BRIGHTNESS CONTRAST IN AMBLYOPIA

A Thesis

Presented to

the Faculty of the Department of Physiological Optics

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By:

Dennis Michael Levi

May, 1973

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to Dr. Ronald Harwerth for his encouragement, suggestions and help during the preparation of this thesis.

I am grateful to the members of my committee for giving so freely of their time in order to guide and encourage me.

Thanks also go to Dr. Steven Cool, for the many hours spent in developing a computer program for statistical analysis of the data.

BRIGHTNESS CONTRAST IN AMBLYOPIA

An Abstract of a Thesis

Presented to

the Faculty of the Department of Physiological Optics

University of Houston

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By:

Dennis Michael Levi

May, 1973

ABSTRACT

The site of the loss of visual acuity in amblyopia is unknown. Although amblyopes appear to have normal absolute thresholds, the contrast requirements of the amblyopic eye reportedly differ from those of normal eyes. An apparatus has been constructed for the investigation of brightness contrast functions using a haploscopic brightness matching technique. Ten subjects, 5 amblyopes with central fixation and 5 control subjects matched for age, were investigated. The psychophysical method of adjustment was used in brightness matching over a wide range of test and inducing field luminances. The results of this study indicate that both amblyopic and control subjects demonstrate brightness contrast function. Amblyopic subjects showed abnormal brightness contrast, most markedly at low and intermediate photopic luminances, but normal contrast function at high luminances. Except for one subject, the amblyopes demonstrated normal brightness matching in the absence of an inducing field; however, one individual showed differences of over 0.5 log units in brightness appreciation between the two eyes. It has been hypothesized that a shift in lateral interactions in the retina, as a result of enlarged retinal receptive fields, contributes to the reduction in visual acuity in amblyopia.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

CHAPTER 1

INTRODUCTION

Brightness contrast or induction is the phenomenon in which a change in the brightness of a light imaged on one area of the retina is brought about by simultaneous illumination of other regions (Heinemann, 1972). A variety of methods has been devised for the study of contrast. In essence, these methods consist of some procedure for comparing the brightness of a test field that is subjected to contrast effects, with a standard or comparison field that is uninfluenced by such effects. The brightness of the test and comparison field can be matched by adjusting the luminance of either the test field or the comparison field, or under some circumstances, by adjusting the luminance of the inducing field. The results do not depend on which luminance is adjusted (Heinemann, 1955; Schouten and Ornstein, 1939). For a simultaneous comparison of the brightness of the test and comparison fields, the test and inducing fields may be positioned as far as possible from the comparison field, but such that they can all be seen simultaneously. Possible influences of test and inducing fields on the comparison field which may result from simultaneous stimulation of the same retina can be eliminated by presenting the test and inducing fields to one eye and the match field to the other eye (Schouten and Ornstein, 1939). The effects of contrast and contour on visual perception have been known for centruies; however, scientific

investigation of brightness contrast began with the study of Hess and Pretori (1894). They investigated the induction effect as a function of test and inducing field luminances for a 1° x 1° square test field, surrounded by a 10° x 10° inducing field. Their measurements were made by monocular brightness matches between a test field and a comparison field of the same dimension, and also surrounded by a 10° x 10° inducing field. Diamond (1953) has pointed out the possible ambiguity of their findings as a result of the many possible interactions among the four (4) fields viewed by the same eye. These types of interactions, resulting from simultaneous stimulation of the same retina can be eliminated by presenting the test and inducing fields to one eye, and the comparison field to the other eye (Schouten and Ornstein, 1939). Provided the fields are imaged on non-corresponding regions of the 2 eyes, interaction between fields presented to opposite eyes has been reported to be negligible (Schouten and Ornstein, 1939; Diamond, 1953). One possible problem arising from binocular matching methods is the difference in response of the two eyes. Heinemann (1955) suggests that the problem can be overcome by accepting the matching luminance of the test field, in the absence of the inducing field, as a measure of the comparison field luminance.

(a) Parameters Affecting Brightness Contrast:

With the binocular matching method, several parameters influencing contrast have been investigated. Fry and Alpern (1953) and Diamond (1953) studied induction as a function of test and inducing field

luminances. Even though Fry and Alpern used a rectangular 2.5° x .5° test field centered between two inducing fields of the same size and shape, and in Diamond's investigation, the test and inducing fields were 33' x 33' adjacent squares, these investigations agree in showing little if any effect upon the apparent brightness of the test field by inducing field luminances less than the test field luminance, and a depression of the apparent test field brightness by inducing field luminances greater than the test field luminance. Heinemann (1955) performed a similar experiment, using an annulus surrounding the test field as an inducing field. He used a haploscopic matching method in which the comparison field was presented to one eye and the test and inducing fields to the other. His results were similar to those reported above. However, Heinemann also found an increase in luminance of the match field required to match the brightness of the test field as the inducing field luminance was increased up to a value near that of the test field. Heinemann concluded that when the inducing field luminance is low, initial increases may enhance the apparent brightness of the test field, until the inducing field luminance exceeds the test field luminance. Further increase in inducing luminance may result in a decrease in brightness of the test field. Results similar to those of Heinemann have been reported by several investigators (Horemann, 1965; Saunders, 1968; and Torii and Uemura, 1965) using a circular test field surrounded by an annular inducing field.

The spatial separation of the test and inducing fields is another important parameter. Leibowitz, Mote and Thurlow (1953) varied the

separation of the test and inducing fields from 0 to 540 minutes of arc. The test comparison and inducing fields were squares 30' x 30'. They found an increasingly greater effect of raising the luminance of the inducing field above that of the matching field when the inducing field was closer to the test field, and also that the rate at which the test field luminance must be increased to maintain constant brightness with increased inducing field luminance is smaller for larger separations. The major changes occur over separation ranges from 0' to 30'. Measurements made at separations of 60', 180' and 540' did not differ consistently from those made at 30'. Fry and Alpern (1953) conducted a similar experiment with inducing field luminances of from 7 to 150,000 millilamberts (ml). In this experiment they varied the separation of the center distance between the test and inducing fields from 0.75 to 4.5 degrees. The angular size of each field was 0.5 degrees to 2.5 degrees. The results of this experiment were similar to those of Leibowitz et al. (1953). At the maximum separation of 4.5° with inducing field luminances of 7000 ml and above, there was still a considerable elevation in the test field luminance required to match the luminance of a reference field seen by the other eye. Fry and Alpern (1953) noted that an intense inducing field, or "glare source," casts stray light over the whole retina. They explained their results on the basis of effects caused solely by stray light surrounding the test field.

Retinal location has been shown (Alpern, 1953) to be another parameter influencing brightness contrast with peripheral inducing fields producing greater contrast effects than do central inducing

fields. Hollins (1971) has shown that brightness contrast effects do occur at scotopic levels, and that rod-cone interactions may occur within the framework of brightness contrast.

(b) The Mechanism of Brightness Contrast:

The mechanism of brightness contrast has not been firmly established. Many of the early researchers implied that lateral inhibition processes in the retina account for contrast effects. Mach (1865) adopted this position and presented a formulation of the contrast phenomena he had observed in which a narrow bright band appears at the bright edge of a uniformly illuminated light area adjacent to a shaded area, and a narrow dark band appears at the dark edge. Mach proposed an explanation of the subjective band effect, now known as Mach bands, and other contrast phenomena in terms of opposed excitatory and inhibitory influences in neural networks in the retina and brain. Brown and Mueller (1965) report that Helmholtz (1886), Brucke (1884), Schneider (1884) and others felt that central influences were more important. Demonstrations of contrast effects in one eye as a result of stimulation of the other eye have been interpreted to indicate a non-retinal basis of these effects (Brown and Mueller, 1965); however, Schouten and Ornstein (1939), Diamond (1953) and Westheimer (1967) have reported negligible interaction between fields presented to opposite eyes. Westheimer's (1967) experiment is discussed in more detail in a later section. Another proposed mechanism for brightness contrast was the physically scattered light from an inducing field which falls on the region of the retina illuminated by the test

field (Fry and Alpern, 1953). However, Heinemann (1972) states that the curves of Leibowitz et al. (1953) describing the test field luminance required for a brightness match with a comparison field of constant luminance, as a function of the luminance of the inducing field, cannot be superimposed on each other by moving them parallel to the abscissa. The fact that the form of these changes as the fields are moved further apart seems to indicate that the influence of the inducing field is transmitted through the nervous system.

Alpern and David (1959) found that the induction effect of 2 rectangular fields that were separated from the test field by 105' was reduced when two more inducing fields that were separated from the test field by 135' were added to the stimulus pattern. The more peripheral inducing fields by themselves did not effect the test field, but they reduced the ability of their neighbors to do so. Heinemann reports that these results indicate that inducing fields may exert a physiologically transmitted influence upon a test field focused on the fovea over angular distances of the order of 1.5° to 2°. More distant inducing fields probably exert their influence through stray light. On the basis of current data, the evidence indicates that contrast effects are a result of lateral inhibition in the visual system. Jameson and Hurvich (1964) base their quantitative predictions of brightness induction on systems of simultaneous equations to represent opponent interactions among all stimulated areas of the visual field. Westheimer (1967) has reported that the site of inhibitory interaction is retinal. Westheimer determined the adaptation state of cone retina by finding threshold for

a small, briefly presented spot of light. With increases in background field diameter, the increment threshold first rises and then falls. The critical area beyond which an adapting light produces inhibition is about 5 minutes of arc for foveal observation. Westheimer has suggested that this is a manifestation of excitatory and inhibitory interaction of adaptation stimuli. The inhibiting action of the surrounding annulus occurred only when the annulus was viewed by the same eye, and not when it was seen by the other eye. This was interpreted by Westheimer as indicating a retinal site for inhibitory interaction.

(c) Electrophysiological Studies:

Although contrast phenomena have been explained in terms of excitatory and inhibitory influences in the retina, for over a century direct evidence of such interactions was not available until methods were devised for recording the activity of single nerve cells. The lateral eye of limulus is a coarsely faceted compound eye connected to the brain by long optic nerves. A single optic nerve fiber may be dissected from the optic nerve and placed on electrodes to record the action potential spikes (Hartline and Graham, 1932). The activity of one of these fibers in response to stimulation of the ommatidium from which it arises is an initial latent period after onset of the stimulus before the first impulse is discharged; the frequency of discharge is relatively high at first, settling down to a lower steady level, and the frequency of discharge depends primarily on the intensity of the

stimulus (Ratliff, 1959). In the limulus the discharge frequency recorded in an optic nerve fiber following stimulation of an ommatidium was found to be reduced by the stimulation of neighboring regions (Hartline, 1949). This interaction is mediated by way of the plexus of lateral interconnections, and is purely inhibitory. The magnitude of the inhibition has been shown to depend upon the intensity, area and configuration of the pattern of illumination on the retina: (1) the greater the intensity on neighboring receptors, the greater the inhibition exerted on the test receptor; (2) the greater the area of illumination, the greater the inhibition exerted on the test receptor; (3) illumination of neighboring receptors close to the test receptor results in greater inhibition than does illumination of more distant receptors (Hartline, Wagner, and Ratliff, 1956). These inhibitory influences are exerted mutually among the receptors, the activity of each ommatidium influencing and being influenced by the activity of its neighbors (Ratliff, 1959). Hartline (1949) has suggested that this inhibitory interaction is important in the enhancement of contrast, increasing temporal and spatial resolution, and "supplying a mechanism for increased versatility of response."

Ratliff and Hartline (1959) investigated the effects of various stimulus patterns on the neural responses of the limulus eye and were able to demonstrate a neural analogy of the Mach band phenomenon. Thus, the kind of lateral inhibition found in the limulus eye seems to provide an analogy for contrast effects in man. Lateral retinal interactions have also been demonstrated in other animals. Kuffler (1953) developed

a technique for introducing a microelectrode into the unopened eye of a cat, and was able to record the impulses from a single retinal ganglion cell. Kuffler found that in the cat a single ganglion cell might exhibit "on", "off", or "on-off" activity under various conditions of stimulation. Complex inhibitory interactions were also found by Kuffler (1953) to exist between two spots stimulated by separate flashes. The antagonistic center-surround arrangement suggests that lateral activation as well as lateral inhibition may occur.

Baumgartner et al. (1965) have described a model for contrast based on lateral inhibition and lateral activation in the cat retina. Their model proposes: (1) inhibitory interactions between neighboring excitatory areas; and (2) an excitatory area will have an excitatory effect on an inhibitory area. This model appears to be somewhat speculative at this time. Michael (1968) has described contrast sensitive units in the mammalian visual system (ground squirrel). These units were found to be much more sensitive to the simultaneous contrast in illumination between the centers and the surrounds of their receptive fields than they were to the absolute intensity of the illuminance itself. Werblin (1973) has shown in the mud puppy that graded activity in the bipolar cells was a function of the contrast across antagonistic zones of the bipolar receptive fields. He further suggested that the mechanism lay within the horizontal cell layer. Maffei and Fiorentini (1971) recorded single unit spike activity from the lateral geniculate body and from optic tract fibers. They reported that in the cat the surround of lateral geniculate body receptive fields results from the

projection of centers of retinal receptive fields different from those projecting onto the lateral geniculate body center. This fact, they suggest, makes it unlikely that the organization of receptive fields at the retinal level subserves contrast analysis. They further hypothesized that the lateral geniculate body may be involved in contrast analysis. The experiment of Maffei and Fiorentini (1971) does not, however, rule out the retina as the first of several successive relays at which contrast analysis takes place. Katsuki (1959) and Mountcastle (1959) both suggest that lateral inhibition occurs at successive relays in sensory pathways. Von Bekesy (1967) has also reported that a large part of the lateral inhibition that occurs in vision is already present in the end organ, and that there is evidence that the effects of edge contrast can be followed all the way to the cortex.

(d) Contrast Functions in Amblyopia:

Contrast effects serve to increase the discriminability of boundaries and contours which divide regions of different luminance; hence, these effects are of significance in the perception of form and the identification of objects in the visual world. The value of lateral inhibition for the enhancement of stimulus differences has been noted in a variety of sensory modalities (Brooks, 1959; Von Bekesy, 1967). It would appear that brightness contrast may be an important factor in visual acuity, since in many cases, visual acuity appears to be a form of brightness discrimination (Riggs, 1965). Functional amblyopia is defined as a unilateral defect in visual acuity in strabismic patients for which no

obvious cause can be detected by physical examination of the eye (Borish, 1970). Burian (1969) has reviewed much of the current literature of the pathophysiology of amblyopia, and has concluded that amblyopia represents a loss of the physiologic superiority of the fovea characteristic of the photopic state. The mechanism responsible may reside in a disinhibition of the fovea owing to a reduction in lateral inhibition.

Classically the site of the reduction of visual acuity in amblyopia has been considered to be the visual cortex, and the concepts of suppression and disuse (amblyopia ex-anopsia) are most commonly accepted (Von Noorden, 1960). The mechanism of loss of acuity still remains unknown. While many of the physiological functions of the amblyopic eye are normal, especially at low levels of intensity (Burian, 1969; Von Noorden, 1960), luminance difference thresholds are raised (Burian, 1969). Lawwill and Burian (1966) have shown that contrast requirements for amblyopic eyes are higher than for normal eyes at high luminances. They investigated detection of the orientation of randomly oriented E's, under various conditions of luminance of the visual acuity targets, and of their background. They plotted the percentage contrast required for detection of 50% of the E's as a function of background luminance. Their data indicates that for "normal" eyes the contrast requirement was highest for very low background luminances, dropped rapidly as the luminance was increased, and reached asymptotically a minimum with further increases in luminance. Lawwill and Burian (1966) state that eyes with functional amblyopia followed the pattern of normal eyes with low background luminances, but increased their contrast requirements

with high background levels. Inspection of their data reveals, however, that at low background luminances the curves are somewhat chaotic, and in one case S-shaped curves were obtained. Flom, Heath and Takahashi (1963) studied the impairment in gap detection in a 4 position Landolt C when critically spaced surrounding bars were presented to the other eye. They concluded that the site of loss of information due to contour interaction in normal subjects occurs at a supra-retinal level. It appears that the amblyopic eye acts normally at scotopic levels but performs at its worst at photopic levels (Burian, 1969). Miller (1954) has explained the reduced photopic functioning of the amblyopic fovea as a result of the absence of inhibition in the retina which leaves the "spread of excitation unsubdued." Miller used narrow bars of variable width to determine the differential luminance threshold for bars of different widths. He found a greater degree of spatial summation in his amblyopic subject than in his normal control. Burian (1969) has suggested that Miller's hypothesis accounts for such clinical findings as the crowding effect. The crowding effect (or the effect of contour interaction) is a commonly occurring clinical finding in amblyopic patients, in which there is a reduction of visual acuity with symbols presented in a line rather than in isolation. Flom, Weymouth, and Kahneman (1963) investigated the effect of contour interaction on visual resolution in normal and amblyopic eyes by evaluating the effect of the separation of black bars on the visibility of a Landolt C. They found that detection of the position of the gap in a Landolt C was adversely affected by black bars placed tangential to the C and at a certain

distance from it. The maximum bar separation affording interaction was proportional to the minimum angle of resolution, both in normal and amblyopic subjects. The investigators hypothesized that this contour interaction was related to the size of the retinal receptive field. Flynn (1967) found that spatial summation in the central field of the light adapted amblyopic eye was greater than normal, and similar to that found in the normal periphery. This adds support to Miller's (1954) hypothesis. Flynn investigated spatial summation using a Goldmann perimeter. Flynn (1967) operationally defined spatial summation as the "ability of the retina to respond to larger targets at a lower brightness threshold than smaller targets." Since the threshold stimulus for a given retinal area under light adapted conditions is proportional to the size of the test object, the luminance of the test object and the summation coefficient of the given retinal area, this can be empirically expressed as: C = logarithm L + K x log A, where C = constant, log L = log of the luminance of the test object, and K = summation coefficient (Flynn, 1967). Flynn determined the logarithm of the threshold as a function of retinal location for various test object sizes in 6 amblyopic and 8 control subjects. By applying the above equation, he was able to determine a "summation coefficient." For normals, the summation coefficient increased progressively from a low of 0.33 at 0° to 0.80 at 30°. For amblyopes the central and peripheral values were of the same order of magnitude. Peripheral thresholds and peripheral summation were normal, but centrally the thresholds were not only depressed, but summation occurred

in a similar manner to that of the periphery. Sawyer (1971) has reported decreased inhibitory function in the amblyopic eye which "limits" the contrast enhancement found in normal eyes. Recently Lawwill, Cox, Tuttle, Meur, and Burian (1973) have recorded the visual evoked response using a stimulus set up similar to that of Westheimer (1967). In his study Westheimer determined the adaptation state of cone retina by finding the threshold for a small, briefly exposed spot of light. With increased background field diameter, the increment threshold first rises and then falls. Westheimer has interpreted this as being a manifestation of excitatory and inhibitory interaction of adaptation stimuli. The inhibiting action of the surrounding annulus occurred only when the annulus was viewed by the same eye, and not when it was seen by the other eye. This was interpreted by Westheimer as indicating a retinal site for inhibitory interaction. Lawwill et al. (1973) determined a critical surround size producing maximum inhibition (i.e. the lowest amplitude and longest latency of the most prominent response) in the "normal" and amblyopic eye of an amblyopic subject. The critical size surround was found to be larger in the amblyopic eye. They noted that both the electrophysiologic and psychophysical responses from the amblyopic eye showed an abnormal inhibitional field. Extrapolating from Westheimer's (1967) findings, deduced from binocular data, Lawwill et al. have concluded that the defect occurs peripherally to the primary visual cortex. Spekreijse, Khoe and Van der Tweel (1972) varied the contrast between adjacent squares of a checker board pattern while keeping the average luminance of the whole field constant. They used

both in phase and counterphase checker board stimulation to study psychophysically and electrophysiologically a subject with anisometropic amblyopia. Their findings indicate that contrast sensitivity of the amblyopic eye is highly reduced as measured with low frequency counterphase checker board stimulation.

A general criticism of all of the above studies is the lack of comparative statistics. In addition, in many of the studies cited, only one or two amblyopic subjects were investigated, with no control group.

The Purpose of the Present Study:

The purpose of the present study is to further investigate contrast effects in amblyopia. A considerable body of evidence exists indicating that brightness contrast is mediated by lateral inhibition in the retina. Lateral interactions in the retina serve to "sharpen up" contrasting boundaries, e.g., Werblin (1972), Ratliff (1972). Miller (1955) has explained the reduced photopic functioning of the amblyopic eye as a result of the "absence of inhibition in the retina." Support for this hypothesis has been added by the studies of Grosvenor (1957), Flynn (1967), Spekreijse et al. (1972), Sawyer (1971), and Lawwill et al. (1973). If indeed a reduction in lateral inhibition in the visual system is the mechanism responsible for the loss of acuity in amblyopia, it seems that a study of brightness contrast in amblyopia may generate further evidence for this hypothesis, and may provide information of prognostic value in the treatment of this condition. The first priority

in this study was the development of an apparatus for the investigation of brightness contrast function using the binocular matching method (Heinemann, 1955) in amblyopic and non-amblyopic "control" subjects over a wide range of test and inducing field luminances.

