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THE MAGNITUDE OF THE PULFRICH STEREOPHENOMENON AS A FUNCTION OF BINOCULAR DIFFERENCES OF INTENSITY AT VARIOUS LEVELS OF ILLUMINATION

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The present experiment is concerned with a phenomenon associated with an hypothesized visual latent period. The effect was first described and analyzed by Pulfrich in 1922 and now bears his name.[1] The phenomenon had been observed frequently, but as merely a peculiar disturbance, by those working with the stereocomparator and stereoautograph. When the stereoscopic plates of a star, for example, were adjusted in a stereocomparator to produce an image which appeared to coincide in space with the stereoscopic image of the "distance indicators" (*Messmarke*), it was frequently noted that if the plates were quickly moved laterally, the image of the star seemed to move either in front of or behind its original position. It was first believed that the disturbance resulted from a loose connection in the plate-bindings. Subsequent investigation showed, however, that it was not a change in separation between the stereoscopic plates which produced the stereo-effect, but that the spatial displacement was caused by a difference in brightness between the two plates.

The stereophenomenon can be more readily demonstrated by means of a pendulum-bob made to oscillate on a level with the eyes in a frontal plane. With fixation main-

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[1] Carl Pulfrich, Die Stereoskopie im Dienste der isochromen und heterochromen Photometrie, *Naturwissenschaften,* 10, 1922, 553-564, 569-574, 596-601, 714-722, 735-743, 751-761.

tained at a point directly below the moving bob, midway between the amplitude of its swing, the bob will appear, correctly, to follow a rectilinear path in a vertical plane of oscillation. If a smoked glass, or any other device which will cut down the illumination, is placed before one of the eyes, the path will no longer seem rectilinear. The pendulum will then appear to be a conical instead of a plane pendulum, the apparent direction of rotation reversing itself as the smoked glass is transferred from one eye to the other. As viewed from above, the apparent rotation will be clockwise when the filter is placed before the left eye, and counterclockwise when it is placed before the right eye. The effect becomes noticeable at some threshold value and increases as the intensive difference between the two eyes is increased. A limiting difference in intensity will be finally reached beyond which the image formed in the eye receiving the feebler impression is suppressed, binocular vision is destroyed, and the path of the pendulum-bob again appears rectilinear.

Theoretical. The explanation of this stereophenomenon was first suggested to Pulfrich by his associate Fertsch. As analyzed by Pulfrich the phenomenon can be readily shown to be consistent with the law of corresponding retinal points[2] and the general principles of space perception.[3] The explanation is based on an hypothesized visual latent period whose magnitude is presumed to be inversely related to the intensity of the illumination.[4] Simultaneous stimulation of corresponding retinal points will

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[2] A. Ames Jr., K. N. Ogle and G. H. Gliddon, Corresponding retinal points, the horopter and size and shape of ocular images, *J. Opt. Soc. Amer.*, 22, 1932, 538-632.

[3] J. von Kries, Appendix to Helmholtz, *Handbuch der physiologischen Optik*, (3d Ed., 1910), J. P. C. Southall, tr., Optical Society of America, 2, 1925, 422-425.

[4] Other visual phenomena in which the inferred magnitude of an hypothesized latent period was found inversely related to the intensity of illumination were reported by S. Exner, Ueber die zur Gesichtswahrnehmung nötige Zeit, *Sitzungsber. Wien. Akad. Wissensch.*, 58, abt. 2, 1868, 601-631; C. Hess, Untersuchungen über den Erregungsvorgang im Sehorgan bei kurz und bei längerdauernder Reizung, *Arch. f. d. ges. Physiol.*, 107, 1904, 226-262; F. W. Fröhlich, Ueber die Messung der Empfindungszeit, *Zsch. f. Sinnesphysiol.*, 54, 1922, 58-78; and F. F. Hazelhoff and H. Wiersma, Die Wahrnehmungszeit, *Zsch. f. Psychol.*, 96, 1924, 171-188; 97, 1925, 174-190; 98, 1926, 366-377. Exner made a systematic series of observations which involved the discrimination of the comparative brightness of the retinal after-images produced by simultaneously extinguishing a pair of equally intense stationary lights presented to neighboring parts of the retina at a small time-interval apart. Hess reported that when two vertical light-slits placed one above the other pass across the fixated eye, the brighter of the two slits seems to move ahead of the other. Fröhlich had observed that when a moving vertical slit of light passes behind a horizontal opening in a screen, it does not seem to come into view at the entrance edge, at which place the eye remains fixated, but is first perceived a small distance within the border of the screen aperture. Fröhlich attributed this displacement to the visual talent period (*die Empfindungszeit*). The magnitude of the 'sensation-time' was calculated as the time-difference between the actual and the seen appearance of the light-slit. The phenomenon reported by Hazelhoff and Wiersma occurs when the eye continuously follows a regularly moving shadow, during the course of which a light of short duration is exposed in its path. The light is not seen at the spot at which it was exposed, but at a displaced distance in the direction of the moving shadow. The

result in simultaneous 'excitations,' but only after a short delay which varies inversely with the intensity of the stimulus. Consequently, except when at its momentarily stationary terminal positions, the oscillating bob is never seen where it actually is, but appears at a place in its path a little farther behind its true position. The more feeble the stimulation, or the greater the velocity of the moving bob, the farther behind in its path will it appear to be.

By placing the smoked glass before one eye, the moving bob is made to stimulate that eye less strongly than the other. As a result, the time course of 'excitations' from corresponding retinal points will no longer be simultaneous. In this situation, synchronous 'excitations,' at any given moment, will have arrived from slightly disparate retinal points, the amount of disparity increasing with the difference in brightness between the two retinal images. Accordingly, the general condition necessary for the binocular perception of depth is obtained, and the resulting stereoscopic illusion produced is that the oscillating bob appears alternately nearer and farther away than it really is, as its direction of motion is alternately reversed.[5]

The stereophenomenon is also elicited when a colored instead of a smoked glass is placed before one of the eyes. By matching the colored illumination with illumination obtained through a graded series of neutral or tinted filters placed before the other eye, the bob can again be made to appear to move in a frontal plane. Pulfrich used this procedure as a new method of heterochromatic photometry.

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magnitude of the displacement was presumed to reflect the visual latent period (*die Wahrnehmungszeit*), and the 'perception-time' was directly calculated from a knowledge of the extent of the localization-error and the velocity of the moving shadow. The results obtained by Exner, and those of subsequent investigators who used somewhat similar techniques, are summarized by M. A. Bills, The lag of visual sensation in its relation to wavelengths and intensity of light, *Psychol. Monog.*, 28, 1920, (no. 127), 1-101. Results obtained from the experiments involving the localization-errors are reported in full by F. W. Fröhlich, *Die Empfindungszeit, Ein Beitrag zur Lehre von der Zeit-Raum und Bewegungsempfindung*, 1929, 1-366, and summarized by his student K. Vogelsang, Die Empfindungszeit und der zeitliche Verlauf der Empfindungen, *Erg. der Physiol.*, 26, 1928, 122-184. Also see E. Rubin, Kritisches und Experimentelles zur "Empfindungszeit" Fröhlichs, *Psychol. Forsch.*, 13, 1930, 101-112, for a criticism of the interpretation that Fröhlich and his students had given to their measurements. The experimental data obtained by electrophysiological methods on the latent period of the retinal or nerve-response which follows stimulation by light have been summarized by R. Granit, *Sensory Mechanisms of the Retina*, 1947, 1-412.

[5] A related stereoeffect was observed in the Mach-Dvořak Phenomenon (V. Dvořak, Ueber Analoga der persönlichen Differenz zwischen beiden Augen und den Netzhautstellen desselben Auges, *Sitzber. d. k. böhm. Gesellsch. d. Wiss, in Prag*, 1872, 65-74). A bob, swinging to and fro in a plane, is made to appear to swing in an ellipse by means of an episcotister which presents alternating views to the two eyes. Here the stereoeffect results from a retinal disparity produced directly by a time-delay in stimulus-presentation to each eye.

Two colors are said to have the same luminosity when the time between stimulation and sensation is the same for both of them, and we can tell when their luminosities are equal by the fact that at the instant the difference vanishes between the times of the two sensations, as shown by the revolving mark, the circular motion becomes rectilinear.[6]

Pulfrich continued his investigation of the stereophenomenon in the attempt to find direct application in the fields of heterochromatic photometry and pyrometry.

