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# THE MAGNITUDE OF THE PULFRICH STEREO-PHENOMENON AS A FUNCTION OF TARGET VELOCITY [1]

ALFRED LIT [2]

*Vision Research Laboratories, University of Michigan*

The present experiment deals with a stereoscopic effect that arises whenever a transversely moving object is viewed under conditions of unequal binocular retinal illuminance. The depth effect was first described and analyzed by Pulfrich (1922) and now bears his name. The stereophenomenon can be simply demonstrated by means of a pendulum-bob that is made to oscillate in a frontoparallel plane and on a level with *O*'s eyes. A small target for binocular fixation is positioned in his vertical median plane, directly below the oscillating bob and midway between the end-points of its swing. If a neutral or colored filter is placed in front of one of the eyes while the pendulum-bob is in motion, the bob will appear to rotate out of its plane of oscillation in a horizontal elliptical path that locates the bob nearer than it really is for one direction of stroke, and farther than it really is for the return stroke. The oscillating bob appears to rotate in a clockwise direction (as viewed from above) when the filter is placed before the left eye, and counterclockwise when the filter is placed before the right eye. The stereoeffect becomes noticeable at some threshold difference in binocular retinal illuminance and progressively increases in magnitude as the difference in binocular retinal illuminance is increased.

The explanation of the stereophenomenon given by Pulfrich (1922) is based on a suggestion by Fertsch that increasing differences in binocular retinal illuminance produce increasing differences in the hypothesized visual latent periods of the two eyes. For either eye, the magnitude of the visual latent period (that is, the magnitude of the hypothesized time delay between the onset of stimulation of any given retinal point in the eye and the arousal of the visual effect that signals the position of the stimulus target in space) is assumed to be a reciprocal function of the prevailing level of retinal illuminance. Hence, for any specified position of the moving target in the frontoparallel plane, the delay in the signal from the given stimulated retinal point in the covered eye will be slightly greater than the signal delay from the simultaneously stimulated corresponding retinal point in the uncovered eye. It must be further assumed that the binocular spatial localization of the moving target, at any given moment, is determined by the given pair of retinal points in the two eyes that yields simultaneously aroused binocular signals. Accordingly, to yield simultaneously aroused binocular signals from corresponding retinal points, the onset of stimulation for the eye that is covered by the filter must occur when the moving target is at a position farther behind in its path than the

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[2] Now with Bendix Systems Division, Ann Arbor, Michigan.

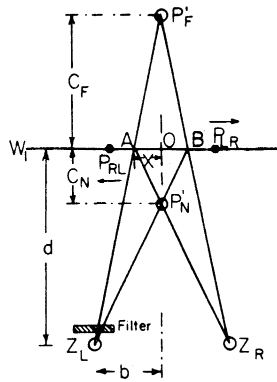


FIG. 1. Geometrical representation of the Pulfrich stereophenomenon indicating the stereoscopic space-image in the horizontal plane of fixation.

position at which the onset of stimulation occurs for the uncovered eye. Thus, simultaneously aroused binocular signals for the transversely moving target are provided by successive pairs of noncorresponding retinal points in the two eyes, and the magnitude of the stereoscopic effect theoretically depends on the amount of the retinal disparity produced as a consequence of the difference in the visual latent periods of the two eyes.

An understanding of the geometric relations involved in the stereophenomenon may be obtained with the aid of Fig. 1. The geometric analysis considers the case of a target that is oscillating in a frontoparallel plane with constant linear velocity, $V$. The oscillating target is placed at eye level in a frontal plane located at a distance $d$ from the midpoint of the line $Z_LZ_R$ which joins the centers of rotation of the two eyes. The linear path of the target in its plane of oscillation is denoted by $W_1W_2$. As indicated, the filter is placed in front of the left eye.

Figure 1 is meant to represent the stereoscopic space-image in the horizontal plane of fixation for the case in which the oscillating target, $P_{LR}$, is moving from left to right, and for the case in which the oscillating target, now designated by $P_{RL}$, is moving from right to left. The points $P'_N$ and $P'_F$ represent the respective near and far positions at which the oscillating target is supposedly localized by $O$ by use of a binocular fixation target movable in the vertical median plane. The distance $OP'_N$ designates the magnitude of the near displacement, $C_N$. The distance $OP'_F$ designates the magnitude of the far displacement, $C_F$.

