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CONTRAST SENSITIVITY AS A FUNCTION OF POSITION ON THE RETINA

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Abstract—Contrast sensitivity has been measured as a function of the eccentricity along several meridians. The measurements were carried out with a two-dimensional sinusoidal grating (cross grating) presented in a surround with a luminance equal to the average stimulus luminance. The advantage of this stimulus over a one-dimensional grating is that it permits presentation of small-sized stimuli, in a surround of the same luminance, without discontinuities at the edges of the stimulus. The results appear to be comparable with contrast sensitivity data obtained with one-dimensional gratings. The decrease in sensitivity is found to be dependent on the meridian along which it is measured. Plots of equal sensitivity curves show that these curves are somewhat ellipsoidal.

INTRODUCTION

Many investigations have been carried out on contrast transfer by the human visual system. For example the spatial modulation transfer function (MTF) has been measured as a function of:

- The luminance (van Nes, 1967);
- The number of periods in the grating (Savoy and McCann, 1975; Estevez and Cavonius, 1974; van der Wildt et al., 1976);
- The orientation (Campbell et al., 1966).

In all these investigations the stimuli were presented to the fovea. Measurements in which the stimuli were presented to the peripheral retina are mostly acuity measurements (Anstis, 1974; Berkley, 1975; Green, 1970). The only results we found in the literature giving information on the contrast sensitivity as a function of eccentricity are those of Bryndahl (1966), Hilz and Cavonius (1974) and Rovamo et al. (1978). Bryndahl (1966) concluded from his results, obtained by measuring the subjective modulation depth of a one-dimensional grating, that the contrast sensitivity reaches a maximum at the periphery. Hilz and Cavonius (1974), using an interference fringe method, showed that the sensitivity is maximum in the fovea. For this reason we have measured the sensitivity for a sinusoidally modulated stimulus, of which the width was as narrow as possible, i.e. one sinusoidal period of grating (Kroon et al., 1980). The stimulus height was 5°. The results obtained with this stimulus also showed a maximum sensitivity for foveal presentation. A disadvantage of this stimulus, however, was that, because of its height, a part of the peripheral retina was always stimulated, even when the stimulus was presented foveally. So the maximum sensitivity for a foveally presented stimulus does not have to be caused by the fovea, but can be caused by a more sensitive peripheral part of the retina, situated above and below the fovea, which also is stimulated because of the stimulus height of 5°. This means that if one wants to measure local contrast sensitivity, especially around the fovea, a stimulus will have to be used which is limited in height as well as in width. One-dimensional gratings limited in height and width always show discontinuities at the upper and lower edges, if presented in a surround with a luminance equal to the average luminance of the grating. The discontinuities at the right and left side of the stimulus can be eliminated by starting the sinusoid at phase zero. To avoid these discontinuities at the upper and lower edges we have chosen to use a stimulus of which the luminance is modulated sinusoidally both in vertical and horizontal directions (cross gratings). The smallest possible sinusoidal stimulus then is 1 x 1 period. We have measured the contrast sensitivity along several meridians as a function of eccentricity with this two-dimensional stimulus.

METHODS

Stimulus

Our stimulus was a two-dimensional grating (referred to as a cross grating from now on), modulated sinusoidally in both the vertical and horizontal directions. The horizontal and vertical signals were multiplied. The stimulus was presented on a TV monitor (Tektronix Picture mode 632 with phosphor WAD 6300). The stimulus surround was a circular field with a diameter of 15°, with a red fixation spot in the middle. The luminance of the surround was 10 cd/m², equal to the mean luminance of the stimulus. The viewing distance was 85 cm. The cross grating was presented at different positions in this field, but the fixation spot was always in the middle. An artificial pupil was not used. Two sine-wave generators (wavetek 144) were used to provide the horizontal and vertical signals on the monitor. The width and the height of the stimulus were determined by pulse
generators (data pulse 100 A). A whole number of periods was always presented. The sine-wave generators were started when the sine-wave crossed the zero level (background luminance) in both the horizontal and vertical directions to avoid discontinuities at the edges. The measurements were carried out monocularly (right eye). A chin and forehead rest were used. We also performed measurements with a one-dimensional grating. In this case, only the horizontal direction was modulated. The orientation was changed by rotating the TV monitor around an axis at right angles to the screen. The amplitude of the stimulus was sinusoidally modulated with a frequency of 1 Hz ($A = A_0 \sin(\omega t)$).

