Spatial-frequency tuning as a function of temporal frequency and stimulus motion

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Spatial-frequency tuning at two different spatial frequencies was determined by measuring the detectability of a signal grating that was made difficult to see by low- or high-pass visual noise. The signals were vertical sinusoidal gratings of different spatial frequencies. The detectability of the signal was measured in two-alternative forced-choice tasks with different temporal envelopes: (1) a slowly changing raised-cosine (Hanning) window, (2) a rectangularly gated 2-Hz counterphase flickering envelope, and (3) a rectangularly gated 10-Hz counterphase flickering envelope. Additional measurements were made using drifting stimuli with the signal and noise drifting in the same or in opposite directions. The temporal envelopes were chosen because they have different effects on the contrast-sensitivity function and it was desired to know how temporal factors affect the spatial-frequency tuning of the relatively narrowly tuned channels thought to underlie contrast sensitivity. The results show that, for counterphase flickering stimuli, spatial-frequency tuning does not depend on temporal envelopes applied identically to the signal and to the masking noise. A similar picture emerges at slow (2.7-deg/sec) but not at fast (10.9-deg/sec) drift rates.

INTRODUCTION

It is well known that the low-spatial-frequency end of the contrast-sensitivity function is affected by the temporal characteristics of the signal; at low spatial frequencies, low temporal frequencies reduce sensitivity. At high spatial frequencies, the results are reversed, and high temporal frequencies lead to reduced sensitivity.[1,2] Further, there is sufficient evidence from neurophysiological studies to establish that the visual system, at least in the early stages, comprises elements more narrowly tuned in spatial frequency than the overall contrast-sensitivity function; for the first few steps in the transmission of information in the visual system, the channel hypothesis put forward by Campbell and Robson[3] seems correct. However, the effects of nonlinear operations on luminance both before and after the channels, the extent of interaction among them, and the implications of their existence for other than the simplest detection and discrimination tasks have yet to be established.[4–7]

Estimates of the spatial-frequency-tuning characteristics (shape) of the channels for the entire system may be based on psychophysical experiments with visual masking noise.[8–10] The principal purpose of the experiments described in this paper is to determine whether temporal factors influence spatial-frequency tuning in the same way in which they influence contrast sensitivity.

In preliminary experiments the effects of counterphase flicker and of motion on contrast sensitivity were measured. The same temporal envelopes were then used in noise-masking experiments to determine the effects of temporal factors on spatial-frequency tuning.

METHOD

Observers were required to detect a vertically oriented sinusoidal grating (the signal) in standard two-alternative forced-choice detection experiments. There were two observation intervals on each trial, and the signal, generated in the manner of Schade[11] on the screen of a Hewlett-Packard 1317B X-Y display (P31 phosphor), appeared in one of them. The probability of the signal's being in the first interval was 0.5 on each trial. Observers indicated whether the signal had appeared in the first or in the second interval by pressing a key. The response produced a tone that indicated whether the signal had occurred in the first or the second interval. The next trial began after the tone, and trials were run in blocks of 50.

In preliminary experiments measuring contrast sensitivity, the signal was detected binocularly against the mean luminance (13.2 cd/m^2) of the display, which subtended either 7 × 7 or 28 × 28 deg of visual angle at whichever of two different viewing distances was used. The signal alternated in the two-field frame with a uniform field of the same mean luminance as the signal; the frame rate was 100 Hz. The signal was presented in separate subexperiments with different temporal characteristics: (1) with a 2-sec raised cosine (Hanning) temporal envelope centered in the observation interval, (2) with an envelope flickering in counterphase at 2 or 10 Hz for the duration of the 2-sec observation interval, and (3) with the stimuli moving at a constant velocity within a temporal Hanning window either to the left or to the right with a speed of 2.73 or 10.9 deg/sec. Two durations were used in the experiments with drifting gratings: 1 sec and 90 msec.

With counterphase flicker, both the noise and the signal were shaped horizontally by a raised-cosine (Hanning) spatial window that filled the display. A rectangular horizontal window was used with drifting gratings. The vertical extent of the display was limited rectangularly at its edges in all cases.

In experiments 2a and 2b, one-dimensional noise was added in each observation interval. The noise patterns, pre-

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sented in the even fields of the two-field frame, usually had the same temporal characteristics as the signal, which, when present, was in the odd fields. (When no signal was present, a uniform field of the same mean luminance as the signal and the noise filled this field.) The addition of neither the noise nor the signal changed the mean luminance of the display.

One example of a set of 14 noise patterns, each generated to have the same statistical characteristics, was used in both observation intervals of a trial; a random selection from a set of 14 was made on each trial, and trials were run in blocks of 50.

The noise samples for the static and flickering stimuli were generated in the following way: First, an approximately Gaussian distribution of values with zero mean was generated for both the real and the imaginary parts of each of 512 equally spaced points in the frequency domain; then the noise was limited either to a low-frequency band (from 0 to the nominal cutoff frequency) or to a high-frequency band [from the nominal cutoff frequency to 18 cycles per degree (c/deg)]. The samples were stored in floating-point form in the computer used to generate them (Hewlett-Packard 9836) and scaled so that the peak values of the most broadband patterns rarely exceeded the range of the 12-bit digital-to-analog converters used to drive the display. (A value that exceeded the linear dynamic range of the display produced an error message when an attempt was made to generate it; the waveform was consequently rejected and replaced.) The samples were then inverted by a discrete Fourier transform to produce four examples of the required pattern: two in the real and two in the (nominally) imaginary spatial cross-sectional luminance profile produced by the inversion. Each of the resulting 256-point patterns was then multiplied by a Hanning[12] window (raised cosine, alpha of 0.5) and stored. A single scale factor was used for all the noise samples so that, taken over the ensemble of noise patterns, the mean noise-power density within the passband was the same for all the noise types.

Fourteen different noise samples of a particular type were used for 50 trials in each temporal condition. For additional sets of trials, new samples were created.

The characteristics of the digitally filtered noise patterns were measured by scaling the numerical representations of the spatially windowed patterns and truncating them (at 12 bits) in the same fashion as in the display program. The resulting fixed-point numbers were then converted back to floating-point representation, and the discrete Fourier transform was used to regenerate spectra that contained the effects of truncation and windowing. The filters produced approximately 35 dB of attenuation in their stop band and achieved an attenuation rate on the skirts of the filters of at least 17 dB per c/deg.

Unlike the static or flickering noises, drifting noises were generated in the space domain as Fourier-series band-limited (approximately) Gaussian noise having the same average power as noise of the same bandwidth generated in the frequency domain. This procedure was adopted to facilitate the production of slow drift rates. The noise comprised the sum of a set of sinusoids with spatial frequencies in the appropriate band. Each component within the passband had a contrast that was approximately Gaussian with zero mean and a constant variance; the phase of each component was distributed uniformly. The frequencies of the components were harmonically related and equally spaced 1/4 c/deg apart. Thus the noise was a Fourier-series band-limited white Gaussian noise.

The number of sample points in the fundamental period of the series was chosen to be a prime number. The noise was constructed this way to permit fine control of the rate of movement by using large frame-to-frame shifts to produce temporally aliased versions of each of the harmonically related components of the noise all drifting at the same rate. The technique is thus a minor extension of Robson's technique for obtaining fine control of the movement of a sinusoidal grating.[13]

The masking effect of (statistically) identical bands of noise, one generated in each way, appeared to be the same in the conditions in which direct comparison was possible.

