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SPATIAL FREQUENCY TUNING STUDIES: WEIGHTING AS A PREREQUISITE FOR DESCRIBING PSYCHOMETRIC CURVES BY PROBABILITY SUMMATION

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Abstract—The visibility of sine-wave gratings was determined as a function of their width and modulation depth. The psychometric curves were described by probability summation, resulting in weighting functions which under certain conditions indicate the existence of tuning, i.e. a maximum sensitivity outside the fovea at an eccentricity inversely proportional to the spatial frequency. The disagreement in the literature about the existence of tuning can be understood in terms of our present findings.

INTRODUCTION

Bryngdahl (1966) found that the subjective modulation depth for visual stimuli has a maximum at a certain eccentricity (measured from the fovea) which is a function of the spatial frequency. This finding is in agreement with the assumption of "tuning" in the perception of visual stimuli. van Doorn *et al.* (1972) confirmed Bryngdahl's observations, on the basis of theoretical considerations using a scaling-ensemble formalism. van der Wildt *et al.* (1976) suggested that their results, obtained with a stimulus of increasing width, could be explained on the assumption that the most sensitive part of the retina for low spatial frequencies is not the fovea. However, measurements of the contrast sensitivity for small stimuli as a function of the eccentricity have not yet yielded definite proof of the existence of tuning (Hilz and Cavonius 1974; Koenderink *et al.*, 1978; Kroon *et al.*, 1980; Rovamo *et al.*, 1978; Rijsdijk *et al.*, 1980).

Evidence for the existence of tuning is only found for stimuli of a certain limited extent. van der Wildt *et al.* (1976) found that a statistical approach to the dependence of sensitivity on width does not give adequate agreement with experiment. They used probability summation, assuming a homogeneous retina. The purpose of the present study is to investigate whether the visibility of a grating as a function of the width can be described by probability summation, if a weighting function is used.

EQUIPMENT AND METHODS

Stimulus

The stimulus in all experiments was a one-dimensionally modulated sine-wave grating, with a height of 5° and a variable width. This pattern was generated on a picture monitor (Tektronix 632, with phosphor WA D6500). The surrounding field was rectangular, with a width of 20° and a height of 5°. A red fixation spot was presented in the centre of this field. The mean stimulus luminance was 10 cd/m^2, equal to the luminance of the surrounding field. The viewing distance was 85 cm. No artificial pupil was used. The measurements were carried out monocularly (right eye). A chin rest and a forehead rest were used.

The sine-wave signal was produced by a function generator (Wavetek 144), the gate input of which was controlled by a pulse generator (Datapulse 100A). The place of the stimulus on the screen could be adjusted with the aid of the pulse delay, and the pulse width determined the width of the stimulus. A whole number of sine-wave periods was displayed, starting at phase zero. The centre of the grating was always presented in the centre of the surrounding field. The contrast is given as the percentage modulation depth (M):

$$M = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} \times 100\%.$$

Experimental procedure

The visibility of the grating (defined as the percentage probability of seeing it) was determined by a two-alternative forced-choice procedure. During each run, two pairs of clicks could be heard. One of these pairs coincided with the beginning and end of the stimulus presentation time; the choice of which pair to use for this purpose was made at random. The subject was asked to indicate which of the two click pairs coincided with the presentation of the pattern. The visibility was determined from the percentage of correct responses.† Each session consisted of 20 runs, and was

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† The visibility (P_v) in percent can be derived from the percentage correct answers (P_c) as follows:

$$P_c = P_v + \tfrac{1}{2}(100 - P_v),$$

so:

$$P_v = 2P_c - 100.$$

When the percentage correct answers was below 50%, which results in a negative visibility, P_v was taken to be 0%.

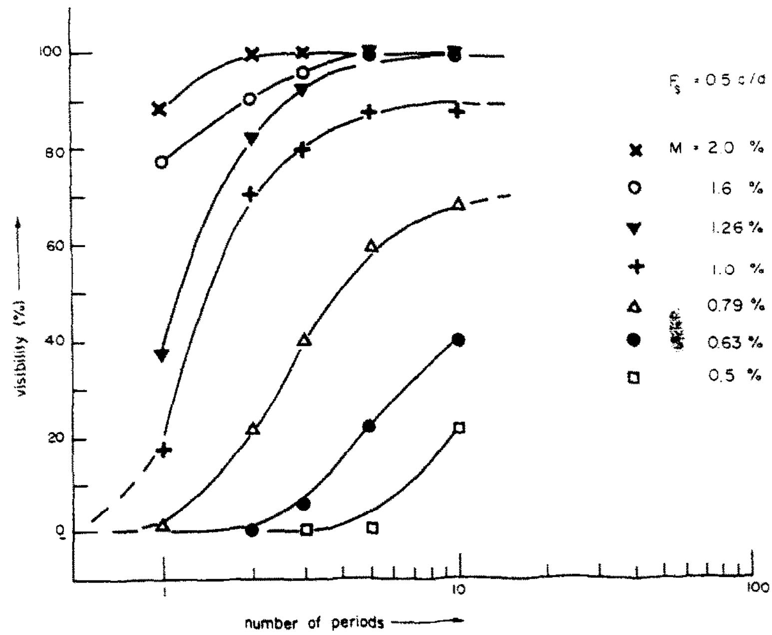

Fig. 1. The visibility of sine-wave gratings as a function of the number of periods. $F_s = 0.5$ c/deg. The lines are drawn by eye through the data.

repeated 4 times. The time interval between the clicks of each pair, and between pairs, was 1 sec.

