Perception: Psychophysics and Modeling

05 | Spatial Vision I

Felix Wichmann

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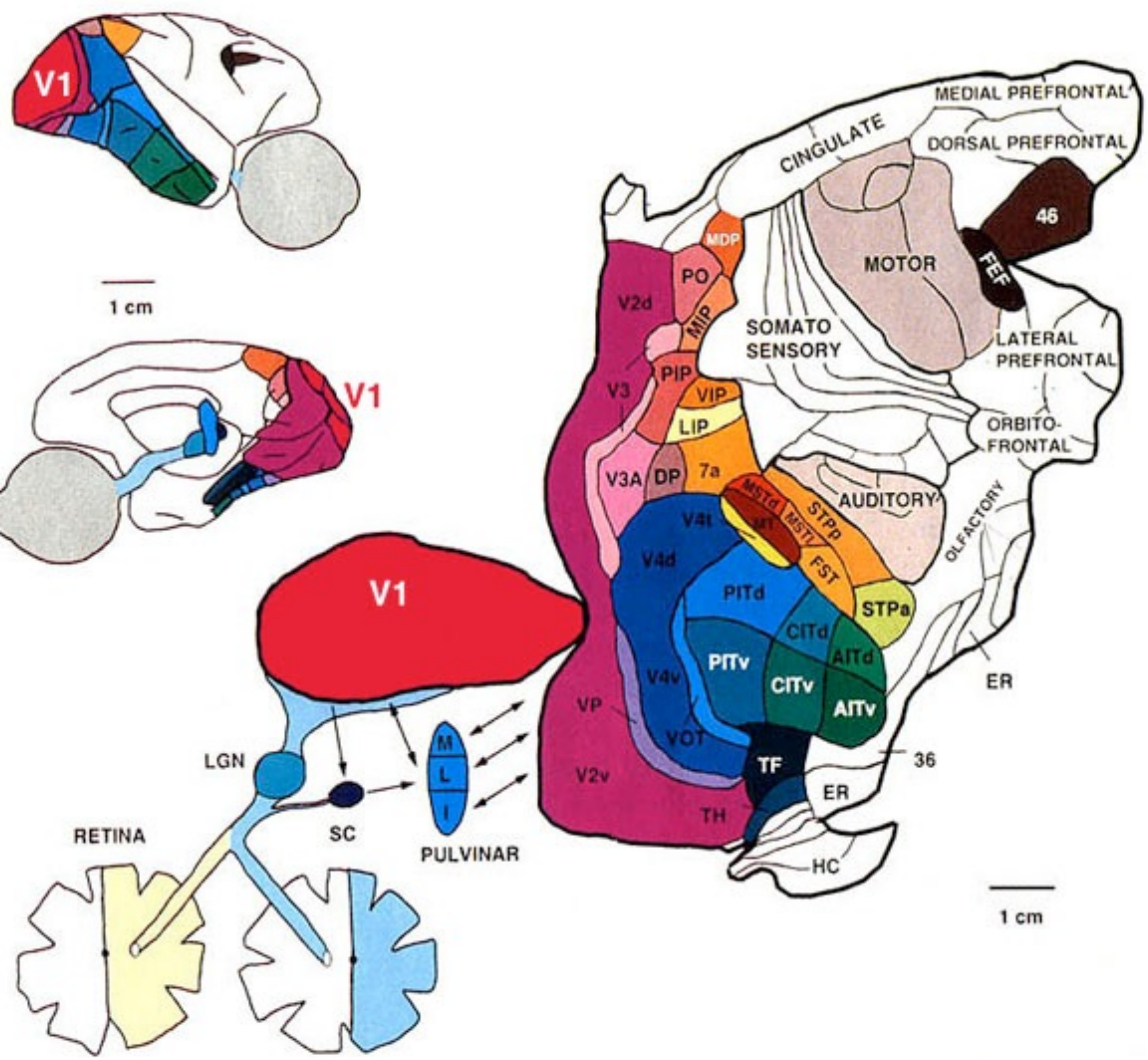
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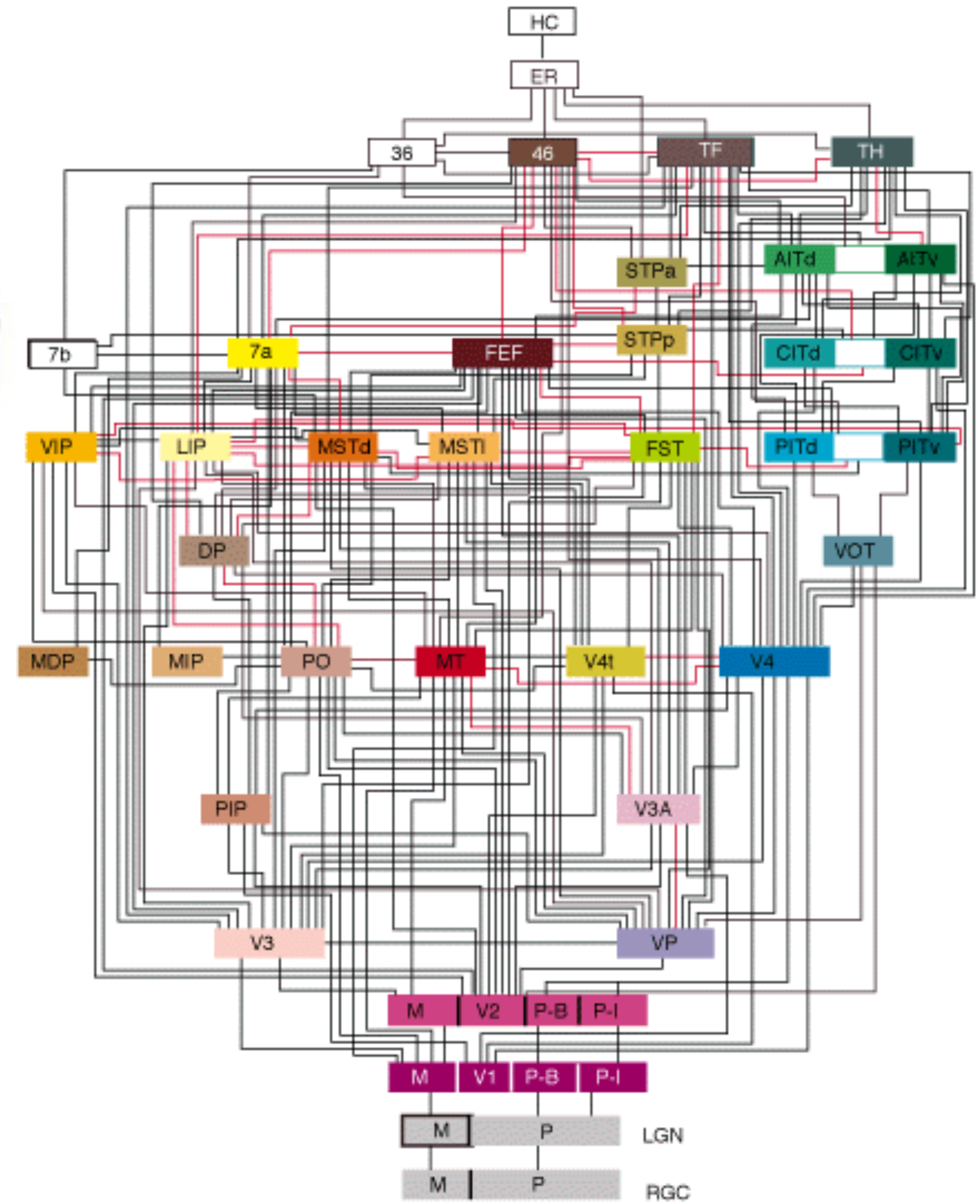
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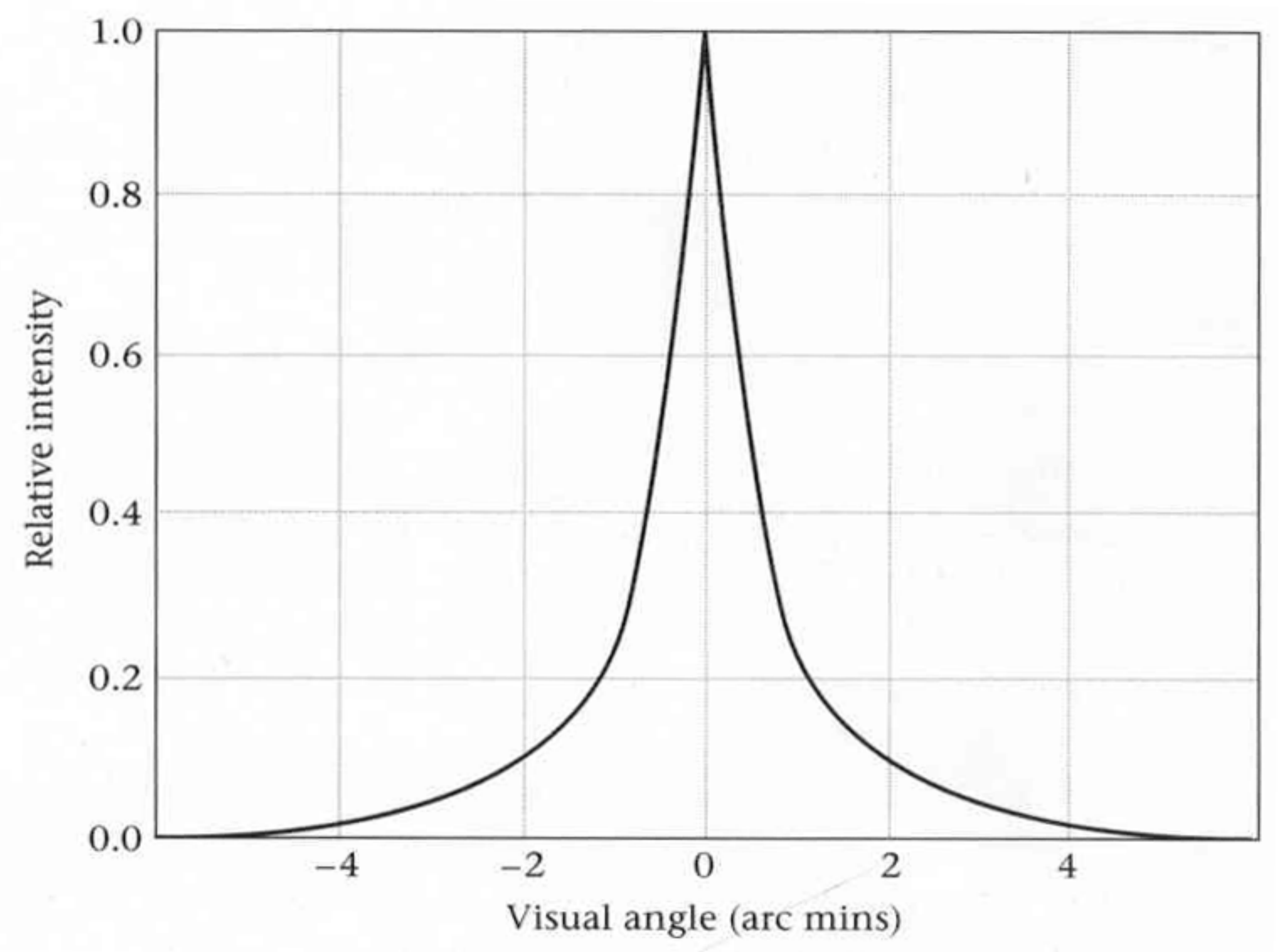
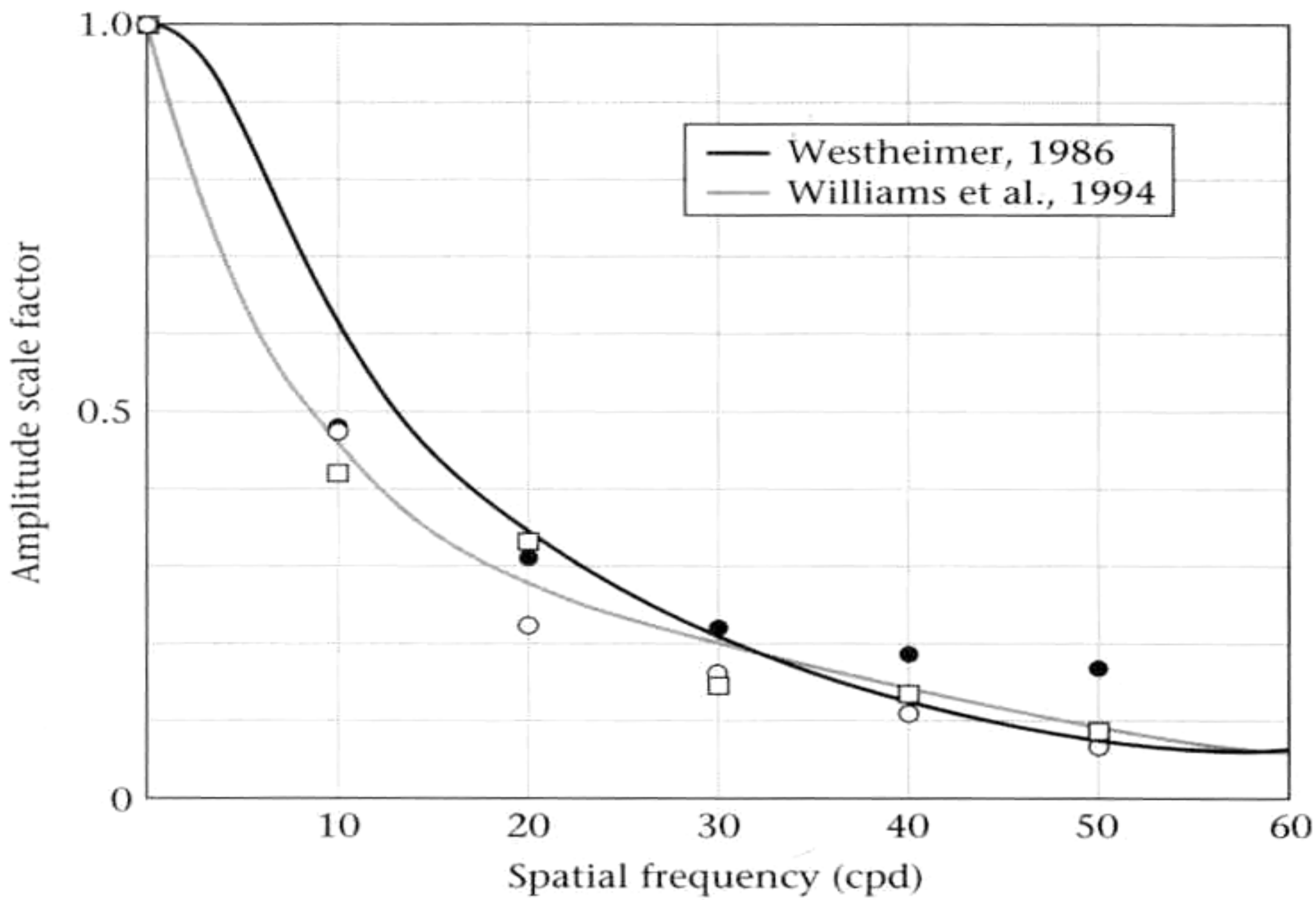
Human LSF



Modern measurement by Westheimer (1986)

Modulation Transfer Function (MTF)



Fourier Theory reminder

Joseph Fourier (1768–1830) developed another useful tool for analyzing signals, the Fourier analysis: A mathematical procedure by which any signal can be separated into component sine waves at different frequencies; combining these component sine waves will reproduce the original signal.

Sine waves from a basis for (practically) any signal: Thus we can re-describe any signal—be it a sound, or an image—as the linear superposition of many sine waves.

Properties of sine waves
Period or wavelength: The time or space required for one cycle of a repeating waveform.
Phase: In vision, the relative position of a grating; in hearing, the relative timing.
Amplitude: The height of a sine wave, from peak to trough, indicating the amount of energy in the signal (corresponding to contrast in vision, loudness in hearing).

