Stereo TV Enhancement Study

DETAILED

FINAL TECHNICAL REPORT

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STEREO TV ENHANCEMENT STUDY

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ABSTRACT

A program was conducted to evaluate the ability of individuals to judge size and distance of targets on a TV-type display with both stereo and non-stereo presentations at different S/N ratios. Its purpose was to determine the effec iveness of stereo TV presentations in allowing an operator to remotely control an extra-terrestrial vehicle.

Sixty subjects, both male and female, were shown 72 photographs of a lunar-type terrain on a dual TV-type projection system. Twenty-four of these pictures were monocular presentations, 24 were stereo taken with a 4-inch inter-camera distance, and 24 were stereo taken with a 12-inch inter-camera distance. The camera-to-target distances ranged from 20 to 200 feet, and the target sizes ranged from 4 to 40 inches. The subtended visual angles of the targets covered a range from 5 to 550 minutes of arc. The noise levels used varied from an S/N ratio of infinity (i.e., no noise) to 10 db peak-to-peak to rms. Stereo presentations were achieved by both a Polaroid projection technique and by optical means using beam splitters and curved mirrors.

The results were that for trained subjects there was no significant difference between either of the stereo presentations and the non-stereo presentation at any noise level. Accuracy in judging size and distance of targets was equally good with all noise conditions, but there was a diminution in the number of targets seen at the higher noise levels. This diminution took place largely among the targets that subtended the smaller visual angles. In general, a target that subtended a visual angle of less than approximately 35 arc-minutes was not seen, whereas targets that subtended larger visual angles were nearly always seen.

Section 1

INTRODUCTION

1.1 STATEMENT OF THE PROBLEMS AND PURPOSE OF THE PROGRAM

The prospect of the surface exploration of extraterrestrial bodies looms as a significant and challenging objective of future space missions. Ultimately, decisions based upon technological and economic factors will determine the direction such missions will take; especially whether manned or unmanned vehicles should explore the surface of such extraterrestrial bodies.

Within the scope of unmanned exploration lie those classes of vehicles that are monitored and controlled by an Earth-based operator. The method for providing visual data for such manned remote control of the roving spacecraft consequently becomes a subject for early investigation by NASA and its supporting industrial organizations. The results of these investigations are intended to provide the guidelines for timely development programs to assure the availability of the appropriate equipment when operational needs so dictate.

One of the principal trade-off decisions recognized by NASA is the format and method for displaying visual data to the remotely located spacecraft operator. In particular, possible advantages for stereoscopic presentation over monoscopic methods were deemed desirable for further study. Within the realm of stereoscopic presentations, it was also desirable to determine the optimum method for such displays. Accordingly, the program presented within this document reports the methods and results of such a study prepared by the Human Factors Department of the Electro-Optics Division of the Kollsman Instrument Corporation for the George C. Marshall Space Flight Center under Contract NAS-8-21201.

It was recognized by NASA that, in addition to research devoted specifically to the problem of stereoscopic versus monoscopic presentation methods under the operational conditions described above, a number of related programs and experiments have been conducted in the past by other organizations. It was deemed appropriate, therefore, to initiate the present study with a rigorous and comprehensive literature survey intended to avoid duplication of previous efforts and to establish the baseline for subsequent experimental efforts to be carried out by the Kollsman Instrument Corporation. This initial task was performed and is described in detail within the body of this document.

Subsequently, an experimental program was established, directed at determining the effectiveness of stereo presentation versus monocular presentations of simulated electronically generated imagery under diverse spatial situations and simulated electronic noise conditions. The apparatus, test procedures, and results of this major task within the study reported herein is described fully within this document. When analyzed in combination with each other the results of this program will help to furnish guidelines for subsequent decisions for the development of the requisite image telemetry and presentation methods.

1.2 NATURE OF STEREOSCOPIC VISION

The ability to see three-dimensionally or stereoscopically, is dependent upon many cues. Stereoscopic vision is a weighing and a summation of these cues, mostly without conscious thought as to the methods or reasons for arriving at the judgment. The value of most of these cues is learned from experience, but on a subconscious level. However, this does not mean they cannot be consciously taught, and it is highly probable that training and practice improve distance judgment.

There are ten well-known cues in distance judgment. Two of these cues rely on use of two eyes, that is, they depend on the two eyes being slightly separated as they view an object. The other eight are monocular; they work with one eye as well as with two eyes.

When a scene is viewed with one eye only, or monocularly, accurate judgment of distance or of the shapes of unfamiliar objects is impossible. However, some idea of relative distance may be obtained by monocular vision. The monoscopic cues give the depth simulation associated with monoscopic television while the binocular cues are associated with stereo TV.

The first of eight monocular cues is the estimation of distance by the angle subtended by an object of known size. Thus an object of known size is judged to be at a distance inversely proportional to its apparent linear dimensions. (This cue also works in reverse: if the distance of an object is known, the dimensions of that object of unknown size can be estimated.) Distance judgment on the basis of angle subtended is equally effective at all distances.

The second monocular cue is aerial perspective. Here, since objects as seen from a distance have indistinct contours, a reduction in apparent color saturation (or a change or loss of color) and a change in brightness occurs so that the object contrast with its background is reduced. These changes are caused by a scattering of the light reflected by the object as the light passes along the visual path between object and eye and an addition of light to the visual path from other sources. Objects that undergo these apparent changes are judged to be at a distance.

This cue is used most often at those ranges at which the changes are most noticeable; these ranges vary depending on the atmospheric condition. For example, on a misty or hazy day, the nearest effective range for this cue is quite shorter than the nearest effective range on a clear day. However, when extremes of atmospheric conditions occur, these atmospheric conditions must be considered in the judgement. If they were not considered, gross errors in the estimation of distance may be made. It is well known for example, that a pedestrian is more likely to be hit by an automobile on a foggy day. This is because the aerial perspective cue, uncorrected for atmospheric condition, incorrectly informed him that the automobile was at a greater apparent distance than was actually the case. Except in misty weather, the effective ranges for the aerial perspective cue are in the middle and distant ranges (approximately a thousand feet or greater).

The third monocular cue is linear perspective. There is an apparent visual change in the geometry of objects that extend to a considerable distance from the observer. Thus, the tracks of a railroad or the lines of a runway seem to converge in the distance.

The fourth monocular cue is lights and shadows. This cue helps disclose the position of objects relative to light sources and to other objects. It may be used at any range.

The fifth monocular cue is overlapping contours. It establishes the order of position of objects toward the observer. It can override other cues for distance judgment. However, absolute distances cannot be estimated only on the basis of overlapping contours. It only discloses an order of position with respect to another object. The cue is effective at any range.

Motion parallax is the sixth monocular cue. This cue is the relative displacement of objects as seen when the observer is moving. When the observer is riding in a car, objects nearer than a fixated object appear to be moving past in the opposite direction. When near objects are fixated, distant objects tend to move in the same direction as the observer.

The seventh monocular cue is accommodation. This cue, being very weak, is used mainly at short ranges. Thus, a reduction in accommodation of 1/2 diopter at 33 cm will change the accommodation to 40 cm. A reduction of 1/2 diopter at 200 cm will change accommodation to infinity. Hence, accommodatively, a change from 33 to 40 cm is the same as a change from 200 cm to infinity. Therefore, accommodation cannot be very sensitive to changes at ranges beyond a few feet. (This cue can also be considered binocular.)

The eighth monocular cue is association. This cue is usually not of any decisive value, but at times, it indicates distance better than any other available cue.

The judgments used in weighing and summating the above cues are, at best, imperfect. Thus, the use of two eyes is required to enable us to obtain more precise visual information concerning our surroundings.

With a correctly balanced pair of eyes the monocular characteristics mentioned above are possessed equally by the two eyes. The superior stereoscopic perception obtained with binocular vision, however, is not due to the fact that the eyes are presented with two identical sets of information. It is on the other hand due to factors which do not enter at all into monocular vision, It is, in fact, the difference, not the similarity, between the two sets of information which is of importance. Thus, stereopsis is based on the facts that:

1. Objects viewed with both eyes are viewed from slightly different angles and form slightly different images on the two retinas.

2. Objects nearer than a fixated object form crossed (heteronymons) images in the two eyes, while objects farther away form uncrossed (homonymous) images.

The two eyes are separated horizontally by a distance between the pupils of approximately 2-1/2 inches. This separation gives rise to the phenomenon known as parallax. In Figure 1-1, L and R represent the eyes of an observer viewing an object (O) from a distance (d). The angle subtended at O by the base b is termed as the parallax of the object (O) or as the angle of convergence. For an object at infinity, the parallax is zero. As the object comes nearer to the eyes, the parallax will increase accordingly, and the effort

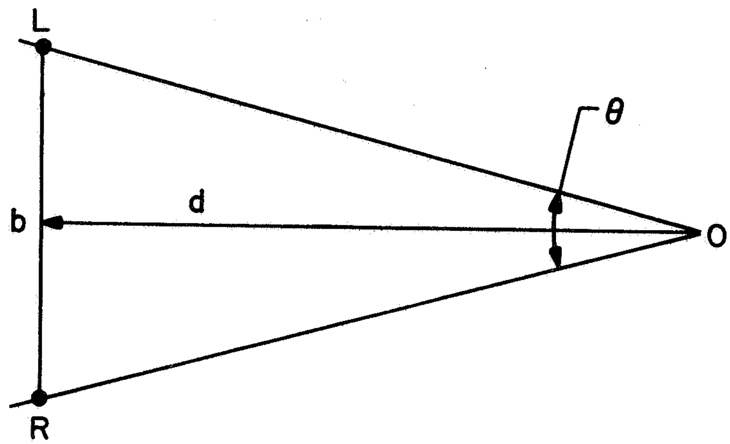


Figure 1-1. Parallax of an Object

which is exerted by the ocular muscles to bring the visual axes towards the points will thus become greater. This effort is known as the effort of convergence. The variation in the magnitude of this effort, according to the distance of the object, is one of the two factors which contribute to binocular depth perception. Convergence is a very weak cue to depth perception and any system for creating depth perception should place little or no reliance on convergence. The other factor is the dissimilarity (disparity) of the two images seen separately by the two eyes. This is why true stereoscopic vision is virtually inoperative for objects beyond 2,000 feet. Stated simply, when viewing very distant objects the separate images are almost identical.

1.3 VISUAL PARAMETERS IN STEREOSCOPIC VISION

1.3.1 Stereoacuity and the Perception of Depth from Disparate Images

a. Threshold

Stereoscopic thresholds are defined as the minimal values of the physical stimulus required to perceive 3-D effects on 50 or 75 percent of the human's responses, depending upon the threshold value.

If Nt (stereoscopic threshold) is taken as 20 seconds of arc (0.00010 radians) with average interpupillary separation of 6.3 cm, the critical distance for perceiving depths stereoscopically would be 630 m ($b = 2a/Nt$). The 630 m corresponds with experimentally determined figures of between 1,500 and 1,900 feet. Some research has indicated that stereoscopic thresholds may be as low as 10 to 12 seconds of arc with average subjects. With very good subjects, thresholds of only 2 seconds of arc have been recorded. The Fry-Shepard Scale used for the Ortho-Rater's tests of stereopsis utilizes a standard of 100 percent Stereopsis at about 15 seconds of arc. Equal increments of disparity do not correspond to equal increments of depth. One can determine the least spatial difference (Δb) in distance between two objects which can be discriminated by $\Delta b = b^2/2a\ Nt$. Thus, the actual difference in distance between two objects which can be discriminated stereoscopically increases as the square of the distance of one of the objects (for objects near the median plane; approximate for peripherally located objects).

b. Fusion and Double Images

Fusion of the disparate images is not a prerequisite for the existence of stereoscopic depth. Experiments have shown that this depth can be seen after disparity has become so large that the images are seen double and consequently fall outside Panum's fusional areas (region in which doubling is not experienced, but in which the images must, except for the one point, be logically disparate). Both half images participate in the depth experience. Disparity cannot be too large or two half-images are indefinitely localized as to depth. Limiting disparities amount to 20 minutes of arc near the fovea, and increase rapidly towards the periphery where at a peripheral angle of 8 degrees of arc, limiting disparities may be serveral arc degrees.

When doubling is relatively small, stereoscopic depth in the sense of subjective magnitude bears a definite relationship to the disparity. As disparities grow larger, stereoscopic depth becomes less definite (images only perceived as farther or nearer than fixation point) until sense of depth vanishes altogether.

c. Vertical Disparity

It has been shown that vertical disparities between the images of an object stimulus point do not give rise to a subjective depth as do transverse disparities. Vertical disparities do have limits in magnitude for which transverse disparity components can no longer give rise to stereoscopic experience (not exceeding 6 minutes of arc at the macular, "all cone area", which surrounds and includes the fovea — subtending about 3 degrees, even in individuals with vertical muscle imbalance).

d. Simultaneity

Disparate retinal elements involved in a given stimuli must be in an excited state at the same time. Stereo can be achieved from disparate images presented successively (first one eye then other), but only to the extent of the afterimage persistence. Limiting delay times of up to about 250 milliseconds have been reported. Stimuli for simultaneous exposure for stereo depth experience can be as short in duration as 0.0001 second.

e. Stability of Retinal Correspondence

The relationship between stereoscopic depth perception and the organization of retinal elements of the two eyes with the brain (basis of corresponding retinal points) appears generally stable.

f. Validity of Stereoscopic Depth

For a given observation distance, it has been shown that there is remarkable validity between stereoscopic depth as related to disparity, and the corresponding objective depth. A valid stereo depth would employ only a proportionality to objective depth, the constant of proportionality being indeterminable because one cannot determine whether the subjective sense of depth is identical with objective depth. Even though two stereo depths produced by two different sets of disparities can be readily compared, an estimate of given depth in terms of a learned scale would be dependent on other and probably central factors. The validity of stereo depth refers to the relative correctness of ordinal values of stereoscopic depth. Even in comparison of different stereo depths, some central factor operates because equal apparent depth intervals are not identical to equal intervals of disparity, and in some manner the observer must know the observation distance.

1.3.2 Parameters Other Than Retinal Disparity

a. Convergence (Kinesthetic sensations produced by convergent and divergent eye movements.)

Convergence plays a role in stereoscopic vision only to the extent that convergence movements of the eye are necessary to provide bifoveal fixation on the object point of attention. Some experiments have claimed evidence of a "muscle sense" which may supply depth information. Critical experiments, however, have failed to support such claims.

b. Accommodation (Kinesthetic sensations of accomodating movement of the shape of the eye lens in changing focus.)

Most experiments have shown that changes in accommodation in distance localization are most unreliable as guides to distance perception (although there is also some disagreement in the literature on this point).

1.3.3 Variables That Influence Stereoscopic Acuity

The following conclusions are based on results reported in the literature which are listed in the reference section of this document.

a. Brightness Contrast and Color Contrast

Binocular stereoscopic acuity under conditions of color contrast with low brightness contrast is inferior to stereoscopic acuity under conditions of high brightness contrast.

b. Observers Interpretation of Stimulus

Binocular fusion does not seem to be effected by whether or not the images to be fused have a common external referent. That is, the strength of fusion is the same whether the observer believes the images to be from the same source or two different sources.

c. Structural Differences Between Two Eyes

Stereoscopic distortion, caused by image-size differences stemming from structural differences between the two eyes, seems to be somehow compensated for by most individuals.

Image size can differ as much as 10 percent and stereopsis still be preserved.

d. Illumination

Experiments have indicated that stereoacuity improves (thresholds become smaller) as brightness increases. Some binocular depth acuity is found even at scotopic levels of illumination.

e. Terrain Effects on Perceived Distance

In one study involving background location in the presence and absence of a terrain surface reference, results indicated that perceived distance to a surface location was inversely proportional to the angle of the viewing plane with the terrain even though all estimated locations were equidistant from the observer.

f. Perceptual Enhancement with Binocular Vision

- Object Brightness

  Several studies have indicated that an object appears brighter when viewed binocularly as compared to viewing the same object monocularly.

- Apparent Size

  Experiments have indicated that a monocular stimulus must be made larger than a binocular stimulus where the two are judged to be equal.

- Reaction Time

  One study found reaction time to be shorter with binocular than with monocular stimulation by the same light.

g. Stereoscopic vs. Monoscopic Performance Studies (General Tasks)

Most field and laboratory investigations on this topic have shown a definite superiority of binocular vision over monocular vision for judging both absolute and relative depths of objects in space. These studies are summarized below according to types of tasks employed:

- Signal Detection

  One experiment found a small depth enhancement in tracking high acceleration targets at a signal-to-noise ratio of zero decibals for increased intensity disparity between the eyes.

- Target Motion and Position

  Several studies have been reported in the literature comparing binocular and monocular viewing as related to judgments on target motion and target position. One study, comparing a real 3-D display and an orthogonal dual projection 2-D display, found judgments of absolute velocity to be better via the 3-D display, but judgments of absolute position, relative position, and relative velocity were better via the 2-D display (the observations, however, were made utilizing a real display area of 10 feet square by 12 feet high, which is certainly a constriction of the usable range of depth perception). Another study found that direct tracking was consistently superior when a depth course was employed as compared with the same course viewed monocularly.

- Target Detection

  Available experimental evidence indicates that observation through binoculars is superior to observation through monoculars for picking up targets under adverse conditions. There is, however, no general agreement to the extent of binocular superiority, since values reported in the literature have ranged from 10 to 15 percent superiority for the binocular instruments.

- Remote Handling

  The following conclusions have been reported in the literature concerning remote handling via binocular vision:

  - On a simple remote handling task, performance times were 20 percent greater for monocular viewing than for binocular viewing. The monocular condition also resulted in greater response variability.

