



Interocular Suppression in the Primary Visual Cortex: a Possible Neural Basis of Binocular Rivalry

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In an attempt to demonstrate a physiological basis for the alternating suppression of perception when the two eyes view very different contours (binocular rivalry), we studied the responses of neurons in the lateral geniculate nucleus (LGN) and area 17 of cats for drifting gratings of different orientation, spatial frequency and contrast in the two eyes. Almost half of the LGN neurons studied exhibited modest inhibitory interocular interaction, but independent of interocular differences in orientation. Monocularly driven units in layer 4 of area 17 behaved similarly. However, for the majority of binocular cortical cells, the response to a grating of optimal orientation in one eye was suppressed by a grating of very different orientation shown to the other eye, over a wide range of spatial frequency and independent of relative spatial phase. This interocular suppression exhibits a remarkable non-linearity: a grating of non-preferred orientation in one eye causes significant interocular suppression only if the neuron is already responding to an appropriate stimulus in the other eye [Sengpiel and Blakemore (1994) *Nature*, 368, 847–850]. We propose that the switches in perceptual dominance during binocular rivalry depend on interocular interactions at the level of binocular neurons of the primary visual cortex, which might involve intracortical inhibition between adjacent ocular dominance columns. The spontaneous alternations in perceptual suppression that occur during prolonged viewing of rivalrous patterns remain to be explained, although significant variation in the strength of neuronal suppression in such conditions was occasionally seen.

Binocular rivalry Suppression Visual cortex Striate cortex Lateral geniculate nucleus Contrast gain control Cat

INTRODUCTION

Binocular rivalry is a powerful, yet largely unexplained phenomenon. It occurs when the images seen by the two eyes are so dissimilar that they cannot be fused: the observer experiences fluctuating dominance and suppression of each monocular stimulus. For instance, if dissimilar patterns of sufficiently high contrast are presented to the two eyes, contour rivalry occurs (e.g. von Helmholtz, 1910; Liu, Tyler & Schor, 1992): the visual field breaks up into a set of fluid patches, within which perception is alternately dominated, for a few seconds at a time, by the contours viewed by each eye. The rate of alternation and the duration of each period of dominance depend on “stimulus strength”, in particular on the brightness and the contrast of the images. Increasing the contrast in one eye results in a decrease in the duration of dominance by the other eye’s image (Levelt, 1965).

Von Helmholtz himself (1910) suggested that rivalry can be influenced by conscious shifts in attention. However, current theories assume the operation of an autonomous “oscillator” at an early stage in the processing of visual information (Lehky, 1988). Although differing in detail, all current models of rivalry (e.g. Matsuoka, 1984; Lehky, 1988; Blake, 1989; Mueller, 1990) postulate that the oscillating circuitry involves reciprocal inhibition between populations of monocular neurons, resulting in alternating blockage of signals from each eye.

The orientation dependence of contour rivalry requires either that the cell pools on which this inhibition acts are themselves orientation selective, or that they receive inhibition from such neurons. This has led Lehky and Blake (1991) to suggest that the site of the alternation is either the lateral geniculate nucleus (LGN), where neurons are monocular and lack obvious orientation selectivity but receive extensive back-projections from orientation selective cells in layer 6 of the primary visual cortex (Gilbert & Kelly, 1975), or in layer 4 of the cortex, where cells tend to be monocular and are

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largely non-oriented in the monkey (Hubel & Wiesel, 1974) but usually orientation selective in the cat (Hubel & Wiesel, 1962).

Despite the compelling nature of this perceptual phenomenon, there is rather little direct evidence about its neural origin. Logothetis and Schall (1989a,b) attempted to relate neuronal activity in area MT of the superior temporal sulcus (STS) of awake monkeys to a behavioural indicator of the perception of rivalry during a motion discrimination task. Although a small fraction of cells in MT varied in responsiveness in a manner correlated with the monkey's judgement of direction of movement, an equal fraction behaved in the opposite fashion; and the majority were unaffected. The results were therefore somewhat inconclusive.

More in line with recent models of binocular rivalry, Varela and Singer (1987) reported suppression of responses in the LGN of the anaesthetized cat when the two eyes were stimulated with stimuli differing in orientation. However, both we (Sengpiel, Harrad & Blakemore, 1992) and Moore, Spear, Kim and Xue (1992) have recently failed to confirm these findings.

In their analysis of binocular interactions for simple and complex cells in cat area 17, Ohzawa and Freeman (1986a,b) also saw no strong interocular influences that might account for binocular rivalry. Most striate neurons showed little or no reduction in response to a correctly oriented grating presented to one eye when an orthogonal grating was simultaneously presented to the other eye. However, we have recently reported that the majority of cortical cells do exhibit cross-orientational interocular suppression if the inappropriate grating is introduced while the neuron is already responding to a correctly oriented stimulus in the other eye (Sengpiel & Blakemore, 1993, 1994).

Here we describe the stimulus dependence of interocular interactions in both LGN and striate cortex of normal cats, and evaluate the part that the suppressive behaviour seen in the striate cortex may play in binocular rivalry.

METHODS

Animals and surgery

All data presented here were obtained from five normal adult cats bred in a closed laboratory colony. Standard electrophysiological techniques for single-cell recording were employed (see Blakemore & Price, 1987). Anaesthesia was induced with ketamine hydrochloride (30 mg/kg) and maintained with alphaxalone/alphadolone (Saffan, Pitman-Moore) i.v. during tracheal cannulation and the exposure of the brain via a very small craniotomy and durotomy. During recording the animal was anaesthetized and paralysed with a continuous i.v. infusion of sodium pentobarbitone (1–2 mg/kg/hr, as needed to maintain anaesthesia) and gallamine triethiodide (10 mg/kg/hr) in glucose–saline. EEG and ECG were constantly recorded to monitor the state of anaesthesia. The animal was artificially hyperventilated with room air

plus carbon dioxide (CO₂), which was adjusted to maintain end-tidal CO₂ at 4.5–5.0%. Body temperature was kept at 38°C by means of a feedback-controlled heating-pad.

The pupils were dilated with atropine hydrochloride, and the lids and nictitating membranes retracted with phenylephrine. Zero-power contact lenses were fitted and 3-mm artificial pupils were placed in front of the eyes, as well as additional lenses for correction of refractive errors.

Recording and visual stimulation

Tungsten-in-glass micro-electrodes were advanced, by means of a stepping-motor microdrive, at stereotaxic positions corresponding to the representation of the centre of the visual field in the LGN (A6.5, L9) and area 17 (P5, L1.5). Isolated single units were characterized qualitatively with moving and stationary, flashed bars or spots of light of medium contrast back-projected by means of an overhead projector on to a translucent tangent screen. Receptive fields were plotted on the tangent screen, on which the projections of the areae centrales and the optic disks were also mapped by means of a reversible ophthalmoscope. LGN cells were classified as ON- or OFF-centre and as linear (X) or non-linear (Y) in their responses to a phase-reversing grating (Enroth-Cugell & Robson, 1966). Cortical neurons were classed as simple or complex according to Blakemore and Price's (1987) description of Hubel and Wiesel's (1962) original criteria. The ocular dominance of cortical neurons was classified on the seven-point scale of Hubel and Wiesel (1962).

For quantitative tests, the two eyes were stimulated independently by means of two high-resolution display screens (Tektronix 608) viewed at a distance of 57 cm via front-silvered mirrors. The total display area on each screen consisted of a circular region subtending 10 deg of visual angle in diameter. Each screen was adjusted in position to bring the receptive field in that eye to the centre of the display. Drifting, sinusoidally modulated gratings (mean luminance 17.5 cd/m²) were generated by a Picasso (Innisfree) image synthesizer. External control of the Picasso as well as data acquisition and analysis were performed by a visual stimulation software package (VS, Cambridge Electronic Design). This package allows the random interleaving of a variety of different stimuli, including a blank stimulus with no modulated pattern on the screen. Responses to each individual stimulus were averaged over a number of presentations included in the randomized sequence.

Cells were first stimulated monocularly with gratings, drifting at a temporal frequency optimized by ear, to determine tuning curves for orientation, direction and spatial frequency; during these trials a uniform field of the same space-averaged luminance was presented to the corresponding region of the field of the other eye. Each individual presentation lasted 1.25 sec while the blank periods between presentations lasted 1 sec.

Binocular interactions were then tested by constantly stimulating one eye (generally the dominant eye) with a full-field (10 deg dia) drifting grating (the "conditioning" stimulus) of optimum orientation and spatial frequency, and medium contrast [0.18–0.35, where contrast = (maximum – minimum luminance)/(2 × mean luminance)], and intermittently presenting to the other eye drifting gratings varying in orientation, spatial frequency, or contrast. The time-course of the onset of those gratings was always a step function. In some experiments we varied the *spatial offset* (phase of the triggering point) of the grating shown to the non-dominant eye while holding the relative phase of the conditioning (dominant eye) grating constant. When both stimuli are optimally oriented, such a spatial offset corresponds to relative *interocular phase disparity* (Ohzawa & Freeman, 1986a). The two gratings always drifted at the same temporal frequency—either 2 or 4 Hz. Each epoch of binocular stimulation lasted 5 sec and the periods of monocular stimulation in between also lasted 5 sec, unless specified otherwise.

Mean discharge rates and SEMs were calculated from at least four trials with each condition. Tuning curves of interaction were obtained by relating the mean response for each particular binocular presentation to the mean response during the immediately preceding periods of monocular stimulation. A cell was considered to show *binocular interaction* if the response to binocular stimulation differed significantly (in a two-tailed *t*-test) in strength from the response to stimulation of the dominant eye alone.

The time-course of suppression for rivalrous stimuli was studied comprehensively in five cells that showed clear suppressive interaction. An optimal conditioning grating was presented to the dominant eye and a few seconds later a grating of orthogonal orientation and high contrast was introduced to the other eye and was left on for a 30-sec stimulation period. The latency and consistency of suppression were judged from peri-stimulus time histograms (PSTHs) of individual trials and from averaged PSTHs accumulated over 8–10 such trials.

Finally, in four cells that showed clear suppression for rivalrous stimulation in the standard procedure, we studied the effects of different temporal sequences of presentation on contrast response curves. The response was averaged over a 5-sec period of binocular stimulation with orthogonally oriented gratings in the two eyes, preceded by (a) a blank screen of the same mean luminance presented to both eyes; (b) the orthogonal grating presented alone to the non-dominant eye; or (c) an optimal conditioning grating shown to the dominant eye alone.

Histology

Electrode tracks were marked with small electrolytic lesions made at intervals during withdrawal of the electrode. Animals were given an overdose of pentobarbital and perfused transcardially with phosphate-buffered saline followed by 4% paraformaldehyde. Electrode

tracks were reconstructed from 50- μ m coronal sections stained with cresyl violet.

