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OPTICAL QUALITY OF THE HUMAN EYE

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SUMMARY

1. Optical quality of the eye was measured at eight pupil sizes between 1·5 and 6·6 mm diameter by recording the faint light emerging from the eye; this light was reflected from the bright image of a thin line on the fundus.

2. The nature of the fundus reflexion was examined; it was found that the fundus acts very much like a perfect diffuser while retaining polarization.

3. Using the result that the fundus acts like a diffuser, the recorded line images were Fourier analysed to provide modulation transfer functions. These functions indicate an optical quality considerably higher than that found in previous physical studies.

4. Linespread profiles were then derived from the modulation transfer functions. These profiles are 40 % narrower than those of previous physical studies for a 3·0 mm pupil. The narrowest profile occurred with a 2·4 mm pupil.

5. Our results demonstrate that physical and psychophysical studies can yield similar estimates of optical quality. The influence of optical factors not common to both techniques is discussed. Evidence for the existence of neural 'image sharpening' mechanisms is reviewed.

INTRODUCTION

Inherent imperfections in the optical components of the human eye, as well as inevitable diffraction effects, limit the fidelity of the retinal image of an external object. If the object is an infinitesimally thin, self-luminous line, its fundal image will be degraded in sharpness into a smooth illuminance distribution which is termed the linespread function (Lamberts, Higgins & Wolfe, 1958). If the object is a grating whose luminance across its width varies up from zero and down again in a sinusoidal manner, the illuminance of its image will nowhere become zero but will modulate equally above and below a constant mean level (Fig. 1). This loss of

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contrast in forming an image of gratings of all possible pitches, constitutes the modulation transfer function of the optics. The linespread and modulation transfer functions are Fourier transforms of one another (Duffieux, 1946; Hopkins, 1962; Linfoot, 1964). An example is given in Fig. 1.

Several attempts have been made to measure physically the optical quality of the human eye. This has been done by forming a bright image on the fundus; the eye's optics acting in reverse form a faint image in space with light reflected from the fundus. This image in space was analysed

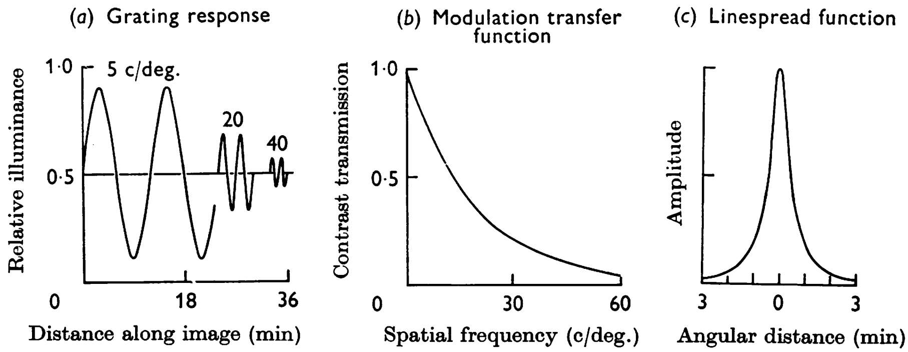

Fig. 1. Equivalent measures of optical quality. (*a*) As the fineness of a black-and-white grating is increased the illuminance modulation of its image decreases. (*b*) The continuous line describing this decrease of contrast is the modulation transfer function. (*c*) The illuminance distribution in the image of a thin line is termed the linespread function; it is also obtained as the Fourier transform of the modulation transfer function.

photoelectrically. Flamant (1955), Westheimer & Campbell (1962), and Krauskopf (1962) used a line source to estimate image sharpness on the fundus in this way. Röhler (1962) and Westheimer (1963), using gratings, obtained the modulation transfer function directly. All of these experimenters got quite similar results; namely, that the fundal image of a thin line is at least twice as broad as the line's diffraction image for the given pupil size.

With interference techniques it is possible to project on to the fundus a sinusoidal grating whose contrast is independent of most optical defects. By viewing an interference grating and an ordinary sinusoidal grating adjusted for equal subjective contrast, Arnulf & Dupuy (1960) and Campbell & Green (1965) obtained measures of the contrast decrease (modulation transfer function) introduced by the optics alone. They found by this psychophysical method that optical quality is much better than indicated by the five previous physical studies and that it becomes limited mainly by diffraction for sufficiently small pupil sizes.

Several factors can possibly account for the different results between these physical and psychophysical methods of estimating optical quality. First, the fundus may act optically as a poor screen and thus degrade the line's image before casting it by reflexion out of the eye. However, the image available to the receptors may not have been appreciably blurred in this manner. Secondly, the fundus may behave as a smooth mirror. If this is so, Fourier analysis, which in the objective experiment depends for its validity upon the presence of a perfect diffuser rather than a mirror, would yield an estimate of poorer optical quality than that which actually exists. Thirdly, light scatter in the optical media must affect all physical measurements of image degradation but will not show up in the psychophysical technique; because scatter occurs in both coherent and incoherent beams and when the difference between two corresponding psychophysical measurements is taken the effect of scatter tends to be cancelled.

In order to establish how well results of psychophysical techniques agree with those obtained by a physical method, we will first determine the nature of the fundal reflexion and then interpret our subsequent linespread measurements accordingly.

METHODS

The subject, whose accommodation and pupil have been paralysed with cyclopentolate hydrochloride, is placed against a forehead and chin rest with his eyes 84 cm from a vertical slit which subtends 0·2 by 30 min of arc (Fig. 2). The slit is illuminated from behind by a 150 W xenon arc-lamp whose brightest point is focused on the slit. A small artificial pupil is placed close to the subject's cornea and his refraction is then corrected to within $\pm 0{\cdot}12$ D using spherical and cylindrical lenses to the point at which he perceives the slit most clearly and the equipment was found to record the narrowest linespread. He fixates the slit continuously. The three subjects' ages and refractions for 84 cm were: G.L. 24 yr, $-1{\cdot}0$ D; F.N. 28 yr, $-2{\cdot}0$ D; R.G. 24 yr, $-1{\cdot}25$ D cylinder at 80°.

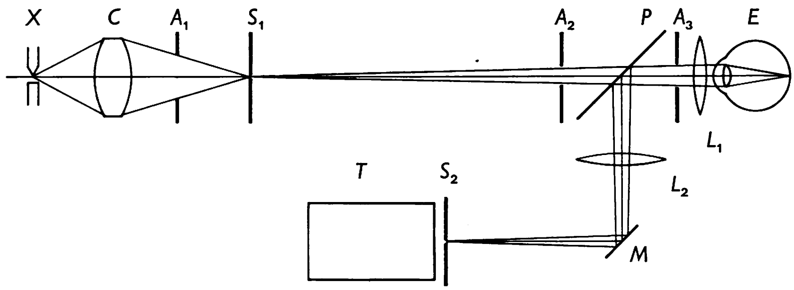

Fig. 2. Optical apparatus. X, Xenon arc lamp; C, collecting lens; A_1, aperture; S_1, source slit; A_2, aperture; P, beam-splitting pellicle; L_1, correcting lens; A_3, artificial pupil; E, eye of observer; L_2, lens in outgoing beam; M, front-surface mirror on rotating mount; S_2, analysing slit; T, photomultiplier.