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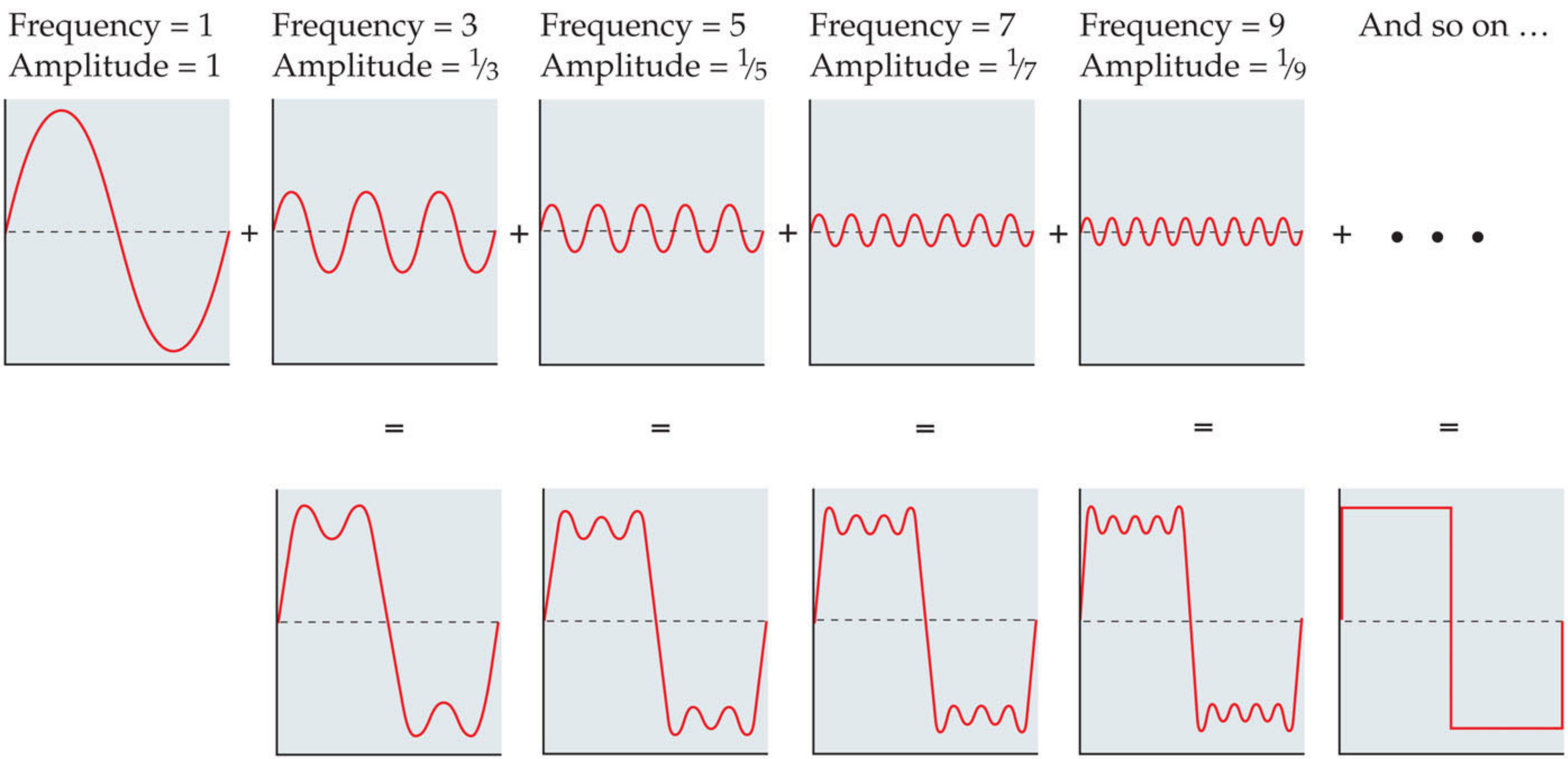
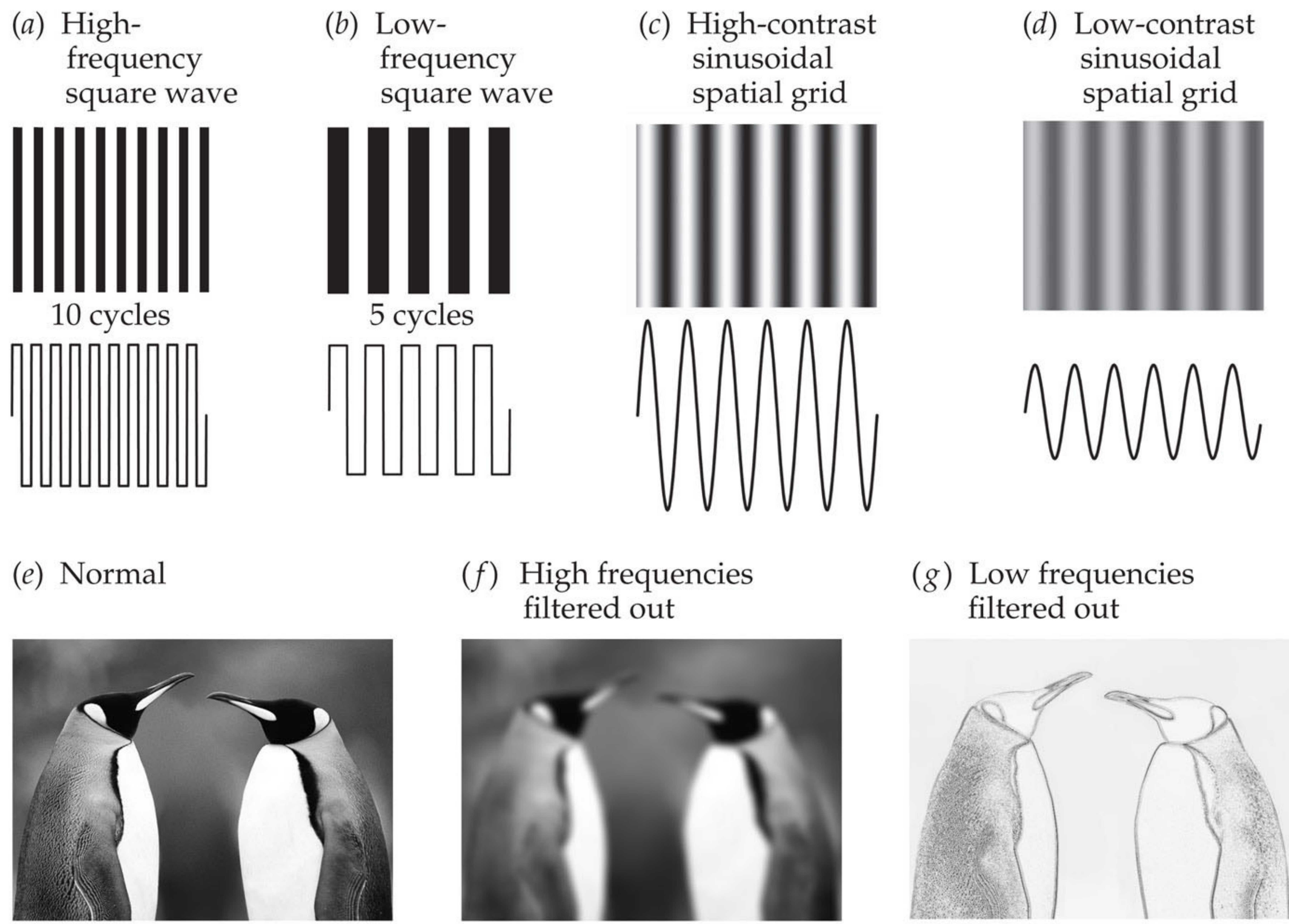
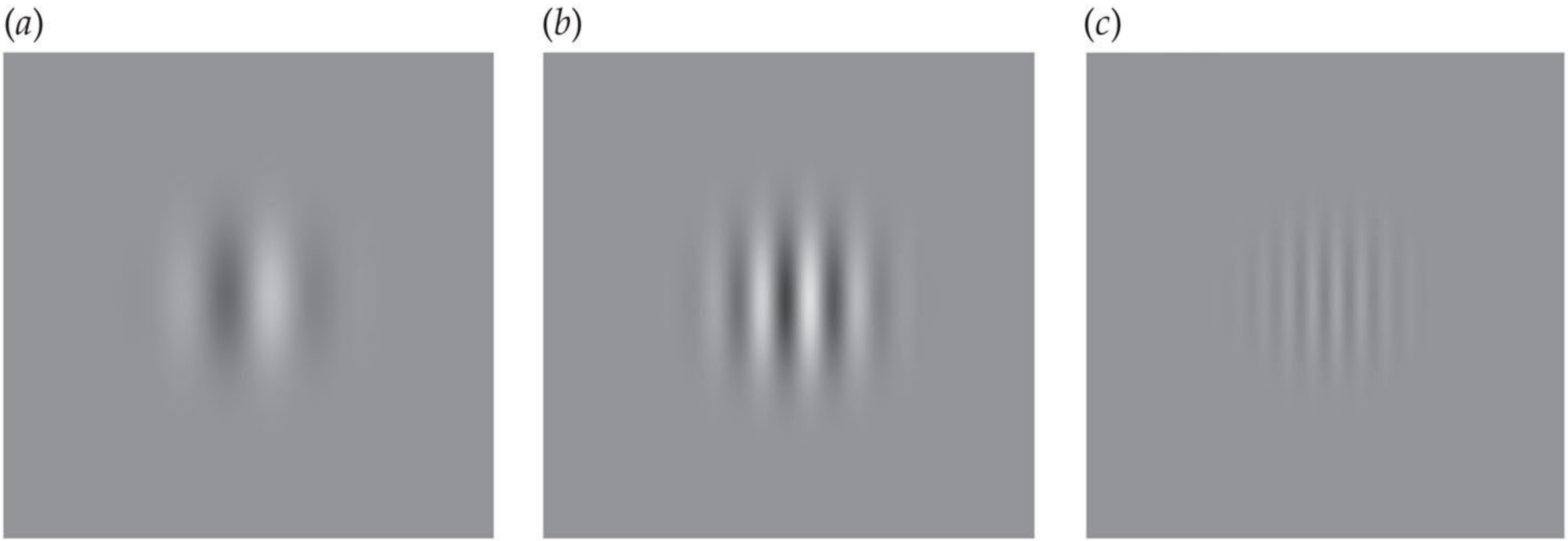


SENSATION & PERCEPTION 4e, **Figure 1.17**



***SENSATION & PERCEPTION 4e,* Figure 1.18**

Spatial frequency



SENSATION & PERCEPTION 4e, **Figure 3.6**

J. Physiol. (1966), **187**, *pp.* 517–552
With 17 *text-figures*
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THE CONTRAST SENSITIVITY OF RETINAL GANGLION CELLS OF THE CAT

By CHRISTINA ENROTH-CUGELL and J. G. ROBSON*
From the Biomedical Engineering Center, Technological Institute, Northwestern University, Evanston, Illinois, U.S.A.† *and the Department of Physiology, Northwestern University Medical School, Chicago, U.S.A.*

(*Received* 19 *April* 1966)

SUMMARY

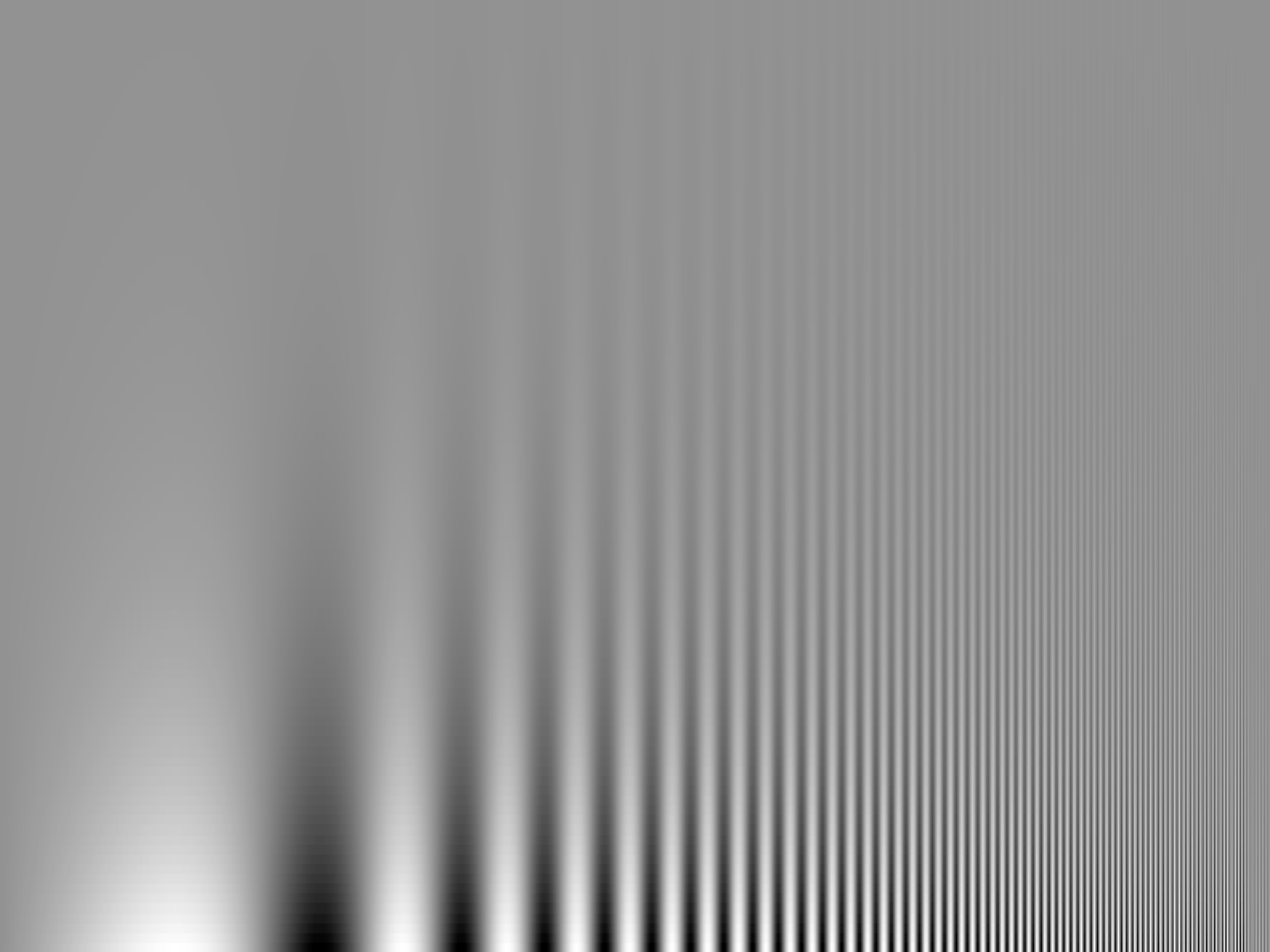
1. Spatial summation within cat retinal receptive fields was studied by recording from optic-tract fibres the responses of ganglion cells to grating patterns whose luminance perpendicular to the bars varied sinusoidally about the mean level.

2. Summation over the receptive fields of some cells (X-cells) was found to be approximately linear, while for other cells (Y-cells) summation was very non-linear.

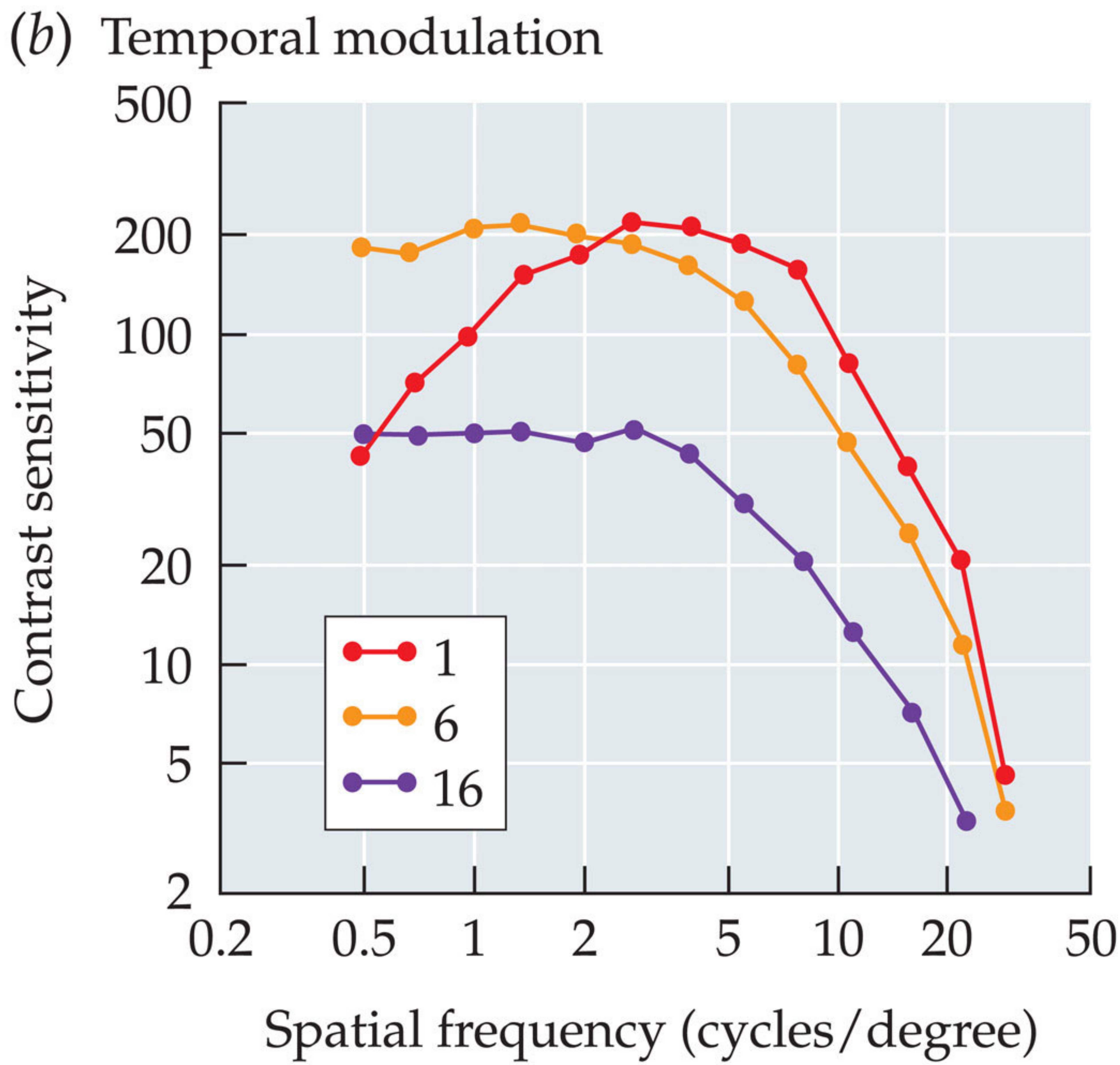
3. The mean discharge frequency of Y-cells (unlike that of X-cells) was greatly increased when grating patterns drifted across their receptive fields.

4. In twenty-one X-cells the relation between the contrast and spatial frequency of drifting sinusoidal gratings which evoked the same small response was measured. In every case it was found that the reciprocal of this relation, the contrast sensitivity function, could be satisfactorily described by the difference of two Gaussian functions.

5. This finding supports the hypothesis that the sensitivities of the antagonistic centre and surround summating regions of ganglion cell receptive fields fall off as Gaussian functions of the distance from the field centre.

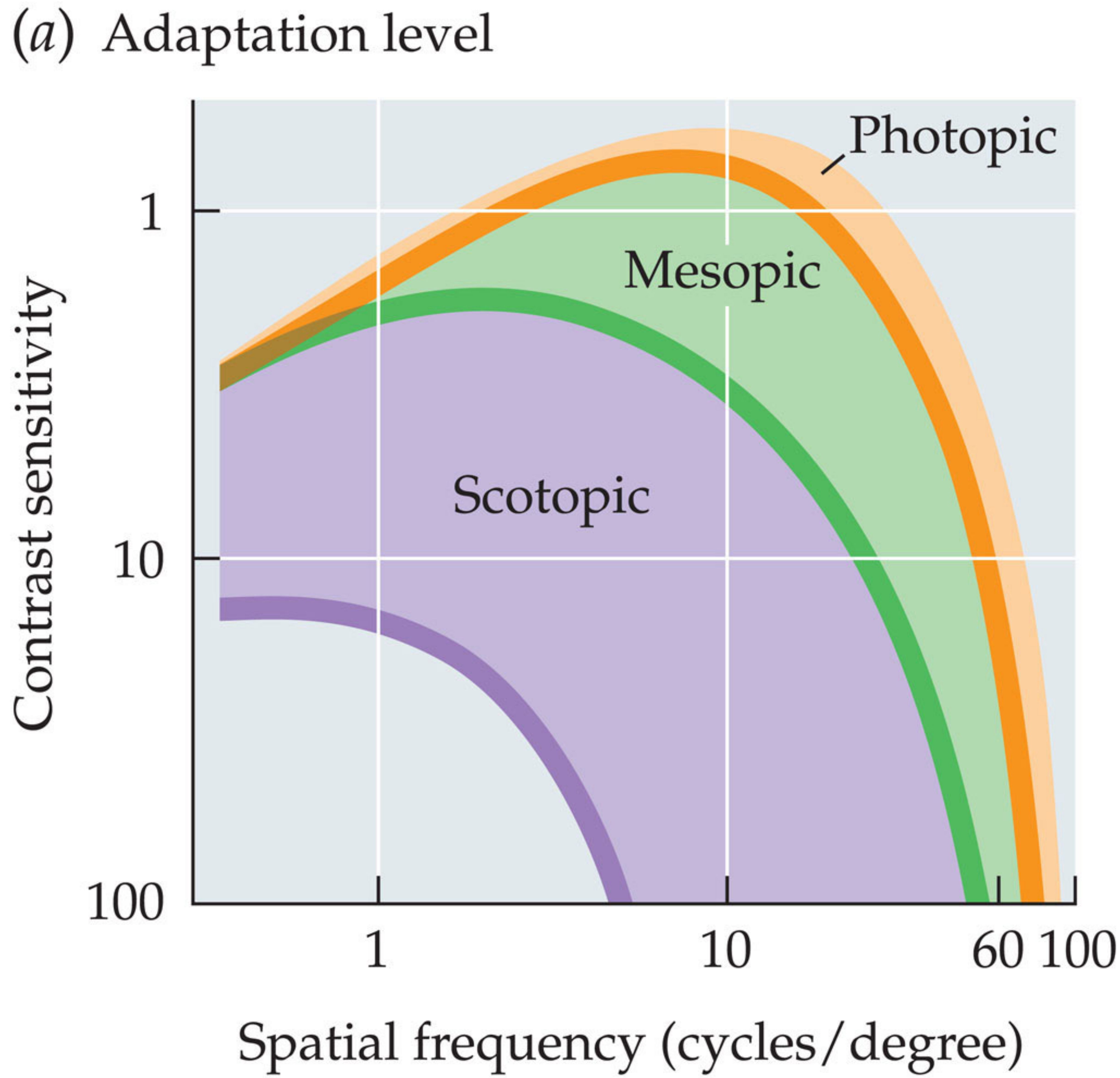


The CSF depends on many factors ... e.g. on temporal frequency



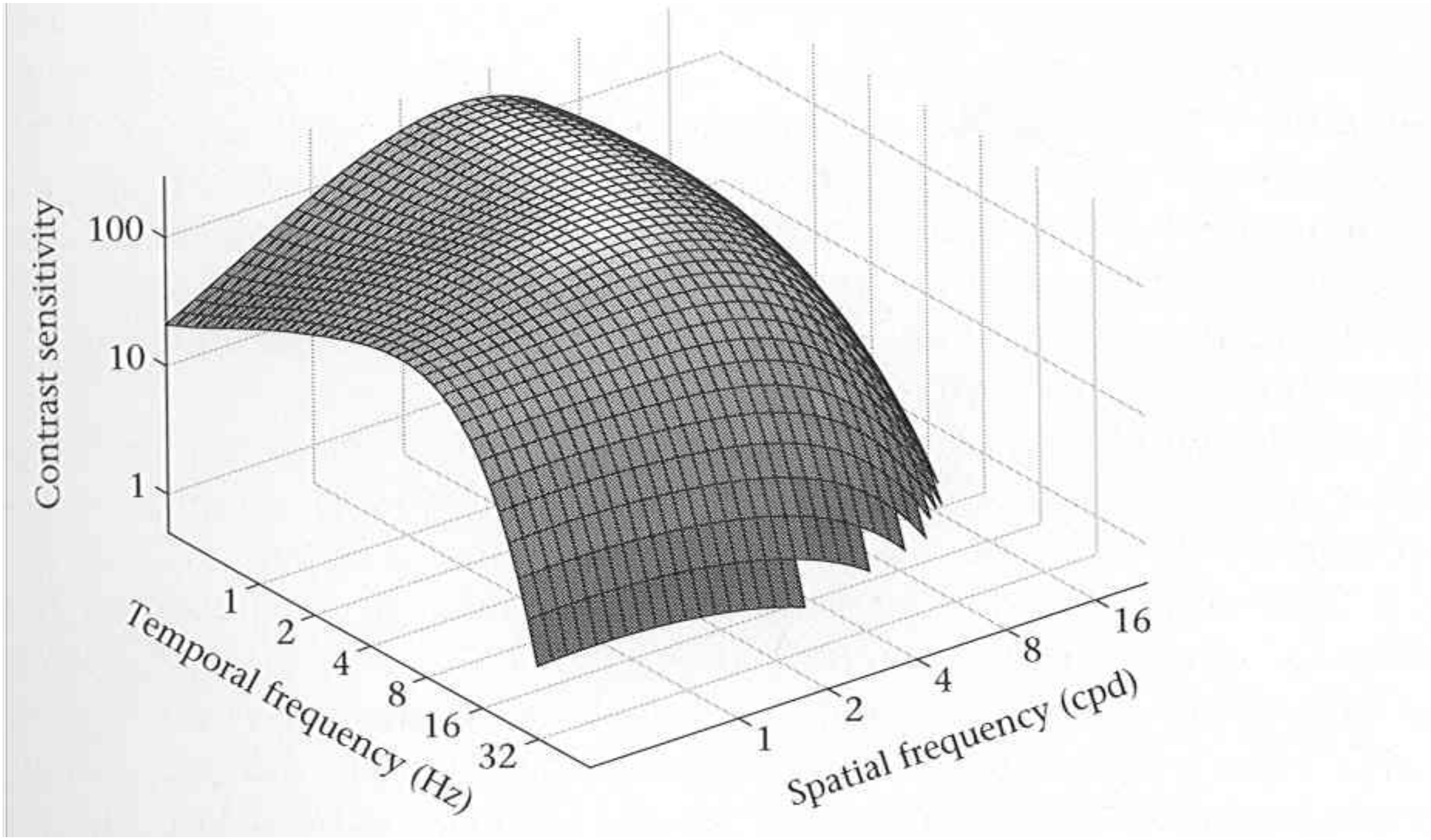
SENSATION & PERCEPTION 4e, **Figure 3.9 (Part 2)**

The CSF depends on many factors … e.g. on state of adaptation/light level



SENSATION & PERCEPTION 4e, **Figure 3.9 (Part 1)**

The CSF surface



This should allow us to predict the detectability of *any* stimulus—and for a wide variety of stimuli this is true!

