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STEREO ACUITY AND RECONNAISSANCE

Phase II: Development of a Foveal-Parafoveal Chromostereopsis Test

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Charles D. Anderson

The Boeing Aerospace Company
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June 1977

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AEROSPACE MEDICAL DIVISION
AIR FORCE SYSTEMS COMMAND
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A Foveola/Parafoveal or circular staircase test (F/P CST) was designed, developed and evaluated. Three small sample populations (total of 30 observers) were used in investigations of stereoscopic acuity and chromostereopsis. Specific attention was paid to the effect of interchanging the color of the stimuli within the foveola and that within the fovea or parafovea. Marked individualistic effects and large chromostereoscopic changes were observed. The form of the test was that of a central 58 arc minutes disc surrounded by a spiral of wedges that gave the appearance of a

Block 20.

circular staircase as viewed from above. For the three versions of the test, the wedges, or comparative stimuli, fell between 2.2° and 5.5°, 2.2° and 8.8°, or 5.5° and 8.8° of diameter, corresponding to stimulation of the fovea, fovea + parafovea or parafovea. The foveola/parafovea circular staircase test (F/P CST) was found to be a valid instrument for the measurement of chromostereopsis, as performance correlated to a high degree with results on the precision chromostereopsis test developed earlier. The achromatic form proved to be easy to administer and provided a good estimate of an individual's stereo acuity. Difference scores between the achromatic and chromatic forms were good predictors of chromostereopsis and of stereo acuity with chromatic imagery. Twenty-six variables of the physical and optical status of nine observers' eyes were measured and correlated with performance measures from all tests of chromostereopsis. The correlations indicated that vertical ocular refraction, total power of the eye, vitreous chamber depth and back vertex distance were four variables highly correlated with chromostereopsis measures on these observers. An individual's perception of the frontal-parallel plane was measured, and corrected by cyclorotation of the stimuli. The amount of correction correlated highly with the back vertex distance of the observer's eye. It was hypothesized that cyclorotational "correction" of the ARC test images would reduce or reverse the "layback" effect observed in earlier studies. The results were inconclusive but with a positive trend.

NOTE: Figures 1, 2, and 3 on pages 18, 19, and 21 are the best copies available. They are not crucial to an understanding of the report.

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NOTICES

TECHNICAL REVIEW AND APPROVAL

AMRL-TR-77-34

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

CHARLES BATES, JR.
Chief
Human Engineering Division
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SUMMARY

PURPOSE

To develop a test for measuring the contribution of the parafoveal retinal regions to stereoscopic acuity and chromostereopsis. To examine the sensitivity, reliability and validity of this test compared with other tests.

To develop methods of alignment of the Badal Optometer and American Optical Troposcope such that high precision measurement of intervisual axes distance, interpupillary distance, and pupil size can be made, and the effect of image cyclorotation upon perception of the frontal parallel plane studied.

METHOD

A new and improved test called the Foveola/Parafoveal Circular Staircase test (F/P CST) was designed, developed and evaluated. Three small sample populations were used, a student population from the U.S. Army and another from the University of Washington, and a group of experienced observers from Boeing. Stereoscopic acuity skill and the amount and direction of chromostereopsis were determined for all 30 observers.

Nine of the experienced observers were examined as to the physical characteristics of their eyes by retinoscopy, ultrasonography, keratometry and photographic ophthalmophakometry. Correlations among these measurements and visual performance with achromatic and chromatic stereoscopic imagery were established. The Badal Optometer was reconstructed with a larger optical bench and more stable stand. Development features included twin adjustable mirror mounts, artificial pupil holder, new target holders.

For six individuals, perception of the frontal parallel plane was measured, corrected by cyclorotation of the stimuli, and the resulting influence on the "Layback" phenomenon in the Alternating Ramp Chromostereopsis Test was evaluated.

RESULTS AND CONCLUSIONS

Performance on the Foveola/Parafoveal Circular Staircase Test correlates highly with the Alternating Ramp Chromostereopsis (ARC) Test, the Critical Limen Stereoscopic Test (CLST) and the Peripheral Scan Chromostereopsis Test (P/S CST). The relative contributions of blue and red when interchanged as foveal and/or parafoveal stimuli were seldom equal in magnitude. The perceived location of the central disc (foveola) stimulus relative to the position of physical equality was different for each observer. Most individuals perceived the disc as displaced, as would be expected from prior chromostereopsis data, with each colored field driving the central disc to the opposite side of physical equality

Chromostereopsis correlated highly with a combination of the total optical power of the eye and the length of the vitreous chamber. Which concentric portions of the retina were stimulated by the comparative stimuli correlated with the total power of the eye and the back vertex (distance and power) from the ultrasonographic eye. However these findings may need to be tempered or modulated as there also exists a correlation between the area of the comparative stimuli and performance. Area is partially confounded with radial distance in the F/P CST.

A similar finding was that individual requirements for correction of the frontal-parallel plane by cyclorotation of the stimuli, and the red field-blue field difference scores in the F/P CST, correlate with axial length (and dioptric power) as measures of vitreous depth. These data suggest that the retina is not spherical within the radius of the parafovea as vitreous depth increases. Therefore chromatic aberration modified by total power and the length of the back portion of the eye modulate chromostereopsis. In addition, concentric and radially distance comparative stimuli of different wavelength than the stimulus in the foveola are modulated by the shorter distance to the parafovea. The adjacency of the stimuli is not as large a factor when 12 comparative steps are displayed as when two or three are to be discriminated.

RECOMMENDATIONS

The Phase I recommendations were confirmed: Chromostereopsis must be measured for each individual before stereoscopic performance with multi-hue imagery can be properly evaluated. More precision in measuring and setting interocular distance in instruments is warranted for chromatic but not for achromatic imagery. Foveola/Parafoveal comparisons with colored imagery extends the individual differences due to chromostereopsis. This appears to be related to elongation of the vitreous chamber and non-spherical aspect of the retina.

The adjacency hypothesis is less pertinent for display design when comparative stimuli have twelve steps compared with the displays using two or three stimuli.

PREFACE

This report was prepared by the Crew Systems Organization of the Guidance and Control Engineering portion of the Research and Engineering Division of the Boeing Aerospace Company, Seattle, Washington. The work was done under USAF Contract F33615-74-C-4037 for the Visual Display Systems Branch, Human Engineering Division of the Aerospace Medical Research Laboratory at Wright Patterson Air Force Base, Ohio.

Captain Frank Gomer, Ph.D., as monitor of this contract has contributed his considered advice and a detailed review for which the authors are most appreciative. Thanks are also due to Herman A. Hausle and James Geiger for their photographic skill and assistance; to S. J. Briggs, Ph.D. for his statistical advice; to Richard J. Farrell for his consultation and assistance in Badal alignment, and to Charles L. Elworth, Ph.d. for his discerning review and communicative counsel. The authors are also very appreciative of the special efforts of Barry E. Dunphy, M.D. and Robert E. Becker, M.D. of Boeing Central Medical organization. They not only arranged for, but made possible the participation of Dr. Racik, an Ophthamologist, for pre and post examinations and the administration of cyclogyl, pilocarpine and opthaine. Their efforts made possible our acceptance of Francis A. Young, Ph.D. and George Leary's FSMC offer to conduct retinoscopy, ultrasonography, keratometry and photographic ophthalmophakometry on our observers. George Leary then applied at Washington State University, his computer program to provide us with a complete set of eye measurements. To these individuals we are indebted for their altruistic support of this program.

Phase I of this program was reported by Anderson and Kraft (1977) in AMRL-TR-76-112, Development of a Precision Chromostereopsis Test and Test Equipment.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

SECTION I. INTRODUCTION

COLOR RESEARCH AND ITS APPLICATION

This research program is looking into the measurement of some characteristics of man's visual skills, especially his perception of color. Color in visual displays may facilitate the extraction of information through improvement in visual contrast, especially when luminous contrast is low. Less generally known is the possibility of using the color stereoscopic effect to add to the perception of displacement in binocular stereoscopic displays. Kraft and Anderson, 1973a, determined that an individual's target acquisition performance on moving strip color imagery could be predicted ($r = .81$) from scores on a chromatic, dynamic, stereoscopic test. However, this relationship is dependent upon the chromostereopsis of the individual, the saturation of the displayed colors, and many other parameters. It was the goal of this research program to determine some specific ways of utilizing color in displays to improve information extraction. Improved utilization of color technology would have an immediate and important application in extraction and transformation of pictorial reconnaissance data into intelligence.

CHROMATIC ABERRATION

The differential bending of light of different wavelengths causes chromatic aberration in optical devices and in the human eye. The control of chromatic aberration in optical equipment is an everyday affair for equipment designers. An almost complete elimination of chromatic aberration is possible by the addition of a special lens (Bedford and Wyszecki, 1957) but such lenses are not prescribed nor worn in general practice.

Chromatic aberration, however, has a special effect on the person viewing a stereoscopic display of saturated multi-colored patches of light seen against a black background. If the viewing instrument has oculars that may be moved laterally (as most instruments do to adjust for the individual differences in distance between the pupils) and the effective exit-pupil size is small in diameter (1 mm), the following may be seen: in/out movement of the oculars, for example first in the temporal direction and then toward the nose, will be associated with a perceived Z-axis motion of the different hues in the display. That is, if the display scene is a line of colored discs seen against a dark field, the temporal-nasal alternation of the oculars induces a perceived motion like pistons in an automobile engine when viewed from above. When moving the oculars from a temporal to a nasal position, the long wavelength hues recede as the short wavelength hues advance, and conversely, the direction of the apparent motion is reversed. The apparent magnitude of the Z-axis motion is a function of individual differences in chromostereopsis, the saturation of the colors and the amount of movement of the oculars.

CHROMOSTEREOPSIS

The term "chromostereopsis" (Vos, 1966) refers to the illusion of differential depth experienced with binocular viewing of variously colored patches on a single frontoparallel plane. The phenomenon has been known for many years by students of vision (Bruecke, 1844), and described as

"Stereoscopie durch Farbendifferenz" (Einthoven, 1885), as "Farbenplastik" (Peucker, 1898), as "retreating and advancing colors," (Luckiesch, 1918), or as "Farben Stereoskopie" (Liesegang, 1944). Several authors have advanced similar theories to explain the phonomenon and the general extent of its influence (Rosch, 1954; Vos, 1960; Kishto, 1965).

In 1972, Kraft, Booth, and Boucek reported a study of depth discrimination with chromatic and achromatic stimuli. The results were consistent with the theory that chromostereopsis is a result of the differential dispersion of colored light. This dispersion is imposed by the chromatic aberration of the human eye, and its magnitude and direction are individualized by the combined effect of eye angles and eye axes. These individual differences were used to separate the observers into three groups: a small neutral representation, and two larger but equal groups, one seeing long wavelength colors nearer than short wavelength colors, and the other group seeing the converse.

The 1973 (AMRL-TR-73-36) study of Kraft and Anderson found similar individual differences in the direction of chromostereopsis and both investigations found about 18 percent loss in performance on a chromatic stereoacuity test, as compared with the test's achromatic version. This decrement encouraged the authors to recommend that chromostereopsis be measured for each individual before stereoscopic performance with multi-hue chromatic imagery is evaluated.

Later the same year (1973, AMRL-TR-73-104) Kraft and Anderson developed a quantitative test for chromostereopsis and administered it to sixty-three individuals. This test only partially predicted ($r = +.65$) the difference between these individual's achromatic and chromatic stereoscopic skill. A factor of accommodation insufficiency may have contributed to this incomplete prediction, but the authors were of the opinion that limitations in the chromostereopsis test may have been the larger contributor. Improvement in the control of accommodation, the quality of the chromostereopsis test, and in matching the separation of the interoculars to the interpupillary distance should significantly improve the measured correlation.

Owens and Leibowitz (1974) added data to the question of the importance of knowing more about chromostereopsis and its relevance to the use of binocular instruments with typically small exit pupils. They concluded: "Under such condition, the size of the illusory depth effect resulting from chromostereopsis not only represents a strikingly large error, but also can be expected to vary with slight changes in the interpupillary distance settings of the instrument. This represents a very real problem for optical instrument design since:

1. Small variations in interpupillar distance result in large changes in chromostereopsis; and

2. Few of the presently available instruments make provision for accurate setting of interpupillary distance."

THE ROLE OF PERIPHERAL AND PARAFOVEAL VISION

Leibowitz and Johnson (1975) have developed the role of the visual periphery as follows: Considerable attention has been directed in the visual literature to the fovea because of the marked superiority of form, resolution, motion and color sensitivity of this central portion of the retina. However, the fovea represents only a small fraction of the total receptive area of the retina (2%). The function of the periphery, as well as its anatomy and physiology, is different from that of the fovea and the role of the periphery and fovea are complementary. Peripheral stimulation triggers eye movements, resulting in foveal fixation. It is widely recognized among clinicians that the integrity of the peripheral visual fields is essential to the optimum functioning of the visual system. Perimetric examinations play a major role in ophthalmology, neurology and optometry. Peripheral vision is a major factor in situations where large areas must be monitored, such as driving a car, flying, or visual inspection in industry.

Two Modes of Processing Visual Information

In the late '60s, a group of neuroscientists in the Boston area suggested a model of visual function based upon two modes of processing information ("two visual systems"), (Ingle, 1967; Schneider, 1967; Trevarthen, 1968; Held, 1968; Humphrey, 1974). They distinguished between a system which analyzes form and contour, is predominantly foveal, and mediated by cortical mechanisms, from a localization system which is predominantly peripheral and mediated by sub-cortical mechanisms. In effect, these reflect separate modes for answering the "what" as compared with the "where" of visual stimulation. This dichotomy is relative rather than absolute and provides a heuristic conceptual model for classifying visual function.

An excellent example of the "two visual systems" concept was reported in separate studies on residual vision among brain damaged humans (Poppel et al, 1973; Sanders et al., 1974). When tested with conventional perimetry, these patients with cortical brain damage showed marked scotomas. However, when they were asked to localize stimuli within the scotomatous regions by means of eye movements, they were able to do so quite accurately. This apparently paradoxical result can perhaps be best understood within the context of the "two visual systems" concept. The "where" system, which is closely coupled with motor mechanisms, remained intact; the "what" system, as reflected by a verbal report process, was relatively nonfunctional.

These data, which were preceded by extensive elegant studies in experimental animals, suggest that accurate assessment of visual function depends upon which mode of visual processing is being evaluated.

Since mobility depends on a function localization system, it may not be appropriate to evaluate this system by verbal report. Rather, a measure based on eye movements, pointing or some non-verbal response would be more relevant and valuable. Indeed Held and his colleagues have dramatically demonstrated behavioral differences in several perceptual functions depending upon the measuring technique, i.e., verbal response vs. motor localization (Held, 1968).

During World War I, the neurologist Riddoch (1912) suggested that cerebral damage selectively impairs the ability to discriminate stationary objects in the periphery, without influencing the appreciation of peripherally presented moving stimuli. Putting aside for the moment the neurological issue as to whether the "Riddoch Effect" is specific to occipital lesions (Zappia et al., 1971), it is heuristic to note the rational thread which appears to be running through a number of studies. The effect of correction of peripheral dioptrics, psychophysical studies of normal and brain-damaged adults, and ablation studies with experimental animals all seem to fit nicely into the two modes of processing, or the "two visual systems" concept. If the functional difference between identification or "what" on one hand, as compared with localization or "where" on the other hand, is viable, it would provide a convenient way of looking at visual function and its deficiencies and provide a rational basis for improvement.

The functional role of peripheral vision is well recognized among sports medicine specialists and athletic coaches. The contribution of the periphery to skill performance has been pointed out by coaches in such sports as basketball, soccer, football, tennis and badminton. The superior ability in use of peripheral vision is an attribute of the skilled athlete.

Burg (1968) studied extensively the visual factors in automotive safety, determining visual fields for more than 10,000 California drivers. Visual field size declined as a function of age after 40, as would be expected from other age related physiological factors. More unexpected was a continued increase in visual field sizes after age 16, continuing into the mid-thirties as though a learning process was more than compensating for the opposite influences of aging. Other examples of learning with respect to peripheral stimulation are easy to find. For example, one is size constancy, which permits us to judge the correct sizes of objects in spite of the variations in retinal image sizes as a function of changing distances. For distant objects, beyond the range of useful oculomotor adjustments, it is essential in adults for size constancy, that the peripheral visual fields be simultaneously visible. If for any reason the peripheral stimulation is blocked off, size constancy for distance objects is lost. In this state of temporary deprivation of peripheral stimulation, the size constancy function of adults is very similar to that of children. The similarity would suggest that children have not yet learned to use the peripheral mechanisms subserving size constancy. The learning of size constancy is extremely slow and is only complete at the time of adolescence.

THE ROLE OF THE PARAFOVEA

The newer convention (Polyak, 1941) of subdividing the retina into seven regions designates the parafovea as region II. This is roughly a circular belt of approximately 500 microns in diameter. The inner edge begins at the edge of the foveola (diameter 1.4°) and extends outward to 8.6°. In the parafovea the rod and cone layer (designated layer 2) is reduced to the thickness that is retained throughout the remainder of the retina. The rod-free area of the foveola is centered on the visual pole of the eye and does not reach the inner edge of the parafovea. However, region I of the central area, called the fovea, extends to 5.2° and overlaps region II, from 1.4° to 5.2°. The parafovea is distinguished by the greatest accumulation of nerve cells in the entire retina, especially of inner nuclei and ganglion cells. The parafovea is in turn encircled from outside by region III, the perifovea. Region III extends from 8.6° to 19.0°. In the anatomical sense the fovea, parafovea, and perifovea regions constitute the central area of the retina. The "true" peripheral area begins at 19°, and is termed the near periphery. The middle periphery begins at 29° and the far periphery at 50°.

Although a basketball player will use the near to outer edge of the far periphery in his sport, the man who uses optical aids such as stereoscopes and microscopes is most frequently limited to 20 degrees or less of the visual field. A microscope with a 5° field limits man's vision to the fovea and the AO Wottring Troposcope used by this contract has a 20° field which just extends to the outer edge of the parafovea with central fixation.

The observers participating in the 1972 and 1973 data collections on stereoscopic skill with color imagery, frequently reported the impression that the disparity of the displaced disc was more easily perceived when its image was located in the parafoveal regions of the retina. In addition, when they changed their visual fixation to these targets, the apparent height diminished. These observations are in contrast to what would be expected from the data of Rawlings and Shipley (1969). Their data indicate that a rapid increase in the stereoscopic threshold occurs as the distance from the line of fixation increases. Their stimuli were two, one-minute sources of light in a dark field, and the observer was asked which of the two peripheral stimuli was nearer the eye. This was a parafoveal/parafoveal judgment even though a central fixation point was provided. Their three observers averaged about 15 times increase in threshold when these stimuli were 8 degrees off the fovea. With this rapid decrease in stereoscopic sensitivity, one would expect to perceive small differences in stereoscopic height only as one fixates the image with the small stereoscopic displacement. The Rawlings and Shipley data and our observers comments are therefore not compatible. The question then is, what is the role of the parafovea in depth perception? The large increase in threshold as they measured it may be in part due to the small size of their stimuli and the minimal amount of visual detail for a comparative judgment. Stereoscopic discrimination is always a relative judgment. The absolute judgment of the distance to a single point-source of light, in a totally dark field, has almost no precision. In contrast, in a structured visual field, stereoscopic discrimination is extremely precise.

In the critical limen stereoscopic tests the visual field is very structured and all the physically displaced stimuli are surrounded by adjacent comparative stimuli. With this test the following events pointed to good parafoveal discrimination: (1) The frequency with which the experimenters noted erroneous answers were the correct answers in the adjacent rows; (2) The high frequency of the observers comments about seeing a displacement when it was off the visual axis but not seeing it when they fixated this particular disc; and (3) A higher frequency of both of the above observations occurring with the chromatic test compared with the achromatic test.

The paradox of low parafoveal discrimination with small stimuli and minimal field texture and the comparatively high parafoveal discrimination with highly structured fields particularly when they include color, appeared to be worthy of further investigation.

SECTION II

THE PROBLEM

The goals of Phase II of this three-phase contract were:

- To develop a test to measure parafoveal stereoacuity.
- To develop a test to measure parafoveal/foveal chromostereopsis.
- To conduct an experimental investigation using the test or tests mentioned above, the ARC chromostereopsis test, and the Critical Limen Stereoscopic Tests, to compare visual performance.
- To continue to develop and evaluate special equipment for the measurement of interpupillary distance, intervisual axes distance and pupil size. This intermediate step is necessary to resolve some anatomical, physiological and behavioral relationships.
- To determine some of the relationships among performance measures of chromostereopsis, stereoscopic acuity and the refractive and physical measurements of the eye.

SECTION III. METHOD

THE EXPERIMENTAL APPARATUS

Rotation Adjustment in Wottring Troposcope

Two pieces of equipment used in previous investigations were also utilized in the present study: the AO Wottring Troposcope and the 381mm focal-length Badal Optometer.

