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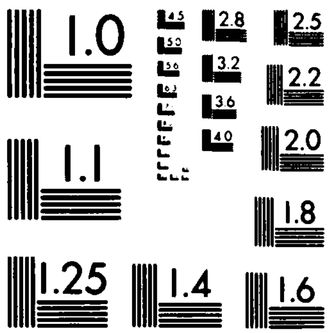

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ABSTRACT

Five subjects (ages 19-22) were monocularly occluded for six days. Their verneir thresholds and fixation integrity measurements (using a modified Haidinger's brush) were determined at pre-occlusion, two, four, and six days of monocular occlusion, and 24 hours after patch removal. The occluded eye demonstrated a significant rise in vernier threshold after the two day occlusion period. The threshold continued at that level throughout the six day occlusion period before returning to normal within 24 hours after removal of the patch. The non-occluded eye did not show a matching enhancement effect characteristic of the competition model. Every subject also manifested an amount of eccentric fixation in the occluded eye. The eccentric fixation did not generally increase with time occluded, but did show an elastic response by returning to normal foveal fixation in 24 hours.

The decrement in verneir performance in the occluded eye is probably best explained as a temporary (elastic) eccentric fixation rather than the loss of channels as theorized in the competition model. Our data did indicate a faster drop off of verneir acuity with retinal eccentricity than did the interpolated data of Westheimer's (1979) postulating that a secondary process was also contributing to the rise

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in threshold. The secondary process could possibly be either a loss of neural channels or an instability of fixation after patch removal. Other experiments demonstrating a decrement in visual performance could be investigating an area of the retina eccentric to fixation.

THE EFFECT OF LONG TERM MONOCULAR OCCLUSION ON VERNIER THRESHOLD: ELASTICITY IN THE YOUNG ADULT VISUAL SYSTEM

BY

RICHARD JAMES DENNIS

Submitted to the faculty of the Graduate School
in partial fulfillment of the requirements
for the degree of Master of Science in
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Indiana University
June, 1986

Accepted by the faculty of the Graduate Committee for Physiological Optics, Indiana University, in partial fulfillment of the requirements for the degree of Master of Science.

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

APPENDIX II (Tables) CONTINUED

INTRODUCTION

I. Vernier Acuity

Some spatial discriminations can be made by a normal subject with thresholds much lower than ordinary resolution acuity. (54) Because of their dramatically lower thresholds these determinations have been classified as hyperacuities. Two well known examples of hyperacuities are vernier or alignment acuity and stereoscopic acuity. (54) Even though stereoscopic acuity and vernier acuity are both classified as hyperacuities, there is disagreement as to whether they are processed by different mechanisms. Shimojo et. al. (1984) have estimated that the time course of development in infants of vernier and stereo acuities are similar which has led to speculation that the mechanisms could be related. Stigmar studied the stereo-vernier relationship in 1970 and concluded that there was a similar "measuring mechanism" for both types of hyperacuities. (49) Despite these similarities some authors (see, for example Westheimer, 1979) believe that there are two separate processing mechanisms. (55)

Vernier acuity is a precise measurement of visual performance that entails moving two line targets to form one continuous uninterrupted straight line. (44) It can also be defined as the ability to detect a defect in a contour or a mis-alignment of edges or bars. (10, 21, 49) Various vernier thresholds have been reported, usually ranging between 0.5 and 12 seconds of arc. In every instance the vernier threshold is strikingly lower than the threshold for resolution. (19, 34, 44, 46, 49, 55, 57) The vernier task is also reported to be a highly repeatable and accurate psychophysical measurement (see, for example, Freeman and Bradley, 1980).

The minimum resolvable angle for grating resolution, Snellen acuity, and other recognition and resolution acuities ranges between 30 to 60 arc seconds which correlates with the diameter of an inner segment of a typical human foveal cone and the limit set by the diffraction of light. (20, 22, 61) The retina and/or the physical nature of light becomes an impasse in the fine tuning of spatial information and do not explain the extraordinary thresholds found using the vernier condition. (54) For example, to explain hyperacuity processing the retina would need a much denser spatial grain than the present arrangement; yet even then, diffraction would prevent such a performance. (57, 61) The neural processing and channelling that determines the level of performance found using a vernier acuity task does not seem to be limited by the anatomical arrangement at the retina. (56, 57) It is most likely then that a significant amount of processing is accomplished at the cortical level by line detecting elements. (49) For instance Westheimer (1984) had theorized that ocular dominance columns in the visual cortex, because of their variance in width, may be the "anatomical site" for hyperacuity integration.

A number of vernier target parameters have been investigated to help explain the sensitivity of vernier acuity. Foley-Fisher (1973) found that vernier acuity improved as the target line length was increased up to one degree (the approximate area of the fovea centralis), but thereafter showed no change. (20) He shows results which demonstrated linear spatial summation up tc a target length of 20 minutes of arc. (20) Lack of linearity beyond 20 minutes of arc was explained by the following: A) The neuronal connections are more divergent beyond this point, B) There is a nonuniformity in the distribution of foveal cones (more densely packed centrally), and C) The effective resolution element becomes larger with more peripheral eccentricities. (20) However, Sullivan et. al., (1972) found no significant difference in vernier threshold (about four seconds of arc) no matter what the length of their target lines. According to their data, the typical vernier task does not involve the averaging of the position of an edge of a line but rather a judgment as to the tilt from vertical of the inner ends of the stimuli. (50) Vernier acuity is also affected by the separation of the line targets with maximum performance when the angle between the two ends of the segments is from three to five minutes of arc. (22, 52) Beyond that separation vernier performance deteriorates, most likely due to the availability of fewer receptors that are able to integrate signals over the wider distances. (22) Separations less than three minutes of arc appear to increase vernier thresholds.

Watt et. al. (1983) studied the effect of corner blur[1] on vernier acuity and found the highest acuity when the corners of the target were clearly defined. (52) Vernier performance drops when any amount of corner blur is introduced. (52) Watt et. al. suggested that two clues are used in vernier acuity: the overall orientation clue and the relative position clue. The experiments of Beck and Schwartz (1978) with dot stimuli support the concept of orientation rather than alignment for vernier definition. Westheimer and McKee (1975) studied the effect of motion across the retina and its impact on vernier performance. Vernier thresholds appeared to be mostly unaffected by target movement although some subjects demonstrated a lower threshold during motion. (58) Most authors agree that eye movements are of limited benefit in refining the vernier task (see for example, Keesey, 1960).

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[1]Corner blur is defined by Watt et. al. as a series of vernier targets with the abruptness of the corner break or offset degraded by varying amounts.

McKee and Westheimer (1978) investigated the training effects in vernier acuity and found that improvement in performance was a function of practice. Subjects reached a plateau in threshold only after 1,000 to 1,500 responses and even then the authors felt some very small additional improvement in performance could be ascertained. (34) McKee and Westheimer believe that this improvement in vernier performance is actually a "fine tuning" of the neural mechanism responsible for vernier alignment, rather than enhancement of motor control or more accurate accomodation; However, traditional improvements due to other aspects of learning were not explicitly considered. (34)

A vernier target seen binocularly should show a lower threshold if the signals are binocularly summated. Stigmar (1970) concluded that there was no significant difference between the binocular vernier threshold and the threshold of the better seeing eye. According to Stigmar there does not appear to be the additive effect for vernier acuity. (49) Freeman and Bradley however, found a binocular vernier threshold improvement (as compared to the mean value of the monocular thresholds) nearly equal to the square root of two, a value of importance in probability and physiological summation. (21)

The assumptions that vernier acuity is processed exclusively at the cortical level and that it is a repeatable, accurate, psychophysical method have recently been used for studying the effect of early monocular deprivation on the visual cortex. Freeman and Bradley (1981) were interested in studying what they thought might be minute differences in the visual performance of the functional eyes of monocular subjects as compared with a control group with normal binocular vision. Using this more sensitive measure, their results show that the functional eyes of the monocular subjects had better vernier acuity than either eye of the binocular subjects. (21) They concluded that the enhancement effect of the monocular subjects could possibly be due to an "active neural recruitment" in the visual cortex because of early monocular deprivation. (21) Johnson et. al. (1982) also used vernier acuity in their experiment which was designed to differentiate visual resolution capacities between the non-deprived eye of a subject with a congenital monocular cataract and that of an identical twin brother with no such anomaly. Their results contradicted that of Freeman and Bradley as they found no statistically significant enhancement of vernier acuity in the non-deprived eye. (32)

II. Monocular Deprivation Experiments-The Animal Model

Plasticity in animals during a "critical period" has been well demonstrated by Hubel and Wiesel and many other authors. (23, 27, 28, 43, 53) This critical period for kittens, in which their susceptibility to the effects of lid closure is especially significant, begins near the fourth week and remains critical until the eighth week. (28) The effects of monocular deprivation during this period can be dramatic, even for short periods of stimulus deprivation. (28) This monocular loss of patterened vision during the critical period can lead to domination of the cortical cells by the non-deprived eye. (7) Blakemore and VanSluyters (1974) explained the critical period in kittens as a time when the afferent connections of the cortical cells are "utterly plastic". Hubel and Wiesel (1970) suggested an analagous critical period for man which could be significantly longer, possibly several years. The critical period for other animal models is not as well defined and most likely varies a great deal.

