'at while hyperstereopsis is successful in promoting stereo acuity in this very simple perceptual judgment task, its effect under more visually complex perceptual and perceptual motor tasks still require study. We cannot simply assume that these variables will be as effective in more complicated stimulus situations. Our approach to obtaining this kind of knowledge consists of carefully designed and carefully controlled studies. While we continue to be occupied with this direction of research, my engineering colleagues at NOSC are making strides in developing the hardware systems for a future generation of general purpose teleoperators. Presently, an isomorphic head-coupled camera-aiming teleoperator system is near completion. It has a flexible spine with a pan and tilt mechanism. The head employs two small CCD Panasonic cameras which permit a close interocular distance, approximating that of the human eye. The teleoperator also has a stereo hearing system with microphones located in the environment. The latest of this type of teleoperator system will be made available with two sets of pan and tilt units, one on the lower back and one at the juncture of the shoulder.

Pepper

When properly controlled with the computer, this new teleoperator will enable us to employ isomorphic movement to determine the contribution of head motion parallax in various perceptual judgment and perceptual motor tasks.

I think it is important to recognize that the complexity of these systems, depending upon the number of variables that you want to build in, need to be carefully evaluated. They may place additional demands on the operator which may or may not be offset by the value of the cues that are available. It is only by measuring performance that you can determine whether this value is worth the cost in maintenance, the cost in reliability, and the initial development cost itself. I think these trade-offs can be best assessed by the systematic gathering of data in the way that we are proceeding. Thank you.

Part III: Panel Discussion -- Applicability of 3-D Display Research to Military Operational Needs

THE APPLICABILITY OF 3D DISPLAY RESEARCH TO MILITARY OPERATIONAL NEEDS

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The Naval Air Development Center is responsible for research and development in support of Naval/Marine Corp aviation. This responsibility includes the research and development associated with control/display technologies and systems for a wide variety of fixed-wing high performance, fixed-wing low performance and rotary wing mission applications. Inherent in this research and development is, in general, an advocacy for appropriate stereo displays. Basic vision research and human factors experiments are focusing on stereo display phenomena and stereo applications. The display technology and hardware system development is being done anticipating the need for stereo, two-eye presentations. This may involve the need for color (depending on the stereo display technique chosen) or the need for modular system configurations to handle single eye vs. two-eye presentation requirements.

In the case of advanced display technology development, the Navy's work in this area is coordinated with the Air Force, Army, and NASA via several Tri-Service working groups. This interaction has further served to coordinate portions of the control/display development for the airborne community with technology development for the ships, land based vehicles and man-portable systems efforts as well. In addressing the topic of military operational requirements for 3D displays, these interactions aided in compiling the listing shown in Figure 1. This listing, while not meant to be comprehensive at all, represents areas where one or more of the Services have been involved in applied research and development associated with stereo displays over the past ten to fifteen years.

The application areas represented in Figure 1 are extremely varied. Much of the early R&D done by the military probably had as its operational objective remote manipulation and ordinance disposal. Many of the applications have dealt with the use of a stereo display presentation as a vehicle control or pilotage aid. These vehicle control applications have encompassed rotary wing, as well as fixed wing manned vehicle flight control, remotely-piloted vehicles (both air and ground based), major efforts in undersea vehicle movement, rescue and manipulation, and upgrading biocular to binocular display

- REMOTE MANIPULATION
- BOMB DISPOSAL
- VEHICLE CONTROL/PILOTAGE
  - ROTARY WING
  - FIXED WING HIGH PERFORMANCE
  - REMOTELY PILOTED VEHICLES (AIR & GROUND BASED)
  - UNDERSEA
  - COMBAT VEHICLES
- RECONNAISSANCE/TARGET ACQUISITION
  - DOWNWARD LOOKING
  - FORWARD LOOKING
  - VISUALLY-COUPLED
- AIR-TO-AIR REFUELING
- FIRE CONTROL/WEAPON DELIVERY
- COMPUTER GENERATED INFORMATION/IMAGERY FOR
  - MANEUVERING FLIGHT PATH GUIDANCE
  - VISUAL SCENE SIMULATION

Figure 1. Military Applications for Three Dimensional Displays

presentations for combat vehicle control. Separate and distinct from vehicle control have been investigations in reconnaissance or target acquisition. Efforts in both downward-looking imagery and forward-looking stereo sensors have been accomplished. In these areas and in some of the vehicle control areas, some investigations have dealt with accentuated stereo display presentations, and some work has been done with visually-coupled stereo presentations using head tracker and helmet-mounted display technologies. Stereo has been investigated as a display aid for the final phase in air-to-air refueling missions. In the fire control and weapon delivery area, various DoD laboratories have looked at the stereoscopic presentation of fire control symbology as a performance enhancement aid in weapon delivery. Finally, in the area of computer generated symbology and/or imagery, whether as a flight control aid such as maneuvering flight path guidance in the air, or groundbased visual scene simulation, biocular and/or binocular display presentations are involved.