  - On a remote handling assembly task, utilizing a 3-D television system, performances were better with a single-camera system.

h. Stereoscopic vs. Monoscopic Performance Studies (Photo-Interpretation Tasks)

Several studies conducted in a military setting specifically oriented to PI tasks have generally produced negative results suggesting that at present, there is no significant advantage in using three-dimensional information. Several of these studies are summarized below according to types of specific PI tasks.

- Target Identification

  One experiment using operational photograhs of militarily significant targets found no significant mean differences between stereo and non-stereo for either correct or incorrect target identifications. In fact, under simulated flash reporting conditions, there was a consistent trend in favor of non-stereo viewing for correct target identifications.

- Total Information Extracted

  Using photographs of military targets it was concluded that the total number of responses was greater under the non-stereo viewing condition without any loss in accuracy.

- Specific Target Type

  It was found that there were no discernible advantages for either 2-D or 3-D viewing for any specific target or object type.

- Measuration

  In measuring actual target heights, it was reported that stereoscopic viewing yielded more accurate data within a shorter period of time required for each measurement.

- Contour Reproduction

  In reproducing terrain contours from photographs after an initial viewing period, it was found that more accurate reproductions could be made after the photograph was viewed stereoscopically.

A recent Armed Forces Committee on Vision concluded the following, . . . "at present, there are no commanding reasons for the adoption of 3-D displays. Claimed advantages are specific to particular system tasks, and no general set of requirements has yet been found."

i. Present Conclusions from Past Research

In spite of this research, experimental studies in other areas have indicated the following specific advantages using stereo rather than monoscopic viewing techniques:

- The quantity of information presented is increased.
- Multi-sensor presentation can be integrated on a single display.
- Targets which cannot be identified in two dimensions become extremely visible in the third dimension.
- Events can be designated priorities on the basis of depth cues.
- Time can be represented in or on the basis of the third dimension.
- Most of the presently available stereoscopic devices have not been fully "human engineered" to maximize the comfort of the Photo Interpreter. Present devices usually result in muscular and ocular fatigue because of restricted head movements and elaborate optics which do not consider the limitations of the eye. This has been verified by informal discussions with experienced PI's and trainees who indicated that they generally resort to their pocket stereoscopes when three dimensional data is required.
- Approximately 10 percent of the general population cannot perceive stereo and a considerably larger percentage of individuals have some visual defect. Even if this is an optically corrected defect, additional restrictions are placed upon the viewer since it is difficult to view through an eyepiece configuration wearing corrective lenses.

1.4 REVIEW OF THE LITERATURE

A computer search was instituted among the approximately two million ASTIA entries at DDC. First-level search terms were: Binocular Adaptation, Binocular Disparity, Cathode Ray Tube Screens, Display Systems, Fluorescent Screens, Ground Position Indicators, Monocular, Motion Picture Screens, Moving Target Indicators, Plan Position Indicators, Space Orientation, Space Perception, Spatial Correlation, Spatial Orientation, Spatial Vision, Steros-scopic Display Systems, Target Position Indicators, Television Display System, Viewing Screens, Visual Acuity, Visual Perception.

Second-level search terms were: Analysis of Variance, Decision Making, Distance, Human Engineering, Human Factors, Judgment, Judgment (Psychology), Perception (Psychology), Performance (Human), Photographs, Psychophysiology, Reaction (Psychology), Size, Size (Dimensions), Space Perception, Stereoscopic Display Systems, Television Display Systems.

From this search 412 reports were obtained and abstracted. Thirty-seven of these reports were considered particularly appropriate to the present investigation and are included in the bibliography. The approximately one hundred other reports included in the bibliography were obtained by a similar search through the files of STAR, A1AA, JOSA, SPIE, and other similar souces as well as using standard bibliographic sources such as Graham (55), Ogle (105), and previously collected works at Kollsman.

It may be concluded that there are relatively few works available in English which are pertinent to the project and have not been included in the bibliography. Some sources in French and German were also consulted as well as English translations of recent Russian work. It cannot, however, be contended that these latter fields have been thoroughly covered, particularly with respect to work produced within the last few years. Other European languages were not consulted.

1.5 SUMMARY REVIEW OF PREVIOUS EXPERIMENTS

With such a large number of studies on similar subjects, it is obvious that there is often considerable overlap between one study and another. Therefore, if several separate studies by different authors come to similar conclusions, it is very reasonable to assume that this conclusion is a true one, and is not an artifact of the particular experimental parameters employed. Some of these conclusions are summarized in the following sections.

1.5.1 Methods of Producing Stereopsis

It seems clear that, of the various methods of producing stereoscopic pictures (stereoscopes, polaroid, anaglyphic, parallax stereogram, Vectographs, etc.), the anglyphic is the least successful method [see Dudley (30), Mengle (90), Morrill (94), and Smith and Gould (122)] . The reasons for this lie partly in the human eye's response to color of different wavelengths and partly in the transmission characteristics of available filters. If one considers color television, these conclusions are even more true: the lack of resolution and various other problems associated with the use of colored phosphors make the problem even more severe than with colored photographs or prints. On the whole, the Polaroid separation technique (which is used in the present study) is as successful, from a physiological standpoint, as any other technique and, in addition, possesses the advantage that it can often be produced with less cost and complexity than other systems as long as the number of simultaneous viewers is small.

1.5.2 Target Detection and Resolution

Before one can discuss other parameters, it is first necessary to establish that the target can be located and identified at all. A considerable amount of work has been done on locating targets from line-scan type displays [cf. Botha (21), Elais (31), Gogel (47), Kosmider L81), Marsetta (87), and

Oatman (99 and 100)] . The problem of resolution here is set not so much by the limits of the human eye as by the number of TV lines through the target. With a simple target of high contrast seen against an essentially plain background, a minimum number of lines (about 3 or 4 lines) through the target will enable it to be identified. Increasing the number of lines by one or two will allow quicker (but not necessarily more accurate) identification. Further increases beyond this do not result in any appreciable improvement. With complex low-contrast targets seen against complicated backgrounds, as many as seventeen lines through the target may be necessary. Although there are interacting parameters (i. e., target size and target distance, target/background contrast, lighting, and number of TV lines per inch), the relationships between these parameters are reasonably well understood so that approximate predictions as to resolution effects can be made. In particular, one can specify in a number of cases where further increase in the number of TV lines will, or will not, make significant increases in target detectability.

1.5.3 Size and Distance Judgments from Displays

Here also a good deal of work is available with reasonably consistent results [cf. Baird (8), Gogel (45, 47, 51), Smith (123 and 125), and Taylor (129) as examples] . Even under the best circumstances, judgment of size and distance from photographs or TV displays is not generally as good as in the real world. Within reason, the characteristics of the photograph are not too important (judgments can be made as accurately from line drawings as from actual photographs): the characteristics of the real world of which the photograph is made has more influence. Thus judgment is quite poor when there are only a few objects of unknown characteristics seen against an uniform background. Judgment is better when there are more objects, seen against a textured surface, in perspective, and when the objects are familiar ones of known characteristics.

1.5.4 Size and Distance Judgment with 2-D and 3-D Vision

In both photographs and other displays, and in the real world, the superiority of 3-D over 2-D vision is a function, to a large extent, of the number of monocular cues present in the situation. With a large field of view, a textured perspective surface, and familiar objects, there is, in general, little superiority of 3-D viewing over 2-D viewing at distances of more than a few feet. These results may be seen in Guttman (60), Leibowitz (84), and Paine (108), among others. The influence of noise is affected partly by the structure of the visual field. If the visual field is highly structured (i. e., there is a good deal of redundant information) then noise has less effect at any given S/N level, and hence the difference between 2-D and 3-D is diminished. This seems to be true for all interocular distances that have been investigated (from 3 to 12 inches).

1.5.5 Effect of TV Noise on Distance Judgment

Relatively few studies have been conducted to investigate the effect of noise in the picture on the ability to judge distance of various targets. One of the few studies in this area is the Anon study (6). Three points should be noted about this study.

First, the order of presentation of the different noise levels was not controlled in order to cancel practice or learning effects. Hence it is possible that a degradation due to noise was overwhelmed by an improvement due to learning. The range of S/N ratios that was used was from 10 to 34 db on a basis of peak-to-peak/rms levels. There was, in fact, some improvement in performance as the noise increased. Of this fact, the authors say: (p. 3-61, section 3.2.3.1)

> "The mean error rate curve shows an improvement from 34 to 22 db. This effect may be caused by the testing procedure which in all cases started at 34 db and proceeded down to 10 db. Therefore, some learning on the part of the subject may well have occurred between 34 and 22 db."

Second, only the degradation in performance under stereo conditions was investigated. The subjects were not tested with monocular or non-stereo binocular presentations at the same noise levels. Hence it is impossible to say what the relative effectiveness of stereo and non-stereo presentations under various noise levels is.

Third, it should be noted that the stereo technique used in the Anon report was an anaglyphic method, using the red and blue channels of a color TV system. The S/N ratio was adjusted as follows: (see p. 3-58, section 3.2.2.1)

> "Since the scene did not change throughout the test, it was necessary only to adjust the red or blue contrast to give the same peak-to-peak video signal, 42 volts at the start of each test session .... The noise voltage gain of each channel was adjusted to be exactly 100."

This quotation suggests that the authors of the report considered the subjective effects of a change in the blue channel to be exactly equal to the effects of a change in the red channel as long as the peak-to-peak/rms ratios were equivalent. That this fact is not true is shown by Bhushan (17). In this experiment a 3-color television set was employed. A random noise generator was connected to each of the three channels (red, blue, and green) with a separate attenuator in each channel.

Noise signals were fed into one of the channels while the other two channels were transmitted with no noise. The observer was then asked to rate the picture on a seven-point scale which ranged from "Not perceptible" to "Extremely objectionable". The procedure was then repeated on the other two channels, one at a time. The results were that a given signal-to-noise ratio in a channel of one color would have results on the observer which were quite different than in a channel of a different color. For example, a ptp/rms ratio of 20 db in the green channel was judged "extremely objectionable" whereas this same level in the red channel was considered to lie between level 3 (definitely perceptible but only slight impairment) and level 4 (impairment but not objectionable). Finally, this same 20 db level in the blue channel was considered by various observers to lie between levels 1 (not perceptible) and 2 (just perceptible). Thus it is obvious that, from the subjective viewpoint of the observer a given S/N ratio has quite different effects depending upon which color channel is being used. The author summarizes his results by saying (p. 309):

> "There is an approximate 10-db difference in the SNR required for the blue, red, and green signals for the same transmission objective (Just perceptible, not objectionable, etc.)."

In regard to this difference, Bhushan states: (p. 308-309)

> "The quality of a television picture cannot be judged, however, by its SNR alone. Though these analytical results and physically measurable tests are often helpful in making gross judgments, it is the perceptual significance of transmission distortion that is the crucial factor in determining the merit of a transmission system. Only a subjective test can lead to a meaningful judgment in the final evaluation of picture quality."

Thus it becomes clear that, of the various factors that affect the judgment of size and distance, either in the real world or more particularly in pictures, the one that has been least investigated is the effect of noise on target detectability and recognition, especially as this is affected by the presence or absence of stereo. Consequently, partly as a result of the literature search, this parameter became one of the more important considerations in the design of the present experiment.

1.6 PREDICTIONS

On the basis of the findings in the literature, it was decided that certain parameters were either known to have little effect upon the results, or else the effect was apparently so thoroughly established that it seemed of little value to investigate it further. Therefore, the major part of the experimental time was concentrated in establishing two main parameters. These were (1) the effect of stereo versus monocular presentations in an environment of different noise levels on determing accuracy of size and distance judgments, and (2) the effect of these different presentations upon the number of targets detected.

It was predicted that at low noise levels there would be no significant difference between stereo and monocular mode of presentation would degrade faster, both in number of targets seen and in accuracy of size and distance judgments.

Finally, it was assumed that at some point the noise level would become so high as to make the picture useless. No exact quantitative values were assigned to these points, since not enough information was available. However, on the basis of the Anon report, it was assumed that at a S/N ratio of 20 or more there would be no difference between monocular and stereo; that between 16 and 10 db there would be a superiority of stereo over monocular presentations and finally, that at an S/N ratio of less than 10 db no picture would be useful.

In regard to the minimum visible angle that would be necessary in order to have the target seen at all, the values assumed were on the order of approximately 15 to 40 minutes of arc as the critical range. That is, it was assumed that all targets which subtended a visual angle of more than 40 arc-minutes would almost always be seen. Between these two limits it was assumed that the probability of seeing would decrease more or less along the lines of the integral of the Poisson distribution, since this is the distribution that has been found for the transition point in all other experiments that have investigated the threshold of perception.

Consequently, as will be explained in the sections of this report on apparatus and procedure, the experimental parameters were chosen to particularly investigate the points just mentioned.

Section 2

APPARATUS

2.1 PREPARATION OF PHOTOGRAPHS

The stimuli used in the experiments were 35 millimeter slides. These were prepared as follows.

2.1.1 The Targets

Twelve targets were made from stiff, light-brown paper. These targets consisted of right circular cones with an apex angle of approximately 30 degrees. The heights of the cones were 4, 6, 10, 16, 26, and 40 inches. Thus there were two cones of each height. The six different sizes were arranged in ascending order to form a geometric progression with a common ratio of 1.5. The common ratio of sizes of the cones was an experimental constant.

2.1.2 The Terrain

It is well known from many previous experiments that the ability of an individual to judge size and distance of any given target depends, to a considerable extent, upon the presence or absence in the visual field of other familiar objects. Since there will not be familiar man-made objects or earth-type vegetation on an extraterrestrial surface, it was important that the terrain used in the experiment be as similar as possible to that which might be expected on a lunar or Martian surface.

The terrain which was selected was a recently abandoned gravel pit where vegetation had not yet begun to appear. The floor of the pit was an amphitheater approximately 500 feet in diameter, surrounded by high banks which were nearly vertical and ranged in height from 20 to 30 feet. The floor was relatively level and horizontal, and consisted of sand and gravel particles of various sizes ranging from very fine sand to boulders approximately 12 inches in diameter. No man-made objects other than the targets were present in the amphitheater.

The terrain was reddish-orange, with albedos in the high mid-range of typical earth colors. Thus the light values were greater than would be found on a typical lunar landscape, and were approximately those that might be found on a Martian terrain.

One further point of difference might be noted. There is no atmosphere on the lunar surface, and very little on the Martian surface. Hence there is no scattering of skylight, and shadows will tend to be darker than on earth. The shadows will not be completely impenetrable (vide the Surveyor photographs) due to the fact the surrounding terrain itself will reflect some light back into shadowed areas that are not reached by direct sunlight. The difference will still be there however, and could, under some circumstances make it difficult to see into shadowed areas.

This effect was taken into account in making the photographs by underexposing the negatives by one or more stops. Several series were taken at different exposures and the final selection made from these test shots.

Since the lunar albedo is low (on the order of 7 to 10 percent over most of the surface), even the highlights would not be too bright. This was controlled in printing by using high-contrast film and slightly overexposing the final positive from the underexposed negative. (See Section 2.1.5 for details). The final effect was a low-albedo landscape with opaque shadows which thus corresponded well with the lunar characteristics.

2.1.3 The Camera Arrangements

Two cameras were used to obtain stereo pairs. These were 35 mm Pentax's with 28 mm lenses. The cameras were mounted on a tripod whose pan head has a specially designed sliding mount which allows the distance between the cameras to be adjusted at will from 4 to 15 inches.

In taking all of the photographs, certain parameters were held constant. The camera height above the terrain was held at 41 inches. The camera was always tilted down approximately 8 degrees from horizontal. Since a 35 mm slide has a 3 x 4 aspect ratio and since a 28 mm lens was used, the visual angle included in the picture was 45 degrees vertically by 60 degrees horizontally. Additionally, a point on the ground 6 feet from the camera was always represented by the bottom of the picture.

One half of the pictures was taken with the centers of the camera lenses 4 inches apart; the other half was taken with the centers of the lenses 12 inches apart to give an enhanced stereo effect.

All photographs were taken at 1/500 of a second with exposures from f/5.6 to f/8. The film used was Panatomic X.

2.1.4 The Arrangement of the Targets

All photographs contained only two targets (see Appendix A). With six target sizes, this yields 6 x 6 or 36 possible combinations of targets. If two targets are to be used, they must be placed some given distance apart. Six distances were chosen. These were 2, 3, 5, 8, 13, and 20 feet. Thus there were 216 combinations of target sizes and separations. In addition, the targets must be placed at some distance from the camera. The distances from the camera to the targets chosen were 20, 31, 50, 80, 127, and 200 feet. Thus the combinations of target size by target separation by target distance from camera totaled 1,296. Finally, the line of sight from the camera to the first target had some particular bearing with respect to the second target. Three values were chosen; they were 0, 45, and 90 degrees. To illustrate what is meant by this, consider a line drawn from the camera to the first cone. If the second cone is assumed to be 8 feet away from the first cone, then for the 0 degree case, the 8 feet would be measured essentially along the line from the camera through the first cone. That is to say, from the standpoint of the camera view, the second cone would be directly behind the first cone. In point of fact, the second (or rear) cone was always offset enough so that it was never obscured by the first cone, in the event that the first cone was the larger cone. In the case of 45 degrees, a line joining the centers of the two cones would form a 135 degree angle with the line from the camera to the first cone and, for 90 degrees, would form a right angle. The second cone was always placed to the right of the first cone (see Figure 4-1). Thus there were 3, 888 possible combinations of cone size, cone distance, and cone orientation.

Since photographs were taken with both a 4 and 12-inch intercamera distance, this would have meant a total of 7, 776 stereo pairs if every possible combination had been included. Obviously this was out of the question from the standpoint of a practical design. Consequently, each of the parameters was partitioned in a stratified-random sample into a total of 36 samples for the 4-inch camera condition and a different set of 36 samples for the 12-inch camera condition. Thus a total of 72 stereo pairs of photographs were taken.

