JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 49, NUMBER 8 AUGUST, 1959

Depth-Discrimination Thresholds as a Function of Binocular Differences of Retinal Illuminance at Scotopic and Photopic Levels*

ALFRED LIT†
Vision Research Laboratories, The University of Michigan, Ann Arbor, Michigan

(Received January 13, 1959)

The precision of depth discrimination has been measured in a two-rod test apparatus involving real-depth cues. The effects of two variables have been studied: (a) the level of equal retinal illuminance presented to the two eyes; and (b) the difference in the level of the retinal illuminance presented to the two eyes. It has been found that depth discrimination in this test varies as a function of the level of equal retinal illuminance presented to the two eyes in much the same way that acuity or intensity discrimination vary with luminance. Stereoscopic threshold angles vary more than 19:1 over some five log units of variation in illuminance.

Unequal retinal illuminance presented to the two eyes at any given illuminance level has a comparatively small deleterious effect upon the precision of depth discrimination. This effect progressively increases as the inequality of retinal illuminance is increased.

These results have significance for photochemical theories of vision and for the classical theory of binocular space discrimination.

1. INTRODUCTION

It has long been known that depth-discrimination thresholds are significantly influenced by the prevailing state of adaptation of the eyes.[1] Only more recently, however, Mueller and Lloyd[2] have obtained extensive data on the effects of this important factor on depth settings. They used a stereoscopic device to obtain "equality" settings from two observers who were highly experienced in making stereoscopic settings. The stimulus targets consisted of black vertical lines that were presented at each of ten background luminance levels ranging from -4.04 to 2.27 log mL. Pupil size was not controlled in their study. During each experimental session, the ten luminance levels were presented in order of increasing magnitude, and a group of 20 equality settings for the "depth" positions of the standard and comparison lines was made by each observer at each level. Three experimental sessions were given to each observer; the combined data obtained at each luminance level was thus based on six groups of 20 readings. The variability (average deviation) of the settings was used as a measure of the stereoscopic threshold angle, η_t. That is, η_t was computed at each luminance level by taking the mean of the six average deviations of the equality settings obtained in each case.

The combined data presented by Mueller and Lloyd showed that η_t undergoes only a threefold change as luminance level is varied by a factor of one million. The value of η_t was greatest (about 26 sec of arc) at the lowest luminance level, and progressively decreased (i.e., stereoscopic acuity increased) as the luminance level was increased to approach a final limiting value of about 9 sec of arc. When η_t was plotted as a function of $\log I$, the curve exhibited a discontinuity at a luminance value of approximately 0.01 mL where the value of η_t was about 22 sec of arc. In accordance with duplicity theory and the supporting data typically obtained for other classes of visual responses,[3] the discontinuity was interpreted as representing the transition from rod to cone vision.

The present experiment is concerned primarily with the effects of unequal binocular retinal illuminance on equidistance (equality) settings. (See Ogle and Groch[4] for a brief account of several classes of investigations that deal with the effects of binocular differences of illumination on spatial localization.) The equality settings are obtained by use of stimulus targets that are presented for binocular viewing with the unaided eyes ("real-depth" situation) under conditions of equal, as well as specified amounts of unequal, binocular retinal illuminance produced at many selected levels ranging from a low scotopic to a high photopic level.

2. APPARATUS AND PROCEDURE

The present data were obtained by use of an apparatus‡ originally employed by Lit and Hyman[5] in connection with experiments on the Pulfrich stereophenomenon. As used here, the device provides stimulus conditions for measuring depth thresholds that are essentially similar to those present in a typical two-rod test apparatus such as the so-called Howard-Dolman apparatus.[6]

---

* This work was conducted by Project MICHIGAN under Department of the Army Contract (DA-36-039 SC-52654), administered by the U. S. Army Signal Corps.

† Now with Bendix Aviation Corporation, Systems Division, Ann Arbor, Michigan.

[1] W. A. Nagel, Z. Psychol. 27, 264–266 (1902).

[2] C. G. Mueller and V. V. Lloyd, Proc. Natl. Acad. Sci. (U. S.) 34, 223–227 (1948).

[3] S. Hecht, Physiol. Revs. 17, 239–290 (1937).

