

# Peripheral contrast sensitivity for sine-wave gratings and single periods

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## PERIPHERAL CONTRAST SENSITIVITY FOR SINE-WAVE GRATINGS AND SINGLE PERIODS

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**Abstract**—The contrast sensitivity of the human eye has been measured as a function of eccentricity. The stimulus used was a sine-wave grating with a fixed height of  $5^\circ$ , in a surround of luminance that equals the average stimulus luminance. The measurements were carried out with stimulus width as the independent variable. The "local" sensitivity for gratings was found to decrease monotonically with increasing eccentricity.

It was further found that the sensitivity for wide gratings is mainly determined by that part which is only  $2^\circ$  wide, situated as close to the fovea as possible.

The results are discussed in view of the possible existence of "tuning", i.e. of a maximal sensitivity outside the fovea, at an eccentricity determined by the spatial frequency.

### INTRODUCTION

It is known that the peripheral visual acuity for normal subjects is always worse than the foveal (except for scotopic luminances) (Anstis, 1974; Berkley, Kitterle and Watkins 1975; Green, 1970). However, only a few investigations have been carried out on contrast transfer as a function of eccentricity. Rovamo, Virsu and Näsänen (1978) and Koenderink, Bouman, Bueno de Mesquita and Slappendel (1978a) measured the modulation transfer function (MTF) as a function of the eccentricity and found a monotonically decrease in sensitivity with increasing eccentricity. Hilz and Cavanaugh (1974), using an interference fringe method, also showed that the sensitivity is maximum at the fovea. In contrast, Bryngdahl (1966) concluded from his results, obtained by measuring the subjective modulation depth of a grating, that the contrast sensitivity reaches a maximum at the periphery. Van Doorn, Koenderink and Bouman (1972) arrived at the same conclusion from theoretical considerations concerning the sensitivity for moving bar patterns. van der Wildt, Keemink and van der Brink (1976) suggested that their results, obtained with a stimulus of increasing width, might be explained by assuming that the most sensitive part of the retina for low spatial frequencies is not the central part of the fovea.

The purpose of the present study is to determine whether threshold measurements, carried out with stimuli within a surround field of a luminance that equals the average stimulus luminance, give any evidence for tuning. Stimulus conditions were chosen such that they are similar to those of Bryngdahl (1966) and van der Wildt *et al.* (1976), who concluded

that tuning might exist. The fact that Rovamo *et al.* (1978) and Koenderink *et al.* (1978a) reported a monotonically decrease in sensitivity with increasing eccentricity may be explained by the fact that they presented their stimuli in a dark surround, in contrast with the illuminated surround in our experiments.

In the present study, contrast sensitivity was measured as a function of eccentricity. In order to co-ordinate the results of van der Wildt *et al.* (1976) and ours, we chose the same height. We also measured contrast sensitivity with gratings of variable width (under otherwise identical conditions), since such measurements may reveal the existence of tuning if it exists.

### METHODS

#### Stimulus

The stimulus in all experiments was a sine-wave grating modulated in one dimension and displayed on a TV monitor (Tektronix 632, with phosphor WA D6500). The surrounding field was rectangular, with a width of  $20^\circ$  of arc and a height of  $5^\circ$ . To prevent luminance steps which are correlated with grating visibility in the vertical direction, we presented the grating over the total height of the surrounding field ( $5^\circ$ ). A red fixation spot was presented in the centre of the surround field. The mean stimulus luminance was  $10 \text{ cd/m}^2$ , if not otherwise stated. The luminance of the surrounding field was always equal to the mean stimulus luminance. The viewing distance was 85 cm. No artificial pupil was used. The measurements were carried out monocularly (right eye). A chin and forehead rest was used. The sine-wave signal was obtained from a function generator (Wavetek 144), the gate input of which was controlled by a pulse generator (Datapulse 100A). The pulse delay was used to adjust the position of the stimulus on the

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screen, and the pulse width determined the width of the stimulus. Only a whole number of sine-wave periods was displayed. The amplitude,  $A$  of the stimulus was sinusoidally modulated at 1 Hz ( $A = A_0 \sin \omega t$ ).

#### Measuring procedure

Measurements were carried out with a microprocessor-controlled attenuator system described by Keemink, van der Wildt and van Deursen (1979). The subject could reduce the contrast of the grating by depressing a push-button. As soon as the grating was subthreshold the subject had to release the button, causing the contrast to increase at a rate of 5 dB/sec. This rate was chosen as a compromise between efficiency on one hand, and obtaining results with a standard deviation that would not exceed 15% on the other. When the grating again became visible the subject had to depress the switch again. This process was repeated several times, causing the modulation depth to vary around the subject's threshold. The higher and lower attenuator reversal values were averaged and this value taken as the threshold. To avoid adaptation effects the attenuator started at its maximum value (99 dB attenuation), and the first four reversal values were not used for determining the average. The threshold was determined from the next eight reversal values. The microprocessor-controlled system printed out the threshold value and the mean difference between successive upper and lower reversals.