It will be noted that the distances from the camera to the left target were chosen to have the same progression as the increase in target size. Thus a 4-inch target at 20 feet subtends the same visual angle as a 6-inch target at 31 feet, a 10-inch target at 50 feet, and so on.

The rationale for this is that by such a design one can test various aspects of the size-constancy hypothesis, since there was a number of different size targets at different distances which all subtended identical visual angles.

Table 2-1 shows the visual angles that would be subtended in the real world by the various targets at each of the selected experimental distances.

Table 2-1

VISUAL ANGLES SUBTENDED BY TARGETS

	Distance to Target in Feet					
Height of Target Cone in Inches	20	31	50	80	127	200
4	55	35	22	14	9	5
6	87	55	35	22	14	9
10	138	87	55	35	22	14
16	219	138	87	55	35	22
26	347	219	138	87	55	35
40	550	347	219	138	87	55

2.1.5 Development and Mounting of Photographs

The negatives were developed with Kodak Microdol, diluted 1 to 4 from stock solution, for 12 minutes at 72°F. This assured very high contrast which simulated the effects of light on a planet where there is little or no skylight. Under these conditions the shadows would tend to be very dark and the highlights relatively bright.

The stereo pairs were mounted in separate cardboard slide holders in exact registration for each pair, so that a given reference mark within each pair would fall at the same point on the slide aperture.

2.2 SLIDE PROJECTION

Two slide projectors were used to project the stereo pairs. Visual separation was achieved by polarizing the images.

2.2.1 Slide Projectors

Two Bell and Howell 960Z slide projectors with drum-type slide holders were utilized. They were equipped with zoom-type lenses so that it was possible to adjust the size of the projected slide until it just filled the screen in the horizontal direction. The projectors were mounted on a platform placed on an equipment table. The light level was controlled with Variacs and by a plate with a small fixed aperture (3/16 of an inch diameter) placed over the projection lenses. Each projector was equipped with a filter made of Polaroid HN 38 filter material; the two sheets (one on each projector) being mounted at 90 degrees to each other. The subjects were equipped with No. 729 Polaroid 3-D glasses. Thus each subject saw with the left eye only the image projected by the left projector, and vice versa.

2.2.2 Projection Screen

The slides were projected on a Radiant Silver Lenticular Super Champion Screen whose size was 40 x 40 inches. A Mylar rear-projection screen was also evaluated in the preliminary trials, but was rejected as a suitable technique since the rear-projection causes partial depolarization of the images, and this causes an objectionable double image to appear which vitiates the stereo effect.

2.2.3 TV Projector Systems

The TV projector systems used to generate television noise were purchased from General Precision Laboratories, manufactured for them by the Tele Beam Division of Waltham Precision Instruments, Brookfield, Connecticut. Each system consists of two assemblies, (1) a TV projector and (2) an electronics assembly containing the power supply and control circuits.

The TV projector is a Schmidt-type optical system containing a spherical mirror and a corrector plate. The source is a standard 5-inch television projection tube. The projector is capable of producing an enlarged television picture on a projection screen.

The electronics assembly generates the standard TV raster of 525 lines across the face of the projection tube. This unit can be used to receive the commercial broadcast band or can be driven from an external source such as a noise generator.

2.2.4 Noise Generator

A random noise generator was used to drive the TV projectors. This was a type 1390B, manufactured by the General Radio Company of Concord, Massachusetts. Noise of 20 KC, 500 KC, and 5 MC bandwidths can be generated.

2.3 TRIMENSION READER

The Kollsman Trimension Reader is a virtual image stereo display system, obtaining the stereo effect without the use of optical elements placed over the operator's eyes.

The optical system, Figure 2-1, consists of two projectors, a spherical mirror and a beam splitter. The projectors are oriented so that their optical axes are offset but converging to the beam splitter. The beam splitter reflects the projected images into the spherical mirror from whence they are returned, through the beam splitter, forming two exit pupils on diverging axes; the exit pupils are the eye positions for the observer.

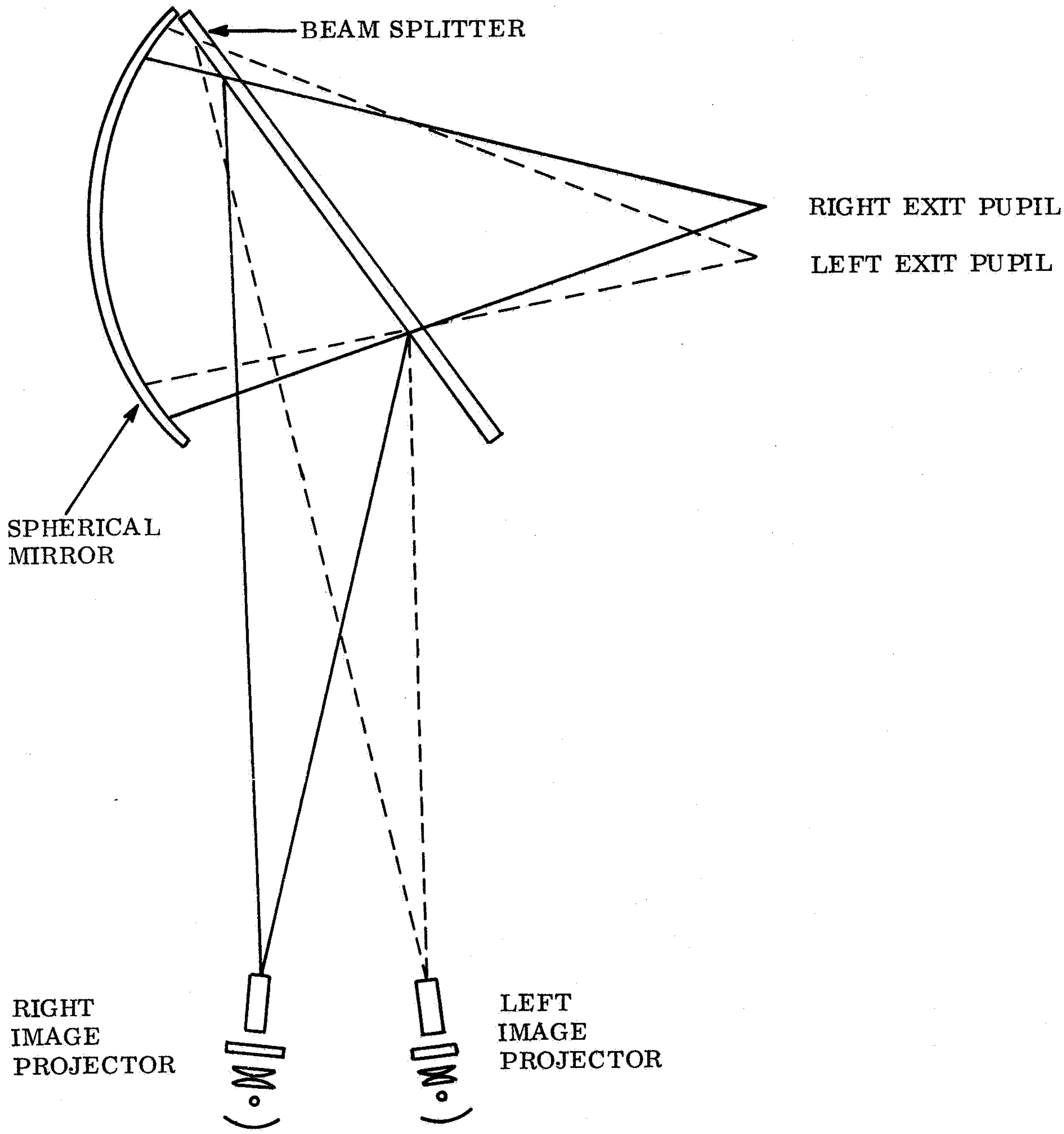


Figure 2-1. Trimension Reader Optical Schematic

Section 3

SUBJECTS AND PROCEDURES

3.1 SUBJECTS

A total of 60 subjects was used in this program. Ten subjects were female and 50 were male. The ages ranged from the early twenties to the middle fifties. All subjects were Kollsman employees with varied backgrounds (engineers, technicians, draftsmen, scientists and secretaries). None had special training, except as described later in this report, where some subjects were recalled and trained.

No effort was made to determine visual capacity of the subjects in the initial runs except to test for the ability to achieve stereopsis. Those subjects who could not achieve stereopsis on the test slides were excused and are not included in the above total.

3.2 EQUIPMENT SET-UP

Figures 3-1 and 3-2 shows the physical layout of the equipment. It will be noted from Figure 3-1 that the lenses of the slide projectors were approximately the same distance from the floor as the center of the projection screen. Thus the projection in the vertical plane was essentially normal to the screen plane and there was no distortion.

However, as indicated in Figure 3-2, the lenses of the slide projectors were separated horizontally by approximately one foot. In order to have the slides fall congruently on the screen, it was necessary to "toe-in" the projectors by about 2.5 degrees each. Thus there was a slight amount of keystoning in each picture, the amount being opposite in sense for each image. The difference in length of the vertical lines at the extreme edge of the screen

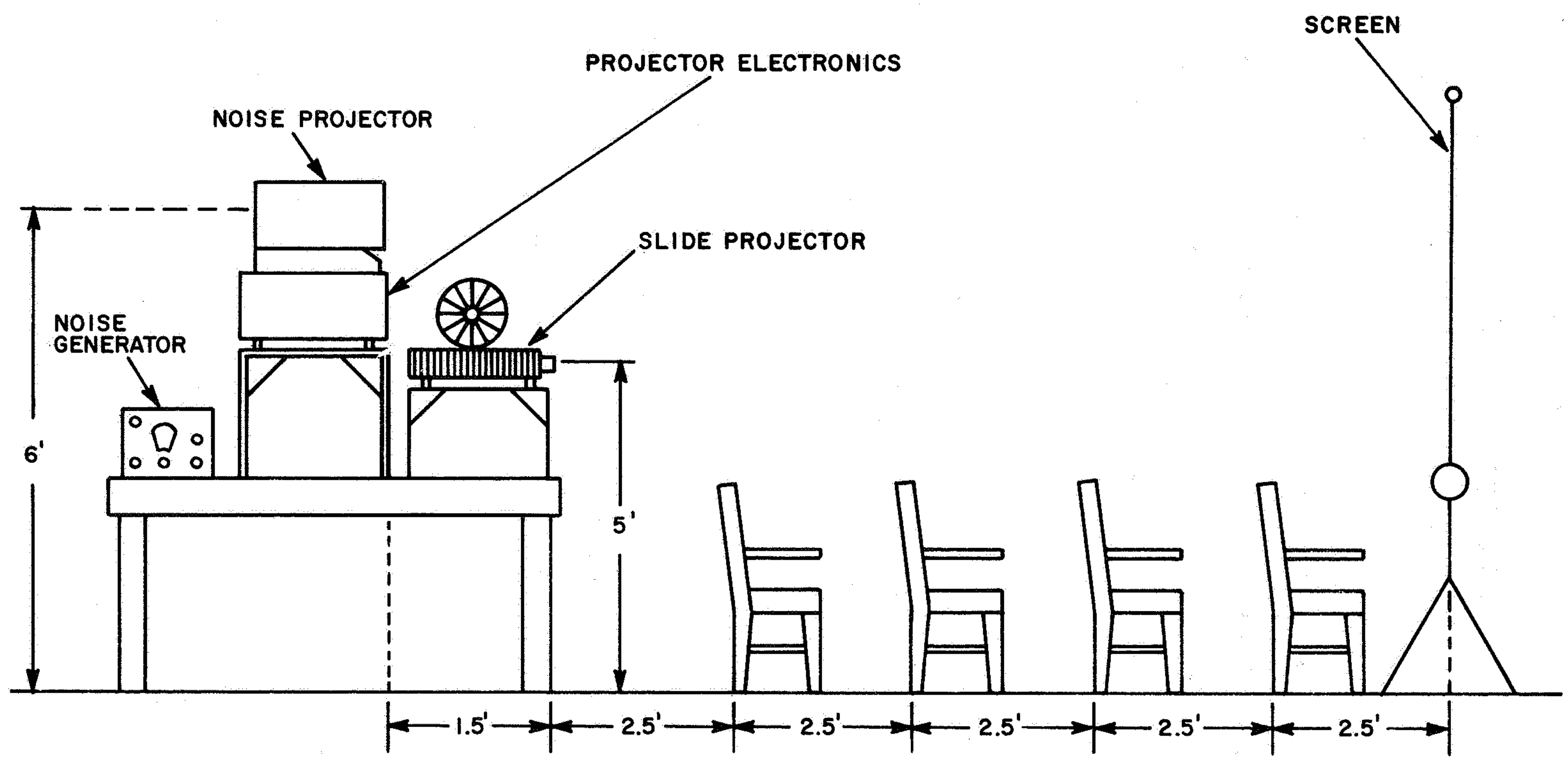


Figure 3-1. Experimental Theatre Used in the Presentation of the Stereo Views with the Polaroid Projection System

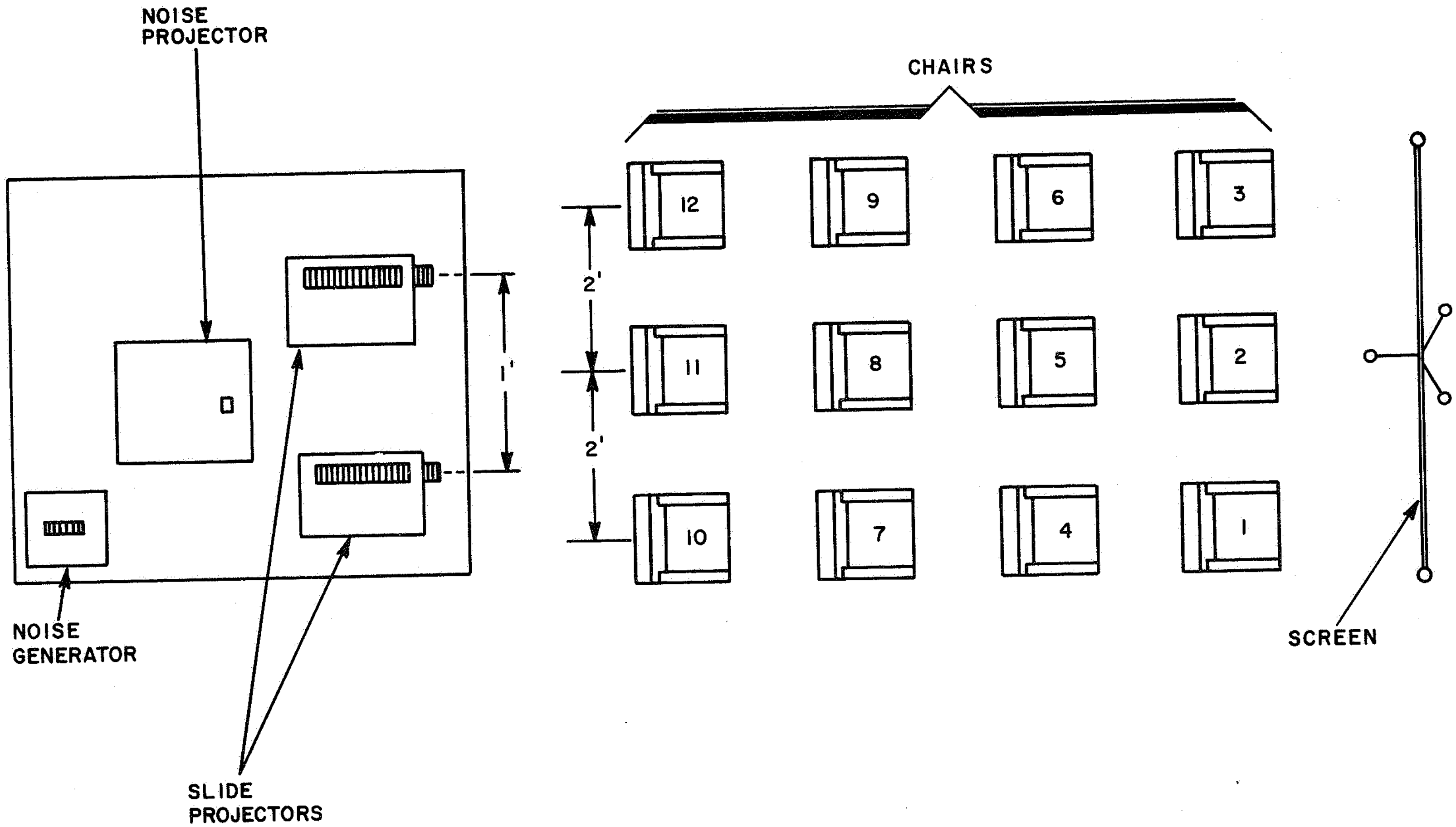


Figure 3-2. Plan View of Theatre Shown in Figure 3-1. Numbers on Chairs Were Used as Coding System to Identify Location of Any Particular Subject During a Given Trial

was, however, only a few percent, and was thus well within the limits of Panum's area (see Appendix B). In the center of the screen, where most of the targets were located, this difference was virtually zero.

The TV projector, which was used to generate the noise, was, as shown in Figures 3-1 and 3-2, located behind and above the slide projectors.

The slide projectors each had a piece of Polaroid HN 38 filter material over the lenses. There was no filter over the TV noise projector. While each slide (left and right) was presented to only one eye, the noise, being unfiltered, was seen by both eyes equally.

The distances of the chairs from the screen were chosen to evaluate the effect of different visual angles on size and distance judgment. For those subjects seated in the first row, the screen subtended a visual angle (horizontally) of 60 degrees; this is the same visual angle as that accepted by the camera in real world. Consequently, the size of the images on the retina would correspond to the size of the images if the subjects had been observing them in the real world. For the subjects seated in the second row, the screen subtended a visual angle of approximately 30 degrees. For the third row it was 20 degrees, and for the fourth and last row the visual angle was 15 degrees. This follows from the fact that the distances of the chairs in the four rows from the screen were 30, 60, 90 and 120 inches.