The onset of the critical period in cats may not be totally age related but may instead be activated by their first experience with light. (39) Mower and Christen (1985) prolonged the onset of the susceptible period by up to two years by rearing their cats in total darkness. Cortical cells were driven binocularly as long as the cats were maintained in an environment of total darkness, but when light was introduced the cats immediately became sensitive to the effects of monocular deprivation. (39) Neural plasticity in the visual cortex as defined by the responsiveness to monocular deprivation began to decline after the first visual experience. (39) Raviola and Wiesel (1978) manifested a similar outcome in an experiment on myopia development with dark reared monkeys. An earlier experiment with monocular deprivation in young rhesus monkeys had shown the development of a substantial amount of myopia in the eye with the surgically fused lid. (53) The fused lid of the monkeys attenuates the light by approxiamtely a half a log unit thus still giving the animal some form of visual experience. (43) Those monkeys reared in total darkness did not develop myopia until the eye with the fused lid was exposed to light. (43) The first visual experience (not necessarily pattern vision) appears to be a trigger mechanism in activating the developmental period for the visual system in the kitten and monkey.

Previous electrophysiological experiments have shown that newborn kittens and monkeys have cortical cells at birth with two properties; binocularity and orientation selectivity. (8,9) In both species monocular deprivation by lid suturing causes a majority of the cells of the visual cortex to be dominated by the open eye. (9) This domination is more profound the earlier deprivation is started in the life-cycle of the animal. Morphological changes, after deprivation, in the visual cortex of these newborns indicate the plastic nature of young kittens and monkeys. Studies using horseradish peroxidase in kittens demonstrated a loss of afferent fibers to the visual cortex from the corresponding lamina of the lateral geniculate body of the deprived eye. (9) Following enucleation or lid suturing in their juvenile macaque monkeys, Hubel, Wiesel, and Levay (1977) noted a significant change in the ocular dominance columns in layer IV C of the visual cortex. The columns of the deprived eye shrunk to a lesser width while those of the open eye showed a definite increase in width. (29) They explained this change in ocular dominance column width as a "sprouting of terminals" from the columns of the seeing eye to the territory of the deprived eye columns or a retraction of fibers from layer IV C after deprivation. (29) Those morphological changes appear to be the foundation of the competition model used to explain many psychophysical experiments.

Neural plasticity in the visual system of adult animals is a topic of current debate and investigation. There is recent evidence that the adult cat may continue to be susceptible to antagonistic binocular interactions (i.e. the neurons of the non-deprived eye gain control of the central channels previously used by the deprived eye) throughout its entire life. (14) The permanence and magnitude of the changes in the cortical connections is a function of the age of the animal. Two experimental paradigms have been used to show plasticity in the adult cat: enucleation of the non-deprived eye and monocular paralysis experiments. Hoffman and Cynader (1977) after enucleating the non-deprived eye in their adult cats, reported an unmasking or a reconnection of synaptic junctions at the level of the visual cortex and superior colliculus for the previously deprived eye: however, they observed no other neuronal changes. Fiorentini and Maffei (1974) immobilized one eye in adult cats and noticed a rapid loss of binocularity in the simple cells of the striate cortex. In a similar experiment, Brown and Salinger (1975) found a decrease of the X-cell[2] population in the lateral geniculate body of the adult cat. These investigators believe that the attrition of X-cells in the LGB provides a new demonstration of neural plasticity in the adult visual system. (13)

Creutzfeldt and Heggelund (1975) used a unique paradigm with their adult cats. They exposed them to a vertically striped environment and noted a decrease in the number of striate cortex neurons sensitive to the vertical orientation in comparison to the horizontal. (14) This result is similar to some psychophysical experiments where the nervous system actually becomes less sensitive to the exposed stimulus.

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[2] An X-cell is defined physiologically as a brisk sustained ganglion cell.

These authors interpret their findings as the cortex being an adaptive cortical network rather than as a "fixed wired system"; however, their results completely contradict the findings of Blakemore and Cooper (1970) who found that the majority of cortical neurons in their study showed an orientation preference in the same direction as the environment. (14, 63) Harwerth et. al., (1984) used the enucleation paradigm with two rhesus monkeys in order to find the possibility of functional but suppressed neural connections in the previously deprived eye. They did not find any functional improvement in the deprived eye as similar experiments with cats had shown, but there were only two monkeys in the sample. (24) Even though plasticity in the adult animal visual system appears evident, the nature of this plasticity is not completely understood nor are the morphological changes fully known. (29)

III. Monocular Occlusion-Psychophysical Experiments

There has recently been a number of psychophysical experiments using monocular occlusion to examine the effect of stimulus deprivation on the visual performance of adult human subjects. This type of research came into vogue following the demonstration of plasticity in the visual system of the post critical period adult cat. (48) The extent and permanence of neural plasticity in the human again seems to depend on age. (41)

The "critical period" for the human, where it is most susceptible to an abnormal visual experience, is still not well defined but of importance in the treatment of amblyopia and other anomalies that cause monocular deprivation (eg. monocular congenital cataract). Banks and Aslin (1975) determined a "specific period of development" for their subjects (convergent esotropes) which ranged from one year at onset to three years of age. This peak period for binocular visual development is probably a conservative estimate for actual visual plasticity as defined by susceptibility to monocular deprivation. Odom et. al. (1981) used the visual evoked potential to determine visual acuity in children with unilateral naturally deprived eyes (i.e. cataracts, vitreous hemorrhage, and esotropia). After patching the previously non-deprived eye and correcting the optical image of the deprived eye, acuity in the younger subjects (ages five and fifteen months) improved rapidly while the older subjects (ages four and eight years) improved slowly if at all. (41) Jastrzebski et. al. (1984) introduced an interesting model for stimulus deprivation in children called the S.P.E. : sensitivity, plasticity, elasticity. Plasticity is defined as that time where permanent changes can be made to the visual system while the elastic period includes the time where changes can be made but they are temporary. (31) According to the model the sensitive period for plasticity ends at about four and one half years and that for elasticity extends to six and one half years or beyond. (31) There are other reports that the plastic period may last ten or eleven years and evidently elasticity in the visual system may remain throughout life. (30)

One explanation of elasticity in the adult human is based on the competition model. According to the competition model, the eye that is deprived of light or pattern stimulation loses control of its central channels while the non-deprived eye gains the competitive edge. (24) These antagonistic binocular interactions probably take place either at the level of the lateral geniculate body or the visual cortex. Since the changes in visual performance of the adult are temporary, the source of this change in cortical ocular allegiance may be a function of synaptic transmission rather than a true morphological change. (35) If the competition model holds true there should be an actual enhancement of visual performance in the non-deprived eye due to neural recruitment. There also should be an accompanying decrement in visual performance of the deprived eye. Both of these observations may be coupled with binocular inhibitions; i.e., binocular visual performance would be poorer than the performance of the non-deprived eye.

Some residual neural plasticity in the adult visual system has been demonstrated by the use of short term (24 hours or less) monocular occlusion experiments. Significant results in some experiments were shown after only a few hours of monocular occlusion. Tyler and Katz (1977) used the human visual evoked potential and a short term monocular deprivation paradigm to test the competition model. They recorded over a nine hour period using both total occlusion and deprivation by induced anisometropia. Their results showed a small nonsignificant decrement in mean VEP amplitude in the deprived eye and a surprisingly large significant enhancement effect in the non-deprived eye. (51) The authors explain their results by the competition model with binocular interaction at the level of the LGB or visual cortex, and not as an atrophy of the deprived pathway. (51) Zubek and Bross (1972) investigated the effect of short term monocular occlusion (24 hours) on the critical flicker frequency threshold on thirty male university students. Again there was no significant change in CFF of the occluded eye but a highly significant enhancement effect following an initial CFF depression in the non-occluded eye. (60)

Other psychophysical investigators have used longer periods of monocular occlusions in their experiments. Brown et. al. (1978) occluded their subjects monocularly for eight continuous days to prove the importance of sustained visual input to the adult human visual system. The acuity in the non-deprived eye as measured by standard eye charts and the high frequency cut off of the contrast sensitivity function did not change; however, there was a decrease in contrast sensitivity for the middle spatial frequencies in the deprived eye. (6) Their subjects also reported a temporary loss of stereopsis and the perception of diplopia with all effects returning to normal after 24 hours. (6) Smith and Harwerth (1979) repeated the eight days of monocular occlusion and found that their subjects demonstrated binocular summation with low contrast stimuli but binocular inhibition with high contrast stimuli. They concluded that the decrease in binocular facilitation (i.e. a binocular to monocular performance ratio in excess of the square root of two) is not due to the loss of visual resolution in the occluded eye, but rather due to a small misalignment between the visual axes. (47) This explanation may be the basis for the reported diplopia in the Brown experiment; futhermore, Smith and Harwerth found normal stereopsis immediately after patch removal.

Other investigators have examined the effects of monocular occlusion on stereopsis and related binocular functions. Herman et. al. (1974) explored the effect of monocular occlusion versus binocular deprivation on stereoscopic acuity. After a relatively short period of deprivation (eight hours), the monocularly deprived group had a deteriorated stereoscopic acuity estimate while the binocularly deprived (i.e. a temporary disuse of the system) group did not have impaired stereoscopic acuity. (25) The authors had two explanations for the decrease in stereoscopic sensitivity. 1) The binocular sensory network became disorganized with dissimilar sensory inputs from corresponding points. 2) Monocular patching interferes in normal oculomotor functions necessary for binocular disparity information in stereopsis. (25) Smith et. al. (1980) found that twelve days of continuous monocular occlusion did not completely disrupt stereopsis for their subjects; however, they corrected the manifested heterotropias with prisms before testing. These authors also conclude that the interruption of the normal oculomotor function would be the cause in any loss of stereoscopic sensitivity following monocular occlusion. (48) An experiment by Bross (1983) also suggests a change in the oculomotor system after monocular deprivation. He found an increase in esophoria especially at the near setting, after a twenty four hour occlusion period. As in other studies with monocular occlusion in the adult, the changes in visual performance were back to normal within twenty four hours. (11) Bross suggests that the length of recovery for visual function may be equal to the time of occlusion, but recovery within twenty four hours has been the rule for experiments with adults even for occlusion up to fourteen days.

