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Interocular intermittence, retinal illuminance, and apparent depth displacement of a moving object

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A moving object was viewed in delayed, interocularly intermittent exposures of equal duration to the two eyes. A range of period-of-common view was presented in conjunction with two levels of luminance manipulated by optical filter. This approach was used to obviate the "average luminance difference" inherent in the use of unequal exposure durations to the two eyes. Apparent depth displacements of the path of the moving object were obtained for combinations of period-of-common view and luminance not specific to either the Mach-Dvořák or Pulfrich-Fertsch phenomena. Physical delay of interocular intermittence was found to be additive with interocular average luminance difference in the sense that the "dimmed eye" was equivalent to the "lead eye." Increased apparent depth was obtained for physical delay when overall luminance was decreased. An explanation of the results based on interocular interaction is suggested.

In 1872, Dvořák observed that the path of a moving object appeared displaced in depth when viewed through an episcotister. The episcotister sequenced the views of the two eyes, left eye before right eye or vice versa, without common view, in *short* repetitive exposures (Lee, 1970a, 1970b; Michaels, Carello, Shapiro, & Steitz, 1977). It was as though the dichoptic views were stereoscopically combined as disparate pairs (Lit, 1978). Harker (1967) used an episcotister that provided relatively *long* and *overlapping* views to the two eyes. He observed that the presence of a period of common view as part of the dichoptic sequence did not disrupt the stereoscopic depth displacement although there could be no geometric disparity during the binocular interval. This finding suggested that stereoscopic combination of the views to the two eyes was point for point from onset to offset negating the simultaneous presence on both retinas of the nondisparate, moving stimulation during the period of common view.

Subsequently, Harker (1973) lengthened to *continuous view* the exposure duration to the lag eye, that is, the eye stimulated second in the dichoptic sequence. (Lengthening the exposure to the lead eye resulted in reversal of the direction of the apparent depth displacement, suggesting that the intermittent stimulation was processed first in the binocular excitation.) Apparent depth displacement of the path of the moving object persisted, even though continuous view to one eye restricted the potential for stereoscopic combination to the nondisparate stimulation from the fixed and moving objects simultaneously present in the binocular view. In this empirical formulation, there was no "disparity" of physical delay in the "dichoptic" sequence. Evidently, the phenomenon, which was originally seen as a way of viewing disparate pairs without a stereoscope (Münsterberg, 1894; Sanford, 1894), utilizes mechanisms fundamental to the association of the excitation from the two eyes, the "correspondence problem" of Poggio and Poggio (1984).

The relation of the direction of apparent depth displacement to the direction of object motion with continuous view to one eye and intermittent view to the other was that of viewing the moving object with different adaptation states of the two eyes, that is, the same as that of the Pulfrich-Fertsch effect (Lit, 1949; Pulfrich, 1922; Rogers & Anstis, 1972; Standing, Dodwell, & Lang, 1968). It was as though luminance to the individual eye averaged over the dichoptic sequence was the equivalent of luminance reduced by optical filter. With the intermittent view—the reduced average luminance— presented to the left eye, the depth displacement relative to object motion, when referred to a pendulum viewed from above, was clockwise. The depth relations were also clockwise when the left eye was the lead eye in the interocular dichoptic sequence with or without a period of common view. The direction of apparent depth displacement was reversed when the right eye was the lead eye.

In the classical Mach-Dvořák situation and explanation, that is, for short exposure durations without a period of common view, the stereoscopic displacement of the path of the moving object was assumed to be a function of the object's velocity and the interocular delay. Fusion of simultaneous cortical excitations was possible because persistence of vision could bridge the interocular delay. Reti-

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nal illuminance or stimulus intensity was not considered. Movement of the object during the delay was sufficient to generate the apparent stereoscopic disparity. Fusion of the equal dichoptic exposures posed no question of theory or explanatory mechanism.

With extended views of potentially *unequal* duration, point for point combination as implied in the classical explanation is not appropriate. Portions of the spatial distribution of stimulation in the longer exposure to the one eye are not complemented in the shorter exposure to the other eye. Points of reference—localization of the moving object within the extended retinal stimulation—could provide the needed basis for stereoscopic association. Such referents have been variously assumed to occur at onset and/or offset of the intermittent stimulation (Harker, 1973), or in a "spatiotemporal integration" of the spatially distributed excitation on the retinas (Lit, 1978). The resultant retinal localizations would provide the disparate corresponding points for classical, geometric analysis of the obtained depth displacement (Brauner, 1973; Lit, 1978). Stereoscopic indices (Harker, 1973) are seen as the neural equivalents of these disparate localizations. They might be generated cortically, at the retinas, or anywhere in between.