RESULTS

We measured the visibility of sine-wave gratings as a function of the number of periods in the stimulus, with the modulation depth M as a parameter. Figures 1, 2 and 3 give the results for the spatial frequencies 0.5, 2 and 8 c/deg. The standard error varies from 2 to 12% with a mean of 5%.

DISCUSSION

The results obtained here with sine-wave gratings of increasing width show a monotonically increasing visibility for all modulation depths. We will first check whether the slopes of the curves of Figs 1, 2 and 3 are comparable to a first approximation with those one would expect if probability summation was operative. Our theoretical curves are based on equation (A1) (see Appendix). We thus start with the assumption that the retina is homogeneous, i.e. that the visibility of a stimulus of a given area is independent of

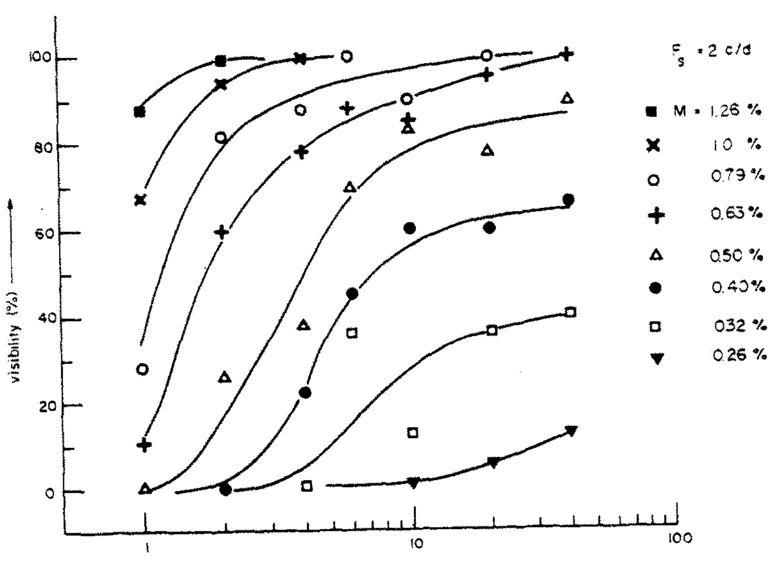

Fig. 2. The visibility of sine-wave gratings as a function of the number of periods. $F_s = 2$ c/deg. The lines are drawn by eye through the data.

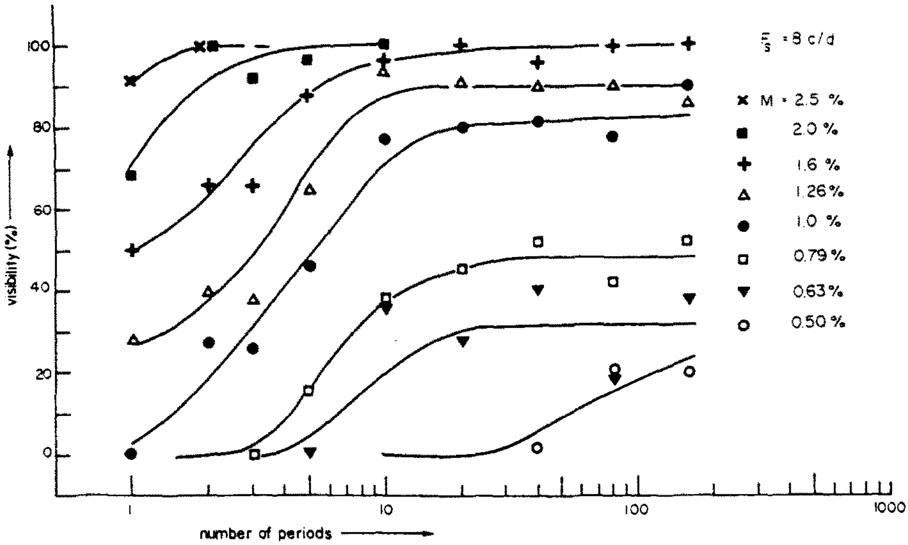

Fig. 3. The visibility of sine-wave gratings as a function of the number of periods. F_s = 8 c/deg. The lines are drawn by eye through the data.

the place of stimulation. The subfields are chosen so as to correspond to exactly one sine-wave period. As indicated in the Appendix, the same result could be obtained with other subfield dimensions and corresponding visibilities per subfield. For the spatial frequencies 0.5, 2 and 8 c/deg the subfields have a width of 2, 0.5 and 0.125° respectively, and a height of 5°. The visibility for one subfield, V^1, is consequently the visibility per sine-wave period. The curves of Fig. 2 for 2 c/deg are replotted in Fig. 4 together with some theoretical curves for different values of V^1.

Comparing the results of the measurements with the theoretical curves, we see that the agreement is not at all good. We will now investigate whether the measured data can be described by probability summation assuming a non-homogeneous retina, i.e. a visibility per period which is a function not only of the modulation depth, but also of the place of stimulation—which is more in agreement with the majority of the views expressed in the literature. For this purpose, we introduce a weighting function defined as the assumed visibility per period, V^1, as a function of the index figure of the period (expressed as the serial number of periods counting from the fixation point). To study the influence of a non-homogeneous retina, we plotted some theoretical

