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THE SENSITIVITY OF THE PERIPHERAL VISUAL SYSTEM TO AMPLITUDE-MODULATION AND FREQUENCY-MODULATION OF SINE-WAVE PATTERNS

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Abstract—The detectability of amplitude modulation and spatial frequency modulation of suprathreshold sine-wave gratings was measured at retinal eccentricities ranging from 0 to 30 deg. The main conclusions to be drawn from the experimental results are: (1) for this visual task it is not possible to bring peripheral sensitivity to the same level as foveal sensitivity by scaling the stimuli with the inverse of the cortical magnification factor M. (2) Increasing the number of cycles in the carrier grating improves modulation detectability. For gratings in the periphery this holds up to the largest stimulus size used (64 cycles). In earlier investigations it has been shown that for central vision the improvement ends at about 16 cycles.

Eccentricity   Sine-wave grating   Number of cycles

INTRODUCTION

For a number of visual tasks peripheral vision seems to be as good as central vision if the stimulus size is scaled with a factor that varies with eccentricity such that the number of stimulated ganglion cells and the stimulated cortical area are almost the same at any eccentricity. In a number of tasks essentially the same visual performance (as measured in the form of e.g. a threshold) is obtained at all eccentricities, provided the stimuli are scaled according to (the inverse of) the cortical magnification factor M for each eccentricity. In other words, visual processing seems to be essentially equal over the whole visual field when distance is measured in mm across the cortex.

This view was first established for visual acuity: acuity is directly proportional to M (Cowey and Rolls, 1974; Drasdo, 1977, Koenderink *et al.*, 1978a). It has also been found to hold for measurements of spatial contrast sensitivity functions (Koenderink *et al.*, 1978a; Rovamo *et al.*, 1978; Virsu and Rovamo, 1979; Rovamo and Virsu, 1979), of colour discrimination (Noorlander, 1981), letter identification (Anstis, 1974), critical size for spatial summation in measuring contrast thresholds for round spots of light (Wilson, 1970) [see Virsu and Rovamo (1979) who plotted the data of Anstis and Wilson against M] and displacement detection (Westheimer, 1979). In addition, movement detection can be made largely independent of eccentricity by scaling of the stimulus size (van de Grind *et al.*, 1983).

There are two exceptions (as far as we know) to the "scaling-according-to-M" rule. Firstly, Westheimer (1982) found that hyperacuity thresholds rise with eccentricity faster than expected from the decrease of M, whereas the "critical distance for hyperacuity" rises more slowly than expected. Secondly Stephenson and Braddick (1982) found that discrimination of the relative phase of two grating components is poorer in the periphery than in the fovea, even when the stimuli are scaled according to M.

In this paper we present data obtained for another suprathreshold contrast task: the detection of amplitude and spatial frequency modulation of sine-wave gratings. It is found that in this case the scaling principle breaks down.

We also present data showing how the thresholds for the detection of amplitude- and frequency-modulation depend on the size of the stimulus in the periphery. The thresholds decrease with increasing stimulus size. This decrease continues up to the largest stimulus size used (64 grating cycles). Jamar and Koenderink (1983) found that in foveal vision the threshold decrease ends at about 16 cycles.

METHODS

The stimuli are generated on the screen of a cathode-ray-tube (white P4 phosphor). For contrast threshold measurements the stimulus is a sine-wave grating; for modulation threshold measurements it is a suprathreshold sine-wave grating, which is amplitude-modulated (AM) or frequency-modulated (FM). For an AM-grating the luminance as a function of position x is given by

$$L(x) = L_0 \cdot \left\{ 1 + c \cdot \left(1 + \frac{m}{100\%} \sin [2\pi f_m x] \right) \cdot \sin [2\pi f_c x] \right\} \quad (1)$$

where: L_0 = mean luminance, c = contrast, m = modulation depth (percent), f_c = spatial frequency of the carrier, f_m = spatial frequency of the modulation and $x = 0$ represents the centre of the stimulus.

For an FM-grating

$$L(x) = L_0 \cdot \left\{ 1 + c \cdot \sin\left(2\pi f_c x - \frac{m}{100\%} \frac{f_c}{f_m} \cos\left[2\pi f_m x\right] \right) \right\}. \quad (2)$$

The apparatus and the stimuli have been described before (Jamar *et al.*, 1982).