In accordance with the laws of binocular space discrimination, lines of sight from each eye are drawn through the two respective points of target localization, $P'_N$ and $P'_F$. The two points of target localization are assumed to have relative positions of depth in the median plane such that the lines of sight drawn through Point $P'_N$ and the lines of sight drawn through Point $P'_F$ intersect the line $W_1W_2$ at the same two points, $A$ and $B$. The intersection points $A$ and $B$ theoretically mark the respective positions in the path of the oscillating target at which onset of stimulation occurred in each of the two eyes. Thus, when the target is moving from left to right and appears to be located at the far position, $P'_F$, the onset of stimulation for the right eye occurred when the target (now at $P_{LR}$) was located at Point $B$, and the onset of stimulation for the left eye covered by the filter occurred when the target was located at Point $A$, a bit farther behind in its path. The time taken for the target to move from $B$ to $P_{LR}$ represents the magnitude of the visual latent period of the right eye, and the time taken for the target to move from $A$ to $P_{LR}$ represents the slightly larger magnitude of the visual latent period of the left eye. Consequently, the time taken for the target to move from $A$ to $B$ represents the difference, $\Delta t_F$, in the visual latent periods of the two eyes, based on the far position of target localization, $P'_F$. Since the velocity of the oscillating target is identical for either direction of movement, it follows by the same reasoning that when the target is moving from right to left and appears to be located at the near position, $P'_N$, the onset of stimulation for the right eye occurred when the target (now at $P_{RL}$) was located at Point $A$, and the onset of stimulation for the left eye covered by the filter occurred when the target was located at Point $B$, a bit further behind in its path. In this case, the time taken for the target to move from $B$ to $A$ represents the difference, $\Delta t_N$, in the visual latent periods of the two eyes, based on the near position of target localization, $P'_N$. It should be noted that the latency differences based on the near and the far positions of target localization are theoretically equal in magnitude, that is, $\Delta t_N = \Delta t_F$.

If, for any given difference in binocular retinal illuminance, the magnitude of the near and far displacements, $C_N$ and $C_F$, are experimentally determined, it is possible to calculate the magnitude of the corresponding near and far latency differences, $\Delta t_N$ and $\Delta t_F$, if the linear velocity, $V$, of the oscillating target is known.

It can be readily seen from similar triangles in Fig. 1 that for target localizations at $P'_N$ and $P'_F$, respectively,

$$X = bC_N/(d - C_N)$$

and

$$X = bC_F/(d + C_F) \qquad [1]$$

where $X = \frac{1}{2}$ the distance from $A$ to $B$ and $b = \frac{1}{2}$ the distance between the centers of rotation of the two eyes. The distance of the plane of oscillation, $d$, and the near and far displacements, $C_N$ and $C_F$, have been previously defined.

For an oscillating target moving with constant linear velocity, $V$, the time taken for the target to pass through the distance $X$ is given by the formula,

$$t = \frac{X}{V} \qquad [2]$$

The time taken for the target to move from $A$ to $B$ (or $B$ to $A$) represents the latency difference, $\Delta t$, between the two eyes. Since $\Delta t = 2t$, we obtain from Equation 2,

$$\Delta t = \frac{2X}{V} \qquad [3]$$

Substituting for $X$ the respective expressions given in Equation 1, we finally obtain the following relationship between the experimentally determined near and far displacements ($C_N$ and $C_F$) and the corresponding computed near and far latency differences ($\Delta t_N$ and $\Delta t_F$):

$$\Delta t_N = \frac{2b}{V} \cdot \frac{C_N}{d - C_N}$$

and

$$\Delta t_F = \frac{2b}{V} \cdot \frac{C_F}{d + C_F} \qquad [4]$$

It should be noted from purely geometric considerations that, for any constant difference in binocular retinal illuminance, the magnitude of the stereoscopic effect as measured by $C_N$ and $C_F$ should progressively increase as the linear velocity of the oscillating target is increased, but the corresponding calculated values of $\Delta t_N$ and $\Delta t_F$ should remain constant for all target velocities used.

The present experiment is a continuation of a research program (Lit, 1949; Lit & Hyman, 1951) designed to obtain systematic data on some of the important stimulus variables that influence the magnitude of the Pulfrich effect. The aim of the research program is to provide appropriate data that ultimately can be directly related to theories and data concerned with several basic visual functions: (*a*) binocular space discrimination, (*b*) the relationship between the magnitude of the monocular visual latent period and level of retinal illuminance, (*c*) intensity discrimination, (*d*) retinal interaction, and (*e*) color vision. In the present experiment, the effect of target velocity is systematically studied. This is an important variable whose effect on the magnitude of the stereoeffect (that is, on $C_N$ and $C_F$) can be predicted on the basis of the geometrical theory of the Pulfrich effect. The present experiment thus provides a direct test of the adequacy of the proposed theory. It will also provide data that can be related to classical theory of binocular space discrimination and to theories concerned with retinal interaction effects of moving targets.

## Apparatus and Procedure

A schematic representation of the apparatus[3] is presented in Fig. 2A. A detailed description is available in a previous report (Lit & Hyman, 1951). The apparatus consists of three major components: (*a*) the oscillating target, (*b*) the fixation target, and (*c*) the lighting and screening units.