CHAPTER 2

APPARATUS AND PROCEDURES

(a) Apparatus:

A three channel Maxwellian view system, mounted on a haploscope, was used to provide a test and inducing field to one eye and a comparison field to the other eye. Brightness matches for various test and inducing field luminances were made by adjustment of a neutral density wedge before the comparison field source. A diagram of the stimulus apparatus is shown in Figure 1. An optical stimulator designed by Pitts (1967) was used to provide the test and inducing fields. The stimulator consists of a two channel Maxwellian view system. Source I_s served as the inducing field source; the test field was provided by source T_s, and the comparison field source is C_s. All of the sources consisted of 6.0 volt, 2.5 ampere tungsten bulbs, powered by a Cepco D.C. power supply. The light from source T_s was collimated by lens L_1 and was focused at aperture A_1 by lens L_2. From A_1 the beam was collimated by lens L_3 and passed through apertures A_2 and A_3. Lens L_4 focused the light beam in the eye in Maxwellian view, subtending a visual angle of 1.6°. The test field intensity was varied by the neutral density wedge $N.D.F._1$. The inducing field light was collimated by lens L_5, reflected by 45° mirror M_1 and focused into the eye in Maxwellian view by lens L_4. In this experiment aperture A_4 was set to provide an inducing field subtending a visual angle of 8°. Since the test field was superimposed

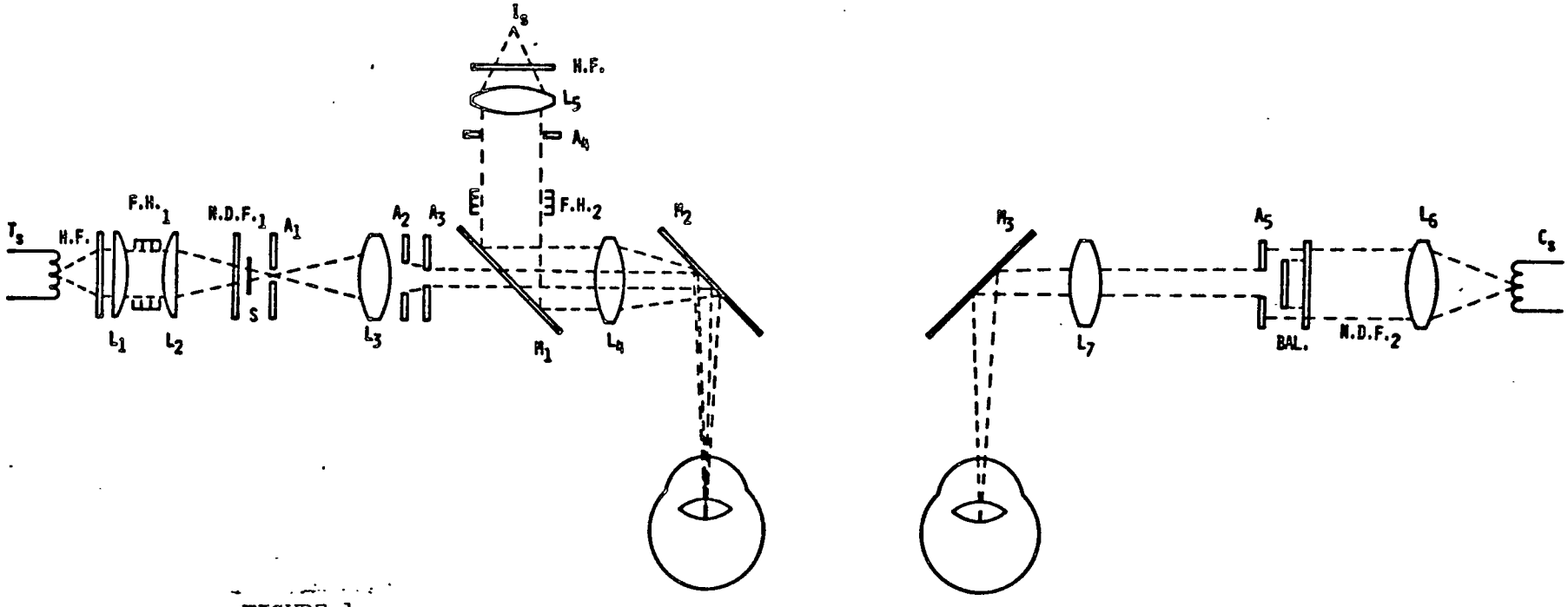


FIGURE 1

Schematic Diagram of Apparatus.
See text for details.

onto the inducing field, it was not possible in this experiment to use inducing fields of higher illuminance values than those of the test field. The optical stimulator was mounted on one arm of a haploscope, and the comparison field system was mounted on the other arm. The comparison field system consists of a light source C_s, a neutral density wedge, N.D.F.$_2$, and a balance (BAL). Light from source C_s was collimated by lens L_6, passed through aperture A_5, and focused in the eye in Maxwellian view by lens L_7, subtending a visual angle of 1.6°. The arms of the haploscope were set so that the subject viewed the test and inducing field with one eye and the comparison field with the other eye, and the two ocular fields were completely separated by approximately 10° (Figure 2). The two arms of the haploscope were interchangeable so that the right and left eye fields could be reversed.

(b) Calibration:

Calibration was accomplished by two methods. Initial photometric calibration in the system was done with the #6800 Macbeth Illuminometer using the standard procedure. The working standard lamp was calibrated initially and then disconnected. The test plate was placed 7 cm from the mirror M_1 in the plane of the eye, and 5 readings each were made of the brightness of the unattenuated test field and the unattenuated inducing field. The test plate was then placed 7 cm from mirror M_2 in the plane of the eye and the procedure was repeated for the comparison field brightness. Calibration of the lamps was checked with a Macbeth Illuminometer twice during the course of the experiment and was not

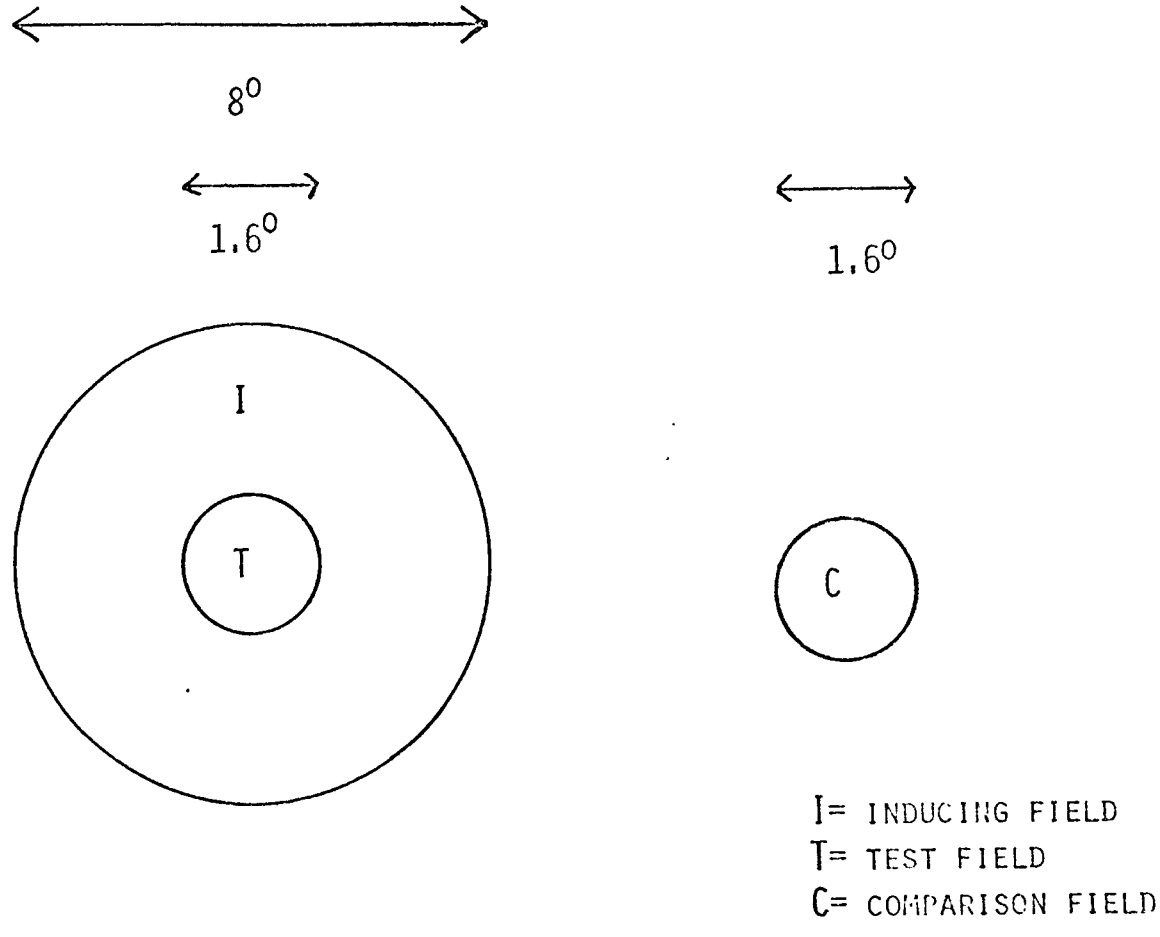


FIGURE 2

Schematic of the stimuli as viewed by the subject.

found to have changed materially. The unattenuated values for background, test field and match field were 551.13, 191.25 and 117.69 mL respectively. The wedges were calibrated on the basis of five readings for each of seven wedge settings. For both wedges and Wratten filters the wedge settings (or filter density values) were plotted against log transmission values, using a linear regression plot (Figure 1 in the Appendix). In each case slope and intercept values were derived for each of the wedges and the filters, and by applying the linear regression formula the transmission values can be calculated. For the wedges and filters the correlation coefficient values demonstrate the goodness of fit of the points to the line; for the inducing field neutral density filters r = .976; for the comparison field wedge r = .998; and for the test field wedge r = .997. The linearity of the wedges was confirmed by thermopile calibrations, both in and out of the system, using an Eppley circular, bismuth-silver, 16 Junction Thermopile with a lamp black coating coupled with a Keithley 150B microvolt ammeter. The responses of the thermopile were read out in microvolt units on the microvolt ammeter and converted into irradiance values with the formula:

$$E_e = K\,V_E\ (\mu V)$$

E_e = Irradiance

$K = 5.648\ \mu Wcm^{-2}/\mu V$

V_E = Voltage response in microvolts.

(c) <u>Data Collection Procedure</u>:

Visual acuity, refractive error, fixation status and binocular coordination status of the subjects was ascertained by standard clinical

methods prior to the experimental sessions. At the beginning of each session, the subject's pupils were dilated with two drops, 10% neosynephrine. After the pupils were fully dilated, the next step in the procedure was the alignment of the two optical stimulus channels. The eye initially viewing the test and inducing fields, i.e. the "tested eye," was varied across subjects in order to eliminate undesired order effects. The subject was seated before the apparatus; the table height and the height of the optics were adjusted. The positions and interpupillary distance of each optical channel were adjusted until the exit pupil images of the channels were coincident in the plane of the subject's pupil. Vertical and lateral adjustments of the chin rest were made until the Maxwellian view lens appeared to the patient to be filled. The position of the exit pupil images were monitored throughout the procedure. The arms of the haploscope were adjusted so that the comparison field appeared to be in apposition to the inducing field surrounding, and then the arm containing the comparison field channel was rotated so that it was completely separated from the inducing field by 10° (Figure 2). The psychophysical method of adjustment (Guilford, 1954) was used for data collection. The subject was instructed to look back and forth from the test to the comparison field and to match the comparison field brightness to the test field brightness by adjusting the N.D.F.$_2$ wedge. The subject was asked to "bracket" in order to make the match "as quickly and accurately as possible." The match values were read directly from the comparison field N.D.F.$_2$ wedge scale. The subject was trained by making eight "trial" matches immediately prior to data

collection. In the data collection trials, the comparison field brightness preceding each match was preset at a lower level than that required for the previous match by varying amounts. Due to the nature of the stimulus apparatus, the test field brightness was superimposed on the inducing field brightness, and, therefore, the test field brightness was the sum of the test field channel and the inducing field channel. The test field $N.D.F._1$ wedge was preset to attenuate the test source brightness by 1.8, 1.5, 1.2, 0.9, and 0.6 log units. These values were determined following a pilot study, which is discussed in a later section. The order of presentation, i.e. from dimmest to brightest, was maintained throughout the experiment to allow the patients to maintain their level of adaptation for each condition. The subjects were required to make a series of 5 matches for each of 5 test field luminance conditions in the absence of an inducing field. These matches were then repeated for each of four inducing field intensity levels; viz. .34, 1.3, 2.26, 3.22 log ml respectively. Each experimental session lasted approximately one hour and fifteen minutes. Subjects returned subsequently and the matching experiment repeated with the eye which initially viewed the test and inducing fields, now viewing the comparison field, and vice versa.

(d) Subjects:

Ten subjects, 5 non-amblyopes who served as the control group and 5 amblyopes with central fixation, served as observers. The operational definition of amblyopia used in this study was 20/40 or poorer acuity

in one eye and at least one line of difference in visual acuity between the two eyes, in the absence of observable pathology, and not correctable with spectacle lenses. Table I shows the important visual characteristics of the subjects. The amblyopic subjects were drawn from the clinic population at the University of Houston College of Optometry. Determination of their visual status was made by the investigator. Determination of fixation status was made on the basis of visuoscopy and Haidinger Brush or Maxwell's spot phenomena. For all subjects, the results of both tests of fixation were in agreement. The normals and amblyopes were approximately matched for age, and ranged from 7 to 36 years.

(e) Pilot Study:

A pilot study was conducted prior to the major investigation in order to: (1) determine whether in fact the experimental apparatus and procedure could be used to investigate brightness contrast; (2) refine the procedure; (3) determine the inducing and test field luminances to be used in the study; (4) determine the number of matches necessary for each condition; and (5) ascertain whether the matches approached a normal distribution, fulfilling one of the assumptions for the use of parametric statistics. The pilot study was carried out using subject S.R., a trained psychophysical observer. He was instructed to match the test field brightness by adjusting the wedge $N.D.F._2$ before the comparison source C_s by the method of adjustment (Guilford, 1954). The procedure in the pilot study differed from the procedure ultimately adopted for the experiment in that the direction

Table I. Visual Characteristics of Subjects Participating in the Study

SUBJECT	AGE	VISUAL ACUITY O.D.	VISUAL ACUITY O.S.	ANISOMETROPIA	STRABISMUS	RETINAL CORRESPONDENCE
Control Group						
M.A.	8	20/20	20/20	No	No	Normal
W.A.	36	20/15	20/15	No	No	Normal
M.L.	23	20/20	20/20	No	No	Normal
S.S.	11	20/20	20/20	No	No	Normal
M.S.B.	26	20/15	20/15	No	No	Normal
Experimental Group						
R.S.	7	20/20	20/200	Yes	Esotrope	Normal
K.B.	22	20/15	20/200-1	No	Esotrope	Anomalous Retinal Correspondence
P.N.	35	20/15	20/200	Yes	No	Normal
B.R.	26	20/50	20/15	Yes	No	Normal
M.B.	7	20/25	20/80-	Yes	No	Normal

of adjustment was not always preset at a lower luminance by the investigator but was counterbalanced using the sequence ABBABAABABBA, where A indicates that the matching wedge was preset at a level higher than that required for the previous match (i.e. descending), and B indicates that the matching wedge was preset at a lower level than that previously required (i.e. ascending). The subject's pupils were dilated with 2 drops 10% neosynephrine, and following 8 trial matches he was instructed to make the twelve matches for each condition by "bracketing." Matches were made over a wide range of test field and background luminances.

The pilot study provided some useful guidelines:

(1) The data was analyzed according to the procedure described in the results section. Linear regression curves of the logarithm of the comparison field brightness versus the logarithm of the test field brightness were plotted for each inducing field condition. From the linear regression equations, curves of the logarithm of the test field brightness versus inducing field brightness for various comparison field levels were derived. In all cases a decrement in apparent brightness of the test field was shown by the increase in test field brightness necessary to match the fixed comparison field brightness. The data of this subject were not qualitatively different from those shown in Figure 8 in the results section. These curves demonstrate brightness contrast function, and are similar to those described by Heinemann (1955), Fry and Alpern (1953), and Hollins (1971).

(2) A t-test revealed no statistically significant difference between the means of the first four or six matches for all conditions versus

the mean of all twelve matches for all conditions. Since twelve matches were exceedingly time consuming, it seemed reasonable to provide an initial training session of eight matches and then require the subjects to make only five matches for each condition.

(3) A t-test revealed no statistically significant difference between ascending versus descending presentations. Since "bracketing" was allowed, it was decided that in order to maintain a fairly constant level of retinal adaptation, the match field luminance during the study would always be set lower than that required for the previous match by varying amounts (the variation to be unsystematic) and the subject required to "bracket" in order to obtain a match.

(4) At times the subject would spend inordinate amounts of time in making a match; however, he reported that the consistency of the match did not seem to be related to the length of time required to make a match; thus, in the actual study the subjects were asked to make the match as quickly and accurately as they could.

(5) The pilot study revealed that at the highest background level matches were less consistent, and the subject reported that judgments were hindered by afterimages. The preliminary data also revealed a paucity of information at low background luminance levels.

(6) If the most intense background condition was omitted, a frequency histogram of all the matches approached a normal distribution (Figure 3), therefore fulfilling the assumption for the use of parametric statistics.

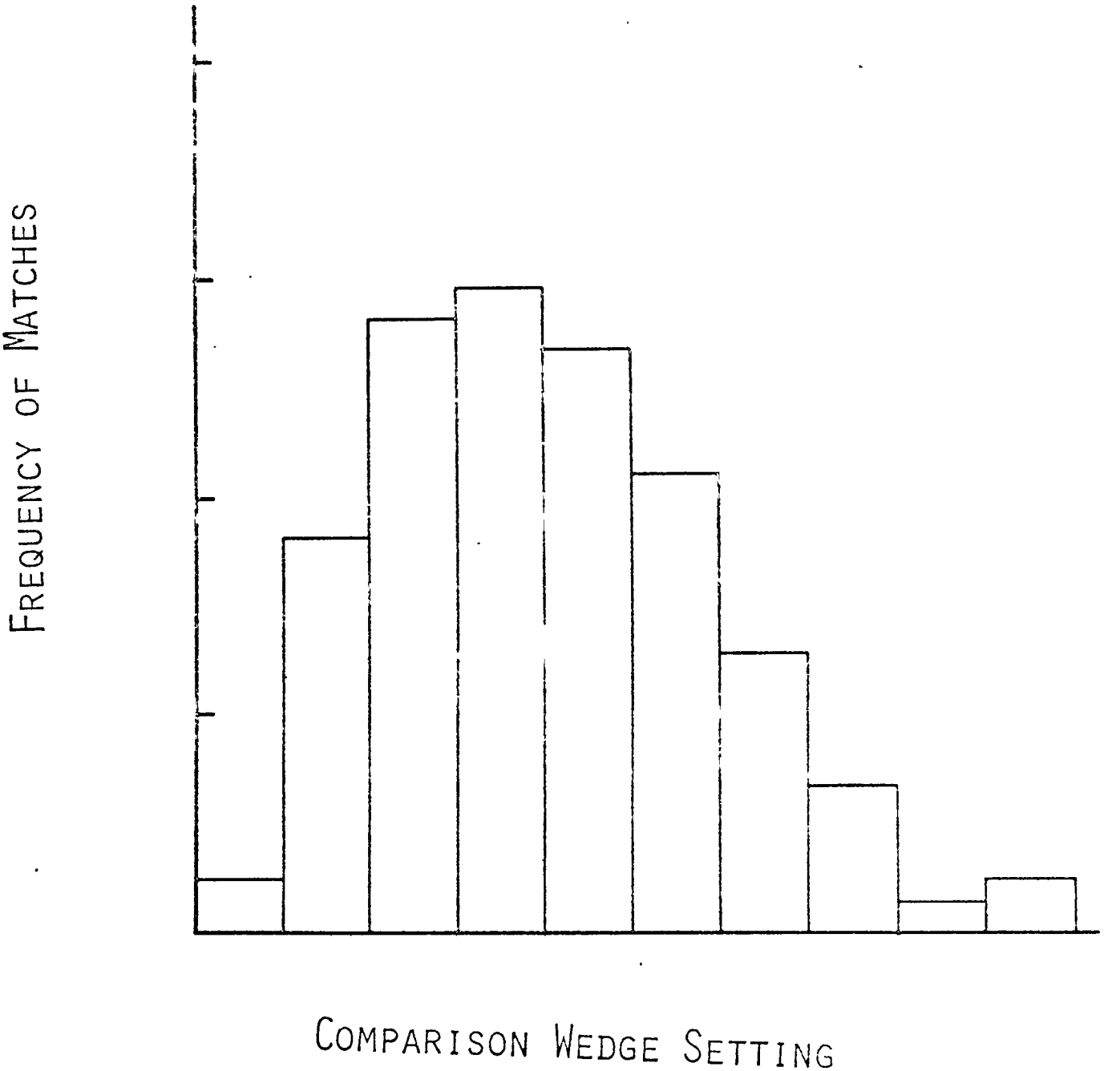


FIGURE 3 Frequency Histogram of matching wedge settings for pilot study.

