J. Physiol. (1971), **219**, *pp.* 355–365
With 5 text-figures
Printed in Great Britain

THE DETECTION OF GRATINGS IN NARROW-BAND VISUAL NOISE*

By BARBARA E. CARTER and G. BRUCE HENNING†
From the Defence Research Establishment Toronto, Downsview, Canada

(*Received 24 May 1971*)

SUMMARY

1. The detectability of sinusoidal gratings comprised of either one or many cycles was measured in veiling luminances the spatial frequencies of which were either narrow- or broad-band.

2. In narrow-band noise, the single-cycle grating was detected with approximately 0·6 log units less contrast than the many-cycle grating. On the other hand when both broad-band and narrow-band noise were present, there was no measurable difference in the detectability of the two types of grating.

3. The results are interpreted as supporting the hypothesis of Campbell & Robson (1968) that spatially varying luminance patterns are processed by mechanisms selectively sensitive to limited ranges of spatial frequencies.

INTRODUCTION

Campbell & Robson (1968), Blakemore & Campbell (1969) and Sachs, Nachmias & Robson (1971) have suggested that the behaviour of the eye in detecting or discriminating among spatial patterns can be described as that of a series of broadly tuned filters sensitive to approximately an octave band of spatial frequencies. The similarity between Helmholtz's theory of frequency representation in the auditory system and the Campbell & Robson model of visual spatial frequency analysis leads readily to the consideration of visual analogues of the many auditory experiments bearing on the frequency selectivity of the ear (Campbell, Nachmias & Jukes, 1970; Graham & Nachmias, 1971; Kulikowski, 1969). The experiment reported here is analogous to some auditory experiments of Wightman & Leshowitz (1970) and Leshowitz & Wightman (1971), and the results, readily predicted from Campbell & Robson's hypothesis, support the suggestion that in representing visual spatial frequencies the behaviour

* D.R.E.T. Paper No. 789.

† Present address: MRC-APU, 15 Chaucer Rd., Cambridge.

of the eye can be considered as similar to the behaviour of Helmholtz's model of the ear.

Consider the effect of a veiling luminance, the spatial frequency components of which are confined to a narrow band of frequencies centred about some frequency f_0 c/degree. If spatially varying luminance patterns are processed by mechanisms selectively sensitive to limited ranges of spatial frequencies, it would be expected that the veiling luminance should significantly affect the detectability only of signal gratings the principal spatial frequencies of which fall within the octave centred on f_0 in a way similar to that demonstrated for sinusoidal veiling luminances by Kulikowski (1969). One such signal grating would consist of many cycles of a sinusoidal grating of frequency f_0 c/degree. On the other hand, the detection of a signal consisting of one cycle of a sinusoidal grating might not be affected by narrow-band noise since the signal may be considered to be composed of a very broad band of frequencies (Kelly, 1970).

The distinction between one and many cycle signals may be made clear by considering the energy density spectrum (Lee, 1963). The 'energy', E, of a grating (assuming a mean luminance component of value 1) is given by

$$E = c^2 \int_{-\frac{1}{2}S}^{\frac{1}{2}S} \sin^2 (2\pi f_0 s)\, ds, \tag{1}$$

where c is the contrast (Campbell & Green, 1965) and S the extent of the grating in degrees. The energy of the grating is distributed over all spatial frequencies in a way dependent on the contrast, frequency, phase, and spatial extent of the grating. The energy density spectrum for a sine grating of finite extent is given by

$$E(f) = \frac{f_0^2 c^2 (2 - 2\cos 2\pi f S)}{(f_0^2 - f^2)^2}. \tag{2}$$

Where f_0 is the frequency of the signal (c/degree) and f the spatial frequency axis. Fig. 1 shows the function of eqn. (2), in the neighbourhood of 5·9 c/degree, for a 5·9 c/degree grating comprised of one or 160 cycles. The ordinate is logarithmic, the abscissa linear. (It should be noted that the 160 c/degree grating has zero energy density at intervals of 0·018 c/degree. The zeros are not shown in Fig. 1.) It can be seen for an extensive grating ($S \gg 1/f_0$), that the energy of the grating is concentrated near the spatial frequency of the signal. On the other hand, for a grating of the same energy comprised of only one cycle there will be energy in frequency regions far removed from f_0, the nominal frequency of the grating. Thus, the energy in a grating comprised of many cycles is confined to a much narrower frequency band than a grating comprised of only a few cycles. If the visual system analyses spatial patterns separately into different frequency regions, then it might be expected (in the presence of a narrow-band noise), that a many cycle grating will be more difficult to detect than a single cycle of a grating of the same nominal frequency. In the single cycle case, the observer should be able to detect energy components of the signal in frequency bands remote from and unaffected by the narrow-band noise in the veiling luminance. The addition of low-level