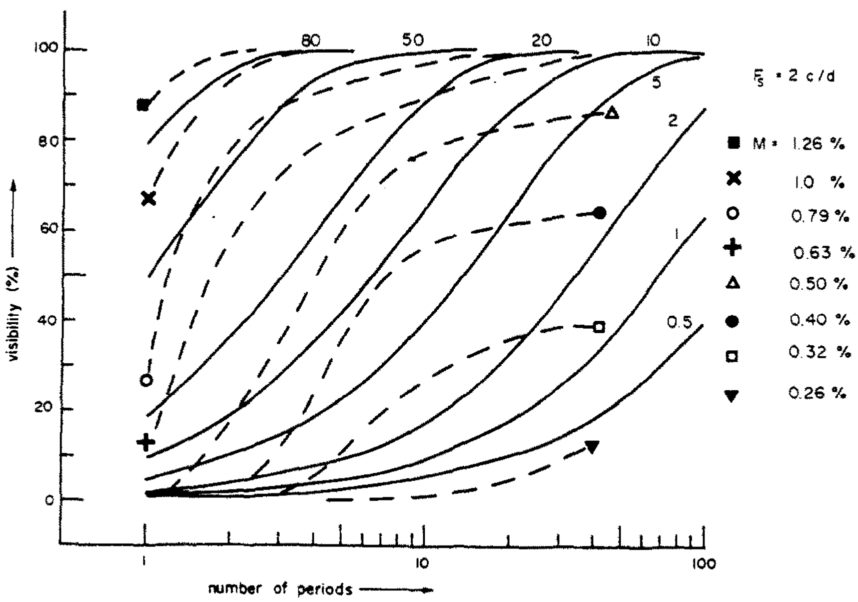

Fig. 4. The visibility of sine-wave gratings as a function of the number of periods. The lines are calculated by probability summation assuming a homogeneous retina. The parameter is the visibility per period (in percent). The broken lines are replotted from Fig. 2, and thus refer to a spatial frequency of 2 c/deg.

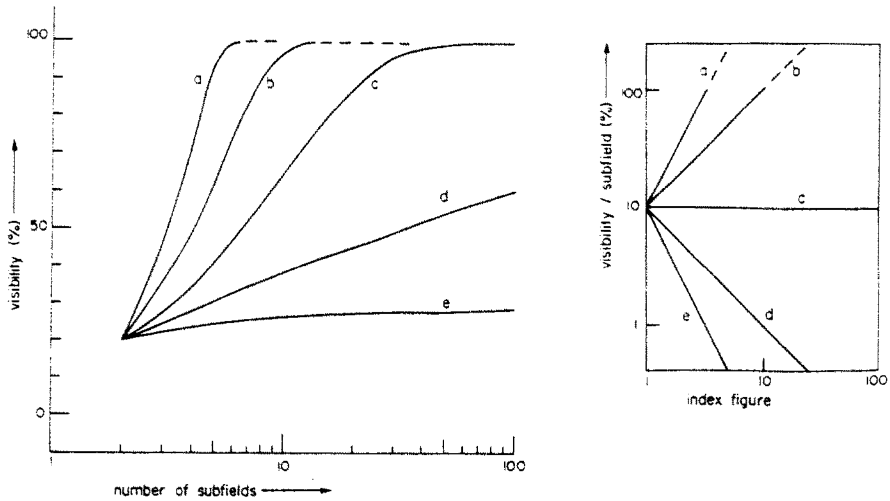

Fig. 5. The visibility as a function of the number of subfields, calculated by probability summation using different weighting functions as shown on the right. The visibility for the subfield with index figure 1 is in all cases equal to 10%.

visibility/stimulus width curves for various linear weighting functions, with the visibility both increasing and decreasing with eccentricity (see right-hand curves in Fig. 5). The results given in Fig. 5 are obtained with the aid of equation (A3) (see Appendix). For the sake of comparison, we also replotted a curve for a homogeneous retina from Fig. 4 (curve c in Fig. 5, corresponding to a horizontal weighting function).

It will be clear that a weighting function with a positive slope gives a steeper curve than those for a homogeneous retina. A weighting function with a negative slope, on the contrary, gives a flatter curve. This knowledge gives us an idea of the form of the weighting function needed for describing the measured data. In Fig. 4 we can see that the experimental curves for gratings consisting of a small amount of sine-wave periods are steeper than the curve for a homogeneous retina, i.e. the weighting function has a positive slope here. On the other hand, the curves for gratings with more than about 10 periods are flatter than the curve for a homogeneous retina. In this range, therefore the weighting function must have a negative slope.

Since the weighting function starts with a positive slope and ends with a negative one, the weighting function must have a maximum somewhere in between. To a first approximation, this maximum for a spatial frequency of 2 c/deg is found at a width of about 6 periods, i.e. about 3°. To determine the weighting functions more accurately, we use equation (A4) from the Appendix. Given the visibility of two sine-wave gratings with different widths, this equation determines the visibility of the periods that must be added to the narrower grating to get the wider. As a result of the experimental error, in some cases the visibility measured for a certain grating is less than that for a narrower one (see for instance the data in Fig. 2 for 6 and 10 periods, $M = 0.79\%$). Equation (A4) will then give a negative visibility for the periods concerned.

Although such negative visibilities could be explained e.g. as being due to inhibition, we will not pursue this subject because it is clear that in the present case this anomaly is simply caused by the experimental error. It may further be noted that a slight variation in the experimental data causes a much greater variation in visibility per period as determined by equation (A4). These two facts indicate the need to reduce the effect of the variation in the data before using them for determination of the weighting functions. By drawing smooth lines through the experimental points in Figs 1, 2 and 3, we are in fact performing a sort of variation reduction. We therefore do not use the experimental data for the calculations of the period visibilities, but the corresponding values as indicated by the smooth lines. The resulting visibilities per period of the sine-wave grating as a function of the index figure of the period are given in Figs 6, 7 and 8 for 0.5, 2 and 8 c/deg respectively.

