Effects of different hypothetical detection mechanisms on the shape of spatial-frequency filters inferred from masking experiments: I. noise masks

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The detectability of a sinusoidal grating was measured in a standard two-interval forced-choice experiment against backgrounds of noise gratings of the same orientation as the signal. The noise gratings were either spatially high-pass or low-pass filtered and were either unchanged in each observation interval (static) or flickering at a rate that depended on their cutoff frequency (dynamic). Spatial-frequency-selective mechanisms are inferred from the data and their characteristics shown to depend on assumptions concerning the detection process thought to follow the spatial-frequency-selective device.

INTRODUCTION

The hypothesis that the visual system is like a set of filters or channels, each selectively sensitive to a limited range of spatial frequencies,[1] forms a particularly simple and attractive basis for models of pattern perception. If those cortical units shown to be selectively sensitive to bands of limited spatial frequency over a limited range of orientations[2–4] could legitimately be treated as elements whose function was to signal the presence of certain spatial frequencies at particular orientations and in particular regions then we should, perhaps, be able to make a start at building adequate models of the way in which we perceive patterns. We cannot, of course, deduce the function of a neural unit from its properties; rather we must attempt to determine the behavior of a system in which elements having certain properties serve particular functions and, comparing the behavior of that system with the behavior of our observers, attempt to establish some evidence that the elements indeed serve the function hypothesized.

In order to incorporate spatial-frequency-selective elements, or channels, into an adequate model of pattern perception, we need to know quite a lot about the elements themselves; we need to know their form of processing—linear or nonlinear; we need to know how restricted the receptive fields of the elements are; and we need to know how their outputs are combined. We need to know the details of the frequency selectivity of the elements—how the sensitivity of a channel changes as the spatial frequency of the stimlus is altered from that which is most effective—before we can use the concept to make rigorous predictions.

One major difficulty is that we cannot readily determine all the relevant aspects of a system in isolation, and each different assumption about any single stage of the process affects our inferences about the characteristics of the others.

Many of these difficulties have been considered in auditory pyschophysics, in which the determination of the spectral sensitivity of elements thought to be tuned to limited bands of audio frequency has been a central problem since Hemholtz's treatise[5] of 1877. Only a few attempts to establish the complete shape of spatial-frequency-selective channels in vision have been made.[6–8] Patterson and Henning[9] have dealt with many of the theoretical issues involved in inferring filter shapes from various sets of data, but Nachmias[10] clearly indicated the most serious difficulty: the shape of the filter one infers from one's data depends on the form of the detection mechanisms assumed to follow the filter.

Our experiment, an adaptation of one of Patterson's auditory experiments,[11] is an attempt to determine the spectral sensitivity of the visual channels. The experiment has some features in common with experiments of Greis and Röhler[12] and Stromeyer and Julesz,[8] and our data are similar to theirs. However, we consider the effects of two common assumptions about subsequent detection mechanisms on the shape of the channels that we infer and, depending on the assumption, reach rather different conclusions about the shape of the filter.

EXPERIMENT 1

Procedure

Two authors[13] served as observers in a standard two-interval forced-choice grating-detection experiment. Two observation

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intervals, each 1 sec in duration and separated by a 600-msec pause, were marked for the observers by bursts of audible noise. The signal (a vertical sinusoidal grating turned on and off with 100-msec rise and fall times) was presented in one of the two intervals, and, in a subsequent 750-msec answer interval, the observers were required to indicate which interval had contained the signal. The signal always occurred in one of the observation intervals on each trial and had 0.5 probability of being in the first interval on each trial. After the answer interval, tones informed the the observers which interval had contained the signal. Each trial took about 3 sec, and trials with a fixed signal contrast and spatial frequency were performed in groups of 50 without a pause. After 50 trials, the signal contrast was changed and another set of 50 trials begun. Psychometric functions relating the percentage of correct responses (in 100 trials) to signal contrast were thus determined.

The vertical, sinusoidal signal grating filled a 6° square aperture in a matte black surround and was turned on and off without altering the mean luminance (5.1 cd/m^2) of the Hewlett-Packard 1300 X–Y display in which it was generated; observers' fixation was unconstrained. Harmonic distortion in the luminance pattern was negligible provided that the contract of the pattern was less than about 63%.

