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THE EFFECT OF ORIENTATION ON THE VISUAL RESOLUTION OF GRATINGS

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SUMMARY

1. Visual resolving power is known to be poorer for objects oriented obliquely as compared with horizontal and vertical orientations. Experiments were designed to evaluate the optical and neurophysiological factors involved.

2. Gratings with a sinusoidal light distribution were generated on the face of an oscilloscope. Spatial frequency and contrast could be varied while keeping the mean luminance of the grating constant.

3. Using a homatropinized eye with an artificial pupil and carefully corrected refraction, high resolution in the vertical and horizontal meridians as compared with the oblique meridians was found for gratings ranging in spatial frequency from 1 to 35 c/deg.

4. It is concluded from the similar behaviour of low and high frequency gratings that neither focus errors nor optical aniseikonia can account for these findings.

5. Additional proof that optical factors cannot significantly account for these preferred directions of resolution was obtained by forming interference fringes directly on the retina using a neon–helium laser as a coherent light source.

6. Similar orientational changes in resolution were found by bypassing the dioptrics with interference fringes. It is concluded that the effect is due to some orientational inequality in the visual nervous system.

INTRODUCTION

A number of studies have shown that thin lines and gratings can be perceived more readily when they are aligned in the vertical or horizontal orientation as compared with the oblique orientation (reviewed by Taylor,

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1963). Several explanations have been advanced to account for these preferred directions of resolution.

An asymmetric orientational distribution in the pattern of eye movements may cause more blurring in certain directions due to retinal image motion (Nachmias, 1960). However, it has already been shown that these orientational differences in resolving power persist when the targets are exposed for periods as short as 1 msec (Higgins & Stultz, 1950).

Small refractive errors are known to cause large decreases in the resolving power for gratings (Campbell & Green, 1965) and the presence of slight astigmatic errors could obviously cause at least one preferred orientation of resolution. Furthermore, it is possible to conceive of two preferred directions occurring in an eye with regular astigmatism, providing that the subject had active accommodation and focused on either of the two image planes caused by the astigmatic optics. As these are at right angles to each other, a result similar to that found could occur. Indeed, Arnulf & Dupuy (1960) and Beck (1965) have demonstrated that an eye, which has no detectable astigmatism when the accommodation is relaxed, can develop sufficient astigmatism on accommodation for near distances to produce marked orientational changes in the resolution of grating targets.

Even if accommodation is eliminated with cycloplegics, and astigmatism is carefully corrected, other optical explanations could be advanced. For example, Weymouth (1959) has concluded that the origin of these orientational variations in acuity could be due to presence of the embryological lens sutures. The optical effects of these sutures are obvious to all of us when we examine a bright star and perceive the spicules which radiate from it.

If the optical origin of this orientational effect could be convincingly disproved, then the explanation would have to be sought in the neurological organization of the visual system. Indeed, it has already become fashionable to account for the effect in terms of the line detectors (Andrews, 1965) so ably demonstrated in the cat by Hubel & Wiesel (1965).

METHODS

Sinusoidal gratings were generated either on the face of an oscilloscope, using television techniques, or by means of a helium–neon laser which produced Thomas Young interference fringes directly on the retina. These techniques are described in detail by Campbell & Green (1965). In their study the gratings were always presented to the subject in the vertical orientation and the following modifications were made to enable the gratings to be presented in any orientation.

The oscilloscope gratings were rotated by viewing the oscilloscope screen through an inverting (Dove) prism which was placed in a rotating mount. A scale was attached to the mount so that the degree of rotation could be determined. Subjects (F. W. C.—41 yr,

J. J. K.—30 yr, R. W. G.—24 yr) observed the gratings through an artificial pupil of 2·8 mm diameter; eyes were optically corrected and homatropinized.