It is striking that most of the weighting functions found show a maximum outside the fovea. No maximum is found in the upper curves, i.e. for a relatively large modulation depth. The results of Figs 6, 7 and 8 can be used to estimate the sensitivity per period of the sine-wave grating as a function of the eccentricity. The sensitivity is defined as the inverse of the modulation depth at threshold, the threshold generally being defined as the condition under which there is a 50% chance of seeing the pattern. The sensitivity per period of the sine-wave grating as a function of the eccentricity was determined by Kroon *et al.* (1980). They found that the sensitivity was sometimes initially constant, and then decreased monotonically with eccentricity. By determining the 50% visibility point in the curves of Figs 6, 7 and 8 we can obtain a measure of the sensitivity for a single period of the

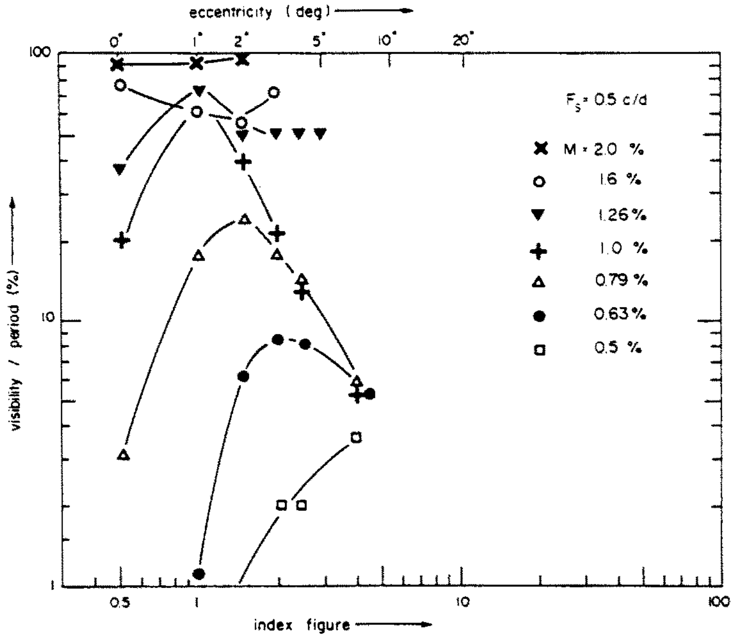

Fig. 6. The visibility per period as a function of the index figure of the period, derived from Fig. 1. The visibility for a grating consisting of one period is given the index figure 0.5 by definition (see Appendix). $F_s = 0.5$ c/deg.

sine-wave grating, as a function of the index figure of the period. The relation between this index figure and the eccentricity can be written as follows:

eccentricity = (index figure $- \frac{1}{2}$) × period width (1)

(since we generally measure the eccentricity at the centre of a period). Inspection of Figs 6, 7 and 8 shows clearly that at higher visibilities the weighting functions are nearly flat for the index figures under 2. This means that the sensitivity is nearly constant up to eccentricities of 3, 0.75 and 0.2° for spatial frequencies of 0.5, 2 and 8 c/deg respectively. Kroon *et al.* (1980) also found a nearly constant sensitivity for these small eccentricities. van der Wildt *et al.* (1976) likewise observed such a homogeneous central part of the retina, but only for a spatial frequency of 16 c/deg. The discrepancy between their results and the present ones can be explained by the different stimulus sur-

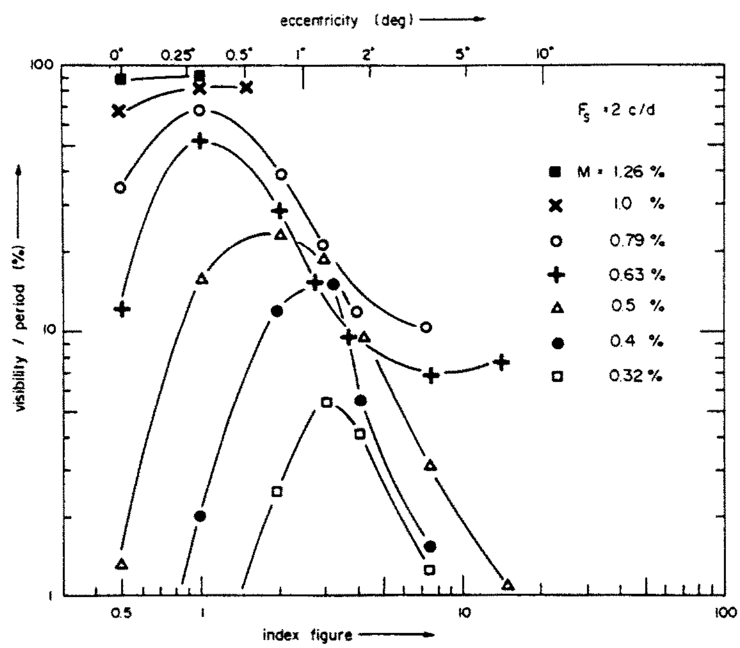

Fig. 7. The visibility per period as a function of the index figure of the period, derived from Fig. 2. $F_s = 2$ c/deg.