[4] K. N. Ogle and J. Groch, Arch. Ophthalmol. (Chicago) 56, 878–895 (1956).

‡ The apparatus was originally constructed at the Pupin Laboratories, Columbia University, partially through funds from a research grant-in-aid generously provided by the American Academy of Optometry.

[5] A. Lit and A. Hyman, Am. J. Optom. 28, 564–580 (1951).

[6] H. J. Howard, Am. J. Ophthalmol. 2, 656–675 (1919).

The standard (stationary) target is a blackened steel rod $\frac{1}{4}$ in. in diameter. It is vertically suspended downward to eye level from a Jacobs chuck that is mounted on the under surface of an elevated supporting carriage. The rod is held at a fixed distance of 100 cm from the observer's eyes and is laterally displaced 1.3 cm (0.75°) to the right of the observer's vertical median plane. At this fixed position, the horizontal angular extent of the standard rod is 21.8 min of arc.

The comparison (movable) target is also a blackened steel rod $\frac{1}{4}$ in. in diameter. It is held vertically upright to eye level in a Jacobs chuck that is mounted on the upper surface of a supporting carriage located below eye level. The comparison rod and its supporting carriage are movable along a horizontal metal track located in the observer's vertical median plane. The supporting carriage is made part of an endless-cable and pulley system so that the observer, by turning a wheel in the dark room, can adjust the position of the comparison rod in a direction either towards or away from his eyes. The distance of the comparison rod from the observer's eyes, as measured along the metal track, can be read by the experimenter from a scale calibrated in millimeters. The use of a vernier index permits the experimenter to estimate the distance of the comparison rod to within 0.01 cm.

The observer is seated in a dark room and binocularly views the upper and lower stimulus rods through a pair of circular artificial pupils that are 2.5 mm in diameter and adjustable for interpupillary separation. The artificial pupils are attached to eye tubes that are mounted on the inner wall of the experimental dark room. In front of each eye tube, a filter box is mounted on the outer wall so that the experimenter can systematically control the retinal illuminance of each eye separately by combinations of neutral density filters. The same number of filters (three) is always used in forming any given combination.

Uniform background illumination is provided by ten 150-w frosted lamps that are mounted in an asbestos-lined, galvanized iron light-box. The light-box is located in a frontal plane 250 cm from the observer's eyes. Lamp voltage is maintained constant (to within 1.0%) at 124 v ac by means of an automatic constant-voltage output regulator. The illuminated surface is a white-matte screen that is attached to the inner rear wall of the light-box. The surface is visible through a horizontal aperture cut out of the front wall of the light-box. Screening units provide the observer with a horizontal rectangular field of view, 21.6°×4.2°. As measured with a Macbeth illuminometer, the white-matte surface has a luminance of 854 ft-L. The color temperature at the given voltage is 2735°K. With the 2.5-mm artificial pupil in use, the retinal illuminance without filters is 14359 trolands, or 4.16 log trolands. When the observer looks through the eye pieces, he sees the upper standard rod and the lower comparison rod against the uniform background produced by the light-box. The lower end of the standard rod and the upper end of the comparison rod lie in the observer's horizontal plane of fixation. His head is kept immobilized by chin and forehead rests.

Two young graduate students, both emmetropic, served as paid observers. Their visual acuity in each eye was better than 20/20 and their ductions were normal at both distance and near. At a fixation distance of 100 cm, the interpupillary separation of observer F.C. measured 6.20 cm and that of observer R.B. measured 6.40 cm. At this fixation distance, both observers showed 3Δ exophoria. Each was an experienced observer in vision experiments but unpracticed in making depth settings.

A three-week training period was accordingly devoted to daily practice sessions in making equality settings. In performing this type of depth setting, the observer is required to adjust the depth position of the comparison target in relation to that of the stationary standard target (using a "bracketing" procedure) until both targets appear to lie in the same frontoparallel plane. The equality settings are made while the observer constantly fixates on the upper end of the movable comparison rod. After each setting is made, the experimenter displaces the comparison target in a direction either toward or away from the observer by varying amounts. The observer requires about 5 to 15 sec to complete a single equality setting.

