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BINOCULAR MASKING LEVEL DIFFERENCES IN SINUSOIDAL GRATING DETECTION[1]

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INTRODUCTION

RECENT experiments of BLAKEMORE and HAGUE (1972) indicate that the detectability of sinusoidal gratings seen binocularly against a uniform background depends on the interocular phase of the gratings. Gratings that are identical in the visual fields of the two eyes are more readily detected than gratings presented 180° out-of-phase, that is with the maxima of the grating in one field in a location corresponding to the minima of the grating in the other. The magnitude of the effect is small, on the order of 0·1 log units. An effect of this magnitude, but not the periodicities discussed by Blakemore and Hague, might be expected from the variation in accommodation associated with vergence changes of the size arising in the Blakemore and Hague experiment (SOUTHALL, 1937; CAMPBELL and GREEN, 1965).

Similarly small but opposite effects of signal phase are found in hearing where, for observers listening in quiet, auditory signals 180° out of phase at the ears are detected at 0·9 dB lower intensity than signal presented in phase (DIERKS and JEFFRESS, 1962).

In noise, however, signal phase becomes much more important. In detecting auditory signals, provided the noise against which the signals to be detected is identical at the ears, signals presented 180° out of phase may be detected at intensities more than an order of magnitude lower than signals presented in phase (JEFFRESS, 1972). In audition the size of the effect depends, as may be imagined, on signal frequency and duration as well as on the bandwidth and intensity of the noise. Several extensive models for the auditory case have been developed (DURLACH, 1972; JEFFRESS, 1972; OSMAN, 1971) and, although no completely adequate model exists, several are well developed and capable of explaining much of the relevant auditory data (HENNING, 1973).

The difference between the signal levels leading to some constant measure of detectability for the case in which the signal is identical at each ear and for the case in which the signal is 180° out of phase at the ears is called the binaural masking level difference. We explored the visual analogue, a binocular masking level difference, in the hope that insights into the auditory phenomena might help shed light on visual mechanisms involved in fusion, rivalry or stereopsis.

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PROCEDURE

Two observers[3] participated in a standard two-alternative forced-choice grating detection experiment. Each trial of the experiment began with a warning interval. This was followed by two observation intervals 1 sec each in duration separated by a 600 msec pause, and a 750 msec answering interval. All the intervals were marked for the observers by bursts of sound. The grating to be detected—the signal grating—was presented in one of the observation intervals and the observer was required to indicate whether the first or second interval had contained the signal grating. The visual signal to be detected was an 8·5° by 8·5° sinusoidal grating with vertical bars presented so that the grating was either identical or 180° out-of-phase in fields seen separately by each eye. The grating was detected against a background of narrow-band visual noise of the same mean frequency and the same orientation as the signal. The probability of the signal being in the first interval was 0·5 on each trial. The observer was informed after responding which interval had in fact contained the signal and a new trial begun. The entire trial required about 5 sec and 50 trials were performed without stopping. Approximately 600 trials could be obtained from a single observer in daily 1 and ½ h sessions. Observers were informed of the signal phase, and psychometric functions relating the percentages correct responses to signal contrast (CAMPBELL and GREEN, 1965) were obtained in both signal phase conditions before the spatial frequency of the signal was changed. Care was taken to ensure that the signal grating could be seen in the absence of noise for every signal contrast used.

In the first experiment to be described, the patterns to be detected were gratings whose luminance varied sinusoidally in the horizontal direction. The gratings and the visual masking noise were generated in a fashion described by CAMPBELL and GREEN (1965) with the apparatus used by CARTER and HENNING (1971).

The signal grating was turned on and off slowly with a 100 msec rise and fall time. The mean luminance (1·55 ft-L) of the HP 1300 X–Y display on which both the signal and noise appeared was constant and not altered by the addition of either signal or noise. The display system produced negligible harmonic distortion; the second and third harmonics in the luminance waveform were approximately 40 dB below the level of the fundamental (CARTER and HENNING, 1971).