The signals to be detected were presented against a background of visual noise–vertical light and dark stripes of random width and contrast. Just as a sinusoidal grating is conveniently specified by the distribution of luminance along the line in the plane of the grating and normal to its orientation, so a noise grating is specified by the averages characterizing the distribution of luminance obtained along the same line. The characteristics of noise gratings, however, are more easily specified in terms of their average spatial-frequency characteristics. We used either low-pass or high-pass filtered noise. The low-pass noise contained a band of spatial frequencies all having the same mean contrast and all having spatial frequencies below some value—the cutoff spatial frequency. The high-pass noise consisted of spatial frequencies above some cutoff frequency with all components again having the same mean contrast. Thus either type of noise can be specified in terms of the mean contrast within the band of noise—the contrast density or the mean contrast per cycle per degree—and the cutoff frequency of the noise. In practice, of course, the high-pass filtered noise was bandpass noise with no components above some high spatial-frequency limit much greater than the nominal cutoff frequency of the filter. Further, the transition from passband to stop band for both types of noise was not abrupt but gradual, with a loss of contrast on the stop-band side of 2.4 log units per doubling of spatial frequency.

Both the signal and the noise were generated in the fashion described by Campbell and Green[14] with the apparatus used by Henning *et al.*[15] The signal and the noise waveforms were both stored in digital form and subsequently converted into analogue waveforms during each frame of the display. The frame rate was 100 Hz. During each 1-sec observation interval, a particular random sample of a noise waveform having the appropriate spatial-frequency characteristics was displayed to the observers. Thus the masking grating was unchanging (static) during the observation intervals. A different random sample of the noise was displayed in each observation interval. The signal, in the interval in which it occurred, always had the same phase. The noise-contrast density was adjusted for each signal frequency to obtain the maximum range of contrasts within the linear region of the display. Thus the noise-contrast density differed across signal frequencies and also between high- and low-pass conditions; it was held constant, of course, across cutoff frequencies within a condition.

Psychometric functions were measured against noise backgrounds with several cutoff frequencies both below and above the spatial frequency of the signal.

RESULTS

Figure 1 shows the relation between the percentage of correct responses and signal contrast obtained in the presence of low-pass filtered noise at several different cutoff frequencies. The spatial frequency of the signal grating was 6 cycles/deg, and each data point was based on 100 observations from observer BGH. When the cutoff frequency (nominally the spatial frequency of the component of the noise with the highest spatial frequency) is far below that of the signal, little

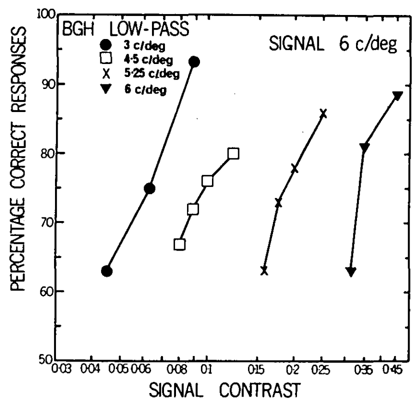

Fig. 1. The percentage-correct detection of a 6 cycles/deg grating in a standard 2IFC experiment as a function of the signal contrast. The parameter is the cutoff frequency of the low-pass filtered visual noise against which the grating was detected. Each data point is based on 100 observations from observer BGH.

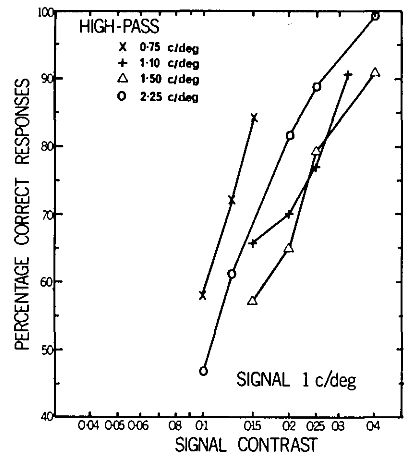

Fig. 2. The percentage-correct detection of a 1 cycle/deg grating in a standard 2IFC experiment as a function of the signal contrast. The parameter is the cutoff frequency of the high-pass filtered visual noise against which the grating was detected. Each data point is based on 100 observations from observer GBH.