Following the practice sessions, a series of preliminary experimental sessions was given to each observer. Equality settings were made at each of 17 selected levels of illuminance ranging from -2.34 to 3.19 log trolands. Testing at a given level constituted an experimental session. The 17 illuminance levels were presented on successive days in order of increasing magnitude. In any experimental session the retinal illuminance of the left eye, $\log E_L$, was kept constant at the given selected level while the retinal illuminance of the right eye, $\log E_R$, was systematically increased, starting always from the initial value that produced binocular equality, i.e., at each selected illuminance level, $\log E_R \geq \log E_L$. The conditions of binocular retinal illuminance, $\log(E_R/E_L)$, used in the preliminary experimental series were: 0.0, 0.1, 0.2, 0.3, 0.4, 1.0, 1.4, 1.6, 2.0, 2.5, 3.0, 3.5, and 4.0. At each of the 17 illuminance levels, a single group of 20 equality settings was made by each observer under each of the conditions of binocular retinal illuminance. Each preliminary experimental session was preceded by a 30-min period of dark adaptation. During the course of an experimental session, a 3-min period of adaptation followed each successive increase of illuminance in the right eye.

The results obtained in the preliminary experimental series provided a basis for selecting the values of $\log E_L$ and $\log(E_R/E_L)$ used in the main experimental sessions. It should be noted that the experimental procedure employed in the main experimental sessions was considerably different from that used in the preliminary series. In the main experimental sessions, six specified conditions of increasing inequality of binocular retinal illuminance, $\log(E_R/E_L)$, were used: 0.0, 0.4, 1.0, 1.6, 2.0, and 2.5. Under each of the six conditions, equality settings were obtained at 11 to 14 selected levels of illuminance of the left eye, $\log E_L$, ranging from -2.34 to 2.75 log trolands. Testing at all selected illuminance levels, under one of the six specified values of $\log(E_R/E_L)$, constituted an experimental session. In any given experimental session, the selected illuminance levels of the left eye were always presented in order of increasing magnitude, and each observer made 20 equality settings at each of the levels. A total of 24 daily sessions was given to each observer during which the six values of $\log(E_R/E_L)$ were presented in a counterbalanced order. This procedure yielded from each observer four sets of 20 equality readings at each selected level for each of the six values of $\log(E_R/E_L)$. Each of the main experimental sessions was preceded by a 30-min period of dark adaptation. During the course of an experimental session, a 3-min period of adaptation followed each successive increase of illuminance in the two eyes.

Two stereoscopic parallax angles were computed for each group of 20 equality settings. One was computed on the basis of the magnitude of the constant error of the settings, and the other on the basis of the magnitude of the variable error. The constant error of any group of 20 equality settings is defined as the mean depth difference (ΔR) existing between the standard rod and the adjusted comparison rod. The variable error is here defined as the average deviation (AD) of the 20 equality settings of the comparison rod. The computations of the two stereoscopic parallax angles for each group of 20 equality settings were based on the formula[7] which geometrically specifies the difference between the visual angle formed by the standard and comparison rods in one eye and the visual angle formed by these same rods in the other eye. That is,

$$\eta_t = [206\,265(b)/R_S][\delta_t/R_V], \qquad (1)$$

where $R_S(=100$ cm) represents the fixed distance of the standard rod; R_V represents the mean adjusted distance of the comparison rod; b represents the observer's interpupillary separation ($b=6.20$ cm for observer F.C. and $b=6.40$ cm for observer R.B.); δ_t represents in one case the constant error, ΔR, and in the other case the variable error, AD, as each is defined above; and 206 265 is the numerical factor that converts η_t from radians into sec of arc when R_S, R_V, b, and δ_t are all measured in the same linear units.