The masking noise was generated using a Spectral Dynamics SD101B filter with a 5 Hz filter width, skirts of 60 dB/3 bandwidth, and with the centre frequency of the noise locked to the signal frequency. The output of the filter, appropriately amplified, was led to the Z-axis of the display, and produced a noise with a bandwidth of less than 0·003 c/deg centred on the spatial frequency of the grating to be detected. The noise contrast had a Rayleigh distribution with a mean of 0·28. At this level, approx. 95 per cent of the noise peaks were within the linear range of the system. The noise grating looked like a vertical sinusoidal grating changing slowly in both contrast and phase. The phase change appears as a slow oscillation of small extent. The noise grating did not drift consistently in either direction because the mean frequency of the noise was locked to the frequency of the signal synchronizing the X-sweep of the display. The rate of change of the contrast and phase, dependent, of course, on the filter bandwidth, was very slow relative to the rate of the X-sweep; thus the noise contrast and phase were essentially constant during any single sweep.

The display was divided into two 8·5° by 8·5° fields in a black surround; each field was visible to only one eye of the observer—a 50 cm matt black septum extended from the display to the observer. The observers, both corrected for myopia, used prisms with a total displacement of 14 dioptres to fuse the two images. The fused image formed a single 8·5° by 8·5° noise field in which the sinusoidal grating was to be detected.

The signal grating was presented in one of two ways; either identical gratings were presented to both eyes or the signal gratings were presented 180° out of phase, that is, with the light bars in one field corresponding to the dark bars in the other. (The phase inversion was accomplished by comparing the voltage of the sawtooth waveform generating the X-sweep with a fixed d.c. voltage corresponding to the value of the sweep voltage at the centre of the display. When the comparator indicated that the sweep was in the centre of the display, i.e. between the two visible fields, the signal was turned off and an inverted copy turned on. The transient produced by this operation was hidden from the observer by the septum dividing the display fields.)

For gratings with horizontal luminance variation (vertical gratings), there were four conditions of viewing: signal in or 180° out of phase with a fixation mark, and the same two phase conditions with no fixation marks. The fixation marks were composed of four thin lines forming 0·7° squares. The fixation marks appeared as a single square in the fused binocular image. (Fusion on the basis of the edges of the 8·5° square aperture on the identical noise gratings in each field was also possible.) The last two conditions were also examined with gratings whose luminance varied vertically, that is gratings which looked like horizontal bars. The horizontal gratings were produced by turning the display on its side and arranging viewing apertures with centres on a 45° angle. Stronger prisms were used with their bases arranged to compensate for both the vertical and horizontal disparities. There were thus six viewing conditions; signals of four different spatial frequencies were used (approx. 0·24, 0·6, 2·4 and 6 c/deg) for all six conditions.

[3] The Observers are the authors.

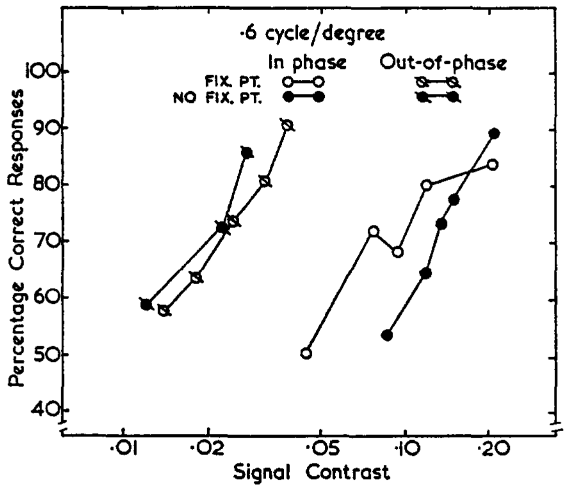

FIG. 1. Percentage correct detection as a function of the signal contrast for 0·6 c/deg vertical gratings. The symbols with a slash are for 180° out-of-phase gratings—those without slashes for in-phase gratings. The filled symbols represent data from conditions in which no fixation point was present—the open symbols data from conditions with fixation points. Each data point is based on 200 observations from observer 2.

RESULTS

Figure 1 shows the percentage of correct responses for observer 2 as a function of the signal contrast for 0·6 c/deg gratings. The symbols with a slash through them represent data from the condition in which the signal to be detected was 180° out of phase in the two fields: the data without a slash are from the in-phase condition. The out-of-phase signals are detected at much lower contrasts than the in-phase signals whether the observer had a fixation point in each field (open symbols) or not (closed symbols). The observer achieved 75 per cent correct responses at a contrast of about 0·024 with out-of-phase signals but required a contrast of about 0·13 with in-phase signals in order to achieve the same level of performance.

Figure 2 shows data for the same observer detecting 6 c/deg gratings. At this spatial frequency, the effect of signal phase is negligible. Signals are detected at about the same contrast regardless of the interocular signal phase.