Light leaving the eye from the fundal image of the slit is reflected from a beam-splitting pellicle and strikes a front-surface mirror which is rocked on two pivots about a vertical axis by a linear moving-coil actuator. The actuator is driven by the sawtooth deflexion voltage provided by a digital averaging computer (Enhancetron; Nuclear Data Inc., Palatine, Ill., U.S.A.). The mirror thus sweeps a degraded replica of the fundal image repetitively past a vertical analysing slit which subtends 0·4 by 30 min of arc. This second slit and the source slit are equidistant from the eye. Behind the analysing slit is a photomultiplier whose output, proportional to light intensity, is displayed and amplified by one channel of a dual-beam oscilloscope. The amplified output of the photomultiplier is entered sequentially into the 1024 addresses of the Enhancetron; the averagers' output is displayed on the second channel and recorded permanently by an x–y plotter.

Optical alignment of the source and analysing slits, and calibration of angular excursion of the mirror, can be done precisely by temporarily replacing the photomultiplier with a tungsten light source focused on the analysing slit. If now a +2 D lens is inserted in place of a subject's eye, images of the slits will be projected about a metre away from the lens; with the Enhancetron functioning, one image will slide repetitively past the other and both can be set parallel and vertical by the experimenter. Exact alignment of the slits is imperative, for lack of alignment will produce apparent broadening of the linespread function. The range of scan of the moving image is adjusted to be precisely 50 min of arc.

RESULTS

Nature of the fundal reflexion

As all previous investigators, we have used an incoherent source of light to measure linespreads. Now it is also important for the validity of the necessary Fourier analyses that there should be no coherence *between* ingoing and outgoing beams. A diffusing screen at the fundus would guarantee this condition. A mirror would violate it, however, and it is thus necessary to distinguish between these two contingencies. We have performed three tests to assess the optical nature of the fundus under the same experimental conditions which are used to measure linespread.

Effects of focus. First consider the fundus as a plane mirror. The image of a thin line focused sharply on its surface at normal incidence will return light along precisely the same path as it arrived and will form a second image coincident with the real line. If the ingoing and outgoing beams are now separated by a beam-splitter, it will be possible to focus the outgoing beam independently of the ingoing one. Let us therefore defocus the image on the fundus and place compensating lenses (L_2 in Fig. 2), in the outgoing beam. If the fundus is a diffuser we cannot regain from the outgoing beam, by any positive or negative lens whatever, an image of the line as sharp as there was previously. But if we are dealing with a smooth mirror, image sharpness in the plane of the analysing slit will be restored completely by a suitable choice of lens in the outgoing beam. This test provides a simple criterion for distinguishing between the presence of either a diffuse and of a specular surface; if a mixture of both properties is present, the operation of refocusing the outgoing beam will improve the image but will not altogether restore it.

The results of this test on one subject (R.W.G.) using a 2·8 mm diameter artificial pupil are illustrated in Fig. 3; they indicate the diffusing properties of the fundus. The optimum lens at L_1 yields the linespread shown at A. Inserting a lens $+0{\cdot}5$ D greater than the optimum degrades the linespread to the width shown at B. If the fundus behaved as a mirror, the recorded linespread would become as narrow as that at A if a $-1{\cdot}0$ D lens ($-0{\cdot}5$ D for each traverse of L_1 made by the measured light) were inserted at L_2.

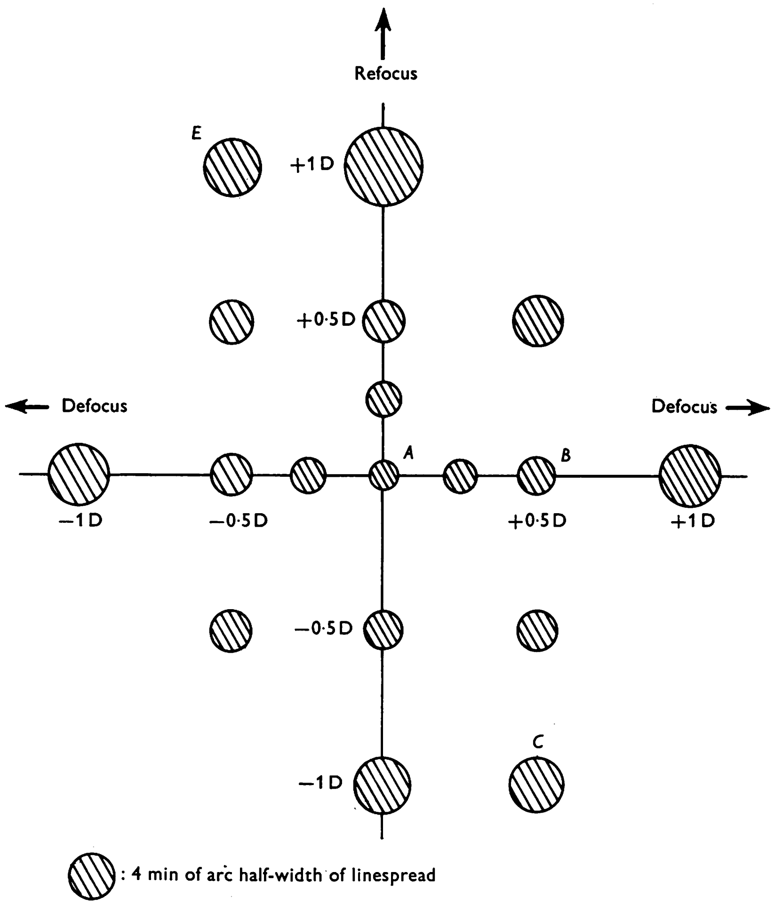

Fig. 3. Test of fundal reflexion. Departures from optimum correcting lens at L_1 are plotted horizontally; lens power at L_2 in outgoing beam is plotted vertically. Diameter of circle is proportional to half-width of measured linespread.

What actually results is the linespread at C, which is broader than that at B instead of narrower. Using $-0{\cdot}5$ D of defocus at L_1 and a $+1{\cdot}0$ D lens at L_2 leads to the same result, shown by the circle at E. Other circles are included to illustrate the smooth variation of linespread width as focus is changed. Linespread width is here taken as the angular distance across the measure illuminance distribution at one-half its maximum amplitude.

Had the fundus behaved as a concave mirror this test would have revealed that fact also. Concavity would add dioptric power to the reflected light. Thus at the optimum lens L_1 a further sharpening of the recorded line image would be effected by introducing a negative correction at L_2. No such improvement can be made, as shown by the circles of Fig. 3 which lie on the ordinate.