RESULTS AND DISCUSSION

Experiment 1: Contrast-Sensitivity Functions

In experiment 1, four or five point functions relating the percentage of correct responses in 50 trials to the logarithm of signal contrast were obtained first; then additional sets of 50 trials were obtained at the two contrast values that corresponded to performance closest above and below 75% correct. Since the resulting functions were essentially parallel in all conditions, it is reasonable to summarize performance by comparing the contrasts corresponding to a single level of performance, which, in this paper, is the conventional 75% correct level obtained by linear interpolation between the two points based on 100 judgments.

Figure 1(a) shows the contrast-sensitivity functions for observer GBH (the author) in the experiment.[1] The reciprocal of the contrast corresponding to 75% correct responses is plotted on the ordinate as a function of the spatial frequency of the signal; both axes are logarithmic, and the contrast is the maximum contrast that occurs within each temporal envelope. Data are shown for three different temporal patterns: the slowly varying Hanning envelope (open circles), the 2-Hz counterphase flickering envelope (half-filled circles), and the 10-Hz counterphase flickering envelope (filled circles). The 7 × 7 deg visual field was used to obtain data at spatial frequencies above 1 c/deg; at below 1 c/deg, where field size made a measurable difference, the data were obtained with the 28 × 28 deg field.

The data serve to confirm the standard results concerning the effects of temporal characteristics on the function relating sensitivity to spatial frequency[1,2]: Signals presented with a low temporal frequency (open circles) show a bandpass characteristic with reduced sensitivity at spatial frequencies below and above the spatial frequency of maximum sensitivity, in this case about 1 c/deg. If the temporal frequency of the signals is raised to 2 Hz (half-filled circles), much of the loss in sensitivity at low spatial frequencies disappears, and the sensitivity at higher frequencies is not much affected. At a temporal frequency of 10 Hz (filled circles), sensitivity is reduced at all spatial frequencies, and the contrast-sensitivity function is nearly a monotonic decreasing function of spatial frequency.

Field size affects sensitivity at low spatial frequencies in much the way reported by Estevez and Cavonious[14] in that additional losses in sensitivity occur if the number of cycles

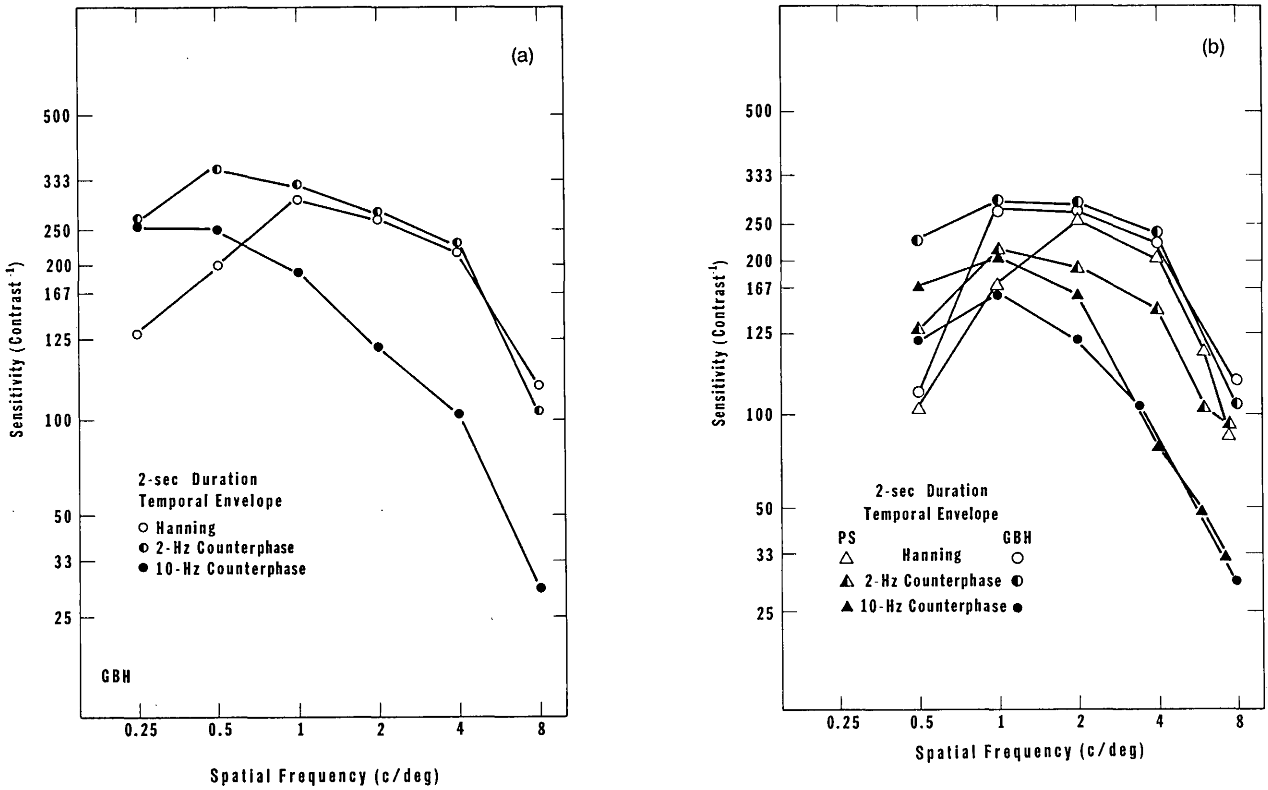


Fig. 1. (a) Contrast sensitivity (the reciprocal of the contrast corresponding to 75% correct detection) as a function of spatial frequency (c/deg); both axes are logarithmic. The nominal duration of the signals was 2 sec; at and below 1 c/deg, the signals subtended 28 × 28 deg of visual angle; above that frequency, they subtended 7 × 7 deg. A spatial (horizontally oriented) Hanning window of the appropriate extent was used in both cases. Data for three different temporal envelopes are shown: open symbols, a raised-cosine (Hanning) temporal window; half-filled symbols, a rectangularly gated, 2-Hz counterphase flickering envelope; filled symbols, a rectangularly gated, 10-Hz counterphase flickering envelope. (b) Data for two observers are shown as in (a) except that the field size was 7 × 7 deg.

of the signal present in the display falls below 7 or so. This effect may be seen in Fig. 1(b), which shows the results obtained for observers GBH and PS at the longer viewing distance.[15]

In Figs. 2 and 3, the signal contrast corresponding to 75% correct responses is plotted against the spatial frequency of the signal for each observer. The duration of the drifting grating was 1 sec for Figs. 2(a) and 3(a) [in which data for static stimuli in the 2-sec Hanning window (open symbols) are also shown for comparison] and 90 msec in Figs. 2(b) and 3(b). The field size was 7 × 7 deg in all cases, and no spatial window was used. The half-filled symbols show the effects of making the signal drift at a rate of 2.7 deg/sec. There is an improvement in sensitivity at low spatial frequencies and a considerable increase in the rate at which sensitivity falls with increasing spatial frequency.

Higher drift rates produce much stronger effects but are difficult to measure without stabilized viewing conditions.[16,17] At drift rates of 10.9 deg/sec, for example, eye movements in the direction of the moving stimulus make it easy to see stimuli that without eye movements are invisible. The effects are clear in Kelly's[17] classical data, and some idea of the effect at a higher temporal frequency can be obtained from Figs. 2(b) and 3(b), which show data from briefly presented stimuli: the temporal Hanning window was reduced to 90 msec in duration. Overall sensitivity is reduced, but the large losses in high-spatial-frequency sensitivity with rapidly moving stimuli are readily apparent.

Thus in experiment 1, with the equipment and procedures to be used subsequently, the generally accepted effects of temporal manipulations on the characteristics of contrast-sensitivity functions were demonstrated.