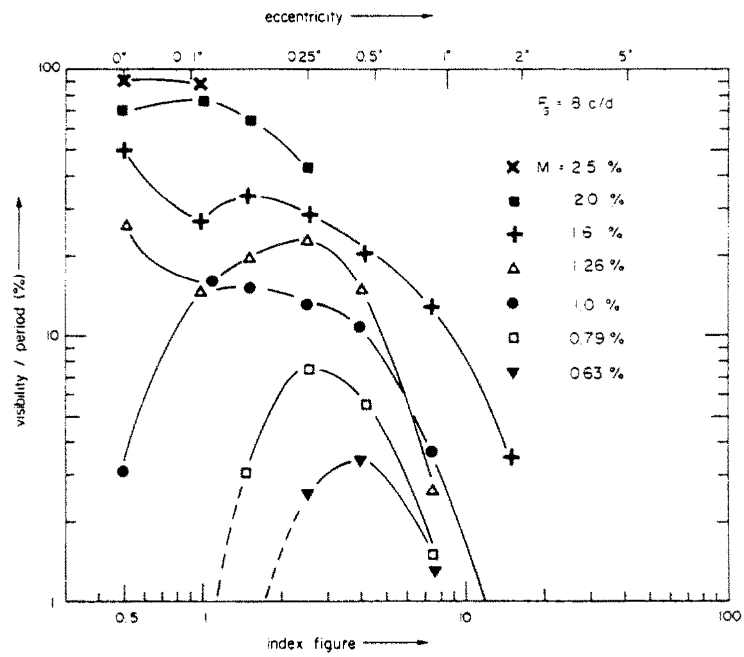

Fig. 8. The visibility per period as a function of the index figure of the period, derived from Fig. 3. F_s = 8 c/deg.

rounds. They used a dark surround, while in the present experiments the surround luminance was equal to the mean stimulus luminance. McCann *et al.* (1978) observed that with small stimuli the sensitivity could changed by a factor 6 when the surround luminance was varied.

By determining the 50% visibility threshold from our results, we obtain the sensitivity as a function of the width. This function is plotted in Fig. 9 together with the results of van der Wildt *et al.* (1976) for the same spatial frequencies.

It is obvious that the surround luminance has a

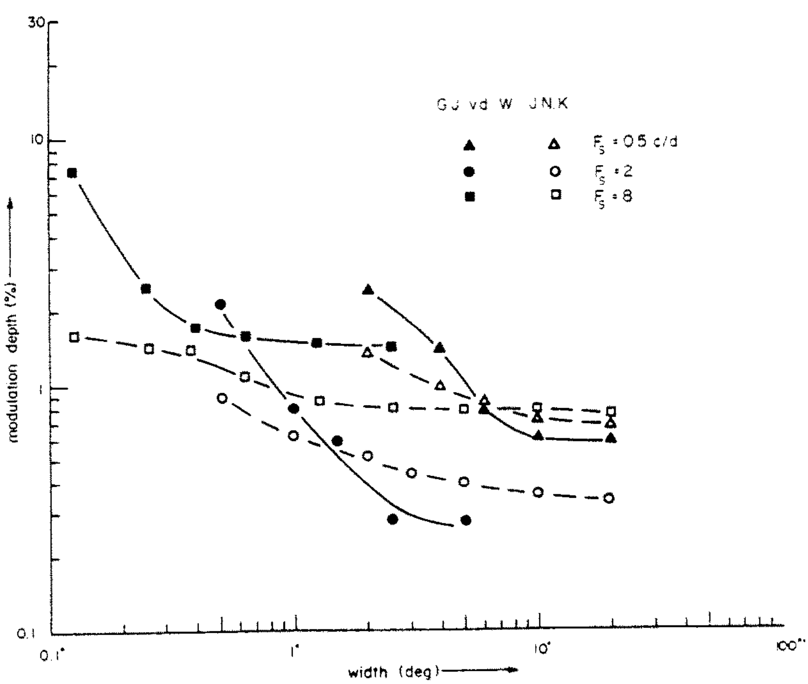

Fig. 9. The modulation depth at threshold (50% visibility) as a function of the width of a sine-wave grating. The solid symbols represent the results of van der Wildt *et al.* (1976), obtained with a dark surround. The open symbols represent our own data, obtained with a surround luminance equal to the mean stimulus luminance.

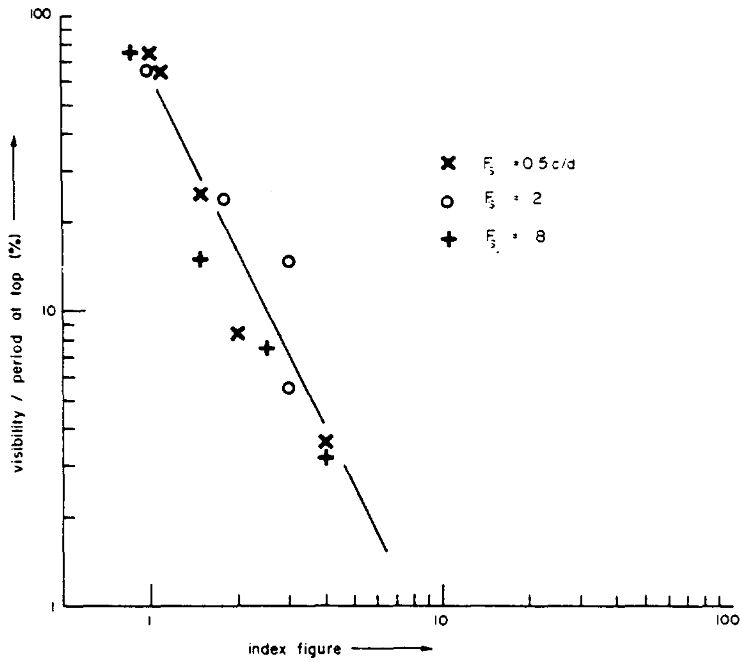

Fig. 10. The height of the maximum of the curves of Figs 6, 7 and 8 as a function of the position of the maximum. The line has a slope of −2.

great influence on the measurement of the sensitivity as a function of the width. Especially the parts of the curves corresponding to a small number of periods show very different slopes, resulting in large differences in approximate weighting functions (the absolute difference between the data can be neglected, because they were obtained with different subjects). The weighting functions of Figs 6, 7 and 8 can be characterized by their form, and the height and place of the possible maximum. The maximum height of each curve is plotted as a function of its position in Fig. 10.

