

## THE CONTRAST DEPENDENCE OF SPATIAL FREQUENCY CHANNEL INTERACTIONS

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**Abstract**—Interactions between spatial frequency channels were tested in two ways: we measured the discriminability by the visual system between two compound spatial-frequency gratings, of components with spatial frequencies in the ratio 1:3, when the difference between the two gratings was an increase (or decrease) in contrast of both components of the compound grating (*contrast discrimination*), or when the difference between the two gratings was an increase in contrast of one component and a decrease in contrast of the other component (*pattern discrimination*). We found that the contrast:pattern discriminability ratio differs significantly from unity in most conditions. Furthermore, this ratio is generally greater when the components of the grating are in peaks-add relative phase than when in peaks-subtract phase. On the other hand, the ratio was close to unity for grating components of spatial frequencies 1 and 9 cycles/deg. These results suggest that the human visual system contains spatial frequency channels with bandwidths of between 1.6 and 3.2 octaves and that these relatively broad channels have peaks-add spatial profiles. The channels appear linear at intermediate contrasts and spatial frequencies, but super-linear at high spatial frequencies and contrasts. Contrast and spatial frequency may be interchangeable for the determination of the linearity of the visual system.

Spatial-frequency Channels Contrast Human Visual Psychophysics  
Discrimination

### INTRODUCTION

Independent spatial frequency selective channels in the human visual system have been the subject of intensive study and speculation for many years (Campbell and Robson, 1968; Blakemore and Campbell, 1969; Sachs *et al.*, 1971; Graham and Nachmias, 1971; Kulikowski and King-Smith, 1973; Quick, 1974; Quick *et al.*, 1976; Wilson and Bergen, 1979; Bergen *et al.*, 1979; articles by Campbell, Georgeson, Frisby and Mayhew and Marr, in Longuet-Higgins and Sutherland, 1980).

One characteristic of independent spatial frequency channels is that the response of one channel is not affected by the response of another. Thus, the overall discriminability by a system between two stimuli will be the same whether the two stimuli differ by an increase in the response of one channel and a decrease in the response of another, or differ by changes in the responses of both channels in the same direction. On the other hand, if the responses of the channels are added in a linear manner, the system will show greater discriminability for the case where the responses in both channels change together.

The degree of independence or interaction between channels may therefore be determined by measuring the relative discriminabilities of a system between stimuli which differ in Contrast or Pattern. When

considering spatial frequency channels, the stimulus used is a compound spatial frequency grating (see Fig. 1). The discriminability between a pair of gratings is measured as a function of the differences between the pair, where both components of both

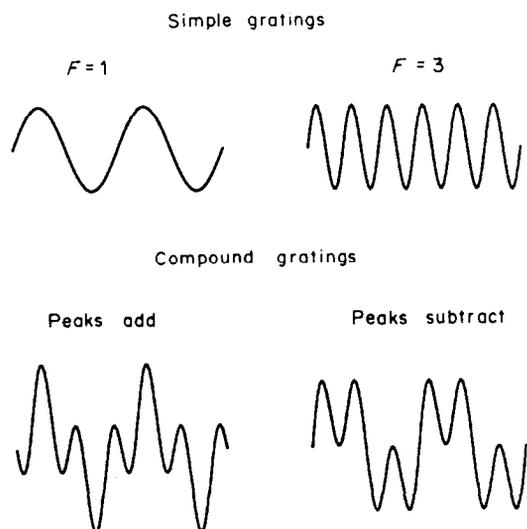


Fig. 1. The spatial luminance profile of simple and compound spatial frequency gratings. The top profiles are for simple gratings of spatial frequencies in the ratio 3:1. The bottom profiles are for sums of the top gratings with relative phases such that the peaks are in peaks-add or peaks-subtract mode, as indicated.

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gratings of the pair may always be supra-threshold. The interdependence of the channels processing the components of the gratings may be determined from the relative discriminabilities between gratings which differ in Contrast—i.e. the spatial frequency content of the pair is constant, but the amplitudes of both components of the compound spatial frequency grating stimulus change together, and stimuli which differ in Pattern—i.e. the relative contrasts of the two components of the compound grating are changed, but the total contrast is kept constant for the pair (see Fig. 2).

Two important advantages of this procedure will be exploited here. The use of a discrimination task allows the use of stimuli all of which are in the natural

supra-threshold range. Furthermore, the base contrast is a parameter of the experiments, and the interaction between channels may be studied as a function of compound grating base contrast. This proves essential for determining possible sources of nonlinearities at specific frequency ranges. In particular, we demonstrate a nonlinear dependence on contrast at high spatial frequencies and determine whether this nonlinearity is due to a lower sensitivity in this range (an approach to threshold) or is due to an essential feature which is present only for high spatial frequency processing.

