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The Pulfrich effect, simple reaction time, and intensity discrimination

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Two observers' Pulfrich displacements and corresponding latency differences increased as the near-threshold inequality of binocular illumination, expressed as log (E_L/E_R), increased. For a constant value of log (E_L/E_R), the latency differences decreased as the illumination at the dimmer eye, log E_R, increased. The expected increase in visual latency at progressively lower illuminations was greater for simple monocular reaction times than for the relative latencies computed from the Pulfrich data, and the intensity-discrimination functions generated by the Pulfrich data at five near-threshold response criteria did not entirely replicate the functions found at higher criteria (Lit, 1949).

The present study is part of a long-range research program on the effects of conditions of illumination on visual latency, as measured by several different monocular and binocular experimental procedures. It is an extension of an earlier study reported by Lit (1949), in which the magnitudes of the near and far displacements of the Pulfrich stereophenomenon were measured at various levels of illumination.

The Pulfrich effect occurs when a target oscillating in the observer's frontal plane is viewed under conditions of unequal binocular illumination (Pulfrich, 1922). The oscillating target will then appear to rotate out of its plane of oscillation: the target will appear to be displaced in *front* of its actual plane of oscillation (near displacement) for one direction of target stroke and *behind* the plane of oscillation (far displacement) for the return stroke. The apparent displacements in depth were accounted for in terms of a hypothetical visual latency whose magnitude was inversely related to level of illumination (Pulfrich, 1922). Lit (1949) has presented a geometric analysis of the Pulfrich effect, including a detailed derivation of the equations that convert the near and far displacements (C_N and C_F) of the oscillating target into their corresponding near and far *latency differences* (Δt_N and Δt_F, the differences in latency between the two eyes at the near displacement and at the far displacement) . Lit (1968) also reported a brief summary of earlier systematic data obtained in his research program on the effects of several basic stimulus variables on the magnitude of the Pulfrich effect, variables such as observation distance (Lit and Hyman, 1951), target velocity (Lit, 1960), and the contrast of luminance of target and background (Lit, 1968).

In an earlier experiment on the Pulfrich effect (Lit, 1949), the effects of unequal binocular illumination -- that is, the effects of differences of illumination between the eyes, expressed as log (E_L/E_R) -- at many levels of illumination -- that is, levels of illumination in the dimmer eye, log E; specifically, log E_R -- were qualitatively consistent with the idea that absolute visual latency is inversely related to the level of illumination, a relationship reported by many investigators since the early study by Cattell (1886) on visual reaction time. In the present experiment, two observers were used to obtain data on both simple monocular reaction times and binocular Pulfrich displacements under comparable illuminations. This procedure allows a more direct and quantitative comparison of the two different response measures used to specify the relationship between visual latency and the level of stimulus illumination. Additionally, if the two measures are accepted as measures of comparable visual latencies, the procedure allows assessment of the role of the motor component in the total reaction-time response.

Data on the Pulfrich effect have also served (Lit, 1949) to test Hecht's theory of intensity discrimination (Hecht, 1935) by using several large magnitudes of the latency difference as constant response criteria. The intensity-discrimination functions were generated for the various latency differences by plotting the average of the near and far latency differences, $(\Delta t_N + \Delta t_F)/2 = \Delta t'$, as a function of increasingly unequal binocular illumination, log (E_L - E_R), or log ΔE, at several levels of illumination in the dimmer eye, log E. The intensity-discrimination functions that were generated in this manner differed systematically from Hecht's theoretical curve: Lit's (1949) empirical curves showed a marked tendency for log ($\Delta E/E$) to increase progressively at the larger values of log E, even more so as the chosen magnitude of the constant visual effect, $\Delta t'$, became greater. An additional goal of the present experiment was to provide a more suitable test of Hecht's theory. This was attempted by obtaining the average latency differences, $\Delta t'$, for just-perceptible displacements produced by near-threshold differences in binocular illumination, log ΔE.

METHOD

Subjects

Two students experienced in making the Pulfrich displacement settings and simple visual reaction-time responses served as paid observers. One observer, A.M., was emmetropic; the second, W.D., was myopic and his distance vision in each eye was corrected to 20/20 by placing a -2.0 diopter ophthalmic lens in front of each eyepiece. The interpupillary separation for both observers was 6.4 cm at the testing distance of 100 cm.