As mentioned earlier, the Naval Air Development Center is focusing on the airborne community with its R&D efforts. If there is truly a requirement to get stereo into the air, that is if a system development or airframe development program manager needs a stereo display capability, there are several hardware options available. One such option is the use of a helmet-mounted display. Shown in Figure 2 is an example of a class of binocular helmet-mounted displays under development for high performance aircraft applications.

Figure 2. Binocular Helmet-Mounted Display For High Performance Aircraft

The binocular helmet-mounted display shown in Figure 3 is typical of rotary wing helmet-mounted display systems. Both of these systems offer the potential for providing two independent images to the airborne crew member. Another stereo display hardware option is the use of a device such as the one shown in Figure 4. This is the optical relay tube in the new AH-64 Advanced Attack Helicopter. Similar devices have been investigated for multi-crewmember high performance aircraft such as F-111. The crewmember puts his face "in the boot" and is presented virtual image display information. A device like this uses the "boot" to maintain exact head/eye position, and could therefore be used to present stereo type display information in a "heads-down mode." A third display hardware option exists in lieu of presenting the two scenes to the operator through two completely independent hardware channels. This option involves using spectral or time coding of the information on a specially modified direct view display, and issuing a set of red/green glasses or PLZT-type switching glasses to the operator. An example of this approach is shown in Figure 5.

Figure 3. Binocular Helmet-Mounted Display for Rotary Wing Aircraft

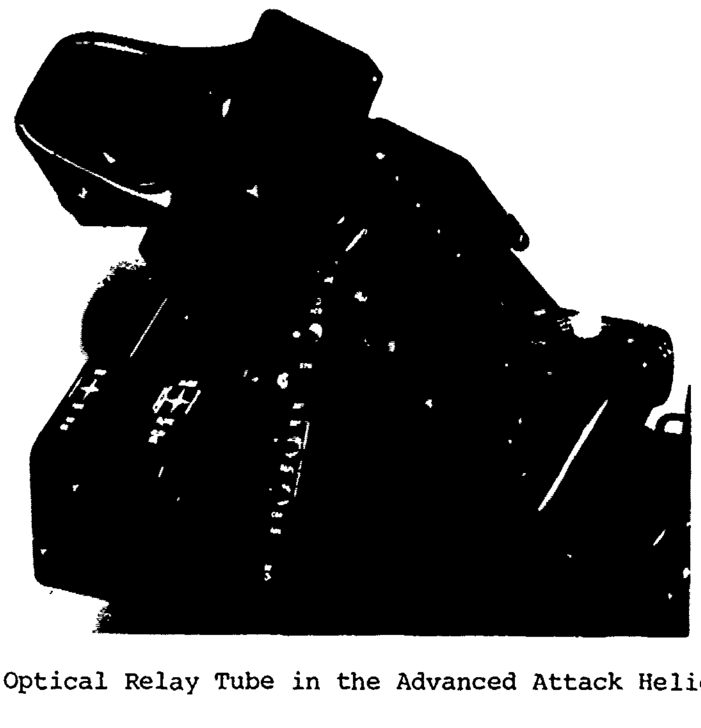

Figure 4. Optical Relay Tube in the Advanced Attack Helicopter

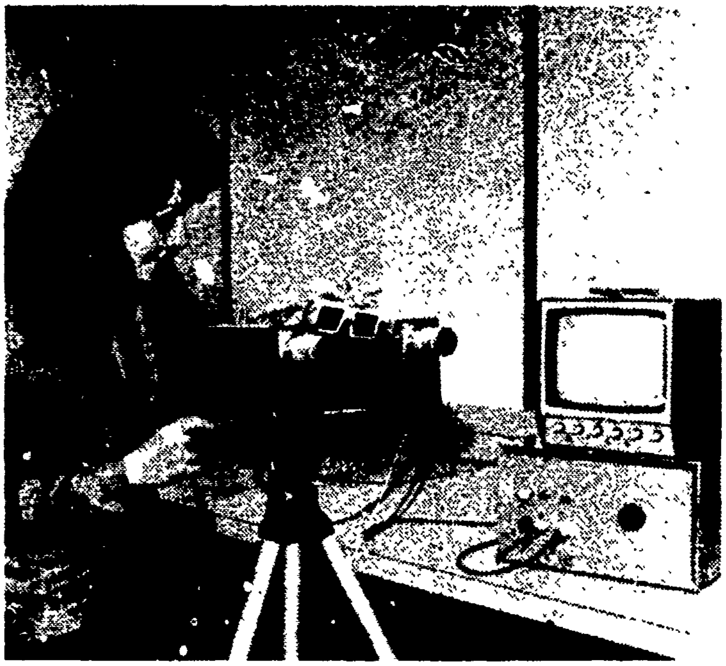

Figure 5. 3-D Display Using PLZT Glasses

Although it seems fairly elementary, the requirements implied in a stereo system should be emphasized. If a system developer needs a stereo system, then at the front end must be a source of stereo information whether it is a pair of high resolution sensors (forward looking infrared (FLIR), low light level TV (LLLTV), or radar) such as the example shown in Figure 6, or a stereo set of symbology which the operator over-lays on the real world such as the example shown in Figure 7, or two computer generated perspectives of a computer generated scene such as the one shown in Figure 8. Of course for airborne applications