The troposcope was used for the presentation of the ARC and F/PCST chromostereopsis tests and for a measure of cyclophoria (the resting state of cyclorotation of the eyes around the visual axes). Since it was hypothesized that the "layback" effect detected in previous administrations of the ARC test might be due either to some natural cyclorotation of the eyes, or to image rotation introduced by instrument misalignment, or to the intentional rotational adjustment of the slide holders in the troposcope by the observer, additional alignment and calibration procedures were developed. Horizontal line gratings with a spatial frequency of 75 cycles per inch were made on Kodalith film and cut to fit in the slide holders with a horizontal error between the grating and the slide holder of less than .004 inches in a distance of 3.25 inches (rotational error of less than 5 minutes of arc). With the line gratings in the slide holders, the illumination sources were turned to their maximum level and the two optical paths of the troposcope adjusted to be slightly divergent. Back projections of the line gratings formed conjugate images on a construction board "screen" attached to a wall at 2.5 meters distance. Through alternating illumination of the slides, each slide holder was levelled with the aid of a builder's level. Simultaneous projection of the two line-gratings showed no perceptual rotational deviation. A second target, consisting of a circle with a vertical bar, (the cyclophoria test stimulus) was then introduced and the troposcope images vertically aligned on the wall. The slide holder rotation indicators were then reset to "zero."

The Badal Optometer

The Badal optometer, as modified for a previous investigation provided control over convergence, accommodation, illuminance and hue. This modification included an adjustable base on which the right-hand 45° mirror was mounted allowing continuous adjustment of intermirror separation for the measurement of intervisual axes distance ($\pm$ 0.05mm) while maintaining parallel visual paths to the "targets." This accuracy (compared to the commonly utilized interpupillary distance) was found to be critical in the determination of chromostereopsis.

Because the optical bench which supported the Badal optometer and associated equipment was not as massive as would be preferred, disturbances such as vibration and accidental slight bumping, when combined with some small but significant variations in the bench fittings, made the alignment and calibration procedure extremely difficult and time consuming. Relocation of the Badal optometer to a new laboratory presented an opportunity to acquire a Boeing-owned 1.6 meter Gaertner optical bench and fittings. (Funds to initiate reconstruction of the Badal optometer were provided by the contractor's facilities organization as a part of the relocation request.) A different base for the optical bench proved to be very stable and permitted a more efficient alignment procedure with increased operational flexibility. Several modifications to increase flexibility and sensitivity eliminated some minor difficulties with the previous equipment. These changes are detailed in figure 1.

Twin Adjustable Mirror Mounts

The Phase I version of the Badal optometer had one stationary and one adjustable mirror mount. A second adjustable mount was incorporated to allow dual adjustment of the inter-mirror distance, thus allowing stationary head positions during the operational phases. Special measurement scales were made on Cronograph film to allow the setting of inter-mirror distances with identical readings of the separation on the scale on each adjustable mount.

Artificial Pupils Holder

With the design for stationary head positions, it was desirable to remount the artificial pupils holder from the adjustable bite-board mechanism to a centralized, fixed position. This was accomplished by the drilling of both registration holes and tapped holes for clamping of the holder onto the two mirror bases.

The registration holes allowed the removal of the artificial pupils holder for the photographic work required to record the interpupillary and interreflections distances and remounting of the holder without any significant change in position. Artificial pupil separation settings and measurements were also provided for by the use of "double" scales on Cronograph film for each artificial pupil. These scales provided measurement accuracies of .1 mm through the utilization of associated vernier scales.

Bite-Board Mechanism

The Gaertner optical bench and support stand necessitated the elevation of the adjustable mount for the bite-board. An aluminum plate 5/8 inch thick was employed to raise the mount mechanism. The position of the mount also required a 4-inch longer extension bar from the Z-axis micrometer to the bite-board itself. With the new design, the mount for the bite-boards provides precise adjustment for head position in three axes in order to bring each observer's eyes into the same relative alignment position.

Development of Target Holders

In the earlier optometer design, the alignment targets or stimulus materials were held in slide holders attached to the DeJur Enlarger light housing illumination sources. This made vertical and horizontal adjustment of the targets (as required in normal alignment

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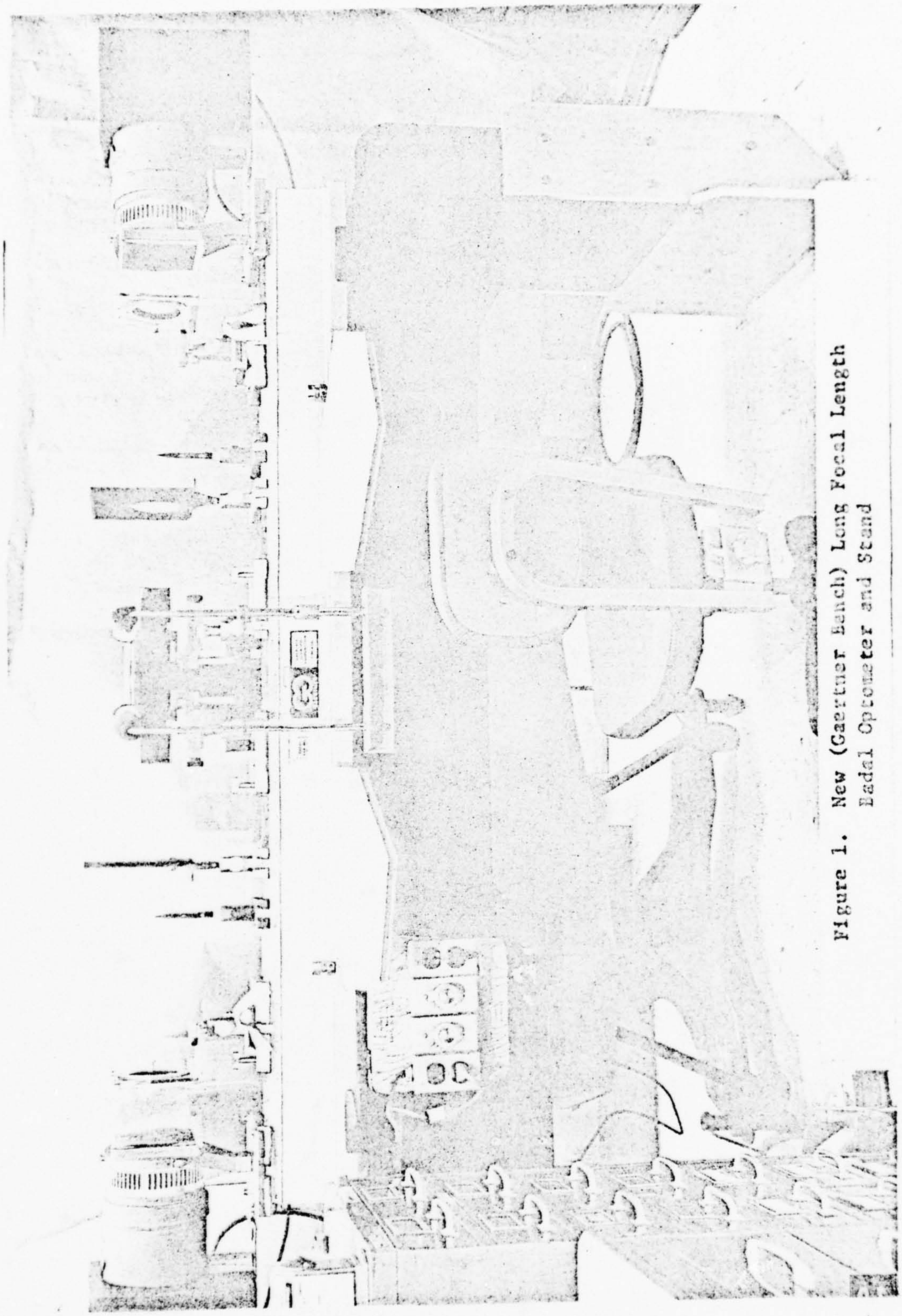

Figure 1. New (Gaertner Bench) Long Focal Length Badal Optometer and Stand

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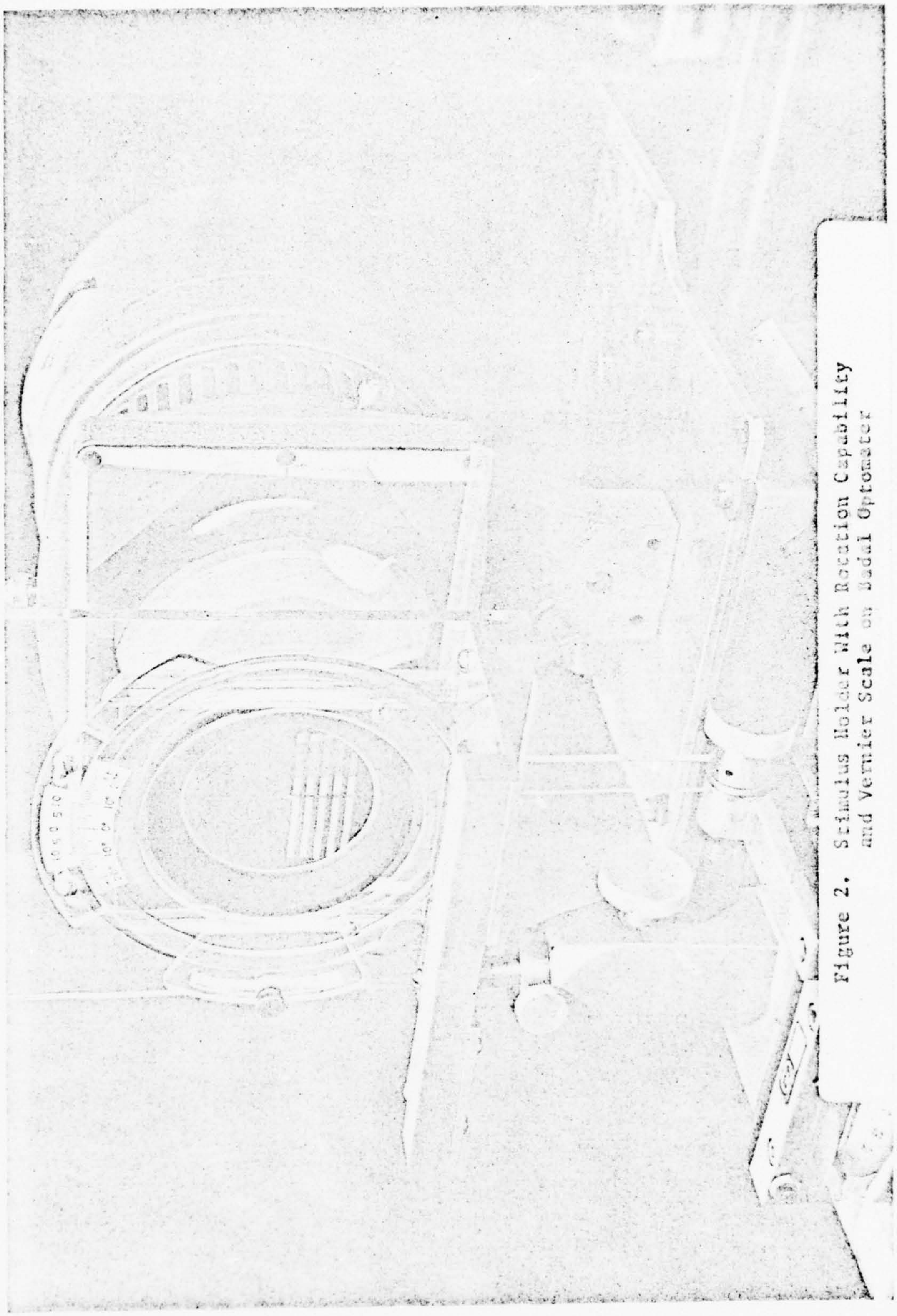

Figure 2. Stimulus Holder With Rotation Capability and Vernier Scale on Badal Optometer

procedures) difficult and did not provide for calibrated rotation of the stimulus material nor for the stacking of color filters and masks along with achromatic stimulus materials. For the new setup, bench mounts with X-axis adjustment were utilized and new stimulus material and color mask slide holders were constructed out of plexiglas. The new holders will accommodate two slides with single or stacked stimulus materials, targets, or color masks. The slides can be rotated 20° in either clockwise or counterclockwise directions, with rotation secured by a lockdown thumbscrew. Circular scales were photographed on Cronograph film and attached to each holder, with the vernier (in units of .1°) mounted on an adjustable arc of plexiglas to permit a precise setting of "zero" rotation. A small extension handle provided ease and increased precision in making rotational adjustments or settings **(see figure 2)**.

The Illumination Sources and Cooling Fans

In the previous optometer setup, a slight but noticeable vibration could be felt at the bite-board, although it did not seem to affect the visual tasks. This vibration was traced to the two muffin fans used to provide cooling air through the DeJur illumination sources and which were attached to the rear of the source's cushioned brackets. In the rebuilt apparatus, the mounting plates for the illuminators were replaced with larger ones that extended to the rear of the **DeJur sources**. An open-cell foam block measuring 9 in. x 10 in. x 6 in. was cut and fitted to the rear of each illuminator so that it would rest on the mounting plate, and a 5 in. x 5 in. window was cut out to accommodate the muffin fan. This proved very effective in reducing the transmitted vibration to an insignificant level.

Chin/Head Support Device

Although the bite-board had proved to be an excellent method of obtaining a spatially fixed visual system for each observer during experimental testing, a more flexible, simpler, and quick method for head restraint was needed for use in alignment and pre-testing procedures and for demonstrations of the Badal optometer. To this end, an adjustable chin-rest/forehead-restraint device was mounted on the front of the optical bench support stand. It was found, in fact, that with the addition of some side padding to the forehead-restraint bracket, this method of head positioning and restraint was adequate enough to give IBXD measurements with standard deviations in the range of .07 to .26mm. In an effort to further stabilize head position and to make the observer more comfortable; thereby reducing fatigue factors, padded elbow rests were also constructed and attached to the optical bench support stand **(figure 3)**.

THE BADAL OPTOMETER ALIGNMENT PROCEDURE

The basic requirements and procedure exchange for aligning the Badal optometer have been outlined in detail in the report on Phase I of this research effort (ref. 1). As mentioned earlier, the Gaertner bench and Substantial Support Stand resulted in more efficient alignment efforts. The procedure was also simplified by the utilization

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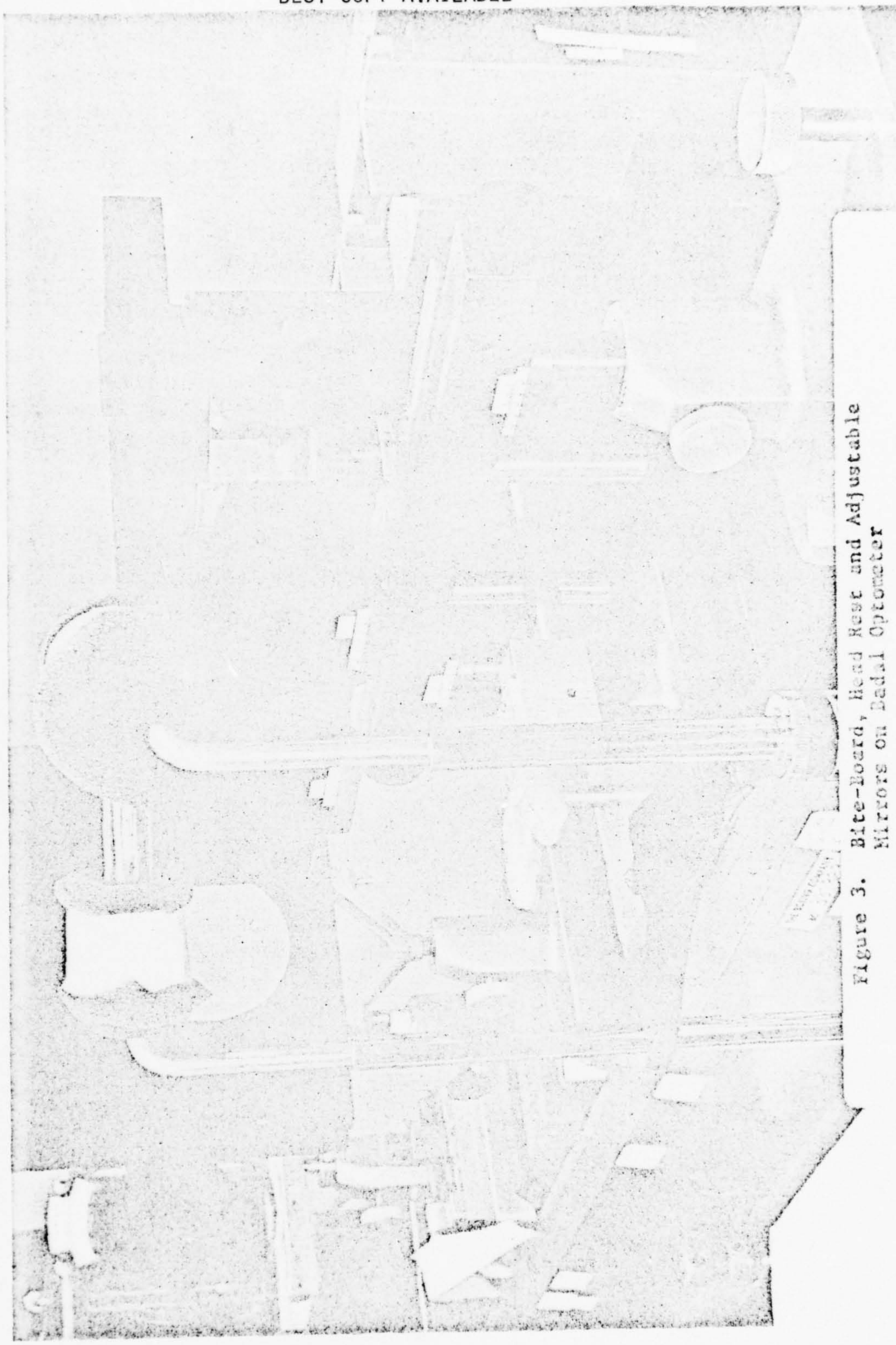


Figure 3. Bite-Board, Head Rest and Adjustable Mirrors on Badal Optometer

of additional equipment as detailed in the following paragraphs.

The Badal principle is based on placing the observer's eye at the focal point of the positive lens, 381mm in this case. With this placement, targets can be moved from just beyond the lens (at about 2.2 Diopters) all the way to optical infinity with no change in the visual angle subtended by the target. For the Badal setup with the Gaertner optical bench as utilized in this phase of research, the target holders were positioned at .2 Diopters to avoid the difficulty many people have of focusing objects set at optical infinity.

The "zero rotation" or null point for the two slide holders was established in the same manner as for the troposcope, i.e., by back projecting the image of a line grating onto a "screen" set several meters away and on which the "horizontality" of the grating could be ascertained. Again, both individual and simultaneous projections of the gratings from the two slide holders were utilized to achieve the smallest rotational error possible between two.

A single laser alignment technique, as compared to the dual-laser method utilized in the Phase I setup, was made possible by the use of a Roof-Penta prism and a Dove right-angle prism. The 2 milliwatt laser was positioned at one end of the optical bench and aligned with the bench by moving a single cone-shaped pointer back and forth on the bench, and adjusting the lateral position and direction of the laser beam until its intersection with the tip of the pointer remained constant over the entire length of the optical bench. With this accomplished, and with the pointer at the far end of the bench, the other elements of the system were added one at a time in the following order, and adjusted to maintain the correct laser beam to pointer tip intersection: first the other pointer, then the two 381mm lenses, and finally the two slide holders. Two slides were made up with targets consisting of a series of concentric rings on film with a small "+" in the center. These targets were very carefully mounted and the slides affixed in the slide holders as alignment targets.

