Masking effects of low-frequency sinusoidal gratings on the detection of contrast modulation in high-frequency carriers

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A modification and extension of Kortum and Geisler's model [Vision Res. **35**, 1595 (1995)] of early visual nonlinearities that incorporates an expansive nonlinearity (consistent with neurophysiological findings [Vision Res. **35**, 2725 (1995)], a normalization based on a local average retinal illumination, similar to Mach's proposal [F. Ratliff, *Mach Bands: Quantitative Studies on Neural Networks in the Retina* (Holden-Day, San Francisco, Calif., 1965)], and a subsequent compression suggested by Henning *et al.* [J. Opt. Soc. Am A **17**, 1147 (2000)] captures a range of hitherto unexplained interactions between a sinusoidal grating of low spatial frequency and a contrast-modulated grating 2 octaves higher in spatial frequency.

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1. INTRODUCTION

Both psychophysical and physiological measurements suggest that the mechanisms responsible for the detection of sinusoidal gratings are selective for orientation and spatial frequency.[1–7] Some masking experiments, however, are difficult to interpret within the conventional framework, which suggests orientation tuning[8] of approximately $\pm 20°$ and spatial-frequency tuning of approximately ± 1 octave.[9–11] This paper concerns masking experiments that reveal interactions between a high-frequency complex grating and a low-frequency sinusoidal grating 2 octaves lower in spatial frequency.[9–11] The low-frequency sinusoidal grating lies well outside the commonly assumed range of spatial-frequency tuning centered on the complex grating, and conversely the complex lies outside the tuning range centered on the sinusoid. The assumption of an early low-order (polynomial) luminance nonlinearity will account for some of the interactions but is inconsistent with the small interaction between a sinusoidal masker and harmonically related sinusoids.[9,12] (Polynomial nonlinearities also fail to account for the masking effects of plaid patterns.[8]) The important masking effects are often ignored in the development of both physiological and behavioral models of early vision; the models either assume a linear system or postulate nonlinearities that are inconsistent with the masking results. There are, of course, very many nonlinear systems to consider; but it appears that one such system,[13] designed to account for the masking effect of Mach bands, inadvertently provides a solution.

2. THE PROBLEM

This problem for conventional models arises when a low-frequency sinusoid, at f_m cycles per degree of visual angle (c/deg), makes it difficult to detect modulation of the same spatial periodicity as f_m in the contrast of a carrier with a spatial frequency f_c that is five times greater than f_m. The effect depends strongly on the phase of the low-frequency masker relative to the phase of the contrast modulation[9–11] and is not predicted from the assumption of linear independent channels tuned to ± 1 octave of spatial frequency.

Consider the task faced by observers in discriminating a high-frequency carrier, a sinusoid of fixed contrast and spatial frequency f_c, from a grating of the same spatial frequency that is sinusoidally modulated in space at a frequency of f_m c/deg. For vertically orientated stimuli, the cross-sectional luminance profile of the unmodulated (carrier) grating L_c presented in one observation interval of a two-alternative forced-choice experiment is given by

$$L_c(x) = L[1 + c \sin(2\pi f_c x + \phi_c)], \tag{1}$$

where L is the mean luminance, c is the contrast of the f_c-c/deg grating, and ϕ_c is a phase term that locates the grating relative to an arbitrary location labeled zero. (The phase ϕ_c is sometimes randomized between observation intervals.) The contrast-modulated grating L_{cm} to be discriminated from the sinusoid of Eq. (1) is given by

$$L_{cm}(x) = L\{1 + c[1 + m \cos(2\pi f_m x + \phi_m)] \times \sin(2\pi f_c x + \phi_c)\}, \tag{2}$$

where f_m and ϕ_m are the spatial frequency and the phase of the modulation and m (often given as a percentage) is the depth of modulation.

