Stereoacuity for oscillating targets exposed through apertures of various horizontal extents¹

ALFRED LIT² AND WILLIAM M. VICARS
SOUTHERN ILLINOIS UNIVERSITY

This experiment assesses the separate effects of several interrelated temporal variables on binocular depth discrimination as measured in a two-rod test apparatus. Equidistance settings were obtained from two Ss for a black target oscillating in a frontal plane at each of five velocities, and viewed against a constant illuminated background (1.20 log td) through 29 different horizontal apertures. Combinations of target velocities and aperture sizes were selected to produce a series of eight constant target viewing times (0.15, 0.25, 0.40, 0.50, 0.80, 1.00, 1.50, and 2.00 sec). Both the constant and the variable errors of the equidistance settings were analyzed in terms of the relative deleterious effects produced by increased target velocity and reduced horizontal aperture. The deleterious effects were discussed with respect to the contribution of presumed loss in neural integration for the changing luminous-energy distribution patterns on each retina, energy losses occurring in each pair of stimulated binocular retinal elements along the path of image movement, decreases in target viewing time, and reduction in the number of binocular retinal elements being stimulated.

The importance of temporal factors in stereoscopic depth perception for stationary targets has long been recognized (see, e.g., Ogle, 1958, 1962, 1967), both for targets presented in real depth (Langlands, 1926-27) and in a stereoscope (Ogle & Weil, 1958; Shortess & Krauskopf, 1961). The experimental results for both classes of target presentation show that stereoacuity undergoes more than a threefold decrease in magnitude as the target viewing time is decreased from 1 sec to about 0.005 sec.

The study of temporal factors in stereoscopic vision for moving targets (e.g., targets oscillating in a frontal plane) has received relatively little experimental attention. A geometric analysis of the

experimental conditions reveals that for targets moving across a visual field of constant horizontal extent an increase in target velocity will result in a decrease in target viewing time as well as in the exposure duration of corresponding binocular retinal elements along the path of image movement. To specify the separate effects of these two temporal variables on depth-discrimination thresholds for moving targets, it is necessary to control experimentally the magnitude of both the target velocity and the extent of the horizontal field of view. Mathematically, the exposure duration of each pair of stimulated corresponding binocular retinal elements is inversely proportional to target velocity (v), and is independent of the size of the field of view. The target viewing time (t), for a given target velocity (v), varies directly with the extent of the horizontal field of view (d), in accordance with the equation $t = d/v$. It should also be noted that as the horizontal field of view is increased, the total number of corresponding binocular retinal elements that are stimulated during the increased target viewing time also increases. These relationships have been taken into consideration in studies on dynamic visual acuity (see, e.g., Elkin, 1962; Ludvig & Miller, 1958; E. F. Miller, 1959; J. W. Miller, 1958) and on stereoacuity (Luria & Weissman, 1968) for rotating targets observed under conditions allowing ocular pursuit movements.

Lit and Hamm (1966) have recently reported data on equidistance settings for black vertical targets oscillating in a frontal plane at many selected velocities. The targets were viewed against a horizontal

rectangular background whose illumination was systematically varied over a wide range of scotopic and photopic levels. Experimental curves were drawn to show how the stereoscopic threshold angle, η_{AD} , varied as a function of retinal illuminance, $\log E$, with target velocity serving as parameter. Each of the curves representing the different target velocities showed that η_{AD} was large at low (scotopic) levels and progressively decreased to a final asymptotic value at a high (photopic) level. A discontinuity occurred in each of the curves, reflecting the dual functioning of the rod and cone mechanisms of the retina, in accordance with Duplicity Theory (Hecht, 1937). The point of discontinuity on each of the curves was systematically displaced to the right (i.e., to larger $\log E$ values) on the abscissa axis as target velocity was increased. The lateral displacements were accounted for on the basis of Bloch's law (Bloch, 1885), which asserts that within a critical duration, a reciprocal relationship exists between stimulus intensity and stimulus exposure duration to produce a constant visual effect. Thus, the study by Lit and Hamm (1966) demonstrates that to achieve a constant level of stereoscopic acuity, proportionately larger $\log E$ values are required as the exposure duration for corresponding binocular retinal elements is reduced by increasing the target velocity. In addition to the lateral displacements, the experimental curves were progressively displaced upward as target velocity was increased. The vertical displacements cannot be accounted for in terms of Bloch's law but probably reflect the increased deterioration in the neural