The *O* is seated in a dark room (*D*) and binocularly observes the fixation target (*FT*) and the oscillating target (*OT*) through a pair of circular artificial pupils (*E*) that are 2.5 mm. in diameter and adjustable for interpupillary separation. The artificial pu-

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

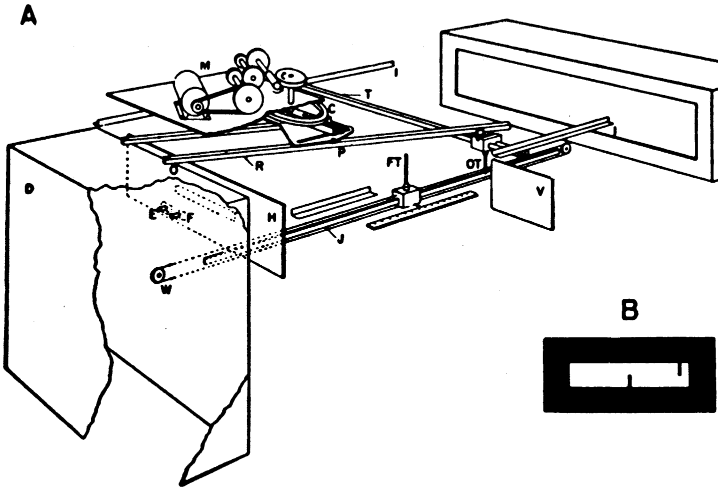


FIG. 2. Schematic representation of the apparatus and *O*'s view of stimulus targets. A. The *O* is seated in a dark room (*D*) and binocularly observes the fixation target (*FT*) located in the lower visual field and the oscillating target (*OT*) located in the upper visual field through a pair of artificial pupils (*E*). Movement of the oscillating target in a frontoparallel plane 100 cm. from *O*'s eyes can be varied over a wide range of constant linear velocities. The fixation target in *O*'s vertical median plane can be moved either toward or away from his eyes by means of a pulley wheel (*W*) located in the dark room. Background illumination is provided by a lightbox (*L*). The retinal illuminance of each eye is controlled by neutral density filters placed in the pair of filter boxes (*F*). Horizontal (*H*) and vertical (*V*) screens provide a constant rectangular field of view. B. The upper rod is the oscillating target; the lower rod is the fixation target. (From Lit & Hyman, 1951.)

pils are attached to eye-tubes which are mounted on the inner wall of the dark room. In front of each eye-tube, a filter box (*F*) is mounted on the outer wall so that *E* can control the retinal illuminance of each eye by combinations of neutral density filters. The *O*'s head is kept immobilized by means of chin and forehead rests.

The oscillating target (*OT*) is a blackened steel rod $\frac{1}{8}$ in. in diameter. It is vertically suspended downward to eye level from a Jacobs chuck in which it is retained. The chuck is centrally mounted on the undersurface of a supporting carriage which rides on horizontal tracks (*T*) located in a frontal plane at a distance of 100 cm. from *O*'s eyes. The carriage receives its movement from a horizontally oscillating drive-rod (*R*) which is pivoted at Position *O*, a point located in *O*'s median plane directly above the midpoint of the line joining the two eyes. Power for the drive-rod is provided by a cam-regulated mechanism (*C*) which converts constant angular velocity into reciprocating linear velocity, with the central 90% of stroke at constant speed. The power to the drive-rod is applied at a vertical pivot point (*P*) permanently mounted on the drive-rod. The electrically driven gear train (*M*) shown in Fig. 2A was replaced by a Zero-Max (Revco, Inc., Model 143) variable speed transmission device to allow adjustments of the linear velocity of the oscillating target over a wide range of values. Calibration of the transmission device was achieved by measuring the time required for the supporting carriage of the oscillating target to move through a fixed distance of 10 cm. in the central region of the elevated tracks (*T*) on which it rides. The time measurements were performed with an Electronic Precision Chronoscope (Wichita Apparatus Supply, Inc., Model 251). Thus, the linear velocity of the oscillating target is specified for all positions of the lever arm of the speed control link.

The fixation target (*FT*) is a blackened steel rod $\frac{1}{8}$ 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 (*J*) located in *O*'s vertical median plane. By means of a pulley wheel (*W*) located in the dark room, *O* can adjust the position of the fixation target in a direction either towards or away from his eyes. The distance of the fixation target from *O*'s eyes, as measured along the metal track, can be read by *E* from a scale calibrated in millimeters. The use of a vernier index permits *E* to estimate the distance of the fixation target to within 0.01 cm. The height of the upper end of the fixation target is set on a level with *O*'s eyes. Thus, when the oscillating target is at a position directly above the fixation target, the targets appear contiguous in *O*'s vertical median plane. At this distance (100 cm.) from *O*'s eyes, the diameter of each rod subtends a visual angle of 10.9 minutes of arc.

