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SPATIOTEMPORAL CONTRAST SENSITIVITY AND VISUAL FIELD LOCUS*

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Abstract—Contrast sensitivity, measured as a function of retinal eccentricity for stimuli differing in temporal and spatial frequency (0.25–9 c/deg; 0–16 Hz, 0–12° eccentricity), was maximum at the fovea and declined linearly with eccentricity. The slope of the decrease depended upon spatial but not temporal frequency. Contrast sensitivity for drifting gratings was approximately twice that for sinusoidal counterphase gratings at all eccentricities. For central viewing log contrast sensitivity increased with grating length. The shape of this function was systematically related to spatial frequency but independent of temporal frequency, indicating that the visual field is homogeneous in sensitivity for change in contrast over time. The implications of these findings for mechanisms of threshold vision in fovea and periphery are discussed.

Vision Psychophysics Spatial frequency Temporal frequency Visual field locus

INTRODUCTION

Wertheim in 1894 showed that visual acuity is maximum at the fovea and declines in a continuous gradient with eccentricity. Weymouth (1958) confirmed these measurements and showed that the gradient extends to the centre of the macula. Thus the fovea is more sensitive to stimuli of high spatial frequency than the periphery and there is a regional variation in sensitivity to spatial frequency across the visual field (Hilz and Cavonius, 1974; Koenderink *et al.*, 1978a, b; Rovamo *et al.*, 1978; Robson and Graham, 1981). Contrast sensitivity declines more steeply with distance from the fovea for high spatial frequency gratings than for low.

The notion that the central visual field is specialised for the detection of spatial detail is well established. The complementary idea that the peripheral visual field is specialised for the perception of motion or detection of contrast change over time has also been advanced (Ikeda and Wright, 1972; Sharpe, 1974). If true, we might expect to find for instance that the contrast sensitivity of peripheral visual field is enhanced by modulation or movement. However there is little or no change in the shape of temporal contrast sensitivity functions with eccentricity (Koenderink *et al.*, 1978a; Virsu and Rovamo, 1982).

We adopted the approach of direct measurements of contrast sensitivity vs eccentricity to see how these functions varied when we changed temporal as well as spatial frequency. This provides a sensitive test for spatial or temporal inhomogeneity and provides information about the organisation of contrast detection mechanisms in central and peripheral visual fields.

METHODS

Stimuli

Gratings with sinusoidal luminance profiles were generated on a Tektronix 608 oscilloscope with a P31 phosphor and linearised Z-axis by a microprocessor function generator, under computer control. The contrast of the grating could be modulated in counterphase or drifted either left or right at a chosen temporal frequency. The frame frequency was 128 Hz, giving apparently smooth movement of drifting gratings up to the maximum temporal frequency used (16 Hz, 2 c/deg). Maximum contrast could be varied in steps of 0.25 dB by a digital attenuator. Vertical gratings were viewed through an aperture in a mask, which was placed 2 cm in front of the oscilloscope screen. The edges of the aperture were "softened" by allowing tracing paper to overlap by 0.25 cm. Dimensions of the apertures were measured from the inner edge of the tracing paper. The masks were constructed of matt white paper and transversely illuminated by a circle of 16 tungsten filament green indicator bulbs. It was possible to obtain even illumination of the masks (outer diameter 15°) and a good match to the mean luminance (100 cd/m^2) and colour of the grating. The aperture masks were viewed through a tube of white card of approximately the same mean luminance, which provided an illuminated surround subtending approx. 50° arc. To determine variation in contrast sensitivity with eccentricity a rectangular patch of grating measuring 5.2 cm horizontally and 1 cm vertically was viewed from 85 cm (or 150 cm for the experiment of Fig. 5). Nine 3′ numbered fixation dots were placed 2 cm

*A preliminary account of these findings was presented to the *5th European Conference on Visual Perception*, Leuven, Belgium.

apart in a vertical line below the grating patch. In some series an additional observation was made with fixation at 0.5 or 1 cm from the centre of the grating. Grating contrast sensitivity was thus measured at intervals along the upper vertical meridian of the visual field, and all eccentricity values given refer to the distance from the fovea of the centre of the rectangular grating patch. For length series the grating was 150 cm from the observer, and had a maximum angular subtense of 4°. Masks were used having an aperture width of 3° and a height varying in logarithmic steps from 0.04 to 2.8°. Viewing was binocular throughout, with natural pupils and normal accommodation. A chin and head rest were used to stabilise the head. Both authors served as subjects.

