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DEPTH-DISCRIMINATION THRESHOLDS FOR TARGETS WITH EQUAL RETINAL ILLUMINANCE OSCILLATING IN A FRONTAL PLANE*

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INTRODUCTION

This paper is a report of several experiments which have now been performed as part of a long-range research program evaluating the effects of the quantity and quality of stimulus illumination on binocular depth (i.e., stereoscopic depth) discrimination.

In designing the total research program, it has been planned that binocular settings of equidistance will be obtained for both stationary and oscillating targets, viewed under conditions of equal as well as unequal binocular retinal illuminance, using both white and colored (i.e., near monochromatic) illumination. Some of the results on depth settings for stationary targets viewed under conditions of both equal and unequal binocular retinal illuminance have already been published.[1,2]

The experimental results[1] on depth settings for stationary targets viewed under conditions of equal binocular retinal illuminance were presented in 1959. Also previously published[3-6] have been many of our results on depth settings for oscillating targets viewed under conditions of unequal binocular retinal illuminance. This viewing situation provides the necessary stimulus conditions for eliciting the so-called Pulfrich stereoeffect. That is, whenever a condition of unequal retinal illuminance is produced in the two eyes, a rod which is actually oscillating in a frontal plane will appear to rotate out of its frontal plane of oscillation in a path that locates the rod nearer than it really is for one direction of stroke and farther than it really is for the return stroke. Thus, the path of the rod which is actually oscillating in a plane will appear to be that of an ellipse.

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This interesting stereoscopic illusion has been described and accounted for by Pulfrich[7] in terms of differences in the hypothesized visual latent period produced in the two eyes as a result of the differences in binocular retinal illuminance.

In the present report, we shall be concerned with depth settings obtained for black oscillating targets viewed only under conditions of equal binocular retinal illuminance. For this viewing condition, a target which is actually oscillating in a frontal plane at a given distance from the observer will, of course, still be reported as oscillating in a frontal plane, unlike the case for the Pulfrich situation.

The data to be presented demonstrate the effects on equidistance settings of two important, but relatively neglected, classes of variables: (1) the velocity of the oscillating target, and (2) the prevailing level of binocuIar retinal illuminance.

Such new data are necessary for the development of an adequate theory of binocular space perception. In addition, the new data should serve to relate the theory and data of space perception to the theory and data in other fields of vision in which such basic stimulus variables are known to have a significant influence.

EFFECTS OF TARGET VELOCITY

We shall consider first the experiments designed to assess the effects of target velocity on equidistance settings.

Apparatus and Procedure: The apparatus and procedure have been given in detail elsewhere.[8] The apparatus* (see Figure 1) provides conditions of stimulation that are essentially similar to those obtained in the Howard-Dolman two-rod device.[9]

The subject is seated in the dark room (*D*) and binocularly observes the fixation target (*FT*) located in the lower visual field and the oscillating target (*OT*) located in the upper visual field through a pair of circular artificial pupils (*E* and *F*) that are 2.5 mm in diameter and adjustable for interpupillary separation. The targets are blackened steel rods, 1/4 inch in diameter. The upper oscillating target moves in a frontal plane 100 cm from the observer's eyes over a wide range of constant linear velocities by means of a variable-speed transmission device. The lower fixation target can be moved by the observer in his median plane either toward or away from his eyes by means of a pulley wheel (*W*) located in the dark room. Uniform background illumination is provided by a light box (*L*) located in a frontal plane 250 cm from the observer's eyes.

*The apparatus was originally constructed in 1950 at Pupin Laboratories, Columbia University, partially through funds from a research grant-in-aid generously provided by the American Academy of Optometry.

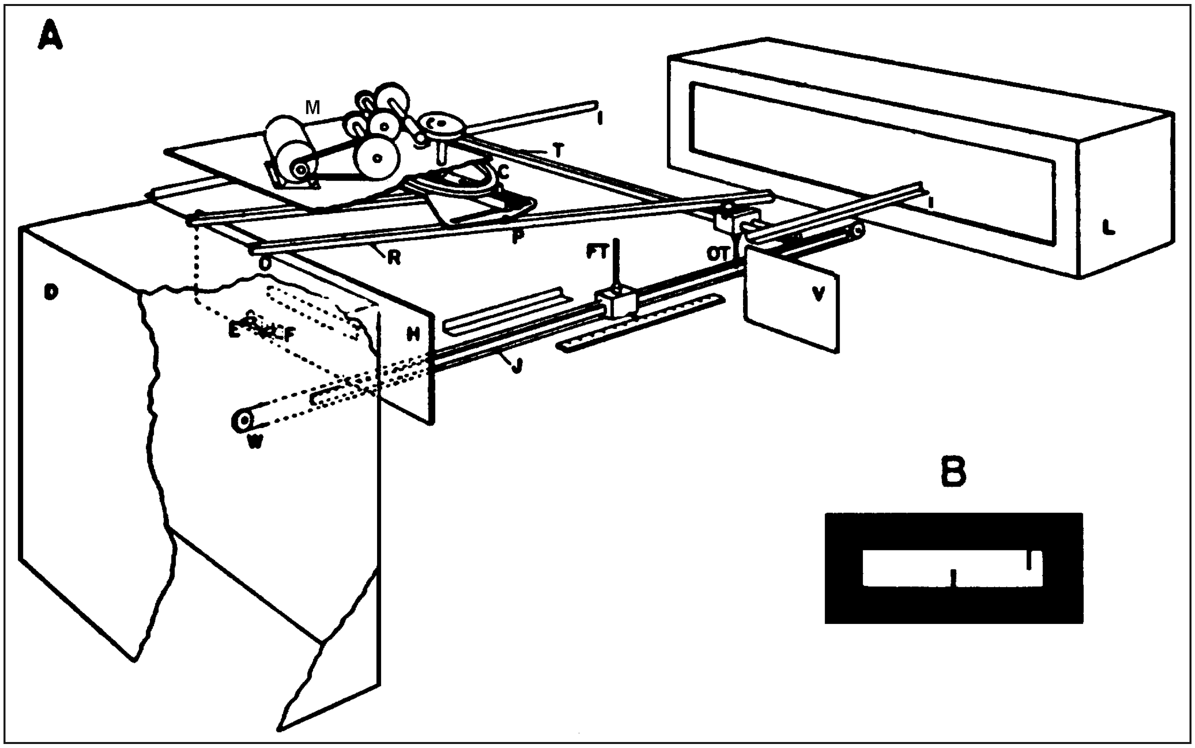

Fig. l. (A) Schematic representation of the apparatus; (B) Observer's view of the stimulus targets. See text for detailed description. (From Lit and Hyman[4].)