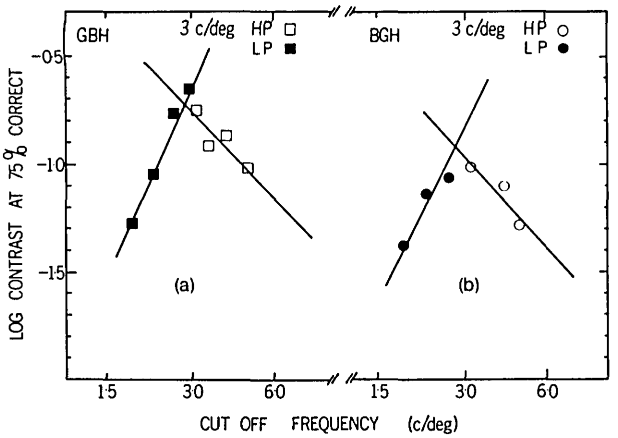

Fig. 3. The log signal contrast corresponding to 75% correct detection of a 3 cycles/deg grating as a function of the cutoff frequency of the visual masking noise. Data for (a) GBH and (b) BGH. Solid symbols, low-pass noise conditions; open symbols, high-pass noise conditions. The contrasts corresponding to 75% correct were obtained by interpolation from psychometric function based on 100 observations per point. (The signal contrasts have been adjusted between high- and low-pass conditions by a factor that depends on the noise-power density used in the two conditions.)

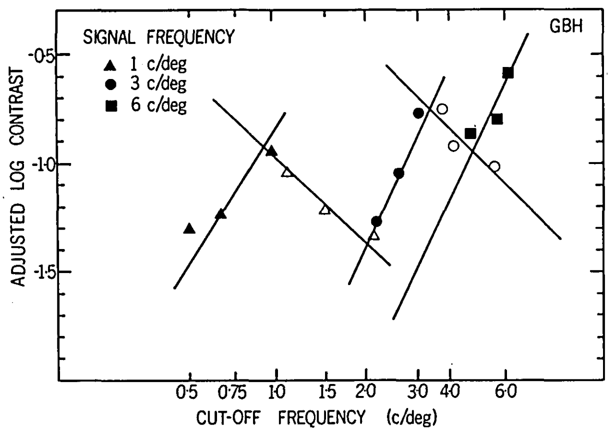

Fig. 4. The log contrast corresponding to 75% correct responses as a function of both high- and low-pass filtered visual noise at three different signal frequencies for observer GBH.

masking occurs; with a cutoff frequency of 3 cycles/deg the signal grating is detected when it has 6.5% contrast—a level that is close to, but still greater than, that which might be expected in the absence of any masking grating. When the cutoff frequency of the noise or masking grating is raised to be closer in frequency to that of the signal, more signal contrast is required to achieve any given performance level; that is, the signal grating becomes more difficult to see.

Figure 2 shows similar results for observer GBH detecting signals having a spatial frequency of 1 cycle/deg but this time in the presence of high-pass filtered noise with different cutoff frequencies. The results are again based on 100 observations per point.

Since we found that functions relating performance (linear) to signal contrast (logarithmic) are virtually parallel whatever the spatial frequency of the signal and whatever the cutoff frequency of the masking noise, it is reasonable to consider the effects of cutoff frequency on the signal contrast required to achieve only one level of performance. We have used the conventional 75% correct level, but any other level would yield similarly shaped functions.

Figure 3(a) shows the log contrast required for 75% correct detection of a 3 cycles/deg signal as a function of the cutoff frequency of both high- and low-pass filtered noise. The data are for observer GBH, and both scales are logarithmic. Figure 3(b) shows similar data for observer BGH. For both observers the data are reasonably well described over their 1-log-unit range by two straight-line segments.

If we were to treat the data as a direct indication of the shape of the visual channels, we should conclude that the channels were asymmetric, with attenuation of about 0.7 log unit of contrast per doubling of spatial frequency (15 dB/octave) below the frequency of maximum sensitivity and 0.4 log unit per doubling of spatial frequency (8 dB/octave) above that spatial frequency.

The results at the other spatial frequencies we used (Figs. 4 and 5) can be described exactly as those obtained at 3 cycles/deg; the data appear asymmetric on double-logarithmic coordinates showing a steeper gradient on the low-frequency side. The slopes are roughly independent of spatial frequency, and this fact might lead us to infer that the bandwidth of a channel (defined as the separation in spatial frequency

