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INHIBITORY REFINEMENT OF SPATIAL FREQUENCY SELECTIVITY IN SINGLE CELLS OF THE CAT STRIATE CORTEX

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Abstract—Single cells in the cat striate cortex are more selective for the spatial frequency of sinewave grating stimuli than are cells of the retina or lateral geniculate nucleus. We have explored the possibility that this enhancement of selectivity results from spatial-frequency-selective inhibition. Stimulation with two superimposed gratings, one to excite the cell and one to probe for inhibition, revealed spatial frequency-dependent response suppression in 74% of the total population studied. Suppression was slightly more prevalent in simple cells (80%) than in complex cells (68%). In 93% of the cases where suppression was found, its tuning was complementary to excitatory spatial frequency tuning, and the strongest suppression was usually found where the excitatory tuning function approached zero imp./sec. Characteristics of the phenomenon were independent of cortical layers. We conclude that organized inhibitory mechanisms serve to refine the spatial frequency bandpass of striate cortical cells. This provides evidence for another degree of nonlinearity in the organization of cortical receptive fields and supports the hypothesis that a fundamental function of the visual cortex is image dissection in the domain of spatial frequency.

Visual cortex Spatial frequency Inhibition Visual channels

INTRODUCTION

The selectivity of single cells for the spatial frequency of a sinusoidal stimulus is progressively refined in the hierarchy of the primary visual pathways (Maffei & Fiorentini, 1973). In the cat, retinal ganglion cells serve as low-pass filters, with minimal low frequency attenuation and high frequency cutoffs ranging from about 0.5 to 2 c/deg (e.g. Enroth-Cugell & Robson, 1966). While LGN cells tend to show more low-frequency attenuation, their filter property is still predominantly low-pass (Kaplan, Marcus & So, 1979). Striate cortical cells are typically more narrowly tuned, with many having sharp cutoffs for both low and high spatial frequencies and average half-amplitude bandwidths of 1.5 octaves (e.g. Movshon, Thompson & Tolhurst, 1978). Low frequency attenuation, which is not prominent in either retinal ganglion cells or geniculate cells, is especially apparent.

Few formal models exist for the mechanisms underlying cortical refinement of selectivity for spatial frequency. However, models can be derived from those proposed for the cortical refinement of selectivity for stimulus orientation, which has been the target of more attention. Two general schemes have been proposed to account for cortical orientation selectivity, one relying principally on excitation, the other on a combination of excitation and inhibition. Hubel and Wiesel (1962) hypothesized that the receptive field of a simple cell is synthesized by excitatory summation of signals from a linear array of LGN receptive fields, which would yield greater activity from a bar oriented parallel to the array. The alternate model (e.g. Bonds, 1989) suggests that selectivity is shaped instead by intracortical inhibition. The inhibition could itself be selective for spatial properties and limit spatially excitatory input that is much less selective; alternatively, the excitatory input could have mild stimulus selectivity and the inhibition could provide a threshold nonlinearity restricting the range of spatial configurations over which the cell will fire (an "iceberg effect"). Qualitative

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evidence for inhibition of cortical cells by nonoptimal stimuli has been reported in the domains of both orientation (e.g. Bishop, Coombs & Henry, 1973; Creutzfeldt, Kuhnt & Benevento, 1974) and spatial frequency (e.g. DeValois, 1978; Movshon et al., 1978).

Purely excitatory refinement of spatial frequency selectivity is not a very attractive hypothesis. The narrowing of spatial frequency bandpass by excitatory convergence would require contributions from a well-defined periodic array of LGN receptive fields. Predictions by Fourier transform indicate that the average bandwidth found in simple cells (about 1.5 octaves) would require four or more excitatory domains. While there is some evidence for as many as six multiple excitatory regions in some simple cells (Mullikin, Jones & Palmer, 1984), this geometry is restricted to cells in layers III and IVab and is not found in many simple cells showing narrow selectivity for spatial frequencies. The enhancement of spatial frequency selectivity by inhibitory mechanisms thus seems much more likely. DeValois and Tootell (1983) tested this hypothesis by stimulation of cortical cells with superimposed pairs of sinusoidal gratings. One grating was presented at a spatial frequency appropriate to generate excitatory activity against which the impact—either excitatory or inhibitory—of a second grating at a different spatial frequency could be seen. Of 86 cells, 64% showed inhibition; the susceptibility of simple cells (97%) was greater than complex cells (38%). In 87% of the cases in which inhibition was found, however, it was at higher spatial frequencies rather than lower spatial frequencies where it would be needed to explain the enhanced attenuation at low spatial frequencies found in cortical cells. The authors concluded that the inhibition "subserves some function other than (or in addition to) the narrowing of spatial frequency tuning functions".

One constraint of the study by DeValois and Tootell was that the grating pairs were rigidly presented. The *velocity* of each grating was identical, which yielded stimulation with different temporal frequencies if the spatial frequencies of the gratings differed. This also resulted in a fixed phase relationship between the two gratings, upon which the interactions were dependent in many cases. We have re-evaluated the role of inhibition in the enhancement of the spatial frequency selectivity of cortical neurons. Our approach is similar to that of DeValois and Tootell in the use of two superimposed gratings, but here the gratings were drifted independently to eliminate any phase relationship (and thus phase-dependency of inhibition) between them. We find that when responses are suppressed by a second grating, the form of suppression (at high frequencies, low frequencies or a band-limiting combination of the two) is predictable from the excitatory tuning function of the cell in over 90% of the cases examined. This suppression also appears to be uniquely cortical in origin, in that it is not found in LGN cells. These results provide evidence for the refinement of spatial frequency selectivity by inhibition and support the proposal of inhibition between adjacent spatial frequency channels that has been reported in the psychophysical literature (e.g. Tolhurst, 1973).