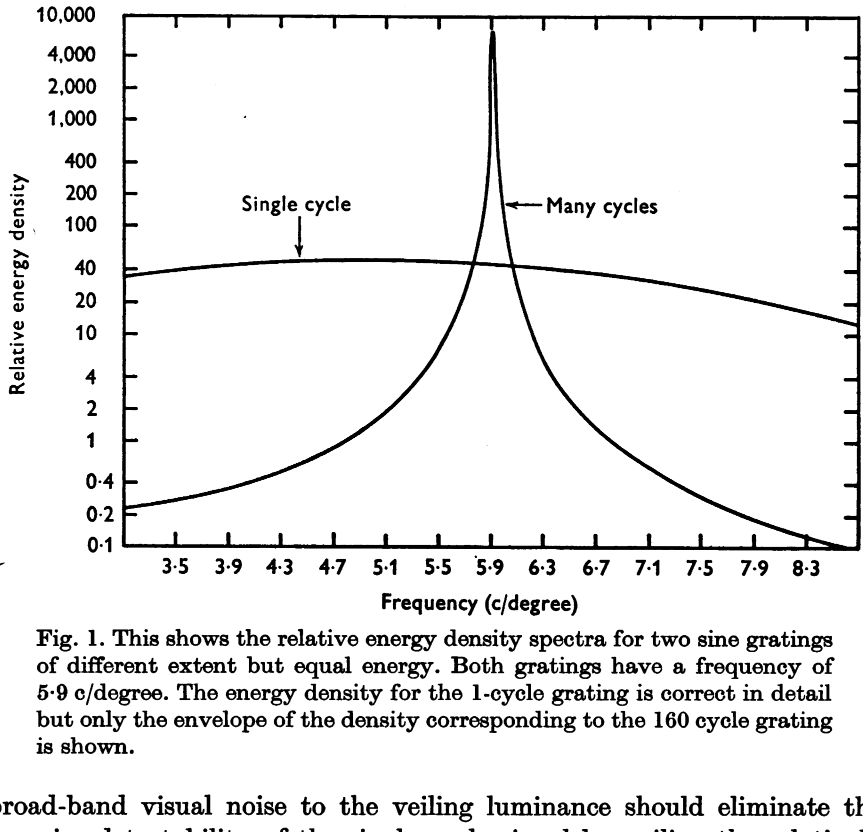

Fig. 1. This shows the relative energy density spectra for two sine gratings of different extent but equal energy. Both gratings have a frequency of 5·9 c/degree. The energy density for the 1-cycle grating is correct in detail but only the envelope of the density corresponding to the 160 cycle grating is shown.

broad-band visual noise to the veiling luminance should eliminate the superior detectability of the single cycle signal by veiling the relatively low levels of signal energy in any given band. These predictions are confirmed in the following experiments.

METHODS

Two trained observers (the present authors) participated in a standard two-interval forced-choice detection experiment. They were required to state in which of two intervals a sinusoidal grating pattern had been presented. Each trial consisted of a 150 msec warning noise, followed by the first 1·1 sec observation period. After a 560 msec pause, a second observation interval was presented, and this was followed by a 750 msec response interval during which the observer was required to state whether the first or second observation interval had contained the signal grating. There was a lapse of 600 msec between trials during which the observers were informed by tones which interval had in fact contained the grating. Bursts of auditory noise were used to indicate all intervals.