One of the favorite compound visual stimuli is a compound spatial frequency grating containing components of frequencies in the ratio 1:3 (Fig. 1). When

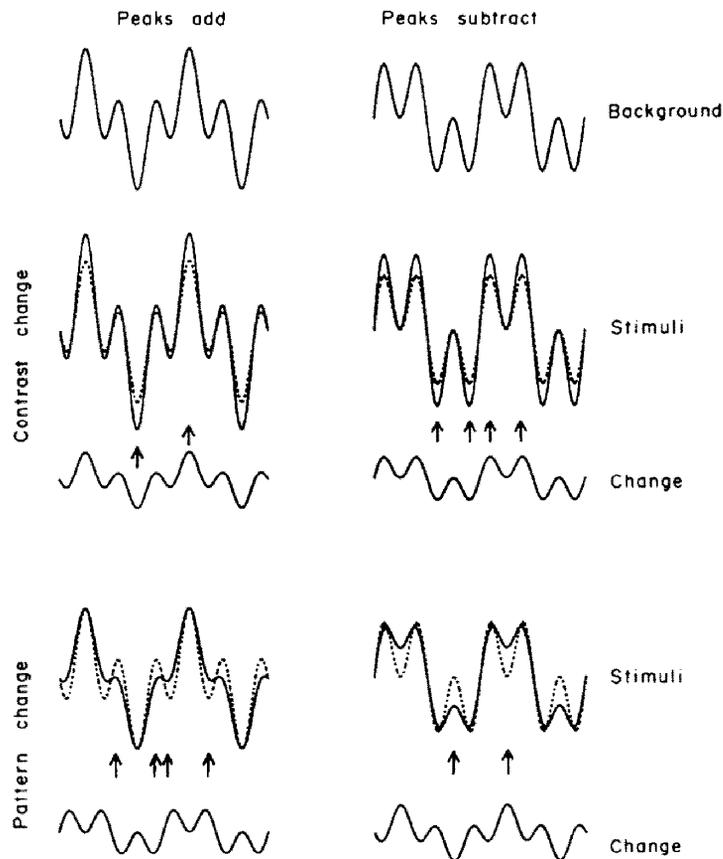


Fig. 2. Contrast and Pattern changes in compound spatial frequency gratings. The top row shows the background spatial luminance profiles upon which the discriminability of changes were measured: on the left, the background grating is in peaks-add phase, on the right in peaks-subtract. The second row (solid curves) shows the same gratings following the addition of a small Contrast change (40% in figure; between 5–40% in the experiment). The dotted curves repeat the background grating, and the difference between the two curves, the Contrast change, is shown in the third row. The bottom two rows show the stimuli, and the difference between them, for Pattern changes—i.e. when the contrast of one of the components is increased while the contrast of the other component is decreased. Note that here the grating change has a peaks-subtract profile when the background is peaks-add and vice versa. The subject had to discriminate between the two gratings of one of the four pairs whose profiles are shown here as superimposed solid and dotted curves. The arrows point to the grating spatial phases of greatest local intensity change. These phases are at the positions of maximal grating intensity for the cases of Contrast change, but not for the cases of Pattern change (see text). The screen was uniformly illuminated between stimuli. The grating called “background” was in fact one of the two stimuli between which the subject had to discriminate. It is called a base or background grating since it was the same for both Contrast and Pattern tasks.

these are added in cosine or peaks-add phase (with contrasts in the ratio 9:1) they are the lowest two components of a triangle wave grating. When they are added in sine or peaks-subtract phase (with contrasts in the ratio 3:1) they are the lowest two components in a square wave grating.

A second important characteristic of a visual system composed of independent spatial frequency channels is that the discriminabilities of changes in peaks-add and in peaks-subtract gratings should be identical (Graham and Nachmias, 1971). This is because, if we assume that the components of the compound grating are detected by separate non-interacting channels, there will be no importance to the relative phases of the two components of the grating. The degree of independence or interaction between channels may be determined by measuring the relative discriminabilities of the visual system of changes in contrast of components of compound gratings when in the peaks-add and the peaks-subtract mode. We have performed these tests for both contrast and pattern changes of the compound gratings.

The theoretical basis for this study has been laid down in previous reports. Several studies have analyzed the relationship between the ability to discriminate between two low-contrast stimuli and the ability to detect these stimuli (Thomas and Shimamura, 1974, 1975; Nachmias and Weber, 1975; Furcher *et al.*, 1977). Olzak and Thomas (1981) compared the threshold for the detection of a grating composed of two spatial frequencies and the threshold for discrimination between simple gratings of each of these frequencies. A similar approach had been used by Watson and Robson (1981) who compared the threshold for detection of a grating and for identification of its frequency. They found channels with a bandwidth of approx. 1 octave.