Fig. 1. (A) Schematic representation of the apparatus. (B) S's view of the stimulus targets as seen through a relatively wide horizontal aperture. See text for detailed description.

integration of the spatio-temporal energy distribution pattern of the moving retinal images.

In their study, Lit and Hamm (1966) used a horizontal aperture of constant angular extent (about 20 deg). Thus, when target velocity was increased, the target viewing time was decreased. The present experiment was designed to assess the separate effects of target velocity and horizontal aperture. The separation of effects was accomplished by combining selected target velocities with specific horizontal apertures so as to produce a series of constant target viewing times ranging from 0.15 to 2.00 sec.

METHOD

Apparatus

The apparatus³ (Fig. 1A) used in the experiment has been described and illustrated in previous reports (Lit, 1960; Lit & Hyman, 1951). It is similar to the Howard-Dolman (1919) two-rod test device. The standard (oscillating) target, OT, is a black vertical rod (5.79 mm in diam) that is located in the upper half of S's visual field; the comparison (fixation) target, FT, is a similar rod located in the lower half of his visual field. The standard target is located 100 cm from S's eyes and can be made to oscillate in a frontal plane at constant speed (within the central 90% of stroke) over a wide range of specified values by means of a variable-speed transmission device, M. The comparison

target can be adjusted by S along a calibrated track, J, in his median plane. When S sits in a darkroom, D, and binocularly views the targets through a pair of circular artificial pupils, E, which are 2.5 mm in diam, the lower end of the standard target and the upper end of the comparison target lie in his horizontal plane of fixation, as shown in Fig. 1B.

Background illumination is provided by a lightbox, L, located in a frontal plane 250 cm from S's eyes. Two pairs of screening units provide a rectangular field of view. The extent of the vertical field of view is kept constant at 2.7 deg by means of horizontal screens, H, located 21 cm from S and separated by 1.0 cm. The variable horizontal field (2.3 to 20.4 deg) is controlled by laterally separating the pair of vertical screens, V, placed directly in front of the lightbox, L. In the present experiment, the vertical screens are placed in front of the lightbox, L, rather than in the plane of target oscillation as illustrated in Fig. 1A, in order to reduce any depth cues which may be provided by the edges of the screens, particularly for small apertures. To avoid the disturbing effects of physiological diplopia for the background field, the minimum horizontal extent of the screen separation is 2.3 deg; the maximum obtainable aperture is 20.4 deg.

Subjects

Two highly trained undergraduate

students, WS and SM, served as paid Ss. Both were emmetropic, with visual acuity in each eye better than 20/20. Phorias and ductions were normal at both distance and near. At a fixation distance of 100 cm, the interpupillary separation for SM was 6.80 cm and that for WS was 6.50.

Procedure

In performing the equidistance settings, S continuously fixated the upper edge of the lower comparison target and adjusted its distance in the median plane by "bracketing" until the rod appeared to lie directly below the path of the oscillating target. At each of the five target velocities used (6.96, 10.05, 15.42, 20.42, and 39.40 deg/sec), four to seven different horizontal apertures were employed to yield a total of eight target viewing times (0.15, 0.25, 0.40, 0.50, 0.80, 1.00, 1.50, and 2.00 sec). Multiple (two to four) groups of 14 equidistance settings were obtained for each S under each of the experimental conditions. A constant background retinal illuminance of 1.20 log td was maintained throughout the experiment.