Experiment 2: Spatial-Frequency Tuning

Experiment 2a: Counterphase Flicker

The purpose of experiment 2 is to measure the way in which temporal characteristics affect the spatial-frequency tuning of the relatively narrowly tuned elements that are thought to underlie the overall characteristic of the contrast-sensitivity function.[3,18–22]

The experimental procedure with masking noise has been described in a preceding subsection. It is assumed in interpreting the data that some form of spatial-frequency tuning narrower than the contrast-sensitivity function exists and that the observers use a mechanism tuned for spatial frequency to detect the spatially windowed sinusoidal signal. The mechanism is assumed to be most sensitive to the spatial frequency of the signal and to be less sensitive to higher and lower spatial frequencies. The purpose of the subsequent experiments was to measure the loss in sensitivity both above and below the signal frequency.

To estimate the tuning characteristic, the experimental technique of Henning *et al.*,[10] itself a modification of a method previously used in hearing[23,24] and in the study of spatial vision,[8,9] was used.

The shape of the spatial-frequency tuning on the low-

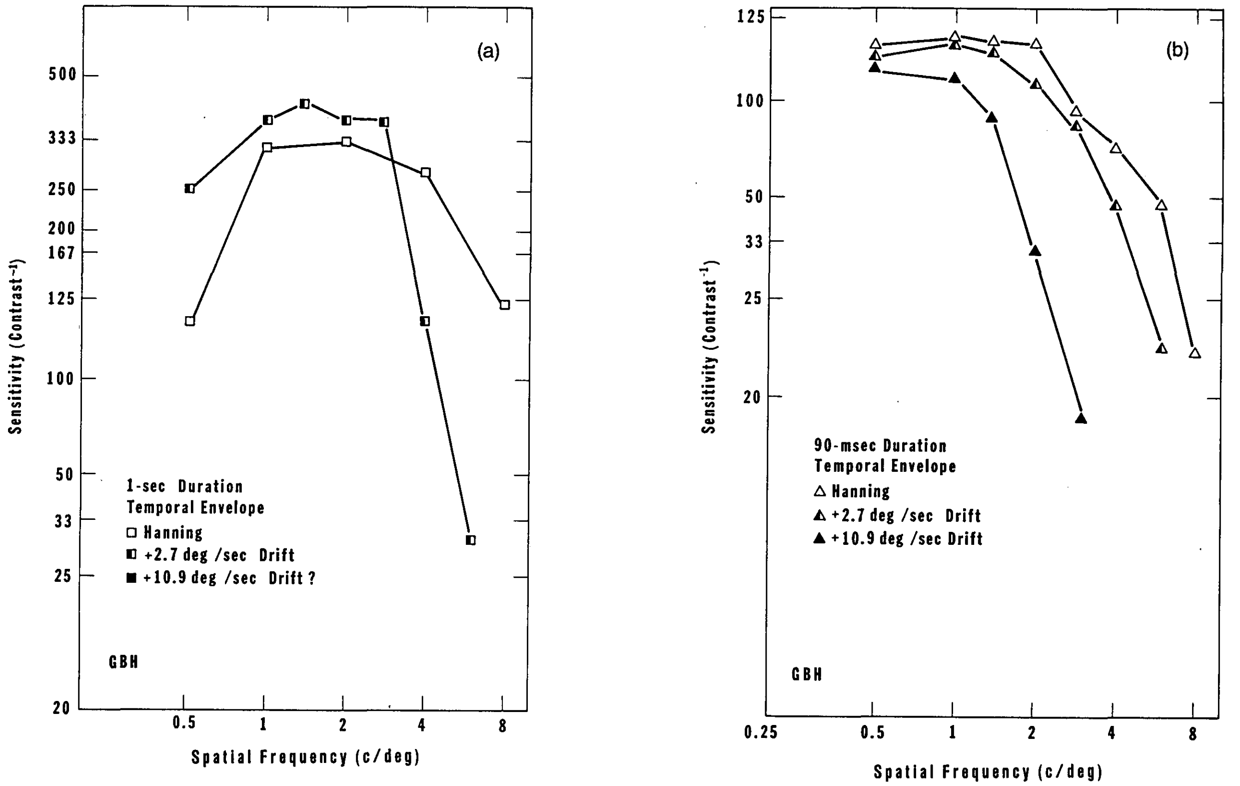


Fig. 2. (a) Contrast sensitivity as a function of spatial frequency for observer GBH; both axes are logarithmic. The nominal duration of the signals was 1 sec, and they subtended 7 × 7 deg. Rectangular spatial envelopes were used. Data for three temporal envelopes are shown: open symbols, a raised-cosine (Hanning) window; half-filled symbols, signals drifting to the left or right within the Hanning temporal window at a rate of 2.7 deg/sec; filled symbols, signals drifting at a rate of 10.9 deg/sec. The direction of motion was chosen at random before each trial but was constant in any observation interval. (b) Same as (a) but for a signal duration of 90 msec.

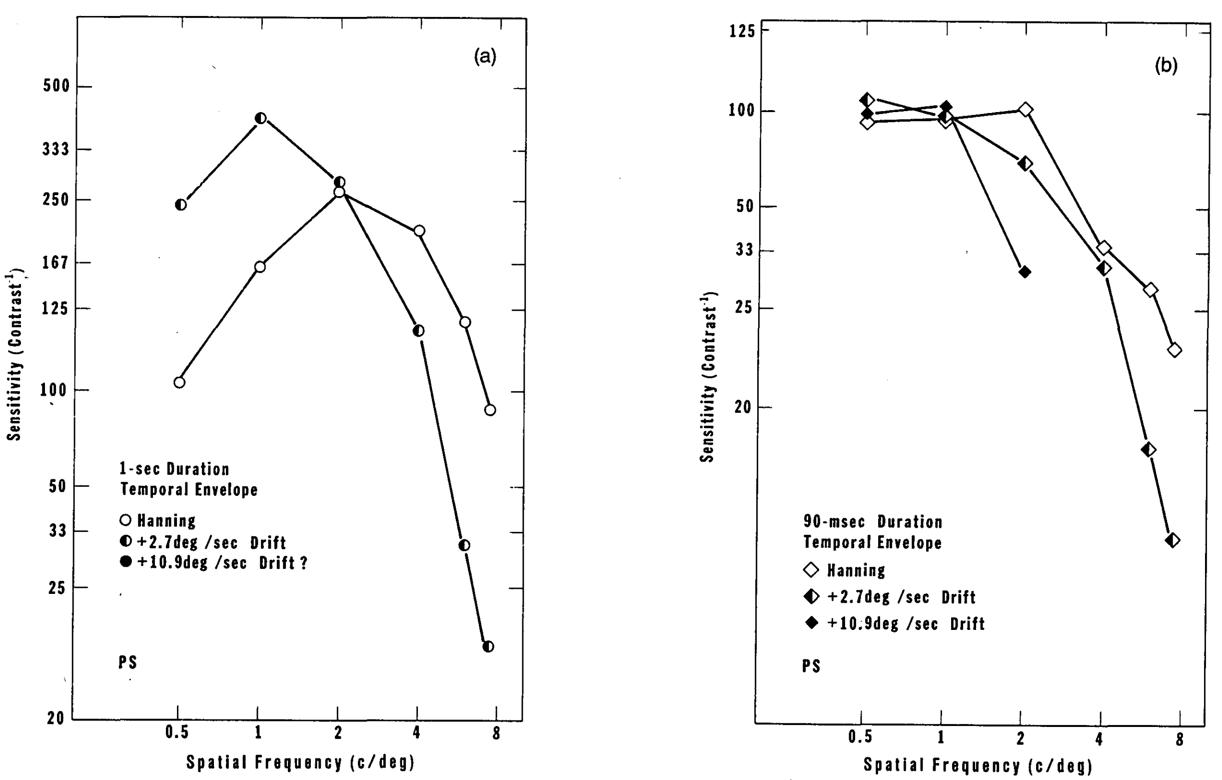


Fig. 3. (a) Same as Fig. 2(a) but for observer PS. (b) Same as (a) except that the signal duration was 90 msec.