In the formulation of Lit (1978), "retinal illuminance" affected the strength of inhibitory processes such that retinal excitation persisted longer with lower luminance. Offset of stimulation to the lag eye controlled the timing of the stereoscopic indices by "updating" the spatiotemporal integrations, that is, termination of the dichoptic sequence initiated neural processing. Thus, the retinal localization of the moving object, at moderate retinal illuminances, would lag the physical termination of stimulation. With "dimming," the stereoscopic index would shift against the direction of object motion, away from the offset of stimulation. Or contrariwise: with an increase in stimulus luminance, the localization of the moving object would shift in the direction of object motion. In Lit's experimental situation, retinal illuminance was a function of the background luminance. The moving object was a silhouette. In the experimental situation of Harker (1973), the moving objects were in bright line on a dimmer background. The luminance of the moving objects and their background were manipulated together, with the same result.

Given a constant velocity, the point-to-point distribution of stimulus energy in the stimulation from the moving object would be constant. An increase in exposure duration would extend that spatial distribution but would not increase the local retinal illuminance. Yet, given optical scatter within the eye and an intermittent sequence of fixed cyclic interval or constant dark interval (RC or RD of Lit, 1978), a higher adaptation state or average retinal illuminance would result with a change in duty cycle. This consequence of intermittent stimulation should be particularly noteworthy when the duty cycle of one eye is held constant and that of the other is changed.

The potential equivalence of manipulating retinal illuminance by optical reduction of the stimulus intensity and/or by the duty cycle of the monocular views complicates the interpretation of results obtained with unequal exposure durations to the two eyes. In the experiments of Harker, Brauner, and Lit cited above, as well as that of Michaels, Steitz, and Carello (1979), the experimental approach was that of holding the exposure duration to one eye constant and increasing the duration of the exposure to the other eye with cyclic interval held constant. The intent was to demonstrate the role of delayed onsets and offsets as separate entities or the role of extended exposure duration per se. The obtained results were definitive and were interpreted in terms of the variables manipulated. However, in every instance, the depth displacements achieved are completely consistent as to direction and relative magnitude with the concomitant variation of differential average retinal illuminance present as a consequence of the unequal exposure durations.

In light of the above, the present study sought to elucidate the role of onset, offset, and luminance with *equal* intermittent exposures of a moving object. Incrementing a period of common view between the onsets and offsets separated in time and retinal distance the asymmetries of stimulation at onset and offset. With a period of common view, interocular delay sequenced the stimulation at onsets, from monocular in the lead eye to binocular, and at offsets, from binocular to monocular in the lag eye. The incremented duration was seen to measure the increased presence of nondisparate stimulation that was expected to oppose the effect of interocular delay. An "exposure duration effect," as formulated by Lit (1978), was not considered a possibility in view of the equal average luminance to the two eyes. Manipulation of differential and overall luminance by optical filter permitted the interaction of retinal illuminance with onsets and offsets of stimulation without confounding.

METHOD

Two luminance levels of the movable stimulus were combined with five durations of common view (Table 1). The two luminance levels permitted an interocular luminance difference favoring either eye as well as equal luminance to both eyes at two levels. The luminance combinations were repeated with continuous view to permit comparison.

To restrict stable, interocular stimulus relations to the delay sequence, a random duration of exponential distribution (0-175 msec duration; median, 46 msec; mode, 0 msec) was added to the cyclic interval (Figure 1). The 45-msec interocular delay, onset to onset, was chosen because it gave a reasonable impression of depth

Table 1
Stimulus Parameters

Period of Common View	Stimulation Interval	Minimum Dark Interval (Dark/Light Ratio 3:1)
0	45	135
15*	60*	180*
30	75	225
45	90	270
60	105	315

Note—Values in milliseconds. Juminance levels: full bright = 108 cd/m², .8 log dimmed = 17.1 cd/m², background = 1.34 cd/m².
**Illustrated in Figure 1.*

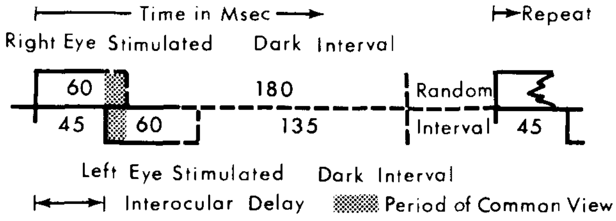

Figure 1. Time order of stimulation sequence. The enclosed intervals were periods of stimulation (moving stimulus illuminated); the open intervals were periods of nonstimulation (moving simulus not illuminated). Intervals in solid line were fixed and held constant; intervals in dotted line were varied. The associated table gives the time parameters and luminances.

displacement in the experimental situation. Since increasing the stimulation interval could have the effect of increasing the average retinal illuminance, the dark interval (neglecting the random increment) was increased in constant ratio (3:1) to the stimulation interval.