Response Measures

For each S, two classes of stereoscopic parallax angles were computed for each group of 14 equidistance settings. One parallax angle ($\eta_{\Delta R}$) is based on the mean value of the constant errors of the groups of equidistance settings. $\eta_{\Delta R}$ is computed

Table 1
Depth-Discrimination Thresholds for Targets Presented at Five Velocities and Viewed Through Various Horizontal Apertures Designed to Yield Eight Specified Target Viewing Times. The stereoscopic threshold angle, $\eta_{\Delta D}$, is given for observers W.S. and S.M. in terms of the mean value of the average deviations of multiple (two to four) groups of 14 equidistance settings taken under each of the conditions. The corresponding mean angular magnitude of the constant errors of the equidistance settings is given by $\eta_{\Delta R}$.

Target Viewing Time (Sec)	Stereoscopic Parallax Measure	Target Velocity (Deg/Sec)									
		6.96		10.05		15.42		20.42		39.40	
		W.S.	S.M.	W.S.	S.M.	W.S.	S.M.	W.S.	S.M.	W.S.	S.M.
0.15	$\eta_{\Delta D}$	* ^a	*	*	*	382.6	228.8	75.6	88.9	118.0	243.5
	$\eta_{\Delta R}$	*	*	*	*	-361.0 ^b	859.5	-3.4	721.7	-74.0	914.8
0.25	$\eta_{\Delta D}$	*	*	142.3	136.6	32.4	57.9	33.7	74.4	78.5	156.6
	$\eta_{\Delta R}$	*	*	-60.5	224.2	-171.2	170.6	-199.4	200.2	-316.6	580.7
0.40	$\eta_{\Delta D}$	217.5	41.8	19.2	32.5	25.9	40.9	29.2	85.9	99.7	109.8
	$\eta_{\Delta R}$	-375.5	134.5	-136.1	62.3	-203.1	26.2	-255.0	69.2	-307.1	420.5
0.50	$\eta_{\Delta D}$	22.0	32.9	19.3	30.3	18.1	45.8	21.4	48.9	72.6	113.3
	$\eta_{\Delta R}$	-76.1	17.5	-159.6	33.9	-204.6	55.7	-240.4	59.9	-253.5	238.6
0.80	$\eta_{\Delta D}$	18.6	30.7	13.7	30.4	19.3	37.6	25.4	45.6	** ^c	**
	$\eta_{\Delta R}$	-138.2	23.4	-174.5	31.3	-206.8	68.4	-196.9	106.4	**	**
1.00	$\eta_{\Delta D}$	17.0	29.7	14.4	29.3	15.0	45.5	27.3	63.8	**	**
	$\eta_{\Delta R}$	-124.1	49.3	-160.4	53.7	-186.4	67.6	-185.1	142.0	**	**
1.50	$\eta_{\Delta D}$	10.9	20.1	12.9	21.7	**	**	**	**	**	**
	$\eta_{\Delta R}$	-132.8	17.0	-149.4	26.1	**	**	**	**	**	**
2.00	$\eta_{\Delta D}$	12.9	26.7	13.8	28.7	**	**	**	**	**	**
	$\eta_{\Delta R}$	-126.8	31.0	-119.0	42.7	**	**	**	**	**	**

^a Cells containing a single asterisk represent the condition in which depth settings could not be obtained because of physiological diplopia of the illuminated background.

^b A negative value of $\eta_{\Delta R}$ indicates that the mean distance of the comparison target from the observer's eye was less than that of the standard target.

^c Cells containing a double asterisk represent the condition in which the horizontal aperture required to yield the specified target viewing time was greater than that available in the apparatus.

Fig. 2. Stereoscopic threshold angle, η_{AD} , on logarithmic scale, as a function of horizontal aperture, with target velocity serving as parameter.

short viewing times (i.e., less than about 0.50 sec) show a tendency to be increasingly displaced upward as the target viewing time is decreased.

The constant errors of the equidistance settings, $\eta_{\Delta R}$, in Table 1 were also analyzed. The obtained values were positive for SM and negative for WS. That is, for SM the comparison target was consistently adjusted to a position farther than that of the standard target, whereas for WS, it was consistently adjusted to a position nearer than that of the standard target. The data are less regular for WS than for SM.