Monocular occlusion has been theorized to have a profound effect on photoreceptor orientation in the occluded eye. (1, 2, 6, 15, 16) Photoreceptors are normally oriented toward the exit pupil and may be maintained by an active phototropic mechanism. (1) The alignment of the receptors appears to be exceptionally stable over time and is present at birth. (1, 16) This alignment and the effect on it by the absence of light has been measured using the Stiles-Crawford function of the first kind. This function measures the directional sensitivity of the photoreceptors (the rho value of the function) and is a parabola that flattens when directional sensitivity is reduced. (6) The loss of directional sensitivity and disorientation of the receptors following monocular occlusion could be an explanation of visual dysfunction in the occluded eye of previously mentioned psychophysical experiments. After four days of patching, Birch et. al. (1980) found the directional sensitivity reduced in all the areas of the retina tested. The flattening of the Stiles-Crawford function recovered to normal within another three to four days. (6) Applegate et. al. (1985) have challenged these results. They concluded that there was a post natal active phototropic mechanism for photoreceptor maintenance but that it was not disrupted by the 6.5 days of monocular deprivation. (1) Birch's group replicated their experiment in 1985 with 7 full days of monocular occlusion and also reported that there was not a broadening of the Stiles-Crawford function. These discrepancies in results are to be reported on in a later publication. (33)

IV. Haidinger's Brushes

Haidinger's brushes are an entoptic phenomenom that can be seen by most observers when viewing a highly illuminated screen through a polarizing material. (40, 45) Haidinger's brushes are enhanced by a blue filter placed before the eye and kept from fading on the retina by rotating the polarizing material. The brushes appear as a rotating sheaf or hourglass with brighter, more visible, light blue areas surrounding them. (45) This phenomenom results from the absorption of blue light (maximally between 430-490 nm) by the macular pigment which is a carotenoid, xanthophyll. (40) This yellow pigment covers the central five degrees surrounding the macula lutea and is located in crystals in Henle's fiber layer between the elongated foveal cones. (37, 40)

Haidinger's brushes have two practical applications for the researcher or clinician.

1. Their absence can be used to determine an early loss of macular function. Since the polarizing xanthophyll crystals are located in front of the photoreceptor layer, macular edema leading to a loss of the brushes can be detected even before visual acuity is affected or the ophthalmoscopic picture has changed. (38)

2. The brushes indicate subjectively the center of the foveal area and are a feedback mechanism in training

of eccentric fixation. (37, 40) It is in this context that the Haidinger brushes will be used as an experimental tool for this work. If a subject is viewing a fixation point and notices the center of the brushes rotating off the object of regard, that subject will be viewing the target eccentrically.

The Haidinger's brush phenomenom may be difficult for some viewers with normal retinas to see, but is usually visualized when enough time is taken. (40) The motion of the brushes may be reversed by having the subject view the pattern through a quarter wave plate such as is provided for by the thickness of cellophane material. (40) The apparent size of the pattern will also decrease as the subject approaches the screen in accordance with Knapps law. (40)

A more recent explanation of the Haidinger's brush phenomenom has been introduced by Shute (1974) and Myrowitz (1979). This theory incorporates the collagen of the corneal stroma as a birefringent surface (i.e. this material refracts light in two slightly different directions to form two rays) supplementing the dichroic property of the macula lutea. Until this concept can be further developed, the Haidinger's brushes remain primarily an entoptic phenomenom of the macula.

V. Purpose

The purpose of this research is to investigate the effect that several successive days of long term monocular occlusion might have on the visual performance of young adult subjects as measured by vernier acuity. Young adult subjects were chosen to be investigated because of the basic premise from previous experiments (see for example, Brown, et. al., 1978) that there is still some remaining elasticity in their visual systems.

The experiment was designed in essence to test the competition model. If the competition model is correct, one would expect to see the following two observations after a reasonable period of monocular occlusion: 1. the occluded eye should show an increase in vernier threshold, a decrement in vernier performance, and 2. the nonoccluded eye should demonstrate a matching decrease in vernier threshold, an enhancement of vernier performance.

If the competition model is incorrect, then the threshold would only be altered using the occluded eye. Furthermore, the experiment was designed to explore the issue of inducing a temporary eccentric fixation by the occlusion procedure. Westheimer (1981) examined the hyperacuity threshold of the perifoveal area and noted a much faster increase in hyperacuity threshold with eccentricity than with visual resolution thresholds. Eccentric fixation, even of small magnitudes, should effect a significant rise in vernier threshold.

It should be reemphasized that we expected the results of the monocular occlusion to be elastic or temporary, and that there would be no long term repercussions for the subjects. Nevertheless, procedure included a measure of the recovery period for each of the subjects.

METHODOLOGY

I. Instrumentation

This experiment was designed to measure both vernier threshold and the integrity of foveal fixation. The vernier apparatus had an adjustable chin rest and head restraint to steady the subject. The subject viewed the vernier stimulus at a two meter distance. The target lines consisted of a series of steadily illuminated yellow LED's placed end to end. Each of the two target line components was mounted to a separate optical rail and driven by a slo-syn synchronous/stepping motor. The gap between the line components and the width of the line targets were both held constant at 3.44 min arc. The field was limited to two bright lines each of 2.46° length seen on a dark background. Data consisted of positional settings as recorded by a digital counter which was connected to the stepping motor. The speed of the stepping motor was held constant at a velocity that enabled it to operate smoothly. The experimenter used a main control unit to introduce an offset in one of the vernier line targets. Control of the target movement could then be transferred to the subject who used a remote control unit connected to the main unit, and she or he would position it so as to give the appearance of one continuous straight line.

Foveal fixation was monitored by determining the posi-

Fig. A The vernier alignment apparatus. Note the vernier target lines mounted to separate optical rails. The master control unit (digital counter) is shown to the right of the vernier stimulus. The remote control unit is positioned on top of the master control unit.

tion of the Haidinger brush an entopic view of the fovea relative to an object of regard. A set of separately motorized rotating polarizing discs from the optical tubes of a synoptophore were used outside the instrument as an independent unit to create this view. The control was equipped with a reversing switch which changes the direction of rotation. A dark blue auxiliary filter was used in front of the rotating polaroid disc to make the Haidinger brushes appear more prominent. The subject viewed a screen monocularly through the rotating polarizing disc at a distance of one meter. The screen was illuminated from the back by a goose neck lamp and measured 38.5 cd/m^2 while viewing through the polarizing filter. It consisted of two glass plates. The back plate was translucent and provided a diffuse light distributed evenly across the field. The front plate was transparent with a series of black concentric circles etched into its surface so as to aid in localizing the center of the rotating Haidinger brushes. These circles measured .5 m/m to 35 m/m in radius subtending a range of angles from 1.72 min arc to 120.27 min arc at the one meter test distance. While fixating the center of the target, the subject used a pointer to locate the center of the brushes on the screen. Responses were verified by having the subject report the direction of rotation of the brushes as viewed before and after changing the direction of motor rotation.

Fig. 3 The modified Haidinger's brush apparatus. The subject is viewing the highly illuminated screen through a rotating polarizing disc used independently outside the optical tubes of a synoptophore.

II. Experimental Protocol

The experiment consisted of obtaining vernier thresholds following various periods of monocular occlusion. Pre-occlusion thresholds were obtained and the precise point of fixation was measured in order to bring these two variables under control. Seven people from a young adult population (ages 19-22) volunteered to serve as subjects for the experiment. Experimental data and analysis were obtained on five subjects that completed all the facets of the experiment. Each subject was given a visual examination before the experiment which included: 1. visual acuities, 2. subjective refraction, 3. distance phoria, 4. stereopsis threshold. Results indicated that each subject had normal acuity, accurate refractive correction, negligible oculomotor deviation, and normal stereopsis (see appendix I). Before each experimental session, the stepping motor was tested to assure smoothness of movement of the vernier targets. Occasionally during the experiment, the stepping motor was noted to cause the master control unit to skip a digit. This was carefully monitored by the experimenter and when this occurred the data was discarded and a new series begun following recalibration to physical alignment. The vernier targets were carefully aligned to physical zero and the master control unit zero. Each subject was given three training sessions with the vernier apparatus. The experiment used the method of adjustment and the experimenter offset the vernier targets randomly at arbitrary distances and directions. Three training sessions were adequate to reach a plateau in vernier performance. McKee and Westheimer (1978) using a forced choice technique found an improvement in vernier performance of nearly forty percent before their subjects plateaued. Each training and experimental session consisted of three individual thresholds per eye. The average of the three thresholds was then used as the threshold for that eye in the statistical analysis. Vernier threshold is defined for this experiment as the standard deviation of the vernier sample settings. Each threshold measurement consisted of eleven separate settings by the subject, one for developing individual alignment criteria and ten for statistically determining the threshold. After finding the standard deviation of each group of ten settings, the following steps were taken to find the threshold in arc secs: 1. The standard deviation was divided by the test distance in m/m (in this case 2000 m/m), 2. The arc tangent function was used to find the angle in degrees, 3. The threshold angle was converted to arc secs by multiplying by 3600.

Each subject was also given experience in localizing the center of the Haidinger brush before the experimental session began. The brushes were reversed and the dark blue filter used until each subject could accurately point out the center of rotation. During the pre-occlusion experimental session, fixation of each eye was measured using the Haidinger brush apparatus in order to assure precise foveal fixation.