Horizontal (*H*) and vertical (*V*) screens provide a constant rectangular field of view 21.6^{o} x 4.2^{o}. The view of the targets as seen by the observer is shown in Figure 1 (*B*).

Two graduate students served as paid observers. Each was emmetropic and had good binocular functioning. At a fixation distance of 100 cm, the interpupillary separation of observer F.C. was 6.20 cm and that of observer M.M. (female) was 6.70 cm.

Equidistance settings were obtained at each of 10 target velocities, ranging from 2.592 to 68.166 cm/sec. In angular measure, the range is from 1.49 to 39.05 deg/sec. Three photopic levels of binocular retinal illuminance were produced: 2.06, 3.13, and 3.64 log trolands. The levels were achieved by use of matched pairs of neutral density filters placed in the filter boxes located in front of the observer's eyes.

In performing his depth settings, the observer was required to fixate continuously on the upper end of the comparison (fixation) rod and to adjust the distance of this rod along his median plane until the rod appeared to lie directly below the frontal path of the oscillating target.

In a given experimental session, only one retinal-illuminance level was used. Ten equidistance settings were obtained at each of the 10 target velocities. In all, 12 experimental sessions were held for each observer, that is, four sessions were held at each level of retinaI illuminance in counterbalanced order. Thus, for each observer, 40 equidistance settings were obtained at a given target velocity under a given level of photopic retinal illuminance.

The experimental data were analyzed in terms of the linear and the angular measures of both the constant and the variable errors of the equidistance settings. The linear constant error of an equidistance setting is defined as the depth difference (ΔR) existing between the actual and apparent plane of target oscillation. That is, $\Delta R = R_V - R_S$, where R_V represents the adjusted distance of the comparison rod measured in the observer's median plane and R_S (= 100 cm) represents the fixed distance of the plane of target oscillation. The linear magnitude of the variable error is defined as the average deviation (*AD*) of a given group of 10 equidistance settings.

The corresponding angular measures of the constant and the variable errors are designated by the symbols $\eta_{\Delta R}$ and η_{AD}. Each is computed* in accordance with the formula[10] which specifies the stereoscopic parallax angle (η_t), defined as 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,

$$\eta_t = \left[(206264.81)(b)/R_S\right]\left[\delta_t/R_V\right], \tag{1}$$

where R_S and R_V are target distances as defined above; b is the observer's interpupillary separation; δ_t in one case represents the magnitude of the constant error (ΔR) of any given equidistance setting, and in the other case, δ_t represents the variable error (*AD*) of any given group of 10 settings; and 206264.81 is the constant which converts η_t from radians into sec of arc if R_S, R_V, b, and δ_t are all expressed in the same linear unit.

The angular magnitude of the constant error, $\eta_{\Delta R}$, of a given group of 10 equidistance setting is obtained by taking the mean of the 10 values of η_t, as computed by Eq. (1) for the 10 separate values of ΔR.

The corresponding angular magnitude of the variable error, η_{AD}, of the 10 equidistance settings is obtained by computing a single value of η_t in Eq. (1) for the separate case where R_V now represents the mean distance of the adjusted comparison rod for the group of 10 settings and R_S now represents the value $(R_V - AD)$. The stereoscopic parallax angle η_{AD} is one traditionally used

*The computations were performed on an IBM 1620 Data Processing System generously provided by the Data Processing and Computing Center of Southern Illinois University. The writer is also indebted to T. Purcell, Manager, for his aid in developing the computer program required for these studies. The assistance of students M. Bartlett, E. DeYoung, and Maryann A. Andolsek is also gratefully acknowledged.

