Visual resolution in the periphery*

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Visual acuity thresholds were determined for two Os with a 3-deg square grating target presented for 0.2 sec within a steadily illuminated surround field matched in luminance to the test field. Measurements were made in the fovea, and at 10, 20, and 30 deg along the horizontal meridian of the temporal retina, at luminances between -3.5 and $3.0 \log \text{mL}$. The foveal acuity-luminance functions showed a large increase in acuity up to 1 or 2 $\log \text{mL}$, but at peripheral locations very little increase occurred above 0 $\log \text{mL}$. The maximum acuity reached at photopic luminances dropped sharply with increasing eccentricity. Visual acuities were two to four times higher than those previously reported for the periphery; methodological and target differences are presented to account for this result.

The classical determination of visual acuity in the periphery was made by Wertheim in 1894, and his graph showing acuity at various retinal locations relative to foveal acuity is still reproduced in standard texts (e.g., Ruch & Fulton, 1960; Graham, 1965; Krech, Crutchfield, & Livson, 1969). Wertheim's results, obtained with a grating target, showed that acuity dropped rapidly within 5 deg from the center of the fovea, and then continued to drop at a slower rate out to the far periphery. These results provided information on the general form of the relation between peripheral and foveal acuity, at a single unmeasured luminance.

Since that time, a number of studies of peripheral acuity using a variety of test objects have been reported (for a review, see Low, 1951). With one exception, the determinations in each of these investigations have been restricted to a single luminance. This limits the usefulness of the results, since luminance changes are known to produce a large change in acuity in the fovea (Shlaer, 1937).

The only data on visual acuity at various retinal locations for a range of luminances were obtained by Mandelbaum and Sloan

(1947) with a Landolt C. At the low photopic luminances which they used, the shape of the function relating visual acuity to distance from fixation was similar to that obtained by Wertheim, the greatest drop occurring between the fovea and 10 deg. At scotopic luminances, very little change in acuity occurred over a range of eccentricities. At 10 deg and beyond, Mandelbaum and Sloan's data show acuity values substantially below those reported by Wertheim.

The results of the Mandelbaum and Sloan study must be evaluated in light of several methodological problems: (1) In their study, it was necessary to vary the viewing distance from 2 to 10 m in order to obtain a wide range of target sizes. This would, of course, change the accommodative state of the O as well as vary the size of the background. (2) Apparently both the fixation point and target were presented on a flat screen. With this arrangement the fixation point and Landolt ring would not be equidistant from the eye at all peripheral locations. (3) Their measurements were made without any prior dark adaptation of the O, and the data were collected in order of decreasing luminance. This procedure may not have allowed sufficient time for complete adaptation of the eye to the lowest luminances. (4) No control for pupil size was used. Furthermore, the psychophysical method used in collecting their data was not reported.

The research reported here determined visual acuity for a grating target at four retinal locations over a wide range of luminances. The advantages in using a grating target to study peripheral acuity, rather than the Landolt C, are threefold. First, Berger (1943) has questioned whether the Landolt C is appropriate for measuring the low visual acuities characteristic of the periphery. Typically, the orientation of the C is varied, and the image of the gap falls on different retinal

regions at varying distances from fixation. When large targets are used, the variation in retinal location of the gap image may be considerable.

Secondly, research has indicated that different aspects of acuity may be measured by the grating and Landolt C targets (Shlaer, 1937; Shlaer, Smith, & Chase, 1942). Shlaer's work showed that the acuity-luminance functions for these two targets differed in central vision. Grating acuities for the periphery would provide a comparison to the Landolt ring data of Mandelbaum and Sloan.

Thirdly, the grating has the advantage that the intensity distribution in the target and its retinal image can be specified quantitatively, providing a basis for relating the results of grating acuity experiments to the optics of the eye and to receptor density. This cannot be done for the Landolt ring.

