Spatial frequency masking in human vision: binocular interactions

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Binocular contrast interactions in human vision were studied psychophysically. Thresholds were obtained for sinewave grating stimulation of the right eye in the presence of simultaneous masking gratings presented to the right eye (monocular masking) or left eye (dichoptic masking). In the first experiment, thresholds were measured at 0.25, 1.0, 4.0, and 16.0 cycle per degree (cpd) as a function of the contrast of masking gratings of identical frequency and phase. Thresholds rose nonmonotonically with masking contrast. At medium and high contrast levels, dichoptic masking was more effective in elevating contrast thresholds than monocular masking, and approached Weber's Law behavior. In the second experiment, spatial frequency tuning functions were obtained for test gratings at five spatial frequencies, by measuring threshold elevation as a function of the spatial frequency of constant-contrast masking gratings. At 1.0, 4.0, and 16.0 cpd, the tuning functions peaked at the test frequencies. The dichoptic tuning functions had a bandwidth of about 1 octave between half-maximum points, narrower than the ± 1 octave bandwidths of the monocular tuning functions. At 0.125 and 0.25 cpd, the tuning functions were broader and exhibited a shift in peak masking to frequencies above the test frequencies.

INTRODUCTION

Two topics that have received a great deal of attention in recent years are binocular interactions and visual contrast processing. Yet, the properties of binocular contrast interaction are poorly understood.

Visual processing of contrast

Sinewave gratings are one-dimensional, sinusoidal luminance modulations in space of a uniform field. The grating's contrast is the ratio of modulation amplitude to mean luminance. Its spatial frequency is the number of periods of modulation per unit visual angle, here measured in cycles per degree (cpd).

Sinewave gratings have been used to study the processing of spatial patterns in vision. There are two main reasons why these stimuli are particularly useful: (i) Spatial frequency and contrast can be varied systematically to study properties of pattern vision, while holding mean luminance constant; (ii) sinewave grating stimuli are mathematically tractable. Patterned stimuli may be quantitatively specified in terms of their spatial frequency compositions. Where applicable, sinewave gratings may be used in the linear systems analysis of human visual pattern processing.[1,2]

The spatial frequency approach has revealed a great deal about visual pattern processing. There exist several good reviews.[3–5] However, the spatial frequency approach has not been widely applied to questions of binocular contrast interaction. In most cases, applications have been restricted to demonstrations that various contrast phenomena occur at or beyond the physiological point of binocular convergence. For example, spatial frequency adaptation shows incomplete interocular transfer.[6–8]

Binocular interaction

Questions concerning the functions, mechanisms, and properties of binocularity may be subdivided into two major classes—those dealing with stereopsis and binocular single vision, and those dealing with the influence or stimuli presented to one eye on the appearance of visibility of stimuli presented to the other eye. This paper is concerned with the latter class of questions, and deals with binocular contrast interactions.

It is well established that binocular thresholds for absolute luminance detection are lower than monocular thresholds. Pirenne[9] concluded that the threshold reduction was no more than could be accounted for by the joint action of two independent noisy detectors. This kind of statistical threshold reduction has been termed probability summation. In a very careful experiment, Thorn and Boynton[10] have shown that the binocular threshold reduction resulting from simultaneous stimulation of corresponding retinal points exceeds the threshold reduction to be expected from probability summation alone. It must therefore be due to neural interaction. For a review of the literature on binocular summation that reaches the same conclusion, see Blake and Fox.[11]

Cohn and Lasley[12] have concluded that probability summation cannot account for the enhancement of binocular sensitivity over monocular sensitivity for luminance increments. They postulate the existence of interocular "summing" and "subtracting" mechanisms to account for detection data in which luminance increments, decrements, and combinations are presented to the two eyes.

Similarly, contrast sensitivities for gratings viewed binocularly are about 40% greater than corresponding monocular sensitivities. This improvement in sensitivity appears to reflect neural summation, since it exceeds the improvement to be expected from probability summation alone.[13–15]

Monocular viewing refers to the presentation of the stimulus to one eye only, binocular viewing to the presentation of the same stimulus to both eyes, and dichoptic viewing to the presentation of different stimuli to the two eyes. (Stereoscopic viewing is roughly synonymous with dichoptic viewing, but carries the added implication that questions of stereo-

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scopic depth perception are under consideration.) In many applications of dichoptic viewing, the detectability or perceived magnitude of a test stimulus presented to one eye is measured in the presence of a masking stimulus presented to the other eye. This dichoptic masking procedure was used in the experiments reported here.

For the monocular detection of a luminance flash, the prevailing state of adaptation, or level of steady-state illumination in the contralateral eye appears to have no effect.[16,17] (Under certain special circumstances, conditions of contralateral preadaptation can influence the time course of monocular dark adaptation.[18–20]) On the other hand, luminance transients in the contralateral eye substantially elevate monocular thresholds.[17]

Several studies have examined the effects of dichoptic pattern masks on the perception of test targets. Typically, metacontrast paradigms are used to determine the effects of masks on form identification or perceived contrast of test stimuli. This work is well reviewed elsewhere.[21–24] Comparatively little is known about monocular contrast detection in the presence of contralateral masking stimuli occupying the same region of the visual field. The purpose of the current research was to discover how the monocular detection of gratings is influenced by the spatial frequency and contrast of dichoptically presented masking gratings. The results of dichoptic masking experiments were compared with the results of comparable monocular experiments in which the masking and test gratings were superimposed and presented to the same eye.

METHOD

Apparatus

Vertical sinewave gratings were presented on a CRT display by z-axis modulation.[25] The display, designed and built at the Physiological Laboratory, Cambridge, had a P31 phosphor. The constant mean luminance was 200 cd/m^2. The raster was derived from a 100-Hz horizontal sweep and 100-kHz vertical triangle wave.

The relation between sinewave-grating contrast and z-axis voltage and frequency was measured with a narrow slit and a UDT 80X Opto-meter. As the grating pattern drifted behind the stationary slit, the Opto-meter obtained 256 luminance samples per cycle. The resulting sequence of values was Fourier analyzed. By this means, the harmonic composition of the modulation was obtained for a given z-axis voltage and frequency. During the experiments, all contrasts were kept within the range for which the amplitudes of harmonic distortion products were less than 3% of the fundamental.