RESULTS

Lateral geniculate nucleus

In two animals we studied quantitatively 17 LGN cells in laminae A and A1, 12 X-cells and five Y-cells, all monocularly driven by conventional stimuli. All receptive field centres were within 5 deg of the area centralis. For binocular stimulation, the display for the "silent" eye was centred on the position corresponding to that of the receptive field in the dominant eye, determined by prior recording from neighbouring cells in the adjacent lamina, dominated by the other eye.

Most of these LGN cells had no obvious selectivity for the orientation of drifting gratings [see Fig. 1(A)], but some showed small but clearly significant biases in preference (Vidyasagar & Urbas, 1982; Shou & Leventhal, 1989). For tests of binocular interaction we employed the procedure which reveals suppressive effects in the striate cortex (Sengpiel & Blakemore, 1994): the receptive field in one eye was stimulated continuously with an optimal stimulus and at intervals drifting gratings of various orientations were exposed to the other eye in a pseudo-randomized sequence. In every case, the orientation and direction of movement giving the largest response were used as the continuous monocular conditioning stimulus during these tests of binocular interaction.

In seven LGN cells (41% of those tested) the responses during binocular stimulation differed significantly from those through the dominant eye alone. In all these cases, the interaction was entirely inhibitory: in this sample we saw no significant augmentation of the response even when the stimuli were identical in the two eyes. Presumably, grating stimuli, like the single light bars employed by Kato, Bishop and Orban (1981), do not reveal binocular facilitation of the type found by Schmielau and Singer (1977) with stationary flashing spots.

Figure 1 shows results for a typical ON-centre Y-cell, recorded in lamina A of the LGN. Figure 1(A) is a polar plot of mean firing rate as a function of direction of drift (and therefore of orientation) for a grating presented monocularly to the receptive field in the contralateral eye. The magnitude of response did not vary consistently with orientation for this cell. The radius of the interrupted circle in the centre indicates the level of spontaneous discharge measured during blank presentations. Figure 1(B) illustrates the results of the binocular stimulation procedure (see Methods). The receptive field in the contralateral eye was continuously stimulated with a conditioning stimulus, in this case a near-vertical grating, drifting leftward. Gratings of various directions of drift were then presented intermittently in random sequence to the corresponding region of the ipsilateral eye. Solid circles plot mean responses during presentations of the particular binocular combination of gratings

indicated on the abscissa, while each open circle plots the mean discharge during the periods of monocular stimulation immediately preceding presentations of that particular binocular combination. Binocular inhibition (about 40% reduction in response for this cell) was essentially independent of the orientation and direction of drift of the gratings shown to the "silent" eye.

The behaviour of all the other LGN cells that showed binocular interaction was essentially similar, the mean response through the dominant eye being inhibited by up to 44% (mean $26.7 \pm 11.1\%$ SD) during stimulation

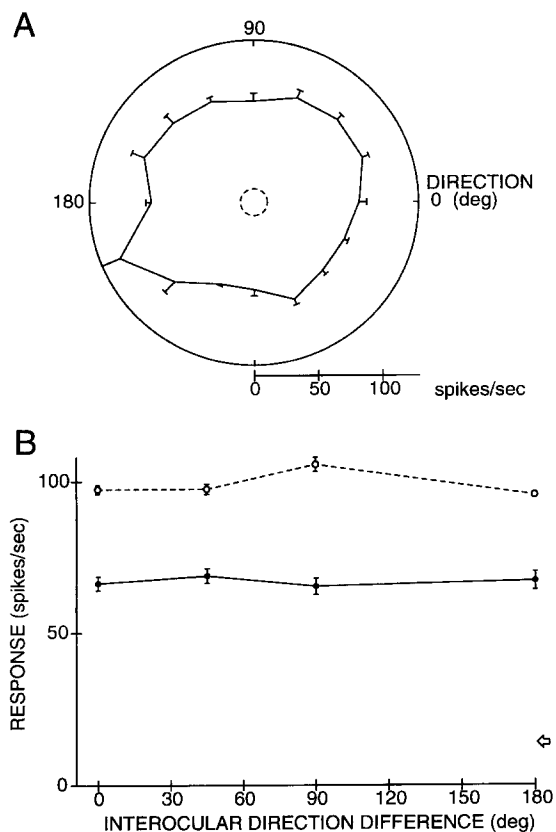


FIGURE 1. Orientation tuning and binocular interaction for an ON-centre Y-cell recorded in lamina A of the LGN. (A) Mean response in spikes/sec (± 1 SEM, $n=4$) is plotted on polar coordinates as a function of the direction of drift of a grating (contrast, 0.7; spatial frequency, 0.28 c/deg) presented to the receptive field in the contralateral eye alone; 0 deg corresponds to rightward motion of a vertical grating, 90 deg to upward drift of a horizontal grating. The radius of the dashed circle in the centre represents the mean spontaneous discharge measured during blank presentations. This LGN cell, like most in this sample, was essentially non-oriented. (B) Results of the binocular interaction protocol. The contralateral eye was continuously stimulated with a conditioning stimulus whose direction of drift was 202.5 deg, corresponding to the largest value on the polar plot in (A) (contrast, 0.7; spatial frequency, 0.28 c/deg). Against this background stimulation, a randomized sequence of gratings of various directions of drift (same spatial frequency and contrast) was presented to the corresponding region of the ipsilateral eye for binocular presentations, each lasting 5 sec with 5-sec periods of the conditioning stimulus alone in between. ● Mean firing rate (± 1 SEM, $n=4$) during binocular stimulation with gratings differing in direction of drift in the two eyes by the angle shown on the abscissa, ○ mean responses (± 1 SEM, $n=4$) during the periods of monocular stimulation preceding those presentations with the particular combination of gratings plotted on the abscissa. The arrow indicates the mean level of spontaneous discharge, measured during blank presentations.

through the silent eye with gratings of any orientation. In addition to the mean discharge (F_0 Fourier component), we also examined the modulated response of these cells (the first harmonic component, F_1) but saw no obvious difference in the inhibitory influence on these two components.

For LGN neurons, inhibition did not vary in strength with the relative interocular spatial phase of the two gratings, either for iso-oriented gratings [confirming the observation of Xue, Ramoa, Carney and Freeman (1987)] or for any other combination of orientations. However, the magnitude of interocular inhibition did depend on the spatial frequency of the gratings presented to the silent eye (cf. Moore *et al.*, 1992), its maximum being at a spatial frequency close to the one eliciting the strongest excitation in the dominant eye. Figure 2(B) shows the results of an experiment (on the same cell as for Fig. 1) in which the spatial frequency of gratings presented to the silent eye was varied. The dependence of interocular inhibition on spatial frequency was similar to the selectivity for spatial frequency of the excitatory response through the dominant eye alone [Fig. 2(A)], whether the gratings in the two eyes were iso-oriented or orthogonal.

Area 17

In five animals we obtained quantitative results from 52 cells of the primary visual cortex, 16 of which were simple and 34 complex. The remaining two cells, both recorded in layer 4, were classified as non-oriented, based on quantitative assessment of their orientational tuning curves. Both were monocularly driven, but they had spike waveforms typical of cells rather than axons, and they did not have the obvious centre-surround organization and vigorous responses typical of LGN cells. 45 cells (87%) were binocularly driven by conventional stimuli. Receptive field centres were all within 4 deg of the area centralis. Stimulation of the non-dominant eye produced statistically significant effects on the conditioning response to stimulation through the dominant eye for 46 cells (88% of the total), including all binocularly driven cells outside layer 4.

Orientation-independent suppression for monocular units in layer 4. Five (28%) of the 18 units recorded within layer 4 were monocularly driven, a higher proportion than in the sample from all other layers (2 of 34 cells, 6%). Four of these 18 layer 4 units (7.7% of the total sample), three simple and one non-oriented, all monocularly driven by conventional stimuli, showed significant suppression for gratings presented to the silent eye (see Fig. 3), independent of the interocular orientation difference, very similar to that described above for LGN neurons. In particular, the suppression exerted by even an iso-oriented grating presented to the silent eye was essentially independent of interocular phase difference, in contrast to the phase-selective (i.e. disparity selective) interaction seen in many binocularly driven cells (e.g. Barlow, Blakemore & Pettigrew, 1967; Ohzawa & Freeman 1986a,b).

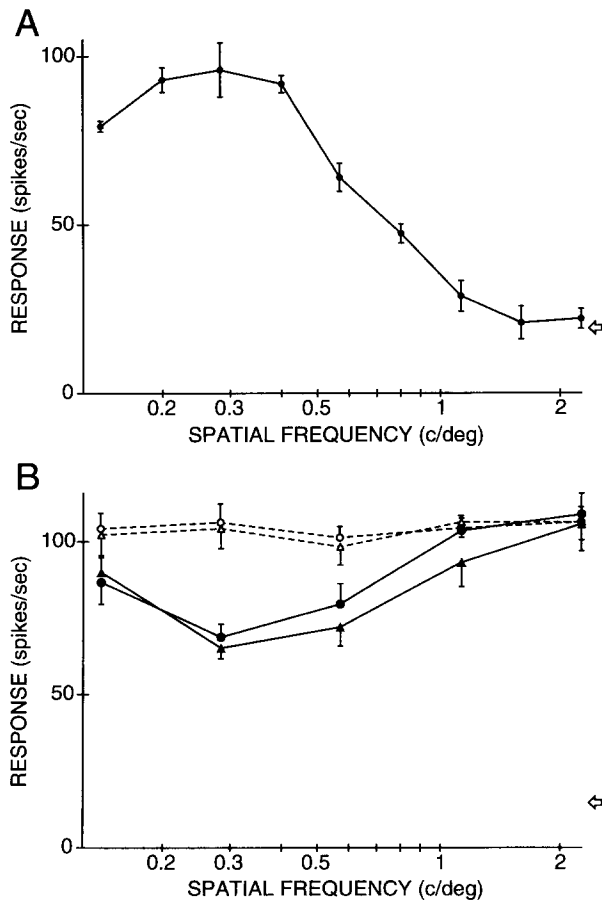


FIGURE 2. Spatial frequency tuning of monocular responses and of interocular suppression for the same LGN cell as in Fig. 1. (A) Spatial frequency tuning curve for the dominant (contralateral) eye alone. The receptive field was stimulated with a randomly interleaved series of drifting gratings (direction of drift, 202.5 deg; contrast, 0.7) which differed in spatial frequency. Mean responses (± 1 SEM, $n=4$) are plotted. The arrow indicates the mean spontaneous discharge during blank presentations. (B) Interocular inhibition as a function of the spatial frequency of gratings presented to the silent eye. The dominant eye was stimulated continuously with an optimal drifting grating (direction, 202.5 deg; spatial frequency, 0.28 c/deg; contrast, 0.35) and high-contrast (0.7) gratings of either the same orientation (●) or the orthogonal orientation (▲), of various spatial frequencies, were presented intermittently to the silent eye. The solid symbols plot mean responses (± 1 SEM, $n=4$) during binocular stimulation, while the corresponding open symbols show the mean discharge rate during the immediately preceding epochs of monocular stimulation. The arrow indicates the mean spontaneous discharge.