The carrier and modulation frequencies are harmonically related, with f_c equal to $5f_m$. The profiles of Eqs. (1) and (2) are shown in Figs. 1A and 1B as solid curves for a contrast c of 0.063 and a depth of modulation m of 17%; the phase terms ϕ_c and ϕ_m are set to zero in both cases. At a mean luminance of 5.31 cd/m^2, these values produce ~75% correct discrimination.[9]

Expansion of Eq. (2) shows that the contrast-modulated grating is a complex of three sinusoids: the carrier, at f_c c/deg with a contrast of c, and two sidebands at $f_c \pm f_m$ c/deg, both with a contrast of $cm/2$. For low f_m and

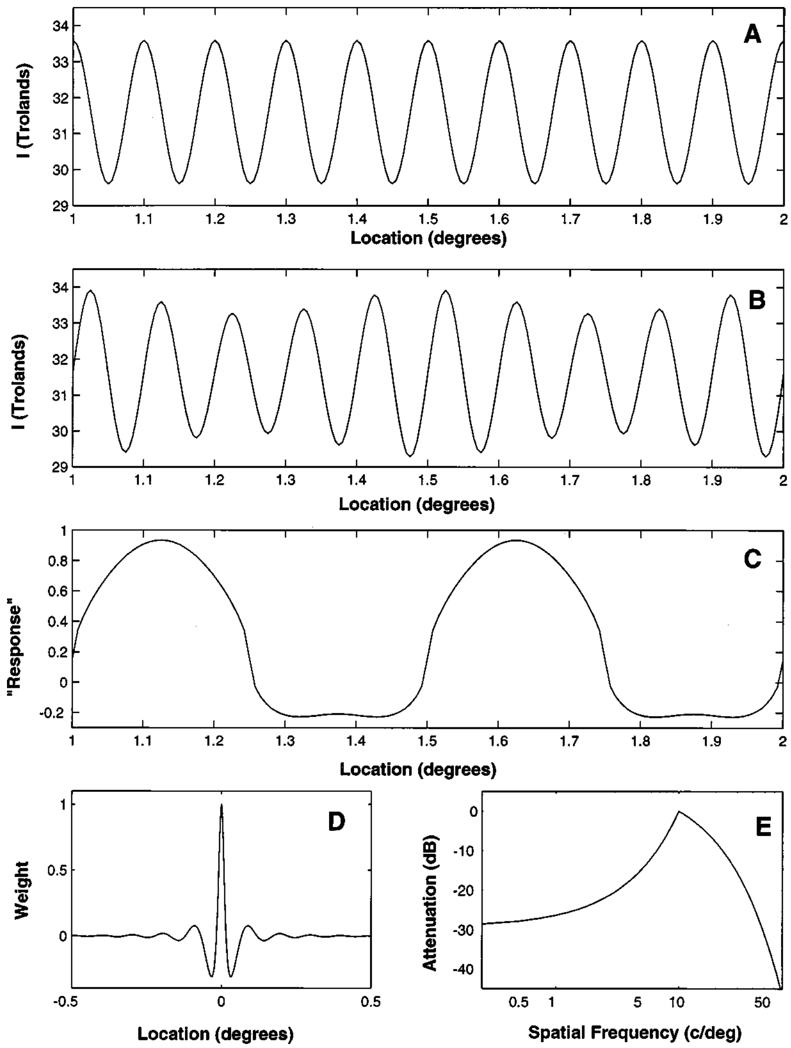

Fig. 1. A, cross-sectional luminance profile of a sinusoidal (carrier) grating [Eq. (1)] of spatial frequency 10 c/deg and a contrast of 6%. B, the same carrier when sinusoidally contrast modulated [Eq. (2)] at a rate of 2 c/deg to a depth of 17%. C, response of the nonlinear system [Eq. (3)] to a 2-c/deg sinusoid of 17.4% contrast. D and E, line-spread function and attenuation characteristic of the 10-c/deg channel that characterizes human spatial-frequency selectivity at that frequency.[3]

high f_c, L_{cm} is confined to a high-spatial-frequency region within f_m c/deg of f_c so that, given the conventional spatial-frequency tuning of ± 1 octave, the discrimination of the two patterns should not be affected by a low-frequency sinusoid at f_m c/deg, 2 octaves below the lowest component of the complex.