The main innovation of the present study is in the contrast range used. A supra-threshold compound grating is characterized by its overall contrast, which increases with the contrasts of its components, and by the relative contrasts of its components. The form or pattern of the grating will appear different if the relative contrasts are different. The extreme cases of this phenomenon are when the contrast of one of the components far exceeds the contrast of the other, giving the compound grating the appearance of a simple grating of the frequency of that component. Thus, when one increases the contrast of one of the components and simultaneously decreases the contrast of the other, the overall contrast of the compound grating may appear fixed but its pattern will change. On the other hand, when one increases the contrasts of both components equally, the overall contrast of the compound grating is increased, but there is no change in its pattern. In this way it is possible to measure the discriminability of Contrast and of Pattern changes in a supra-threshold compound grating.

## METHODS

Visual stimuli were generated on the face of a Tektronix 5103 oscilloscope with P31 phosphor, by modulation of the beam intensity while producing a t.v.-type raster (100 kHz triangle-wave in *Y*, 200 Hz sawtooth wave in *X*; see Campbell and Green, 1965; Shapley and Rosetto, 1976). The mean screen luminance due to the raster was 10 cd/m<sup>2</sup>. Sinusoidal gratings were produced by reading out of a PDP-11 computer DAC, a 500-word list of numbers via an analog multiplier circuit to the oscilloscope *Z*-axis. The analog multiplier was used to multiply the fixed-amplitude sine wave by an appropriate d.c. signal, produced by the computer on a separate DAC, to attenuate the sine wave to the desired contrast. To produce a compound spatial-frequency grating, two simple gratings of appropriate spatial frequency were interleaved on alternate raster frames. This rate (5 msec each frame, 10 msec each compound grating) was sufficiently rapid to ensure full visual integration (Watson and Nachmias, 1977).

Experiments were controlled by the PDP-11 computer. It received a clock signal synchronized to the raster *X* sawtooth and produced in pseudo-random order the sets of compound sine-wave gratings. The computer recorded the subject's response (the type key), stored the data for later analysis, and produced on-line analysis of response correctness and discriminability.

The subject sat 120 cm from the oscilloscope so that the screen subtended  $6 \times 5$  deg of visual angle. At the lowest spatial frequency used, 1 cycle/deg (cpd), the display contained six grating cycles. The gratings were always vertically oriented.

Each experiment comprised 50 pairs of grating presentations, to which the subject responded by striking one of two keys to indicate the order of the presentations discerned by him, a 2-alternative forced-choice (2AFC) procedure.

Each grating was presented for 0.5 sec with a 2 sec interval between the pair. The subject typed a third key to initiate the following pair. Each experiment was preceded by a learning period during which a bell rang following "error" responses. When the subject felt comfortable with his knowledge of the stimulus-response relationship, he typed a fourth key which completed the learning session and began the experiment. From the rate of errors and normal distribution tables, the discriminability  $d'$  was calculated in the usual manner for 2AFC procedures (Green and Swets, 1966).

Each session contained two experiments with the same grating parameters—one for Contrast discrimination and one for Pattern discrimination (in random order). The main results of this report depend only on the relationship between the pairs of discriminabilities found, and not on their separate absolute values. Thus, the ratio of the discriminabilities was determined for each session, and these ratios were averaged for sessions using the same parameters. This

method reduced the influence of the variability of the results from session to session. The results presented are mainly for a single subject (D.S.) and were partially corroborated by other (naive) subjects.

The grating stimuli were supra-threshold compound spatial-frequency gratings containing two spatial frequencies ( $f_1, f_3$ ) in the ratio 1:3. The pairs used were (1,3) (2,6) and (3,9) cycles/deg of visual angle. The relative phases of the grating components were in peaks-add (PA) or in peaks-subtract (PS) mode, so that the intensity of screen illumination  $I(x)$  for the

base grating was

$$I(x) = I_0 + C_1 \cos(f_1 x) + C_3 \cos(f_3 x) \quad \text{peaks-add (1a)}$$

$$I(x) = I_0 + C_1 \cos(f_1 x) - C_3 \cos(f_3 x) \quad \text{peaks-subtract (1b)}$$

where  $I_0$ , the mean illumination, was constant and was the same as that of the uniform screen between grating presentations. The two grating presentations of a pair differed in the contrast of both grating