Uniform background illumination is provided by ten 150-w. frosted lamps that are appropriately mounted in an asbestos lined, galvanized iron lightbox (*L*). The lightbox is located in a frontal plane 250 cm. from *O*'s eyes. Lamp voltage is maintained constant (to within $\pm 1.0\%$) 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 lightbox. The surface has a luminance of 854 ft.-L. as measured with a Macbeth illuminometer. 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. The field of view in the vertical direction is kept constant at 4.2° by a horizontal slit (26 cm. × 1.5 cm.) cut at eye level in a black vertical screen (*H*) located 21 cm. in front of *O*. The field of view in the horizontal direction is kept constant at 21.6° by means of a pair of vertical screens (*V*) (only one screen is shown in Fig. 2A) adjusted symmetrically in the plane of the oscillating target, 0.5° beyond the end-points of its reciprocating stroke. The view of the targets as seen by *O* is shown in Fig. 2B.

Two trained graduate students who were emmetropic served as paid *O*s. The monocular visual acuity of each *O* was better than 20/20, and the ductions of each were normal at both distance and near. At a fixation distance of 100 cm., the interpupillary separation for Observer F. C. was 6.20 cm. and that for Observer M. M. was 6.70 cm. At this fixation distance, the phoria for Observer F. C. was $3^{\Delta}$ exophoria and that for Observer M. M. was $1^{\Delta}$ esophoria.

Daily practice sessions were held for a period of about a month during which *O*s were trained in the procedure of localizing the apparent near and far positions of the oscillating target at various target velocities and under different amounts of unequal binocular retinal illuminances, $\log(E_R/E_L)$. In performing his settings, *O* continuously fixates the upper end of the movable fixation rod and adjusts this rod in the vertical median plane until it appears to lie directly below the near and far paths of the oscillating target. The apparent near and far positions of the oscillating target are each localized first when the fixation rod is moved away, and again when it is moved toward *O*. In this way, multiple pairs of determinations of $C_N$ and $C_F$ can be obtained under any given set of viewing conditions. With filters of equal optical density in front of the eyes, only a single path of the oscillating target was reported; that is, no Pulfrich effect was elicited at any given velocity under conditions of equal binocular retinal illuminance.

Settings for the apparent near and far positions of the oscillating target were obtained from both *O*s at each of 11 target velocities, *V*: 2.59, 5.90, 8.16, 10.28, 13.76, 19.96, 26.86, 35.56, 45.01, 55.53, and 68.17 cm./sec. For target movement in a frontoparallel plane located 100 cm. from *O*'s eyes, these values of linear velocity correspond to the following angular velocities: 1.49, 3.38, 4.68, 5.89, 7.88, 11.44, 15.39, 20.37, 25.78, 31.81, and 39.05 deg./sec. In a given experimental session only one target velocity was used and five pairs of settings (10 readings each for $C_N$ and $C_F$) were obtained from each *O* for each of four conditions of increasing inequality of binocular retinal illuminance, $\log(E_R/E_L)$. The retinal illuminance of the left eye ($\log E_L$) was held constant at 2.06 log trolands by use of a neutral filter of optical density 2.10. The retinal illuminance of the right eye ($\log E_R$) was successively increased by use of neutral filters of optical densities 1.98, 1.52, 1.03, and 0.52. Thus, the four values of $\log(E_R/E_L)$ used at each of the 11 target velocities were: 0.12, 0.58, 1.07, and 1.58. A total of 22 experimental sessions was held for each *O*. A counterbalanced order was introduced for target velocity. That is, for the first 11 sessions the target velocity was presented in order of increasing magnitude, and for the second 11 sessions the target velocity was presented in decreasing order.

## RESULTS

The results for both *O*s are presented in Table 1. Each entry of

TABLE 1

Depth Displacements (in centimeters) Obtained at Each of 11 Target Velocities under Four Conditions of Unequal Binocular Retinal Illuminance, log $(E_R/E_L)$