When the stereoscopic parallax angle η_t is computed in terms of the constant error of the settings, it will be designated by the symbol $\eta_{\Delta\mathrm{R}}$. When η_t is computed in terms of the average deviation of the settings, it will be designated by the symbol η_{AD}. In accordance with convention, η_{AD} will be used as the measure of the stereoscopic threshold angle. It should be noted that a negative value of $\eta_{\Delta\mathrm{R}}$ means that $\Delta\mathrm{R}(=R_V-R_S)$ must be negative, and that the mean distance of the comparison rod from the observer's eyes was less than that of the fixed standard rod. It may be seen from Eq. (1) that for each constant error or average deviation of 0.01 cm (that is, for $\delta_t=\pm0.01$ cm and $R_V=100.00\pm0.01$ cm), the computed stereoscopic parallax angle η_t is 1.28 sec of arc for observer F.C. and 1.32 sec of arc for observer R.B. The values of $\eta_{\Delta\mathrm{R}}$ and η_{AD} for each observer were computed on the basis of these proportionality factors, that is, for observer F.C., $\eta_t=1.28\delta_t$ and for observer R.B., $\eta_t=1.32\delta_t$.

3. RESULTS

The data obtained in the main experimental sessions are summarized for both observers in Table I. Each entry represents a mean value of $\eta_{\Delta\mathrm{R}}$ or η_{AD}, based on the four sets of 20 equality readings taken at the indicated level of illuminance, $\log E_L$, for the given magnitude of the inequality of binocular retinal illuminance, $\log(E_R/E_L)$. The stereoscopic parallax angles are reported in sec of arc.

Two significant differences between the observers are to be noted. The first concerns the magnitude of the inequality of binocular retinal illuminance that could be tolerated by each observer without disrupting normal binocular functioning. As indicated by footnote b in Table I, observer R.B. reported double vision (exotropia) for the two stimulus rods whenever the retinal illuminance of his left eye was at a scotopic or near-scotopic level while that of his right eye was at a photopic level. Observer F.C., on the other hand, maintained binocular single vision for all six magnitudes of $\log(E_R/E_L)$ used in the main experimental sessions. In fact, observer F.C. maintained binocular single vision during the entire preliminary experimental series even when values of $\log(E_R/E_L)$ as large as 4.0 were used at each of the lower illuminance levels. It should be pointed out with respect to observer R.B. that binocular single vision could be restored by the use of base-in prisms, but equality readings were not taken under these special conditions. The second difference between the observers is concerned with the sign of $\eta_{\Delta\mathrm{R}}$. Observer R.B. characteristically adjusted the comparison rod to positions nearer than that of the stationary standard rod, thus giving rise to negative values of $\eta_{\Delta\mathrm{R}}$. Observer F.C., contrariwise, characteristically adjusted the comparison rod to positions more distant than that of the standard rod to yield positive values of $\eta_{\Delta\mathrm{R}}$.

Inspection of Table I reveals that, for conditions of

---

[7] C. H. Graham, *Handbook of Experimental Psychology*, edited by S. S. Stevens (John Wiley & Sons, Inc., New York, 1951), p. 888.

TABLE I. Depth-discrimination data. Depth-discrimination (stereoscopic) thresholds obtained at various illuminance levels of the left eye, $\log E_L$, under each of six specified conditions of increasing inequality of binocular retinal illuminance, $\log(E_R/E_L)$. The magnitude of the stereoscopic threshold angle, η_{AD}, is given for observers F.C. and R.B. in terms of the mean value of the average deviations of four sets of 20 equality readings taken under each of the given conditions of illuminance. The corresponding mean angular magnitude of the constant errors of the equality settings is given by $\eta_{\Delta\mathrm{R}}$.