Split-screen viewing was arranged in which independent patterns were presented on the left and right halves of the display. One function generator triggered the cathode-ray tube (CRT) sweep. A TTL pulse from the display, true during the sweep, triggered a pulse generator and gated on a second function generator. The pulse generator's output pulse controlled a high-speed two-input/one-output analog switch. The outputs of the two function generators were the inputs to the analog switch. The output of the analog switch was the z-axis input. By setting the pulse generator's output to a delay of 5 ms after triggering, and a pulse width of 5 ms, the switching occurred when the sweep was halfway across the screen. Hence, the outputs of the first and second function generators produced modulation on the left and right halves of the display, respectively.

A vertical, black cardboard divider stood between the center of the display and the observer's nose, for dichoptic viewing. The left and right halves of the screen were visible only to the left and right eyes, respectively. The separate half-fields were 13 cm wide by 20 cm high, and had dark surrounds. 1.5-mm diam black fixation dots were placed at the centers of the half-fields. 4.5-mm vertical nonius lines were placed above and below the fixation dots in the left and right half-fields, respectively, to aid in precise binocular alignment. Observers wore base-in prisms in trial frames to aid in the binocular fusion of the half-fields. No stimulus trials were begun until the nonius lines appeared in vertical alignment and the fixation dots were fused.

In the monocular masking experiments, both the masking and test gratings were presented to one eye. This was accomplished by electronically adding the outputs of the two function generators and applying the sum to one side of the analog switch. As a result, a superposition of gratings was presented to one eye, and a uniform field of the same average luminance to the other eye.

When the masking and test gratings were the same spatial frequency, both signals were derived from the same function generator.

A PDP-8 computer controlled stimulus durations and contrast levels with D/A converters and analog multipliers. The computer sequenced stimulus presentations and collected data.

Experimental procedure

For test gratings of 1.0 cpd and below, the viewing distance was 57 cm, and the half-fields subtended 13° horizontally by 20° vertically. For test stimuli at 4.0 and 16.0 cpd, the viewing distance of 228 cm was used to avoid beating of high frequency z-axis modulation with the 100-kHz raster. At 228 cm, the half-fields subtended 3.25° by 5°.

Psychophysical threshold estimates were determined by a version of the two-alternative forced-choice staircase procedure.[26] The observer began by adjusting test grating contrast to a level just above threshold by turning a handheld potentiometer. The observer was then given a block of self-initiated trials. Each trial consisted of two 200-ms exposures, marked by auditory tones, and separated by 750 ms. Only one exposure contained the test grating but both exposures contained the masking grating. The observer identified the test interval by pressing one of two keys. A correct choice was followed by a tone. Three correct choices at one contrast level were followed by a constant decrement in contrast, and one incorrect choice was followed by an increment of the same size. The mean of the first six contrast peaks and valleys in the resulting sequence was taken as an estimate of the 79% frequency-of-seeing level.[26] Typically, a block consisted of 30 to 35 trials. For each condition, the threshold measure was the geometric mean of the threshold estimates from several blocks. The error bars in Figs. 2 and 4 correspond to ±1 standard error of the mean.

Thresholds were measured for test gratings presented to the right eye. Under dichoptic conditions, masking gratings were presented to the left eye. Under monocular conditions, masking gratings and test gratings were superimposed and presented to the right eye, while the left eye viewed a field of the same average luminance. All stimulus gratings were in cosine phase with the fixation marks. Masking and test patterns were always presented simultaneously with abrupt onsets and offsets.

Contrast thresholds were obtained in two experiments:

(i) Contrast threshold as a function of masking contrast: Test-grating thresholds at 0.25, 1.0, 4.0, and 16.0 cpd were measured as a function of the contrast of masking gratings of identical frequency and phase. Six masking contrasts were used, spanning nearly two log units from near threshold. Since test and masking gratings had identical frequency and phase, these measurements may be regarded as monocular and dichoptic increment threshold measurements. Six threshold estimates were obtained from six blocks of forced-choice trials at each masking contrast and each test frequency, for each of two observers. A given one to two hour session was devoted to one test frequency, with masking contrasts randomly assigned. About three sessions were required to obtain all the data at one test frequency for one observer. Data collected in separate sessions showed no systematic differences.

(ii) Test threshold as a function of masking frequency: For test gratings at 0.125, 0.25, 1.0, 4.0, and 16.0 cpd, thresholds were measured as a function of the spatial frequency of constant-contrast masking gratings. Masking contrast was maintained constant at 0.19, but masking frequencies ranged above and below the test frequency. Three threshold estimates were obtained from three blocks of trials for each test-mask combination, and for each of two observers. (For the test frequency of 16.0 cpd, data were available from observer CF only.) A session was devoted to a single test frequency, and masking frequencies were randomly assigned to blocks of trials. Approximately two sessions were required to collect all the data at one test frequency for one observer.

Observers

There were two observers, both well practiced with the methods and stimuli. CF is a male in his early twenties (both eyes: sphere = −0.5 D, cyl. = −0.5 D, axis = 0.) During the experiments he was optically corrected. JG is a 19-year-old emmetropic female. Fig. 1 shows contrast-sensitivity functions for the two observers (see below). Both observers have normal color vision and normal stereopsis.

RESULTS AND DISCUSSION

Contrast sensitivity functions

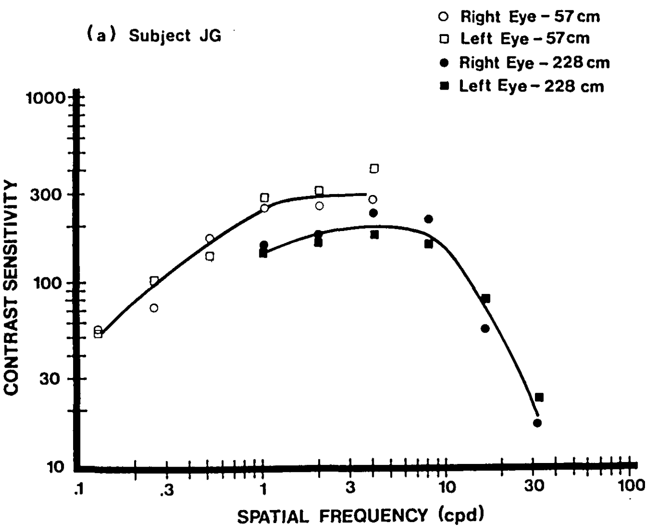
Figure 1 presents contrast sensitivity functions for both eyes of both observers. Separate functions are shown for the two viewing distances of 57 and 228 cm. Contrast sensitivity is the reciprocal of threshold contrast. Each point is the geometric mean of two threshold estimates, derived from two blocks of forced-choice trials.