METHOD

Apparatus

The apparatus was designed to present to the eye a 211-msec exposure of a 3-deg square grating field, centered within a steadily illuminated 9-deg square surround field matched in luminance to the test field. A 0.5-deg separation between the test and surround fields was used to reduce variations in brightness which occurred at the borders of the fields when they were contiguous. The arrangement of the two fields as they appeared during the presentation of the grating is shown in Fig. 1A. The apparatus provided for testing foveal acuity and peripheral acuity at 10, 20, and 30 deg along the horizontal meridian of the temporal retina.

The optical system was designed to present both test and surround fields in Maxwellian view. However, modifications in the test pathway were necessary in order to avoid producing a diffraction pattern at the pupillary plane when a grating was placed in collimated light. For this reason, the secondary light source used for the test pathway was a vertical slit, and the modified artificial pupil was a horizontal slit which restricted the light in the plane of the pupil to a square, $2.5 \times 2.5 \text{ mm}$. This arrangement was devised in order to control for variations in pupillary diameter while still allowing peripheral viewing.

The optical system is shown in Fig. 1B. S_1 and S_2 are tungsten ribbon filament lamps operated at 17 A and supplied by transformers which were run from a constant-voltage regulator. The light from the test source, S_1 , was focused by a condensing lens, L_1 , onto a vertical slit, A_1 . The surround source, S_2 , illuminated a circular aperture, A_3 . The light in the test and surround pathways was collimated by

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achromatic lenses, L_2 and L_4 , respectively, and brought to a focus at the eye by lenses, L_3 and L_5 . A first surface mirror, M , and beamsplitting cube, B , were used to reflect the surround light into the eye. A field stop, A_4 , which defined the 9-deg surround area, was positioned so that its virtual image was at the same distance from the eye as the grating.

In the test pathway, the grating holder, G , was placed immediately behind and the field stop, A_2 , immediately in front of the focusing lens. Neutral density filters were placed at F_1 and F_2 . The test field exposure was limited to 211 msec by a sector disk, Sh , attached to a 60-rpm synchronous motor. The shutter, which was triggered by depressing a microswitch in the O's booth, was mechanically stopped at the end of one revolution.

The fixation system for peripheral viewing was enclosed in a tube, T , which could be attached to the optical system housing at one of three locations. Within this tube, a 6-V tungsten lamp, a white diffusing surface, and two black threads provided fixation crosshairs within a 0.5-deg circular field. Various attempts to provide a fixation point for testing foveal vision did not prove successful (cf. Brown, Phares, & Fletcher, 1960), and the O was instructed to fixate the center of the dark square within the surround field, using the inner edge of the surround field as a check for focus. The accommodation required of

an (ideally) emmetropic O for both central and peripheral measurements was 2.4 diopters.

Small variations in grating line width were achieved by rotating the grating along the horizontal axis of the lines in the partially collimated light. The width of the lines varies with the angle of rotation, r , according to the equation, $w_r = w_0 \cos r$, where w_0 is the line width at 0 deg rotation (grating perpendicular to the light path). The measure of visual acuity used was the reciprocal of the visual angle, in minutes of arc, subtended by the width of one line.

Eighteen gratings with opaque and transparent lines of equal width were used. In addition to the engraved gratings used by Shlaer (1937), 10 gratings with lower line frequencies were made photographically. The two sets of gratings were checked both psychophysically and densitometrically to ensure that they would give comparable results.

The line widths of all gratings were calibrated with a Geneva comparator. Calibration of the luminance of the test field was made by a binocular match to a diffuse field, whose luminance was measured with an SEI (Ilford) photometer. The luminance of the test field was 3.33 log mL with no grating in the system. The color temperature of the test source, as measured with an optical pyrometer, was 2,700°K. All Wratten neutral density

filters were calibrated with a Martens polarization photometer.

The surround luminance was matched to within 0.1 log unit of the test field luminance, with an unresolved grating in the test pathway, at the beginning of the experiment. Neutral density filters were used in both pathways during the experiment to maintain this match.

The exposure duration (211 msec) and the residual ac ripple of the test source (2.5% at 120 Hz) were measured with a solar cell placed at the eyepiece, an operational amplifier, a Beckman timer, and an oscilloscope. No variation in light output due to the rotation of the gratings or diffraction produced by gratings of different line widths could be detected.