METHODS

Physiological preparation

Adult cats (2–4 kg; $n = 16$) were initially anesthetized with 5% Fluothane in O_2. A forelimb vein was cannulated and anesthesia was maintained with 2.5% sodium thiamylal (Surital). A tracheal cannula was inserted and a craniotomy performed at Horsley–Clark coordinates P4–L2. In some experiments, the electrode was positioned in the lateral geniculate nucleus (LGN) at coordinates A10–L8. Paralysis was induced with an initial 1 mg injection of gallamine triethiodide (Flaxedil) and maintained at an infusion rate of 10 mg/kg-hr in a mixture of lactated Ringer's solution and Surital (1 mg/kg-hr) to stabilize anesthesia. Animals were artificially ventilated (N_2O:O_2:CO_2 of 75%:23.5%:1.5%) at a rate of 30 breaths/min and a stroke volume adjusted to maintain an expired CO_2 of 3.9%. The EEG and EKG were continually monitored to insure adequate anesthesia and the rectal temperature was maintained at 38°C. Pupils were dilated with 1% atropine sulfate and nictitating membranes were retracted with 10% phenylephrine HCl. The corneas were protected with fitted contact lenses having 4 mm artificial pupils. Correcting lenses were added to render the retinae conjugate with a viewing screen 57 cm distant. By reversible ophthalmoscopy, the optic disk and area centralis of each eye were projected onto a plotting screen; the receptive fields of all cells recorded were located within 5 deg of *area centralis*. Recordings were all taken from Area 17 (H–C coordinates L2–P4)

with the exception of seven LGN cells recorded directly within the LGN.

Stimuli and data analysis

Receptive fields were first mapped for location and optimal orientation with a manually-controlled light bar. Stimulus patterns were then presented on a Tektronix 608 display (110 cd/m^2 mean luminance) driven by a microprocessor-based digital pattern generator. The display was masked to a circle of 10 cm, which subtended 10 deg visual angle at the standard viewing distance. Single sine-wave gratings were first presented to determine quantitatively the stimulus orientation, spatial frequency and temporal frequency which would optimally drive a cell. Cells were classified as simple or complex both on the basis of the usual tests with a light bar and by means of the modulation index (see, e.g. DeValois & Tootell, 1983). As a rule, response amplitude was specified by the d.c. response component (mean firing rate) for complex cells and the fundamental response component for LGN and simple cells. In all experiments, each stimulus condition in a set was presented for 4 sec with a 1 sec interval of mean luminance between presentations. Each stimulus set was presented 10 times in random interleaved fashion (e.g. Henry, Bishop, Tupper & Dreher, 1973) to minimize the impact of endogenous drift and adaptation; each stimulus condition was thus presented 40 sec altogether. With a grating adjusted to those spatial parameters yielding an optimal response, a response vs log contrast function was also measured.

Two superimposed gratings were used to test whether inhibition was involved in the spatial frequency tuning of cortical neurons. One grating, the BASE, was set at the optimal orientation and spatial frequency for each cell to provide excitatory activity against which the impact of the second grating, the MASK, could be viewed. The mask was also set to the optimal orientation but its spatial frequency was systematically varied. The two gratings were drifted at different temporal frequencies—usually 2 Hz (base) vs 3 Hz (mask)—to time-average the impact of any phase-dependencies or interference. The contrast of each grating was set so that the algebraic sum of the two contrasts ranged between 60 and 85% of the contrast that caused the cell to saturate.

Double grating stimuli were generated by alternating frames of each grating at 256 Hz (128 frames of each grating per second). Each set of presentations included a control condition in which the base was presented in alternation with a mean luminance field instead of a mask. The contrast of this control stimulus was thus half the nominal contrast of the base. The resulting response level was the standard against which the impact of the mask was measured. It was possible for the mask to facilitate responses above this level or to suppress responses below this level, depending on mask spatial frequency and the extent to which the cell demonstrated spatial-frequency-specific suppression.

The Michelson convention defines contrast on the basis of maximum and minimum luminance, which will not lead to a consistent representation of the amount of luminance modulation when two dissimilar gratings are superimposed. The maximum and minimum luminances in a two-grating stimulus will correspond to the signed algebraic sum of the maximum and minimum luminances of the two constituent gratings. This predicts that the contrast of the aggregate is the simple sum of the two Michelson contrasts. However, destructive interference between dissimilar gratings will reduce the contrast energy in the field. If contrast is arbitrarily defined as the standard deviation of luminance from the mean integrated over the stimulus field, by Parseval's theorem the contrast of two superimposed dissimilar gratings will be 0.707 times the sum of their individual contrasts. For this reason, the response to dissimilar grating pairs is less than that from a single grating of a contrast that is the sum of the two. In this paper, contrast of a grating pair will be described by stating the *effective contrast* of each constituent grating, which is the Michelson contrast of that grating when presented in alternation with a field of uniform mean luminance.

The results of double-grating stimulation can be interpreted differently for simple and complex cells due to the synchronous nature of simple cell responses, as opposed to the steady firing of complex cells. Shown in Fig. 1 are hypothetical examples of our treatments of simple and complex cell responses. The solid curves represent the excitatory (normal, single-grating) response vs spatial frequency tuning functions; for this demonstration, the shape of the function is of no significance. The horizontal line (short dashes) represents the response level elicited by the control stimulus condition (consisting of the base grating presented in alternation with a field of uniform mean luminance). The curves with long dashes represent the responses in the

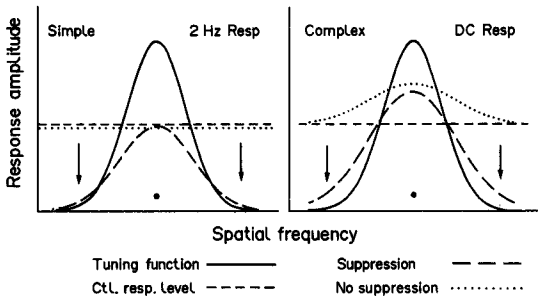

Fig. 1. Schematic of possible responses to double-grating stimulation. For both simple and complex cells, the normally-measured (excitatory) spatial frequency tuning function is represented by a solid line and the optimal spatial frequency by a dot on the abscissa. The control response level generated by a grating of this frequency alternated with a uniform field (i.e. half contrast) is represented by the horizontal line (short dashes). For the simple cell, response amplitudes are measured at the fundamental frequency of stimulation by the base (control) grating. Addition of a mask grating might or might not suppress the base-generated response. If suppression is generated by the mask (long dashes) the response will fall below the control level (arrows) at certain spatial frequencies. Excitatory contributions by the mask at the best spatial frequency will not be seen since its drift rate is asynchronous with the base grating. Lack of suppression would be indicated by a response level near that of the control (dotted line). For the complex cell, mask-generated suppression would also drive the response rate below that of the control (arrows). Excitatory contributions from the mask would be evident, since the d.c. response contains contributions from both. Summation may not be perfect (see text). If suppression were not present, the response level would never fall below that of the control (dotted line).

presence of both a base and mask grating as a function of mask spatial frequency, assuming that the mask causes response suppression. The dotted curves represent these same responses if the cell is not suppressed.