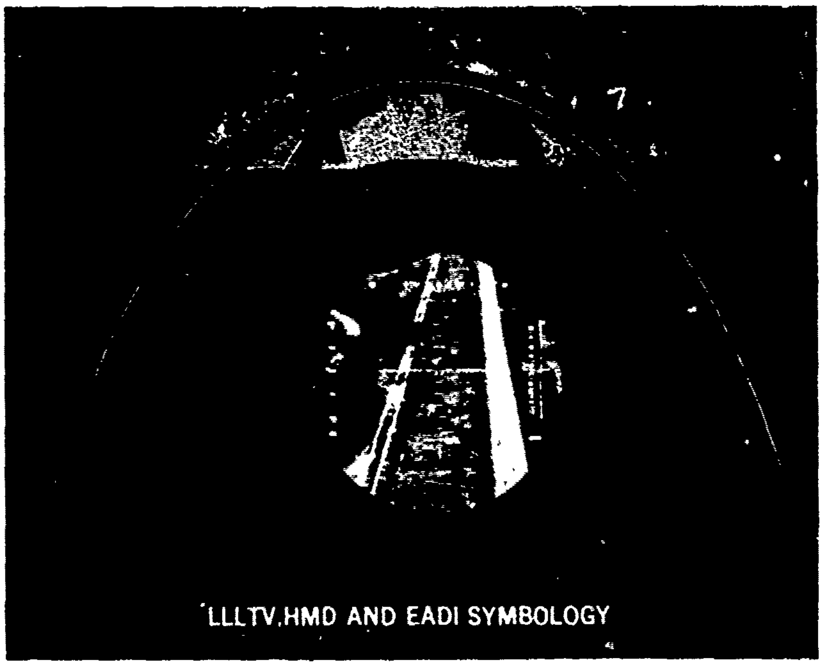

Figure 6. Low Light Level Television Imagery

Figure 7. Hot Line Gun Sight Symbology
Displayed on Pilot's Visor

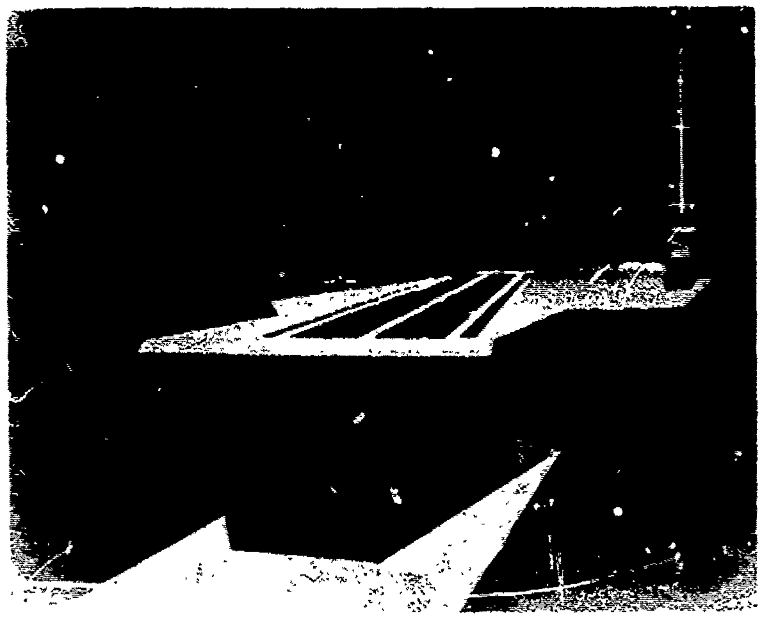

Figure 8. Computer Generated Imagery

two onboard sensors or a single sensor with sophisticated optics/ electronics to achieve a perspective view of the world are required to supply real world stereo video. For on-board computer generated symbology or imagery, the information obviously must be computed twice to achieve the stereo or perspective information display. The display end of the system has similar two channel requirements. The conceptual layout of a helmet-mounted display shown in Figure 9 can be used generically in discussing stereo display options. The requirement exists for two generated images, two sets of relay optics, and two final presentation elements for the operator to experience a stereo display presentation.