$\log E_L$ (trolands)	Stereoscopic parallax measures (sec of arc)	$\log(E_R/E_L)$											
		0.0		0.4		1.0		1.6		2.0		2.5	
		F.C.	R.B.	F.C.	R.B.	F.C.	R.B.	F.C.	R.B.	F.C.	R.B.	F.C.	R.B.
−2.34	$\eta_{\Delta\mathrm{R}}$	343.6	−274.3[a]	224.4	−214.1	264.9	−417.5	160.2	b	−9.7	b	−0.5	b
	η_{AD}	162.1	177.0	206.1	164.7	172.4	213.5	172.6	b	158.4	b	129.7	b
−1.94	$\eta_{\Delta\mathrm{R}}$	321.8	−183.5	235.8	−156.5	239.8	−278.9	110.5	b	84.1	b	56.8	b
	η_{AD}	101.4	114.3	100.5	100.8	143.6	133.9	161.1	b	150.9	b	129.9	b
−1.65	$\eta_{\Delta\mathrm{R}}$	295.1	−141.1	229.8	−137.9	198.6	−289.5	178.6	b	111.6	b	48.2	b
	η_{AD}	75.9	94.2	83.0	90.6	87.6	139.8	109.2	b	116.6	b	111.0	b
−1.55	$\eta_{\Delta\mathrm{R}}$	268.1	−89.6	253.3	−88.5	235.7	−335.4	108.8	b	195.6	b	48.1	b
	η_{AD}	70.9	72.8	77.0	83.6	114.5	133.6	105.7	b	123.5	b	120.8	b
−1.25	$\eta_{\Delta\mathrm{R}}$	278.6	−70.2	255.9	−105.9	177.3	−291.7	119.3	b	149.8	b	127.1	b
	η_{AD}	66.6	82.8	68.4	64.9	71.8	106.1	92.8	b	118.2	b	112.5	b
−0.96	$\eta_{\Delta\mathrm{R}}$	233.8	−89.9	150.0	−121.1	113.6	−97.7	63.1	b	115.7	b	131.2	b
	η_{AD}	52.7	58.2	46.4	53.6	51.0	61.1	72.9	b	92.6	b	112.5	b
−0.60	$\eta_{\Delta\mathrm{R}}$	136.9	−68.3	77.7	−53.3	75.0	−86.6	52.8	−96.2	57.7	−146.2	70.1	b
	η_{AD}	26.5	32.0	25.3	30.5	29.7	40.5	38.1	54.2	53.2	78.3	44.6	b
−0.26	$\eta_{\Delta\mathrm{R}}$	89.4	−41.3	52.7	−32.2	60.3	−70.4	61.6	−40.3	48.9	−34.9	68.1	b
	η_{AD}	18.0	23.1	19.1	17.2	18.3	20.4	22.1	22.3	23.8	18.9	25.7	b
0.03	$\eta_{\Delta\mathrm{R}}$	62.3	−40.4	49.2	−34.2	61.8	−46.3	66.1	−31.8	70.3	−11.7	88.5	−20.1
	η_{AD}	13.2	14.5	13.9	14.6	15.3	19.4	17.7	18.6	17.5	19.0	19.2	16.6
0.51	$\eta_{\Delta\mathrm{R}}$	51.9	−31.2	47.6	−27.3	59.4	−23.5	76.0	−19.7	90.5	−7.3	108.1	−4.3
	η_{AD}	10.9	11.8	12.7	11.9	12.9	12.9	15.3	11.4	21.5	15.7	18.5	13.2
1.09	$\eta_{\Delta\mathrm{R}}$	50.9	−25.7	58.5	−30.6	71.1	−23.6	102.1	−11.5	103.5	−3.2	114.8	2.2
	η_{AD}	10.7	10.3	12.7	10.3	16.0	12.4	22.4	12.2	16.6	12.6	14.3	11.4
1.77	$\eta_{\Delta\mathrm{R}}$	53.3	−27.5	66.9	−24.6	80.1	−24.2	88.3	−16.7	79.1	−2.9		
	η_{AD}	10.8	10.8	14.0	8.5	13.8	10.4	13.4	10.4	14.1	9.1		
2.07	$\eta_{\Delta\mathrm{R}}$	47.3	−28.9	63.1	−28.3	74.9	−28.6	69.9	−13.9				
	η_{AD}	9.3	8.8	13.5	9.8	11.6	11.5	12.6	9.6				
2.75	$\eta_{\Delta\mathrm{R}}$	45.1	−28.8	48.4	−29.3	48.5	−39.4						
	η_{AD}	8.3	9.4	10.1	8.9	9.9	10.3						

[a] A negative value of $\eta_{\Delta\mathrm{R}}$ indicates that the mean distance of the comparison rod from the observer's eyes was less than that of the fixed standard rod.