Two types of patches were tried for the occlusion part of the experiment. A black patch with an elastic band was found to be uncomfortable and also exerted pressure on the cornea. A hard formed black patch (Bernell) with cloth ties was found to be more successful and help insure corneal integrity. A foam adhesive strip was positioned inside the patch to make it more comfortable and to help achieve total occlusion. The corners of the patch were secured with surgical tape and covered with black plastic tape to occlude all light. Each subject was given extra tape in case the patch loosened or leaked any light. After patching, subjects were questioned on whether the lid was free to blink to insure that the patch exerted no pressure on the cornea. All the subjects had their left eye occluded. Applegate et. al. (1985) used a similar technique of monocular occlusion and reported no significant change in mean corneal thickness as measured by pachometry after six continuous days of occlusion.

Experimental sessions were held during the same hour of day to guard against minor changes in threshold due to circadian rhythms; although a pilot study for this experiment indicated no significant change in vernier thresholds over experimental sessions conducted at 9A.M., 12A.M., 3P.M., and

5P.M. Each subject performed vernier settings after being monocularly occluded for two, four, and six days. A final experimental session was conducted 24 hours post occlusion to see if all visual functions had returned to normal.

The protocol for the experimental sessions started with a determination of vernier threshold for the non-occluded eye (O.D.). This was followed by a foveal fixation measurement with the Haidinger brush apparatus for the right eye. The patch was then removed from the occluded eye in the darkened room and a vernier threshold and foveal fixation integrity measurement taken for that eye (O.S.). All subjects viewed both the vernier stimulus and the Haidinger brush screen through natural pupils. The patch was immediately resecured and the process repeated until a total of six days of occlusion had elapsed. Each subject was monitored for an hour after the sixth day of continuous monocular occlusion to assure recovery from any effects of diplopia. Brown, et. al. (1978) and other investigators have reported subjects with severe diplopia following several days of monocular occlusion. In this experiment all subjects recovered from any transient diplopia in no more than twenty minutes.

RESULTS

I. Training Sessions

Three training sessions were accomplished by each of the five subjects. Each eye was considered independent for this part of the experiment. Each of the three sets of training data were analyzed in two different ways: 1. the overall percentage of vernier performance improvement between sessions was calculated, and 2. the mean values of the groups for each session were compared by applying the t statistic.

There was a 38% improvement between the first training session and the second training session (see Fig. 1). The t value was highly significant for this comparison ($t = 4.28$, $p < .002$). There was an actual nonsignificant ($t = -.35$) rise in vernier performance between the second training session and the third training session indicating that a plateau in vernier performance had most likely been reached. At this point it did not appear that anymore alignment training would have a significant effect on subsequent experimental data.

Each subject was also trained to localize the center of the Haidinger brush phenomenon. Every subject noted the center of rotation of the brushes to be exactly on the point of regard with each eye, indicating that they all had normal central foveal fixation.

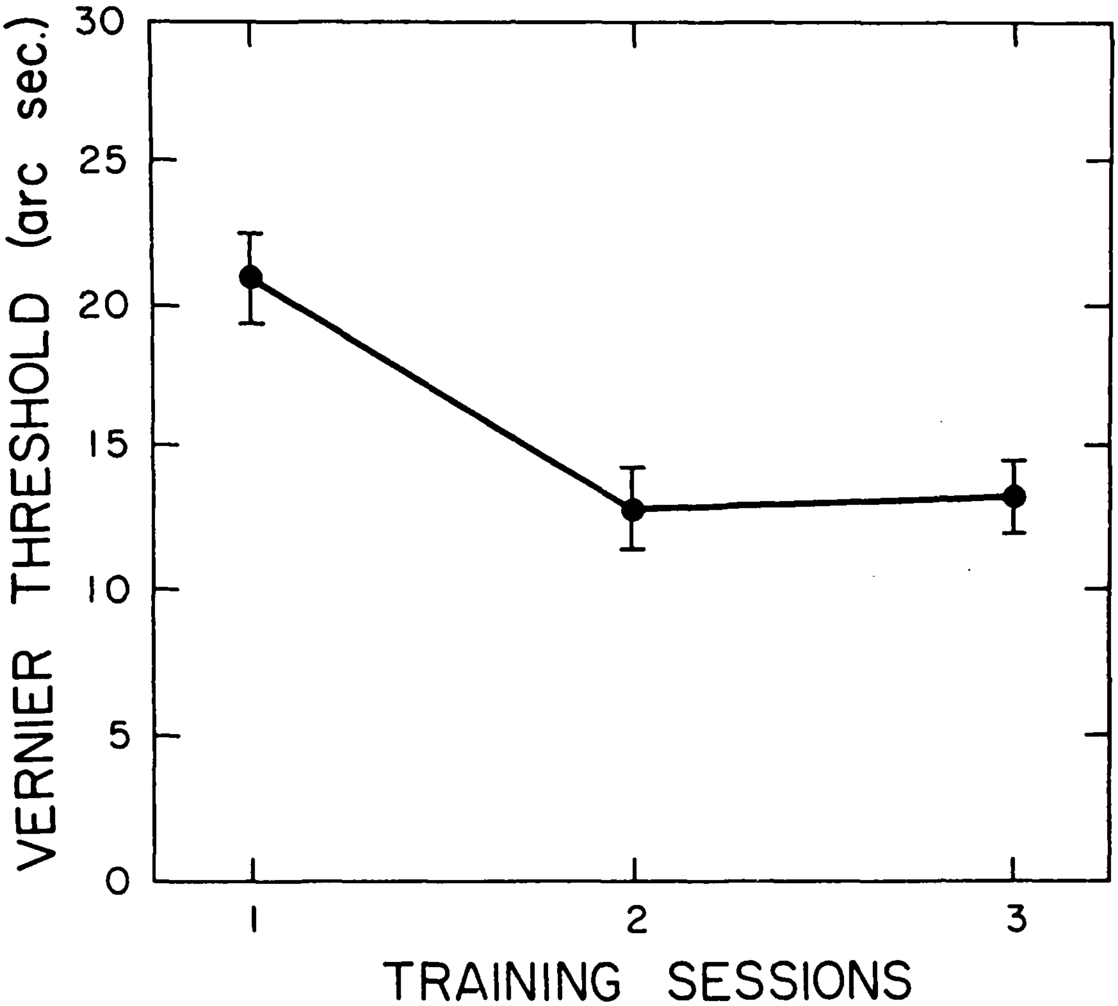

Fig. 1 Learning function showing a 38% improvement in vernier threshold between training session one and two. Thresholds for both eyes are combined in each point. (n= 10) Vertical bars represent ± one S.E. of the mean threshold.

II. Vernier Acuity Data

Vernier thresholds for the group ($n= 5$) were compared across the number of days of occlusion for each eye and compared with a pre-occlusion threshold. A 24 hour post-occlusion threshold was added as a fifth treatment to document recovery (see Fig. 2). The occluded eye (O.S.) was also compared at each treatment level with the non-occluded eye (O.D.).

A repeated-measure-design analysis of variance was applied to the data (see App. II, Tables K and L). The non-occluded eye data failed to show an improvement as a result of its exclusive use over a period of six days ($F= .54$). While a slight decrease in threshold might have been most reasonably interpreted as improvement due to continued practice, there appears to be a complete absence of any such tendency. On the other hand the repeated measure analysis of variance for the occluded eye was significant ($F= 5.60$, $p< .01$) indicating a real decrement in verneir performance for the group of five subjects tested. Three planned comparisons were calculated among treatments to determine the locations of peak variability. The first null hypothesis tested was H_o: $(1)\ M_1+(-1)M_5= 0$. This comparison between the means of the pre-occlusion and post-occlusion vernier thresholds was not significant ($t= .89$, two tailed at the .01 significance level). H_o could not be rejected indicating that the vernier threshold had returned to its normal range within the 24 hour recovery period. The second H_o: (1) $M_1+(-1/3)M_2+(-1/3)M_3+(1/3)M_4=0$ was rejected because the t value was 4.08, which is significant with a $p< .002$. This means that all three periods of occlusion showed a significant rise in vernier threshold when compared with the pre-occlusion threshold. The final null hypothesis considered H_o: $(1)M_3+(-\frac{1}{2})M_2+(-\frac{1}{2})M_4=0$ could not be rejected as the t value was insignificant ($t= 1.68$). Although the rise in vernier threshold with occlusion was a significant event, there was no continued trend in vernier threshold elevation over more days of occlusion (seeFig. 2). Once the decrement in vernier performance had been reached, further occlusion had little effect on the threshold.

Approximate one tail t tests(i.e., using the estimate for the standard deviation for populations with unequal variances) were calculated between eyes at each treatment level. There was no significant difference between means at the .05 significance level for the pre-occlusion, four day occlusion, and post-occlusion periods; however, the two day occlusion period had a p value $<.05$ and the six day occlusion period a near significant p value $<.1$. This method of analysis, which uses the data from the non-occluded eye for day-to-day comparison, illustrates that the extent of the changes in threshold resulting from occlusion over a period of days are relatively small.