Procedures

Contrast thresholds were determined using a staircase method under computer control. Blank trials at mean luminance were included on a 50% random basis to provide a comparison for the subject. The number of false positives was minimal (less than one per 30 blank trials). On each trial, while steadily fixating the appropriate marker, the subject had to decide whether or not a grating was visible and press the appropriate response button. Initial contrast was 0.3 and the exposure was terminated by the subject's response. If a correct "Yes" response occurred contrast was reduced by the current step size (originally 4 dB). If a miss occurred contrast was increased by the step size until a correct "Yes" response was made; for this contingency the direction of the staircase was reversed and the step size halved. No change in step size or contrast occurred after a blank trial. Thirty positive trials were presented on each threshold determination and the threshold contrast was taken to be an average of the last six contrasts presented. The data from five staircases to a standard grating (6 c/deg, 8 Hz) were re-analysed in terms of the the percentage correct at each contrast level. It was found that our method yielded estimates of threshold at a contrast giving approximately 50% correct detection. Each data point is based on the average of two staircase measurements, in an increasing and a decreasing series of lengths or eccentricities. Standard errors were approximately 1 dB. To control for possible effects of a temporal transient occurring when a grating trial was preceded by a blank trial, the blanks were omitted in certain series. Where appropriate the transient was minimised by starting each trial at the zero contrast part of the temporal modulation cycle.

RESULTS

(1) *Eccentricity functions*

We measured contrast sensitivity for a 3.5 × 0.67° patch of grating as a function of eccentricity of viewing using gratings of two spatial frequencies (2 c/deg, 6 c/deg). Each grating was presented at three temporal frequencies (unmodulated, 8 Hz, 16 Hz counterphase). Log contrast sensitivity is plotted against eccentricity in degrees of visual angle in Figs 1 and 2.

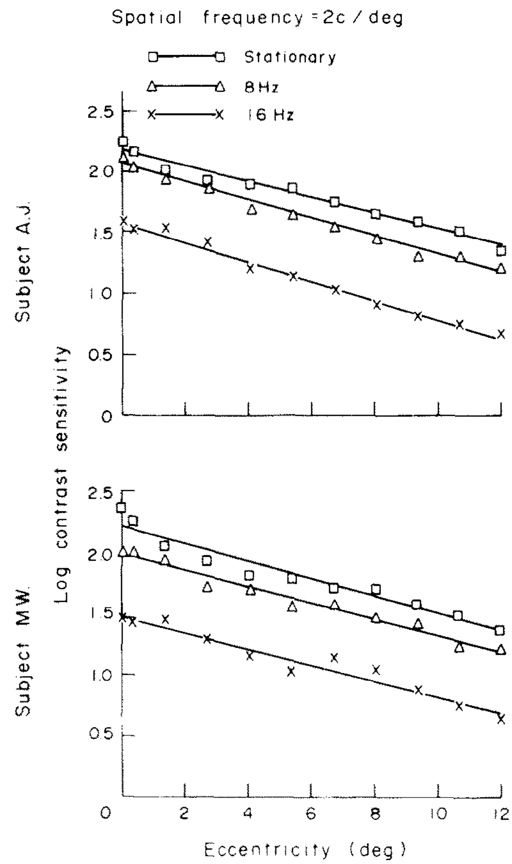

Fig. 1. Contrast sensitivities (log scale) for 2 c/deg as a function of eccentricity for a steady grating and sinusoidal counterphase gratings of 8 and 16 Hz.