CHAPTER 3

RESULTS

Data Manipulations:

The logarithm of the comparison field brightness was plotted against the logarithm of the test field brightness for each inducing field condition. The mean of the five matches for each condition was converted to the logarithm of the comparison field brightness (ml) using the formula:

$$V = \text{Log } T + \text{Log } I$$

where Log T = Log % transmission (from thermopile calibration data)

Log I = unattenuated comparison field brightness (from Macbeth calibration data)

V = log comparison field brightness (ml).

A Hewlett-Packard 9100 computer with a plotter was used to plot the logarithm of the comparison field brightness (ml) versus the logarithm of the test field brightness (ml). A linear regression program based on the formula $y = mx + c$ was used to plot best fit straight lines for each inducing field condition. The correlation of the individual points to the line in all cases ranged from 0.9 to 1.00. Each point presents the mean of 5 settings. The linear regression equations were used to derive curves of test field brightness as a function of inducing field brightness for various comparison field levels arbitrarily chosen. Since these graphs involve extrapolation of data from the linear regression formuli, they offered little additional quantitative information

to the data analysis; however, they were used to determine graphically whether brightness induction was occurring.

Results:

Table II shows the mean of five brightness matches for each of the ten subjects (1-10) for each of the five test field luminances (C_1-C_5) across all five inducing field luminance conditions (B_1-B_5). Subjects one through five comprise the amblyopic group (A_1). The mean brightness match for the amblyopic eye viewing the test and inducing fields and the non-amblyopic eye viewing the comparison field for each condition is shown in column D_1. The values for the non-amblyopic eye viewing the test and inducing fields and the amblyopic eye viewing the comparison field for each condition are shown in column D_2. Subjects six through ten comprise the "control" group (A_2). The right and left eyes of the "control" group were randomly assigned across D_1 and D_2 (i.e. amblyopic and non-amblyopic eyes).

The values shown in the table represent the mean of 5 readings from the comparison field wedge N.D.F.$_2$ scale. The scale ranges from 0 to 49 representing one centimeter intervals around the wedge. Zero is the brightest value (unattenuated matching field) and 49 the dimmest, representing approximately two and one-half log units of attenuation. Using the above procedure, linear regression curves of the logarithm of the comparison field brightness (ml) versus the logarithm of the test field brightness (ml) were plotted for each eye of all subjects.

Table II: Mean Data of Five Brightness Matches for Each of the Ten Subjects Across All Test and Inducing Field Luminance Conditions

A_1 = Amblyopic subjects (1 through 5)

A_2 = Control subjects (6 through 10)

B_1-B_5 = Inducing field luminance conditions (0.00, 0.34, 1.3, 2.26, 3.22 log inducing field brightness)

C_1-C_5 = Test field brightness conditions

D_1 = Amblyopic eyes of amblyopic subjects] right and left eyes of "control" subjects randomly assigned.

D_2 = Non-amblyopic eyes of amblyopic subjects]

		B_1									
		C_1		C_2		C_3		C_4		C_5	
		D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2
	1	26.86	27.34	21.26	21.26	18.86	16.74	15.1	9.26	12.82	2.00
	2	22.34	25.72	15.94	17.38	13.68	12.14	6.2	5.04	1.24	2.18
A_1	3	29.56	19.88	22.80	15.9	19.64	12.14	15.9	9.56	14.76	4.7
	4	28.16	24.64	19.56	16.92	15.06	13.12	8.32	9.42	3.34	5.72
	5	20.6	22.34	20.4	14.52	16.52	3.52	10.68	1.52	4.2	0.0
	6	26.0	22.98	19.7	16.06	17.88	11.76	13.54	8.60	10.3	4.18
	7	27.62	26.84	21.78	17.72	16.1	11.26	12.88	10.94	9.64	9.12
A_2	8	26.68	25.16	19.36	17.3	14.74	12.62	8.94	7.76	5.34	3.56
	9	27.32	25.68	18.56	18.00	12.96	12.62	10.92	8.46	6.66	4.22
	10	24.38	27.28	18.7	21.94	12.6	17.	9.18	14.12	5.36	10.

Table II (continued)

		B_2									
		C_1		C_2		C_3		C_4		C_5	
		D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2
	1	38.62	20.68	25.16	22.78	18.98	17.88	12.92	10.04	10.58	1.68
	2	29.28	24.62	21.6	19.24	15.42	13.64	11.88	11.0	3.66	5.42
A_1	3	39.5	22.18	27.8	18.02	20.40	14.7	16.38	11.78	16.06	9.74
	4	36.22	23.14	28.08	18.28	23.16	15.5	12.38	12.16	5.90	9.62
	5	38.08	18.20	31.8	9.28	22.18	2.68	18.74	1.74	16.64	0.0
	6	25.16	22.02	18.0	19.18	14.24	14.06	10.34	12.32	5.82	6.46
	7	24.4	25.78	24.22	21.08	19.56	15.86	13.02	11.06	9.34	5.94
A_2	8	22.14	21.6	15.12	14.86	11.86	10.78	6.82	7.66	3.64	4.48
	9	20.3	19.08	16.3	13.74	10.52	10.1	6.58	7.58	1.42	2.88
	10	26.32	22.8	19.14	15.66	16.8	10.08	13.06	7.14	11.06	4.76

Table II (continued)

		B_3									
		C_1		C_2		C_3		C_4		C_5	
		D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2
	1	29.84	29.46	27.50	23.90	21.44	17.44	13.74	10.88	8.06	3.90
	2	25.5	25.22	20.42	18.14	16.66	13.50	8.46	11.94	5.08	6.66
A_1	3	37.84	21.88	28.54	18.44	23.96	14.88	19.38	9.72	16.26	4.12
	4	26.06	18.14	21.04	17.12	13.96	14.34	11.84	12.76	9.08	10.22
	5	19.48	24.66	13.06	21.00	11.34	13.36	7.96	9.8	5.14	2.06
	6	21.1	22.12	17.08	19.10	11.74	15.86	9.6	12.48	6.48	6.52
	7	24.92	24.74	18.86	15.78	15.32	14.48	12.4	13.70	7.64	9.72
A_2	8	18.38	18.08	15.06	14.96	11.52	12.06	8.44	8.28	2.96	3.08
	9	20.8	18.04	16.6	13.86	12.6	9.34	9.6	6.26	5.94	2.30
	10	28.32	23.02	23.16	13.88	17.74	11.24	14.78	9.68	10.58	6.36

Table II (continued)

		B_4									
		C_1		C_2		C_3		C_4		C_5	
		D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2
	1	27.76	27.76	22.56	19.16	18.10	11.82	15.06	6.32	12.06	1.14
	2	20.38	23.44	16.64	20.22	14.22	14.54	10.50	9.06	5.84	6.16
A_1	3	35.44	12.18	26.14	10.92	22.26	8.20	21.28	4.54	15.38	1.62
	4	23.70	15.98	14.26	13.54	12.96	10.98	11.36	11.06	8.08	4.58
	5	17.64	32.8	14.48	27.4	12.04	19.96	9.64	16.88	8.22	13.64
	6	21.96	20.7	17.3	17.18	16.42	13.32	13.9	10.52	11.66	9.2
	7	25.88	25.64	22.12	16.4	17.26	10.56	9.7	7.8	5.96	4.18
A_2	8	24.06	21.4	18.42	17.34	13.56	14.6	8.66	10.88	3.2	7.5
	9	21.24	16.86	16.84	12.82	11.98	8.78	9.36	4.34	8.84	1.5
	10	29.94	20.96	24.	16.18	19.88	15.02	15.46	6.7	11.42	4.56

Table II (continued)

		B_5									
		C_1		C_2		C_3		C_4		C_5	
		D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2	D_1	D_2
	1	30.86	23.42	24.58	9.9	18.10	2.66	14.10	1.84	8.26	0.0
	2	15.48	11.68	10.84	4.60	8.2	1.66	3.96	2.34	2.14	1.5
A_1	3	21.81	6.98	20.14	2.62	16.78	1.9	16.28	1.16	13.40	1.00
	4	17.30	14.32	9.48	9.98	6.58	8.5	4.74	5.08	1.74	2.54
	5	22.4	27.38	16.3	26.68	5.42	23.70	2.18	17.36	1.00	7.82
	6	18.94	16.9	13.92	14.5	12.18	13.26	9.1	7.92	4.80	7.76
	7	20.1	21.24	17.18	13.16	12.34	8.76	11.08	6.12	6.32	1.94
A_2	8	19.66	18.26	13.54	14.48	10.12	11.26	8.12	7.72	4.52	4.98
	9	19.54	17.68	20.28	16.58	15.18	12.44	10.84	6.96	9.7	1.5
	10	21.9	20.36	22.68	20.68	17.96	18.18	13.46	15.32	13.58	13.74

Figure 4A and B shows the plot of log comparison field brightness versus log test field brightness for the mean data of the non-amblyopic subjects. Figure 4A presents the 5 linear regression curves for each of the inducing field brightness conditions, for the right eye (O.D.) viewing the test and inducing fields, and the left eye (O.S.) viewing the comparison field. Figure 4B presents the 5 linear regression curves for the same 5 inducing field brightness conditions, for the left eye viewing the test and inducing fields while the right eye views the comparison field. It may be noted that for each inducing field brightness condition, as the test field brightness is increased, the comparison field brightness increases. Comparison of the slopes, Y intercepts and positions of the points on corresponding linear regression curves for each eye viewing the test and inducing fields shows little difference between the matches made by the right and left eyes. Statistical testing for differences between the two eyes with respect to slope and intercept of each curve is described on page 46.

Figure 5A and B shows the graph of the logarithm of the comparison field brightness versus the logarithm of the test field brightness for control subject M.L., which is typical of the data for the non-amblyopic subjects. Figure 5A presents the 5 linear regression curves for each of the 5 inducing field brightness conditions, for the right eye viewing the test and inducing fields and the left eye viewing the comparison field. It may be noted that as test field brightness increases, for each inducing field brightness level, the comparison field brightness increases. Figure 5B displays the 5 linear regression curves for the

MEAN DATA FOR NORMAL SUBJECTS

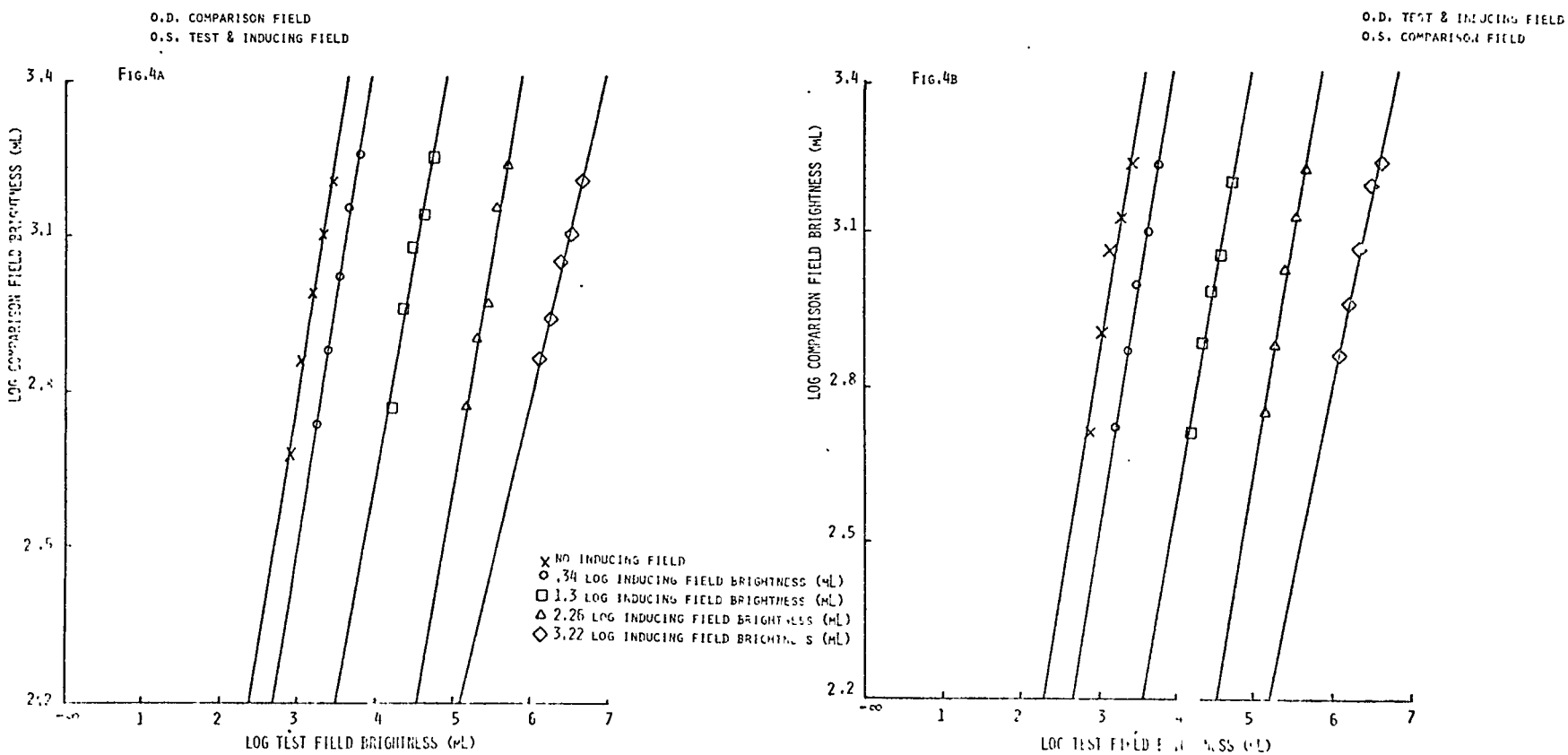


FIGURE 4 Log comparison field brightness (ml) vs. Log test field brightness (ml) for mean data of non-amblyopic subjects.

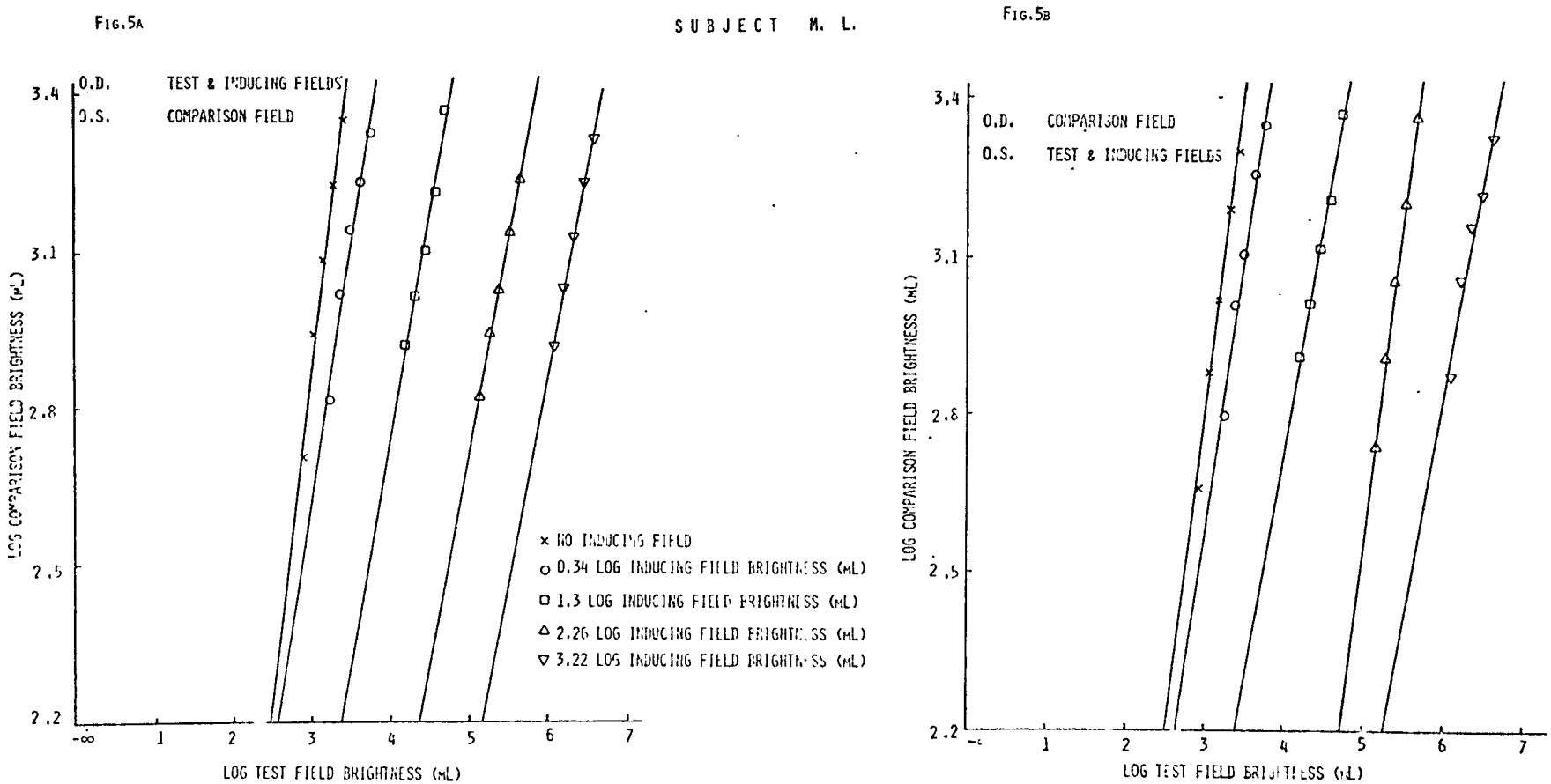
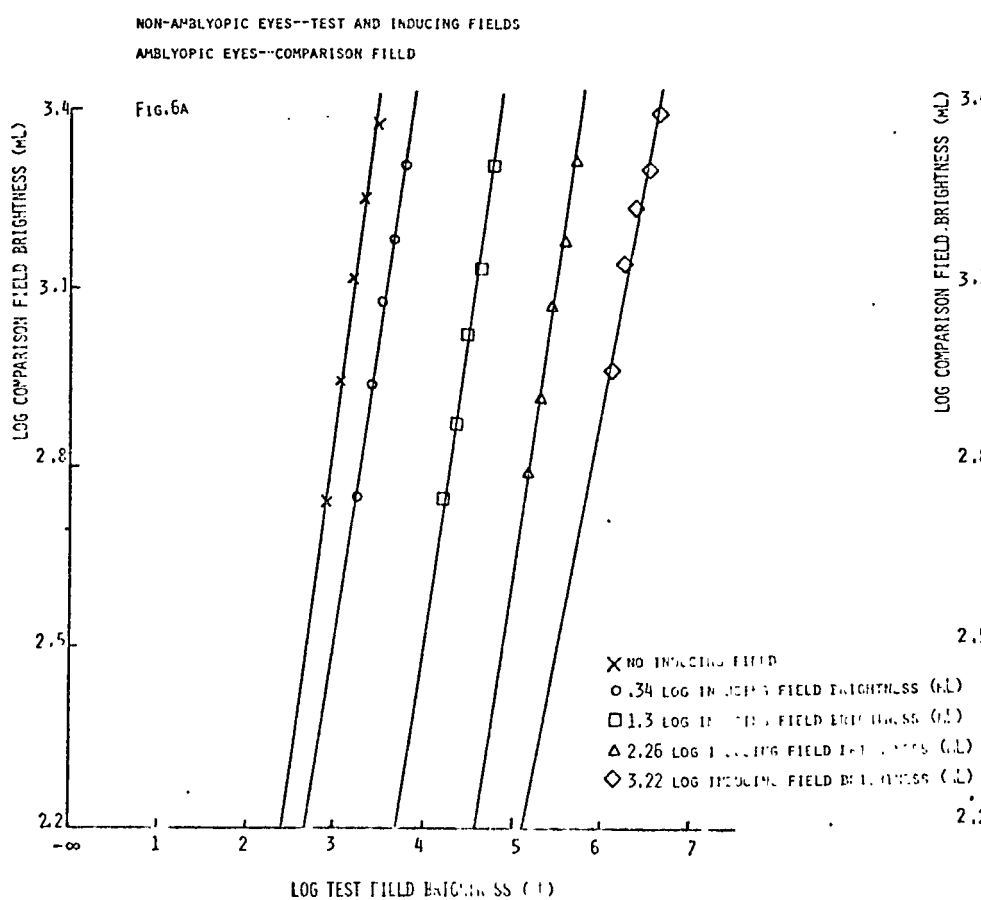


FIGURE 5: Log comparison field brightness vs. log test field brightness for non-amblyopic subject. M.L. (visual acuity O.D. 20/20. O.S. 20/20.)

left eye viewing the test and inducing field, and the right eye viewing the comparison field. Inspection of the slopes, Y-intercepts and positions of the data points on corresponding linear regression curves for each eye viewing the test and inducing fields reveals little difference between the two eyes.