Effect of aperture size. As in a simple camera, the luminance of an image on the fundus varies directly with the area of the pupil. If an image is formed from diffusely reflected light leaving the eye this image too will vary in illuminance with pupil area, as well as varying with the fundal image's illumination. Hence the linespread measured external to the eye will change in luminance as the square of pupil area.

If light entering the eye encounters a *mirror* normal to its path, the bundle of rays leaving the eye will be confined to the same area defined by the ingoing pupil. Although the fundal image would still vary in luminance with pupil area, that pupil would have no further effect on the outgoing rays and the subsequently formed external linespread would change illuminance only linearly with pupil area.

We have used a model eye to verify the foregoing predictions and the results from it, and one subject (R.W.G.), are displayed in Fig. 4. The 'fundus' of the model was either a sheet of aluminium smoked with MgO to a depth of about 0·7 mm or a front-surface mirror. Although the eye and its model both perform slightly short of theory, the data are quite unequivocal and emphasize the diffuse character of fundal reflexion.

Polarization. Linear polarization of light is retained on specular reflexion normal to a surface and destroyed with most diffuse reflexion. By polarizing a light source and observing its fundal image through an analyser, one can detect the polarization of any reflected light as a fluctuation of its intensity as the analyser is rotated. Upon examining the fundal image in this manner one observes its colour varying from almost white (the colour of the source) to deep red. This red hue occurs when the analysing and polarizing axes are perpendicular and arises from depolarized light penetrating the choroid and assuming the colour of haemoglobin (Alpern & Campbell, 1962). Averaged among several subjects, the polarized component of fundal reflexion constitutes about 80 % of the total; this fraction decreases at longer wave-lengths. This retention of polarization has been recently studied by Weale (1966); his observation that bleaching the visual pigments increases the reflexion of polarized and unpolarized components equally indicates that the light is being reflected from a surface posterior to the receptors.

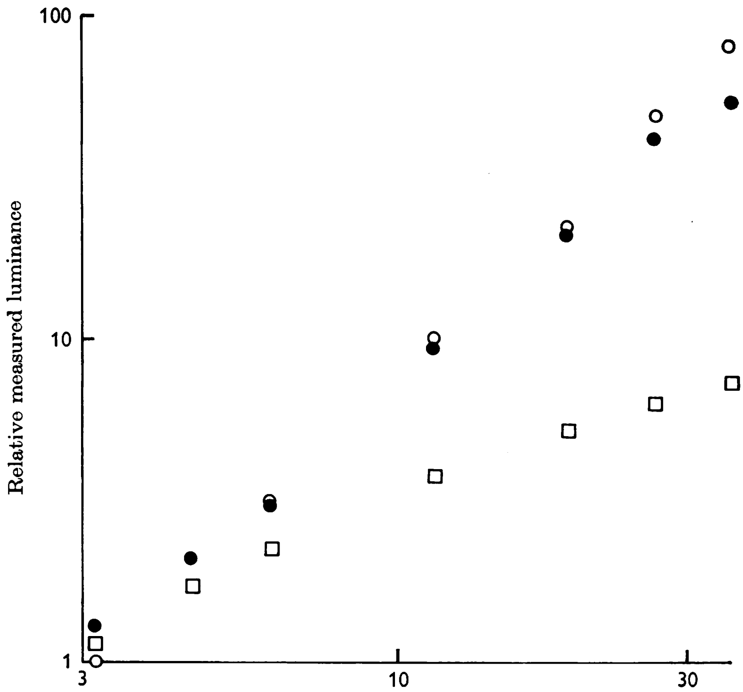

Fig. 4. Test of fundal reflexion. ●, Observer R.G.; ○, artificial eye with MgO 'fundus'; □, artificial eye with mirror 'fundus'. Artificial pupil diameters used are 2·0, 2·4, 2·8, 3·8, 4·9, 5·8 and 6·6 mm.

Conclusion

The human fundus in white light may be regarded as a nearly perfectly diffuse reflector, for in two of the tests we applied it followed the behaviour of diffuse reflexion to a high degree of accuracy. Its retention of polarization need not detract from this conclusion; an aluminized projection screen has these same reflexion characteristics and may be regarded as a simple optical analog of the fundus. Such a screen, consisting of a layer of small aluminium granules, is used commonly for stereoscopic presentations which require the use of polarized light. The screen is not a mirror because, for example, one sees a projected image on it and not a virtual image beyond it.

Linespread functions

Records of the linespread profiles of one subject measured external to his eye are shown in Fig. 5. They exhibit the general trend of narrowing with decreasing pupil size until the smallest aperture diameter, 1·5 mm, is reached. Although more averages were taken as the aperture decreased, the amount of light available dropped so rapidly (see Fig. 4) that a high signal-to-noise ratio could not be maintained. About 200 sweeps of the mirror were made at the smallest pupil size, corresponding to 100 sec of continuous averaging time.

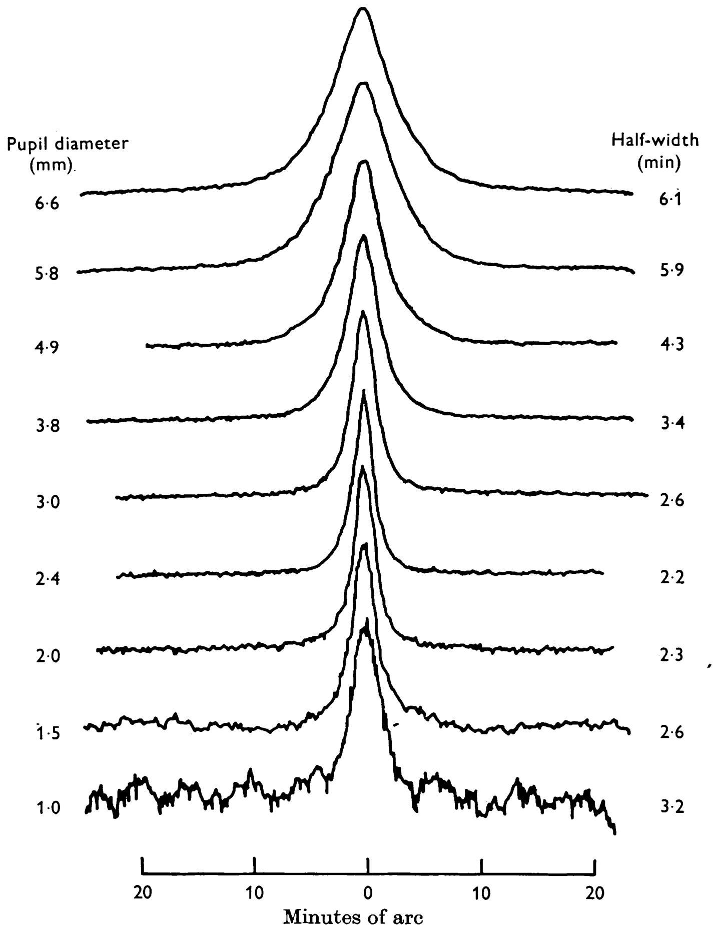

Fig. 5. Linespreads measured external to the eye. Each record is reproduced from a tracing of the averaged response scaled to a constant maximum height. The half-width given at the right is measured across the entire linespread at one-half its maximum height. The subject is R.G.