Apparatus

Pulfrich settings

The apparatus used in the measurement of the Pulfrich settings has been fully described and illustrated in previous reports (Lit, 1949; Lit and Hyman, 1951; and Lit, Finn, and Vicars, 1972). It requires a judgment similar to that with the two-rod Howard-Dolman depth-testing device (Howard, 1919).

The standard (oscillating) target is a self-illuminated vertical glass rod, .58 cm in diameter, located in the upper half of the observer's visual field at an observation distance of 100 cm. The target is suspended downward to eye level from a lightbox mounted on the undersurface of a carriage that rides in a frontal plane on horizontal tracks. A variable-speed transmission device produces a reciprocating and linear movement of the target at a constant speed of 28.75 cm per sec (16.36 deg per sec) throughout the middle 90% range of its movement, by means of a specially designed cam-and-shaft system (Lit and Hyman, 1951).

The variable (fixation) target is a similar illuminated vertical glass rod located in the lower half of the observer's visual field. It is held vertically upright to eye level from a lightbox similar to the one used for the oscillating target, and it rides on a calibrated horizontal metal track along the observer's median plane. Each observer was seated in a darkroom and binocularly viewed the upper and lower targets through a pair of circular artificial pupils, 2.5 mm in diameter, adjustable for interpupillary separation. He was required to maintain continuous fixation on the upper edge of the lower (fixation) target while making his equidistance settings. He could adjust the distance of the fixation target in his median plane along the calibrated track by means of a pulley wheel located in the observer's darkroom. A vernier index on the experimenter's side of the calibrated track allowed estimation of the distance of the fixation target from the observer's eyes to within .1 mm.

Both the oscillating and the fixation targets, when illuminated, produced an unfiltered retinal illumination of 3.78 log trolands, as calculated from measurements obtained with a Macbeth illuminometer. No background illumination was used (i.e., the contrast of luminance of target and background was 100%). Discrete variations in illumination could be produced by placing Kodak Wratten neutral-density filters in a pair of filter boxes located in front of the eyepieces on the outside wall of the observer's room.

Monocular reaction times

The measurements of reaction time were obtained on the same two observers by use of a two-channel Harvard tachistoscope (Gerbrands model T-1C series).

Each subject monocularly viewed with his right eye an illuminated vertical slit that had the same retinal size and shape as the glass targets used to measure the Pulfrich settings. An artificial pupil, 2.5 mm in diameter, was provided. A target exposure of 20 msec was used in order to provide for each retinal receptor an exposure duration approximately equal to that produced by the oscillating Pulfrich target. The reaction times were measured with a Beckman EPUT and timer, model 5230, to a decimal fraction of 1 msec. The onset of stimulation was signaled by a photocell mounted at the rear of the light housing; the signal served to trigger the timer. When the observer depressed a microswitch with the forefinger of his preferred hand, the timer was stopped.

The stimulus channel contained a ground-glass plate that was illuminated from behind by four fluorescent (G.E. F4T5-cw) lamps whose rise time was approximately 10 msec and whose fall time was about 5 msec. The glass plate was masked by a centrally located screen to provide a rectangular stimulus target, 3.42 cm long and .42 cm wide. Because of shelf-space limitations, the rectangular target was at an observation distance of 72.5 cm (rather than at 100 cm); but the desired angular size of the target was maintained (162 by 20 min of arc). The target light provided an unfiltered retinal illumination of 4.24 log trolands. Wratten neutral-density filters were placed in the eyepiece to vary the target illumination in discrete steps.

Procedure

Pulfrich settings

Each observer was dark adapted for a period of 20 min before the start of each session. For the measures of the Pulfrich settings, he was required to make equidistance settings by manually adjusting the distance of the lower (fixation) target until it appeared to lie in the same frontal plane as that of the upper (oscillating) target. Experimental testing began with the condition of equal binocular illumination, in which the upper target appears to oscillate in a single frontal plane. The observer was required to make 10 successive equidistance settings under this control condition.

Displacement settings were then made under each of five conditions of increasingly unequal binocular illumination. In these conditions, the retinal illumination of the right eye (log E_R) was held constant during a given session and that of the left eye (log E_L) was increased in steps of .1 log units. For each condition of unequal binocular illumination at a given constant value of log E_R, the observer made six pairs of equidistance settings: six at the apparent near displacement and six at the apparent far displacement. A total of 10 levels of log E_R was used, ranging from -1.00 to 3.47 log trolands in steps of approximately .5 log unit. Each experimental session was replicated, so that a total of 20 sessions was held for each observer.