Although the data for $\eta_{\Delta R}$ are less systematic than those for η_{AD} , the absolute values of $\eta_{\Delta R}$ exhibited essentially the same functional relationships as those obtained for η_{AD} in Figs. 2, 3, and 4, when corresponding plots (not shown here) were made for each S.

DISCUSSION

The deleterious effects on equidistance settings produced by increased target velocity may stem from three interrelated sources of reduction in target clarity: (1) an impairment in neural integration resulting from the changing stimulus-energy patterns on the retinas, (2) the loss of stimulus energy in each retinal receptor when target velocity is increased without a proportional increase in stimulus luminance, and (3) the decrease in target viewing time that occurs for a constant horizontal aperture.

The separate effects on stereoscopic vision of (1) the impairment in neural integration and (2) the loss of stimulus energy have been demonstrated in the earlier study by Lit and Hamm (1966). Their experimental curves relating η_{AD} as a function of scotopic and photopic levels of retinal illuminance, with target velocity serving as parameter, exhibited a systematic horizontal displacement of the positions of the rod-cone discontinuity; this effect was attributed to (2), the progressive loss of stimulus energy impinging on each receptor as target velocity was increased. The curves also exhibited systematic vertical displacements which were attributed to a residual reduction in target clarity associated with (1), the progressive impairment in neural integration for targets oscillating with increasing speed, rather than with (3), the decrease in target viewing time, because of the wide (20-deg) aperture used. The

on the basis of the linear depth difference (ΔR) existing between the actual and the apparent plane of oscillation. The second parallax angle (η_{AD}) is one that is traditionally used in specifying stereoscopic acuity. η_{AD} is based on the mean value of the variable errors (average deviation, AD) of the corresponding groups of 14 equidistance settings. The computations for the two parallax angles are based on the formula (Graham, 1965, p. 524) that specifies the difference between the visual angle formed by the standard and comparison targets in one eye and the visual angle formed by these targets in the other eye.

RESULTS

The data for the constant and the variable errors, $\eta_{\Delta R}$ and η_{AD} , are presented for each S in Table 1. The variable errors for the two Ss combined are shown graphically in Figs. 2, 3, and 4.

In Fig. 2, η_{AD} is plotted in log units as a function of angular aperture for four of the five velocities used. To avoid crowding, the curve representing the 10.05-deg/sec target velocity is not included; its position essentially overlaps that of the 6.96-deg/sec curve. The curves for all target velocities show that η_{AD} decreases rapidly from initially high values to approach asymptotic levels as aperture is increased.

The curves are systematically displaced upward as target velocity is increased. There is a tendency for the curves to begin leveling off at smaller aperture values, the slower the target velocity.

In Fig. 3, η_{AD} is plotted as a function of target viewing time (= aperture/velocity) for the same four target velocities as those shown in Fig. 2. The curves for all target velocities show that η_{AD} decreases abruptly from initially high magnitudes to reach asymptotic levels at a target viewing time less than about 0.50 sec. As in the case of Fig. 2, the curves are systematically displaced upward as a function of increasing target velocity. There is a tendency for the curves to begin leveling off at shorter target viewing times, the higher the target velocity.

In Fig. 4, η_{AD} is plotted as a function of angular target velocity, with target viewing time serving as parameter. For long target viewing times (above about 0.50 sec), η_{AD} increases at about the same rate for all curves as target velocity increases from 10 to 40 deg/sec. For target viewing times shorter than 0.50 sec, η_{AD} exhibits a marked upturn at progressively lower target velocities, the larger the target viewing time. The curves representing long target viewing times essentially overlap, each having a slope of about three over the linear portion; the curves representing

Fig. 3. Stereoscopic threshold angle, η_{AD} , on logarithmic scale, as a function of target viewing time (= aperture/velocity), with target velocity serving as parameter.

associated reduction in the total number of retinal elements stimulated). The evidence for a critical aperture effect can be clearly seen in Fig. 4, where a systematic upturn occurs in the curves representing target viewing times shorter than about 0.50 sec, where the associated apertures are all smaller than 5 deg.