A linear regression line (computer-fitted by method of least squares) provided a good fit to all log contrast sensitivity vs eccentricity functions. For a grating of 2 c/deg (Fig. 1) sensitivity was maximum for central fixation and log contrast sensitivity declined in a linear fashion with eccentricity. Temporal frequency affected the absolute level of sensitivity but not the slope of the decrease; relative sensitivity to unmodulated gratings and to 8 and 16 Hz counterphase gratings was approximately constant across 12° of eccentricity.

For a grating of 6 c/deg (Fig. 2) contrast sensitivity was again greatest at the fovea and declined linearly with eccentricity. Temporal frequency affected the absolute level of sensitivity; thus a steady grating was more visible than 8 Hz counterphase which was more visible than 16 Hz counterphase at all eccentricities. Temporal frequency did not affect relative sensitivities; these were the same at all eccentricities. The slope of the decline in sensitivity with eccentricity was however greater at 6 than at 2 c/deg. We can conclude that the central visual field is relatively more sensitive to higher spatial frequencies than the peripheral

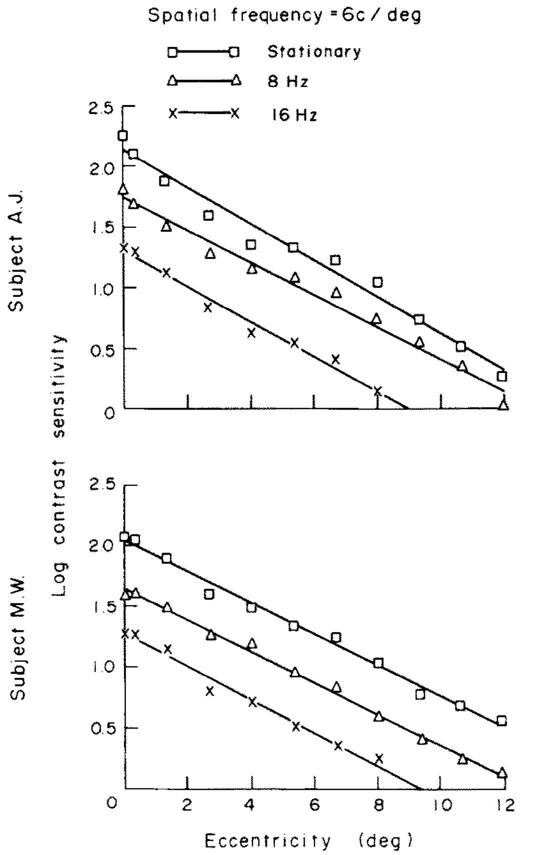

Fig. 2. Contrast sensitivities (log scale) for 6 c/deg as a function of eccentricity for a steady grating and sinusoidal counterphase gratings of 8 and 16 Hz.

visual field, but there is no such variation in relative sensitivity to temporal frequencies.

In order to test our impression that relative sensitivities to temporal, unlike spatial frequency, are independent of eccentricity, an analysis of covariance was performed with eccentricity as the covariate. We tested the homogeneity of within-class regression, which allows us to determine whether fitting regression lines of different slopes to each condition accounts for significantly more of the variance than a line of the same slope for all conditions. In this and all subsequent data to be presented there was no significant improvement when optimum regression lines of differing slope were fitted for each temporal frequency condition. This sensitive test confirms that there were no significant differences in the slope due to temporal frequency. Since the inverse correlation between eccentricity and log contrast sensitivity was high (-0.95) and the error term in the analysis of covariance was always small, we can be confident that the lack of an effect of temporal frequency was not due to insufficiently precise measurements.

We next compared drifting and counterphase gratings at various eccentricities. Levinson and Sekuler (1975) showed that a sinusoidal counterphase grating of unit contrast is identical to two superimposed drifting gratings with half unit contrast and opposite directions of drift. If counterphase and drifting gratings were detected by directional mechanisms, and there is no pooling of signals from the detectors responding to opposed motions, then twice as much contrast would be required to detect the counterphase than the drifting grating. Levinson and Sekuler found that the ratio of contrast sensitivities to centrally-fixated drifting and counterphase gratings was 2:1, suggesting that the directional components of a counterphase grating are detected independently.