Monocular reaction times

Each observer was dark adapted for a period of 29 min before the start of each session. For these measures of reaction time, each observer made 11 responses at each of the 11 levels of illumination, presented monocularly to the right eye in increasing order of illumination during an experimental session. The illumination values ranged from -1.0 to 4.0 log trolands in steps of .5 log unit.

Each session was replicated six times for each observer, yielding a total of 66 responses at each level of illumination for each observer.

RESULTS AND DISCUSSION

Pulfrich settings

The average of the near and far latency differences, $\Delta t'$, or $(\Delta t_N + \Delta t_F)/2$, was computed from the corresponding displacements, C_N and C_F, at the 10 values of log E_R. Since the results for the two observers were highly similar, the combined data for $\Delta t'$ are plotted in Figure 1 as a function of log (E_L/E_R).

A detailed derivation and analysis of the equations used to compute the near and far latency differences (Δt_N and Δt_F), based on the corresponding near and far displacements (C_N and C_F), is given by Lit (1949, 1960, 1968). The specific equations used are

$$\Delta t_N = [2b/V]\,[C_N / (d - C_N)] \text{ and } \Delta t_F = [2b/V]\,[C_F / (d + C_F)],$$

where $2b$ represents the observer's interpupillary separation, V is the target velocity, and d is the distance of the plane of target oscillation from the observer's eyes.

The curves in Figure 1 indicate that as log (E_L/E_R) increased, the average latency difference, $\Delta t'$, systematically increased at all levels of

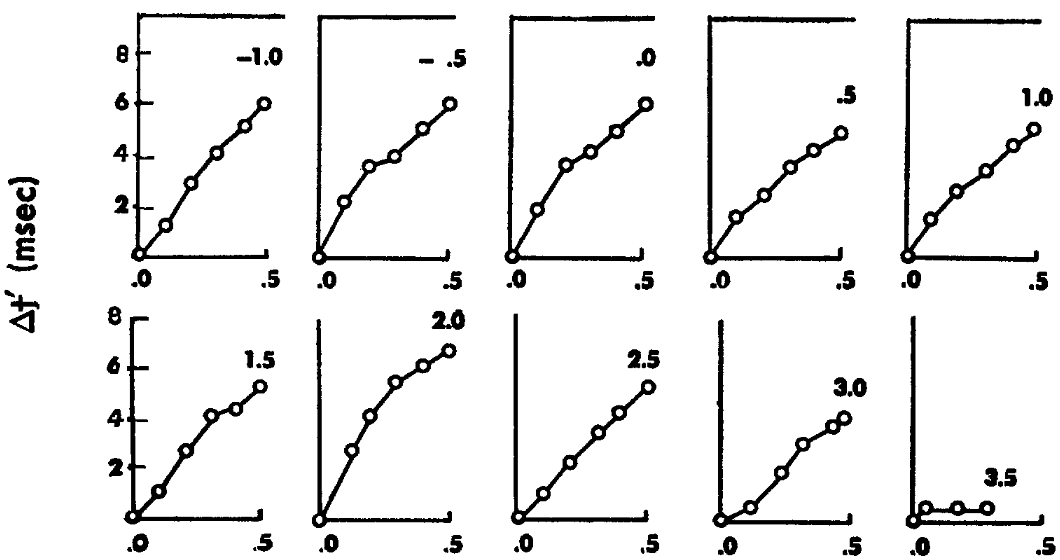

Figure 1. Average latency differences, $\Delta t'$, as a function of inequality of binocular illumination, log (E_L/E_R). The curve for each of the 10 levels of illumination, log E_R, represents the combined data of two observers, W.D. and A.M.

illumination, log E_R. At the highest level of illumination (log E_R = 3.5), observer W.D. reported no displacement (i.e., $\Delta t'$ = 0 msec) under any variation of binocular illumination. At this same level, observer A.M. reported very small displacements under log (E_L/E_R) = .1, but the increasing differences in the inequality of binocular illumination did not produce any appreciable increase in $\Delta t'$.

The variability of the data for each observer (i.e., the average deviation of each group of six near and far settings), expressed in terms of average latency difference, $\Delta t'$, decreased from 1.1 msec at the lowest level of illumination (log E_R = -1.0) to an asymptotic value of about .8 msec for levels of illumination greater than 1.0 log troland. For both observers, no systematic difference in variability was noted for the five conditions of unequal binocular illumination produced at each of the 10 levels of illumination.