Data were obtained from observer 2 at two other spatial frequencies and from observer 1 at all four spatial frequencies. The slopes of the psychometric functions relating performance (linear scale) to contrast (log scale) were similar for all spatial frequencies, and both conditions of signal phase; it is thus reasonable to compare performance in the two conditions of signal phase on the basis of the 75 per cent correct performance levels only. The comparisons are shown in Figs. 3 and 4 for observers 1 and 2 respectively.

In these figures, the contrast for 75 per cent correct detection of the out-of-phase signal relative to that for the in-phase signal is plotted, in log units, as a function of the spatial frequency of the signal. The standard deviation of the ratios plotted on the ordinate is not greater than 0·05 log units when binomial variability is reflected through the appropriate psychometric functions. From Fig. 3 (data for observer 1) it is clear that there is a large advantage in detectability at low spatial frequencies for out-of-phase signals. This advantage

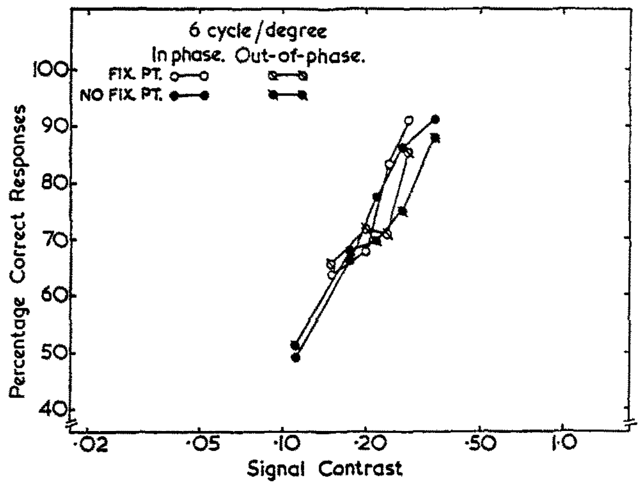

FIG. 2. Percentage correct detection as a function of the signal contrast for 6·0 c/deg vertical gratings. The symbols with a slash are for 180° out-of-phase gratings—those without slashes for in-phase gratings. The filled symbols represent data from conditions in which no fixation point was present—the open symbols data from conditions with fixation points. Each data point is based on 200 observations from observer 2.

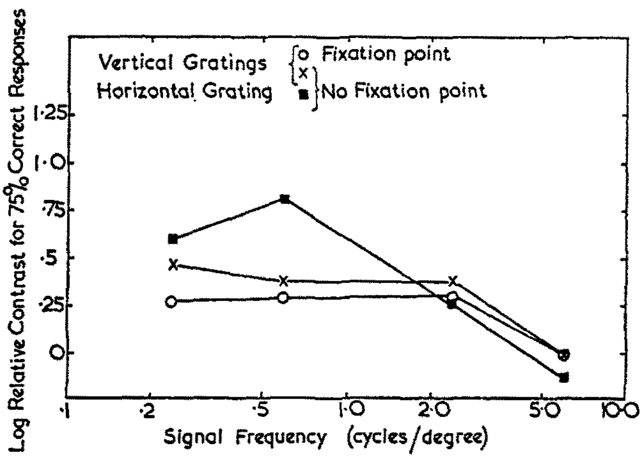

FIG. 3. The logarithm of the ratio of signal contrast leading to 75 per cent correct detection with in-phase compared to out-of-phase gratings as a function of the spatial frequency of the gratings. Data are from observer 1.

decreases with increasing spatial frequency, but does not depend on the presence of a fixation mark. Further, horizontal gratings show an effect as large as or larger than vertical gratings.

Similar data for observer 2 are shown in Fig. 4. The effect of interocular phase for this observer is independent of the orientation of the grating as well as of the presence or absence of fixation points.

DISCUSSION

The most striking result of the experiment just described is the finding that, in the same noise, out-of-phase gratings are detected at much lower contrast than in-phase gratings.