| Target Velocity Cm. per Sec.) | log $(E_R/E_L)$ = 0.12 | | | | log $(E_R/E_L)$ = 0.58 | | | | log $(E_R/E_L)$ = 1.07 | | | | log $(E_R/E_L)$ = 1.58 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | F. C. | | M. M. | | F. C. | | M. M. | | F. C. | | M. M. | | F. C. | | M. M. | |
| | $C_N$ | $C_F$ | $C_N$ | $C_F$ | $C_N$ | $C_F$ | $C_N$ | $C_F$ | $C_N$ | $C_F$ | $C_N$ | $C_F$ | $C_N$ | $C_F$ | $C_N$ | $C_F$ |
| 2.59 | 0.13 | 0.20 | 0.33 | 0.39 | 0.48 | 0.46 | 0.63 | 0.59 | 0.74 | 0.75 | 0.85 | 0.82 | 0.95 | 0.98 | 1.07 | 1.03 |
| 5.90 | 0.27 | 0.19 | 0.44 | 0.42 | 0.80 | 0.70 | 0.85 | 0.94 | 1.28 | 1.16 | 1.37 | 1.35 | 1.63 | 1.48 | 1.93 | 1.93 |
| 8.16 | 0.41 | 0.27 | 0.35 | 0.62 | 1.12 | 0.97 | 1.09 | 1.22 | 1.55 | 1.48 | 1.67 | 1.63 | 1.99 | 1.90 | 2.17 | 2.27 |
| 10.28 | 0.54 | 0.21 | 0.49 | 0.70 | 1.43 | 1.07 | 1.26 | 1.50 | 2.05 | 1.68 | 2.04 | 2.18 | 2.45 | 2.14 | 2.49 | 2.77 |
| 13.76 | 0.83 | 0.38 | 0.61 | 1.01 | 1.91 | 1.36 | 1.58 | 1.88 | 2.57 | 2.09 | 2.42 | 2.77 | 3.08 | 2.79 | 3.24 | 3.45 |
| 19.96 | 1.31 | 0.19 | 0.61 | 1.29 | 2.69 | 1.61 | 2.15 | 2.64 | 3.52 | 2.73 | 3.30 | 3.76 | 4.12 | 3.45 | 3.74 | 4.99 |
| 26.86 | 2.01 | 0.82 | 0.72 | 1.67 | 3.54 | 2.23 | 2.67 | 3.60 | 4.64 | 3.24 | 3.74 | 5.18 | 5.98 | 4.54 | 4.80 | 6.38 |
| 35.56 | 2.58 | 0.57 | 0.87 | 2.23 | 4.77 | 2.21 | 2.42 | 4.21 | 6.07 | 3.49 | 4.52 | 6.74 | 7.41 | 5.27 | 5.77 | 8.88 |
| 45.01 | 3.15 | 0.58 | 0.97 | 2.01 | 5.45 | 2.50 | 3.43 | 4.64 | 7.32 | 4.33 | 5.37 | 7.85 | 9.08 | 6.35 | 6.82 | 9.48 |
| 55.53 | 3.72 | 0.05 | 0.77 | 2.79 | 6.62 | 2.13 | 4.41 | 6.63 | 8.93 | 3.73 | 6.88 | 9.45 | 10.70 | 6.21 | 8.42 | 12.33 |
| 68.17 | 4.22 | 0.02 | 0.60 | 5.70 | 7.50 | 1.45 | 4.46 | 9.89 | 10.66 | 3.46 | 7.64 | 13.30 | 12.57 | 5.95 | 9.40 | 15.74 |

Note.—The retinal illuminance of the left eye, log $E_L$, was kept constant at 2.06 log trolands. $C_N$ and $C_F$ refer, respectively, to the near and far displacements of a black vertical rod oscillating in a frontoparallel plane located 100 cm. from *O*'s eyes. Each entry for the two *O*s (F[illegible] and M. M.) is based on the mean of 20 settings. The thickness of the stimulus target used was 0.125 in.

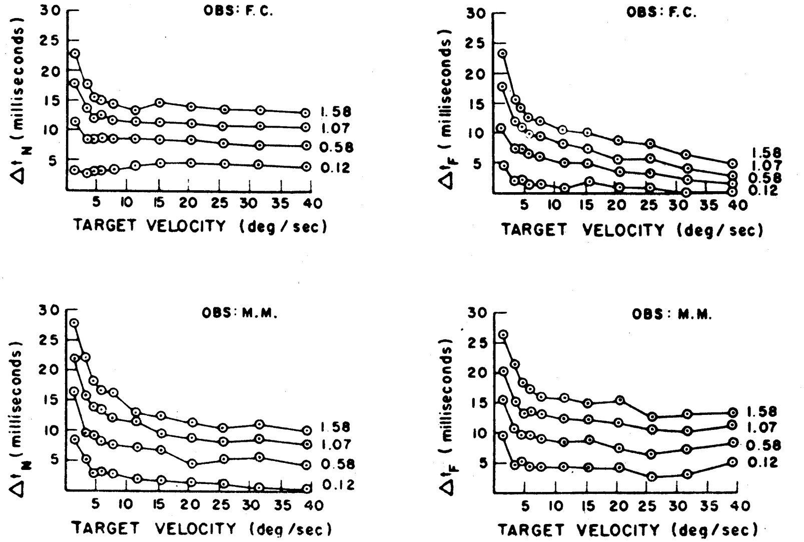


FIG. 3. Latency differences as a function of target velocity for four conditions of unequal binocular retinal illuminance. The latency differences ($\Delta_N$ and $\Delta_F$) were computed from Equation 4 for the corresponding near and far displacements ($C_N$ and $C_F$) given in Table 1. The number accompanying each curve represents the prevailing magnitude of log $(E_R/E_L)$, where the retinal illuminance of the left eye, log $E_L$, is kept constant at 2.06 log trolands. Each point is based on the mean of 20 readings.