The rotating prism was not suitable for rotating the laser fringes as the reflexions within the prism generated spurious interference effects in the field of view. Although the optical table carrying the laser and its additional optics could have been mounted so as to rotate around the axis of the viewing eye, this would have necessitated the construction of a heavy and large rotating mount to hold the optical gear. Instead, the subject was rotated around the axis of the laser beams. This was done by placing the subject on a horizontal board, the head end of which pivoted around a vertical axis. The eye of the subject was accurately positioned on this axis. The horizontal laser beams were deflected through a right angle by means of a surface silvered mirror so that they were vertical. The subject could now look up into the laser apparatus and view the fringes. To change their orientation relative to the retina the subject could be rotated around the optical axis of his viewing eye by rotating the board upon which he was lying. This arrangement was found to give most comfortable viewing conditions, and had the additional advantage that it was easy to keep the head still and in line with the laser optics (for further details see Appendix).

RESULTS

In the initial oscilloscope experiment, the subject could control the spatial frequency of a sinusoidal grating of fixed contrast (0·274). The subject determined the highest possible spatial frequency at which the grating could be resolved at nineteen orientations spaced at 10° intervals The mean of two such runs was determined, each run being in opposite directions.

The results obtained on subject F. W. C. are shown in Fig. 1 (upper curve). It is clear that the highest resolving power for a grating occurs at the vertical and horizontal orientations (35·5 c/deg). The oblique orientations have a lower resolving power (25·5 and 29 c/deg). Similar results were obtained on two other subjects, but the difference between the two oblique orientations was smaller.

The finding that resolution in the vertical and horizontal orientations is better than in the obliques agrees with most of the findings of previous investigators (reviewed by Taylor, 1963). However, their experiments and our initial experiment (Fig. 1) used a fairly high contrast test object. The next experiment was designed to determine whether similar orientational differences in resolution are found for low contrast gratings. In this instance, the experimenter adjusted the spatial frequency and the subject controlled the contrast of the grating, setting it at threshold contrast for each particular frequency.

The results are given in Fig. 2 for a wide range of spatial frequencies. The $\log_{10}$ of the reciprocal threshold (log contrast sensitivity) is plotted against the linear spatial frequency in c/deg. The advantage of using these particular co-ordinates is that the data can be readily approximated by straight lines over a wide range at higher spatial frequencies (Campbell & Green, 1965). The results show the well established low frequency and high frequency attenuation, originally described by Schade (1956). For subject F. W. C., the vertical and horizontal orientations have practically the same slope although there is a parallel displacement. Again, the oblique orientations have an approximately similar slope with some parallel displacement. But there is definite difference in the gradient of the vertical and horizontal orientations as compared with the two oblique orientations. The lines, drawn through the data by eye, were found on extrapolation to zero frequency to meet at a common place on the contrast sensitivity scale. Figure 2 shows similar results for the other two subjects.

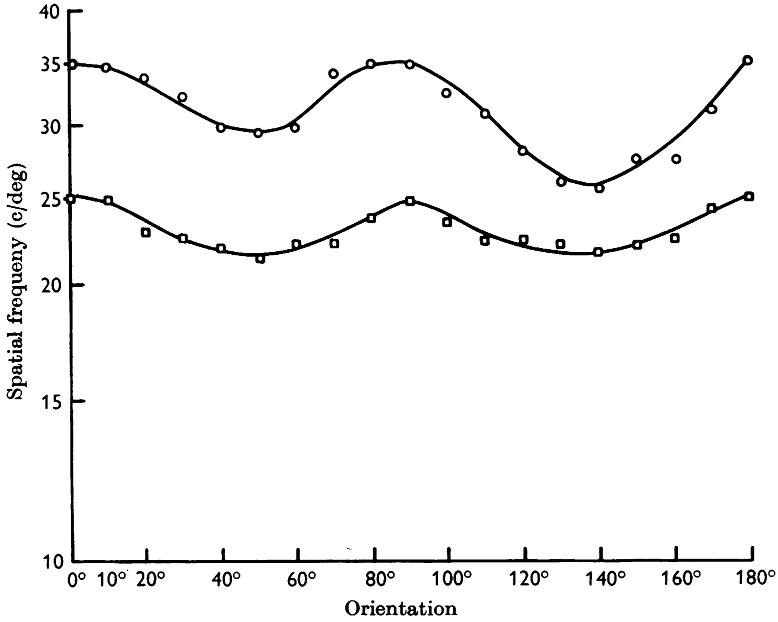

Fig. 1. Changes in the resolvable spatial frequency for different orientations. Subject F.W.C. ○ Gratings generated on the oscilloscope. □ Interference fringes generated by the laser (recomputed from Fig. 4). Notice that the characteristic obtained with the laser is symmetrical with respect to 90°: | = 0°, ╱ = 45°, — = 90°, ╲ = 135°.