A more complete description of the effects of aperture size can be obtained from Fig. 2. For apertures above about 10 deg, η_{AD} is independent of aperture at all target velocities used. Below about 10 deg, an upturn in η_{AD} occurs at a progressively smaller aperture, the lower the target velocity. The critical aperture at which the upturn in η_{AD} occurs for each of the target-velocity curves does not yield a computed constant target viewing time, as can be directly seen in Fig. 3. To determine more precisely the value of the critical aperture required for each target velocity, additional data must be collected at target viewing times below 0.50 sec. Thus, it is clear from the experimental data, that a constant target viewing time will not yield a constant level of stereoscopic acuity (i.e., a constant value of η_{AD}). This stems from the fact that any increase in target velocity invariably produces a deterioration in binocular depth discrimination, whereas a reduction in aperture produces a deterioration at a value below that of the critical aperture associated with the given target velocity.

The results of current experiments with stationary targets, designed to assess the effects of exposure duration at various intensity levels, should yield new data necessary for determining the properties of the binocular temporal-integrating mechanism of the visual system. The new data will allow comparisons of the magnitude of the critical duration for binocular depth discrimination with those reported for other basic visual functions. Additional experiments, using oscillating targets that produce a wide variety of energy-distribution patterns on the retinas, should also provide new data on the nature of the spatio-temporal integrating mechanism of the visual system. Finally, if it is desired to assess the deleterious effects of (2), the loss of stimulus energy resulting from increases in target velocity, the present experiment should be replicated at many additional retinal-illuminance levels.

results of the present experiment (Fig. 2) do, indeed, rule out (3), the decrease in target viewing time, as a possible influencing variable for wide apertures: the values of η_{AD} begin to level off at apertures well below 20 deg, even for the highest target velocity curve.

To achieve a more complete analysis of the effects of (2), the loss of stimulus energy, independent of the effects of (1), the impairment in neural integration, experiments (now in progress) are required to measure depth-discrimination thresholds for stationary targets presented at various exposure durations under a wide range of retinal illuminances. Also relevant to the analysis of the separate effects of (1) and (2) will be the results of current experiments on stationary targets dealing with systematic variations in the spatial distribution of stimulus-energy patterns on the retinas produced directly by the use of ophthalmic convex and concave lenses.

When the data of the present experiment are plotted to show how η_{AD} varies as a function of target velocity, for each of the 29 apertures used, the curves (not shown

here) that join data points having essentially equal aperture values reveal that for all apertures above about 5 deg, η_{AD} progressively increases as target velocity is increased. These curves essentially overlap and exhibit a slope value of about three. That is, as target velocity is increased from 7 to 40 deg/sec, η_{AD} increases from about 20 to 120 sec of arc. This functional relationship between η_{AD} and target velocity is in good quantitative agreement with the results obtained in the previous studies (Lit, 1960, 1964; Lit & Hamm, 1966) which used a wide (20-deg) aperture. For small apertures (below about 5 deg) a deleterious effect is noted: The curves become progressively displaced upward on the η_{AD} axis as the selected constant aperture value is decreased. Thus, η_{AD} values exceeding 100 sec of arc were obtained for apertures averaging about 2.5 deg, even for target velocities as low as 7 to 15 deg/sec. This deterioration in stereoscopic acuity for small apertures⁴ probably reflects the effects of (3), the decrease in target viewing time (as well as a possible effect inseparably produced by the

Fig. 4. Stereoscopic threshold angle, η_{AD} , on logarithmic scale, as a function of angular target velocity, with target viewing time serving as parameter.