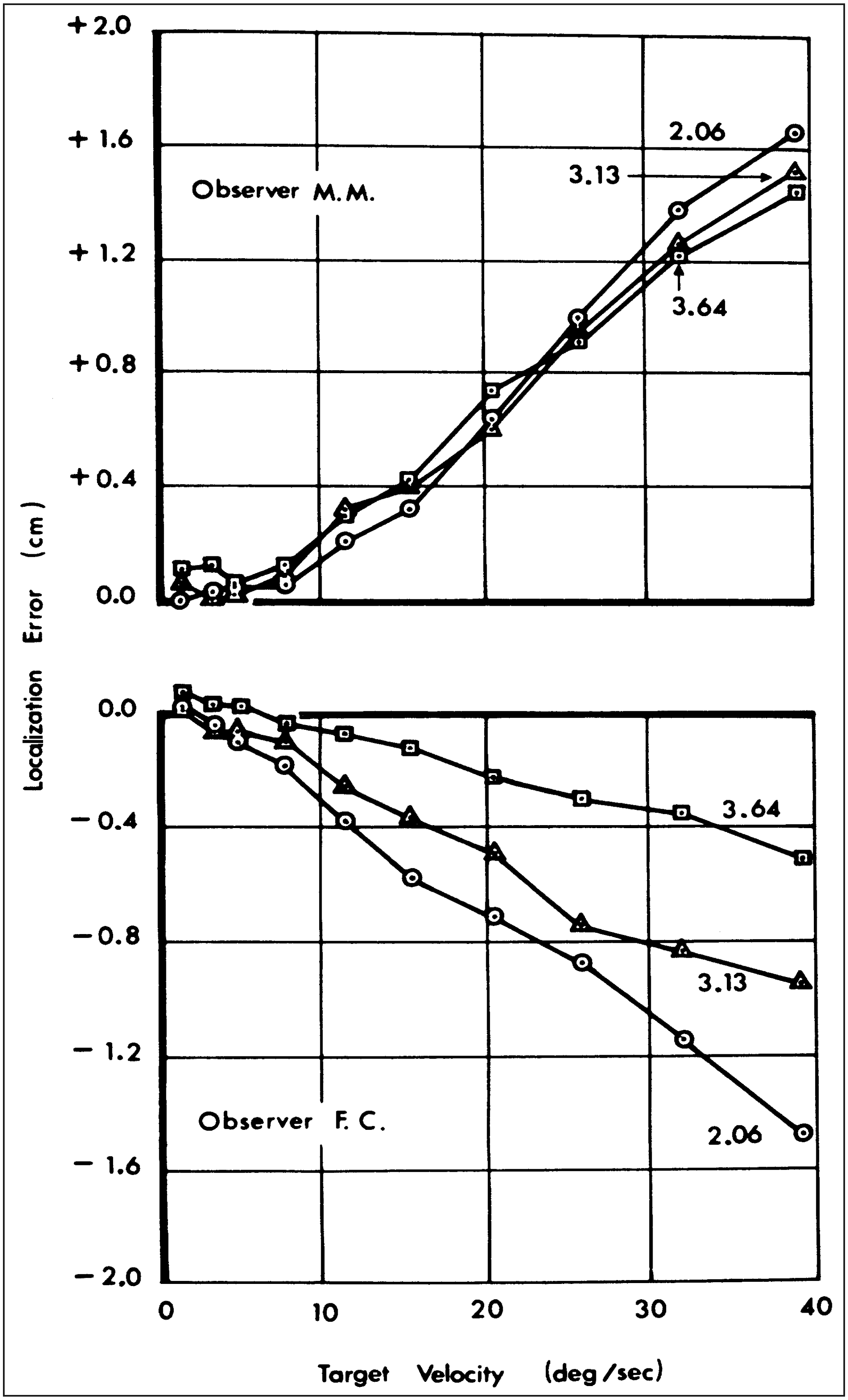

Fig. 2. Localization error of equidistance settings as a function of target velocity, with level of binocular retinal illuminance (in log trolands) serving as parameter.

in specifying stereoscopic acuity.

Results: The effects of target velocity on the magnitude of the constant error (ΔR) are shown in Figure 2 for each of the three retinal-illuminance levels. It is to be noted that no appreciable constant error exists for very slow-moving targets. As target velocity is increased, the absolute magnitude of the constant error progressively increases, but the effect is in opposite directions for the two observers. Thus, for observer M.M., the average constant error for the three retinal-illuminance curves increases from a value of 0.05 cm (= 7 sec of arc) at the lowest target velocity to an average value of 1.53 cm (= 208 sec of arc) at the highest target velocity. The corresponding data for observer F.C. show that the absolute magnitude of the average constant error increases from a value of 0.03 cm (= 6 sec of arc) at the lowest target velocity to an average absolute value of 0.98 cm (= 128 sec of arc) at the highest velocity. It is to be understood that a progressively increasing negative value of ΔR (and its corresponding $\eta_{\Delta R}$) indicates that the mean position of the adjusted comparison target was located progressively nearer the observer than the actual plane of target oscillation.

The effects of level of retinal-illuminance on the localization error, ΔR, are more marked for observer F.C. than for observer M.M. For observer F.C., an increase in retinal illuminance level at all target velocities reduces the absolute magnitude of the depth difference, $|\Delta R|$, existing between the actual and discriminated plane of target oscillation. For observer M.M., however, any decrease in localization error which accompanies an increase in retinal-illuminance level occurs only at the three highest target velocities.

The experimental results on the effects of target velocity on the magnitude of the variable error, η_{AD}, are given in Figure 3. The data of both observers are combined in each of the three curves of retinal-illuminance level. The data show that the stereoscopic threshold angle, η_{AD}, progressively increases as target velocity is increased: η_{AD} increases from an average value of about 13 sec of arc to an average value of about 52 sec of arc as target velocity is increased from 1.5 to 39.1 deg/sec. Thus, η_{AD} undergoes about a 4-fold increase as target velocity undergoes about a 26-fold increase.

The effects of level of retinal illuminance on the variable error, η_{AD}, are not clearly marked. The data obtained at high target velocities show some tendency for η_{AD} to take on its largest values at the lowest retinal illuminance level. That is, at high target velocities, the variability of the equidistance settings tends to increase as retinal illuminance is decreased. It should be noted in Figure 3, however, that the curves designating the two highest