For all three spatial frequencies investigated, the height-place relation for the maxima can be described by one single straight line (when plotted on a log–log scale). Since the position of the maxima, expressed as the index figure only depends on their height, the position of the maxima as a function of the eccentricity for a given height is roughly inversely proportional to the spatial frequency. This indicates the existence of "tuning", i.e. a maximum in the sensitivity outside the fovea, whose position depends on the spatial frequency. Our weighting functions, however, only show evidence of tuning at lower modulation depths. The sensitivity as a function of the eccentricity should therefore only show a maximum outside the fovea when a lower visibility is used as threshold criterion, e.g. 10–30%. To our knowledge, such measurements have never been carried out. The slope of the common line of Fig. 10 is −2, equal to the slopes of the trailing edge of the weighting functions. This fact led us to consider whether is was possible to describe the measured psychometric curves in terms of simple weighting functions consisting of various straight lines as leading edge, and a common trailing edge. On the basis of the data of Figs 6, 7 and 8, we determined the weighting functions consisting of at most three straight lines, viz. one with a slope of +2, one horizontal line (if applicable) and one with a slope of −2, which gave the best fit with the experimental data using equation (A3). The weighting functions found in this way are shown in Figs 11a, 12a and 13a, while the resulting theoretical psychometric curves are plotted together with the measured data in Figs 11b, 12b and 13b.

CONCLUSION

Inspection of Figs 11, 12 and 13 shows that the measured psychometric curves can be described very well by probability summation, assuming a non-homogeneous retina. The weighting functions required for this purpose can be described by a relatively simple model, and are basically the same for all three spatial frequencies. They show a common trailing edge, with only one exception for 8 c/deg, $M = 0.79\%$. In that case the weighting function with the broken line (Fig. 13a) gives a significantly better fit. The common trailing edge has almost the same position for all three spatial frequencies. The weighting functions have the property that the maximum visibility is reached outside the fovea, at lower modulation depths. This finding seems to clear up the disagreement in the literature about the existence of tuning. The investigators who found that tuning exists did so on the basis of threshold measurements with fairly large gratings which permit the use of relatively low threshold values. This corresponds to our finding

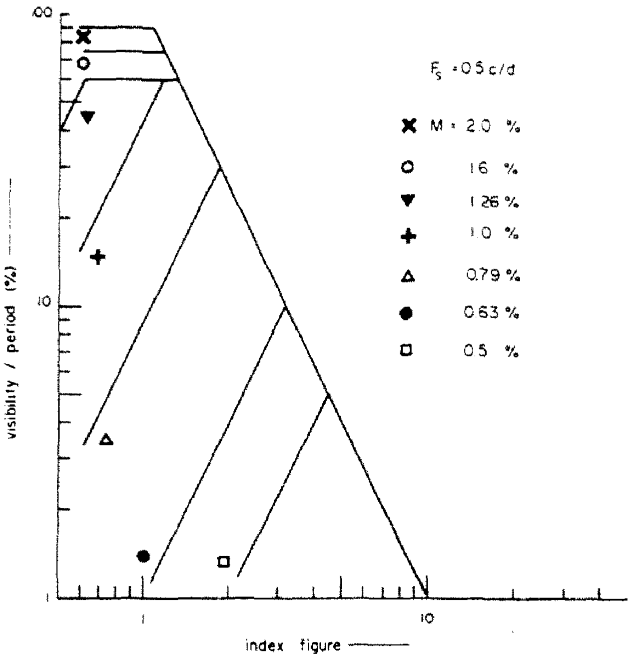

Fig. 11a. The weighting functions used to determine the psychometric curves for $F_s = 0.5$ c/deg of Fig. 11b.

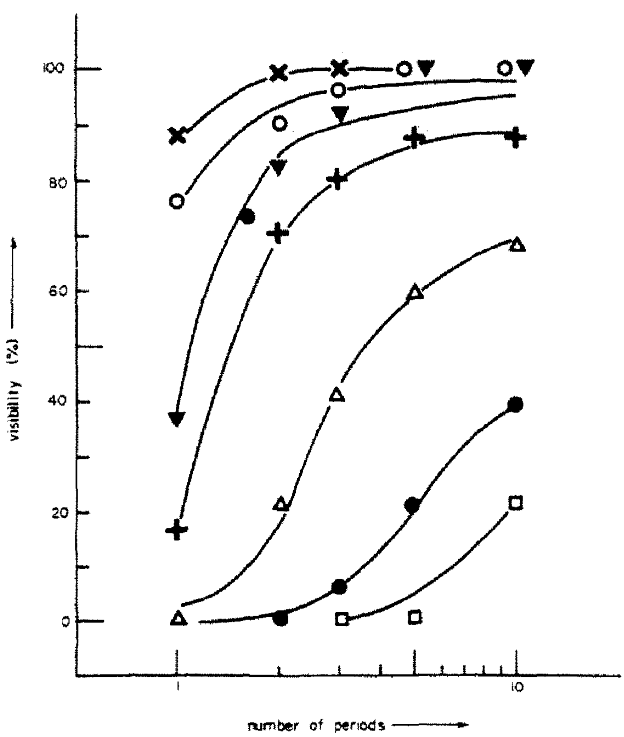

Fig. 11b. The psychometric curves for $F_s = 0.5$ c/deg calculated according to equation (A3) and the corresponding weighting functions of Fig. 11a. The experimental points are replotted from Fig. 1.