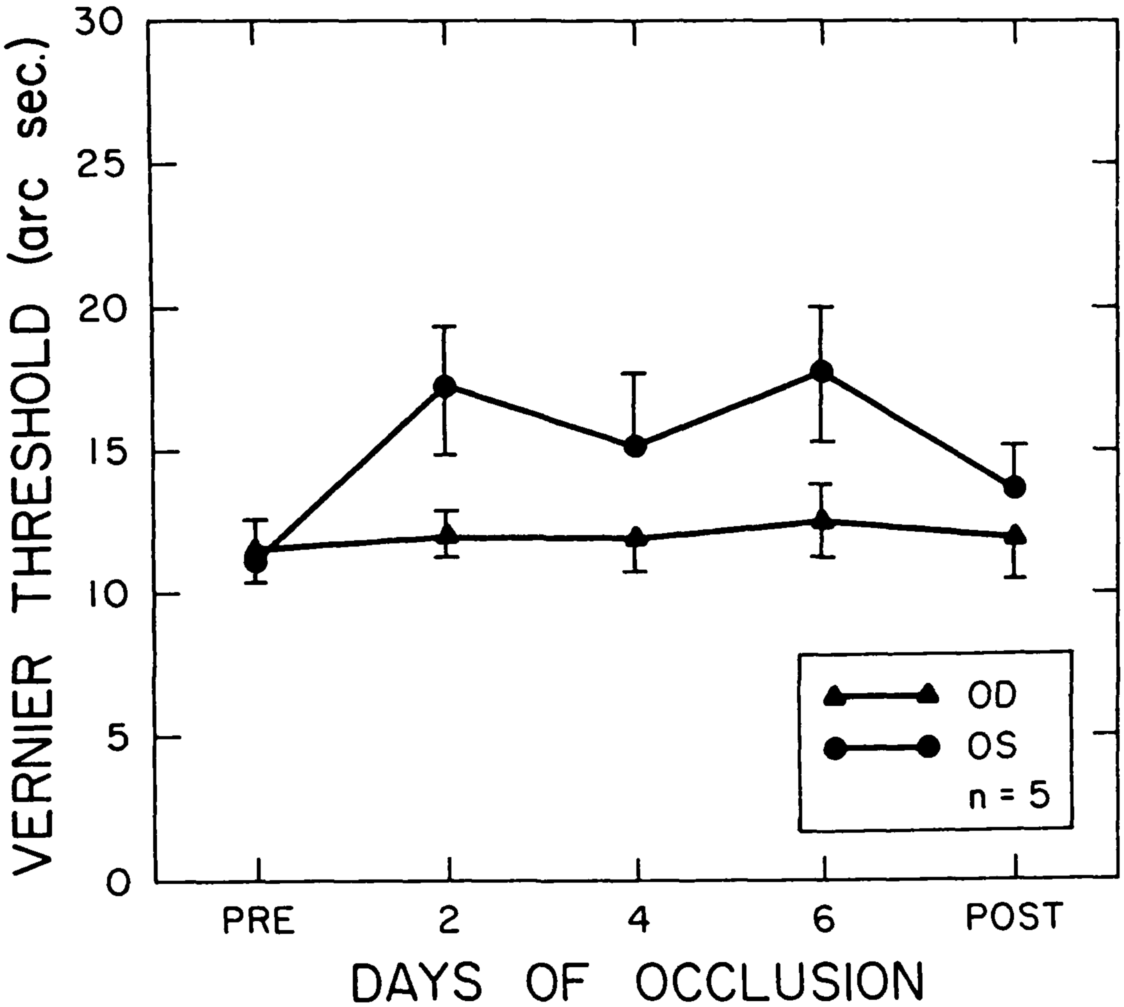

Fig. 2 Vernier threshold data as a function of days of monocular occlusion. The left eye (O.S.) was the occluded eye for all subjects. Pre-occlusion thresholds and 24 hour post-occlusion thresholds are included for comparison. Each data point is the mean for five mean thresholds. Vertical bars represent ± one S.E.

III. Fixation Data

During the occlusion part of the experiment, the Haidinger brush apparatus was used to measure the integrity of foveal fixation in both eyes. Every subject demonstrated exact foveal fixation throughout the experiment in the non-occluded eye; however, each subject manifested some magnitude of eccentric fixation in the occluded eye at each phase of occlusion. The amount of eccentricity for each individual subject was plotted on circular coordinates in minutes of arc (see Fig. 3). The magnitude of eccentric fixation increased with time occluded for some subjects. For example subject MB increased from 18.91 min arc (two days) to 36.95 min arc (four days) to 42.87 min arc (six days). Nevertheless, the majority of the subjects did not show this trend: for example, subject GV who started at 10.31 min arc (two days) and remained at this same level for four days. He then decreased to 7.39 min arc on the sixth day. Group data did not indicate an increasing trend in magnitude of eccentric fixation with longer periods of treatment.

Every subject was consistent in term of the direction of eccentricity, i.e., if a subject fixated eccentrically to the nasal side of the object of regard, he continued to do so throughout the occlusion part of the experiment. Following final removal of the patch every subject manifested normal foveal fixation in the occluded eye when measured

24 hours later. It was not determined if the full 24 hours was needed to return to normal foveal fixation.

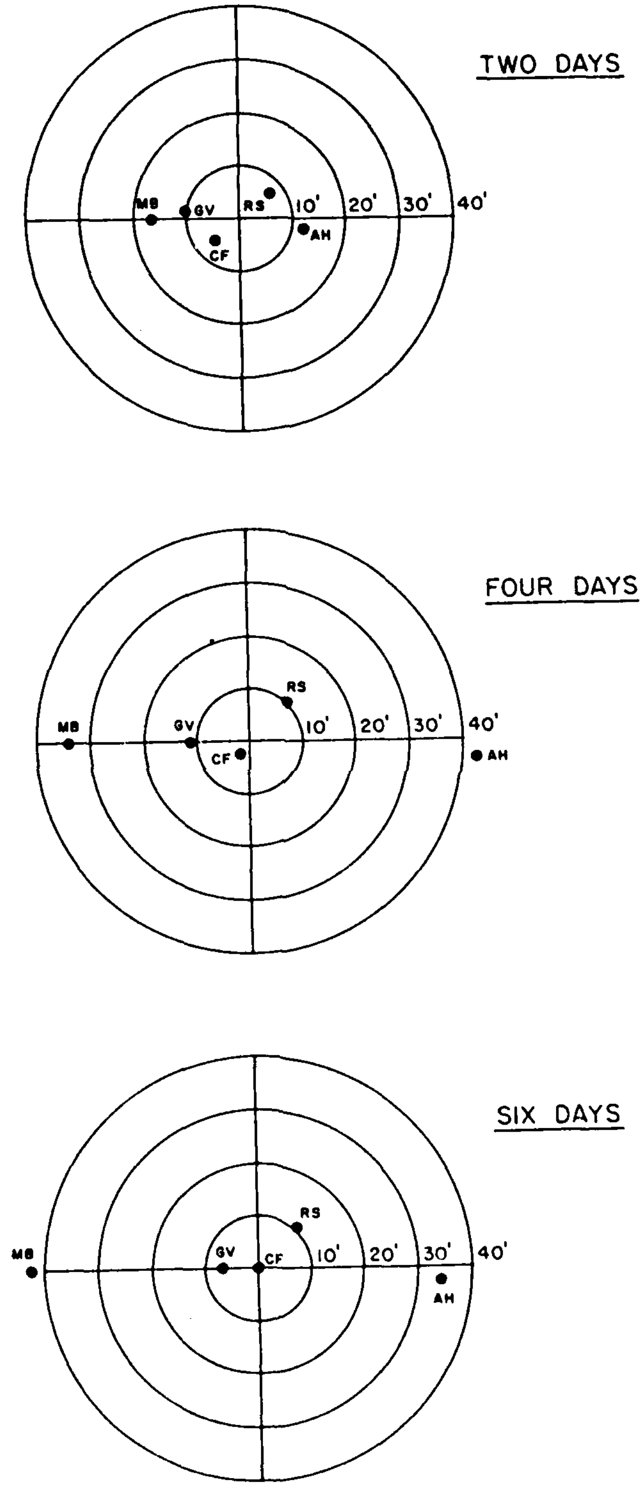

Fig. 3 Fixation Eccentricities (see following page).

Fig. 3 Fixation eccentricities as measured by the Haidinger brush apparatus. Measurements are in minutes of arc and are for the left eye (O.S.) following two, four, six days of monocular occlusion. Data plotted on the right half of the grid represent nasal eccentric fixation while the left half is temporal.

IV. Correlation Data

The final step in the data ana^l sis process was to try and correlate the amount of eccentric fixation with the amount of decrement in vernier performance. A *n of fifteen* was obtained by assuming that threshold and fixation readings on different days for each subject were separate and independent events. Two methods of normalizing the vernier data were used and correlated with the degree of fixation eccentricity.

The first method used was to find the vernier deficit. The vernier deficit is defined as that value in arc secs where the pre-occlusion threshold for each subject is subtracted from that threshold obtained after the two, four, and six day occlusion periods (seeApp. II,Table J). In this manner the amount of decrement in vernier performance could be compared with magnitude of retinal eccentricity. A Pearson product-moment correlation coefficient was calculated for the two populations, ($r= .47$) and H_o: $P_{xy}=0$ tested but not rejected as there was no significance at the .05 significance level.

A vernier ratio (i.e., the vernier threshold relative to the foveal threshold; see App. II, Table M) was also developed to try and correlate with retinal eccentricity. The data and best fit line are plotted in Figure 4. The Pearson correlation coefficient ($r= -.32$) was again tested and was nonsignificant with this method. The data points using either method were quite scattered although there appeared to be a nonsignificant linear trend in vernier acuity fall off.

Data for vernier threshold as a function of eccentricity within one degree were difficult to find. Westheimer (Proctor Lecture 1979, 1982) displays data for step displacement within the parafoveal area with data points at 2.5° and 5° while Freeman (1966) has vernier data points for .75° and 2° of eccentricity. Interpolation of their data to find an approximate function for vernier threshold within one degree was difficult and offered limited information. Our data points were quite scattered possibly due to different times of recovery to foveal fixation in individual subjects. A majority of data points demonstrated a faster decline in threshold than could be explained by retinal eccentricity alone. Factors such as the loss of neural channels or variable fixation may have to be incorporated into the explanation of these data ponts.