JG's two eyes have approximately equal sensitivity. CF's right eye is slightly more sensitive than his left.

At 1.0, 2.0, and 4.0 cpd, thresholds were obtained at both 57 and 228 cm. Sensitivity at the greater viewing distance was slightly reduced, confirming observations made by Campbell and Robson.[1] For equal spatial frequencies, displays viewed from 57 cm contain four times as many cycles as displays viewed from 228 cm. Legge[27] has argued that the increase in contrast sensitivity with increasing number of cycles is due to probability summation over space of the outputs of contrast detecting mechanisms. The probability summation model predicts that sensitivity increases approximately as the cube root of the number of cycles. In Fig. 1, the probability summation model predicts that contrast sensitivity at 57 cm should be $4^{1/3} \approx 1.6$ times greater than sensitivity at 228 cm. The mean ratio of increased sensitivity for equal spatial frequencies at 57 and 228 cm, pooled over eyes, observers, and frequencies, is 1.67, with a standard error = 0.10.

Test threshold as a function of masking contrast

Figure 2(a) presents test thresholds as a function of the contrast of dichoptically presented masks. The test targets were sinewave gratings of 0.25, 1.0, 4.0, and 16.0 cpd, presented



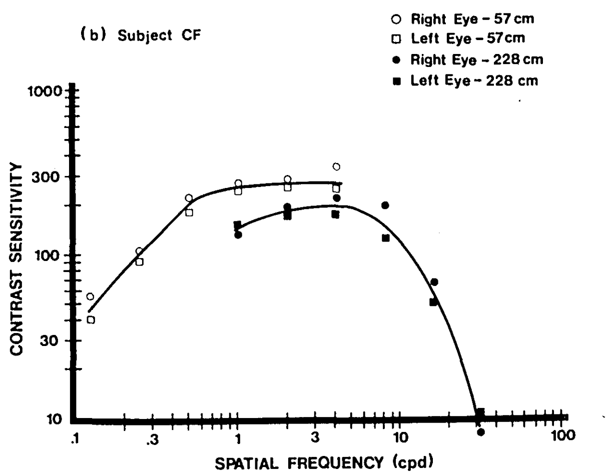


FIG. 1. Contrast sensitivity functions for two observers. Contrast sensitivities (reciprocals of thresholds) are plotted as a function of spatial frequency for two observers, at viewing distances of 57 and 228 cm, for right and left eyes separately. Each data point is the geometric mean of two threshold estimates from two blocks of forced choice trials. All data were obtained in one session. (a) Subject JG. (b) Subject CF.

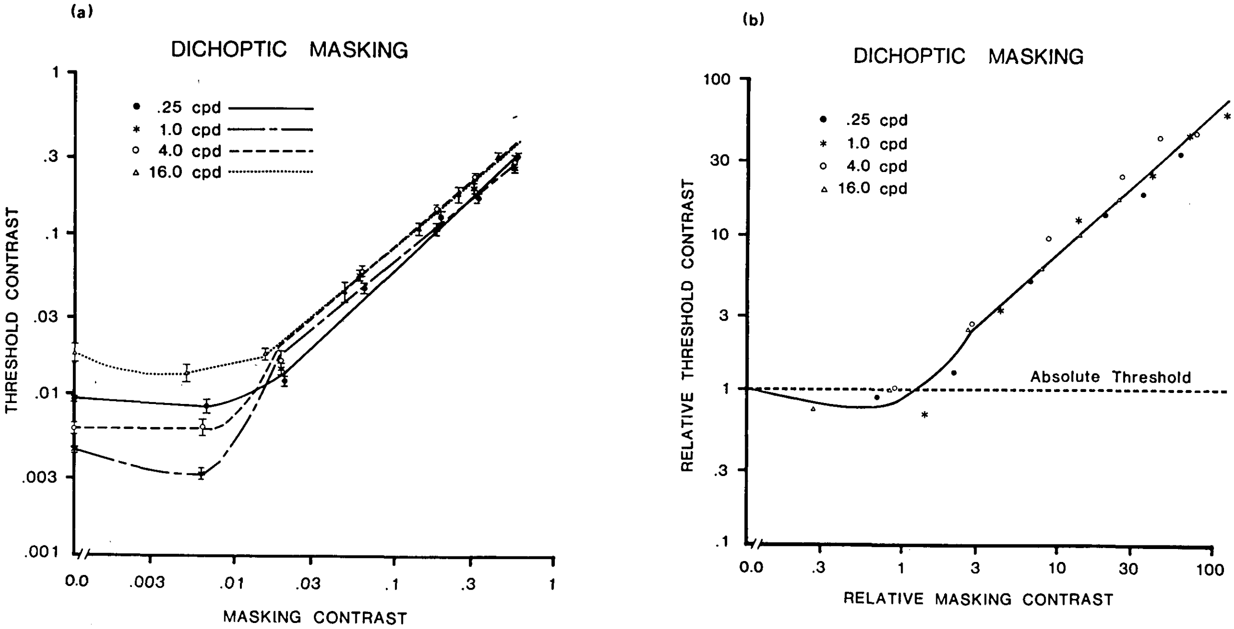


FIG. 2. Threshold as a function of dichoptic masking contrast. (a) Contrast thresholds for gratings at four spatial frequencies, presented to the right eye, are plotted as a function of the contrast of masking gratings of the same frequency presented to the left eye. Test and masking gratings were in cosine phase with the fixation marks and were presented simultaneously for 200 ms. Data points are geometric means of 12 threshold estimates, each from a block of forced choice trials, from two observers. Error bars represent ±1 standard error (s.e). Best fitting straight lines have been drawn through the data at medium and high contrasts. See Table I. Smooth curves have been drawn through the data at low contrasts. (b) The axes in (a) have been rescaled in units of unmasked threshold contrast. Values in (a) have been divided by the unmasked threshold at the appropriate frequency and replotted. A best fitting straight line has been drawn through the points at medium and high contrasts. A smooth curve has been drawn through the low contrast points.

to the right eye. The masks were sinewave gratings of identical frequency, presented to the left eye. Both patterns were in cosine phase with their fixation marks. They were presented simultaneously for 200 ms. The data points are geometric means of 12 threshold estimates from two observers (see **METHOD**). There were no systematic differences in the threshold functions for the two observers. The masking contrasts ranged over nearly two log units, from a lowest contrast near 0.006 to a maximum contrast near 0.6. The points lying on the vertical axis at the left of Fig. 2(a) were obtained with 0 masking contrast (absolute thresholds).