Simple cells (left panel) permit a comprehensive analysis. Their approximation of spatial linearity enables us to separate, by Fourier analysis of the response histograms, the responses from the 2 Hz base grating and the 3 Hz mask grating. The control response level for simple cells represents the 2 Hz response component induced by the base grating. If there are no interactions betweeen the base and mask, this response would remain unchanged as a function of mask spatial frequency (dotted line). Since the mask is drifted at 3 Hz, it produces no excitatory contribution of 2 Hz even when its spatial frequency falls within the range of spatial frequencies that are excitatory to the cell. The output of the cell is a common path that reflects integration of all input signals. Synaptic inhibition will produce either hyperpolarization or increased membrane leakage that will reduce the amplitude of *all* other signals passing through the cell regardless of origin, although this reduction may not be uniform if the inhibitory synapse is located on a peripheral dendrite. Thus, any synaptic inhibition resulting from stimulation by the mask will result in suppression of *all* response components (including the 2 Hz base-elicited activity) coming from the cell. The inhibitory influence of the mask will therefore be visible in the reduction of the base-generated response, whether the mask is within or beyond the excitatory range of spatial frequencies. The arrows illustrate suppression of the base response component in the case that suppression falls outside the excitatory band. It will be shown that the 3 Hz mask response component is always seen to resemble the excitatory spatial frequency tuning function, thus reflecting an excitatory contribution that is synchronous with stimulation, but an inhibitory contribution that is not.

Complex cell responses (right panel) are represented by the d.c. response component, which inseparably combines signals generated by both the base and the mask gratings. The mask contributes to excitation when presented at the optimal spatial frequency (visible in the central humps in the long dashed or dotted lines) but will cause the aggregate response to fall below the control level if inhibition is present outside the excitatory spatial frequency band (long dashed line). In this case no conclusions can be drawn concerning any suppressive impact of an excitatory mask on the base-generated signal since the excitatory contributions of both are pooled.

RESULTS

Population characteristics

Studies were completed on a total sample of 42 cells, 20 simple and 22 complex. Orientation bandwidths (half-width at half-height) ranged between 20 and 40 deg, and optimal temporal frequencies were usually 2 or 3 Hz. The spatial frequency tuning of each cell was measured by exposure to a single grating of 40% contrast. Throughout the experiments we used a standard set of seven spatial frequencies spanning 0.2–2 c/deg at approximately 0.18 log intervals. The spatial frequency selectivity of the cell sample was consistent with other population studies, in that half-height bandwidths averaged 1.4 octaves for simple cells and 1.8 octaves for complex cells (e.g. Movshon et al., 1978). Maximum responses

were found at spatial frequencies ranging from 0.3 to 1.4 c/deg. A linear regression was fit to the response vs log contrast function of each cell; its intercept with the cell's resting discharge level yielded an average contrast sensitivity of 21 (ranging from 11 to 77).

Types of inhibition

Cells were first categorized into three general classes based on the spatial frequency which yielded the greatest response. The categories were defined relative to the limited spatial frequency range (0.2–2.0 c/deg) shown to all cells. Cells with response peaks at 0.2–0.4 c/deg and little or no low frequency attenuation were classed as *low-pass*; those with peaks between 0.4 and 0.9 c/deg and noticeable low-frequency attenuation were classed as *band-pass*; and those with peaks at or above 1 c/deg were classed as *high-pass*. Of the 42 cells studied, 15 were low-pass, 19 were band-pass and 8 were high-pass. Simple cells predominantly showed band-pass characteristics whereas complex cells tended to have low-pass characteristics.

The double-grating test showed that 31 (74%) of the total cell sample demonstrated response suppression that was selective for spatial frequency. This is somewhat higher than the 64% reported by DeValois and Tootell (1983). Those cells demonstrating suppression were additionally categorized on the basis of the spatial frequency dependence of the suppression and its relationship to the spatial frequency tuning of the cell. Suppression found at spatial frequencies below the peak frequency for the cell was termed *low-frequency* suppression and that found above the peak frequency was termed *high-frequency* suppression. In some cases both types of suppression were found in the same cell; this combination was called *band-limiting* suppression. Examples of each variety of inhibition are shown in Figs 2–4. The spatial frequency tuning function (measured at 40% contrast) is represented by the open circles above the solid horizontal line, which for the upper sections of the graphs denotes the resting discharge level. In the lower sections of the figures the horizontal line represents the response level obtained by stimulation with the base grating in combination with a uniform field (the *control* response level). The ordinate below this line expresses the amount of mask-induced suppression from this level, and is calibrated in negative imp./sec. The curves in the lower sections represent the response functions measured by double-grating stimulation in which the spatial frequency of the mask grating was varied. Suppression resulting from testing at three different mask contrasts below, equal to, and above the base contrast is shown.