The subject measures a threshold by varying the amplitude of the contrast (or the modulation) up and down in 0.05 log unit steps (max 1 step/sec). The threshold is estimated as the average of the last 8 of 13 turning points. All reported thresholds are averages of 4–6 of such estimates. Standard errors were about 0.05 log unit for contrast thresholds and 0.05–0.10 log unit for modulation thresholds.

This procedure was chosen because we wanted to study the effect of eccentricity under conditions of continuous stimulus presentation. The continuous presence of the stimulus on the screen comes closer to the conditions in every-day vision than the short presentations used in a forced-choice paradigm. The temporal mode of stimulus presentation needs some comment. It is known that a stationary stimulus in the periphery tends to fade (contrast tends to disappear) after prolonged viewing. In a pilot experiment (see below) we examined this effect by using both stationary and flickering gratings. Results obtained with stationary gratings did not seem to have suffered from fading effects. In Experiments 1 and 2 (see below) with suprathreshold stationary gratings fading never seemed to occur. An adjustment procedure like the one we used carries the disadvantage that the experimenter has little control over the criterion adopted by the subject. The criterion for modulation detection may change in going from the fovea to the periphery, because the task may become more difficult. Our subjects (the first two authors) were fully familiarized with the tasks of contrast detection and modulation detection in both fovea and periphery before the data reported here were collected. The subjects reported that the determination of a modulation threshold was *not* more difficult in the periphery than at the fovea, and that they used the same criterion (the grating being "irregular") for modulation detection in both cases. We therefore believe that our results are largely free from effects of criterion shifts.

The stimuli had an average luminance of 2.5 cd/m^2 and a dark surround. No artificial pupil was used (except for the foveal experiments the results of which are shown in Fig. 3(b); in this case an artificial pupil with 2.8 mm diameter was used). For foveal experiments the subjects fixated a small black dot in the centre of the stimulus; for peripheral measurements (nasal visual field) a green LED was used for fixation. Two subjects participated in the experiments: L.K. (emmetropic) and J.J. (−0.75 D myopic).

The subjects viewed the stimuli and the fixation mark monocularly with their right eye. In some of the experiments at 12, 18 and 30 deg eccentricity L.K. viewed the fixation LED with his left eye. J.J. used a corrective lens (−0.75 D) for eccentricities up to 18 deg (in this paper, unless otherwise stated, the eccentricity of a stimulus will refer to the position of its centre).

In the modulation detection experiments the contrast of the stimuli was set a constant factor above the threshold contrast. For L.K. this factor was 4 and for J.J. 8.

Pilot experiment

Before measuring AM- and FM-thresholds (Experiment 1, see below) we performed a pilot experiment to determine how the stimulus size had to be scaled for eccentricity in order to make contrast thresholds for different eccentricities comparable. We also ascertained the optimum temporal condition for