It could be maintained that these results are due to differences in focus at each orientation, even although considerable care was taken to correct their astigmatic and spherical errors. This criticism can be evaluated as follows. It has been shown that the contrast sensitivity function over the high spatial frequency range is uniformly decreased when the dioptrics of the eye are out of focus (Campbell & Green, 1965). To illustrate this point (Fig. 3), we defocused the homatropinized left eye of F. W. C. by +0·5D and he made observations through a 2·8 mm diameter artificial pupil. His contrast sensitivity for spatial frequencies higher than 5 c/deg is uniformly decreased by 0·35 log units. The parallel shifts found in the results of Fig. 2 are of the order of 0·1 log units and this could be accounted for by irregular residual astigmatic errors of about 0·14D. Thus, we may conclude that parallel shifts and also asymmetry of the upper curve in Fig. 1 could be due to focus errors.

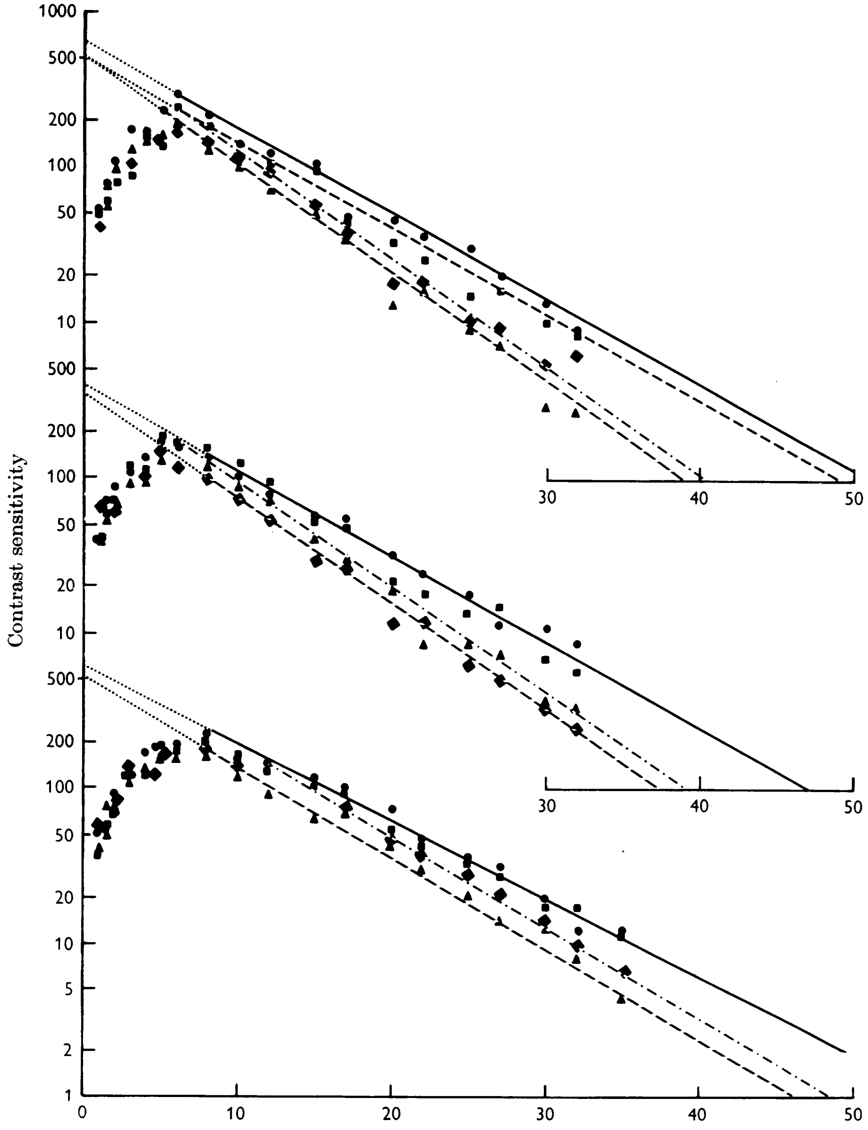

Fig. 2. Contrast sensitivity as a function of the spatial frequency for four orientations. ● Vertical (0°); ■ horizontal (90°); ▲ oblique (45°); ◆ oblique (135°). Subjects: F.W.C. (41 yr), R.W.G. (24 yr), J.J.K. (30 yr) from above down.