Measuring procedures

Two procedures were used.

1. **The adjustment method.** The subject decreased the modulation depth by 1 dB steps until the contrast threshold was reached. The average result of at least three adjustments are taken as threshold. The standard error of mean was 0.7 dB.

2. **Von Békésy tracking.** In this method the attenuation is controlled by a micro-processor. A more detailed description of this method is given by Keemink et al. (1979). The subject can cause the contrast of the grating to fall by depressing a switch. As soon as the contrast is subthreshold, the subject releases the switch which causes the contrast to increase. When the grating is just visible, the subject depresses the switch again. This process is repeated a dozen times, so that the modulation depth fluctuates around the subject's threshold. The higher and lower contrast reversal values are averaged and this value is taken as the threshold. To avoid adaptation effects, the first four reversal values are not used. The threshold determined from the next eight reversal values is printed out automatically. The presented threshold data are obtained by averaging the results of at least two measurements. The standard error of mean was 1 dB.

Experiments

We measured the MTF for one-dimensional gratings presented over the full stimulus field of 15' with different orientations, using Von Békésy tracking, to see if it makes any difference if the threshold for cross gratings is determined by the frequencies present in the cross grating other than in the horizontal direction.

We needed this finding as a basis for comparison of the MTF for cross gratings and one-dimensional gratings, for which purpose we measured the MTF for cross gratings also presented over the full stimulus field, again using Von Békésy tracking, and compared the results with our measured values for one-dimensional gratings (Kroon et al., 1980). Using cross gratings of limited dimensions (one period in the horizontal and one in the vertical direction), we measured the sensitivity as a function of the eccentricity of the stimulus (see Fig. 1), using Von Békésy tracking. To check for circular symmetry we measured the sensitivity in several directions using the adjustment method.

**RESULTS**

The results are obtained for two subjects, JPR and JNK. As there are no large differences between the results of both subjects, mostly the results of one subject are given (JPR). As mentioned above, our two-dimensional stimulus was obtained by multiplying the horizontal and vertical sinusoidal signals. Now Carlson et al. (1977) found the same contrast results with one-dimensional gratings and two-dimensional gratings obtained by adding the vertical and horizontal sinusoidal signals. The difference between two-dimensional gratings obtained by addition and multiplication includes a difference in orientation of 45° (see Appendix). As we want to compare the results for two-dimensional and one-dimensional gratings, we checked whether the MTF for one-dimensional gratings depends on the orientation of the gratings by measuring the effect of orientation on the contrast threshold under the same conditions as for cross gratings. The results are given in Fig. 2.

We may conclude that our results do not depend on the orientation of the one-dimensional gratings. Now results published in the literature indicate that there is an orientation dependence for one-dimensional gratings. We will return to this point in the discussion.

Figure 3 gives the MTF measured with cross gratings presented over the full stimulus field of 15° dia. The frequencies plotted as abscissae are those presented in both horizontal and vertical directions. By

![Fig. 1. Cross-section of the stimulus field in the horizontal direction. F = fixation point. E = eccentricity, L = luminance, X = coordinate.](image-url)
Contrast sensitivity

Fig. 2. The MTF for one-dimensional gratings, covering the full 15° field, with different orientations. Dark surround.

way of comparison, the curve fitted to the results of Fig. 2 is reproduced here. We will return to the difference between these results in the discussion.