We measured eccentricity functions for 2 c/deg grating drifting at 8 and 16 Hz. The data from Fig. 1 for the 2 c/deg grating are redrawn with the data for drifting gratings and are presented in Fig. 3. We can see that the slopes for the drifting and counterphase eccentricity functions and for different temporal frequencies are near identical, again an indication of the homogeneity of the visual field for temporal parameters of a stimulus. Contrast sensitivities for drifting gratings are approximately double those for sinusoidal counterphase gratings at all eccentricities (i.e. approx. 0.3 log units higher) suggesting that independent direction specific channels operate in the peripheral as well as the central visual field.

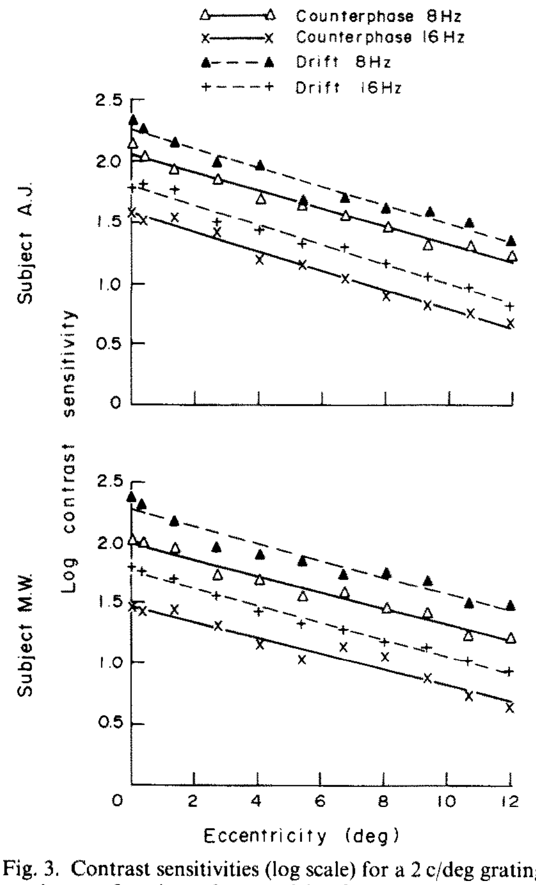

Fig. 3. Contrast sensitivities (log scale) for a 2 c/deg grating patch as a function of eccentricity for two temporal frequencies (8, 16 Hz). Comparison of contrast sensitivity to drifting gratings (solid symbols) with that to sinusoidal counterphase gratings (open symbols), reproduced from Fig. 1.

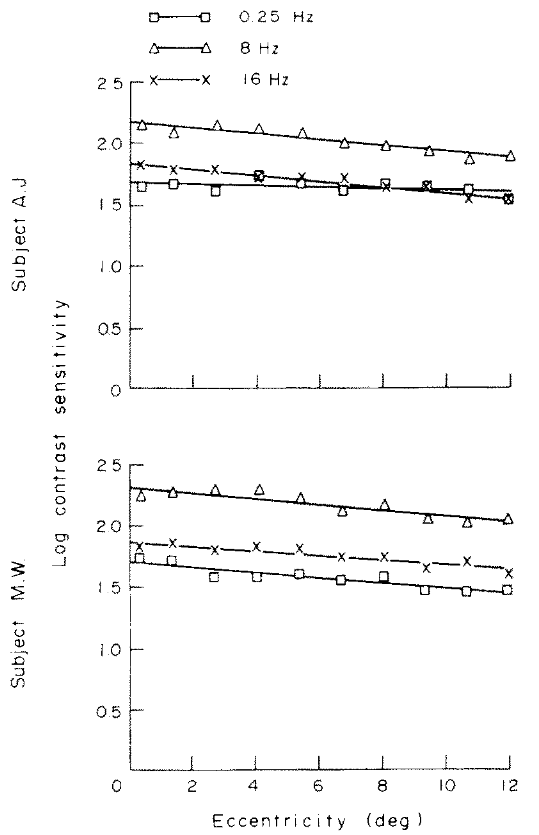

Fig. 4. Contrast sensitivity as a function of eccentricity for a grating of low spatial frequency (0.25 c/deg) at three temporal frequencies (0.25, 8 and 16 Hz).