Figure 2A shows a simple cell responsive to low spatial frequencies that has high-frequency suppression. The suppression increases coincident with the drop from the peak response level. As in 80% of the cases the strongest suppression is seen just where the excitatory response reaches zero (the *limit* of the spatial frequency tuning function), in this case 0.6 c/deg. Note that increases in mask contrast yield consistently greater suppression. Figure 2B shows the 3 Hz

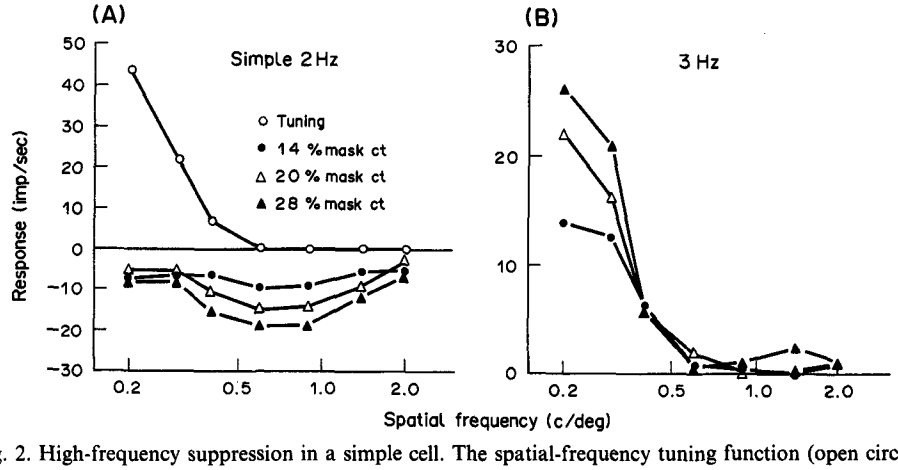

Fig. 2. High-frequency suppression in a simple cell. The spatial-frequency tuning function (open circles) was measured at 40% contrast. The base grating was fixed at 0.2 c/deg and 20% effective contrast (e.c.). (A) Masks presented at 14% (solid circles), 20% (open triangles) and 28% (solid triangles) e.c. yielded monotonically increasing suppression peaking at 0.6–0.9 c/deg. The control firing level was 22.6 imp./sec. (B) The response component at the mask temporal frequency resembles the tuning function in A; same contrast conventions. Cell LV9:R4.

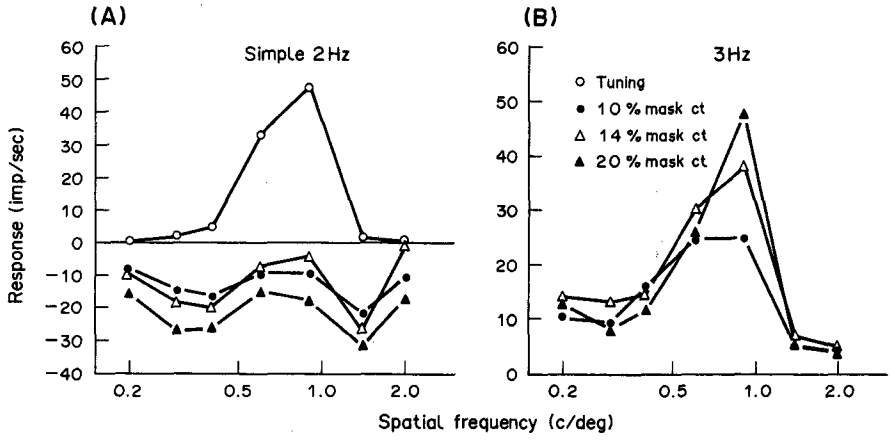

Fig. 3. Band-limiting suppression in a simple cell. The spatial-frequency tuning function (open circles) was measured at 40% contrast. The base grating was fixed at 0.9 c/deg and 14% e.c. and masks were presented at 10% (solid circles), 14% (open triangles) and 20% (solid triangles) e.c. (A) Response at base fundamental (2 Hz) showing little suppression at 0.9 c/deg and strong suppression at 0.4 and 1.4 c/deg. The control firing level was 38.8 imp./sec. (B) Mask (3 Hz) response component resembles the excitatory tuning function. Symbol conventions as in A. Cell LV7:R2.

component extracted from the same response histogram (generated in the recorded cell by the mask) as a function of mask spatial frequency. The shape of the curve resembles that of the control measurements (open circles, Fig. 2A) and excitation is seen to grow monotonically as mask contrast is increased. Little or no 3 Hz component is apparent at spatial frequencies above 0.6 c/deg, suggesting that when the mask is at spatial frequencies that result only in suppression (and not excitation), any modulatory impact the mask might have on the base response is temporally incoherent. Similar behavior is seen in Fig. 3, which shows band-limiting suppression in another simple cell. Suppression peaking at 0.4 and 1.4 c/deg denotes both upper and lower limits of the excitatory tuning function. Again, suppression grows as mask contrast is increased and the mask (3 Hz) response component resembles the excitatory tuning function. A high-pass complex cell with low-frequency suppression is seen in Fig. 4A, and a broadly-tuned band-pass complex cell with no discernible suppression is shown in Fig. 4B.

Correlation of suppression with excitatory response

Of the cells in which response was suppressed by the mask grating, 93% showed a clear correlation between the type of suppression (as

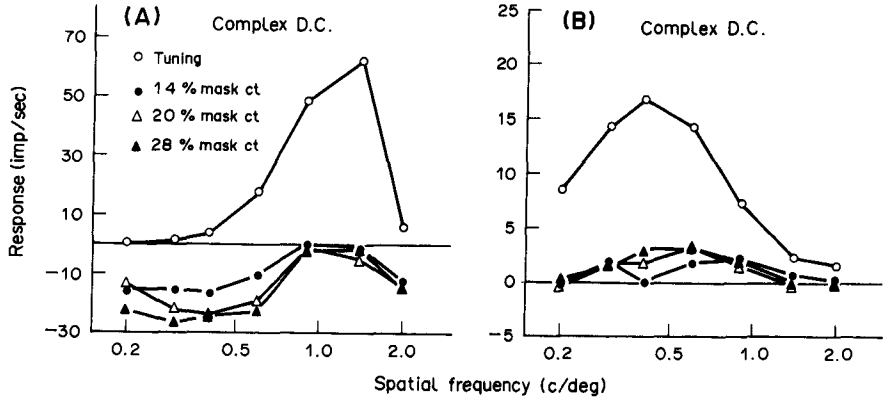

Fig. 4. (A) Low-frequency suppression in a complex cell. The spatial-frequency tuning function (open circles) was measured at 40% contrast. The base grating was fixed at 1.4 c/deg and presented at 20% effective contrast. Response suppression is found at spatial frequencies of 0.2–0.4 c/deg with mask gratings of 14% (solid circles), 20% (open triangles) and 28% (solid triangles) effective contrast. The control firing level was 35.1 imp./sec. Cell LV7:R1. (B) Complex cell showing no noticeable suppression. Contrast conventions as in (A); base presented at 0.4 c/deg. Control firing level was 4.9 imp./sec. Cell LV11:R3.