frequency side of the channel used to detect the signal was inferred from the function relating the threshold contrast of the signal to the cutoff frequency of low-pass-filtered noise. Cutoff frequencies ranged from the signal frequency to 1 octave below it. The high-frequency attenuation of the channel was estimated by using the detectability of the signal measured in the presence of a high-frequency bandpass noise with its lower-frequency cutoff at the signal frequency

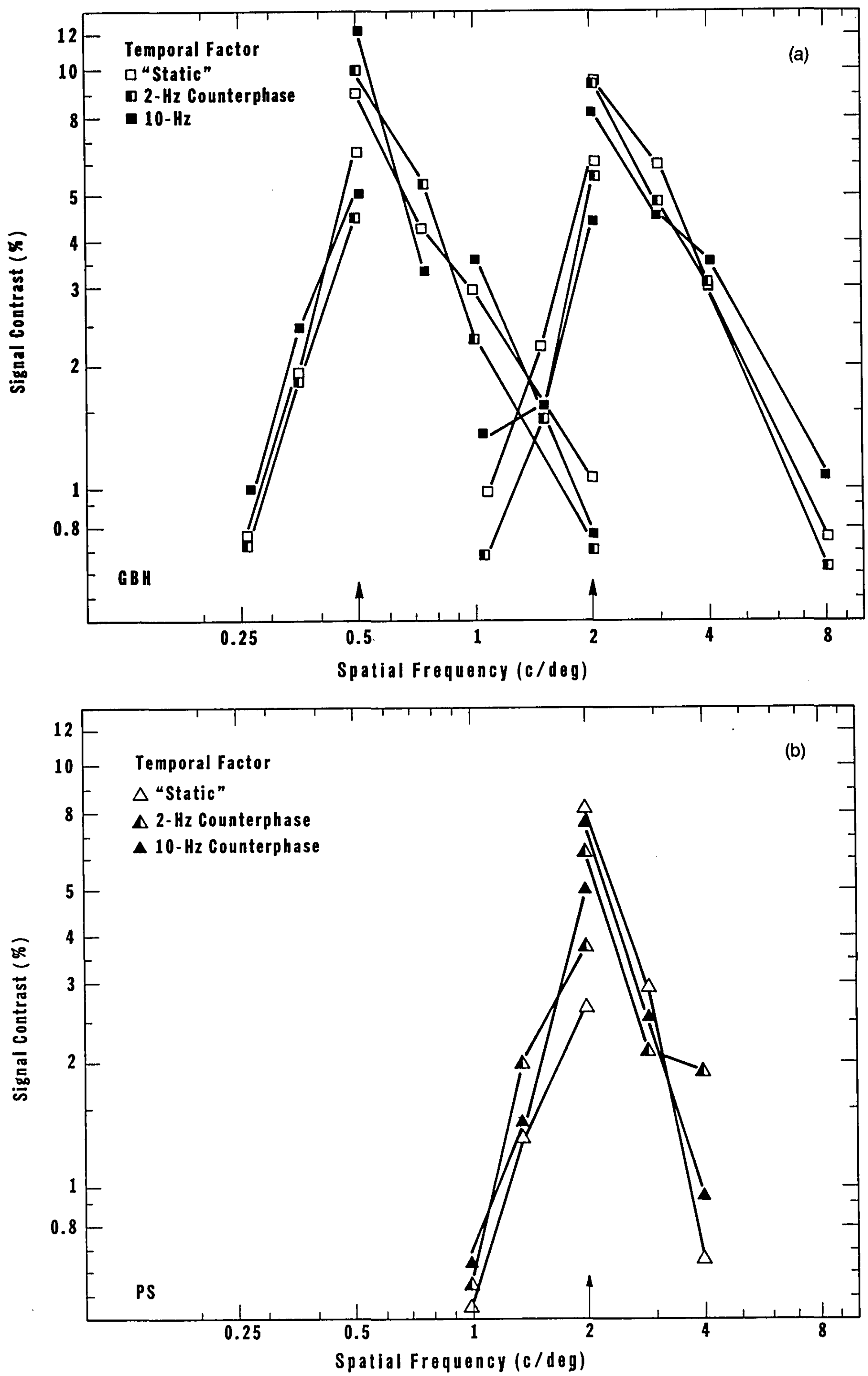
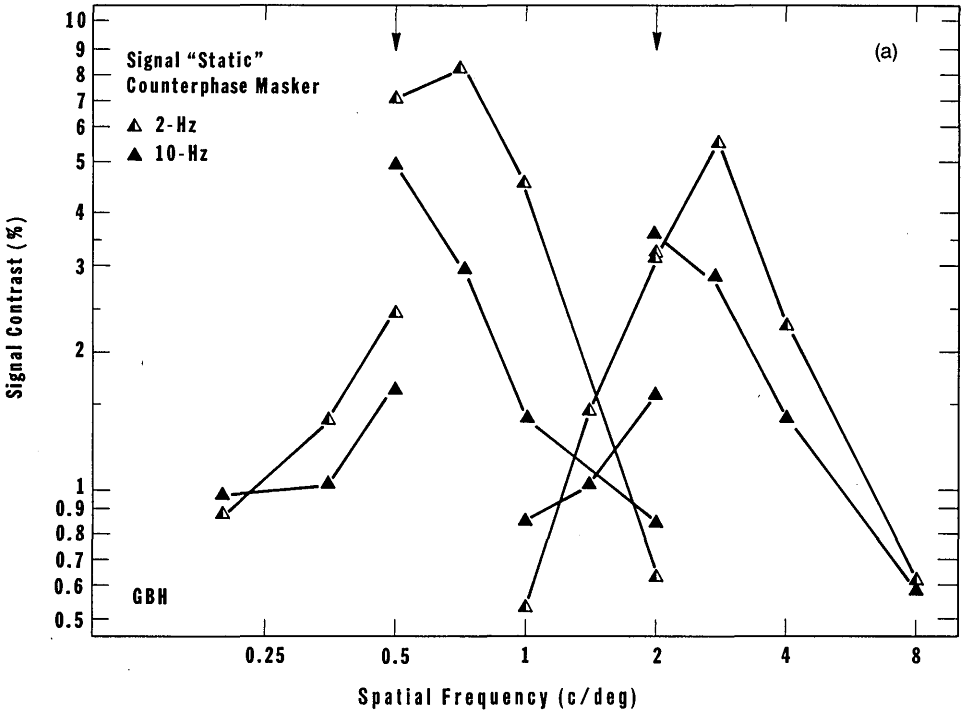


Fig. 4. (a) Signal contrast (percent) as a function of the cutoff frequency of the noise used to mask either a 0.5- or a 2-c/deg signal for observer GBH. Both axes are logarithmic. Data shown to the left of each signal frequency (marked by vertical arrows) were obtained with low-pass noise with the cutoff frequency shown on the abscissa; data to the right of the signal frequency were obtained with high-pass noise filling the band from the cutoff frequency to 18 c/deg. Data for the temporal envelopes of Fig. 1 are shown. Both the masker and the signal, when it was present, had the same temporal envelope. (b) Same as (a) but for observer PS with 2-c/deg signals only.