3.3 BRIGHTNESS AND NOISE DETERMINATIONS

All measurements were made using a Pritchard Light Meter with a 2 degree acceptance angle plate inserted. In a darkened room, one slide in turn would be projected on the screen and measurements were made at 12 to 16 points distributed evenly over the screen. These measurements were made with a piece of Number 729 Polaroid 3-D glass material over the Pritchard meter so that the light level would be identical to that reaching a subject's eye during a test. The mean value for the picture was computed by summing the readings taken at the various points and taking the mean.

Because of slight differences in cloud cover that occurred during the taking of the pictures — and other differences due to the terrain albedo itself — there was some variation of light level among the pictures. Most of the pictures, however, had a value of approximately 6 ft-L. as measured by the above stated procedure.

The noise levels actually employed were determined by utilizing some subjects in preliminary runs. The subjects were asked to make two judgments. These were stated as follows: (1) "How severe can the noise be, in your opinion, before it begins to affect your ability to detect targets at all?" and (2) "How severe must the noise become in order to render the picture totally useless?".

These determinations were made by alternately varying the noise along ascending and descending series. The subject was first presented with a noiseless picture. The level was then increased until he indicated that he thought the noise was beginning to affect his ability to detect the targets. The noise was then increased further until he indicated that the picture was useless. Notes were made of the voltages on the noise generator at these two points. After this the voltage was turned up to the maximum that the projection tube would allow (thereby completely saturating the picture with noise) and a descending series was made, the subject again indicating the same two points.

Subjects were remarkably consistent in this phase of calibration. There was little variability either between one series of judgments and another or between subjects.

After this, the slide projectors were turned off and the noise projector only was left on. Again a series of measurements were made over the entire screen, and the mean value was taken as representative.

It was found that for the two points indicated by the subjects (i.e., just beginning to degrade the picture and totally useless) the S/N ratios were 22 db and 10 db. These values were computed on a peak-to-peak/rms basis. The actual measurements, of course, were both made on an rms basis. However, if one assumes a random distribution (as was true here) then the conversion can be made by adding 9 db to the observed values. That is, 1 db rms/rms is equal to 10 db peak-to-peak/rms, 13 db rms/rms is equal to 22 db peak-to-peak/rms, and so on. The conversions were made so that a comparison could be made directly with the results obtained in another study. It is interesting to note that, although the method of producing both the picture and the noise was quite different here than in the Bendix report, nevertheless the reported break points (i.e., where the noise begins to be objectionable, and where it renders the picture useless) are almost identical in both studies (see pp 3-61 through 3-77 of reference (6)).

The other three noise values (13, 16, and 19 db peak-peak/rms) were obtained by dividing the working range into three additional equal steps. These were calibrated in the same fashion.

The brightness values given for the pictures (approx. 6 ft-L) were true for the subjects sitting on the ends of the rows. For those subjects seated in the middle of the rows (seats 2, 5, 8 and 11), the values were a few foot-Lamberts higher, since the screen was of the high-gain retro-reflective type. This type of screen tends to return most of the light along the direction of incidence. Thus the overall light values were approximately the same as a commercial TV set operated under normal conditions.

3.3.1 Noise Frequency

After the S/N ratios were worked out, the next preliminary step was to select a noise frequency to be used in the experiment. The noise generator had the capability of generating noise at 20 KC, 500 KC or 5 MC bandwidths. Ten more preliminary subjects were used. These subjects were shown all 72 slides to be used in the main experiment. Twenty-four of these slides had 20 KC noise, another 24 slides had 500 KC, and a third set of 24 slides had 5 MC noise added at each of the 5 noise levels (i.e., 10, 13, 16, 19, and 22 db ptp/rms). This data was analyzed to see if the frequency of the noise had any appreciable effect on number of targets detected or on the ability to judge size and distance. It was found that there was no appreciable difference for any frequency. The subjective effect of these frequencies on the picture was quite different. 20 KC causes long horizontal streaks, 500 KC causes large-grained "snow", and 5 MC causes small-grained "snow". Since there was no objective difference, however, it was decided not to make frequency an experimental parameter; all subsequent data in the main body of the program was collected using 5 MC as the noise bandwidth. This value was chosen since it closely resembled, in general appearance, that noise which is seen on commercial television during periods of severe atmospheric disturbances.

3.3.2 Picture and Noise Correlation

Another preliminary experiment was run to determine the effect of the amount of correlation between the noise presented to the left and right eye with respect to its position on the retina. This experiment was also designed, as a secondary set of observations, to determine what effect the amount of convergence might be on size and distance judgments. This experiment was carried out as follows. The left picture was projected on the screen. The projectionist then moved the right projector slightly so that one of three conditions were obtained:

(a) the target projected by the right-hand projector appeared on the screen to the left of the target projected by the left-hand projector;

(b) the target projected by the right-hand projector appeared on the screen superimposed, as nearly as possible, directly over the target projected by the left-hand projector;

(c) the target projected by the right-hand projector appeared on the screen to the right of the target projected by the left-hand projector.

Since the noise was being projected by only a single projector, which, being unfiltered, appeared equally to both eyes, any given noise spot had a different geometrical relation with respect to the fused stereo image of the target. This can be seen in Figures 3-3, 3-4, and 3-5, which indicate the geometry of the three situations (a), (b), and (c).

In situation (a), the visual geometry of the situation indicates that the subject should see the target very close to himself, and the noise should appear in back of it. This, according to the subjects' reports, was partly true. The terrain and the targets seemed to be transparent, especially in the darker portions of the picture, and the observer seemed to be looking through the scene at a background of noise which lay beyond. However, the targets did not appear to be particularly close. In situation (b) the target and the noise should appear to be in the same plane, and in situation (c) the noise should appear to lie in a plane in front of the target. These predictions were observed to be true.

In fact, in all three presentations the visual geometry taken alone indicates that the noise should always be perceived at the same visual distance as the actual distance of the observer from the screen; and the targets and terrain should appear to the observer to be closer or further away than the screen depending upon which presentation is being used. What actually occurred in all presentations was that the relative position of the noise and target

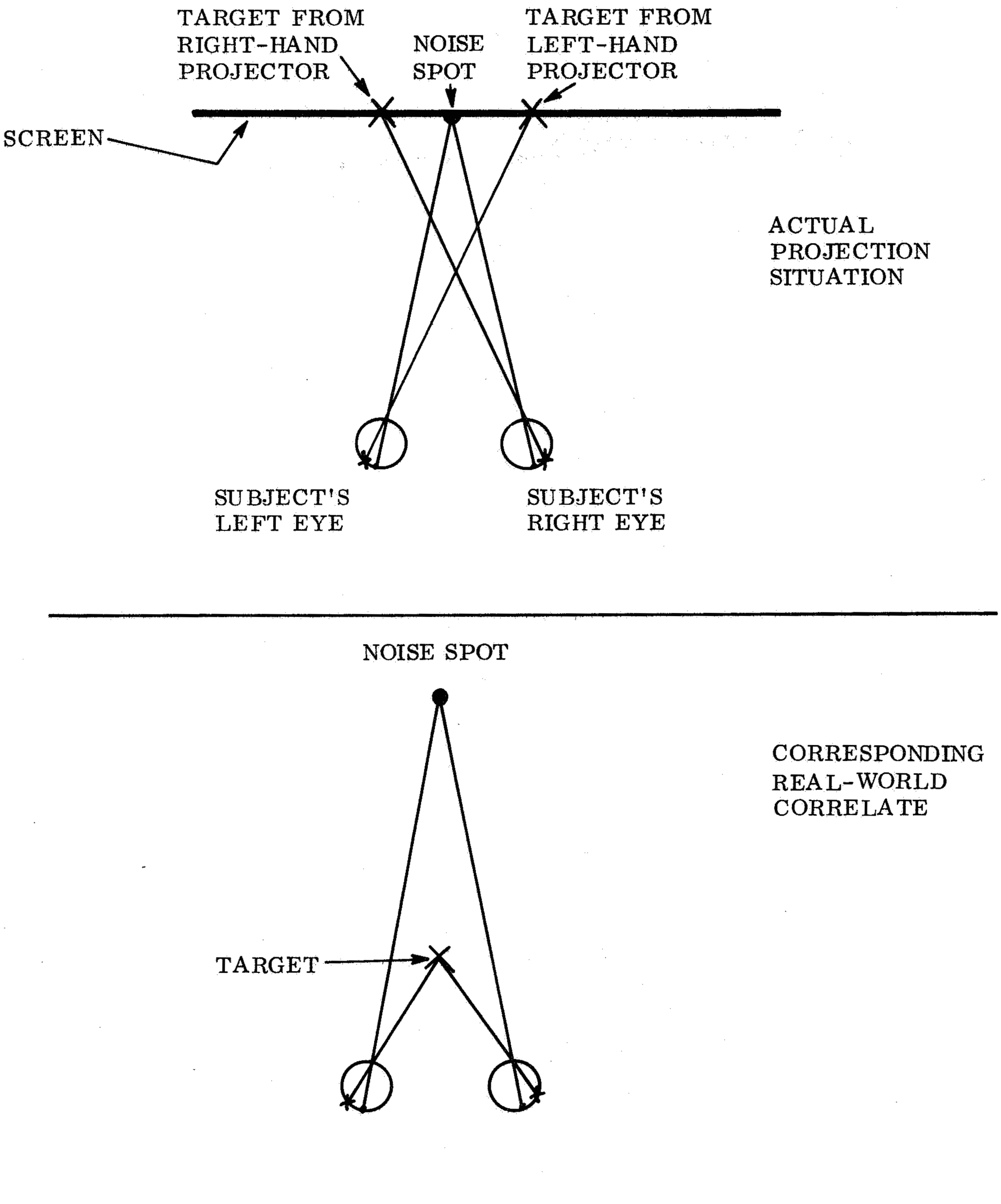


Figure 3-3. **Projection Situation and Its Real-World Visual Correlate for Situation (a)**

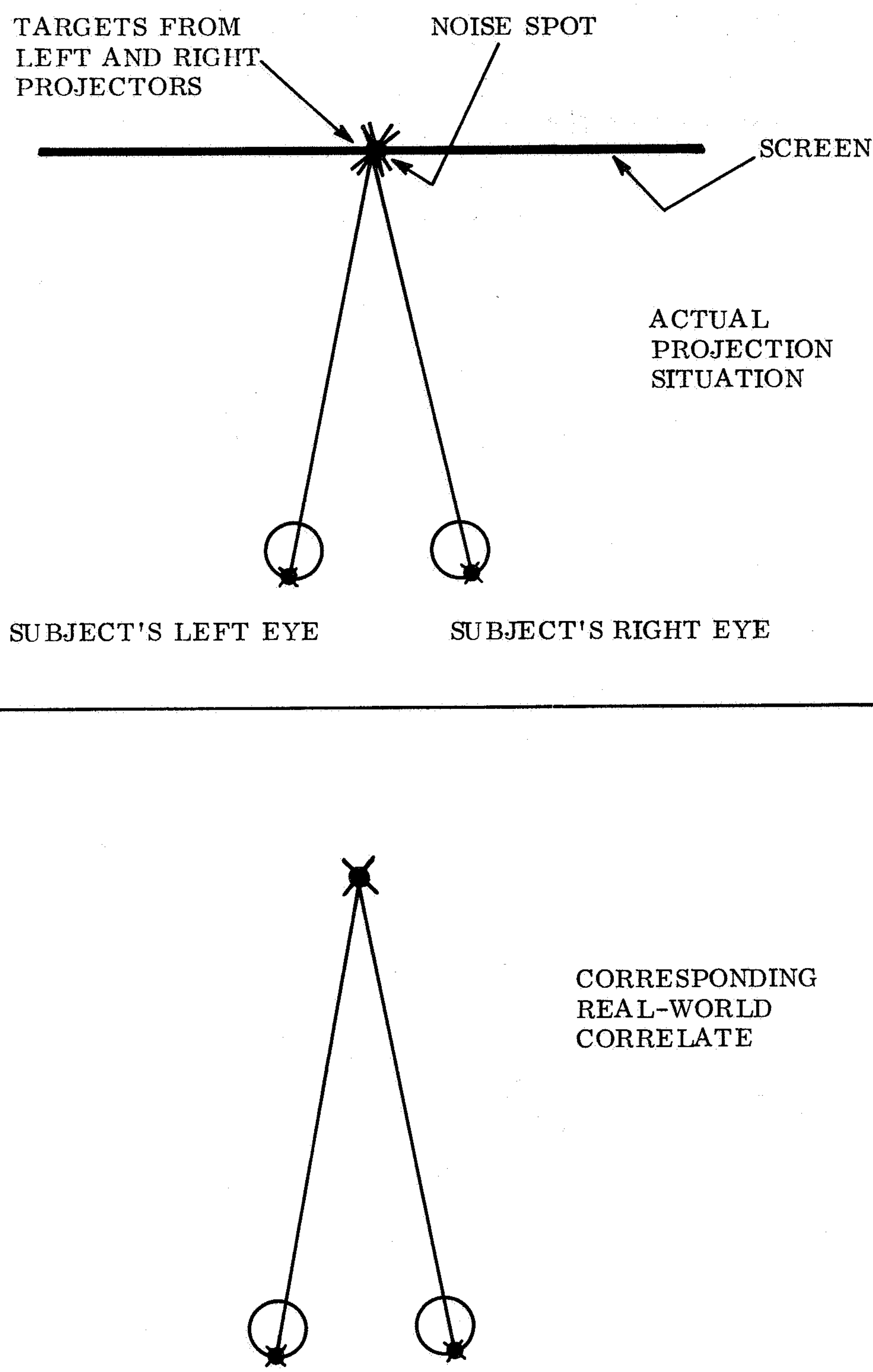


Figure 3-4. Projection Situation and Its Real-World Visual Correlate for Situation (b)

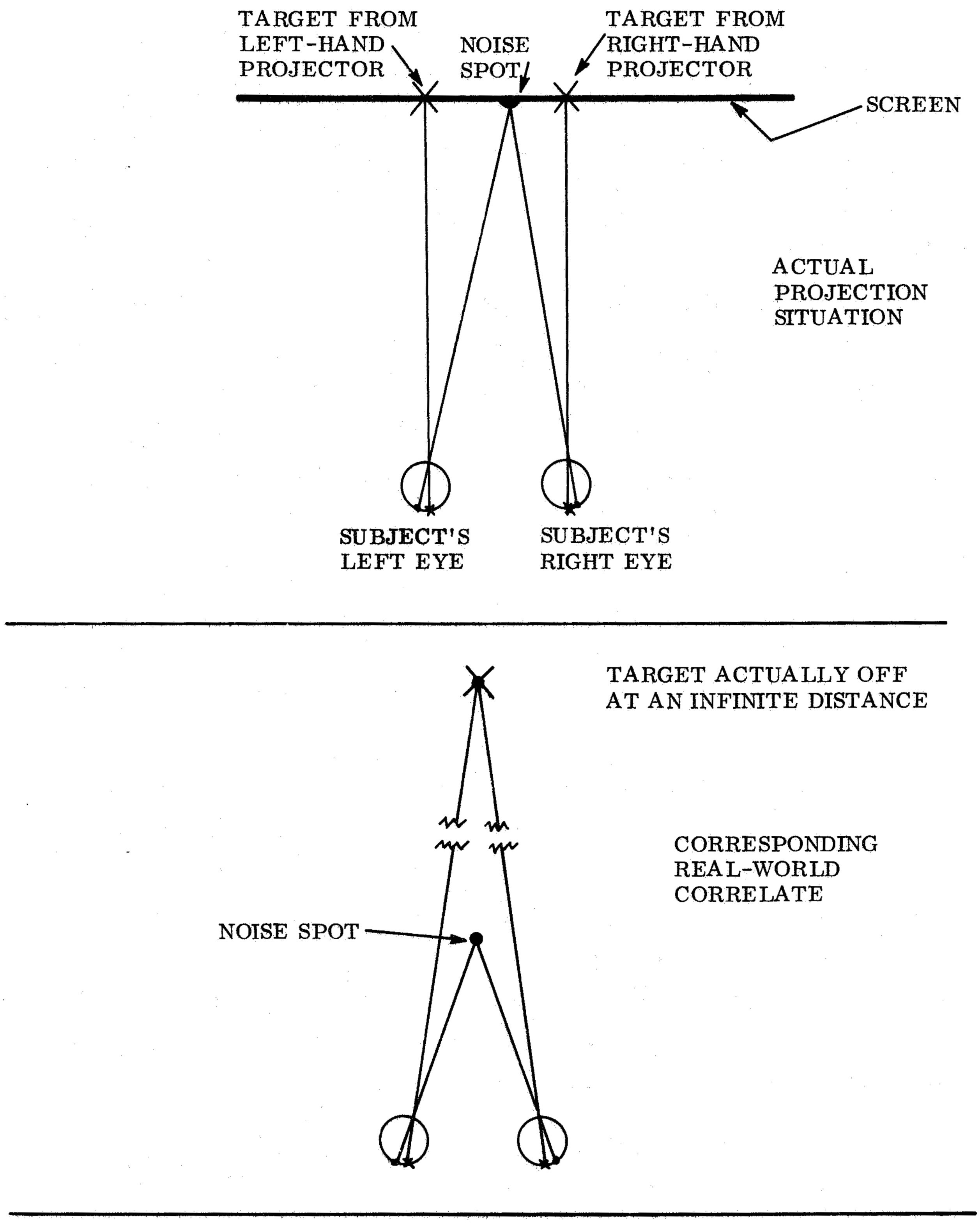


Figure 3-5. Projection Situation and Its Real-World Visual Correlate for Situation (c)

was as predicted from the visual geometry, but the absolute visual distance was often indeterminate. This indicates that other aspects of the slide besides the geometry also have some effect upon the observer's judgment of apparent spatial location of an image. This fact is supported by many other studies of visual phenomena.