Table 1

Cell class	Type of tuning	Type of inhibition: Low frequency	Band limiting	High frequency	None
Simple	Low pass	1	1	3	—
	Band pass	4	3	3	2
	High pass	1	—	—	2
Complex	Low pass	1	—	7	2
	Band pass	—	2	2	3
	High pass	2	1	—	2

classified by criteria described earlier) and the excitatory tuning of the cell (Table 1). Cells with a low-pass excitatory tuning function usually showed high-frequency suppression and those with a high-pass tuning function usually showed low-frequency suppression. Cells with a band-pass tuning function showed all possibilities, either low-frequency suppression alone, high-frequency suppression alone or a combination of the two (band-limiting suppression). The fact that both low- and high-frequency suppression is found in varying combination in these cells is not inconsistent with the notion that response suppression is associated with inhibitory refinement of spatial frequency selectivity, since the refinement can be expressed on either or both sides of the tuning function. In only two cases (of 31) was the form of suppression directly in conflict with this notion; both were examples of low-frequency suppression associated with low-pass tuning.

When the mask is set to spatial frequencies that are most effective in driving the cell, suppression appears to be minimal. This observation is of little significance in the case of complex cells, since the high firing level simply reflects the activation of the cell due to contributions from both the base and the mask. However, with simple cells, the individual excitatory contributions from base and mask can be separated (assuming response linearity; see below) through Fourier analysis of the response, which can reveal suppressive effects of the mask on the base-generated response even when the mask is excitatory. In these cases, suppression of the base response component is lowest—although rarely absent—with masks of the optimal spatial frequency (e.g. Figs 2A and 3A). While this remaining suppression could result from nonoptimality of the 3 Hz temporal frequency of the mask, this is unlikely since there was usually little difference in temporal tuning between 2 and 3 Hz. We feel instead that the component of mask-induced suppression that is independent of spatial frequency is simply a consequence of added contrast (Bonds, 1989).

Are the responses separable?

The separation of response components by Fourier transformation is valid only if responsiveness is linear, i.e. if responses are summed additively without significant interaction. When the mask is set to a spatial frequency that provides excitation, the cell fires robustly due to stimulation from both base and mask. It is possible that spectral "crosstalk" could occur that would artificially elevate the amplitude of the base response component due to high activity at the mask temporal frequency. This would override suppression that might be present within the range of spatial frequencies that appear effective at driving the cell, leading to the conclusion that suppression appears weaker than is actually the case.

The question that arises is the extent to which response power from the mask can influence response amplitude at the fundamental frequency of the base. If one models the transduction process of a simple cell as a perfect half-wave rectifier, the nature of the nonlinearity is such that the base and mask fundamental response components still act independently (i.e. do not "pollute" each other). It is only when a threshold elevation above the half-wave rectification level is introduced (i.e. the sinusoidal waveform is sliced higher than its midpoint) that significant interaction between the response components can be seen. For example, if the threshold is raised 20% (of the peak amplitude of the sine wave) the base response amplitude is elevated 16% by "spillage" from a mask component of equal amplitude. While this simple model is incomplete due to differences in the organization of nonlinearities across simple cells, it illustrates that crosstalk between response components depends on threshold elevation.

The degree of threshold elevation can be estimated by measuring the duty cycle of the response, i.e. the ratio of the duration of response activity to the total duration of the stimulus period. For a 2 Hz stimulus the stimulus period is 500 msec; response activity of 250 msec duration would yield a 50% duty cycle. Duty cycle and threshold elevation are remarkably stable within a given cell across a broad range of stimulus conditions, but vary somewhat from cell to cell. Of the 16 simple cells showing suppression in this study, the duty cycle ranged from 39% to just over 50%, averaging 47.2%.

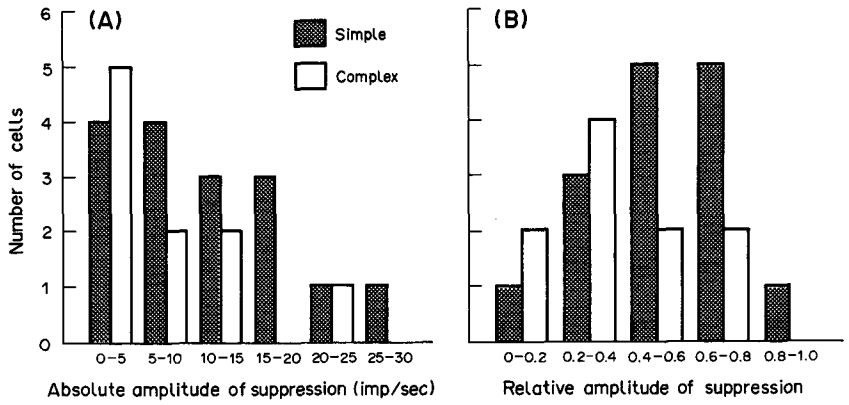

Fig. 5. Comparison of amplitude of suppression in simple and complex cells. (A) Absolute amplitude. The abscissa scales indicate the amount of suppression found for a mask presented at the spatial frequency yielding maximum suppression and an effective contrast of 40%. (B) Relative amplitude. Here the figures used in (A) were normalized to the firing rate generated by the control stimulus.