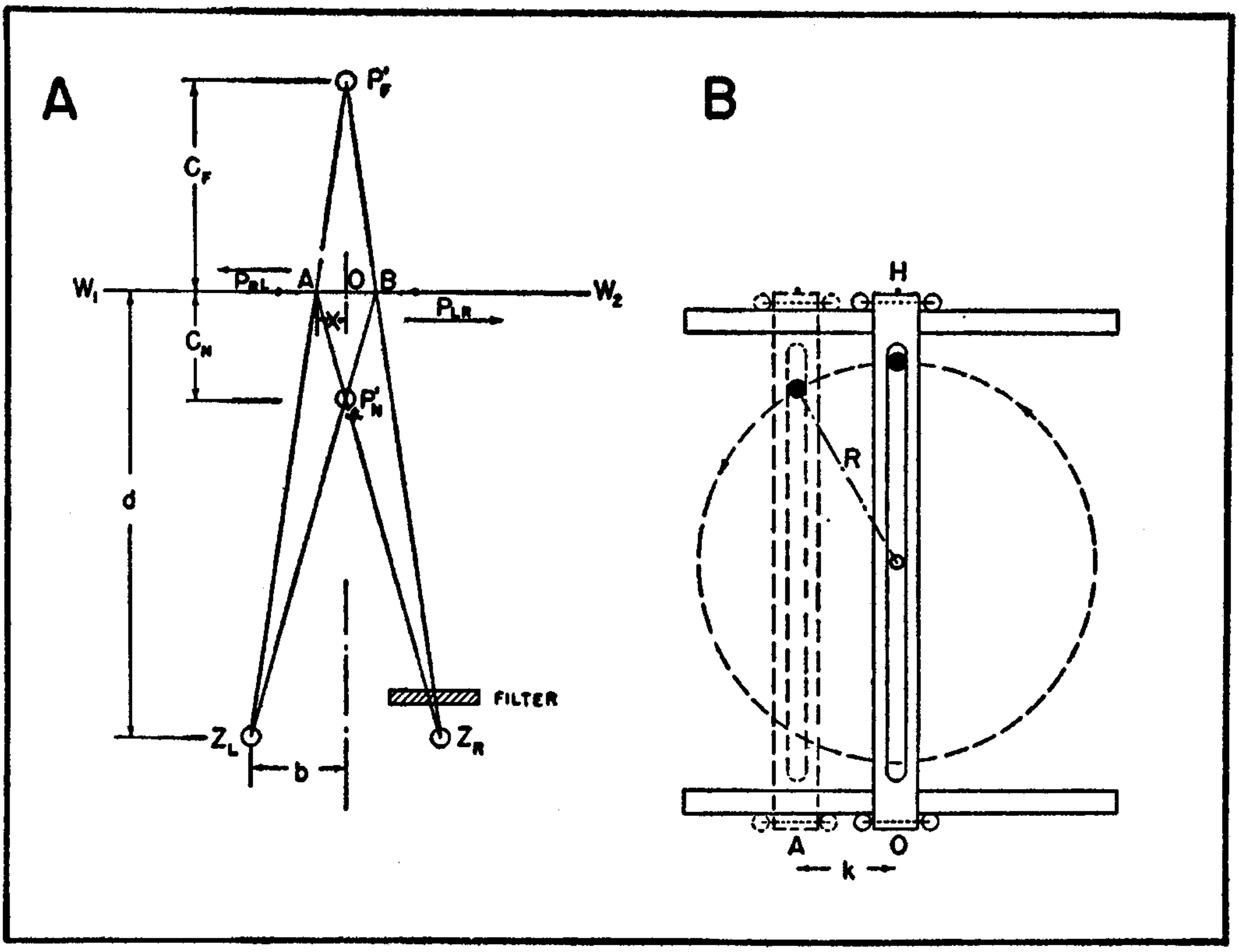

FIG. 1A. SCHEMATIC REPRESENTATION OF THE PULFRICH PHENOMENON INDICATING THE STEREOSCOPIC SPACE-IMAGE IN THE HORIZONTAL PLANE OF FIXATION

FIG. 1B. SCHEMATIC REPRESENTATION OF A SCOTCH-YOKE ARRANGEMENT BY MEANS OF WHICH *H* MAY BE MADE TO OSCILLATE IN A HORIZONTAL PLANE WITH SIMPLE HARMONIC MOTION

Geometric analysis. An understanding of the Pulfrich phenomenon may be obtained by an analysis of the geometrical situation of Fig. 1A, which is drawn to represent the horizontal plane of fixation of the two eyes and contains the centers of rotation of the eyes designated by Z_R and Z_L.

The smoked glass, as indicated, is situated before the right eye. The figure is meant to represent the streoscopic space-image at the exact moment that the bob,

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[6] Von Kries, *op. cit.*, 423.

P_{LR}, moving from left to right in its rectilinear path, W_1W_2, seems to be passing *in front of* its plane of oscillation directly over the point P'_N located in the vertical median plane towards which the eyes are converged. Also represented is the situation when the bob (now designated by P_{RL}) is moving from right to left and seems to be passing *behind* its plane of oscillation, directly above the point P'_F located in the vertical median plane towards which the eyes are now supposed to be converged.

When the bob is moving from left to right and appears to be passing directly above the fixation-point P'_N, at the near position, then in accordance with the laws of space-projection, the excitation of the left eye was initiated when the bob (now at P_{LR}) was at the point B. Synchronous excitation for the right eye was initiated when the bob was at the point A, a bit farther behind in its path. The time taken for the bob to move from B to P_{LR} represents a theoretical absolute latency for the left eye, and the time taken for the bob to move from A to P_{LR} represents the slightly longer absolute latency for the right eye possessing the filter. The latency difference (Δt_N) between the two eyes for the near position can then be expressed as the time taken for the bob to move from A to B.

By the same process of reasoning, when the bob is moving from right to left and appears to be passing directly above the fixation point P'_F, at the far position, the time taken for the bob to move from B to A represents the latency difference (Δt_F) between the two eyes. Since the velocity of the moving bob is symmetrical on both sides of the vertical median plane, then $\Delta t_N = \Delta t_F$.

If the velocity of the moving bob is known, it is possible to calculate the latency difference which results from any intensive difference between the two eyes by experimentally determining the distances OP'_N (C_N) or OP'_F (C_F). From Fig. 1A it is evident that for the apparent positions of the bob at P'_N and P'_F respectively,

$$X = bC_N/(d - C_N), \text{ and } X = bC_F/(d + C_F) \quad \ldots\ldots\ldots\ldots\ldots\ldots [1]$$

where $X = \frac{1}{2}$ the distance from A to B; $b = \frac{1}{2}$ the interpupillary distance; and d = observation distance.

Given the amplitude and period of the pendulum, the time taken for the bob to move from A to O (X) can be readily calculated. The latency difference (Δt_N or Δt_F) is obviously double this value.[7]

Consider the case in which a vertical rod is made to oscillate in a frontal plane by means of the Scotch-yoke[8] arrangement shown in Fig. 1B. A drive shaft (R) has its driving-pin sliding in a central slot of a yoke. The rod is vertically suspended at H, a point at the center of the far edge of the yoke. The movement of the yoke is restricted to a horizontal linear direction by a pair of fixed tracks. When the drive-shaft rotates with constant angular velocity, the rod oscillates with simple harmonic motion through an amplitude 2R. Let the rod lie in the vertical median plane of fixation when the drive-shaft is in its mid-position. The displacement (k) of the rod from its mid-position after any time, t, is given by the formula:

$$k = R \sin 2\pi t/T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots [2]$$

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[7] For details of the calculation, see H. Banister, Retinal action time, in *Report of a Joint Discussion on Vision,* 1932, 227-234.

[8] A. Sloane, *Engineering Kinematics,* 1941, 253.

where R is the radius of the drive-shaft, and T is the time for one complete revolution of the drive shaft.

In the case where this displacement represents the distance AO (Fig. 1A), then $k = X$, and the time taken for the rod to move from A to O is given by the relationship

$$t = (T/2\pi) \sin^{-1} (X/R) \quad [3]$$

The time taken for the rod to move from A to B (or B to A), which represents the latency difference between the two eyes, can then be calculated from the formula

$$\Delta t = (T/\pi) \sin^{-1} (X/R) \quad [4]$$

Substituting for X the relations obtained in Equation [1], we obtain:

$$\Delta t_N = (T/\pi) \sin^{-1} (b\,C_N)/(d - C_N)\ (R), \text{ and}$$
$$\Delta t_F = (T/\pi) \sin^{-1} (b\,C_F)/(d + C_F)\ (R) \quad [5]$$

When the magnitude of the angles is so small that the sine of the angles equals the value of the angles in radians, we obtain, finally,

$$\Delta t_N = (Tb/\pi R)\ [C_N/\ (d - C_N)], \text{ and } \Delta t_F = (Tb/\pi R)\ [C_F/(d + C_F)] \quad [6]$$

In Fig. 1A, the apparent rotation of the moving bob is counterclockwise. If the smoked glass is placed before the left eye, the same general relationship holds true, except that the apparent direction of rotation is clockwise. The distances OP'_N or (C_N) and OP'_F or (C_F) are hereafter referred to, respectively, as the near and far displacement of the oscillating target. The greater the displacement, the greater is the stereoeffect.

It is to be noted from purely geometric considerations that, for any constant intensity difference between the two eyes, an increase in either the observation-distance or the velocity of the oscillating target results in an increased stereoeffect for a constant calculated latency difference. It is to be further noted that under any given set of conditions, the displacement is theoretically greater when the rod appears to move behind the plane of oscillation than when it appears to move in front of its plane of oscillation ($C_F > C_N$). The difference between the two displacements becomes theoretically more marked as the observation distance is increased and also as X is made larger through an increased intensive difference between the two eyes or by increasing the velocity of the oscillating rod.

Experiments. The Pulfrich phenomenon has been investigated from many aspects. Its limitations as a method of heterochromatic photometry were first established by Von Kries[9] and Engelking and Poos.[10] They reported peculiar effects when observations were made with one eye dark-

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[9] Von Kries, Ueber das Stereophotometrische Verfahren zur Helligkeitsvergleichung ungleichfarbiger Lichter, *Naturwissenschaften,* 11, 1923, 461-470.

[10] E. Engelking and F. Poos, Ueber die Bedeutung des Stereophänomens für die isochrome und heterochrome Helligkeitsvergleichung, *Arch. f. Ophth.,* 114, 1924, 340-379.

adapted and the other eye light-adapted.[11] These effects they attributed to a greater latency of the rod mechanism. Heterochromatic matches were consistent with those obtained by other photometric methods only when the observations were made with the photopic eye under strong illumination. Kronenberger,[12] who also investigated these effects, attempted to explain them without invoking the duplicity theory.

The stereophenomenon has also been used to test individuals possessing defective color vision. The responses obtained during the course of dark-adaptation to different colors were correlated with retinal physiology.[13] Its use in clinical practice for the early detection of ocular pathology was suggested by Grimdale[14] and used by Sachs,[15] who found it an extremely sensitive method. Experiments were also performed to investigate the relationship between the stereophenomenon and stereoscopic vision.[16]

Despite the considerable work done, a systematic investigation of the variables necessary for complete stimulus-specification has not been undertaken. The velocity of the moving target has been the only stimulus-variable to receive special study.[17] The magnitude of the absolute values reported

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[11] Despite the fact that the image seen by the dark-adapted eye looked brighter, the direction of rotation of the pendulum indicated a greater latency for that eye. Again, despite the shift in maximal sensitivity towards the blue end of the spectrum (Purkinje phenomenon) when colored filters were used, the magnitude of the stereoeffect indicated a smaller latency when a red instead of a blue filter was placed before the dark-adapted eye.