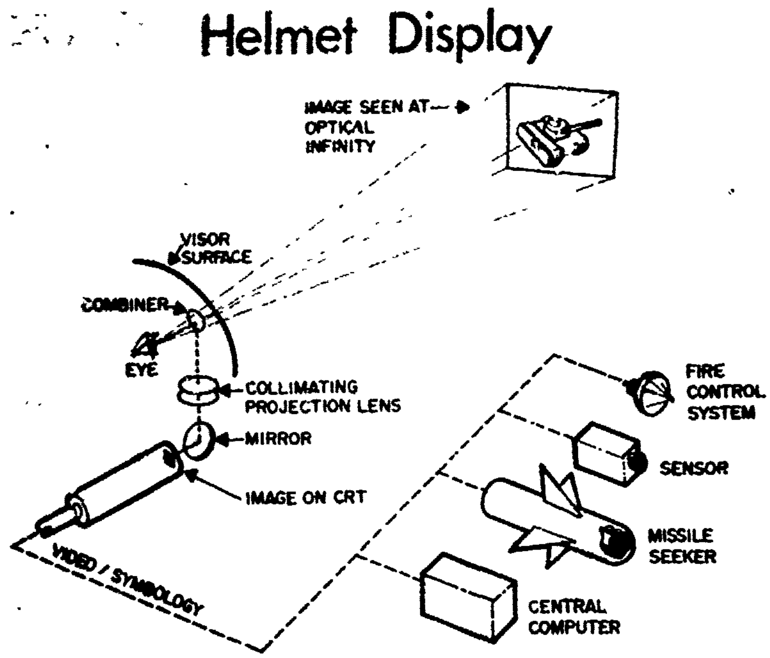

Figure 9. Helmet-Mounted Display Conceptual Layout

At this point the following discussion may appear to be a digression, but its relevancy to the point to be made will become apparent. Figure 10 shows the Navy's new F-18 cockpit. The Air Force F-16 could just as appropriately be represented here, since the F-18 crewstation is representative of a trend in the airborne community across the Services. The trend is toward the use of cathode-ray tube displays in the cockpit replacing electro-mechanical instruments. Technology

Figure 10. Navy F-18 Cockpit Configuration

development efforts are aimed at augmenting the displays shown with multi-line-rate video compatible head-up and helmet-mounted displays. So these trends are starting to get electro-optical display capability (a necessity for stereo) into the cockpit. The displays shown, however, are multifunction displays and the trend in system architecture is toward a bus-type architecture, such as the one shown in Figure 11, which provides the crewmember tremendous capability and flexibility. With this type of system architecture any information can be put up on

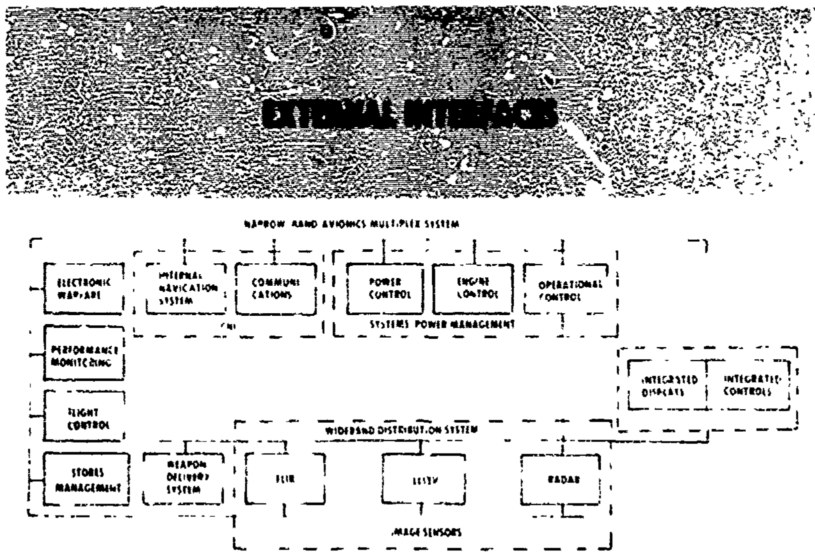

Figure 11. System Architecture Using Parallel Bus Concept

any of the displays in the crew station. If one display, or a symbol generator goes down, the multi-function-display/bus-architecture capability allows that information to be presented to the crew member using other displays and/or symbol generators. Another advantage of the trend toward multi-function displays is the ability to configure an aircraft cockpit for multiple missions. In this way, by reconfiguring the cockpit displays an aircraft can be configured for air-to-air, air-to-ground, or reconnaissance missions. For the display hardware developer this means a non-dedicated, non-specialized display with a standardized interface requirement.

It should also be pointed out that there are signs that the ground-based combat vehicles community may be headed in the same direction. This is occurring with the trend toward increased use of thermal sensors (thermal drivers viewer, independent commanders sight) and potential use of milimeter-wave radar. The situations, and the needs, for the tank community are very similar to those for the airborne community; namely, multiple operators, multiple sensors, and the need to distribute different sensor video signals for viewing by different crewmembers at different times during the mission. The combat vehicles community, therefore, will probably follow the trend toward a bus-type system architecture with standardized multi-function displays and a standardized display interface.