With these elements aligned, the Roof-Penta prism was placed at the approximate location of the right-hand 45° mirror and a Dove prism (used as a right-angle prism) placed out in front of the bench at a distance of about 1 meter. Figure 4 illustrates this alignment configuration, with the position of the two 45° mirrors also shown along with the desired path of the laser beam. Since the Roof-Penta prism provides a 90° deflection of the laser beam within a wide rotational range, it reduces the need for a critical and difficult procedure to achieve this necessary condition. Thus it was a relatively simple matter to adjust the Dove right-angle prism to reflect the beam back at the same elevation and at an appropriate separation distance. The left-hand mirror and mount were placed on the bench at a point dictated by the average IPD of the observer population (64mm) and by the design of the adjustable mirror holder aligned with the bench axis. Then with the laser on, the mirror was rotated until the desired alignment image was obtained at the left-hand target holder and the mirror locked down. Next, the Roof-Penta prism was replaced with the right-hand mirror and mount and the same

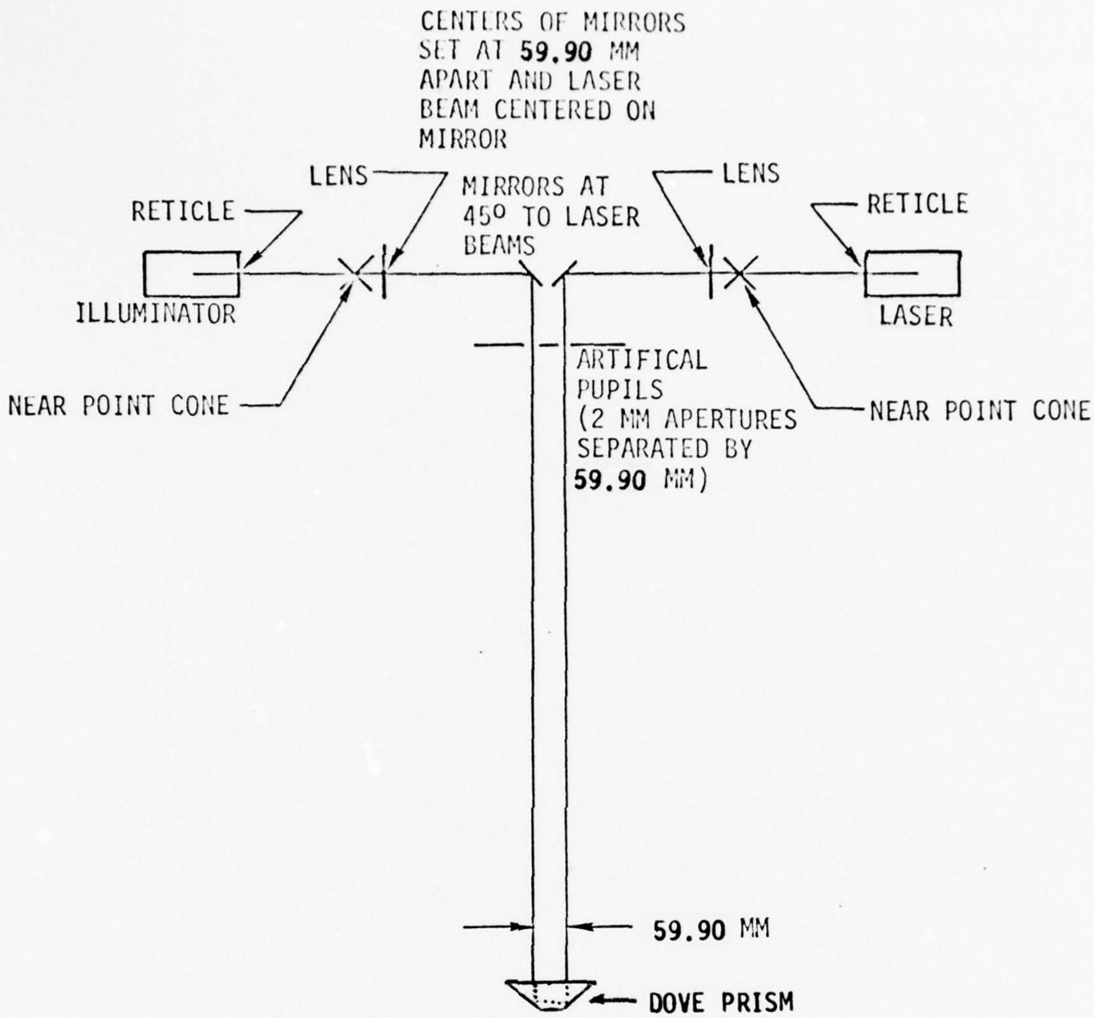


Figure 4. Plan View of Badal Alignment Procedures

procedure followed to acquire the desired 45^{o} rotation of this mirror. At this point the separation of the laser beam as it enters and exits the reversing prism was carefully measured using adjustable artificial pupils and precision calipers, and the Cronograph scales attached to the proper locations on the mirror translator mechanisms. Finally the artificial pupils holder was mounted, the pupils lined up on the laser beam, and their alignment verified by turning the laser off and visually checking the alignment by centering on the artificial pupil and observing the alignment of the pointer and the target in the slide holder. With this verification, the Cronograph scales were attached to the artificial pupils and holder at the appropriate locations. This completed the alignment procedure for the Badal optometer.

THE FOVEOLA/PARAFOVEA CHROMOSTEREOPSIS TEST

This test was developed as both a complement to the concentric circle test and a potential improvement of the initial development. The concentric circle test elicited comments from our observers about the outer circles being further from the disc were deemed more difficult to assess than the smaller circles. The Gogel "adjacency principle" would support such comments. However, a series of rings has the advantages of sampling narrow bands in the parafovea and also avoiding the cyclorotational resting state bias that may be causing the "lay-back" effect in the ARC test.

The new form of the foveola/parafovea test was designed to give specific distances between the comparative stimuli and different areas of stimulation. The physical parameters were designed to conform to topographic features of the retina.

The subdivisions of the primate retina according to Polyak (1941) are seven regions that extend from the axial center to the anterior retinal boundary. These are shown in the following table.

TABLE 1
SUBDIVISIONS OF THE PRIMATE RETINA

			Diameter	Diameter	Radius
I.	Central fovea	Foveola	400μ	1.4°	0.7°
		Central fovea	1,500μ	5.2°	2.6°
II.	Parafoveal region		2,500μ	8.6°	4.3°
III.	Perifoveal region		5,500μ	19.0°	9.5°
				(Limit of Troposcope)	
IV.	Near periphery		8,500μ	29.0°	14.5°
V.	Middle periphery		14,500μ	50.0°	25.0°
VI.	Far periphery		40,000μ		
VII.	Extreme periphery		44,000μ		

New stimulus materials were developed and photographed with the Borrowdale camera to make four different formats and three step intervals of the "circular staircase" test. The circular staircase name arises from the pattern match with a "birds-eye" view of a circular staircase. A staircases' center pole, seen from above, would appear like the central disc (foveola stimuli) of the test, see figures 5 - 8. The twelve parafoveal stimuli look like the treads of a circular staircase when viewed from above. The similarity is even more striking when the pattern is seen as three dimensional with the steps rising unit-by-unit in a clockwise direction. The physical model that was developed to make Form II of the CLST test, with the primary dimensions of the spacers used in the ARC chromostereopsis test, was used in the photography. The truncated "pie shaped" wedges were 1/6" thick aluminum sheets painted with aluminum paint and then a diffusing coat.

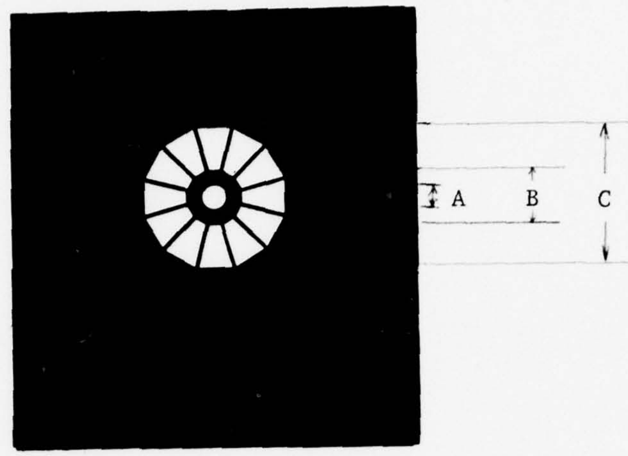


Figure 5. Circular Staircase Chromostereopsis Test

Foveola / Fovea

A	=	Central Disc's Diameter	54.9 min of arc (In Troposcope)
B	=	Inside Diameter of "Stair Treads"	2.24°
C	=	Outside Diameter of "Stair Treads"	5.54°

Areas:

Central Disc	8.53 mm^2	(On slide)
Of 12 "Stair Treads"	211.3 mm^2	

Stereoscopic Displacement: [Stereoscopic height between Treads]

"18" Series	22.6 arc seconds
"36" Series	11.3 arc seconds
"72" Series	5.54 arc seconds

(In Troposcope)

Adjacency: [Angular separation between edge of central disc and nearest edge of "Stair Treads"]

All Series	39.8 arc minutes

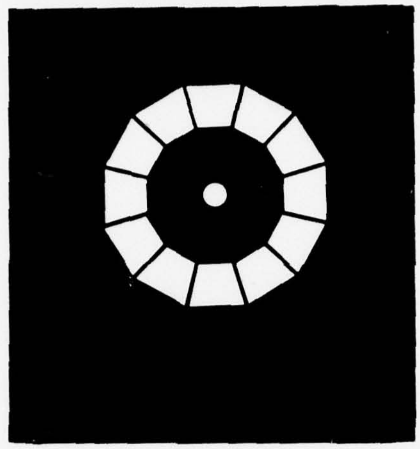


Figure 6. Circular Staircase Chromostereopsis Test [Foveola / Far Parafovea]

A = Central Disc's Diameter		54.9 min. of arc (In Troposcope)
B = Inside Diameter of "Stair Treads"		5.54^{o}
C = Outside Diameter of "Stair Treads"		8.81^{o}
Areas:	Central Disc	$8.53\ mm^2$ (On Slide)
	Of 12 "Stair Treads"	$431.3\ mm^2$

Stereoscopic Displacement: [Stereoscopic height between treads]

"18" Series	22.6 arc seconds
"36" Series	11.3 arc seconds

Adjacency: [Angular separation between edge of central disc and nearest edge of "Stair Treads"]

Both Series	138.8 arc min.

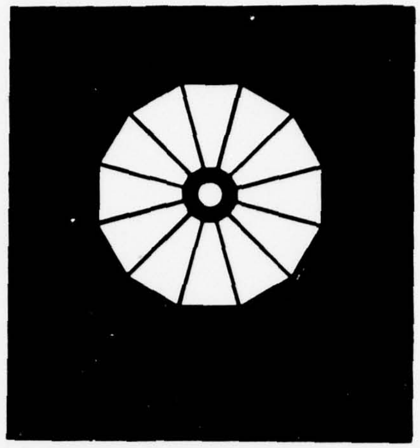


Figure 7. Cricular Staircase Chromostereopsis Test [Foveola/Parafovea]

A = Central Disc's Diameter — 54.9 min. of arc (In Troposcope)

B = Inside Diameter of Stair Treads — 2.24^{o}

C = Outside Diameter of Stair Treads — 8.81^{o}

<u>Areas:</u> Central Disc — 8.53 mm^2 (On Slide)

Of 12 "Stair Treads" — 643,4 mm^2

<u>Stereoscopic Displacement</u>: [Stereoscopic height between treads]

"18" Series — 22.6 arc seconds

"36" Series — 11.3 arc seconds

<u>Adjacency</u>: [Angular separation between edge of central disc and nearest edge of " Stair Treads"]

Both Series — 39.8 arc minutes

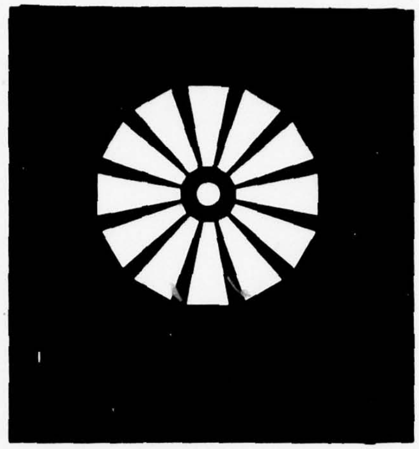


Figure 8. Circular Staircase Chromostereopsis Test [Foveola/Parafovea]
[Common Center Truncated Arcs]

A = Central Disc's Diameter	54.9 min. of arc (In Troposcope)
B = Inside Diameter of Stair Treads	2.24^{o}
C = Outside Diameter of Stair Treads	8.81^{o}

Areas:

Central Disc	$8.53\ mm^2$ (On Slide)
Of 12 Stair Treads	$531.2\ mm^2$

Stereoscopic Displacement: [Stereoscopic height between treads]

"18" Series	22.6 arc seconds
"36" Series	11.3 arc seconds

Adjacency: [Angular separation between edge of central disc and nearest edge of "Stair Treads"]

Both Series	39.8 arc minutes

Sizes of Arcs:

"Stair Treads"	21.2^{o}
Inter Tread Space	8.69^{o}

All photographs were made with the 9 o'clock step as the lowest and the 8 o'clock step the highest. The stereobases between the right and left eye were achieved by physically moving the whole model to the right and left of camera centerline. The three stereobase distances provided series "18", "36", and "72" with the interstep intervals of 22.6, 11.3 and 5.65 arc seconds.

These step by step stereoscopic displacements are twice as large as the "response steps" given in Appendix III as half-step responses were requested of the observers. The initial photographs were done on high contrast milar-based orthochromatic film, then printed by contact exposure on the same material to give the positive transparencies **illustrated in figures 5 to 8. The photographic reduction was at a scale of 15.563 times smaller than real** model. The following table gives the physical sizes on the film as measured with a Mann-Comparator Model 1945, Serial 9146 x 10, with magnification set at 60X.

TABLE 2.

FOVEOLA/PARAFOVEA CIRCULAR STAIRCASE CHROMOSTEREOPSIS TEST STIMULUS MODEL SIZES AND TROPOSCOPE IMAGE SIZES

(Reduction Ratio 15.563X)

	Physical Model	As Displayed In Troposcope
Index to Index	860.425 mm	14.95°
Disc (Foveola) Diameter	51.5 mm	54.94 arc min
Radius to Inner Step Edge	63.5 mm	67.75 arc min
Radius to Outer Edge 1/2 Field	157.0 mm	2.79°
Radius to Outer Edge Full Field	2480. mm	4.402°
Maximum Radius with Gap & Full Step	253 mm	4.490°

There were four formats made which would be used as achromatic stimuli, and which, when stacked with special color filters, could also be used as chromatic stimuli.

The Foveola/Fovea formation of the "stair treads" had an inside diameter of 2.24° and an outside diameter of 5.54°. Therefore, the off-axis stimuli are beyond the foveola and extend just beyond the edge of the fovea. The central disc is well within the foveola and is 5 arc minutes smaller than the diameter of the rod-free area. The adjacent edges, outer disc edge and inner "stair tread" edge (see figure 5) are separated by 12.4 arc minutes. Of this format, there are three stereoscopic pairs, F, B and A. The disc matches the height of the 1 o'clock step in F, the 2 o'clock step in B and the 3:30 o'clock step in A. This is shown as the zero position in the data sheet found in Appendix III.

The Foveola/Far Parafovea set, seen in figure 6, is the same as the Foveola/Fovea set with the exception that the "stair treads" extend in diameter from 5.54° to 8.81°. Therefore, the off-axis stimuli do not include the fovea but only the external half ring of the parafovea. The area of stimulation is larger in this set by a 2-to-1 ratio compared with the 2.2 to 5.5° "stair treads." The adjacency aspect has become 112.5 arc minutes and this factor may increase the variability of the observer's judgement.

The third set, called the Foveola/Parafovea set has "stair treads" which cover almost all of the parafovea. The area is three times larger than the Foveola/Fovea set and the adjacency of the disc to the tread is the same at 12.5 arc minutes. See figure 7 for the appearance of this set.

The fourth set (figure 8) is also a Foveola/Parafovea test, however, the "stair treads" or parafoveal stimuli are constructed to have a common center, and equal angular size (21.2°) and inter-tread space of 8.69°. If area of stimulation is important, the two 2.2 to 8.8° sets should differ in performance.

The color filters were made from Ektachrome Professional Color film, 2-1/4 x 2-1/4 inches in size. For half of the filters, the background was blue and a central area just larger than the foveal disc (1.5°) was red. The field and disc colors were reversed in the other half of the filters. These were made by translighting Wratten filters with 5500 K illumination and copying with a 4 x 5 camera fitted to hold roll film. The two Wratten filters were modulated with neutral density film to give similar apparent brightness in the finished product when translighted in the Troposcope with Wratten 87 filters raising the color temperature of the conventional troposcope sources.

Two sets of all films were made. One for delivery to the U.S. Air Force and the second for the performance research at Boeing.

CYCLOROTATION TEST DEVELOPMENT

Background

The Phase I report of this research effort indicated a curious rhythmic response pattern to the ARC test. This pattern was dubbed the "layback" effect in alluding to the only consistent perceptual phenomenon of the effect, i.e., that in comparing any two rows of discs in the test, the top row was perceived as being set further back (away) than the bottom one relative to their true locations. This effect was fairly consistent for both achromatic and chromatic stimuli and dictated that the difference scores (chromatic score minus achromatic score) be used as the measure of chromostereopsis. This effect was consistent for 11 of the 12 observers who took the ARC test.

During continuing exploratory work with the ARC Test, it was noticed that contra-rotation of the images in the slide holders of the troposcope seemed to have an effect on the perceived crossover point (answer) in the test, although little or no tilting of the overall field was observed. The initial study of this effect showed that a combined excyclorotation (right image counterclockwise and left clockwise) of 3° or 4° was enough to reverse one observer's "layback" effect on one format of the ARC test, while encyclorotation exaggerated the effect. Careful observation of the whole ARC test field while rotating the images seemed to indicate a tilting of the entire field. However, when rotation was stopped, even at several degrees, a tilting of the entire field was perceptually at a minimum although large shifts in the relative depth of adjacent (vertically) discs were obvious. It is possible that size and shape constancy of the image tends to minimize the perception of tilt in the entire non-continuous field, while still allowing a depth displacement between two adjacent discs or rows of discs.

That cyclorotations of stereo pair images (or cyclophoria) can cause "erroneous" depth perception has been known for some time (Cibis, 1952), and over a century ago Nagel observed cyclofusional eye movements as they occurred in response to horizontal lines in a stereoscope being rotated in opposite directions (Nagel, 1868). However, two things were surprising. First, that cyclotorsion or cyclorotation could cause disparity shifts between vertically adjacent discs (or rows) in the ARC test of 48 ARC seconds (not an extreme case) without the observer's awareness (mention) of any field tilt (which, at 48 arc sec per row pair, would equal 432 arc seconds from top to bottom, not counting the column numbers); or secondly, that the effect would occur when the images (and the instrument) were supposedly set at "zero" rotation.

Procedure for Measuring Cyclotorsional Resting State

In order to determine whether the observers had cyclotorsional resting points that deviated from the true rotational zero, a test stimulus was devised which consisted of a circle (or ring) with a vertical bar bisecting it and extending slightly beyond the ring. The design shown in figure 8, was made at 15 times final size on Ruby Studnite and photographically reduced onto Kodalith (achromatic) film. Two identical copies were made and very carefully mounted on slide frames.

When the Circle/Bar test stimuli are viewed stereoscopically, and the images rotated in opposite directions, the perception is of the circle remaining in the vertical frontal plane while the bar tilts. The top of the bar tilts toward the observer and the bottom of the bar tilts away when the left image is rotated clockwise and the right image counter-clockwise. Reversing the direction for each image rotation reverses the tip of the bar. The effect is very strong and fusion can be maintained even up to near-perpendicularity between the circle and the bar.

Alignment of the stimuli on the slides was achieved by sandwiching the two images/slides together in one side of the troposcope and then, while observing through the lens in this arm of the instrument, moving the slides back-and-forth relative to each other. This results in the vertical bar going from being completely blacked out to a barely perceptible line - to its full width - and then decreasing in width again until it disappears. Misalignment of the two images results in a wedge shaped vertical bar, and adjustment was made until the bar, visible as just a very thin line before total eclipse, is uniformly visible from top to bottom.

Cyclorotation Resting State Test Procedure

Six observers were tested with the Circle/Bar Cyclo-Rotation test in both the Badal Optometer and the A.O. Wottring troposcope. The perceptual concept was explained to each observer and a demonstration given with the experimenter manipulating rotation of the images. The observers were asked to work with both slide holders, rotating the two images in opposite directions simultaneously, which tends to minimize the perception of rotation in the bar, and results in a smooth, dynamic tilt in the median plane. The Badal, with a magnification of .67 compared with the troposcope's magnification of 1.23 made the rotation nulling task seemingly more difficult, although only one of six observers expressed any difficulty in selecting a "null" position. This individual, a strong myope, felt that there was some latitude in the null perception which was difficult to differentiate. The degree of variance in the settings between the Badal and the troposcope is covered in the Results and Discussion section. Settings in the Badal optometer could be read on the Cronograph scale to .05 degrees, while the lack of a vernier on the troposcope limited these readings to .1 degree interpolations.

IBXD MEASUREMENT PROCEDURE

The basic technique utilized to determine an observer's inter-visual or inter-behavioral axes distance (IBXD) was detailed in the Phase I report. The new setup of the Badal optometer, however, dictated some modifications of the procedure for the current investigation. Chief among these was dual-mirror adjustment with stationary head position versus the Phase I method of first adjusting head position to line up the left eye with the stationary left mirror, and then adjusting the right mirror to obtain the desired "picture." With the new procedure, lateral head position itself was not critical as long as it was stable. The function of the bite-board is to provide this stability; however, because the preliminary tasks of selecting a bite-plate, molding the dental wax, making the wax impression, and setting up the initial head position were quite time consuming and sometimes uncomfortable for the observer, it was decided to use the forehead/chin rest instead for both the rotation and IBXD tasks. It was hoped that the variability in settings with this head rest would be close enough to the variability using the bite-board to justify the more convenient procedure. The forehead/chin rest allows vertical adjustment and the lateral head position was made somewhat more stable by the addition of foam cushions at the sides of the forehead rest.

The alignment "pointers" used to line up with the "targets" in the IBXD determination task were also changed for the current investigation. While the old ones consisted of two aluminum rods, one with a cone-shaped point and one with a forked tip, and new pointers were of steel, both with identical cone-shaped tips. With the former pointers, the observer had to work with two different "pictures" instead of only one, although this could possibly be an advantage if both left and right pictures are worked with at the same time.