### EXPERIMENTS

Sensitivity for sine-wave gratings was measured as a function of stimulus eccentricity. In order to get the highest possible resolving power, we initially used stimuli of minimum width, i.e. of one single period. The luminance distribution of these stimuli in the horizontal direction is given in Fig. 1a.

The stimulus was presented in the right half of the field. We also measured the contrast sensitivity for the grating as a function of the stimulus width under the same conditions. In this case (see Fig. 1b) the grating was also situated in the right-hand half of the field, starting from the middle.

The contrast sensitivity was also measured as a function of the width, starting from the edge of the field (Fig. 1c) instead of the fixation point. We further repeated the measurements according to Fig. 1b, starting at several eccentricities (Fig. 1d). Finally, sensitivity was measured as a function of the eccentricity, with a grating  $2^\circ$  wide (Fig. 1e).

### RESULTS

The results are given for two subjects, JNK and JPR. The standard deviation is about 12%. The first experiment was the measurement of the sensitivity for single period gratings as a function of eccentricity,

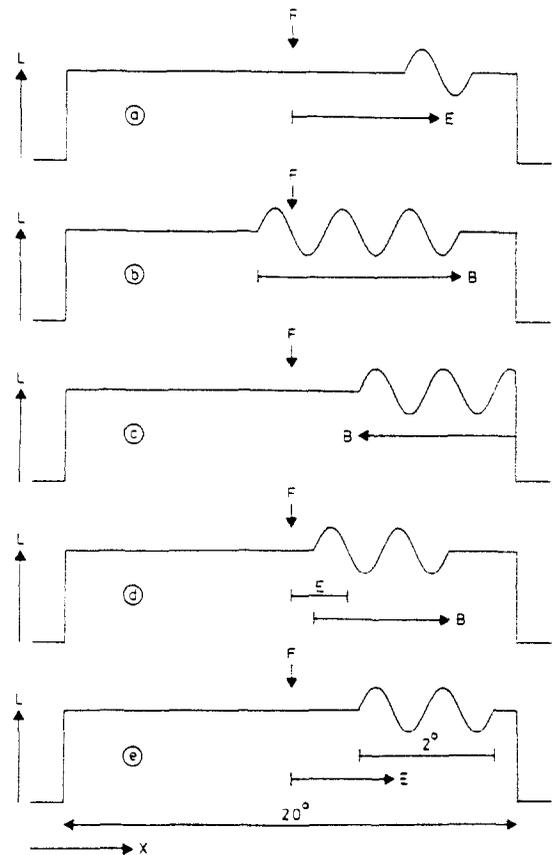


Fig. 1. The horizontal luminance distributions used in the different experiments.  $F$  = fixation point,  $E$  = eccentricity,  $L$  = luminance,  $X$  = coordinate.

according to Fig. 1a. The results are presented in Fig. 2.

As can be seen, the contrast sensitivity decreases monotonically with eccentricity for all spatial frequencies. When this experiment was repeated at a higher luminance ( $100 \text{ cd/m}^2$ ), similar results were found (see Fig. 3).

The contrast sensitivity measured as a function of the width of the grating (Fig. 1b) is given in Fig. 4.

To facilitate comparison with the results of Fig. 2, we extended the grating in the nasal direction only (starting from the centre of the field). The sensitivity increases rapidly and reaches a constant value within a width of about  $2^\circ$ .

Measurements with a grating starting from the peripheral edge of the field (Fig. 1c) gave the results shown in Fig. 5.

Measuring with gratings of variable width, starting from a point of variable eccentricity (Fig. 1d), we obtained the results shown in Fig. 6.

Finally, Fig. 7 gives the results for the contrast sensitivity as a function of the eccentricity of the least peripheral period, measured by using a grating with a width of  $2^\circ$ .