- MILLER, E. F. Effect of exposure time upon the ability to perceive a moving target. Research Project NM 17 01 11, Subtask 2, Report No. 2, U.S. Naval Aviation Medical Center, 1959.
- MILLER, J. W. Study of visual acuity during the ocular pursuit of moving test objects. II. Effects of direction of movement, relative movement, and illumination. *Journal of the Optical Society of America*, 1958, 48, 803-808.
- OGLE, K. N. Present status of our knowledge of stereoscopic vision. *American Medical Association Archives of Ophthalmology*, 1958, 60, 755-774.
- OGLE, K. N. Spatial localization through binocular vision. In H. Davson (Ed.), *The eye*. Vol. 4. *Visual optics and the optical space sense*. New York: Academic Press, 1962. Pp. 271-324.
- OGLE, K. N. Some aspects of stereoscopic depth perception. *Journal of the Optical Society of America*, 1967, 57, 1073-1081.
- OGLE, K. N., & WEIL, M. P. Stereoscopic vision and the duration of the stimulus. *American Medical Association Archives of Ophthalmology*, 1958, 59, 4-17.
- SHORTESS, G. K., & KRAUSKOPF, J. Role of involuntary eye movements in stereoscopic acuity. *Journal of the Optical Society of America*, 1961, 51, 555-559.

REFERENCES

- BLOCH, A. M. Expériences sur la vision. *Société de Biologie Comptes Rendus*, 1885, 2, 493-495.
- ELKIN, E. H. Target velocity, exposure time and anticipatory tracking time as determinants of dynamic visual acuity (DVA). *Journal of Engineering Psychology*, 1962, 1, 26-33.
- GRAHAM, C. H. Visual space perception. In C. H. Graham (Ed.), *Vision and visual perception*. New York: Wiley, 1965. Pp. 504-547.
- HECHT, S. Rods, cones and the chemical basis of vision. *Physiological Reviews*, 1937, 17, 239-290.
- HOWARD, H. J. A test for the judgment of distance. *American Journal of Ophthalmology*, 1919, 2, 656-675.
- LANGLANDS, N. M. S. Experiments on binocular vision. *Transactions of the Optical Society of London*, 1926-27, 28 (2), 45-82.
- LIT, A. Effect of target velocity in a frontal plane on binocular spatial localization at photopic retinal-illuminance levels. *Journal of the Optical Society of America*, 1960, 50, 970-973.

- LIT, A. Equidistance settings at photopic retinal-illuminance levels as a function of target velocity in a frontal plane. *Journal of the Optical Society of America*, 1964, 54, 83-88.
- LIT, A., & HAMM, H. D. Depth-discrimination thresholds for stationary and oscillating targets at various levels of retinal illuminance. *Journal of the Optical Society of America*, 1966, 56, 510-516.
- LIT, A., & HYMAN, A. The magnitude of the Pulfrich stereophenomenon as a function of distance of observation. *American Journal of Optometry*, 1951, 28, 564-580.
- LUDVIGH, E., & MILLER, J. W. Study of visual acuity during the ocular pursuit of moving test objects. I. Introduction. *Journal of the Optical Society of America*, 1958, 48, 799-802.
- LURIA, S. M. Stereoscopic and resolution acuity with various fields of view. *Science*, 1969, 164, 454-455.
- LURIA, S. M., & WEISSMAN, S. Relationship between static and dynamic stereo-acuity. *Journal of Experimental Psychology*, 1968, 76, 51-56.

NOTES

- This study was supported in part by a research grant from the National Science Foundation (NSF GB-2553) and by a Public Health Service research grant (NB 07617) from the National Institute of Neurological Diseases and Blindness awarded to Professor Alfred Lit, principal investigator.
- Address: Department of Psychology, Southern Illinois University, Carbondale, Illinois 62901.
- The apparatus was originally constructed at Pupin Laboratories, Columbia University, partially through funds from a research grand-in-aid generously provided by the American Academy of Optometry to Professor Lit.
- This analysis does not apply to experiments (e.g., Luria, 1969) in which extraneous objects are located in the field, such that restriction of the field of view also reduces peripheral depth cues.

(Accepted for publication January 28, 1970.)