None of the binocularly excitable cells in layer 4 showed this type of non-orientation-selective suppression, nor was it seen in other layers, even among monocular units. The other monocular cell and three of the 13 binocular cells recorded in layer 4 lacked any significant binocular interactions. Ten binocular cells showed facilitatory interactions and five of them showed interocular suppression dependent on orientation, as described below. Table 1 summarizes the results for all cells with respect to their laminar position.

Orientation-dependent interocular suppression. For 42 out of the 45 binocular units we observed the expected facilitation of the dominant eye's response when the other eye was simultaneously stimulated with a grating of

optimal orientation. For most complex cells (and they constituted the majority of our sample), this facilitation was virtually independent of spatial offset in the non-dominant eye (i.e. the interocular phase disparity of the gratings), while all simple cells and some complex cells showed facilitation at one spatial phase and inhibition when the gratings were 180 deg out of phase in the two eyes, with cyclical variation in the strength of response as the relative phase was progressively shifted (Fig. 4; cf. Ohzawa & Freeman, 1986a,b).

All 45 binocular cells were tested for the orientation selectivity of binocular interaction. When the non-

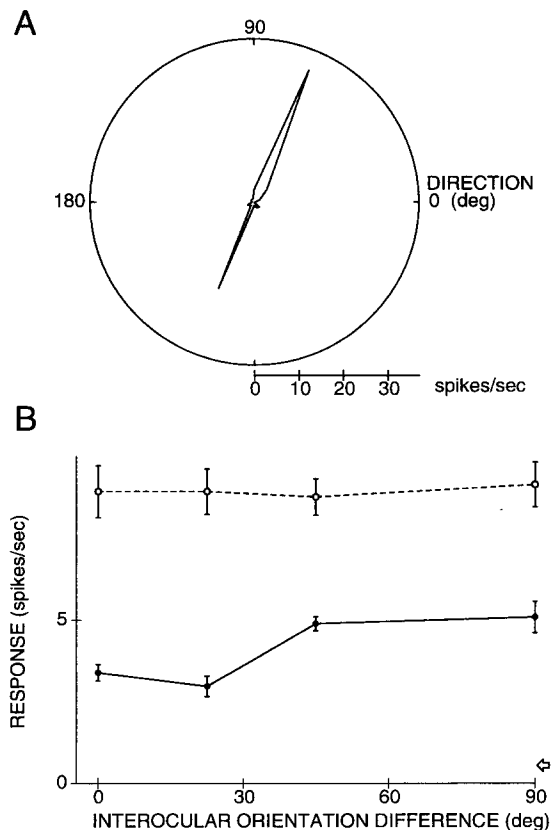


FIGURE 3. Orientation tuning of binocular interactions in a simple cell recorded in layer 4 of area 17, which was monocularly driven by conventional stimuli. (A) Polar plot of orientation selectivity for gratings (contrast, 0.7; spatial frequency, 0.8 c/deg) presented to the dominant (contralateral) eye alone. In this case the spontaneous discharge rate, which was only 1.3 spikes/sec, and the SEMs (4.3 spikes/sec at the optimal orientation) are not plotted to avoid confusion. (B) Results of the binocular stimulation procedure, plotted as in Fig. 1(B), except that the abscissa indicates the difference in *orientation* between the two eyes, rather than direction of motion. Gratings (contrast, 0.7; spatial frequency, 0.8 c/deg) were presented to the non-dominant eye at four different orientations, over a 90-deg range, clockwise from the orientation of the optimal conditioning stimulus, which was being presented continuously to the dominant eye (contrast, 0.35; spatial frequency, 0.8 c/deg). ● Mean responses (± 1 SEM, $n=6$) during binocular stimulation, ○ means during the preceding periods of monocular stimulation, as in Fig. 1(B). The low level of monocular response compared to that in (A) is largely due to the lower stimulus contrast, partly to fatigue during continuous stimulation. Note that even identically oriented gratings (zero on the abscissa) produced strong suppression: variation of spatial phase under these conditions revealed no obvious disparity-dependent facilitation in this and three of the four other monocular units recorded in layer 4.

TABLE 1. Occurrence of orientation-dependent suppression (ODS) and orientation-independent suppression (OIS) in area 17

| Cortical layer | Total number of cells | OIS: Number of cells | ODS: Number of cells | Percentage of suppression with orthogonal gratings (± 1 SD) |
|----------------|-----------------------|----------------------|----------------------|--|
| 2/3 | 28 | 0 | 17 | 41.4% ($\pm 24.4\%$) |
| 4 | 18 | 4 | 5 | 30.1% ($\pm 20.5\%$) |
| 5/6 | 6 | 0 | 3 | 34.8% ($\pm 32.2\%$) |
| All | 52 | 4 | 25 | 36.8% ($\pm 24.6\%$) |

The final column gives the average percentage suppression, below the monocular level, caused by orthogonally oriented gratings.

dominant eye was stimulated with a high-contrast (0.7) grating oriented *orthogonal* to the optimal orientation being shown to the dominant eye, 25 cells (56% of the binocularly driven units) showed statistically significant suppression (*t*-test, $P < 0.05$), reducing the mean spike rate by between 15% and 90% of the monocular response through the dominant eye (average, 52.4%; SD, 20.5%). The suppression with orthogonal stimulation did not vary convincingly with the spatial offset of the grating in the non-dominant eye in any of the cells tested. This held for not only complex but also simple cells, in which the facilitatory and inhibitory effects with matched gratings were always clearly disparity selective. Figure 4 analyses the effects of spatial offset, for both iso-oriented and orthogonal gratings, for a typical disparity selective simple cell recorded in the supragranular layers. In Fig. 4(A), solid circles plot the response of the cell during binocular stimulation with gratings of the same (optimal) orientation in the two eyes, as a function of the spatial offset of the gratings, while the open circles show the corresponding control responses with monocular stimulation in the dominant eye alone. In order to take account of any chance fluctuations in responsiveness, as indicated by variation in these monocular control values, we calculated the level of response during binocular stimulation as a percentage of the corresponding monocular response:

$$\frac{(\text{binocular response} - \text{monocular response}) \times 100}{(\text{monocular response} - \text{spontaneous discharge})}$$

Figure 4(B) plots this *response difference* as a function of spatial offset for iso-oriented gratings (solid curve) and orthogonal gratings (dashed curve). For matched gratings the variation in response is roughly sinusoidal, from occlusion to facilitation, as the relative disparity is changed (cf. Ohzawa & Freeman 1986a,b). By comparison, with orthogonally oriented gratings the clear (roughly 30%) suppression is essentially independent of spatial phase.

Both facilitation (with matched orientations) and suppression (with inappropriately oriented gratings) increased in strength with the contrast of the stimulus in the non-dominant eye. So, for comparison between cells, the orientation dependence of interocular interactions was always tested with gratings of 0.7 contrast presented to the non-dominant eye. For cells that were clearly disparity selective, we took care to optimize the spatial

offset, to generate the maximum facilitation with matched and near-matched orientations (Blakemore, Fiorentini & Maffei, 1972). Figure 5 shows the analysis for a representative complex cell recorded in layer 2/3, in a form similar to that for Fig. 1. Figure 5(A,B) are polar plots of the individual tuning curves for the orientation and direction of gratings in the dominant and non-dominant eye, respectively. Figure 5(C) shows the results of binocular stimulation with different interocular

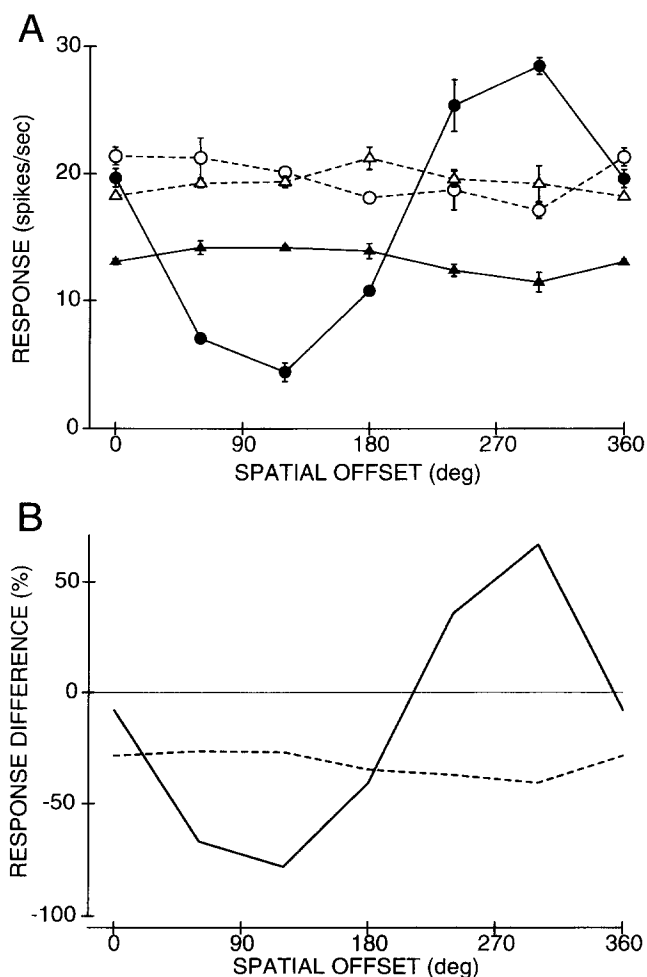


FIGURE 4. Binocular responses of a layer 2/3 simple cell as a function of the spatial offset of the grating in the non-dominant eye relative to that of the stimulus in the dominant eye. The initial spatial phase of the optimally oriented drifting grating presented to the dominant eye was fixed at an arbitrary value while that of the grating presented to the other eye was varied. The spatial offset or phase angle between the two gratings is plotted on the abscissae. (A) ● The results for iso-oriented gratings (contrast, 0.35; spatial frequency, 0.56 c/deg in both eyes), ○ the control values during preceding periods of monocular stimulation. Triangles plot comparable data for orthogonally oriented gratings. There was no spontaneous activity for this cell. (B) *Binocular interaction functions*, plotting the response during binocular stimulation, expressed as a percentage of the control, monocular response (see text), at each spatial phase. The solid curve plots this *response difference* for iso-oriented gratings, and the dashed curve shows results for orthogonal gratings. Note the characteristic cyclical variation as a function of spatial offset with matched gratings (Ohzawa & Freeman, 1986a,b), shifting from 67% binocular facilitation at the optimum disparity to 78% inhibition at the worst. On the other hand, presentation of an orthogonal grating in the non-dominant eye simply suppressed the response by about 30% regardless of its spatial phase.