Figure 6A and B gives the plot of log comparison field brightness versus log test field brightness for mean data of amblyopic eyes and the non-amblyopic eyes of the amblyopic subjects. Figure 6A shows the 5 linear regression curves for each inducing field brightness for the non-amblyopic eye viewing the test and inducing field and the amblyopic eye viewing the comparison field. Figure 6B gives the data for the amblyopic eye viewing the test and inducing fields and the non-amblyopic eye viewing the comparison field. It may be noted that for each inducing field luminance, as the test field brightness increases, the comparison field brightness is increased for both the amblyopic and non-amblyopic eyes. Comparing the graphs for each eye viewing the test and inducing fields, the slope, Y-intercepts and position of the points for the 0.00 inducing field condition (X's in the figure) do not differ significantly. Inspection of the 0.34 log inducing field brightness curves (O's in the figure) shows that the slope, Y-intercepts and position of the data points differ for the 2 eyes. The most apparent difference is the fact that the first data point is approximately 0.3 log units lower for the amblyopic eye viewing the test and inducing fields than for the non-amblyopic eye. Only for the two brightest test field conditions is the match made with the amblyopic eye viewing the test and inducing fields

MEAN DATA FOR ALL AMBLYOPIC SUBJECTS



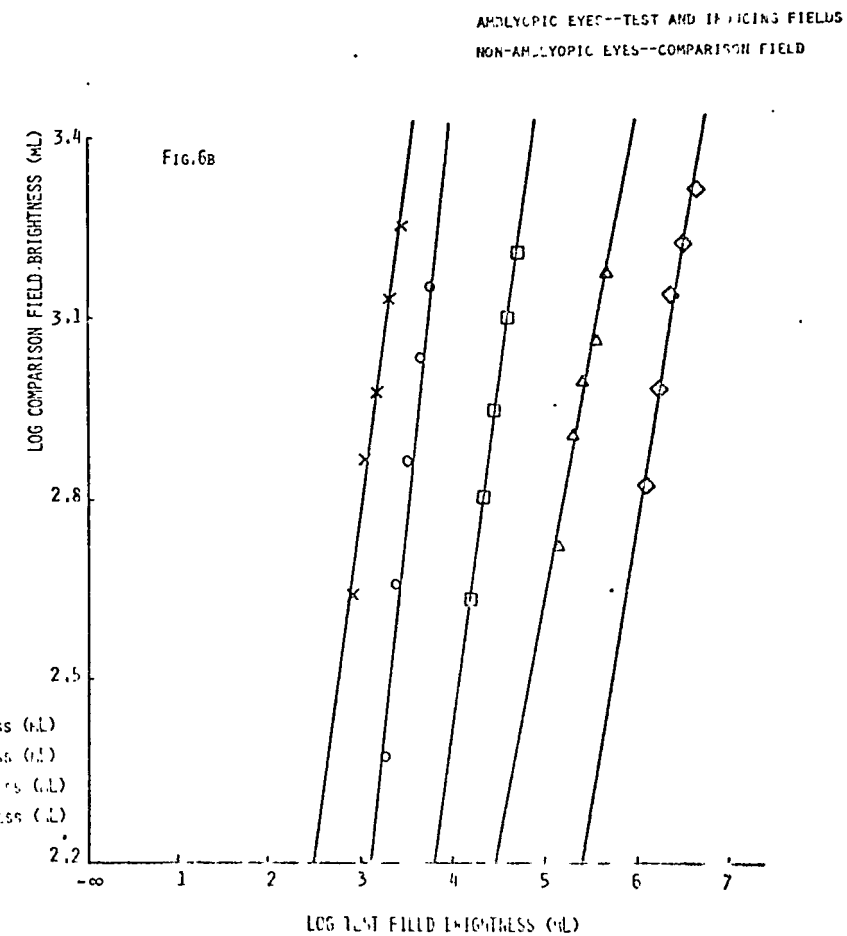


FIGURE 6 Log comparison field brightness vs. log test field brightness for mean data of amblyopic subjects.

similar to that with the non-amblyopic eye viewing the test and inducing fields. The slope of the 0.34 log inducing brightness curve for the amblyopic eye viewing the test and inducing fields is steeper than that of the non-amblyopic eye, and as a function of the altered slope, the Y-intercept is shifted to the right in the graph of the amblyopic eye viewing the test and inducing fields. Comparing the 1.3 log inducing field condition (squares in the figure) while the locus of the points is shifted down for the amblyopic eye viewing the test and inducing fields, the difference between the two eyes is much less marked (slightly over .1 log units) than for the previous condition. The slopes and Y-intercepts appear to be very similar. Any difference between the linear regression curves of the 2.26 and 3.22 log inducing field brightness conditions for the two eyes is not detectable by inspection. Statistical testing revealed that only the 0.34 log inducing field brightness condition significantly differentiated between the amblyopic and non-amblyopic eyes.

The data shown in figures 4, 5 and 6 were not corrected for equal absolute brightness matching in the two eyes in the absence of an inducing field, as has been suggested by Heinemann (1959). Apparently there is a slight downward shift in the locus of the points on the 0.00 inducing field linear regression curve of the amblyopic eyes relative to the non-amblyopic eyes (Figure 6A and B); however, this difference was within one standard deviation and was not statistically significant. Equating the curves for absolute brightness matching in the absence of an inducing field did not significantly alter the slopes

of the lines, although the locus of the points along the linear regression curves was raised slightly for the amblyopic eyes viewing the test and inducing fields.

Figure 7A and B shows the data for subject R.S. In this figure, the logarithm of the comparison field brightness (ml) is shown on the ordinate and the logarithm of the test field brightness (ml) is shown on the abscissa. This was typical of the data for the amblyopic subjects although some individual differences were noted. Consistent differences between amblyopic and non-amblyopic eyes of the same subject were noted with the lowest inducing field level (0.34 log ml); the slope and the locus of the points on the line were different for the amblyopic eye viewing the test and inducing fields than for the non-amblyopic eye. In general, as was the case for subject R.S. the slope, Y-intercept, and locus of the points on the lines for the 0.00 inducing field condition (X's in the figure) did not differ in the two eyes. For the 0.34 log inducing field brightness level (O's in the figure) the slope of the curve is steeper, and the locus of the matches for the brightest test field luminance is raised when the amblyopic eye views the test and inducing fields (Figure 7B). As was the case for all the amblyopic subjects, the apparent brightness of the two dimmest test field conditions was reduced. The 1.3 log inducing field brightness level (squares in the figure) too showed a steeper slope, and raised apparent brightness of the brightest test field conditions when comparing the amblyopic eye to the non-amblyopic eye viewing the test and inducing fields. The differences between the two eyes were less marked for this condition

SUBJECT R.S.

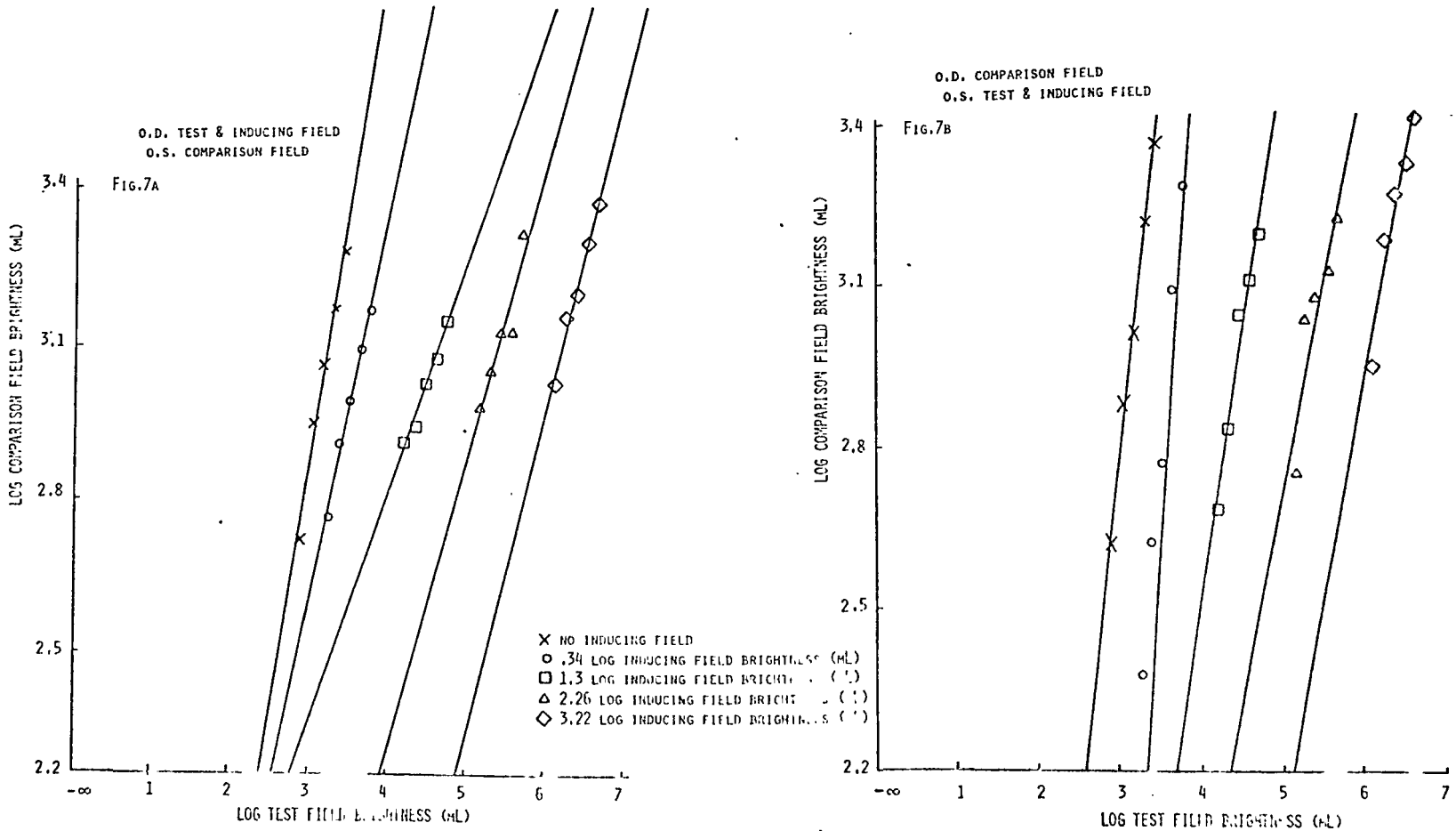


FIGURE 7 Log comparison field brightness vs. log test field brightness for amblyopic subject R.S. V.A. O.D. 20/20 : O.S. 20/200

than for the previous, and were not significantly different statistically. None of the higher background levels differentiated statistically between amblyopic eyes and non-amblyopic eyes.

From the linear regression equations, it is possible to derive curves of the logarithm of the test field brightness (ml) as a function of the logarithm of the inducing field brightness (ml). This kind of plot shows the test field intensity needed to achieve a constant apparent brightness as the inducing field is varied. This type of plot has been referred to as an equal brightness contour by Heinemann (1955). A plot of the mean data for the non-amblyopic subjects is shown in Figure 8A and B. Each curve presents the extrapolated curves of log test field brightness versus log inducing field brightness for a constant comparison field brightness. This provides a qualitative display of brightness contrast. The curves in Figure 8A and B demonstrate that for each comparison field brightness a decrease in the apparent brightness of the test field occurred as the inducing field brightness was increased. This was shown by the increase in test field brightness necessary to match the fixed comparison field brightness. Figure 8A displays the curves for the right eye viewing the fixed comparison field and the left eye viewing the test and inducing fields. Figure 8B gives the same curves for the left eye viewing the fixed comparison field and the left eye viewing the test and inducing fields. The curves for the two eyes do not differ materially. Although these curves could possibly have been fit with a straight line, this might result in a loss of information, and since changes occur in the slopes

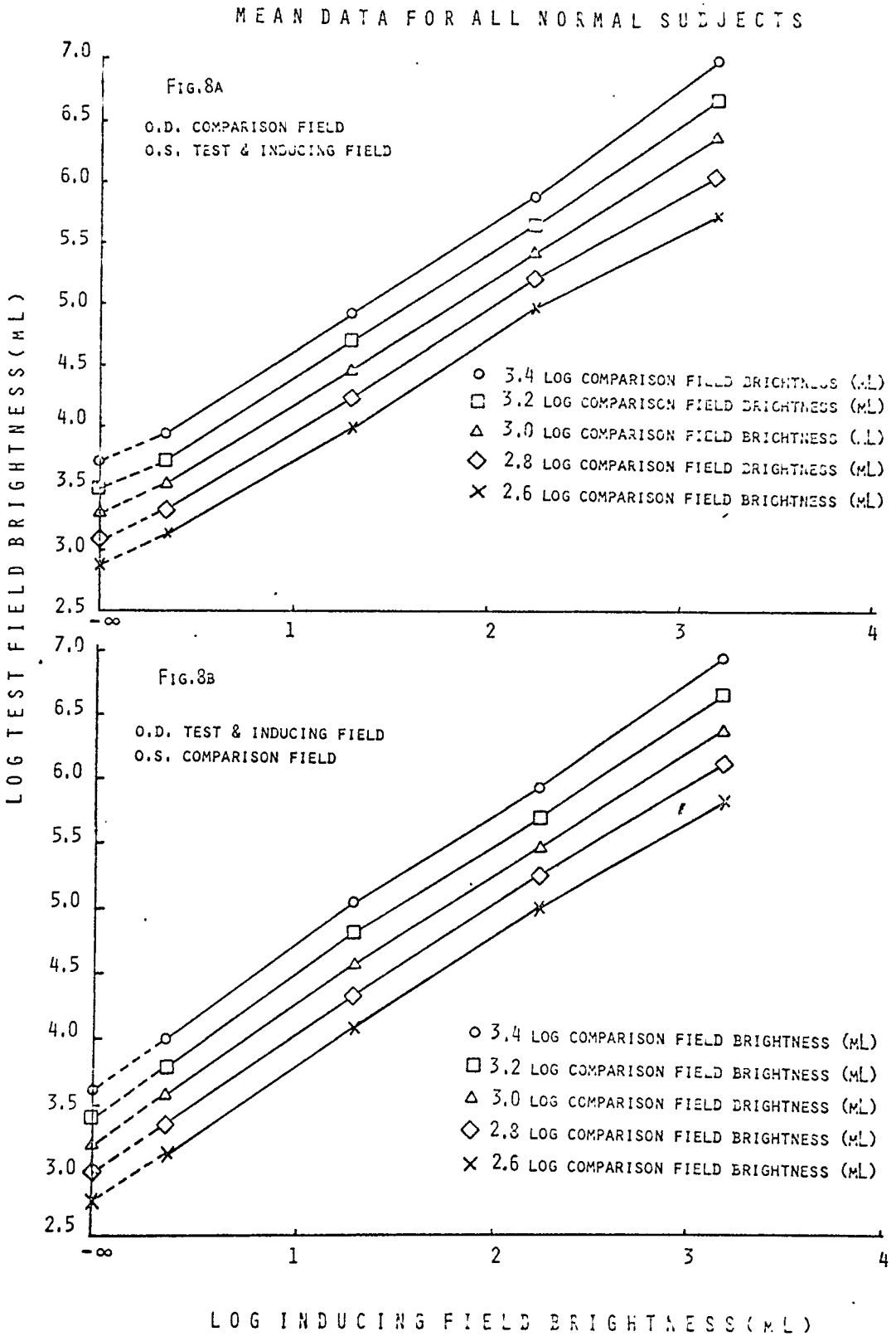
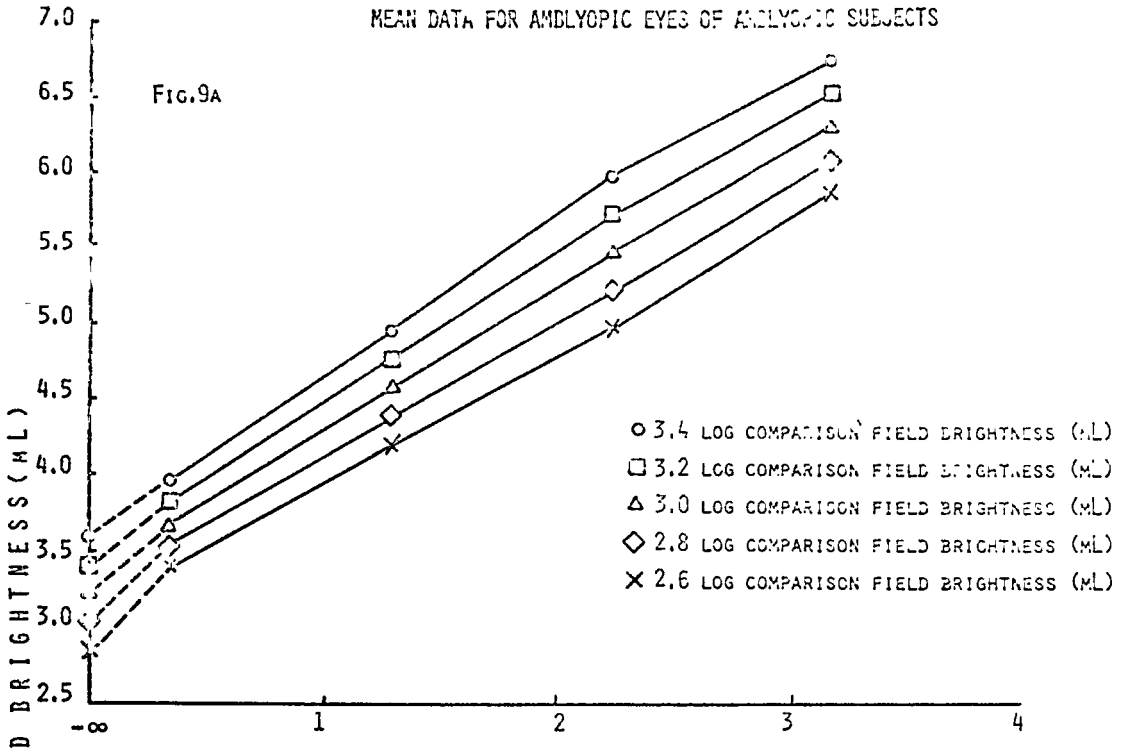


FIGURE 8 Log test field brightness vs log inducing field brightness for mean data of non-amblyopic subjects.

of different areas of the curves, they were not plotted as a straight line function.

Figure 9 displays the logarithm of the test field brightness (ml) versus the logarithm of the inducing field brightness (ml) for the mean data of all the amblyopic subjects. Figure 9A presents the curves for the amblyopic eye viewing the test and inducing fields and the non-amblyopic eye viewing the fixed comparison field. Figure 9B presents the curves for the non-amblyopic eyes viewing the test and inducing fields and the amblyopic eye viewing the fixed comparison field. It is apparent that brightness contrast does occur in both figures; however, there is a difference in the slopes of the lines. In figure 9A the lines first converge, then splay out whereas in figure 9B the lines remain closer to parallel. An effect that is apparent in this graph is the steepness of the slope of the initial part of the curves for the two dimmest fixed comparison field luminances. It is not clear whether this indicates an increase in brightness contrast at this level or whether this represents an inability of the subjects to differentiate between the test and inducing fields.

