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REGIONAL VARIATIONS IN THE VISUAL ACUITY FOR INTERFERENCE FRINGES ON THE RETINA

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SUMMARY

1. The visual acuity of the peripheral retina was measured using both sinusoidal gratings viewed in the usual way and interference fringes formed on the retina directly.

2. It is shown that optical aberrations cause a reduction in peripheral visual acuity for eccentricities of less than 5°. However, the hypothesis that optical defects are a major cause of the well-known decrease in acuity with eccentricity is rejected.

3. The fringe acuities at various retinal positions are compared with Osterberg's counts of the distribution of cones. It is shown that at eccentricities of less than 2°, resolution approaches the theoretical limits for a mosaic of receptors.

INTRODUCTION

The resolving power of the human eye is greatest in the fovea and falls off rapidly with increasing angular distance from the point of fixation. This fall in visual acuity with eccentricity is usually explained as being due to both the fall in density of cones and the changes in synaptic organization as one moves away from the fovea. However, in addition there is a third possible factor to be considered. The quality of the images formed on the retina might vary with eccentricity. Even on the fovea optical factors are important determinants of visual resolving capacity (Campbell & Green, 1965). In addition to the aberration of the foveal image, peripheral imagery involves off-axis aberrations, such as oblique astigmatism and coma, of unknown magnitudes.

To determine how optical factors limit the intrinsic abilities of the human eye to appreciate fine detail the visual acuity of the peripheral retina has been measured in two ways. First, a gas laser was used to produce sinusoidal interference fringes directly on the retina. The fringes on the retina are of high contrast and are not degraded by ordinary optical defects (Campbell & Green, 1965; Campbell, Kulikowski & Levinson, 1966; Mitchell, Freeman & Westheimer, 1967). Secondly, for comparison, visual acuities were measured with sinusoidal gratings of high contrast viewed in the ordinary manner. The image of a sinusoidal target is again sinusoidal but reduced in contrast by optical defects. The extent to which the quality of the retinal image formed by dioptric components of the eye limits visual resolution can be estimated from the difference between the visual acuities measured with interference fringes and those determined with sinusoidal targets.

METHODS

A neon-helium gas laser (λ = 632·8 nm) was used as the coherent source with which interference fringes were formed. The set-up is shown diagrammatically in Fig. 1*a*.

The collimated beam from the end of the laser was made divergent with a 20 D spectacle lens (L_3). To divide the beam into two parts a Ronchi ruling (RR) was placed before a + 3·5 D convex lens (L_2). A mask M placed in the image plane of L_2, occluded all but the first order spots in the diffraction pattern from the ruling.

The subject viewed the interference fringes by placing his eye before a 105 cm photographic objective (L_1). This lens formed double images of the first-order diffraction spots in the plane of the observer's pupil. To vary the separation between successive maxima in the sinusoidal pattern formed on the retina the spacing between the double images in the pupil was changed by means of a set of rulings. A field stop (FS) conjugate with the retina limited the size of the fringe pattern seen by the observer to 0·54° of visual angle. Visual acuity was determined by having the subject carefully fixate on a set of cross-hairs (FP) while the field stop was moved along a horizontal meridian in the temporal visual field until the vertical interference fringes could just be detected. Figure 1*b* illustrates the stimulus configuration.

High-contrast vertical sinusoidal gratings were generated on the face of a cathode ray tube (CRT) using techniques described in detail elsewhere (Campbell & Green, 1965; Green, 1967). The CRT had a red phosphor (Silvania, P 22 R) with a nearly monochromatic output at λ = 619 nm. The magnitude of the voltage on the control grid of the tube was adjusted to produce approximately 100 % modulated stripes on the face of the tube. A circular mask in front of the CRT limited the size of the field to 0·54° as viewed from a distance of 105 cm. The subject's right pupil was dilated with 1 % Cyclogyl. A 4 mm artificial pupil with suitable correcting lenses was placed before the eye of the observer. By fixating at various distances along a horizontal meridian from the centre of the test field and varying the spatial frequency of the grating pattern, the subject determined the highest frequency at which the striped pattern could be resolved.