One might reason that in situation (a) or (c), where the noise and the targets seem to lie in physically different planes, the observer could make better judgments than in (b), where the noise and the targets are in the same plane. However, the subjects generally reported that, with any appreciable noise, it was harder to maintain stereopsis with (a) or (c) than with (b), and there was a feeling of greater eye strain. In addition, the apparent "transparency" of the visual world in (a) was disturbing to at least some subjects, and they reported that it reduced their feeling of certainty in making judgments. For these reasons, then, situation (b) was chosen as the single presentation method to be used in all of the main body of the program.

Logic alone dictates that situations (a) or (c) should be superior since the picture and the noise lie in different visual planes. Thus one might expect that there would be less interference caused by the noise. However, this level of analysis ignores a very important fact in the real world, whenever one is observing an object at close range, accomodation and convergence are identical. In Section 1.3.2 it was pointed out that accommodation and convergence, in themselves, are little or no help in actually determining depth. However, this is not the same thing as saying that conflict between these cues may not be important in disturbing judgments which are made on the basis of other cues.

If one refers to Figures 3-3, 3-4, and 3-5 it can be seen that in all three situations the actual images were on the screen. Thus in order to have a clear view, the subject would have to be accommodated at the screen distance (which might be anywhere from 2.5 to 10 feet, the latter distance being about the effect limit for changes in accommodation to have any importance). However, in situation (a) the subject would be converged on a point much closer to himself than the screen distance; in situation (c) the subject would be converged on a spot at infinite distance. Thus the accommodation cue and the convergence cue would be in conflict. Only in situation (b) would they be in agreement.

In the real world, these cues are never in conflict. Thus all individuals with reasonably normal vision have, throughout their entire life, built up perceptual habit patterns so that, in the adult, convergence and accommodation are almost always controlled together by the central nervous system. This is so true that, in fact, it requires considerable practice for an individual to learn to converge at one distance and accommodate at another. Consequently, if an individual in an experimental situation is presented with a situation where these two cues are not in agreement, the most probable result will be that his automatic control system for the eyes will constantly attempt to bring the cues into agreement by shifting back and forth in a servo-like fashion. This, of course, results in excessive muscle movement and consequent eye strain.

Only in situation (b) would these two cues not be in conflict. Consequently one would expect less eyestrain here, and thus somewhat better results, not because the accommodation and converges cues themselves assist the subject in determining distance, but simply because in this situation only these cues are not in conflict.

3.4 EXPERIMENTAL DESIGN

The experimental variables were cone sizes (6), distance-to-targets (6), distance-between targets (6), noise levels (6), and cone orientations (3). With two cones per slide, this makes a total of 23,328 possible combinations. Obviously it was impossible to investigate all of these, so a stratified-random method of allocating variables was employed. The slides were arranged in sets of 12 each, yielding a total of six sets, with a total of 72. Each set of 12 had all 6 cones appearing four times, all six distances-to appearing twice, all six distances-between appearing twice, and the three orientations appearing four times each. In addition, the three modes of mono, 4-, and 12-inch inter-camera distance stereo were also equally distributed within each set so that each appeared four times.

Mono presentations were achieved by blocking the image from the right-hand projector. Thus the subjects saw the image from the left-hand projector with their left eyes only. This was done for 12 of the 4-inch stereo views and 12-inch ones. The total mono sample was, therefore, 24 slides:

Thus the total number of all possible experimental conditions would have been 69,984. The actual 72 conditions selected from this is shown in Table 3-1, showing the order in which the slides were presented to all 36 subjects used in the main part of the program.

In order to investigate the effect of noise, the 36 subjects were divided into six groups of six subjects each. Each group had a different noise level with each slide, so that, by the time the entire 36 subjects had been tested, each slide had been shown with all six noise levels. The arrangement of noise in relation to the slides for the different groups is shown in Table 3-2.

3.5 PROCEDURE - MAIN EXPERIMENT

The subjects were allowed to choose any seat they wished, and a notation was made of the seat chosen so that it could be determined if its distance from the screen had any effect upon judgment.

The subjects were then instructed in the general purpose of the experiment, and were given data sheets to fill out. (See Appendix A for a sample sheet). Their task was to make four judgments:

Table 3-1

ORDER OF PRESENTATION OF SLIDES FOR ALL 36 SUBJECTS IN MAIN BODY OF EXPERIMENTAL PROGRAM

SLIDE NUMBER	(INCHES) LEFT	RIGHT	DISTANCE FROM CAMERA TO LEFT CONE (FEET)	DISTANCE BETWEEN CONES (FEET)	ORIENTATION OF CONES (DEGREES)	MONOCULAR 4-INCH OR 12-INCH STEREO CONDITION
1	4	6	20	2	00	4
2	40	4	20	3	90	Mono
3	16	10	50	8	90	4
4	4	10	80	8	00	12
5	26	40	200	20	45	Mono
6	16	26	200	2	45	12
7	16	6	31	2	45	4
8	26	26	31	3	00	Mono
9	26	10	80	5	90	Mono
10	6	4	50	5	45	12
11	6	40	127	13	00	4
12	10	16	127	20	90	12
13	10	4	80	3	90	4
14	4	4	50	2	90	Mono
15	40	16	127	5	00	4
16	10	10	127	5	45	12
17	4	26	31	13	45	Mono
18	40	26	31	20	00	12
19	40	6	50	3	45	Mono
20	10	40	80	2	00	12
21	4	16	200	8	00	4
22	26	6	200	8	90	12
23	10	26	20	20	90	Mono
24	6	16	20	13	45	12
25	26	4	127	2	00	Mono
26	16	4	127	3	45	Mono
27	6	10	20	5	45	4
28	26	16	31	5	00	12
29	16	40	80	13	90	Mono
30	4	40	50	20	90	12
31	6	6	200	3	00	4
32	6	26	200	2	90	Mono
33	16	16	31	8	90	4
34	10	6	20	8	45	12
35	4	16	50	20	00	4
36	26	6	80	13	00	12
37	6	40	31	3	45	4
38	40	10	20	2	00	12
39	16	6	80	5	90	Mono
40	6	26	50	5	90	Mono
41	26	10	127	13	00	4
42	10	6	127	20	45	12
43	10	26	20	20	90	Mono
44	4	10	31	2	45	12
45	26	4	50	8	45	Mono
46	16	26	80	8	00	12
47	6	10	200	20	00	4
48	40	4	200	13	90	12
49	40	26	50	2	45	Mono
50	16	16	80	3	00	Mono
51	6	4	200	8	00	4
52	26	40	200	8	90	12
53	10	16	20	20	90	4
54	6	6	31	13	45	12
55	4	26	80	2	00	Mono
56	26	16	50	3	45	12
57	10	4	127	5	45	4
58	4	40	127	5	90	Mono
59	40	16	31	13	90	4
60	16	4	20	20	00	12
61	10	26	200	3	45	Mono
62	6	16	200	2	45	Mono
63	40	6	31	8	90	4
64	10	40	20	8	90	Mono
65	40	40	80	20	45	4
66	40	10	50	13	00	12
67	26	26	127	2	90	Mono
68	16	10	127	3	00	12
69	4	4	20	5	00	4
70	40	40	31	5	45	12
71	10	10	50	13	45	4
72	4	6	80	20	90	12

Table 3-2

SIGNAL-TO-NOISE (S/N) RATIOS FOR EACH OF THE 72 SLIDES FOR ALL SIX OF THE EXPERIMENTAL GROUPS USED IN THE MAIN BODY OF THE PROGRAM. S/N IS BASED ON PEAK-TO-PEAK/RMS VALUES

SLIDE NUMBER	GROUP NUMBER					
	1	2	3	4	5	6
1	∞	22	19	16	13	10
2	22	19	16	13	10	13
3	19	16	13	10	10	16
4	16	13	10	10	13	19
5	13	10	10	13	16	22
6	10	10	13	16	19	∞
7	10	13	16	19	22	∞
8	13	16	19	22	∞	22
9	16	19	22	∞	∞	19
10	19	22	∞	∞	22	16
11	22	∞	∞	22	19	13
12	∞	∞	22	19	16	10
13 through 24	repeat of above					
25 through 36	repeat of above					
37 through 48	repeat of above					
49 through 60	repeat of above					
61 through 72	repeat of above					

(1) size of left cone, in inches

(2) size of right cone, in inches

(3) distance to left cone, in feet

(4) distance between cones, in feet.

The subjects were given no information whatever about the sizes of the cones used or the range of the distances. For scaling purposes they were told only three things: (1) they were told the height of the camera from the ground, which was 41 inches; (2) they were told that the horizontal included angle of the picture, as taken by the camera, was 60 degrees, and that this was the same subtended angle for those subjects who sat in the front row; (3) they were told that, in all pictures, the terrain that appeared at the very bottom center of the picture was six feet away from the camera. Since the distance-to judgment was to be the distance from the camera to the cone, it was necessary to know the amount of unseen "dead space" from ground zero to the bottom of the picture.

The subjects viewed each slide in total darkness for a period of approximately 30 to 40 seconds. No fixed interval was used, but the time was regulated according to the amount of time required for all subjects to feel that they had made a judgment. A dim light was then turned on, and the subjects wrote down their judgments on the data sheet. The light was then turned out and the procedure repeated for the other slides.

When the subjects viewed the monocular presentations, the picture was presented only by the left projector to the left eye. However, since the noise projector was unfiltered, the noise could be seen in both the left and the right eyes. The right eye, of course, would not see the left picture because of the Polaroid filters. Therefore the subjects were instructed to cover the right eye on all monocular presentations.

It would not have been technically correct to have the subjects remove the glasses to look at the picture with both eyes, since the signal-to-noise ratio had been established using the transmission characteristics of the glasses with the polarized slide projection and the unpolarized noise projection. If the glasses had been removed, the S/N ratio would have changed considerably.

After 36 slides had been presented, the subjects were given a short break of 5 to 10 minutes, and the remaining 36 slides were then shown in the same manner. The entire procedure thus occupied approximately two hours.

3.6 PROCEDURE - TRIMENSION READER

Because of the design of the Trimension Reader, it was impossible to introduce noise into the picture as was done in the projected slides. Therefore, when the best subjects were recalled for testing on this device, each subject had, as test slides, only those slides that he had previously seen in the stereo no-noise condition. Since these subjects came from different groups, they were not all presented — on the Trimension Reader — with the same slides. That is, however, unimportant, since each subject's results were compared, not with the other subjects', but only with his own on the same slides as presented by the Polaroid-projection method.

In this presentation the brightness of the light was regulated by a Variac controlling the voltage on the bulb in the Trimension Reader projector, so that the light levels were approximately the same as in the Polaroid projection display (see Figure 2-1 for the Trimension Reader schematic).

3.7 PROCEDURE - RETRAINING STUDY

After the exposure to the Trimension Reader, the five best subjects were retested on the Polaroid projection system, this time to measure the effects of training. The training consisted of two parts. One part was general information about making size and distance judgments. For example, the subjects were told that one of the laws of projective geometry is that a target whose height is such that its top is flush with the horizon is exactly as tall as the observer's eye level above the terrain, given that the observer is viewing out over an essentially flat terrain. Since the camera (eye) height was known to be 41 inches, they could now use this cue to determine target height. Other similar cues were also explained. The other training consisted of showing 9 demonstration slides, which used 3 of the target sizes and 3 of the 6 target distances, to the subjects. The subjects were allowed to make estimates of the size and distance and were then told the actual values. Only some of the target sizes and distances were used in this demonstration so that the subjects would not learn what all of the true values were.

Finally, the subjects were tested on 24 of the 72 slides that had previously been shown. The comparison again was made for each subject only between the same slides used before and after the training.

3.8 DATA REDUCTION

Because of the large mass of data, and because of the various possible sorts, all of it was put on punch cards and a program was developed to evaluate the data with respect to the various parameters of noise, stereo versus monocular presentations, cone size, cone distance, etc. This data was run off on an IBM 1130 computer and printed out for the various parameters, which are shown in Section 4.

Section 4

RESULTS

Some of the results are straightforward, and can be understood without elaborate analysis. Others, however, are apparently anamolous, and, in order to have complete understanding, it is necessary to realize that there were qualitative as well as quantitative differences among the various subjects. Therefore it is well to begin by examining the differences among subjects before considering the differences among conditions, since there are occasionally complex interactions between these two variables.

4.1 INTER-SUBJECT DIFFERENCES

For all subjects, and for all conditions to be discussed, two kinds of errors were computed. These were absolute and relative.

In computing relative errors, the sign of the error was taken into account. That is, if the judged size or distance was greater than the actual size or distance, the error was scored positive. If the judged size or distance was less than the actual size or distance, the error was scored negative. Thus for a cone that was 10 inches high, an estimate of 12 inches would be called +2, and an estimate of 9 inches would be called -1. All errors were added, and the sum was divided by the number of judgments (N). A plus value would mean that the subject tended, on the whole, to overestimate; a minus value would indicate that the subject tended to underestimate.

Thus the relative error allows one to make a judgment of subject tendency; but it is a poor measure of the subject's over-all accuracy, since a subject who had large errors in both the plus and minus direction would end with a mean of nearly zero whereas a subject who had, on the whole, smaller erros, but all in one direction,would wind up with a larger mean eror even though each judgment was closer to being correct.

Table 4-1

ABSOLUTE MEAN ERROR FOR EACH SUBJECT FOR CONE SIZE, DISTANCE-TO, AND DISTANCE BETWEEN CONES

SUBJECT NUMBER		CONE SIZE				DISTANCE TO LEFT CONE		DISTANCE BETWEEN CONES	
		LEFT		RIGHT					
GROUP	SEAT	N	ERROR (inch)	N	ERROR (inch)	N	ERROR (feet)	N	ERROR (feet)
1	4	52	15.42	52	13.73	53	39.32	50	18.04
1	5	45	10.02	42	10.23	53	48.07	34	7.14
1	6	47	15.55	47	12.80	53	63.11	41	20.31
1	7	43	17.76	39	15.07	51	127.41	31	7.77
1	8	44	18.06	45	20.93	53	65.77	36	22.58
1	9	37	14.51	32	12.46	46	68.58	23	50.04
2	4	64	20.18	60	21.55	69	90.88	55	55.30
2	5	43	11.32	42	12.45	51	58.47	34	14.52
2	6	42	9.16	39	9.92	49	26.42	32	6.59
2	7	53	18.81	44	21.79	56	34.53	41	26.60
2	8	59	13.35	59	14.50	64	38.92	54	23.96
2	9	29	18.44	29	15.79	40	32.67	18	16.16
3	4	45	171.02	44	148.70	53	304.28	35	133.02
3	5	39	13.64	37	11.86	48	109.60	28	15.78
3	6	50	7.32	51	5.86	59	42.18	42	6.28
3	7	43	66.58	39	65.82	49	145.40	33	44.54
3	8	35	14.62	33	15.51	43	43.23	25	10.88
3	9	43	11.23	34	12.88	51	43.29	26	8.07
4	4	39	17.84	35	17.42	44	26.20	30	4.90
4	5	39	12.00	40	9.40	47	42.29	31	5.48
4	6	30	93.23	29	82.68	37	86.27	22	42.59
4	7	22	7.36	23	6.86	31	61.90	14	26.85
4	8	28	104.32	31	70.41	43	33.44	14	6.78
4	9	24	26.58	24	24.25	33	18.42	15	8.20
5	4	40	11.25	40	10.80	49	24.38	30	6.60
5	5	27	69.66	22	59.13	33	68.81	19	30.57
5	6	53	33.88	51	30.84	56	23.82	48	6.47
5	7	43	9.23	42	8.95	48	26.60	37	6.45
5	8	39	10.87	37	10.27	50	48.04	26	11.92
5	9	17	21.52	14	16.00	23	20.78	7	32.71
6	4	41	7.92	41	5.90	52	27.51	30	3.30
6	5	40	11.55	40	10.72	50	25.18	30	2.96
6	6	41	13.07	41	12.63	51	35.33	31	6.09
6	7	40	30.35	36	26.05	51	34.33	25	15.44
6	8	44	9.09	40	8.82	54	106.79	31	21.00
6	9	50	51.52	46	47.52	51	260.50	42	133.80

Thus the second computation was the absolute error, where all errors were summed without regard to error sign, and again divided by the number of judgments.

In Table 4-1 the mean absolute errors for all 72 observations are shown separately for each of the 36 subjects. Several points can be noted immediately. First, N is always less than 72, which indicates that none of the subjects saw all of the cones. Second, it will be noted that there are marked differences among subjects. Some subjects contribute much larger error scores than others. This is clearly shown in Table 4-2, where the contribution of various groups of subjects to the total error score is shown.

Table 4-2

PERCENT OF ERROR CONTRIBUTED BY EACH OF SIX GROUPS ARRANGED ACCORDING TO ABILITY.

GROUP	PERCENT OF TOTAL GROUP	PERCENT ERROR CONTRIBUTED	CUMULATIVE PERCENT ERROR
A	16.67	4.97	4.97
B	16.67	6.57	11.54
C	16.67	8.05	19.59
D	16.67	10.22	29.81
E	16.67	15.01	44.82
F	16.67	55.18	100.00

The data in this table were obtained by selecting the six subjects who had the smallest absolute error score in judging the sizes of the left cones; this is group A. Group B was then formed by selecting the six subjects who had the next larger absolute error scores than those in A,and so on until all subjects were included. Since there were six groups of six subjects each, 16.67 percent of all the subjects was in each group. If there had been little difference among the subjects, each group would have contributed approximately 16 percent of the total error. Actually, the best group contributed only about 5 percent of the error, while the worst group (F) contributed 55 percent of the total error. Thus group F had, on the average, about 11 times as large an error as the members of the best group (A). Similar results are obtained for the other measures, such as distance to the cones, and distance between the cones.