[12] Paul Kronenberger, Die Empfindungszeit des hell- und dunkeladaptierten Auges, *Arch. f. d. ges. Physiol.*, 211, 1926, 454-484; Ein Beitrag zur Raum-physiologie: Ueber die Umkehr des Pulfrich-Effektes und einige verwandte Erscheinungen, *Zsch. f. Sinnesphysiol.*, 57, 1926, 255-261.

[13] E. Engelking, Ueber den Stereowert und Zeitdifferenzwert verschiedenfarbiger Lichter und die relative Empfindungszeit der Stäbschen und Zapfen bei den angeborenen Störungen des Farbensinnes, *Klin. Monatsbl. f. Augenheilk.*, 73, 1924, 1-28; E. Wölfflin, Ueber das Verhalten des Totalfarbenblinden am Pulfrichschen Stereoeffekt, *ibid.*, 74, 1925, 581-586; Ueber physiologische Beobachtungen an Totalfarbenblinden, *ibid.*, 78, 1927, 596-601.

[14] H. Grimdale, A note on Pulfrich's phenomenon with a suggestion on its possible clinical importance, *Brit. J. Ophth.*, 9, 1925, 63-65.

[15] E. Sachs, Abnormal delay of visual perception, *Arch. Neurol. & Psychiat.*, 56, 1946, 198-206.

[16] F. Saeger, Ueber die Bedeutung des Stereophänomens für die Beurteilung des stereoskopischen Sehens, *Klin. Monatsbl. f. Augenheilk.*, 78, Beilageheft, 1927, 204-208; E. Wölfflin, Untersuchungen über den Pulfrichschen Stereoeffekt, *Arch. f. Augenheilk.*, 95, 1925, 167-179; R. H. Kahn, Ueber den Stereoeffekt von Pulfrich, *Arch. f. d. ges. Physiol.*, 228, 1931, 213-224; Wilhelm Neuhaus, Das Pulfrichsche Stereophänomen und die räumliche Wahrnehmung, *Zsch. f. Psychol.*, 135, 1935, 192-201.

[17] Pulfrich, *op. cit.;* Engelking and Poos, *op. cit.;* Banister, *op. cit.;* G. Arndt, Ueber die Abhängigkeit des Stereoeffektes von der Geschwindigkeit der bewegten Marke, *Zsch. f. Biol.*, 90, 1930, 574-588; J. Holz, Der Stereoeffekt Pulfrich's und die Empfindungszeit, *ibid.;* 95, 1934, 502-516; T. Liang and H. Piéron, Recherches sur la latence de la sensation lumineuse par la méthode de l'effect chronostéréoscopique, *Année Psychol.*, 43-44, 1947, 1-53.

by these investigators showed considerable variability, but these results, obtained under different stimulus-conditions, cannot be directly compared because the requisite inter-relationships among stimulus-variables have not been established.

The present problem. The present investigation is concerned with an analysis of the basic stimulus-variable responsible for eliciting the phenomenon; namely, difference in retinal brightness between the two eyes. An exploratory study is made to determine the manner in which the stereoeffect produced by any given retinal brightness-difference is altered when the basic level of illumination is systematically changed.

Engelking and Poos[18] (1924) presented data on the relationship between retinal brightness-difference and the magnitude of the stereoeffect. In their experiments the moving target was a pendulum-rod made to swing in a frontal plane by a motor-driven connecting rod. Either a black or a white target could be attached to the bottom of the rod. An adjustable fixation-mark of the same size and color (7 cm. long and 10 mm. wide), set directly below the target, was used by the *S* to locate the apparent positions of the moving target in the median plane when various retinal brightness-differences were created by a calibrated filter-wedge placed before one eye. The observation distance was 50 cm.

A change in any stimulus-variable which produced an increased stereoeffect was reflected in an increased displacement of the moving target when the position of the filter-wedge was held constant; when the displacement was held constant, the position of the filter-wedge was altered in the direction to produce a decrease in the retinal brightness-difference.

The results of Engelking and Poos showed that, for both neutral and colored filters, increases in displacement were linearly related to the corresponding changes in filter-position. Unfortunately, the general level of illumination was not specified and could not be rigorously maintained or controlled under the testing conditions reported.

Engelking and Poos also made measurements to determine the influence of dark-adaptation on the magnitude of the stereoeffect. They found that a given displacement produced under conditions of light-adaptation increased when the same observations were made following a period of dark-adaptation. It was also noted that the magnitude of the displacement produced by a given retinal brightness-difference under light-adaptation could be maintained at the same value by a decreased retinal brightness-difference when the observations were made during dark-adaptation. No complete functional analysis was attempted.

Banister[19] (1932), using essentially the same experimental devices as Engelking and Poos, found a non-linear relationship between the ratio of retinal illumination between the two eyes and the calculated latency difference ("difference in

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[18] Engelking and Poos, *op cit.*

[19] Banister, *op. cit.*

retinal action-times"). Furthermore, he found that the general level of illumination (bright daylight, dull twilight and artificial light) showed no significant differences, so that this factor was not controlled in the experiment. A measure of the general level of illumination was not reported.

Holz[20] (1934) found that, for a given ratio of retinal brightness between the two eyes, the resultant stereoeffect could be made to disappear when the observations were made under very high levels of illumination.

Lythgoe[21] (1938), using a pendular arrangement, reported a linear relation between the logarithm of the ratio of the two retinal illuminations and the calculated latency difference. Unlike Banister, and more in accordance with the results obtained by Engelking and Poos and by Holz, Lythgoe found that for any given retinal brightness-difference (produced by placing a filter before one eye), the calculated latency difference decreased when the general illumination was 'considerably' increased. No experimental details were supplied regarding the range in general levels of illumination used, or the range of the retinal brightness-differences produced between the two eyes. No experimental data were given. Crawford considered the results obtained by Lythgoe to be "almost entirely in accord with the hypothesis that the 'latent period' of vision varies in the same sense as the concentration of photochemical substance in the retina of the eye, and is controlled mainly, if not entirely, by this concentration."[22]

Liang and Piéron[23] have recently published data on the relation between the calculated latency difference and the retinal brightness-difference between the two eyes. They report that the calculated latency-difference increases when the general level of illumination decreases, but they made no systematic study of the effect.

The present experiment was designed to answer the following questions. (1) What is the functional relation between the apparent displacement of the oscillating target (or the corresponding calculated latency difference between the two eyes) and the difference in retinal brightness? (2) How are these relations altered when the general level of illumination is systematically changed? (3) How are these results related to (a) the relationship between the absolute visual latent period and the intensity of illumination, to (b) the principles of visual space perception, and to (c) the theory of visual intensity-discrimination?

APPARATUS AND PROCEDURE

The apparatus used is presented schematically in Fig. 2A. The subject (*S*) is seated in a dark room (D) and makes observations through a pair of artificial pupils (E) attached to the inner wall surface. The artificial pupils are 2.5 mm. in diameter and adjustable for any interpupillary sepa-

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[20] Holz, *op. cit.*

[21] R. J. Lythgoe, Some observations on the rotating pendulum, *Nature*, 141, 1938, 474.

[22] B. H. Crawford, Some observations on the rotating pendulum, *ibid.*, 792-793.