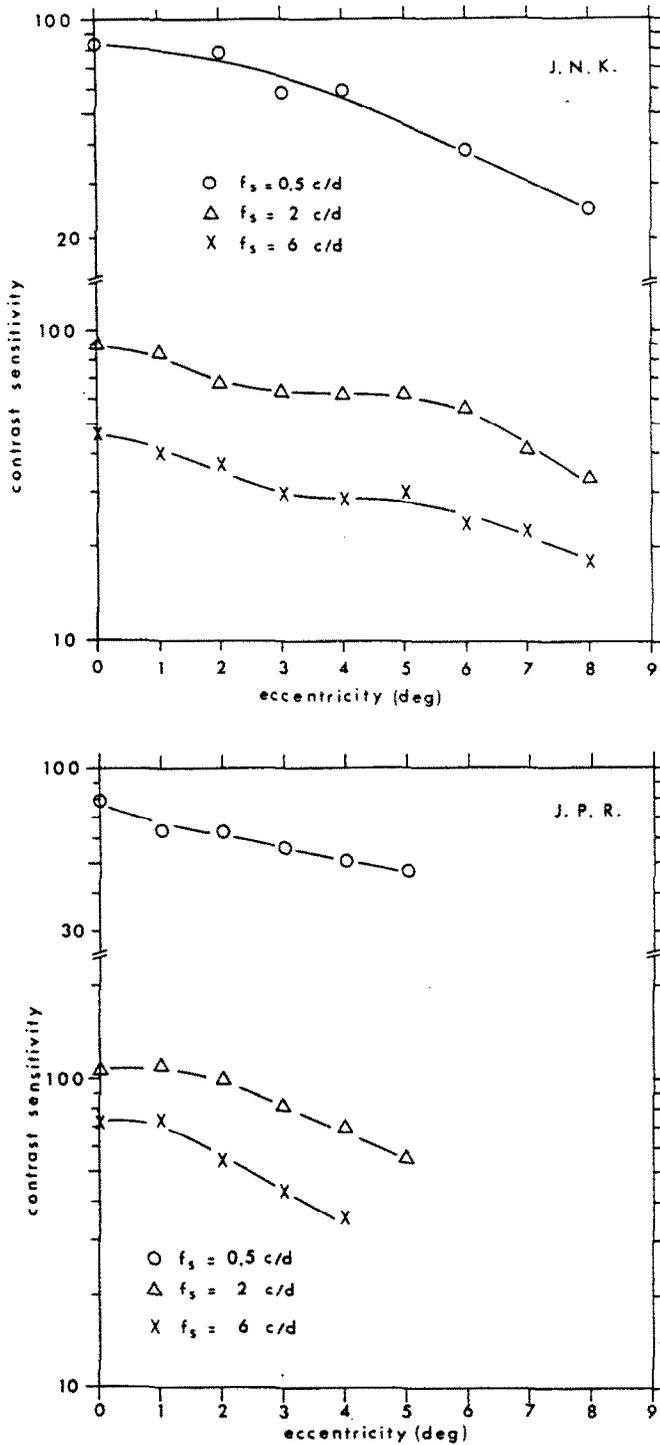


Fig. 2. Contrast sensitivity as a function of eccentricity for sine-wave gratings one period wide (corresponding to Fig. 1a).

#### DISCUSSION

The results obtained with the smallest stimulus, a vertically oriented "grating" with a width of one period, show a monotonic decrease in contrast sensitivity as eccentricity is increasing. One should expect a different curve to result if tuning was operative. Such a curve would have maximum contrast sensi-

tivity at some point outside the fovea, whose position depends on the spatial frequency. These measurements are repeated for a higher stimulus luminance in connection with other measurements with higher stimulus luminances (175 and 4000 cd/m<sup>2</sup>; see Kroon and van der Wildt, 1980). These measurements can be described by assuming probability summation, and