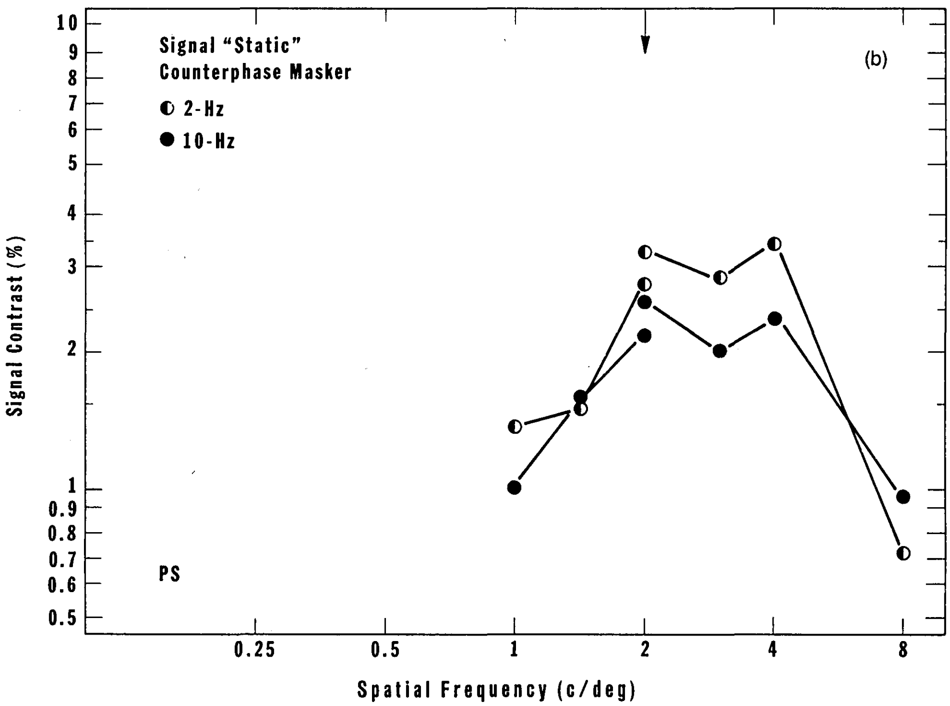
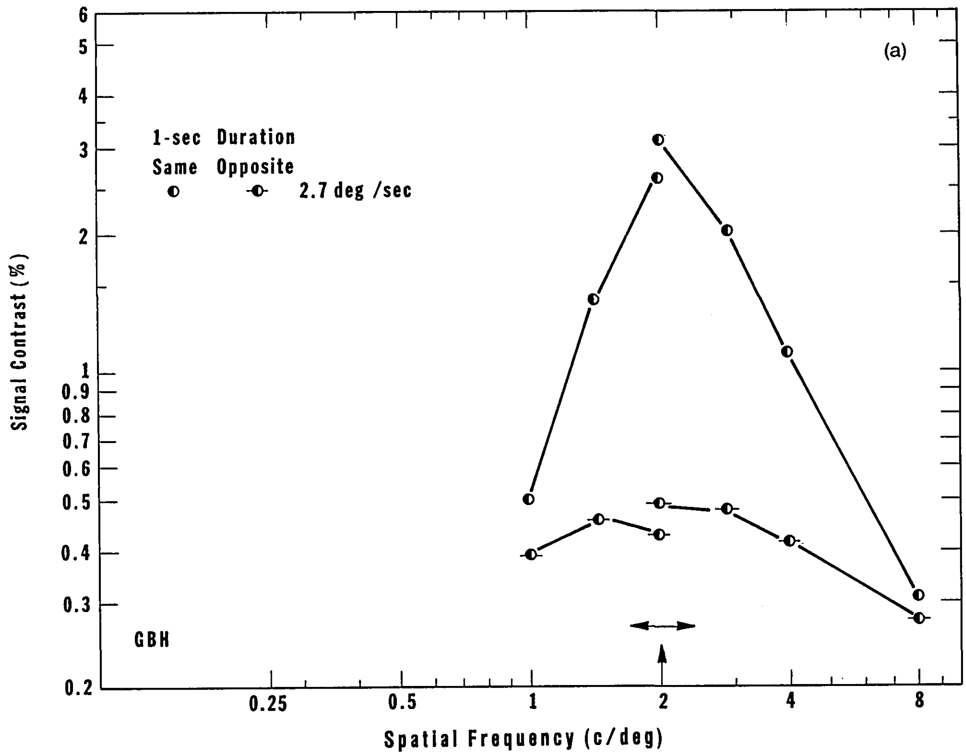


Fig. 5. (a) Same as Fig. 4(a) except that the signal appeared only with the slowly changing Hanning temporal envelope, whereas the noise had either the rectangularly gated, 2-Hz counterphase flickering envelope (half-filled symbols) or the rectangularly gated, 10-Hz counterphase flickering envelope (filled symbols). (b) Same as Fig. 4(b) except that the signal appeared only with the slowly changing Hanning temporal envelope, whereas the noise had either the rectangularly gated, 2-Hz counterphase flickering envelope (half-filled symbols) or the rectangularly gated, 10-Hz counterphase flickering envelope (filled symbols).

as well as 1/2, 1, and 2 octaves above that frequency. Under certain assumptions [namely, that the observer uses the integral, taken across the display, of the squared deviation (from the mean luminance) of the cross-sectional luminance profile as the statistic on which to base his judgments[10,20,25] and that the function relating threshold contrast to cutoff frequency is approximately linear on semilogarithmic coordinates], the signal contrast corresponding to a constant performance level reflects the spatial-frequency tuning of the mechanism directly.[10]

The experimental procedure of experiment 1 was used again. The data (percent correct against signal contrast on semilogarithmic coordinates) again fell on contours that were approximately parallel, permitting the results to be represented solely by the contrast corresponding to 75% correct detection. Two signal frequencies were used: 0.5