[23] Liang and Piéron, *op. cit.*

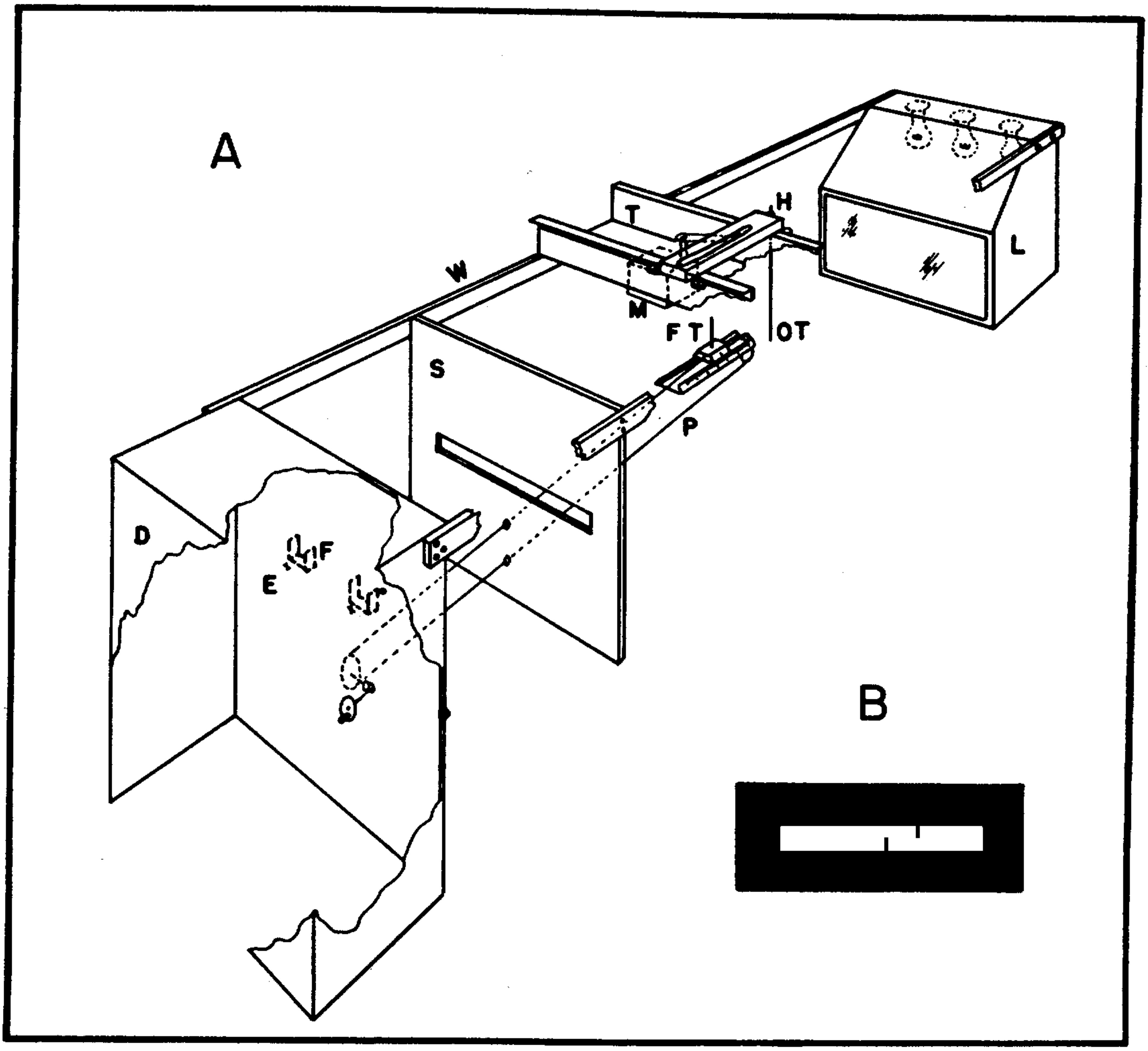

FIG. 2A. SCHEMATIC REPRESENTATION OF THE APPARATUS

The subject is seated in a dark room (D) and binocularly observes the oscillating target (OT) and fixation-target (FT) through a horizontal aperture in a large black screen (S). Background illumination is provided by a light box (L). The observations are made through a pair of artificial pupils (E). The conditions of retinal illumination may be varied by the use of filters placed in a filter-box (F) set before each eye. The fixation-target is made part of a pulley-system (P), and may be moved in the vertical median plane either towards or away from the subject by means of a pulley-wheel placed in the dark-room. The position of the fixation-target is read directly from a millimeter-scale.

FIG. 2B. THE RELATIONSHIP BETWEEN THE UPPER END OF THE FIXATION-TARGET AND THE LOWER END OF THE OSCILLATING TARGET AS SEEN BY THE SUBJECT

Both targets are seen beyond the horizontal aperture of the large black screen against a uniform white background produced by the light-box.

ration. In front of each artificial pupil a filter box (F) is attached to the outer-wall surface so that the experimenter may control the illumination presented to each eye. The head is kept immobilized by means of a headrest.

The apparatus consists of three component parts: (a) the oscillating target, (b) the fixation target, and (c) the lighting unit.

(a) Oscillating target. The oscillating target (OT) is a long metal rod 2 mm. in diameter and painted black. It is made to oscillate in a frontal plane with simple harmonic motion by means of a motor-driven Scotch-yoke arrangement (See Fig. 1B). The rod is rigidly suspended, vertically downward, from (H) a point at the center of the far edge of the yoke. The yoke consists of a strip of laminated plastic 13 in. long and 3 in. wide. Near each edge of its length a pair of horizontally placed metal wheels are attached. The yoke is restricted to a horizontal plane of movement by a pair of horizontal metal tracks 24 in. long and 12 in. apart on which it rides. The tracks are attached perpendicularly to the sides of a wooden trough (T) whose dimensions are 24 in. x 12 in. x 3 in. A governor-controlled constant-speed motor (M) is mounted to the under-surface of the bottom of the trough through which a hole has been drilled. This arrangement brings the free end of the motor-shaft almost to the level of the tracks. By means of a gear-system the shaft of the motor is connected to a drive shaft of 15.50 cm. length; the drive-shaft has its driving pin sliding in a central slot of the yoke. The entire compact unit is rigidly mounted on a pair of wooden supports (W) slightly above the level of *S*'s head in order to position the lower end of the oscillating rod on a level with his eyes. When the drive-shaft is in its mid-position, the oscillating rod is located exactly in the vertical median plane of fixation. At the observation-distance used in this experiment ($d = 83.00$ cm.) the angular size of the rod is about 10 min. When in operation, the period (T) of the oscillating rod is 3.36 sec.; its amplitude (2R) is 31.00 cm. (21° of visual angle). The velocity of the rod at the mid-position is 28.97 cm. per sec. (19° per sec.).

(b) Fixation-target. The fixation-target (FT) is an upright metal rod of the same form, color and size as the oscillating rod. It is held upright by a pin-vise which is fixed in a metal block by a set-screw. The metal block is made part of a pulley-system (P) and may be moved along tracks in either direction for a total distance of 30 cm. The pulley-system is mounted on a board and set slightly below the level of *S*'s head to bring the upper end of the fixation-target on a level with his eyes. By means of a pulley-wheel located in the dark room, *S* is able to adjust the position of the fixation-target in the vertical median plane in a direction either towards his eye or away from it. A centimeter scale, calibrated in ½-mm. units, permits the position of the fixation-rod to be estimated within 0.1 mm. When the fixation-rod is directly below the oscillating rod, the rods appear contiguous, and the scale position of the fixation-rod reads 15.05 cm. Both displacements (C_N and C_F) were measured from this scale position.

(c) Lighting unit. The lighting unit provides illumination from three 100-w. frosted bulbs mounted in a light-box (L) set behind the oscillating rod at a distance of 100 cm. from the eye. The lamps are operated at 110 v. DC by a rheostatic control. A frosted plate-glass 18 in. x 8 in. on the face of the light-box produces a uniformly illuminated field over the whole excursion of the oscillating rod. The brightness of the frosted plate-glass was calculated from measurements with a Macbeth illuminometer to be 610 millilamberts. For a 2.5 mm. pupil the corresponding retinal brightness is 9510 photons. Differences in retinal brightness between the two eyes at various levels of illumination are obtained by systematically placing neutral Wratten filters in the filter-boxes provided.

A fixed black screen (S), 50 cm. before *S*, has its aperture adjusted in height to permit only the upper 1½ in. of the fixation-rod and the lower 1½ in. of the oscillating rod to be seen. The horizontal extent of the aperture and the extent of the oscillating rod when in its extreme positions are of the same angular size. When *S* looks through the artificial pupils he sees only a large black screen with its horizontal aperture. The two black vertical rods are seen beyond the aperture against a uniform white background of the illuminated frosted plate-glass, as shown in Fig. 2B.

Two well trained *S*s (*C.G.M.* and *A.H.*) were used in the experiment. Both were emmetropic and possessed normal visual acuity with good stereopsis. Their interpupillary separations for the observation-distance of 83.00 cm. were 6.30 cm. and 6.50 cm. respectively ($b = 3.15$ cm. and $b = 3.25$ cm.). A preliminary practice-series in observing the visual objects was given each *S* and the lowest level of illumination under which the test could be made was determined for each. A 30-min. period of dark-adaptation preceded the measurements taken at each of the levels of illumination. Any given level was obtained by placing filters of equal density in front of each eye. The greater the filter value (density) of each pair, the lower was the corresponding level of illumination produced. For *C.G.M.*, the test was made at 7 different levels of illumination, ranging from 951 to 2 photons. The density of the filters used at each of the levels was 1.00, 1.60, 2.00, 2.60, 3.00, 3.30, and 3.60. Data for *A.H.* could not be obtained at the two lowest levels. The order of testing at the various levels of illumination was randomized. Testing at any one of the levels constituted a session. Only one session was held on a day for a given *S*.

In any single session, differences in retinal brightness between the two eyes were obtained by keeping the illumination of the right eye constant and increasing the retinal brightness of the left. The density of the filters before the left eye was reduced in steps of about 0.3 log units. The retinal brightness-difference was increased until either no filter remained before the left eye, or the object under observation was abolished by suppression, whichever occurred first. A 2-min. period of light-adaptation followed each increase. In making the measurements, *S* was required to locate the oscillating rod in both its near and its far apparent positions, first when the fixation-rod was moved away, and again when it was moved towards him. A total of six readings was made at each of the two positions.

RESULTS

The data obtained for each *S* are presented in Table I. The log of the retinal illumination for each eye (log I_R for the right eye and log I_L for the left eye) is given in log photons. The apparent displacements of the oscillating rod for both the near and far positions (C_N and C_F) are expressed in cm.; each entry is the mean of six readings.

Figs. 3 to 7 give graphic representations of the data. The curves drawn through the points have been fitted by inspection, and the number accompanying each curve represents the value of log I_R holding for that curve.

(1) Displacement. Figs. 3 and 4 show the effects of two conditions of

TABLE I

DISPLACEMENTS PRODUCED BY DIFFERENCES IN RETINAL BRIGHTNESS AT VARIOUS LEVELS OF ILLUMINATION

C_N and C_F refer, respectively, to the near and the far apparent displacements; and each is based on the mean of 6 readings.