However, the changes in slope between the vertical and horizontal orientations as compared with the oblique orientations cannot be accounted for by focus errors. Other than astigmatism, there is one further optical factor which could account for orientational changes in resolution and which is suggested by the change of slope found in these experiments. In a compound thick-lens system, like the human eye, an image can come to a precise focus on the retina and yet still possess orientational distortions due to magnification differences. This anomaly is known to occur in some human eyes (Ogle, 1964) and it is known as aniseikonia (not equal size images). It could arise if both the cornea and eye-lens had astigmatic surfaces. If orientational aniseikonia is present it might account for some of our results. It would be as if the frequency scale had been expanded uniformly for the vertical and horizontal orientations as compared with the obliques by a magnification factor of about 1·2. The next experiment was designed to determine whether orientational aniseikonia is present.

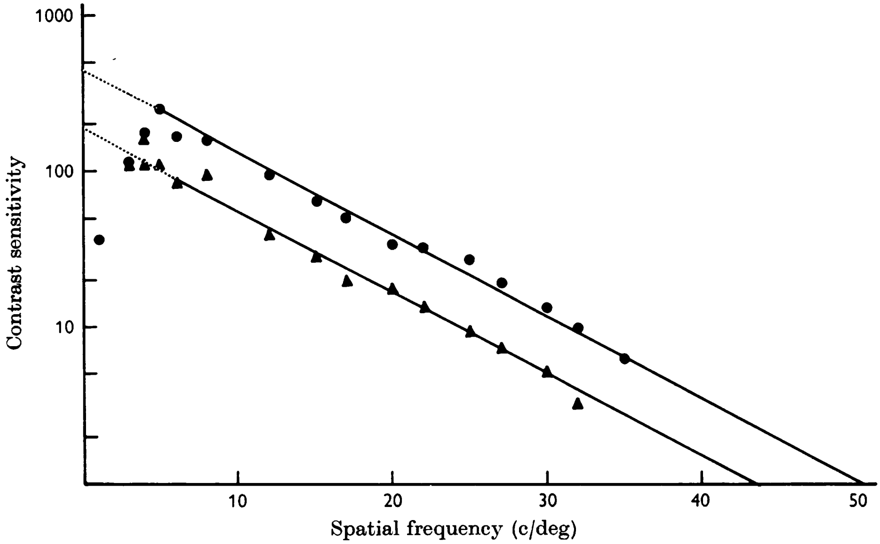

Fig. 3. Effect of defocusing on the contrast sensitivity ● in focus, ▲ +0·5 D out of focus.

Thomas Young interference fringes were formed directly on the retina using a neon–helium laser as a coherent light source (Campbell & Green, 1965). This technique by-passes the effects of the dioptrics of the eye. Orientational changes in refractive power, such as astigmatism, for example, could not change the contrast or frequency of the interference fringes on the retina (see Appendix). It was found on subject F. W. C. (Fig. 4) that the orientational changes in the contrast using interference fringes were of the same direction and magnitude as that obtained in the first experiment using gratings presented on the face of an oscilloscope. Similar results were obtained on subject J. L. Thus it seems certain that the origin of this effect is not optical.