The alignment targets were also changed, from a simple tri-circle format with vertical and horizontal bisecting lines, plus partially bisecting lines at every 30°, to a format with a single thin vertical gap in the upper half of the target augmented with horizontal alternating bars and gaps in the lower half of the target. This target may be seen in the slide holders shown in figure 2. The task for the IBXD alignment task then, was to align the cone-tipped pointers (which were painted flat black) with the vertical gaps in the targets. Usually, the observer found it easier to work with one eye (and image) at a time, alternately closing each eye until both images looked "good." Although the procedure of alternately closing/opening each eye worked well with most observers, a dual-channel episcotister (rotating shutter) was constructed to provide the alternating interruption of the two optical pathways. While the episcotister worked well for one observer in preliminary tests, it was unsuccessful for another and therefore was not utilized for the data-gathering sessions.

ARC TEST AND CIRCULAR STAIRCASE TEST PROCEDURE

The "B", "D", and "F" formats of the ARC test and the complete Circular Staircase Chromostereopsis test were administered to the six observers in the AO Wottring troposcope. The inter-ocular distance was adjusted to each observer's mean IBXD as determined in the Badal optometer with convergence set at 2 degrees, as in the earlier investigations. Although each observer first made the "null rotations" adjustments in the troposcope, the physical "zero" for rotation was used for the basic ARC and Circular Staircase (CSC) tests in order to have comparative data with previous sessions involving these same observers. The ARC test formats with the two-color filters (Red/Blue) were given first, followed by the achromatic versions. Then, in an effort to explore further the effect of rotation, two levels of rotation were used, corresponding to 1 x and 2 x the mean rotational adjustment made by the observer with the rotation test in the troposcope. It was hypothesized that supplying rotation of the image in the direction of the individual's correction would reduce or even reverse the layback effect on the ARC test. Following this, the nine format x field size/location combinations of the

Circular Staircase Chromostereopsis test were administered, first the chromatic versions and then the achromatic version. The red-vs-blue-field versions were randomly administered, with the format x field size/location combinations administered in a balanced/random order within each field-color set. Responses on the Circular Staircase (CSD) test were allowed at either full-step or half-step locations, e.g., "one-o'clock", or "one-thirty", etc. For each field chroma in the CSC test (red, blue, and achromatic), the observer's pupil size was measured and recorded. Pupil size was also acquired for the chromatic and achromatic versions of the ARC test.

SECTION IV. *RESULTS AND DISCUSSION*

PRELIMINARY EVALUATIONS OF THE F/PCST

The Purpose:

1. To make a preliminary assessment of the difficulty of administering and responding to the Foveal/Parafoveal Circular Staircase Test with people who had no knowledge of the test or the concept of chromo-stereopsis.

2. To determine if the exchange of colors between the foveal (disc) stimuli and the twelve parafoveal (staircase treads) stimuli would alter the apparent distance of the steps and disc in a predictable manner.

3. To determine if confining the parafoveal stimuli to different segments and areas of the parafoveal region would alter the results mentioned in 2. above.

4. To determine if stereoscopic performance with a foveola target and parafoveal comparison steps and achromatic imagery is similar to more conventional stereoscopic acuity tests.

DESCRIPTION OF TWO SMALL SEPARATE OBSERVER SAMPLES

The two small samples of individuals, the 12 U.S. Army officers and the 12 University of Washington students, were "accidental" samples; "accidental" in that there were no special criteria for selection and any similarities between or within these groups are due to chance. They were members of two separate classes, one taught by each of the authors of this report.

The Army sample was slightly older, mean age of 29.2 years, with a standard deviation of 4.7 years. Ten had very good (105%) A.O. stereoscopic thresholds, one had 95%, and one had an average of 45% stereoscopic skill. The University of Washington students were younger (23.0 years) with a standard deviation of 1.54 years. Both groups were comprised of males who were seniors or college graduates.

The U.S. Army student group had better visual acuity and more skill in stereoscopic discrimination as measured with the American Optical Sightscreener. The groups were of the same naivete as concerns the visual tests that they took and administered. In our procedures with both groups, the administration of the AO tests was done on a student to student basis. This was true with the University of Washington students for the troposcopes and the Foveal/Parafoveal Circular Staircase Test; however, the procedure differed for the F/P CST test with the Army officers. In this instance the F/P CST was administered by the contract personnel.

The order of testing was to have each individual participate in an American Optical Sightscreener assessment of his own visual skills. The appraisal included, at both far (0.1 diopter) and near (2.5 diopters) accommodation: (1) visual acuity in both right and left eye; (2) vertical and lateral phoria (disassociated positional balance of the eyes); (3) stereoacuity with high contrast, single object size, and 1 out of 5 choices at each displacement; (4) binocular fusion (tested only at 0.1 diopter of accommodation). There were available two separate instruments which did not have exactly the same vectographic plates; however the results were converted to a common metric by the experimenters.

Following the visual skill tests, the 24 individuals participated in testing with a short form of the F/P CST. There was one pattern used under each of the parafoveal fields.

Each observer had been provided with a personalized folder with all data sheets identified and stapled to this folder. All scoring was done on the F/P CST by the contract personnel after the data collection.

<u>Fixation and Retinal Locus of Stimuli</u>

The design of the F/P CST stimuli was such that if the center of the central disc was used as a fixation point this disc fell within the foveola. The twelve comparison stimuli would then be concentric and located within the outer portion of the fovea and parafovea.

There was no instrumental control of where the observer was fixated. It might have been ideal to have a system of removing the illuminance if a corneal reflection indicated a non-control fixation. To build such a device was outside the economics of the contract so the decision was to use the conventional viewing situation of freedom of eye movement with instructions that recommended central fixation. Most observers scanned the parafoveal steps and then fixated centrally, or scanned back and forth from the central disc to the near edge of the parafoveal steps.

The most stable impression of the disc's position in space was obtained by a concentric distribution of the parafoveal steps. Most observers reported that after scanning the parafoveal steps and selecting the steps that most nearly matched the disc's location, the final judgments were made with central fixation.

The two groups of observers were able to perform as both test administrators and as test subjects with a minimum of verbal instruction and with a single visual aid. This aid was a simple three dimensional model of the central disk and its relationship to the spiral steps.

The achromatic presentations of the three forms of the F/P CST were combined to give an estimate of the observer's stereoscopic skill. The average perceptual displacement (in arc seconds) of the central disc from its true physical position along the "Z" axis (along the line of sight) was used in plotting the F/P CST performance of the individuals. In figure 9, the graphs show the distribution found among these two groups of 12 individuals each. The distributions are surprisingly similar. To provide an estimate of the individual's stereoscopic skill the average deviation in arc seconds was doubled. The logic behind this multiplication was that there is an equal freedom of reporting the disc in front of or behind the comparative stimulus. Therefore doubling the average error provides an estimate of the interval of uncertainty as in the method of limits in psychophysics. The same scoring technique is used for the Howard-Dolman and Verhoeff stereoscopic tests.

The achromatic F/P CST appeared to be a rapid and effective scan test in assessing an individual's stereoscopic skill. The two samplings, the U of W students ($N = 12$) and the U.S. Army personnel ($N = 12$) were ranked from first through 12th on their individual F/P CST achromatic scores. Both groups had identical ranges of 0 to 61 arc seconds. The means were very similar, 25.8 and 27.5 respectively. The standard deviations were also similar being 19.33 and 20.45 arc seconds. The individual scores of the two groups (matched by rank) correlate + .92 (Pearson's r). The difference between means was not statistically significant ($t = 1.13$ with $df = 11$). The regression of Y on X is $Y = 1.0270\ X + 0.9864$. The "goodness of fit" of this regression to a straight line is $r_{regression} = .97$. This regression is depicted in the top drawing of figure 10. However such an apparent match in stereoscopic skill is not reflected in the results from the A.O. Sightscreener Stereoscopic Skills Test.

ACHROMATIC CIRCULAR STAIRCASE TEST

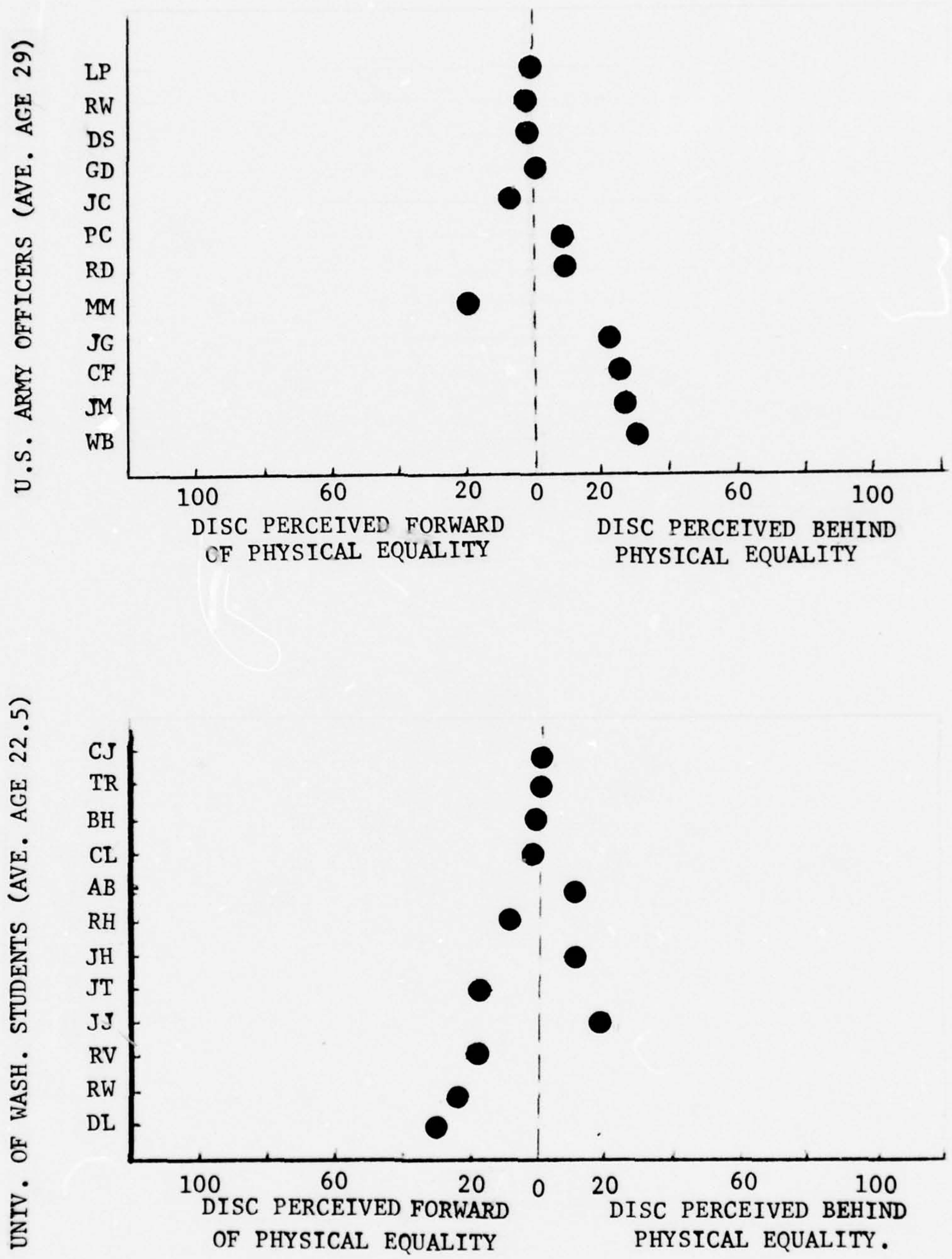


Figure 9. Perceived Location of the Foveal Disc When the Disc and Parafoveal Steps are 5500K White.

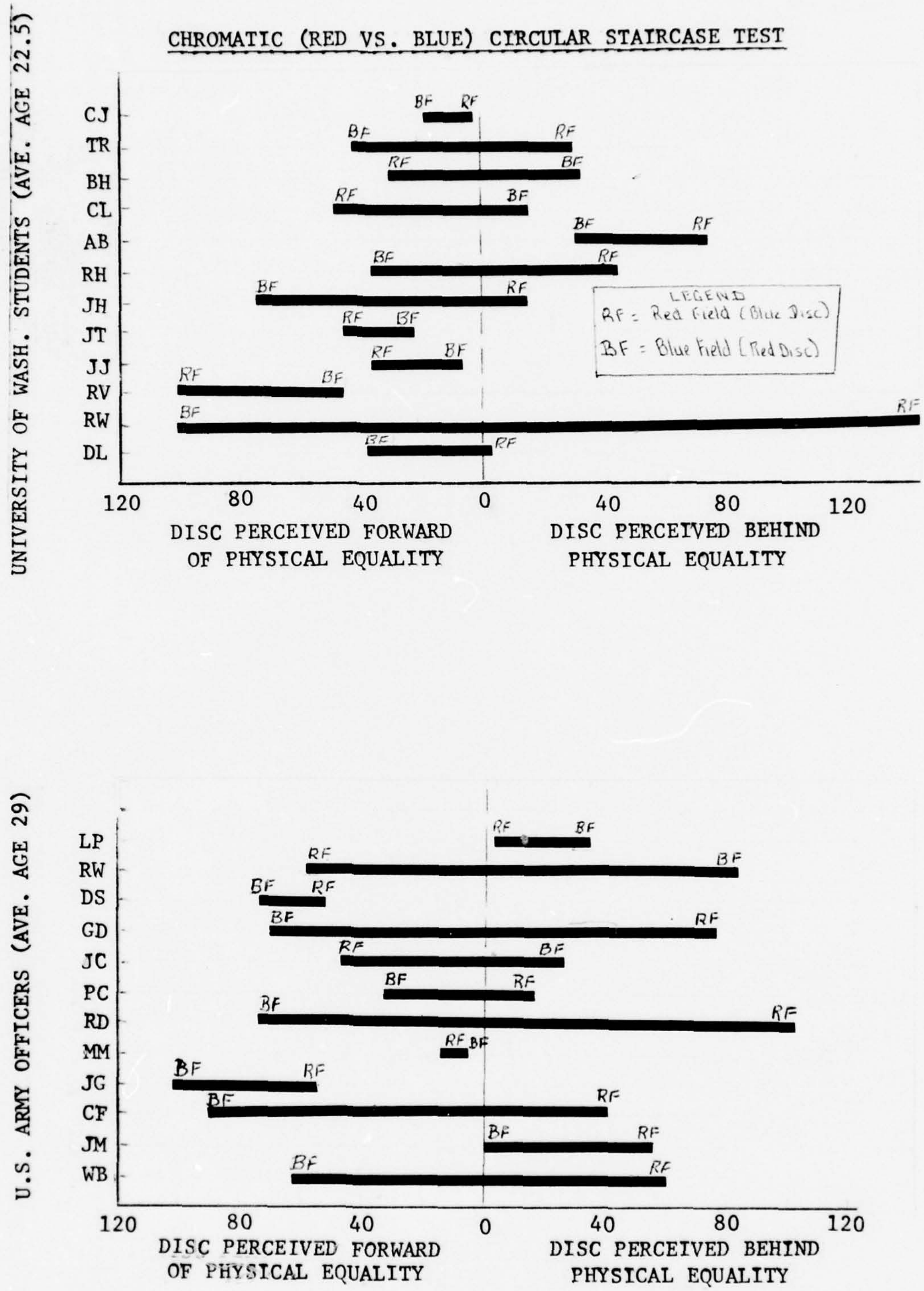


Figure 10. The Perceived Location of the Foveal Disc as its Color is Interchanged With That of the Parafoveal Steps

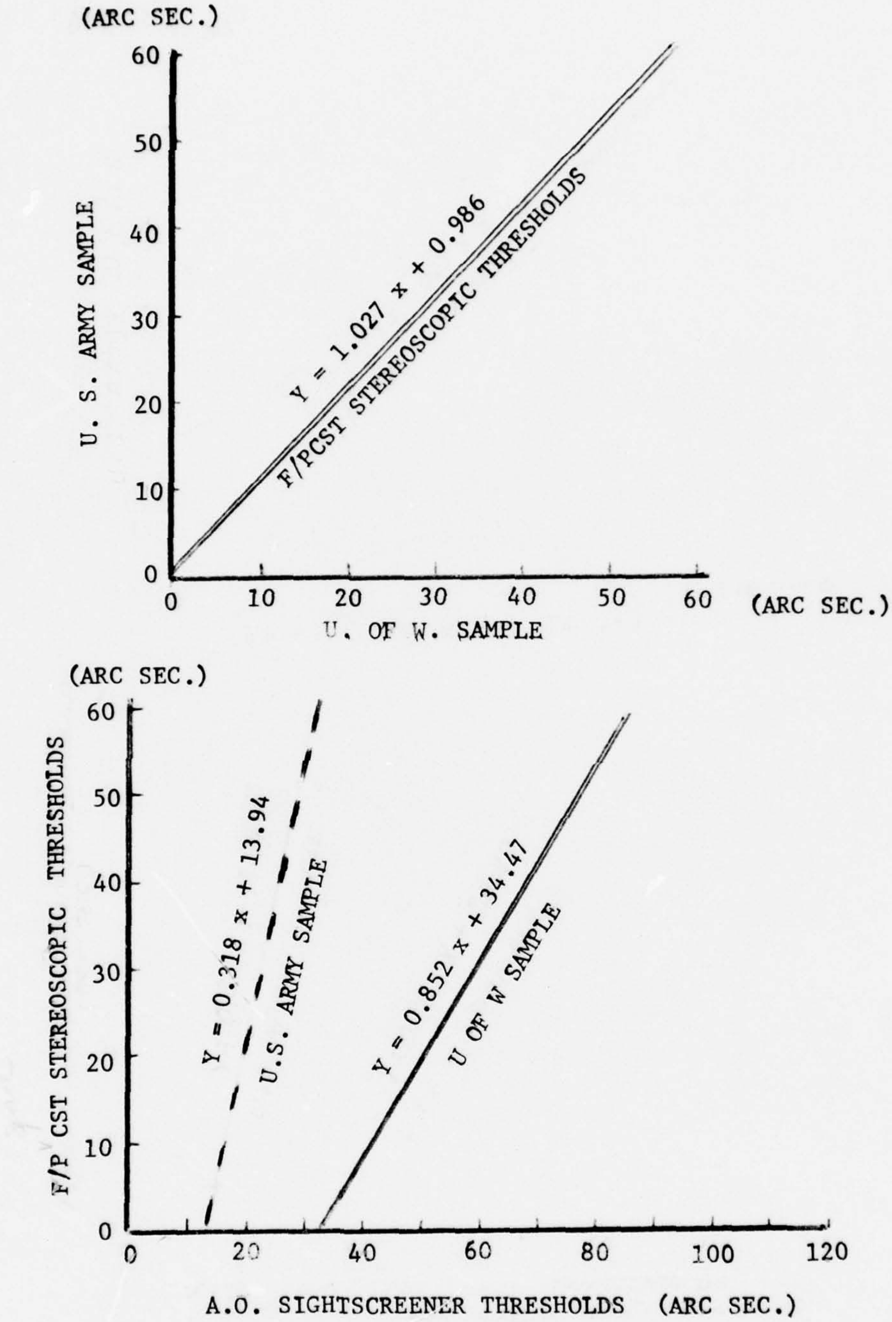


Figure 11. Comparative Achromatic Stereoscopic Measurement for the F/P CST and A.O. Sightscreener Tests.

Higher performance scores on the American Optical (A.O.) Sightscreen stereoscopic acuity test indicated that this test was "easier" than the Keystone Telebinocular DC series or the short form of the CLST (Kraft and Anderson, 1973). The respective correlations of + .09 and - .08 are at least partially due to the Keystone's confusion variable of pattern, and to the CLST's confusion variables of size and contrast. A similar correlation was determined between performance on the A.O. and the F/P CST achromatic stereoscopic tests for the 12 U of W students. The average stereoscopic skill measured with the F/P CST was 25.8 arc seconds ($\sigma = 19.3$), and with the A.O. 57. arc seconds with a σ of 46.6. The coefficient of correlation was + .15 with a σ_r of 0.26. The mean difference was statistically significant ($t = 2.47$ with 11 degrees of freedom). The regression ratio is $Y = 0.8525\,X + 34.47$ with a "goodness of fit" regression of 0.35. This regression is depicted in the bottom drawing of figure 11.

The same correlational and regression statistics were applied to the U.S. Army sample. This sample, with very similar scores on the F/P CST (Ma = 27.48; σ 20.45), were able to achieve a much better mean score on the A.O. test, 22.7 as compared with the U of W sample with 57. arc seconds.

Ten of the older and more experienced Army personnel achieved the highest possible A.O. score (13 arc seconds), one reached 26 arc seconds, and one achieved the lowest A.O. score of 116 arc seconds. The Pearson "r" correlation was + .16 between the F/P CST and A.O. scores for this group and the mean difference of 4.8 arc seconds was not significant. The regression of Y on X is $Y = 0.3176\,X + 13.94$ and the "goodness of fit" to a straight line was + 0.22. This relationship is also depicted in the lower drawing of figure 11.