The grating to be detected was turned on and off slowly with a 100 msec rise and fall time and was either 1 or 160 cycles of a 5·9 c/degree sinusoid. The display had a mean luminance of 1·33 foot-lamberts unchanged by the addition of either noise or signal. In one set of conditions, the signal was presented in a background of continuous narrow-band visual noise of the same mean frequency as the signal. The narrow-band noise appeared as a uniformly striped screen with slow (2 Hz) changes in contrast and phase. The contrast changes were large and noticeable but the phase changes were slight. The contrast of the narrow-band noise was Rayleigh distributed in time (Davenport & Root, 1958) and had an average value of 57·58 %. In a second set of conditions, broad-band Gaussian masking noise of uniform spectral density over the range of spatial frequencies three octaves above and below the signal frequency was used in addition to the narrow-band noise. The broad-band noise had a contrast of 4·74 % per c/degree and appeared as a non-uniform and rapidly changing (in both space and time) field of stripes much like the projection of an extremely badly scratched motion picture film. (The finite decay-time (to 1 % in 475 μsec) of the display phosphor undoubtedly lowered the contrast of the highest frequencies in the broad-band noise.) In all conditions, the contrast of the signal was varied to trace a function relating the signal grating contrast to percentage of correct responses in two blocks of fifty trials for each condition.

The stimuli, viewed monocularly with corrected vision but natural pupils, were presented on a Hewlett-Packard 1300 A X-Y display having a P-4 phosphor (with green filter). There was a small, roughly circular fixation spot subtending about 0·2 degrees in the centre of the screen. (The spot was used by observer 2 but not by observer 1.) Relative to the centre of the fixation spot, the signal gratings were in sine phase. The roughly rectangular 8 by 10 in. screen was placed 21 in. from the observer in an otherwise dark room, and subtended 27 degrees horizontally and 22 degrees vertically at the observer's eye. The display had a nearly linear luminance gradient of less than 0·09 log units over the full width. The signal was generated in the manner described by Campbell & Green (1965), by a system of two independently operating Wavetek Model 116 oscillators and the sweep generator of a Philips PM 3231 oscilloscope. The narrow-band noise was generated by passing Gaussian noise through a 1·5 Hz band pass filter (Spectral Dynamics Corporation Dynamic Analyzer, Model SD 101B), whose centre frequency was locked to that of the signal. The broad-band noise was Gaussian noise of uniform average power-density passed through a Kron-Hite filter set at the appropriate high and low pass limits.

Luminances were measured with a Pritchard Spectra Photometer which was also used to determine the maximum contrast possible without harmonic distortion. The harmonic distortion of the grating was checked by permitting the oscillators and oscilloscope to run independently, generating a nominally sinusoidal, low frequency grating which drifted past the 30 min aperture of the photometer at the rate of 30 Hz. The output of the emitter-follower of the photometer (whose frequency response is independent of frequency up to about 200 Hz at the luminance used) was monitored by a filter having a 6 Hz passband. The onset of harmonic distortion in the grating was readily determined as an abrupt change in the level of the third harmonic. The contrast just below which distortion began was taken as the maximum contrast (73 % in the present case) for which a truly sinusoidal grating could be produced. This level corresponded closely with the limits of the linear range of luminance versus voltage plots of the entire system.

RESULTS

In Fig. 2, the percentages of correct responses in one hundred trials are shown for one observer as a function of contrast. The results for single cycle (0·169 degree) signals are represented by triangles and the 160 cycle (27·04 degree) signals by squares. With narrow-band noise alone (filled symbols), the single cycle grating is detected at much lower contrasts