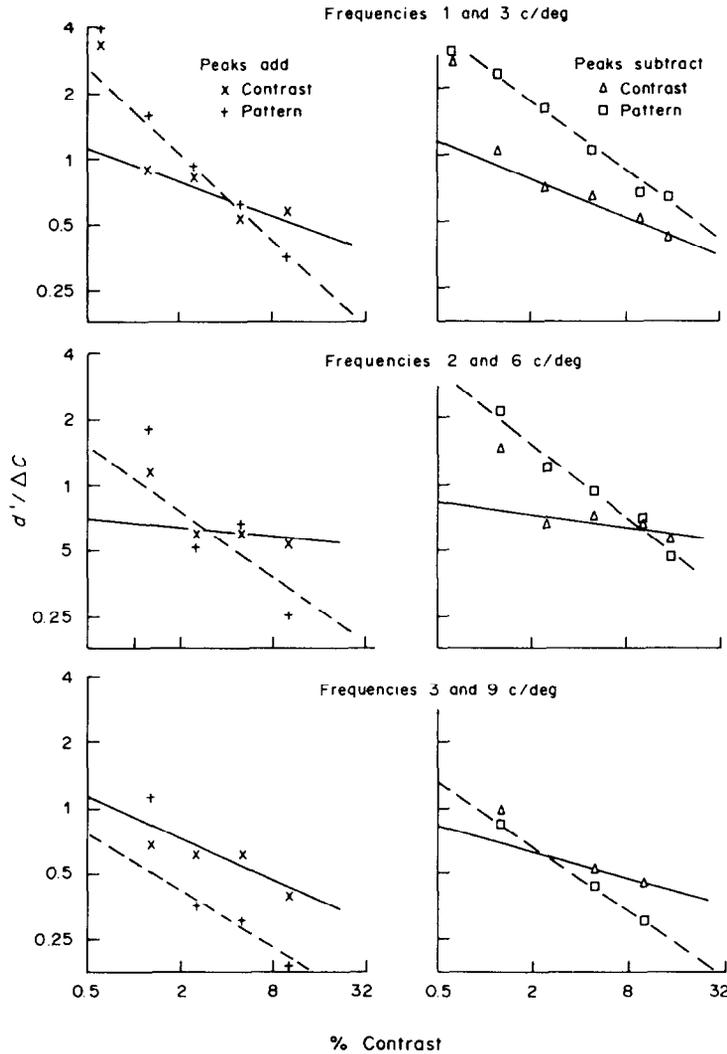


Fig. 3. The dependence on background contrast of the discriminability of Contrast and of Pattern changes in compound spatial frequency gratings. The graphs plot discriminability  $d'$ , divided by contrast change  $\Delta C$ , where  $\Delta C$  was varied to keep  $d'$  in the sensitive range (1.0–3.0). The three rows of graphs are for compound gratings of different spatial frequency components, as indicated. In each case, we tested the discriminability of grating changes of Contrast ( $\times$  and  $\Delta$ ) and of Pattern ( $+$  and  $\square$ ) (see Fig. 2.) The left and right columns of the graphs are data for background in peaks-add and in peaks-subtract relative phase, respectively (data for Subject DS). The greater the base grating contrast, the lower the discriminability of changes of a fixed percent of that contrast. These negative slopes are greater than  $-1$ , however, and the slope for Contrast changes is greater than for Pattern changes. Thus, the ratio  $R$  of the discriminabilities for Contrast and for Pattern changes is an increasing function of background contrast (see Fig. 5).

frequency components in the same direction (Contrast) or in opposite directions (Pattern) so that the coefficients in equations (1a) and (1b) varied between

$$(C_1, C_3) \rightarrow (C_1 + \Delta C_1, C_3 + \Delta C_3) \quad \text{Contrast} \quad (2)$$

$$(C_1 + \Delta C_1, C_3) \rightarrow (C_1, C_3 + \Delta C_3) \quad \text{Pattern} \quad (3)$$

Figure 2 displays the stimulus pairs with Contrast and pattern changes for peaks-add (left column) and peaks-subtract (right column) gratings\*. The base contrasts ( $C_1, C_3$ ) were in the range 1–20% and the change in contrast between the two presentations ( $\Delta C_1, \Delta C_3$ ) in the range 5–40% of the base contrast. Generally, the lower the base contrast, the greater the percent change required to achieve a particular discriminability. For the higher spatial frequencies 6 and 9 cpd slightly higher base contrasts ( $\times 1.5$  and  $\times 2$ , respectively) were used than for the other spatial frequencies 1, 2 and 3 cpd. The dependence of the discriminability of these changes on both background contrast and contrast change is an important aspect of this study. We used a range of stimulation parameters, thus avoiding the assumption of a visual system with an extended linear range. We have shown previously (Sagi and Hochstein, 1983) that there is a wide range of linear dependence of  $d'$  on  $\Delta C$ . Though we call ( $C_1, C_3$ ) a background grating, the screen was uniformly illuminated between stimuli.