This corresponds to threshold elevation ranging from 22 to 0% and averaging 8%, respectively. Fourier analysis using this simple model predicts contamination of the base response by the mask of at *most* 18% and averaging 7%. Such contamination is thus not a major factor, so the minimization of suppression at optimal spatial frequencies appears to be real. Perhaps more compelling is the observation that in many cases there was no apparent threshold elevation in the simple cell response; the cell acted purely as a half-wave rectifier, producing a response with a duty cycle of exactly 50%. In these cases, where no contamination between base and mask is predicted, there is no less tendency for suppression to be minimal for optimal spatial frequencies. An example of the suppression pattern from such a cell is seen in Fig. 3.

Comparison of suppression in simple and complex cells

Suppression was found slightly more often in simple cells (80%) than in complex cells (68%). Simple cells typically showed band-pass tuning associated with mixed types of suppression. Complex cells typically showed low-pass tuning and high frequency suppression. Of those cells showing suppression, simple cells tended to have stronger suppression than did complex cells (Fig. 5). This statement is based on two methods of evaluation. Absolute suppression was determined by observing the maximum suppression elicited by a mask grating of 40% contrast. By this measure, 16 simple cells showed stronger average suppression (13 imp./sec) than did 11 complex cells (9 imp./sec). Relative suppression was calculated as the ratio of the maximum suppression to the maximum excitatory response amplitude at the same contrast. Again suppression was stronger in simple cells than in complex cells, with this ratio averaging 0.6 vs 0.4, respectively. This is consistent with a causal relationship between strength of suppression and narrowness of tuning in view of the tendency for simple cells to have somewhat narrower tuning than complex cells (e.g. Movshon et al., 1978).

Layer analysis

Stained histological sections of lesioned electrode tracks were used to determine the location of all cells within the separate cortical layers. Neither the type nor the strength of inhibition was found to be organized within a specific layer. However, cells with no inhibition tended to be located in layer III and absent in layer IV.

Origin of inhibition

Thus far it has been assumed that the spatial frequency selective response suppression was intracortical, insofar as the tuning of the suppression is generally inconsistent with the broader spatial frequency selectivity of LGN neurones. This assumption was tested explicitly by double-grating stimulation of 9 LGN cells whose fibers were recorded in either the LGN or the optic radiation. Figure 6A shows the results from one fiber. Graphical conventions are the same as in Fig. 2. Note that only a slight tendency for suppression is observed and that it is not systematically correlated with the (low-pass) tuning apparent in the LGN cell.

This lack of patterned suppression was consistently seen in all LGN cells. Figure 7 shows the average suppression (open circles) normalized to the control response level, flanked by the *total* envelope (denoted by the vertical bars) of re-

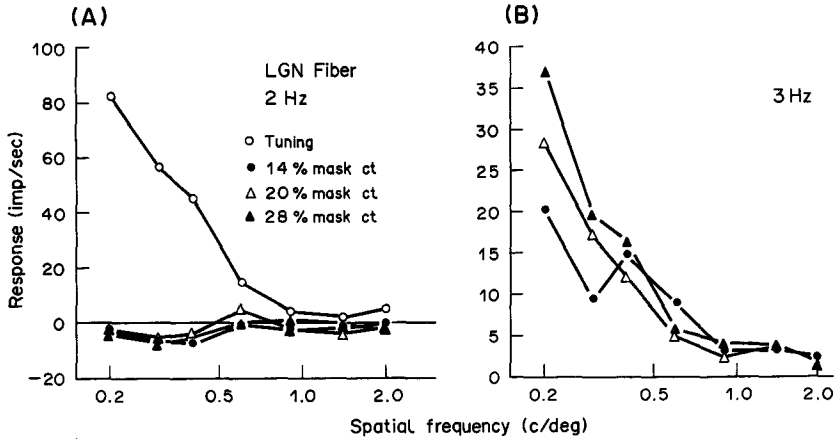

Fig. 6. Lack of response suppression in an LGN fiber. (A) The excitatory tuning curve (open circles) was measured at 40% contrast. The base was fixed at 0.2 c/deg and 20% e.c. No organized deviation from the control response level is seen with mask effective contrasts of 14% (solid circles), 20% (open triangles) and 28% (solid triangles). The control firing level was 34.7 imp./sec. (B) Mask response component reflecting excitatory tuning. Contrast conventions as in (A). Cell LV16:R4.

sponse suppression from all 9 fibers. The general trend was modest suppression at low spatial frequencies, which is not consistent with the low-pass tuning characteristic of LGN cells, although it may contribute to the tendency of LGN cells to show rather more low-frequency attenuation than retinal ganglion cells. The absence in the LGN of the strength and variety of response suppression demonstrated in the visual cortex suggests strongly that the spatial-frequency-dependent suppression seen in cortical cells originates in the cortex.

DISCUSSION

Inhibition or artifact?

Thus far the impact of the mask grating has been referred to as *suppression* in order to avoid a direct implication that the process results from synaptic inhibition. A reduction of the response amplitude of a neuron can result from either a reduction of excitation, an increase in inhibition (either subtractive or divisive) or some combination of the two. The form of the stimulus itself could contribute to the first alternative. When two gratings of different spatial frequency are superimposed with different drift rates, the phase relationship between them will differ as a function of both space and time. If one then examines the contrast visible at some defined locus of the display, the contrast will periodically be cancelled as the gratings pass through a phase difference of 180 deg at that locus. The temporal periodicity of this contrast cancellation will be the difference of the drift rate between the two gratings, in this case, 1 Hz. However, even when the contrast is cancelled at one locus in the field, contrast that could still be sufficient to provide some stimulation of the cell will be present at other loci. The problem is exacerbated in the special case of matching spatial frequencies; in this condition, the temporally periodic contrast cancellation will result in uniform luminance over the entire stimulus field. It is thus possible that the response suppression demonstrated in all of the observations here is simply a consequence of periodically reduced contrast in the stimulus.