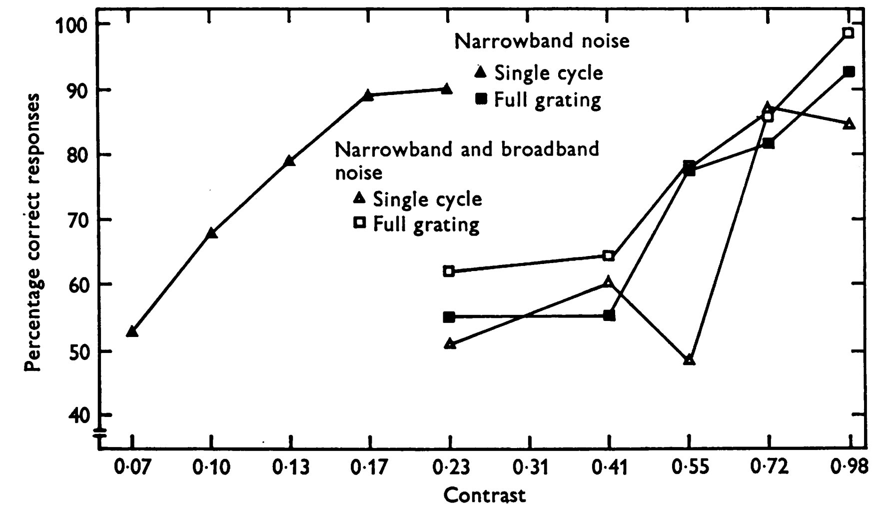

Fig. 2. This shows the percentage of correct responses in a standard two-alternative temporal forced-choice detection experiment (on a linear scale) as a function of the signal grating contrast (on a logarithmic scale). The signal gratings had a nominal spatial frequency of 5·9 c/degree. The triangles indicate data for gratings comprised of a single cycle – the squares for full gratings comprised of 160 cycles. The filled symbols indicate data taken with a narrow-band veiling luminance having a mean contrast of 57·58 % and the open symbols data taken with the same narrow-band noise plus broad-band noise having a mean contrast of 4·74 % per c/degree. Data are for Observer B.E.C.

than the 160 cycle grating. For example, a 75 % correct response level is obtained at a contrast of 12 % for single cycle grating whereas the 160 cycle grating requires 55 % contrast to achieve the same performance level.

The addition of broad-band noise (open symbols) produces no measurable change in performance for the 160 cycle grating. However, for the single cycle grating, there is a substantial decrease in performance with the addition of broad-band noise. When both the broad-band and narrow-band noise are present, there is no measurable difference between the detectability of the single cycle and many cycle signals.

Similar results for a second observer are shown in Fig. 3.

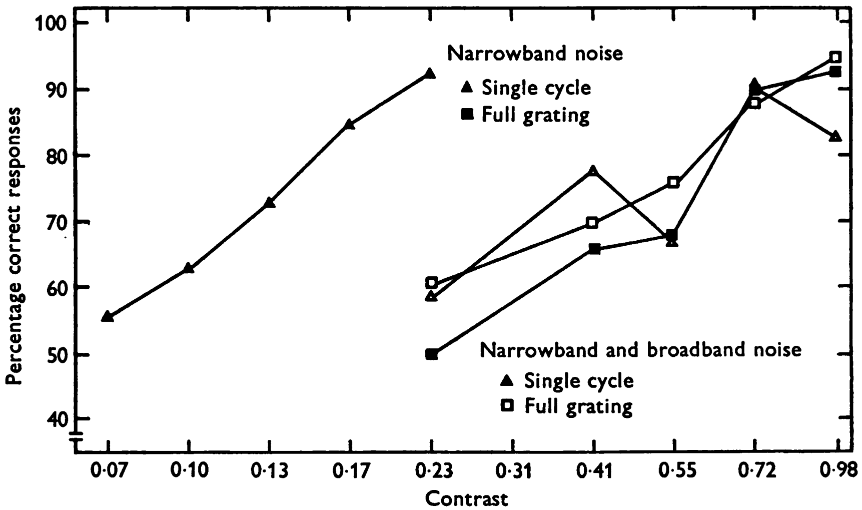

Fig. 3. This shows the percentage of correct responses in a standard two-alternative temporal forced-choice detection experiment (on a linear scale) as a function of the signal grating contrast (on a logarithmic scale). The signal gratings had a nominal spatial frequency of 5·9 c/degree. The triangles indicate data for gratings comprised of a single cycle – the squares for full gratings comprised of 160 cycles. The filled symbols indicate data taken with a narrow-band veiling luminance having a mean contrast of 57·58 % and the open symbols data taken with the same narrow-band noise plus broad-band noise having a mean contrast of 4·74 % per c/degree. Data are for Observer G.B.H.

DISCUSSION

Although the results of the experiment just described seem clearly to support Campbell and Robson's hypothesis, other detection schemes capable of producing similar results should be considered. For example, Campbell, Carpenter & Levinson (1969) have considered the possibility that the 'peak-to-trough' ratio in the output of a linear system having the spatial modulation transfer function of the eye might be the appropriate variable in determining the detectability of gratings. The many cycle and single cycle gratings of the present experiment were among several stimuli used by Campbell *et al.* (1969). At high spatial frequencies the predictions derived from the peak-to-trough ratio of the wave form resulting from the convolution of the stimulus gratings with the appropriate line-spread function were confirmed. Moreover, at low spatial frequencies, as their model predicts and unlike our findings with narrow-band noise, Campbell *et al.* (1969) found a many cycle (full) grating to be detected at lower contrast than a single cycle grating of the same nominal frequency. In the study by Campbell *et al.* (1969), however, signal gratings were detected against a uniform veiling luminance having no spatially varying components. It might be expected that the results from an experiment with broad-band noise alone should produce similar results (assuming the limiting spatially varying 'internal noise' or 'dark light' in the study by Campbell *et al.* to be more or less broad-band). Fig. 4 shows the results of a supplementary experiment in which the observers were required to detect one or many cycle gratings in broad-band noise of the same average contrast used in the main experiment.