The achromatic portion of the F/P CST was designed to be used in obtaining the difference between results on the achromatic versions of the test. It is an added benefit if this test proves to be useful as another rapid scan test of an individual's stereoscopic skill. The data from these two samplings are insufficient to provide the critical evidence needed on either reliability or validity of the test however. It would be necessary to use this test on a sampling of at least 100 people in direct comparison with the achromatic CLST, Verhoeff or other previously standardized and sensitive tests to obtain an estimate of reliability and validity. Even the arbitrary multiplication of the average error as a measure of stereoscopic threshold is open to question. However there is a little added support for this technique in that the average error for the six experienced observers, to be discussed later in the report, when multiplied by a factor of 2, equals 5.0 arc seconds. The same group's achromatic skill on the CLST is 5.33 arc seconds as reported in Phase I documentation. This average error is compiled across all three series, as the 2 to 9°, 2 to 5° and 5 to 9° parafoveal distribution forms give higher estimates of stereoscopic skill in the order listed.

Chromostereopsis in the two student groups

The F/P CST was used to estimate the magnitude of the chromostereopsis effect within the two student samples. Chromostereopsis scores for the individuals were derived for the F/P CST by subtracting the achromatic response from that made on the red-field/blue-disc and blue-field/red-disc forms of the test. Since the pattern of achromatic responses was similar for the two groups, the groups were combined for the analysis of chromostereopsis. The F/P CST perhaps did not give as good a measure of chromostereopsis as the ARC test, particularly Form II of the ARC test. In an earlier study using Form I, a sample of 61 individuals was completed, and this may be used as a comparative standard. The ARC Form I results produced a nearly normal distribution of chromostereopsis, with a range from 43 arc seconds blue advancing to 68 arc seconds red advancing. The F/P CST scores appear to have a bimodal tendency in their distribution with the blue advancing mode near 40 arc seconds and the red advancing mode near 28 arc seconds. The neutral group (± 5 arc seconds) with the ARC test, included 14 (23%) of the 61 people. With the F/P CST, the neutral group included only one (4%) of the 24 observers.

The range of average chromostereopsis scores for this group went from 71.2 arc seconds blue advancing to 124.3 arc seconds red advancing (total range = 195.5 arc seconds). These average chromostereopsis scores are represented in figure 10 by the midpoints indicated on the horizontal bars, the end points of which represent the red field and blue field F/P CST chromostereopsis scores after adjusting for the corresponding achromatic responses. These comparisons are summarized below:

	DISTRIBUTION			RANGE		
	BLUE ADV.	NEUTRAL (± 5 ARC SEC)	RED	BLUE-END	RED-END	TOTAL
ARC FORM I (N=61)	36%	23%	41%	43	68	111
ARC FORM II (N=12)	50%	0%	50%	89.8	116.4	206.2
F/P CST FORM I (N=24)	37%	4%	59%	71.2	124.3	195.5

Although these data imply a shift from neutral responses to red advancing in comparing the results on the F/P CST to those on the ARC Form I, the smaller number of observers in the F/P CST group makes such comparisons unreliable.

With only 12 observers used in the ARC Form II group, comparison of the distribution and range of chromostereopsis scores is even more uncertain. However, the greatly increased number of responses gathered for each individual in the Phase I study resulted in much better precision and reliability in the determinations of an individual's chromostereopsis.

Differential Influence of the Red/Blue Fields in the F/P CST

Of particular interest in this study was the potential influence of the red versus blue fields in the F/P CST on the perceived displacement of the center disc. The influence of chroma in the F/O CST is not limited to chromostereopsis. The interchange of wavelength composition for the foveal and parafoveal stimuli, produces marked changes in the perceived location of the central disc. Note in figure 10 the marked individual differences in the effect of blue and red fields on the central disc. Note the differences in range reported by the Washington University students RW and DL with the color fields. These differences in magnitude would not be predicted by their achromatic thresholds or by their chromostereopsis scores. In figure 12 , the end points of the horizontal bars crossover the separation between red and blue advancing perception of the disc's location. These data are difference scores, i.e., the achromatic error has been removed. Therefore if chromostereopsis were the only influence, the lengths of the bars should be short (representing only observer error) and both on the same side (red or blue) of the zero chromostereopsis point.

Nine of the twenty four individuals show chromostereopsis reversals and four or five others have large red field versus blue field displacements.

The total influence of chroma changes the average estimate of stereoscopic threshold by a factor of 3.66 when the parafoveal steps are red and the central disc is blue. The achromatic estimate for the U of W and U.S. Army students combined was 26.6 arc seconds ($\sigma = 19.90$); the chromatic estimate for the red field condition was 97.32 arc seconds ($\sigma = 67.4$). The standard deviation also increases by a value greater than 3 times, (3.39x). The use of blue in the parafoveal area with a red central disc also increases the average estimate of stereoscopic threshold by 3.54 times (ave = 94.4 arc sec) with somewhat less increases in variance, 3.02 x or 60.08 arc sec. The chromatic means are statistically different from the achromatic, $t = 5.16$ and 5.33 with $df = 23$. However the difference between the two chromatic means is not significant, $t = 0.213$. These ts include correlations of achromatic vs. red field of + .07, achromatic vs. blue field + .12 and red field vs. blue field of + .531.

The significant difference between the achromatic stereoscopic acuity and the chromatic stereoscopic acuity with either color field is due to individual differences in chromostereopsis and to at least one other variable. Chromostereopsis (arc seconds) when added to an individual's achromatic stereoacuity predicts to a fair degree ($r = .71$) his score on a chromatic stereo test. This was established with the ARC test in the Phase I report (Anderson and Kraft, 1976).

Chroma and Accommodation

However, the prediction was not perfect and some other variables certainly exist. One was postulated as "accommodation insufficiency," or incomplete accommodation; i.e., individuals may work with a visual task using only the necessary amount of focus necessary to complete the task. The latter is supported by improving performance by adding supplemental minus lenses.

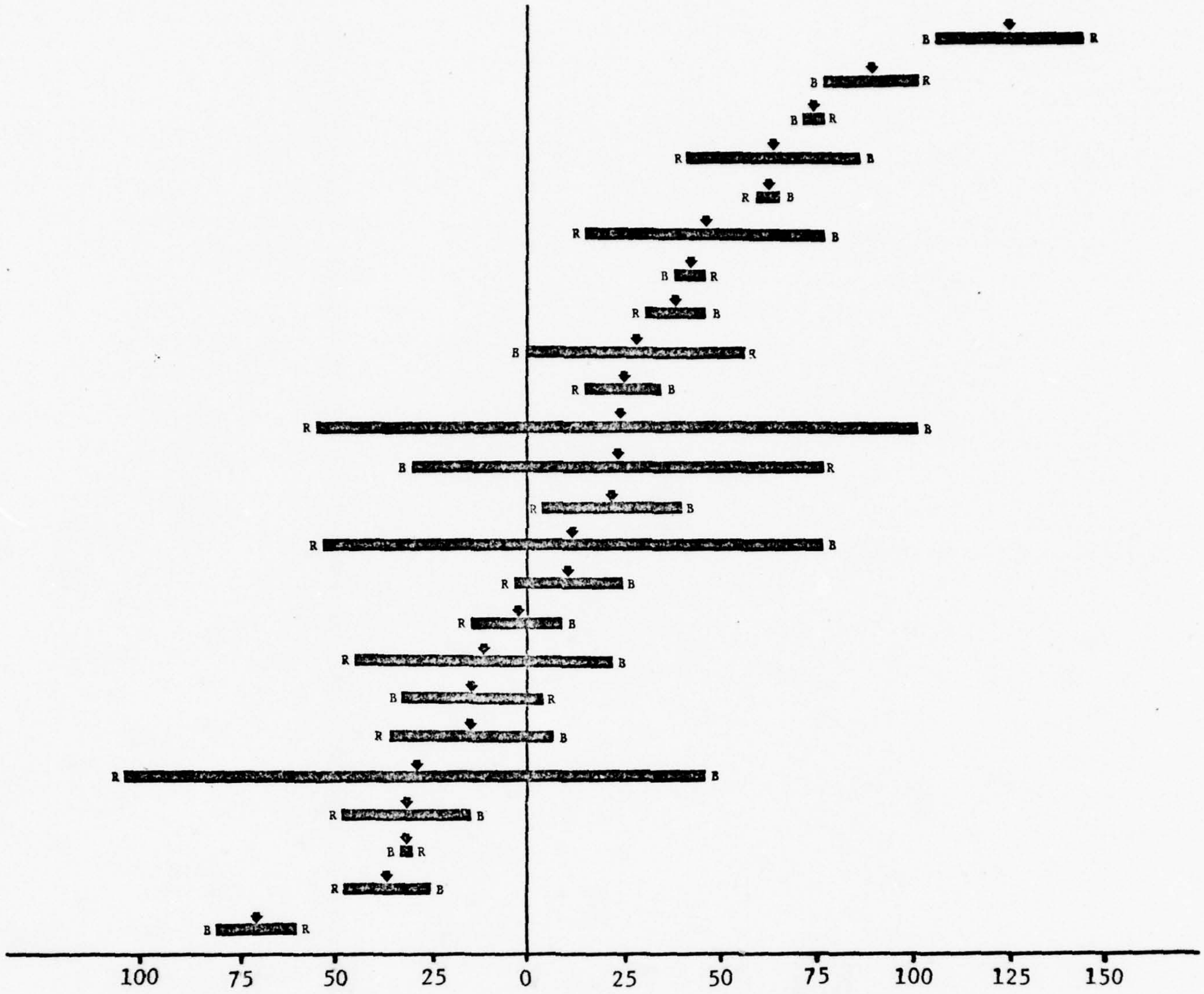
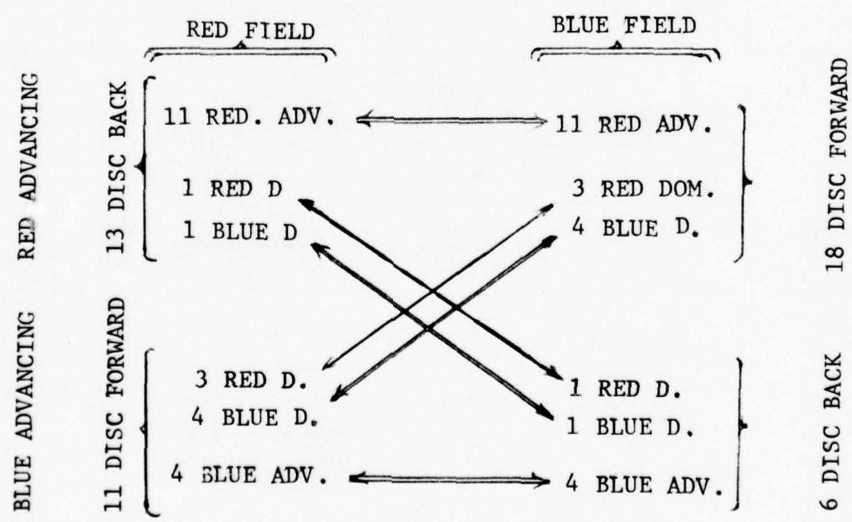


Figure 12. Direction and Magnitude Shifts in Chromostereopsis as a Function of Interchanging Central Disc and Off-axis Tread Colors (arc seconds).

The proof that an individual focuses differentially when the scene is achromatic, monochromatic or heterochromatic has not been measured while the observers are working with a display. In a separate study we have found that for eighteen pilots the range of additional minus lenses is from 0.12 to 3.0 diopters to see checkboard targets with equal clarity when they are viewed simultaneously and adjacently against a red and a blue background. This study used the same instrument, the troposcope, as employed in this investigation of the F/P CST.

The theoretical position that the fovea controls the accommodative mechanism without major influence from the parafovea or periphery, suggests that the parafoveal stimuli would appear out of focus if any differential focus was observed. The observers who have participated with the F/P CST have never reported the blue comparison steps to be out of focus. The blue in the 2 to 5^{o} series is within the outer edge of the fovea, 5^{o} to 8.8^{o} series in the parafovea, and 2 to 8.8^{o} series in both fovea and parafovea. However when the central disc of 58 minutes is blue and the concentric comparative stimuli red, a number of observers reported the blue central disc to be blurred. The observers found themselves unable to clear the blue disc as an image without the aid of minus lenses. With some selected power fitted between the eyes and the Troposcope lenses both the blue disc and red comparison (parafoveal stimuli) appeared clear.

If accommodation or asymmetry of the corneal surface in the parafoveal region are contributors, there should be some shifts in the disc position as a function of chroma not attributable to chromostereopsis. One way to examine this is to look at the distribution of disc positions.



If the two colors had the same influence when they are the field colors, then the location of the disc (back versus forward) should be equal in magnitude but opposite in direction for the two fields. This is not the case and

	FIELD	
	RED	BLUE
DISC FORWARD	11	18
DISC BACK	13	6

$\chi^2 = 8.22$

$P < .01$

a X^2 test indicates that a difference in frequency of this magnitude would occur by chance less than one time in 100 replications. If chromostereopsis were a cause this matrix would be analyzed with the expectancy being that the 11 observers perceiving "disc forward" under the red field condition would see 'disc back' with the blue field, and vice versa for the 13 observers in the other group. This was not the case however, again lending supporting evidence for an influence other than chromostereopsis operating here. However many factors are influencing the individual's stereoscopic skill with chromatic imagery, the effect is to lower stereoscopic performance. That is, a very few individuals have the same stereoscopic skill with both achromatic and chromatic imagery, and for the remainder the effect is always that of attenuation with chromatic imagery. In Figure 13 are the cumulative distributions of the 24 individuals in the two student samples. The achromatic distribution reaches 100% before relative disparity reaches 32 arc seconds, the criterion the USAF uses for pilot training acceptance. However with colored stimuli 32 arc seconds include less than 25% of the sample and 250 arc seconds displacement would be necessary to include 100% of this sample.

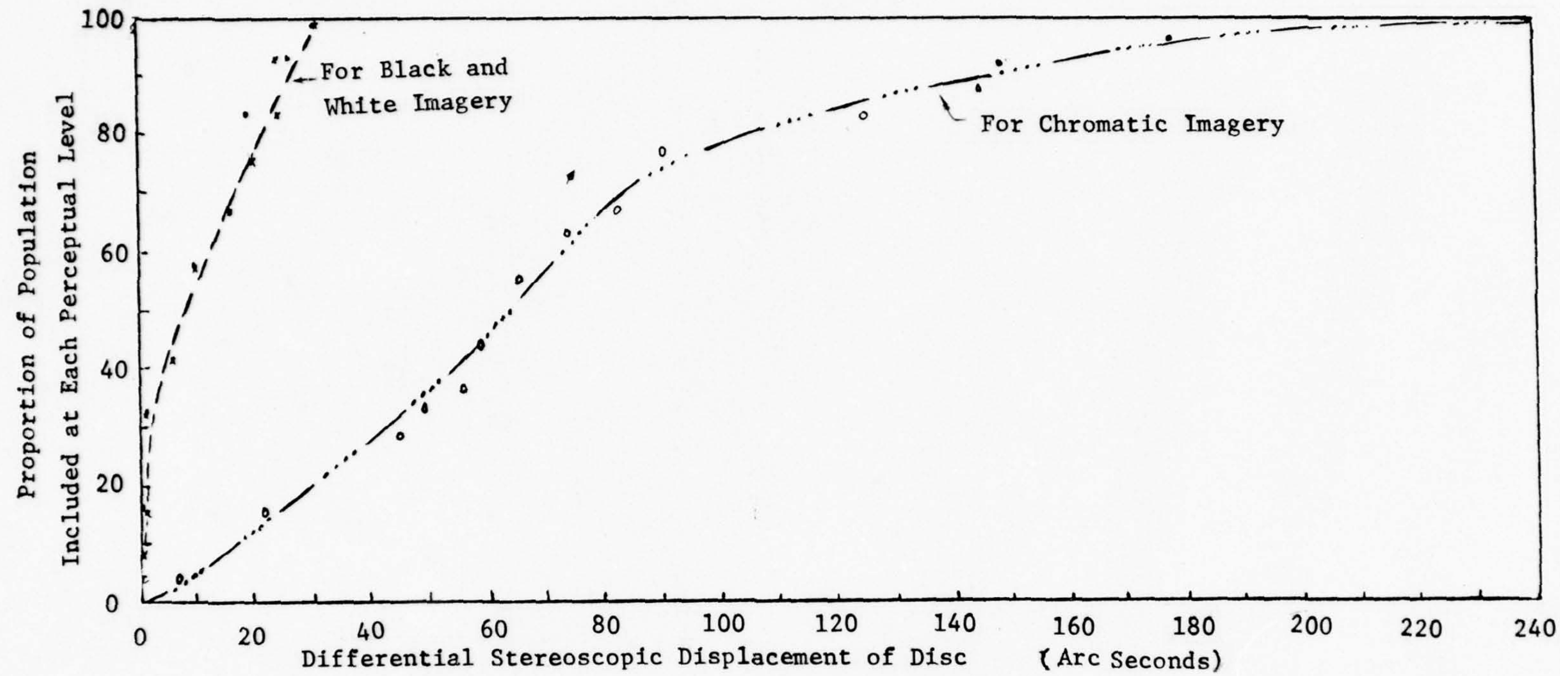


Figure 13. Cumulative Distribution of 24 Observers by Stereo Skill

THE SAMPLE OF SIX EXPERIENCED OBSERVERS

Background

In an effort to obtain more reliable data on the F/P CST, a group of six experienced observers who participated in testing with other, earlier chromostereopsis tests, was given the F/P CST under controlled experimental conditions. The results from this testing could therefore be compared with other determinants of each individual's chromostereopsis. These six observers were selected for their exceptional stereoscopic skill and for their previously determined chromostereopsis - three were red advancing and three blue with a range of 91.6 arc seconds blue to 69.3 arc seconds red according to results on the short form of the ARC test. There was also fairly good balance in the amount of chromostereopsis evidenced by these six observers.

Achromatic Performance on the F/P CST

The perceived shift in the location of the disc in the achromatic F/P CST by these six observers is depicted in figure 14.

Effect of Retinal Location of Comparative Stimuli

The twelve steps of the comparative stimuli are located within the fovea (2.2^o to 5.5^o series), parafovea (5.5^o to 8.8^o series), and in both fovea and parafovea in the (2.2^o to 8.8^o series). The area in the slides and on the portions of the retina representing these steps increases in the order given above, 211.3, 431.3 and 643.4 as square millimeters on the slides. These values were given earlier in this report in figures 5 through 7.

For the six experienced observers who were given three different stereoscopic pairs under each series and with each luminous color a difference in performance was noted, figure 15.

The average displacement (for all six observers) of the central disc was organized as a two x three matrix. The visual performance as difference scores (chromatic-achromatic) was reviewed for each series (3) under each field illumination color (2). The following distribution is of displacement in units equivalent to one comparison step.