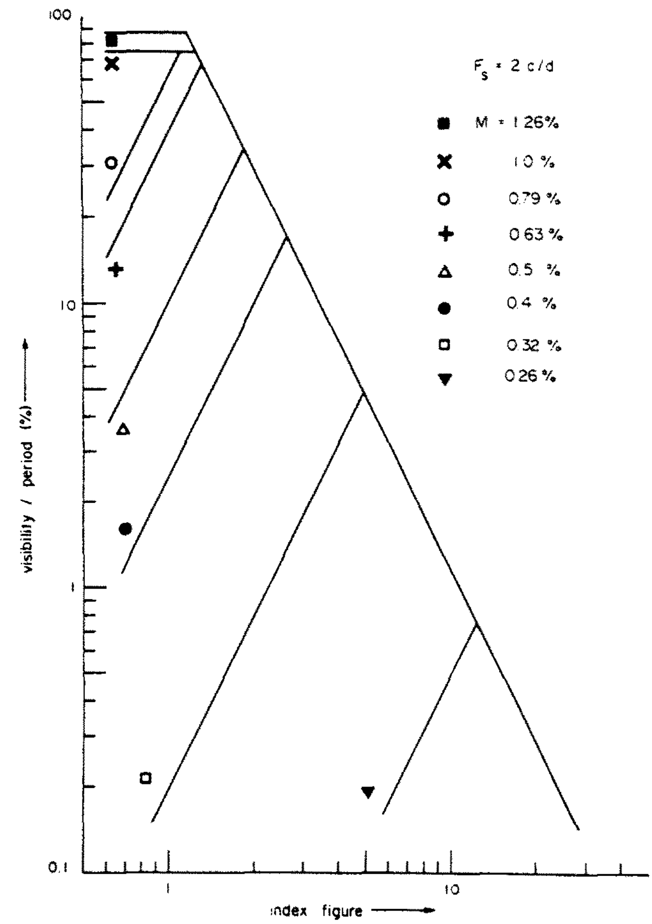

Fig. 12a. The weighting functions used to determine the psychometric curves for $F_s = 2$ c/deg of Fig. 12b.

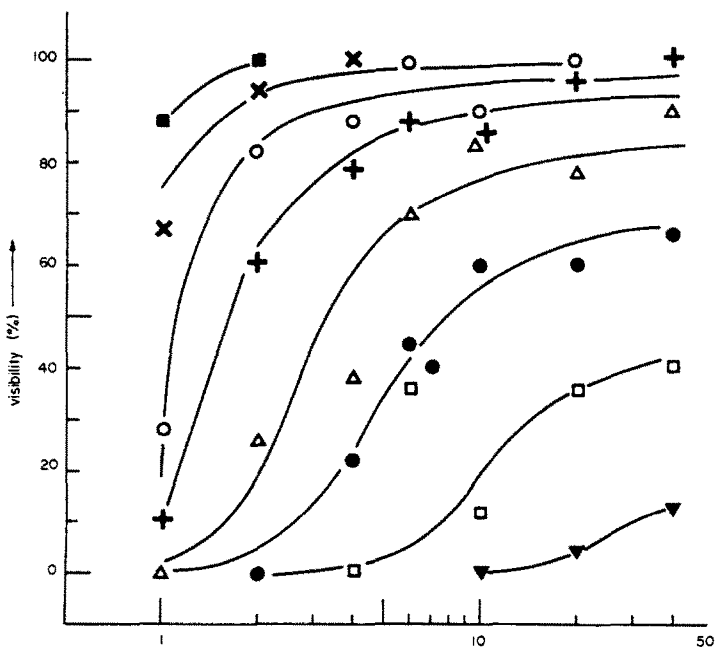

Fig. 12b. The psychometric curves for $F_s = 2$ c/deg calculated according to equation (A3) and the corresponding weighting functions of Fig. 12a. The experimental points are replotted from Fig. 2.

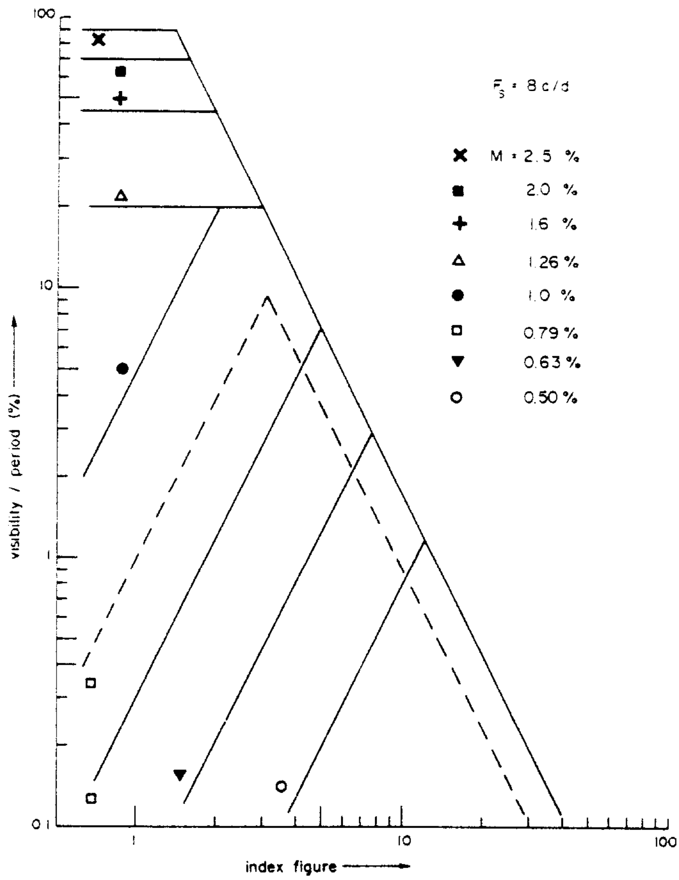

Fig. 13a. The weighting functions used to determine the psychometric curves for $F_s = 8$ c/deg of Fig. 13b.