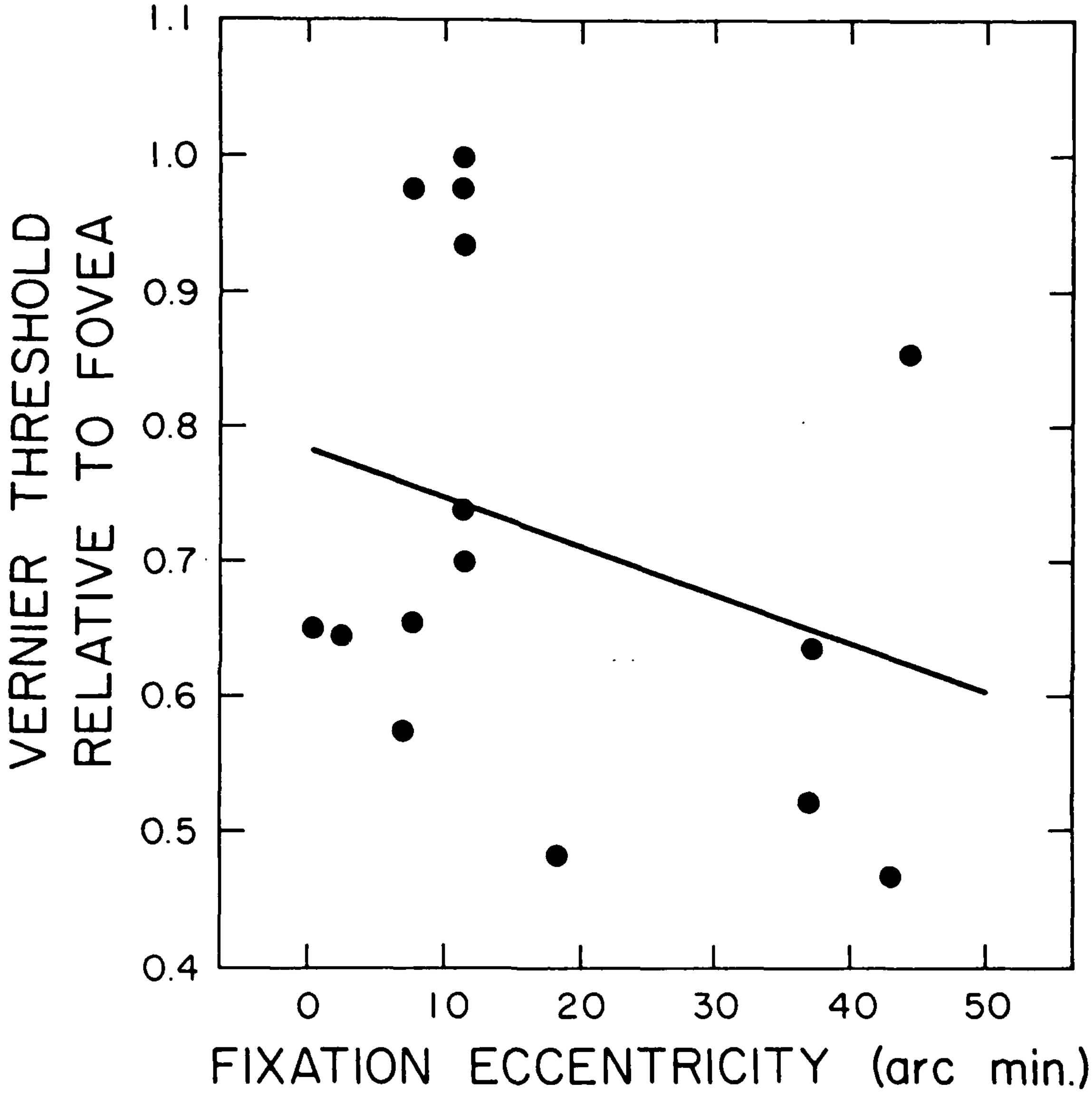

Fig. 4 Scatter plot showing the relationship between fixation eccentricity in minutes of arc and the vernier ratio (vernier thresholds after two, four, and six days of occlusion relative to the foveal threshold of each subject). n= 15 r^2= .102

DISCUSSION AND CONCLUSIONS

A number of conclusions can be inferred from the results of this experiment.

1. There was a definite training effect that needed to be addressed before beginning the experiment.

The results of this type of experiment could easily be contaminated without the proper amount of training. Whether the improvement in vernier performance comes from achieving familiarity with the apparatus, developing better concentration, or an actual "fine tuning of the neural mechanism", it seems apparent that a fairly constant level of vernier performance must be reached before initial experimental data is taken. Three training sessions were adequate in this experiment to reach a plateau, and even with continued experimental sessions with the non-occluded eye (which could be equated to practice sessions) no improvement was elicited.

2. There was a temporary (elastic) decrement in vernier performance in the occluded eye of the young adult, but the decrement did not increase significantly after the initial two-day period of occlusion.

This statistically significant rise in vernier threshold in the occluded eye indicated that a temporary suspension of visual stimulation had a measureable effect on the visual system of young adults. It was rather surprising to see the threshold elevate after only two days of occlusion and then remain at that same level through the sixth day of occlusion. It was expected that either a loss of neural channels or of central fixation would have an increasing influence on the data over the total period of stimulus deprivation. This may be explained by the concept that elasticity in these young adult subjects was fully extended after the initial two days of occlusion. Another experiment with increased days of occlusion would be required to determine if a higher level of elasticity could be demonstrated. The fact that the vernier thresholds resumed to normal within 24 hours, and possibly sooner, would indicate that any alteration in the visual system with this age group would be elastic in nature and not permanent (plastic).

3. There was no matched enhancement effect in vernier performance in the non-occluded eye which would be appropriate in the classical sense for the competition model.

Any neural recruitment in the non-occluded eye should have lowered the vernier threshold as theorized by the competition model. Either the competition model does not hold true or this aspect of the model (i.e., the recruiting side) is not as sensitive to vernier measurement or requires more time to incorporate the effects of any new channels. It also seems possible that the visual system is more elastic to losing channels with stimulus deprivation than it is in acquiring those channels for the non-deprived eye. In any case the classical competition model would have to be altered to explain the results of this experiment.

4. After occlusion, every subject experienced eccentric fixation of some magnitude in the occluded eye, but returned to normal foveal fixation within 24 hours.

The fixation data would suggest that any subject undergoing stimulus deprivation for whatever reason would be thrust into fixating eccentrically. This could have some reprecussion when discussing occlusion therapy for those young patients still in a "critical period". Since the young adult subjects used here seem to be in an elastic period, they returned to normal foveal fixation within 24 hours; but would those in the critical period do the same? The important point is that in most cases the maximum amount of eccentric fixation was reached within a two day period, so that even a short period of occlusion during a time of visual system development might be crucial. This may be an argument for those who support shorter periods (one day) of alternate occlusion in amblyopia therapy.

5. The decrement in vernier performance in the occluded eye can probaly be better explained as temporary (elastic) eccentric fixation in that eye rather than as the loss of neural channels as explained by the competition model.

6. Even though eccentric fixation seems to be the most plausible explanation for the rise in vernier threshold with occlusion, the amount of vernier drop off cannot be exclusively explained by retinal eccentricity.

Westheimer (1982) reported that hyperacuity thresholds in the perifoveal area rose more rapidly with eccentricity than visual resolution thresholds. Although this may be the case, our thresholds rose even more drastically with eccentricity than did Westheimer's data. This magnitude of drop off in vernier acuity can be interpreted as both a function of retinal eccentricity and some other secondary process. There indeed may be some secondary effect from the loss of channels in the occluded eye.

7. The linear relationship between vernier deficit or vernier ratio and fixation eccentricity was probably affected by the dynamics of the occluded eye seeking foveal fixation after removal of the patch.

Foveal fixation was reacquired within 24 hours following removal of the patch, but the exact length of time to reach it was not determined. If the process to reacquire foveal fixation had begun immediately following patch removal, a variability in the retinal fixation site was likely to occur while assessing the vernier threshold. Since the threshold was determined following the retinal fixation measurement with the Haidinger brush, this variability in fixation would make it difficult to correlate an exact retinal point with a threshold. The instability of fixation could also be another factor in the higher than expected drop off in vernier acuity and the large intersubject variability.

8. Other monocular occlusion experiments that indicate

a decrement in visual performance of the occluded eye may actually be investigating an area of the retina eccentric to the fovea.

A good example would be to examine the experiment of Brown, et. al., (1978). They state that the visual acuity of the occluded eye (following eight days of continuous monocular occlusion) estimated from standard eye charts as well as from the high frequency cut off of the contrast sensitivity function was slightly reduced, a finding that would be typical of nonfoveal fixation. They also report that all of the visual functions for their subjects were back to normal in 24 hours as was the foveal fixation for our subjects.

SUMMARY

According to a model introduced by Jastrzebski (1984) for explaining stimulus deprivation in children, the term elasticity implies the connotation of a temporary change in the visual system. The competition model in the young adult is based on this elasticity. With the competition model, the deprived eye loses control of its central channels causing a decrement in visual performance while the non-deprived eye gains the competitive edge and induces an enhancement in performance.

Five subjects (ages 19-22) were monocularly occluded for six days. Their vernier thresholds and fixation integrity measurements (using a modified Haidinger brush) were determined at pre-occlusion, two, four, and six days of monocular occlusion, and 24 hours after patch removal. The occluded eye demonstrated a significant rise in vernier threshold after the two day occlusion period. The threshold continued at that level throughout the six day occlusion period before returning to normal within 24 hours after removal of the patch. The non-occluded eye did not show a matching enhancement effect characteristic of the competition model. Every subject also manifested an amount of eccentric fixation in the occluded eye. The eccentric fixation did not generally increase with time occluded, but did show an elastic response by returning to normal foveal fixation in

24 hours.