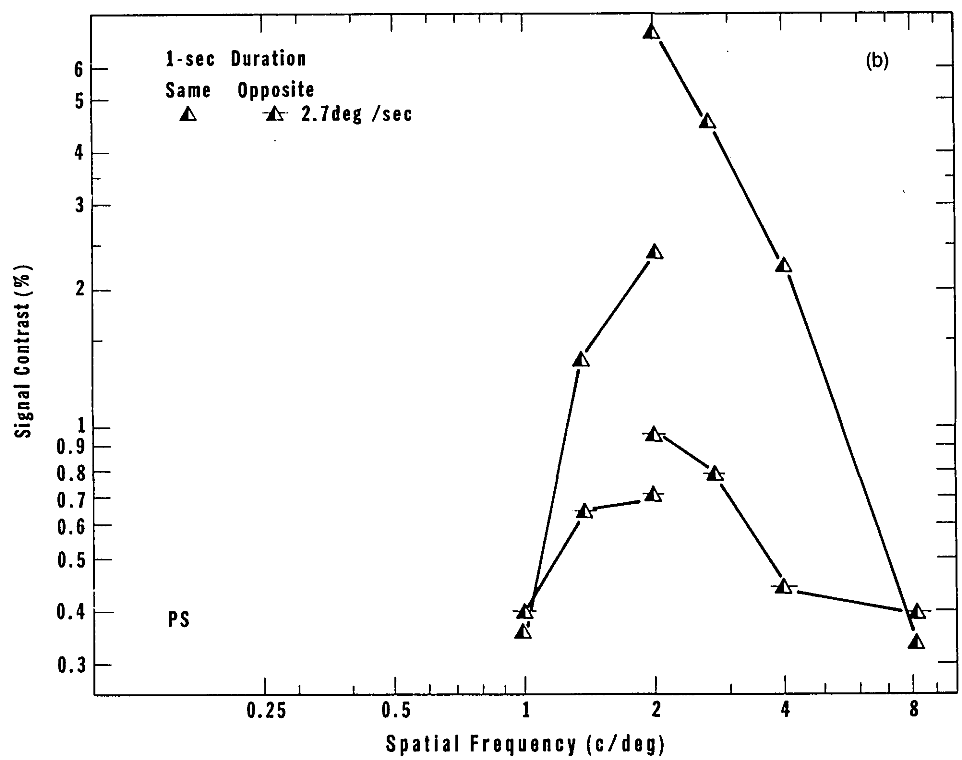


Fig. 6. (a) Same as Fig. 5(a) except that the 2-c/deg signal and the noise drifted at 2.7 deg/sec. The signal duration was 1 sec, and there was a temporal Hanning window within which the stimuli drifted. The symbols without a stroke show the results obtained when the signal and the masker drifted in the same direction; the symbols with a stroke show the results obtained when the masker and signal drifted in opposite directions. The horizontal double-headed arrow indicates the threshold of the signal when there was no noise. (b) Same as (a) but for observer PS.

and 2 c/deg. For the former signals, the 28 × 28 deg field was used; for the latter, the 7 × 7 deg field was used.

Results: Tuning with Counterphase Flicker

Figure 4 shows the signal contrast corresponding to 75% correct responses as a function of the cutoff frequency of the masking noise. Both axes are logarithmic. Results for two signal frequencies, 0.5 and 2 c/deg, are shown in Fig. 4(a) for observer GBH; data for 2-c/deg signals for observer PS are shown in Fig. 4(b). The data obtained with the temporal Hanning envelope of 2-sec duration are shown as open symbols, the data obtained with 2-Hz counterphase modulation are shown as half-filled symbols, and the data obtained with 10-Hz counterphase modulation are shown as filled symbols. Data shown at cutoff frequencies below the signal frequencies (marked by vertical arrows on the abscissas) were ob-

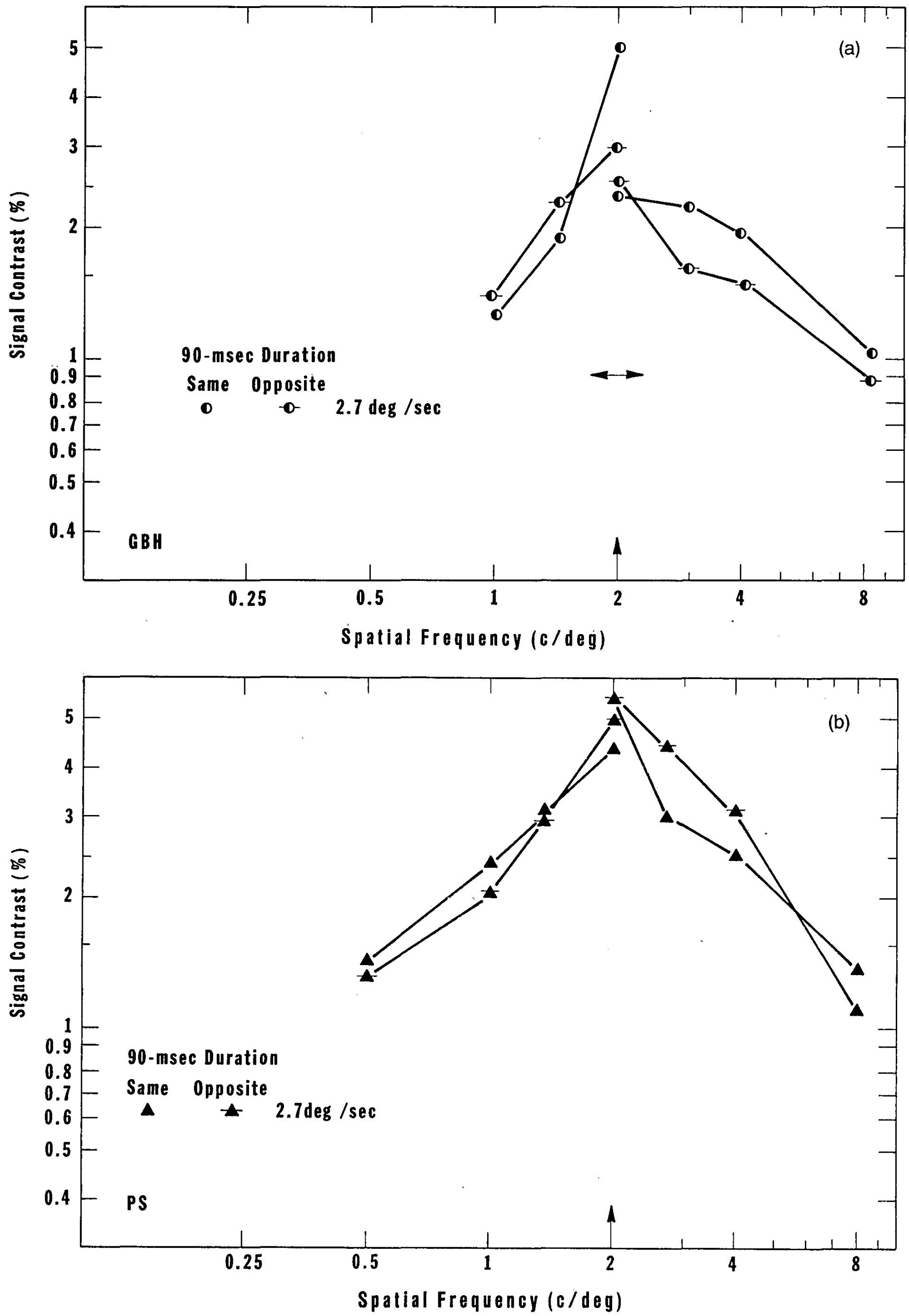


Fig. 7. (a) Same as for Fig. 6(a) except that the signal duration was 90 msec. (b) Same as for Fig. 6(b) except that the signal duration was 90 msec.