Apparatus

Data were taken in a large stereoscope with transilluminated stimuli. Both the movable and the fixed stimuli were presented stereoscopically. Intermittence and sequencing of the movable stimuli were achieved by electronic control of matched light sources that were interchanged halfway through each session of data collection to counterbalance any residual luminance difference. The timing circuits, based on a pulse counter, were capable of 1-msec accuracy. The luminance of the bright portions of the displays without filter reduction was 108 cdm^{-2}, as measured from the observer's position with a Spectra Pritchard photometer. The reduced level of luminance, 17.1 cdm^{-2}, was achieved by viewing the displays through neutral gelatin filters of .8 optical density. Binocular association of the eyes was facilitated by a referent configuration and the stereo-wandermark, which were always in view. Disappearance of the moving stimuli during the off interval was assured, and the general adaptation of the observer's eyes maintained, by a background luminance of 1.34 cdm^{-2}. All light sources were dc-operated cool white flourescent tubes diffused by translucent sheet acrylic. To obviate potential difficulties in aligning the stereoscope to the observer, the displays were viewed with natural pupils. Any discrepancy between conditions consequent to pupil changes with illumination should have been minimal and relatively constant for each observer since the background luminance was constant—only the luminance of the stereoscopic displays was manipulated.

The line-of-sight distance in the stereoscope to the physical stimuli was 383 cm from the observer's eyes (Figure 2). The vergence of

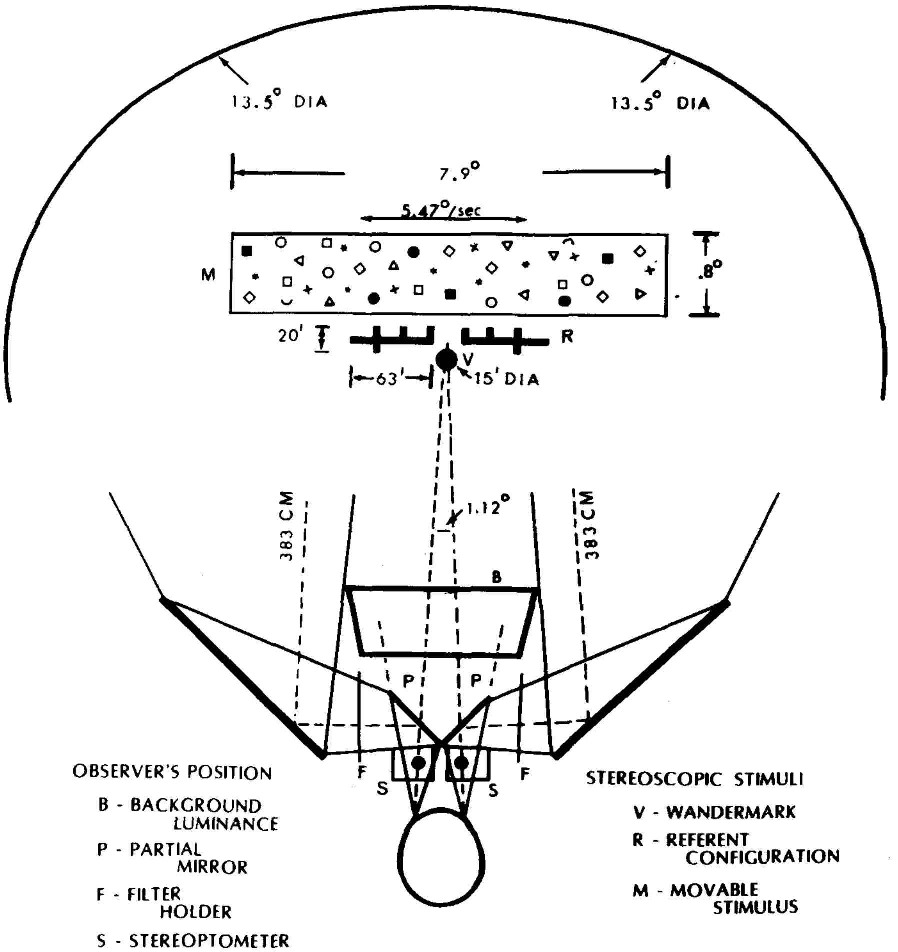

Figure 2. Schematized apparatus and stimuli. Vergence angle is for 67.3-mm interpupillary distance. Outer mirrors were adjusted to place the stereoscopic stimuli on sagittal projection with the referent configuration at a radial distance of 345 cm. Stimulus motion was in one direction only at any one time.

the outer mirrors of the stereoscope was adjusted symmetrically to place the fused referent configuration on midsagittal projection at a distance of 345 cm, or a binocular vergence angle of 1.12° on an interpupillary distance of 67.3 mm. For two observers, P.D.J. and G.S.H., the fused movable stimulus was set toward the observer an additional distance approximating the largest expected depth displacement by adjustment of the sprocketed pulleys and precision timing belts used to maintain the monocular stimuli in registry. Stimulus movement was in one direction only at any one time at a constant velocity of 19.7′ $msec^{-1}$ (5.47° sec^{-1}, or 36.7 cm sec^{-1}).