The qualitative features of the masking functions at the four spatial frequencies are similar. For a range of low masking contrasts, test thresholds remain at or slightly below absolute threshold. With increasing masking contrast, the functions turn upward abruptly, and then straighten out to rise steeply in the log-log coordinates. Best-fitting straight lines (least-squares criterion) have been drawn through the data points at high masking contrast. The slopes of these lines range from 0.83 to 0.95. See Table I.

TABLE I. Threshold as a function of masking contrast: Slopes of best-fitting straight lines in log-log coordinates.

Spatial frequency	Dichoptic masking Fitted range (masking contrast)	Slope	Monocular masking Fitted range (masking contrast)	Slope
0.25	0.020–0.577	0.95	0.064–0.577	0.28
1.0	0.019–0.548	0.83	0.061–0.548	0.63
4.0	0.019–0.548	0.86	0.061–0.548	0.67
16.0	0.016–0.437	0.85	0.048–0.437	0.70
combined*		0.90		0.50

* These slopes are computed from the best-fitting lines through the combined normalized data at the four test frequencies. See text.

The data of Fig. 2(a) are replotted in Fig. 2(b) in a means better suited for comparison across frequencies. The axes have been rescaled in units of absolute threshold contrast. The horizontal dashed line marks the absolute threshold ordinate value of 1.0. In these relative coordinates, data at the four spatial frequencies appear to follow a single function. The characteristic dipper shape of the masking function is apparent. Relative masking contrasts near or below 1.0 (absolute threshold contrast) have little effect on test thresholds. With higher masking contrasts, there follows a rapid transition to a straight line increase. The slope of the best-fitting straight line through the combined, rescaled data is 0.90. Hence, under dichoptic masking conditions, threshold contrasts rise almost linearly with high masking contrasts at spatial frequencies ranging from 0.25 to 16.0 cpd, and very nearly obey Weber's law. The data in Fig. 2 illustrate that there are very substantial binocular interactions in visual pattern processing. The results differ markedly for corresponding monocular masking measurements (see below).

Threshold contrasts from the straight lines in Fig. 2(a), as well as absolute threshold data, are replotted in Fig. 3 as a function of spatial frequency. The ordinate is contrast sensitivity, and six masking contrasts are parameter values. Line segments have been drawn to connect the points. The curve for 0 masking contrast is the usual contrast sensitivity function for absolute detection. It has the typical peaked shape. However, the masked contrast sensitivity functions flatten out in the presence of even very low masking levels. For a masking contrast of only 0.02, the function is already quite

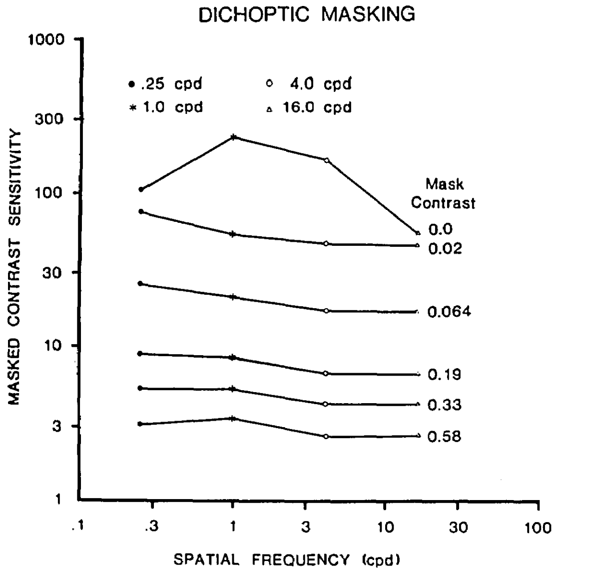


FIG. 3. Contrast sensitivity functions with sichoptic masking. Values from the straight lines through the data in Fig. 2(a) have been replotted as masked contrast sensitivity as a function of spatial frequency. Values at each of the six masking contrasts have been connected by line segments.

flat. At middle frequencies, a low masking contrast of 0.02 is already several times suprathreshold, and is effective in elevating test grating thresholds. At low and high spatial frequencies, the same masking contrast is near absolute threshold and has little effect in elevating test thresholds. At still higher masking contrasts, sensitivity is uniformly depressed across frequencies, and the masked contrast sensitivity functions remain nearly flat, and move down the ordinate.

Corresponding data for monocular masking are shown in Figs. 4 and 5. Here, the mask and test gratings were identical in frequency and phase, and were presented to the right eye. The left eye viewed a uniform field (apart from fixation marks) of the same mean luminance. Note that the monocular masking measurements may be regarded as measurements of monocular contrast increment detection.

In Fig. 4(a), test thresholds are plotted as a function of monocular masking contrast for the same set of four spatial frequencies. The same set of masking contrasts were used in the monocular and dichoptic measurements.

Qualitatively, the four functions are similar. There is a region of low masking contrasts for which test thresholds are reduced below the absolute detection threshold. With increasing masking contrast, there is a rapid transition to a straight line increase in the log-log coordinates. Best-fitting straight lines have been drawn through the right-hand portions of the four functions. The slope of the line at 0.25 cpd is 0.28, and is considerably less than the slopes at the three higher spatial frequencies. See Table I.

In Fig. 4(b), the axes of Fig. 4(a) have been rescaled in units of absolute threshold contrast. In these relative coordinates, data at the four spatial frequencies appear to lie near a single dipper-shaped monocular masking function. Relative masking contrasts below about 3.0 have a definite tendency to reduce test thresholds. For relative masking contrasts above 3.0, there is a rapid transition to a straight line increase. The slope of the best-fitting straight line through the combined, rescaled data is 0.50. This suggestive value appears to be somewhat fortuitous. It arises from combining data at 0.25 cpd with a considerably lower slope, and data at the three higher spatial frequencies having slopes slightly higher than 0.50. Nevertheless, it is clear that under monocular masking conditions, increment threshold detection is more nearly described by a square root law (log-log slope of 0.50) than by Weber's Law (log-log slope of 1.0).