The contrast sensitivity as a function of eccentricity, measured with a stimulus of 1 x 1 period, is given in Fig. 4.

The contrast sensitivity decreases monotonically with eccentricity for all spatial frequencies. We measured the sensitivity along several meridians to check whether or not the dependence on the eccentricity is the same in all directions. The results are given for two spatial frequencies in Figs 5 and 6. We see that the decrease in sensitivity as a function of eccentricity is monotonic in all directions, and

Fig. 3. The MTF for cross gratings (open circles) and for one-dimensional gratings (full line from Fig. 2).

Fig. 4. Contrast sensitivity as a function of eccentricity for a stimulus of one period in both horizontal and vertical directions.

Fig. 5. Contrast sensitivity along several meridians \( f_s = 0.5 \text{ c/d} \) Stimulus width 2 x 2°. For symbols see inset in figure.

depends on the meridian along which the eccentricity is varied.

DISCUSSION

We may conclude from our results that the contrast threshold does not depend on the orientation of the grating. In the literature, however, results are given indicating that the contrast threshold does depend on the orientation of the gratings (Campbell et al., 1966; Berkley et al., 1975). If we examine these results more
closely, we can see that the dependence on the orientation appears at spatial frequencies above 8–10 c/deg. We did not measure at spatial frequencies above 10 c/deg. There is thus no real contradiction between our results and those published in the literature. The MTF measured with cross gratings is not the same as that for one-dimensional gratings, as we can see from Fig. 3. Carlson et al. (1977) showed that the MTF for two-dimensional gratings obtained by adding the vertical and horizontal signals was equal to the MTF for one-dimensional gratings. As mentioned above, we generated our stimulus by multiplying the vertical and horizontal sinusoidal signals. One of the differences between stimuli obtained by adding and multi-

Fig. 6. Contrast sensitivity along several meridians $f_s = 6$ c/deg. Stimulus $1 \times 1'$. For symbols see inset in figure.

Fig. 8. Contrast sensitivity decrease as a function of eccentricity for cross gratings (△, ▲) and for one-dimensional gratings (□ and ■). The data of Rovamo et al. (1978) for one-dimensional gratings (○) are included by way of comparison.

Fig. 7. The MTF for cross gratings, the frequencies and modulation depth being measured at an angle of 45° with the horizontal. The full line is the same as in Fig. 2 (best fit for one-dimensional gratings).

Fig. 9. Contrast sensitivity decrease as a function of eccentricity for cross gratings (△, ▲) and gratings (□ and ■). The data of Rovamo et al. (1978) for one-dimensional gratings (○) are included by way of comparison.
Contrast sensitivity

Fig. 10. Isocontrast sensitivity curves for $f_x = 0.5$ c/deg. The data are obtained from Fig. 5.

plying the vertical and horizontal signals is a difference in orientation. As we can see from the results of Fig. 2 the difference in orientation cannot cause the measured difference between the MTFs. In the Appendix we show that the stimulus obtained by multiplying can also be obtained by adding two sinusoidal signals with frequencies a factor $\sqrt{2}$ larger, modulation depth a factor 2 smaller and rotated through 45°. We can thus also characterize the cross gratings by the spatial frequencies at an angle of 45° with the horizontal if we multiply the frequencies in the horizontal direction by $\sqrt{2}$ and divide the modulation depth by 2. Figure 7 shows the data for cross gratings corrected in this way, together with the curve for one-dimensional gratings from Fig. 2.