RESULTS

Fig. 2 shows visual acuity as a function of eccentricity for two subjects. Visual acuity is plotted on a linear scale in terms of the reciprocal of the angle subtended by a single bar of the sinusoidal pattern. Therefore, a spatial frequency of 30 cycles/degree corresponds to an acuity of 1 (minute of arc)$^{-1}$. The open circles indicate the acuities when viewing interference fringes formed directly on the retina. The filled circles were determined using sinusoidal gratings imaged onto the retina by the optics of the eye. Both targets were adjusted to produce a retinal illumination of 1200 td. Smooth curves have been drawn through the two sets of measurements. These data show that with both conditions of viewing, visual acuity is a

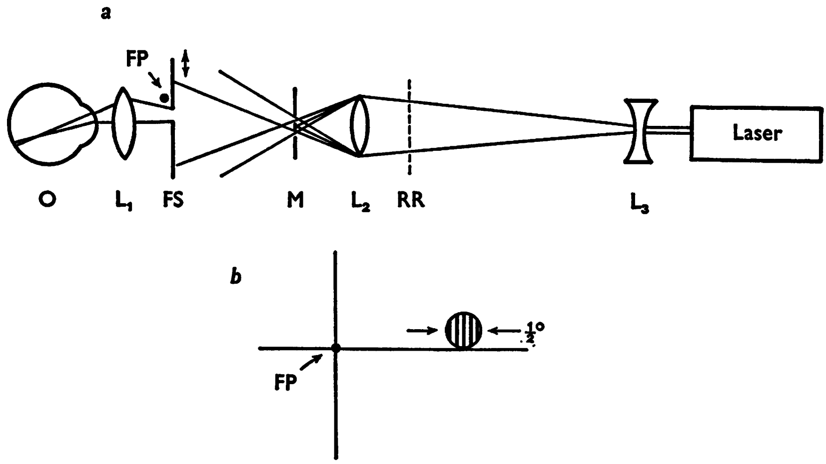

Fig. 1*a*. Schematic diagram of the apparatus used to produce interference fringes. *b*. Stimulus configuration. For details see text.

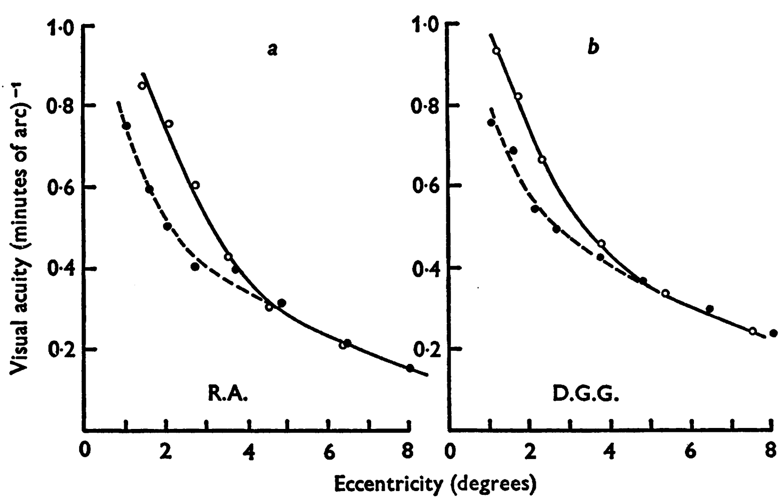

Fig. 2. Visual acuity at various positions eccentric from the fovea. Measurements for two subjects are shown in (*a*) and (*b*). The open circles are for interference fringes formed on retina. Filled circles show results obtained with high contrast sinusoidal gratings viewed from a distance of 105 cm through a 4 mm artificial pupil. Each point is the average of five measurements. Both targets produced a retinal illumination of 1200 td.

steadily decreasing function of eccentricity. At small angles the acuity is highest for the interference fringes. At larger eccentricities the acuities for fringes and gratings are essentially the same.