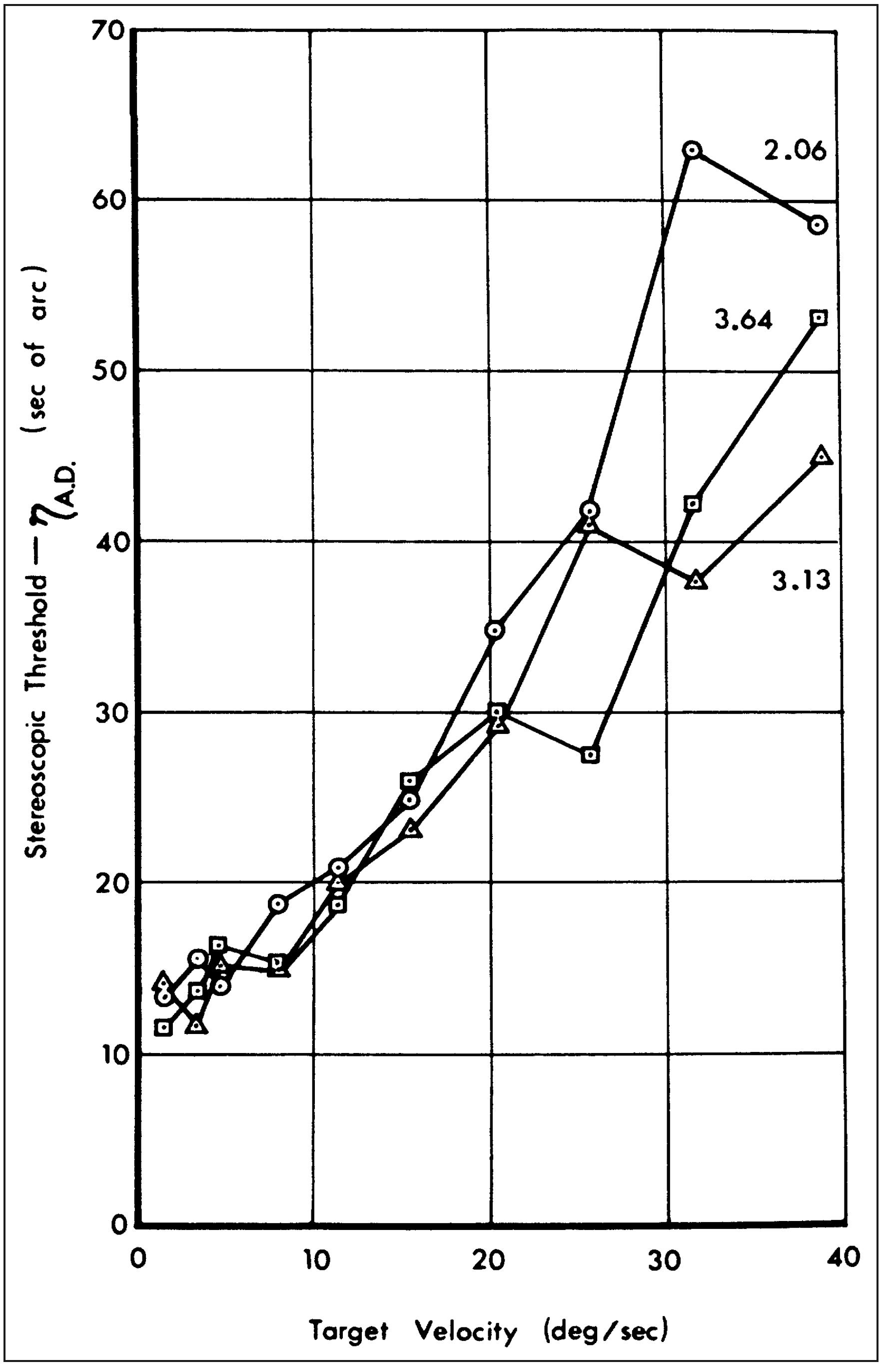

Fig. 3. Stereoscopic threshold angle, η_{AD}, as a function of target velocity, with level of binocular retinal illuminance (in log trolands) serving as parameter. (From Lit[8].)

retinal illuminance levels show considerable overlapping at all target velocities.

The experimental data just presented clearly demonstrate that target velocity has a significant influence on both the constant errors and the variable errors of the equidistance settings.

However, the role of retinal-illuminance level as a controlling stimulus variable has not been clearly demonstrated by these data. The lack of systematic effect of retinal-illuminance level on the variability of the depth settings may be accounted for by the fact that only relatively high photopic levels were used. At such high intensities of light the enhancing effect of increased retinal illuminance on depth-discrimination thresholds may well have already reached its maximum asymptotic value.

Accordingly, it was felt desirable to perform an additional series of experiments in which depth settings for targets oscillating at several selected velocities were to be obtained under a wide range of scotopic and photopic retinal-illuminance levels. As a control feature, equidistance settings for a stationary target were also to be obtained under this same wide range of retinal-illuminance levels.

EFFECTS OF LEVEL OF RETINAL ILLUMINANCE

The additional experiments were designed to assess the effects of retinal-illuminance level on equidistance settings for both stationary and oscillating targets. These were performed with the aid of Harlyn D. Hamm, a graduate student in the Department of Psychology at Southern Illinois University.†

Apparatus and Procedure: The same apparatus was used as that described earlier.* Three highly trained undergraduate students served as new experimental observers. All were emmetropic and possessed good binocular functioning. At a fixation distance of 100 cm, the interpupillary separation of observer A.F. was 5.80 cm, that of observer H.G. was 6.20 cm, and that of observer A.W. was 6.40 cm.

Six target velocities were selected: 0.000, 8.964, 18.212, 45.565, 56.734, and 69.117 cm/sec. At the observation distance of 100 cm, the corresponding angular velocities are: 0.00, 5.13, 10.40, 25.67, 31.67, and 38.12 deg/sec. In the case of the stationary target, the standard rod was displaced 1.30 cm (= 0.75^{o}) to the right of the observer's median plane.

For each condition of target velocity, equidistance settings were made at 9 - 12 levels of binocular retinal illuminance, ranging from – 2.34 to 4.16 log trolands. In any given experimental session 14 settings were obtained for one target velocity at each of the 9-12 levels of retinal illuminance. To control for adaptation effects the levels were always presented in order of increasing magnitude during the experimental session. A counterbalanced order

† See: Lit, A., and Hamm, H. D., Depth-discrimination thresholds for stationary and oscillating targets at various levels of retinal illuminance. *J. Opt. Soc. Am.*, **56**(4): 1966.

* Apparatus modifications and calibrations were performed with the aid of graduate student Charles Popp.

of presentation was used with respect to target velocity sequence. The total experimental design yielded, for each observer, four groups of 14 equidistance settings (56 readings) at each combination of retinal illuminance and target velocity.

All three observers were not available for testing at each of the six target velocities. All three performed equidistance settings for the stationary target and the slowest moving (5.13 deg/sec) target. Two of the observers (H.G. and A.W.) in addition performed settings for targets oscillating at the two higher velocities (10.40 and 25.67 deg/sec). Observer A.W. performed settings at the two highest target velocities (31.67 and 38.12 deg/sec).

As in the case of the previous experiments, an IBM 1620 Data Processing System was used to compute the two desired stereoscopic parallax angles: one, $\eta_{\Delta R}$, was based on the constant errors of the depth settings and the second, η_{AD}, was based on the variable errors (that is, on the average deviations) of the settings.