Threshold contrasts from the straight lines in Fig. 4(a), as well as absolute detection thresholds, are replotted in Fig. 5

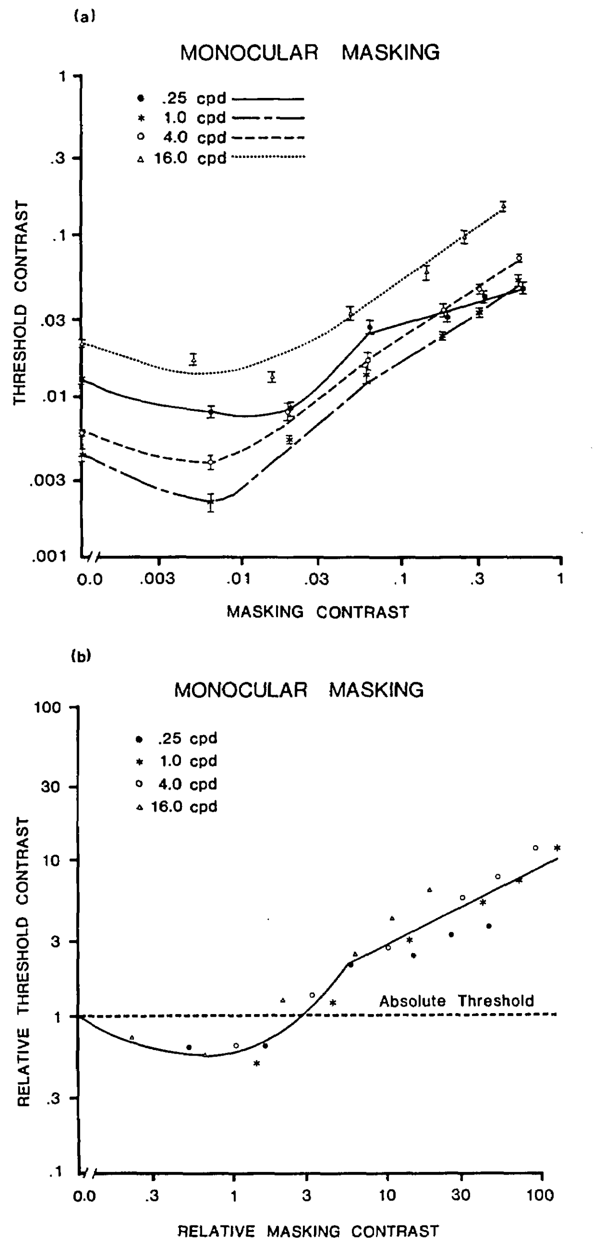


FIG. 4. Threshold as a function of monocular masking contrast. Contrast thresholds for gratings at four spatial frequencies, presented to the right eye, are plotted as a function of the contrast of identical masking gratings presented to the same eye. The left eye viewed a uniform field of the same average luminance. Other details as in Fig. 2.

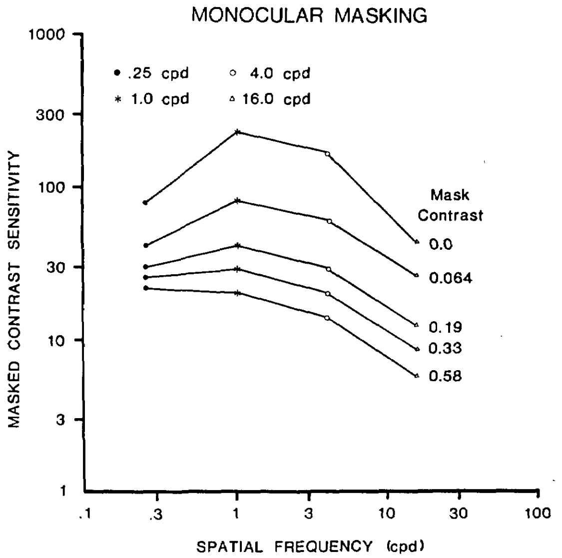


FIG. 5. Contrast sensitivity functions for monocular masking. Values from the straight lines through the data in Fig. 4(a) have been replotted as masked contrast sensitivity as a function of spatial frequency. Values at each of the five masking contrasts have been connected by line segments.

as a function of spatial frequency. The ordinate is contrast sensitivity, with masking contrast as a parameter. Introduction of masking tends to flatten the contrast sensitivity function, but not as rapidly and as completely as in the dichoptic masking case, Fig. 3.

Comparison of dichoptic and monocular masking

The surprising result is that dichoptic masking (Fig. 2) is more effective in elevating test grating threshold than monocular masking (Fig. 4). For instance, comparing the straight lines through the data in Figs. 2(b) and 4(b), a relative masking contrast of 20 (20 times absolute threshold) yields relative contrast thresholds of 14.2 and 4.15 for dichoptic and monocular masking, respectively. Dichoptic thresholds rise almost linearly with medium and high masking contrasts, but monocular masking thresholds more nearly follow a square root dependence on masking contrast. Clearly, under the conditions of this experiment, simultaneous pattern stimulation of the contralateral eye leads to strong inhibition of the eye involved in sinewave grating detection.

Compare binocular interaction effects exhibited by dichoptic spatial frequency masking with binocular summation of thresholds. Dichoptic pattern masking is stronger than monocular masking. On the other hand, although there is no longer doubt of neural interaction in the binocular threshold detection of contrast[13–15] and luminance,[10] this neural "summation" is certainly incomplete.

It is possible that the strength of dichoptic masking may be associated with binocular suppression. If different patterns are presented continuously to corresponding locations in the two eyes, observers may report a phenomenological rivalry. The two patterns are seen alternately, and the pattern not seen at any given time is said to be suppressed. During periods of binocular suppression, luminance thresholds for test spots are elevated as much as 0.5 log units.[28–30] Blake[31] has shown that pairs of orthogonal gratings of the same frequency, presented dichoptically, produce rivalry, but the thresholds for the gratings during their "seen" phases are unaffected by the contralateral stimulus.