Data from all three subjects are given in Fig. 6. The ordinate is now logarithmic. Linespread profiles obtained at 1·5 and 2·4 mm have been omitted for the sake of clarity. For small pupils the respective curves from each subject are quite similar but not perfectly congruent; as pupil size increases the profiles match less well. The most striking feature of these records is that they are narrower than those similarly obtained by

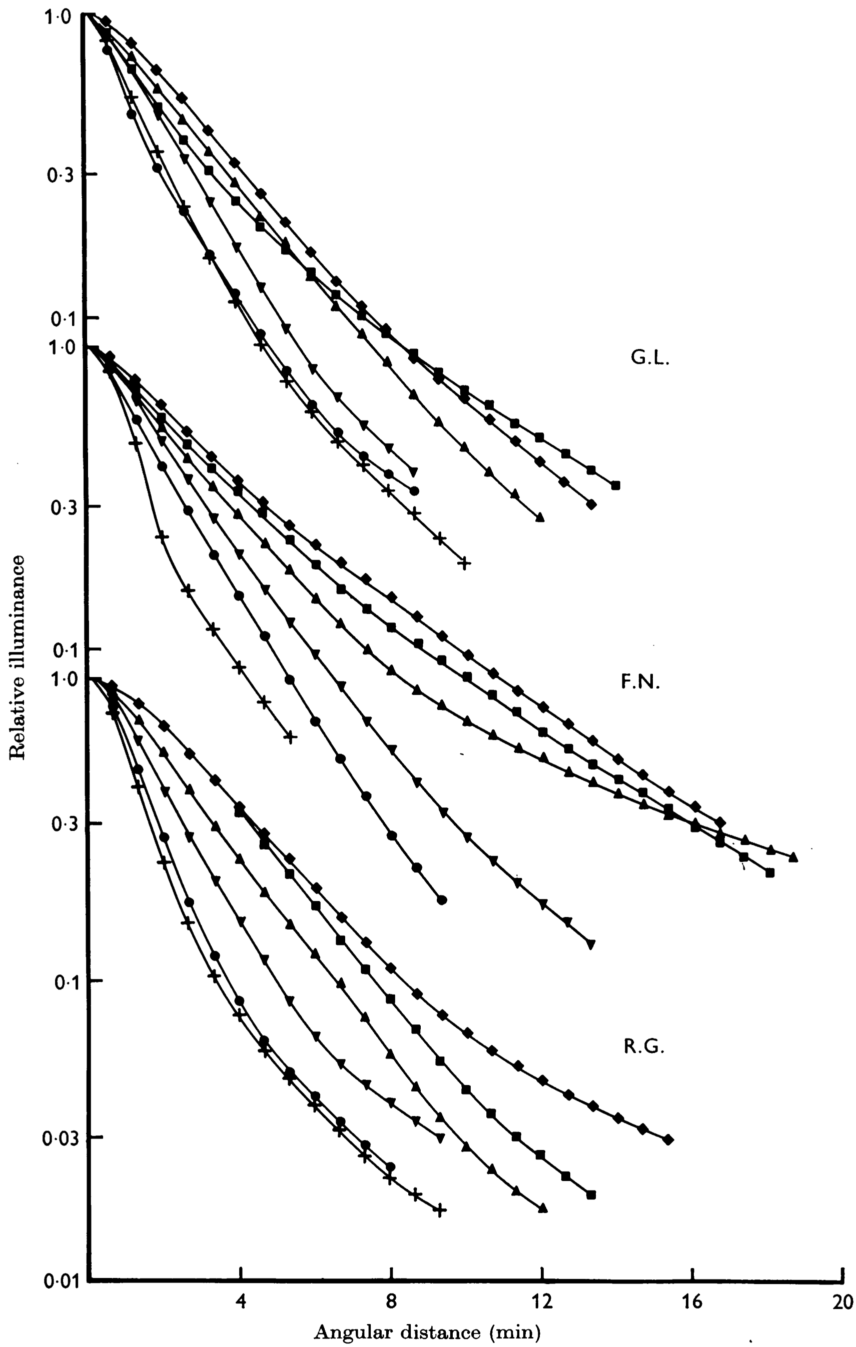

Fig. 6. Linespreads measured external to the eyes of three subjects. Angular distances are taken from the centres of the symmetrical curves and only the right halves are shown. Pupil diameters in mm are: +, 2·0; ●, 3·0; ▼, 3·8; ▲, 4·9; ■, 5·8; ◆, 6·6.

previous investigators. Although direct comparison of our results with those of psychophysical methods cannot be made at this point, we would expect the former disparity between estimates of optical quality to be much smaller using our present results.

The profiles of Fig. 6 have been Fourier transformed numerically by the method of Flamant (1955), using a Titan digital computer; they appear in Fig. 7 as modulation transfer functions, displaying the variation of contrast transmission with spatial frequency. The data are here corrected for the double traverse of the eye made by the measured linespread functions, using the fact that light was reflected from a perfect diffuser. They have also been compensated for the error introduced by using slits of finite widths; the correction increases from zero at the lowest spatial frequencies to about 10% at the highest ones. The optical quality indicated by Fig. 7 is better than previous linespread studies have shown and is similar to that found by Campbell & Green (1965) who used a psychophysical method. Our results show a somewhat greater attenuation of contrast than theirs for frequencies greater than 15 c/deg.

With two subjects (G.L. and F.N.) the curves for 2·0 and 3·0 mm pupils cross each other. A similar crossing is shown in Fig. 10 of Campbell & Green for 2·0 and 2·8 mm pupils. In most subjects the eye's optics transmitted fine detail better with a 3 mm pupil than one 2 mm, but coarse structure was rendered more faithfully with the smaller aperture.

To check the validity of these numerically computed transforms we fitted by eye one experimental curve with the sum of two analytical functions, Gaussian and exponential, whose Fourier transforms are well known. The frequency response calculated in this manner agreed with the computer results; in general the curves cannot be fitted readily by eye and the use of numerical analysis is much quicker and more accurate.

To facilitate comparison of our results with those of Arnulf & Dupuy (1960) and with an ideal, diffraction-limited system, we measured the spectral transmission of our apparatus with a subject placed as for a linespread measurement. The source-slit was replaced by a grating monochromator whose wave-length and transmission characteristics had been previously calibrated; the otherwise moving mirror was fixed so that maximum linespread illuminance was continuously seen by the analysing slit. With the subject in place, the output voltage of the photomultiplier was recorded at 10 nm increments of wave-length and the data from two trials averaged. The spectral response of the system measured in this way was found to be close to the C.I.E. photopic luminous efficiency but with a mean wave-length of 570 nm (Fig. 8).