In order to test for statistical differences between amblyopic and control subjects, further statistical analysis was performed. A four-way analysis of variance (Winer, 1962) of the data was undertaken. The results are summarized in Table III. The analysis of variance yielded relatively few significant factors and only one interaction of statistical significance. Across inducing field conditions there was a significant effect (at $P<0.001$ level) and this was different for



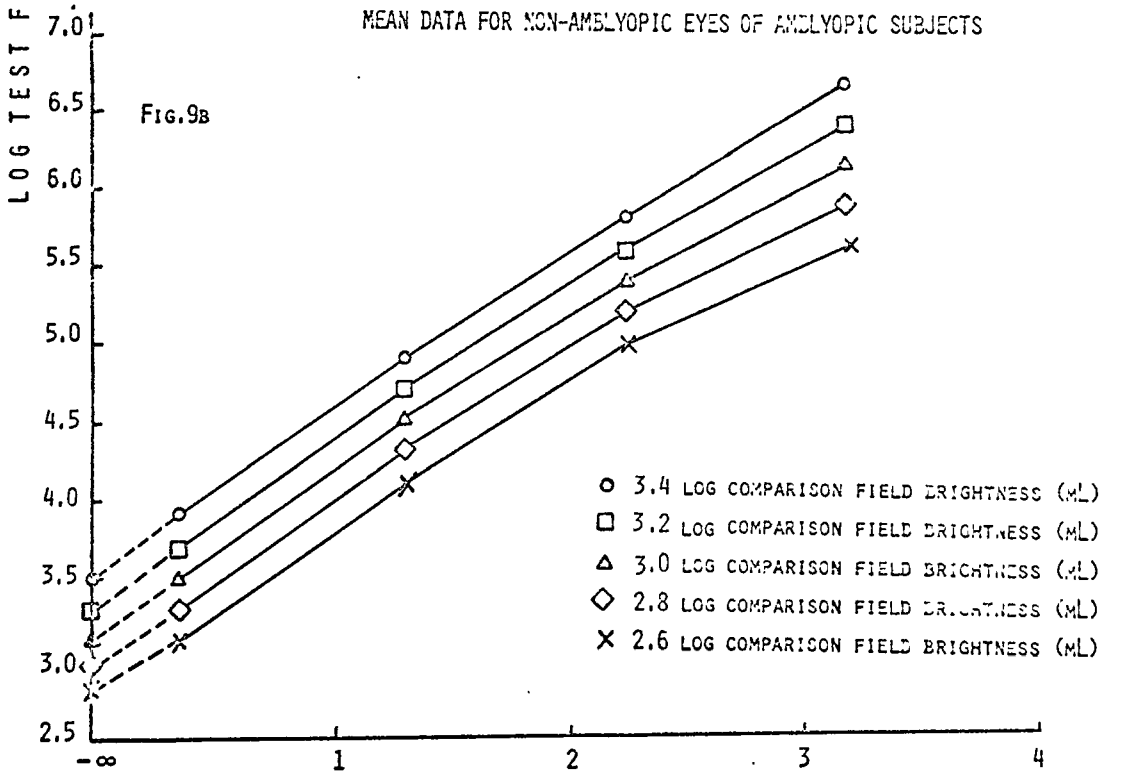


FIGURE 9 Log test field brightness vs. log inducing field brightness for mean data of amblyopic subjects.

Table III. Analysis of Variance Summary

The A B C D factors refer to:

A_1 = the mean of the comparison field wedge (N.D.F.$_2$) settings for both eyes of the amblyopic subjects

A_2 = the mean of the comparison field wedge (N.D.F.$_2$) settings for both eyes of the control subjects

B_1 through B_5 = inducing field brightness conditions for both amblyopic and control subjects (0.00, 0.34, 1.3, 2.26, 3.22 log inducing field brightness)

C_1 through C_5 = test field brightness conditions for both amblyopic and control subjects

D_1 = the mean of the comparison field wedge (N.D.F.$_2$) settings for amblyopic eyes*

D_2 = the mean of the comparison field wedge (N.D.F.$_2$) settings for non-amblyopic eyes*

*D_1 and D_2 have been randomized across left and right eyes of the control subjects to minimize any selective bias in terms of right versus left eye.

Table III (continued)

Source of Variance	Sum of Squares	Degrees of Freedom	Mean of Squares	F
A	86	1	86	+.595
Error a	1156	8	144.5	
B	904	4	226	+6.90****
A B	654	4	163.5	+4.99***
Error b	1048	32	32.75	
C	18391	4	4597.75	449.88****
A C	98	4	24.5	2.4
Error c	327	32	10.22	
D	662	1	622	3.33
A D	488	1	488	2.46
Error d	1590	8	198.75	
B C	327	16	20.44	.42
A B C	82	16	5.13	.11
Error b c	6225	128	48.63	
B D	110	4	27.50	.04
A B D	166	4	41.50	.06
Error b d	22434	32	701.06	
C D	17	4	4.25	.02
A C D	10	4	2.50	.01
Error c d	6473	32	202.28	
B C D	83	16	5.19	.02
A B C D	66	16	4.13	.02
Error b c d	29060	128	227.03	

F Ratio Significance * Levels	
****	<.001
***	<.005

amblyopic and control groups ($P<.005$ level). The A. x B. interactions between the amblyopic subjects' mean comparison field wedge setting (A_1) and the control subjects' mean comparison field wedge setting (A_2) as a function of inducing field conditions (B_1-B_5) are shown in Figure 10. It may be noted that for the B_1 inducing field condition, i.e. 0.00 log inducing field brightness (ml), the comparison field luminances for both groups are similar. For inducing field condition B_2, i.e. 0.34 log inducing field brightness (ml), the greatest discrepancy between amblyopic and control subjects' mean comparison field luminances occurs. For the amblyopic subjects (A_1) a decrease in apparent brightness occurs when log 0.34 inducing field is introduced. The control group (A_2) showed a relative increase in apparent brightness when log 0.34 inducing field was introduced, as might be anticipated. For conditions B_3 and B_4 the difference between A_1 and A_2 was reduced. A surprising phenomenon is noted for condition B_5 (i.e. log 3.22 inducing field brightness); the experimental group perceived the test field as being brighter than did the control group.

Since A_1 and A_2 included both eyes of the experimental and control groups the analysis was further broken down to investigate A. x B. x D. interactions between the comparison field wedge settings for the amblyopic (D_1) and non-amblyopic (D_2) eyes of the amblyopic (A_1) and control (A_2) subjects as a function of inducing field conditions (B_1-B_5). As may be noted from Table III the F ratios for the A. x B. x D. interaction proved to be insignificant due to the great degree of variance; however, the A. x B. x D. interaction graph (Figure 11) shows some interesting

FIG.10 A.B. INTERACTION

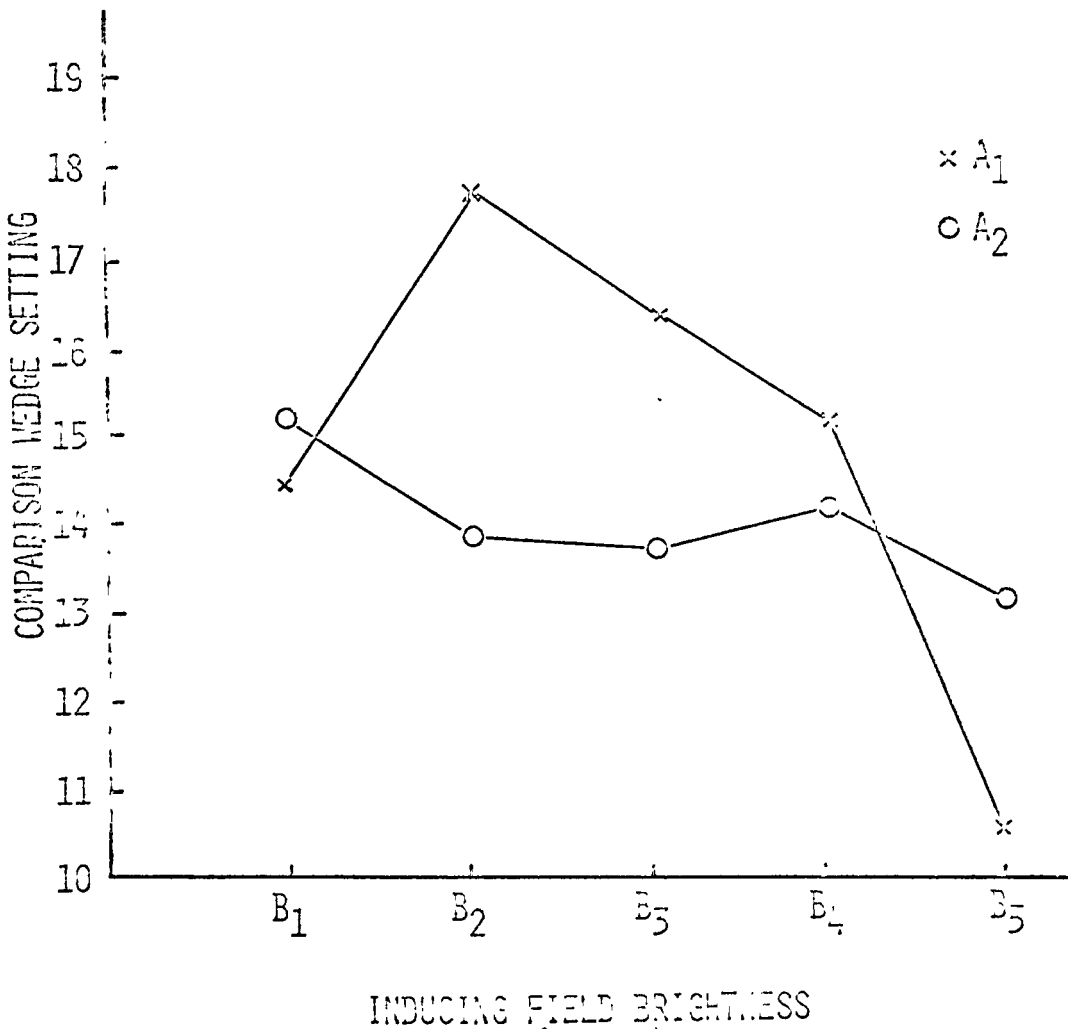
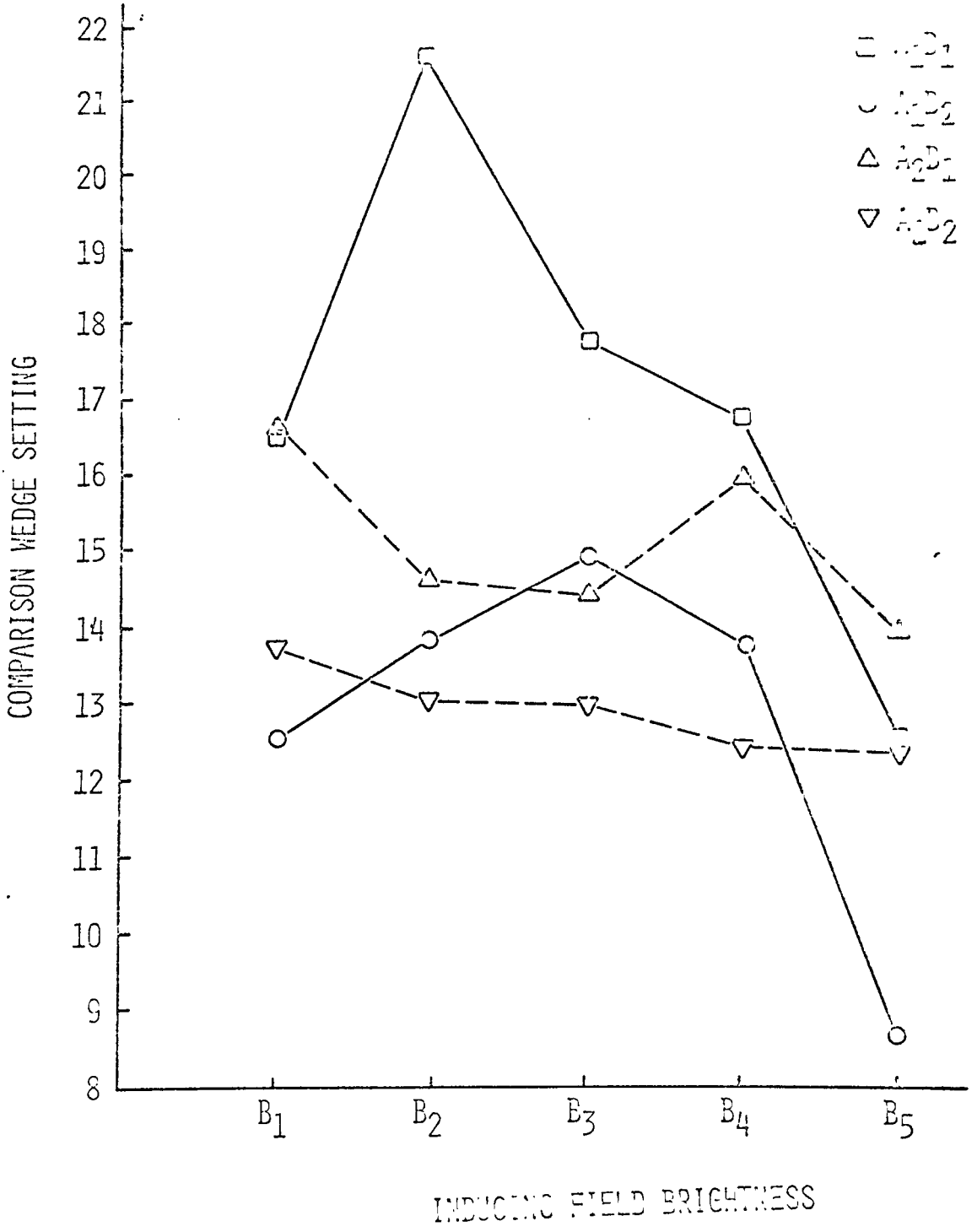


FIG. 11 A.B.D. INTERACTION



trends. The mean comparison field luminances for the two eyes of the control subjects (A_2D_1 and A_2D_2) did not differ materially across inducing fields (B_1-B_5). The mean comparison field luminances for the non-amblyopic eyes of the amblyopic group (A_1D_2) did not differ greatly from the curves for the control group except at condition B_5 (3.22 log inducing field brightness) where the non-amblyopic eyes of the amblyopic subjects (A_1D_2) perceived the apparent brightness of the test field as being greater than did the control eyes. The mean comparison field luminances for amblyopic eyes of the amblyopic subjects (A_1D_1) differed from the other curves most markedly at condition B_2 and diminished with increasing inducing field intensity.

From Table III it may be noted that test field brightness (C) was a significant source of variance at the .001 level. The A. x C. interactions between the mean comparison field luminances for the amblyopic subjects (A_1) and the control subjects (A_2) as a function of the test field luminances (C_1-C_5) are shown in Figure 12. As test field brightness increased, so did the matching field brightness. This was not significantly different for amblyopic (A_1) and control (A_2) subjects. Due to the large amount of variance, both D_1 and D_2 (amblyopic and non-amblyopic eyes), and the A. x D. interactions between the mean comparison field luminances of the amblyopic eyes and the non-amblyopic eyes of the amblyopic subjects (A_1D_1 and A_1D_2 respectively) and the mean comparison field luminances of the two eyes of the control group (A_2D_1 and A_2D_2) were not significant factors; however, Figure 13 (A. x D. interaction) demonstrates some trends. The control group (A_2) showed very little

FIG.12 A.C. INTERACTION

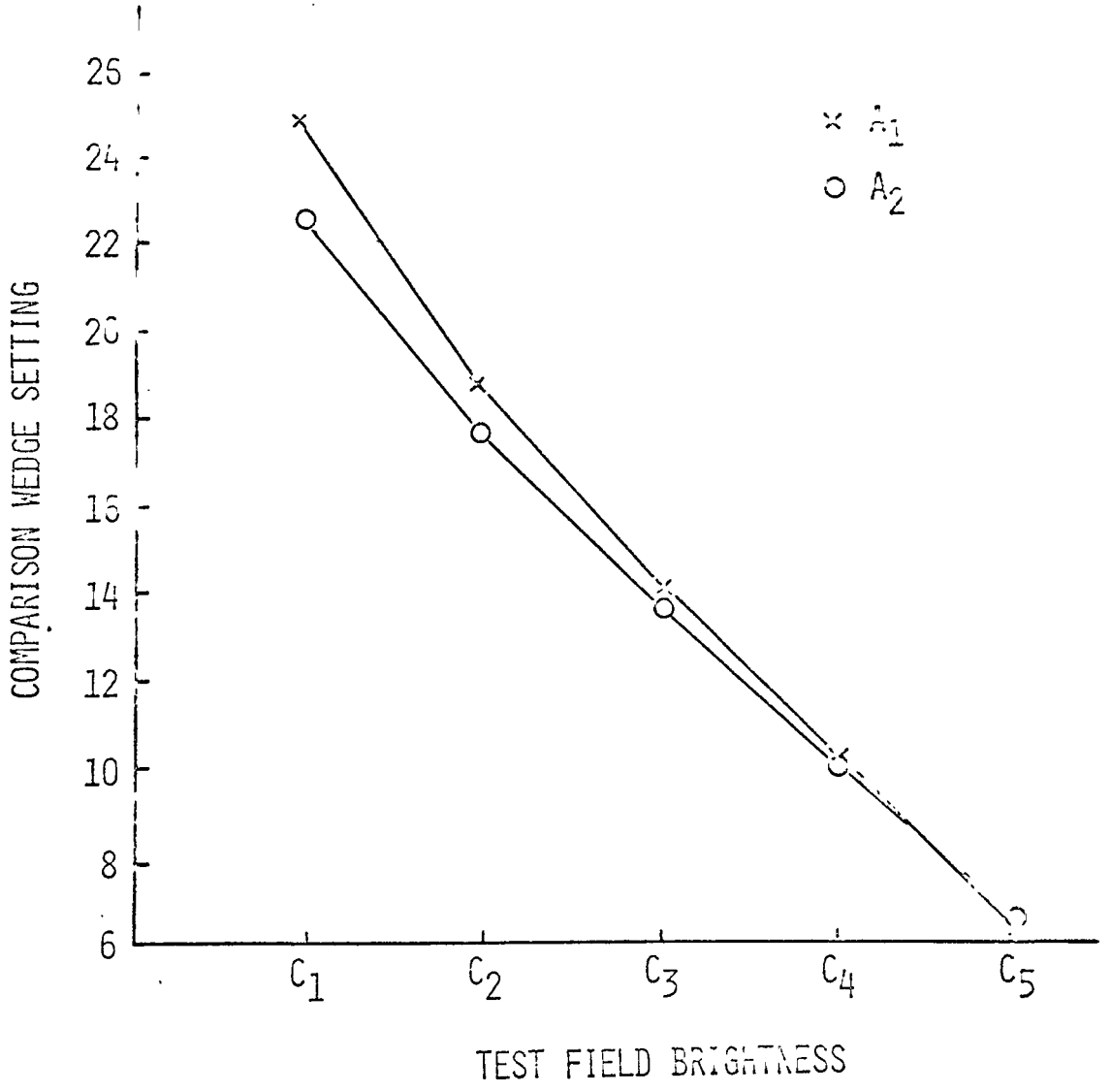
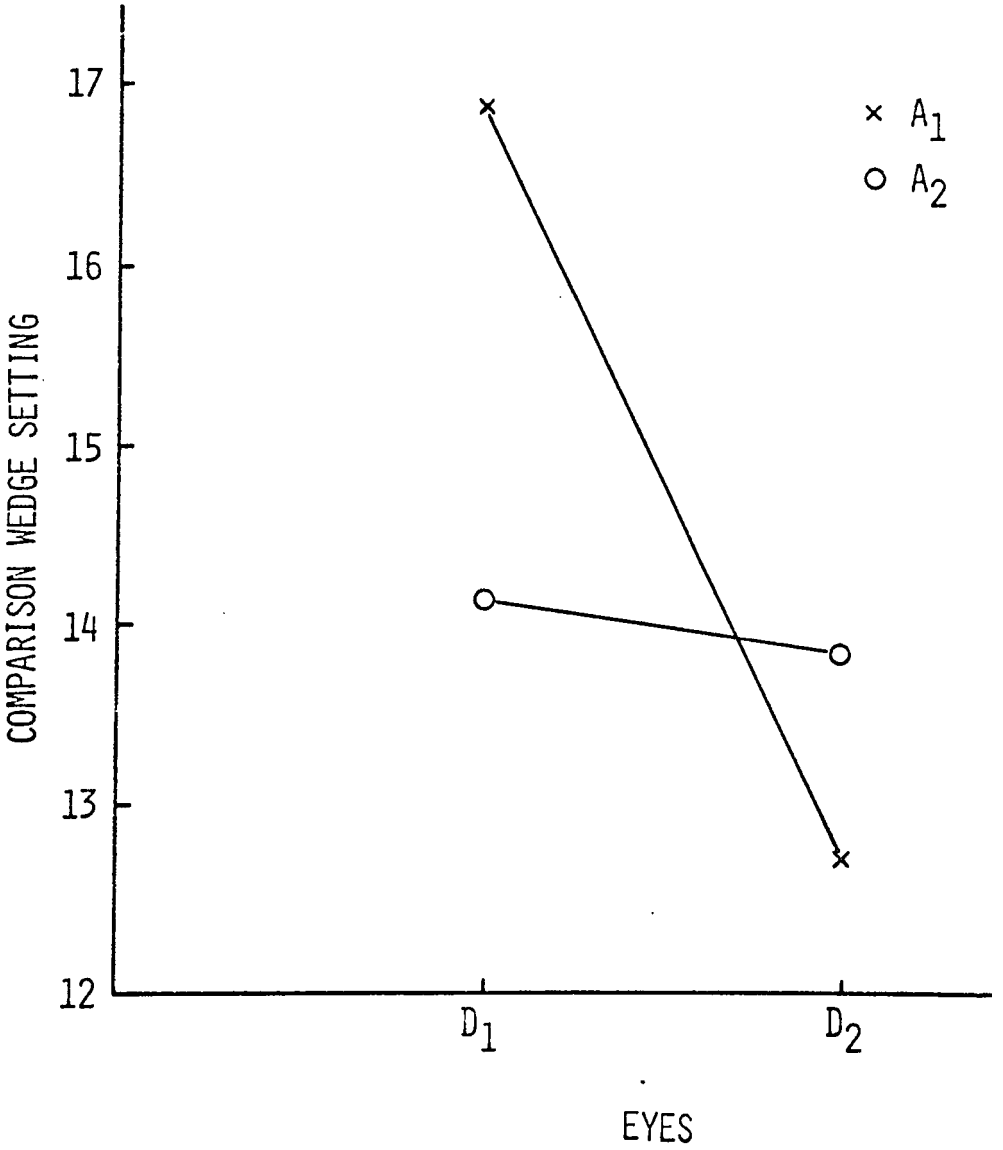


FIG.13 A.D. INTERACTION



difference between the two eyes, while the amblyopic group (A_1) showed a much lower level of apparent brightness across all conditions for the amblyopic eye (D_1) than for the non-amblyopic eye (D_2). None of the other interactions were statistically significant. To further investigate the above-mentioned trends further statistical analysis was undertaken. A series of T-tests was undertaken comparing the slope and intercept values derived from the linear regression formuli for:

(a) right eye versus left eye of all control subjects;

(b) amblyopic eyes versus non-amblyopic eyes of amblyopic subjects;

(c) amblyopic eyes versus right and left eyes of control subjects;

(d) non-amblyopic eyes of amblyopic subjects versus right and left eyes of control subjects.