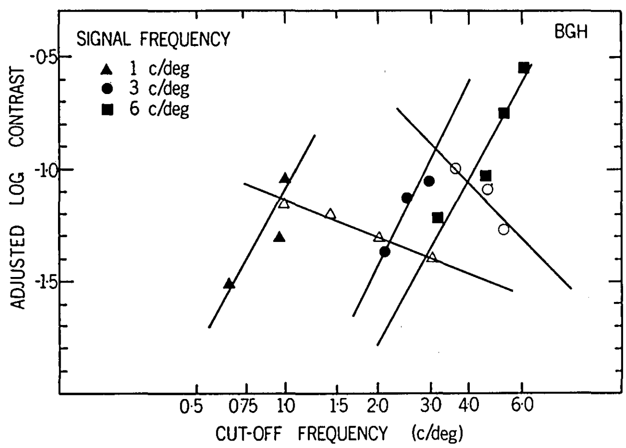

Fig. 5. The log contrast corresponding to 75% correct responses as a function of both high- and low-pass filtered visual noise at three different signal frequencies for observer BGH.

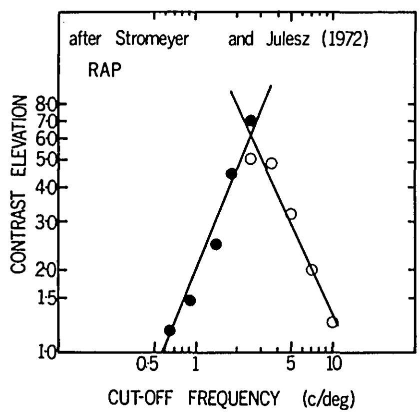

Fig. 6. Data calculated from Stromeyer and Julesz (Ref. 8). The ordinate, to facilitate comparison with Figs. 4 and 5, shows the ratio of the threshold contrast for masked signals to that for unmasked signals. The abscissa shows cutoff frequency, and both coordinates are logarithmic.

between the frequencies corresponding to some fixed attenuation) is proportional to spatial frequency.

Figure 6 shows, for comparison, results of Stromeyer and Julesz[8] at 2.5 cycles/deg. Although there are considerable differences between the signals and the experimental methods in the two studies, the results are similar. The chief difference is in the slope of the low-frequency side—0.37 log unit per halving of spatial frequency in the results of Stromeyer and Julesz, 0.7 log unit per halving in ours. The data of Greis and Röhler[12] show about 0.4 log unit per halving. The similarity of the results is somewhat surprising in that Stromeyer and Julesz[16] increased their noise-contrast density as they moved the cutoff frequency away from the signal frequency, whereas, in our experiment and that of Greis and Röhler,[12] the noise-contrast density was constant.[18,19]

DISCUSSION

In order to see how our data might be used to gain detailed knowledge of the spatial-frequency tuning of the mechanisms used to detect gratings, we must make some assumptions about the way in which the information derived from limited-band channels is processed; without some notion of the processing, it is impossible to see what data of the sort we have acquired might mean.

We must be concerned, for example, whether we can treat the frequency-selective aspect of the system as linear over the range of signal contrasts we used. Further, it is important to know whether results obtained with our level of mean noise-power density would be obtained at other contrasts. Both questions are addressed in a subsequent paper using sinusoidal masking stimuli. We show there that, over a wide range of masker frequencies, masking is roughly proportional to the contrast of the masking stimulus over a 1.2-log-unit range of masker level containing the masker contrasts used in this study. Consequently, we felt it reasonable to proceed as if the frequency-selective aspect of the system were effectively linear.

A second problem concerns the question of whether observers change from using one spatial-frequency-selective mechanism to another as the masking conditions change. Patterson[20] has shown that in hearing, in which frequency-selective mechanisms have attenuation characteristics with slopes of 5.0 log units per doubling of frequency, observers change the filter through which they listen in order to improve their performance, and Pelli[21] has suggested analogous behavior in vision. The relatively poor attenuation characteristics in vision make shifts of this sort unlikely; nonetheless, we felt obliged to confirm that the spatial-frequency-selective device (or channel) through which we assume our observers to be detecting signals did not change significantly from condition to condition.