log I_R (photons)	log I_L (photons)	C.G.M.		A.H.	
		C_N (cm.)	C_F (cm.)	C_N (cm.)	C_F (cm.)
2.98	3.18	0.98	0.34	0.74	0.55
	3.38	1.53	0.91	1.18	1.12
	3.68	2.02	1.28	2.00	2.03
	3.78	2.18	1.47	1.97	2.06
	3.98	2.33	1.42	2.33	2.51
2.38	2.68	1.50	0.78	1.67	0.97
	2.98	2.63	1.74	3.37	1.93
	3.38	3.72	2.65	4.12	3.18
	3.68	4.42	3.10	4.43	4.72
	3.78	4.52	3.41	4.59	4.24
	3.98	4.74	3.55	4.60	4.31
1.98	2.18	1.25	0.51	0.99	0.88
	2.38	2.14	1.19	1.94	1.85
	2.68	3.12	2.51	3.71	3.01
	2.98	4.29	3.43	4.58	4.91
	3.38	5.45	4.40	5.64	5.79
	3.68	5.90	4.93	5.97	7.01
	3.98	6.18	5.35	6.96	6.79
1.38	1.68	2.06	1.39	0.98	3.70
	1.98	3.78	2.68	2.88	5.11
	2.38	5.75	4.20	4.50	7.43
	2.68	6.80	4.84	5.83	8.78
	2.98	7.37	6.00	6.96	10.46
	3.18	7.69	6.55	7.32	10.73
	3.68	8.73	7.68	8.32	12.83
	3.98	8.94	8.33	8.15	12.63
0.98	1.18	2.62	1.00	2.54	3.09
	1.38	4.18	2.47	3.80	3.28
	1.68	5.17	3.84	5.01	4.28
	1.98	7.13	5.32	6.14	7.51
	2.38	8.30	6.55	8.13	9.25
	2.68	8.44	8.25	8.49	10.28
	2.98	9.81	8.61	9.37	12.07
	3.38	10.31	10.00		
	3.98	10.59	11.24		
0.68	0.98	2.73	1.04		
	1.38	5.32	3.38		
	1.68	7.16	4.19		
	1.98	9.11	6.20		
	2.18	9.76	7.20		
	2.38	10.61	7.89		
0.38	0.48	3.25	2.10		
	0.68	4.52	3.30		
	0.78	5.58	3.39		
	0.98	7.17	5.40		
	1.38	9.98	5.47		
	1.48	10.25	5.17		

retinal illumination upon the magnitude of the near and far displacements, C_N and C_F, for each *S*. In Fig. 3, the retinal condition of illumination existing between the two eyes is expressed on the abscissa as $\log I_L/I_R$. This variable is equivalent to $\log I_L - \log I_R$ $(= \Delta \log I)$. In Fig. 4, the retinal condition is expressed on the abscissa as $\log (I_L - I_R)$, which is equivalent to $\log \Delta I$.

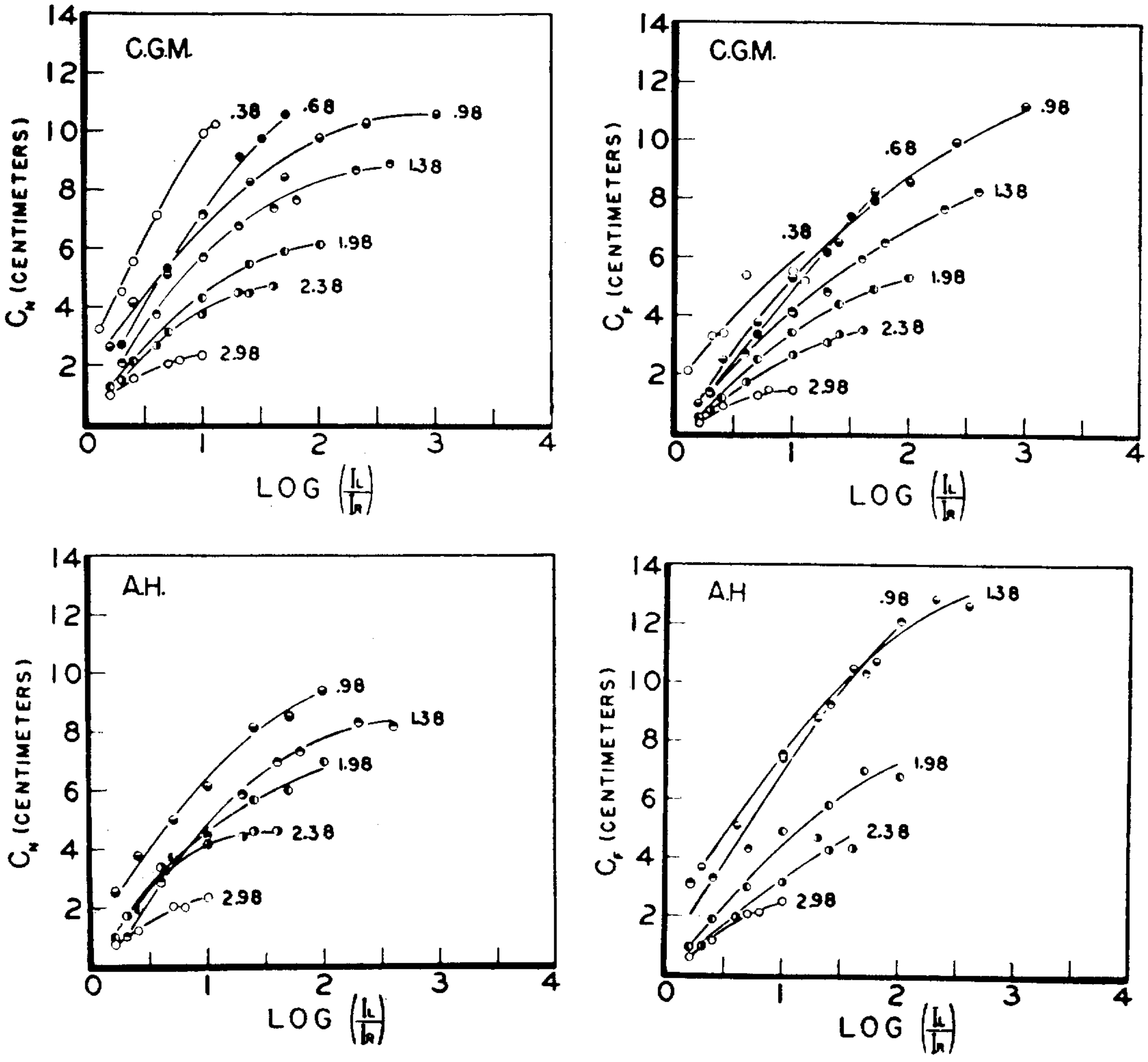

FIG. 3. DISPLACEMENT AS A FUNCTION OF LOG I_L/I_R
The near and the far displacements (C_N and C_F) produced by the respective values of $\log I_L/I_R$ under each of the levels of illumination, $\log I_R$, are shown separately for each *S*. Each point is the mean of six readings, and the curves drawn through the points have been fitted by inspection. The number accompanying each curve represents the value of $\log I_R$ holding for that curve.

(a) Displacement as a function of log I_L/I_R. Fig. 3 shows the relationship obtained between near and far displacements (C_N and C_F) and $\log I_L/I_R$, under each of the levels of illumination, $\log I_R$. The results for the two *S*s are shown separately to demonstrate essential similarities.

The relationship existing between displacement and $\log I_L/I_R$ may be characterized by the following general observations: (a) both C_N and C_F increase as log I_L/I_R increases; (b) the curves show a tendency to level off (C_N and C_F approach a maximal value) as log I_L/I_R increases; (c) the rate of increase is not the same for each of the curves; slope increases as level of illumination decreases; (d) for a given value of log I_L/I_R, both C_N and C_F increase progressively as the level of illumination is progressively decreased; and (e) for any magnitude of C_N or C_F, the value of log I_L/I_R necessary to produce a given displacement becomes progressively smaller as the level of illumination is progressively decreased.

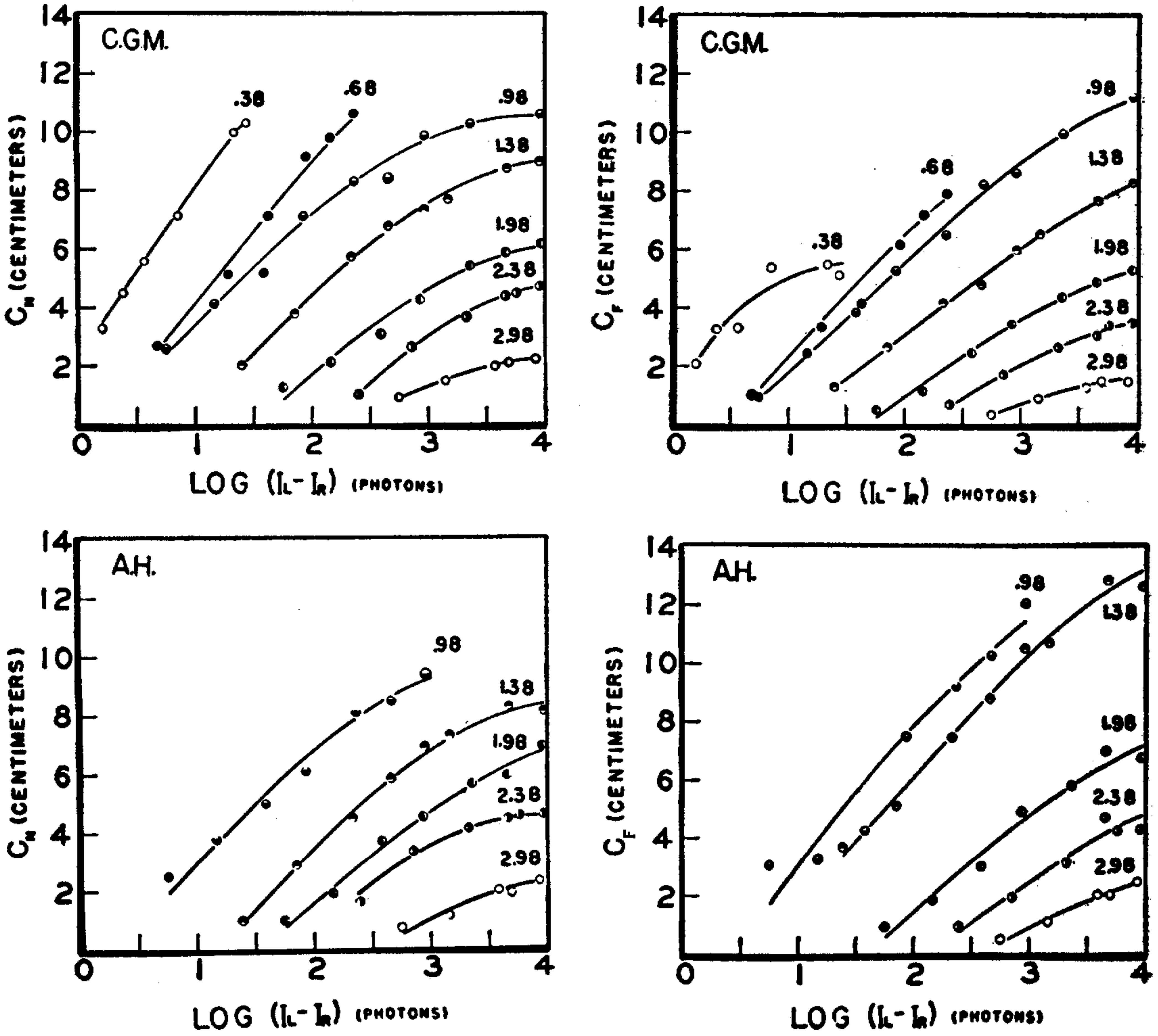

FIG. 4. DISPLACEMENT AS A FUNCTION OF LOG (I_L — I_R)

Individual differences in performance may be noted in the curves. Measurements could not be made by *A.H.* at the two lowest levels of illumination at which *C.G.M.* could give data (log I_R = 0.68 and log I_R = 0.38). In addition, at the lowest level of illumination for which observations were made by both *Ss* (log I_R = 0.98), *A.H.* suspended vision in the right eye when the ratio of illumination between the two eyes exceeded 100:1 (log I_L/I_R = 2.00), whereas *C.G.M.* still obtained the stereo-effect for an illumination ratio of 1000:1 (log I_L/I_R = 3.00).