Procedure

Two female graduate students, both experienced in psychophysical research, served as Os. Optometric examination showed both Os to be emmetropic, and the right eye was used without any spectacle correction. A single retinal location was selected for testing in each session, and a mouthbite made from dental impression wax was positioned at the beginning of the session for that retinal location.

The double staircase method described by Cornsweet (1962) was used to determine acuity thresholds. According to the O's response of "Yes, I see lines," or "No, I don't see lines," the grating line width was decreased or increased by adjusting the angular setting of the grating to give a step size of 0.012 log acuity unit. A total of 60 trials, 30 for each staircase, was used for each acuity determination. An intertrial time of 5 sec was used, after determining that no progressive light adaptation due to the test flash occurred with this interval.

In each session, acuity thresholds were determined at four to six predetermined luminances, in order of increasing luminance. The O was allowed 15 min of dark adaptation at the beginning of the session when central vision was to be tested, and 30 min when peripheral locations were to be tested. Two minutes of light adaptation to the surround, which was matched in luminance to the test field, were given before starting each staircase.

RESULTS

Acuity thresholds were calculated by averaging the log acuity values for the settings of the gratings at which a change in response occurred, providing an estimate of the 50% point of the psychometric function (Wetherill & Levitt, 1965). Only the last half of the double staircase was used, and if fewer than 12 response reversals occurred within these trials, the

Fig. 1. (A) Configuration of the test and surround fields as they appeared during the 211-msec presentation of the grating target. (B) Schematic diagram of the optical system (see text).

Fig. 2. Log visual acuity as a function of log luminance at four retinal locations. O DV.

determination was repeated. The final acuity thresholds are the averages of two determinations made on different days.

The log visual acuity data are plotted as a function of log target luminance (averaged over the light and dark lines) in Figs. 2 and 3. The acuity values and the general shapes of the functions for the two Os are similar. At all retinal locations, the ability to resolve a grating increased with luminance. The magnitude of this increase depended upon retinal location, the greatest increase occurring in the fovea. At peripheral locations, little or no increase in acuity occurred above 0 log mL.

The maximum acuity obtained (O DV, at 3 log mL in the fovea) was 1.65 (visual angle = 36 sec), which is almost identical to the limit of resolution obtained with

Fig. 4. Log visual acuity as a function of retinal location at selected luminances. O DV.

techniques in which the retinal image is unaffected by dioptrics (Westheimer, 1960). This maximum acuity is also similar to values obtained in experiments in which the target exposure was indefinite (Shlaer, 1937).

At peripheral locations, measurements were obtained at both scotopic and photopic luminances. At 20 and 30 deg from fixation, an indication of a transition from rod to cone functioning occurs between -1.5 and -0.5 log mL, but the absence of a well-defined discontinuity in most of the curves suggests some overlap in the functioning of rods and cones. No evidence of a rod-cone transition was observed in the 10-deg functions.

The relationship between log visual acuity and retinal location is shown more clearly in Figs. 4 and 5, in which acuity thresholds interpolated from Figs. 2 and 3 are plotted. The sharpest drop in acuity with eccentricity occurred between the fovea and 10 deg at 2.75 log mL. At scotopic luminances, retinal location had less of an effect, and at -3.25 log mL, close to absolute threshold, acuity changed very little with distance from fixation.

The shapes of the functions relating log visual acuity to log luminance are similar to those obtained by Mandelbaum and Sloan with a Landolt ring. However, the luminance at which an asymptotic acuity was reached was higher for the grating data than for the ring data at all retinal locations. A considerable difference also appeared in the absolute values of the acuity thresholds obtained with the two targets. A comparison of log visual acuities from the two studies at 0 log mL is shown in Fig. 6 as a function of retinal location. Acuity was almost identical for the two targets in the fovea, but a difference of 0.50 to 0.58 log acuity unit separates the functions from 10 to 30 deg in the periphery. This means that the threshold visual angle for the Landolt C is three to four times greater than that for the grating.