The movable stimulus was the fused stereoscopic image of two identical 70-mm film negatives of assorted chart symbols, the smallest of which subtended 2.7′ of arc on its shortest dimension. Potential for false fusions was obviated by the diversity in shape and size of the symbols and the restriction that no symbol be repeated such that stereoscopic disparity might occur for an individual symbol separate from that of the stimulus as a whole. The movable stimulus was presented in the upper visual field and occupied an area 7.9° laterally and .8° vertically at the observer's eyes. The horizontal line of the referent configuration was centered 40′ of arc below the bottom edge of the movable stimulus. The center of the circular stereo-wandermark was 30′ of arc below the bottom of the gap between the left and right halves of the referent. Circular apertures of translucent sheet acrylic in the eye cups of the observer's position restricted the field of view to approximately 13.5°. In the darkened experiment room, the edges of this field faded to physiological gray in the surround.

The stereoptometer used to measure the binocular vergence angle was calibrated to read the angle of vergence to a precision of ±2″ of arc (Harker, 1955). The stereo-wandermark (V in Figure 2) was focused for optical infinity and was reflected into the observer's eyes by partial mirrors shown as rectangles (S). The partial mirrors (P) permitted view of the background (B) as well as the stereoscopic presentation (M & R). Filters were placed at (F) to reduce the luminance of the movable stimulus.

Observers and Task

Three observers were used. All were optically corrected to 20/30 or better, and each was balanced in monocular acuity with correction to within one Snellen line. Observer P.D.J. wore contact lenses and had no experience with the phenomenon or the measuring device prior to three short practice sessions. His interpupillary distance (IPD) was 67.3mm. The other observers, G.S.H. and H.W.M., wore spectacles and were highly practiced with both the measuring device and the phenomenon. G.S.H.'s IPD was 69.1 mm and H.W.M.'s IPD was 64.0 mm. Since individual differences appeared strongly in the data, it is of interest that H.W.M. habitually worked at her desk without her prescription, using only her unaided right eye, which required 3 diopters more negative correction for distance vision than her left eye.

The observer's task was to place the wandermark of the stereoptometer at the seen distance of the moving stimulus. The resultant vergence angle setting was read directly in seconds of arc. The observers were instructed to fixate the vertical gap between the left and right halves of the referent configuration when making the final adjustment of the wandermark.

Data and Data Categories

A vergence angle setting of the stereoptometer was made for each combination of stimulus direction (left or right) and stimulus luminance condition (neither, both, right, or left eye dimmed). Order of condition combinations was pseudorandom within period of common view (0, 15, 30, 45, or 60 msec), which was also sampled in pseudorandom order. For data collection, continuous view was treated as an added level of period of common view. Eye order (the right eye stimulated before the left eye or vice versa) was held constant within each session and counterbalanced over sessions. All combinations of direction of stimulus movement, stimulus luminance, and period of common view (including continuous view) were repeated four times within each session to provide multiple measures for analysis. Two sessions provided a set of data. One set of data was taken for H.W.M.; three sets were taken for P.D.J. and G.S.H.

A total of eight settings to the movable stimulus while stationary and eight settings to the referent configuration were made at various times during each data session. The vergence angle to the movable stimulus when stationary was algebraically added to the vergence settings for the experimental conditions to obtain vergence angle differences—the data of the experiment. The settings to the referent configuration served to monitor the apparatus and the visual state of the observer. No significant change in either was noted during any session.

RESULTS

The vergence angle differences for each observer were analyzed separately for intermittent and continuous view. The measures for intermittent view were of primary interest. Both were subjected to repeated measures analyses of variance. Uninformative statistical interactions that would result from known reciprocal change in the direction of apparent depth displacement with change of eye order, direction of interocular luminance difference, or direction of stimulus movement were avoided in the analyses by change of algebraic sign and selective grouping. In spite of the above, a statistically significant interaction of eye order and stimulus direction occurred in the overall analysis for all sets of data for each observer ($p < .001$). Therefore, the principal analyses were conducted within the four combinations of these variables.