## RESULTS

### (A) Discriminability as a function of contrast and spatial frequency

The discriminabilities of Contrast and of Pattern

\*As long as the contrast increment  $C$  is kept small, as was done in this study, stimulus pair (3) may be replaced by  $(C_1, C_3) \rightarrow (C_1 - \Delta C_1, C_3 + \Delta C_3)$  [equation (4)]. The latter form is the one demonstrated in Fig. 2.

changes on peaks-add (PA) and on peaks-subtract (PS) backgrounds were measured as a function of background contrast for different pairs of spatial frequencies. Figure 3 shows the dependence on background contrast of the discriminabilities of changes of Contrast ( $\times$  and  $\Delta$ ) and of Pattern ( $+$  and  $\square$ ) for the spatial frequencies indicated and with background grating relative phases in peaks-add (left column) and peaks-subtract (right column) mode. The contrast changes

$$\Delta C = |\Delta C_1| + |\Delta C_3|$$

were varied to keep  $d'$  in the sensitive range (1.0–3.0). Data for various contrast changes were pooled by plotting  $d'/\Delta C$ , since we are in a linear range of the dependence of  $d'$  on  $\Delta C$  (Sagi and Hochstein, 1983). This normalization of  $d'$  will not be involved in the central theme of this paper, where we analyzed ratios of  $d'$  for Contrast and for Pattern discrimination, and use the same  $\Delta C$  for both measurements [sub-sections (B) and (C) below].

If the discriminability followed Weber's law, the points on the log-log graphs of Fig. 3 would fall along a straight line with slope of  $-1$ . Best fit straight lines are drawn for each set of points in Fig. 3 (disregarding in each case the lowest contrast point where threshold nonlinearities may be significant). In every case, the slope is greater than  $-1$  (between  $-1$  and  $0$ ) and the slope for the Contrast change is somewhat greater (closer to zero) than that for Pattern change. Thus, the ratio of the discriminabilities for Contrast and for Pattern changes will be an increasing function of background contrast [see sub-section (C) below]. The departure from the straight line at very low contrasts may be related to threshold phenomena (Tolhurst and Barfield, 1978) and the finding that discrimination may be better than detection in this range.

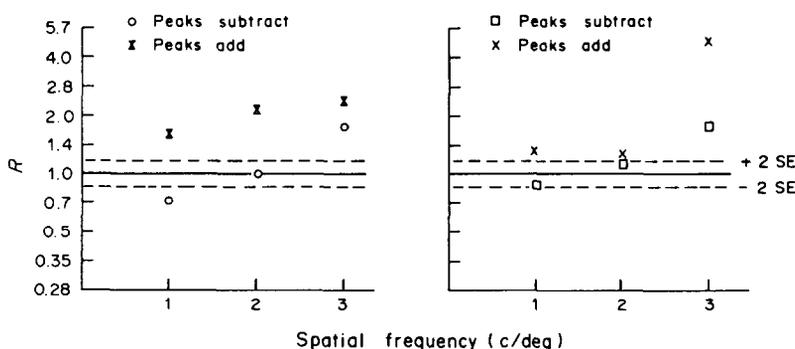


Fig. 4. The ratio of the discriminabilities of changes in Contrast and in Pattern of compound gratings as a function of spatial frequency. The ratio  $R$  should be unity if the components of the grating are processed by independent channels. The ratio is generally different from unity indicating that the visual system has broad band spatial frequency channels. The discriminability ratio is always greater for peaks-add than for peaks-subtract gratings, supporting the conclusion that the channels are broad-band, and suggesting that the channels have a peaks-add profile. The ordinate indicates the spatial frequency of the lower component of the pair, where the higher was a factor of three greater. The base contrast was kept constant [10% for 1, 2, 3 cycles/deg (cpd), 15% for 6 cpd and 20% for 9 cpd—see Methods]. Data for subject DS (left graph) and for subject MB (right graph).

(B) *The ratio of Contrast and Pattern discriminabilities, as a function of spatial frequency*

The ratio of the discriminabilities of changes in Contrast and in Pattern of a compound grating should be unity if the components of the grating are processed by independent channels. Figure 4 plots this ratio as a function of spatial frequency for two subjects. (The axis indicates the lower of the pair of spatial frequencies, where the higher was always three times the lower.) The base contrast level was kept constant here (10% for 1, 2 and 3 cpd, 15% for 6 cpd and 20% for 9 cpd—see Methods). The ratio is clearly

almost always different from 1, indicating that the processing of spatial frequencies differing by a factor 3 are not independent. The same test was performed for spatial frequencies (1,9) cpd and the ratios for both peaks-add and peaks-subtract were not significantly different than unity:  $1.07 \pm 0.11$  and  $1.06 \pm 0.07$ , respectively.

When the background is in peaks-add phase, in Fig. 4, the discriminability of Contrast is always greater than that of Pattern (at these contrast levels). This suggests the existence of a broad band mechanism which matches this peaks-add stimulus form.