Using this mean wave-length, we have averaged data from the three subjects and normalized the abscissae with respect to the highest spatial

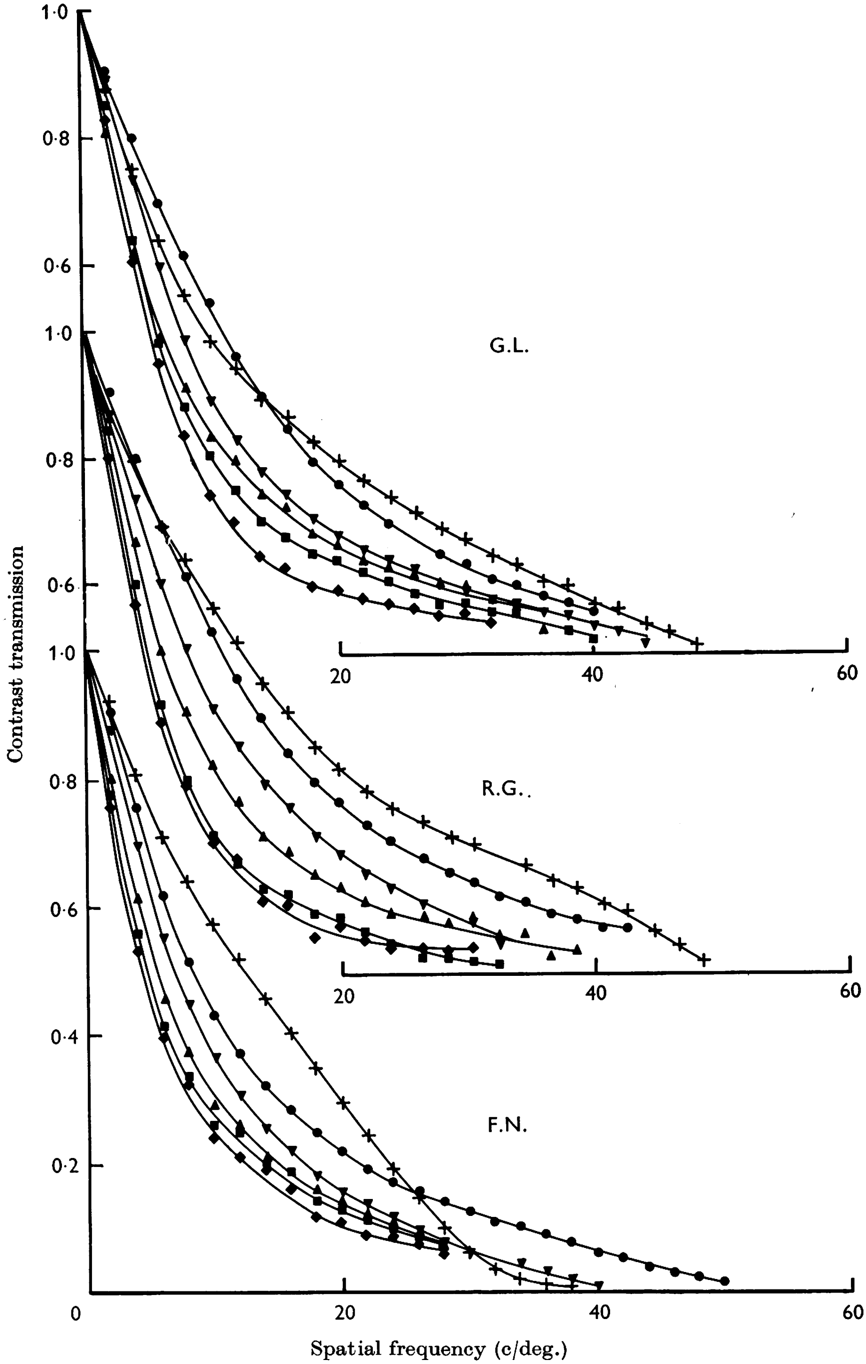

Fig. 7. Modulation transfer functions for the eyes of three subjects. The curves display for various pupil sizes the transmission of contrast to an object imaged on the fundus; they are corrected for the double traverse of the eye made by the measured linespread function. Symbols are as in Fig. 6.

frequencies transmitted by an ideal optical system working in monochromatic light at 570 nm. The theoretically maximum transmitted frequency is proportional to reciprocal pupil diameter; therefore curves from the larger pupils of Fig. 7 appear compressed to the left in Fig. 9. This normalization, commonly applied in physical optics (Hopkins, 1962) and employed extensively by Arnulf & Dupuy (1960), emphasizes the fact

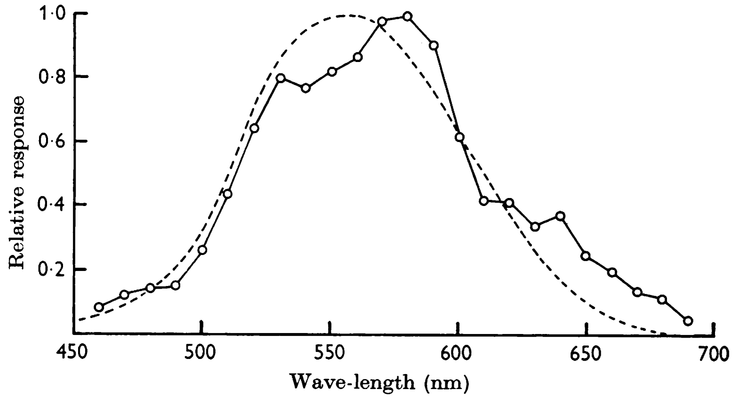

Fig. 8. Spectral transmission of apparatus with an eye in place. O, measured response, with mean wave-length of 570 nm; interrupted line, C.I.E. photopic luminous efficiency of mean observer, with mean wave-length of 555 nm.

that optical quality falls increasingly short of perfection as the pupil dilates, even though measured performance does not change by any large amount. Presented in this manner, our results show a similarity to those of Arnulf & Dupuy but indicate somewhat more attenuation at frequencies below 20 c/deg.

From the information in Figs. 7 or 9, we can calculate optical linespread functions at eight pupil sizes, by evaluating numerically the inverse Fourier transform of each curve (Flamant, 1955). The resultant linespread profiles (Fig. 10) portray the normalized illuminance distribution on the fundus from an infinitesimally thin bright line in optimum focus. Small oscillations of the data points arise from unavoidable end-effects which occur during numerical computation of the inverse transforms and do not represent any real illuminance variations. The diffraction image of a line with an ideal achromatic lens in light of the same spectral composition that we have used (Fig. 8) is indicated for comparison. These 'photopic' diffraction images were calculated by summing twenty-four monochromatic diffraction images (Hopkins, 1953) between 460 and 690 nm whose amplitudes are proportional to the spectral response of the system at the given wave-length. There is very little difference between the shape of a monochromatic and a 'photopic' diffraction image at the same pupil size.

The greatest difference in intensity between the two at any distance from their centres is about 0·5 % of their common maximum intensity.