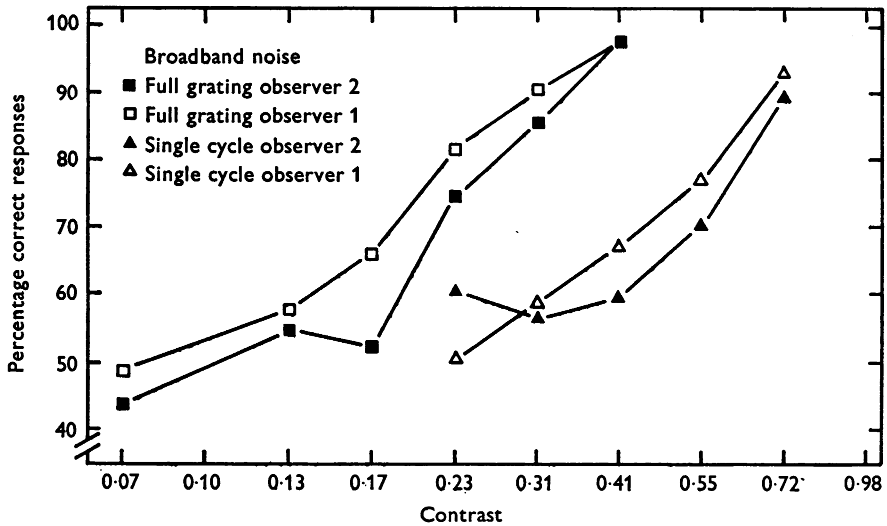

Fig. 4. This shows the percentage of correct responses in 100 trials of a standard two-alternative temporal forced-choice experiment (linear scale) as a function of the contrast (logarithmic scale) of the 5·9 c/degree sinusoidal gratings to be detected. The squares represent full grating data and the triangles data for gratings of 1 cycle only. The open symbols are for observer 1, the filled for observer 2. Broad-band visual noise having a mean contrast of 4·74 % per c/degree was used.

In broad-band noise, the many cycle grating is detected at between 0·3 and 0·4 log units less contrast than the single cycle grating. This finding is comparable to the 0·24 log unit difference at 6 c/degree found by Campbell *et al.* (1969). They attribute 0·15 log units of this difference to 'criterion' changes. However, given the forced-choice procedure used, it is unlikely that our broad-band detection data can be attributed to criterion changes in the usual detection theory sense of the word (Green & Swets, 1966).

The discrepancy between the 0·3 log unit effect and the small effect predicted by Campbell *et al.* (1969) on the assumption that the peak-to-trough ratio of the image is the appropriate variable may be due to errors in the estimation of the peak-to-trough ratio introduced by using an approximation good only at high spatial frequencies.

A further implication of the assumption that the peak-to-trough ratio of the image is the variable used by observers in detecting gratings is the shape of the psychometric function. With full gratings, the only effect of convolution with the line spread function is attenuation. Thus the peak-to-trough ratio in the image will be proportional to that in the object grating. The same proportionality constant will relate the mean noise contrast of the object to that of the image if the noise is narrow-band. Thus, in this case, the performance of an observer basing his judgment on the image peak-to-trough ratio can be readily determined from the characteristics of the object signal and noise.

Because the narrow-band noise changes slowly relative to the observation interval, we can reasonably assume the noise contrast to be fixed for any given observation but to vary from observation to observation. The contrast, C, then is Rayleigh distributed from trial to trial (Davenport & Root, 1958) with probability density, $p_n(C)$, given by

$$p_n(C) = \begin{cases} [C/\sigma^2]\,[\exp-(C^2/2\sigma^2)] & (C \geqslant 0) \\ 0 & \text{otherwise,} \end{cases} \qquad (3)$$

where σ is proportional to the mean noise contrast. Similarly, the contrast produced in intervals in which a signal grating of contrast k is added to the noise has a probability distribution, $p_{\mathrm{s+n}}(C)$, given by