It should be noted, however, that the subjects who were the best in judging the sizes of the targets were not necessarily the ones who were also the best in judging the distances to the targets. This can be shown for the various measures by arranging the subjects in a rank order separately for each measure (i.e., left cone size, right cone size, distance to left cone, and distance between cones). Rank order correlations (rho) were computed between these various ranks. The results are shown in Table 4-3.

Table 4-3.

RANK-ORDER CORRELATIONS BETWEEN SUBJECTS' ABILITIES TO JUDGE SIZE AND DISTANCE OF TARGETS.

RHO between sizes of left and right cones	+0.97
RHO between cone size judgment and distance to cones	+0.17
RHO between distance-to and distance between cones	+0.63
RHO between cone size judgment and distance between cones	+0.50

The values in Table 4-3 indicate that those subjects who were very good at judging distances to the cones were not as good, comparatively, in judging size, and vice versa. The judgment of distance between cones was affected by the judgments of distance to the cones and by the judgments of the cone sizes themselves. Since the distance between cones was small (compared to the distance to the cones), a number of the subjects reported that they attempted to check their estimate of this distance by mentally counting off the number of cone heights that would fit into the estimated distance. Thus this estimate correlates equally well with the distance-to estimates and with the cone height estimates.

The same results are shown in a more marked fashion if the relative error scores are used instead of the absolute error scores. These scores are given in Table 4.4. If the subjects are arranged into six groups, from best to worst on the basis of the relative scores, the differences are even more striking. Now the best group contributes less than one percent of the total error while the worst group contributes approximately 2/3 of all of the errors.

If the respective absolute and relative error scores for the subjects are compared, it can be seen that the poor subjects tend to overestimate all judgments. Thus there is a constant bias in all of their errors. Consequently, the mean of a number of judgments made by poor subjects is not noticeably better than the mean of the judgments made by any one individual.

The good subjects, however, do not tend to display this bias to such a pronounced extent. Not only is any given single judgment more likely to be correct than in the case of the poor subjects, but — since the good subjects sometimes overestimate and sometimes underestimage the distance or the size — the group mean is usually very much better than any single judgment. Thus, by using several observers making independent judgments, one can obtain a quite accurate estimate of the actual size or distance.

Since a relatively small part of the entire group contributes nearly all of the group error, it seems reasonable to eliminate these subjects from further analysis. Thus the rest of the data presented herein is based, for the most part, upon 28 subjects; the 8 worst subjects have been removed.

Table 4-4

RELATIVE MEAN ERROR FOR EACH SUBJECT FOR CONE SIZE, DISTANCE-TO, AND DISTANCE BETWEEN CONES

SUBJECT NUMBER		CONE SIZE				DISTANCE TO LEFT CONE		DISTANCE BETWEEN CONES	
		LEFT		RIGHT					
GROUP	SEAT	N	ERROR (inch)	N	ERROR (inch)	N	ERROR (feet)	N	ERROR (feet)
1	4	52	8.34	52	4.03	53	-13.35	50	10.96
1	5	45	-4.46	42	-5.47	53	-45.81	34	-1.50
1	6	47	10.82	47	8.42	53	31.41	41	16.56
1	7	43	16.74	39	13.43	51	119.37	31	7.45
1	8	44	15.93	45	18.62	53	52.45	36	21.25
1	9	37	-1.43	32	-5.28	46	38.41	23	47.78
2	4	64	19.84	60	20.41	69	89.26	55	54.94
2	5	43	7.97	42	9.78	51	44.54	34	13.05
2	6	42	5.97	39	6.58	49	-23.69	32	4.78
2	7	53	16.05	44	17.65	56	-24.53	41	26.60
2	8	59	10.98	59	11.93	64	-26.29	54	22.81
2	9	29	8.24	29	6.13	40	-19.52	18	13.16
3	4	45	171.02	44	148.70	53	302.39	35	133.02
3	5	39	8.10	37	4.45	48	97.93	28	13.28
3	6	50	3.00	51	-0.29	59	15.61	42	0.00
3	7	43	62.67	39	64.74	49	127.69	33	43.75
3	8	35	11.65	33	12.42	43	23.88	25	9.20
3	9	43	-9.09	34	-10.35	51	-42.90	26	6.23
4	4	39	16.25	35	15.77	44	-20.38	30	-0.83
4	5	39	6.56	40	4.70	47	-41.91	31	-0.19
4	6	30	92.56	29	82.68	37	73.56	22	42.13
4	7	22	-3.00	23	-0.95	31	45.90	14	26.71
4	8	28	100.96	31	66.09	43	-14.27	14	2.50
4	9	24	23.58	24	23.58	33	2.54	15	6.86
5	4	40	6.5	40	6.00	49	-10.75	30	2.93
5	5	27	67.74	22	56.59	33	63.90	19	30.57
5	6	53	33.66	51	30.76	56	1.64	48	1.60
5	7	43	5.09	42	5.38	48	-20.39	37	4.89
5	8	39	6.25	37	2.70	50	12.56	26	9.30
5	9	17	8.35	14	2.85	23	-5.65	7	32.42
6	4	41	3.04	41	2.09	52	-25.59	30	1.76
6	5	40	9.75	40	9.12	50	-21.66	30	1.10
6	6	41	6.63	41	5.51	51	-28.62	31	1.25
6	7	40	28.95	36	23.38	51	·14.64	25	14.24
6	8	44	-2.27	40	-1.12	54	86.98	31	19.06
6	9	50	51.52	46	47.52	51	260.50	42	133.80

4.2 MONOCULAR VERSUS STEREO PRESENTATIONS

Here also there are interactions between the level of ability of the subjects and the effect of stereo. In general the results are that poor subjects tend to do better with the stereo presentations than with the monocular presentations. However, they are quite poor with both presentations. The good subjects do almost equally well on all presentations. This is shown in Table 4-5.

Table 4-5.

PERCENT OF TOTAL ERROR FOR EACH GROUP THAT IS CONTRIBUTED BY THE MONOCULAR, 4-, AND 12-INCH METHODS OF PRESENTATION

SUBJECTS	MONOCULAR	STEREO	
		4 inch	12 inch
3 worst subjects	43.8	29.2	27.0
All 36 subjects	40.6	28.9	30.4
28 (the 36 subjects with the 8 worst subjects removed)	38.9	29.8	31.3
5 best subjects	34.5	33.3	32.2

These errors are contributed largely, for the poor subjects, by the difference between mono and stereo presentations in judging distance-to and distance between the targets. There is very little difference between the three conditions when it comes to estimating the size of the cones. This is true for all subjects, as shown in Table 4-6.

The interactions between method of presentation (mono, 4-, and 12-inch stereo), ability of subjects, and type of judgment to be made (cone size,

Table 4-6

ABSOLUTE AND RELATIVE ERROR FOR MONOCULAR, 4- AND 12-INCH STEREO PRESENTATIONS. DATA IS SHOWN FOR ENTIRE GROUP OF 36 SUBJECTS AND AGAIN FOR THE SAME GROUP WHEN THE 8 WORST SUBJECTS' DATA HAVE BEEN REMOVED

METHOD OF PRESENTATION	LEFT CONE SIZE (in.)	RIGHT CONE SIZE (in.)	DISTANCE TO LEFT CONE (feet)	DISTANCE BETWEEN CONES (feet)	
ABSOLUTE ERROR					DATA FOR ALL 36 SUB-JECTS
Mono	25.75	23.26	81.02	34.66	
4-inch Stereo	27.77	25.18	57.76	22.53	
12-inch Stereo	27.23	24.89	60.50	20.48	
RELATIVE ERROR					
Mono	20.28	17.11	43.79	32.74	
4-inch Stereo	24.72	20.64	21.72	19.94	
12-inch Stereo	21.67	20.60	26.42	17.42	
ABSOLUTE ERROR					DATA FOR THE 28 BETTER SUB-JECTS
Mono	13.96	13.75	52.24	18.78	
4-inch Stereo	15.16	14.01	39.96	13.29	
12-inch Stereo	14.98	13.93	40.99	10.00	
RELATIVE ERROR					
Mono	7.38	6.29	7.05	16.37	
4-inch Stereo	11.40	8.32	-2.68	10.13	
12-inch Stereo	8 17	8.80	0.36	6.23	

distance to target, diatance between target) then make for a rather complicated picture which may be summarized as follows.

4.2.1 Judging Cone Size

Estimates made with the monocular presentations tend to be somewhat better than those with stereo for all subjects, both good and poor. The difference is small but it is consistent. That is, there is no change in the relative standings of the three methods of presentation as the ability of the subjects changes. The differences between the two stereo methods (4-inch and 12-inch) is insignificant.

4.2.2 Judging Distance to Targets

Estimates made with the monocular presentations tend to be markedly inferior to the stereo presentations for the poor subjects. But this difference is progressively reduced as the subjects improve, until, finally, for the group of very good subjects, there is no significant difference between any of the methods of presentation. Although both stereo presentations are superior to the monocular presentation with the poor subjects, there seems to be relatively little difference between the 4-inch and 12-inch presentations. What small difference does exist between these two seems to favor the 4-inch presentation with the very poor subjects, but this disappears as the subjects improve.

4.2.3 Judging Distance Between Targets

Both of the stereo presentations tend to be superior to the monocular presentation for the estimates made by the poor subjects. The difference tends to be reduced as the subjects improve, but the reduction is not as large as in the case of judging distances to the targets. Although the estimates made with both stereo presentations are superior to those made with the mono, there seems to be a small, but consistent, superiority of the 12-inch display over the 4-inch display.

At this point a question might be raised as to why the 4-inch presentation is slightly superior in judging distance to targets and the 12-inch is superior in judging distance between targets. The first point to be born in mind is that the differences are not, in fact, statistically significant: differences this small could easily have arisen by chance. This can be seen by consulting the table in Appendix C which gives the standard distributions for each subject for the various conditions. It will be noted that the variability in most cases is quite large. By comparing this appendix with Table 4-1 it will also be noted that there is quite good correlation between absolute errors for a given subject and his variability. That is, a subject who was a poor judge of size or distance was also quite variable in his error. On the other hand, those subjects who had small mean errors were also quite consistent from one judgment to another.

4.3 EFFECT OF NOISE

The effects of noise are also complex because of interactions. Here, however, the interactions are not due to the level of subject ability. Table 4-7 presents the data for error as a function of noise level.

From this table it can be seen that the effect of noise is as follows:

(a) with an increase in noise there is a steady reduction in the number of targets that are seen;

(b) there is no change in the accuracy with which cone size is judged;

(c) there is a steady, and marked, improvement in the mean absolute error of the distance-to judgments as noise increases;

(d) there is an equally steady, but not as marked, improvement in the mean absolute error of the judgments of distance between targets as the noise increases;

Table 4-7

NUMBER OF TARGETS VISIBLE AND ABSOLUTE ERROR AS A FUNCTION OF SIGNAL-TO-NOISE RATIO FOR ALL SUBJECTS AND FOR THE SMALLER GROUP OF THE BETTER SUBJECTS

	MEAN ABSOLUTE ERROR						
S/N RATIO	N	CONE SIZE (inch)	N	DISTANCE TO CONES (feet)	N	DISTANCE BETWEEN CONES (feet)	
Infinite	458	14.19	277	63.17	180	17.06	
22	396	14.17	241	44.65	156	11.92	DATA
19	360	13.63	217	35.40	143	11.06	FOR THE
16	352	14.86	216	43.93	136	17.49	28
13	344	14.65	209	36.96	134	11.84	BETTER
10	320	14.33	198	38.61	120	12.90	SUBJECTS
Infinite	596	26.28	357	92.95	235	33.31	
22	597	22.83	304	67.09	194	22.32	DATA
19	458	24.72	280	61.41	180	20.78	FOR ALL
16	451	25.33	276	58.75	175	28.09	36 SUB-
13	452	26.54	274	55.97	176	20.96	JECTS
10	416	23.29	253	58.04	160	26.00	

(e) these results are similar for all subjects, good and poor, and are essentially uncorrelated with subject ability.

4.4 ERROR AS A FUNCTION OF THE DISTANCE TO THE TARGETS

As explained in the apparatus section, all targets were placed at one of six distances from the camera. These distances were 20, 31, 50, 80, 127 and 200 feet. In Table 4-8, the error as a function of the distance at which the target was placed is shown.

Table 4-8.

ABSOLUTE AND RELATIVE ERROR IN JUDGING DISTANCE TO TARGET AS A FUNCTION OF THE ACTUAL TARGET DISTANCE. DATA FOR THE 28 BETTER SUBJECTS.

DISTANCE TO TARGET (ft.)	N	ABSOLUTE ERROR IN DISTANCE JUDGMENT (ft.)	RELATIVE ERROR IN DISTANCE JUDGMENT (ft.)
20	259	17.27	13.00
31	306	14.84	3.16
50	255	26.41	2.27
80	232	45.89	6.75
127	186	90.81	7.96
200	120	145.96	-44.63

From this table several facts become obvious. These are as follows:

(a) as the distance increases, the number of targets that are seen becomes smaller. (Note that the apparent discrepancy for N at 20 feet is actually an artifact of the experimental situation. Two slides that had targets at 20 feet occasionally jammed in the projection mechanism. Thus the actual number of 20 foot distance targets that was presented to the subjects was smaller than those at the other distances, so the total possible number of targets that could occur at this distance was also smaller. Except for this artifact, however, the decrease of N with increasing distance is consistent);

(b) as the distance increases, the absolute error becomes larger, but the relative error becomes smaller, and eventually becomes negative. This means that, in common with many previous reports in the literature, individuals tend to overestimate small distances and underestimate large distances. Added to this source of error is the Weber-Fechner effect which is that the size of the error tends to be proportional to the size of the distance to be judged;

(c) from the above two facts, then, it can be seen that the effect of noise is to obscure the targets at greater distances more than the targets at closer distances.

The effect, then, of the above is that the more distant the target, the greater the error. At each noise level the subjects received presentations of equal numbers of targets at each distance. However, as the noise level increased, there was a steady decrease in the number of targets that was seen. This decrease did not occur equally among all targets at all distances: the more distant targets tended to disappear more often than did the closer targets. However, since it was the distant targets that contributed the greatest amount of error, at the high noise levels the mean error was based mostly upon the closer targets, which had smaller mean errors. Thus the net result was that there was a decrease in the mean error of the distance judgments as the noise increased. These results were true for all subjects regardless of level of ability.

4.5 ERROR AS A FUNCTION OF SIZE OF TARGETS

The results here were very similar to those shown in Section 4.4. That is, cones that subtended a small visual angle gave the greatest absolute error, and had the smallest N. These results are shown in Table 4.9.

Table 4-9.

DATA FOR ABSOLUTE AND RELATIVE ERROR AS A FUNCTION OF THE SIZES OF THE CONES USED. DATA FOR THE 28 BETTER SUBJECTS

CONE SIZE (in.)	N	ABSOLUTE ERROR (in.)	RELATIVE ERROR (in.)
4	137	19.22	18.99
6	253	13.66	13.07
10	269	14.62	13.60
16	450	13.76	11.04
26	497	12.77	6.93
40	602	15.16	0.77

Here again, as in the previous section, it can be seen (by comparing the absolute and relative error) that the subjects tended to overestimate the sizes of the smaller cones and, as the cones became larger, more and more estimates were underestimates. For the largest cone, however, there were still a few more overestimates than underestimates. Furthermore, the number of cones that was seen became smaller as the cones decreased in size.

Thus one may treat distance of the cones and size of the cones in the same way since both effects result in a reduction of the visual angle. However, with any appreciable amount of noise, the cones that subtend small visual angles are not seen, and hence do not contribute any error effect to the total. Thus we have the result that the mean errors under the noise conditions are less than under the no-noise condition.

4.6 ERROR AS A FUNCTION OF DISTANCE BETWEEN TARGETS

A breakdown of the error as a function of the distance-between is shown in Table 4-10.

Table 4-10.

ERROR AS A FUNCTION OF THE DISTANCE BETWEEN CONES FOR THE 28 BETTER SUBJECTS.

Distance between cones (feet)	N	Absolute error in feet	Relative error in feet
2	156	18.24	17.98
3	123	7.01	6.49
5	160	13.88	12.86
8	155	11.78	10.09
13	136	14.91	10.05
20	139	16.13	5.01

From this table it can be seen that almost all of the subjects over-estimated all of the distances, although this tendency is less pronounced at the larger distances. One reason that this tendency may be less pronounced is the fact that N is nearly equal for all distances. Thus the distribution of error due to seeing or not seeing a given set of cones is not so pronounced as in the case of the distance-to or the size of the cones. Some support of this hypothesis is offered by the fact that the lowest N is 123 and occurs for the 3-foot distance. This distance also has a markedly lower error than the other distances, even though it is a short distance and thus should logically be overestimated almost as much as the two-foot distance.

4.7 ERROR AS A FUNCTION OF THE ORIENTATION OF THE CONES

It will be remembered that the right-hand cone was always placed in one of three orientations in regard to the line of sight from the observer to the left-hand cone. These orientations were 0, 45, and 90 degrees. In the 0 degree orientation the second, or right-hand cone, was set behind the left-hand cone in essentially a straight line from the camera to the left cone, being displaced just enough so that the first cone did not obscure it. The following diagram will illustrate the three arrangements.