To provide this check, we used Patterson's[20] technique of measuring the masking effect of the sum of low-pass and high-pass filtered noises that, by themselves, produce the same masking effect. In hearing, Patterson found very big differences—the sum of the two masking stimuli produced a masking effect that was 0.5 log unit greater than that produced by either stimulus used separately. (It was this large effect that suggested that observers were improving their performance in the presence of a single-sided noise by changing the frequency band through which they detected the signal.) Had Patterson's observers used only frequency-selective mechanisms centered on the signal frequency, Patterson would have obtained only about a 0.15-log-unit increase in masking, resulting from the addition of the power in the high- and low-pass noise through the auditory filter. Since we do not know what aspect of the visual "image" seen through a spatial-frequency-selective device is used by observers in detecting gratings, we cannot readily specify the magnitude of the effect that is predicted on the assumption that the observers do not alter the center frequency of the channel in different masking conditions. We should expect a 0.15-log-unit effect if observers use the equivalent of signal "power" or "energy" but a 0.3-log-unit effect if the observers use something like the peak-to-trough ratio in reaching their decisions. In fact we obtain effects of 0.3 log unit in each of three observers with two different combinations of high- and low-pass filtered noises. The two most reasonable interpretations of this result are either (1) that observers do not alter their frequency-selective mechanism and use the peak-to-trough ratio in the image or output of the device on which to base their decisions, or (2) that the observers use an energylike or powerlike quantity and shift the center frequency of the channel to improve their performance by 3 dB when different cutoff frequencies of the masking noise are used. A 3-dB improvement is within the range found by Pelli.[21]

We must now turn to the related and more difficult problem of interpretation and consider how the form of processing assumed to follow the frequency-selective device influences the channel shape inferred from our data.

We have assumed that we are dealing with a frequency-selective system that, at least with low-contrast signals, is not unreasonably approximated by a linear one and that the earliest stage in the system we use to detect gratings can be represented by the mechanism that limits the spatial-frequency response of the whole system. (These are common assumptions for psychological models but are unlikely to represent realistic sequences in neurophysiological systems. Nonetheless, the simple system might well have behavior similar to more complicated neurophysiological realizations of visual processing.)

We wish to determine the form of the spatial-frequency selectivity of a channel—the function $H(f)$—in which, because our stimuli are treated as one-dimensional displays, we need only one dimension of spatial frequency. If the system is to behave as a conventional bandpass filter, we should expect the function that represents the attenuation of the spatial-frequency filter $|H(f)|^2$ to have a maximum at some spatial frequency and to decrease monotonically on either side of that frequency. In order to determine its shape from our data, we must decide how the output of the filter (in response both to our masking stimuli and to our signal gratings) is processed.

One simple assumption is that our observers use the square of the contrast in the image of our stimuli seen through the spatial-frequency-selective channel and integrated over the extent of the display, as the measure on which to base their decisions. Such a decision statistic is analogous to the energy in a signal of finite extent and is given by

$$D = \int_{-S_0/2}^{S_0/2} \left[\int_{-\infty}^{\infty} x(s) h(\sigma - s) \mathrm{d}s \right]^2 \mathrm{d}\sigma, \qquad (1)$$

where $x(s)$ is the stimulus, $h(s)$ is the Fourier integral trans-form of $H(f)$, which is the spatial-frequency representation of the channel, and S_0 is the extent of the filtered grating. The integral within the square brackets is a convolution integral expressing the response of a channel in terms of its response to a narrow line.

Because $x(s)$ always contains a noise grating that varies from observation interval to observation interval, the quantity D is a random variable and must be treated as such; we must determine the distribution of D in those conditions when noise alone is present and when both noise and signal are present in order to see how our observers' behavior depends on the several parameters of the signal, of the noise, and of the shape of the filter. (The reader who is unfamiliar with these elementary notions of detection theory might wish to consult Nachmias's[22] excellent chapter reviewing detection theory with vision in mind.)

Fortunately, a much simpler form of Eq. (1) results if we consider how the probability distribution of D might be determined from the frequency-domain representation of the stimuli. In the spatial-frequency domain, D is given by

$$D = \int_{-\infty}^{\infty} X(f)|H(f)|^2 \mathrm{d}f, \tag{2}$$

where $X(f)$ is the spectral density of the stimulus.[23] When low-pass filtered noise is presented alone, then, for each particular sample of noise,

$$D = 2 \int_0^{Fc} N(f)|H(f)|^2 \mathrm{d}f, \tag{3}$$

where Fc is the cutoff frequency of the noise and $N(f)$ is the square of the noise-contrast density in that noise sample. The probability distribution of D does not have a recognized form, but the mean and variance of the distribution can be determined readily.

We need to know at least the mean and variance of two distributions of D (1) when the noise is presented along and (2) when both signal and noise are present, in order to determine the ability of a system basing its decision on D (or some monotonic function of it) to detect the signal. The ratio of the difference in the means of the two distributions to the square root of the sum of the variances determines the percentage of correct responses that is obtained. When the distributions can be approximated by normal distributions—and they can, provided that the effective bandwidth and extent of the noise are sufficiently large—the ratio can be taken as the z value used in elementary statistics, and the percentage of correct responses can be determined from standard tables of the normal probability integral.