Diameter of "Staircase Treads"	Red Field Ave. Step	Blue Field Ave. Step
2.2^o to 5.5^o	33 (blue advancing)	31 (blue advancing)
2.2^o to 8.8^o	7 (blue advancing)	41 (blue advancing)
5.5^o to 8.8^o	10 (blue advancing	27 (blue advancing)

The distribution should be the same in each cell if neither the illumination color or the location of the comparative stimuli had any effect. A X^2 test was applied to the differences in the cells under each field

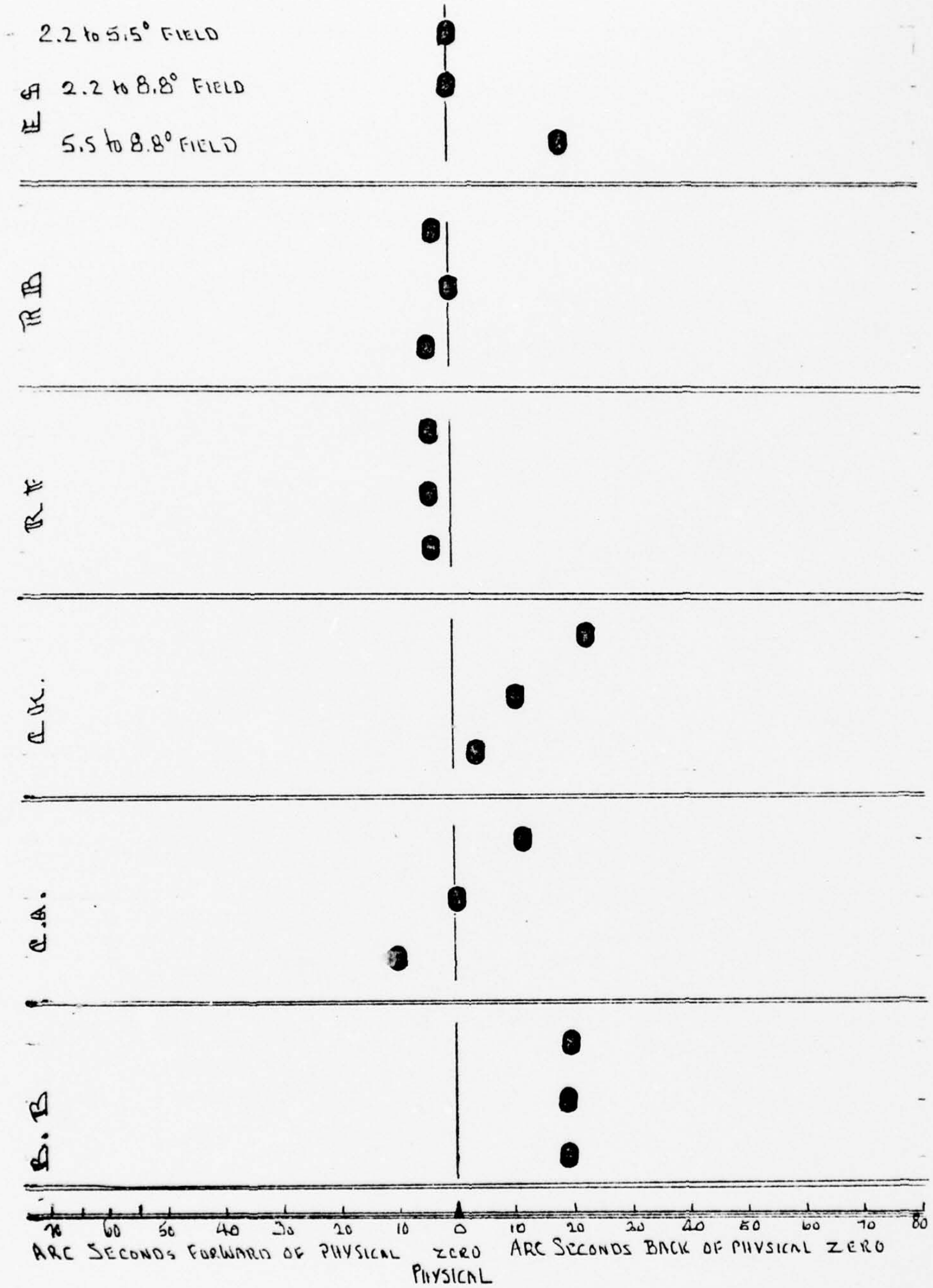


Figure 14. **Perceived Displacement of Foveal Disc in Achromatic F/P Circular Staircase Test as a Function of Parafoveal Field Stimulated for Six Individuals**

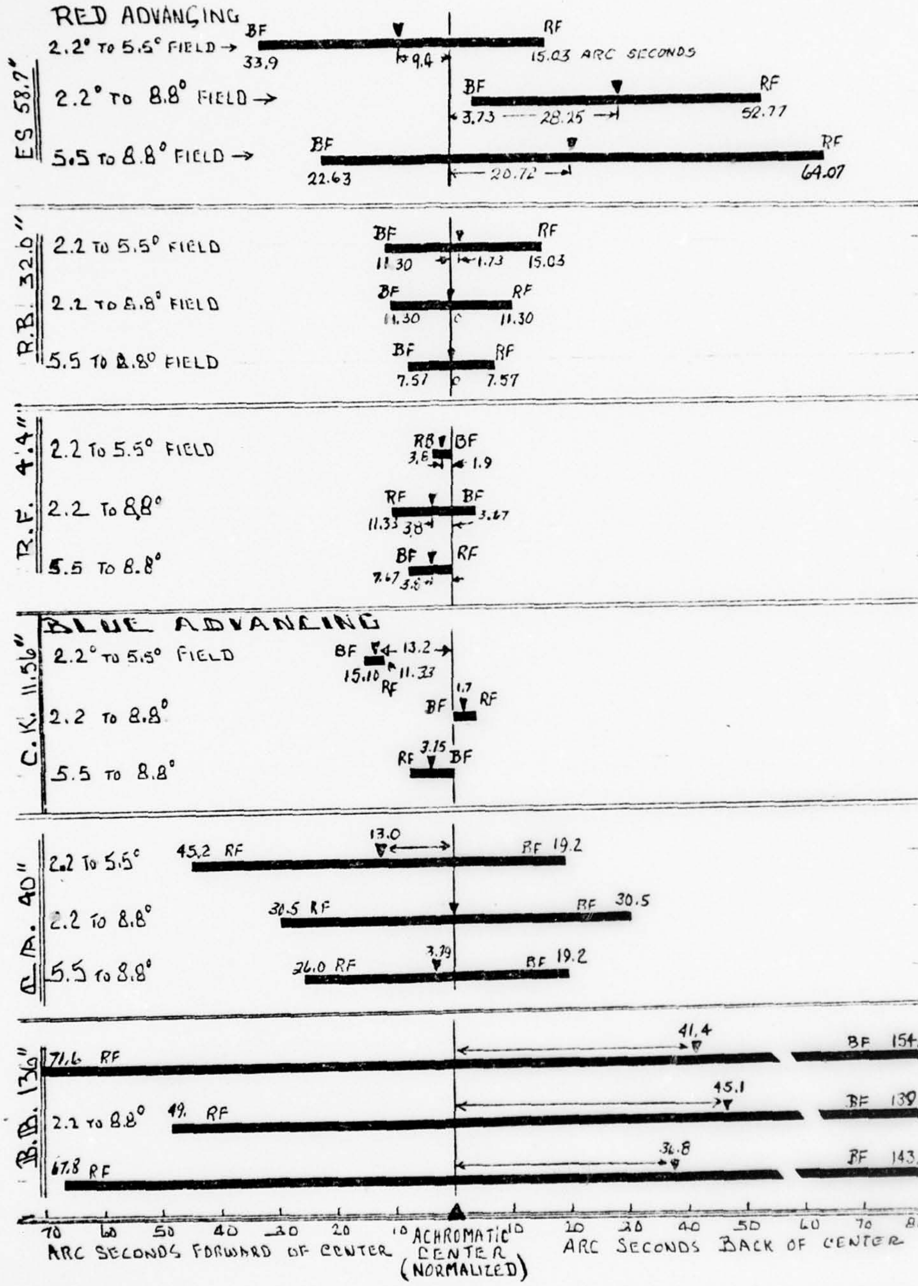


Figure 15. Shift in the Midpoint of the Chromostereopsis Effect as a Function of the Parafoveal Field Stimulated

color. This test indicated that differences of these magnitudes could be due to chance less than once in 100 replications of this experiment. The blue illuminance when applied to the field produced three times as many units of displacement compared to the red illuminance.

These changes in apparent position of the central disc were converted into "shifts." These shifts were the differential displacement of the disc due to the hue of the field illuminance. The results indicated the following average shift for each series when the shift was arbitrarily chosen as a red to blue field shift.

Series Name and Angular Diameter of Comparative Steps	Magnitude and Direction of Shift
Foveola/Fovea 2.2^{o} - 5.5^{o}	-1.26 arc second (red advancing)
Foveola/Parafovea 5.5^{o} - 8.8^{o}	10.67 arc second (blue advancing)
Foveola/Fovea + Parafovea 2.2^{o} - 8.8^{o}	21.34 arc second (blue advancing)

It was noted that the proportionately larger shifts were of the same order as the area of the comparative stimuli. A regression analysis was made with the area paired with the magnitude of the shift. The regression line is plotted in figure 16. The "goodness of fit" ($r = .9997$) indicated a very close approximation to a linear regression.

A similar conversion of the data for the 24 students, the combined U of Washington and U. S. Army samples did not confirm the findings obtained with the six experienced observers. This may be accounted for by the experience level of the observers combined with three times as many comparisons made under each condition by the experienced observers.

The direction of the effect may also be controlled by the one observer who had a very large blue advancing chromostereopsis, in the six experienced observer sampling.

Two important findings appear in this section: One, the much larger contribution of the blue illuminance when it is distributed over the off visual axis area. Secondly, the area of the comparative stimuli must be taken into account, particularly when the comparative stimuli are concentric and assigned to the far fovea and parafovea.

Correlations Among Different Forms of Chromostereopsis Tests

Since 1974, one or more forms of the chromostereopsis tests developed by the authors have been available. Six experienced observers have been given six different versions (or different administration conditions) over the ensuing years. In table 3, the performance of these individuals in threshold units are given along with the intercorrelation table of 15 comparisons. The long form of the ARC test is the most

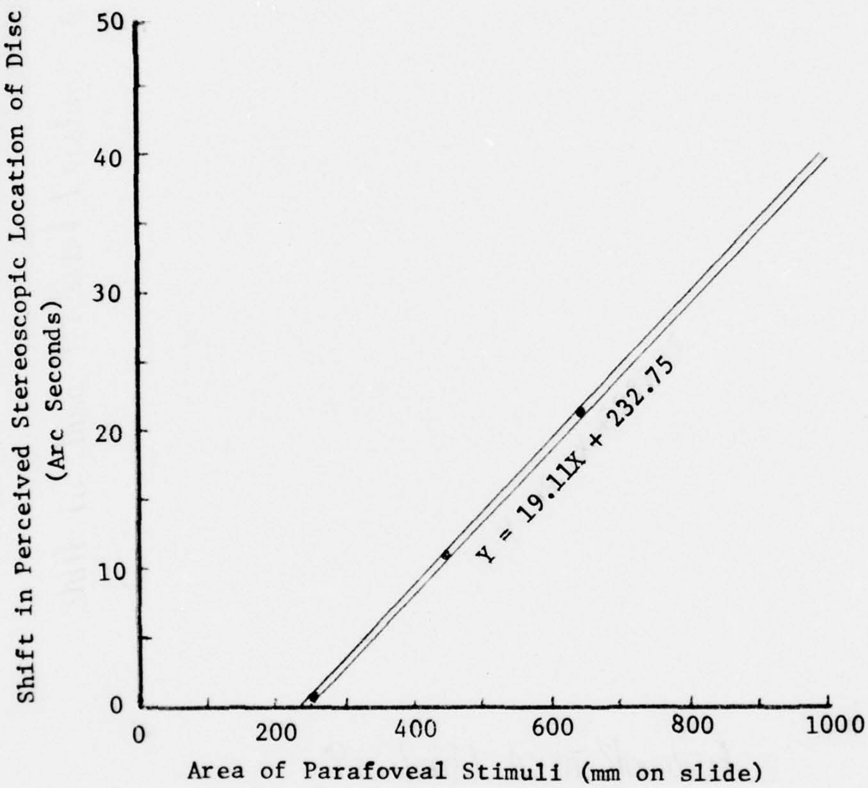


Figure 16. The Relationship of Area of Parafoveal Stimulation to Shifts in Perceived Location of the Foveal Disc in the F/P CST.

TABLE 3. COMPARISONS AMONG DIFFERENT FORMS AND ADMINISTRATIONS OF CHROMOSTEREOPSIS TESTS FOR SIX EXPERIENCED OBSERVERS

	(1)	(2)	(3)	(4)	(5)	(6)
TEST FORM	ARC	ARC	ARC	F/P SCAN	F/P CST	ARC
LENGTH	LONG	SHORT	SHORT	SHORT	MEDIUM	SHORT
ROOM ILLUM.			2.0 Ft.L.		2.0 Ft.L.	LOW
AVE. PUPIL SIZE	MEDIUM	MEDIUM	LARGE	MEDIUM	LARGE	MEDIUM
ADMIN. DATE	10/74	10/74	10/75	10/74	04/76	11/26/75

AVERAGE CHROMOSTEREOPSIS SCORES (IN ARC SECONDS)

OBSERVERS	(1)	(2)	(3)	(4)	(5)	(6)
1	15.6-B	13.3-B	40.0-B	8.0-B	28.5-B	26.7-B
2	89.8-B	91.6-B	136.0-B	52.8-B	104.0-B	157.0-B
3	5.4-B	9.8-B	11.6-B	11.5-B	1.5-B	1.5-B
4	64.4-R	69.3-R	58.7-R	11.6-R	30.8-R	24.0-R
5	6.2-B	5.3-R	4.4-R	19.0-R	0.6-B	2.7-R
6	28.9-R	28.4-R	32.0-R	13.7-R	10.6-R	64.0-R

CORRELATIONS (PEARSON 'r') AMONG TEST FORMS

	(1)	(2)	(3)	(4)	(5)
(2)	.955				
(3)	.977	.983			
(4)	.853	.845	.926		
(5)	.957	.957	.988	.915	
(6)	.892	.901	.950	.933	.957

TESTS OF SIGNIFICANT DIFFERENCES BETWEEN MEANS:

For (2) vs. (3): $t = 1.78$ with $df = 5$.
For (4) vs. (5): $t = 1.00$ with $df = 5$.

extensive and reliable test, and within our limited testing, the most valid. We, therefore, have used it as our standard reference in looking at the newer F/P CST. Only the first form of the Foveola/Parafovea test, referred to in the table as the F/P Scan, has Pearson r values of below +.90. This scan test had 12 concentric rings as parafoveal stimuli. Most observers reported difficulty in making the comparative judgments, although their performance was better than their expectancy. The difficulty was a product of: (1) twelve different adjacencies between disc and rings; (2) ring and interspace reversals in perception; and (3) range and inter-ring steps which were not compatible nor perceptually linear.

The F/P CST test correlated very well with each administration of the ARC test. An almost perfect correlation was found when the F/P CST and the ARC (Short Form) were both administered under the same luminance (imposing large natural pupils as a condition for observation).

Tests of significance of the differences between the means of the ARC (long form, higher luminance) and the ARC (short form, 2.0 ft. L or low luminance) determined that this difference was insignificant. The two F/P tests were also not different under two luminance levels.

These results imply that all three of these tests may be used to measure chromostereopsis under room luminances approximating 2 to 25 foot Lamberts at the entrance pupil of the eye, with fairly high reliability. Their differences in design permit chromostereopsis measurements to be made with tests that satisfy a variety of experimental objectives, such as speed, ease of adminstration, precision, or while simultaneously getting at some other problems such as the influence of chromatic parafoveal fields.

A CONTRIBUTION TO THE ADJACENCY HYPOTHESIS

Gogel (1956 and 1963), developed the hypothesis that in the assessment of depth perception, the more adjacent the comparative stimuli, the lower the depth perception threshold.

Matsubayashi (1937), studied the relationship between the adjacency of stimuli and the stereoscopic threshold. He reported data from tests using two and three rods separated by distances of 7 to 120 minutes of arc.

The use of two rods gave stereoscopic thresholds that were a function of:

$$y = .114667X + 3.74$$

where y = the stereoscopic threshold in arc seconds (h_t)

and x = separation of stimuli in arc minutes

The three rod investigation indicated that the stereoscopic threshold changed less rapidly with the separation of the stimuli:

$$y = .052367X + 1.6129$$

The Foveola/Fovea series and the Foveola/Fovea-Parafovea series of the F/P CST have the same adjacency of the central disc and the inner edge of the comparison steps. The central disc's radius is 27.45 arc min. and the inner edges of the steps are at a radius of 67.2 arc min. The difference is 39.75 arc minutes, and represents the closer adjacency in the F/P CST.

In the Foveola/Far-Parafoveal series, where the steps go from 5.54° to 8.81°, the adjacency is 138.75 arc minutes. The radius of the inside step is 166.2 arc minutes, with the radius of the disc at 27.45 arc min.

These two adjacencies of about 40 and 139 arc minutes are comparable to the range of the Matsubayashi data. The F/P CST presents a central disc with 12 alternative matching steps for comparison, while the Matsubayashi tests used two and three rod comparisons.

The Matsubayashi data represent two psychophysical methods, the two-rod comparison being made with the "Method of Limits," and the three-rod comparison employing the "Method of Constant Stimuli." The F/P CST employed the "Method of Average Error" so in comparing these tests and data, methodology is confounded with the adjacency factor.

The point of interest is that the two-rod comparison had a slope of 0.114X, the three rod a slope of 0.052X and the thirteen stimuli comparison had a slope of 0.01252X. These slopes indicate that as a number of comparisons increase, the stereoscopic threshold increases more slowly with increases in the separation of the comparison stimuli.

Figure 17 illustrates the slopes and the intercepts of the three

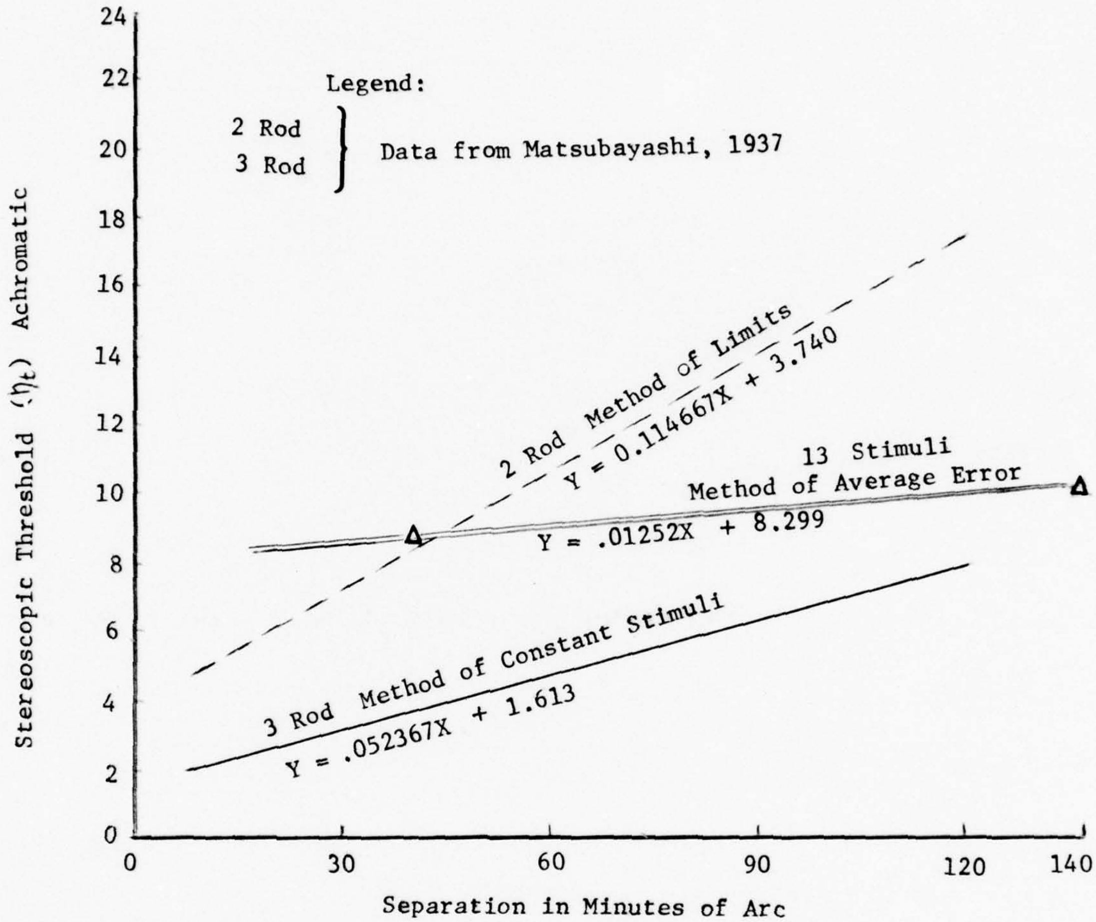


Figure 17. Adjacency, Number of Stimuli, and Stereoscopic Threshold

regressions. These data suggest that when we have 13 stimuli for comparison, adjacency differences within the range of 30 to 140 arc minutes have little differential effect. However, this may be specific to the test condition in which the central disc is compared to the concentric stimuli and all fall within the 9^{o} diameter of the parafovea.

These data suggest that avenues of research might be designed to answer the following questions: (1) What number of comparative stimuli should be used in a display where adjacency varies, such as on a radar PPI display? (2) Is a display with a central moving variable more easily discriminated when the comparative stimuli are concentric rather than displaced horizontally or vertically? Systematic changes in adjacency through five steps could be done within the parafovea with very small wedges matched as to area.

CYCLOROTATION TEST RESULTS

Cyclotorsional Resting State

As outlined in the method section, the six highly skilled and experienced observers were given the Circle/Bar Cyclo-Rotation test in both the Badal and Troposcope. The purpose here was to determine if there was an image cyclorotation null point (a correlate of the hypothesized cyclotorsional resting state) other than "instrument zero" for each of these observers. The following table summarizes the means of five settings (for most observers) in each instrument.

TABLE 4.

MEAN CYCLOROTATIONS OF CIRCLE/BAR TEST
(Positive Values are Excyclorotation)

	Badal			Troposcope			
Observer	$\bar{X}$	σ	N	$\bar{X}$	σ	N	Ave.
CA	2.42°	(.40)	5	1.73°	(.23)	5	1.96°
BB	.72°	(.91)	5	0.00°	(1.86)	5	.36°
CK	1.64°	(.48)	5	2.77°	(.60)	3	2.16°
ES	1.11°	(1.85)	5	-.76°	(.15)	3	.18°
RF	-.73°	(.55)	5	-.43°	(.57)	3	.67°
RB	-1.18°	(1.20)	5	-1.14	(.21)	5	-1.16°
Ave:	.94°			.45°			
σ:	1.20°			1.43°			

The relatively high standard deviations evidenced for the individual settings are indicative of a need for more setting trials, or increased ease in making the settings, or a combination of these. Nevertheless, there were strong indications of individual differences in the cyclorotational null points, with means ranging from 1.18° encyclorotation to 2.42° excyclorotation for the Badal and from 1.14° encyclorotation to 2.77° excyclorotation for the Troposcope. The standard deviations for these means were large (1.20° and 1.43° respectfully), again reflecting hetereogeneity in the cyclorotation null points.