There are two reasons for believing that dichoptic masking is a fundamentally different phenomenon from binocular suppression:

(i) There was no phenomenological evidence for suppression in experiments of this paper. The 200-ms stimulus duration was apparently too short a time for rivalry to develop. Although rivalry was reported by the observers for continuous, dichoptic presentation of different suprathreshold spatial frequencies, they did not report rivalry during the 200-ms stimulus intervals. Instead, they reported that the dichoptic displays looked like the monocular superposition of the two patterns. Kaufman[32] has reported similar binocular mixtures resulting from the 50-ms dichoptic exposures of orthogonal bar patterns. It is interesting to note that there was little difference in appearance between corresponding monocular and dichoptic masking displays.

(ii) Binocular suppression appears to show selectivity properties that are very different from those of spatial frequency masking. In the discussion of tuning functions below, it will be shown that at medium and high spatial frequencies, dichoptic masking is maximum when the masking and test gratings are the same spatial frequency, Fig. 6. It is very likely that dichoptic masking, like monocular masking, is orientation specific.[33] On the other hand, the occurrence of binocular rivalry between dichoptically presented gratings depends upon *differences* in their spatial frequencies or orientations. Moreover, the suppressed eye appears to be insensitive to large changes in stimulus spatial frequency and orientation.[34]

The spatial frequency tuning and postulated orientation selectivity of dichoptic masking suggest that it is a phenomenon of the visual cortex. It is likely that binocular suppression is a consequence of pattern processing at higher levels.

Shapes of the masking functions

At medium and high contrasts, the dichoptic masking functions of Fig. 2 have slopes only slightly less than 1.0 (Weber's Law). The monocular masking functions (Fig. 4) have much lower slopes. Data obtained with similar procedures for binocular masking (in which both eyes are presented with both the masking and test gratings) show masking functions like those for monocular viewing.[57]

There have been several studies that have measured grating thresholds as a function of masking contrast. Campbell and Kulikowski[33] used a method of adjustment and monocular viewing. They found a Weber's Law relation between threshold contrast for 1-s increments and the contrast of a continuously present 10-cpd background grating. Bodis-Wollner, Hendley, and Kulikowski[35] used binocular viewing and a yes/no detection procedure. They measured the detection threshold for 8-Hz amplitude modulation of a 6-cpd steady background grating. The increase in threshold modulation depth with background contrast was noticeably less than would be expected from Weber's Law. Bodis-Wollner, Hendley, and Tajfel[36] report similar measurements at spatial frequencies ranging from 1.5 to 12 cpd. They found that Weber's Law holds at 12 cpd, but departures from it become increasingly apparent with decreasing spatial frequency.

Pantle[37] used two-alternative forced choice. He found that the threshold contrasts for 1.7-s increments increased as the 0.6 power of the contrast of continuously present background gratings. This result is in good agreement with the monocular data of this paper (Fig. 4). Stromeyer and Julesz[38] measured grating thresholds as a function of the average contrast of broadband noise. With binocular viewing, continuous presentation, and the method of adjustment, they found close adherence to Weber's Law. (By comparison, it is interesting to note that monaural intensity discrimination functions for briefly pulsed sinusoids, obtained with forced-choice procedures, can be described by power functions with exponents near 0.9 for frequencies ranging from 200 Hz to 8 kHz.[39])

In light of these diverse findings, do monocular or binocular increment contrast thresholds obey Weber's Law or not? Experimental variations, such as differences in psychophysical procedures and differences in the temporal relations between masking and test stimuli, may account for some of the disagreement. There are two other explanations of the differences:

(i) In Fig. 4(a), best-fitting straight lines have been drawn through portions of the masking functions. At 4.0 cpd, the straight line spans masking contrasts from 0.061 to 0.548, and has a slope of 0.67, far from Weber's Law. However, a best-fitting straight line may be drawn through the data from the bottom of the "dipper", covering masking contrasts from 0.006 to 0.548. This straight line has a slope of 0.94, very close to Weber's Law. Hence, the choice of fitting range strongly influences the slopes of the straight lines through the data. In the studies cited above, slopes were generally determined for straight lines through all suprathreshold masking contrasts used. However, the dipper shape of the masking functions indicates that it may be appropriate to fit straight lines only through a particular range of medium and high masking contrasts.

(ii) Bodis-Wollner *et al.*[35] and Kulikowski[40] argue that Weber's Law behavior is approached under conditions of spatial frequency adaptation, but departures from it occur in the absence of adaptation. (Spatial frequency adaptation is the decrease in contrast sensitivity at a given spatial frequency following prolonged viewing of a high contrast grating at that spatial frequency.[41,6]) Kulikowski[40] has measured thresholds for the detection of 0.5-Hz modulation of adapting background gratings of 5.0 cpd. By decreasing the time permitted for pattern adaptation from 4 to 2 min, and readaptation intervals from 45 to 30 s after each trial, the slope of the masking curve decreased from 0.88 to 0.75. Since most of the increment threshold studies cited above have been done with continuously present background gratings, some spatial frequency adaptation is likely to have occurred, and to have influenced the measured slopes.

The slope for monocular masking at 0.25 cpd is 0.28, lower than the slopes at the three higher spatial frequencies. This deviation represents the only major frequency-selective effect in Table I. Bodis-Wollner *et al.*[36] report a decrease in slopes from 12.0 to 1.5 cpd. Kulikowski[40] obtained a slope of 0.304 for the forced-choice increment detection of a 0.25-cpd "edge". He proposed that the slopes at very low spatial frequencies are shallower than those at higher spatial frequencies because low frequency detection is due to transient mechanisms. Further, he argues, transient mechanisms do not adapt and have shallower increment threshold functions than sustained mechanisms at higher spatial frequencies. However, the evidence presented by Kulikowski[40] for the effects of pattern adaptation cannot account for the differences in monocular slopes in Table I, let alone for the much greater differences in slopes that he reports. It seems probable that differences in slope at low and high spatial frequencies are related to the different operating characteristics of sustained and transient mechanisms,[42,43] but their relationship to spatial frequency adaptation is unclear.

The masking procedure is one way of probing the visual system's response to suprathreshold stimuli. Contrast matching and magnitude estimation techniques have also been used to study suprathreshold pattern response.