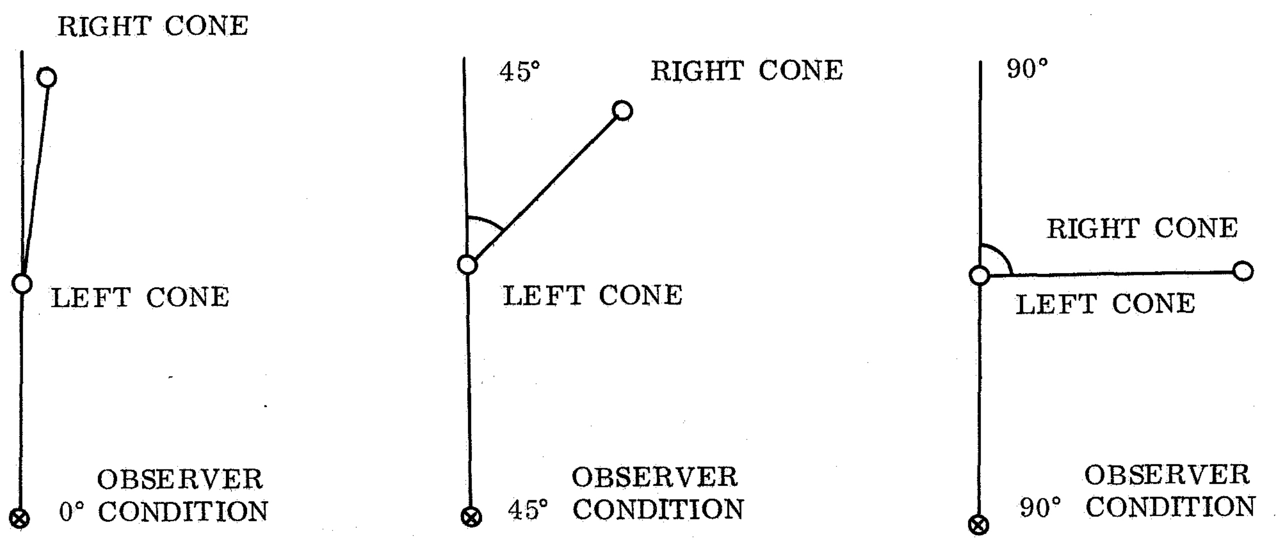


Figure 4-1. Cone Orientations

It was thought that perhaps some difference in judging distance might emerge from this arrangement, since it seemed reasonable to assume that the 0 degree orientation would be the most difficult to judge and the 90 degree one the easiest. The reasoning behind this is that in the latter case no depth perception was necessary because the distance between cones was orthogonal to the line of sight of the camera. In point of fact this hypothesis was not proven. All judgments were made with about the same amount of error, as shown by Table 4-11.

Table 4-11.

ABSOLUTE AND RELATIVE ERROR FOR DISTANCE BETWEEN CONES AS A FUNCTION OF THE TWO CONES IN RESPECT TO THE LINE OF SIGHT OF THE OBSERVER. DATA FOR THE 28 BETTER SUBJECTS.

ORIENTATION OF CONE (Degrees)	N	ABSOLUTE ERROR IN FEET	RELATIVE ERROR IN FEET
0	283	15.50	11.56
45	309	11.66	8.59
90	277	14.56	12.14

4.8 PROJECTION VERSUS TRIMENSION READER PRESENTATIONS

There was no consistent difference between judgments made by the same subjects on the two methods of presentation. In some cases one subject would be consistently better on one presentation and a different subject would be better on the other. About half of the subjects' judgments fluctuated, so that some of their estimates were better with one presentation and the rest of their judgments were better with the other.

All subjects who were tested on both presentations were queried as to their preferences. The subjects divided approximately evenly in the method of presentation that they preferred. The reasons given for preferring one presentation or the other were either (a) less eye strain, or (b) greater feeling of assurance in making judgments. There was, however, no consistency about these preferences. The assignment of less eye strain was made about equally to both presentations by different subjects. Again, there was no correlation between feeling of assurance in making judgments and the actual accuracy of those judgments.

It has been indicated by some authors that the accuracy of judgment of size and distance from photographs is at least partly a function of the subtended visual angle of the photograph as related to the real-world included angle. In this experiment the fact that the Trimension Reader image subtended a smaller visual field than the Polaroid projection image had obviously no effect upon the accuracy of judgment, since, as just shown, there were no significant differences in accuracy with the two presentations.

4.9 ERROR AS A FUNCTION OF SEATING DISTANCE FROM SCREEN

This same fact is illustrated even more clearly if a separate analysis is made of subjects on the basis of the distance from the screen at which they were placed when viewing the Polaroid projections. It is true that, as the subjects sat farther and farther away from the screen, there was a slight reduction in the number of targets seen. Except for this, however, there were no differences in the mean accuracy of judgment of size or distance as a function of seating distance from the screen.

4.10 ERROR AS A FUNCTION OF SEX OF SUBJECT

Of the 36 subjects used in the main part of the experiment, 8 were female and 28 were male. The <u>overall</u> error averages of the two groups show no significant differences. That is, the group means are essentially the same for male and female subjects. However, the distribution within the male group is essentially normal, given the small sample size, but the distribution within the female group tends to be bimodal. That is, the female subjects tend to be either very good or rather poor. Only two female subjects fell in the middle group that contained about 55 percent of the male subjects. The same tendency was seen in the smaller group of subjects that was used in the preliminary study. Because of the relatively small number of female subjects used in this study these conclusions should be treated as tentative ones, and the safest conclusion is that there are no really significant differences as a function of the sex of the subject.

4.11 EFFECTS OF PRACTICE AND TRAINING

The results of practice and training may be seen in Table 4-12. It can be seen from this table that even a relatively small amount of training can result in immediate improvement. There is little doubt that the results could be improved somewhat more by further practice. In any case, there is still no significant difference between the stereo and monocular presentations for the good subjects, either before or after practice. What is perhaps even more impressive is the relative error after practice. This is shown in Table 4-13.

This table indicates that the means of group judgments are far closer to the truth than the value of any single judgment, even when the subject is highly trained. This is almost equally true for all methods of presentation.

4.12 SUMMARY OF RESULTS

There were consistent qualitative, as well as quantitative, differences between good and poor subjects. The poor subjects showed a consistent bias to overestimate <u>all</u> sizes and distances. This bias was more pronounced on the smaller sizes and distances.

Good subjects tended to overestimate small sizes and distances and underestimate large sizes and distances.

Estimates made with stereo presentations were superior to those made with monocular presentations for the poor subjects in judging distance-to

Table 4-12

CHANGE IN NUMBER OF TARGETS SEEN AND IN ABSOLUTE ERROR FOR BEST FIVE SUBJECTS AS A FUNCTION OF PRACTICE AND TRAINING

METHOD OF PRESENTATION	N	ABSOLUTE ERROR: CONE SIZE ERROR IN INCHES	ABSOLUTE ERROR: DISTANCE-TO ERROR IN FEET	ABSOLUTE ERROR: DISTANCE-BETWEEN ERROR IN FEET
		Data for five best subjects before practice (data from 24 slide presentations only).		
Mono	53	7.39	26.17	4.52
4-inch Stereo	40	11.98	45.16	5.80
12-inch Stereo	28	9.00	37.50	9.75
		Data for same subjects on same slides after practice and training.		
Mono	77	4.64	17.42	3.40
4-inch Stereo	57	3.83	15.31	3.33
12 inch Stereo	81	4.59	25.25	5.81

Table 4-13

RELATIVE ERROR OF FIVE BEST SUBJECTS AFTER PRACTICE DATA TAKEN FROM 24 SLIDES OF SERIES ONLY

METHOD OF PRESENTATION	RELATIVE ERROR: CONE SIZE ERROR IN INCHES	RELATIVE ERROR: DISTANCE-TO ERROR IN FEET	RELATIVE ERROR: DISTANCE-BETWEEN ERROR IN FEET
Mono	+2.04	+1.87	-1.68
4-inch Stereo	+0.79	0.31	+0.42
12-inch Stereo	+0.27	-8.34	-0.08

and distance between targets. Little difference was found in judging the size of cones.

For good subjects there was very little difference between stereo and monocular presentations for cone size or distance.

The effect of noise is primarily to eliminate those targets which subtend small visual angles. The presence of noise did not change the accuracy with which judgments were made of those targets which were seen. However, since it is usually the small and distant targets which contribute the greatest error, increasing the noise has the effect of reducing group mean error in noisy environments, since those targets which contribute most to the overall error are now no longer seen.

There is no significant difference between monocular and stereo presentations at any noise level. However, with no noise at all, there is a slight tendency to see more targets with the monocular presentations. Since the additional targets that are seen are the small, distant targets that contribute the greatest amount of error to the mean of the group, this has the effect of spuriously raising the mean error level of the group in the no-noise condition and especially in the monocular no-noise condition.

There is no significant difference in preference or in accuracy of subjects in making judgments with either the Polaroid projection or with the Trimension Reader method of presentation.

There were no significant differences in results as a function of sex of subject.

Those subjects who sat farther from the projection screen saw somewhat fewer targets than those who sat closer, but the accuracy of judgment was the same for those targets that were seen.

Improvement can be made in good subjects by additional special training, but it is more important to select good subjects in the first place by empiric tests. These tests should be realistic ones, since the results of this study show little general ability to make all sorts of judgments of a spatial nature. For example, those subjects who were best at judging target size were seldom the same subjects who were best at judging distance to targets or distance between targets. (Rank order correlation coefficients between ability to judge cone size and ability to judge distance-to were positive, but very low.) Thus "spatial judgment ability" appears to be a compound of rather specific sub-capabilities.

Section 5

DISCUSSION

5.1 EVALUATION OF EFFECTIVENESS OF METHODS OF PRESENTATION

Although the ultimate purpose of this program is to predict the efficiency of a stereo or non-stereo system on a remotely controlled extra-terrestrial vehicle, the data presented thus far have been from laboratory results. The question now arises as to how far one may safely extrapolate these results to the actual operational situation. The answer to this question depends, in part, upon the operating characteristics of the vehicle.

The Bendix study (5) assumes that, because of antenna-pointing problems, the pictures will only be transmitted while the vehicle is stationary. If this is true, the present experiment bears a high degree of validity, since the stimuli used here were also stationary pictures.

It is, however, conceivable that it might be possible to transmit TV pictures while the vehicle is moving. If this is the case, a new cue, motion parallax, will be present in the real world situation which was not present in the experimental situation. Motion parallax is a cue that can be utilized quite effectively with monocular vision. Thus it is to be expected that judgments will be even more accurate, with both methods of presentation (i. e., stereo and mono) improving equally. Evidence for this is presented by Fox (36) and by Kerle (78) who indicated that a remotely controlled vehicle can be operated quite well, even at high speeds, with only a monocular view of the world over the TV channel. It is clearly shown in these two reports that the transmission lag is responsible for the very slow rate of vehicle movement, not the time required for operator decision in evaluatating the display.

There is another aspect of the real world situation, however, which may well militate against the success of a stereoscopic presentation. In this study, as in the Bendix study, care was taken to have the camera level at all times. In the real world, however, the vehicle, traversing rough terrain, will frequently be anything but level. This fact has some important implications for stereo. The TV cameras can be mounted firmly on the vehicle so that their tilt is the same as that of the vehicle, or they may be gimbal-mounted so that they will always be level. Both of these approaches present problems, albeit of a different nature. These problems shall be considered in turn.

Assume that the cameras are gimbal-mounted. This poses the obvious problem of additional weight, cost, and complexity. If the direction cosines-or, equivalently, the Euler angles-of the cameras (with respect to an orthogonal set of axes fixed in the vehicle) are not equal, stereopsis may not be achieved. Within the limits of a few degrees, stereopsis can, in fact, be achieved by most observers. The price one pays, however, is severe eye strain.

It was stated earlier that, in this experiment, the cameras were always kept level and that the left and right slides were carefully calibrated during mounting. The projectors, however, did not always drop each slide into the viewing slot with perfect precision. Hence, the effect described above was achieved inadvertently in the experiment, although the disparity between one picture and another was seldom more than 2 degrees of visual angle, almost all the subjects achieved stereopsis. Even so, most of them reported eye strain, and five of the subjects found this so severe that they would not continue with the study. The relative orientations of the cameras must, therefore, be carefully controlled to eliminate this problem. But over and above this, there is a real human engineering problem in that the only information the operator has about the vehicle position is what he sees on the TV display. If the display is stabilized, the vehicle may be perilously tilted on an incline and the operator will never know it, since the scene will always appear level. This approach, obviously, cannot be recommended.

If the cameras are fixed to the vehicle, the gimbal mounts and controls are eliminated, and another orientation uncertainty arises; if the observer sees a tilted display, he may not be able to tell if the vehicle is tilted or the terrain is.

One way to obviate these effects would be to mount both TV cameras securely on a gimbaled platform,so that the display would always be level,and include on the vehicle an inertial reference system which would transmit continuous orientation information to the ground station.

However, in view of the very small difference between stereo and non-stereo presentations with selected and trained subjects, it is doubtful if the additional complexity is worthwhile in order to achieve a stereo presentation.

This is especially true when it is remembered that, in this experiment, the non-stereo presentation was a monocular one. Numerous reports have indicated a slight, but consistent, superiority of binocular vision over monocular vision even in non-stereo situations (i. e., in viewing pictures). A monocular presentation was used in this experiment to maintain consistent S/N ratios. In order to achieve stereo it was necessary to use Polaroid filters over the slide projectors. In order to achieve noise in both eyes, the noise projector had to remain unfiltered. However, the S/N ratio was measured and computed on the basis of the light loss through the glasses that the subjects would be wearing in the stereo presentations. Thus, if they were to use both eyes and not remove the glasses, they would have had a picture in only one eye and noise in both eyes, which would change the S/N ratio by a considerable amount. On the other hand, if they were to remove the glasses and used both eyes, they would have had a picture in both eyes, and noise in both eyes. But now the noise itself would be brighter since it would be unpolarized without the glasses. Here also, then,the S/N ratio would be changed. Hence the only safe thing to do would be to view the picture with one eye only while wearing the glasses.

Even under these circumstances, as the results have shown, there was no significant difference between non-stereo and stereo. Therefore, it is a reasonable assumption that, if no attempt is made to use stereo and if the operator can use binocular vision, the results may even be slightly superior to those with the stereo presentation.

5.2 ESTIMATE OF INCREASED EFFICIENCY BY MEANS OF GROUP JUDGMENTS

In any case, the differences in results are small as a function of the method of presentation, given that the subjects are carefully selected and trained. What is perhaps more important is that a way of achieving great increases in accuracy is presented not so much by the method of presentation but by the method of employing the presentation, whatever it may be.

The results indicate that trained subjects could make reasonable estimates of size and distance. Even so, the errors were possibly too large for some purposes. For example, even after practice, the average distance-to error for the best subjects was on the order of 15 feet. Doubtless, further practice and training could reduce this figure somewhat, but it would still probably be somewhere from 4 to 10 feet over a range of 200 feet, based on the Weber-Fechner fraction of two to five percent for distance judgments.

However, the relative error for the group was only about one foot. This was because, while each separate subject may have had an individual error of 10 or 12 or 15 feet, the net error (given the elimination of any group bias) was much less: some subjects' over-estimates were cancelled by other subjects' underestimates. Thus, a new technique of utilizing this fact in an optimum man-machine interface promises the potentiality of very accurate judgments.

One technique might be as follows. Assume that the returning video signal is viewed by 5 or 6 subjects simultaneously. If each subject is equipped with a small digital keyboard, rather like an adding maching, he can manually insert any number he wishes. If we assume that all of these judgments go to a central adding network where they are stored, added, and divided by N (and the result displayed on some visible indicator),then any given target visible within the picture can be estimated with great accuracy.

It would not be feasible for all the individuals to attempt to operate the vehicle. But assume that the operator has, in addition to the picture display itself, a readout for distance-to and one for size-of-target, calibrated in any convenient units. Then, if a small electronic marker (a dot or a circle, for instance) were placed by the operator over any target about which he was doubtful, he would then shortly obtain a displayed judgment on the readout of the distance and size of that particular target, as arrived at by the above group method.

Since this additional mechanism would be entirely in the control center, it would add nothing to the weight of the vehicle itself, and reliability problems would be minimal.

5.3 RELATION BETWEEN PREDICTED AND OBSERVED RESULTS

As discussed in the introduction, there were two predictions made on the general nature of the results. One prediction related to the effect of stereo versus non-stereo in noise, the prediction being that stereo would be considerably more effective in enabling the operators to "see through" the noise at some levels, and thus detect more targets. This prediction was unfounded. In fact, there was a slight tendency for more targets to be seen at all noise levels with the monocular presentation than with either of the stereo presentations. This is shown by the percent of targets seen in each of the three presentations: monocular, 59.6%; 4-inch stereo, 53.9%; 12-inch stereo, 54.8%. Since all of the target sizes and all of the distances were counterbalanced evenly among all methods of presentation as far as possible, if the small difference is at all significant, then the monocular presentations are slightly superior to the stereo presentations.

The second prediction was in regard to the minimum visual angle that would be seen. The prediction was that this would be somewhere in the range of 15 to 40 minutes of arc. Targets smaller than 15 minutes, it was predicted, would not be seen; targets larger than 40 minutes of arc would almost always be seen. Between these two limits there would be a probability distribution, with the chances of seeing the target better with increasing visual angle. This prediction was fulfilled with considerable precision. Table 2-1 indicates the visual angles that would be subtended by the targets as seen by an operator seated 2.5 feet from the screen. In general, those targets which subtended a visual angle of more than 35 minutes were almost always seen. Note that 58 percent of the targets subtended a visual angle more than 35 minutes. However, all of subjects used in the main body of the experiment chose to sit in either the second or the third rows (e.g. either 5.0 or 7.5 feet from the screen). For the subjects in the second row, 58 percent of the targets subtended a visual angle of approximately 28 minutes of arc or more, and for those in the third row (seats 7, 8 and 9) the 58 percent level was for targets subtending a visual angle of 18 minutes of arc or more. This is almost exactly the percent of targets that were actually seen.