But the discrimination is seriously affected; with ϕ_m, the phase of the masker, chosen randomly from observation interval to observation interval, observers require the depth of modulation to be about four times greater to detect the contrast modulation in the presence of the low-frequency masker than to detect the contrast modulation without it.[9]

3. SOME EXPLANATIONS

One possible explanation that has been considered (and rejected[9]) and that has been raised again by Cropper[14] is that, from the point of view of the (restricted) receptive field of a mechanism tuned to high spatial frequencies, the low-frequency masker produces, in effect, spatial variation in mean luminance. The contrast of an unmodulated high-frequency grating might consequently appear modulated: lower contrast near the peak of the masker luminance and higher contrast in its low-luminance region. The "induced modulation" of the unmodulated carrier might make it difficult to discriminate a contrast-modulated carrier from an unmodulated carrier. We rejected this explanation of our results because the depth of modulation induced by a low-frequency masker (with contrast 0.174) in our unmodulated carrier (with contrast 0.063) was equivalent to a real contrast modulation of ~17%—a level that is only just detectable. It seemed unlikely to us that such a small effective modulation of the unmodulated carrier could produce a fourfold decrease in the detectability of real modulation. Recent experiments[13] with Mach bands, however, suggest that a related approach may explain the findings.

The explanation of the masking effect of a Mach-band-generating luminance ramp on the detection of a bar begins with the Naka–Rushton equation[15,16]:

$$R[I(x)] = R_{\max}\frac{[I(x)]^n}{[I(x)]^n + \alpha^n}. \quad (3)$$

The equation was modified in three ways following Kortum and Geisler[13,17]: (1) the retinal illumination term, $I(x)$, in the denominator of the modified Naka–Rushton equation was replaced by an average retinal illumination, I_{av}, taken over a restricted local region centered on x. Then, (2) the multiplicative term m and the subtractive term s used by Kortum and Geisler[17] to account for certain nonlinear adaptation effects were added. Both m and s are functions of retinal illumination.[17] This produces an equation relating a response measure R to the pattern of retinal illumination $I(x)$:

$$R[I(x)] = R_{\max}\frac{\{m[I(x) - s]\}^n}{\{m[I_{av}(x) - s]\}^n + \alpha^n}, \qquad (4)$$

where $R_{\max}$ is the maximum response, and the positive exponent n, unlike that of Kortum and Geisler,[17] was taken to be 2.0 for consistency with physiological measurements.[18] The saturation constant α, which in the Naka–Rushton equation determines the retinal illuminance at which the response reaches half its maximum value, was 100. Finally, (3) a compressive nonlinearity (square root) was applied to the absolute value of the difference between the response of Eq. (3) and the response calculated by replacing $I_{av}(x)$ in Eq. (3) with $I(x)$. This in effect separately compresses the responses in "on channels" and "off channels."[11,13,19]

The net result of all this in response to a low-frequency sinusoid, for example, is to produce the distorted response pattern shown in Fig. 1C. With a stimulus contrast of 0.174 and a spatial frequency of 2 c/deg, the second harmonic of the distorted response to the sinusoid is 17 dB below that of the fundamental, and the third and fifth harmonics are 16 and 24 dB down, respectively. The fourth harmonic is too small to measure but is at least 42 dB down.

Figure 2A shows the responses to the carrier alone (thin black curve) and to the contrast-modulated carrier (thick gray curve) of Figs. 1A and 1B, respectively. The stimulus is close to 10 c/deg, and the response shown is