Results: The combined data for all three observers on the effects of level of retinal illuminance on the stereoscopic threshold angle, η_{AD}, for the case of a stationary target, are shown in Figure 4. Also included are the data on equidistance settings for a stationary target obtained in an earlier experiment[2] in which two different observers were used. It is to be noted that the curve drawn through the data points (by visual inspection) provides a good fit for both sets of data.

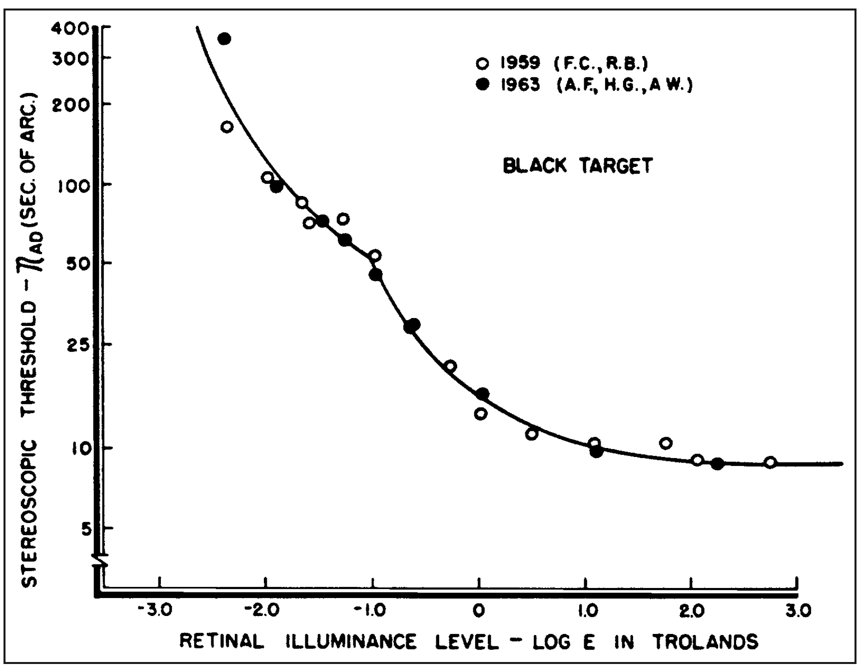

Fig. 4. Stereoscopic threshold angle, log η_{AD}, as a function of retinal-illuminance level, log *E*. A single curve has been drawn by visual inspection through the data of the present study and those obtained in an earlier experiment on different observers.

The data in Figure 4 on the effects of level of retinal illuminance on the stereoscopic threshold angle for stationary targets can be readily summarized: η_{AD} has its largest value (261 sec of arc) at the lowest retinal-illuminance level (–2.34 log troland) and progressively decreases to a final asymptotic value (9 sec of arc) as retinal-illuminance level is increased (above 1.5 log trolands). A sharp "break" in the curve occurs at about –1.00 log troland. This discontinuity is completely in accord with predictions (see Hecht[11]) based on the duplicity theory of vision. The discontinuity reflects the transition from rod to cone vision at the specified retinal-illuminance level. The shape of the curve is essentially similar to that obtained by Hecht and Mintz[12] in their measurements of visual acuity. The present data show a considerably larger range of variation of the stereoscopic threshold angle than that reported by Mueller and Lloyd[13] in their experiment on equidistance settings in a stereoscope under comparable conditions of illumination (e.g., a six-fold change in η_{AD} for our data as compared to a 2.5-fold change in theirs, with respect to the "cone" segment of the curve).

The data obtained on oscillating targets are shown in the next three figures. Figure 5 presents the combined data for two observers on the relationship

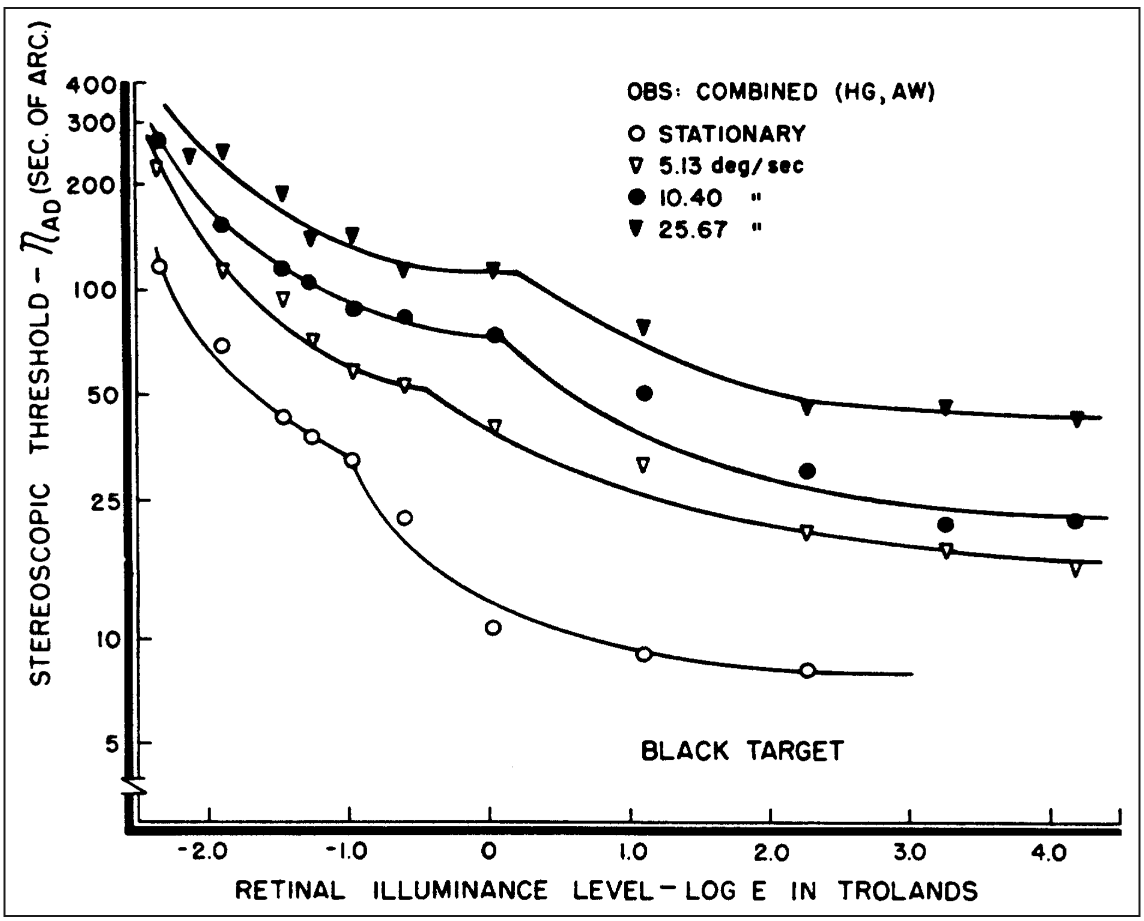

Fig. 5. Stereoscopic threshold angle, log η_{AD}, as a function of level of retinal illuminance, log *E*, for stationary and oscillating targets.