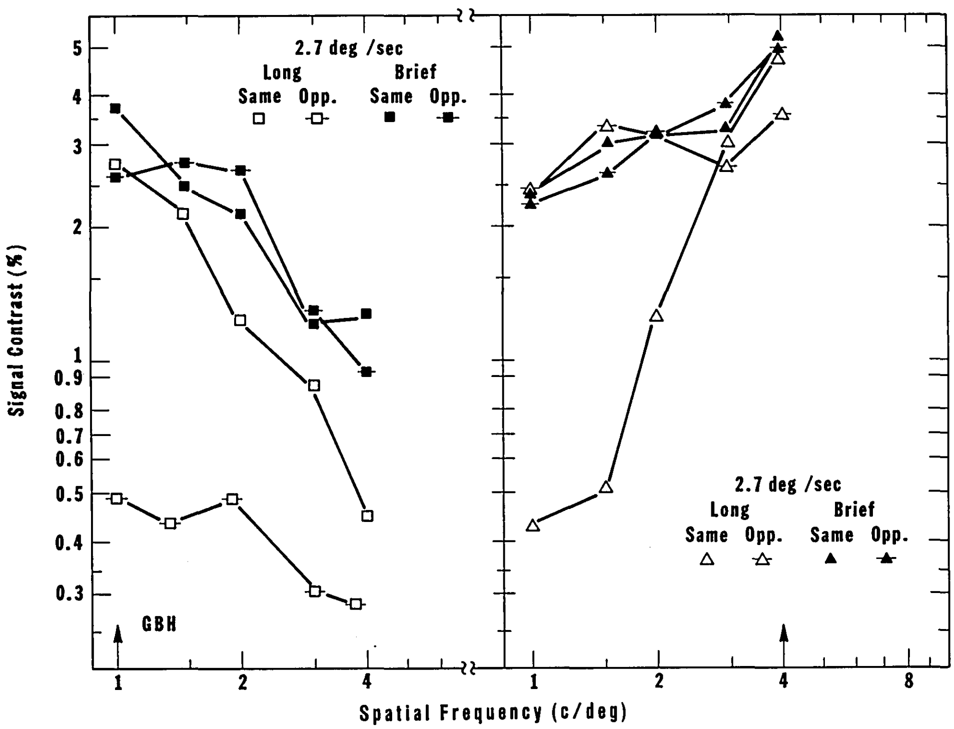


Fig. 8. Results obtained in the fashion described in Fig. 6 and 7, with high-pass noise and signal frequencies of 1 c/deg (squares) and 4 c/deg (triangles). The drift rate was 2.7 deg/sec, and data for both long (1-sec) and short (90-msec) exposure durations are shown. Symbols without strokes denote results obtained with the signal and the masker moving in the same direction; symbols with a stroke denote results obtained with signal and masker moving in opposite directions.

tained with low-pass-filtered noise; data at cutoff frequencies above the signal frequency were obtained with high-pass noise.

It is clear at the spatial frequency of both signals, as well as at a 1-c/deg intermediate frequency (data not shown), that the temporal characteristics of the counterphase flickering stimuli have no obvious effect on the spatial-frequency selectivity of the mechanism used to detect the signal. That is the principal result of experiment 2a.

If we accept the assumptions outlined above, we might take the data as giving the slopes of the attenuation characteristic of the channels directly. The asymmetry in the shapes shown on these double logarithmic coordinates (steeper attenuation on the low-frequency side) is characteristic of noise-masking experiments; the similarity in the shapes obtained for signals of different spatial frequency is also characteristic. The equation approximating the low-frequency side of the spatial-frequency-selective mechanism is given by

$$\log(\mathrm{At}) = 2.68 \log(f/f_0), \tag{1}$$

where At is the attenuation factor; both f_0, the spatial frequency of the signal, and f are in cycles per degree. The high-frequency side of the mechanism has its attenuation related to the relative spatial frequency by

$$\log(\mathrm{At}) = -1.62 \log(f/f_0). \tag{2}$$

Similar slopes, also obtained from noise-masking experiments, were reported previously.[10]

It should be noted that, in Eqs. (1) and (2), unity gain at the peak sensitivity of the mechanism is assumed. The data, however, show a sizable difference between the masking effect of a low-pass noise running from 0 to the frequency of the signal and the masking effect of an high-pass noise running from the signal frequency to 18 c/deg.

The difference provides an easy (joint) test of the assumed filter shape and the assumptions about the decision statistic that the observers use. Since the noise-power density is, on the average, constant within the passband and (effectively) zero outside it, the square of the signal contrast, Ps, should be given by

$$Ps = k \cdot N_0 \int f \mathrm{d}f, \tag{3}$$

where the constant N_0 is the mean (over the ensemble) of the noise-power density in the passband and k is the slope constant taken from Eqs. (1) and (2) for the low- and high-frequency sides of the mechanism, respectively. For the low-pass-noise case, the integral is taken from 0 to the signal frequency, f_0, and for the high-pass case it is taken from the signal frequency to 18 c/deg, the upper limit of the high-pass noise. The calculated powers imply ratios of 2.3 and 2.1 between the contrasts obtained with low- and high-frequency cutoffs set to the frequencies of the 0.5- and 2-c/deg signals, respectively. The measured ratios, averaged across the three temporal conditions shown in Fig. 4(a), are reasonably close: 1.99 at 0.5 c/deg and 1.3 at 2 c/deg.

An assumption implicit in the treatment of the data is that the masking effect of noise is proportional to its level within the frequency-selective range of the channel, and the previous calculations are not inconsistent with this assumption. Nonetheless, a direct test was performed with broadband noise that had a constant average noise-power density from 0 to 18 c/deg. The same signal frequencies and viewing distances were used but with two levels of noise-power density: the one used in experiment 2a and a level 1 log unit lower. [The limited dynamic ranges of the visual system on the one hand and the display system on the other make this an inconvenient experiment. It is desirable that (1) the noise be clearly visible at the lower level, (2) the noise not force the signal contrast above the generating capacity of the display at the higher level, and (3) there be as large a difference as possible between the two noise levels: 1 log unit was the best that could be arranged.]

Over the 1-log-unit range, masking was found, within the error of measurement, to be proportional to the noise-power density.

Figure 5 shows results of a masking experiment in which the temporal envelope of the signal and the masker were different: the signal had a slowly varying (Hanning) temporal window, but the masker had either (1) a rectangularly gated, 2-Hz counterphase flickering envelope or (2) a rectangularly gated, 10-Hz counterphase flickering envelope. In Fig. 5 the signal contrast corresponding to 75% correct responses is again shown as a function of the cutoff frequency of the masking noise. Both axes are logarithmic. The vertical arrows at 0.5 and 2 c/deg indicate the spatial frequencies of the two signals. Note that the lowest threshold contrasts are only a factor of 2 above absolute threshold.

There are a number of features to note in a comparison of Figs. 4 and 5. First, there is less masking when the signal and the masker have different temporal envelopes, and the reduction in masking is particularly pronounced at the spatial frequency of the signal. In Fig. 5(a), the reduction is so large at the signal frequency with high-pass noise that with the 2-Hz counterphase flickering envelopes (half-filled symbols) there is more masking when the cutoff frequency lies half an octave above the signal frequency than when the cutoff lies at the signal frequency. This result was reported previously.[26,27]

One possible cause is evident to the observers; when the signal and the masker have similar spatial-frequency components, observers report that spatially local variations in the apparent motion resulting from counterphase flicker are a potent cue. Analysis of the stimulus and potentially analogous mechanisms in hearing and stereoscopic vision were published previously,[28,29] but little is known about human sensitivity to differential local variations of stimuli in space and time,[30,31] nor do we know much about the capabilities of channels to convey information about either location or temporal frequency.[32–34]

Experiment 2b: Drifting Stimuli

In experiment 2b only one moving component of the counterphase flickering stimuli was used to produce moving (drifting) stimuli. The signal was the 2-c/deg vertical sinusoidal grating used in experiment 2a. However, the noise was generated in the space domain rather than in the spatial-frequency domain.

One of a set of seven different maskers, each having the same statistical characteristics, was selected at random and used in both observation intervals of a given trial. The noise moved in one direction in the first observation interval and in the opposite direction in the other. The initial direction was chosen at random, and the interval in which the signal occurred was chosen randomly from an independent process.

Two drift rates were used: 2.7 and 10.9 deg/sec. Further, in different experiments, the signal and the masker were made to drift in the same direction or in the opposite directions.