Several aspects of the computed linespread functions are worth noting. Although the actual linespread departs increasingly from its ideal counterpart as the pupil increases, there exists an optimum pupil diameter of 2·4 mm at which the half-width of the linespread is at a minimum. At

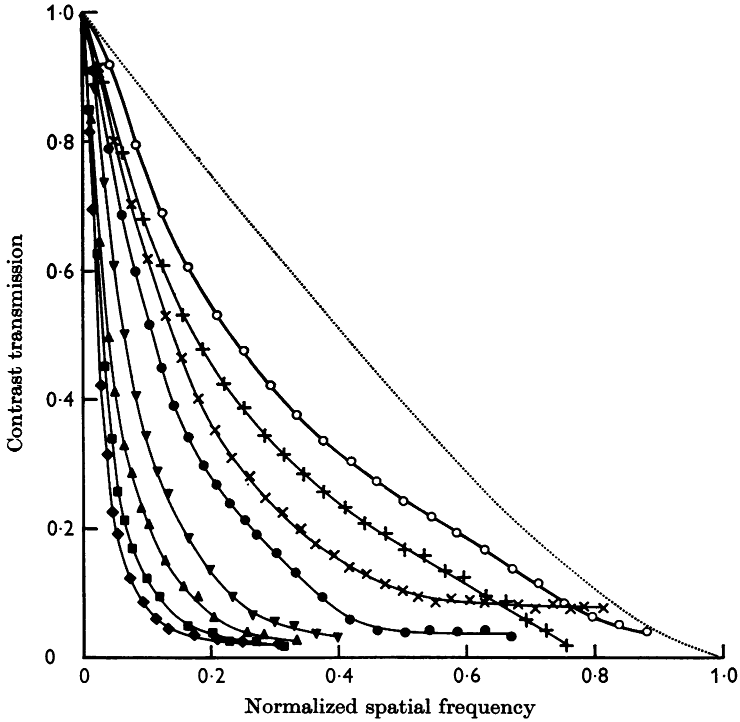

Fig. 9. Normalized modulation transfer functions of the human eye, averaged among three subjects. The results are normalized to the highest spatial frequency transmitted by an ideal optical system with light of 570 nm wave-length. Symbols are as in Fig. 6, with: ○, 1·5 mm pupil; ×, 2·4 mm pupil. Dotted curve gives performance of ideal system.

smaller pupils the curve is widened by diffraction. Shlaer (1937) found visual acuity optimum with a 2·3 mm diameter pupil and attributed lower acuity with smaller pupils to diffraction effects. The way in which the linespread function degrades as pupil diameter is increased is clear from Fig. 10. At 2·4 mm the curve consists roughly of a Gaussian core and exponential 'skirt', the core fitting the diffraction image. As the pupil increases the 'skirt' of the function becomes more predominant and finally constitutes the entire curve. The approximately Gaussian core (most obvious at 1·5 mm) is the ideal line image; the skirt represents stray light coming from scatter (Fry, 1965) or defects of focus which increase with pupil diameter. A comparison of the linespread estimates of Flamant (1955), Westheimer & Campbell (1962), and Krauskopf (1962) with ours is given in Fig. 11.

The linespread functions in Fig. 10 are about twice as narrow as the

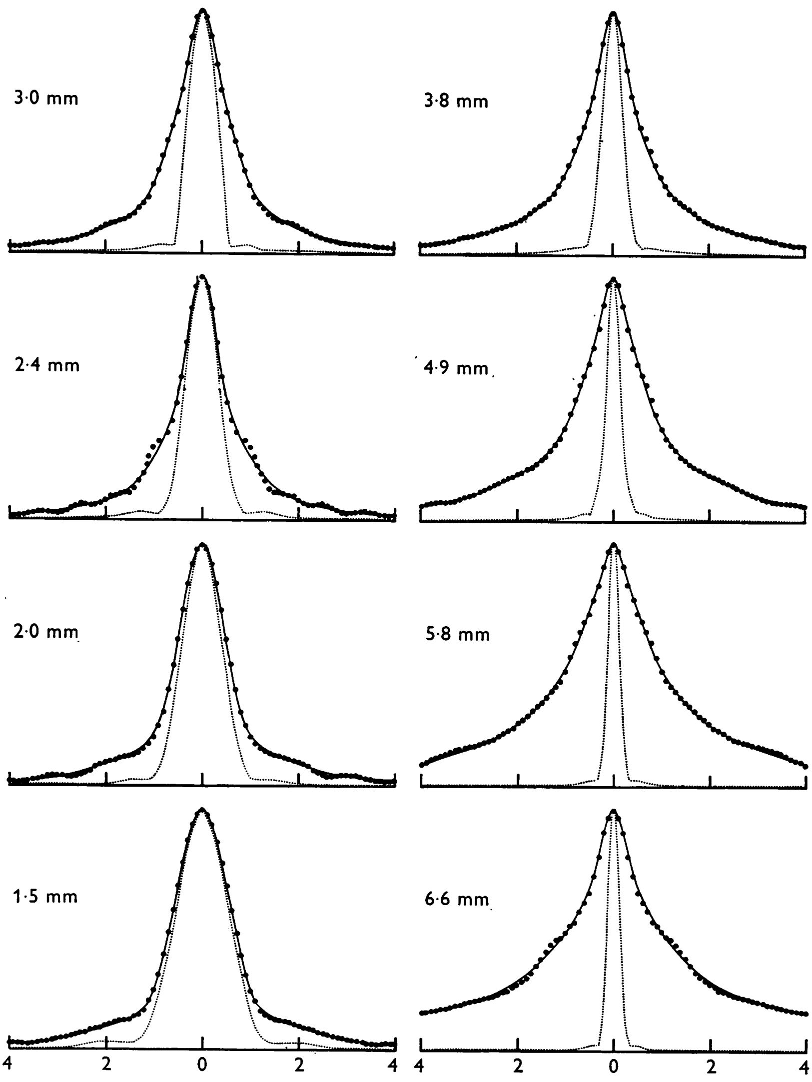

Fig. 10. Optical linespread functions of the human eye. Each curve represents the normalized distribution of illuminance occurring on the fundus for a thin line source of light. Dots occur at 0·1 min increments. Narrower curve indicates the diffraction image of a line at the given pupil diameter.

respective curves in Fig. 5 as a result of the image's double traverse of the eye. They are also narrower than the previous results of those authors using a physical technique. We therefore conclude that with care this determination of human linespread functions can be made to agree reasonably well with independent psychophysical tests. The present results are worse than these to the small extent to which the psychophysical tests are freer from the influence of chromatic aberration, light scatter in the fundus, and to the extent of experimental error.