In contrast matching experiments, the perceived contrast of a test grating is matched to the contrast of a standard grating of fixed spatial frequency. In several studies, it has been observed that the function relating the matching contrast of the test grating to its spatial frequency becomes flatter with increasing contrast of the standard.[44–46] As a consequence, gratings of the same high physical contrast have the same apparent contrast, despite large differences in their thresholds. Kulikowski[40] found that suprathreshold gratings appeared to have the same contrast when the difference between their physical and threshold contrasts were equated. The masked contrast sensitivity functions of Figs. 3 and 5 provide an interesting parallel to these "contrast constancy" results. Just as the apparent contrast functions flatten out at high contrast levels, the threshold functions flatten out with high masking contrast.

In magnitude estimation experiments, observers assign numbers to gratings to represent the perceived contrast magnitude. In an intermodality matching variant of this procedure, Franzén and Berkley[47] have scaled contrast at three spatial frequencies. They have fitted power functions to the data relating perceived contrast to physical contrast. Exponents at 3.5, 9.0, and 18.0 cpd were 0.58, 0.66, and 1.7, respectively. Compare these values with the slopes obtained from the monocular masking data in Table I. Unfortunately, investigators using other variants of the magnitude estimation procedure find different results when scaling contrast.[40,48]

Notice the nonmonotonicity of the masking functions in Figs. 2(b) and 4(b). It is more pronounced in the monocular case. For monocular masking levels below about 3.0 (three times the absolute threshold), test thresholds are reduced. The mask may be said to facilitate test grating detection. The two-alternative forced-choice paradigm is one in which a mask of intensity I is presented in both intervals of a trial, and a test stimulus of intensity ΔI is presented in only one. The observer must discriminate between stimuli of intensities I and $I + \Delta I$. (This discrimination procedure should be distinguished from the subthreshold summation procedure[49] in which an observer adjusts the intensity I_1 of a superimposed pair of stimuli $I_1 + I_2$ until the combination reaches threshold. The two procedures would not, in general, be expected to yield the same results.) Absolute detection occurs when the mask intensity is 0. Nonmonotonicity occurs when there is a range of low masking intensities for which the increment threshold is actually lower than the absolute threshold. This nonmonotonicity occurs for discrimination of luminance increments,[50,51] and grating contrast discrimination.[52,27]

Threshold as a function of masking frequency

Spatial frequency masking has been used to generate spatial frequency tuning functions.[38,42] The shapes of these functions are similar to the shapes of tuning functions obtained with spatial frequency adaptation.[6,41] The two kinds of tuning functions have been presumed to reflect properties of the same underlying *spatial frequency channels.* These spatial frequency channels have been ascribed to cortical mechanisms because they show orientation selectivity in masking,[33] and spatial frequency adaptation.[53] The partial interocular transfer of spatial frequency adaptation[6] is a further argument for the central locus of spatial frequency channels.

In an effort to establish the spatial frequency selectivity of dichoptic masking, test grating thresholds were measured in the presence of masking gratings whose spatial frequencies varied both above and below the test frequency. The masking contrast was kept constant at 0.19. Masking and test gratings were maintained in cosine phase with the fixation marks.

Figure 6 presents dichoptic masking tuning functions at five test grating frequencies. The abscissa is the frequency of the masking grating. The ordinate is relative threshold elevation, the ratio of masked threshold to unmasked threshold minus 1. An ordinate value greater than 0 represents an increased threshold due to masking. The five arrows point to the test grating frequencies. The data points are geometric means of six threshold estimates, three from each of two subjects. Curves have been drawn through each set of data in the figure.

For the three highest test frequencies, 1.0, 4.0, and 16.0 cpd,

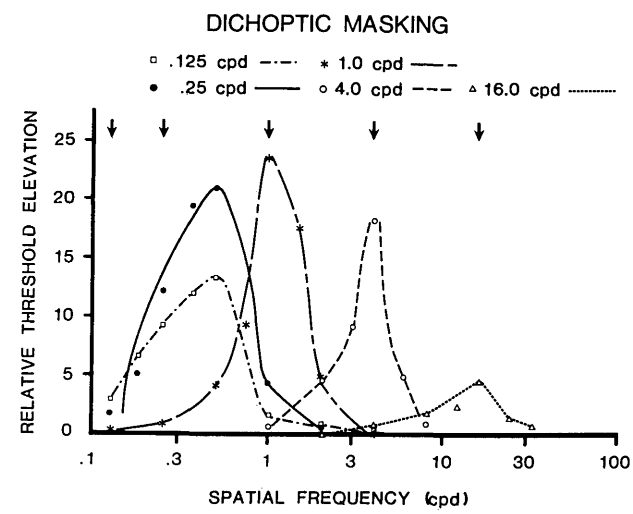


FIG. 6. Dichoptic tuning functions. Contrast thresholds for test gratings at five spatial frequencies, presented to the right eye, were measured as a function of the spatial frequency of masking gratings presented to the left eye. Both gratings were in cosine phase with the fixation marks, and the mask had a constant contrast of 0.19. Test and mask were presented simultaneoulsy for 200 ms. The ordinate is relative threshold elevation, the ratio of masked threshold to unmasked threshold minus 1. Data points are geometric means of six threshold estimates, each from a block of forced choice trials, obtained from two observers. Data at 16.0 cpd were available from observer CF only. Smooth curves have been drawn through the data at a given test frequency. The five arrows point to the test frequencies.