Thus far our argument has been based on a relatively limited range of spatial and temporal frequencies. Such measurements are probably not in the range of attenuation of contrast sensitivity at low spatial and temporal frequencies (Robson, 1966; Kelly, 1972). A very low spatial frequency (0.25 c/deg) was therefore selected. A larger, square aperture (6 × 6) was used equal to one an a half grating cycles in both horizontal and vertical dimensions. A low temporal frequency (0.25 Hz) of counterphase modulation was used here replacing the unmodulated condition. Each grating presentation began and ended at zero spatial and temporal phase and consisted of one or more complete temporal cycles. This prevented afterimages and minimised spatial and temporal edges in the display. The results are shown in Fig. 4.

The decline in sensitivity with eccentricity was much more gradual than at higher spatial frequencies and smaller field sizes, and indeed was undetectable over the central 6 . The sensitivity to 8 Hz counterphase modulation was greater than to 0.25 or 16 Hz, which proves that we are operating in the region of low spatiotemporal attenuation. Nevertheless, relative log sensitivities to different temporal frequencies are again approximately constant across the visual field. Analysis of covariance revealed that there were no significant differences in the slope of regression lines for the different temporal frequency conditions, but there was a significant (negative) correlation between log contrast sensitivity and eccentricity, as for higher spatial frequencies [$F(1, 48) = 91.9$; $P < 0.001$].

All visual stimuli must be localised in time and space and have spatial and temporal frequencies associated with the spatial and temporal "window" in which they appear. Inclusion of blank stimuli in our staircase procedure meant that our gratings had a transient onset. Our results with steady gratings in particular may have reflected to some degree these onset transients (Legge, 1978; Tulunay-Keesey and Bennis, 1979). The experiment was therefore repeated without blank stimuli, so that a grating was always present. This "sustained" presentation was compared with a "transient" condition, again without blanks but with 8 Hz squarewave counterphase modulation. The contrast is constant over time and identical in these two conditions.

The spatial frequency was 9 c/deg and we found an even steeper decline in sensitivity with eccentricity than at 6 c/deg. Analysis of covariance established that the slope of the decline was not significantly different for the continuous and the 8 Hz grating. Controlling for stimulus onset transient there was still no sign of a temporal inhomogeneity.

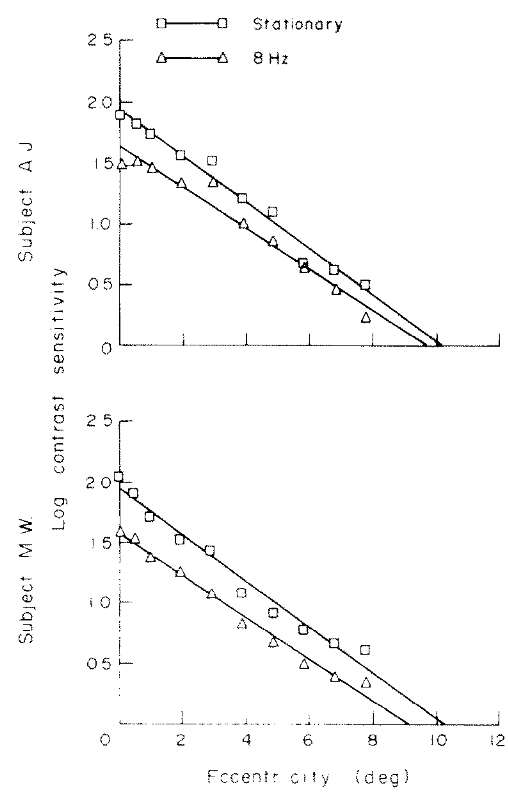

Fig. 5. Contrast sensitivity as a function of eccentricity for a 9 c/deg grating for continuous (0 Hz) presentation and 8 Hz squarewave counterphase modulation. Blank stimuli were eliminated from the staircase for this determination.