Figure 6 also shows the log relative visual acuities obtained by Wertheim with a grating target. Although the position of his function on the ordinate is arbitrary, since only relative visual acuities were reported, the slope of the function would not be changed if the log absolute acuities could be plotted. Alignment of the peripheral points on Wertheim's curve with those of the present experiment would require a foveal log acuity of 0.3, a value which is rarely reported for a grating target (Westheimer, 1964). It appears that Wertheim's measures of peripheral acuity are too low, and could be attributed to one or more of the following factors: psychophysical method (method of adjustment), absence of a surround field

Fig. 3. Log visual acuity as a function of log luminance at four retinal locations. O JK.

(Lythgoe, 1932), averaging of readings from different orientations of the grating (Leibowitz, 1953; Campbell, 1958), and the blurring and fading of a steadily illuminated target, known as Troxler's effect (Clarke, 1960).

The differences between the three sets of data shown in Fig. 6 would be more striking if visual angles were compared. At 30 deg, for example, the threshold detail is 31.3 min in Mandelbaum and Sloan's experiment, 17.8 min for Wertheim's data (assuming a foveal acuity of 1.0), and 8.6 min in the present experiment.

DISCUSSION

Although the decrease in peripheral acuity with increasing distance from the fovea was demonstrated 75 years ago, the

Fig. 5. Log visual acuity as a function of retinal location at selected luminances. O JK.

Fig. 6. Comparison of visual acuity data from three investigations. Log visual acuity is plotted as a function of retinal location. All measurements were made along the horizontal meridian of the temporal retina. The data of Mandelbaum and Sloan (1947) were obtained with a Landolt ring at 1 mL. Wertheim's (1894) data are relative visual acuity measures obtained with a grating at a photopic luminance. Data for Os DV and JK were interpolated from Fig. 2 and Fig. 3 for a luminance of 1 mL.

present study shows that previous determinations have underestimated the acuity of the periphery; visual acuities at 10, 20, and 30 deg from the fovea were found to be two to four times higher than those reported previously. The reason for these higher peripheral acuities can be attributed to the careful control of the experimental conditions. Some of the areas in which the present study improves upon earlier research will be indicated.

It is apparent that the use of the grating test object in the present study resulted in peripheral acuities much higher than those obtained with the Landolt C by Mandelbaum and Sloan (1947). This is the opposite of the situation in the fovea, where maximum acuity for the Landolt C slightly exceeds that for the grating. At least part of the superiority of the grating in the periphery can be attributed to the redundancy provided by a repetitive pattern which can be resolved anywhere over its entire area. This redundancy is probably more important in the periphery, where receptor size and density vary less over the target area than for a comparable area in the fovea.

In using the grating for peripheral work, attention has been given to the orientation of the lines. Since it has been shown that the oblique orientations of grating lines result in lower acuities than do the

orthogonal positions (Leibowitz, 1953), averaging the readings from different grating orientations would result in lower acuities. In addition, Campbell (1958) has shown that with oblique incidence of the light, acuity decreases by a factor of eight for orientations at right angles to the displacement of the light. Since for peripheral stimulation the light must necessarily enter the pupil obliquely, higher acuities would be expected when a horizontally oriented grating is used for determinations along the horizontal meridian of the eye, or a vertical grating is used for determining acuity along the vertical meridian. For this reason, only the horizontal orientation of the grating was used to determine acuity along the horizontal meridian.

The selection of the exposure time of the test field was another important consideration in this acuity study. Unlimited viewing time is unsatisfactory for peripheral work; not only is there no control over saccadic eye movements, but the constantly illuminated peripheral field tends to fade and disappear (Troxler's effect). Therefore, a flash duration of approximately 200 msec was chosen in order to obtain maximum effectiveness of the available light, while still avoiding both Troxler's effect and the influence of any saccadic eye movements at the onset of the peripheral stimulus. The selection of this duration also permitted the results to be compared more readily with those of Mandelbaum and Sloan, who also used a 200-msec exposure duration.