J. Physiol. (1968), **197**, *pp.* 551–566
With 7 text-figures
Printed in Great Britain

APPLICATION OF FOURIER ANALYSIS TO THE VISIBILITY OF GRATINGS

BY F. W. CAMPBELL AND J. G. ROBSON
From the Physiological Laboratory, University of Cambridge

(*Received* 10 *November* 1967)

The advent of modern spatial vision

All visual stimuli can be represented by the sum of (infinitely many) sinusoidal gratings of different frequency, orientation, phase and amplitude

If the visual system was an (approximately) shift-invariant linear system (SILS), then its response to any stimulus can be predicted from its response to sinusoidal gratings, because they are the eigenfunctions of a SILS

Visual stimuli might thus be beneficially thought of in the Fourier domain, i.e. to predict visibility of a stimulus we consider its Fourier spectrum rather than its pixel values (as sinusoids are "impulses" in the Fourier domain).

Campbell&Robson (1968) first realized and tested this: the Fourier Series expansion of a square-wave grating and the ominous number $4/\pi$

Michelson Contrast (... useful mainly for Periodic Patterns ...)

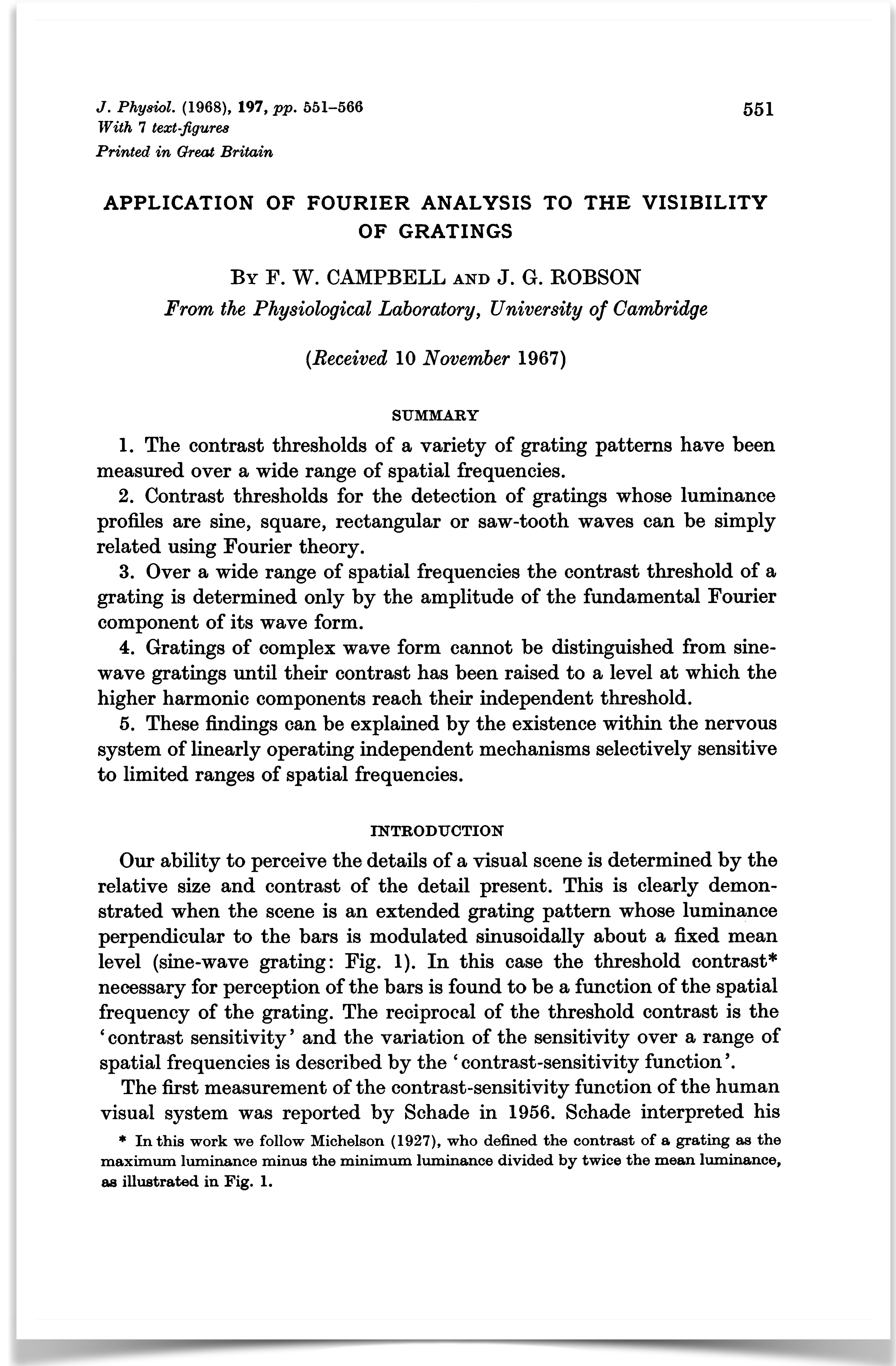
1. Michelson contrast:

$$c = \frac{L_{max} - L_{min}}{L_{max} + L_{min}} = \frac{L_{max} - L_{min}}{2L_{mean}}$$

1

The advent of modern spatial vision

Detectability of periodic patterns can be predicted from their Fourier spectrum. (*Campbell & Robson*, 1968)



J. Physiol. (1968), **197**, *pp.* 551–566
With 7 text-figures
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551

APPLICATION OF FOURIER ANALYSIS TO THE VISIBILITY OF GRATINGS

By F. W. CAMPBELL and J. G. ROBSON
From the Physiological Laboratory, University of Cambridge

(*Received* 10 *November* 1967)

SUMMARY

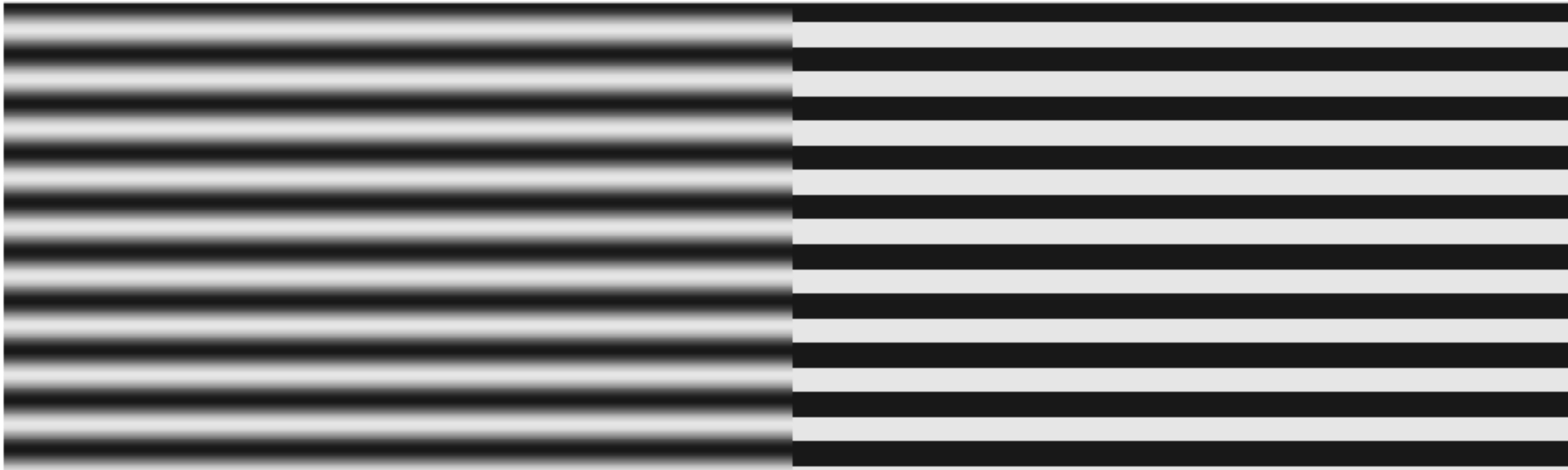
1. The contrast thresholds of a variety of grating patterns have been measured over a wide range of spatial frequencies.
2. Contrast thresholds for the detection of gratings whose luminance profiles are sine, square, rectangular or saw-tooth waves can be simply related using Fourier theory.
3. Over a wide range of spatial frequencies the contrast threshold of a grating is determined only by the amplitude of the fundamental Fourier component of its wave form.
4. Gratings of complex wave form cannot be distinguished from sine-wave gratings until their contrast has been raised to a level at which the higher harmonic components reach their independent threshold.
5. These findings can be explained by the existence within the nervous system of linearly operating independent mechanisms selectively sensitive to limited ranges of spatial frequencies.

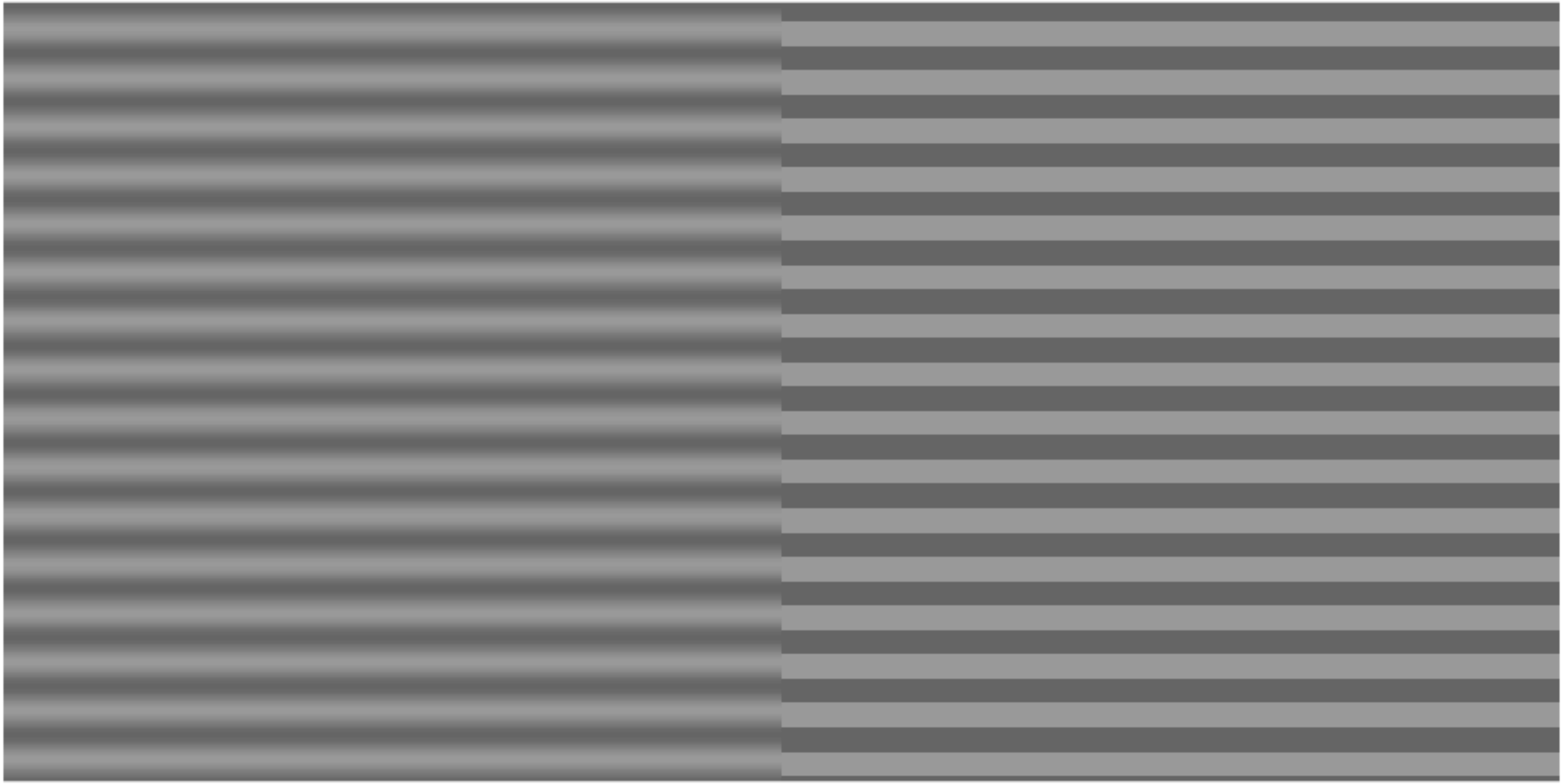
INTRODUCTION

Our ability to perceive the details of a visual scene is determined by the relative size and contrast of the detail present. This is clearly demonstrated when the scene is an extended grating pattern whose luminance perpendicular to the bars is modulated sinusoidally about a fixed mean level (sine-wave grating: Fig. 1). In this case the threshold contrast* necessary for perception of the bars is found to be a function of the spatial frequency of the grating. The reciprocal of the threshold contrast is the 'contrast sensitivity' and the variation of the sensitivity over a range of spatial frequencies is described by the 'contrast-sensitivity function'.

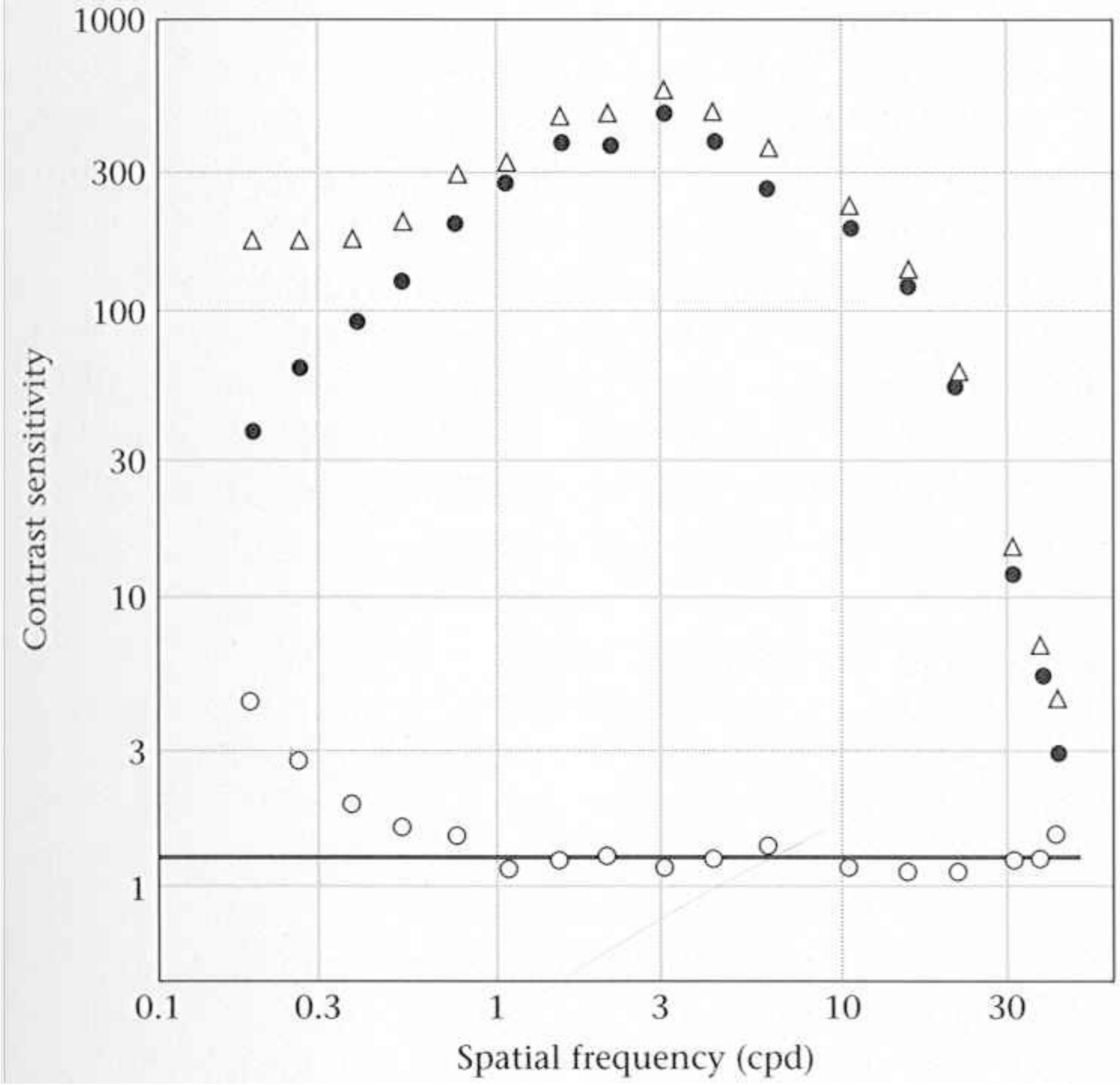
The first measurement of the contrast-sensitivity function of the human visual system was reported by Schade in 1956. Schade interpreted his

* In this work we follow Michelson (1927), who defined the contrast of a grating as the maximum luminance minus the minimum luminance divided by twice the mean luminance, as illustrated in Fig. 1.