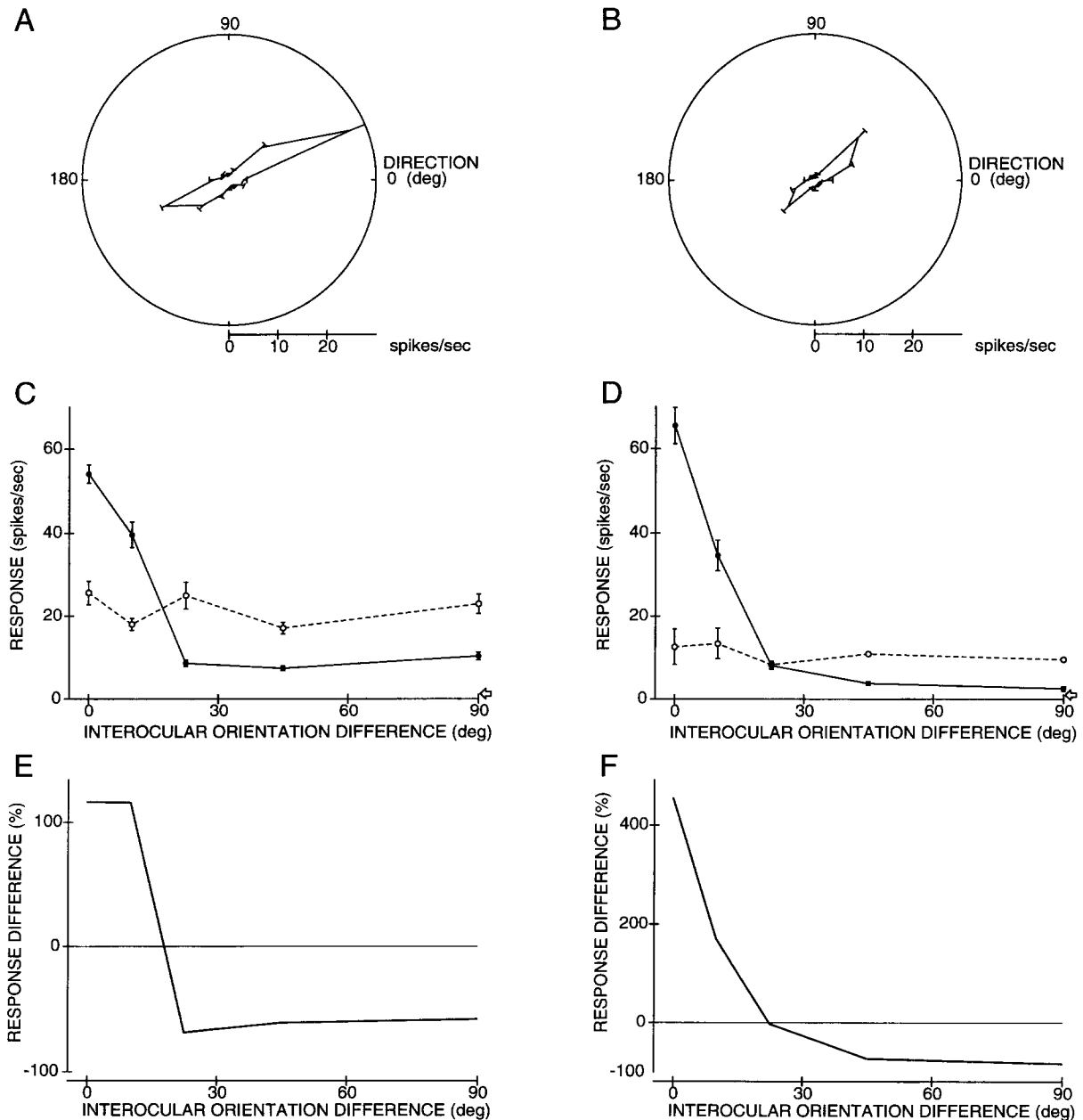


FIGURE 5. Orientation dependence of binocular interactions in a layer 2/3 complex cell of ocular dominance group 5 (slightly dominated by the ipsilateral eye). (A,B) Polar plots of orientation tuning curves obtained with monocular stimulation through the ipsilateral eye (A) and the contralateral eye (B), with gratings of 0.7 contrast and a spatial frequency of 0.56 c/deg. Mean levels of spontaneous discharge were 0.9 and 1.5 spikes/sec during data collection for (A) and (B), respectively. (C,D) Results of the binocular interaction protocol, as in Fig. 3(B). For (C), a drifting conditioning grating of optimal orientation (direction, 22.5 deg; spatial frequency, 0.56 c/deg; contrast, 0.35) was presented continuously to the dominant, ipsilateral eye and gratings of various orientations (same spatial frequency, contrast, 0.7) were shown intermittently to the contralateral eye ($n=8$ presentations per point). For (D), the conditioning grating (direction, 22.5 deg; spatial frequency, 0.56 c/deg; contrast, 0.7) was presented continuously to the contralateral eye and gratings of various orientations (same spatial frequency and contrast) were shown to the ipsilateral eye ($n=5$). In this complex cell, the facilitation for matched orientations was independent of spatial phase. (E,F) Binocular interaction functions, plotting the response difference [see Fig. 4(B)] as a function of the interocular difference in orientation. By contrast with the monocular layer 4 unit shown in Fig. 3, this cell exhibited strong facilitation for gratings of similar orientation in the two eyes and suppression for gratings differing in orientation by more than 20 deg.

orientation differences, the continuous conditioning grating being presented to the dominant eye, while for Fig. 5(D) the conditioning stimulus was shown to the non-dominant eye and the suppressive stimulus to the dominant eye. The two binocular interaction functions

[Fig. 5(E,F)] reveal a sharp change from facilitation for small orientational differences to marked suppression for larger values. Facilitation in this particular cell was independent of spatial phase, so these functions were definitely not contaminated by variations in spatial phase.

Many binocular cells had small but distinct differences in optimal orientation between the two eyes [Fig. 5(A,B) show a clear example]. These were undoubtedly partly caused by the slight in-cyclotorsion that commonly occurs on paralysis; but, since the angular difference in tuning varied from cell to cell in individual animals, some of the variation was due to genuine orientational disparity, as described by Blakemore *et al.* (1972) and Nelson, Kato and Bishop (1977). Since the abscissae of the raw interaction functions, such as those of Fig. 5(E,F), do not take into account differences in monocular orientational preference, maximum binocular facilitation did not always occur at zero orientational difference. In order to compensate for these lateral shifts in the binocular interaction functions, we have pooled the functions for 27 cortical cells (chosen to represent the range of variation) in Fig. 6, normalizing them on the abscissa by shifting them to bring maximum facilitation to zero. Examination of this family of functions suggests that there is a continuum of tuning for interocular orientational difference, although it is surely significant that the four cells for which suppression was virtually independent of orientational difference (interrupted functions) were all monocular units recorded in layer 4 (like that illustrated in Fig. 3).

Among all the cells that exhibited iso-orientational facilitation and cross-orientational suppression, the transition between the two occurred at between 5 and 70 deg from the peak (after normalization), although for most it was between about 15 and 35 deg, with a mean of 22 deg. There was a weak ($r=0.31$) but not quite significant correlation between the threshold normalized

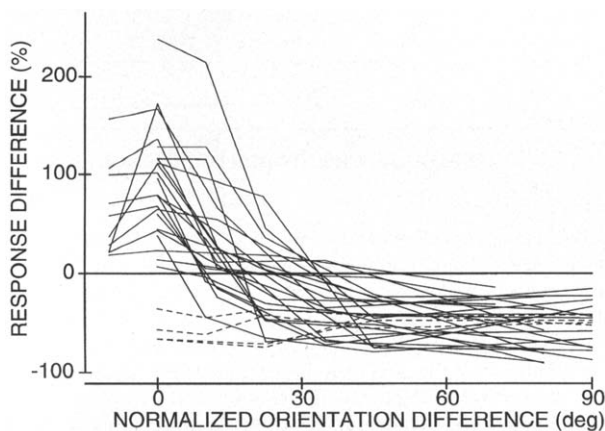


FIGURE 6. Binocular interaction functions for 27 cortical cells, as in Fig. 5(E,F), showing the range of variability in the depth of suppression and in the threshold interocular orientation difference for the transition between facilitation and suppression. For comparison of the relation between strengths of facilitation and of suppression on the one hand, and the threshold orientational difference for the transition between the two on the other hand, all tuning curves with maximum facilitation at an orientational difference other than zero have been normalized by shifting them leftwards to peak at zero. Included are the four monocular units recorded in layer 4 (data plotted as interrupted lines) that were judged to have suppression essentially independent of interocular difference in orientation (see Fig. 3). Results from binocularly driven neurons, which showed clear variation of suppression with orientational disparity, are plotted as solid lines.

orientation difference to elicit suppression and the half-width of monocular orientation tuning. Moreover, there was also a clear correlation between the depth of suppression with orthogonal gratings and the half-width of monocular orientation tuning ($r=0.64$; $P<0.002$). In other words, cells with narrower orientation tuning tended to be suppressed at smaller orientational differences and to have stronger suppression than did cells with broader orientational tuning.

Spatial frequency tuning of suppression. For 12 cells, we determined the spatial-frequency tuning of suppression by presenting a conditioning grating of optimal orientation and spatial frequency to the dominant eye and intermittently introducing orthogonal gratings of various spatial frequencies to the other eye, always drifting at the same temporal frequency. Although maximal or near-maximal suppression was generally observed when the two stimuli were matched in spatial frequency, the spatial-frequency tuning of suppression was nearly always wider than that for the monocular responses elicited through either eye alone. In some cases, clear suppression was exerted by gratings of spatial frequencies too high to elicit any excitatory monocular responses from the cell in question (Fig. 7).

Influence of the order of stimulus presentation. Sengpiel and Blakemore (1994) have reported that interocular suppression is strong only if the neuron is already responding through one eye when a rivalrous stimulus is introduced in the other eye. This non-linearity explains why such striking suppression was not seen in previous studies in which the onset of stimulation was synchronized in the two eyes (Ohzawa & Freeman, 1986a,b; DeAngelis, Robson, Ohzawa & Freeman, 1992). We examined in more detail the dependence of suppression on the temporal pattern of stimulation and the nature of the reduction in responsiveness by examining peri-stimulus time histograms (PSTHs) during stimulation with various protocols of monocular and binocular stimulation.