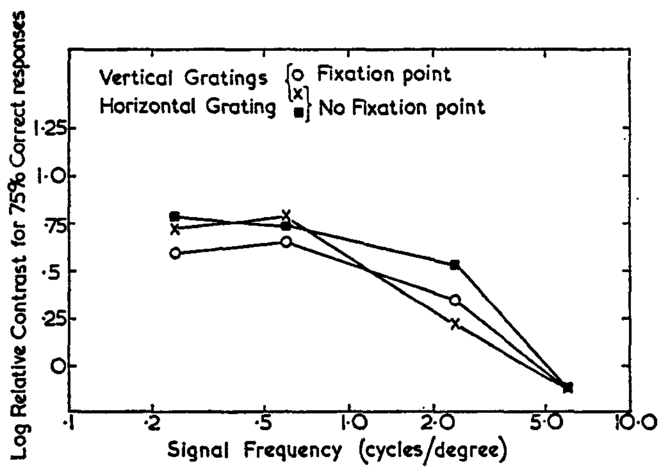

FIG. 4. The logarithm of the ratio of signal contrast leading to 75 per cent correct detection with in-phase compared to out-of-phase gratings as a function of the spatial frequency of the gratings. Data are from observer 2.

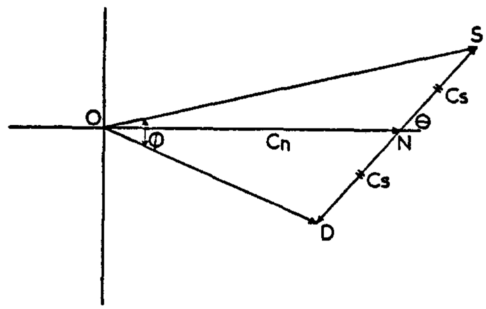

FIG. 5. A vector representation of the stimuli resulting from the addition of signals 180° out of phase with each other to noise that is identical in each field and in phase θ to one of the signals. The signal contrast is C_s, the noise contrast C_n. The projection of the vector OS on the Y axis represents the stimulus for the left eye, the projection of OD the right. The resultant interocular phase angle is ϕ.

The difference in detectability is comparable in size to the analogous auditory effect and, as in the auditory case, the interocular phase effect becomes small with increasing spatial frequency of the signal.

Before discussing the condition in which the signal grating is out-of-phase, it is perhaps worth describing the task faced by the observer in detecting in-phase gratings.

Consider the effect of adding signal and noise. The luminance of the signal can be represented by a simple sinusoid. The noise can also be represented by a sinusoid with the same frequency as the signal but varying in both phase and amplitude. With narrow band noise, the variations in phase and amplitude are slow so that at any point in time the luminance distribution of the stimulus resulting from adding the signal and the noise may be represented as the sum of two sinusoids fixed in both amplitude and phase. The result will be another sinusoid different from the noise and the signal in phase or amplitude, or both.

It is convenient to use a vector diagram to represent the addition of sinusoids. Such a diagram is shown in Fig. 5 (after JEFFRESS, 1972). In this form a sinusoid is represented by a vector of fixed length (corresponding to the amplitude of the sinusoid and thus proportional to the contrast of the grating) rotating at a constant speed proportional to the spatial frequency of the grating. The location of the vector at time zero defines the phase of the grating. The projection of the rotating vector on the y-axis will be a sinusoid representing the luminance variation in space.

In Fig. 5, the sinusoidal luminance distribution of a signal grating is represented by the vector **NS**. The vector has an amplitude, C_s, proportional to the signal contrast and an angular rate of rotation proportional to the spatial frequency of the grating. The narrow-band noise is represented by the vector **ON**, with amplitude C_n, and a mean rate of rotation also proportional to the spatial frequency of the signal. Both the amplitude and phase of the noise are random variables changing slowly as the vector rotates. The amplitude, taken at suitable intervals, is in fact Rayleigh distributed; the phase is uniformly distributed (DAVENPORT and ROOT, 1958). The noise grating may thus be considered to be generated by the projection of an amplitude and phase modulated vector. If the signal grating is added to the noise in some random phase (θ in Fig. 5), the resulting signal-plus-noise vector is **OS**. In general, the resultant vector **OS** will have a different amplitude and phase from that of the noise vector, **ON**. Thus, the signal-plus noise grating generally differs in both contrast and phase from the noise grating.

At low signal-to-noise ratios the addition of the signal can produce either an increment in the contrast of the field or a decrement. The observer, in order to use relative contrast as indicating the presence of a signal, must note changes in any direction from the mean contrast of the continually present noise grating which is itself continually changing in contrast.

The resultant vector will usually have a different phase from the noise alone. At high signal-to-noise ratios the phase of the resultant will be close to that of the signal so that grating phase is another potential cue available to the observer.

Another cue available at high signal-to-noise ratios results from the fact that the signal phase was stationary whereas the noise phase changed slowly with time. Thus the presence of signal at relatively high contrast appeared to slow down the rate of change in the grating phase.