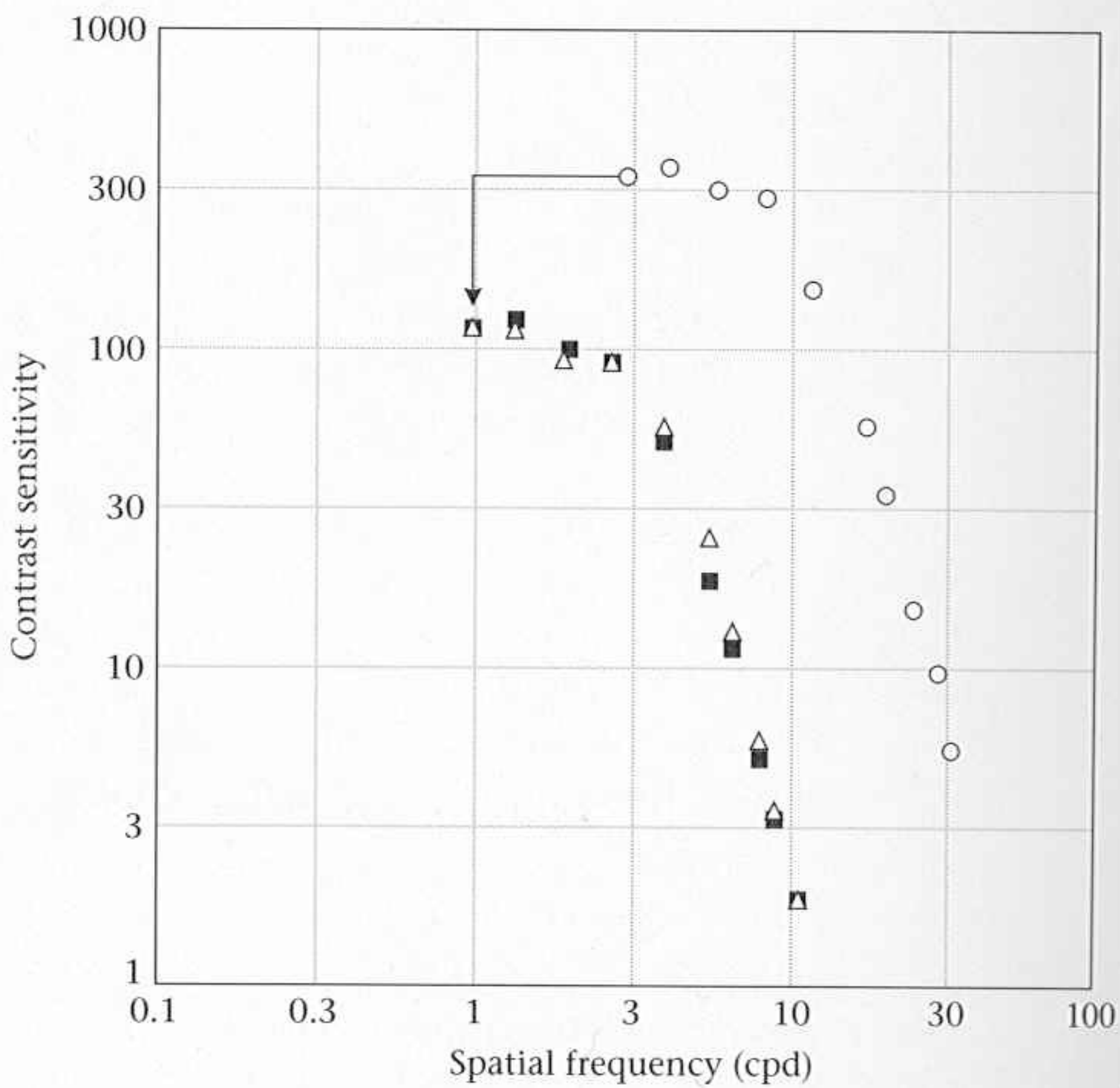
The advent of modern spatial vision



7.13 CONTRAST SENSITIVITY MEASURED USING SQUARE-WAVE GRATINGS greater than 1 cpd can be predicted from the contrast of the square-wave fundamental frequency. The open triangles and filled circles show contrast sensitivity to square waves and sine waves, respectively. The open circles show the ratio of contrast sensitivities at each spatial frequency. The solid line is drawn at a value of $4/\pi \approx 1.273$, the amplitude of a square-wave fundamental in a unit-contrast square wave. Source: Campbell and Robson, 1968.

The advent of modern spatial vision

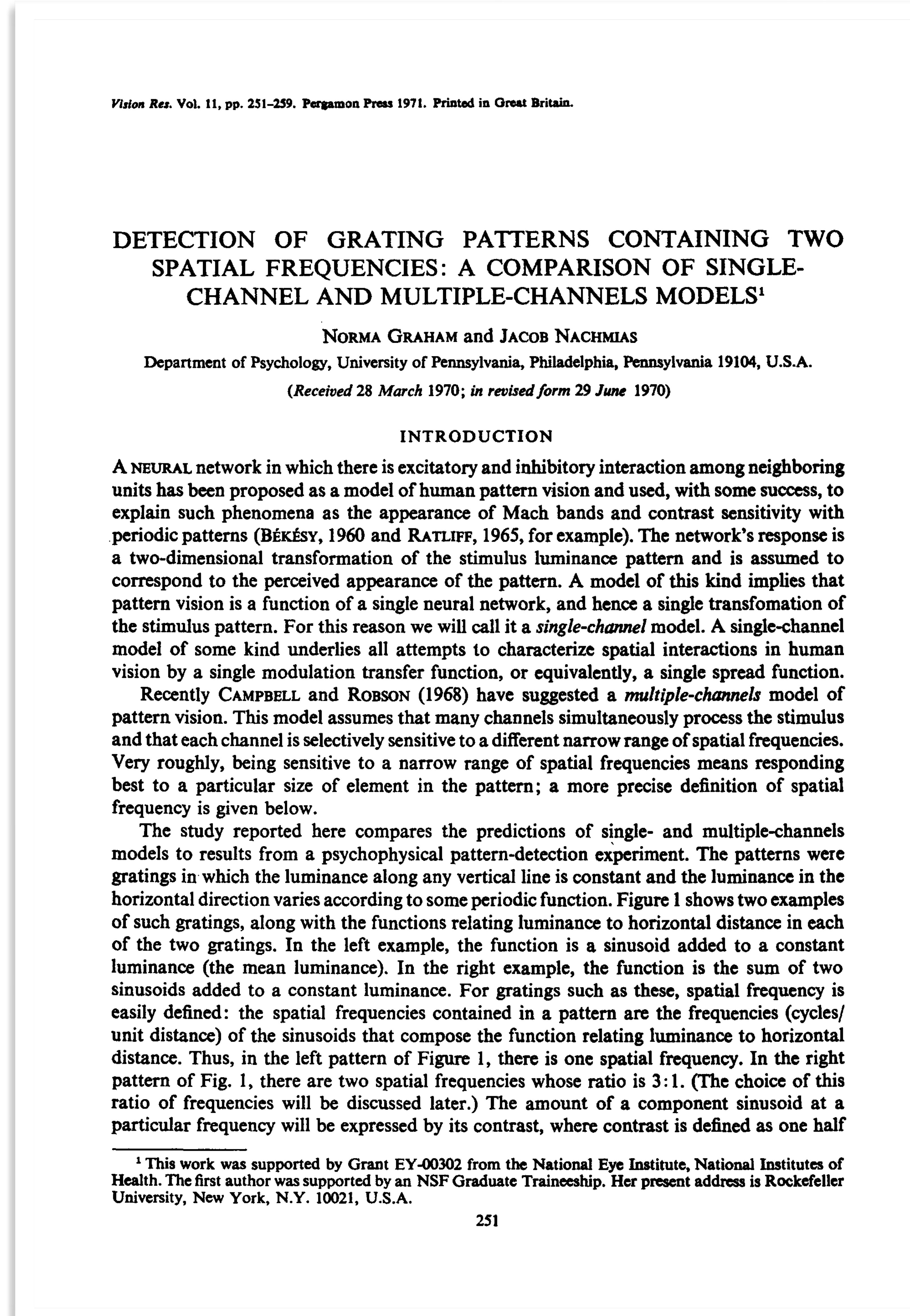
7.14 DISCRIMINATION OF SINUSOIDAL AND SQUARE-WAVE GRATINGS becomes possible when the third harmonic in the square wave reaches its own independent threshold. The open circles plot the contrast-sensitivity function. The open triangles show the contrast level at which a square wave can be discriminated from its fundamental frequency. The filled squares show the square-wave discrimination data shifted by a factor of 3 in both frequency and contrast. The alignment of the shifted curve with the contrast-sensitivity function suggests that square waves are discriminated when the third harmonic reaches its own threshold level. Source: Campbell and Robson, 1968.



The advent of modern spatial vision

Detectability of periodic patterns can be predicted from their Fourier spectrum. (*Campbell & Robson*, 1968)

Detection of compound patterns with sufficiently different spatial frequency is independent of local phase ("summation experiments"). (*Graham & Nachmias*, 1971)



Vision Res. Vol. 11, pp. 251–259. Pergamon Press 1971. Printed in Great Britain.

DETECTION OF GRATING PATTERNS CONTAINING TWO SPATIAL FREQUENCIES: A COMPARISON OF SINGLE-CHANNEL AND MULTIPLE-CHANNELS MODELS[1]

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(*Received* 28 *March* 1970; *in revised form* 29 *June* 1970)

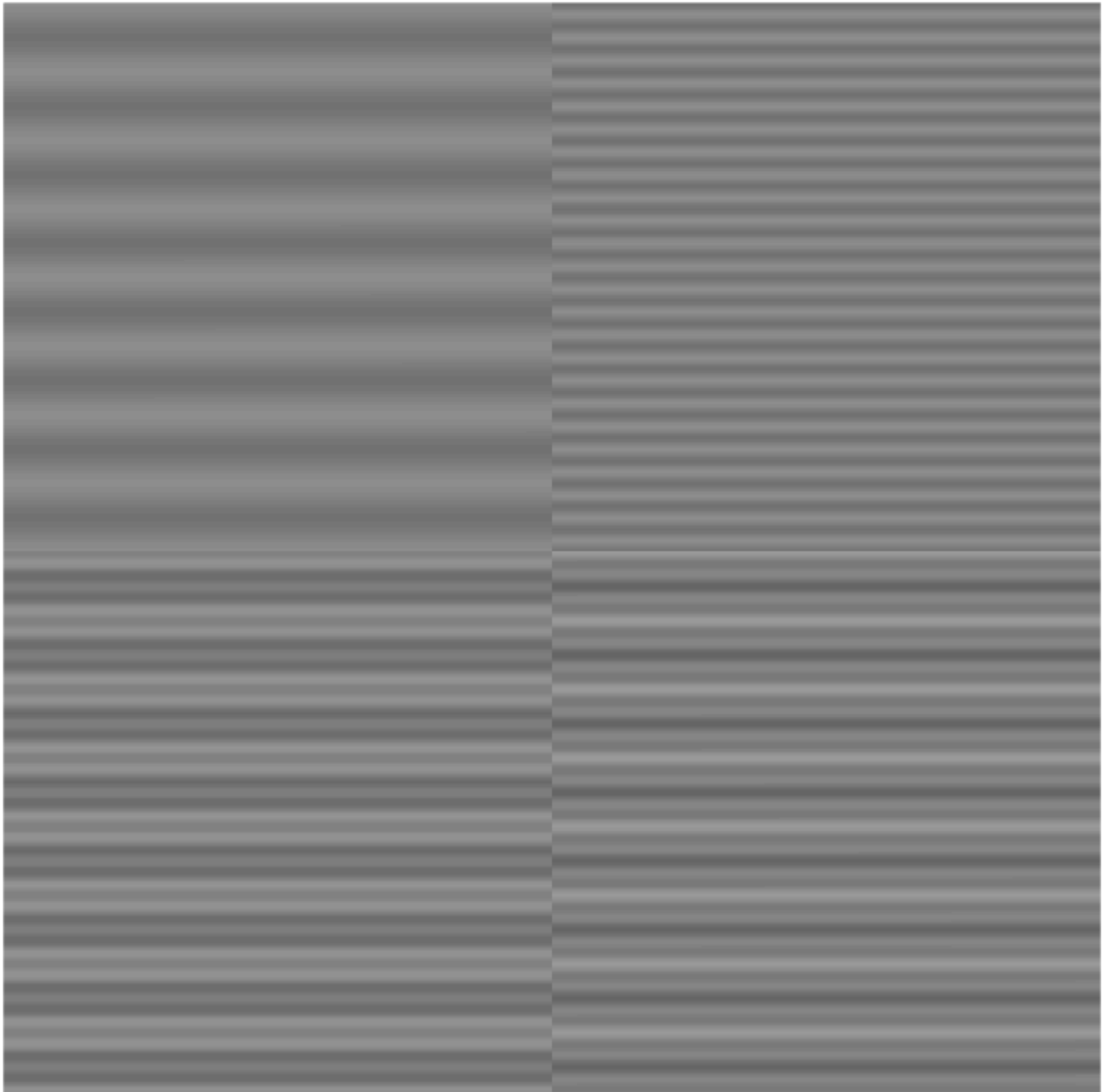
INTRODUCTION

A NEURAL network in which there is excitatory and inhibitory interaction among neighboring units has been proposed as a model of human pattern vision and used, with some success, to explain such phenomena as the appearance of Mach bands and contrast sensitivity with periodic patterns (BÉKÉSY, 1960 and RATLIFF, 1965, for example). The network's response is a two-dimensional transformation of the stimulus luminance pattern and is assumed to correspond to the perceived appearance of the pattern. A model of this kind implies that pattern vision is a function of a single neural network, and hence a single transfomation of the stimulus pattern. For this reason we will call it a *single-channel* model. A single-channel model of some kind underlies all attempts to characterize spatial interactions in human vision by a single modulation transfer function, or equivalently, a single spread function.

Recently CAMPBELL and ROBSON (1968) have suggested a *multiple-channels* model of pattern vision. This model assumes that many channels simultaneously process the stimulus and that each channel is selectively sensitive to a different narrow range of spatial frequencies. Very roughly, being sensitive to a narrow range of spatial frequencies means responding best to a particular size of element in the pattern; a more precise definition of spatial frequency is given below.

The study reported here compares the predictions of single- and multiple-channels models to results from a psychophysical pattern-detection experiment. The patterns were gratings in which the luminance along any vertical line is constant and the luminance in the horizontal direction varies according to some periodic function. Figure 1 shows two examples of such gratings, along with the functions relating luminance to horizontal distance in each of the two gratings. In the left example, the function is a sinusoid added to a constant luminance (the mean luminance). In the right example, the function is the sum of two sinusoids added to a constant luminance. For gratings such as these, spatial frequency is easily defined: the spatial frequencies contained in a pattern are the frequencies (cycles/unit distance) of the sinusoids that compose the function relating luminance to horizontal distance. Thus, in the left pattern of Figure 1, there is one spatial frequency. In the right pattern of Fig. 1, there are two spatial frequencies whose ratio is 3:1. (The choice of this ratio of frequencies will be discussed later.) The amount of a component sinusoid at a particular frequency will be expressed by its contrast, where contrast is defined as one half

[1] This work was supported by Grant EY-00302 from the National Eye Institute, National Institutes of Health. The first author was supported by an NSF Graduate Traineeship. Her present address is Rockefeller University, New York, N.Y. 10021, U.S.A.



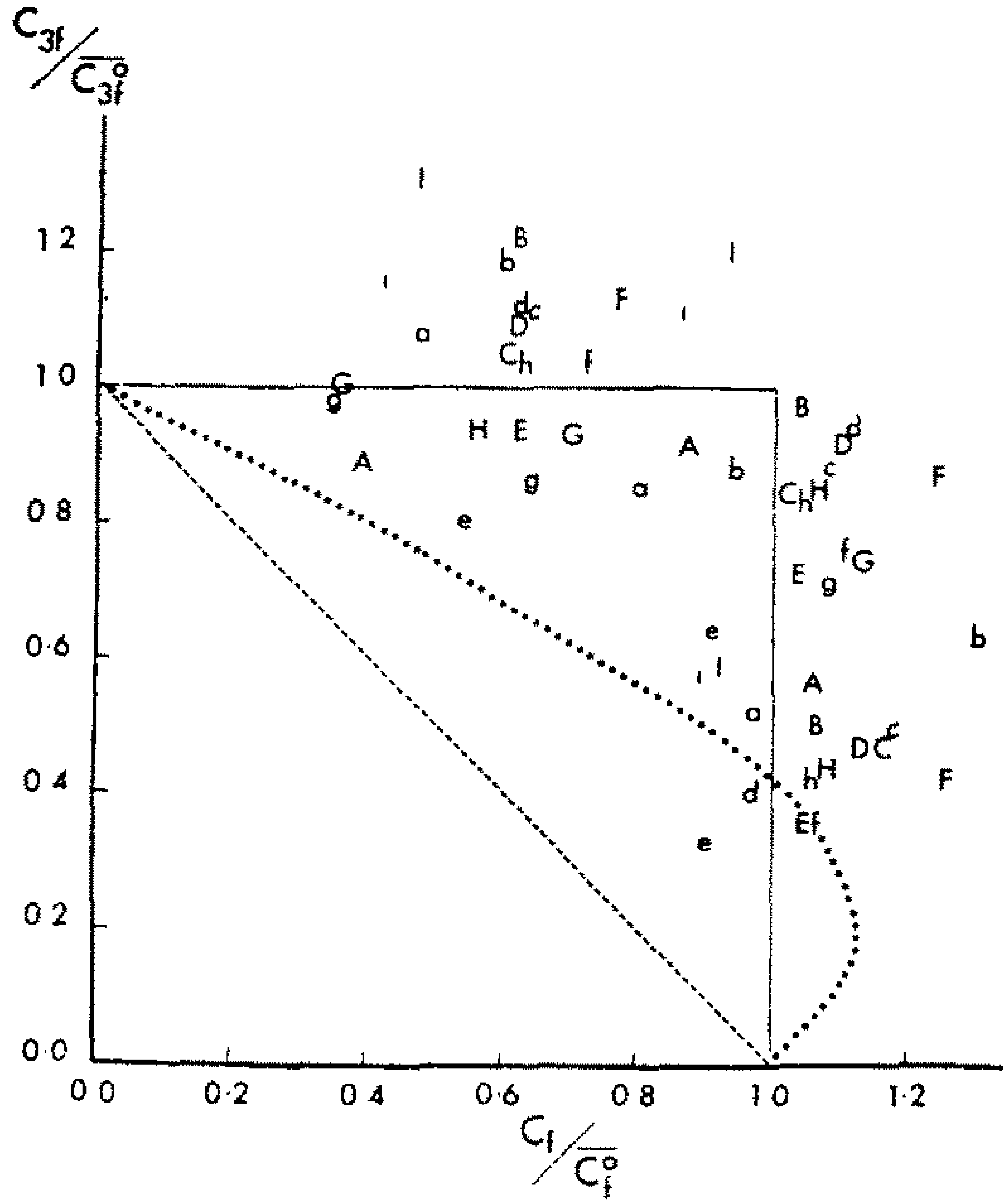


FIG. 3. Contrast thresholds for complex grating patterns containing two frequencies, f and $3f$, in two different phases. The coordintes are the contrast of each component in the complex grating at threshold relative to the threshold contrast of the corresponding simple grating. Results obtained with the peaks-add form of complex gratings and with the peaks-subtract form are plotted as capital and small letters, respectively. The corresponding predictions of the single-channel model are represented by the diagonal dashed line and the dotted curve. The upper and right edges of the square represent the predictions of the multiple-channels model for both peaks-add and peaks-subtract gratings.