[b] For these specified inequalities of binocular retinal illuminance, observer R.B. reported a double image of both the comparison rod and the standard rod.

equal as well as unequal binocular retinal illuminance, the magnitudes of $\eta_{\Delta\mathrm{R}}$ and η_{AD} are significantly influenced by illuminance level. The variability of the settings, η_{AD}, is greatest at the lowest level of illuminance and progressively decreases to a limiting low value as illuminance level is increased. The influence of illuminance level on the absolute magnitude of the constant error is considerably more irregular, but the same general trend is noted: $|\eta_{\Delta\mathrm{R}}|$ is large at low illuminance levels and decreases as illuminance level is increased.

A graphical representation of the effect of illuminance level on η_{AD} is given by Fig. 1. The combined data of both observers were used in plotting $\log\eta_{\mathrm{AD}}$ as a function of $\log E_L$, with $\log(E_R/E_L)$ serving as parameter. Only the three curves which are based on common data that extend to the lowest illuminance level are presented, that is, the curves for $\log(E_R/E_L)=0.0$, 0.4, and 1.0. It is to be noted that the average value of η_{AD} is largest (about 180 sec of arc) at the lowest level of illuminance (-2.34 log troland) and that η_{AD} progressively decreases to a minimum value (about 10 sec of arc) at the highest illuminance level (2.75 log trolands). A clearly marked discontinuity occurs in the three curves at an illuminance level of approximately -1.25 log troland, where η_{AD} takes on an average value of about 75 sec of arc. The scotopic (rod vision) section of the curves shows that η_{AD} exhibits an approximately

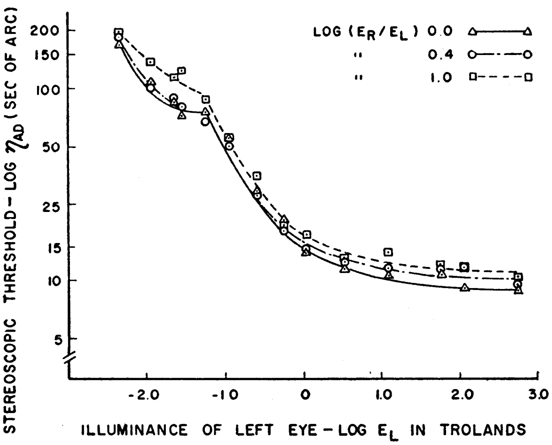

FIG. 1. Stereoscopic threshold angle, logη_{AD}, as a function of level of illuminance of the left eye, logE_L. The number accompanying each curve specifies the magnitude of the prevailing inequality of binocular retinal illuminance, log(E_R/E_L). Each point is based on the combined data of two observers and represents the mean value of the average deviations of eight sets of 20 equality readings.

2.5-fold decrease in magnitude as illuminance level is increased; the photopic (cone vision) section shows that η_{AD} exhibits more than a sevenfold decrease. Thus, η_{AD} undergoes nearly a twentyfold decrease in magnitude as illuminance level is increased by a factor of 100 000.

A similar plot (not shown here) was drawn in terms of the absolute angular magnitude of the corresponding constant errors, log$|\eta_{\Delta R}|$. In this case, curves were obtained that reveal considerable irregularities and marked individual differences, particularly for the data representing conditions of unequal binocular retinal illuminance. Despite the irregularities in the values of log$|\eta_{\Delta R}|$, a discontinuity could be detected in all three curves at an illuminance level of about -1.25 log troland, as in the case of the corresponding logη_{AD} curves presented in Fig. 1. It was noted also that the magnitude of $|\eta_{\Delta R}|$ undergoes only a fivefold to tenfold decrease over the total range of illuminance levels used.

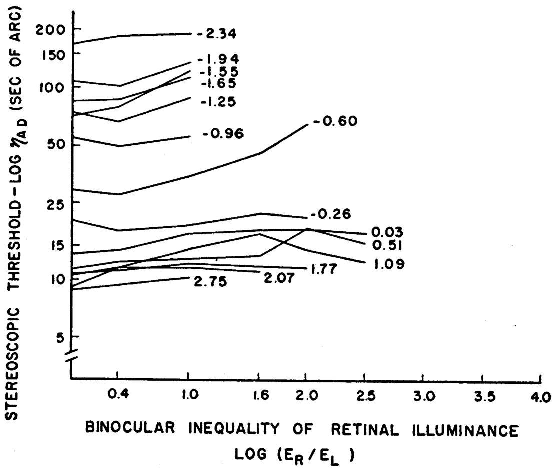

FIG. 2. Stereoscopic threshold angle, logη_{AD}, as a function of magnitude of inequality of the binocular retinal illuminance, log(E_R/E_L). The number accompanying each curve specifies the magnitude of the prevailing level of illuminance of the left eye, logE_L. Each point is based on the combined data of two observers and represents the mean value of the average deviations of eight sets of 20 equality readings.