The single set of data for H.W.M. is summarized as means ($n = 4$) in Figure 5. To provide a comparable visual presentation, only the vergence angle differences of the third replication for P.D.J. and G.S.H. are similarly summarized in Figures 3 and 4. The findings for the first two replications were comparable. Statistical anal-

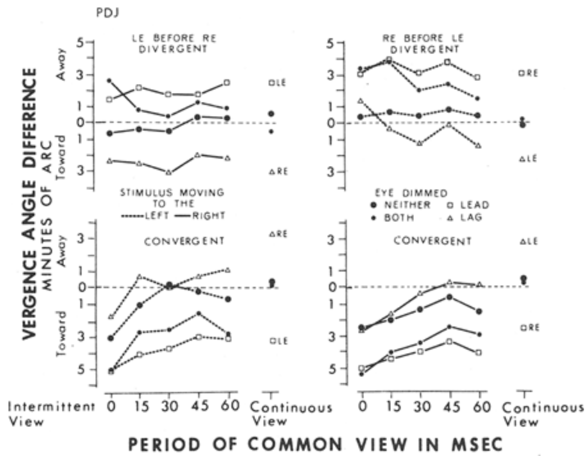

Figure 3. Apparent depth displacement as a function of period of common view for P.D.J., the naive observer. Data are summarized by combination of eye order and stimulus direction—four measures per point. The referent configuraton was 9.3′ of vergence angle difference beyond the position of the stimulus when stationary.

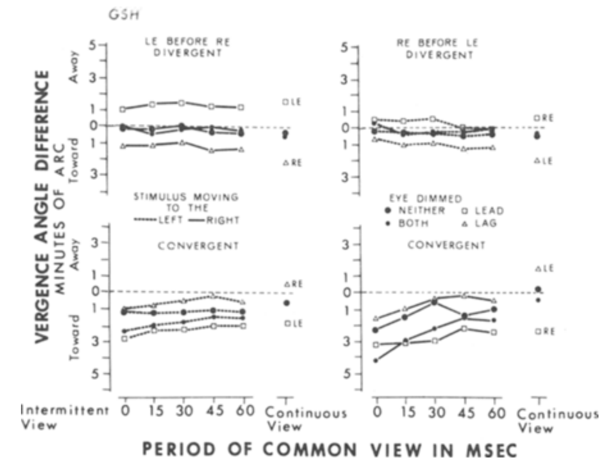

Figure 4. Apparent depth displacement as a function of period of common view for G.S.H., a highly experienced observer. Data are summarized by combination of eye order and stimulus direction—four measures per point. The referent configuration was 5.7′ of vergence angle difference beyond the position of the stimulus when stationary.

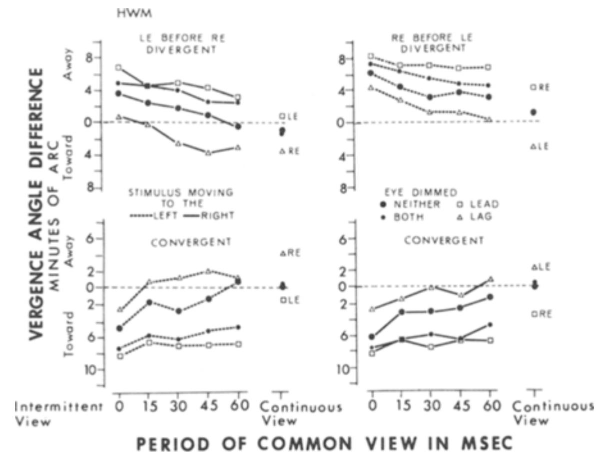

Figure 5. Apparent depth displacement as a function of period of common view for H.W.M., a highly experienced observer. Data are summarized by combination of eye order and stimulus direction—four measures per point. The referent configuration was at the position of the stimulus when stationary.

yses of all sets of data for each observer are presented in the text. The independent variable—period of common view—is presented on the abscissa of the figures. Since a constant 45-msec delay was used, the individual eye views were 45 msec longer than the designated period of common view. The dependent variable, seen depth dislacement, is dimensioned on the ordinate as vergence angle difference with the stationary position of the movable stimulus at zero. Positive values indicate uncrossed disparity, that is, depth displacements away from the observer; negative values indicate crossed disparity, that is, depth displacements toward the observer.

The figures illustrate the data summed to the principal level of analysis. The data points as graphed show the uninformative interactions that were eliminated from the statistical analyses as well as the statistically significant interaction identified by the overall analyses. The latter is evident in the relative slopes (without regard to sign) of the sets of graphed lines in the four sections of each figure. Particularly for P.D.J. and G.S.H., the effect of common view was minimal with divergent depth displacement.

An appropriate error measure ($\alpha = .01$) for evaluation of any two points as graphed for observer P.D.J. is .87′ of vergence angle difference. This value is the average of the four Newman-Keuls two-point criteria for the data of Figure 3 (Winer, 1962). Comparable values for Observers G.S.H. and H.W.M. are, respectively, .41′ and .95′ of vergence angle difference.