(2) *Length functions*

Contrast sensitivity to gratings depends upon the area of the grating; either increasing the number of bars or the length of the bars improves detectability (Howell and Hess, 1978; Robson and Graham, 1981; Wright, 1982). There appears to be a critical length and critical width after which increments in grating extent have little influence on threshold. These values are a function of the spatial frequency of the grating; Virsu and Rovamo (1979) have shown that the contrast sensitivity depends upon grating area expressed in square cycles.

We determined contrast sensitivity as a function of grating length using centrally-fixated gratings of two spatial frequencies (2, 6 c/deg) both stationary, and sinusoidally modulated in counterphase at two temporal frequencies (8, 16 Hz).

There was a negatively-accelerating increase in sensitivity with log length (Fig. 6). Estimates of the critical value at which the function becomes approximately level were greater for the 2 than the 6 c/deg grating as expected. Considering the data for the largest area gratings we can see that contrast sensitivity was reduced with increasing temporal frequency (Robson, 1966; Kelly, 1972). We can also confirm these earlier studies in that the difference in sensitivity for a stationary and a 8 Hz temporally modulated grating was less for 2 c/deg gratings than for 6 c/deg gratings but the difference between 8 and 16 Hz was roughly equivalent for both spatial frequencies.

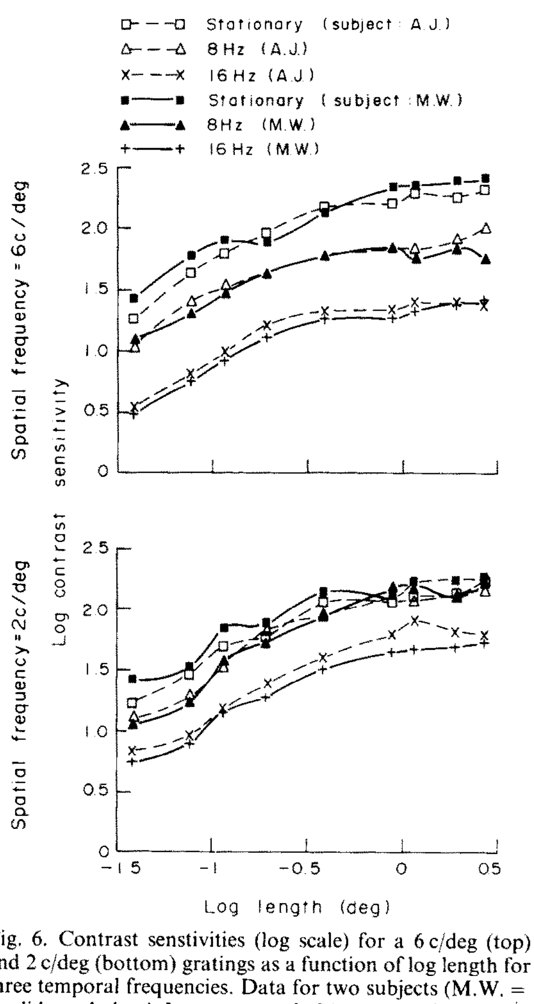

Fig. 6. Contrast senstivities (log scale) for a 6 c/deg (top) and 2 c/deg (bottom) gratings as a function of log length for three temporal frequencies. Data for two subjects (M.W. = solid symbols, A.J. = open symbols) are superimposed.

The most striking finding was that the length functions are almost perfect translations of one another along the sensitivity axis. Therefore the contrast sensitivity function for temporal frequency unlike that for spatial frequency is independent of grating length. The shape of summation functions differ if the regions of visual space over which the summation process operates have differing sensitivity distributions (Robson and Graham, 1981). The observation that the shape of the summation function does not vary for different temporal frequencies supports the conclusion that there is no regional variation in sensitivity for temporal frequency.