existing between η_{AD} (on a logarithmic scale) and log E, for four specified conditions of target oscillation. The curves (drawn by visual inspection) show that, for each target velocity, η_{AD} has its largest value at the lowest retinal-illuminance level and progressively decreases to a final asymptotic value as log E is increased. Of special interest is the discontinuity in the stereoscopic threshold – retinal illuminance function for each target velocity. This new finding clearly reveals the existence of a new class of threshold responses (to be added to those already dealt with by Hecht[11]) in which a typical rod-cone transition occurs when level of illumination is varied over a wide range of values.

It should be noted that the discontinuities in the curves of Figure 5 occur at progressively higher log E values as target velocity is increased. This finding is in complete quantitative agreement with expectations based on the Bunsen-Roscoe law (that is, on the reciprocal relationship existing between stimulus intensity and duration required to produce a constant visual effect) . Thus, if it is assumed that an increase in target velocity produces a proportional decrease in stimulus exposure duration of any given retinal element in each eye, then a five-fold increase in target velocity (from 5.13 to 25.67 deg/sec) may be considered equiva- lent to a five-fold decrease in exposure duration (from 0.071 to 0.014 sec for a target diameter of 0.635 cm) . Accordingly, this should result in a log 5 (= 0.70) increase in the value of log E at which the discontinuities occur as target velocity is increased from 5.13 to 25.67 deg/sec. The observed increase in the corresponding values of log E from about –0.40 to 0.25 log troland for the two specified curves in Figure 5 is in very good agreement, indeed, with predicted results.

Finally, it should also be noted that the curves in Figure 5 are progressively displaced upward on the ordinate axis as target velocity is increased. These vertical displacements obviously cannot be accounted for in terms of the Bunsen-Roscoe law and are probably associated with the increased "blurring" which accompanies increases in target velocity. In any event, the data suggest the need for additional studies designed to assess the effects of exposure duration on equidistance settings, both for stationary targets and for oscillating targets presented at different velocities while being viewed through horizontal apertures of varying extent.

The effect of target velocity on equidistance settings at each of the specified retinal-illuminance levels is shown in Figure 6 and Figure 7. The combined data of observers H.G. and A.W. on the relationship existing between stereoscopic threshold angle, η_{AD}, and target velocity are presented in Figure 6; the corresponding relationship with respect to the magnitude of the angular