The results are summarized in Tables IV through VII. Thus, statistically, there is no significant difference between right and left eyes of the non-amblyopic subjects; however, for the 0.34 log inducing field brightness (ml) condition, the amblyopic eye differed significantly from both the non-amblyopic eyes of the amblyopic subjects and the "normal" eyes.

In comparing mean data for "normal" eyes versus the non-amblyopic eyes of the amblyopic subjects, greater variability was noted among the amblyopes. Although not statistically significant it may be noted that for all inducing field conditions slopes were lower for the non-amblyopic eyes than for normals.

While none of brighter inducing fields statistically differentiated the amblyopic and non-amblyopic eyes, it was of interest to determine

Table IV: T-Test. Right Eye Versus Left Eye of Control Subjects

Inducing Field Brightness (log ml)	Degrees of Freedom	T Slope	T Intercept
0.00 inducing field brightness (ml)	8	.45	.55
0.34 log ml inducing field brightness (ml)	8	.25	.12
1.3 log ml incuding field brightness (ml)	8	.46	.09
2.26 log ml inducing field brightness (ml)	8	.88	.83
3.22 log ml inducing field brightness (ml)	8	.16	.16

Table V: T-Test. Amblyopic Eyes Versus Non-Amblyopic Eyes of Amblyopic Subjects

Inducing Field Brightness (log ml)	Degrees of Freedom	T Slope	T Intercept
0.00 inducing field brightness (ml)	8	.41	.22
0.34 log inducing field brightness (ml)	8	2.35*	2.73*
1.3 log inducing field brightness (ml)	8	.27	.36
2.26 log inducing field brightness (ml)	8	.96	.82
3.22 log inducing field brightness (ml)	8	.66	.69

* Significant at the .05 level

Table VI: T-Test. Amblyopic Eyes Versus

Right and Left Eyes of Control Subjects

Inducing Field Brightness (log ml)	Degrees of Freedom	T Slope	T Intercept
0.00 inducing field brightness (ml)	13	.59	.77
0.34 log inducing field brightness (ml)	13	6.53***	7.6****
1.3 log inducing field brightness (ml)	13	3.15**	3.14**
2.26 log inducing field brightness (ml)	13	.76	.61
3.22 log inducing field brightness (ml)	13	1.42	1.141

** Significant at the .01 level

*** Significant at the .001 level

Table VII: T-Test. Control Eyes Versus

Non-Amblyopic Eyes of Amblyopic Subjects

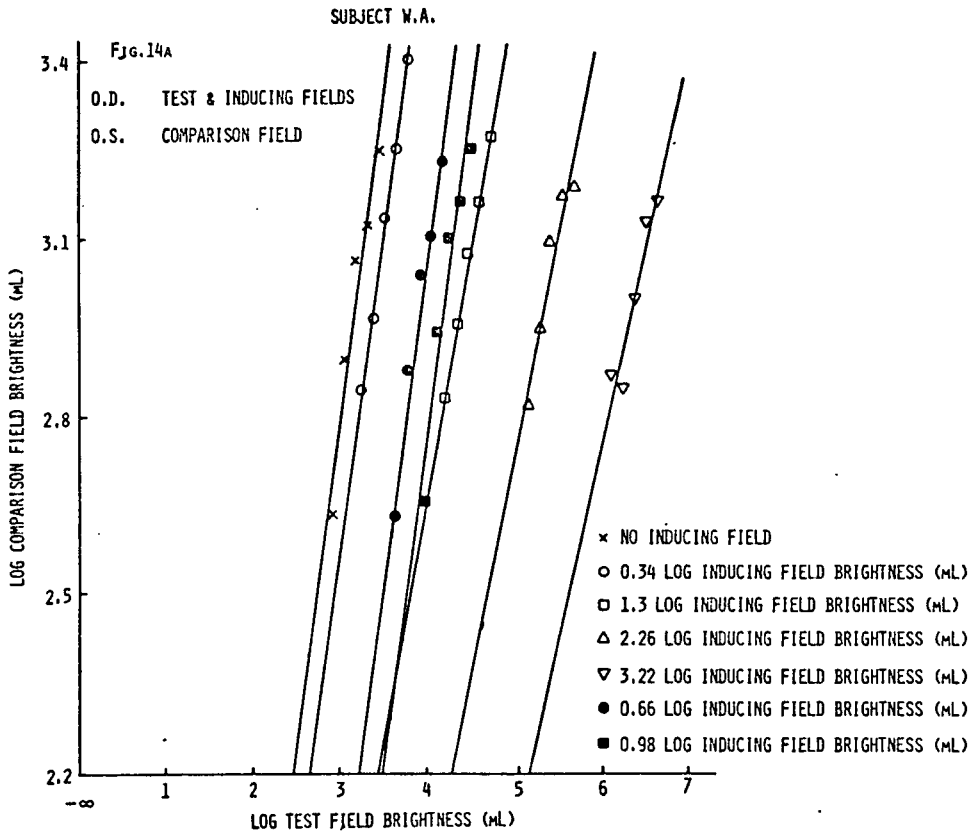
Inducing Field Brightness (log ml)	Degrees of Freedom	T Slope	T Intercept
0.00 inducing field brightness (ml)	13	1.41	1.22
0.34 log inducing field brightness (ml)	13	.43	.40
1.3 log inducing field brightness (ml)	13	1.45	1.49
2.26 log inducing field brightness (ml)	13	.64	.59
3.22 log inducing field brightness (ml)	13	.27	.15

whether inducing fields of luminances between 0.34 and 1.3 log inducing field brightness (ml) would have an effect similar to that of the 0.34 log inducing field.

Figure 14 presents the linear regression curves for non-amblyopic subject W.A. Two additional inducing field levels, 0.66 log inducing field brightness (ml) and 0.98 log inducing field brightness (ml), have been included. The same curves for O.S. amblyope K.B. are shown in Figure 15.

Inspection of the graphs reveals little difference between the curves for the two eyes of subject W.A.; however, fairly marked differences may be noted in the curves of subject K.B. with respect to the slopes and locus of the points for inducing fields 0.34, 0.66 and 0.98 log (ml). The locus of the points on the linear regression lines is shifted down for all conditions with the amblyopic eye (O.S.) viewing the test and inducing fields; however, this shift is most marked for conditions 0.34 and 0.66 log inducing field brightness (ml).

A 6th amblyopic subject, J.M., was initially included in the study. Unfortunately after collecting data on her non-amblyopic eye the patient began a course of direct occlusion, and upon presentation for testing of her amblyopic eye, her acuity was found to have improved from $20/40^{-2}$ to $20/30^{+2}$, thus no longer fulfilling the operational definition of 20/40 or poorer acuity for inclusion in the study. Her data was of interest in that although her absolute brightness matches, in the absence of an inducing field, differed somewhat for the two eyes, the slopes of the curves for the 0.34 and 1.3 log inducing field brightness



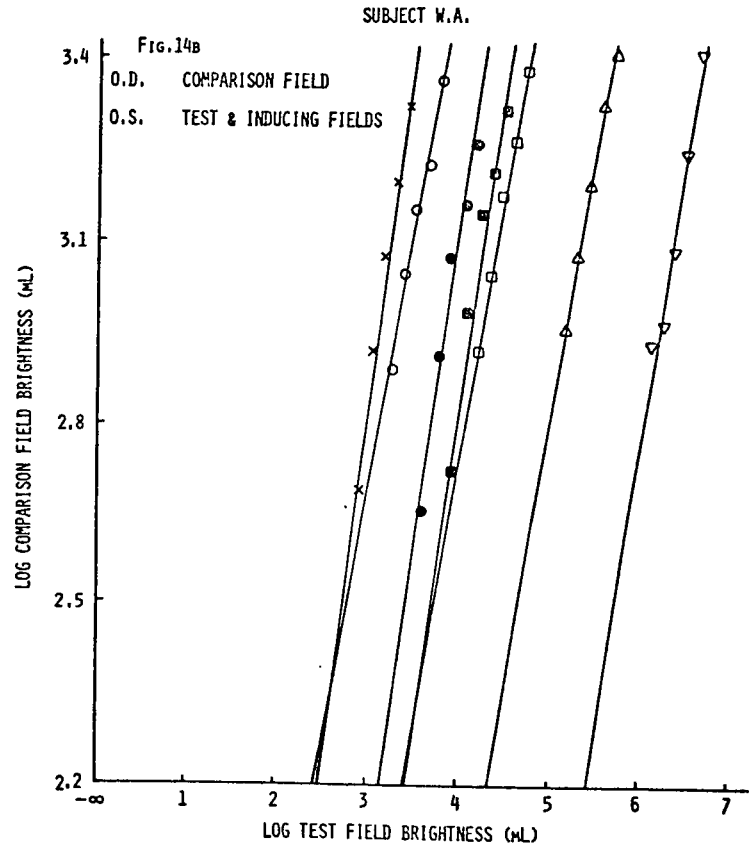


FIGURE 14 Log comparison field brightness vs. log test field brightness for control subject W. A. (visual acuity: O.D. 20/15 O.S. 20/15).

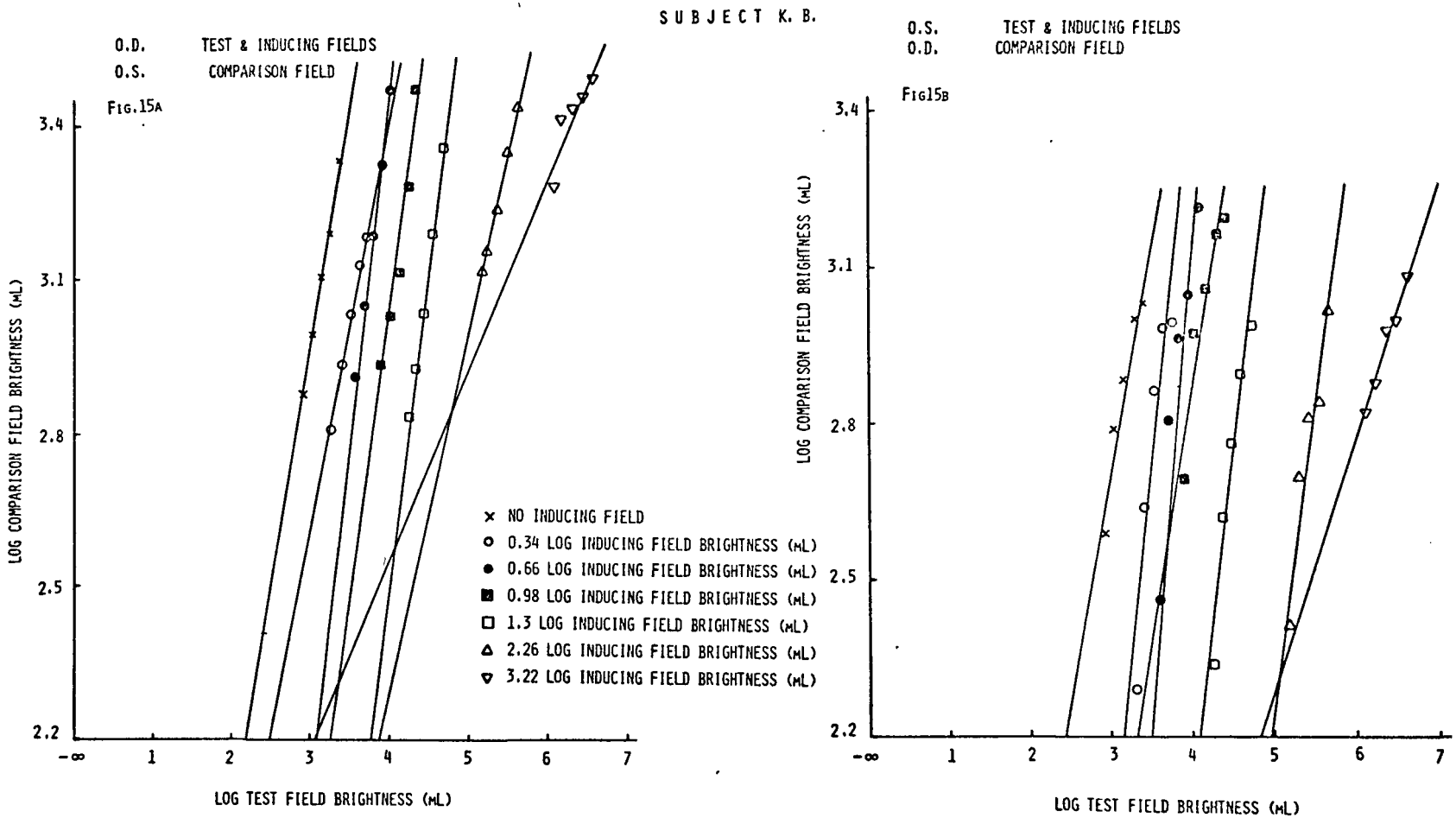


FIGURE 15 Log comparison field brightness vs log test field brightness for amblyopic subject K.B. (visual acuity O.D. 20/100 O.S. 20/15)

conditions were not significantly different in the two eyes. She did, however, manifest a slight downward shift of the locus of the points on those two curves for the "amblyopic" eye viewing the test and inducing fields.

Since the slope of the 0.34 log inducing brightness (ml) curve appeared to differentiate amblyopic and non-amblyopic eyes, a correlation coefficient of the slope value derived from the linear regression formuli with the visual acuity of the amblyopic eyes was determined and was found to be -.70, which is significant at the .01 level for a two-tailed test. Therefore the higher the slope value, for this inducing field condition, the poorer the visual acuity.

CHAPTER 4

DISCUSSION

Brightness contrast function in amblyopic eyes with central fixation appears to be shifted at low photopic inducing field brightness levels. With a low test field brightness the amblyopic eye shows a large decrease in apparent brightness of the test field. This is shown in Figures 6, 7, 10 and 11. As the test field brightness is increased, the decrement in apparent brightness occurs at a lower rate in the amblyopic eye than occurs in the normal eye. This effect appears to occur most markedly at 0.34 log inducing field brightness, and to a lesser extent at 1.3 log inducing field brightness. This is evidenced by the steepness of the slope of the linear regression curve when the amblyopic eye views the test and inducing fields, and is demonstrated in Figures 6, 7 and 17. The slope of the linear regression curves appears to be an important determinant of the degree of brightness contrast occurring. For a given inducing field brightness, as the test field brightness increases, the induction or simultaneous contrast effect would reduce the apparent brightness of the test field. This would be reflected in a lower comparison field setting; therefore, the greater the degree of contrast function occurring, an increase in test field brightness should result in a smaller increase in apparent brightness, resulting in a relatively lower comparison field brightness setting. When plotting the logarithm of the comparison field brightness versus the logarithm of the test field brightness, the greater the degree of contrast function occurring, the

more the slope of the linear regression curve should deviate from verticality. The lower the degree of contrast function occurring, the closer to vertical should be the slope of the line.

The exact explanation for these findings is unclear; however, they may be explained on the basis that a shift in contrast function has occurred in the amblyopic eye due to abnormal retinal lateral interactions. The effect of such a shift is to increase brightness contrast when physical contrast is low (e.g. the dimmest test field condition presented with the dimmest inducing field condition). This might explain the decrement in apparent brightness of the low luminance test field conditions for inducing field 0.34 log inducing field brightness. As the physical contrast and the inducing field brightness increase, the system of lateral interaction rapidly saturates, resulting in lowered brightness contrast. This is evidenced by the steepness of the slope of the linear regression curve for the 0.34 log inducing field brightness, when the test and inducing fields are seen by the amblyopic eye. Such a hypothesis might serve to explain the S-shaped curve of percent contrast required for criterion acuity as a function of background luminance described by Lawwill and Burian (1966) for one of their amblyopic subjects. Unfortunately, they provide no detail regarding the status of fixation for this iniividual; thus it is difficult to draw any comparisons.

When physical contrast is low, at a relatively low inducing field luminance, the apparent brightness of the test field decreases, and the amblyopic eye makes a brightness judgment on the basis of not only the

test field, but also the inducing field brightness, as though it were integrating across the two fields. It should be noted that for the condition of the lowest test field luminance at the 0.34 log inducing field brightness, several amblyopic subjects expressed difficulty in differentiating the test field from the background when viewing the test and inducing fields with the amblyopic eye. Since the test field subtends a visual angle of 2°, somewhat larger than normal central receptive field centers, it is difficult to explain the data in this manner without hypothesizing that the receptive fields in amblyopic eyes are enlarged. Such an hypothesis is attractive since it explains not only the reduced brightness contrast evidenced in this study but also the abnormal spatial summation in amblyopic eyes reported by Flynn (1967), and the raised differential thresholds in amblyopic eyes (Miller, 1954; Grosvenor, 1957). In this regard, Hubel and Wiesel (1963) found that in experimental light deprivation "amblyopia" in kittens, greatly enlarged receptive fields resulted in twenty percent of the geniculate cells serving the amblyopic eye. Caution should be exercised, however, in extrapolating from the data in experimental animal light deprivation "amblyopia" (amblyopia exanopsia) to strabismic and anisometropic amblyopia occurring in humans.

Of interest is the fact that the amblyopic subjects perceived the test field as being less bright than did the control subjects for inducing fields 0.34 and 1.3 log inducing field brightness. However, the amblyopic subjects perceived the test field as being markedly brighter than the control group at the highest inducing field level. Figure 11

(A. x B. x D. interaction) reveals that this finding is a result of the non-amblyopic eye of the amblyopic subjects. At this extremely bright inducing field brightness level, the results were generally more variable. Patients reported difficulties in making matches, and after-images may have created problems. While purely speculative the possibility remains that the amblyopic eye had some inhibiting effect on the non-amblyopic eye at high intensity levels, since the amblyopic eye was viewing the comparison field. This phenomenon has been demonstrated electrophysiologically by Shipley (1969).

It appears that in 4 of the amblyopic subjects, brightness perception in the absence of an inducing field is normal. Although this experiment did not include an investigation of absolute thresholds, Wald and Burian (1944) report that absolute thresholds in the amblyopic eye appear to be normal. Their study was conducted primarily on dark adapted eyes using a small circular test field. No increment thresholds were measured.