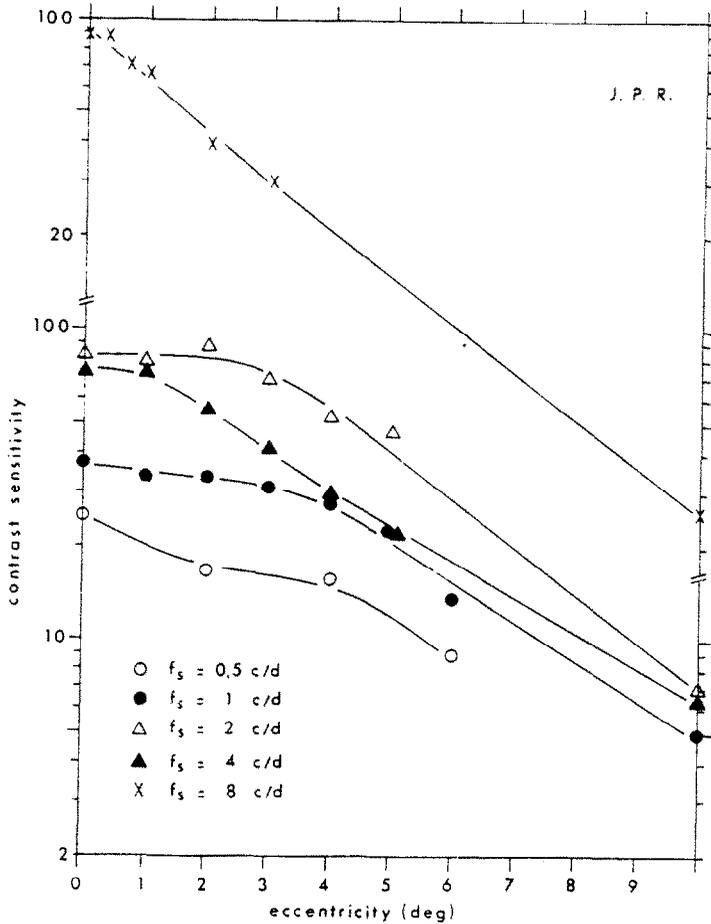


Fig. 3. Contrast sensitivity as a function of eccentricity for sine-wave gratings one period wide (corresponding to Fig. 1a) with a mean stimulus luminance of  $100 \text{ cd m}^{-2}$ .

using a weighting function with its maximum outside the fovea (tuning). The results obtained with luminance of  $100 \text{ cd/m}^2$  (see Fig. 3) show steeper slopes than those measured with a luminance of  $10 \text{ cd/m}^2$ . However, they do not show the form one would expect based on the assumption of tuning, as measured by Bryngdahl (1966), and as needed to describe the visibility of gratings in an equal luminance surround, as a function of the width of the grating (for a further discussion on this see Kroon and van der Wildt, 1980).

In our opinion, however, the results of Figs 2 and 3 do not necessarily preclude the existence of tuning. Consider the possibility that the contrast sensitivity is of circular symmetry. If we assume that tuning exists under these conditions, then the area of highest sensitivity will be annular, as indicated by the hatched area in Fig. 8.

With stimulus height greater than the external diameter of this stimulus, one can expect constant sensitivity as long as the stimulated area overlaps the annulus (see Fig. 8a and b). Decrease in sensitivity can not be measured as long as the stimulus and the annulus are not completely separated. Indeed, the results show a constant sensitivity for small eccentrici-

ties and a drop in sensitivity beyond a certain eccentricity. If an annulus of maximum sensitivity exists, this can only be detected using gratings of reduced height, although the connection with the findings of van der Wildt *et al.* (1976) is then lost. With the same surround, such a reduced height would involve luminance steps at the upper and lower edges of the grating, which could influence the contrast sensitivity. This effect can be eliminated by using two-dimensional gratings. The results of a study which used such two-dimensional gratings were described elsewhere (Rijsdijk, Kroon and van der Wildt (1980).

To check whether the data measured with single-period gratings can be used to describe the results obtained with larger stimuli, we also carried out measurements with gratings more than one cycle wide. Starting with a single-period grating in the fovea, contrast sensitivity was measured for gratings whose width increased in the nasal direction only. The results (Fig. 4) for the spatial frequencies of 2 and  $6 \text{ c/deg}$  have nearly the same form. Contrast sensitivity increases fast with increasing stimulus width, until a constant level is reached at a width of about  $2^\circ$ . The curve for  $0.5 \text{ c/deg}$  shows a slight increase in contrast sensitivity for larger widths, while below  $2^\circ$