Consider now, the task with out-of-phase signals. The noise is identical in both fields; the vector **ON** may thus represent the noise in both fields. The signal to the left field, **NS**, is added to the noise at some random phase θ. The signal, **ND**, is added to the other field, with the same amplitude but 180° out of phase with **NS**. Adding the signals in different phase produces two different signal-plus-noise vectors, **OS** and **OD**, one for the visual field of each eye. In general the displays in each field will differ in two respects: first, there will be an interocular phase difference (φ in Fig. 5). There will also be an interocular contrast difference (the ratio **OS**/**OD** in Fig. 5). Differences in either interocular phase or interocular contrast may contribute to the improved detectability of out-of-phase gratings.

Interocular phase seems likely to be an important variable; changes in interocular phase produce interocular disparities which might lead to changes in the apparent distance of the noise field when the signal is added out of phase. The observer might then recognize the presence of a signal by the apparent change in the plane of the display field, by detecting changes in accommodation or vergence associated with the apparent change in depth, or by detecting changes in the appearance of fixation points or display edges produced by accommodative or vergence shifts. [Such explanations are equivalent to those suggested in the Webster–Jeffress model of the binaural masking level differences (JEFFRESS, 1972).]

The change-in-depth hypothesis, however, seems unlikely. Changes in the apparent plane of the fused field (and cues dependent on such changes) are unlikely to be a major factor since the interocular phase effect occurs with horizontal gratings as well as vertical ones. With horizontal gratings the vertical disparity produced by adding a signal grating is in the vertical dimension and vertical disparity does not normally lead to changes in apparent depth. Observers, moreover, do not report changes of the apparent plane of the display with either grating orientation; loss of fusion (which may be noticed particularly when fixation marks are present and the observers forced to fuse the fields without the help of prisms) can be produced only at high signal-to-noise ratios.

None the less, interocular phase difference may be an important cue although one not simply related, as might be hoped, to apparent depth. An interocular phase dependent cue has the advantage of conveniently predicting the decrease in the interocular phase effect with increasing signal frequency since interocular disparity ΔD, given by,

$$\Delta D = \frac{\varphi}{f_s 2\pi}$$

where ΔD is disparity (degrees of visual angle), φ is the interocular phase difference (rad) and f_s the spatial frequency of the grating (c/deg), is inversely proportional to signal frequency. It is difficult to evaluate this argument quantitatively without knowing the effect of the spatial frequency and of the grating orientation (as well as of its contrast) on disparity detection; rough calculations can be made, however, and indicate that the average disparities produced with an out-of-phase signal at 75 per cent correct detection are 5·0′, 2·6′ and 1·6′ at 0·24, 0·6 and 2·4 c/deg. Such disparities are of the order of those on the vertical boundaries of Panum's fusional areas (Ogle, 1950) and, when certain special conditions are met, of the horizontal boundaries as well (Mitchell, 1966). It may also be noted that disparity produced by 2·4 c/deg gratings is close to that produced by just noticeable changes in the binocular parallax of broadband signals.

We have assumed in the above discussion that disparity is the only cue for detection. We do not believe this to be the case. Interocular contrast differences are also important. In viewing real objects binocularly, interocular contrast at any retinal location will of course be closely related to disparity—interocular luminance differences being zero only for perfectly fused points.

In our experiments differences in interocular contrast result from adding signals out-of-phase in the two fields. Interocular contrast and phase differences are, in fact, different functions of the same two random variables (noise amplitude and phase) and are thus not independent in our experiments. In looking briefly at the effects of interocular contrast differences alone, however, we noticed several striking effects: observers reported, when observing in-phase signals with interocular contrast difference, that the field appeared to shimmer with a sort of lustrous granular luminosity, that one eye appeared to have a veil drawn across it, or that they "felt" something happen to one eye rather than saw an effect when the signal was added. Similar reports were given by observers detecting out-of-phase gratings with identical contrast. Such subjective reports are extremely difficult to evaluate, but suggest the observers' detecting some sort of rivalry (Levelt, 1966). "Rivalry" effects are not so clearly dependent on particular grating orientations and might result from either interocular phase or contrast differences. It is hardly adequate to explain the effect of interocular signal phase on detectability in terms of rivalry effects themselves unexplained;

however, we can do little more. The effects of interocular contrast and phase on rivalry are not fully understood.