We see that there is good agreement between the results for one-dimensional and two-dimensional gratings. Our results are thus compatible with those of Carlson et al. (1977). Because of this finding, we decided to characterize the cross gratings by the spatial frequencies and modulation depth at an angle of 45° with the horizontal, to facilitate comparison with one-dimensional gratings. Measuring with our two-dimensional "local" stimulus (1 x 1 period), we found that the contrast sensitivity decreases monotonically with eccentricity (Fig. 4). The contrast sensitivity is maximum in the fovea. For one-dimensional gratings, we also found a monotonic decrease in sensitivity with eccentricity. Our results obtained with (1 x 1 period) cross gratings (from Fig. 4) are compared with results obtained with one-dimensional gratings in Figs 8 and 9 to see whether the dependence on eccentricity is the same for both cases. The data of Rovamo et al. (1978) for one-dimensional gratings are included in Figs 8 and 9 by way of comparison.

There is reasonable agreement between our results obtained with one-dimensional and two-dimensional stimuli and, taking the different stimulus conditions into account, there is also reasonable agreement between our results and those of Rovamo et al. (1978). We used the two-dimensional stimuli to measure the contrast sensitivity as a function of position of the retina. Some qualitative remarks may be made about the results given in Figs 5 and 6. First, the slope of the curves is dependent on the spatial frequency. Over a range of 6° the decrease in sensitivity changes from a factor of 3 for $f_x = 0.5$ c/deg to a factor of 16 for $f_x = 6$ c/deg. Secondly, the contrast sensitivity decreases for all spatial frequencies more rapidly in the vertical direction than in the horizontal one.

Finally, for the results measured along the 45°/225° and the 135°/315° meridians the data are not symmetrical with regard to the fovea. This is expressed in Figs 5 and 6 by the fact that in the left-hand half of the figures the open circles are situated above the closed ones, while in the right-hand half the open circles are underneath. This means that the contrast sensitivity in the upper half of the visual field is somewhat lower than in the lower half. We can map the contrast sensitivity of the retina, on the basis of the results of Figs 5 and 6. Contours for constant contrast sensitivity based on these data are given in Figs 10 and 11.

The full lines are drawn by eye through the data and represent curves of equal contrast sensitivity.
These maps provide a clear illustration of some of the remarks made above. The more rapid decrease in sensitivity in the vertical direction than in the horizontal one gives somewhat ellipsoidal contours.

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REFERENCES


APPENDIX

Carlson et al. (1977) showed that the contrast sensitivity is the same for one-dimensional and two-dimensional gratings. They obtained their stimuli by adding the horizontal and vertical sinusoidal signals. We however multiplied these signals to obtain a stimulus of one sinusoidal period horizontally and one period vertically. Addition of these single-period signals would give a stimulus which was partially one-dimensional and partially two-dimensional, though under "full" field conditions there is no essential difference between the two stimuli. We will now show that the stimulus obtained by multiplying can also be obtained by adding two sinusoidal signals.

\[ L_{\text{add},x,y} = L(1 + M(\cos x_i \cos y_i)) \]  

\[ L_{\text{mul},x,y} = L(1 + M(\cos x_i \times \cos y_i)) \]

\[ = L(1 + M(\cos(x_i - y_i) + \cos(x_i + y_i))) \]

\[ = L(1 + \frac{M}{2} \cos(x - y) + \cos(x + y)) \]  

Rotation of the axes through 45° gives:

\[ x' = \frac{1}{\sqrt{2}} (x + y) \]

\[ y' = \frac{1}{\sqrt{2}} (1 - x + y) \]
We can now rewrite (3) as:

\[ L_{\text{multi},x,y} = L \left[ 1 + \frac{M}{2} \left( \cos \sqrt{2} f_s \left( \frac{-x + y}{\sqrt{2}} \right) \right) + \cos \sqrt{2} f_s \left( \frac{x + y}{\sqrt{2}} \right) \right] \]

\[ - L \left[ 1 + \frac{M}{2} \left( \cos \sqrt{2} f_s x' + \cos \sqrt{2} f_s y' \right) \right] \]  

(7)

This means that the stimulus obtained by multiplying two given signals can also be obtained by adding two signals with frequencies a factor \( \sqrt{2} \) larger, modulation depth a factor 2 smaller and rotating the resulting stimulus through 45°.