The system configuration diagram shown in Figure 12 is an example from another high-technology type aircraft, the new Advanced Attack Helicopter. Again the bus-type architecture is evident. This example is presented here because it contains some of the elements needed to

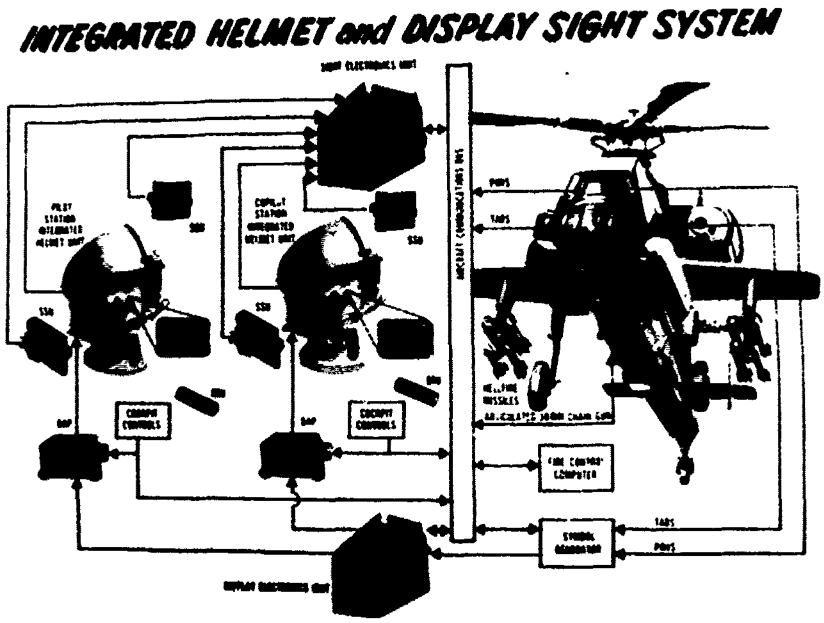

Figure 12. Integrated Helmet and Display Sight System Configuration Diagram

provide a stereo system capability. Each crewmember is provided with a monocular version of the helmet-mounted display shown earlier. There are two independent FLIR sensors in a pod on the nose of the helicopter. Normally the pilot is interfaced via his helmet-mounted sight/display to one FLIR and the co-pilot/gunner is interfaced to the other. The system shown does not represent a stereo system, but does begin to include some of the ingredients needed to provide stereo such as the two sensors and "half" of a binocular helmet-mounted display and/or the optical relay tube shown earlier. It should be emphasized again that these controls/displays are multi-function controls/displays Referring back to the mission applications shown in Figure 1, they are used for the vehicle control/pilotage part of the mission particularly in the nap-of-the-earth flight at night. They are used for navigation, reconnaissance, and target acquisition portions of the mission. They are also the primary control/display interface with the weapon systems onboard during the fire control/weapon delivery portions of the mission.

There is some interest in transitioning a portion of this capability to the Marine Corps for use on a different airframe with only some of the mission application areas represented by the Advanced Attack Helicopter system, primarily vehicle control/pilotage. For this application only a single FLIR system is affordable, and the decision to use two monocular helmet-mounted displays will probably be tied to overall system cost and budget constraints.

With all of this information as background, it is now appropriate to return to the subject of stereo and make the point of this paper by putting a question mark after its title. We would all love to have stereo displays in the cockpit. The display presentation shown in black and white in Figure 13 is a stereo display of ground terrain encoded in red/green format. Pilots would jump at the chance to have a presentation of this type as a 3-D electronic moving map display. Given a set of red/green stereo glasses, terrain features such as mountains and ridges would appear to "stand out" and even the display of buildings and vehicular targets would be enhanced. Presentations of this type are very exciting, and the display technology and hardware development community is certainly capable of developing the display system capability required to provide them but it is not obvious that they will find their way into the cockpit. What may get

Figure 13. Black and White Version of a Stereo Display of Ground Terrain Encoded in Red/Green Format

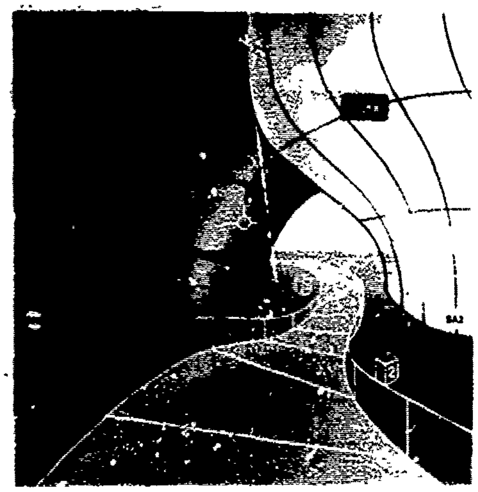

Figure 14. Analog Maneuvering Flight Path Guidance Type Display

into the cockpit is a two-dimensional version similar to the analog pictorial presentation of a maneuvering flight path guidance type display shown in Figure 14. This is only a two-dimensional analog presentation, but it provides the pilot all of the motion, depth, and flight control cues to allow him to fly the vehicle according to a directed flight profile and avoid threat areas as well. This type presentation does not meet the strict definition of stereo, the subject of discussion, but neither does it require a specialized display device to convey it to the the crew member. For a true stereo presentation with perspective, a binocular display capability is required along with the true "stereo" information to present. The question raised as a "devil's advocate" in Figure 15 is raised from the point of view of the major system or airframe Program Manager responsible for the development and successful operational implementation of, for example, over 500 Advanced Attack Helicopters or over 1000 F-18 aircraft. Does two plus two equal too much? Does a two channel