DISCUSSION

(1) *Variation in contrast sensitivity with eccentricity and spatial frequency*

We found that contrast sensitivity to grating patches was maximum at the fovea and declined linearly with eccentricity. The regularity of the decline (the correlation between log contrast sensitivity and eccentricity was often better than −0.99) was perhaps surprising in a system built from variable anatomical elements. There is evidence that the linearity of the relationship breaks down at greater eccentricities (Hilz and Cavonius, 1974; Konderink *et al.*, 1978b). It is possible also that the slight departure from linearity at 4–6° seen in some of our data is a real effect, and that there would be slight differences along different meridia (Rijsdijk *et al.*, 1980). Nevertheless, a linear function does provide a very adequate description of all our data, and offers an appealing simplification for quantitative modelling. The effects of the patch size must also, presumably, be taken into account, since a rectangular patch extends over a range of eccentricity values (see Koenderink *et al.*, 1978c).

The slope of the eccentricity function increased with spatial frequency. Previous studies have either obtained slightly irregular functions, or have concentrated on relatively few eccentricity values, but support a similar regional variation in contrast sensitivity with spatial frequency. On the basis of the determination of the mean slope of our log contrast/eccentricity functions at four different spatial frequencies (0.25, 2, 6 and 9 c/deg) we find that the decrement in sensitivity with distance from the fovea is proportional to the spatial frequency of the grating. Robson and Graham (1981) reached a similar conclusion. They normalised log contrast sensitivity versus eccentricity functions with respect to the spatial frequency of the gratings, i.e. expressed eccentricity as the number of grating periods from the fixation point. The curves for different spatial frequencies could then be superimposed by translation along the log contrast axis.

Thus each spatial frequency can only be detected within a patch centred on the fovea, whose diameter is inversely related to that spatial frequency (Hilz and Cavonius, 1974; Rijsdijk *et al.*, 1980; Rovamo *et al.*, 1978; Koenderink *et al.*, 1978a; Robson and Graham, 1981).

The most obvious interpretation of the nested series of eccentricity functions for different spatial frequencies is that the fovea contains a greater range of spatial channels than the periphery. A contrary view is proposed by Wilson and Bergen (1979) who have produced human psychophysical evidence favouring a small number of spatial frequency channels (i.e. 4) coexisting at any one locus in the visual field. Since the preferred spatial frequency of each of the four channels decreases with eccentricity, a consequence of the latter view is that the peripheral visual field should be specialised for the detection of stimuli of low spatial frequency. We found no evidence for such specialisation; with our lowest spatial frequency (0.25 c/deg) there was a plateau of high sensitivity extending from the fovea to about 6° eccentricity and a gradual decrease in sensitivity over a full 12° eccentricity. In addition to the present findings, other workers employing contrast sensitivity measurements have generally found that patterns are preferentially detected at the fovea, regardless of their spatial or temporal frequency (Hilz and Cavonius, 1974; Koenderink *et al.*, 1978a; Robson and Graham, 1981).

Neurophysiological evidence from cat retina is seemingly at variance with a maximum sensitivity at the central visual field for low spatial frequencies and supportive of the Wilson and Bergen model. There is a positive correlation between receptive field diameter of X- and Y-retinal ganglion cells with eccentricity and the scatter of sizes within each group is rather small at a given eccentricity, so that the larger X- or Y-receptive field sizes found in the periphery simply are not present at the area centralis (Peichl and Wassle, 1979). However, the finding of greater sensitivity at the fovea to all spatial frequencies may be reconciled with a small, constant number of spatial channels at each eccentricity if those channels have certain properties. Most retinal ganglion cells do not have a sharp low-frequency cut (Linsenmeier *et al.*, 1982) and so many area centralis ganglion cells would respond, even if not optimally, to low spatial frequencies. Since there are many more central than peripheral cells per unit area of retina, either pooling of signals at higher levels of the visual pathway, or probability summation, could improve the sensitivity of the central visual field relative to the periphery. Assuming that psychophysical channels detecting the lowest spatial frequency at a given eccentricity resemble cat ganglion cells in lacking an abrupt low frequency cut and in their greater distribution density in the central visual field, the high sensitivity of the fovea to all spatial frequencies could be explained.