The details of the calculation involved in determining the z ratio from our stimuli can be found in Patterson and Henning,[9] and their results have a feature that is particularly fortunate when the shape of our visual masking functions is considered, for, if the function relating the square of the signal contrast corresponding to some performance level (75% correct, say) to the cutoff spatial frequency is exponential on linear coordinates, the filter or channel shape will also be exponential.[19] [That this is so may be seen by assuming an exponential form for $|H(f)|^2$ and making an appropriate substitution into Patterson and Henning's Eq. (A16)]. Since our data have an exponential form (and only because they have an exponential form), and if we are prepared to assume that the observers use a quantity like D in reaching their decision, then the channel shape is given directly by the data. From Figs. 4 and 5, then, the channels are asymmetric and have different exponential skirts above and below their center frequencies. Their bandwidths are roughly proportional to their frequencies. In the latter respect they are similar to channels derived from adaptation experiments of Blackemore and Campbell[6] and from multiple-component detection experiments similar to those of Sachs *et al.*[7]

It should be noted that the filter shapes shown in Figs. 4 and 5 arise only by assuming that observers detect gratings by using a quantity like D on which to base their decisions. There is little enough evidence that observers use such a quantity; Carter and Henning[24] provide only slim support for the notion that observers use such a variable.

At least as likely a decision statistic is the peak-to-trough ratio in the stimuli, and we need to know what channel shape we would infer from our data if we were to assume that observers use the peak-to-trough ratio, or a monotonic function of it, in reaching their decision.

Campbell *et al.*[25] have considered the effect of the overall contrast sensitivity function on the peak-to-trough ratio of a number of different waveforms. The waveforms they treated were deterministic, however, and ours are random. Moreover, we do not have the filter shape to begin with; rather, we have the effect of the filter shape implicity in the form of the behavior of our observers, and we wish to infer the filter shape implied by their behavior.

We could proceed as we did when we were inferring filter shape on the assumption that observers use the energy at the output of the unknown filter. However, when observers are presumed to use the peak-to-trough ratio, the resulting integral equation relating their performance and the unknown filter shape is exceedingly complicated.[23,26] It is given implicitly by

$$P(c) = (1/\sigma_x{}^2) \int_0^{\infty} V_t \exp[(V_t{}^2 + C_s{}^2)/2\sigma_x{}^2] \times [1 - \exp(-V_t{}^2/2\sigma_x{}^2)] I_0(C_s V_t/\sigma_x) \mathrm{d}V_t, \tag{4}$$

where $2C_s$ is the peak-to-trough ratio of the grating corresponding to some percentage of correct responses $P(c)$ in the presence of a noise with a given cutoff frequency, $I_0(x)$ is a modified Bessel function of the first kind and first order, and the quality $\sigma_x{}^2$ is related to the channel shape $|H(f)|^2$, the cutoff frequency of the noise F_c, and the mean noise-contrast density $\sqrt{2N_0}$ by

$$\sigma_x{}^2 = N_0 \int_0^{F_c} |H(f)|^2 \, \mathrm{d}f. \tag{5}$$

Equations (4) and (5) determine the probability that a sample from the distribution of the contrast of a sinusoid plus a filtered Gaussian noise exceeds the contrast of noise alone and hence the percentage of correct responses in a two-interval forced-choice (2IFC) detection task. It is assumed that the reciprocal of the effective extent of the display is small compared with the bandwidth of the noise; the effect of relaxing this assumption is considered by Henning.[26]

Nothing much analytical can be done with a relation as complex as this, and, whereas numerical solutions could undoubtedly be found, the effort involved is hardly justified by the amount of data we have. Consequently, we have adopted an alternative, though less elegant, approach.

Since we know the value of the signal contrast corresponding to 75% correct at each cutoff frequency, we can manipulate the quantity $\sigma_x{}^2$ in Eq. (4) until we find a value that produces the percentage of correct responses that our observers obtained with that signal contrast. By repeating this operation for different cutoff frequencies, we obtain a function relating $\sigma_x{}^2$ to cutoff frequency. Now Eq. (5) shows the relation between $\sigma_x{}^2$ and $|H(f)|^2$ so that it is an easy matter to deduce to filter shape; it is given by

$$|H(f)|^2 = \mathrm{d}(\sigma_x{}^2)/\mathrm{d}F_c, \tag{6}$$

where $\sigma_x{}^2$ is the empirically determined function relating F_c and signal contrast through Eqs. (4) and (5).