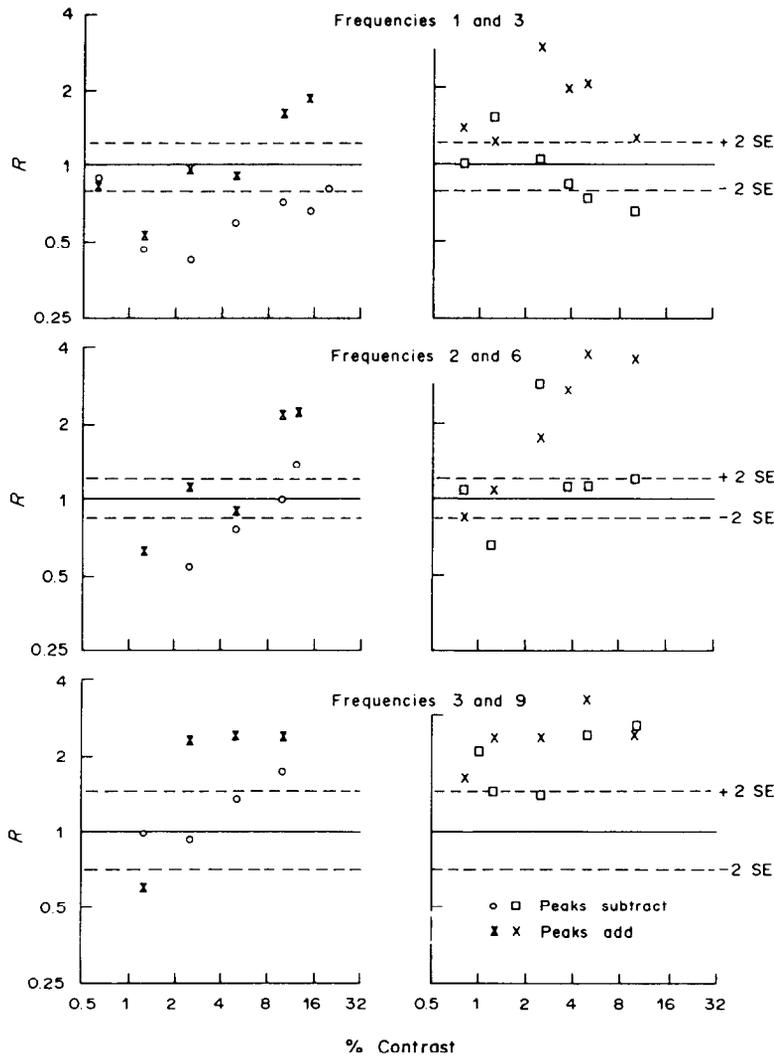


Fig. 5. The ratio of the discriminabilities of changes in Contrast and in Pattern of a compound grating as a function of grating contrast. The ratio  $R$  should be independent of contrast in a linear system, and the product of  $R$  for peaks-add and for peaks-subtract gratings should be unity. This is the case only for intermediate spatial frequencies and contrasts. Generally  $R$  is seen to increase with contrast as it does for spatial frequency (see Fig. 4). The ratio is also higher for peaks-add than for peaks-subtract gratings. Two types of nonlinearities are seen: at high spatial frequencies and contrasts, the product of the ratios for peaks-add and for peaks-subtract gratings is greater than unity, a super-linearity, and at low spatial frequencies and contrasts, it is lower than unity, a sub-linearity. See text and discussion for possible sources of these nonlinearities. The rows of graphs are for measurements with different spatial frequencies, and the left and right columns are for different subjects (DS and the averaged results for RS and BS respectively).

A peaks-add stimulus will be well detected by such a mechanism, and a Contrast change will be easily discriminated by it. On the other hand, a Pattern change, which has, in this case, a peaks-subtract form, is less easily discriminated by such a mechanism, as seen by the results.

(C) *The Contrast:Pattern discriminability ratio as a function of contrast*

The Contrast:Pattern discriminability ratio was studied as a function of background contrast for the two background conditions, PA and PS, and for three spatial frequency pairs. Figure 5 demonstrates the results. In each graph, the ratio for PA ( $\times$  and  $\mathbf{X}$ ) and for PS ( $\circ$  and  $\square$ ) are presented. The graphs are for spatial frequency pairs (1,3), (2,6) and (3,9) cpd, respectively, as marked. Left graphs are data for a single experienced subject (author DS) while the right-hand graphs are averages for two naive subjects (BS and RS).

A clear dependence on background contrast is seen in every case. In general, the Contrast:Pattern discriminability ratio increases with increasing background contrast. This is reminiscent of the increasing discriminability ratio with increasing spatial frequency. It appears that increases of spatial frequency and of contrast are interchangeable in this system. The ratio for PA backgrounds is generally higher than for PS backgrounds, supporting the inference made above of the existence of a PA mechanism.

Thus, for peaks-add backgrounds, Contrast discrimination is better than Pattern discrimination for high spatial frequencies, and at high contrasts also for low spatial frequencies. For peaks-subtract backgrounds, Pattern discrimination is better than Contrast discrimination, except for high spatial frequencies, and at high contrasts for intermediate frequencies.