The procedure used and the results obtained are illustrated in Fig. 8 for a supragranular simple cell. For the PSTHs in Fig. 8(A,B,C) spikes were accumulated over 10-sec stimulus presentations, the second half of which always consisted of simultaneous stimulation of the dominant eye with a grating of optimal orientation and of the other eye with an orthogonal grating of identical contrast and spatial frequency. The only difference between these *experimental* runs was the nature of stimulation during the 5-sec period immediately *preceding* each binocular presentation, which was:

- a *blank screen* of the same mean luminance presented to both eyes; or
- the *orthogonal grating* presented alone to the other eye; or
- the *optimal conditioning grating* shown alone to the dominant eye (as in the standard procedure described above).

For *control* data, we also examined the response as a function of contrast during 5-sec presentations of the

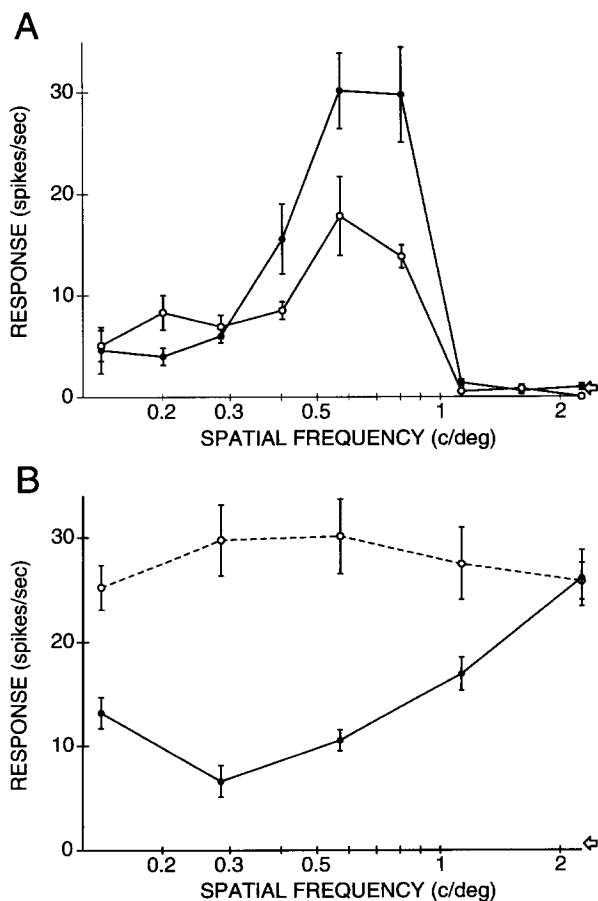


FIGURE 7. Spatial frequency dependence of rivalrous suppression in a layer 2/3 complex cell (same cell as for Fig. 5), analysed as in Fig. 2. (A) Spatial frequency tuning of monocular responses obtained through the dominant eye ($\bullet \pm 1$ SEM, $n=4$) and the non-dominant eye (\circ). The arrow indicates the spontaneous discharge. (B) The dominant eye was stimulated with an optimally oriented grating of optimal spatial frequency (0.56 c/deg), while the non-dominant eye was intermittently stimulated with orthogonally oriented gratings whose spatial frequency varied in random sequence. Responses during binocular stimulation are plotted as \bullet (mean ± 1 SEM, $n=8$) and the comparable monocular responses as \circ . Note that a grating of 1.13 c/deg (to which the cell did not respond when presented at the optimum orientation to either eye) produced profound suppression when presented at the orthogonal orientation in the non-dominant eye.

optimal grating to the dominant eye alone with the other eye viewing only a blank screen, preceded by *either*:

- (1) a blank screen to both eyes; or
- (2) an initial 5-sec period of stimulation of the dominant eye [to control for possible effects of "fatigue" caused by the prior monocular stimulation in condition (c) above].

The magnitude of the response during the second 5-sec epoch of each of the five conditions is compared in Fig. 8(D). There were no significant differences except for condition (c), where the sudden introduction of the orthogonal grating in the non-dominant eye while the cell was already responding through the dominant eye resulted in pronounced suppression. When orthogonal gratings were exposed to the two eyes with synchronized onset [condition (a)] no obvious suppression was seen,

confirming the observations of Ohzawa and Freeman (1986a,b) and DeAngelis *et al.* (1992).

For four representative cells (one simple, three complex), distinctive in no respect other than that they showed clear suppression in the standard binocular interaction experiments, we used the procedure described by Sengpiel and Blakemore (1994) to examine the effect of interocular suppression on stimuli of different contrast in the dominant eye and hence to determine the nature of the change in gain (response vs contrast) underlying the reduction in response during suppression. For each cell, the various sequences of stimulation described above for Fig. 8 were performed with the contrast of the suppressive grating in the non-dominant eye fixed at 0.7, while that in the dominant eye varied from presentation to presentation. This provided data for the construction of contrast gain functions under each of the five experimental and control conditions. For all four neurons, these functions were very similar for all control and experimental conditions except for condition (c), which results in suppression.

A reduction in the response to a grating of a particular contrast in the dominant eye could be due to either a simple rightward shift of the response vs contrast function (i.e. an elevation of contrast threshold), or a reduction of the slope or gain of the function (or a combination of both effects). Sengpiel and Blakemore (1994) showed, in one example, that the suppression elicited under condition (c) was characterized by a reduction in slope of the function rather than an obvious horizontal shift. Figure 9 illustrates the nature of the change in gain for four cells studied in detail. Average firing rate over the second 5-sec period in each trial is plotted against the contrast of the grating in the dominant eye. Solid circles show responses in the suppressed state [condition (c)] while open circles plot results for the corresponding control condition (2). Figure 9(A) shows results for the same cell as for Fig. 8, while Fig. 9(B,C,D) summarizes the results for the other three cells. For all four cells the absolute reduction in response was greater the higher the contrast of the stimulus in the dominant eye (with contrast in the "suppressing eye" fixed). In other words, suppression results from a reduction in contrast gain. Although we did not explicitly determine the contrast thresholds of cells in the suppressed and unsuppressed states, extrapolation of the gain curves back to the level of background activity in each part of Fig. 9 suggests that there is little difference in threshold.

Time-course and stability of suppression. In order to judge the latency and consistency of suppression produced by rivalrous stimuli we examined PSTHs from both the standard binocular stimulation procedure described above and from experiments in which orthogonally oriented gratings were presented to the two eyes for as long as 30 sec, after an initial 5-sec period of monocular stimulation through the dominant eye. For most cells suppression of the response to the optimal conditioning stimulus appeared to commence quite sharply, some 60–250 msec (mean of 13 cells, 120 msec; SD, 54 msec) after the presentation of an orthogonally

oriented grating in the other eye [e.g. Fig. 10(B)]. In some accumulated PSTHs suppression appeared to turn on more gradually [Fig. 10(A)], but examination of single trials [e.g. Fig. 10(A)] suggests that, in these cases, onset was sharper on individual presentations but varied in latency from trial to trial. Suppression was generally strongest over the initial 1–3 sec, with slight recovery to a tonic level, which was then sustained over the remainder of the period of binocular stimulation [Fig. 10(A,B)].

We were interested to see whether the pattern of response during prolonged binocular stimulation would reveal spontaneous shifts between two stable states, suppressed and unsuppressed, which might be expected in

view of the fact that perceptual dominance switches from one eye to the other every few seconds during binocular rivalry. PSTHs accumulated over several presentations with prolonged binocular stimulation never showed clear switches in firing rate. Figure 10 shows representative results for a layer 2/3 complex cell. Of course, averaging might conceal such shifts if they are not synchronized from trial to trial. However, for most cells, spike trains from individual trials also revealed no obvious variation of suppression over time after the initial few seconds of each presentation [Fig. 10(B)], nor did the overall depth of suppression vary substantially from trial to trial.