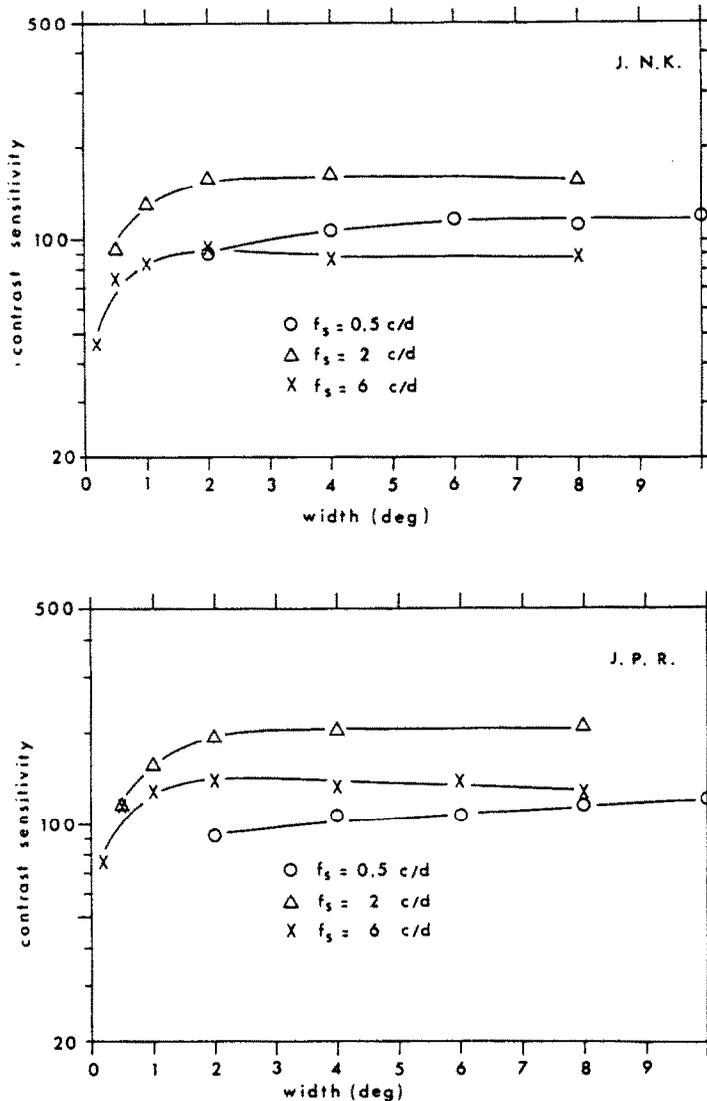


Fig. 4. Contrast sensitivity as a function of width for gratings extending from the fovea towards the nasal periphery (corresponding to Fig. 1b).

the stimulus cannot be measured because the minimum width (one period) is  $2^\circ$ . These results are in disagreement with those of Hoekstra, van der Goot, van den Brink and Bilsen (1974), Savoy and McCann (1975) and van der Wildt *et al.* (1976), who reported finding a critical number of periods beyond which the sensitivity is constant. This critical number was constant for spatial frequencies between 0.5 and 8 c/deg, and only depended on the mean stimulus luminance. Our results (see Fig. 4) indicate rather a critical width (about  $2^\circ$ ) which is independent of the spatial frequency, at least at higher spatial frequencies. It should be noted, however, that stimulus configurations were not identical in the different experiments. The above mentioned authors presented the gratings in variable sizes, in a dark surround, while we used a surround of constant size with a luminance level equal to the mean grating luminance. It is not impossible that the variation in dimensions of the illuminated field will

influence the contrast sensitivity, e.g. by changing the adaptation of the eye. The most appropriate way to measure the sensitivity as a function of the width is with a surround of constant dimensions. Savoy and McCann (1975) performed some measurements using a surround of luminance equal to the mean stimulus luminance. They found the same threshold for targets of  $2.7$  and  $7.6^\circ$  in width, for spatial frequencies above 1 c/deg, in agreement with our findings.

Further inspection of Figs 2 and 4 shows that in both these figures the curves for 2 and 6 c/deg have the same shape and are only shifted vertically with respect to one another, roughly by a factor of 2. It appears from the results of Fig. 4 (for 2 and 6 c/deg) that only the small part around the fovea determines the grating's threshold. As may be seen from Fig. 2, it is precisely this part that has the highest contrast sensitivity. The more peripheral, less sensitive, parts do not contribute significantly to the contrast sensitivity