Replication

For Observers P.D.J. and G.S.H., comparison over replications indicated that the apparent depth displacements developed differently for the two observers. For P.D.J.—the naive observer—the displacements overall moved toward the observer. For G.S.H.—the experienced oberserver—the depth displacements generally reduced with replication. Otherwise, the general picture with replication was one of increasing consistency between and within the levels of the variables.

Period of Common View

The transition from contiguous exposures (zero common view) to a period of common view did not evidence a discontinuity. Incremented increase of common view generally decreased the apparent depth displacement ($p < .001$). For P.D.J. and G.S.H., this response to period of common view was evident only with convergent depth displacement. With divergent depth displacement for G.S.H., common view was nonsignificant ($p > .10$), whereas, for P.D.J., common view was nonsignificant for LE before RE ($p > .10$) and marginally significant for RE before LE ($p < .05$). Only 2 of 28 tests for interaction of common view with luminance were statistically significant.

Luminance

Stimulus luminance produced statistically significant main effects in all analyses ($p < .001$) without interaction as noted above. Interocular luminance difference modified the depth displacement induced by physical delay. Dimming the stimulus to the lead eye increased the seen depth displacement. Dimming the stimulus to the lag eye decreased the seen depth displacement. However, although the dimming of the eyes was symmetrical, the resultant change of depth displacements was considerably greater for dimming the stimulus to the lead eye. This is evident in the lines graphed with open symbols relative to the lines graphed with large filled dots.

The presumed redundant condition of equal luminance at a reduced level (both eyes dimmed) induced depth displacements in the directon of, and almost equal to, those induced by dimming the stimulus to the lead eye only. This outcome is evident in the lines graphed with large and small filled dots relative to the line graphed with open squares.

Newman-Keuls procedures (n = 20, df = 60; Winer, 1962) applied to the differences between mean depth displacements for the luminance conditions within the combinations of stimulus direction and lead eye were generally significant. The displacements of seen path of the moving object relative to the neither-eye-dimmed condition were ordered from small to large without regard to sign as lag, both, and lead eye dimmed. The both-eyes-dimmed condition was clearly unique and different from the neither-eye-dimmed condition.

Continuous View

The depth displacements achieved with continuous view for the lead and lag eye dimmed (the points identified in the figures as RE and LE) demonstrate that the Pulfrich-Fertsch effect was operative in the experimental situation. Since the data are grouped by stimulus direction as they were taken, the back-front difference seen when a pendulum is viewed with one eye dimmed is partitioned between the upper and lower portions of the figures. Extrapolation of the depth displacements achieved with intermittent views of like luminance conditions suggests that the response with incremented period of common view was not—within the limits of the experimental conditions—converging on that for continuous view.

Individual Differences

The depth displacement evident in the plotted points for neither and both eyes dimmed with continuous view apparently are an individual bias to movement in the stimulus. For P.D.J., there was a generally divergent displacement with movement (42 of 48 measures); for G.S.H., displacement was convergent (38 of 48 measures); for H.W.M., displacement was both divergent and convergent, depending upon the direction of stimulus movement (8 of 8 divergent with movement to the left and 5 of 8 convergent with movement to the right).

DISCUSSION

The single value of interocular delay was effective and produced apparent depth displacements consistent with the eye order of stimulation and direction of object movement established for the Mach-Dvořák phenomenon. The apparent depth displacements were reduced as expected with increased period of common view, particularly for the convergent conditions. There was no indication, given the limited exposure durations, that the depth displacement measures were converging on those obtained for the same luminance conditions with continuous view. Nonetheless, the manipulation of stimulus luminance produced additional apparent depth displacement of the path of the moving object to that induced by delay in a pattern consistent with that of the Pulfrich-Fertsch effect.

Eye Movements

The data of the divergent conditions for Observers P.D.J. and G.S.H. probably represent the variables of the study reduced by the presence of synchronous eye movements (Westheimer, 1954). Disjunctive following movements initiated by the lead eye could have negated the relative movement of the object consequent to the delay interval. The intrusion of such movements, or at least the stimulus to them, could have pertained since the stimulation was cyclic and the exposure durations, in total, were considerably longer than the latency for initiation of an eye movement. The presence of the random segment in the dark interval and the instruction to fixate should have negated eye movements per se, although switching the random segment in or out did not influence the obtained data. The failure of H.W.M.'s depth responses to evidence the dichotomy could have resulted from the tenuous nature of her binocular vision. Her response to stimulus motion seemed to be dependent upon the direction of that movement. Such an overlay of eye movement on the data would leave only the response to delay and luminance to be explained by neural mechanisms.