On the assumption that the observers use the peak-to-trough ratio in making the decision, the derived function is the only one that could yield our observers' performances. Figure 7 shows, as solid lines, the function $|H(f)|$ at each of the three spatial frequencies we used. (The filter shapes inferred from the same data by using the energy-detection assumption are shown as dotted lines.) The data on which the figures are based are those of observer BGH, and it is clear that the detection mechanism assumed to follow a spatial-frequency-selective device significantly influences the spatial-frequency-selective characteristics one infers from a given set of data. Comparisons of the two different predictions in Fig. 7 show that the skirts of the frequency-selective device inferred when the observer is assumed to use the peak-to-trough ratio of the stimulus to make decisions (solid lines) have exactly one half the slope inferred when the observer is assumed to use an energylike quantity (dashed lines). The change in slope implies a change in bandwidth, and the bandwidths inferred on the basis of a peak-to-trough detection mechanism are twice that inferred from the same data on the assumption of an energy detector; differences in the frequency-selective mechanism inferred under the two hypotheses are nontrivial.

The two detection criteria that we have considered are by no means exhaustive, and there are no really general techniques for considering classes of detection mechanism.[27] It would be fruitless to attempt to test the implications of every possible detection mechanism, but it is as well to bear in mind that a given set of data bearing on the question of spatial frequency selectively implies different spatial-selectivity characteristics depending on the assumptions made about the detection process assumed to follow the spatial-frequency-selective elements.

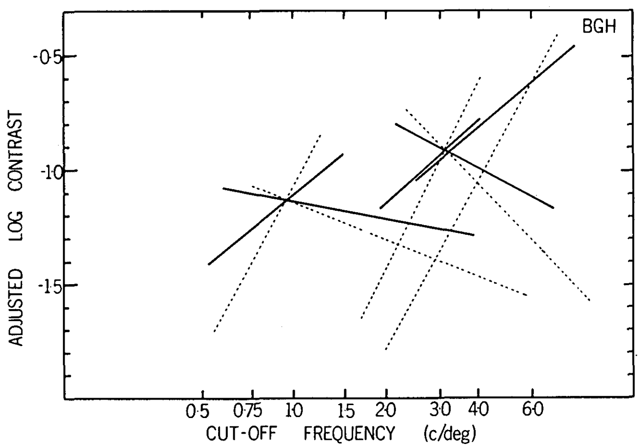

Fig. 7. Solid lines show the attenuation characteristics of the frequency-selective mechanisms inferred from the data of BGH on the assumption that observers use a decision statistic that is a monotonic function of the peak-to-trough ratio of the filtered stimulus. Dotted lines show the characteristics inferred from the same data when observers use a decision statistic that is a monotonic function of the energy in the filtered stimulus.

SUPPLEMENTARY EXPERIMENT: TEMPORAL FACTORS

The major difference between our results and those of Greis and Röhler[12] and of Stromeyer and Julesz[17] is that the data of Stromeyer and Julesz, taken with signals at 2.5 cycles/deg, indicate symmetric filter shapes (on double logarithmic coordinates), whereas ours are asymmetric on the same coordinates. The data of Greis and Röhler, from a low-pass filter condition with static masking stimuli, are consistent with the low-frequency skirt of Stromeyer and Julesz. One particularly important difference between the stimuli used in the two studies is that our noise gratings and those of Greis and Röhler were static for the duration of each observation interval, whereas those of Stromeyer and Julesz were changing throughout their observation interval. There are marked effects of temporal changes on the detectability of gratings, particularly in the low-spatial-frequency region,[28,29] and, in order to determine whether temporal factors in the stimuli might account for the differences between our data and those of Stromeyer and Julesz, we repeated our experiment using noise gratings that changed continually in time.