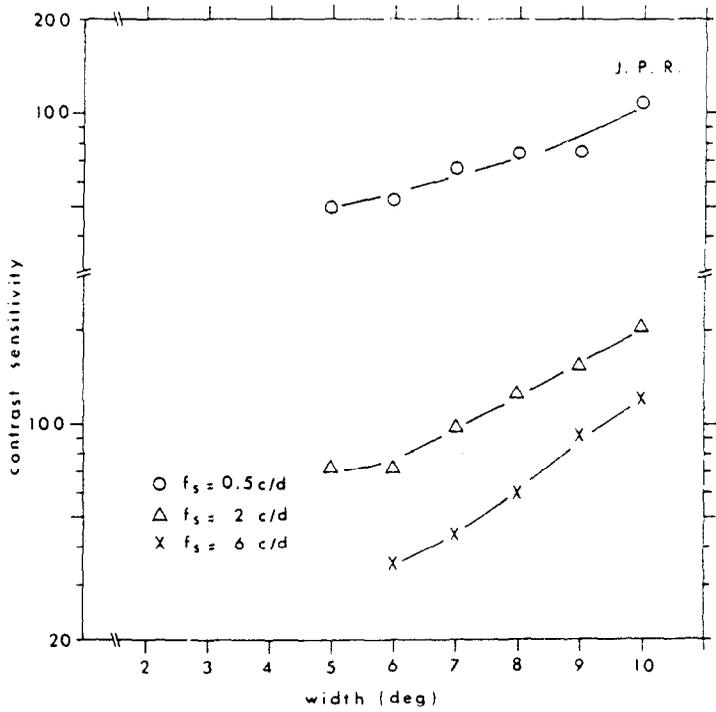
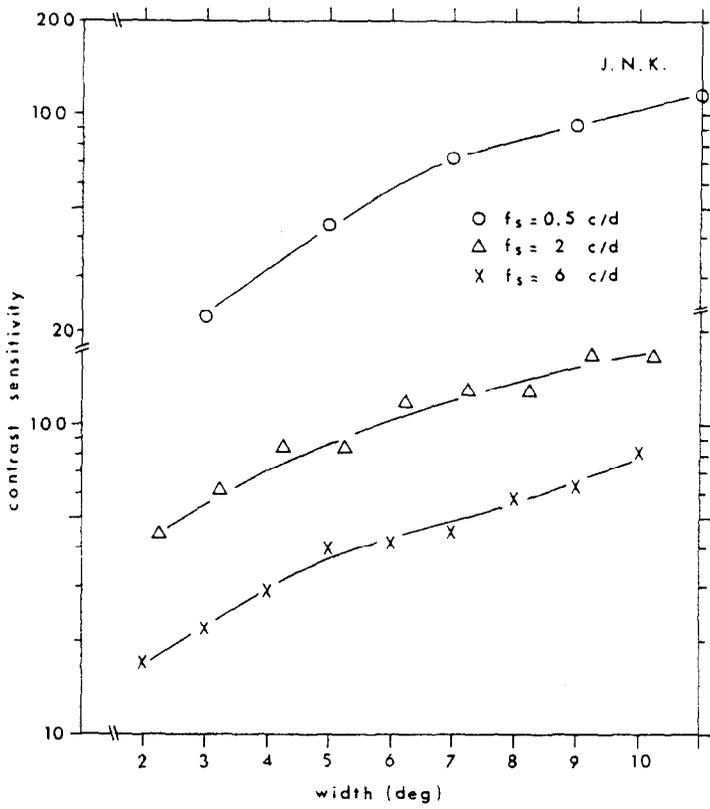


Fig. 5. Contrast sensitivity as a function of width for gratings extending from the nasal edge of the surround field towards the fovea (corresponding to Fig. 1c).

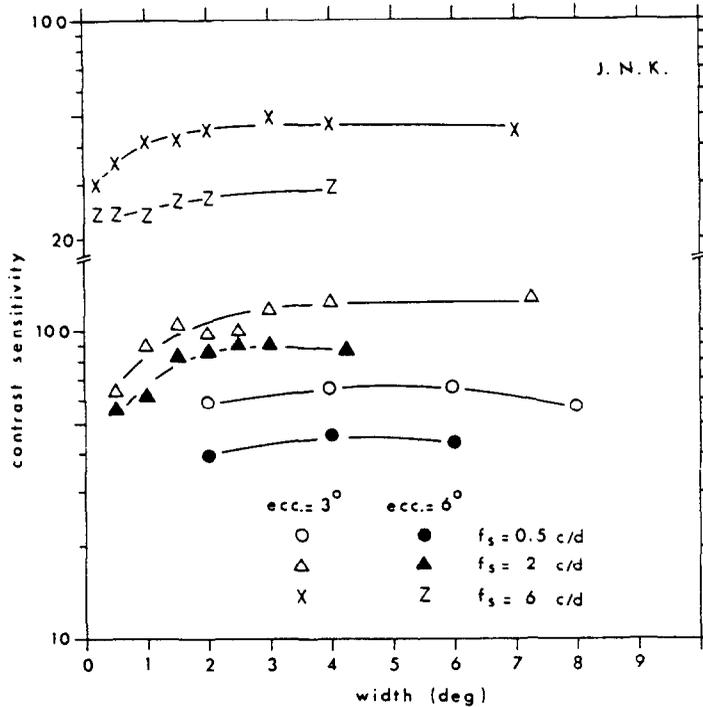


Fig. 6. Contrast sensitivity as a function of width for gratings extending from a given nasal eccentricity towards the periphery (corresponding to Fig. 1d).

for the wider gratings. Apparently the grating is already detected by the most sensitive parts of the retina. If contrast sensitivity is measured as a function of the width of the grating, starting from the nasal edge and extending towards the fovea, increasingly sensitive parts of the retina get involved in the detection as the grating width increases. In this case we expect a more direct relation between the contrast sensitivity as a function of the eccentricity and the threshold of a grating as a function of the width. As

the width increases in this situation, an extra threshold-determining part of the retina is involved in the detection. The results do indeed show an increase in sensitivity with increasing width (see Fig. 5). These results should be predictable on the basis of those of Fig. 2. For the sake of simplicity, let us first suppose that the sensitivity for a peripheral grating is determined only by one period, viz. the one exiting the most sensitive retinal area, i.e. the one closest to the fovea. Replotting the sensitivity for peripheral