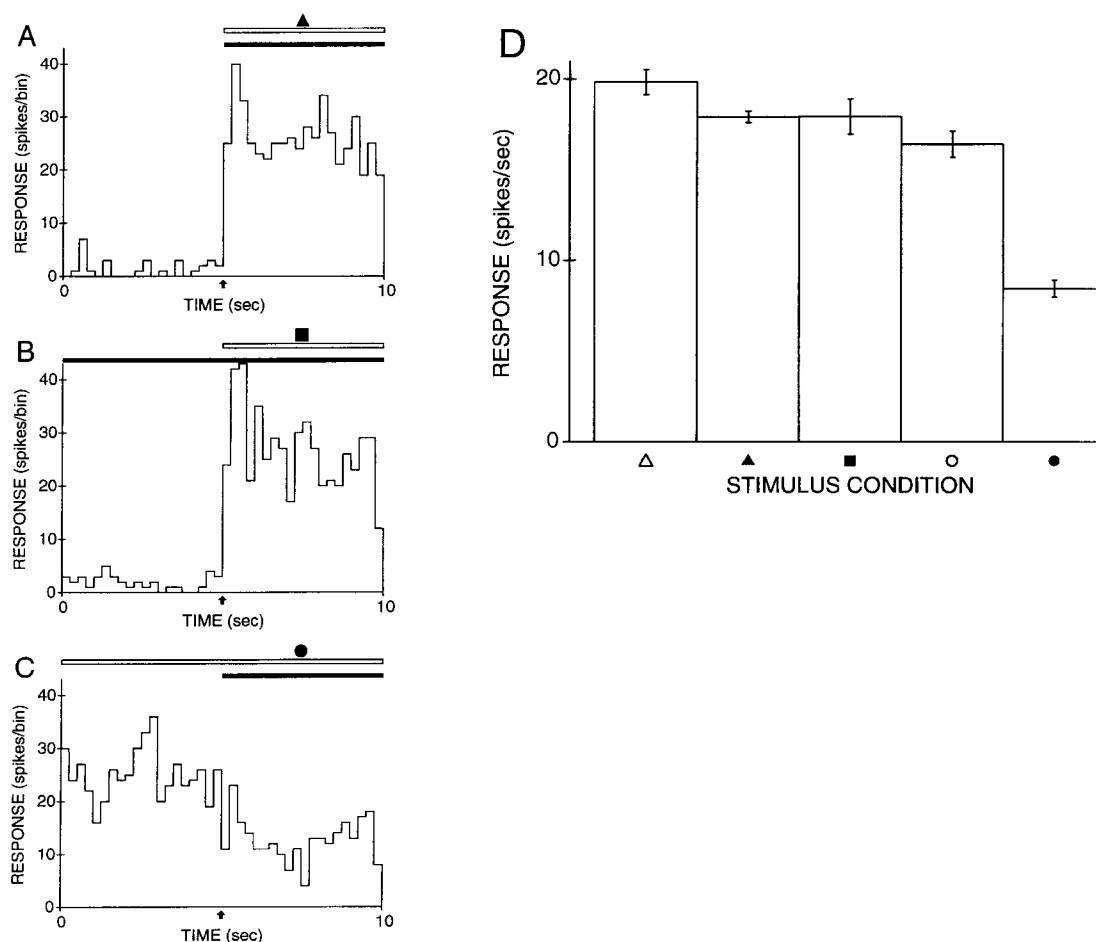


FIGURE 8. Dependence of *binocular suppression* on the temporal sequence of stimulation for a representative layer 2/3 simple cell. Three experimental conditions were employed in which the cell was stimulated for 10-sec periods. In each case, during the second half of the 10-sec epoch a drifting grating of optimal orientation was shown to the dominant eye together with an orthogonal grating presented to the non-dominant eye. The only difference between these three conditions was the nature of stimulation during the 5-sec period immediately preceding this binocular exposure: (a) blank screen presented to both eyes, with simultaneous onset at the start of the period of binocular stimulation (\blacktriangle); (b) orthogonal grating presented alone to the non-dominant eye with the dominant eye viewing a blank screen (\blacksquare); (c) optimal grating presented alone to the dominant eye (\bullet). (A,B,C) PSTHs (each the average of six 10-sec presentations) of responses in the three experimental conditions (a), (b) and (c) above. For these results the contrast of the gratings in both eyes was set at 0.7. The open and solid bars above each PSTH indicate the periods of stimulation of the dominant and the non-dominant eye, respectively. Only when the stimulus appeared in the non-dominant eye while the cell was already responding through the dominant eye (C), was there obvious suppression during the period of binocular stimulation, the start of which is marked by small arrows. (D) Histogram comparing responses (mean \pm 1 SEM, $n = 6$) under the three experimental conditions (a,b,c) described above and two further controls: (1) the dominant eye alone was stimulated during the second 5 sec, preceded by 5 sec of presentation of a blank screen of the same mean luminance (Δ); (2) the dominant eye was stimulated for the entire 10-sec period and the response was measured during the latter 5 sec of each presentation (\circ), in order to control for adaptation or "fatigue" under experimental condition (c) above. In both cases, the non-dominant eye viewed a blank screen.

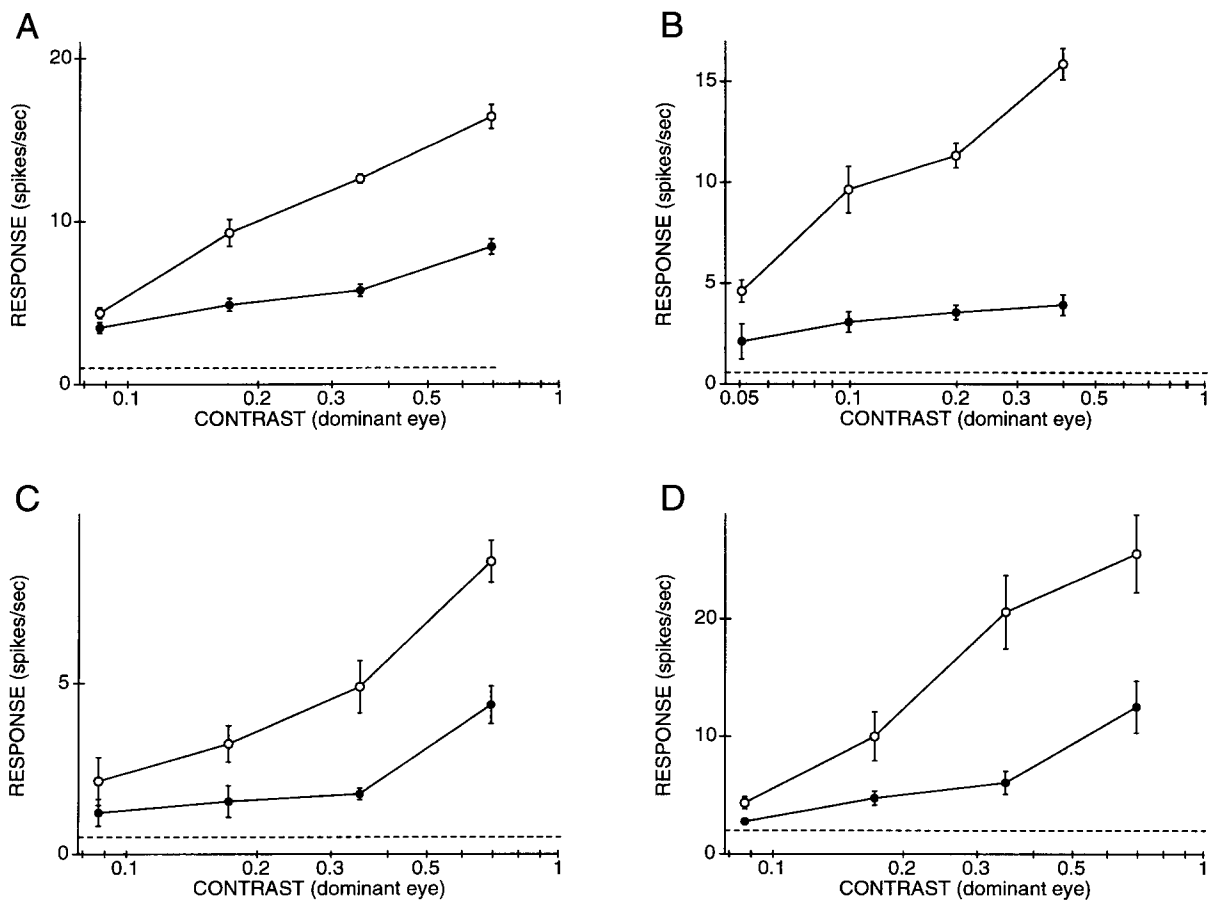


FIGURE 9. Response vs contrast functions for experimental condition (c), in which binocular stimulation with orthogonal gratings was preceded by monocular presentation of an optimal grating to the dominant eye (●), and the corresponding control condition (2) (○; see caption to Fig. 8). The contrast of the grating shown to the dominant eye was varied under each condition to provide the data for these functions. Mean responses in spikes/sec (± 1 SEM, $n = 6$ presentations per data point in all parts) are plotted against the contrast of the optimally oriented drifting grating shown to the dominant eye. The interrupted lines indicate the mean level of spontaneous discharge measured during blank presentations with no pattern presented to either eye. (A) Responses from the simple cell of Fig. 8, and (B), (C) and (D) show results from three complex cells recorded from layers 2/3 (B,C) and 5 (D).

For most cells, fluctuations of response during suppression (after the onset transient) appeared to be within the normal range of response variability seen when stimulating one eye alone. In no case did trial-by-trial Fourier analysis reveal significant cycling within this prolonged phase of suppression. However, in some cells the overall magnitude and/or pattern of suppression did differ substantially from trial to trial. Figure 11 shows a particularly striking case of a simple cell recorded in the supragranular layers that exhibited distinct inter-trial differences in its response to cross-oriented gratings. On some trials, profound suppression was observed immediately after the onset of binocular stimulation, but the cell's response recovered considerably after several seconds [Fig. 11(C)]. On others, the response seemed unaffected for several seconds after the onset of the rivalrous stimulus but then was clearly suppressed for a further period of several seconds [Fig. 11(A,D)]. On one presentation, the neuron ceased responding completely from shortly after the onset of the rivalrous stimulus and this total suppression was sustained for the full half-minute period [Fig. 11(B)].

DISCUSSION

The site of rivalry

Although binocular rivalry has been well known for more than a century and its characteristics have been thoroughly defined by psychophysical investigation, the neural mechanism responsible for this phenomenon has remained elusive. Even the site of its occurrence in the visual pathway is still a matter of conjecture, though the wide variety of stimulus parameters that evoke rivalry if dissimilar in the two eyes (e.g. contour, colour, or motion) suggests that the process takes place in the periphery of the visual pathway, prior to the postulated parallel streaming of visual information (e.g. Van Essen & Maunsell, 1983; Livingstone & Hubel, 1988). This notion receives further support from the fact that rivalry occurs independently in patches of the visual field whose angular dimensions seem to relate to the magnification factor in the precise topographic representations of the field that are seen only early in the pathway (see Blake, O'Shea & Mueller, 1992).

At first thought, the fact that rivalry manifests itself as blanking of perception in one eye at a time suggests that the underlying physiological mechanism resides at a point prior to the combination of signals from the two eyes. Indeed, current theoretical models of rivalry postulate reciprocal inhibition between or on to groups of *monocular* cells (Matsuoka, 1984; Lehky, 1988; Blake, 1989). Furthermore, since contour rivalry is orientation dependent, these cells should themselves be orientation selective or should derive inhibition from orientation selective neurons. Cells of the LGN seem good candidates because they generally receive excitatory input (or at least suprathreshold excitation) from only one eye, and they have extensive back-projections from orientation selective binocular cells in layer 6 of primary visual cortex (Gilbert & Kelly, 1975), which can exert inhibition as well as facilitation (Schmielau & Singer, 1977; Tsumoto, Legendy & Creutzfeldt, 1978). Indeed, Varela and Singer (1987) reported that a majority of LGN cells in the anaesthetized cat showed long-latency suppression of

activity when stimulated binocularly, specifically with gratings differing substantially in orientation in the two eyes.

As part of the present study, we also investigated binocular interaction in the LGN but did not see a single case of orientation selective suppression during dichoptic stimulation. Our sample of LGN cells was not large, but these results do agree with recent findings by Moore *et al.* (1992). Although almost half the cells we studied showed clear interocular inhibition when a grating was presented to the silent eye, it was independent of the orientation of the stimulus. Our procedure more closely resembled that of Varela and Singer (1987) than did that used by Moore *et al.* (1992). In particular, we employed dichoptic gratings that were always matched in drift frequency, and the stimulus was presented to the dominant eye before the onset of the stimulus to the silent eye, rather than both starting simultaneously, as in the protocol of Moore *et al.* (1992). The remaining minor differences in Varela and Singer's experiment (square-wave rather than sinusoidal gratings and slightly higher contrast) seem unlikely to be critical. In searching for reasons for the discrepancy in results we wonder whether the lack of randomized interleaving in Varela and Singer (1987) study might have led chance fluctuations in excitability to produce the apparent effects of relative orientation that they saw in some cells.

Four out of five monocularly driven units recorded in layer 4 of area 17 displayed a pattern of binocular inhibition strikingly similar to that seen in the LGN, being independent of interocular differences in orientation or spatial phase. Just as for these monocular cells of layer 4, Ohzawa and Freeman (1986a, b) reported that 7.8% of simple cells as well as 8.2% of complex cells showed non-phase-specific suppression by iso-oriented gratings: all but one of those cells were monocular but their laminar position was not described.