Method and Results

The experimental technique differed only trivially from that used in the experiments already described, except that the noise gratings were present continuously and constantly changing instead of being static for the duration of an observation interval. The spatial-frequency characteristics were as before, but the temporal characteristics were simply those produced by the audio-frequency noise used to generate the gratings. This means that both the contrast and the phase of the noise gratings changed at rates that were random and contained all temporal frequencies below a number that was proportional to the spatial bandwidth of the noise.[23] The signal was sinusoidal, of fixed spatial phase, and had a spatial frequency of about 2 cycles/deg. The noise-contrast density was not changed when cutoff frequencies were changed, and in this the procedure is like that of Greis and Röhler and unlike that of Stromyer and Julesz. The square display had a mean luminance of 102 cd/m^2 and subtended 10° per side. The three observers, two of whom are authors,[30] were seated side by side and viewed the screen simultaneously against a black background.

Figure 8 shows the results for the three observers. The log contrast corresponding to 75% correct responses is plotted as a function of the cutoff spatial frequency of the masking noise. Both axes are thus logarithmic, and the results for the observers have been offset vertically so that the data for each can be seen clearly. We have used the 75% correct performance level because the functions relating the percentage of correct responses to log contrast were again parallel. The contrast corresponding to 75% correct responses was obtained by linear interpolation.

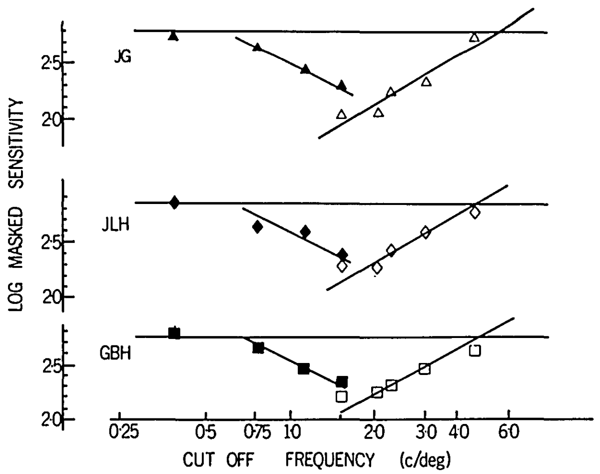

Fig. 8. Log masked sensitivity (the reciprocal of masked contrast) as a function of the cutoff frequency of the visual masking noise. Data for three different observers are shown. The noise was continously present and continuously changing.

The data for all three observers are symmetric on these coordinates and have slopes of about 0.4 log unit per doubling of spatial frequency. This suggests that the steeper loss in masking with decreasing frequency obtained when static noise was used is a result of the loss in effective contrast of static, low-frequency gratings. Lennie[31] has described this effect and attributes it to the fact that stimuli containing only components of low-spatial frequency are, in a sense, stabilized on the retinas of fixating viewers because small eye movements produce virtually no local change in luminance when the spatial frequency of the stimulus is low.

The effect of temporal factors on the shape of masking functions is pursued in another paper in which the temporal characteristics of sinusoidal masking gratings are manipulated.

SUMMARY

We have measured the effect of low-pass and high-pass noise gratings on the detectability of sinusoidal gratings and found the functions relating the contrast corresponding to 75% correct detection to the cutoff spatial frequency to be roughly linear on double logarithmic coordinates.

With static noise the functions are asymmetric (on double logarithmic coordinates), having a slope of about 0.7 log unit of contrast per halving of spatial frequency below the signal and 0.4 log unit per doubling above it. These characteristics appear to be independent of frequency with the signals of low-spatial frequency that it was possible for us to use.

When the spatial masking noise changed throughout the duration of the observation interval (dynamic noise), the functions became symmetric, similar to those reported by Stromeyer and Julesz[8] with both slopes showing about 0.4-log-unit change per doubling of frequency.

If it is assumed that the observers base their decisions on a quantity that is a monotonic function of the square deviation of the spatially filtered stimulus from the mean luminance, then the features of the functions described above also characterize the frequency-selective elements. However, if the observers use a quantity related to the peak-to-trough ratio in the stimulus for their decisions, the attention characteristics of the frequency-selective elements implied by the data are more broadly tuned and have only half the slope.

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16. Stromeyer and Julesz kept the product of the square of the noise contrast and the bandwidth of their masking noise constant when changing cutoff frequencies.[17] If we assume that masking is proportional to noise-contrast density, then we might adjust the data in Fig. 6 to show the contrast elevation that would have occurred had Stomeyer and Julesz kept their noise-contrast density constant. The correction steepens the low-frequency side from about 0.35-log-unit change of contrast per halving of spatial frequency to 0.52 log unit per halving. The steepening of the high-frequency side is negligible when the correction is applied on the basis of the bandwidths used by Stromeyer and Julesz.
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