#### DISCUSSION

As outlined in the Introduction, two conditions would result from the presence of narrow-band, independent channels in the processing of sinusoidal spatial frequency components of compound gratings where the frequencies are in the ratio 3:1. Contrast and pattern discriminabilities would be equal (their ratio would be unity), and the discriminability of changes in a peaks-add compound grating would be the same as that of changes in a peaks-subtract grating. Neither of these conditions is fulfilled at supra-threshold contrasts: the Contrast:Pattern discriminability ratio differs from unity in most conditions (Figs 4-6), and this ratio is almost always greater for peaks-add gratings than for peaks-subtract gratings. On the other hand, these conditions are fulfilled for compound gratings composed of spatial frequencies (1,9) cpd. Thus, we may conclude that the human visual system contains spatial frequency channels with bandwidths of between 1.6 and 3.2 octaves.

These interactions, which are apparent at supra-threshold contrasts, have not been found at threshold levels. Graham and Nachmias (1971) found, for example, that the threshold detection of compound gratings is independent of the relative phases of the components (PA or PS). One difference between threshold and supra-threshold studies may be due to the stimulus uncertainty at low contrasts which would tend to prevent the channels from emphasizing in a nonlinear way particular grating positions or phases. Thus, the particular pattern of the stimulation, whether PA or PS, may become of less importance at threshold contrasts. On the other hand, at supra-threshold levels, there could be a nonlinear emphasis of those positions where the largest stimulus occurs, positions where, for a PA channel, there is considerably less change visible for a PS grating than for a PA grating. Wilson and Bergen (1979) and Bergen *et al.* (1979) have shown that the results at threshold are not inconsistent with the existence of broad-band rather than narrow-band channels, assuming a spatial probability summation nonlinearity.

If we disregard the background grating (as may be done when analyzing linear systems) then the four experimental cases divide into two pairs of identical stimulations: the case of PA background with Contrast change is a case of PA stimulation change. The case of PS background with Pattern change has an identical PA stimulation change. Similarly, the case of PA background/Pattern change and PS background/Contrast change, are both cases of PS stimulation change (cf. Fig. 2). Thus, we would expect for a linear system that the disciplinary ratio  $R$  for PA should be the inverse of that for PS backgrounds. For a PA detector mechanism, we expect Contrast discrimination to be easier for PA background (ratio  $R > 1$ ) and Pattern discrimination to be easier for PS background (ratio  $r < 1$ ). This is just what is found at higher contrasts for the spatial frequency pair (1,3) cpd: the ratio of Contrast to Pattern discrimination is greater than 1 for PA and less than 1 for PS backgrounds.

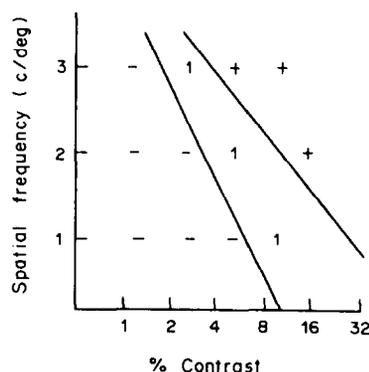


Fig. 6. The spatial frequency and contrast domains of linearity ("1"), sub-linearity ("-") and super-linearity ("+") in the processing of spatial frequency grating pairs (subject DS).

The results for higher spatial frequencies are different, however. For gratings with spatial frequencies (3,9) cpd Contrast discrimination is better than Pattern discrimination (ratio  $R > 1$ ) even for PS backgrounds, although the ratio is somewhat smaller than for PA backgrounds. That the two ratios for PA and PS backgrounds are not symmetric about 1 indicates a nonlinearity at these spatial frequencies since, as discussed above, the cases of PA background/Contrast and PS background/Pattern have the same stimulus change (although on different backgrounds); a similar stimulus change identity applies for the cases of PA background/Pattern and PS background/Contrast. The dependence of the discriminability of a change on the constant background indicates a nonlinear mechanism.

The nonlinearity for high spatial frequencies ( $R > 1$  for both PA and PS backgrounds) not only does not appear at lower spatial frequencies for low contrasts, but on the contrary, it is diminished or disappears at low contrasts even for the high spatial frequencies. This suggests that the nonlinearity at high spatial frequencies does not originate from a comparatively low sensitivity in that range.

An additional nonlinearity appears at low contrasts for low and intermediate spatial frequencies. Here we find  $R < 1$  for both PA and PS backgrounds. This is a different type of nonlinearity from that found at high spatial frequencies for high contrasts in that precedence is given to the channel which is *less* stimulated by the background grating.