Our data imply that monocular cells in the LGN and layer 4 of area 17 are unlikely to provide the physiological substrate for the suppression underlying binocular rivalry. The results are incompatible with models predicting the site of rivalry to be prior to binocular convergence (Blake, 1989; Lehky & Blake, 1991). Rather, they indicate that orientation selective binocular neurons in the primary visual cortex represent the earliest stage (at least in cats) at which such interaction occurs.

One line of psychophysical evidence that has been extensively explored involves the measurement of perceptual aftereffects induced by prior adaptation to a stimulus that is only intermittently perceived because it is presented to one eye, with a rivalrous stimulus shown to the other eye (see Lehky & Blake, 1991). If the site of rivalry were prior to that of the neural process underlying adaptation, aftereffects induced under such conditions of partial visibility should be weaker than following uninterrupted viewing of the adapting stimulus. Some years ago, a variety of aftereffects, e.g. the threshold elevation aftereffect (Blake & Fox, 1974; Blake & Overton, 1979) and the motion aftereffect (Lehmkuhle & Fox, 1975; O'Shea & Crassini, 1981), were reported to be

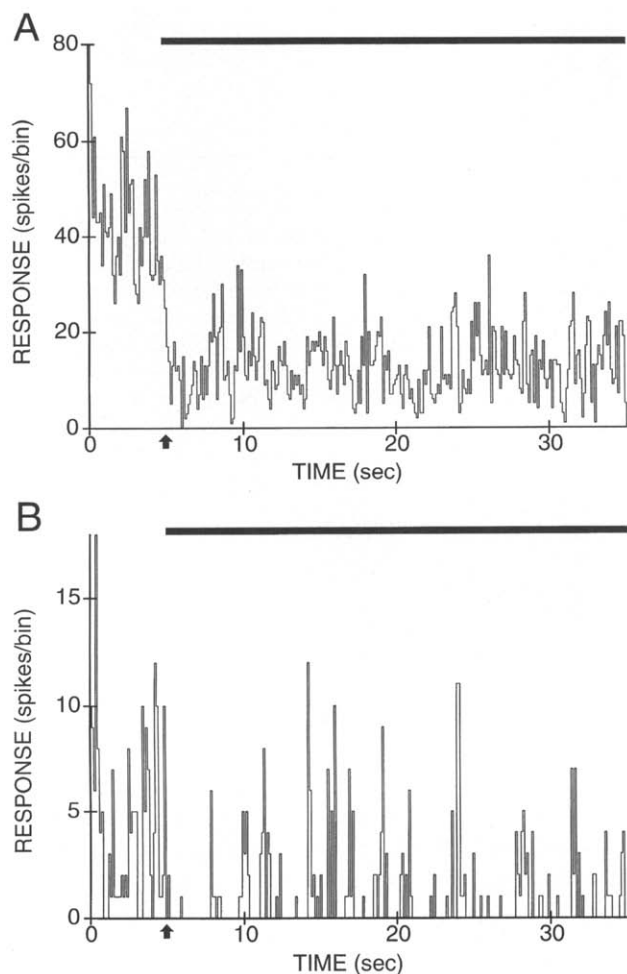


FIGURE 10. PSTHs of the response of a layer 2/3 complex cell during rivalrous stimulus. (A) PSTH accumulated over 10 trials. The cell was initially stimulated through the dominant eye alone with a grating of optimal orientation and spatial frequency (contrast, 0.35). After 5 sec (marked with an arrow), an orthogonally oriented grating of optimal spatial frequency (contrast, 0.7) appeared in the non-dominant eye. Binocular exposure continued for the entire 30-sec period marked by the horizontal bar. Bin width, 116 msec. (B) PSTH for a typical single trial.

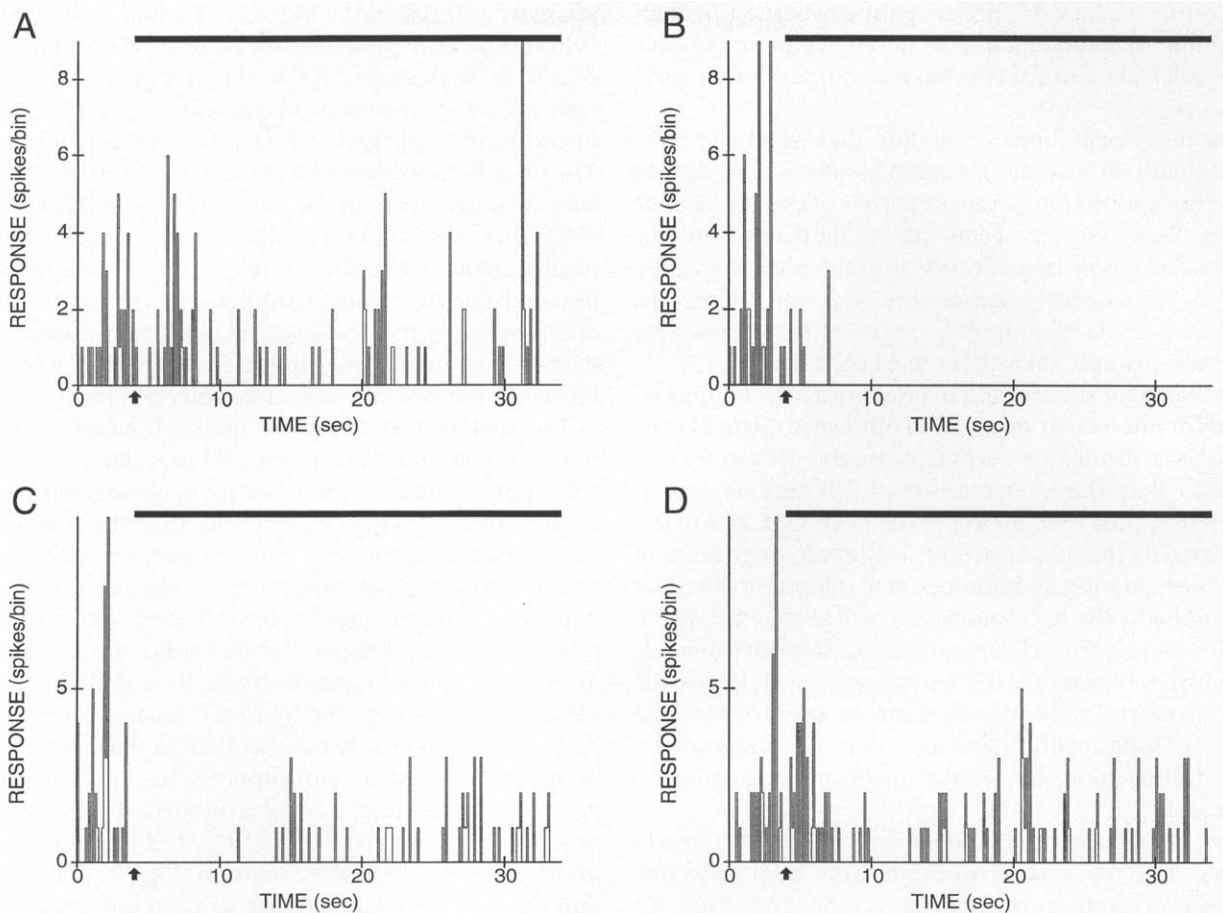


FIGURE 11. PSTHs of the response of a layer 2/3 simple cell to a rivalrous stimulus, as in Fig. 10. All histograms represent single-trial responses. For 4 sec, the cell was stimulated through the dominant eye alone with a grating of optimum orientation and spatial frequency (contrast, 0.35). Arrows mark the onset of stimulation of the non-dominant eye with an orthogonal grating of optimum spatial frequency (contrast, 0.4). Bin width, 116 msec. Note the enormous variation in the pattern of response during the periods of rivalrous stimulation.

of equal strength after normal adaptation and after adapting monocularly with a rivalrous stimulus present in the other eye. This was taken to imply that the adaptation process occurs before the site of rivalry suppression. However, recently Lehy and Blake (1991) did find a reduction of the threshold elevation aftereffect when the adapting grating was visible only 10% of the time during rivalry, suggesting that neurons undergoing adaptation are located at or after the site of rivalry suppression. Taking into account the orientation selectivity of such aftereffects (Blakemore & Campbell, 1969; Blakemore & Nachmias, 1971) and the fact that they partially transfer from one eye to the other (Gilinsky & Doherty, 1969; Mitchell, Reardon & Muir, 1975), it seems likely that the earliest site for the relevant adaptation is the primary visual cortex and that at least some of the neurons involved are binocularly driven. Thus the psychophysical findings of Lehy and Blake (1991) are compatible with our neurophysiological results.

Logothetis and Schall (1989a,b) recorded from area MT in the STS of awake monkeys trained to perform a motion discrimination task. They found that only about two-fifths of direction selective cells displayed variation of responsiveness with the perceptual choice of the monkey, and in about half of these responsiveness was inversely

correlated with perceived direction of motion. By comparison, we found that more than half the binocular cells studied in cat area 17 were significantly and selectively suppressed by rivalrous stimuli; this type of suppression, if it also occurs in primates, could be the origin of the properties of those cells in MT whose behaviour does parallel the animal's behavioural indication of rivalry.

Stimulation procedures that reveal suppression in the cat cortex could be employed in experiments on various stages of the visual pathway in awake primates, trained to indicate their perceptual experience, in order to define the site or sites of rivalrous interaction. Very recent evidence indicates that, as in cats, orientation-dependent suppression does not occur in the monkey's LGN (Lehy & Maunsell, 1993).

The nature of interocular suppression

The origin of the non-oriented inhibition seen in about half the LGN cells we studied (Fig. 1) remains uncertain. It could conceivably be due to direct inhibitory interaction between right-eye and left-eye laminae of the LGN, via inhibitory interneurons (Guillery, 1966); but it could also involve the feedback projection from layer 6 of

the cortex, the lack of selectivity for orientation perhaps being due to a combination of inhibitory inputs to each LGN cell from cortical neurons in a range of orientation columns.

The non-orientational inhibition that we saw in most monocularly driven cells recorded in layer 4 (Fig. 3) may be a simple reflection of the properties of their geniculate inputs. However, it seems likely that most of the interocular suppressive effects seen at the cortical level are due to intracortical mechanisms. For one thing, the maximum levels of suppression seen at the cortex were generally stronger than those in LGN cells.

The fact that suppression in most cortical cells appears tuned for interocular orientation difference might also be taken as a distinctive cortical property. However, it is possible that the characteristic orientation-dependent interaction functions for suppression (Figs 5 and 6) are generated by the sum of strong facilitation for gratings of similar orientation and non-oriented inhibition [like that seen in the LGN, for monocular cortical cells in layer 4, and for the majority of cortical cells in strabismic animals (Sengpiel & Blakemore, 1994)]. Indeed, our data provide some support for the idea that suppression is generated at all orientational differences, but is swamped by conventional binocular facilitation when the orientations are matched.