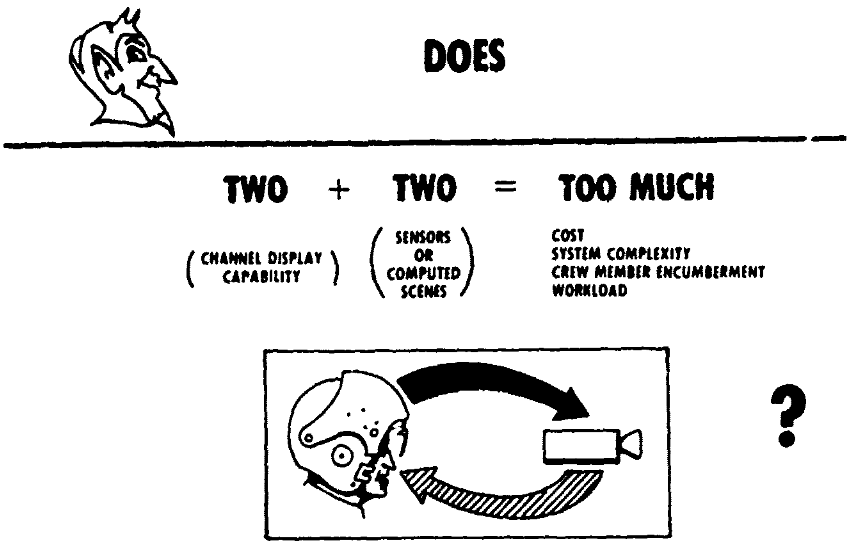

Figure 15. Question to be Considered -
Does Two Plus Two Equal Too Much?

display requirement plus two sensors or sets of computer information result in too much in terms of overall system cost, increased system complexity/for both sensors and controls/displays, crewmember encumberment in the form of a binocular helmet-mounted display or head constraint in the "boot" of an optical relay tube type device, or increased workload perhaps in a single seat, multiple task/multi-mission environment? This question is raised to instigate and to challenge. It is raised to instigate a healthy technical interchange and debate among the various communities involved in the DoD process including those involved in the basic vision research, human factors, sensor and control/display technology development, major system development, and the operational side of the house, the military user. It is raised as a challenge to the basic research and technology development communities to maintain a constant awareness of real operational problems and required capabilities within the fleet, and to focus the basic research on those areas of high payoff, and technology development on providing the required increased capability in on-board systems in a way that is both cost effective and compatible with the trend in multi-function crew stations and multi-mission aircraft.

PANEL DISCUSSION - APPLICABILITY OF 3D DISPLAY RESEARCH TO OPERATIONAL NEEDS

Dr. Roger P. Neeland
Chief, Airborne Systems Branch
Systems Research and Development Service
Federal Aviation Administration

I would like to say a personal word before I start, as I am really here wearing two hats today. There has been very little Air Force representation so I'll wear my Air Force hat, as well as my FAA hat. I am assigned to FAA at the present time, but I also fly once a week with the Air Force so I am also active in flying as well as engineering. Within FAA, I have a branch of engineers to answer cockpit-crew interface questions for the Systems Research and Development Service. I would like to talk about the FAA perspective on operational needs for 3-D displays and cover this divided into two generic areas of FAA interest. The first area is airborne or aircraft applications, with which I feel most comfortable. The second area is, obviously, the ground side air traffic control responsibilities of FAA.

First of all I feel, especially with the changing political environment, I need to mention something about the FAA's responsibilities. Perhaps today they may be a little different than the responsibilities that those of you who have worked with FAA in the past may recall. Within the area of airborne applications, FAA is primarily pursuing the certification responsibilities we must accomplish to assure that aircraft and systems operating in the national airspace are safe. We will be doing less actual development of airborne systems, and will rely more on private enterprise to come to FAA with systems that need to be certified. This may be a display by itself or displays as part of a total system. I personally feel that knowledge of the potential display methods -- and certainly these you mentioned today fall in that category -- are important to FAA in being able to exercise this certification responsibility as well as in exercising our responsibilities in the areas of some systems we have to design. FAA is responsible for such things as collision avoidance, landing guidance systems, navigation systems, and air traffic control procedures, so we do need to know about potential displays for these systems. On the air traffic control side, it is a slightly different situation than airborne because FAA has responsibility to design and implement these systems, including the displays. A note on air traffic control: please remember that these responsibilities cover a very large geographic area. I only mention that because it will come back later when I pass on the comments that I have from our air traffic control people. This is a very widely-spread geographic responsibility. Within FAA, air traffic control system planning for the next 20 years is pretty well underway right now. Some of you may have seen news releases in the last few days. Yesterday, Mr. Helms, our Administrator, released officially his 20-year plan oriented toward the air traffic control system of the future. This has some implications for hardware and certainly for displays.