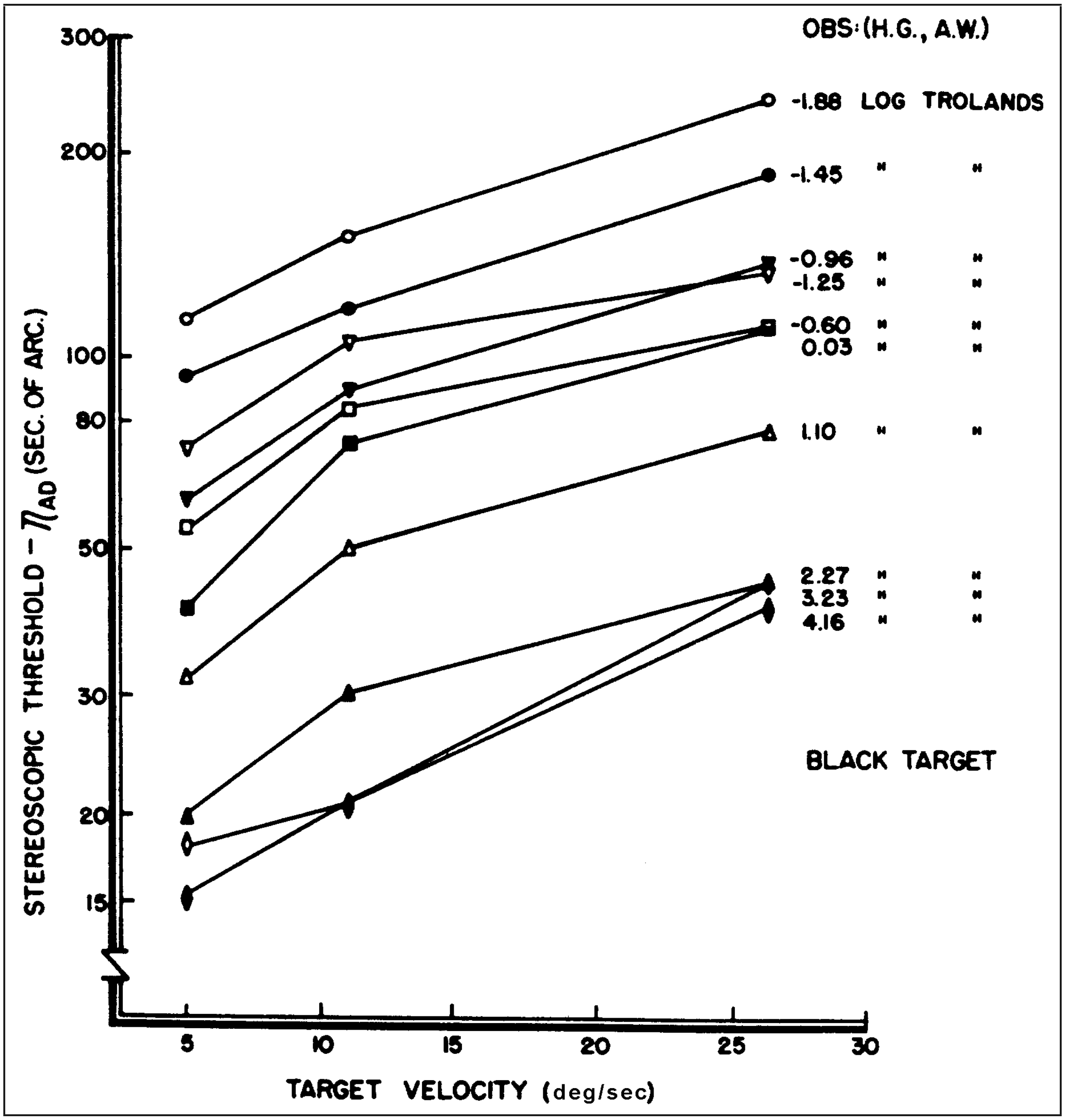

Fig. 6. Stereoscopic threshold angle, log η_{AD}, as a function of target velocity, with level of retinal illuminance, log *E*, serving as parameter.

constant error, $\eta_{\Delta R}$, is displayed in Figure 7. In both cases, the parallax angles progressively increase as target velocity is increased. The vertical separation of the curves in the two figures should be noted: the curves representing low retinal-illuminance levels are characteristically displaced above the curves representing high levels of retinal illuminance. The trend, however, is more systematic for the case of η_{AD} than for $\eta_{\Delta R}$.

Level of retinal illuminance also has a marked effect on the magnitude of the angular constant error, $\eta_{\Delta R}$. The curves (not shown here) relating $\eta_{\Delta R}$ and log *E* for each of the three observers used in this experiment on stationary targets show a clearly marked discontinuity, as in the case of η_{AD}, at a

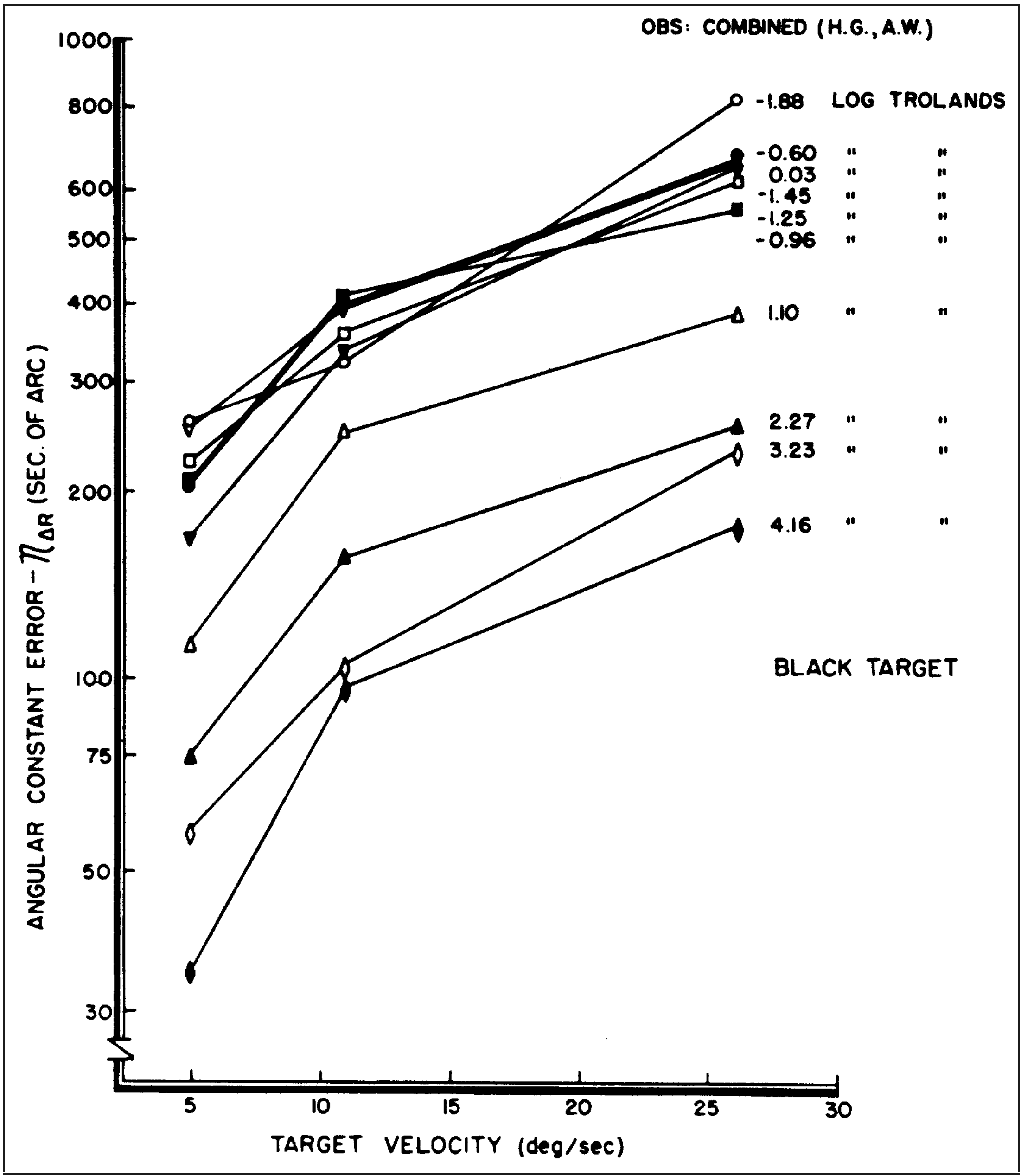

Fig. 7. Angular constant error, log $\eta_{\Delta R}$, as a function of target velocity, with level of retinal illuminance, log *E*, serving as parameter.

retinal-illuminance level of about –1.00 log troland. For each of the three observers, $\eta_{\Delta R}$ is positive at low levels of retinal illuminance and progressively reduces to a value near zero as the level is increased. The shape of the curves, however, is concave downward. The corresponding curves for the oscillating targets (not presented here) are aIso shaped concave downward and exhibit slight discontinuities at values of log *E* which progressively increase from –1.00 to 0.00 log troland as target velocity is increased. As in the case of η_{AD}, the curves are progressively displaced upward on the ordinate axis as target velocity is increased.