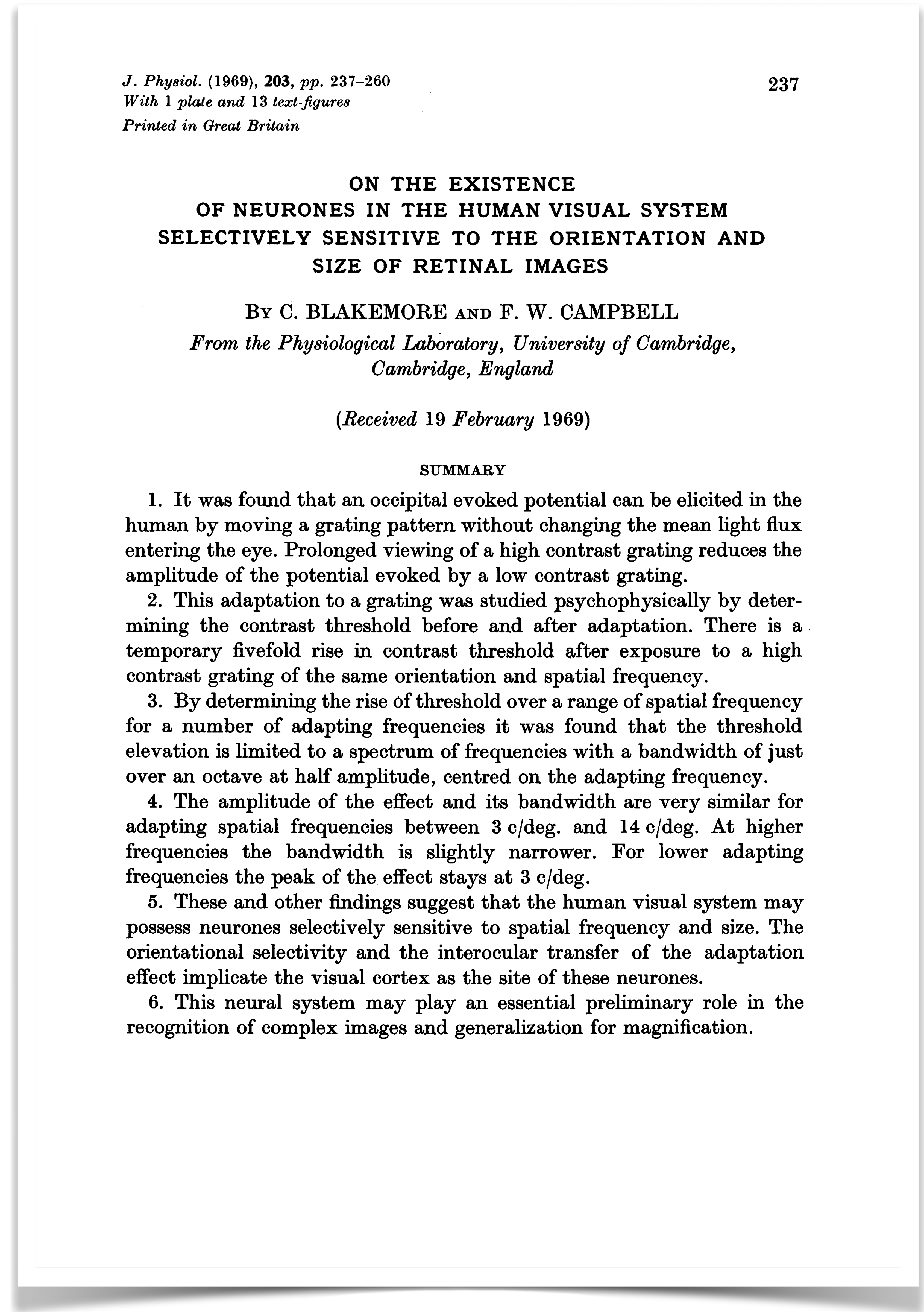
1

The advent of modern spatial vision

Detectability of periodic patterns can be predicted from their Fourier spectrum.
(*Campbell & Robson*, 1968)

Detection of compound patterns with sufficiently different spatial frequency is independent of local phase ("summation experiments").
(*Graham & Nachmias*, 1971)

Adaptation is spatial frequency selective.
(*Blakemore & Campbell*, 1969)



J. Physiol. (1969), **203**, *pp.* 237–260 237
With 1 plate and 13 text-figures
Printed in Great Britain

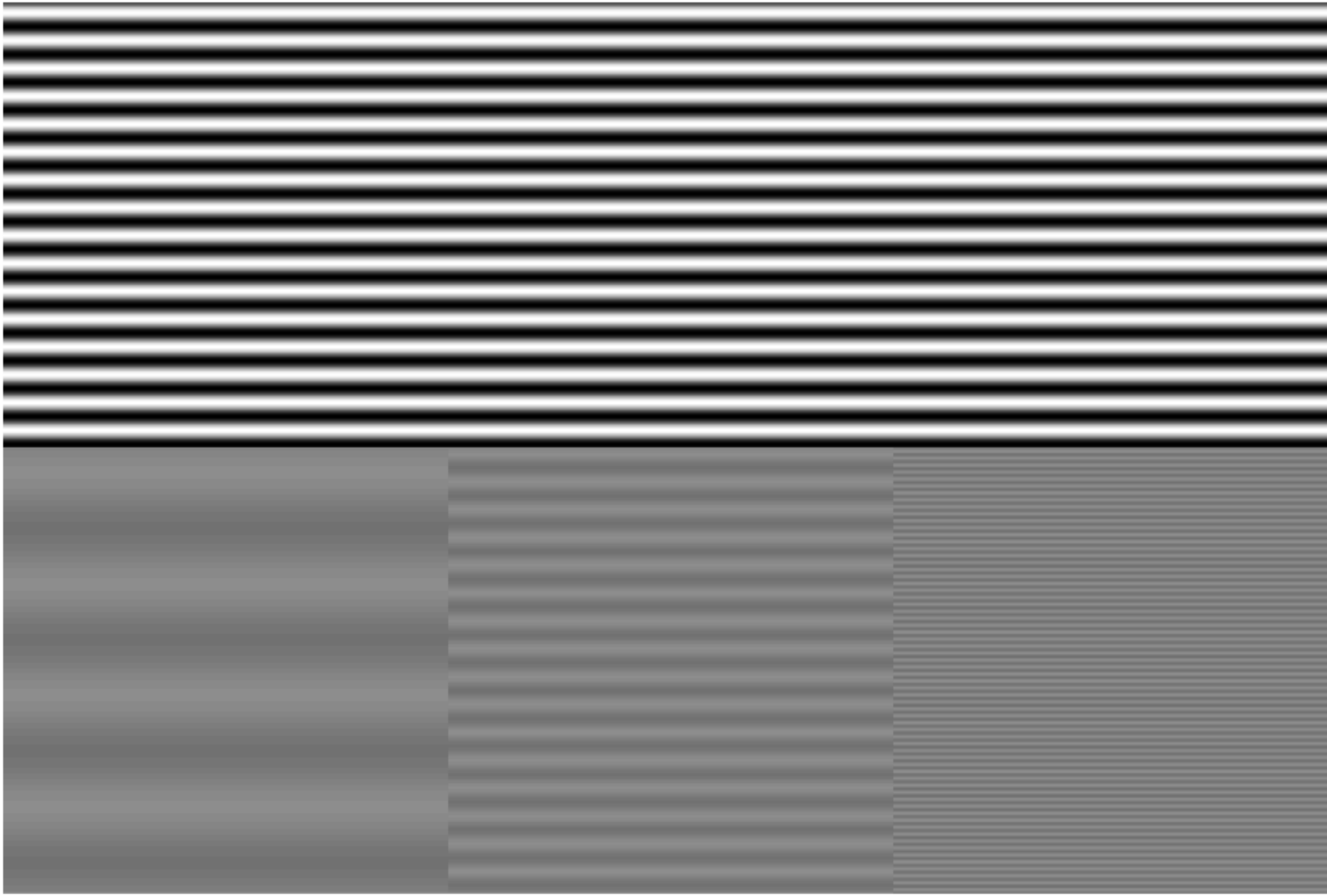
ON THE EXISTENCE
OF NEURONES IN THE HUMAN VISUAL SYSTEM
SELECTIVELY SENSITIVE TO THE ORIENTATION AND
SIZE OF RETINAL IMAGES

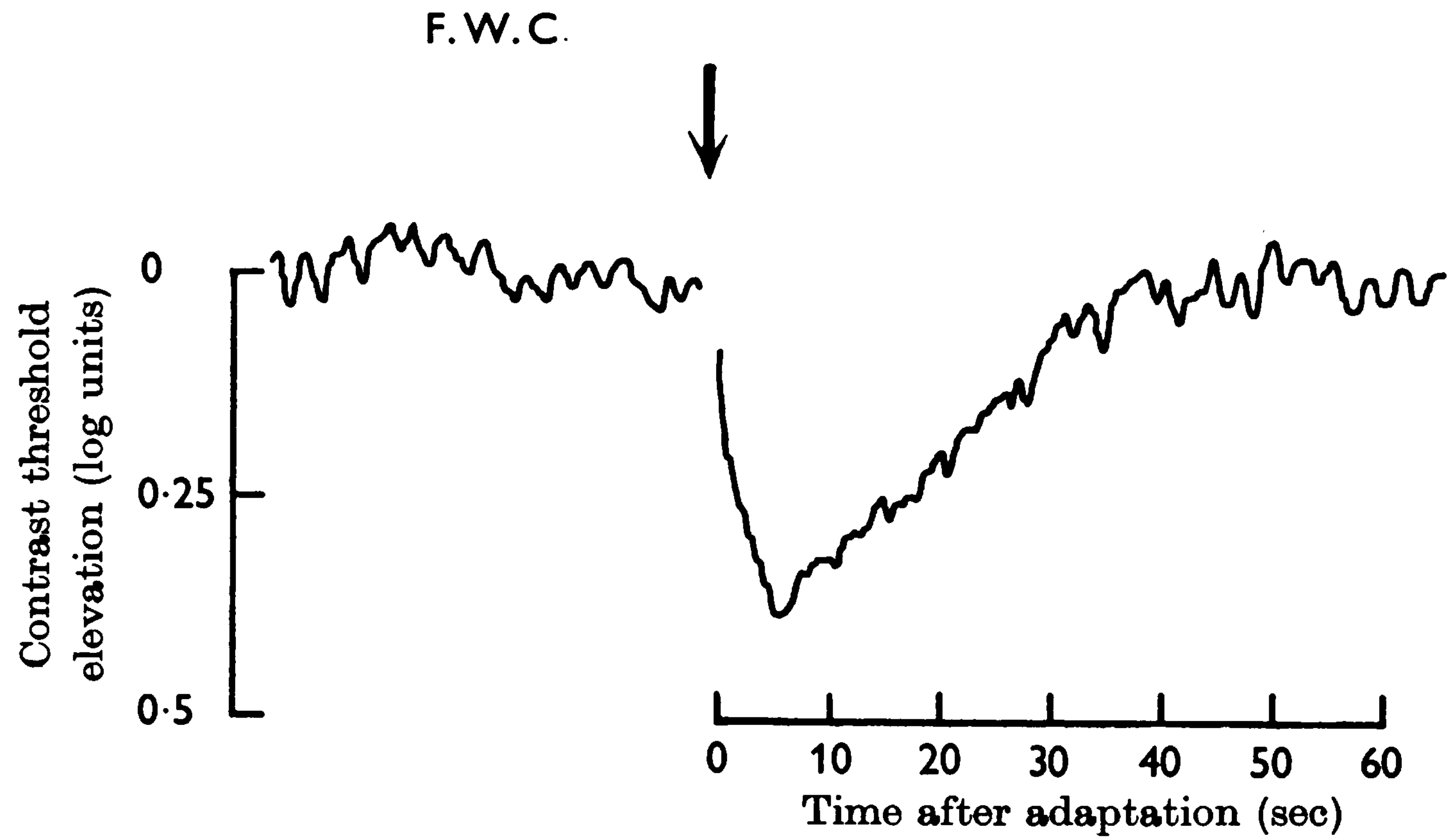
BY C. BLAKEMORE AND F. W. CAMPBELL
From the Physiological Laboratory, University of Cambridge, Cambridge, England

(*Received* 19 *February* 1969)

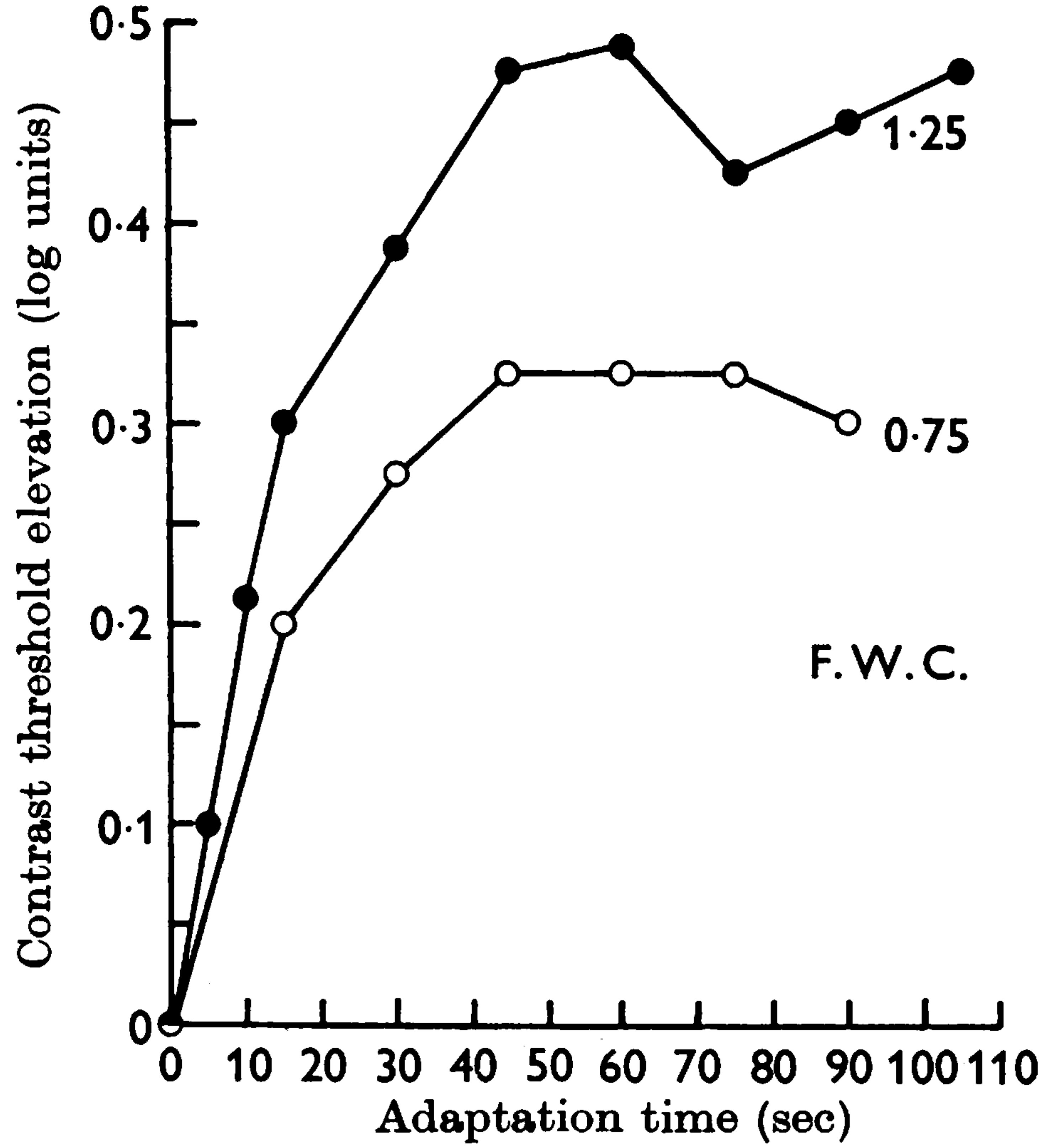
SUMMARY

1. It was found that an occipital evoked potential can be elicited in the human by moving a grating pattern without changing the mean light flux entering the eye. Prolonged viewing of a high contrast grating reduces the amplitude of the potential evoked by a low contrast grating.
2. This adaptation to a grating was studied psychophysically by determining the contrast threshold before and after adaptation. There is a temporary fivefold rise in contrast threshold after exposure to a high contrast grating of the same orientation and spatial frequency.
3. By determining the rise of threshold over a range of spatial frequency for a number of adapting frequencies it was found that the threshold elevation is limited to a spectrum of frequencies with a bandwidth of just over an octave at half amplitude, centred on the adapting frequency.
4. The amplitude of the effect and its bandwidth are very similar for adapting spatial frequencies between 3 c/deg. and 14 c/deg. At higher frequencies the bandwidth is slightly narrower. For lower adapting frequencies the peak of the effect stays at 3 c/deg.
5. These and other findings suggest that the human visual system may possess neurones selectively sensitive to spatial frequency and size. The orientational selectivity and the interocular transfer of the adaptation effect implicate the visual cortex as the site of these neurones.
6. This neural system may play an essential preliminary role in the recognition of complex images and generalization for magnification.

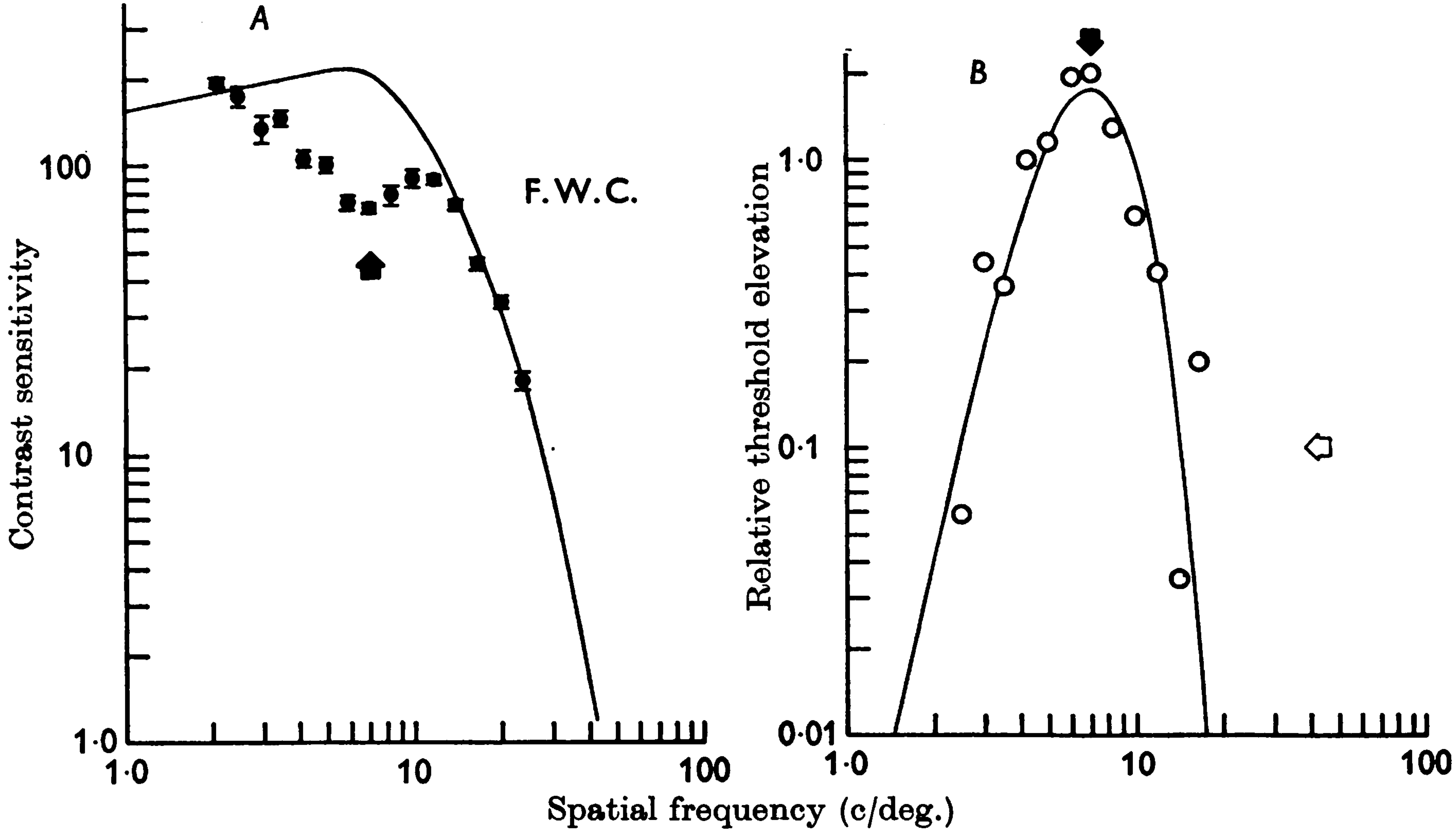




Text-fig. 2. The time course of recovery from adaptation. F. W. C. turned a potentiometer to adjust the contrast of the grating (12·5 c/deg.) until it was just visible. His searching movements oscillate around threshold in the first part of this record from an *x–y* plotter, after logarithmic conversion. The arrow indicates a period of 60 sec during which the record was stopped and F.W.C. viewed a high contrast grating (1·5 log units above threshold). The trace re-starts as he searches for his elevated threshold and gradually tracks the recovery back to normal contrast sensitivity, which is complete in about 60 sec.