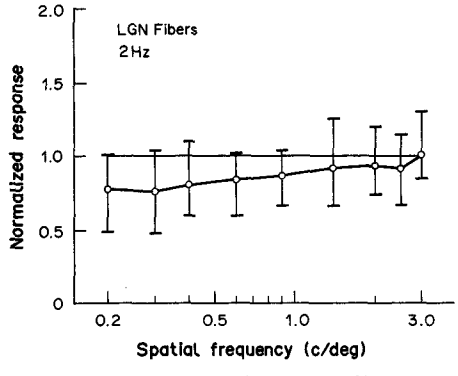

Fig. 7. Response suppression in 9 LGN fibers. For all 9 fibers, the control response level was normalized to 1. The open circles represent the average amount of response suppression among all cells. The deviation lines show the *total envelope* of response suppression among all 9 examples. Marked suppression or facilitation is not seen.

While this possibility might be amenable to analysis through modelling, results would be inconclusive due to incomplete information on the nonlinearities and inhomogeneities in the receptor fields of the actual cells studied. Instead, we base our claim that the response suppression is a result of intracortical synaptic

inhibition on three observations. (1) Spatial-frequency-dependent response suppression was *absent* in every LGN cell and 26% of the cortical cells studied. If the suppression were a consequence of contrast reduction in the stimulus, one would expect that this would be reflected in suppression at earlier stages (the LGN) and in most, if not all, cortical cells. As mentioned earlier, the failure to observe suppression in the LGN also implies that the suppression is uniquely cortical in origin. (2) As demonstrated in Fig. 2, the amount of response suppression monotonically increased as the contrast of mask gratings increased from less than, to equal to and greater than that of the base grating. If the suppression were primarily dependent on contrast cancellation, one would expect that the greatest amount of suppression would result from the condition of equal contrast, where the cancellation is most complete; this is however not found. (3) Perhaps the least objective but most compelling indication that the suppression is somehow linked to spatial-frequency-dependent inhibition is the observation that in the vast majority of cases the suppression is found exactly where one would expect it to be if its purposes were to refine spatial frequency selectivity. The suppression is usually least at the optimal spatial frequency of a cell and greatest at the cutoff spatial frequency. Such an arrangement steepens the slopes of the response vs spatial frequency function, thereby enhancing spatial frequency selectivity.

Cortical sources

Although spatial frequency-selective inhibition is known to appear first in the visual cortex, its exact origins remain to be determined. There is some reason to suspect that it stems from complex cells. When the mask grating was set to spatial frequencies outside the excitatory range, no 3 Hz response component was seen in any of the simple cells (e.g. Figs 2B and 3B). This implies that the suppression was incapable of synchronous temporal modulation of the 2 Hz base signal, which might be expected if the suppression originated in simple cells. There is, however, no evidence to support synaptic inhibition of simple cells by complex cells. Inhibition is believed to come primarily from smooth stellate cells, which have the appropriate synaptic structure (LeVay, 1973; Peters & Fairen, 1978) and chemistry (Ribak, 1978), but functional characterization of smooth stellate cells suggests that they are simple (Gilbert & Wiesel, 1979). Moreover, cross-correlation experiments find no evidence for inhibition of any kind from complex cells (Toyama, Kimura & Tanaka, 1981). Given these observations, a likely source for the inhibition is a pool of simple cells with spatially incoherent receptive fields so as to eliminate any temporal pattern in the suppressive signal.

The actual organization of this pool remains unknown. Columnar architecture to support lateral inhibition in the orientation domain (e.g. Bonds, 1989) is well-documented, but a similar physical organization to support spatial frequency has yet to be found. The lack of a robust anatomical structure may be reflected in the observation that spatial frequency-dependent inhibition is not as powerful as orientation-dependent inhibition.

Another unresolved issue is the sharpness of tuning of the inhibition itself. If inhibition that is narrowly tuned for spatial frequency must be invoked to create cells that are narrowly tuned for spatial frequency, a problem in causality emerges. The system could be recurrent (i.e. cell A inhibits cell B and vice-versa), although this configuration has potential instability. Enhancement of selectivity need not necessarily depend, however, on highly tuned inhibition. A simple subtractive interaction between two broadly-tuned cells with different tuning peaks can result in a steeper slope at their intersection, as demonstrated in the space domain by center-surround interaction in the retina.

Psychophysical corroboration

Inhibitory interactions between spatial frequency channels cannot be measured directly using psychophysical methods, but much indirect supportive evidence has accumulated. Tolhurst (1972) as well as Nachmias, Sansbury, Vassilev and Weber (1973) found that adaptation to a squarewave grating produces less adaptation at the third harmonic than adaptation to the third harmonic (of equal amplitude) presented alone. This was interpreted as indicating an inhibition between the fundamental and third harmonic frequencies, in that the adaptive efficacy of the third harmonic was reduced in the presence of the fundamental. DeValois (1977) and Tolhurst and Barfield (1978) showed that adaptation by a single spatial frequency reduced sensitivity at that spatial frequency, but raised sensitivity at spatial frequencies one to two octaves away. The adaptation is presumed to have reduced tonic inhibition on distant channels.

The band-limiting suppression indicated in Fig. 3A is suggestive of the "Mexican hat" model of retinal receptive fields, which yields Mach-band behavior in the space domain. A spatial frequency analog to Mach bands has been described by McCarter and Roehrs (1976). Apparent changes in spatial frequency were observed at spatial frequency gradients; such changes were systematically related to the steepness of the gradient in a way that is similar to luminance-based Mach bands. The effect suggested lateral inhibition between spatial frequency channels if the spread of the neural mechanisms processing spatial frequency were broader than one octave. Similar lateral inhibition is implied by a study of the visibility of unstructured patterns, where narrow-band noise was found to be much more visible than broad-band noise (Mitchell, 1976). Visibility was dependent on a one-octave band, again suggesting that spatial frequencies beyond this range were inhibitory. The effect was found to be sensitive to the orientation of the noise, implying a basis within or beyond cortical cells.