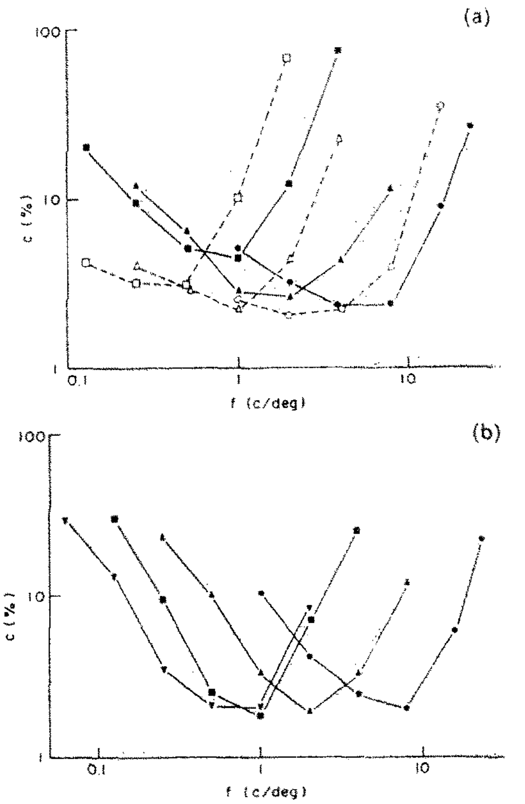

Fig. 1. (a) Contrast thresholds for sine-wave gratings flickering in counterphase with a temporal frequency of 2 Hz. The detection criterion was either pattern detection (solid symbols) or flicker detection (open symbols). Subject L.K. Circles: eccentricity 0 deg, stimulus size 1 × 1 deg^2. Triangles: ecc. 6 deg, size 4 × 4 deg^2. Squares: ecc. 21 deg, size 8 × 8 deg^2. (b) Contrast thresholds for stationary gratings for four eccentricities. Combinations of eccentricity and stimulus size were selected to yield contrast threshold curves that are almost identical except for shifts along the frequency axis. Circles: eccentricity 0 deg, stimulus size 1 × 1 deg^2. Triangles: ecc. 6 deg, size 4 × 4 deg^2. Squares: ecc. 18 deg, size 8 × 8 deg^2. Inverted triangles: ecc. 30 deg, size 16 × 16 deg^2. Subject L.K.

the stimuli. The latter was required in order to determine to what extent the Troxler-effect might interfere with the scaling procedure. We first tried stimulus sizes of 1 × 1, 4 × 4 and 8 × 8 deg^2 at eccentricities of 0, 6 and 21 deg. Fig. 1(a) shows some results. The contrast sensitivity curves in Fig. 1(a) were measured with gratings flickering in counterphase with a temporal frequency of 2 Hz. Two different detection criteria were used: pattern detection (solid symbols) and flicker detection (open symbols). The results show that the scaling between 0 and 6 deg of eccentricity is correct: at both eccentricities we find almost the same contrast sensitivity curves. The only difference is in their position on the frequency axis: the curves for 6 deg are shifted to the left by a factor of 4 (the scale factor). The contrast thresholds at 21 deg are higher than at 0 and 6 deg. This means that the scaling factor for 21 deg was not correct (the 8 × 8 deg stimulus is too small at 21 deg). We corrected for this by presenting the 8 × 8 deg stimulus at an eccentricity of 18 instead of 21 deg. Figure 1(b) shows results for stationary gratings (eccentricities 0, 6, 18 and 30 deg, stimulus sizes 1 × 1, 4 × 4, 8 × 8 and 16 × 16 deg^2; viewing distance 3.43, 3.43, 1.71 and 0.86 m). With these combinations of stimulus size and eccentricity we find comparable contrast sensitivity curves at all eccentricities. Therefore these combinations were used in Experiment 1. These results confirm the findings of Koenderink *et al.* (1978a,b) and Rovamo and Virsu (1979). The pilot experiment shows that the same scaling factors apply to both stationary gratings and flickering gratings (for both detection criteria). The curves for pattern detection in a flickering grating and for detection in a stationary grating are almost identical. We decided to perform Experiments 1 and 2 with stationary gratings, because the scaling rule works well for these and because the subjects felt that in the modulation threshold experiments the presence of flicker only made more difficult the (spatial) judgement required.

Figure 2 shows that the scaling factors (stimulus sizes) determined in the pilot experiment are in accordance with previous estimates of the cortical magnification factor. The figure shows the dependence on eccentricity of the cortical magnification factor M [according to the equation of Rovamo and Virsu (1979) for the nasal visual field; dashed line] and the stimulus sizes used in Experiment 1 (squares). The figure further shows how (grating) acuity (solid circles) and optimum spatial frequency (the spatial frequency for which the contrast threshold is lowest; open symbols) vary with eccentricity. The fact that the curves can be made to coincide by choosing the vertical axes suitably illustrates that there is direct proportionality between all the quantities plotted.