Results: Tuning with Drifting Stimuli

Figures 6–8 show the signal contrast corresponding to 75% correct responses as a function of the cutoff frequency of the

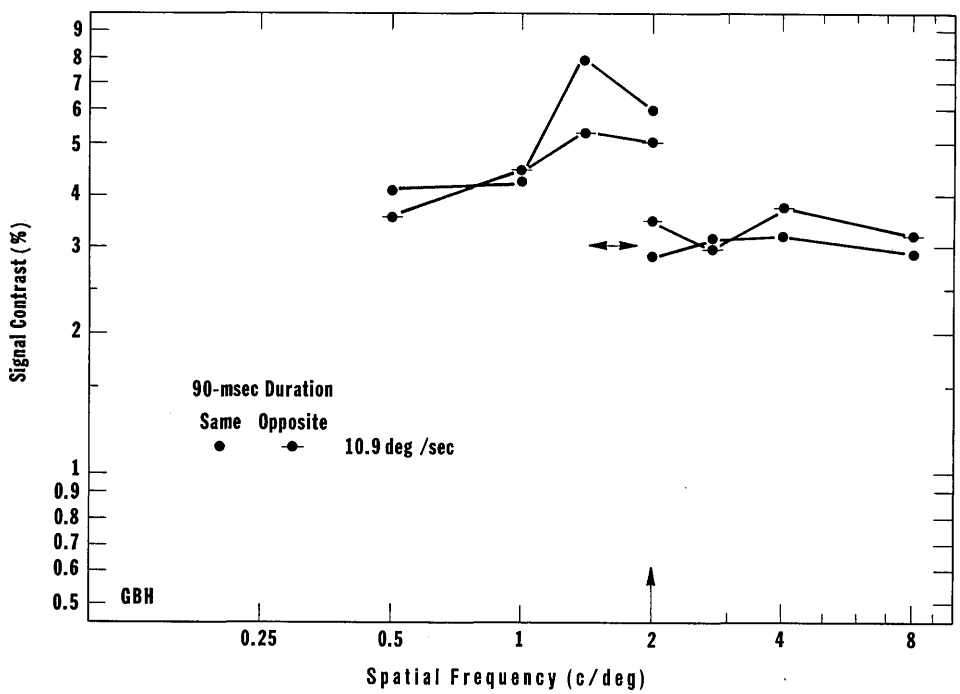


Fig. 9. Same as Fig. 7(a) except that the drift rate was 10.9 deg/sec.

noise. Both axes are logarithmic in each figure. The stimulus duration was 1 sec, and both the signal and the noise appeared within a Hanning temporal window; rectangular spatial windows were used. The signal frequency was 2 c/deg.

It may be seen from Fig. 6 that, when both the noise and the signal move in the same direction at moderate speeds, the spatial-frequency tuning, at least at 2 c/deg, is virtually the same as that obtained either with static stimuli or with stimuli having identical counterphase flickering envelopes.

When the masker and the signal move in opposite directions, that is, when there is relative motion of the signal and the masker, there is almost no masking. [The horizontal arrows at the signal frequency in Figs. 6(a) and 7(a) indicate absolute threshold for the signal.] Consequently it appears as if there were no spatial-frequency tuning. The cue used by observers to infer the presence of the signal is either the appearance of flicker in the stimulus or, if the observers move their eyes in the direction and at the angular speed of the signal, the appearance of a low-contrast noise through which the signal is readily seen. The former observation suggests that it would be difficult to model the output of spatial-frequency-tuned mechanisms as one dimensional (univariant); indeed, with respect to detectability measurements, one-dimensional outputs seem somewhat improbable.[35,36]

Figure 7 shows the results obtained with a 90-msec signal duration. This duration is shorter than the time required to initiate eye movements, and here there is little difference in performance between the conditions in which the signals and the masker move in the same direction and in the opposite directions. The loss in masking with increasing cutoff frequency in the high-pass case is much less than with either static or counterphase flickering stimuli. This effect is much more pronounced with higher drift speeds, at which sensitivity is low (Fig. 9 and Ref. 17).

Figure 8 shows additional data for one observer obtained at the 2.7-deg/sec drift rate. The left-hand panel shows the effects of high-pass-filtered noise of two different durations (open symbols, 1 sec; filled symbols, 90 msec) on the detection of a 1-c/deg signal. The effects of motion of the masker in both the same direction and the opposite direction relative to the signal are shown. The right-hand panel shows the effect of low-pass-filtered noise on the detection of a 4-c/deg signal. The conclusions drawn from Figs. 6 and 7 with 2-c/deg signals are merely confirmed at these spatial frequencies.

Finally, Fig. 9 shows the results obtained when the drift rate is high: 10.9 deg/sec. There is no masking by the high-frequency band and little by the low-frequency band. Further, it makes no difference whether the signal and the masker move in the same direction or in opposite directions.

DISCUSSION

It is well known that the low-spatial-frequency end of the contrast-sensitivity function is affected by the temporal characteristics of the signal; at low, but not at high, spatial frequencies, low temporal frequencies result in reduced sensitivity. At high spatial frequencies, the results are reversed, and low temporal frequencies lead to greater sensitivity.[1,2] The results of experiment 1 merely confirm this observation and illustrate the effects of field size on contrast sensitivity.[14] Further, the differences in sensitivity obtained with drifting stimuli and with counterphase flickering stimuli with similar temporal rates are consistent with the observations of Kelly.[16,17]

The question of whether temporal factors influence spatial-frequency tuning was addressed in experiments 2a and 2b, and it is apparent from Fig. 3 that counterphase flicker at and below 10 Hz has no effect on the shape of spatial-frequency tuning below 4 c/deg, provided that both the masker and the signal have the same temporal characteristics. Temporal factors may affect the gain of the low-frequency channels revealed in noise-masking experiments, but temporal factors do not affect the spatial-frequency tuning.

The measured attenuation characteristics are consistent with estimates from other types of psychophysical procedure.[18,22,26,37–39] Within the error of measurement they are described readily by a number of different equations as, for example, in Eqs. (1) and (2).

When the masker and the signal have different temporal characteristics, a number of different things happen: first, the cue by which the signal is detected changes. When the signal has a higher temporal frequency than the masker, flicker is often detected, and when the masker has the higher temporal frequency, differential local phase modulation of the masker is commonly the cue. Both cues have some spatial-frequency dependence, but, without explicit models of the detection process involved in the two cues, inferences about the characteristics of the spatial-frequency tuning of the processes cannot be made.

Nonetheless some features emerge from Fig. 4. With high-pass noise flickering in counterphase at 2 Hz, performance is better when the signal and the masker have spatial-frequency components in common. This appears to be because the observers can use local differences in the extent of apparent spatial-phase modulation at the spatial frequency of the signal as a cue. The phase variations are not so pronounced when the signal and the masker differ significantly in their spatial-frequency content.

Although differences in the appearance of stimuli and observers' descriptions of the cues that they use in performing tasks that they are set can hardly be taken as infallible guides to the underlying mechanism, it is as well not to reject them out of hand.

The results with drifting stimuli are similar to those obtained with counterphase flicker when the signal and the masker have the same characteristics and there is sufficient masking to measure an effect. With high drift rates, there is so little masking that spatial-frequency tuning cannot be estimated. The lack of masking may indicate the presence of some mechanism that precedes the one responsible for spatial-frequency tuning and that is unable to pass high temporal frequencies.

When the signal and the masker move in opposite directions for long durations, the observers see flicker (as in the case with counterphase flickering signals and static maskers), or else they see the signal drifting through the veil of the masker. With long durations, tracking eye movements may play a role by stopping the retinal motion of the signal and doubling the temporal frequency of the mask, thereby reducing its effective contrast. This observation is not inconsistent with a scheme in which the stimuli are processed in different mechanisms tuned to different directions of motion.[40–42] At short durations, the relative direction of the signal and the masker ceases to be a factor, but the lack of masking precludes much being inferred about spatial-frequency tuning.

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