It can be seen from Table I that variations in the magnitude of the inequality of binocular retinal illuminance produce systematic changes in η_{AD}. The effect is shown graphically in Fig. 2, where the combined data of both observers were used to plot logη_{AD} as a function of log(E_R/E_L), with logE_L serving as parameter. A consistent trend is to be noted: at each of the selected levels of illuminance, logη_{AD} increases by a small and nearly constant amount as the magnitude of log(E_R/E_L) is increased. This effect is more noticeable in Fig. 3, where the comparable data obtained in the preliminary experimental series are presented graphically. These data extend over a greater range of values of log(E_R/E_L) than the data of Fig. 2, and hence the trend in the data is more obvious. These data are actually more suitable for an analysis of the effect of illuminance inequality than the data from the main experiment since the various values of log(E_R/E_L) at each value of E_L were in this case studied in the same experimental session.

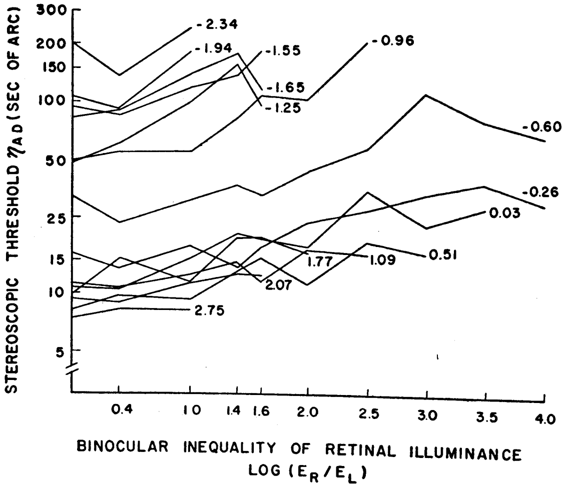

FIG. 3. Stereoscopic threshold angle, logη_{AD}, as a function of magnitude of inequality of the binocular retinal illuminance, log(E_R/E_L). The number accompanying each curve specifies the magnitude of the prevailing level of illuminance of the left eye, logE_L. Each point is based on the combined data of two observers and represents the mean value of the average deviations of two sets of 20 equality readings obtained in the preliminary experimental series.

The effect of variations in the inequality of binocular retinal illuminance on $|\eta_{\Delta R}|$ is considerably more complex. The effect at high illuminance levels is opposite to that at low levels. Furthermore, the effect on observer R.B. is reversed for observer F.C. Thus, when log$|\eta_{\Delta R}|$ was plotted as a function of log(E_R/E_L), with logE_L serving as parameter, the obtained curves (not shown here) reveal that as $\log(E_R/E_L)$ is progressively increased at low illuminance levels, $|\eta_{\Delta R}|$ decreases for observer F.C. and increases for observer R.B.; as $\log(E_R/E_L)$ is progressively increased at high illuminance levels, $|\eta_{\Delta R}|$ increases for observer F.C. and decreases for observer R.B.

4. DISCUSSION

The present data on equal binocular retinal illuminances for the real-depth situation are in general agreement with the experimental findings of Mueller and Lloyd[2] for the stereoscope. Both studies clearly demonstrate that the stereoscopic threshold angle is large at low illuminance levels and progressively decreases to a final low value as illuminance level is increased. The final threshold value is approximately the same (9 sec of arc) in the two studies. Both studies also show a similar discontinuity in the functional relationship existing between stereoscopic threshold angle and illuminance level, an effect which, in accordance with duplicity theory, presumably is caused by the transition from rod to cone vision.