This has some interesting implications in regard to the velocity with which the remotely controlled vehicle can operate. If we assume that an obstacle must subtend approximately 20 minutes in order to be seen, then the size of the obstacles of importance is a function of the characteristics of the vehicle: any obstacle so small that the vehicle can move over it is of no importance; any obstacle larger than this must be avoided. Thus the operator must see the obstacle in time in order to stop the vehicle before there is a collision. Let us assume a one-second reaction time in order to allow the operator to see the obstacle and interpret it correctly as an obstacle, (instead of, for instance, merely a shadow). The round-trip time to the moon for signals is about 2.5 seconds. Thus 3.5 seconds will elapse before the command-stop signal reaches the vehicle. After this, one must allow sufficient time for braking to bring the vehicle to a stop.

The maximum braking force will be equal to the force of friction between the vehicle and the lunar surface:

$$F = \mu m G_M$$

where μ is the coefficient of friction, m is the mass of the vehicle, and G_M is the acceleration due to the moon's gravity. By Newton's second law, we can solve for the deceleration:

$$F = ma, \quad a = \frac{F}{m} = \frac{\mu m G_M}{m} = \mu G_M$$

Now the distance a body moves under the influence of a constant deceleration a is given by

$$d = vt - \frac{1}{2} at^2 .$$

Substituting for a from above, we get

$$d = vt - \frac{1}{2} \mu G_M t^2 .$$

We can eliminate t by noting that it would take the vehicle the same time t to accelerate from rest, with an acceleration a, to the velocity v:

$$v = at = \mu G_M t.$$

Solving this for t and substituting into the equations for d , we get

$$d = \frac{v^2}{\mu G_M} - \frac{1}{2} \mu G_M \left[\frac{v}{\mu G_M} \right]^2, \text{ or}$$

$$d = \frac{v^2}{\mu G_M} - \frac{1 \, v^2}{2 \mu G_M} = \frac{v^2}{2 \, \mu G_M}.$$

If we assume $\mu = 0.8$ and G_M is 1/6 that on Earth, then

$$d = 0.1172v^2.$$

If we let h be the height of the obstacle in feet, 172h is the distance at which it can be seen if we assume an angular detection threshold of 20 minutes of arc, and if the target in the display subtends the same visual angle as it does in the real world.

If, however, the TV cameras have zoom-type lensed and/or the operator is sitting close to the screen, the target on the screen would subtend a larger visual angle at the operator's eye than it does in the real world, i. e., there would be a magnification. This magnification M can be expressed as

$$M = \frac{\text{visual angle subtended by the display at the operator's eye}}{\text{visual angle subtended by the TV lens}}$$

In the event that M is less than unity - that is, a minification rather than a magnification- the above ratio is still valid. Therefore, the equation that gives the maximum safe velocity with which the vehicle can operate over essentially open, flat terrain with a few scattered obstacles is

$$0.1172v^2 + 3.5v - 172hM = 0,$$

where

v = the vehicle velocity in feet per second;

h = the height of the obstacle in feet (limited by the vehicle clearance);

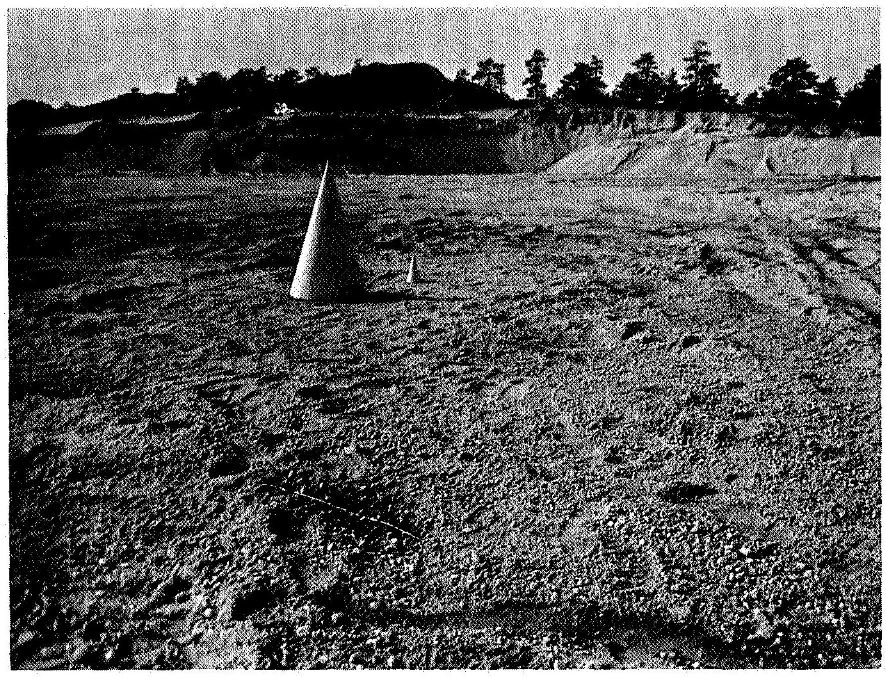
M = the magnification or minification determined by the visual angle of the TV lens, the size of the display screen, and the distance from the screen to the operator's eyes.

This equation is quadratic in v and can easily be solved. The constants are appropriate for the particular assumptions made, i.e., a coefficient of friction of 0.8, a gravitational field 1/6 that of Earth's, a time delay of 3.5 seconds, and a minimum visual angle of 20 minutes of arc. Obviously, for other situations, the equation can be modified by insertion of appropriate constants.

Appendix A

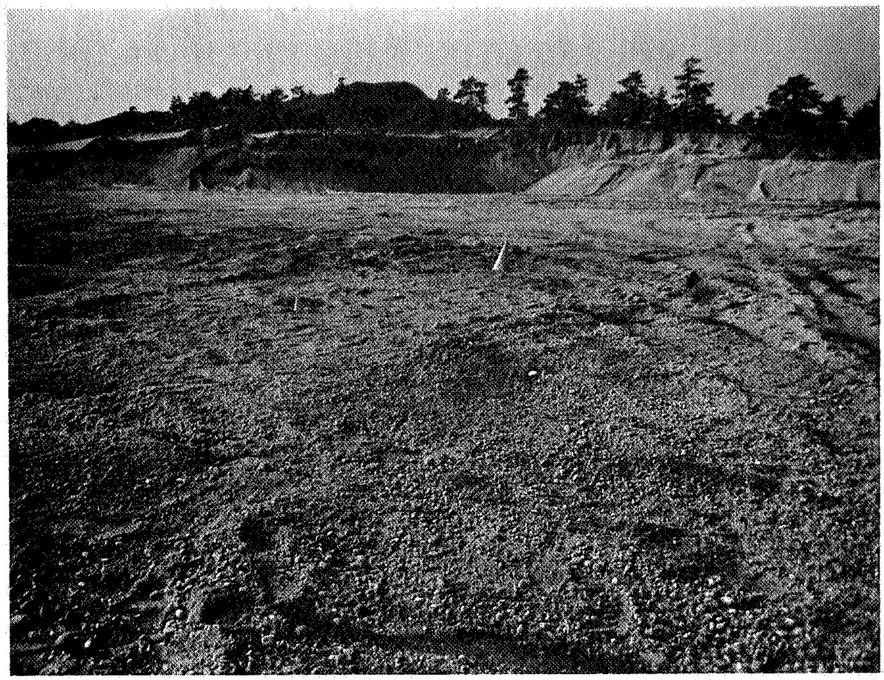
SAMPLE PHOTOGRAPHS AND DATA SHEET

Contained herein are four typical slides from the main experimental series.



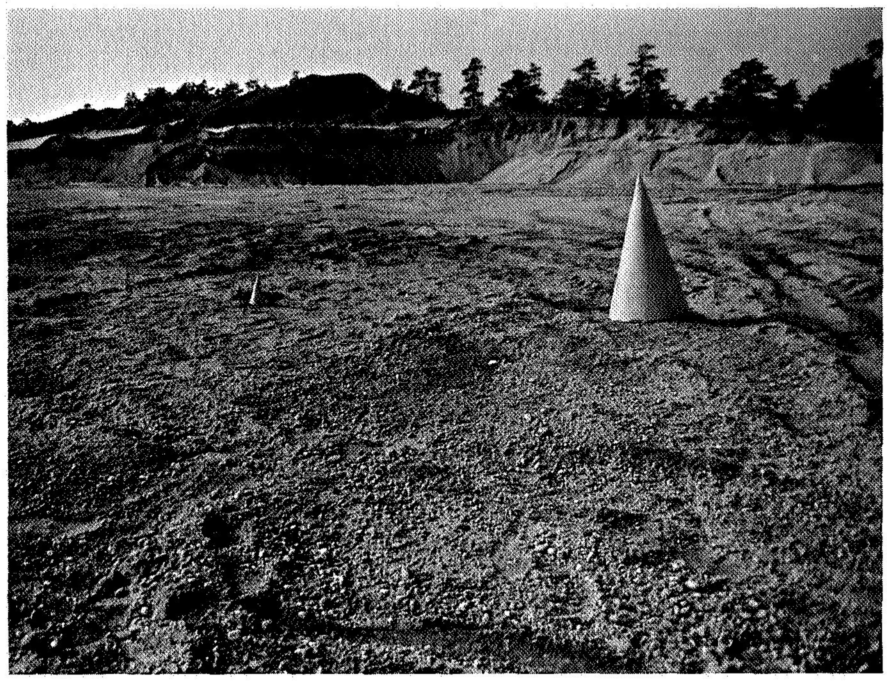
Slide No. 38

Height of left cone in inches	40
Height of right cone in inches	10
Distance to left cone in feet	20
Distance between cones in feet	2
Orientation of cones in degrees	00



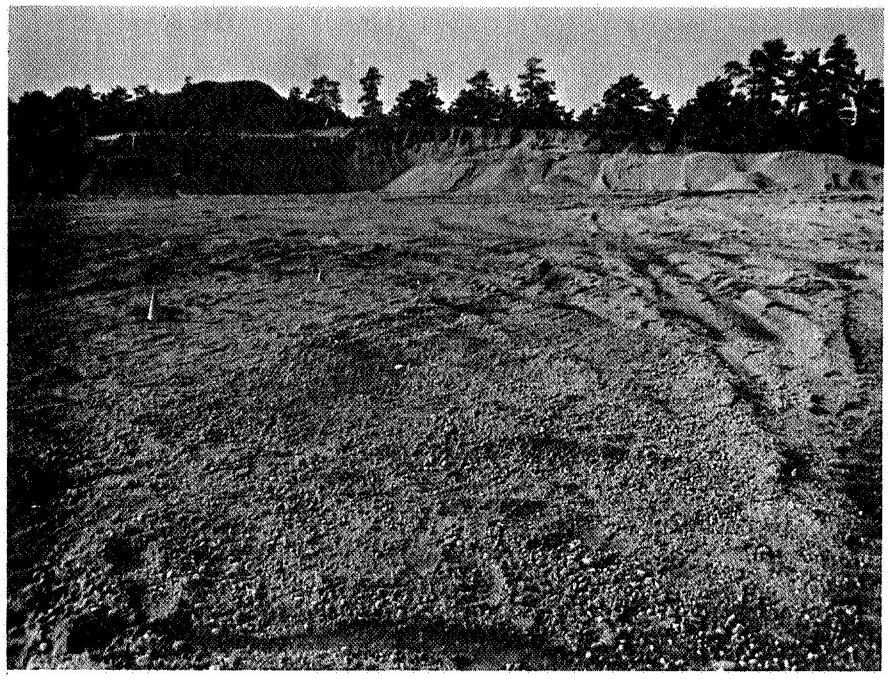
Slide No. 24

Height of left cone in inches	6
Height of right cone in inches	16
Distance to left cone in feet	20
Distance between cones in feet	13
Orientation of cone in degrees	45



Slide No. 64

Height of left cone in inches · · · · · · · · · ·	10
Height of right cone in inches · · · · · · · · ·	40
Distance to left cone in feet · · · · · · · · · ·	20
Distance between cones in feet · · · · · · · ·	8
Orientation of cones in degrees · · · · · · · ·	90



Slide No. 34

Height of left cone in inches	10
Height of right cone in inches	6
Distance to left cone in feet	20
Distance between cones in feet	8
Orientation of cones in degrees	45

SAMPLE DATA SHEET USED IN THE EXPERIMENT

	CONE HT. INCHES		DISTANCE TO LEFT CONE	DISTANCE BETWEEN CONES		CONE HT. INCHES		DISTANCE TO LEFT CONE	DISTANCE BETWEEN CONES		CONE HT. INCHES		DISTANCE TO LEFT CONE	DISTANCE BETWEEN CONES
	L	R				L	R				L	R		
1					25					49				
2					26					50				
3					27					51				
4					28					52				
5					29					53				
6					30					54				
7					31					55				
8					32					56				
9					33					57				
10					34					58				
11					35					59				
12					36					60				
13					37					61				
14					38					62				
15					39					63				
16					40					64				
17					41					65				
18					42					66				
19					43					67				
20					44					68				
21					45					69				
22					46					70				
23					47					71				
24					48					72				

Appendix B

DISCUSSION OF PANUM'S AREA

Because of the limitations of the apparatus utilized in this study, there were two sources of distortion of the images as presented to left and right eyes respectively. These sources were, (1) slight keystoning of the image, and (2) occasional misalignment of the two slides within the respective projectors, so that, on the screen, one slide might be slightly tilted, or raised, with respect to the other. The question then arises as to whether these slight inaccuracies might have prejudiced the results. The answer is most probably not.

The reason for this is to be found in the phenomena that allows images which are disparate on the left and right retinas to be perceived, nevertheless, as a single unitary object in space, after perceptual fusion has taken place in the higher centers of the visual system.

As an example, consider a situation that frequently occurs in the real world, where an object is viewed by turning the eyes in the head, rather than turning the head. Consider first a situation where a rod, (a 3-inch pencil for instance) is held vertically directly in front of the face at a distance of 10 inches. The rod is now the same distance from both eyes, and therefore the object subtends a visual angle of 16 degrees and 50 minutes on both retinas. If, without moving the head, the eyes follow the pencil as it is moved until it is well off to the left eye, a different situation ensues. Assume that it is still 10 inches away from the left eye, and at an angle of 45 degrees to the normal plane of regard. With a nominal interpupilary distance of approximately 2.5 inches, the pencil is now 12 inches from the right eye.

Consequently, the visual angle at the left eye is still 16 degrees, 50 minutes, but it is only 14 degrees at the right eye. Thus there is a disparity of a little over twenty percent in the size of the images in the two retinas. Yet the normal observer still perceives a single object in space, and is unaware of this marked difference in the size of the visual images, even though there is only one point in the two eyes which has a common image. At all other points there will be a greater or lesser difference between the retinal image projected upon corresponding anatomical points.

Obviously, this disparity has some limit. Two images that are too unlike cannot be fused, and are seen as double images, rather than as a single image in space. The area over which this fusion can take place is known as Panum's area.

Panum's area has been investigated by a number of individuals. In general, one may conclude that near the fovea the area is small: on the order of 10 minutes of arc only. However, as one moves out into the periphery, the area becomes larger and larger. In general, Panum's area is a linear function of the peripherial visual angle once one has gone beyond 5 degrees from the fovea, and the value is approximately 4 percent. Thus, at 20 degrees in the periphery, Panum's area would have an extent of 4 percent of 20 degrees or about 48 minutes, and so on.

In addition, the eyes possess considerably more independent mobility than is usually realized. The eyes can rotate about their own centers up to almost 8 degrees (these are called cyclofusional eye movements) and thus reduce retinal disparities to a point where they can be accommodated by Panum's fusional areas.

Therefore, one may conclude that slight discrepancies in the projected visual images can be easily compensated for by the observer, and he can still obtain adequate stereopsis. The only price that the observer may pay is a temporary feeling of eye strain due to the unaccustomed eye movements which may be necessary.

Appendix C

RMS ERROR FOR EACH SUBJECT FOR CONE SIZE, DISTANCE-TO, AND DISTANCE BETWEEN CONES

		CONE SIZE		DISTANCE BETWEEN CONES	DISTANCE BETWEEN CONES
		LEFT	RIGHT		
SUBJECT NUMBER GROUP	SEAT	ERROR (inch)	ERROR (inch)	ERROR (feet)	ERROR (feet)
1	4	17.9	17.5	64.8	51.5
1	5	7.9	6.5	15.4	5.7
1	6	16.1	14.8	133.8	63.0
1	7	19.6	20.4	225.8	13.4
1	8	17.7	24.0	146.1	49.5
1	9	12.1	9.7	171.6	170.7
2	4	15.1	14.4	112.6	66.8
2	5	14.1	16.3	86.8	18.4
2	6	12.9	11.6	25.3	9.7
2	7	21.4	18.9	29.5	23.2
2	8	11.7	10.7	40.9	32.8
2	9	19.8	18.9	42.7	24.7
3	4	72.0	79.4	243.6	127.5
3	5	19.0	18.7	238.2	17.9
3	6	15.3	12.8	88.9	15.3
3	7	136.2	110.7	241.6	57.9
3	8	17.9	15.7	72.7	17.1
3	9	4.5	4.1	6.6	11.6
4	4	21.1	20.5	29.4	6.1
4	5	21.0	14.2	13.1	6.7
4	6	108.2	92.0	159.0	67.6
4	7	10.2	12.8	141.9	74.1
4	8	245.8	206.1	51.1	12.7
4	9	17.9	16.7	52.6	7.0
5	4	15.5	13.6	24.5	8.3
5	5	45.0	53.9	65.9	34.3
5	6	22.1	18.2	45.9	7.0
5	7	11.5	11.3	26.6	8.8
5	8	18.3	13.7	80.6	19.5
5	9	27.4	21.6	27.7	48.0
6	4	14.0	10.3	21.8	4.9
6	5	13.3	12.4	29.7	6.4
6	6	13.0	14.5	30.1	9.6
6	7	23.7	23.0	31.3	15.5
6	8	12.1	11.5	239.4	86.8
6	9	30.5	28.7	249.2	176.5

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