The decrement in vernier performance in the occluded eye is probably best explained as a temporary (elastic) eccentric fixation rather than the loss of channels as theorized in the competition model. Our data did indicate a faster drop off of vernier acuity with retinal eccentricity than did the interpolated data of Westheimer's (1979) postulating that a secondary process was also contributing to the rise in threshold. This secondary process could possibly be either a loss of neural channels or an instability of fixation after patch removal. Other experiments demonstrating a decrement in visual performance could be investigating an area of the retina eccentric to fixation.

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APPENDIX I

ADDITIONAL INFORMATION

DEPARTMENT COMMITTEE APPROVAL

1.
2.
3.

Requires approval by Campus Committee prior to project initiation

☐ yes ☒ no

Date 12-4-85

Indiana University/Bloomington Campus

Committee for the Protection of Human Subjects

DOCUMENTATION OF REVIEW AND APPROVAL

of

Research Project Utilizing Human Subjects

CAMPUS COMMITTEE USE ONLY:

1.
2.
3.
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5.
6.
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8.
9.

PROJECT TITLE: THE EFFECT OF LONG TERM MONOCULAR OCCLUSION ON VISUAL RESOLUTION AS MEASURED BY VERNIER ACUITY- PLASTICITY IN THE ADULT VISUAL SYSTEM

AGENCY GRANT NUMBER (IF KNOWN): N/A

As the signature below testifies, the principal investigator(s) is pledged to conform to the following precepts:

As one engaged in investigation utilizing human subjects, I acknowledge the rights and welfare of the human subject or patient involved.

I acknowledge my responsibility as an investigator to secure the informed consent of the subject by explaining the procedures, in so far as possible, and by describing the risks as weighed against the potential benefits of the investigation.

I am in agreement with the Indiana University Statement of Principles Regarding the Use of Human Subjects in Research. I understand that in research a fundamental distinction must be recognized between research in which the aim is essentially therapeutic for a patient, and research, the essential object of which is purely scientific and without therapeutic value to the person subjected to the research.

If there is reason for me to deviate from these precepts, I will seek prior approval in writing from the Bloomington Campus Committee for the Protection of Human Subjects.

PRINCIPAL INVESTIGATOR(S):

Richard J. Dennis		October 7, 1985
(typed name)	(signature)	(date)
(typed name)	(signature)	(date)

STATUS: ☐ FACULTY ☒ STUDENT ☐ OTHER (specify)

If student, name of faculty sponsor: R.W. Reading, M.D. , Ph.D.
(typed name) (signature)

CHECK LIST FOR PRINCIPAL INVESTIGATOR:
- ☒ FORMS COMPLETED (ALL required spaces filled in)
- ☒ FORMS SIGNED (ALL signature spaces)
- ☐ COPY OF PROPOSAL ATTACHED (if required)
- ☒ INFORMED CONSENT DOCUMENTS ATTACHED (if required)

* This protocol for use of human subjects has been reviewed and approved by the Indiana University Bloomington Campus Committee for the Protection of Human Subjects.

Paul Gebhard — DEC 10 1985

CHAIRPERSON OF THE COMMITTEE — DATE

June 1983

A. A copy of the cover page from the approved application requesting university approval for the use of human subjects in this research project. This form has been reduced in size for convenience.

INFORMED CONSENT STATEMENT

FOR

PROJECT
TITLE: THE EFFECT OF LONG TERM MONOCULAR OCCLUSION ON VISUAL RESOLUTION AS MEASURED BY VERNIER ACUITY - PLASTICITY IN THE ADULT VISUAL SYSTEM

You will be asked to perform a series of simple visual judgements that will allow us to determine a particular visual function. The purpose of this research is to find if the adult visual system must have continual visual input to sustain normal visual resolution. The results may help determine whether the adult visual system retains any plasticity.

You will be asked to participate in several practice periods that should last no more than one half hour on a given day. After you have reached a degree of accuracy, we will begin the occlusion part of the experiment.

During this phase of the experiment you will be required to patch your non-dominant eye for time periods of 24 hours, 48 hours, 4 days, and 8 days. The patch will exclude all light and must be worn continuously. Compliance will dictate the success of the project. Testing after the patch is removed will last no more than two hours. There will be at least a week in between patching periods.

In case of any discomfort during a patching period, immediately contact the researcher. The researcher will check and repatch the occluded eye every two days during the long occlusion sessions. In the unlikely event of physical injury resulting from your participation in this research, emergency medical treatment will be provided at no cost to you.

We would request that you do not drive a vehicle while one eye is occluded. Your normal depth perception will be affected making it more difficult to judge distances.

Your participation in this project will aid the understanding of the visual system and will also be important in the visual research program of the U.S.A.F.

Having been informed of the conditions listed above, I consent to serve as a subject.

(Witness)	(Subject's Signature)
(Investigator)	(Date)

For further questions contact: R.J. Dennis
Home: 333-0798

B. A copy of the informed consent statement. Each subject was required to read and sign the statement before being accepted into the research project.

Subject	Age	BVA	Stereo Threshold
MB	21	O.D. 20/15	< 20 arc secs
		O.S. 20/15	
CF	19	O.D. 20/15	< 20 arc secs
		O.S. 20/20-	
AH	22	O.D. 20/20	< 20 arc secs
		O.S. 20/25-	
RS	20	O.D. 20/15	< 20 arc secs
		O.S. 20/15	
GV	21	O.D. 20/15	< 20 arc secs
		O.S. 20/15	

Subject	Refraction	Distance Phoria
MB	O.D. +.25 sph.	ortho.
	O.S. +.50-.50x180	
CF	O.D. +.50 sph.	4 exophoria
	O.S. pl. sph.	
AH	O.D. pl. sph.	2-3 p.d. LET
	O.S. pl.-.25x045	
RS	O.D. +.50-.25x080	2 esophoria
	O.S. -.25 sph. (c.l.'s)	
GV	O.D. pl. sph.	ortho.
	O.S. pl. sph.	

C. Subject visual profile.

Name: G.V.

Date: February 3, 1986

Eye Occluded: OS

Hours Occluded: X 2 days

TRIAL	OD			OS		
1	10.04	9.95	10.18	9.60	9.54	9.48
2	9.93	10.10	9.84	9.61	9.62	9.57
3	10.04	9.71	9.85	9.82	9.62	9.61
4	10.04	9.97	10.10	9.64	9.77	9.58
5	10.03	9.91	10.22	9.79	9.53	9.46
6	9.99	10.09	10.04	9.70	9.56	9.56
7	9.97	9.93	10.04	9.65	9.67	9.57
8	9.89	9.91	9.99	9.70	9.62	9.79
9	9.88	9.81	10.07	9.78	9.58	9.74
10	9.98	10.00	9.86	9.64	9.79	9.72
$\bar{X}$	9.979	9.938	10.019	9.693	9.63	9.608
s	.062	.118	.135	.079	.090	.109
arc sec	6.39	12.17	13.92	8.15	9.28	11.24

D. A sample of the form use to record the vernier data during each experimental session. Three thresholds per eye were determined and the mean of the three used as the threshold for that session .

APPENDIX II

TABLES OF DATA

Right Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	29.29	16.36	19.38	21.68	6.764
CF	28.05	15.57	12.99	18.87	8.054
AH	24.85	17.84	30.94	24.54	6.555
RS	22.90	15.99	17.12	18.67	3.707
GV	12.40	12.64	16.91	13.98	2.537
				$\bar{X}$=19.55	s=3.927

Left Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	14.44	23.41	21.25	19.70	4.682
CF	34.55	29.60	19.29	27.81	7.785
AH	35.48	18.98	26.61	27.02	8.258
RS	27.12	22.59	23.72	24.48	2.358
GV	16.31	10.65	16.44	14.47	3.306
				$\bar{X}$=22.70	s=5.583

A. Data for training session one. All vernier thresholds are in arc seconds.

Right Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	17.84	16.91	15.16	16.64	1.361
CF	10.42	11.86	11.45	11.24	0.742
AH	23.00	17.22	24.03	21.42	3.671
RS	10.00	12.58	15.37	12.65	2.686
GV	06.39	12.17	13.92	10.83	3.941
				$\bar{X}$=14.56	s=4.471

Left Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	14.13	07.32	14.23	11.89	3.961
CF	10.93	08.46	12.99	10.79	2.268
AH	10.11	15.26	14.95	13.44	2.888
RS	13.61	10.93	10.42	11.65	1.714
GV	08.15	09.28	11.24	09.56	1.563
				$\bar{X}$=11.47	s=1.432

B. Data for training session two. All vernier thresholds are in arc seconds.

Right Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	16.80	18.46	07.73	14.33	5.776
CF	11.96	21.45	17.33	16.91	4.759
AH	11.55	06.29	16.40	11.41	5.056
RS	16.60	12.99	07.73	12.44	4.461
GV	07.32	09.18	07.01	07.84	1.174
				$\bar{X}$=13.91	s=4.430

Left Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	21.14	15.88	12.79	16.60	4.222
CF	12.99	14.13	20.32	15.78	3.887
AH	12.69	19.90	16.09	16.23	3.607
RS	15.78	12.79	18.15	15.57	2.686
GV	10.83	06.70	07.12	08.22	2.273
				$\bar{X}$=14.51	s=3.151

C. Data for training session three. All vernier thresholds are in arc seconds.

Right Eye

Subject	Threshold# 1	2	3	$\bar{X}$	s
MB	16.80	18.46	07.73	14.33	5.776
CF	10.42	11.86	11.45	11.24	0.742
AH	11.55	06.29	16.40	11.41	5.056
RS	16.60	12.99	07.73	12.44	4.461
GV	07.32	09.18	07.01	07.84	1.174
				$\bar{X}$=11.45	s=2.364