Text-fig. 3. The effect of adapting time. The initial elevation of threshold for F.W.C. is plotted against the adaptation time. For the filled circles the adapting grating of 15 c/deg. was 1·25 log units above threshold. For the open circles it was 0·75 log units above threshold.



Text-fig. 6. The effect of adapting at 7·1 c/deg. *A*. The continuous curve from Text-fig. 5 is reproduced. The filled circles and vertical bars are the means and S.E. ($n = 6$) for re-determinations of contrast sensitivity at a number of spatial frequencies while F. W.C. was continuously adapting to a grating of 7·1 c/deg., 1·5 log. units above threshold. The exact procedure is described in the text.

B. The depression in sensitivity due to adaptation at 7·1 c/deg. is plotted, with open circles, as relative threshold elevation against spatial frequency. The vertical difference between each point and the smooth curve in Text-fig. 6*A* is the ratio of sensitivity before and after adaptation. The relative threshold elevation is the anti-logarithm of this difference minus 1, so that no change in threshold would give a value of zero on the ordinate. The continuous curve is the function $[e^{-f^2} - e^{-(2f)^2}]^2$, fitted by eye to the data points. The filled arrows show the adapting frequency of 7·1 c/deg. The open arrow marks the value on the ordinate for a threshold elevation equivalent to $2\sqrt{2}$ times an average S.E. for determining contrast sensitivity.

Binocular transfer of pattern adaptation. To find out whether this adaptation effect transfers from one eye to the other we performed the following experiment.

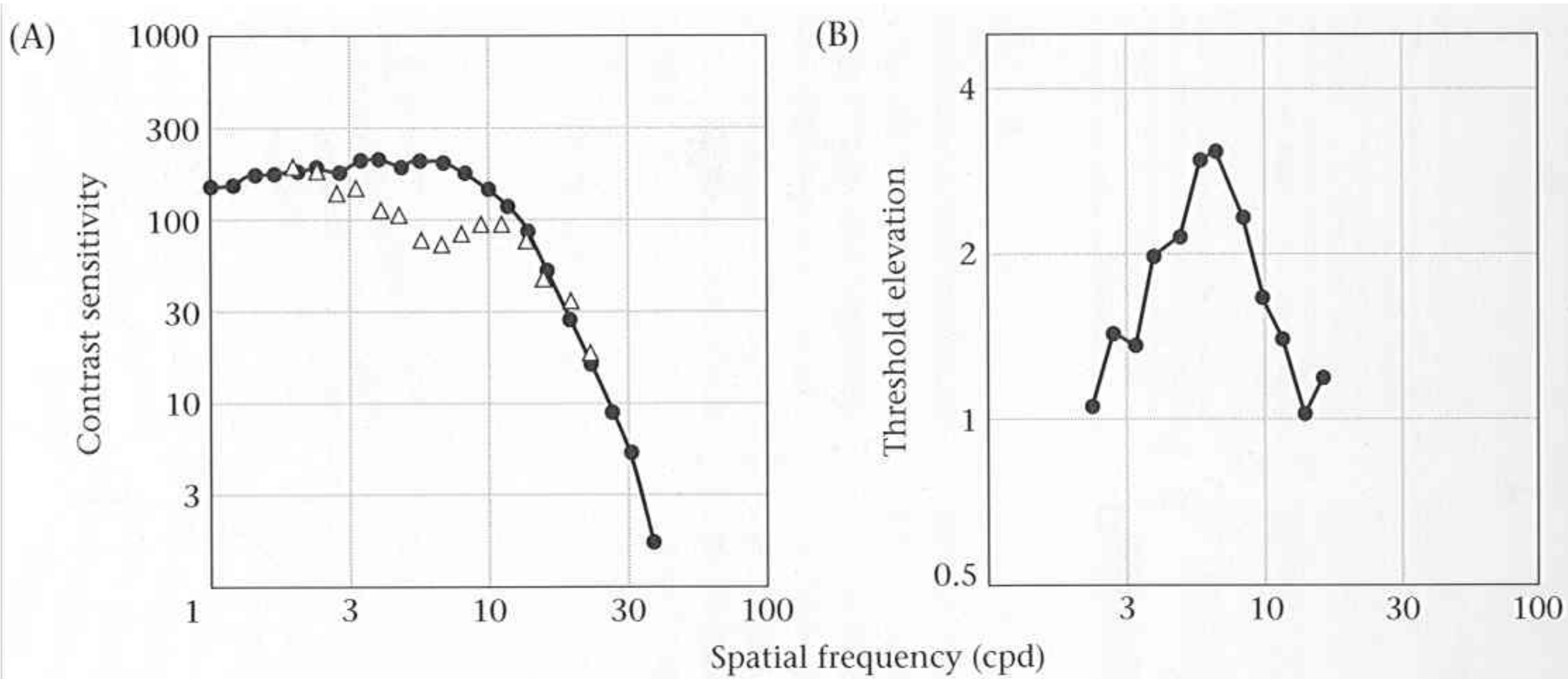
Initially the contrast threshold of each eye was independently determined in subject F.W.C. for a spatial frequency of 10 c/deg. The left eye alone was then adapted as in the previous experiment to a grating of this frequency, 1·5 log units above the left eye's threshold. The contrast threshold was then re-determined for each eye separately. Ten readings were taken for each eye, the high contrast grating being substituted in the left eye between each reading to maintain adaptation.

As expected, there was the usual elevation of threshold in the adapted eye. Moreover, there was a significant rise of threshold ($P < 0{\cdot}001$) in the right eye which had not been adapted. However, the rise of threshold in the adapted eye was 1·6 times greater than that in the unadapted.

We therefore conclude that there is definite, but incomplete, interocular transfer of the adaptation phenomenon.

Blakemore & Campbell (1969), p. 245

Multi-resolution theory: the CSF is the sum of more narrowly tuned elements



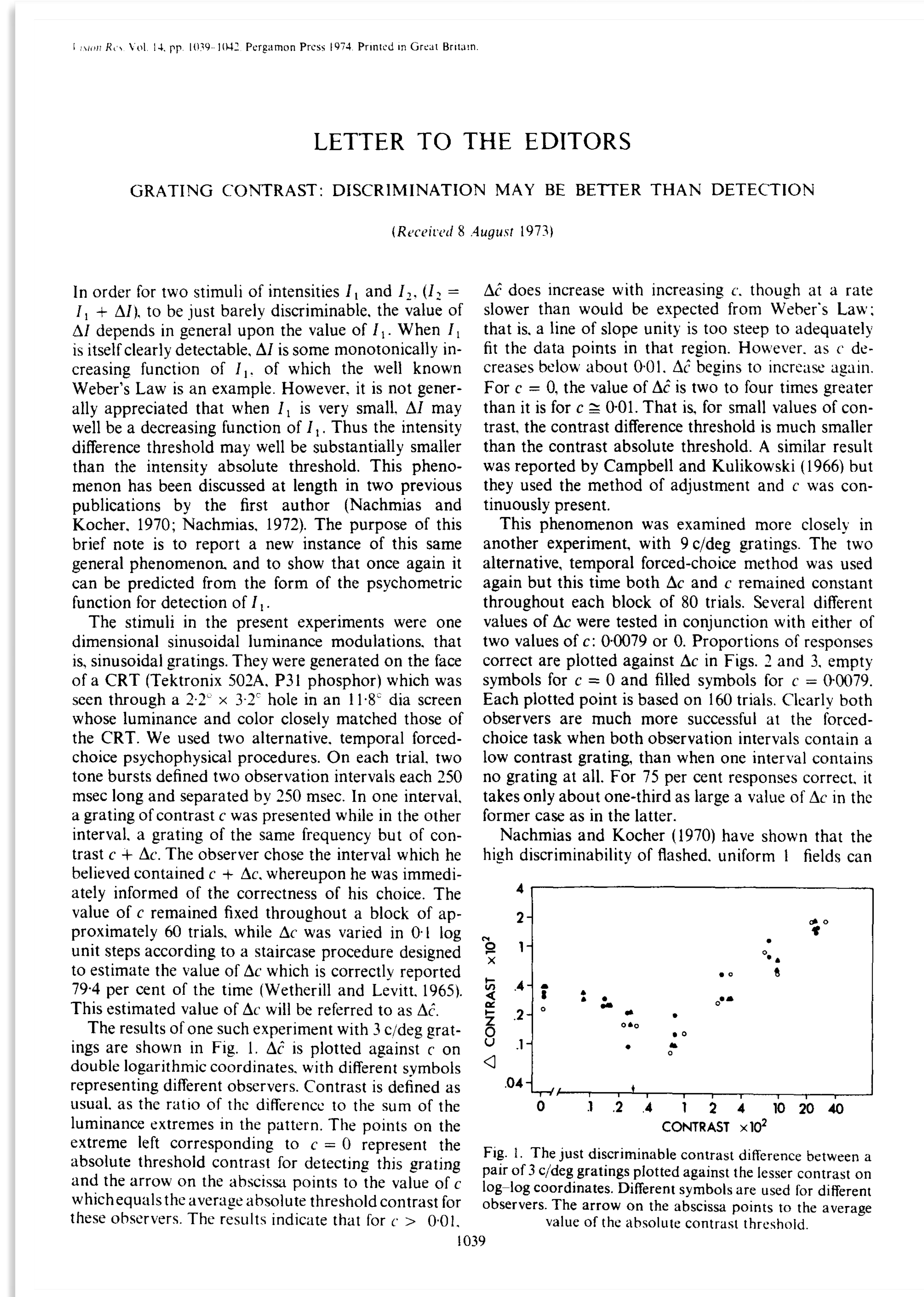
The advent of modern spatial vision

Detectability of periodic patterns can be predicted from their Fourier spectrum.
(*Campbell & Robson*, 1968)

Detection of compound patterns with sufficiently different spatial frequency is independent of local phase ("summation experiments").
(*Graham & Nachmias*, 1971)

Adaptation is spatial frequency selective.
(*Blakemore & Campbell*, 1969)

Contrast discrimination may be better than detection.
(*Nachmias & Sansbury*, 1974)



Vision Res. Vol. 14, pp. 1039–1042. Pergamon Press 1974. Printed in Great Britain.

LETTER TO THE EDITORS

GRATING CONTRAST: DISCRIMINATION MAY BE BETTER THAN DETECTION

(*Received* 8 *August* 1973)

In order for two stimuli of intensities I_1 and I_2, ($I_2 = I_1 + \Delta I$), to be just barely discriminable, the value of ΔI depends in general upon the value of I_1. When I_1 is itself clearly detectable, ΔI is some monotonically increasing function of I_1, of which the well known Weber's Law is an example. However, it is not generally appreciated that when I_1 is very small, ΔI may well be a decreasing function of I_1. Thus the intensity difference threshold may well be substantially smaller than the intensity absolute threshold. This phenomenon has been discussed at length in two previous publications by the first author (Nachmias and Kocher, 1970; Nachmias, 1972). The purpose of this brief note is to report a new instance of this same general phenomenon, and to show that once again it can be predicted from the form of the psychometric function for detection of I_1.

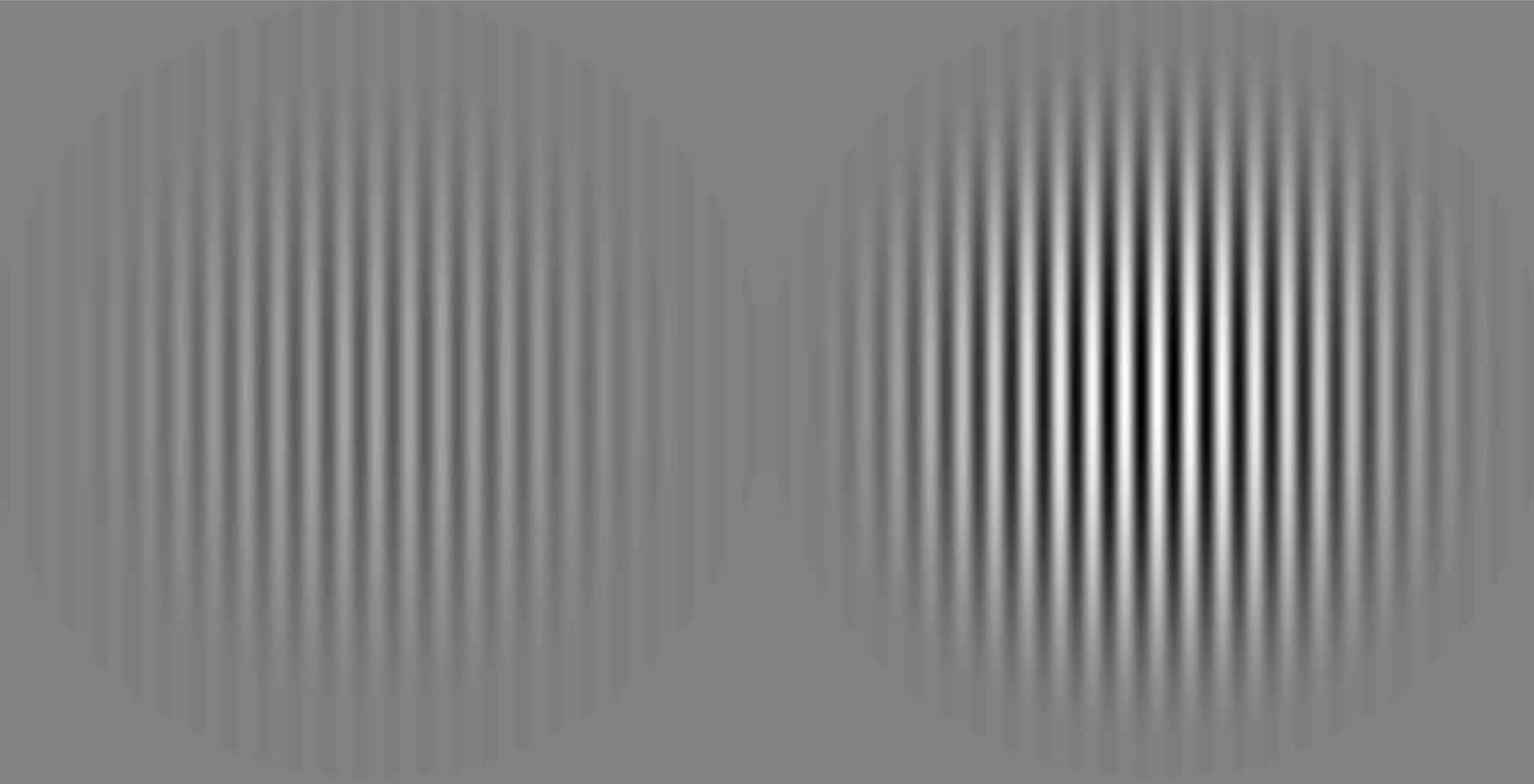
The stimuli in the present experiments were one dimensional sinusoidal luminance modulations, that is, sinusoidal gratings. They were generated on the face of a CRT (Tektronix 502A, P31 phosphor) which was seen through a 2·2° × 3·2° hole in an 11·8° dia screen whose luminance and color closely matched those of the CRT. We used two alternative, temporal forced-choice psychophysical procedures. On each trial, two tone bursts defined two observation intervals each 250 msec long and separated by 250 msec. In one interval, a grating of contrast c was presented while in the other interval, a grating of the same frequency but of contrast $c + \Delta c$. The observer chose the interval which he believed contained $c + \Delta c$, whereupon he was immediately informed of the correctness of his choice. The value of c remained fixed throughout a block of approximately 60 trials, while Δc was varied in 0·1 log unit steps according to a staircase procedure designed to estimate the value of Δc which is correctly reported 79·4 per cent of the time (Wetherill and Levitt, 1965). This estimated value of Δc will be referred to as $\Delta \hat{c}$.

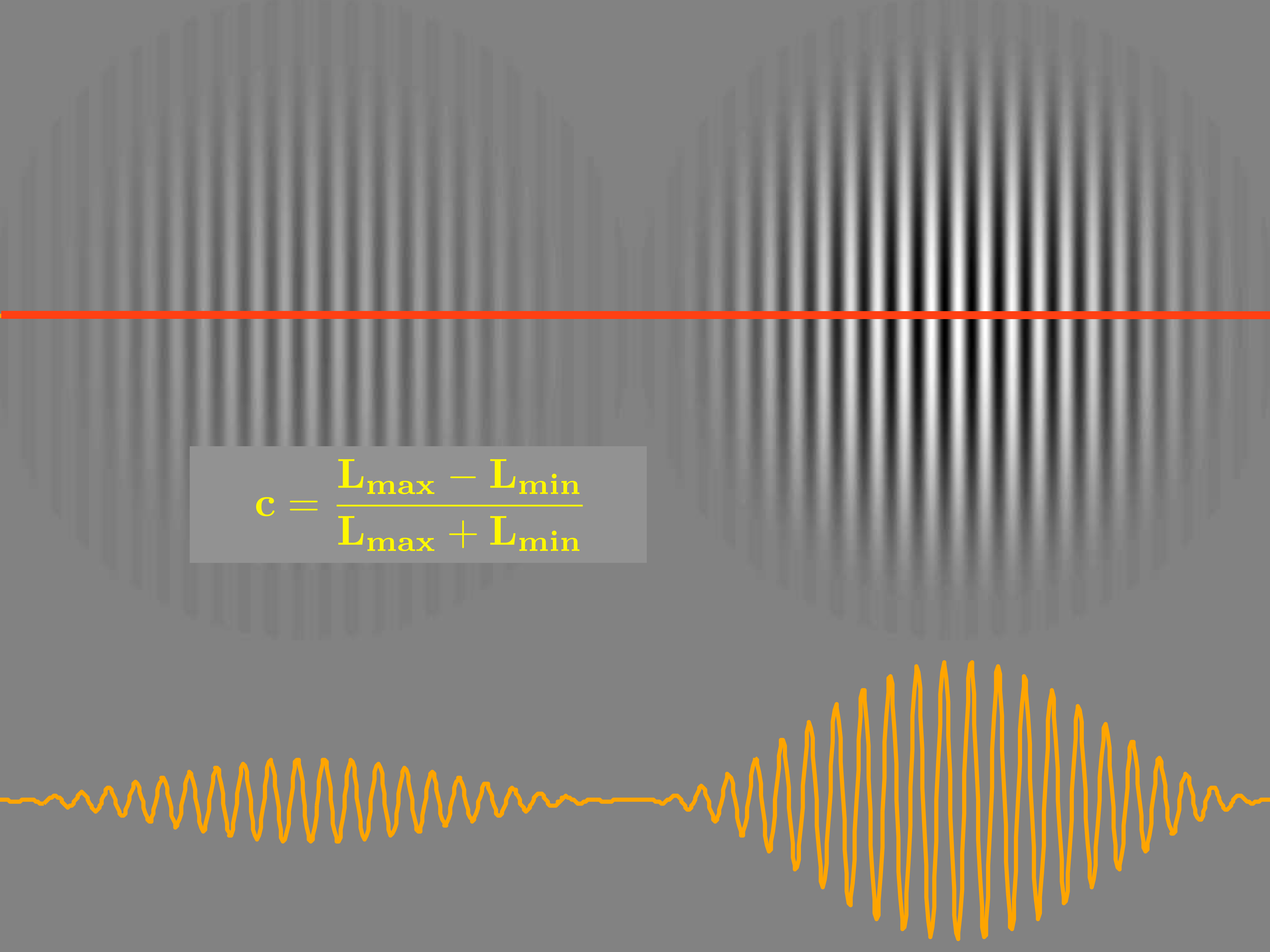
The results of one such experiment with 3 c/deg gratings are shown in Fig. 1. $\Delta \hat{c}$ is plotted against c on double logarithmic coordinates, with different symbols representing different observers. Contrast is defined as usual, as the ratio of the difference to the sum of the luminance extremes in the pattern. The points on the extreme left corresponding to $c = 0$ represent the absolute threshold contrast for detecting this grating and the arrow on the abscissa points to the value of c which equals the average absolute threshold contrast for these observers. The results indicate that for $c > 0·01$, $\Delta \hat{c}$ does increase with increasing c, though at a rate slower than would be expected from Weber's Law; that is, a line of slope unity is too steep to adequately fit the data points in that region. However, as c decreases below about 0·01, $\Delta \hat{c}$ begins to increase again. For $c = 0$, the value of $\Delta \hat{c}$ is two to four times greater than it is for $c \cong 0·01$. That is, for small values of contrast, the contrast difference threshold is much smaller than the contrast absolute threshold. A similar result was reported by Campbell and Kulikowski (1966) but they used the method of adjustment and c was continuously present.