Several important quantitative differences in the results of the two studies should, however, be pointed out. The first concerns the difference in the range of variation of the stereoscopic threshold angle. In the Mueller and Lloyd study, the stereoscopic threshold angle undergoes only about a threefold over-all change as background luminance was varied by a factor of one million. In contrast, the present data on equal binocular retinal illuminance show that η_{AD} undergoes about a 19-fold over-all change as illuminance level is varied over a somewhat smaller range. A similar difference in threshold range is also to be noted for the data obtained within the limits of the photopic range of illuminance levels. In the Mueller and Lloyd study, the photopic stereoscopic threshold angles undergo about a 2.5-fold change (from 22 sec of arc at cone threshold to a final threshold value of 9 sec of arc). In the present experiment, on the other hand, η_{AD} undergoes about an eightfold change within the photopic range (from a value of 75 sec of arc at cone threshold to a final threshold value of 9 sec of arc).

A second important difference in the results of the two studies concerns the shape of the experimental curve that relates stereoscopic threshold angle and illuminance level. Mueller and Lloyd specified the shape of their experimental curve in terms of the family of equations derived by Hecht[3] in his photochemical theory of intensity discrimination. Their manner of curve fitting followed the procedure used by Hecht and Mintz[8] in a study of the visual resolution of opaque wires observed binocularly under various levels of background illumination. The extension of this treatment of data on the threshold visual angle ($\propto$) to data on the stereoscopic threshold angle (η_t) was made by Mueller and Lloyd on the assumption that "threshold differences in brightness in some part of the two fields provide one of the bases for the discrimination of differences in depth. Therefore η_t may be considered proportional to $\Delta I/I$ and a solution for η_t may be obtained in a manner similar to that followed by Hecht and Mintz in determining $\propto$."

On the basis of visual inspection, Mueller and Lloyd selected Hecht's equation of intensity discrimination for the bimolecular chemical reactions, where $m=n=2$, as representing the best fitting curve for their photopic and scotopic data on stereoscopic thresholds. (No correction was made for the variations in retinal illuminance which accompanied the uncontrolled variations in pupil size). If the present photopic threshold data on equal binocular retinal illuminances are given similar treatment, the best fitting curve based on visual inspection is obtained rather by Hecht's equation for monomolecular reactions, where $m=n=1$. This means that the present data show that the progressive decrease in the magnitude of η_{AD} from cone threshold value to final threshold value occurs at a faster rate (that is, occurs within a smaller range of illuminance levels) than would be predicted by Hecht's equation for the bimolecular reactions, $m=n=2$. A similar treatment of the present scotopic threshold data on equal binocular retinal illuminance shows that these data can be visually fitted equally well by either of the two theoretical equations.

An important feature of the present experiment is the new data obtained on the effects of unequal binocular retinal illuminances. These data show that, at any given illuminance level of the left eye, the magnitude of η_{AD} progressively increases as the retinal illuminance of the right eye is increased. This means that any difference produced in the retinal patterns of illumination in the two eyes consistently increases the variability of the equality settings; the greater the difference in binocular patterns, the greater is the increase in variability of the settings. The increase in variability occurs at low and moderate illuminance levels, despite the fact that any increase in retinal illuminance of the right eye presumably increases its visual acuity. The increase in variability occurs also at high illuminance levels where, presumably, the right eye has already attained its maximum visual acuity before any monocular increase in retinal illuminance was introduced. These results suggest the need for an experimental program in which depth settings are made for stimulus targets of unlike size and shape that are presented separately to each eye under many conditions of equal and unequal binocular retinal illuminances.

No simple explanation can be given to account for the marked individual differences in angular magnitude and sign of the constant errors, $\eta_{\Delta R}$. The present

---

[8] S. Hecht and E. U. Mintz, J. Gen. Physiol. **22**, 593–612 (1939).

experiment does not provide an adequate basis for specifying the precise retinal regions in the two eyes on which the stimulus targets were imaged at any given moment. Neither does it indicate which portions of these extended retinal images in the two eyes are utilized to signal the positions of the stimulus targets in space. A population study, performed under a wide variety of specifiable stimulus conditions, could be helpful in identifying some of the major influences on the angular magnitude and sign of the constant errors. The study would also help to specify for each condition of stimulation how much inequality of binocular retinal illuminance can be tolerated without producing double vision.