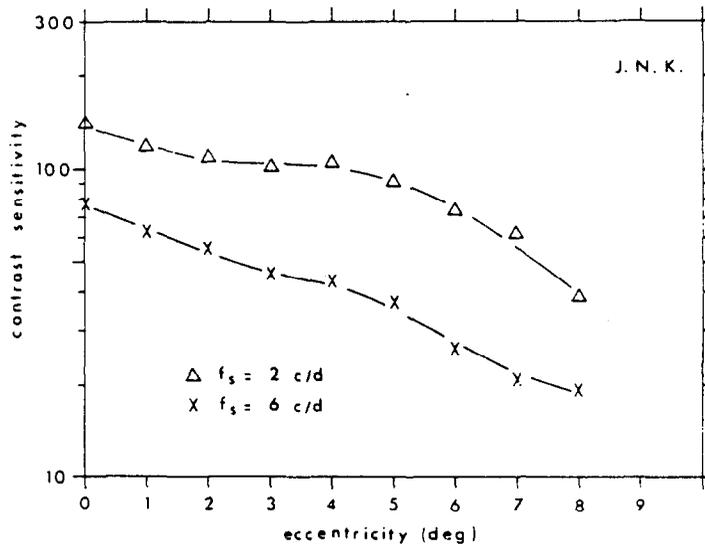


Fig. 7. Contrast sensitivity as a function of the eccentricity of the least peripheral period for gratings with a width of  $2^\circ$  (corresponding to Fig. 1e).

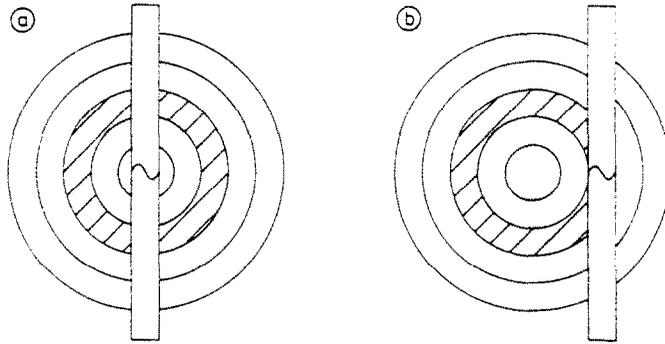


Fig. 8. The annular "tuning" zone with the stimulus in two positions giving equal contrast sensitivity. For explanation see text.

gratings from Fig. 5 as a function of the eccentricity of this period, we obtain the curves given in Fig. 9. The corresponding results of Fig. 2 are also plotted in this figure, by way of comparison.

The curves for  $f_s = 0.5$  c/deg do not show a significant difference, except at the fovea. Here, the contrast sensitivity does indeed seem to be determined only by the least peripheral period. For 2 and 6 c/deg, however, the corresponding curves do not coincide and show an increasing difference in sensitivity as eccentricity decreases. Thus, our assumption that one period determines the sensitivity is not confirmed by

the data (at least, not for the spatial frequencies tested in our experiments).

Apparently, a larger area determines the threshold of the grating as a whole. As can be seen from Fig. 4, a width of about  $2^\circ$  determines the threshold for foveal presentation. This could be the reason for the coincidence found with  $f_s = 0.5$  c/deg, since in this case one period is just  $2^\circ$ . In order to check whether this width of  $2^\circ$  depends on the eccentricity, we carried out the following measurements: Contrast sensitivity for a grating was determined as a function of the width, starting not from the fovea but from a