One amblyopic subject in the present study (subject B.R.) did, however, demonstrate a large difference in brightness appreciation, in the absence of an inducing field. Over the range actually tested, this difference was negligible at low test field luminances, increasing up to .5 of a log unit at the highest test field luminance. Equating the two eyes for equal brightness appreciation in the absence of an inducing field, the slope of the 0.34 log inducing field brightness curve remained steeper in the amblyopic eye than in the non-amblyopic, indicating reduced brightness contrast function.

Using the linear regression formuli it is possible to extrapolate to both higher and lower test field brightness levels than were actually tested, and plot log ratio of the comparison field brightness for right and left eyes of the control subjects versus log test field brightness. Since the curves were linear, extrapolation was justified in order to compare the curves for various inducing field luminances over the same range of test field luminances. These curves provide an effective means of comparing the performance of the two eyes of a given subject under the same test and inducing field conditions.

Figure 16 shows log ratio of the comparison field brightness for right and left eyes of all the control subjects versus log test field brightness for 0.00 inducing field, 0.34 log inducing field and 1.3 log inducing field brightness (ml). If there were no differences between the two eyes all the lines should be horizontal and superimposed on each other for each inducing field. A reduction in brightness appreciation in one eye would be evidenced by a downward slope of the line. In the presence of an inducing field, reduced brightness contrast in one eye would be shown by a line above horizontal, and increased contrast by a line below horizontal, since the slope of the line shows the rate of change in contrast. In Figure 16 the lines are not exactly horizontal, nor are they superimposed, but they are within .20 log units. The individual data did not differ materially.

Figure 17 shows the plot of log ratio of the comparison field brightness for amblyopic to non-amblyopic eyes of all the amblyopic subjects. For the 0.00 inducing field condition, the line, while not

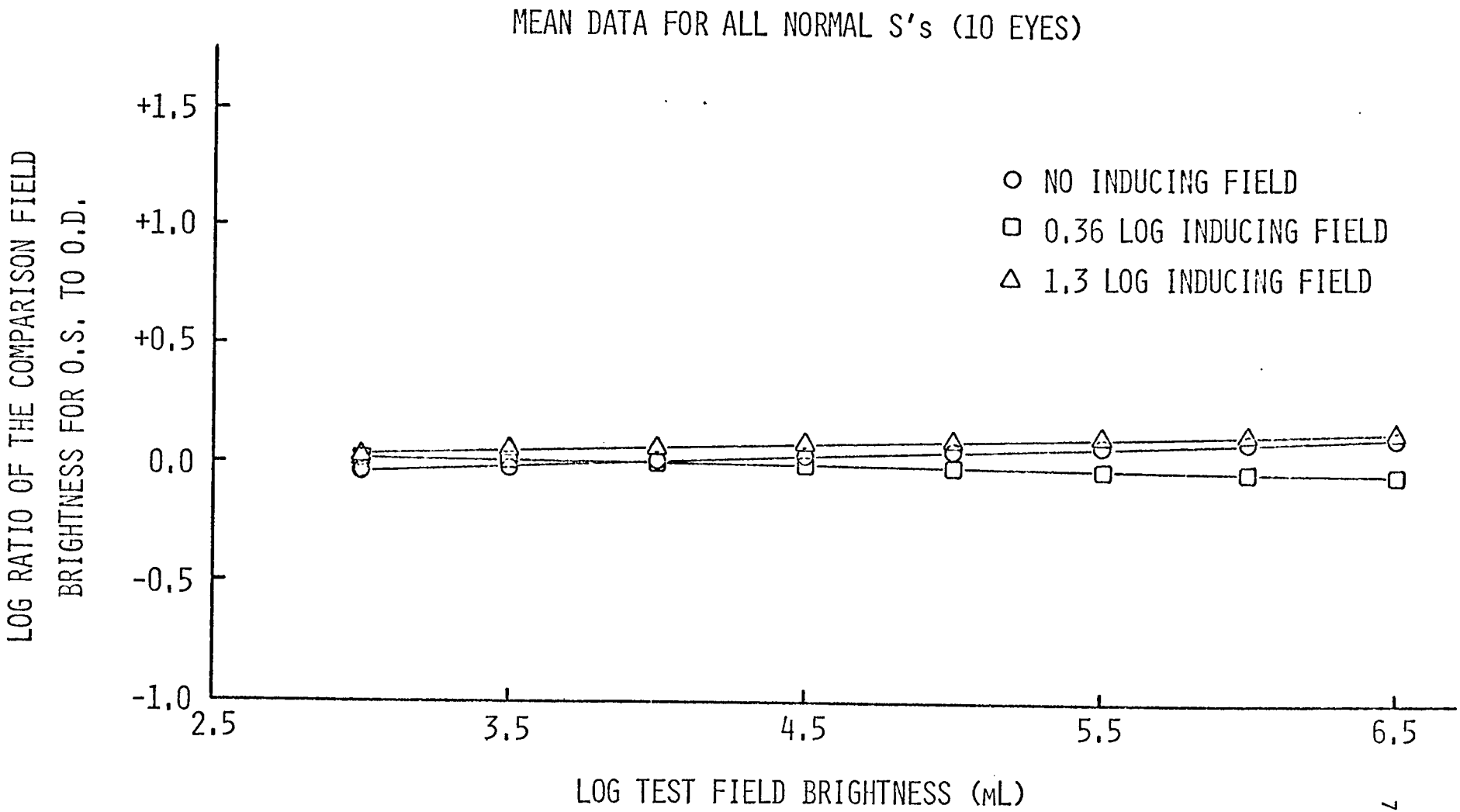


FIGURE 16 Log ratio of the comparison field brightness for right to left eyes of all normal subjects, vs. log test field brightness for no inducing field, 0.34 log inducing field and 1.3 log inducing field brightness.

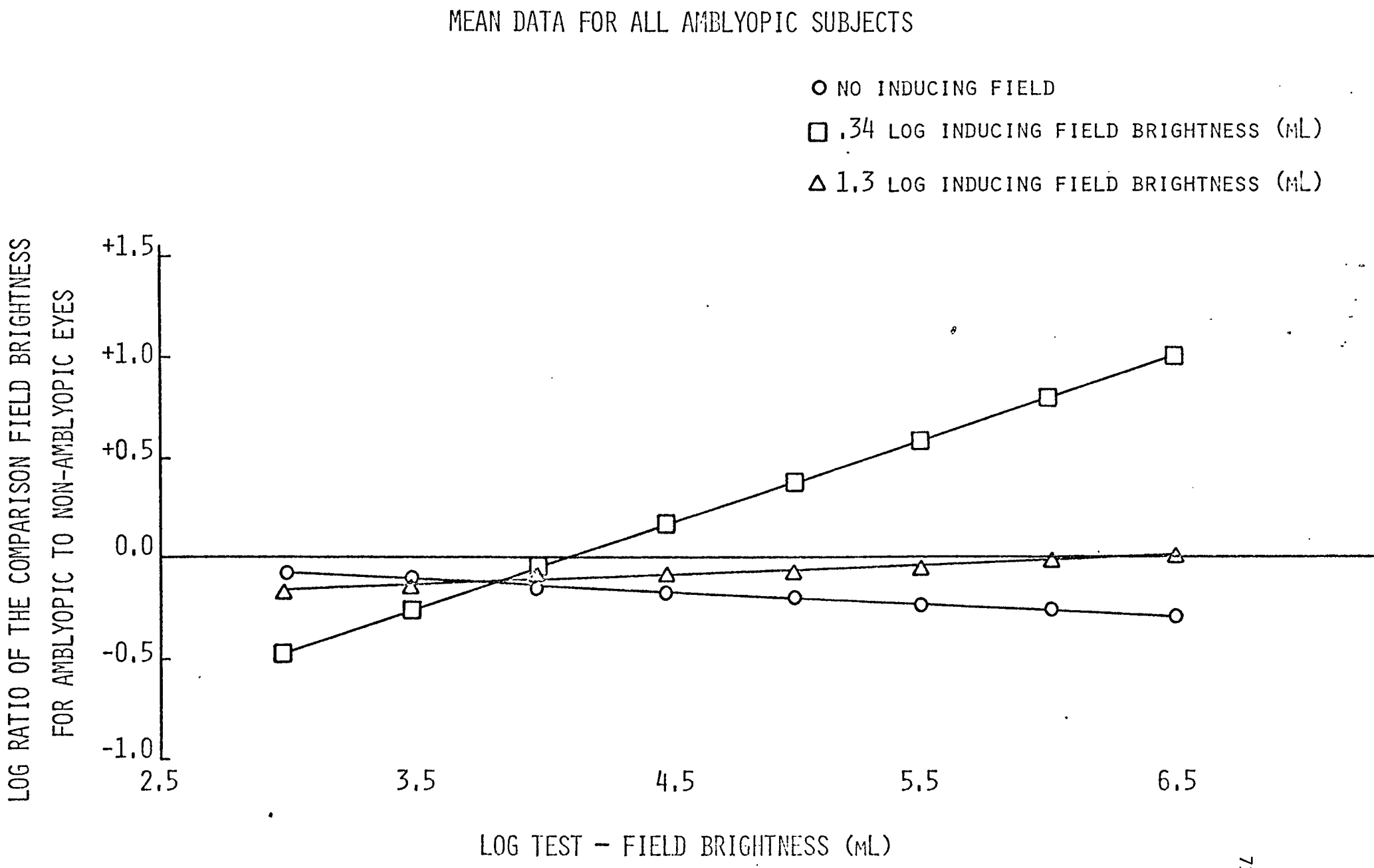


FIGURE 17 Log ratio of the comparison field brightness for amblyopic to non-amblyopic eyes of all amblyopic subjects, vs. log test field brightness for no inducing field, 0.34 log inducing field and 1.3 log inducing field brightness.

exactly parallel to the base line, is fairly close to being a horizontal line. For inducing field 0.34 log (ml), at low test field brightness levels, the decrease in apparent brightness is quite large, being in the order of -0.5 log units. As the test field brightness increases, the decrease in apparent brightness occurs at a much lower rate in the amblyopic eyes. When the test field brightness exceeds 4.5 log (ml), the amblyopic eyes actually show an increase in the apparent brightness of the test field relative to the non-amblyopic eyes. At test field 6.5 log (ml), this difference is equivalent to one log unit or ten times. This plot demonstrates the initial dimming of the apparent brightness of the test field, followed by a reduction in brightness contrast.

Although a reduction in decrement in the amblyopic eye also occurs with the 1.3 log (ml) inducing field, the magnitude is much smaller. This data is typical of the amblyopic subjects except for subject B.R. (Figure 18). Although it has been reported that the light sense and absolute thresholds in amblyopic eyes is normal, subject B.R. showed impaired brightness appreciation in the absence of an inducing field at high test field brightness levels. However, the rate of decrement in apparent brightness, when 0.34 log (ml) inducing field was introduced, followed that of all the amblyopic eyes but occurred at a lower rate than that of the non-amblyopic eye. In view of Wald and Burian's (1944) data and the findings of the other amblyopic subjects in this experiment, this is difficult to explain. It remains possible that subject B.R. was not a functional amblyope, in spite of the fact that she showed no ophthalmoscopic

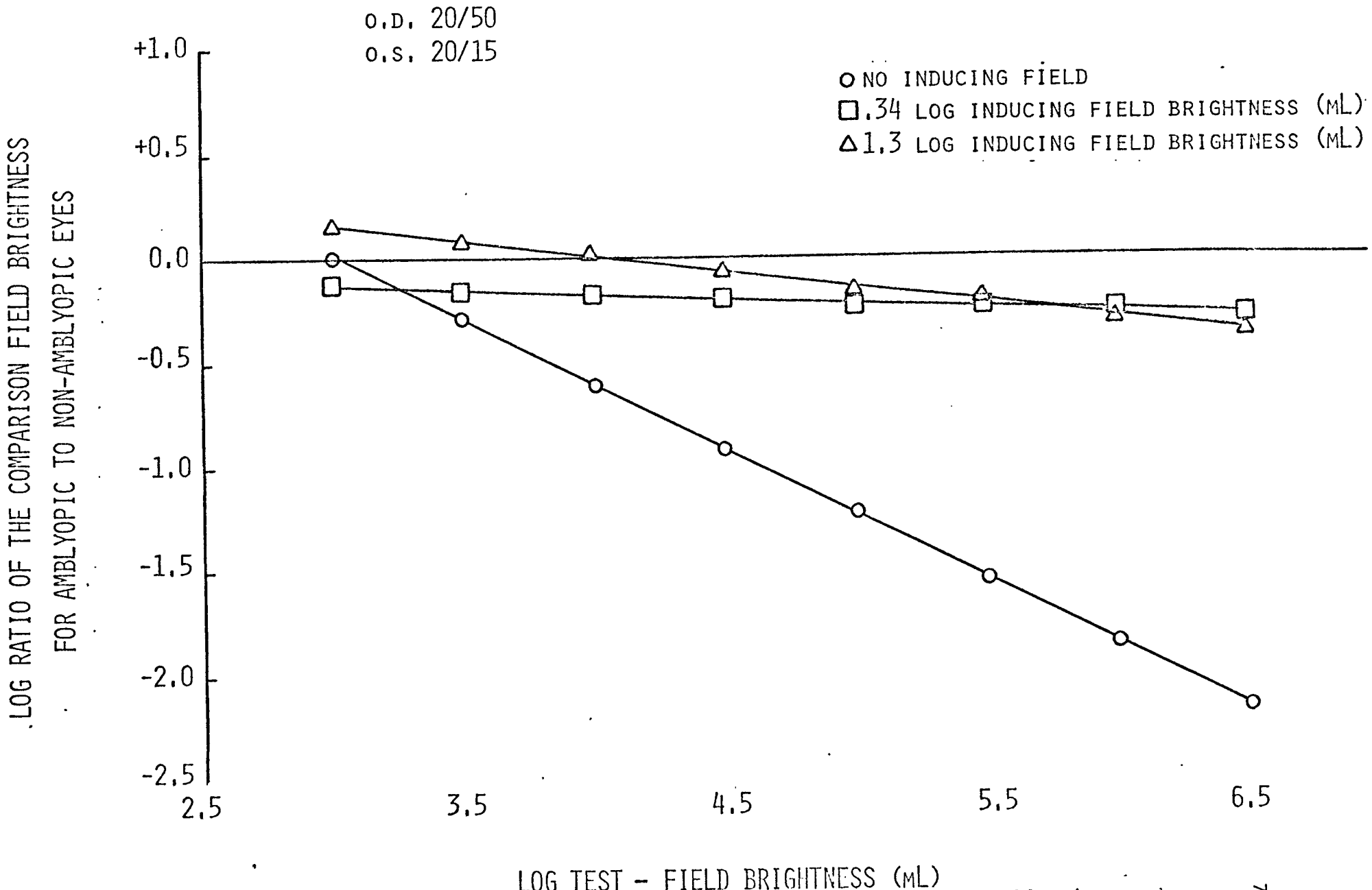


FIGURE 18 Log ratio of the comparison field brightness for the amblyopic to the non-amblyopic eye of subject B.R. (visual acuity: O.D. 20/50: O.S. 20/15), vs log test field brightness for no inducing field, 0.34 log inducing field and 1.3 log inducing field brightness.

abnormalities and she was able to appreciate the Maxwell's Spot. The ability to appreciate Maxwell's Spot as the Haidinger brush phenomenon has been suggested as a means of differentiating functional from organic amblyopia (Borish, 1970). Wald and Burian (1944) have suggested that since their amblyopic subjects displayed normal dark adaptation curves, absolute thresholds, and spectral sensitivity, the entire apparatus of simple light perception and spatial localization within the visual field is therefore virtually normal in these patients. They further suggest that the reduced visual acuity is a result of cortical inhibition of pattern vision. They pointed out that this theory is supported by experiments on dogs, cats and monkeys, in which an animal deprived of its occipital lobes retains light perception, but loses form vision. The loss of occipital lobes in man, however, results in permanent and complete loss of all sensations of light (Miller, 1954). It is interesting that subject B.R. (Figure 18) was the only right eye amblyopic subject out of 5 randomly chosen centrally fixating amblyopes. Nothing in the literature suggests a difference in the incidence of amblyopia occurring in the left and right eyes; however, a study of this factor might provide valuable information.

Wald and Burian (1944) used a circular target to measure absolute thresholds in amblyopic subjects. Miller (1954) has taken issue with Wald and Burian's use of a circular target, rather than using a narrow bar type target, such as he used. Since Wald and Burian concluded that amblyopia is a defect of form vision, Miller felt that bar type targets may be more closely related to the mechanisms involved in

visual acuity. Miller (1954) and Grosvenor (1957) later showed that differential luminance thresholds were elevated and contrast function reduced under photopic conditions. Miller has suggested that this represents a "special manifestation of impaired brightness discrimination" and that the cause is an absence of inhibition in the retina. The findings of the present study and other studies indicate that the use of the bar targets was not the important factor, but that the study was one of increment threshold under photopic conditions.

Grosvenor (1957) studied brightness discrimination on two amblyopic subjects over a wide range of background luminances and exposure durations. He found the threshold for the amblyopic eye to be somewhat higher than that for the normal eye except at the absolute threshold level and at high luminance levels (70 and 700 foot lamberts). The ratios between absolute threshold values for the 2 eyes were virtually equal to one. At high luminance levels (70 and 700 foot lamberts), the ratios between the threshold values amount to only about one-fifth of a log unit. This is consistent with the findings of the present study, in that there are no statistically significant differences in brightness contrast function between amblyopic and non-amblyopic eyes at high intensity levels (1.3 log inducing field brightness and greater). Since Grosvenor used just two subjects, one normal and one amblyopic, no statistical analysis was performed. In addition, although his amblyopic subject had central fixation, no attempt was made to demonstrate foveal integrity using Maxwell's Spot or the Haidinger brush phenomenon. Grosvenor has explained the difference between the two

eyes by assuming a photochemical deficiency in the amblyopic eye, and in addition postulating a decreased amount of inhibition. Grosvenor states that if the defect is at a photochemical level, "one would not suppose that it could be corrected by orthoptics." It would seem that if his theory is correct it holds for only a relatively small percentage of amblyopes, since therapy (occlusion, pleoptics, etc.) reportedly results in improvement in 80 to 90 percent of amblyopes (Borish, 1970). It appears rather that orthoptic training in amblyopia is concerned with training visual discrimination and contrast discrimination.

No further evidence has been generated in support of the photochemical theory; however, the studies of Flynn (1967), Lawwill et al. (1973), Sawyer (1972), and the present study lend support to the theory of reduced lateral inhibition in the visual system. Flynn found abnormal spatial summation in the fovea of the amblyopic eyes. The amblyopes summated over a larger area than did the non-amblyopes, and in a manner similar to that of normal peripheral retina. Flynn has suggested this is a result of enlarged retinal receptive fields. In this regard Hubel and Wiesel (1963) have reported that in kittens with experimental amblyopia, enlarged lateral geniculate receptive fields are found in 20% of the geniculate cells serving the amblyopic eye. Lawwill et al. (1973) using the visual evoked response have shown electrophysiologically on one amblyopic subject that inhibition is decreased. Their stimulus configuration has been shown by Westheimer (1967) to produce inhibition only when the annulus is seen by the same eye as the test field and not when it is seen by the other eye, indicating that the site of inhibitory

interaction is retinal. Lawwill et al. therefore conclude that "at least part of the defect in functional amblyopia is located peripheral to the primary visual cortex."

It would seem then that in the centrally fixating amblyopic eye there exists increased spatial summation and decreased lateral inhibition. These findings are difficult to generalize to all amblyopes, however; reportedly some 80% of amblyopes fixate eccentrically (Brock, 1952). Flom and Weymouth (1961) using the displacement of Maxwell's Spot from a fixation target as an index of eccentric fixation have shown a correlation of +0.94 between visual acuity, expressed as minimum angle of resolution and the degree of eccentricity. Thus, they conclude that the low acuity of the amblyopes is explained on the basis of the lowered parafoveal acuity. This explanation has been challenged on the basis that it doesn't explain the reduced acuity in centrally fixating amblyopes.

It would be of great interest to determine foveal brightness contrast function in eccentric fixators; however, to date control of fixation remains difficult in eccentric fixators. In normal animals the retinal receptive fields are larger in the peripheral retina than in the fovea, and therefore greater spatial summation occurs peripherally. If the foveal receptive fields in amblyopic eyes were enlarged to a greater extent than the parafoveal or peripheral receptive fields, this would result in greater summation, and therefore poorer visual acuity centrally than peripherally. This might explain the preference for eccentric fixation in many amblyopes (Von Noorden, 1967).