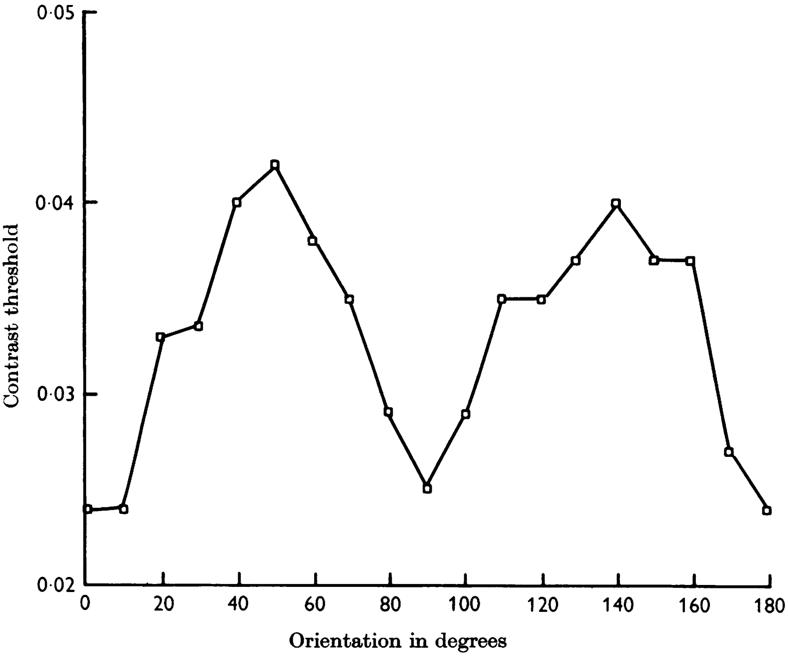

Fig. 4. Changes in the contrast threshold for different orientations of interference fringes 25 c/deg. Subject: F.W.C.

Further inspection of the results shown in Fig. 2 gives additional support to this conclusion. If the orientational differences were due to optical aniseikonia all spatial frequencies should be equally magnified. The results in Fig. 2 are so displayed that it is difficult to appreciate the results at spatial frequencies less than 6 c/deg. In order to illustrate this region better the results have been replotted for the vertical (0°) and an oblique (45°) orientation on a logarithmic abscissa (Fig. 5). If the differences in resolving power in these two orientations were due to a magnification difference due to optics then the smooth curve fitting the results for the vertical orientation should, on displacing the curve to the left by a factor of 1·2, fit the oblique data. The fit is good for frequencies higher than 10 c/deg. but the fit is poor for spatial frequencies less than this. All three subjects show similar results. We may again conclude that the results cannot be accounted for by an optical aniseikonia.

Polyak (1941) has shown histologically that the cones in the centre of the fovea are tightly packed into a hexagonal mosaic. If this mosaic is uniformly regular it might affect the resolution of fine gratings. If so, the preferred directions of orientation should be spaced at 60° intervals. However, careful inspection of all the results obtained by both methods did not show any preference for 60° intervals.

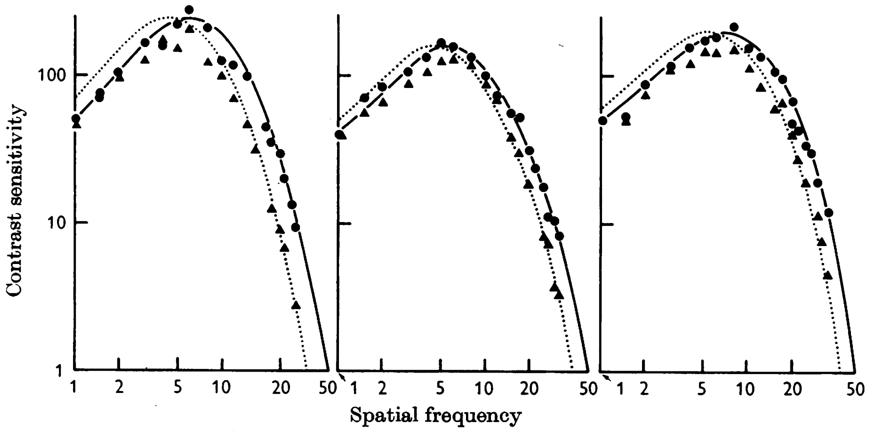

Fig. 5. Contrast sensitivity versus spatial frequency for two orientations. ● Vertical; ▲ oblique (45°).

DISCUSSION

Inspection of Fig. 2 shows that the slope of the log contrast sensitivity characteristic is greater for oblique gratings than for vertical or horizontal ones. The ratio of the slopes varies rather little between subjects (F. W. C. 1·25; R. W. G. 1·23; J. J. K. 1·19).