These results suggest a division of the spatial frequency/contrast plane into three regions, as demonstrated in Fig. 6. At high spatial frequencies and high contrasts, there is a nonlinearity favoring changes which have the same form as the background grating, i.e. a stimulus-response transducer function with power greater than unity. At low spatial frequencies and low contrasts, there is a different nonlinearity favoring changes which have a different form than that of the background grating; i.e. a transducer function with power less than unity. Between these regions of nonlinearity, there is a linear band. In Fig. 6, we used the product of the discriminability ratios for peaks-add and for peaks-subtract to indicate whether the power of the nonlinearity was greater than ("+" ) or less than ("−") unity. The linear band is indicated by the symbol "1".

The mechanisms underlying the interaction found between spatial frequencies  $f$  and  $3f$  appear to have a spatial profile matching a peaks-add form. This is suggested by the findings that in the linear region where the product of the ratios for PA and for PS is close to unity (in the linear band of Fig. 6), the PA grating ratio is greater than unity and the PS grating ratio less than unity. This strongly suggests that grating changes of the PA form are more easily discriminated and that the channels have this form. In addition, the Contrast:Pattern discriminability ratio for PA is generally greater than 1 and nearly

always greater than the ratio for PS gratings. Furthermore the ratio for PS gratings is usually, although not always, less than 1. Thus, there seems to be channels with a PA form even at high spatial frequencies. However, because of the nonlinearity in this range, we cannot exclude the possibility of the existence of PS channels as well.

The discriminability ratio shows a strong dependence on spatial frequency (Fig. 4), since the detectability per unit Contrast change ( $d'/\Delta C$ ) does not fall with rising background grating contrast as quickly as the detectability per unit Pattern change (Fig. 3). The discriminability ratio shows a strong dependence on background grating contrast (Fig. 5), suggesting that increases in spatial frequency and in contrast are interchangeable for the visual system (Fig. 6).

Finally, we speculate as to the origins of the nonlinearities. At high spatial frequencies and high contrasts, there appears a super-linearity: both PA and PS gratings have discriminability ratios greater than 1. One possible mechanism which would predict a discriminability ratio greater than 1 for PS gratings is the presence of PS channels. These would have to exist for high spatial frequencies and to interact nonlinearly with the PA channels there, in mutual inhibitory fashion. An alternative source is nonlinear spatial summation: having found that the channels are broad-band in the spatial frequency domain ( $\sim 2$  octaves wide), they could have a limited spatial extent. We may then ask how such channels interact over space. If the interaction were such as to give extra weight to the local channel with the greatest response, we have a superlinearity similar to that found at high spatial frequencies and contrasts. As demonstrated in Fig. 2, emphasis would be given to those local channels which are centered at the positions of greatest contrast, indicated by the arrows. These positions are also the points of greatest change for Contrast discrimination, and not for Pattern discrimination. Hence, the Contrast:Pattern discriminability ratios would be greater than 1 for both PA and PS backgrounds, even assuming only the existence of local PA channels. The interaction responsible for the nonlinearity may be lateral inhibition between neighboring channels, which may be limited in spatial range (e.g. by limited cortical lateral interactions). We report separately supporting evidence for the existence of lateral inhibition between neighboring channels at high spatial frequencies and contrasts (Sagi and Hochstein, 1984).

At low contrasts, especially for low spatial frequency gratings sublinearity is found: the Contrast:Pattern discriminability ratio is less than 1 for both PA and PS gratings. One possible source of this nonlinearity is that the system noise increases with response magnitude. Thus, a low response, low noise, channel might well produce a more significant signal than a high response, high noise channel. Alternatively, a change in power law from the low contrast

region near threshold (where the transducer function might have a power much greater than 1) to the high contrast region (where the power might be closer to 1) may pass an intermediate region where the power appeared less than 1 (Stromeyer and Klein, 1974). This may be understood in terms of its being easier to discriminate between signals which are respectively just below and just above a sharp threshold, than between signals which are both above threshold.

### CONCLUSIONS

The visual system appears to process supra-threshold compound patterns using relatively broad-band spatial frequency channels (bandwidths of 1.6–3.2 octaves). These broad channels have a peaks-add spatial profile. Thus, Contrast and Pattern changes are not equally discriminable in compound gratings with components of spatial frequencies in the ratio 3:1, unlike compound gratings with components in the ratio 9:1. Furthermore, the ratio of Contrast discrimination to Pattern discrimination is almost always greater for Peaks-add backgrounds than for Peaks-subtract backgrounds, again when the components are in the ratio 3:1 but not when in the ratio 9:1.

There are strong changes in the modes of visual processing with both contrast and spatial frequency. Though the channels appear linear at intermediate contrasts and spatial frequencies, there is a super-linearity at high spatial frequencies and contrasts and a sub-linearity at low spatial frequencies and near threshold contrasts. These dimensions may be interchangeable over part of their ranges for the visual system. We have discussed the possible sources of the super-linearity at high spatial frequencies: peaks-subtract channels and nonlinear spatial summation. The sub-linearity may be due to response-dependent noise or to an effect whereby threshold discrimination is better than supra-threshold discrimination.

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