(b) Displacement as a function of log (I_L — I_R). Fig. 4 shows the results obtained

for each S between the near and far displacements (C_N and C_F) and log ($I_L - I_R$), under each of the levels of illumination, log I_R. The relationship which exists, at any basic level of illumination, log I_R, between displacement and log ($I_L - I_R$) is similar to that obtained in the log I_L/I_R plot. The same general observations which characterized the previously discussed relationship may be applied here by merely replacing the term log I_L/I_R with log ($I_L - I_R$) in all the statements made except for the fact that the curves for successively greater values of log I_R are more clearly differentiated on the abscissa.

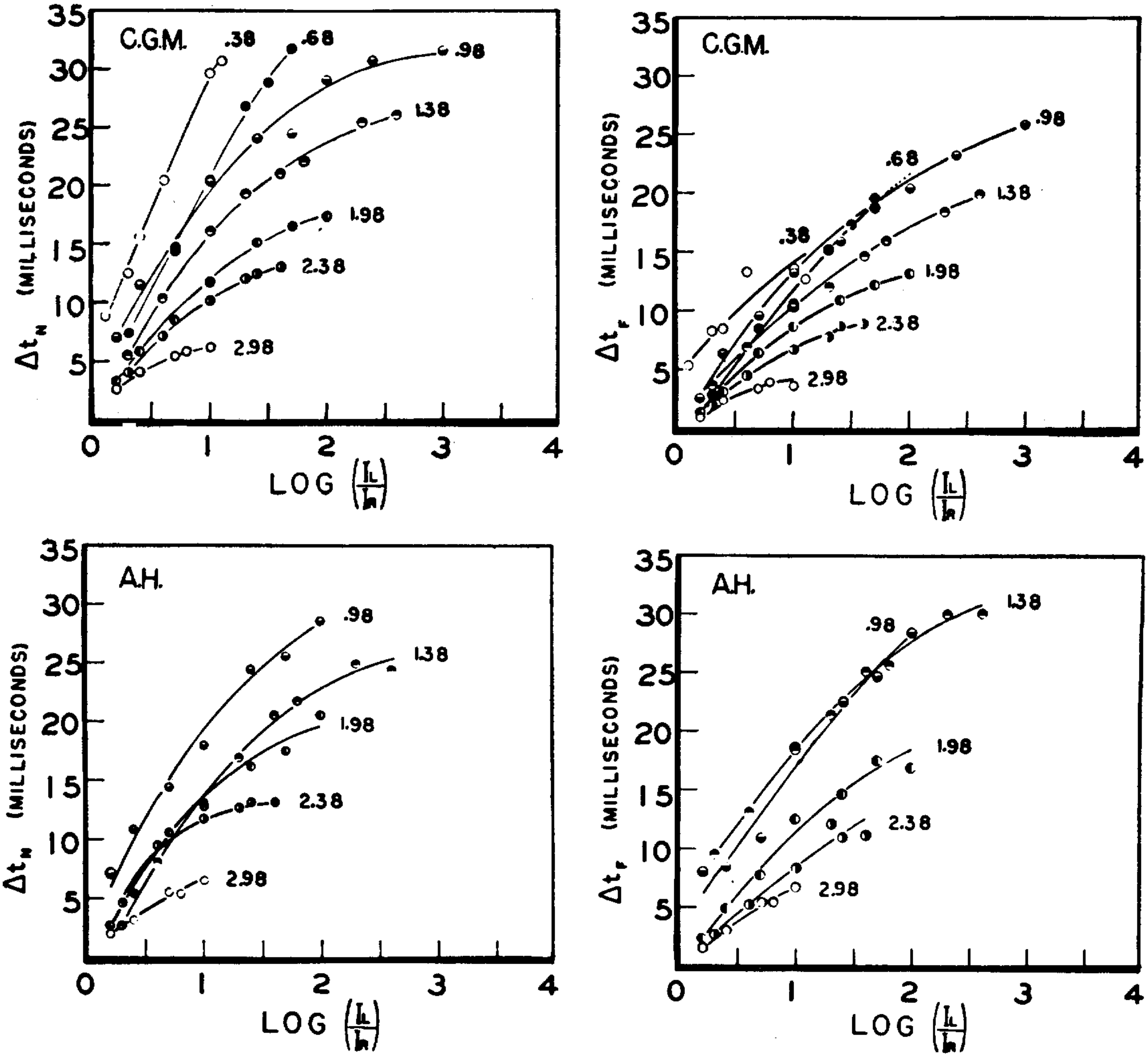

Fig. 5. Latency-Difference as a Function of log I_L/I_R

The latency-differences (Δt_N and Δt_F) were computed from Equation [6] for the corresponding values of C_N and C_F produced by the respective values of log I_L/I_R under each of the levels of illumination, log I_R. The data for each S are shown separately.

(2) *Latency difference.* Figs. 5 and 6 show the effects of the two conditions of retinal illumination upon the magnitude of Δt_N and Δt_F for each S. The latency differences were computed from Equation [6] for each of

the corresponding values of C_N and C_F. In Fig. 5, the condition of retinal illumination is expressed as log I_L/I_R. In Fig. 6, the condition of retinal illumination is expressed as log $(I_L - I_R)$. Fig. 7A shows the averaged data of both *S*s, with Δt_N and Δt_F combined, as obtained from Fig. 5. Fig. 7B shows the averaged data similarly obtained from Fig. 6. Each point

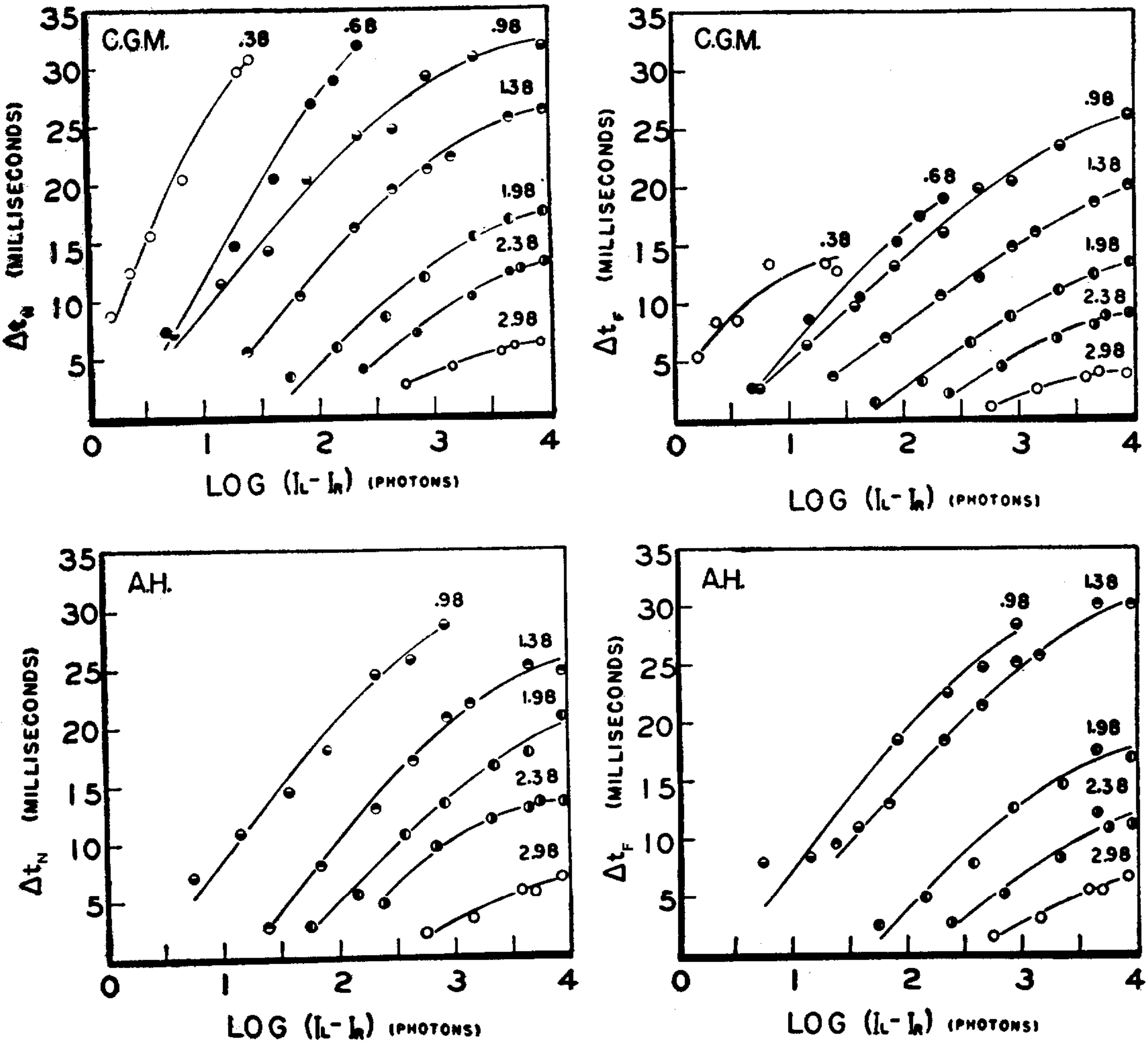

FIG. 6. LATENCY-DIFFERENCE AS A FUNCTION OF LOG (I_L — I_R)

on the curves of Fig. 7A and 7B is based on the mean of 24 readings.