The same figure also shows that log contrast sensitivity is a linear function of grating frequency over a surprisingly wide range, i.e. the data are well approximated above 7 c/deg by the equation

$$S(f) = A\exp(-ak_{\alpha}f). \tag{1}$$

Alternatively

$$f = (ak_{\alpha})^{-1}(\ln A - \ln S). \tag{2}$$

In eqns. (1) and (2) f is the grating spatial frequency, A is a coefficient strongly dependent on focal factors, a is a slope for the vertical grating and k_{α} is a correction coefficient for a given orientation angle α.

It should be noted that the value of 'a' for vertical gratings (photopic foveal vision) has been found constant and approximately equal to 0·13 deg/c in various measured conditions such as focus (Green & Campbell 1965), luminance (Robson & Campbell, 1964) and the frequency of temporal modulation (Robson, 1966). Thus the angle of orientation is so far the only factor which has been shown to influence the slope of the contrast sensitivity characteristic. The good fit of eqn (1) to so much data and the invariance between subjects of the ratio of the slopes for various orientations, k_α, suggest that this ratio may reflect a structural neurophysiological effect.

APPENDIX

Fringe spacing is independent of accommodation

Suppose the two versions of the laser beam (Fig. 6) are focused at P_1 and P_2, and that A' and B' are two adjacent points of maximum brightness of the grating pattern on the retina. Let the points conjugate to A' and B' be A and B, for the particular state of accommodation of the eye. Light at P_1 is in phase with that at P_2 for maximum brightness, therefore the optical path difference between P_1A' and P_2A' differs by one wave-length from the path difference between P_1B' and P_2B'. The same one wave-length difference will apply to the conjugates of A' and B', A and B. If the angle subtended at P_1 and P_2 by AB is $\delta\phi$, then $\delta\phi = \lambda/d$, where d is the separation P_1 to P_2. On the other hand, let the angle subtended by AB at the nodal point of the eye be $\delta\theta$. Then it is easy to show that $\delta\theta = (v-D)/v.\ (\lambda/d)$ where v and D are the distances from A, B to the nodal point and from P_1, P_2 to the nodal point respectively.

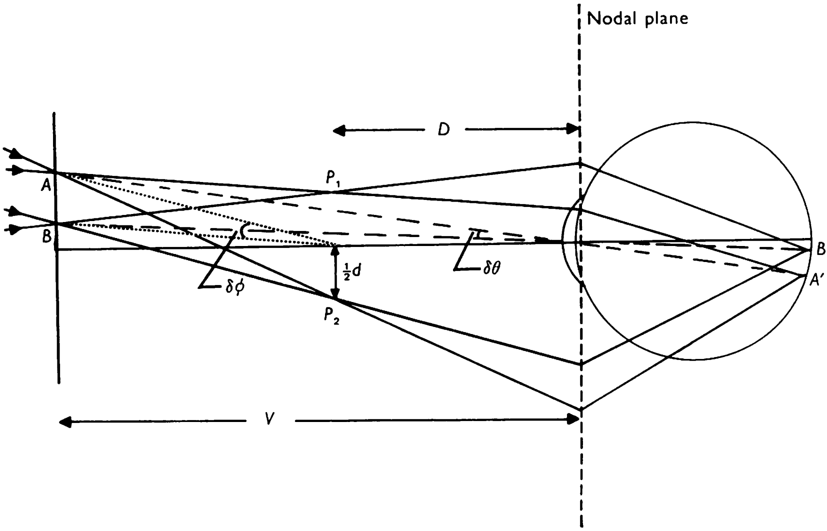

Fig. 6. Interference fringes on the retina from the neon-helium laser.

Thus the angular fringe spacing, $\delta\theta$, is exactly independent of the accommodation of the eye (v) when $D = 0$, i.e. $\delta\theta = \lambda/d$. In any case, as long as $v \gg D$, the fringe spacing depends very little on accommodation.

The same independence applies to astigmatism, where, as in this experiment, the points P_1 and P_2 may fall along various orientations on the lens.

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Note added in proof. Mitchell, D., Freeman, R. & Westheimer, G. (1966), *J. opt. Soc. Am.* (in the press), using a gas laser, find a similar effect of orientation on resolution on four subjects.