$C_N$ and $C_F$ represents the mean value (in centimeters) of two sets of 10 readings obtained at each target velocity under each of the four specified conditions of unequal binocular retinal illuminance.

Inspection of Table 1 reveals that, for any given value of log $(E_R/E_L)$, $C_N$ and $C_F$ progressively increase as target velocity is increased. $C_N$ and $C_F$ also progressively increase as log $(E_R/E_L)$ is increased at any given target velocity. A characteristic individual difference in performance should be noted: for Observer F. C. the values of $C_N$ are consistently larger than the corresponding value of $C_F$; for Observer M. M., contrariwise, the values of $C_N$ are consistently smaller than the corresponding values of $C_F$.

To facilitate analysis of these data in terms of the geometrical theory of the Pulfrich effect, the corresponding latency differences, $\Delta t_N$ and $\Delta t_F$, have been computed from Equation 4 for each set of values of $C_N$ and $C_F$ given in Table 1. The results of the computation are shown graphically in

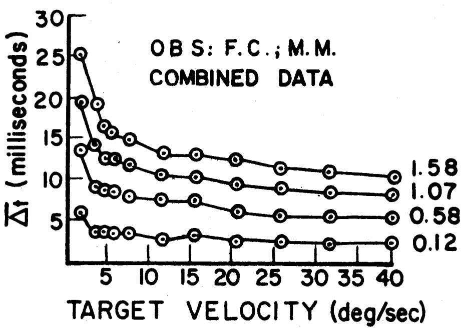


FIG. 4. Average latency difference as a function of target velocity for four conditions of unequal binocular retinal illuminance, log $(E_R/E_L)$. The average latency differences, $\overline{\Delta t}$, were obtained by combining the values of $\Delta t_N$ and $\Delta t_F$ in Fig. 3 for both *O*s. Thus, each point is based on the mean of 40 readings.

Fig. 3 where $\Delta t_N$ and $\Delta t_F$ (in milliseconds) are plotted for each *O* as a function of target velocity (in deg. per sec.) with log $(E_R/E_L)$ serving as parameter. A similar plot of the averages of the near and far latency differences, $\overline{\Delta t}$, for the combined data of both observers is shown in Fig. 4.

The curves in Fig. 3 and 4 for log $(E_R/E_L) = 0.12$ show that the computed values of $\Delta t_N$, $\Delta t_F$, and $\overline{\Delta t}$ remain essentially constant as target velocity is progressively increased. A slight upturn occurs, however, at the lowest target velocity for the curves representing this condition of slightly unequal binocular retinal illuminance. For the remaining curves, the upturn above their respective constant levels becomes more marked and occurs at progressively higher values of target velocity as the magnitude of inequality of binocular retinal illuminance is increased; for the curves representing log $(E_R/E_L) = 1.58$, the computed latency differences seem to be independent of target velocity for velocities greater than about 20 deg./sec. It is also to be noted from Fig. 3 and 4 that at any given target velocity the computed latency differences progressively increase in magnitude as log $(E_R/E_L)$ is increased.

The individual difference previously noted with respect to the relative magnitudes of $C_N$ and $C_F$ also prevails with respect to the relative magnitudes of $\Delta t_N$ and $\Delta t_F$: for Observer F. C., the values of $\Delta t_N$ are consistently larger than the corresponding values of $\Delta t_F$; for Observer M. M., the values of $\Delta t_N$ are consistently smaller than the corresponding values of $\Delta t_F$.