(2) *Spatiotemporal eccentricity functions*

A principal aim of the present study was to establish whether the sensitivity to spatial pattern with eccentricity may depend on the temporal characteristics of the pattern. It has been considered by some that peripheral vision is preferentially sensitive to certain types of moving or flickering stimuli (Sharpe, 1974; Ikeda and Wright, 1972). Our results clearly show that this is not the case. Variation in temporal frequency across a considerable range does not affect the relative sensitivity of fovea and periphery. The slope of log contrast versus eccentricity function was constant for steady, drifting and counterphase gratings. The ratio of sensitivities for counterphase and drifting gratings is a little less than 2 at all eccentricities and this finding is consistent with detection by independent directionally-selective channels whose properties are temporally invariant with eccentricity. This finding is, again, in accord with neurophysiological data from cat (Peichl and Wassle, 1979). Cell-types which are thought to differ in their spatiotemporal tuning characteristics (X- and Y-cells) co-exist in approximately constant proportions across the visual field.

(3) *Contrast sensitivity and the cortical magnification factor*

Virsu *et al.* (1982), in an independent study, reached similar conclusions to the present one regarding the invariance of temporal frequency sensitivity with visual field position. Rather than measuring sensitivity gradients they adopted the approach of normalising gratings in area, spatial frequency and cortical translation velocity (this being inversely proportional to spatial frequency for stimuli of the same temporal frequency). When this was done, in proportion to estimates of the cortical magnification factor (M-scaling), temporal and spatial contrast sensitivity functions for different eccentricities could be superimposed. Temporal frequency did not affect this normalisation; a spatial normalisation was sufficient (see also Koenderink *et al.*, 1978a, b, c).

(4) *Spatiotemporal grating sensitivity for centrally-viewed gratings*

An important property of the visual system is that the detectability of a spatial pattern, replicated over the visual field, is dependent in part on the total spatial extent of the pattern. For grating stimuli with sine wave luminance profiles, displayed at threshold contrast, detectability is improved both by increasing the length of the grating and by increasing the number of bars (Howell and Hess, 1978; Virsu and Rovamo, 1979; Robson and Graham, 1981; Wright, 1982). If log contrast sensitivity is plotted with respect to log extent (in terms of grating width or length) we find a decelerating improvement in sensitivity with increasing extent. There appears to be a critical length and a critical width after which increments in grating extent have little influence on the contrast detection threshold. These critical values are inversely proportional to the spatial frequency of the test grating.

Robson and Graham (1981) argue that it is regional variation in sensitivity to spatial frequency across the visual field which results in the dependence of length summation curves upon spatial frequency. If the visual system is differentially sensitive to movement across the visual field we should expect that the shape of the summation function and the critical length value should differ for moving and steady gatings. There was no apparent change in shape. We can conclude from direct measurement and from a lack of variation in the shape of length summation curves with temporal frequency that the visual field is uniform in its sensitivity to temporal parameters.

We may now summarise our main conclusions. (1) Log contrast sensitivity to small grating patches declines with eccentricity in approximately linear fashion. (2) The visual field is not uniform in its sensitivity to spatial frequency; this declines rapidly with increasing distance from the fovea for high spatial frequencies but slowly for low spatial frequencies. (3) No such regional variation exists for temporal frequency at any eccentricity or spatial frequency within our range. (4) There is no change in relative sensitivity to drifting and counterphase gratings with eccentricity. (5) The improvement in contrast sensitivity with increasing length of a centrally-fixated grating depends upon spatial but not temporal frequency.

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