The results in Figure 1 are in qualitative agreement with predictions based on the latency hypothesis of the Pulfrich effect and with the results of earlier studies by Lit (1949, 1960) and Lit and Hyman (1951). The latency hypothesis predicts that at all levels of illumination, the magnitude of the apparent displacements should progressively increase as the inequality of binocular illurnination is increased. The rate of increase in the apparent displacements should, however, become larger in magnitude as the differences in binocular illumination are produced at progressively lower *levels* of illumination. The curves in Figure 1 do not clearly exhibit the expected marked and progressive increase in slope as the level of illumination (log E_R) was decreased, particularly for the lowest values of log E_R.

When the binocular illumination of the two eyes was equal, both observers reported that the target's motion appeared to be restricted to a single frontal plane. Under these control conditions, the obtained equidistance settings yielded threshold data on the angular magnitude of the constant errors, $\eta_{\Delta R}$, and that of the variable errors, η_{AD}, as measured by the average deviation of the settings. The results (not presented here) showed that the localization error, $\eta_{\Delta R}$, did not vary systematically with illumination, log E_R, but that the variable errors, η_{AD}, progressively decreased to a final asymptotic value as illumination increased. These results are completely consistent with comparable data on stereoscopic acuity for oscillating targets reported in earlier studies (e.g., Lit and Hamm, 1966).

Because Pulfrich settings arise from a difference in binocular illumination, ΔE, Lit (1949) proposed using the average latency difference, $\Delta t'$, as a constant response criterion for generating (binocular) intensity-discrimination functions. The data of the present experiment uniquely allow selecting such criteria at near-threshold values ($\Delta t'$ = 1, 2, 3, 4, and 5 msec). These values of $\Delta t'$ supplement the much larger ones used by Lit in his 1949 study. In this experiment, the curves in Figure 1 were used to determine, at each of the 10 levels of illumination, what increases in the illumination of the left eye were required in order to produce each of the five specified values of $\Delta t'$. The obtained differences in binocular illumination, log ΔE, or log (E_L - E_R), at each of the 10 levels of illumination, log E_R, were used to plot five intensity-discrimination functions; that is, to plot log ($\Delta E/E$) versus log E, with the five values of $\Delta t'$ serving as parameter. The experimental curves (not shown here) revealed that that the values of log ($\Delta E/E$) for a given value of $\Delta t'$ were essentially *constant* at all log E values. The curves were, however, vertically displaced upward on the log ($\Delta E/E$) axis in the expected systematic manner: the larger the selected $\Delta t'$, the more the corresponding curve was displaced toward larger values of log ($\Delta E/E$). The marked upturn of the curves at high levels of illumination that Lit (1949) had unexpectedly obtained with high criteria did not occur with the near-threshold criteria of the present experiment. But neither did the upturn typically found at low levels of illumination. Further analysis and experimentation are required to clarify these discrepancies, particularly in view of the fact that Vicars and Lit (1975) have shown that classical intensity-discrimination funtins can be generated from experiments in which various magnitudes of monocular reaction time are selected as constant response criteria.

Monocular reaction time

The results of the measurements of reaction time of the same two observers were combined and are presented in Figure 2. The ordinate scale on the left gives the values in msec. Each data point represents the combined mean of six median reaction times obtained from each observer at each of the 11 levels of illumination used. The data show, as expected, that reaction time decreased with negative acceleration as log E_R increased. At the highest level (log E_R = 4.0 log trolands), reaction time approached an asymptotic low value.

Both measures

The combined data on the Pulfrich effect for the two observers were used to generate a relative latency (t) versus log E function. The method of successive summation of latency differences, starting at the highest level of illumination, was used, in a manner similar to that employed by Alpern