## Discussion

Of all stimulus factors known to influence the magnitude of the Pulfrich stereophenomenon, target velocity has been the variable most frequently studied by previous investigators (Arndt, 1930; Banister, 1932; Engelking & Poos, 1924; Holz, 1934; Liang & Piéron, 1947; Pulfrich, 1922; Wölfflin, 1925). Although in most of these experiments displacement settings were obtained for only limited ranges of target velocity or for only a single condition of unequal binocular retinal illuminance, the results invariably showed that the values of $C_N$ and $C_F$ were smallest at the lowest target velocity and progressively increased as target velocity was increased. The corresponding absolute magnitudes of the computed latency differences, $\Delta t_N$ and $\Delta t_F$, reported by these investigators, revealed considerable variability. When a dense blue filter was placed in front of one eye, Arndt (1930) found a computed latency difference of 1917 msec. for a target velocity of 0.04 deg. per sec. and a computed latency difference of 110 msec. for a target velocity of 6.67 deg. per sec. These data thus show a 17-fold decrease in latency difference as target velocity undergoes a 170-fold increase in magnitude. In contrast, the data of Holz (1934) revealed that, for a given blue filter, a computed latency difference of 97 msec. was obtained for a target velocity of 0.65 deg. per sec. and a computed latency difference of 16 msec. was obtained for a target velocity of 23.23 deg./sec. In this case, latency difference undergoes only about a 6-fold change. Holz also reported that the computed latency difference showed no further decrease in magnitude (below 16 msec.) as target velocity was respectively increased to values of 40.42 and 130.53 deg./sec.

The data of the present experiment (that is, the curves given in Fig. 4) seem to show better agreement with predictions based on the geometrical theory of the Pulfrich effect. For each of the specified differences of binocular retinal illuminance used, the respective magnitude of the computed average latency difference, $\overline{\Delta t}$, remains essentially constant as target velocity is systematically varied. Discrepancies appear primarily at low target velocities, particularly for the experimental curves representing large values of log ($E_R/E_L$). These discrepancies reflect the fact that as target velocity is progressively decreased the values of $C_N$ and $C_F$ obtained for the given curve become systematically slightly larger than the respective theoretical values required by Equation 4 to yield a given constant $\overline{\Delta t}$ for all target velocities.

A similar discrepancy for low target velocities occurs in the so-called sensation–time (*Empfindungszeit*) experiments of Fröhlich (1923) in which a vertical slit of light is moved in a frontoparallel plane directly behind a horizontal opening in a screen. To *O* seated directly in front of the screen, the moving target typically does not appear to come into view at the entrance edge of the horizontal opening but rather at some small lateral distance within the border of the screen aperture. Fröhlich attributed this effect to the visual latent period (*die Empfindungszeit*). He proposed that the magnitude of the sensation–time for any given set of observation conditions could be computed from the time difference between the actual and seen appearance of the moving target, that is, sensation–time = $d/v$, where $d$ is the lateral distance from the entrance edge at which the vertical target first appears to come into view and $v$ is the linear velocity of the target in its frontoparallel path. Experiments on the effects of target velocity (e.g., Holz, 1934) yielded sensation–time vs. target velocity curves for various target luminances that also characteristically show an upturn at low target velocities. That is, as target velocity is progressively decreased, the respective lateral distances from the entrance edge at which the target is localized by *O* become progressively smaller but at a rate considerably slower than that required to yield a given constant computed sensation–time for all target velocities. Holz (1934) obtained sensation–time measures under stimulus conditions that were identical to those prevailing in his experiment on the Pulfrich effect, that is, target velocities and target luminances were identical in the two studies. His results showed that, for each of the given target velocities, the algebraic difference between the magnitude of the sensation–time for the target having the lower luminance and the magnitude of the sensation–time for the target having the higher luminance yielded a value that was numerically equal to the respective computed latency difference obtained in his experiment on the Pulfrich effect.

Additional experiments on the effects of target velocity are required to clarify the reasons for the upturns in the latency difference vs. target velocity curves of Fig. 4. Of particular interest in this connection would be the results of additional experiments in which the thickness of the oscillating target is systematically varied and in which specified differences of binocular retinal illuminances are produced at many basic levels of illuminance.

The present experiment also provides data on the effects of specified differences in binocular retinal illuminance on the magnitude of the near and far displacements and their corresponding computed latency differences. The data show that, for each of the given target velocities, displacements $C_N$ and $C_F$ and their corresponding calculated latency differences, $\Delta t_N$ and $\Delta t_F$, progressively increase as log ($E_R/E_L$) is increased. As in the case of similar data obtained in an earlier experiment (Lit, 1949) the effects of variations in the magnitude of log ($E_R/E_L$) can be accounted for if the assumption is made that the hypothesized absolute visual latent period, $t$, is an inverse function of retinal illuminance, log $E$. A schematic representation of this relationship is shown in Fig. 5. In this figure, log $E_L$ represents the constant retinal illuminance of the left eye, and log $E_{R1}$, log $E_{R2}$, and log $E_{R3}$ represent the increased retinal illuminance successively produced in the right eye. It can be readily seen with the aid of Fig. 5 that the difference in absolute latency ($\Delta t$) theoretically increases as the difference in binocular retinal illuminance [log