Effect of Cyclorotation Upon Layback Effect

In a pilot study, two formats (B and D) of the ARC test were used in their achromatic form to study the effect of image cyclorotation upon the rhythmic "layback" effect. These formats were chosen for their previous uniformity and consistency in eliciting this effect in the responses of the 12 skilled observers used in Phase I of these studies. The testing was done in the Troposcope, with image cyclorotation set in by the experimenter. Two cyclorotation values were selected for each of the five observers used (the sixth was unavailable), based roughly upon the individual's cyclorotation null points established on the Circle/Bar test. *Positive or excyclorotation* values were used in each case with the value used for format B being approximately doubled for format D. Appendix I presents the conditions and raw data from this test session. The following table summarizes the results:

TABLE 5.
RESULTS OF CYCLOROTATIONAL STUDY

	Format B			Format D		
		Cyclorotation			Cyclorotation	
Observer	"Layback" Shift (1)	Effect (2)	Amount (3)	"Layback" Shift (1)	Effect (2)	Amount (3)
CA	10	-5	1.5°	12	-3	3.0°
BB	-	-	-	4	-11	2.0°
CK	1	+1	2.6°	1	+17	5.2°
ES	17	+3	1.6°	22	-8	2.4°
RB	7	-3	1.2°	12	-10	2.2°
Totals	35	-4	Ave: 2.1°	51	-15	Ave: (4) 3.2°

(1) Net shift across the nine responses in the format and in response steps in direction of layback effect with Troposcope at "zero" rotation.

(2) Change (in response steps) with image cyclorotation from shift shown under zero rotation (minus equals corrective shift - plus equals exaggerated shift).

(3) Amount of image rotation set into Troposcope (half into each image holder).

(4) This average, to be comparable with that for format B, excludes observer "BB."

The results show no consistent effect of image cyclorotation upon the layback effect. Although there is an overall trend toward correction (four steps overall for format B and 15 steps for format D), one observer showed a mixed effect and one showed an exaggerated layback effect rather than correction. The overall results represent average corrective shifts of 2.67 arc sec/response for format B and 8.0

arc sec/response for format D. There was a little more consistency in an increasing corrective effect from format B to format D with the corresponding increase in cyclorotation. All but one observer (the reversal) showed increased reduction of the layback effect, the average increase (for these three observers) being 5.3 response steps/ format, or 14.2 arc sec/response. Although the results were not conclusive, they did present justification for further study of this phenomenon under refined experimental conditions.

IBXD DETERMINATIONS WITH RECONSTRUCTED BADAL

With the reconstructed Badal, it was felt important to verify its precision and reliability of measurement by a method other than the criteria used in the alignment procedure. A natural for this purpose was the determination of IBXD. With the "old" Badal, the IBXD for two observers (CK and CA) was determined with ten settings each. This procedure was repeated with the reconstructed Badal except that with the new Badal, since the bite-board and head restraint were fixed in the center of the optical bench, both the left and right mirrors were adjustable for alignment with the targets. The scales on the mirror stands on the reconstructed Badal were configured to give independent measurements from an "instrument zero." Thus, the IBXD measurement was determined by averaging the two (left and right) settings, a potential source of increased variance with the new Badal. New alignment targets were used with the reconstructed Badal, and although these were generally easier to work with, again they might contribute to variance in the settings from those made with the "old" targets.

Table 6 summarizes the results of the IBXD determination, and compares

TABLE 6.

COMPARISON OF IBXD DETERMINATIONS FOR TWO OBSERVERS WITH "OLD" AND "RECONSTRUCTED" BADAL

Settings of alignment mirrors with reconstructed Badal (from instrument zero in mm):

	Observer: CK			Observer: CA		
Trial	Left Eye	Right Eye	Ave.	Left Eye	Right Eye	Ave.
1	63.9	63.5	63.70	68.4	66.3	67.35
2	64.6	63.4	64.00	66.5	68.2	67.35
3	65.2	62.8	64.00	66.1	68.6	67.35
4	67.8	60.0	63.90	66.8	67.9	67.35
5	68.1	59.4	63.75	67.3	67.3	67.30
6	65.8	62.0	63.90	66.0	67.9	66.95
7	65.5	62.4	63.95	68.0	65.6	66.80
8	67.8	59.5	63.65	67.0	67.1	67.05
9	69.7	57.7	63.70	65.2	69.0	67.10
10	65.4	62.3	63.85	64.7	69.3	67.00
		Mean =	63.84		Mean =	67.16
		σ =	.131		σ =	.205

VALUES FROM SETTING WITH "OLD" BADAL:

Mean = 63.89 σ = .180 Mean = 67.46 σ = .086

TESTS OF SIGNIFICANCE (DIFFERENCE BETWEEN MEANS)

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\sigma_{M_1}^2 + \sigma_{M_2}^2}}$$

$$t = \frac{(63.89 - 63.84)}{\sqrt{(.06)^2 + (.044)^2}} \qquad t = \frac{(67.46 - 67.16)}{\sqrt{(.029)^2 + (.068)^2}}$$

$$t = .674 \qquad t = 4.05 \text{ (significant at .01 level)}$$

these findings with those from earlier settings made with the "old" Badal. As with the earlier set of determinations, the settings made with the reconstructed Badal had low standard deviations (.131 and .205 mm for CK and CA respectfully). For one observer (CK) the variance is less than the "old" settings, and for the other (CA), the variance is greater. It is noteworthy that for CK, the mean of the "new" settings is not significantly different than that of the "old", while for CA, the means of the two groups of settings are significantly different ($t = 4.05$ with $df = 9$).

It was concluded from these data that the reconstructed Badal provided reliable measurements of IBXD, but that small differences in magnitude might be found between settings with the old and reconstructed Badal. It was hypothesized that this was likely due to slight perceptual differences in two targets which might effect some observers more than others. It was felt that the new targets were easier to work with however, and therefore perhaps resulted in the more valid measurements. A second source of "error" was also indicated for observer CA. For this observer, the ten setting trials were interrupted at the midpoint for some measurements at a lower illumination level. Since the five settings before and the five made after this interruption were different ($\bar{X}_1 = 67.34$, $\bar{X}_2 = 66.98$, and $t_{Diff} = 6.14$), it is certainly possible that a residual effect was felt from this interruption.

PHYSICAL VARIABLES OF THE EYE AND PREDICTION OF VISUAL PERFORMANCE

Physical Variables of the Eye

The frequency with which the authors have found chromostereopsis to be a good, but incomplete, predictor of visual stereoscopic performance with colored imagery made for many a conversation with those peers who share our interest in vision. Francis A. Young and George A. Leary of Washington State University were two willing listeners. They suggested that they could bring their equipment to Boeing Aerospace Company at Kent, Washington and measure the physical characteristics of our observers' eyes. They needed an ophthamologist to administer drugs and to examine for narrow angle glaucoma. Boeing's central medical department arranged and supported the participation of Dr. Racik.

Through the combined efforts of three investigators and our observers , we were able to conduct pre and post examinations, retinoscopy, ultrasonography, keratometry and photographic ophthalmophakometry on most of our observers. The raw data are organized and treated through the application of a special computer program by George Leary. The authors were supplied with the data on 32 variables, those listed across the top of table 8.

The 32 variables included "Vertical Optical Refraction," vitreous chamber length expressed in mm and diopters, interior ocular pressure in mm Hg. etc.

The large matrix of physical measurements vs. performance tests represents three combinations of correlations. The combinations were dictated by the incompleteness of some data from the performance and some from the physical measurement side of the correlation matrix. The variables in each combination are listed under 1st, 2nd and 3rd headings in the upper left corner.

The performance measurements are listed as the row headings on the left.

The Cut-Off Criteria

The large number of variables gave 672 combinations. This number of correlations was made on the IBM 360/165E. Those that have been examined and recorded met a statistical criterion. In Appendix IV is the development of a Z transformation of the correlation coefficient to determine the cut-off value of our reporting a correlation. The criterion used was (1) the high cut off point for two variables whose true population correlation is 0.50. The high cut off values for analysis one = 0.857, analysis two = 0.840, and analysis three = 0.905, and the correlations meeting these criteria are starred in tables 7 and 8. (2) The low cut-off values were based on two variables with a population correlation of .350. These low cut-off values were: for analysis one = 0.801; for analysis two = 0.778; and for the third

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TABLE 7. INTERCORRELATIONS BETWEEN PERFORMANCE VARIABLES AND PHYSICAL VARIABLES OF EYE (FOR CUTOFF LEVELS FOR INCLUSION SEE APPENDIX IV)

		1st	2nd	3rd	1 Vertical Ocular Refraction (D)	7 Lens Front Surface Radius (mm)	8 Lens Front Surface Power (D)	9 Lens Thickness (mm)	10 Lens Back Surface Radius (mm)	11 Lens Back Surface Power (D)	12 Lens Equivalent Power (D)	13 Lens Power at Corneal Vertex (D)	14 Total Power of the Eye	15 Total Power of Eye at Corneal Vertex (D)	16 Vitreous Length (Plus 0.5 mm Retinal Thickness) (mm)	17 Vitreous Chamber Expressed in Diopters	18 Axial Length (mm)	19 Reduced Axial Length, Expressed in D	20 Interior Ocular Pressure (mm Hg)	21 Front Vertex Power of Lens (D)	22 Front Vertex Distance for Lens (mm)	23 Back Vertex Power of Lens (D)	24 Back Vertex Distance for Lens (mm)	25 Front Vertex Power of Total Optical System (D)	26 Front Vertex Distance for Total Optical System (mm)	27 Back Vertex Power of Total Optical System (D)	28 Back Vertex Distance for Total Optical System (mm)	29 Back Vertex Power for Ultrasonographic Eye (D)	30 Back Vertex Distance for Ultrasonographic Eye (mm)	31 The 1st (and 2nd) Principal Focal Distance of Equivalent Lens (mm)	32 The 1st Principal Focal Distance of the Total Eye Optical System (mm)	33 The 2nd Principal Focal Distance in the Total Eye Optical System (mm)	35 [illegible]	41 [illegible]	53 [illegible]	57 [illegible]
	2nd				1			7				8		9	10	11	12	13	14									15	16					17	31	32
	3rd				1	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	35	41	70	71
Phase I	Arc Test Diff Score (Arc Sec)	46	19	46	.912* .923* .925*		-.833	-.870				.853		-.820														.819	.817					[illegible]		[illegible]
	PSCT Test Diff Score (Arc Sec)	47	20	47	.942* .974* [illegible]							-.884*		-.796					.785									-.793	.782					.780		[illegible]
	Long Wavelength Usage in CLST (%)	48	21	48	.969* .934 .884	.966*	-.912*																													[illegible]
	Attenuation Model Prediction - Arc Test (Arc Sec)	52	25	52	-.850*							.778																								[illegible]
✓	Attenuation Model Prediction - PSCT (Arc Sec)	53	26	53	-.813 -.875						.913*	.939*			.837 .874	-.842 -.803	.799	-.861 .768		.916*	.892*	.921*	-.899							-.889					[illegible] .784	[illegible]
Phase II	After Arc - Before Drops (Diff Score Arc Sec)	54	27	54	.949* .966*													-.832																		[illegible]
	Pupil Size - Before Drops (in mm)	55	28	55					.875	.876														.929*	.92[illegible]*											
	Pupil Size - After Drops (in mm)	56	29	56			-.815	-.851																									.862*		[illegible]	
	Layback Effect (Arc) - Corr with Traditional	57	30	57				-.803																											[illegible]	
	Pupil Size After Drops (#56) - Pupil Size Before Drops (#55)	61	34	73																				-.881*	-.88[illegible]*	-.846	.846				-.898	.842				
	Rotation Correction in Radial (in Degrees)			58											.957*	-.969*	.877*	-.903*																		
	Rotation Correction in Transverse (in Degrees)			59	.909*										-.912*	.893*	-.941*	.923*																		
	Arc Test Diff Score (B-D-F) (in Arc Sec)			60	.958*									-.860														-.882	.837					[illegible]		[illegible]
	Effects of Rotation on Arc (Arc Sec/Degree)			61									-.825 -.988*	-.980*										-.924	-.930	[illegible]	.976*	[illegible]	.985*		[illegible]	.953*		[illegible]		
	Circular Staircase Diff Score (Arc Sec)			62	.958*									-.915*														-.915*	.907*					[illegible]		[illegible]
	Diff Score CSC Test Red vs Blue Field (Arc Sec)			63	-.909*							.893			.920*	-.912*	.936*	-.930*																		[illegible]
	CSC Test 2°-5° Diff Score (Arc Sec)			64	.963*									-.899														.899	.829					[illegible]		[illegible]
	CSC Test 2°-9° Diff Score (Arc Sec)			65	.935*									-.912*														-.912*	.904					[illegible]		[illegible]
	CSC Test - 5°-9° Diff Score (Arc Sec)			66	.951*									-.920*														-.930*	.919*					[illegible]		[illegible]
✓	Pupil Size - CSC Test - Achromatic Field (mm)			67				-.872																												
Phase I -	Arc Test - B-D-F (Old) Diff Score (Arc Sec)			69	.939*																														[illegible]	

TABLE 8. INTERCORRELATIONS BETWEEN PERFORMANCE MEASURES FOR PHASES I AND II. (FOR CUTOFF LEVELS FOR INCLUSION SEE APPENDIX IV.)

		1st	2nd	3rd	ARC Test Difference Score (Arc Seconds) 46/19/46	PSCT Test Difference Score (Arc Seconds) 47/20/47	Long Wavelength Usage in CLST 48/21/48	PSCT Test Red vs Blue Field Scores (Arc Sec) 49/22/49	CLST Achromatic Test (Arc Seconds) 50/23/50	CLST Chromatic Test (Arc Seconds) 51/24/51	Attenuation Model Prediction - Arc Test (in Arc Sec) 52/25/52	Attenuation Model Prediction - PSCT (in Arc Sec) 53/26/53	Aberr. ARC - Before Drops (Diff Score in Arc Sec) 54/27/54	Pupil Size - Before Drops (in mm) 55/28/55	Pupil Size - After Drops (in mm) 56/29/56	Laydack Effect - Correlation with Theoretical (Arc) 57/30/57	Chrom CLST (#51) - Achrom. CLST (#50) 60/33/72	Pupil Size - after drops #57 - Pupil Size Before Drops #55 61/34/73	Rotation Correction in Baoal (in Degrees) 58	Rotation Correction in Tropscope (in Degrees) 59	ARC Test Diff Score (B-D-F) (in Arc Sec) 60	Effects of Rotation on ARC Test (Arc Sec change per degree) 61	Circular Staircase Diff Score (Arc Sec) 62	Diff Score - CSC Test Red vs Blue Field (Arc Sec) 63	CSC Test - 2°-5° Field - Diff Score (Arc Sec) 64	CSC Test - 2°-9° Field - Diff Score (Arc Sec) 65	CSC Test - 5°-9° Field - Diff Score (Arc Sec) 66	Pupil Size - CSC Test - Achromatic Field (in mm) 67	Pupil Size - CSC Test - Red/Blue Field Ave (in mm) 68	ARC Test - Formats (B-D-F) - Diff Score (Arc Sec) 69
					← PHASE I							→	← ORTHOPHTHALMETRY SESSION					→	PHASE II										→	Ph I
Phase I	ARC Test Diff Score (Arc Seconds)	46	19	46	●																									
	PSCT Test Diff Score (Arc Seconds)	47	20	47	[illegible]* [illegible]*	●																								
	Long Wave Length Usage in CLST (%)	48	21	48	[illegible]* .917* [illegible]*		●																							
	PSCT Test Red vs Blue Field Score (Arc Sec)	49	22	49	.812		.814	●																						
	CLST Achromatic Test (Arc Sec)	50	23	50				.884	●																					
	Attenuation Model Prediction - Arc Test (Arc Sec)	52	25	52		-.830				[illegible]* .884* .98[illegible]*	●																			
↓	Attenuation Model Prediction - PSCT (Arc Sec)	53	26	53		-.800					.824	●																		
Phase II	Aberr. ARC - Before Drops (Diff Score - Arc Sec)	54	27	54	.915* [illegible]	.97[illegible]* .925*	-.833						●																	
	Pupil Size - After Drops (in mm)	56	29	56				-.919*				.837		●																
	Chrom CLST (#51) - Ach CLST (#50)	60	33	72						.997* .961* .981*	.98[illegible]* [illegible] .989*						●													
	Pupil Size After Drops (#56) - Pupil Size Before (#55)	61	34	73		.9[illegible]*								-.878		-.811* -.965* -.969*		●												
	ARC Test Diff Score (B-D-F) (Arc Sec)			60	.918*	.924*	.926*						.950*								●									
	Circular Staircase - Diff Score (Arc Sec)			62	.951*	.915*	.870						.946*				.788*						●							
	Diff Score - CSC Test Red vs Blue Field (Arc Sec)			63		-.859				.912		.965	-.864*				.925*							●						
	CSC Test - 2°-5° Field Diff Score (Arc Sec)			64	.946*	.925*	.870						.962*				.983*						.95[illegible]*		●					
	CSC Test 2°-9° Field Diff Score (Arc Sec)			65	.96[illegible]*	.928*	.930						.954*				.990*						[illegible]*		.985*	●				
	CSC Test 5°-9° Field Diff Score (Arc Sec)			66	.961*	.961	.928*						.966*				.991*						.95[illegible]*		.952*	.95[illegible]*	●			
↓	Pupil Size - CSC Test - Red/Blue Ave (mm)			68																								.97[illegible]*	●	
Phase I -	ARC Test (B-D-F) Diff Score (Arc Sec)			69	.995*	[illegible]	.979*						.901*				.983*						.957*		.945*	.985*	.964*			●

analysis = 0.865. The correlations listed in table 8 are all above the low cut-off value; those starred are above the high cut-off value.

The same cut-off scores were used for the performance vs. performance correlational study, which is included as table 8.

The Performance Measures

The high positive correlations among the chromostereopsis related tests reported previously are reflected in this table. The chromatic vs. achromatic difference scores on the ARC, PSCT, CLST are between .87 and .99. These tests also correlate with the long wavelength usage in the CLST. The newer test, F/P CST correlates with the three tests mentioned above with correlations ranging between +.90 and .99.

In this discussion then, we will use this group of performance tests to look for physical measures of the eye that may be related.

Relationships Among Performance and Physical Variables

The variable titled Vertical Optical Refraction (in Diopters) correlates positively and with values that reached our upper criteria with each of the tests mentioned above. Vertical Ocular Refraction (VOR), is the objective measurement of the simple refraction of the eye accomplished with a retinoscope and white light. This variable correlates highly with most chromostereopsis performance measures. The exceptions are the special condition measures, such as pupil size before and after dilation, rotation correction in the Troposcope and the quantity of the "Layback Effect." The direction of this relationship is that those individuals with the larger chromostereopsis have a larger minus dioptric value for their VOR. For three of our observers with large chromostereopsis, these values were -6.78, -4.04, -5.59 as averages of the right and left eye VOR. The direction of the chromostereopsis is not reflected in these values as two of these three observers are blue advancing. Individuals with intermediate minus VORs of -0.25 + -1.7 diopters have chromostereopsis of intermediate values. The individuals with the least chromostereopsis have VORs of +.5 to +.76 diopters.

These data suggest that overall system refractive state is associated with the magnitude, and not the direction of chromostereopsis. The individual who is emmetropic or slightly hyperoptic will tend to be among those individuals with chromostereopsis of lesser magnitudes.

The total power of the eye at the corneal vertex (15) and the total power of the eye (14) correlated with each other at .981. Utilizing variable 15 in conjunction with the length of the vitreous chamber in millimeters an interesting trend appears. The two observers with the largest blue advancing chromostereopsis have both high total power of the eye and a long vitreous chamber. The observers with intermediate chromostereopsis have less total power and shorter vitreous chambers. The red advancing high chromostereopsis observers are less clearly defined but tend to have low total power and long vitreous chambers.

The relationship developed above is logical in that the longer the vitreous chamber the greater lateral displacement on the retina of blue from red for the same chromatic interval. The chromatic interval will grow larger with an increase in total power of the eye. These data can be divided into an arbitrary dicotomy that separates the red advancing from blue advancing observers.

T.O.P. $<$ 54 diopters and vitreous length $>$ 18.4 millimeters = red advancing.

T.O.P. $>$ 54 diopters and vitreous length $>$ 17.0 millimeters = blue advancing.

Whether such a dicotomy would hold in a larger sample is a matter of conjecture.

Relationships That are Modulated by Retinal Areas

Vitreous depth, vitreous chamber expressed in diopters, axial length and reduced axial length in diopters are physical variables that correlate with four specific performance measures. These performance measures were: (1) Attenuation Model Prediction Peripheral Scan Chromostereopsis Test (PSCT); (2) Difference score between the red field from the blue field in the F/P CST; (3) Rotational Correction in the Badal in degrees; (4) Rotational correction in the Troposcope in degrees.