(a) Latency-difference as a function of log I_L/I_R. The relationship obtained between Δt_N and Δt_F and log I_L/I_R, under each of the levels of illumination, log I_R, is shown separately for each *S* in Fig. 5. The combined data for both *S*s are given in Fig. 7A.

The results obtained are all essentially similar in showing that the relationship existing between latency-difference and log I_L/I_R may be characterized in the following terms: (a) latency-difference increases as log I_L/I_R increases, to approach a final limiting value at large values of log I_L/I_R; (b) the curves show a tendency to level off at lower values of Δt as log I_R increases; (c) the rate of increase is not the same for each of the curves; the slope increases as the level of illumination decreases; (d) for a given value of log I_L/I_R, the latency-difference increases progressively as the level of illumination is progressively decreased; and (e) for any specified latency-difference, the value of log I_L/I_R necessary to produce the given latency-difference becomes progressively smaller as the level of illumination is progressively decreased.

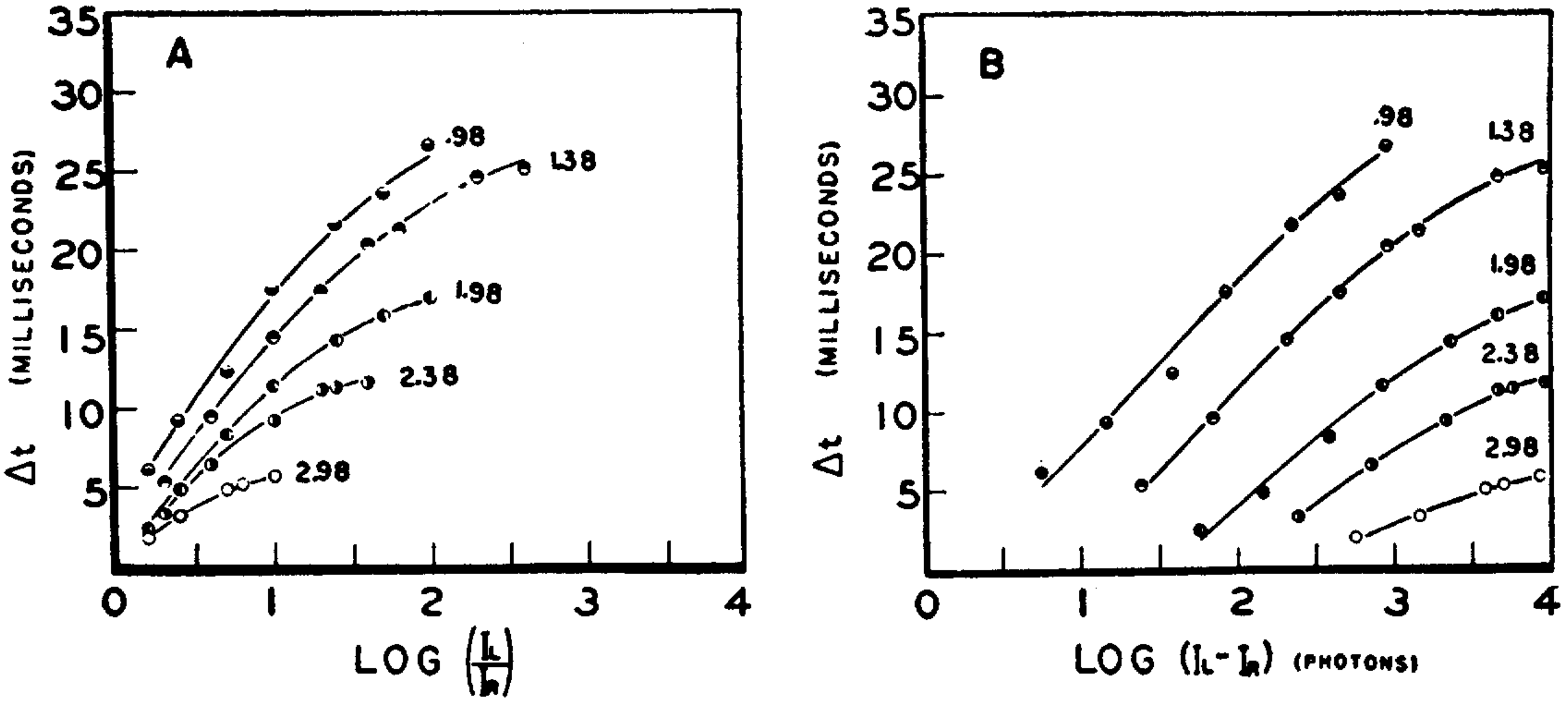

Fig. 7A. Average Latency-Difference for Two Subjects as a Function of log I_L/I_R

Data obtained under the conditions described in Fig. 5.

Fig. 7B. Average Latency-Difference for Two Subjects as a Function of log ($I_L - I_R$)

Data obtained from Fig. 6.

The average latency-difference was obtained by combining Δt_N and Δt_F for both Ss. Each point is the mean of 24 readings.

(b) Latency-difference as a function of log ($I_L - I_R$). Fig. 6 shows the results obtained separately for each *S* between Δt_N and Δt_F and log ($I_L - I_R$) under each of the levels of illumination, log I_R. The combined data for both *S*s are given in Fig. 7B. The results of the separate and combined data are essentially similar, and the relationship existing between latency-difference and log ($I_L - I_R$) may be characterized by the same general observations which were applied to its relationship to log I_L/I_R, except for abscissa displacements.

Discussion

The results of the present investigation may be accounted for on the basis of an hypothesized absolute visual latent-period, whose magnitude is presumed to be inversely related to the stimulus-intensity of illumination. Fig. 8 is a schematic representation of the relationship postulated to exist between the absolute visual latent period and the log of the intensity of illumination. At a low intensity, log I_R, the latent period is long. At a high intensity, log $I_{R'}$ the latent period approaches a final low physiological limit.

Log I_R and log $I_{R'}$ are meant to represent, respectively, the retinal illuminations existing in the right eye at a given low and high level of illumination. Log I_{L1} and log I_{L2} represent the increased retinal illuminations successively produced in the left eye at the given low level of illumination. Log I_{L3} and log I_{L4} similarly represent the increased illuminations produced in the left eye at the given high level of illumination. The difference in retinal illumination between the two eyes is shown to be successively increased by a constant amount, Δ log I, at each of the levels of illumination. The corresponding differences in the absolute latencies produced by the increase in Δ log I at the low and high levels of illumination may be represented by Δt_1, Δt_2 and Δt_3, Δt_4 respectively.

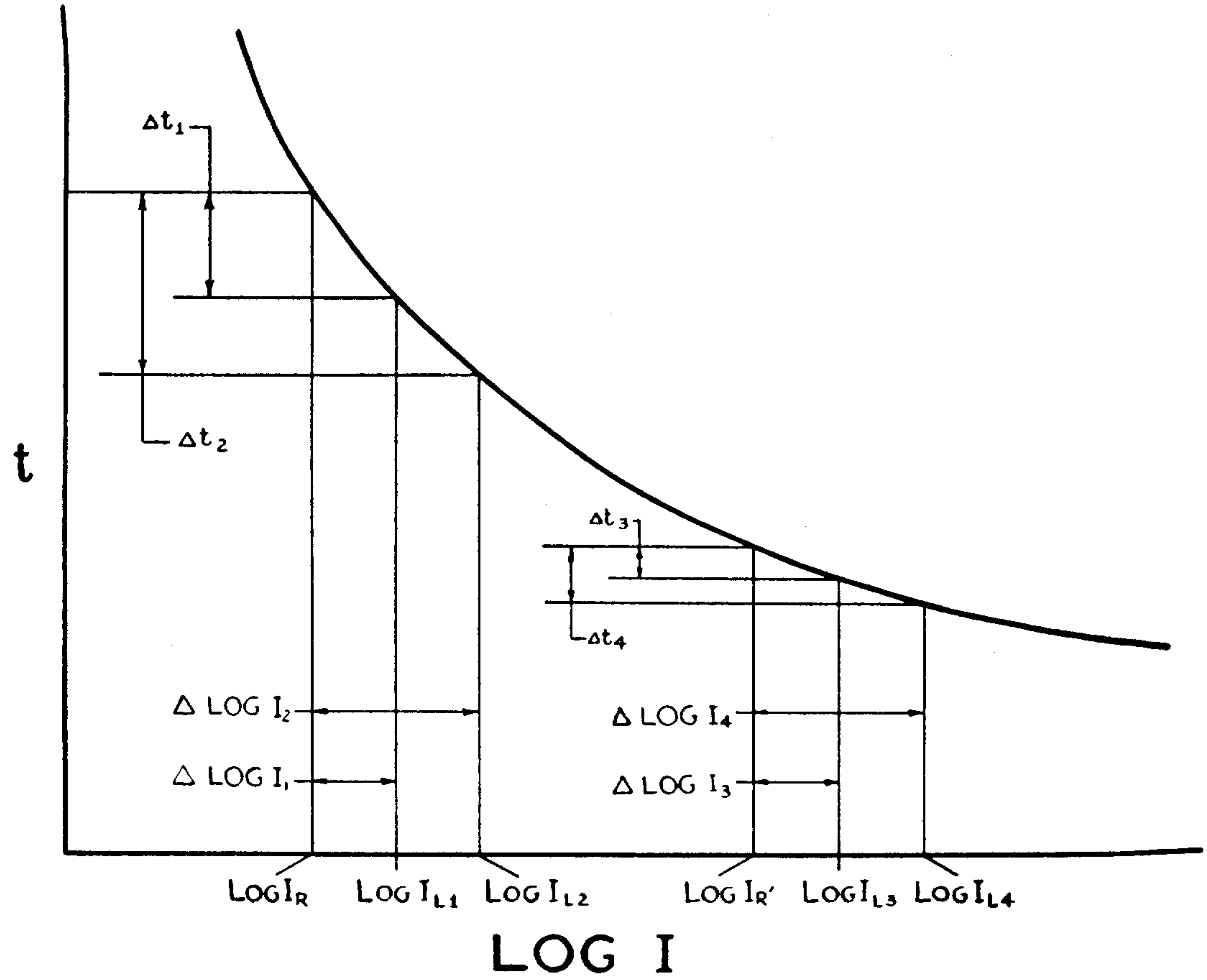

Fig. 8. The Hypothesized Absolute Visual Latent-Period (t) as a Function of the Log of Illumination (log I)

The curve is a representation of a relationship proposed to account for the experimental results.