Left Eye

Subject	Threshold# 1	2	3	$\bar{X}$	s
MB	14.13	07.32	14.23	11.89	3.961
CF	10.93	08.46	12.99	10.79	2.268
AH	10.11	15.26	14.95	13.44	2.888
RS	13.61	10.93	10.42	11.65	1.714
GV	10.83	06.70	07.12	08.22	2.273
				$\bar{X}$=11.20	s=1.920

D. Data for pre-occlusion session. All vernier thresholds are in arc seconds.

Right Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	20.73	08.56	10.30	13.20	6.582
CF	11.96	14.95	11.55	12.82	1.856
AH	12.58	12.89	10.52	12.00	1.288
RS	13.72	16.29	12.38	14.13	1.987
GV	09.18	06.70	12.48	09.45	2.900
				$\bar{X}$=12.32	s=1.778

Left Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	31.04	25.06	17.84	24.65	6.610
CF	11.14	23.31	22.07	18.84	6.697
AH	22.38	18.46	15.26	18.70	3.566
RS	11.96	12.48	11.34	11.93	0.571
GV	13.82	10.42	11.14	11.79	1.792
				$\bar{X}$=17.18	s=5.419

E. Data for vernier thresholds after two days of monocular occlusion. (O.S.) Thresholds are in arc seconds.

Right Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	19.70	10.00	16.81	15.50	4.980
CF	08.97	10.31	15.57	11.62	3.489
AH	06.60	12.99	15.47	11.69	4.576
RS	18.36	12.99	10.21	13.85	4.143
GV	09.28	07.73	06.60	07.87	1.345
				$\bar{X}$=12.11	s=2.869

Left Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	24.85	26.61	17.74	23.07	4.696
CF	16.70	17.33	16.70	16.91	0.364
AH	19.29	13.10	15.37	15.92	3.131
RS	13.72	09.28	12.89	11.96	2.361
GV	10.42	08.56	04.54	07.84	3.005
				$\bar{X}$=15.14	s=5.702

F. Data for vernier thresholds after four days of monocular occlusion (O.S.) Thresholds are in arc seconds.

Right Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	10.21	17.84	09.08	12.38	4.765
CF	19.81	10.62	13.92	14.57	4.323
AH	09.39	13.61	12.27	11.76	2.156
RS	10.73	17.74	18.87	15.78	4.409
GV	09.69	08.87	09.69	09.42	0.473
				$\bar{X}$=12.78	s=2.485

Left Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	24.75	27.33	24.44	25.51	1.587
CF	17.22	12.99	19.90	16.70	3.484
AH	25.99	24.24	14.03	21.42	6.459
RS	15.68	10.42	11.65	12.58	2.751
GV	09.39	07.43	20.73	12.52	7.180
				$\bar{X}$=17.75	s=5.676

G. Data for vernier thresholds after six days of monocular occlusion (O.S.) Thresholds are in arc seconds.

Right Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	08.66	15.16	10.11	11.31	3.412
CF	13.82	11.14	06.70	10.55	3.596
AH	12.89	08.56	09.80	10.42	2.230
RS	19.39	15.06	13.72	16.06	2.963
GV	10.93	11.34	12.27	11.51	0.687
				$\bar{X}$=11.97	s=2.334

Left Eye

	Threshold#				
Subject	1	2	3	$\bar{X}$	s
MB	17.22	14.23	15.26	15.57	1.519
CF	20.52	10.00	10.11	13.54	6.042
AH	13.51	23.20	21.04	19.25	5.087
RS	11.65	12.99	07.94	10.86	2.616
GV	10.11	11.96	04.54	08.87	3.862
				$\bar{X}$=13.62	s=4.052

H. Data for vernier thresholds post 24 hours following six continuous days of monocular occlusion. Thresholds are in arc seconds.

Left Eye

	Days Occluded				
Subject	2	4	6	$\bar{X}$	s
MB	18.91	36.95	42.87	32.91	12.48
CF	07.09	01.72	00.00	02.94	3.698
AH	10.31	42.97	36.95	30.08	17.38
RS	07.39	10.31	10.31	09.37	1.686
GV	10.31	10.31	07.39	09.37	1.686
	$\bar{X}$=11.00	20.45	19.50		
	s=5.212	18.27	19.12		

I. Data for fixation eccentricity after two, four, and six days of continuous monocular occlusion of the left eye. Measurements are in minutes of arc.

Subject	Days Occluded	Vernier Deficit	Fix. Ecc.
MB	2	24.65-11.89 = 12.76	18.91
	4	23.07-11.89 = 11.18	36.95
	6	25.51-11.89 = 13.62	42.87
CF	2	18.84-10.79 = 08.05	07.09
	4	16.91-10.79 = 06.12	01.72
	6	16.70-10.79 = 05.91	00.00
AH	2	18.70-13.44 = 05.26	10.31
	4	15.92-13.44 = 02.48	42.97
	6	21.42-13.44 = 07.98	36.95
RS	2	11.93-11.65 = 00.28	07.39
	4	11.96-11.65 = 00.31	10.31
	6	12.58-11.65 = 00.93	10.31
GV	2	11.79-08.22 = 03.57	10.31
	4	07.84-08.22 =-00.38	10.31
	6	12.52-08.22 = 04.30	07.39
		$\bar{X}$ = 5.491	16.92
		S = 4.383	14.54

J. Data comparing the vernier threshold deficit in seconds of arc to the fixation eccentricities in minutes of arc. The vernier threshold deficit was found by subtracting the pre-occlusion threshold from the threshold following two, four, and six days of monocular occlusion.

Right Eye

Subj.	Pre	2 Day	4 Day	6 Day	Post	Total
MB	14.33	13.20	15.50	12.38	11.31	66.72
CF	11.24	12.82	11.62	14.57	10.55	60.80
AH	11.41	12.00	11.69	11.76	10.42	57.28
RS	12.44	14.13	13.85	15.78	16.06	72.26
GV	07.84	09.45	07.87	09.42	11.51	46.09
Total	57.26	61.60	60.53	63.91	59.85	303.15

RS	SS	DF	MS	F	P
M 3675.99		1			
C 3680.73	4.7349	4	1.1837	.5351	NS
R 3754.99	79.0016	4	19.7504		
AB 3795.12	35.3925	16	2.2120		
Tot.	119.129	24			

K. Table for Analysis of Variance for the right eye. Repeated measure design.

Left Eye

Subj.	Pre	2 Day	4 Day	6 Day	Post	Total
MB	11.89	24.65	23.07	25.51	15.57	100.69
CF	10.79	18.84	16.91	16.70	13.54	76.78
AH	13.44	18.70	15.92	21.42	19.25	88.73
RS	11.65	11.93	11.96	12.58	10.86	58.98
GV	08.22	11.79	07.84	12.52	08.87	49.24
Total	55.99	85.91	75.70	88.73	68.09	374.42

RS	SS	DF	MS	F	P
M 5607.61		1			
C 5751.03	143.4183	4	35.8546	5.60	<.01
R 5961.97	354.3616	4	88.5904		
AB 6207.84	102.4498	16	6.4031		
Tot.	600.2297	24			

L. Table for Analysis of Variance for the left eye. Repeated measure design.

Subject	Days Occluded	Vernier Ratio	Fix. Ecc.
MB	2	11.89/24.65= .482	18.91
	4	11.89/23.07= .515	36.95
	6	11.89/25.51= .466	42.87
CF	2	10.79/18.84= .573	07.09
	4	10.79/16.91= .638	01.72
	6	10.79/16.70= .646	0.00
AH	2	13.44/18.70= .719	10.31
	4	13.44/15.92= .844	42.97
	6	13.44/21.42= .627	36.95
RS	2	11.65/11.93= .977	07.39
	4	11.65/11.96= .974	10.31
	6	11.65/12.58= .926	10.31
GV	2	08.22/11.79= .697	10.31
	4	08.22/07.84= 1.00	10.31
	6	08.22/12.52= .657	07.39
		$\bar{X}$= .716	16.92
		S= .179	14.54

M. Data comparing the vernier threshold relative to the fovea and the fixation eccentricities in minutes of arc. The vernier ratio is found by dividing the preocclusion threshold for each subject by the threshold following two, four, and six days of monocular occlusion.

VITAE

Richard J. Dennis was born on the 22nd of October 1944 in Platteville, Wisconsin. He graduated from Platteville High School in 1962 and attended the University of Wisconsin-Platteville for pre-Optometry. He received a Bachelor of Science degree in 1966 from Illinois College of Optometry, and then was granted the degree Doctor of Optometry by I.C.O. in 1967. He was in private Optometric practice in Platteville, Wisconsin from 1967 to 1969. In 1969 he was awarded a direct commission in the United States Air Force Biomedical Science Corps.

As an Air Force Optometry Officer, he has held the following positions:

Chief of Optometry	1969-71	Blytheville AFB, AR
Clinical Optometrist	1972-74	Travis AFB, CA
Chief of Optometry	1974-76	Andersen AFB, Guam
Clinical Optometrist	1976-80	Offutt AFB, NE
Chief of Optometry	1980-84	Little Rock AFB, AR
Post-Graduate Student	1984-86	Indiana University
(Physiological Optics)		Bloomington, IN

During his military career he has been awarded the Biomedical Science Corp Chiefs badge, The Air Force Commendation Medal, and the Meritorious Service Medal with one Oak Leaf

Cluster. He graduated from Squadron Officers School, Air Command and Staff College, and National Security Management as a distinguished graduate. He presently holds the rank of Lieutenant Colonel.

From 1980-1984 he served as an adjunct professor for the University of Houston's Optometry School. He is a member of the Armed Forces Optometric Society and a student member of the American Academy of Optometry.

END
DTIC
9-86