These correlations imply that as the physical dimension of the vitreous changes, so does the shape of the eye. The longer eye may not have an approximation of a sphere. The elongation may be greater along the optical axis than perpendicular to this axis. The performance tests that use the parafoveal vs. foveola comparisons reflect this change, i.e. 1 and 2 above. That performance measures that reflect distortions in the projection of the frontal parallel plane also reflect this asymmetries of the parafoveal regions for some observers.

The Back Vertex Power for the ultrasonographic eye (mm) correlates with the distortions in the frontal parallel plane and with the Foveola/Parafoveal Circular Staircase Test (F/P CST). Of specific interest is that for both of these physical variables the correlations increase as the comparative stimuli are positioned on a greater radial distance from the foveola. These data imply that these two variables predict the chromostereopsis of the individual as measured by the F/P CST more accurately when the comparative stimuli are in the parafovea than in the combination of fovea/parafovea and are in the foveola/fovea when the prediction is poorer than either of the above.

In these comparisons of the physical and performance measures we have just "broken the ground" in what appears to be a measurable relationship between anatomy, physical optics and performance.

SECTION V

CONCLUSIONS

A new form of the Parafoveal Scan Stereopsis Test was developed and evaluated. This test, called the Foveola/Parafoveal Circular Staircase Test, is most descriptively named as it looks like a birds-eye view of a circular staircase. The observer's task is to discriminate the stereoscopic height of the central disc relative to the spiralling staircase treads. The performance of three groups of observers lead to the following conclusions:

1. This test appeared to be valid as it's results correlate well with the precision chromostereopsis (ARC) test in measuring chromostereopsis in terms of the difference scores between chromatic and achromatic imagery. This correlation was .951; the relationship with the Peripheral Scan Chromostereopsis Test (PSCT) results was also high ($r = .879$). Performance on the Critical Limen Stereo Test (CLST) and that on the F/P CST correlated exceptionally well ($r = .988$).

2. Results on the achromatic portion of this test discriminated individuals as to their stereoscopic acuity as did the ARC and CLST tests. For two samples of 12 individuals each, the F/P CST indicated very similar means, standard deviations and regressions.

3. The achromatic portion of the F/P CST results, with six trained observers, indicated that stereoscopic acuity was related to area of the parafoveal stimulus. Area and radial distance are, to a degree, confounded in the F/P CST.

4. Observers reported that discrimination appeared easier to make with the F/P CST form of peripheral chromostereopsis test than with the PSCT, the latter having concentric ring comparison stimuli. The variances in our data confirm their opinion.

5. As a measure of chromostereopsis, the results of the F/P CST correlated with the Vertical Ocular Refraction, total power of the eye, and vitreous chamber length for a sample of six observers.

6. A trend was observed in that when the comparative stimuli (stair treads) in the F/P CST were in the far parafovea, performance correlated with back vertex distance in the eye to a higher degree than when the comparison was foveola/parafovea.

7. With the small sample of experienced observers, lower total optical power in the eye combined with longer vitreous chamber showed a positive correlation with red advancing chromostereopsis. T.O.P. of greater magnitude was associated with intermediate and long vitreous chambers for the blue advancing chromostereopsis group.

8. When long wavelength hues were assigned to the parafoveal comparison stimuli, the perceived location of the central disc moved less from the physical match than when short wavelength hues illuminated the parafoveal stimuli. The magnitude of the apparent shift of the central disc as hues are interchanged between foveal and parafoveal stimuli is different for each individual and not predicted by chromostereopsis as the single factor.

9. The adjacency hypothesis is less pertinent when comparative stimuli have twelve steps and are concentric to the foveola, than when the comparison is between only two or three stimuli.

The Badal Optometer was reconstructed on a larger optical bench and massive stand. Many changes were incorporated to improve its precision and reliability. New alignment procedures were adopted. Some of these procedures were applicable to the Troposcope. With these changes came an improved capability in measuring intervisual axes distance, interpupillary distance, image rotational control and interartificial pupil distance and size. With these improved capabilities short studies were conducted on the following topics:

IBXD (interbehavioral axes distance or intervisual axes distance) measurement for two observers was used to test the equipment and technique of the reconstructed Badal Optometer. With new targets designed for this purpose, it was concluded that the reconstructed Badal provided reliable measures.

The cyclotorsional resting state of an individual may induce a visual null, wherein he sees the frontal parallel plane as perpendicular to his line of sight, which will be different from the "instrument zero." It was hypothesized that the layback effect in the ARC test might be the result of just such a condition We found a trend, but no consistent effect of applying counter cyclorotation as an individual's correction. Interestingly, the cyclorotational correction applied to the observers correlated highly with measures of the length of the back of the eye, and the vitreous chamber. It was concluded that this hypothesis warranted further study as it was also found that vertical ocular refraction, total ocular power, vitreous chamber depth and back vertex distance were four variables highly correlated with chromostereopsis measures on these observers. An individual's perception of the frontal parallel plane was measured and corrected by cyclorotation of the stimulus. The amount of correction correlated with back vertex distance of the observer's eye. It was hypothesized that cyclorotational "correction" of the ARC test images would reduce or reverse the "layback" effect observed in earlier studies. The results were inconclusive with a positive trend.

APPENDIX I: CYCLOROTATION PILOT STUDY CONDITIONS AND RESULTS

FORMAT B

Row Pairs	Direction of Layback Effect	Response Shift With Zero Rotation CA	CK	ES	TB	Response Shift With Cyclorotation CA(1.5)	CK(2.6)	ES(1.6)	RB(1.2)	Net Correction (1) CA	CK	ES	RB
A/B	+	+1	-1	+1	0	0	0	+1	-1	-1	+1	0	-1
B/C	-	-1	+1	0	0	0	0	-2	0	-1	+1	+2	0
C/D	+	0	+1	+1	0	0	0	+2	0	0	-1	+1	0
D/E	-	-1	0	-1	0	-1	0	-2	+1	0	0	+1	-1
E/F	+	+1	0	+1	+1	0	-1	+2	0	-1	-1	+1	-1
F/G	-	-2	-1	-3	-2	-1	-1	-2	-2	-1	0	-1	0
G/H	+	+1	0	+4	+2	+1	0	+4	+2	0	0	0	0
H/I	-	-2	0	-3	-1	-1	-2	-3	-1	-1	+2	0	0
I/J	+	+1	+1	+3	+1	+1	0	+2	+1	0	-1	-1	0
										-5	+1	+3	-3

(1) Response steps (plus is in layback direction - minus is in corrective direction)

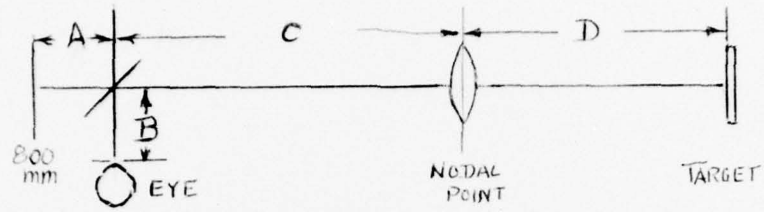
FORMAT D

Row Pairs	Direction of Layback Effect	Response Shift With Zero Rotation CA	BB	CK	ES	RB	Response Shift With Cyclorotation CA(3.0)	BB(2.0)	CK(5.2)	ES(2.4)	RB(2.2)	Net Correction (1) CA	BB	CK	ES	RB
A/B	-	-1	-1	+2	-2	-1	-1	+2	-2	-1	+1	0	-3	+3	-1	-2
B/C	+	+1	+1	0	+4	+1	+1	-1	+2	+2	-1	0	-2	+2	-2	-2
C/D	-	-1	-1	0	-1	-2	-1	+1	-2	-2	-1	0	-2	+2	+1	-1
D/E	+	+2	0	0	+2	+2	+1	0	+2	+2	0	-1	0	+2	0	-2
E/F	-	-2	0	-1	-3	-2	-2	0	-3	-1	-2	0	0	+2	-2	0
F/G	+	+1	0	+1	+3	+2	+1	0	+2	+2	0	0	0	+1	-1	-2
G/H	-	-1	+1	0	-1	0	-1	+1	-1	-1	+1	0	0	+1	0	-1
H/I	+	+1	+1	0	+3	+1	0	-1	+2	+1	+1	-1	-2	+2	-2	0
I/J	-	-2	-1	0	-3	-1	-1	+1	-2	-2	-1	-1	-2	+2	-1	0
												-3	-11	+17	-8	-10

(1) Response steps (plus is in layback direction - minus is in corrective direction)

APPENDIX II. LOCATION OF LENSES, ETC. ON BADAL

Midpoint of bench = 800 mm.



Used aluminum bar to measure (set) initial mirror-to-lens distance.
Aluminum bar = 328 mm.

1. Assume eye nodal point-to-cornea distance of 7 mm.
2. Assume cornea-to-mirror distance ("B") of 98 mm.
3. Focal length of lenses = 381 mm.
4. Front crown (vertex) of lens-to-nodal point = ~10 mm.
5. Assume lenses, etc. setup for IBXD of 64 mm.
6. ∴ Distance "A" = 32 mm.
7. From (1) and (2) above, distance "C" = 276 mm.

Procedure: Used aluminum bar to set mirror-to-lens vertex distance at 328 mm.

Readings on scale were: Left - 429 mm. Right - 1170 mm. (all "left" readings taken at "10" of vernier instead of "zero")

Correcting for difference between bar length and desired distance: (328 - 276 = 52 mm)

Left = 429 + 52 = 481 mm.
Right = 1170 - 52 = 1118 mm.

Correcting for lens-to-nodal point distance:

Lenses should be set at:

Left: 481 + 10 = 491 mm.
Right: 1118 - 10 = 1108 mm.

Mirror-to-cornea distance (98 mm) consists of:

(A) Mirror-to-front surface of artificial pupil holder (not pupils themselves) of 74 mm.

(B) Artificial pupil holder-to-cornea distance: D = 98 - 74 = 24 mm.

OR

(A) Mirror-to-front surface of artificial pupils themselves of 77 mm.

(B) Artificial pupils-to-cornea distance = 98-77 = 21 mm.

LENS-TO-TARGET DISTANCE

(1) Aluminum bar used to set lens vertex-to-front surface of target (set in front slot and against holder) *distance of 328 mm.*

Scale reads:	Left	-	242 ("10")
	Right	-	1359 ("zero")

(2) Assume rear lens vertex-to-nodal point distance of $\sim$12.5 mm.

$\therefore$ To get lens nodal point-to-target distance of 381 mm.

(optical infinity): Δ = 381-(328+12.5) = 40.5 mm.

For ∞ , scales should read: Left: 242-40.5 = <u>201.5 mm</u>.

Right: 1359 + 40.5 = <u>1399.5 mm</u>.

POINTER CONE LOCATION

(1) To set at 2.0 diopters: $Q = F^2u - F$ where

Q = target distance in diopters

F = power of lens in diopters

u = distance from lens to target in meters

$$-2.0 = (2.625)^2(u) - 2.625$$

$$u = \frac{(2.0) + 2.625}{6.89}$$

$$u = \sim 91 \text{ mm.}$$

(2) Scale Readings:

Left: "10" at 430 mm = 12.5 + 58.5 = 71 mm.
Right: 1170 mm = 12.5 + 53.5 = 66 mm.

For u = 91 mm, readings should be:

Left: 430-20 = <u>410</u>

Right: 1170 + 25 = <u>1195</u>

OPTICAL DISTANCE OF TARGET IN BADAL

$Q = F^2 u - F$ where Q = diopter value image distance
F = power of lens in diopters
u = distance in meters of target from lens.

$F = \frac{1000 \text{ mm}}{381 \text{ mm}} = 2.625$

NOTE: "Q" should be expressed as negative to get positive values for "u".

$Q = 6.89(u) - 2.625$

for target at focal length (381 mm):

$Q = 6.89\ (.381) - 2.625 = 0$ (zero)

for Q = 1.5 diopters:

$-1.5 = 6.89\ (X) - 2.625$

$X = 163$ mm

for Q = 2.5 diopters:

$-2.5 = 6.89\ (X) - 2.625$

$X = 18$ mm

for Q = 2.3 diopters:

$-2.3 = 6.89\ (X) - 2.625$

$X = 47$ mm

$-2.0 = 6.89\ (X) - 2.625$

$X = 91$ mm

$-.2 = 6.89\ (X) - 2.625$

$X = 352$ mm

$\Delta = 381 - 352 = 29$ mm

$-.16 = 6.89\ (X) - 2.625$

$X = 358$ mm

$\Delta = 381 - 358 = 23$ mm

APPENDIX III

DATA SHEET

CIRCULAR STAIRCASE MODEL OF FOVEA/PARAFOVEA
CHROMOSTEREOPSIS TEST

Observer________________
IPD_____ or IBX__________
Corrective Lenses__________
Series 18 36 72

RED CHROMATIC FIELD

Order	Field Area	Format	13	12	11	10	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	2.2 to 5	F		-		-		9		10		11		12		1		2		3		4		5		6		7		8
		B		-		9		10		11		12		1		2		3		4		5		6		7		8		-
		A	9		10		11		12		1		2		3		4		5		6		7		8		-		-	
	2.2 to 9	F		-		-		9		10		11		12		1		2		3		4		5		6		7		8
		B		-		9		10		11		12		1		2		3		4		5		6		7		8		-
		A	9		10		11		12		1		2		3		4		5		6		7		8		-		-	
	5.5 to 9	F		-		-		9		10		11		12		1		2		3		4		5		6		7		8
		B		-		9		10		11		12		1		2		3		4		5		6		7		8		-
		A	9		10		11		12		1		2		3		4		5		6		7		8		-		-	

BLUE CHROMATIC FIELD

Order	Field Area	Format	13	12	11	10	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	2.2 to 5	F		-		-		9		10		11		12		1		2		3		4		5		6		7		8
		B		-		9		10		11		12		1		2		3		4		5		6		7		8		-
		A	9		10		11		12		1		2		3		4		5		6		7		8		-		-	
	2.2 to 9	F		-		-		9		10		11		12		1		2		3		4		5		6		7		8
		B		-		9		10		11		12		1		2		3		4		5		6		7		8		-
		A	9		10		11		12		1		2		3		4		5		6		7		8		-		-	
	5.5 to 9	F		-		-		9		10		11		12		1		2		3		4		5		6		7		8
		B		-		9		10		11		12		1		2		3		4		5		6		7		8		-
		A	9		10		11		12		1		2		3		4		5		6		7		8		-		-	

Response Steps Series 18 = 11.3 Series 36 = 5.54 Series 72 = 2.77

APPENDIX III

DATA SHEET

CIRCULAR STAIRCASE MODEL OF FOVEA/PARAFOVEA

CHROMOSTEREOPSIS TEST

Observer______________
IPD______ or IBX__________
Corrective Lenses__________
Series 18 36 72

ACHROMATIC TEST

Order	Field Area	Format	13	12	11	10	9	8	7	6	5	4	3	2	1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	2.2 to 5	F		-		-		9		10		11		12		1		2		3		4		5		6		7		8
	2.2 to 5	B		-		9		10		11		12		1		2		3		4		5		6		7		8		-
	2.2 to 5	A	9		10		11		12		1		2		3		4		5		6		7		8		-		-	
	2.2 to 9	F		-		-		9		10		11		12		1		2		3		4		5		6		7		8
	2.2 to 9	B		-		9		10		11		12		1		2		3		4		5		6		7		8		-
	2.2 to 9	A	9		10		11		12		1		2		3		4		5		6		7		8		-		-	
	5.5 to 9	F		-		-		9		10		11		12		1		2		3		4		5		6		7		8
	5.5 to 9	B		-		9		10		11		12		1		2		3		4		5		6		7		8		-
	5.5 to 9	A	9		10		11		12		1		2		3		4		5		6		7		8		-		-	

FRONTAL PLANE ROTATION TEST

ROTATION TEST (Circle/Line)

	Rotation								
	Top Nasal					Top Temporal			
Line Slope	4	3	2	1	0	1	2	3	4
Top Near									
Bottom Near									

Self Adjustment to Zero	Trial			
	1	2	3	
Right Eye				
Left Eye				

APPENDIX IV.

CALCULATION OF CUT-OFF VALUES FOR PEARSON "r"

Using the Z transformation for r:

The standard error of Z' is given in Edwards, 1962, as:

$$\sigma_{z'} = \frac{1}{\sqrt{n-3}}$$

For Anal. #1 (n = 8): $\sigma_{z'} = \frac{1}{\sqrt{8-3}} = .447$

For Anal. #2 (n = 9): $\sigma_{z'} = \frac{1}{\sqrt{9-3}} = .408$

For Anal. #3 (n = 6): $\sigma_{z'} = \frac{1}{\sqrt{6-3}} = .577$

For an α = .05 and a one-tailed test:

Z must be $\geq$ *1.645 to be significant*

Test of the Null Hypothesis is made by: $Z'' = \frac{Z' - \bar{Z}'}{\sigma_{Z'}}$

(1) High cut-off point (for two variables whose true population correlation is .500):

$$\bar{Z}'_{.500} = .549$$

$\therefore$ For Anal. #1 (n = 8):

$$1.645 = \frac{Z'_1 - .549}{.447}$$

$Z'_1 = 1.645\ (.447) + .549 = 1.284 \quad r'_{H1} = 1.284 = .857$

For Anal. #2 (n = 9):

$Z'_2 = 1.645\ (.408) + .549 = 1.220 \quad r'_{H2} = 1.220 = .840$

For Anal. #3 (n = 6):

$$Z'_3 = 1.645\ (.577) + .549 = 1.498 \quad r'_{H3} = 1.498 = .905$$

(2) Low cutoff values:

H: Two variables with population correlation = .350

$$\bar{Z}'_{r = .35} = .365$$

For Anal. #1 (m = 8):

$$Z'_1 = 1.645\ (.447) + .365 = 1.1003$$

$$r_{L1} = .801$$

For Anal. #2 (m = 9:)

$$Z'_2 = 1.645\ (.408) = .365 = 1.0362$$

$$r_{L2} = .778$$

For Anal. #3 (m = 6):

$$Z'_3 = 1.645\ (.577) + .365 = 1.3142$$

$$r_{L3} = .865$$

Reference:

Edwards, A. L. Experimental Design in Psychological Research. New York: Holt, Rinehart and Winston, 1962, pp. 79-85.

APPENDIX V.

DATA ON PUPIL SEPARATION FOR TROPOSCOPE AND ARTIFICIAL PUPIL DEVICE

To confirm the physical separations of the exit pupils in the troposcope (V1195) and the 2mm artificial pupil attachment, inside/outside calipers with a 0.001 inch capability were used to measure separations of left and right edges of the lenses and artificial pupils.

A. Exit Pupils on Troposcope V1195 (older model)

With the Troposcope IPD set at 64.00mm, the following measurements were made:

LEFT EDGE TO LEFT EDGE:	2.522 in. (CDA)
RIGHT EDGE TO RIGHT EDGE:	2.520 in. (CDA)
LEFT EDGE TO LEFT EDGE:	2.521 in. (CLK)
RIGHT EDGE TO RIGHT EDGE:	2.520 in. (CLK)
AVE.=	2.5207 in. = .00096 in.

2.5207 in. = 64.026mm.
Ave. Error in Setting = .026mm.

B. Artificial Pupil Holder

With the artificial pupils set at 63.50mm, the following measurements were made:

OUTSIDE EDGE SEPARATION:	2.500 in.
INSIDE EDGE SEPARATION:	2.492 in.
AVE. (pupil center separation):	2.496 in.

2.496 in. = 63.398mm.
Ave. Error in Setting = .102mm.

APPENDIX VI

MEASUREMENT OF ILLUMINANCES IN EXPERIMENTAL EQUIPMENT AND LABORATORY

		J6503 Probe	Ft.L. Calculated	Ft.C J6511 Probe
1.0	AMBIENT ROOM ILLUMINANCE			
1.1	Fluorescent and Tungsten Overhead Sources On			
1.1.1	BADAL: At observer's head position and at eye level	73*	89	80
1.1.2	TROPOSCOPE: At observer's head position and eye level	91*	112	101
1.2	Tungsten Overhead Sources at Performance Data Collect Setting			
1.2.1	BADAL: At observer's head position and eye height	2.2*	2.45	2.2
1.2.2	TROPOSCOPE: At observer's head position and eye height	1.8*	2.20	2.0

		SETTINGS MAXIMUM	HIGH	INTER.	LOW
2.0	BADAL SOURCES				
2.1	Right Eye Source (Before Lens) Maximum (Single Source on)	3600			270
2.2	Left Eye Source (Before Lens) (Single Source on)	5400			37
2.3	Both On	3200 (R) 5100 (L)			
	Both on and Balanced	3200	2700	1700	270

3.0 PHOTOMETER

Tektronic, J16 Digital Serial B-020495, calibrated 5/10/76. The calibration was with the "Luminance Probe" J6503. This probe measures in foot Lamberts (ft.L.) and is used for measuring the intensity of light emitted or reflected from a surface.

*NOTE: Measurements were made of light reflected from a MacBeth plate of 82% reflectance with the J6511 probe: This probe called an illuminance probe is used for the same purpose. However, when it is used with a cosin head and its diffusing hemisphere the units are Ft.C.

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