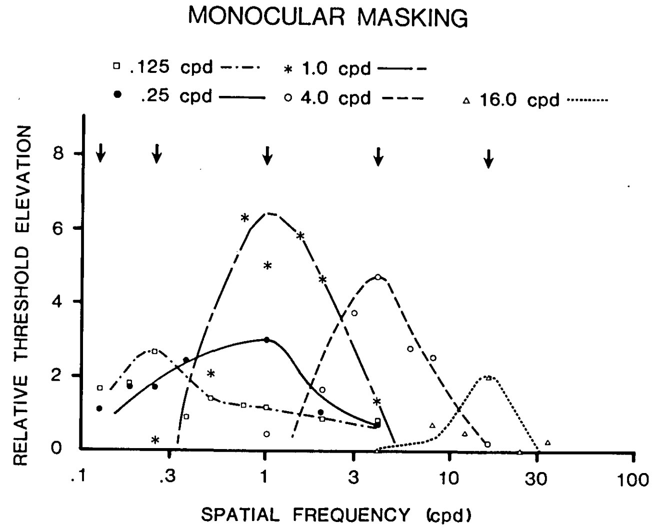


FIG. 7. Monocular tuning functions. Contrast thresholds for test gratings at five spatial frequencies, presented to the right eye, were measured as a function of the spatial frequency of masking gratings presented to the same eye. The left eye viewed a uniform field of the same average luminance. Other details as in Fig. 6.

the tuning functions peak at the test frequencies, and are rather narrow. The bandwidth between half-maximum points is about one octave. The corresponding tuning functions at the low test frequencies of 0.125 and 0.25 cpd differ from those at the higher frequencies in two important ways: (i) Peak masking occurs for a masking frequency higher than the test frequency; (ii) below the peak, the tuning functions are relatively broader than the tuning functions at higher frequencies.

Figure 7 shows the corresponding tuning functions at the five test frequencies for monocular masking. The monocular tuning functions are qualitatively like those for dichoptic masking, but differ in three quantitative ways: (i) Peaks of the tuning functions were always higher for the dichoptic masking, reflecting its greater effectiveness; (ii) the monocular functions are more broadly tuned than the dichoptic functions. They are about ±1 octave between half-maximum points; and (iii) the low frequency monocular tuning functions show greater frequency spread, but less peak shift, than the corresponding dichoptic tuning functions. The breadth of the low frequency monocular tuning may be illustrated by noting that the threshold for a 0.125-cpd test grating is elevated by a factor of almost 3 for a masking grating four octaves away at 4.0 cpd.

The tuning functions of Figs. 6 and 7 were measured with a fixed masking contrast of 0.19. Since the absolute thresholds at the five test frequencies differed (Fig. 1), this fixed masking contrast fell at different levels relative to the different test thresholds. Legge and Foley[57] have examined the effects of masking contrast on the shape of tuning functions at a test frequency of 2.0 cpd. They used binocular viewing. Their psychophysical procedures were like the ones described in this paper. For masking contrasts ranging from 0.032 to 0.512, the tuning functions were scaled versions of one another, and the half-maximum frequencies were approximately invariant. Extrapolation of these results to dichoptic and monocular masking suggests that it is appropriate to compare bandwidths, estimated from the measured tuning functions of Figs. 6 and 7, across test frequencies.

The frequency-selective nature of dichoptic masking is very strong confirmatory evidence for the view that there are spatial frequency selective mechanisms at or beyond the physiological point of binocular convergence. Since the first locus of binocular interaction in the primary visual pathway of primates appears to be cortical area 17,[54–56] it may be concluded that dichoptic masking tuning functions manifest properties of frequency-selective neural mechanisms at or beyond the cortex.

The broadening of the low-frequency tuning functions on a log frequency scale, and the tendency of peaks of the tuning curves to shift to frequencies higher than the test frequencies have been observed under different masking conditions.[42] Legge[42] has hypothesized that these characteristics of the tuning functions may be accounted for by a transient mechanism having low-pass spatial frequency sensitivity coexisting with a set of bandpass sustained mechanisms. Alternatively, the broadening of the tuning functions may be related to the small number of cycles in test and masking gratings of very low spatial frequency.

It has been pointed out that the peaks of the tuning curves are higher for dichoptic than for monocular masking. This difference decreases as the masking frequency departs from the test frequency. Accordingly, dichoptic tuning functions are not simply scaled versions of the monocular tuning functions. Instead, the dichoptic functions are more narrowly tuned. Notice also that dichoptic tuning functions show relatively sharper high frequency cutoffs than the monocular tuning functions.

There are at least two possible origins for the differences between monocular and dichoptic tuning functions: (i) the functions may reflect the operations of different, underlying neural mechanisms, having different spatial frequency tuning properties; and (ii) differences may be due to differences in the monocular and dichoptic transmission of pattern information to the neural site of binocular interaction. In the case of monocular masking, both masking and test grating information must be transmitted along a single monocular channel, whereas in dichoptic masking, they travel independently. It may be speculated, for instance, that a high contrast, dichoptically presented masking grating generates a neural signal that travels with shorter latency to the cortex than a neural signal resulting from a low contrast test grating presented to the other eye. In monocular masking, on the other hand, the test and masking gratings are superimposed and presented to the same eye. The superposition generates a single neural signal, and the effects of test and mask reach the cortex together. If cortical mechanisms responsible for detection are briefly desensitized by stimulation, dichoptic masking might be expected to have greater potency than monocular masking because the slower test signal would arrive during the refractory period following arrival of the masking signal. This "latency hypothesis" is under investigation.

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Temperature dependence of absorptance in laser damage of metallic mirrors: I. Melting

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Naval Weapons Center damage thresholds for ultraclean metals (45 J/cm^2, 100 ns, 10.6 μm, Cu) are a milestone in laser-damage studies, being reproducible, with no isolated-spot damage, and showing the first excellent agreement ($\sim$ 15%) with a first-principles theory (developed here) for any metal or transparent material. An exact premelting temperature result for the case of optical absorptance $A = A_i + A_1 T_s$ indicates that the surface-temperature rise T_s reduces the theoretical threshold $(It_p)_m$ for raising T_s to the melting temperature T_m by a factor of 3.6 to 1.6, typically. Raising T_s to T_m is a good damage criterion for 100-ns pulses, but not for single subnanosecond pulses. The previous scaling $It_p \sim t_p^{1/2}/A$ is invalid in general, but $It_p \sim t_p^{1/2}$ is valid for $(It_p)_m$ even with $A = A_i + A_1 T_s$. Approximating a Gaussian $I(t)$ pulse by a square pulse makes $(It_p)_m$ 17% too small in the constant-A approximation.

I. INTRODUCTION

Most previous calculations[1–4] of laser-damage thresholds of metals have neglected the increase in the optical absorptance with increasing temperature, though one rough estimate of the lowering of the threshold was given.[4] Since the theoretical absorptance of a pure metal increases by a factor of 5–6 typically as the temperature is increased from room temperature to the melting point (according to the Drude theory and experimental value of the dc electrical resistivity), large errors in the theoretical values of the damage threshold can result from formally neglecting the increase in absorptance A with

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