Experiment 1

In this experiment we measured AM and FM thresholds for vertical gratings for eccentricities of 0, 6, 18 and 30 deg along the horizontal meridian in the temporal retina (nasal visual field). For each eccentricity the stimulus size was chosen such that contrast thresholds for different eccentricities would be comparable. The pilot experiment showed that the stimulus sizes needed were 1 × 1, 4 × 4, 8 × 8 and 16 × 16 deg^2. The carrier spatial frequencies for the four eccentricities were 8, 2, 1 and 0.5 c/deg respectively. Thus, the gratings used in Experiment 1 all contained 8 cycles of the carrier grating. At each eccentricity modulation frequencies were used that were 0.125, 0.25, 0.35, 0.5, 0.65 and 0.8 times the carrier frequency.

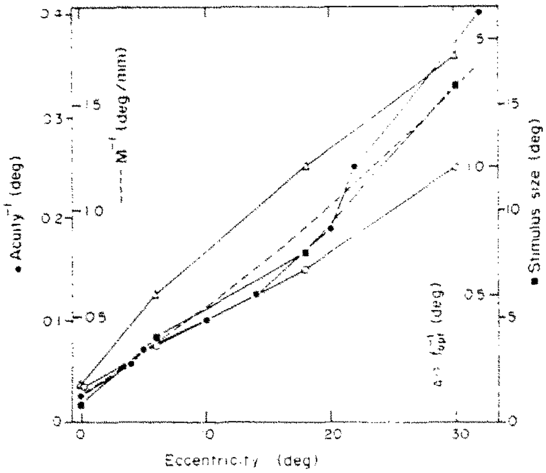

Fig. 2. Solid circles: the inverse of grating acuity as a function of the eccentricity of the part of the stimulus nearest to the fovea. [Determined by extrapolation to $c = 100\%$ of the high-frequency branch of contrast threshold curves like those of Fig. 1(b)]. Subject J.J. Dashed curve: the inverse of the cortical magnification factor [according to the equation of Rovamo and Virsu (1979) for the nasal visual field] as a function of eccentricity. Squares: the size (width and height) of the stimuli we used in experiment 1 as a function of the eccentricity of their centres. Open symbols: the inverse of the optimum spatial frequency (the spatial frequency for which the threshold contrast is lowest). These optimum frequencies were determined from Fig. 1(b) for L.K. and from a similar figure for J.J. Triangles: subject L.K. circles: subject J.J.

Experiment 2

Both contrast thresholds and modulation thresholds were measured as a function of stimulus size at eccentricities of 12 and 18 deg on the horizontal meridian of the temporal retina. To ensure that the stimuli were presented in an approximately homogeneous part of the retina we used vertical strips of horizontal grating having widths of 2 and 4 deg at eccentricities of 12 and 18 deg respectively. [A similar stimulus configuration was used by Robson and Graham (1981) for measuring peripheral spatial summation in a threshold contrast task.] The height of the grating (and thus the number of grating cycles contained in it) was varied. Heights up to 16 deg were used. In Experiment 2 the viewing distance was always 0.86 m. This experiment was performed only by L.K. FM thresholds were measured only at 18 deg eccentricity.

RESULTS

Experiment 1

The results of Experiment 1 are shown in Figs. 3 and 4. Figure 3(a) shows, for four eccentricities, AM- and FM-thresholds as a function of the modulation frequency f_m (the spatial frequency of the modulation signal). With each carrier grating, f_m was varied in such a way that the number of cycles of f_m varied from 1 (leftmost point on each of the curves) to 6.4. (The number of cycles of the carrier frequency f_c was always 8.) Figure 3(a) shows that, as expected, AM- (or FM-) curves for different eccentricities are shifted with respect to each other along the frequency axis (in accordance with the different scale factors). However, there is also a marked shift in the vertical direction: AM and FM thresholds increase with eccentricity. One might suggest that the small eye movements that occur even under fixation are relatively more important for small stimuli than for larger ones and thus lower the thresholds for the smaller stimuli at lower eccentricity. Figure 3(b) however shows that this is not the case. Here AM and FM thresholds are shown for the same stimuli viewed centrally. Thresholds for large stimuli are not higher than those for small ones. In Fig. 4 some of the results from Fig. 3(a) are replotted to show more clearly how AM and FM thresholds depend on eccentricity.