This phenomenon was examined more closely in another experiment, with 9 c/deg gratings. The two alternative, temporal forced-choice method was used again but this time both Δc and c remained constant throughout each block of 80 trials. Several different values of Δc were tested in conjunction with either of two values of c: 0·0079 or 0. Proportions of responses correct are plotted against Δc in Figs. 2 and 3, empty symbols for $c = 0$ and filled symbols for $c = 0·0079$. Each plotted point is based on 160 trials. Clearly both observers are much more successful at the forced-choice task when both observation intervals contain a low contrast grating, than when one interval contains no grating at all. For 75 per cent responses correct, it takes only about one-third as large a value of Δc in the former case as in the latter.

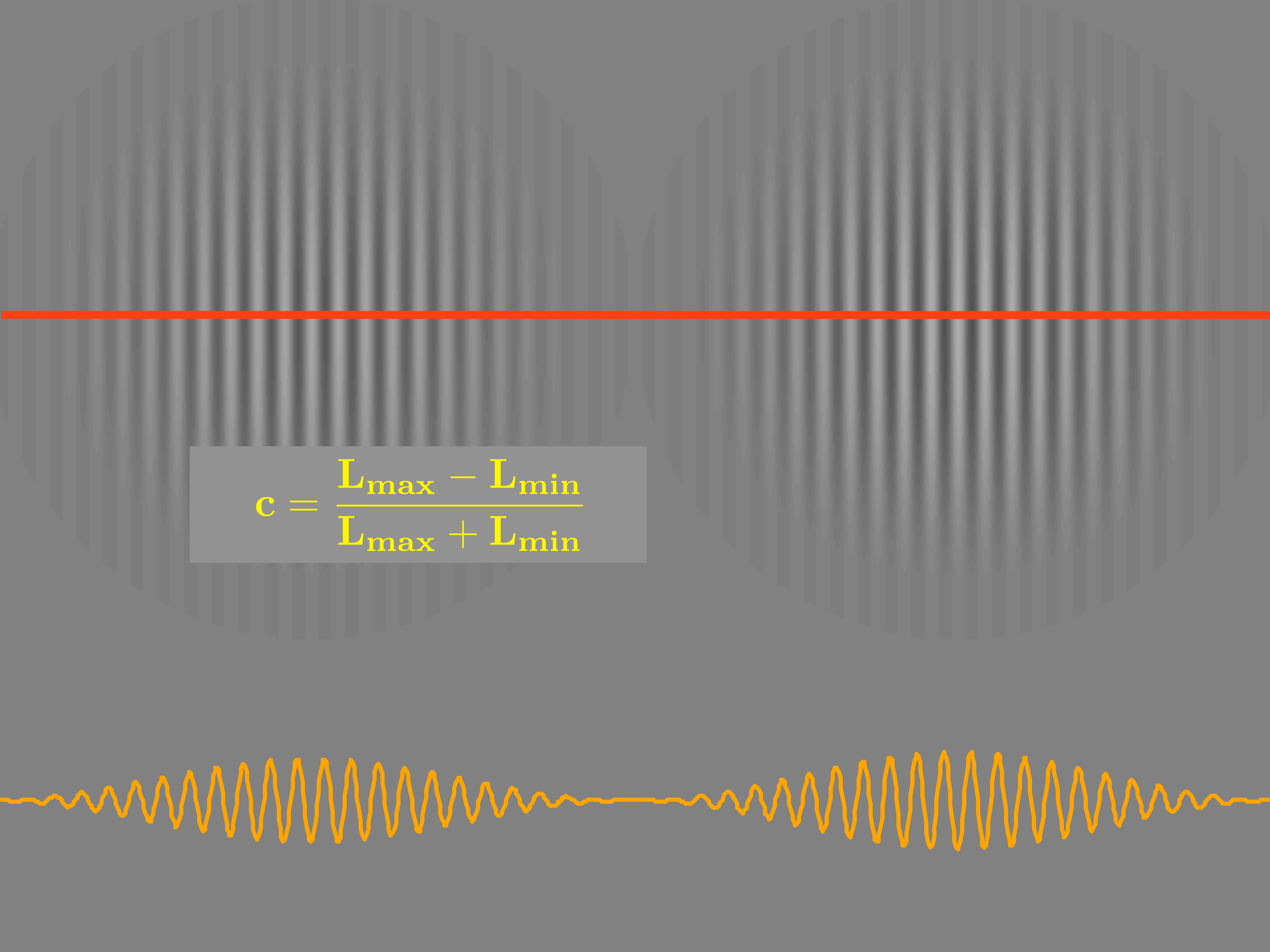
Nachmias and Kocher (1970) have shown that the high discriminability of flashed, uniform 1 fields can

Fig. 1. The just discriminable contrast difference between a pair of 3 c/deg gratings plotted against the lesser contrast on log–log coordinates. Different symbols are used for different observers. The arrow on the abscissa points to the average value of the absolute contrast threshold.





$$c = \frac{L_{max} - L_{min}}{L_{max} + L_{min}}$$



$$\mathbf{c} = \frac{\mathbf{L_{max}} - \mathbf{L_{min}}}{\mathbf{L_{max}} + \mathbf{L_{min}}}$$

$c = \Delta c + c_p$
("signal+pedestal")
("contrast increment+pedesal")

c_p
("pedestal")

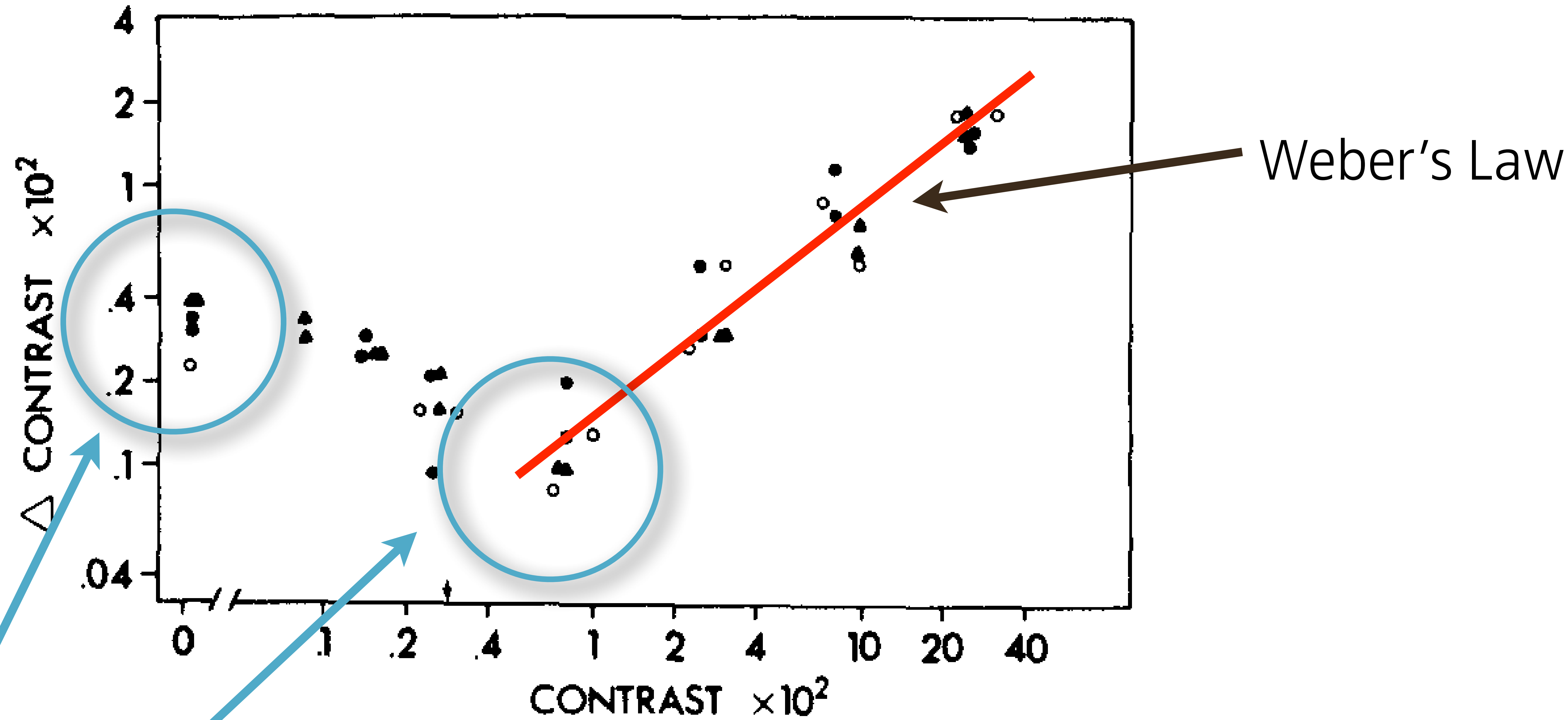


Fig. 1. The just discriminable contrast difference between a pair of 3 c/deg gratings plotted against the lesser contrast on log–log coordinates. Different symbols are used for different observers. The arrow on the abscissa points to the average value of the absolute contrast threshold.

Discrimination "easier" than detection!

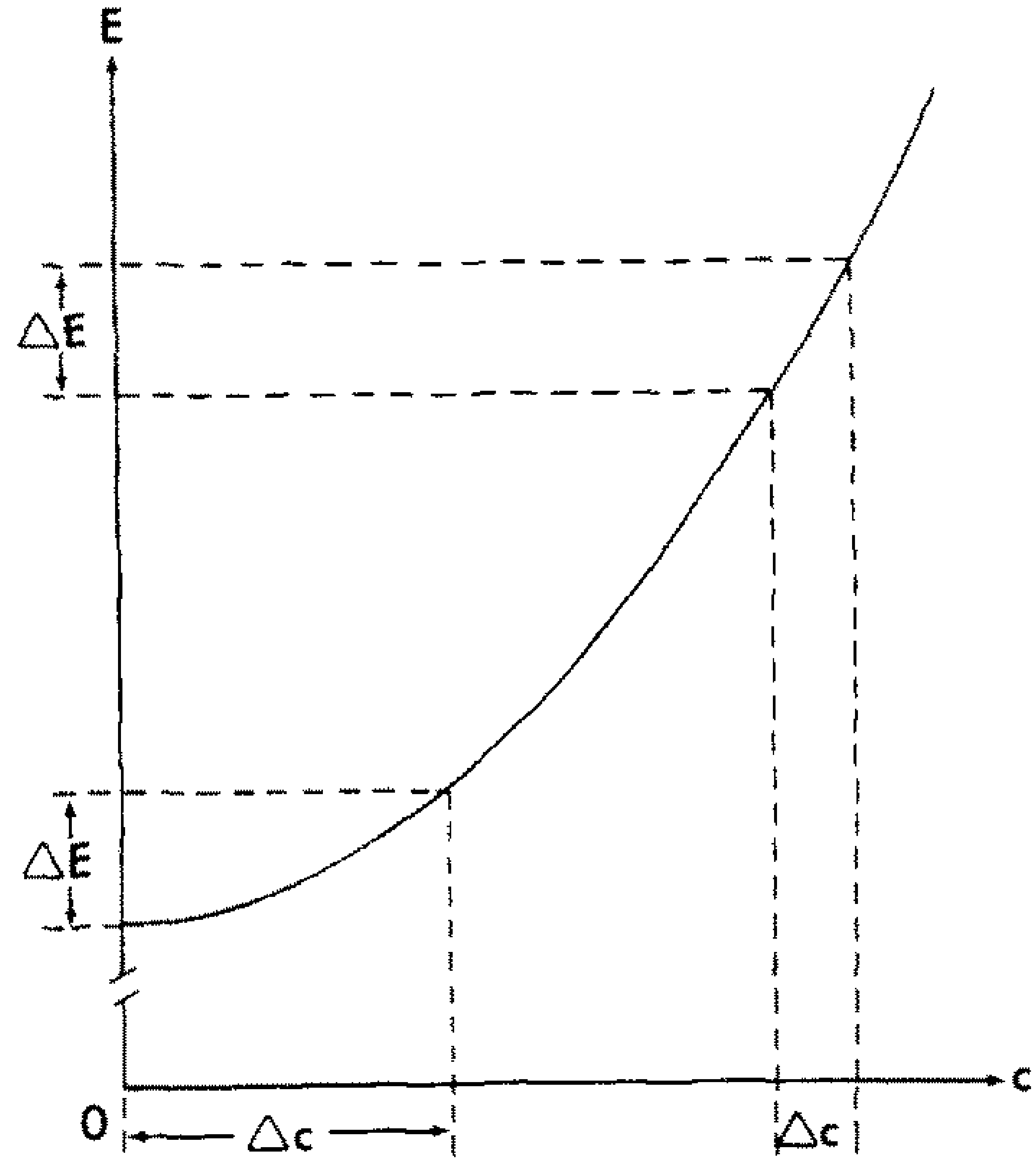
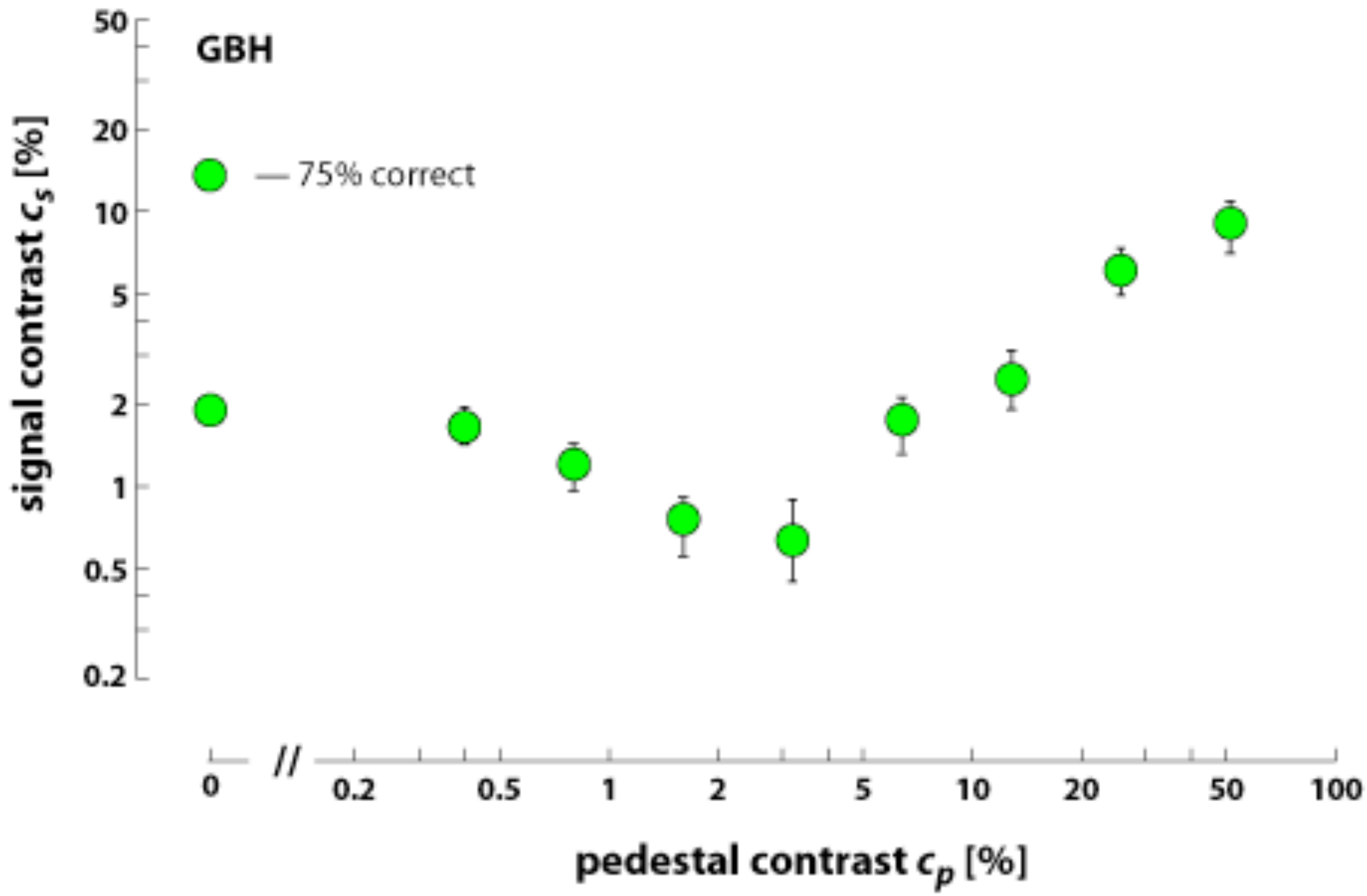
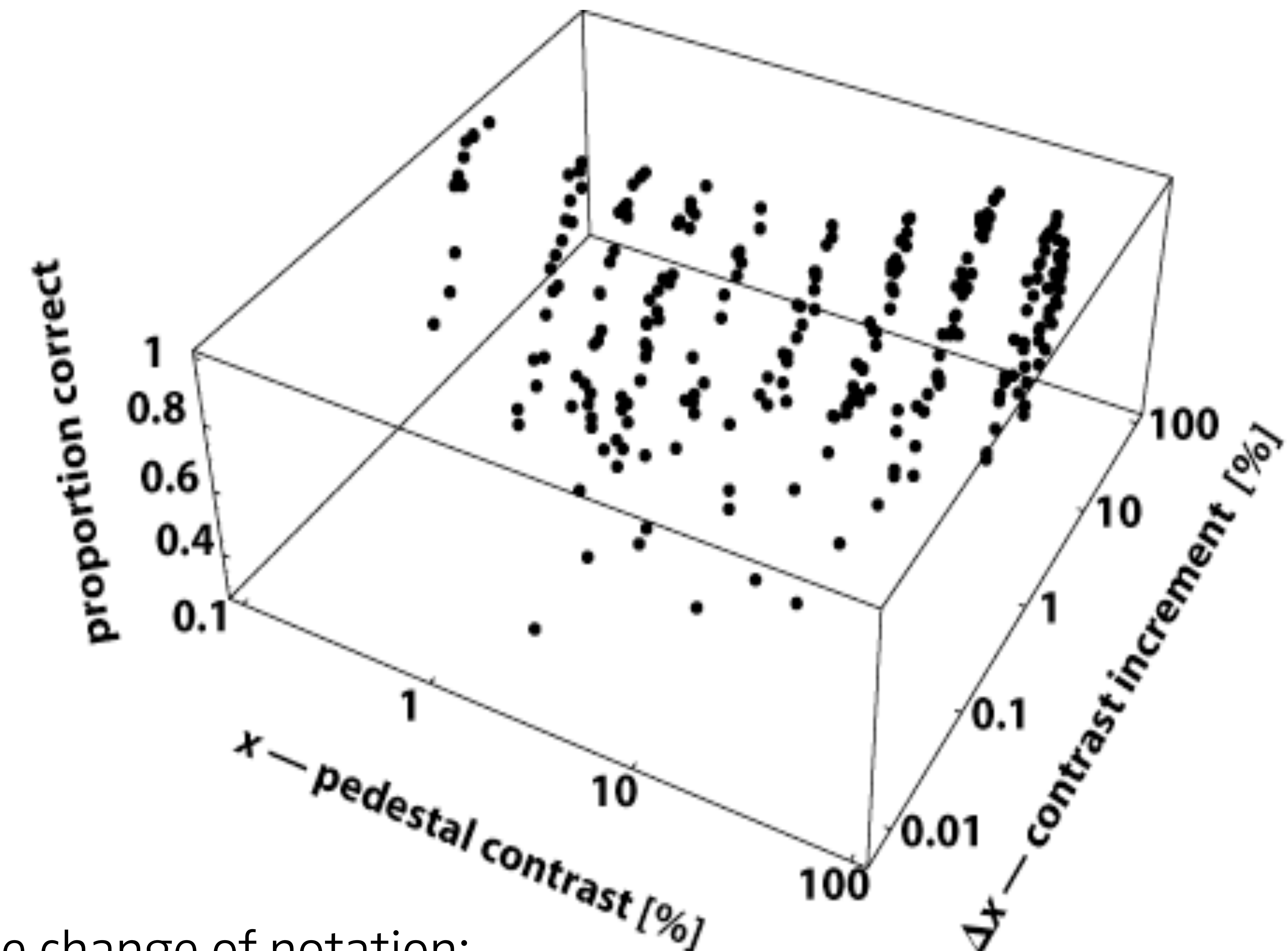


Fig. 4. A hypothetical relation between E, internal effect of a grating, and c, its contrast: $E \propto c^2$. The two ΔE intervals are equal; corresponding Δc intervals are not, the one starting at $c = 0$ being four times larger.