$$p_{\mathrm{s+n}}(C) = \begin{cases} [C/\sigma^2]\,[\exp-((C^2+k^2)/2\sigma^2)]\,[I_0(kC/\sigma^2)] & (C \geqslant 0) \\ 0 & \text{otherwise,} \end{cases} \qquad (4)$$

where $I_0(x)$ is a modified Bessel function of the first type and zero order. The percentage of correct responses, P_{c}, predicted for the two-alternative forced-choice task used in this experiment is thus given by,

$$P_{\mathrm{c}} = \int_0^\infty p_{\mathrm{s+n}}(C) \int_0^C p_{\mathrm{n}}(y)\,\mathrm{d}y\,\mathrm{d}C. \qquad (5)$$

The right-hand curve of Fig. 5 shows the prediction of this model for the full grating in narrow-band noise condition together with the data from observer 2. The prediction appears not unreasonable but requires the assumption that σ equal 0·1265. Since σ^2 is equal to $2/\pi$ times the square of the mean noise contrast (0·5758, in this case) multiplied by the band width of the noise, the estimated noise band width is 0·113 c/degree. This is contrary to fact since the noise band width was of the order of 0·001 c/degree, i.e. two orders of magnitude smaller than that obtained from the model. This failure might be interpreted as indicating a high level of internal noise or that some variable other than 'peak-to-trough' ratio, such as phase, is being used.

Again, under the assumption that peak-to-trough ratio is the crucial variable, we may calculate the effective band width of the broad-band noise. The left-hand curve of Fig. 5 shows a reasonable fit to the data for the detection of a 160 cycle grating in broad-band noise based on eqn. (5). The parameter σ in this case had the value 0·5771. Since σ is equal to the product of the mean noise contrast per c/degree and the square root of the effective band width, estimates of that band width may be obtained. The estimated band width is 7·02 c/degree (very nearly two octaves); a factor of two greater than the findings of other masking and adaptation studies.

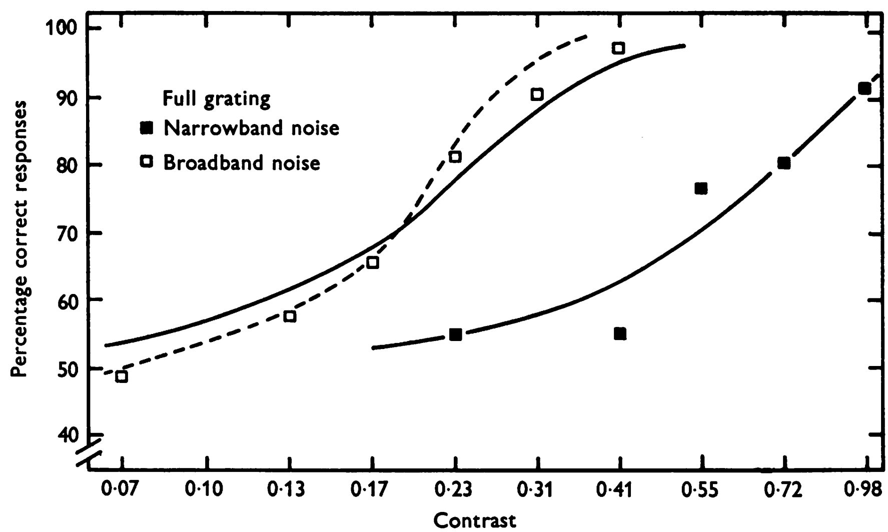

Fig. 5. In this Figure the continuous curves show the percentage of correct responses predicted from the assumption that the observer based his decision on the 'peak-to-trough' ratio of his image of the 160 cycle grating. These predictions are presented with the data for observer 2 (from Figs. 3 and 4) for a full grating in broad-band and in narrow-band noise. The dashed line indicates the predictions derived from the assumption that the observer based his decision on the energy in the grating.

There are, of course, a number of variables (such as, possibly, the differences in the temporal properties of the narrow- and broad-band noise) which might lead to significant differences in visual processing between the narrow- and broad-band noise conditions even though the peak-to-trough ratio remain the dimension on which observers base their judgments.

Another possible dimension on which observers might depend is the energy of the image grating. However, since grating energy (eqn. (1)) is a monotonic function of grating contrast, identical psychometric functions can be predicted for both peak-to-trough and energy based decisions. Nevertheless, some calculations for energy based decisions follow.