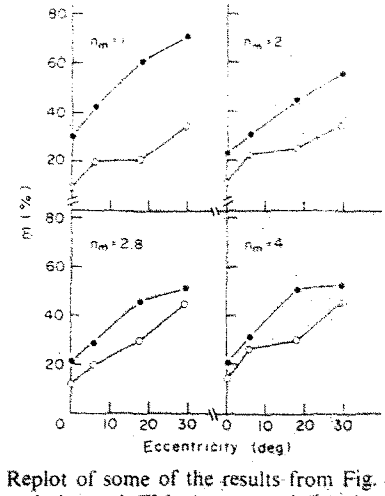

Fig. 4. Replot of some of the results from Fig. 3(a). AM- (*solid symbols*) and FM- (*open symbols*) *thresholds* are plotted directly as a function of eccentricity. In each panel the number of modulation cycles is fixed. This means that all points on a single curve are results for the same stimulus (containing 8 carrier cycles and n_m modulation cycles), which was scaled according to the eccentricity at which it was presented.

Experiment 2

The results of Experiment 2 are given in Figs. 5 and 6. Figure 5 shows the dependence of contrast thresholds on the height of the (horizontal) grating (and

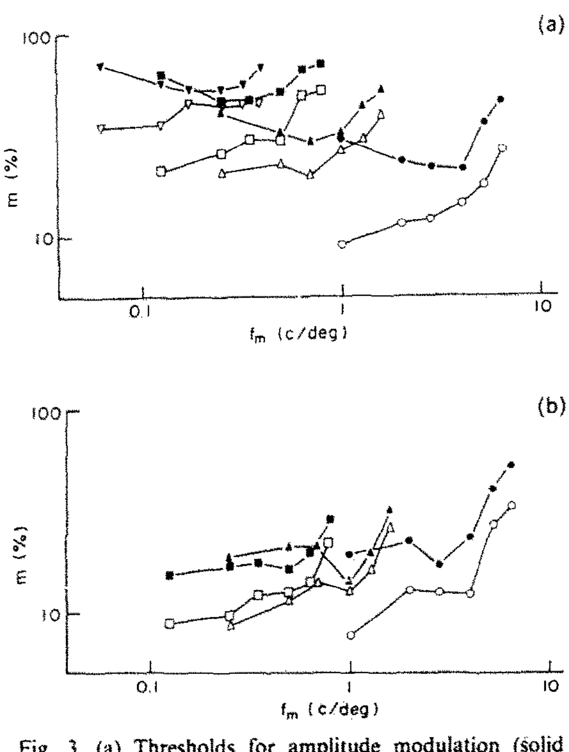

Fig. 3. (a) Thresholds for amplitude modulation (solid symbols) and frequency modulation (open symbols) as a function of modulation frequency. All stimuli contained 8 cycles of the carrier spatial frequency f_c, and were scaled with eccentricity according to the cortical magnification factor. Subject L.K. Circles: eccentricity 0 deg, stimulus size 1×1 deg^2, $f_c = 8$ c/deg. Triangles. ecc. 6 deg, size 4×4 deg^2, $f_c = 2$ c/deg. Squares ecc. 18 deg, size 8×8 deg^2, $f_c = 1$ c/deg. Inverted triangles: ecc 30 deg, size 16×16 deg^2, $f_c = 0.5$ c/deg. (b) Same stimuli as in Fig. 3(a), except that all were viewed centrally (using an artificial pupil with 2.8 mm diameter). Subject J.J.

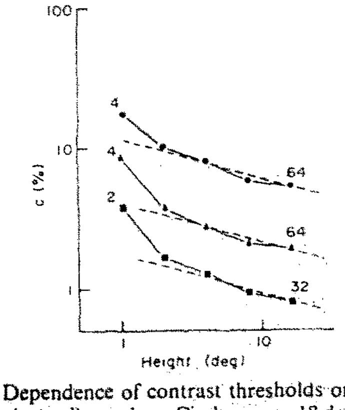

Fig. 5. Dependence of contrast thresholds on the height of the (horizontal) grating. Circles: ecc. 18 deg, $f_c = 4$ c/deg, stimulus width (length of the bars) 4 deg. Triangles: ecc. 12 deg, $f_c = 4$ c/deg, width 2 deg. Squares: ecc. 18 deg, $f_c = 2$ c/deg, width 4 deg. The curves marked with triangles and squares have been shifted downwards by factors of 2 and 4 respectively. The dashed lines denote a slope of $-1/3.5$ (see text for explanation). For some of the data points the number of grating cycles is indicated by a number close to the symbol. Subject L.K.