We have investigated only two of the many possible combinations of interocular signal and noise phase; no attempt has been made to study effects of interocular intensity or frequency differences in either the signal or noise grating; no measurements have been made with uncorrelated noise; no measurements have been made with interocular phase other than zero and 180° or with different mean noise contrast. However, we have briefly investigated two of the potentially interesting conditions with low frequency vertical gratings: (1) differences between monocular detection in noise and binocular detection of in-phase gratings in in-phase noise are small (as in the experiments of GREEN and CAMPBELL, 1965); (2) in-phase gratings are more readily detected in noise that is 180° out-of-phase than in in-phase noise—the difference at low frequencies being of the order of the effects obtained in our experiments with in-phase noise but signals of different phase.

It seems to us likely that the mechanism responsible for the phase effect reported here is that responsible for detecting vergence errors, that this mechanism is sensitive to interocular contrast differences as well as disparity, and that "rivalry" is the subjective accompaniment of the operation of this mechanism.

In spite of our inability to provide adequate numerical predictions for the effect of interocular phase on grating detection, the magnitude of the effect is large at low spatial frequencies and appears sufficiently interesting to bear further investigation.

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Abstract—Observers were required to detect sinusoidal gratings in a background of noise composed of a narrow band of spatial frequencies centred on the frequency of the grating to be detected. The visual noise was identical in two fields, one for each eye. The grating to be detected—the signal grating—was presented in one of two conditions: either the signal grating was identical in both fields or 180° out-of-phase; that is, with the dark bars in one field in locations corresponding to the locations for light bars in the other. Signal gratings of low spatial frequency presented out-of-phase were detected at much lower contrast than in-phase gratings. The difference in detectability with vertical gratings, approx. 0·6 log units of contrast, was at least as large with horizontal gratings.

Résumé—Des observateurs doivent détecter des réseaux sinusoïdaux sur un bruit de fond composé d'une bande étroite de fréquences spatiales centrées sur la fréquence du réseau à détecter. Le bruit visuel était identique sur deux champs, un pour chaque oeil. Le réseau à détecter—le réseau signal—était présenté dans deux conditions: soit identique dans les deux champs, soit en opposition de phase, c'est-à-dire les barres noires d'un champ à des emplacements correspondant aux barres claires de l'autre. Les signaux à faible fréquence présentés en opposition de phase étaient détectés pour un contraste beaucoup plus faible que dans le cas de réseaux-signaux en phase. La différence de détection pour des réseaux verticaux, soit environ 0,6 unité log de contraste, était au moins aussi grande avec des réseaux horizontaux.

Zusammenfassung—Beobachter wurden aufgefordert, Sinusgitter in einem verrauschten Umfeld zu entdecken. Das Umfeld setzte sich aus einem schmalen Band von Ortsfrequenzen zusammen, dessen Mitte die zu entdeckende Frequenz enthielt. Das optische Rauschen war in zwei binokularen Beobachtungsfeldern das gleiche. Das aufzufindende Signalgitter wurde entweder in beiden Feldern gleich oder 180°-phasenverschoben dargeboten, d.h. dass hier die Lage der dunklen Balken des einen Feldes der der hellen des anderen entsprachen. Signalgitter niedriger Ortsfrequenzen wurden bei der phasenverschobenen Darbietung bei viel geringerem Kontrast entdeckt als bei der gleichphasigen Darbietung. Dieser Unterschied in der Erkennbarkeit war bei vertikalen Gittern mindestens so gross wie bei horizontalen-rund 0,6 log. Kontrasteinheiten.

Резюме—От испытуемых требовалось обнаружить синусоидальные решетки на фоне имеющим помехи, состоящие из узкой полосы пространственных частот, центрированных на частоте решетки, которую нужно было обнаружить. Зрительный шум был одинаков в двух полях (для каждого из глаз). Реметка, которую нужно было обнаружить, —сигнальная решетка—предлагалась испытуемым при двух условиях: либо сигналы были идентичными в обоих полях, либо же они находились в противофазе, разаличаясь на 180°: последнее означает, что локали3ация темных полос В одном поле соответствовала локализации светлых полос в другом. Сигнальные решетки низкой пространственной частоты, представляемые в противофазе, обнаруживались при значительно меньшем контрасте, чем решетки представяемые в одинаковой фазе. Различие в контрасте, необходимое для обнаружения вертикальных реметок (приблизительно около 0,6 лог. единиц), было, по меньшей мере, также велико и для горизонтальных решеток.