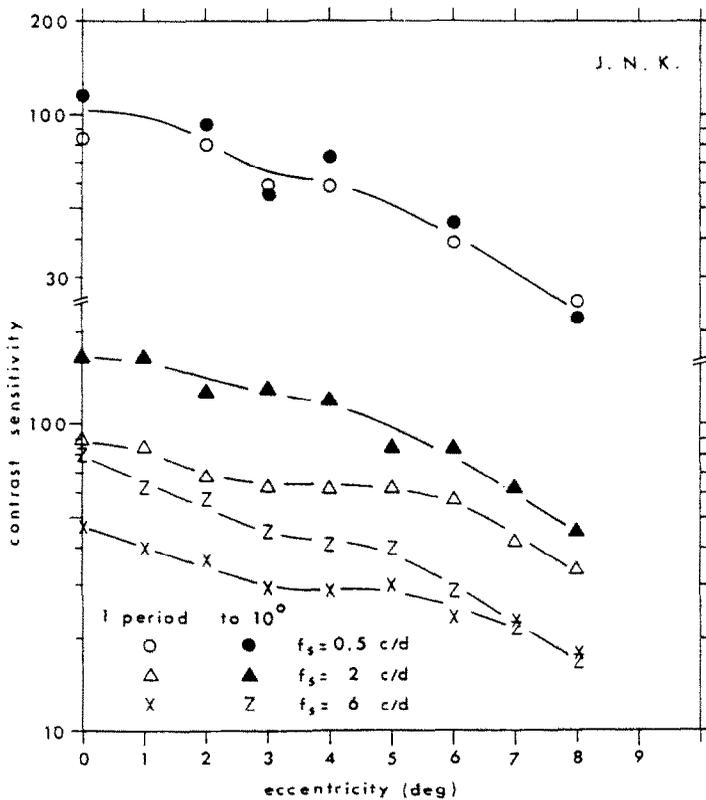


Fig. 9. Contrast sensitivity as a function of eccentricity of the least peripheral period, for gratings extending to the edge of the surround field (derived from Fig. 5), and for single-period gratings (replotted from Fig. 2).

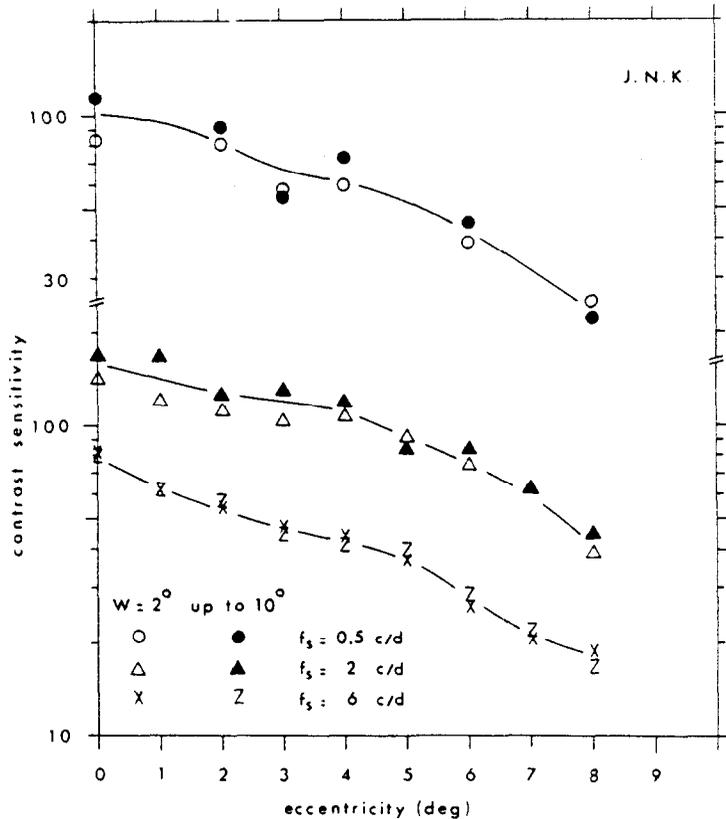


Fig. 10. Contrast sensitivity as a function of eccentricity of the least peripheral period, for gratings extending to the edge of the surround field (derived from Fig. 5), and for gratings with a width of  $2^\circ$  (replotted from Fig. 7).

point of variable eccentricity. The results are given in Fig. 6. The sensitivity as a function of the width reaches within  $2^\circ$  a value that is not significantly different from the value for the greatest width. We conclude that the contrast sensitivity for a peripherally presented grating is determined by the part with a width of  $2^\circ$  closest to the fovea. For foveally presented gratings the threshold is determined by the central area, again with a width of 2 degrees. In summary, our investigations lead us to the following proposition: *The contrast sensitivity for a wide sine-wave grating, presented in a surround with equal luminance, is determined by a part only  $2^\circ$  wide, situated as close to the fovea as possible.*

Finally, this proposition was tested by determining the sensitivity for a grating with a width of  $2^\circ$ , as a function of eccentricity. To facilitate comparison, the results of Fig. 7 were replotted in Fig. 10, together with the results of Fig. 5, both plotted as a function of the eccentricity of the least peripheral period.

Comparing the results, one can see that the threshold of the grating which extends up to the edge of the surround is indeed determined by the first  $2^\circ$ .

Koenderink *et al.* (1978b) and Rovamo *et al.* (1978) reported that the difference between results obtained foveally and peripherally could be understood on the assumption of a cortical magnification factor.

When the grating was presented peripherally they corrected the spatial frequency and the target size by the cortical magnification factor. As result, they found the modulation transfer function to be independent of the eccentricity at which it was measured. The results of these authors, however, cannot be described in terms of the sensitivity of the least peripheral part  $2^\circ$  in width. In our opinion, also this discrepancy is caused by the difference in stimulus surround illuminations. As shown by McCann and Hall (1977) contrast sensitivity can significantly be altered by the amount of average-luminance surround.

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