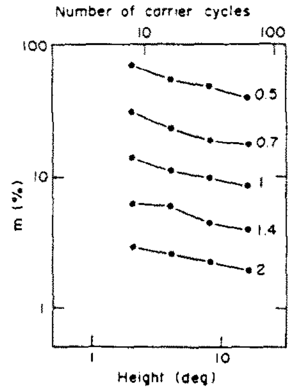

Fig. 6. (a) Dependence of AM-thresholds on the height (and the number of cycles) of the (horizontal) grating at an eccentricity of 12 deg. Carrier frequency $f_c = 4$ c/deg; modulation frequencies as indicated in the figure. Stimulus width was 2 deg. Subject L.K. The curve for $f_m = 0.5$ c/deg is plotted in its correct position. The others are shifted downwards progressively by factors of two.

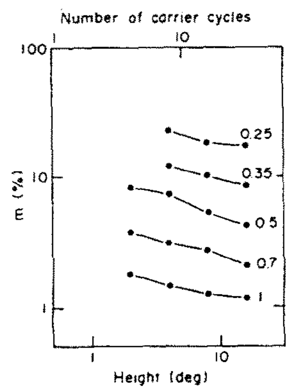

Fig. 6. (b) Dependence of FM-thresholds on the height (and the number of cycles) of the (horizontal) grating at an eccentricity of 18 deg. Carrier frequency $f_c = 2$ c/deg; modulation frequencies as indicated in the figure. Stimulus width was 4 deg. Subject L.K. The curve for $f_m = 0.25$ c/deg is plotted in its correct position. The others are shifted downwards progressively by factors of two.

thus on the number of cycles of the grating). Note that the curves marked with triangles and squares have been shifted downwards by factors of 2 and 4 respectively. The dashed lines indicate a slope of $-1/3.5$, corresponding to the probability summation exponent of 3.5 which Robson and Graham (1981) used to fit their results from similar experiments. Our results are in good agreement with those of Robson and Graham. Like them we find that the decrease of thresholds with increasing number of cycles continues over the full range of stimulus sizes (i.e. up to 64 cycles). Figure 6 shows the dependence of AM and FM thresholds on the height (and on the number of cycles) of the grating. (Note that most of the curves have been vertically displaced for clarity; see figure captions.) Again, thresholds continue to decrease up to the largest stimulus (64 cycles). The slopes of the curves in Fig. 6 are very similar to the slopes of the contrast threshold curves in Fig. 5. The slope of the best fitting straight lines through the curves in Fig. 6 range from $-1/5.4$ to $-1/2.9$, the average being $-1/4.1$.

DISCUSSION

The stimuli used in Experiment 1 were scaled for each eccentricity according to the cortical magnification factor (Fig. 2). This ensures that the number of stimulated ganglion cells, and the stimulated area of cortex, are about the same for all eccentricities. The scaling that was applied to the stimuli made the contrast sensitivity functions for different eccentricities absolutely comparable, both in shape and absolute height [Fig. 1(b)]. Despite this careful scaling procedure, the detectability of AM and FM is very much worse peripherally than it is centrally (Figs 3, 4). Apparently, although the peripheral visual system performs as well as the fovea in detecting contrast, it is much less able to use the information presented in a suprathreshold grating for comparing contrast or spatial frequency across retinal positions.

However, this result should be taken with some reserve. Stimulus presentation time is an important parameter in these experiments. We are currently examining the effect of presentation time on peripheral and foveal modulation thresholds. Preliminary observations with short presentation times (less than 1 sec) suggest that in this case peripheral and foveal modulation thresholds for scaled stimuli are much more similar than with the long presentation times used here. If these preliminary results would prove to be correct this would imply that after prolonged viewing some adaptation to the modulation occurs, which is stronger or faster for more peripheral locations in the visual field. Therefore the results presented here should be taken to apply to the case of long presentation times only.