In summary, the results presented in this report demonstrate that both level of retinal illuminance and target velocity have systematic effects on the stereoscopic threshold angle η_{AD}: The variability of the equidistance settings progressively increases either as level of retinal illuminance is decreased or as target velocity is increased. The magnitude of the angular constant error, $\eta_{\Delta R}$, is also influenced, but in a less systematic way, by these stimulus variables: The localization error of the settings is zero at high retinal-illuminance levels for stationary targets and progressively increases or decreases (depending on, as yet, unspecified characteristics of the observer) as either target velocity is increased or as level of retinal illuminance is decreased.

RELATIONSHIP TO THE PULFRICH STEREOPHENOMENON

In concluding this report, I should like to discuss briefly the relationship of the present data on equidistance settings for oscillating targets to some peculiar effects which had been noted in our earlier experiments on the Pulfrich stereophenomenon. One of the peculiar effects noted[3] was that, contrary to predictions based on an analysis of the geometric theory of the Pulfrich stereophenomenon, the near depth displacements (C_N) of the oscillating target were consistently larger than the corresponding far depth displacements (C_F). A second peculiar effect noted[4] was that the apparent horizontal path of the oscillating target, when viewed under conditions of small inequalities of binocular retinal illuminance, was often localized by the observer at positions lying completely in front of the actual plane of target oscillation. That is, the apparent far position of the oscillating target as well as the apparent near position were consistently localized at distances nearer than that of the actual plane of oscillation.

The present results on localization errors for equidistance settings at various target velocities and levels of retinal illuminance have direct bearing on the analysis of data obtained in experiments on the Pulfrich stereophenomenon and help to account for the peculiar effects previously noted. As may be seen with the aid of Figure 8, the near and far depth displacements (C_N and C_F) in the Pulfrich situation are each measured from the actual plane of target oscillation, W_1W_2. If a localization error exists for the oscillating target when it is viewed under conditions of equal binocular retinal illuminance while it is moving with constant linear velocity in the mid-region of its stroke, then in the Pulfrich situation both the near and far apparent linear paths of the oscillating target should theoretically be displaced either towards or away from the observer's eyes, depending on whether the sign of the localization error (ΔR) is, respectively, negative or positive. As shown in Figure 8, when ΔR is negative,

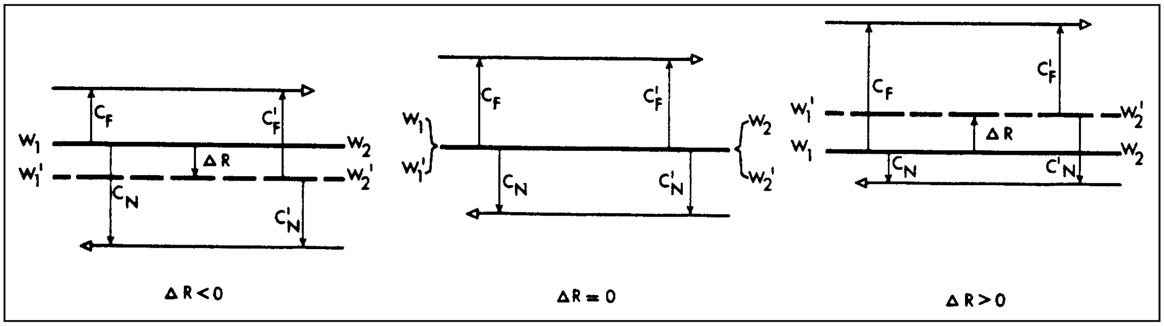

Fig. 8. Relationship between the constant error (ΔR) of equidistance settings for oscillating targets and the near and far depth displacements (C_N and C_F) for oscillating targets viewed under conditions of unequal binocular retinal illuminance (Pulfrich situation). (From Lit[8]) .

$C_N > C_F$. This will result in making the computed near latency difference (Δt_N) systematically larger than, instead of equal to, the corresponding computed far latency difference (Δt_F). Contrariwise, when ΔR is positive, $C_N < C_F$, and Δt_N will now be smaller than its corresponding Δt_F. It should be noted that, when ΔR is large and negative, for small inequalities of binocular retinal illuminance, both the near and far linear segments of the apparent path will be localized in front of the plane of target oscillation, W_1W_2.

In the presence of a localization error, i.e., when ΔR is not equal to 0, the depth displacements C_N and C_F in the Pulfrich situation should be "corrected" before computing the corresponding near and far latency differences. This is accomplished by measuring the near and far depth displacements, now designated by C'_N and C'_F in Figure 8, from the position of the apparent plane of oscillation, $W'_1W'_2$, before performing the computations.

The results obtained from several observers on localization errors (ΔR) for equidistance settings and on near and far depth displacements (C_N and C_F) in the Pulfrich situation completely confirm the predicted relationship between the relative magnitude of C_N and C_F (and their corresponding computed latency differences, Δt_N and Δt_F) and the prevailing sign of the localization error, ΔR. When the depth displacements are "corrected" for their respective localization errors, a small unexplained residual discrepancy still remains between C'_N and C'_F required to satisfy the condition $\Delta t_N = \Delta t_F$.

The rather large values of ΔR obtained in the present experiment at low retinal-illuminance levels and at high target velocities suggest the need for specifying the magnitude of ΔR in experiments on the Pulfrich stereophenomenon, particularly when only either C_N or C_F (or its corresponding computed latency difference) is reported.

Finally, it must be emphasized that the factors which influence the magnitude and sign of the constant errors still require specification. Of special interest is the need to account for the marked individual differences. Current experiments with self-illuminated targets, both white and colored, which are presented against varying background retinal illuminances should yield useful data on this important problem.

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