Contrast Discrimination—The "Dipper" Function

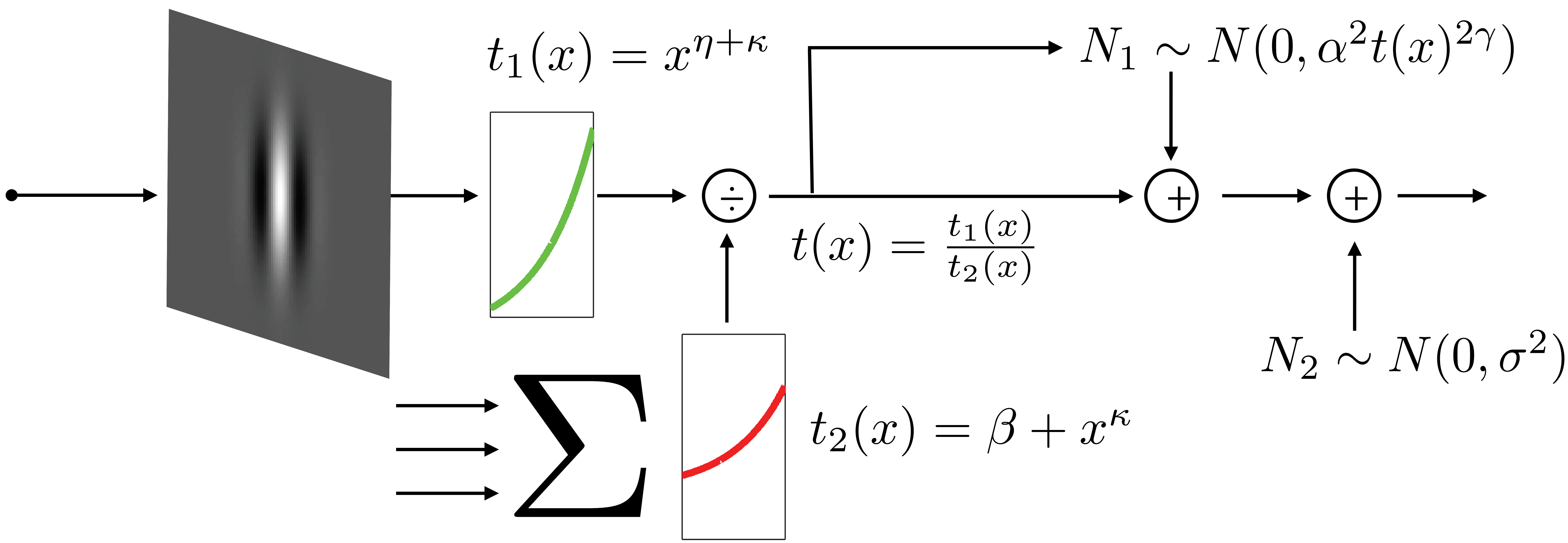


Contrast Discrimination—Real Data



Note the change of notation:
x for the pedestal contrast, Δx for the contrast increment.

Contrast Discrimination Models



Contrast Discrimination Models

Given the transduction mechanism and noise sources as previously discussed, the function f provides the model predictions on the range $[0 \ldots 1]$ (proportion correct) during 2-AFC. It is given by:

$$\mathrm{f}(\Delta x, x) = \int_0^\infty \left(\sqrt{2\pi \mathrm{h}(\Delta x, x)}\right)^{-1} \exp\left(-\frac{(z - \mathrm{g}(\Delta x, x))^2}{2\,\mathrm{h}(\Delta x, x)}\right) \mathrm{d}z,$$

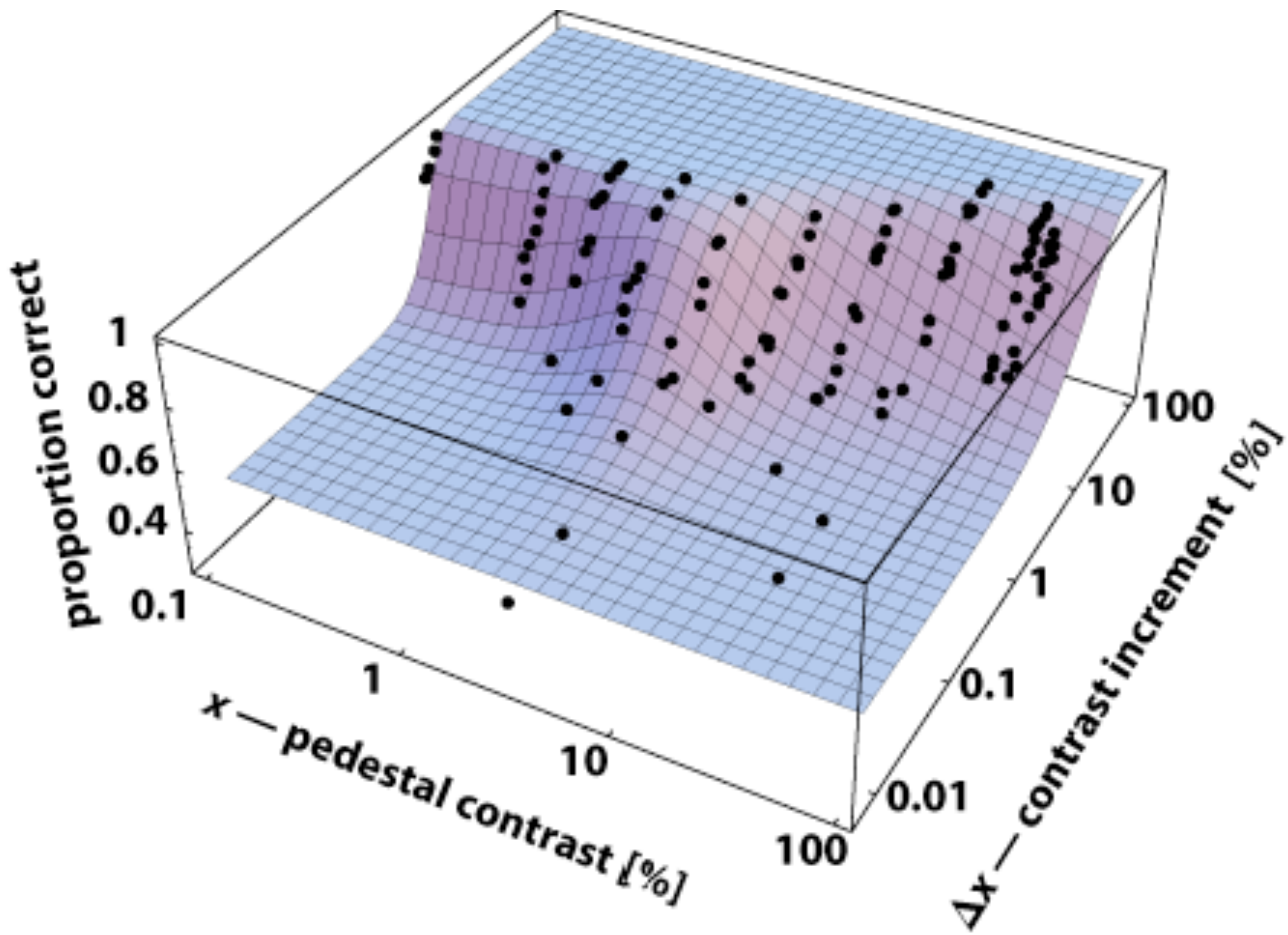
where

$$\mathrm{g}(\Delta x, x) = \frac{(\Delta x + x)^{\eta+\kappa}}{\beta + (\Delta x + x)^\kappa} - \frac{x^{\eta+\kappa}}{\beta + x^\kappa},$$

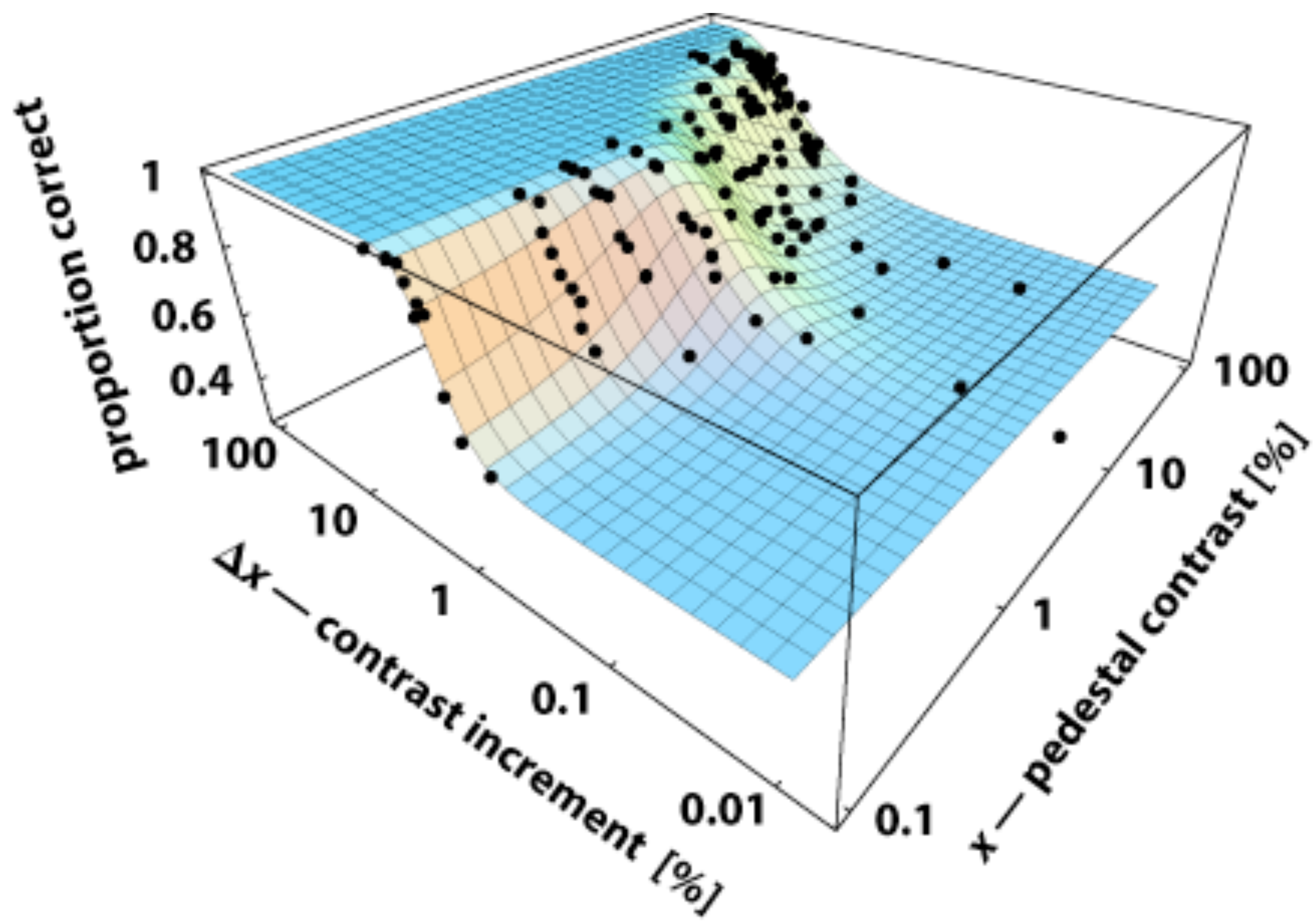
and

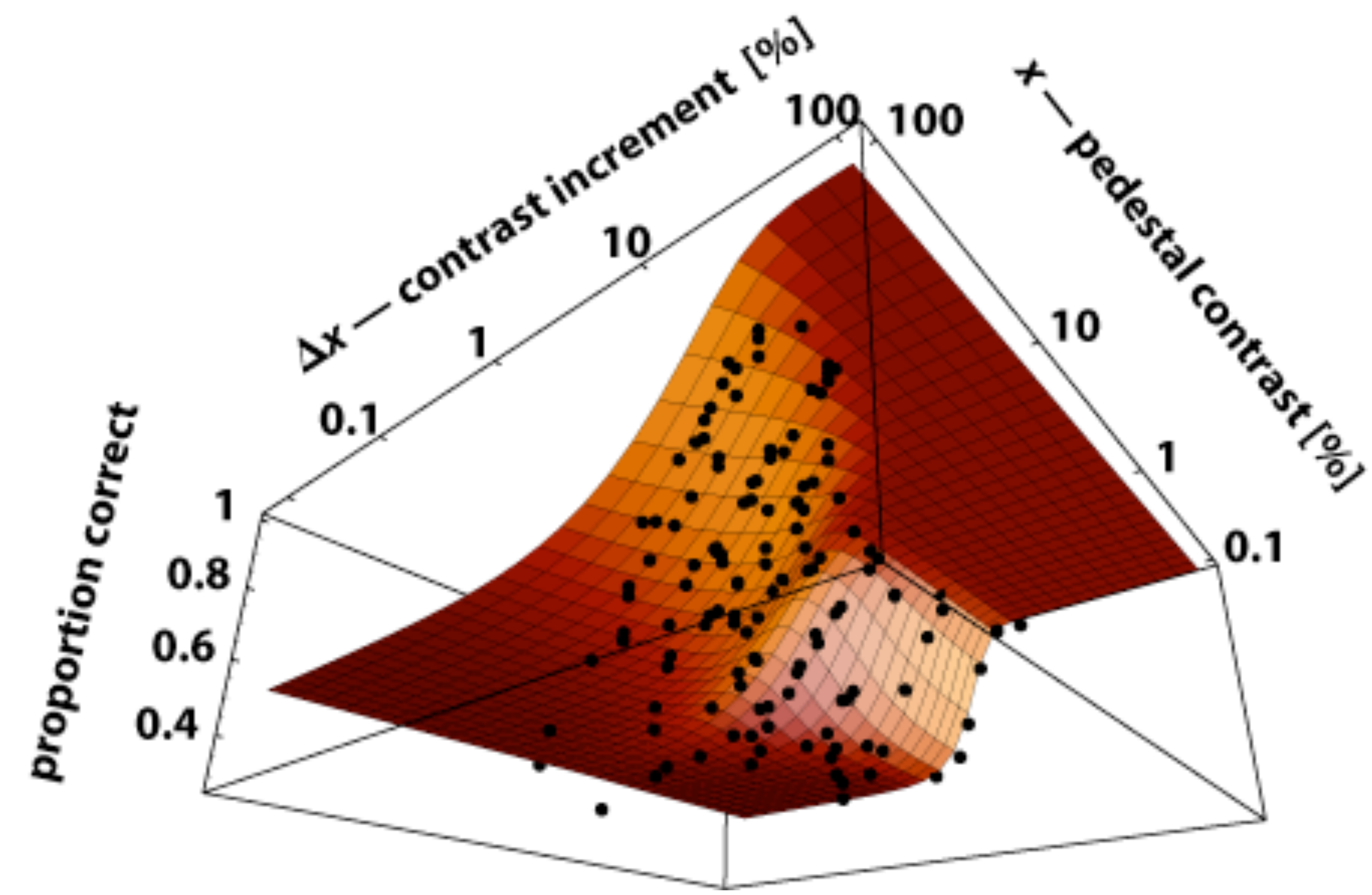
$$\mathrm{h}(\Delta x, x) = 2\sigma^2 + \alpha^2 \left(\left(\frac{(\Delta x + x)^{\eta+\kappa}}{\beta + (\Delta x + x)^\kappa} \right)^{2\gamma} + \left(\frac{x^{\eta+\kappa}}{\beta + x^\kappa} \right)^{2\gamma} \right).$$

Contrast Discrimination Models—Model Fit

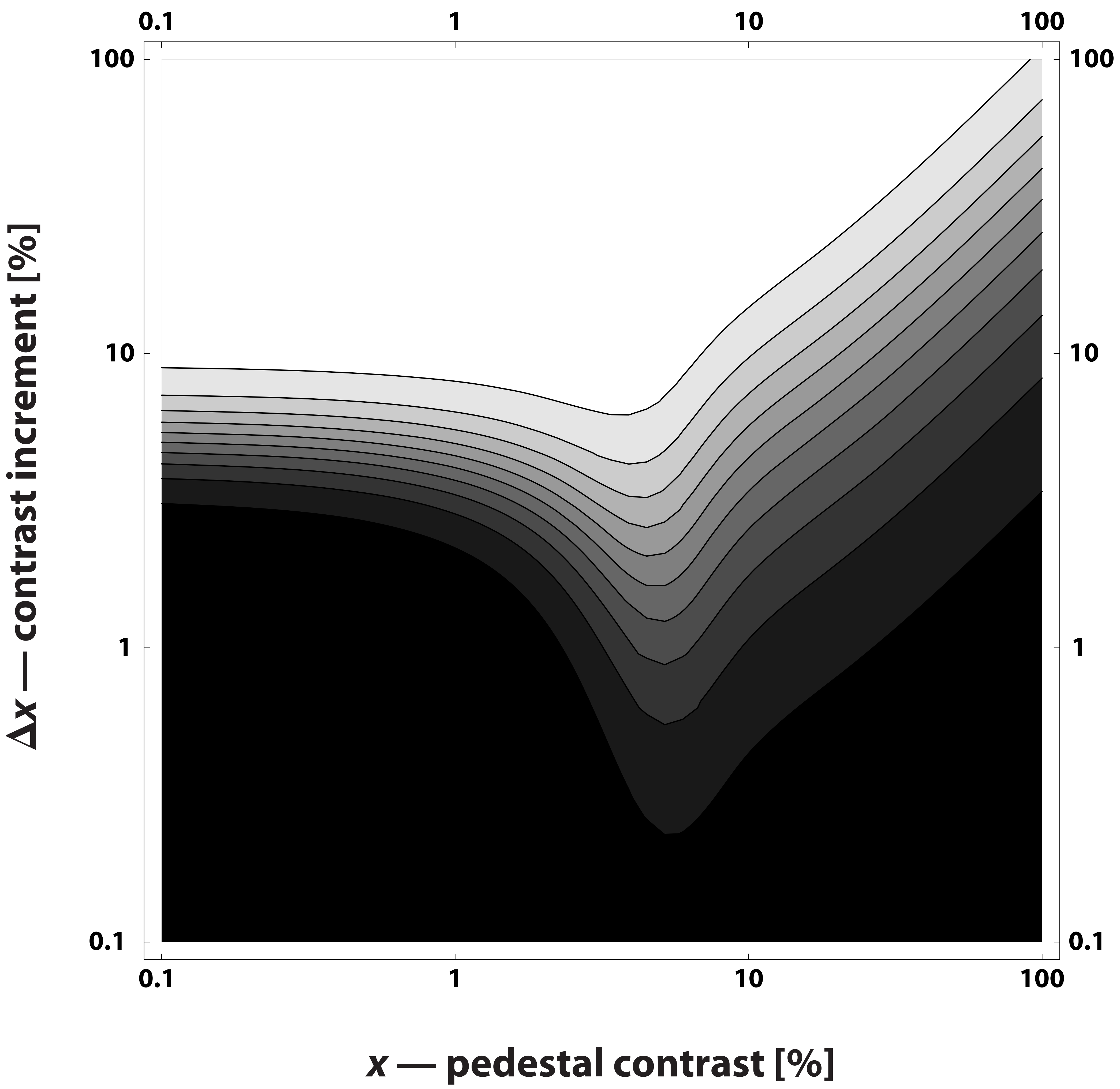


Contrast Discrimination Models—Model Fit





Contrast Discrimination Models—Dipper Predictions



The End

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