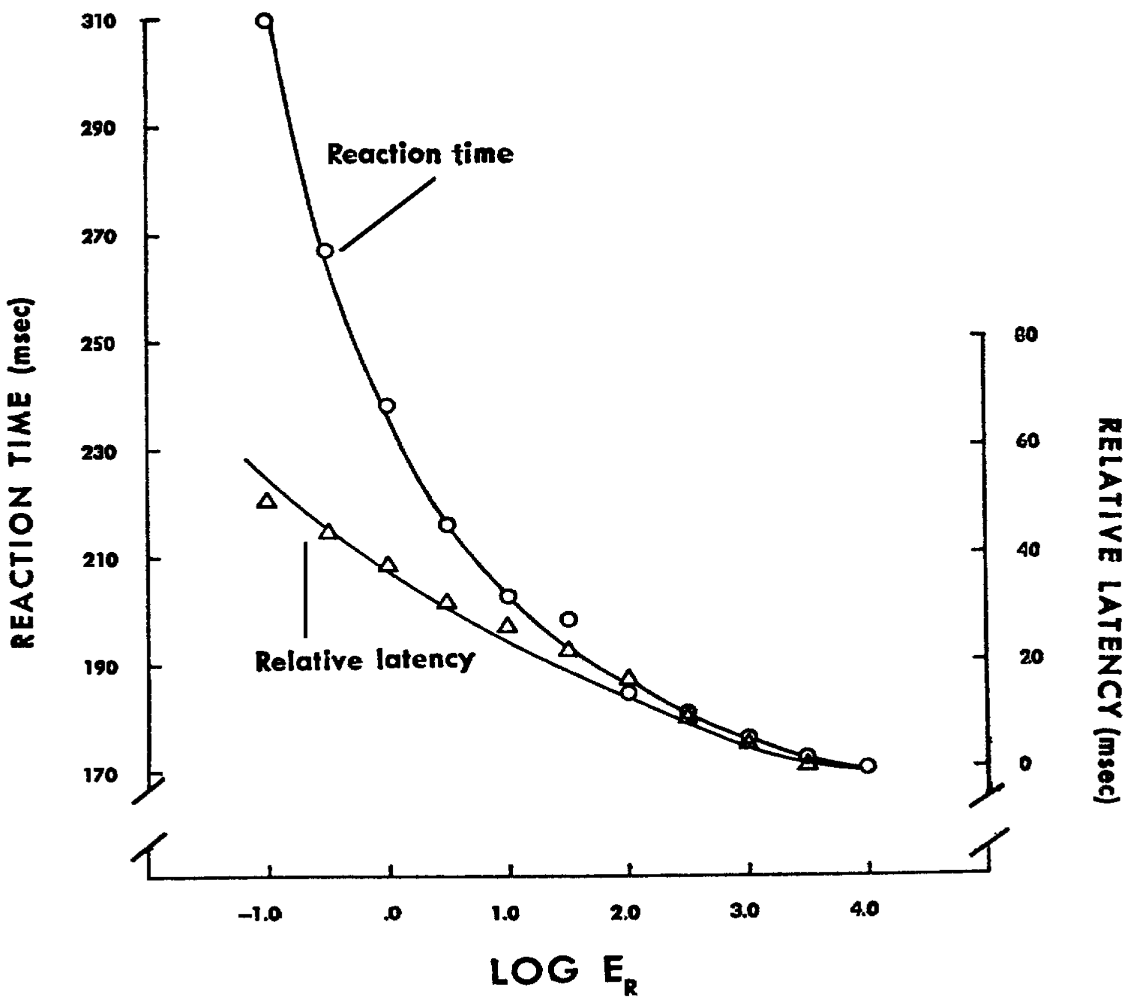

Figure 2. Average median reaction time (circles) and relative latency based on the Pulfrich settings (triangles) plotted as function of level of illumination, log E_R. The curves represent the combined data of two observers, W.D. and A.M.

(1968) and by Wilson and Anstis (1969), to obtain measures of relative latency, t, at each level of illumination, log E_R. That is, the relative-latency curve was generated by using successive unit-intensity steps of log $(E_L/E_R) = .50$. The ordinate scale on the right gives the relative latencies based on the Pulfrich settings. It was anticipated that the two curves in Figure 2 would have the same shape, since earlier experimental results on such settings obtained under conditions of increasing binocular differences at various levels of illumination could be qualitatively accounted for on the basis of an absolute visual latency whose magnitude was presumed to be inversely related to level of illumination (Lit, 1949).

Comparison of the two curves in Figure 2 indicates that while the relative latency based on the Pulfrich settings decreased as the level of illumination increased, the two curves coincide only at high levels of illumination. The progressive upturn of the two curves at increasingly lower levels of illumination is much greater for the reaction times than for the Pulfrich settings. The discrepancy between the shapes of the two curves could reflect the effects of differential increments in latency contributed by the motor component of the reaction-time response at different levels of illumination; that is, the motor contribution to the total reaction-time response may not be of equal magnitude at all levels of illumination. A comparison of the effects of level of illumination on reaction times, on relative latencies based on Pulfrich settings, and on measures of the implicit times of various wave components of the visual evoked cortical potential should help to clarify the discrepancy of the shapes of the curves in Figure 2.

Notes

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