From an analysis of Fig. 8, the following relationships between the difference in absolute latency and Δ log I may be inferred: (a) the latency-difference increases as Δ log I is increased at both low (log I_R) and high (log $I_{R'}$) levels of illumination; (b) the latency-differences produced at both low and high levels of illumination tend to approach a constant value as Δ log I is increased; the constant value is lower in amount and is produced by a smaller Δ log I at the higher level of illumination, log $I_{R'}$; (c) the rate at which the latency difference is increased by a constant increase in Δ log I is not the same at all levels of illumination; the rate is higher at the low level of illumination, log I_R; (d) a given magnitude of Δ log I produces a latency-difference which increases progressively as the level of illumination is progressively decreased; and (e) a given latency-difference is obtained by a progressively smaller value of Δ log I as the level of illumination is progressively decreased.

It is to be noted that the above relationships, derived from Fig. 8, are identical with those reported for Figs. 5 and 7A, in which the condition of retinal illumination, log I_L/I_R, is equivalent to Δ log I. Predictions relating Δt to log I_L/I_R, based on alternative curves for Fig. 8 (linear and concave downward), are inconsistent with the relationships obtained from the experimental data.

It is an undisputed fact that the stereophenomenon is elicited by differences in retinal illumination between the two eyes. The theory of the effect has, however, been propounded in terms of a stereoscopic function on the part of *S* which obeys the laws of binocular projection. Such laws are based on 'normal' conditions, and certainly the influence on these laws of conditions existing in the Pulfrich effect, *i.e.* different illumination in the two eyes, has not been examined. It becomes important to make such an examination because the measure of the magnitude of the stereoeffect may conceivably—due to the differences in illumination in the two eyes—exhibit effects not readily deducible from the laws of projection. The following experiment with *C.G.M.* was designed to investigate the effect of differences in retinal brightness, produced at various levels of illumination, upon stereoscopic acuity. The oscillating rod is held stationary and displaced 10 mm. to the left of the vertical median plane. *S* is required to align the fixation-target with respect to the oscillating target until both appear to be in a frontal plane. The conditions of retinal illumination used in the main experiment are duplicated, and 10 determinations of alignment are made under each of the retinal conditions. The results showed a range in the obtained means of 2 mm.; the range in average deviations was 0.6 mm. This range of obtained means corresponds to a stereoscopic difference-angle of

37″; the range in average deviations corresponds to a difference angle of 11″. No trend was observed between the mean positions of alignment or the magnitude of the average deviations and the degree of diversity in retinal illumination. The results clearly indicate that the differences in the illumination between the two eyes existing in the present experiment have a negligible effect upon depth settings in a situation in which stereoscopic acuity may be measured. The average mean deviation obtained in these observations corresponds to a stereoscopic acuity of 8″. There is good ground for believing, therefore, that the method of measuring the Pulfrich displacement is uninfluenced by the special condition of unequal illumination in the two eyes; hence application of the projection laws may be made legitimately.

It is to be noted from Table I, for *C.G.M.*, that under all conditions of retinal illumination, the near displacement is consistently larger than the far displacement. As a consequence, the corresponding calculated latency-differences for the near positions are larger than for the far positions. Under the given conditions of testing in which the illumination of the left eye is gradually increased, the oscillating rod is moving from left to right when it appears at the near position. If conditions of testing are reversed whereby the illumination of the *right* eye is gradually increased, the oscillating target will then be moving from right to left when it appears at the near position. *C.G.M.* was tested under the reversed conditions at only the highest level of illumination used in the main experiment (log $I_L = 2.98$), and the obtained results showed the near displacement again to be consistently larger than the far displacement. It is concluded from these observations that for *C.G.M.* a consistently larger near displacement is obtained independently of the direction of motion of the oscillating target.

Further investigation of the causes for this difference in magnitude of the displacements obtained by *C.G.M.* revealed the existence of a localization-error of the oscillating target when in motion. Under all conditions of equal retinal brightness, at each of the levels of illumination, the oscillating target seemed to be moving in a plane nearer than the plane defined by the true distance of the oscillating rod. This was verified by a series of 10 measurements, at each of the levels of illumination, in which *S* was required to place the adjustable fixation-rod directly below the plane of oscillation. At all levels of illumination, the fixation-rod was adjusted about 5 mm. in front of the 'true' plane of oscillation. The reverse localization-error was obtained by Wölfflin[24] who reported that, for many *S*s,

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[24] Wölfflin, *op. cit.*, Cf. footnote 16.

the plane of oscillation appeared beyond the fixation-mark when the fixation-mark was adjusted directly below the 'true' plane of oscillation. These effects are possibly related to 'fixation disparity' observed in measurements of the frontal-plane horopter.[25] The position of the horopter was found to be either behind or before the fixation-point, depending on whether the phoria for the given fixation-distance was exophoric or esophoric, respectively. For *C.G.M.*, who is esophoric at the fixation-distance, the direction of the localization-error is in accord with this finding.

The obtained displacements were 'corrected' for the localization-error, and the relationships previously noted remained essentially unchanged. The magnitude of the correction was still insufficient to establish equality between the latency-differences calculated for near and far positions, particularly for the displacements produced by the larger differences in retinal brightness at the lower levels of illumination.

Hecht has formulated a theory of visual intensity-discrimination which predicts the expected changes in log $\Delta I/I$ as a function of log I.[26] Smith obtained data which supported the theory, and in one of his experimental situations presented the standard and comparison stimulus-fields separately to each eye for binocular judgment.[27] The results obtained under the experimental conditions showed that "the binocular integration leads to a response which is essentially similar to that due to monocular excitation."[28] A further extension to include binocular judgments was made by Mueller and Lloyd,[29] who present supporting data on stereoscopic acuity obtained under different levels of illumination. The data obtained in the present experiment could conceivably provide a test for the theory proposed by Hecht extended to binocular judgments. For example, Fig. 7B might provide values of $\log (I_L - I_R) = \log \Delta I$, required for each level of illumination, $\log I_R$, to produce a constant latency-difference. These data can be plotted to show the relationship existing between log $\Delta I/I$ and log I. It is apparent that a whole family of such curves would result, in which the parameter is the magnitude of the latency-difference. The obtained curves (not shown here) differ from Hecht's theoretical curve in showing a marked tendency for log $\Delta I/I$ to increase progressively

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[25] Ames, Ogle and Gliddon, *op. cit.*, 586-595.

[26] S. Hecht, A theory of visual intensity discrimination, *J. Gen. Physiol.*, 18, 1935, 767-789.

[27] J. R. Smith, Spatial and binocular effects in human intensity discrimination, *J. Gen. Psychol.*, 14, 1936, 318-345.

[28] *Ibid.*, 343.

[29] C. G. Mueller and V. V. Lloyd, Stereoscopic acuity for various levels of illumination, *Proc. Nat. Acad. Sci.*, 34, 1948, 223-227.

for large values of log I, as the chosen magnitude of the constant visual effect is progressively increased. A more suitable test of theory might be obtained from data representing threshold ΔI for just perceptible displacements. In any case, further analysis is required.

SUMMARY

(1) The present investigation is concerned with a stereophenomenon first described and analyzed by Pulfrich: with unequal illuminations in the two eyes, the bob of an oscillating plane-pendulum appears to rotate out of its plane of oscillation. The apparent displacement has been accounted for in terms of differences in visual latent-periods for the two eyes. Appropriate theory allows for calculation of latency-differences when the apparent displacement of the oscillating object in the vertical median plane is determined.

(2) Determinations are made of the relationships existing between (a) the magnitude of the near and far displacements (or the corresponding calculated latency-differences) and (b) the difference in retinal illumination existing between the two eyes for (c) many basic levels of illumination.

(3) The apparatus and procedure used in the experiment are described.

(4) Curves are drawn separately for each subject showing the near and far displacements (C_N and C_F) and the corresponding latency-differences (Δt_N and Δt_F), obtained at each of the levels of illumination, as functions of conditions of retinal illumination. The curves relating C_N, C_F, Δt_N, and Δt_F to conditions of retinal illumination show the following relationships: (a) displacement and latency-difference increase as the difference in retinal illumination increases; (b) displacement and latency-difference approach maximal values as the difference in retinal illumination increases; (c) the rate of increase depends on level of illumination; slopes of the curves increase as level-of-illumination decreases; (d) for a given difference in retinal illumination, displacement and latency-difference increase as level of illumination decreases; and (e) the difference in retinal illumination necessary to produce a constant displacement or latency-difference becomes smaller as level of illumination decreases.

(5) The results obtained may be accounted for on the assumption that the absolute visual latent-period and the logarithm of the stimulus-intensity are inversely related.

(6) The results are analyzed in terms of laws of space-perception, and additional experiments have been performed to test the relations.