Not all psychophysical studies are supportive of cross-channel inhibition. A study of contrast masking (Legge & Foley, 1980) concluded that a model consisting of a linear spatial-frequency filter (without inhibition) followed by a compressive nonlinearity was sufficient to account for all effects measured. It is worth noting however that this work concentrated on the influences of spatial frequencies ranging from 1 to 4 c/deg on a test frequency of 2 c/deg. A one-octave deviation may not have been sufficiently far from the center frequency to reveal the remote facilitation noted by DeValois (1977) and Tolhurst and Barfield (1978). In any event, the failure to find interactive nonlinearities over such a limited range of spatial frequencies is not contradictory to direct physiological observation of such interactions across a broader range.

CONCLUSION

Evidence has been presented demonstrating spatial-frequency-dependent intracortical inhibition that is coordinated with the tuning of individual cortical cells. At least in simple cells, this inhibition is organized so as to enhance spatial frequency selectivity. Two major conclusions may be drawn from these findings. (1) The existence of these mechanisms provides support for the hypothesis that one feature of cortical image processing is a crude form of spatial frequency analysis. While neither the bandwidth nor linearity of the cells is sufficient for true Fourier analysis, it is reasonable to assume that cortical cells parse visual scenes into limited domains within a two-dimensional polar coordinate system representing orientation and spatial frequency, and that these inhibitory mechanisms constrain the area of such domains. (2) Because of the obvious nonlinearities introduced by the inhibition, the model of cortical processing as a series of stationary linear spatial filters is no longer sufficient; responsiveness is clearly affected by patterns that do not excite the cell under study. The spatial processing characteristics of cortical cells are thus more dynamic and flexible than previously thought, and detailed analysis through direct methods such as receptive field mapping may not completely reveal the foundations of the cortical response.

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REFERENCES

Bishop, P. O., Coombs, J. S. & Henry, G. H. (1973). Receptive fields of simple cells in the cat striate cortex. *Journal of Physiology, 231*, 31–60.

Bonds, A. B. (1989). The role of inhibition in the specification of orientation selectivity of cells in the cat striate cortex. *Visual Neuroscience, 2*, 41–55.

Creutzfeldt, O. D., Kuhnt, U. & Benevento, L. A. (1974). An intracellular analysis of visual cortical neurons to moving stimuli: Responses in a cooperative neuronal network. *Experimental Brain Research, 21*, 251–274.

DeValois, K. K. (1977). Spatial frequency adaptation can enhance contrast sensitivity. *Vision Research, 17*, 1057–1065.

DeValois, K. K. (1978). Interactions among spatial frequency channels. In Cool, S. J. & Smith, E. L. (Eds.), *Frontiers in visual science* (pp. 277–285). Berlin: Springer.

DeValois, K. K. & Tootell, R. B. H. (1983). Spatial-frequency-specific inhibition in cat striate cortex cells. *Journal of Physiology, 336*, 359–376.

Enroth-Cugell, C. & Robson, J. G. (1966). The contrast sensitivity of retinal ganglion cells of the cat. *Journal of Physiology, 187*, 517–552.

Ferster, D. (1986). Orientation selectivity of synaptic potentials in neurons of cat primary visual cortex. *Journal of Neuroscience, 6*, 1284–1301.

Gilbert, C. D. & Wiesel, T. N. (1979). Morphology and intracortical projections of functionally characterized neurones in the cat visual cortex. *Nature, London 280*, 120–125.

Henry, G. H., Bishop, P. O., Tupper, R. M. & Dreher, B. (1973). Orientation specificity of cells in cat striate cortex. *Vision Research, 13*, 1771–1779.

Hubel, D. H. & Wiesel, T. N. (1962). Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *Journal of Physiology, 160*, 106–154.

Kaplan, E., Marcus, S. & So, Y. T. (1979). Effects of dark adaptation on spatial and temporal properties of receptive fields in cat lateral geniculate nucleus. *Journal of Physiology, 294*, 561–580.

Legge, G. E. & Foley, J. M. (1980). Contrast matching in human vision. *Journal of the Optical Society of America, 70*, 1458–1471.

LeVay, S. (1973). Synaptic patterns in the visual cortex of the cat and monkey. Electron microscopy of Golgi preparations. *Journal of Comparative Neurology, 150*, 53–86.

Maffei, L. & Fiorentini, A. (1973). The visual cortex as a spatial frequency analyzer. *Vision Research, 13*, 1255–1267.

McCarter, A. & Roehrs, T. (1976). A spatial frequency analog to Mach bands. *Vision Research, 16*, 1317–1321.

Mitchell, O. R. (1976). Effect of spatial frequency on the visibility of unstructured patterns. *Journal of the Optical Society of America, 66*, 327–332.

Movshon, J. A., Thompson, I. D. & Tolhurst, D. J. (1978). Spatial and temporal contrast sensitivity of neurones in areas 17 and 18 of the cat's visual cortex. *Journal of Physiology, 283*, 101–120.

Mullikin, W. H., Jones, J. P. & Palmer, L. A. (1984). Periodic simple cells in cat Area 17. *Journal of Neurophysiology, 52*, 372–387.

Nachmias, J., Sansbury, R., Vassilev, A. & Weber, A. (1973). Adaptation to square-wave gratings: In search of the elusive third harmonic. *Vision Research, 13*, 1335–1342.

Peters, A. & Fairen, A. (1978). Smooth and sparsely-spined stellate cells in the visual cortex of the rat: A study using a combined Golgi-electron microscope technique. *Journal of Comparative Neurology, 181*, 129–172.

Ribak, C. E. (1978). Aspinous and sparsely-spinous stellate neurons in the visual cortex of rats contain glutamic acid decarboxylase. *Journal of Neurocytology, 7*, 461–478.

Tolhurst, D. J. (1972). Adaptation to square wave gratings: Inhibition between spatial frequency channels in the human visual system. *Journal of Physiology, 226*, 231–248.

Tolhurst, D. J. & Barfield, L. P. (1978). Interactions between spatial frequency channels. *Vision Research, 18*, 951–958.

Toyama, K., Kimura, M. & Tanaka, K. (1981). Cross-correlation analysis of interneural connectivity in cat visual cortex. *Journal of Neurophysiology, 46*, 191–201.