The fact that similar contrast thresholds are found with scaled stimuli at different eccentricities suggests that a constant amount of spatial information necessary for contrast detection is transmitted and processed by the stimulated parts of the visual system. In contrast detection the relevant spatial information is information about the *presence* of spatial contrast. In modulation detection, however, the relevant spatial information is quantitative information about the *intensity of the contrast* (AM) or about the *spatial structure* (FM). These considerations lead us to the following conclusion: Information concerning the presence of spatial contrast is processed just as efficiently peripherally as it is foveally, information about either the local quality of the spatial structure (intensity of contrast; bar width/spatial frequency) or the local sign (position; phase), or both, is processed less efficiently (or, at least, is partially lost after prolonged viewing). Most of the experiments mentioned in the introduction in which peripheral vision is as good as foveal vision with appropriate scaling do not depend critically on accurate encoding of suprathreshold spatial information, but instead involve brightness or colour discrimination (see Westheimer, 1981, on this issue). When the task is purely spatial however (hyperacuity tasks, phase discrimination, AM-/FM-detection) the scaling principle breaks down. It should be noted that this conclusion was reached by Westheimer (1982) for hyperacuity and by Stephenson and Braddick (1982) for phase discrimination on the basis of results obtained with short presentation times.

The relative inability of the peripheral visual system to use supratheshold spatial information is very reminiscent of the situation found for foveal vision for some amblyopes, who exhibit a normal contrast sensitivity function, yet have seriously impaired suprathreshold vision (Hess, 1979, 1982). There is also some evidence that vernier acuity is worse than in normal foveal vision for both peripheral vision (Westheimer, 1982) and some instances of amblyopic vision (Levi and Klein, 1982). Further, phase discrimination is found to be relatively poor for both peripheral vision in normals (Stephenson and Braddick 1982) and for amblyopes (Pass and Levi, 1982, Lawden, 1982; Lawden *et al.*, 1982). These observations suggest that peripheral vision in normal eyes may be similar (at least in some respects) to foveal vision in certain amblyopic eyes. Hess (1982) discusses a possible relation between peripheral and amblyopic vision.

The results shown in Fig. 5 indicate that contrast thresholds in the periphery continue to decrease with increasing number of grating cycles up to as much as 64 cycles. Robson and Graham (1981) obtained the same result. They were able to show that their results for both fovea and periphery could be explained by probability summation over the full spatial extent of the stimulus, with a probability summation exponent of 3.5. According to them, the fact that in central vision contrast thresholds hardly decrease with increase in the number of cycles beyond about 10 cycles is a consequence of the decrease of contrast sensitivity towards the periphery. Our results confirm their conclusion.

The very good agreement between the slope of our summation results (slope in Fig. 5) and those of Robson and Graham is remarkable, since Robson and Graham used an average-luminance surround, whereas we used a dark surround. For foveal vision it is known that when the surround is dark, contrast thresholds depend more strongly on stimulus width and height than when the surround is matched to the stimulus (Howell and Hess, 1978; McCann and Hall, 1980).

AM- and FM-thresholds [Figs. 6(a) and (b)] show the same dependence on stimulus size as contrast thresholds (Fig. 5): they continue to decrease up to the largest sizes used [64 cycles in Fig. 6(a); 32 cycles in Fig. 6(b)]. Also, their rate of decrease is approximately the same as for contrast thresholds (slopes are about $-1/4.1$ in Fig. 6 and $-1/3.5$ in Fig. 5). This means that the threshold decrease for both contrast thresholds and modulation thresholds may be modelled as probability summation with an exponent of about 4.

In earlier experiments (Jamar and Koenderink, 1983) we have found that in central vision modulation thresholds decrease only for sizes corresponding to up to about 16 cycles. Since the situation is analogous to the situation for contrast thresholds, an explanation analogous to that of Robson and Graham may apply: the peripheral AM- and FM- results show that the visual system is able to use simultaneously ("sum") suprathreshold spatial information from a retinal area of at least 64 cycles. In central vision, only contrast detecting units within an area about 16 cycles wide around the fovea can contribute significantly to the summation mechanism because of the lower sensitivity of contrast detecting units outside the fovea.

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