Before we get into the actual applications, I just want to say there are some filters that I apply when I start thinking about this technology and whether or not to use it in a particular application. Hopefully we all do this. We need to look at what task has to be performed — what really is the job? Can we do it with simpler displays — with two-dimensional displays? If we can do it satisfactorily, perhaps we don't need to go any further. Then we need to ask the question — is there an enhanced capability that would really come about by adding, in this case, the third dimension? Is there a new capability that can be defined by using this third dimension? That may be the case in some of the airborne applications I am familiar with. Perhaps it is not a matter of improving old tasks — doing them better — but perhaps being able to do new tasks. Practical aspects that we just can't lose track of include the fact that we have to have sensors to feed these devices. A lot of times we can come up with very nice displays, but we can't get the information really necessary to drive that display. That doesn't mean that we stop developing the display, but we don't really expect to be able to implement it until we get the sensors we need. The total operating environment must be considered. Cockpits get pretty noisy and vibrate a lot. There is limited physical space in the cockpit for some things such as volumetric displays, and this has to be taken into account. Other tasks that have to be done have to be considered. I can imagine a pilot flying and trying to use stereographic displays. Usually this implies wearing some glasses of some sort, such as polarized or colored. This might interfere with other tasks, such as looking out of the window and combining visual display information inside the cockpit. I am not sure you are aware, but right now I cannot fly with polarized lenses in my sunglasses. I think the same thing would hold true for stereographic display lenses because of irregular windshields, etc. There may be some practical limitations there. There are other tasks the pilot has to do so that he may be trying to use 3-D information, but he has to be able to transfer back and forth between looking at a display and looking outside. It was brought up by Dr. Fox and others this morning that we have to look at differences between individuals, whether we are talking about using a display for a controller or a pilot. The screening and the training of individuals that I have heard people talk about is very important also.

As far as airborne cockpit applications I can see in the future, final approach guidance for landing is going to be made possible in a practical sense in the near future. I think we will have the sensors to do this because of the new microwave landing systems with precision distance information. There has been some work done on this already by some of you here and others who are making these types of displays using at least a 2-D projection of 3-D information. Personally, I would be very interested to see if we can compare a 2-D projection of 3-D information with true 3-D information and see if there is any difference in capability between them. This is a possible area of application. It may be necessary to enlarge or distort the vertical dimension in this case for final approach guidance because you typically have dimensions longitudinally of perhaps 5 miles, vertically 1500 feet, and laterally 200 feet. There are order of magnitude differences here that may need some enlarging to give useful visual cues to the pilot. An extension beyond final approach guidance would be vertical guidance, metering, and spacing. Standard arrival routings that we fly now require both course and altitude guidance, so there is a three dimensional problem. This might be something we can use in the cockpit. If we go to metered arrivals, this casts time as a true fourth dimension. Some approaches have been tried by the National Aeronautics and Space Administration; for example, having a moving box along a flat projected 3-D display, but there may be, in fact, a need for true 3-D displays. Cockpit display of other traffic for spacing purposes is being pursued by NASA and FAA, and this could very well use a 3-D type of display. Collision avoidance is something FAA is actively pursuing, and my branch is looking at various display mediums and techniques for collision avoidance. Perhaps there is a use for 3-D displays in this area. If we have what we are calling a full-capability collision avoidance system that has 3-D information, that is, angular information as well as range and altitude difference, perhaps we could feed the 3-D display. We might need that for a proximity warning. If another aircraft is close enough that I need to maneuver, it would be good for me to have this 3-D information. If I only need to know that he is somewhere in the vicinity, it may not be worthwhile going to that extra complexity. Another area of possible application, a little further out again because of sensors, would be the display of atmospheric anomalies in the cockpit. For example, I have responsibility for looking at wake vortices, the turbulent air following behind aircraft. We have to do some extra spacing between aircraft because these vortices are out there. If there could be developed a sensor to track those and a display to present them to the pilot, we might be able to space aircraft a little closer together. I think a lot of us airborne would like to see thunderstorms 3-dimensionally. If I had a way of looking at a cell and seeing how deep and how wide it was, that would be very useful to me. Another aircraft oriented application, but not strictly in the cockpit, would be the enhancement of simulation techniques and aircraft simulators. We are now in a situation of having what are called Phase II simulators that don't have a 3-D capability, and yet we have shown we can safely progess a pilot through to a final check in them. It is possible that the first time he would see an airplane would be to go out and fly people in it. Simulators are that good right now. Is there anything to be gained by adding three-dimensional displays to a simulator? I don't know but it is a possibility. Certainly since we are using computer graphics in a lot of simulator displays right now, the information would be there.

Now to go to the other general area of ground side air traffic control. The comments that I have here are gleaned from other people within FAA that I have worked with. I know they run counter to the feelings of some of you here, and I expect to hear some questions on these later. In general, there is not a positive attitude towards the use of 3-D displays at this time for air traffic control. There are several reasons, and I will try to explain them. Attempts have been made in the past with some type of a volumetric three-dimensional display. There were several questions which came up during testing and it was felt that this was not, at least at that time, a feasible way to go. The consensus was that the accuracy of tabular data was needed for the responsibility of the air traffic controller. For him to grant separations, issue clearances, and authorize descents, he needs to have the accuracy that he gets from actually reading altitude on the plan view that he uses right now. If he still has to have that, there is not much sense in going to a 3-D display. I think that this has been one of the major problems — this idea of precision requirements which controllers feel are too tight to allow human perceptual capabilities to give them that data.