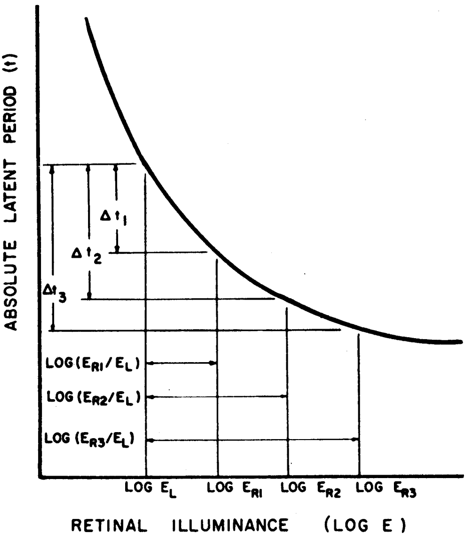


FIG. 5. The hypothesized absolute visual latent period ($t$) as a function of retinal illuminance (log $E$). The curve represents an assumed relationship proposed to account for the experimental fact that, for the given constant retinal illuminance of the left eye (log $E_L$), latency difference ($\Delta t$) increases progressively as the difference in binocular retinal illuminance [log $(E_R/E_L)$] is increased.

$(E_R/E_L)$] is increased. The specific rate of increase theoretically depends, of course, on the initial magnitude selected for the retinal illuminance of the left eye (log $E_L$).

When the data of the present experiment are plotted to show how $\overline{\Delta t}$ varies as a function of log $(E_R/E_L)$, with target velocity serving as parameter, the obtained curves (not given here) are in quantitative agreement with predictions based on the analysis of Fig. 5. The curves do not, however, overlap nor show the same shape for all target velocities. The curves representing low target velocities (below 10 deg./sec.) are considerably displaced progressively upward on the ordinate axis. The curves show a relatively more rapid rise in $\overline{\Delta t}$ as log $(E_R/E_L)$ is increased, an effect, of course, which reflects the lack of parallelism exhibited in the curves of Fig. 4.

From data obtained in an earlier experiment (Lit, 1949), it was possible to determine an empirical equation which describes the relationship existing between the hypothesized absolute visual latent period ($t$) and level of retinal illuminance (log $E$). The necessary computations were deferred pending the outcome of additional experiments concerned with evaluating the effects of systematic variations in distance of observation of the oscillating target, target velocity, and target thickness. It has since been established (Lit & Hyman, 1951) that latency difference is independent of distance of target oscillation. The present experiment demonstrates that, for small differences of binocular retinal illuminance, latency difference is independent of target velocity over a very wide range of velocities. The effects of systematic variations in target thickness will be studied next and the results reported separately.

Finally, mention should be made of the localization error that exists for the moving target when viewed under conditions of equal binocular retinal illuminance. For *O*s used in the previous experiments (Lit, 1949; Lit & Hyman, 1951) the oscillating target appeared to be moving in a frontoparallel plane located nearer than the plane defined by the "true" distance of the oscillating rod. The localization error occurred at all levels of equal retinal illuminance (Lit, 1949) and at all distances of observation (Lit & Hyman, 1951). A similar localization error occurred for *O*s used in the present experiment. At all target velocities, the oscillating target appeared nearer than the true plane of oscillation for Observer F. C. and farther than the true plane of oscillation for Observer M. M. It should be pointed out that the magnitude of the localization error for each *O* was insufficient to establish equality between the corresponding near and far computed latency differences. Thus, when the corresponding values of $C_N$ and $C_F$ were "corrected" for the localization error, it still turned out that $\Delta t_N > \Delta t_F$ for Observer F. C. and that $\Delta t_N < \Delta t_F$

for Observer M. M., particularly for the displacements produced by the larger differences of binocular retinal illuminance. In all cases, the computed average latency difference, $\overline{\Delta t}$, remained virtually unchanged when the respective values of $\Delta t_N$ and $\Delta t_F$ were each "corrected" for the localization error.

## Summary

When filters of unequal optical density are placed in front of the two eyes, a target which is actually oscillating in a frontoparallel plane appears nearer than it really is for one direction of stroke and farther than it really is for the return stroke (Pulfrich stereophenomenon). Measurements of the near and far displacements of a black vertical rod have been obtained for a wide range of target velocities under each of several conditions of unequal binocular retinal illuminance.

The experimental data show that, for any given difference in binocular retinal illuminance, the near and far displacements progressively increase as target velocity is increased. The data show also that, for any given target velocity, the near and far displacements progressively increase as the difference in binocular retinal illuminance is increased.

The obtained results are analyzed in terms of an hypothesized absolute visual latent period whose magnitude is assumed to be an inverse function of level of retinal illuminance. The results are shown to be in good quantitative agreement with predictions based on the geometrical theory of the Pulfrich effect. Discrepancies at low target velocities are noted and discussed.

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