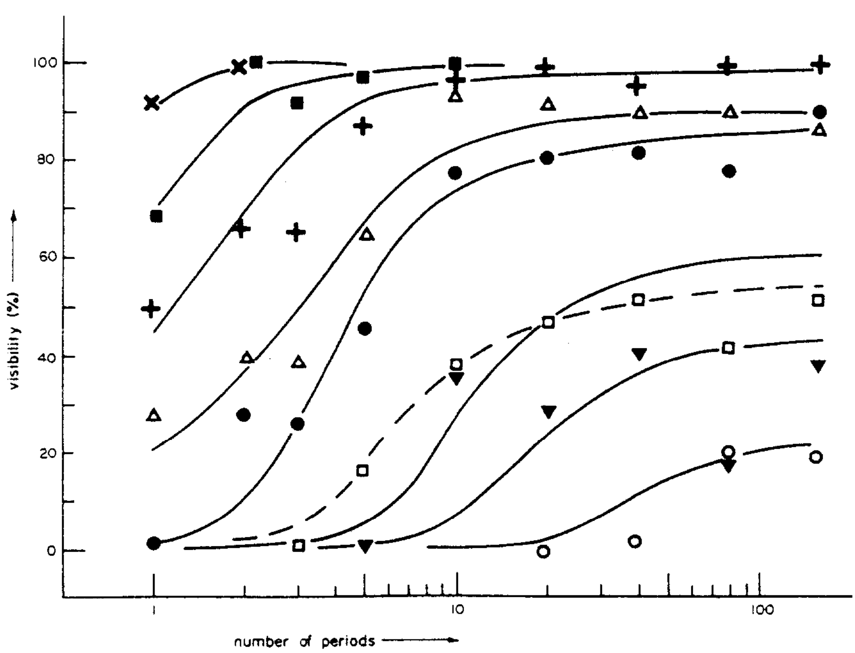

Fig. 13b. The psychometric curves for $F_s = 8$ c/deg. calculated according to equation (A3) and the corresponding weighting functions of Fig. 13a. The experimental points are replotted from Fig. 3.

that a weighting function with a maximum outside the fovea only exists for relatively low modulation depths. Attempts to detect tuning with small stimuli are frustrated by the fact that the modulation depth at threshold is relatively high in this situation. The question remains why tuning only occurs at lower modulation depths. And this leads to the question: what causes the tuning? Is the need of a fairly large grating the origin of the existence of tuning, e.g. owing to interaction between the sine-wave periods presented, or is it the result of it? In the latter case the explanation must be sought in a modulation-depth-dependent retinal detection system.

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APPENDIX PROBABILITY SUMMATION

For the purposes of probability summation, we divide the visual field into equal subfields of small width and extending over the total height of the grating. A visibility, expressed as the percentage chance of seeing the stimulus, is assigned to each subfield. The visibility V_n for a combination of n subfields, each having the same visibility V^1, is given by:

$$V_n = 1 - (1 - V^1)^n \tag{A1}$$

The visibility V_p for p combinations of m subfields, each having the same visibility V_m, is given by:

$$V_p = 1 - (1 - V_m)^p \tag{A2}$$

Comparison of equations (A1) and (A2) shows that we do not need to know the exact number of subfields for computation, but only the ratio between the numbers. We can therefore replace the number of subfields n by a variable proportional to n, e.g. the width in degrees or the number of sine-wave periods. If the theoretical and experimental results are plotted on the same scales, while the horizontal one is logarithmic, the figures can be compared by shifting them horizontally.

So far we have assumed that all subfields have the same visibility. However, we can also compute the total visibility of a number of subfields with different visibilities:

$$V_n = 1 - \prod_{i=1}^{n/2} (1 - V_i^1)^2 \tag{A3}$$

where n is the (even) number of subfields, V_n the total visibility, and V_i^1 the visibility of the subfield with index figure i. We introduce the weighting function as the relation between the visibility of the subfields and the index figure, counted from the fixation point to the right or to the left. The retina is supposed to be symmetrical round the fovea. The numbers 2 in equation (A3) and also in the following equation (A4) are the result of the fact that the field of vision extends in both directions from the fixation point. Because application of equation (A3) and (A4) gives problems for V_1, the visibility for one subfield, we use $V_1 = V_{\frac{1}{2}}^1$ by definition. Equation (A3) enables us, by assuming a certain weighting function, to determine the visibility as a function of the amount of subfields. It is also possible to work the other way round. Given the visibility as a function of the width, we can determine the visibility of successive subfields from:

$$V_i^1 = 1 - \exp\left[\frac{\ln(1 - V_n) - \ln(1 - V_m)}{2(n - m)}\right] \quad \text{for} \quad i = (m + 1)/2 \text{ to } n/2. \tag{A4}$$

In this case the visibility for m and for n subfields is given ($m < n$). Equation (A4) determines the mean visibility for the subfields with index figures ranging from $(m + 1)/2$ to $n/2$.