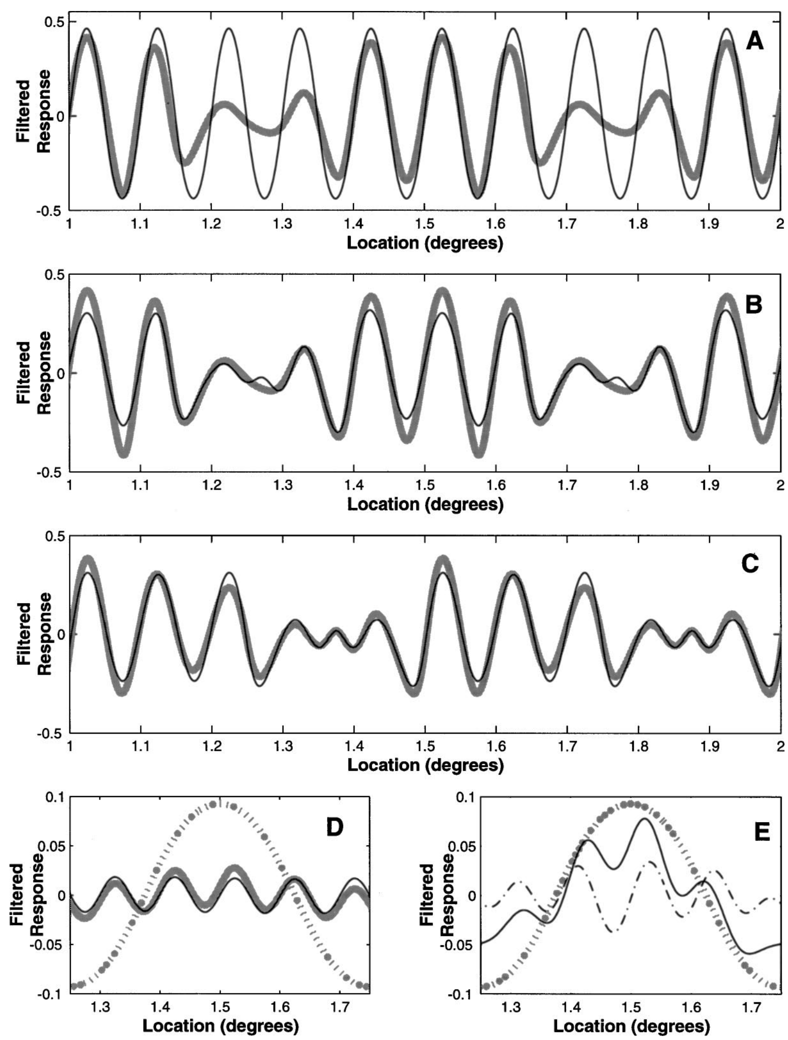

Fig. 2. Responses to channels driven by the nonlinear system of Eq. (3). A, response of a 10-c/deg channel to an unmodulated carrier (thin black curve) and to a carrier of the same spatial frequency the contrast of which was sinsoidally modulated at a rate of 2 c/deg and having the same phase as the contrast modulation. B, response to the same two stimuli in the presence of a 2-c/deg sinusoidal masking stimulus with a contrast of 17.4% added in the same phase as the contrast modulation. C, same as B save that the 2-c/deg masker was added 90° out of phase with the modulation. D and E, response to a channel at 2 c/deg to stimuli described in the text.

that of Eq. (3) seen through a filter chosen to represent our 10-c/deg spatial-frequency tuning. The response at 10 c/deg depends on the form of the filter used to extract the information near 10 c/deg, and any number of plausible filter shapes might be used. I have used an asymmetrical filter centered on 10 c/deg with skirts that fall 8 dB in the first octave above the center frequency and 15 dB in the first octave below it. The filter, with zero response to uniform fields and no phase shift, is one of many that might be derived from noise-masking experiments.[3] Its receptive field is shown in Fig. 1D; the attenuation characteristic, on double logarithmic coordinates, is shown in Fig. 1E. (A similarly shaped filter, again based on the results of masking experiments,[3] was constructed for the 2-c/deg region.)

The response at 10 c/deg to the unmodulated carrier has no spatial variation in contrast, of course, and the just-detectable contrast modulation produces spatial variation in the response, which can be seen in Fig. 2A. This, presumably, is what the observers use to detect contrast modulation in the absence of a low-frequency masker.

Figure 2B shows the 10-c/deg responses to the unmodulated carrier (thin black curve) and to a contrast-modulated carrier (thick gray curve) when a low-frequency masker is added to both. The masker, with a contrast of 0.174, is in phase with the modulation, which is 17%. Adding the low-frequency masker produces large spatial variations in the contrast of both the modulated and the unmodulated stimuli. The responses in the low-response region are lower than that produced by an unmodulated carrier with a contrast equal to its contrast threshold (at the mean luminance of 5.31 cd/m^2)[20,21] so that 10-c/deg stripes are unlikely to be visible in these regions. There is, however, a difference of $\sim$11% between the two responses in the high-response region. This is the same difference that appears to produce threshold discrimination with no masker and suggests that there should be a very modest masking effect when the masker is added in this phase relative to the modulation. In this phase condition observers show similarly small masking effects.[9,10]