The energy of the observers' image when noise alone is present is proportional to a χ-square distribution with $2WS$ degrees of freedom. The parameter W is the noise band width in c/degree and S is the extent of the noise field in degrees. If a signal of contrast, z, is added to the noise, then the energy is proportional (with the same proportionality constant) to a non-central χ-square distribution with $2WS$ degrees of freedom and non-central parameter $2z^2S/c_n^2$ where c_n is the mean noise contrast per c/degree (Green & Swets, 1966). Reasonable fits to the data are readily obtained by choosing an appropriate value for the quantity $2WS$ and substituting the normal approximations of the appropriate densities into eqn. (5). Moreover, under the assumption that the observer bases his decision on grating energy, realistic estimates of the noise band width, W, can be taken, together with the physical parameters of the experiment and the performance levels achieved, to yield estimates of a single undetermined parameter, S, the width of the field used by the observer. Using the octave band width (4·2 c/degree) at 5·9 c/degree, the estimate of the field size is 26·2 degrees surprisingly close to the very large 27 degree field actually used.

However, a significant difficulty with the assumption that the observer bases his decisions on the energy of the image grating is the prediction, for the broad-band noise conditions, that the 26·2 degrees of the many cycle grating used by the observer should be at least 1·42 log units more detectable than the single cycle grating. The obtained difference was closer to 0·3 log units.

It is not clear, then, whether observers base their decisions on the peak-to-trough ratio of their image of the grating. On the other hand, in view of the not unreasonable fit of the energy model predictions to the obtained psychometric functions, one might wish to conclude that the energy in the observers' image of the gratings is used. In any case, it is clear that the concept of the energy density spectrum of the object grating, together with the Campbell & Robson (1968) hypothesis that the visual system analyses spatial frequencies in separate bands, leads to qualitatively predictable results.

We acknowledge our gratitude to Professor J. Nachmias of the University of Pennsylvania for his criticism and encouragement and to Mr B. Crabtree of this establishment for his technical assistance.

REFERENCES

BLAKEMORE, C. & CAMPBELL, F. W. (1969). Adaptation to spatial stimuli. *J. Physiol.* **200**, 11–13*P*.

CAMPBELL, F. W. & GREEN, D. G. (1965). Optical and retinal factors affecting visual resolution. *J. Physiol.* **181**, 576–593.

CAMPBELL, F. W., CARPENTER, R. H. S. & LEVINSON, J. Z. (1969). Visibility of aperiodic patterns compared with that of sinusoidal gratings. *J. Physiol.* **204**, 283–298.

CAMPBELL, F. W., NACHMIAS, J. & JUKES, J. (1970). Spatial-frequency discrimination in human vision. *J. opt. Soc. Am.* **60**, 555–559.

CAMPBELL, F. W. & ROBSON, J. G. (1968). Application of Fourier analysis to the visibility of gratings. *J. Physiol.* **197**, 551–556.

DAVENPORT, W. B. Jr. & ROOT, W. L. (1958). *Random Signals and Noise*. New York: McGraw-Hill Inc.

GRAHAM, N. & NACHMIAS, J. (1971). Detection of grating patterns containing two spatial frequencies: a comparison of single-channel and multiple-channel models. *Vision Res.* (In the Press.)

GREEN, D. M. & SWETS, J. A. (1966). *Signal Detection Theory and Psychophysics*. New York: John Wiley and Sons, Inc.

KELLY, D. H. (1970). Effects of sharp edges of the visibility of sinusoidal gratings. *J. opt. Soc. Am.* **60**, 98–103.

KULIKOWSKI, J. J. (1969). *Warunki graniczne percepcji wzrokowej*. Warsaw: Prace Instytutu Automatyki Pan.

LEE, Y. W. (1963). *Statistical Theory of Communication*. New York: J. Wiley and Sons, Inc.

LESHOWITZ, B. & WIGHTMAN, F. L. (1971). On-frequency tonal masking. *J. acoust. Soc. Am.* **49**, 1180–1190.

SACHS, M. B., NACHMIAS, J. & ROBSON, J. G. (1971). Spatial-frequency channels in human vision. *J. opt. Soc. Am.* **61**, 1176–1186.

WIGHTMAN, F. L. & LESHOWITZ, B. (1970). Off-frequency tonal masking. *J. acoust. Soc. Am.* **47**, 107(A).