Previous peripheral acuity studies have made no attempt to control for pupillary diameter. Not only does the retinal illumination vary with the dilation and contraction of the pupil, but as the viewing angle is increased, the horizontal dimension of the pupillary aperture decreases, reducing the amount of light reaching the retina. In acuity work, the size and shape of the pupil have an added importance in determining the diffraction pattern on the retina, and Weale (1956) has shown that this pattern becomes distorted as the result of the elliptical pupil at large viewing angles. While it is unlikely that acuity in the periphery is limited by the diffraction pattern on the retina (Kerr, 1969), eliminating the variation in the retinal light distribution for different viewing angles is desirable. For these reasons, in this study a method was devised to assure that neither the obliquity of the pupil nor the pupillary reflex to light would alter the results.

Furthermore, the use of a background field matched in luminance to the test field

served to maximize visual acuity (Craik, 1939), and control of the adaptation, accommodation, and fixation of the eye helped to reduce variability.

REFERENCES

- BERGER, C. The problem of peripheral visual acuity. *American Journal of Psychology*, 1943, 56, 603-604.
- BROWN, J. L., PHARES, L., & FLETCHER, D. E. Spectral energy thresholds for the resolution of acuity targets. *Journal of the Optical Society of America*, 1960, 50, 950-960.
- CAMPBELL, F. W. A retinal acuity direction effect. *Journal of Physiology*, 1958, 144, 25P.
- CLARKE, F. J. J. A study of Troxler's effect. *Optica Acta*, 1960, 7, 219-236.
- CRAIK, K. J. W. The effect of adaptation upon visual acuity. *British Journal of Psychology*, 1939, 29, 252-266.
- CORNWELL, T. N. The staircase-method in psychophysics. *American Journal of Psychology*, 1962, 75, 485-491.
- GRAHAM, C. H. (Ed.) *Vision and visual perception*. New York: Wiley, 1965.
- KERR, J. L. Visual resolution in the peripheral retina. (Doctoral dissertation, Columbia University) Ann Arbor, Mich: University Microfilms, 1969, No. 69-17, 598.
- KRECH, D., CRUTCHFIELD, R. S., & LIVSON, N. *Elements of psychology*. (2nd ed.) New York: Knopf, 1969.
- LEIBOWITZ, H. Some observations and theory on the variation of visual acuity with the orientation of the test object. *Journal of the Optical Society of America*, 1953, 43, 902-905.
- LOW, F. N. Peripheral visual acuity. *Archives of Ophthalmology*, 1951, 45, 80-99.
- LYTHGOE, R. J. The measurement of visual acuity. Medical Research Council, Special Report Series, No. 173. London: H.M. Stationery Office, 1932.
- MANDELBAUM, J., & SLOAN, L. L. Peripheral visual acuity. *American Journal of Ophthalmology*, 1947, 30, 581-588.
- RUCH, T. C., & FULTON, J. F. (Eds.) *Medical physiology and biophysics*. Philadelphia: Saunders, 1960.
- SHLAER, S. The relation between visual acuity and illumination. *Journal of General Physiology*, 1937, 21, 165-188.
- SHLAER, S., SMITH, E. L., & CHASE, A. M. Visual acuity and illumination in different spectral regions. *Journal of General Physiology*, 1942, 25, 553-569.
- WEALE, R. A. Problems of peripheral vision. *British Journal of Ophthalmology*, 1956, 40, 392-415.
- WERTHEIM, T. Über die indirekte Sehschärfe. *Zeitschrift für Psycholog. und Physiolog. Sinnesorg.*, 1894, 7, 172-187.
- WESTHEIMER, G. Modulation thresholds for sinusoidal light distributions on the retina. *Journal of Physiology*, 1960, 152, 67-74.
- WESTHEIMER, G. Pupil size and visual resolution. *Vision Research*, 1964, 4, 39-45.
- WETHERILL, G. B., & LEVITT, H. Sequential estimation of points on a psychometric function. *British Journal of Mathematical & Statistical Psychology*, 1965, 18, 1-10.

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