Spatiotemporal Integration

The explanation for apparent depth displacement with extended intermittent views formulated by Lit (1978) derives the observed direction of depth displacement for dimming each eye separately but not that for dimming both eyes together. As formulated, the shift—against the direction of motion—of retinal localization with reduced luminance would be a function of the extended excitation trailing the moving object in the eye of interest. This would mean that at "update"—offset of the exposure to the lag eye—the extended retinal excitation in the lead eye relative to that in the lag eye would always be less by the spatial equivalent of the interocular delay. Thus, the shift of localization in the lead eye for a given condition of reduced luminance must always be less than what would occur for the lag eye.

Specifically, dimming the lead eye only would nominally increase the effective disparity (A − B; Lit, 1978). Dimming the lag eye only would decrease the effective disparity, but to a greater degree, since the residual excitation would be greater—not reduced by the interocular delay. These predictions agree in direction but are opposite in relative magnitude to the observed displacements for dimming the eyes individually. The predicted greater shift of the localization against the direction of object motion in the lag eye means that when both eyes are dimmed equally, the net effect would be to *reduce* the effective disparity. This follows, in that the greater shift in the lag eye would reduce the effective disparity more than the shift in the lead eye would increase the effective disparity. A sizable *increase* was observed.

AN EXPLANATION

Appropriate explanatory mechanisms and their functioning can be inferred from the apparent depth displacement of a moving object observed with combinations of intermittent and continuous view (Harker, 1973). With continuous view to one eye, the "dichoptic sequence" is solely a period of "common view." The moving object and its background can provide only nondisparate stimulation to the two eyes. Since there is no inherent referent in the continuous excitation from which to derive a stereoscopic index, the evident disparity must originate with binocular excitation.

Interocular inhibition of the ongoing excitation by the intermittent excitation could establish the needed index for stereoscopic association. However, such interocular interaction could occur only after the visual tracts from the two eyes are joined. Conceivably, such interaction could take place at the lateral geniculate nucleus (LGN). The layered structure of the LGN brings neurons from corresponding areas of the two retinas into close proximity. The structure exhibits inhibitory processes among its elements, and the presence of sustained and transient channels has been demonstrated (Freund, 1973; Rakic, 1981).

Intermittent and Continuous View

The control conditions of Harker's (1973) study involved two paradigms of interest. Interocular average luminance difference was manipulated by optical filter in one and by the duty cycle—the exposure duration of the intermittent view—in the other. The cyclic interval of the intermittent durations was held constant at 110 msec. Thus, the average luminance for the four exposure durations, 12.5, 35, 55, and 75 msec, could be expressed as filter equivalents. These equivalent filters were used in binocular combination to present continuous view to one eye and intermittent view to the other eye (Harker, 1973, Figure 8).

In the first paradigm, the observer viewed the moving object at a constant average luminance with one eye (the 12.5-msec intermittent exposure) while the luminance to the other eye in continuous view was increased by reduction of optical filter density. The four filters were used twice in order of decreasing density, once with and once without an additional 1 log density filter to reverse the direction of the interocular, average luminance difference—the continuous view dimmer than the intermittent view, and vice versa.

The apparent depth displacement of the path of the moving object increased continuously with increased luminance of the continuous view. The direction of the depth displacements for the full range of luminance differences was consistent with the index for stereopsis of the short intermittent view preceding, in the combined excitation, that from the eye in continuous view; that is, the stereoscopic index of the eye in continuous view was shifted from that of the intermittent view in the direction of object motion.

The second and converse paradigm opposed a constant luminance in continuous view (the filter equivalent of 12.5 msec) to incremented average luminance increased by increasing the exposure duration of the intermittent view. The four exposure durations were presented twice from short to long, once with and once without the 1 log density filter, to sample both directions of interocular, average luminance difference. The apparent depth displacement with the shortest exposure duration and either direction of retinal illuminance difference was consistent with the index for stereopsis of the intermittent view preceding that of the continuous view, as noted above. For both repetitions of the exposure durations, the apparent depth displacements decreased with increased duration of the intermittent exposure. With the higher stimulus luminance, that is, without the 1 log density filter before the eye in intermittent view, the depth displacements decreased to zero and increased in the opposite direction at the longer exposure durations. Use of the 1 log density filter to oppose interocular luminance difference to exposure duration reduced the magnitude of the change in depth displacements, but did not alter the direction or trend of the displacements.

Interpretation

The apparent depth displacements observed with the first paradigm would follow if the excitation from the eye in continuous view was inhibited by excitation from the intermittent view—onset and offset combined. The reduction in the excitation from the eye in continuous view would provide the index for stereopsis. The observed increase of apparent depth displacement would follow if, when luminance to the eye in continuous view was increased, the resultant increased excitation resisted inhibition and the index for stereopsis was delayed, that is, shifted in the direction of object motion.