DISCUSSION

It seems that for eccentricities greater than 5°, under optimum viewing conditions, the visual acuity of the eye is not appreciably reduced by the quality of the images formed on the peripheral retina. This does not necessarily imply that the images formed in the periphery are ot high

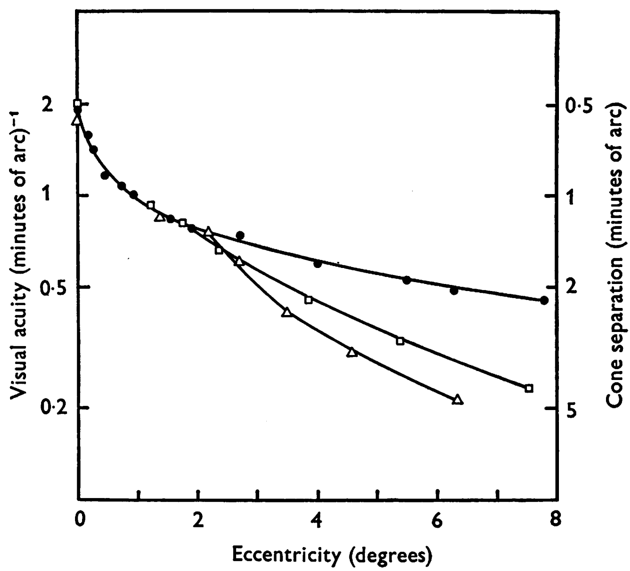

Fig. 3. Comparison of interference fringe acuity and intercone separation. The measurements of acuity (□, D.G.G.; △, R.A.) are from Fig. 2 with the addition of the foveal acuity of both subjects. The intercone separations are from Osterberg (1935). Equation (1) has been used to relate intercone separation to visual acuity.

quality. It most probably only reflects the fact that the visual acuity of the peripheral retina is low and all optical transfer functions approach unity at low spatial frequencies (Born & Wolf, 1964). The fall in acuity with eccentricity exhibited by the interference fringe data must be associated with some property of the retina and/or visual pathways since these measurements are independent of the image forming properties of the eye's optics. Is the fall in acuity simply due to the decreased density of cones or is it in addition necessary to postulate increased convergence in the pathways?

It is clear that the fineness of the retinal mosaic ultimately determines the limits of acuity. For example, from the Shannon sampling theorem (Shannon & Weaver, 1949) we know that a bandwidth limited signal having no spatial frequency components higher than BW can be represented by taking independent samples of the signal at intervals of 1/2BW. If the receptors are considered as samplers of the intensity distribution on the retina, it follows that the highest spatial frequency that can be transmitted through such a sampler is equal to the reciprocal of twice the interreceptor spacing. In other words, visual acuity (V) is related to intercone separation (s) by

$$V = 1/s. \tag{1}$$

Equation (1), of course is consistent with the intuitive idea (Helmholtz, 1867) that between every stimulated receptor there must be at least one relatively unstimulated receptor to resolve the lines of a grating. To ascertain the extent to which visual acuity approaches the limit set by the fineness of the mosaic of cones, intercone separations (from Osterberg, 1935) have been plotted against eccentricity with V and s related by eqn. (1). The acuities plotted in the Figure are those for interference fringes on the retina and in contrast to previous comparisons between visual acuity and cone density (Ludvigh, 1941; Polyak, 1949; Weymouth, 1958; LeGrand, 1967) the effects of the optics of the eye have been circumvented. Up to about 2° there is reasonable agreement between acuity and cone spacing. While these findings do not mean that each foveal cone is connected exclusively to one optic nerve fibre, it is interesting to note that visual resolution approaches the limit that a system connected in this way could achieve.

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