While the mechanism of brightness contrast is not fully understood, Werblin (1973) has shown that in the mudpuppy, on the basis of the retinal anatomy and intracellular recordings, the narrow operating range of the bipolar cell can be shifted according to the luminance level in the local surround of each bipolar cell. This shifting appears to be mediated by horizontal cells carrying information across the retina and serves to "fine tune" each bipolar cell operating curve to the appropriate intensity range. Apparently the retinal lateral interneurons (horizontal and amacrine cells) have synapses such that they can transmit back to cells that drive them, across to one another and on to succeeding input output cells. Thus, an anatomical basis exists for feedback and feedforward loops in the retina.

In the past amblyopia has been considered to be either a result of cortical inhibition, and therefore amenable to training, or due to a structural retinal defect, and therefore not curable. A third possibility that should be considered is that a functional defect in the retinal physiology, rather than an anatomical defect, resulting in reduced lateral interactions may be at least in part responsible for the reduced visual acuity in amblyopia. Intracellular electrophysiological recordings from the retina of experimental "amblyopic" animals may provide useful evidence.

The present study has indicated a reduced brightness contrast function in amblyopic subjects. Reduced lateral interaction in the retina has been proposed as a possible mechanism for this finding, and for the reduced visual acuity in amblyopes. Several avenues of further research appear necessary to further investigate this hypothesis.

Investigation of differential thresholds, using the same target configuration as in the present study, seems to be indicated to determine whether Miller (1954) or Grosvenor (1957) were looking at the effects of the bar targets, rather than brightness discrimination. In addition it would be valuable to investigate visual acuity under the various inducing field luminance conditions. The present study has raised some important questions as to the effect of luminance on the visual acuity of amblyopes. It is apparent that at intermediate photopic levels brightness contrast function is abnormal in amblyopic subjects; however, at higher inducing field luminances, brightness contrast function appears to be normal. This may indicate a shift in contrast function, requiring greater physical contrast in order to activate the horizontal cell "fine tuning" operation suggested by Werblin (1973). Possibly the feedback and feedforward loops proposed by Werblin (1973) are not well developed in the amblyopic eye. Since normal contrast function apparently does occur at high inducing field luminance levels, the question of the degree to which contrast function influence visual acuity is raised. Conceivably a saturation point occurs above which further increase in lateral interaction no longer influences visual acuity. It would be of great interest to measure visual acuity under the various inducing luminance conditions used in the experiment.

Another area deserving of further investigation is the condition in which the inducing field is brighter than the test field. Since the apparatus used was principally designed for measurement of increment thresholds, this was not possible. Spectral sensitivity is

reportedly normal in amblyopes (Wald and Burian, 1944). Sperling and Harwerth (1971) have investigated increment threshold spectral sensitivity in rhesus monkeys. Their model seems to reflect neural interaction between cones contrasting photopigments with 535 and 575 nanometer peaks. Investigation of this nature may provide further information on neural interactions in amblyopic patients. Of great importance is the question of whether the findings of this study have implications in terms of predicting prognosis for the training of amblyopic patients. At least 2 of our subjects are involved in a program of orthoptics treatment. A follow-up study of these and other amblyopes seems essential in investigating whether contrast function provides prognostic information in terms of expected recovery of acuity.

Summary and Conclusions:

The site of the loss of visual acuity in amblyopia is unknown. Many of the physiological functions of the amblyopic eyes are normal; however, the contrast requirements of amblyopic eyes reportedly differ from those of normal eyes. An apparatus has been constructed for the investigation of simultaneous brightness contrast in amblyopic and control subjects using a haploscope brightness matching technique. Ten subjects, 5 amblyopes with central fixation, and 5 control subjects matched for age, were tested. The psychophysical method of adjustment was used, and the subjects were required to make brightness matches over a wide range of test and inducing field luminances. The results of this study lead to the following conclusions:

(1) Both amblyopic and control subjects demonstrate brightness contrast function.

(2) Except for one amblyopic subject, brightness matching in the absence of an inducing field was normal.

(3) Amblyopic subjects with central fixation show abnormal brightness contrast function most markedly at low and intermediate photopic levels, but normal contrast function at high luminances.

(4) At low and intermediate luminances when physical contrast between the test and inducing fields is low, amblyopic subjects show a decrease in the apparent brightness of the test field of over .3 log units.

(5) At low and intermediate luminances with high levels of physical contrast between the test and inducing fields, amblyopic eyes showed an increase in apparent brightness of the test field.

(6) It has been hypothesized that a shift in lateral interactions in the retina, as a result of enlarged retinal receptive fields, contributes to the reduction in visual acuity in amblyopia.

(7) Further research is necessary to determine the role of lateral interactions and spatial summation in visual acuity.

BIBLIOGRAPHY

Alpern, M. and H. David. The additivity of contrast in the human eye. J. Gen. Physiol., 43, 1959, 109-126.

Alpern, M. Metacontrast. J. Opt. Soc. Amer., 43, 1953, 648-657.

Baumgartner, G., J. L. Brown, and A. Schulz. Responses of single units of the cat visual system to rectangular stimulus patterns. J. Neurophysiol., 28, 1965, 1-18.

Borish, I. M. Clinical Refraction, 3rd Edition. Professional Press, Inc., 1970, 1175-1253.

Brooks, V. B. Contrast and stability in the nervous system. Trans. N.Y. Acad. Sci., 21, 1959, 387-394.

Brown, J. L. and C. G. Mueller. Brightness Discrimination and Brightness Contrast. Vision and Visual Perception. Graham. John Wiley and Sons, Inc., 1965, 208-250.

Burian, H. M. Pathophysiological basis of amblyopia and of its treatment. Am. J. Ophth., 67, (11), 1969, 1-12.

Diamond, A. L. Foveal simultaneous brightness contrast as a function of inducing and test field luminances. J. Exp. Psychol., 45, 1953, 304-314.

Diamond, A. L. Foveal simultaneous brightness contrast as a function of inducing and test field luminances. J. Exp. Psychol., 500, 1955, 144-152.

Flom, M. C., G. G. Heath, and E. Takahashi. Contour interaction and visual resolution. Contralateral effects. Science, 142, (3594), 1963, 979-980.

Flom, M. C., F. W. Weymouth, and D. Kahneman. Visual resolution and contour interaction. J. Opt. Soc. Amer., 53, (9), 1963, 1026-1032.

Flynn, J. T. Spatial summation in amblyopia. Arch. Ophthal., 178, (41), 1967, 470-474.

Fry, G. A. and M. Alpern. The effect of a peripheral glare source upon the apparent brightness of an object. J. Opt. Soc. Amer., 43, 1953, 189-206.

Grosvenor, T. The effects of duration and background luminance upon the brightness discrimination of an amblyope. Am. J. Optom., 34, (12), 1957.

Guildord, J. P. Psychometric Methods. McGraw Hill. 1954.

Hartline, H. K., H. G. Wagner, and F. Ratliff. Inhibition in the eye of limulus. J. Gen. Physiol., 39, 1956, 651-673.

Hartline, H. K. Inhibition of activity of visual receptors by illuminating nearby retinal elements in the limulus eye. Fed. Proc., 8, 1949, 69.

Hartline, H. K. and C. H. Graham. Nerve impulses from single receptors in the eye. J. Cell. Comp. Physiol., 1, 1932, 277-295.

Heinemann, E. G. Simultaneous brightness induction as a function of inducing and test field luminances. J. Exp. Psychol., 50, 1955, 89-96.

Heinemann, E. G. Simultaneous Brightness Induction Handbook of Sensory Physiology. Visual Psychophysics. Edited by D. Jameson and L. M. Hurrich. Springer-Verlag, New York, 1972.

Hess, L. and H. P etori. Messende Untersuchungen ueber die Gesetzmassigkeil des simultanen Helligkeitskontrastes. Graefes Arch. Ophthalmol.,

40, 1894. Described by J. L. Brown and C. G. Mueller. Brightness Discrimination and brightness contrast. Vision and visual perception. Graham, John Wiley and Sons, Inc., 1965, 208-250.

Hollins, M. Brightness contrast at low luminances. Vision Res., V of 11, 1971, 1459-1472.

Horemann, H. W. Inductive brightness depression as influenced by configurational conditions. Vision Res., 3, 1963, 121-130.

Jameson, D. and L. R. Hurrich. Complexities of perceived brightness. Science, 133, 1961, 174-179.

Katsuki, Y. Neural Mechanism of Auditory Sensation in Cats. Sensory Communication. W. A. Rosenblith, Editor. M.I.T. Press, 1959.

Kuffler, S. W. Discharge patterns and functional organization of mammalian retina. J. Neurophysiol., 16, 1953, 37-68.

Lawwill, T. and H. M. Burian. Luminance, contrast function and visual acuity in functional amblyopia. Am. J. Ophthal., 62, (3), 1966, 511-520.

Lawwill, T., W. E. Cox, D. Tuttle, G. Meur, and H. M. Burian. Lateral inhibition and the V.E.R. in the central field of an amblyopic subject. Invest. Ophthal., 12, (2), 1973, 154-156.

Leibowitz, H., F. A. Mote, and W. R. Thurlow. Simultaneous contrast as a function of separation between test and inducing fields. J. Exp. Psychol., 46, 1953, 453-456.

Mach, E. On the Effect of Spatial Distribution of the Light Stimulus on the Retina. Mach Bands: Quantitative Studies on Neural Networks in the Retina. Ratliff. Holden Day, 1965, 253-270.

Maffei, L. and A. Fiorentini. Retinogeniculate convergence and analysis of contrast.

Michael, C. R. Receptive fields of single optic nerve fibers in a mammal with all-cone retina. I: Contrast-sensitive units. J. Neurophysiol., 31, 1968, 249-255.

Miller, E. F. Investigation of the nature and cause of impaired acuity in amblyopia. Am. J. Optom. and Arch. Am. Acad. Optom., 32, 1955, 10.

Miller. E. F. The nature and cause of impaired vision in the amblyopic eye of a squinter. Am. J. Optom. and Arch. Am. Acad. Optom., 31, 1954, 615.

Mountcastle, V. B. Some Functional Properties of the Somatic Afferent System. Sensory Communication. W. A. Rosenblith, Editor. M.I.T. Press, 1959.

Pitts, D. G. L.G.N. single cell responses as a function of intense light flashes. A preliminary report. Symposium on Flash Blindness. The Army Natick Laboratories and National Research Council, Natick, Mass., 1967.

Ratliff, F. Inhibitory Interaction and the Detection and Enhancement of Contour. Sensory Communication. W. A. Rosenblith, Editor. M.I.T. Press, 1959.

Ratliff, F. Contour and contrast. Scientific American, June, 1972, 91-101.

Ratliff, F. and H. K. Hartline. The responses of limulus optic nerve fibers to patterns of illumination on the retinal mosaic. J. Gen. Physiol., 42, 1959, 1241-1255.

Riggs, L. A. Visual Acuity. Vision and Visual Perception. Graham. John Wiley and Sons, Inc., 1965, 321-349.

Saunders, J. E. Adaptation, its effect on apparent brightness and contribution to the phenomenon of brightness constancy. Vision Res., 8, 1968, 451-468.

Sawyer, D. What the A.O.F. means to optometry--and to me. Opt. Weekly, May 18, 1972, 517.

Schouten, J. F. and L. Ornstein. Measurements on direct and indirect adaptation by means of a binocular method. J. Opt. Soc. Amer., 29, 1939, 168-182.

Shipley, T. The visually evoked occipitogram in ophthalmoscopy. J. Ped. Oph., 6, 1969.

Spekreijse, H., L. H. Khoe and L. H. van der Tweel. A case of amblyopia; electrophysiology and psychophysics of luminance and contrast. From The Visual System: Neurophysiology, Biophysics, and Their Clinical Applications. Proceedings of the 9th ISCERG Symposium, Brighton, England, July, 1971. Ed. by G. B. Arden. Plenum Press, 1972.

Sperling, H. G. and R. S. Harwerth. Red-green cone interactions in the increment-threshold spectral sensitivity of primates. Science, 172, 1971.

Torri, S. and Y. Uemura. Effects of inducing luminance and area upon the apparent brightness of test field. Jap. Psychol. Res., 7, 1965, 86-100.

Von Bekesy, G. Sensory Inhibition. Princeton University Press, 1967.

Von Noorden, G. K. Pathogenesis of eccentric fixation. Doc. Ophth., 23, 1967, 263.

Von Noorden, G. K. Pathophysiology of amblyopia: diagnostic and therapeutic principles of pleoptics. Am. Orthoptic J., 10, 1960, 7-16.

Wald, G. and H. M. Burian. The dissociation of form vision and light perception in strabismic amblyopia. Am. J. Ophth., 27, 1944, 950-963.

Weisel, T. N. and D. H. Hubel. Effects of visual deprivation on morphology and physiology of cells in the cat's lateral geniculate body. J. Neurophysiol., 26, 1963, 978-993.

Werblin, F. S. The control of sensitivity in the retina. Scientific American, 1973, 71-79.

Webblin, F. S. Functional organization of a vertebrate retina: sharpening up in space and intensity. Annals of the New York Academy of Sciences, 193, 1972, 75-85.

Westheimer, G. Spatial interaction in human cone vision. J. Physiol., 90, 1967, 139-154.

Winer, B. J. Statistical Principle in Experimental Design. New York, McGraw-Hill, 1962.

APPENDIX

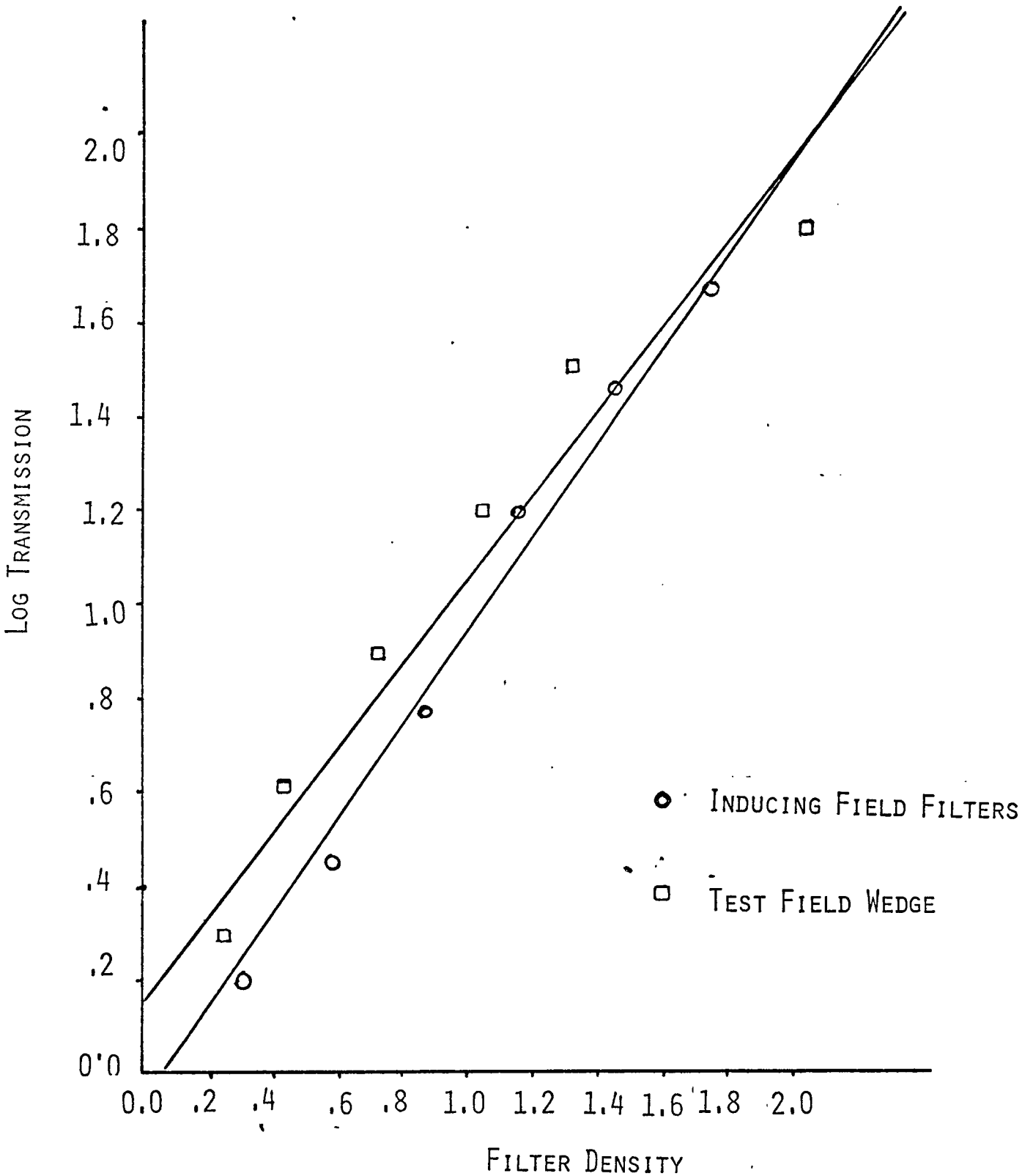


Fig.1 Calibration Curves for Test Field Wedge and Inducing Field N.D. Filters.

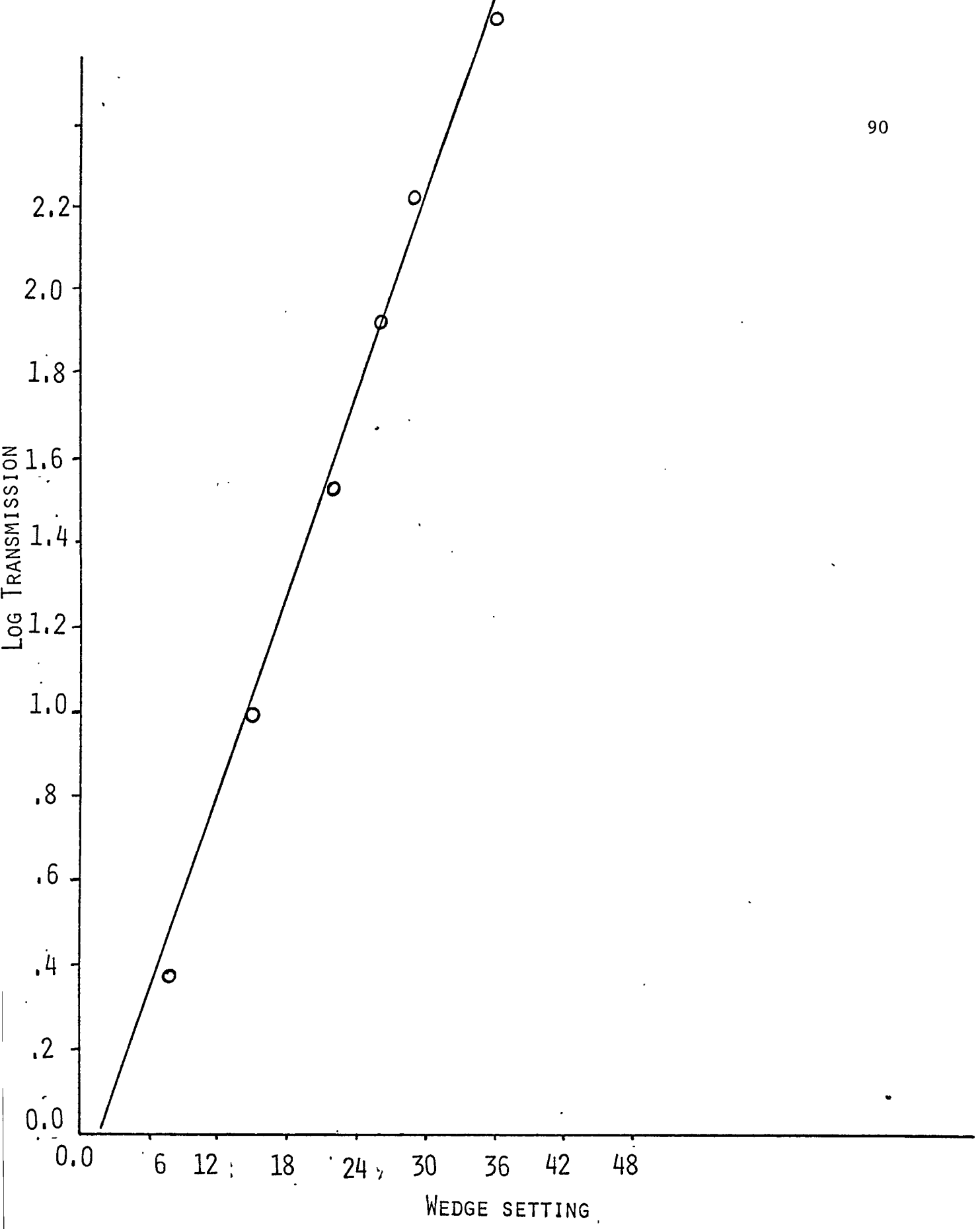


Fig.2 Calibration Curve for Comparison Field Wedge