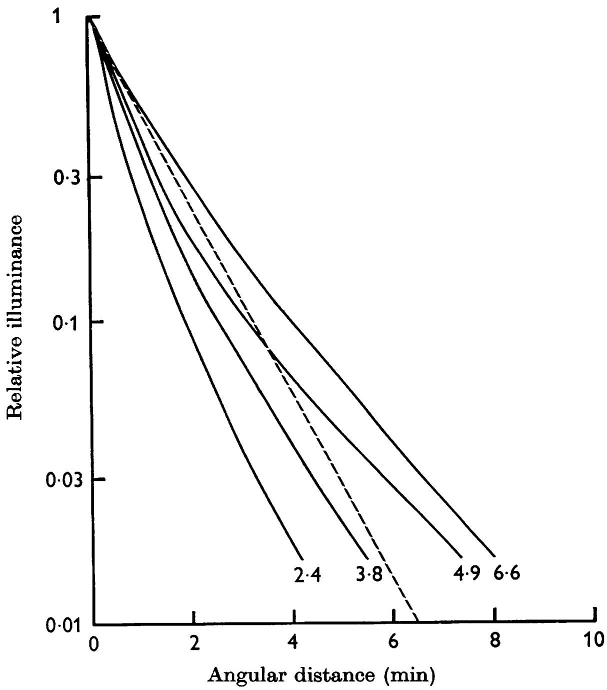

Fig. 11. Optical linespread functions on a log scale; only the right halves are shown. Number at the base of each curve gives the pupil diameter in mm. Interrupted line gives exp $(-0{\cdot}7x)$, the linespread found by Flamant (1955), Westheimer & Campbell (1962) and Krauskopf (1962).

DISCUSSION

Physical and psychophysical differences. The subjective matching of grating patterns placed on the fundus by coherent and incoherent light sources, as used by Arnulf & Dupuy (1960) and Campbell & Green (1965), provides information about only the eye's *dioptrics*—its refractive parts—as distinguished from the remaining optical media. Coherent and incoherent gratings are diffused similarly by scatter in the aqueous and vitreous humours and in the retina (Vos, 1963); this diffusion is common to both patterns and therefore affects a subjective match only slightly.

The influence of chromatic aberration is also negligible as these experiments use monochromatic light sources.

On the other hand, the physical measurements made in the present experiment necessarily include the effects of refraction, chromatic aberration, and scatter. In this context scatter is taken to mean a diffusion of energy in both the optic media and at the fundal surface reflecting the light we measure. We thus expect our modulation transfer functions to be lower than those obtained by interference methods by an amount corresponding to the influences of scatter and chromatic aberration existing in the eye.

It is possible to estimate the effect of chromatic aberration on optical quality by considering only several wave-lengths. The fundal image of a polychromatic target can be regarded as the superposition of several monochromatic images, each of which has been degraded by the eye's chromatic difference of focus (Hartridge, 1947; Ivanoff, 1947; Campbell, 1957) and added to the sum in proportion to the luminance of each colour.

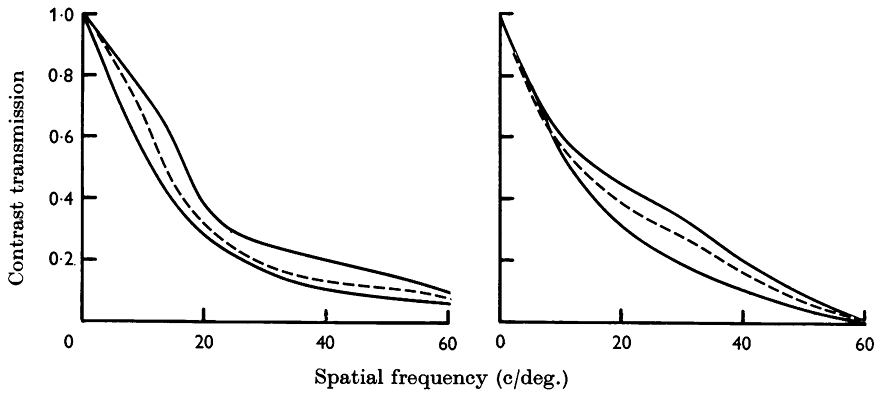

Fig. 12. Interrupted curves show the theoretical influence of chromatic aberration on human optical quality as measured by Arnulf & Dupuy (1960) (left, 2·5 mm pupil) and Campbell & Green (1965) (right, 2 mm pupil). Topmost curve in each case is original result of these authors; lowest curve gives our result for a 2·4 mm pupil (left) and a 2 mm pupil (right).

As the Fourier transformation from an image to its spatial frequency content is a mathematically linear process, the result of adding chromatic aberration to an ideal modulation transfer function can be computed as the weighted sum of several transfer functions for differing amounts of defocus. Campbell & Green (1965) demonstrated that the performance of a defocused eye agrees well with theory; hence the use of theoretical functions here is justified. The transfer functions for small amounts of defocus are given by Linfoot (1964); the required curves for greater defocus were kindly computed for us by Dr Linfoot.

Taking the eye to be optimally focused at 570 nm, we have added to the results of Arnulf & Dupuy (1960) and Campbell & Green (1965) the modulation transfer functions resulting from chromatic defocus of +0·37D at 520 nm and −0·27D at 620 nm. These three curves were scaled by 0·477, 0·322 and 0·201 respectively in proportion to the spectral response of the apparatus (Fig. 8) and then added together. The resultant functions, shown as an interrupted line in Fig. 12, lie about halfway between the original curves of Arnulf & Dupuy (1960) and Campbell & Green (1965) (upper curves) and the present results (lower curves). Chromatic aberration thus appears to account for about half the difference between the physical and psychophysical estimates of human optical quality.

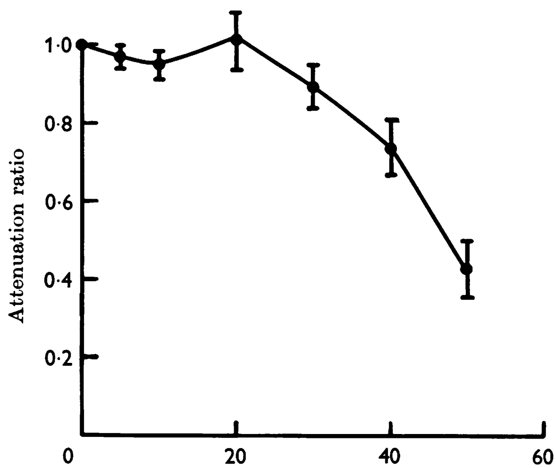

Fig. 13. Ratios of modulation transfer functions of Fig. 9 to those of Arnulf & Dupuy (1960) and Campbell & Green (1965), to which the effects of chromatic aberration have been added as in Fig. 12. The ratio at each spatial frequency is formed by comparing optical transmission for five pupil diameters between 1·5 and 5·8 mm; vertical bars indicate ±1 S.E.

A more quantitative comparison of this difference is shown in Fig. 13. For each different pupil size used, the results of Arnulf & Dupuy and Campbell & Green have been altered by the method outlined above to include chromatic aberration. The ratios of our modulation transfer functions to these altered ones at pupil sizes in common have been calculated and the average at several frequencies plotted in Fig. 13. There are no systematic changes in the ratios with pupil size, and the large standard errors arise partly from the disagreement in results between Arnulf & Dupuy and Campbell & Green. The gradually decreasing ratios can be regarded as the spatial frequency transmission of that optical scatter which is not common to the physical and psychophysical experiments. However, it is difficult to assign any accuracy to this interpretation as errors in our results could have the same effect.