Increasing the view duration, the converse paradigm, had the opposite effect. This would follow if the index for stereopsis in the excitation from the eye in intermittent view was delayed, that is, shifted in the spatial distribution of excitation from the combined onset and offset of the short exposure to the offset per se of the longer exposure durations. The index in the excitation from the eye in continuous view would retain its position relative to the onset of the intermittent view. Thus, the result would be to reverse the apparent eye order for the longer exposure durations.

As interpreted, the direction and magnitude of the change in depth displacement with these paradigms makes it clear that the index for stereopsis is associated with reduction—an "offset"—of excitation. Such an offset would signal termination of the advance of retinal stimulation in the direction of object motion (Harker, 1967). In addition, the pattern of the response, particularly the insensitivity to direction of interocular average luminance difference, identifies relative stimulus intensity or its counterpart, relative excitation, as the critical variable.

Present Data

In the present study, the sequence of delayed, equal duration exposures to the two eyes gave rise to asymmetrical apparent depth displacements to equal reduction of the luminance to either eye. The onset and offset stimulation that defined the period of common view, and would be the source for interocular inhibition, must have been differentially effective. Extending to the delay sequence the mechanisms formulated with the intermittent-continuous paradigms, the transient of onset of stimulation in the excitation from the lag eye would inhibit ongoing excitation from the lead eye. The resultant reduction—''offset''—of excitation from the lead eye would combine with the physical offset of the lead eye to move the index for stereopsis against the direction of object movement. This would increase the effective delay of offsets and increase the apparent depth displacement. Similarly, the transient of offset of stimulation in the excitation from the lead eye would inhibit ongoing excitation from the lag eye, except that the lead eye excitation would have been reduced consequent to the delay sequence and the period of common view. The combined index for stereopsis of the lag eye would also move against the direction of object motion, but would decrease the effective delay of offsets and decrease the apparent depth displacement. Thus, the noted asymmetry would be a function of the relative strengths of the excitation at the interactive sites.

The observed depth displacements to reduced luminance of either eye alone follows from the direction of the interocular difference of stimulus luminance and the hypothesized inhibition at the noted interactive sites. The observed increase in depth displacement to an overall reduction of luminance, given the symmetry of the stimulation, would seem to need an additional mechanism that is nonlinear with stimulus luminance. Inhibition of sustained excitation by transient excitation and the tendency of transient excitation to saturate at higher luminances could be the source for this finding (Breitmeyer & Ganz, 1976). Given an increase in strength of the excitation at onset, through desaturation of the onset and offset transients, the result for the both-eyes-dimmed condition (increased depth displacement, as if only the lead eye were dimmed) would follow from the delay sequence favoring the onset of the lag eye over the offset of the lead eye.

The potential for nonoverlapping exposures and the negation thereby of interocular inhibition as an explanatory mechanism need comment. Given that the classical explanation is essentially correct for ''short'' nonoverlapping exposures, reduced luminance with spatiotemporal integration of excitation within the areas stimulated would shift object localizations against the direction of motion. This shift would affect the apparent depth displacement as a function of the relative interocular luminance difference. The critical feature is the response to dimming both eyes equally; it should not occur with nonoverlapping exposures and did occur with overlapped exposures.

With extended views, as in the present study, pilot work has given no clear outcomes. The data with vertical-line targets are complicated by disjunctive eye movements which can result in false fusions that oppose the expected depth displacement. Interocular stimulus intervals—offset to onset—within the dichoptic sequence of 20 msec or less eliminated these false fusions, suggesting that the contiguous condition of the present study was not unique.

SUMMARY AND CONCLUSIONS

1. Interocular delay of sequential intermittent views of equal exended duration resulted in apparent depth displacements in the path of a moving object consistent with the Mach-Dvořák phenomenon. Incremented increase of period of common view generally reduced the seen depth displacements, possibly as a function of induced eye movements.

2. Interocular, average luminance differences induced depth displacements consistent in direction with those obtained for the Pulfrich-Fertsch phenomenon. Dimming the lead eye increased, dimming the lag eye decreased, and dimming both eyes increased the seen depth displacement. The depth displacements achieved did not converge on those obtained for comparable luminance conditions with continuous view.

3. Transition from contiguous exposures to a period of common view occurred without evident discontinuity in the observed depth displacements.

4. An interocular interactive explanation was offered for the obtained results. Interocular inhibition, possibly at the LGN, of sustained excitation by transient excitation with onset and offset of the period of common view was suggested as a possible neural mechanism to account for the findings. The strength of interocular inhibition was seen to be a function of the stimulus luminance. Spatiotemporal indices associated with offset of neural excitation in the two eyes were identified as the source of the apparent cortical disparity.

5. The response to viewing a moving object with interocular, sequential intermittence as observed in this experimental situation, was subject to individual differences.

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