Figure 2C shows the 10-c/deg responses to the unmodulated carrier (thin black curve) and to a contrast-modulated carrier (thick gray curve) when the low-frequency masker is added in quadrature with the modulation. Adding the low-frequency masker again produces large spatial variations in the contrast of both the modulated and the unmodulated stimuli, and again the responses in the low-response region are lower than that produced by an unmodulated carrier with a contrast equal to its contrast threshold, so that 10-c/deg stripes are again unlikely to be visible in these regions. There is an 11% difference between the two responses in the high-response region, but, since it was necessary to raise the depth of modulation to 51% to produce this difference, the threshold for discriminating the modulated from the unmodulated carrier should be three times higher with the masker in this phase than without the masker. That is as the observers behave.[9,10]

Thus the modification[13] of Kortum and Geisler's model[17] to include an expansive nonlinearity—a region of integration for the normalizing factor, just as Mach[22] suggested—and a subsequent compression account for the observed interactions and their dependence on the relative phase of the low-frequency masker and the modulation.

This argument hinges on the observers' using the response of a channel tuned to 10 c/deg to make their judgments, but it is difficult to determine what information observers actually use.[23–25] This is true even when observers are required to detect only an unmodulated grating in narrowband noise.[25]

Another spectral region that might provide information for the discrimination centers on 2 c/deg, where intermodulation distortion products from the contrast modulated signal are likely to be largest. Indeed, it was speculated that the masking effect of the low-frequency grating might arise because in the absence of the masker, observers based their detection of contrast modulation on the presence of a 2-c/deg distortion product that was generated in response to the contrast-modulated carrier (but not to the unmodulated carrier).[9] The two solid curves of small amplitude in Fig. 2D show one cycle of the responses from the contrast-modulated (thick gray curve) and the unmodulated (thin black curve) gratings seen through a filter centered on 2 c/deg. (The filter shows responses to the 10-c/deg variation partly because of the nonlinearity and partly because the asymmetrical filter has a shallow high-frequency skirt.)[3] There are obvious differences between the responses at 2 c/deg, but the amplitude of the response is about one fifth the amplitude of the response produced by a 2-c/deg grating at the average of the contrasts corresponding to 75% correct detection for our observers.[9] (This threshold response is shown as the thick dashed–dotted gray curve.) In terms of this model, then, it seems unlikely that the masking effect of the low-frequency grating stems from its effect on information carried in the 2-c/deg channel.

Finally, the solid black curve in Fig. 2E shows one cycle of the response at 2 c/deg produced by 100% contrast modulation of a 10-c/deg grating with mean contrast again at 0.063. The response at 2 c/deg is almost as large as the response to a 2-c/deg grating at its (unmasked) threshold (shown by the thick dashed–dotted gray curve). It is probably the response to the contrast-modulated, 10-c/deg grating that produces the masking of a 2-c/deg sinusoidal signal by such a grating[9,10] as well as the pronounced dependence of the amount of masking on the relative phase of the 2-c/deg signal and the modulation.[10] The thin dotted–dashed black curve in Fig. 2E shows the response to the quasi-frequency-modulated high-frequency complex produced from the three components of the contrast-modulated waveform by inverting the phase of the sideband at $f_c + f_m$ c/deg.[10] It is little more than half the amplitude of the response to the contrast-modulated pattern and has much less spatial variation. Thus the masking effect of the quasi-frequency-modulated pattern should be smaller and show a less pronounced dependence of the phase of the signal. This is the behavioral result.[10]

4. CONCLUSION

It is somewhat surprising that a model developed to account for the masking effect of Mach bands on bars should capture so many of the features of the masking interactions of low-frequency sinusoids and high-frequency contrast-modulated gratings. The width of the window of integration in Eq. (3), for example, was chosen to predict the apparent width of the Mach bands in a briefly flashed, 1.3-deg-wide ramp.[13] If such a mechanism were implemented in the visual system, one might expect the window to vary inversely both with luminance[13,26,27] and with the spatial frequency of the stimulus so that the window subtends the width of the receptive field that corresponds to channels tuned to any given spatial frequency. (The window of integration subtends 23 arcmin and is thus ~20 times the size of the integration window for the contrast-gain-control mechanism seen in the masking of bars by sinusoidal gratings of the same orientation.[28]) Nonetheless, even with a fixed window size, the model captures quite a few aspects of spatial vision and appears to reconcile the existence of spatial-frequency channels with some masking effects that occur over frequency ranges that were inconsistent with the bandwidth of the channels determined from experiments that used simple sinusoidal gratings.

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