An attempt to measure linespreads in monochromatic light with small pupils was unsuccessful. Even a relatively broad-band green filter inserted between the analysing slit and photomultiplier reduced the signal-to-noise ratio below the point where accurate measurements could be made.

There are several reasons possible for the improved accuracy of the present study:

(1) The optical parts were few and simple and could be aligned accurately (see Methods).

(2) The *effective* spectral sensitivity of the apparatus was confined to a narrow range; correspondence between objective and subjective best focus not only reflects the similarity between colour sensitivity of apparatus and observer (Fig. 8) but indicates also that light reflected from the fundus is returning from an area near the receptors.

(3) High intrinsic luminance of the light source and the use of averaging techniques yielded a signal with little noise.

Previous users of the physical technique have employed complex optical systems and wide analysing slits (Krauskopf, 1962), very broad spectral response (Westheimer & Campbell, 1962) or have noted difficulty with the signal-to-noise ratio (Röhler, 1962).

The curves depicted in Fig. 10 can be used to compute the fundal illuminance from extended one-dimensional intensity patterns by convolution, or from two-dimensional patterns by first deriving a point-spread function from each curve (Marchand, 1965) and performing the convolution with this point-spread function. For simple targets, the fundal image may be found more easily by multiplying the spatial frequency content of the target with the modulation transfer function of the eye, and then obtaining the inverse Fourier transform (Linfoot, 1964) of this product. Illuminance computation is only valid, however, in the immediate vicinity of the visual axis, along which our measurements were made.

Image sharpening. We are now in a favourable position to discuss the possibility that some neural interconnexions in the retina serve to restore images blurred by the eye's optics. The concept of an 'image sharpening' mechanism is appealing, and there is some evidence to support its existence. Ratliff & Hartline (1959) and Kirschfeld & Reichardt (1964) demonstrated on Limulus that a sharp border between light and dark near an ommatidium evokes discharge frequencies which overshoot values obtained from ommatidia more remote from the border.

A subjective observation of this 'overshoot' phenomenon was first reported by Mach (1865). He generated two concentric fields of different intensities separated by a uniform intensity gradient extending from the dimmer to the brighter one; he observed a band which did not exist physically along both edges of the gradient. A dark band, dimmer than the dim field, appeared at the junction of the gradient and the dim field; a light band, brighter than the bright field, appeared at the junction of the gradient and the bright field. These bands appear in a variety of experimental circumstances and are termed Mach bands.

Ratliff (1965) examines Mach bands in detail and concludes from animal and psychophysical experiments that inhibitory interaction 'plays a fundamental role in the rectification of blurred contours' (p. 159). Our results indicate that less blur is occurring optically than previously shown and they justify a careful examination of the 'image sharpening' hypothesis.

First of all, there is no agreement about what it means to 'sharpen' an image. Does it involve the overemphasis of borders? Or is it merely to restore image fidelity lost through poor optics? The Mach effect is often quoted in support of the former interpretation of sharpening; but the Mach effect can *cause* errors in estimating the locations of edges (Seeliger, 1899) rather than obviating them. Mach's own conclusion (Mach, 1865) seems more likely: that heightened contrast at borders is a by-product of the eye's attempt to make visual sensation independent of average illumination. Barlow (1961) has illustrated this concept clearly.

The second interpretation, that poor optical quality is compensated neurally, has little support. If complete compensation were occurring, one's sensitivity to contrast would parallel the contrast transmission of an ideal optical system for spatial frequencies up to an optical diffraction limit. But human contrast sensitivity does not follow at all the performance of an ideal optical system, and it even overcompensates for optical losses up to about 10 c/deg. (Campbell & Green, 1965).

Now it would be unreasonable to expect complete compensation; the visual pathway's response to spatial frequency would have to be precisely the ratio of ideal to actual optical transmission, to guarantee that the product of nervous and optical responses be identical to that of a perfect optical system. The extent of any such rectification can be judged from Fig. 14. Reciprocals of relative (actual/ideal) optical transmission for three pupil sizes are plotted from our present results, along with a curve of the retina's sensitivity to contrast from Campbell & Green (1965). Image sharpening occurs to the extent that these optical and retinal curves rise together and fall together. It is obvious that any effect of sharpening is confined below 10 c/deg. For higher spatial frequencies, which help to define edges and points, the very *opposite* of image sharpening occurs. Hence where sharpening is needed most it does not exist; and the region where it exists in too great an amount occupies only $\frac{1}{3}$–$\frac{1}{5}$ the range of spatial frequencies passed by optics.

There is evidence that the neural compensation which exists in Limulus is more successful in overcoming optical defects than that in the human being (Kirschfeld & Reichardt, 1964); even there the mechanism falls short of what is theoretically possible.

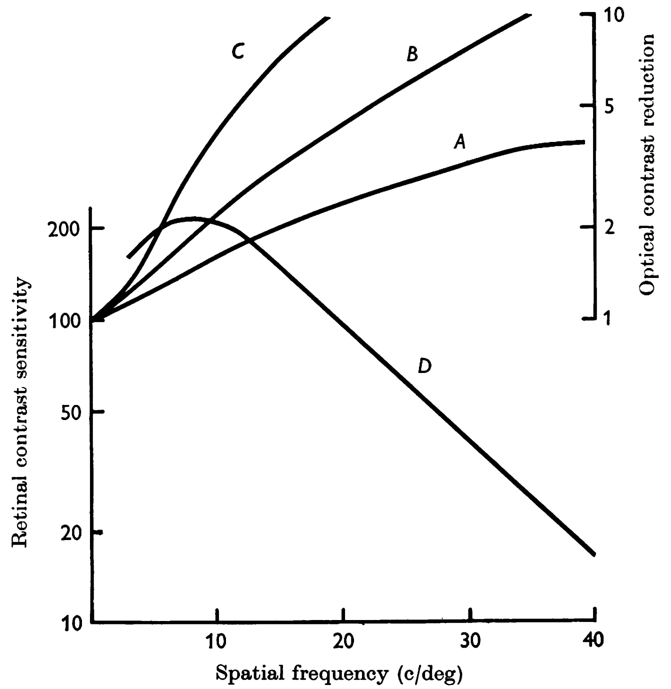

Fig. 14. Comparison of retinal contrast sensitivity (curve *D*) with contrast reduction resulting from optical blurring for pupil diameters of 2·4 mm (*A*), 3·8 mm (*B*), and 6·6 mm (*C*). Contrast reduction is computed as reciprocal optical transmission. Neural 'image sharpening' occurs in so far as contrast sensitivity follows optical contrast reduction.

Our measurements indicate that neural mechanisms of image sharpening are unnecessary to reconcile the results of visual acuity tests with the quality of the retinal image. They demonstrate that by its more reasonable definition 'image sharpening' is not occurring significantly in the processes of vision.

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