The second problem is one of scaling. The fact is that the typical controller may have a 4000-foot slice of altitude with a 20-, 30-, 40-, or even 50-mile radius of responsibility so you have quite a disparity among the three dimensions. In this case, a volumetric display would not help him that much as a 3-D cue. Perhaps on final approach that might be a little different, but a large variance in scaling still exists as I have indicated. As I mentioned earlier, Mr. Helms has just briefed how the future ATC system may look, and it is going to be moving toward automation. As you know, we don't have as many controllers as we did a year ago, and we are likely to have a reduced number for some time. The movement was already afoot toward more automation even before the current situation. We are going to move that way, and as the controller becomes more of a supervisor, I think 3-D displays will have the capability of allowing him to visualize the total traffic flow while allowing him to concentrate his effort as a human monitor on intervening in the system in a particular geographic area. We are talking 15-20 years for this. It is a very evolutionary system. I think a lot of the applications I mentioned in the cockpit could very well have controller applications also — collision avoidance, final approach guidance, weather display, metering and spacing. All could apply to a controller, at least a terminal area controller.

I would say, in conclusion, that going to 3-D displays must be in reponse to some sort of a validated need or some perceived capability that is available by going to 3-D displays. Practically, you have to consider the sensor, physical size, weight, and procedures that you are going to follow. There are several potential aircraft applications that I mentioned — approach guidance, vertical guidance, collision avoidance, weather display, and simulation technology. The groundside applications may not be as immediate because of the accuracy requirements for the granting of clearances and the fact that the controller has many targets, but these applications may increase as the controller becomes more of a monitor.

APPLICABILITY OF THREE-DIMENSIONAL DISPLAY RESEARCH TO MILITARY OPERATIONAL NEEDS

John J. Pennella
Naval Explosive Ordnance Disposal Technology Center
Indian Head, Maryland 20640

My name is John Pennella and I am with the Naval Explosive Ordnance Disposal Technology Center. The Explosive Ordnance Disposal Technology Center is a relatively small activity located about 30 miles south of Washington in Indian Head, Maryland. Our activity is a joint service center. That means that we do work for all four services under the Administrative Management of the Naval Sea Systems Command. Our basic mission is in developing tools, equipment, and techniques for the military EOD technician. These tools and equipment are utilized by the EOD technician when performing their functions in disarming hazardous ordnance. The basic tasks required by the EOD technician are detection, location, gaining access to, final identification of, and lastly, but definitely most importantly, is neutralization of the hazardous item.

Currently, we are investigating a myriade of ways of reducing and, hopefully at some point, eliminating the hazard to the EOD technician when performing these tasks. In this regard, the EOD Technology Center is pursuing small, relatively simple, remotely controlled vehicles to aid in the performance of a variety of these hazardous tasks. These tasks include the underwater and surface detection, location, identification, final placement of tools on or near the hazardous items, and remote recovery and removal of the hazardous item to a disposal area.

I have been asked to comment on the applicability of the topics discussed today to the problem faced by the EOD technician. As a general overall comment, I see two areas where three-dimensional displays would assist the EOD technician in the performance of his tasks:

(1) Placement of tools on or near a hazardous item is aided when the operator of a remotely controlled vehicle has depth perception.

(2) Scene interpretation is greatly aided by the added third-dimension.

A number of the topics discussed today need, in my opinion, further investigation. Of these the effects of training are very important. Earlier, the fact that training effects have an impact on the ability of the operator to perform his tasks were discussed. EOD technicians are highly trained specialists in rendering ordnance safe, however, they have very little training in the use of exotic equipment. They are trained on specific equipment once and then get periodic on-the-job training. They may not use that specific equipment again for six months to a year, but then are called upon to use it at a moments notice. In this regard, does the use of three-dimensional displays make it easier to train the equipment operator? Is re-training accomplished more efficiently, and does the operator perform more consistently?

Another topic that was applicable to EOD systems is the need to define minimal system requirements to adequately perform the tasks required by EOD technicians. For example, are the minimal three-dimensional system requirements different from requirements for identification and detection for tool placement? How does the system designer determine what those minimal three-dimensional system requirements are?

The topic of scene interpretation is highly applicable to the EOD technician's tasks during training. The technician has a known, well defined scene he is required to interpret. During an actual incident, however, a very unknown scene may and often is presented to the operator; Yet the operator is required to search, locate, and finally disarm the item. The first problem the operator may encounter is the detection of the hazardous item from the remainder of the unknown scene. Scene interpretation is an important research area which needs further investigation.

Operator fatigue, especially with minimally trained personnel is another topic that requires further investigation. Do three-dimensional displays, or three-dimensional video presentations decrease or increase operator fatigue?

One of the topics discussed which is of importance in the EOD task is the effects of three-dimensional displays on operator-manipulator performance on degraded visual conditions, such as highly turbid water. Can the system designer expect better performance from the operators when utilizing three-dimensional versus two-dimensional systems?

In conclusion, three-dimensional video displays appear to solve many of the operational problems and limitations associated with two-dimensional video systems. I believe that in the near future the applicability and utility of three-dimensional video displays will be demonstrated.

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