First, binocular interaction functions (Fig. 6) nearly always showed a smooth transition from facilitation, for gratings of similar orientation in the two eyes, to suppression, for larger angular differences. Hence, the narrower the tuning of binocular facilitation for orientational disparity, the smaller the angular difference at which suppression appeared. If suppression were restricted to a narrow range of angular differences centred on the orthogonal, one would expect to find no binocular interaction at all over an intermediate range of orientational differences.

Second, the family of binocular interaction functions in Fig. 6 suggests that there is a continuum of tuning, between equal suppression at all orientational differences to broad facilitation with a narrow range of suppression around the orthogonal. In these terms, the monocular units of layer 4 might differ from the rest of the population only in lacking facilitatory interaction for matched stimuli.

If the dependence of response on the orientation difference of binocular stimuli were indeed the result of facilitatory interactions, of various strengths, being superimposed on a background of uniform, non-orientational suppression, the apparent tuning of dichoptic suppression would simply depend on the range of orientation differences over which inhibition exceeds facilitation.

An obvious candidate for the origin of suppressive effects in the cortex is intrinsic inhibitory connections between adjacent ocular dominance columns, linking regions with both similar and dissimilar orientation preference (Kisvárdy & Eysel, 1993). Since the majority of excitatory synapses on neurons in area 17 derive from closely neighbouring cells rather than from thalamic

afferents (Kisvárdy, Martin, Freund, Maglóczy, Whitteridge & Somogyi, 1986; Douglas & Martin, 1991; Nicoll & Blakemore, 1993) the responses of cortical neurons are likely to depend crucially on "amplification" operating through this local excitatory circuitry (Douglas, Martin & Whitteridge, 1989; Douglas & Martin, 1991), at least in some layers of the cortex (Nicoll & Blakemore, 1993). Perhaps inhibitory interactions between adjacent ocular dominance columns, responsible for suppressive interocular interactions, modulate the gain of this local excitatory circuitry. The resultant interocular suppression might be overcome by binocular facilitation when the images in the two eyes are sufficiently similar.

The similarity of the peak spatial frequency for the monocular excitatory responses of binocular neurons and the suppressive effects produced by an orthogonal grating in the other eye (Fig. 7), suggests that the interaction responsible occurs mainly between neurons with similar preference for spatial frequency. Compatible with this finding is a recent psychophysical study showing that rivalry occurs most readily for dichoptic stimuli matched in spatial-frequency content (Yang, Rose & Blake, 1992). On the other hand, the spatial-frequency tuning for suppression was clearly broader than that for facilitation in most cells tested and suppression could often be generated by gratings too high in spatial frequency to produce any response from the cell in question when presented at the optimal orientation (Fig. 7). This implies that the suppressive signal derives from a population of cortical neurons whose spatial frequency preferences cover a broader range than that of the tuning curve of the receiving cell. Similarly, the lack of sensitivity to spatial phase for suppressive effects presumably means that the suppressive signal is drawn from a group of cells whose receptive fields are spatially scattered.

The fact that perceptual rivalry takes place independently in patches of the visual field, scaled in size in relation to the magnification factor of the representation in the striate cortex (Blake *et al.*, 1992), implies that the suppressive influences operate over small domains within ocular dominance columns, roughly constant in anatomical size across the visual cortex.

The population of cells showing powerful interocular suppression was not distinctive in any obvious respect. Indeed the continuous variation in the strength of suppression across the population (see Fig. 6) suggests that suppression is a general phenomenon in the cortex, simply graded in potency and not restricted to a particular class of neuron.

Interocular suppression as the basis of perceptual switching in rivalry

Perhaps the best evidence that suppression in the striate cortex does play a part in contour rivalry is its dependence on the sequence of stimulation (Sengpiel & Blakemore, 1994). Only when a conflicting stimulus is introduced into one eye while the cell is already responding through the other eye does obvious suppression occur (see Fig. 8). To some extent, this gross non-linearity has a parallel in

perceptual rivalry. If perception is already dominated by a grating in one eye and a contrasting stimulus suddenly appears in the other eye, the latter will usually capture and dominate perception for some time. On the other hand, if two different gratings are simultaneously exposed to the two eyes, they are initially both perceived [false fusion (see Wolfe, 1983)].

The reductions in responsiveness that occur after adaptation to a high-contrast stimulus and during exposure to superimposed iso-oriented gratings (of different drift frequency) in one eye are characterized by an elevation of the threshold contrast of cortical cells and a rightward shift of the response vs contrast function without a change in its slope (Bonds, 1991; Ohzawa, Sclar & Freeman, 1985; Morrone, Burr & Speed, 1987). By comparison, interocular suppression, like "cross-orientation inhibition" seen with superimposed orthogonal gratings (Morrone *et al.*, 1987), is manifested as a reduction in the gain of response as a function of contrast in the suppressed eye without an obvious increase of threshold contrast (Fig. 9).

Imagine the overall pattern of activity in the striate cortex under conditions that provoke suppression (and perceptual rivalry in humans). Initial stimulation with, say, a vertical grating in the left eye will activate cells in columns tuned to vertical, especially strongly within ocular dominance columns devoted to the left eye. Now, the sudden appearance of a horizontal grating in the right eye will suppress activity extensively throughout the left-eye ocular dominance columns, while evoking a sudden surge of activity in columns tuned to horizontal in the right-eye ocular dominance columns. Interpretative mechanisms might assign perception according to local maxima of activity across the entire population of neurons in the striate cortex, a procedure that may be of general utility in resolving perceptual interpretations.

Perceptual suppression of one eye is not just an entertaining phenomenon seen only under laboratory conditions. Situations that lead to rivalry occur all the time during the normal viewing of three-dimensional scenes containing a large range of binocular disparities (Blake & Camisa, 1978). The images of objects much closer and further than the fixation point obviously fall on entirely non-corresponding retinal areas, outside the range of receptive field disparities of cortical neurons. For these parts of the scene, each cortical region will receive conflicting inputs from the two eyes. Local suppression, equivalent to rivalry, eliminates confusion by allowing only one eye at a time to see within each area that cannot be fused. Thus the suppressive mechanism revealed in binocular rivalry may be valuable in vetoing input from one eye under normal conditions of interocular conflict.

The origin of spontaneous perceptual alternation

One of the most distinctive characteristics of rivalry (and of other forms of unstable perception, such as that of ambiguous figures) is the alternation between the two sensory experiences, typically occurring every few seconds during continuous viewing (Levelt, 1965; Mueller

& Blake, 1989). Theories of rivalry have postulated the existence of oscillating circuitry, driving groups of monocularly dominated neurons alternately into one of two relatively stable states, with a duty cycle of switching dependent on the "strengths" of the stimuli in the two eyes (Levelt, 1965; Lehky, 1988). The arrangement of intracortical circuitry that we suggest is responsible for suppression might indeed generate oscillatory behaviour, perhaps because of gradual fatigue in the inhibitory output from the ocular dominance column that happens to be dominant, leading to sudden "capture" of dominance by inhibition from the other column (see Lehky, 1988). It might then be expected that individual neurons would show such temporal patterns of activity, switching from responsive to suppressed states every few seconds during the presentation of rivalrous stimuli.

No such switching behaviour was seen in the standard binocular interaction procedure, but this is not surprising in view of the fact that individual binocular exposures were short (only 5 sec). However, in the few experiments in which we examined activity during prolonged (30-sec) exposure to orthogonal gratings, only one unit, illustrated in Fig. 11, clearly showed the kind of unstable behaviour that might be expected. On some trials, this cell's response to an optimal stimulus in the dominant eye was completely and tonically suppressed by the appearance of a rivalrous stimulus in the other eye: on other trials there did appear to be switching between suppressed and virtually unsuppressed states over the 30-sec period. It is conceivable that the apparent instability displayed by this cell was simply due to inherent variability of response during long period of continuous stimulation. Further work is needed to determine whether instability is indeed a feature of suppressive interactions and particularly to see whether fluctuations in suppression are correlated between groups of neurons, which might be expected if perceptual alternation is determined by the behaviour of populations of cells. Perhaps the perceptual alternation in rivalry depends on the properties of a sub-population of cells, or maybe its temporal characteristics are simply different in the cat. Of course, there is also the distinct possibility that the characteristics of the circuitry involved were affected by the anaesthetized state of the animals in this study. The lack of eye movement might also have reduced spontaneous alternation of suppression: certain perceptual switches in rivalry are often triggered by changes in fixation (see von Helmholtz, 1910).

It is also conceivable that, although interocular suppression resulting from initial conflict between the eyes appears to originate in the striate cortex, subsequent *spontaneous* switches in eye dominance, may only occur in some "higher" visual area. They may be triggered by the reduced level of response during rivalrous stimulation (due to suppression of activity in the striate cortex) and, hence, increased response variability. Although the circuitry of area 17 seems to provide a mechanism by which an image in one eye can veto perception of a conflicting stimulus in the other eye, further work is needed to explain the spontaneous perceptual alternations that occur in rivalry.

REFERENCES

- Barlow, H. B., Blakemore, C. & Pettigrew, J. D. (1967). The neural mechanism of binocular depth discrimination. *Journal of Physiology, London*, 193, 327–342.
- Blake, R. (1989). A neural theory of binocular rivalry. *Psychological Review*, 96, 145–167.
- Blake, R. & Camisa, J. (1978). Is binocular vision always monocular? *Science*, 200, 1497–1499.
- Blake, R. & Fox, R. (1974). Adaptation to invisible gratings and the site of binocular rivalry suppression. *Nature*, 249, 488–490.
- Blake, R. & Overton, R. (1979). The site of binocular rivalry suppression. *Perception*, 8, 143–152.
- Blake, R., O'Shea, R. P. & Mueller, T. J. (1992). Spatial zones of binocular rivalry in central and peripheral vision. *Visual Neuroscience*, 8, 460–478.
- Blakemore, C. & Campbell, F. W. (1969). On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. *Journal of Physiology, London*, 203, 237–260.
- Blakemore, C. & Nachmias, J. (1971). The orientation specificity of two visual after-effects. *Journal of Physiology, London*, 213, 157–174.
- Blakemore, C. & Price, D. J. (1987). The organization and postnatal development of area 18 of the cat's visual cortex. *Journal of Physiology, London*, 384, 263–292.
- Blakemore, C., Fiorentini, F. & Maffei, L. (1972). A second mechanism of binocular depth discrimination. *Journal of Physiology, London*, 226, 725–749.
- Bonds, A. B. (1991). Temporal dynamics of contrast gain in single cells of the cat striate cortex. *Visual Neuroscience*, 6, 239–255.
- DeAngelis, G. C., Robson, J. G., Ohzawa, I. & Freeman, R. D. (1992). Organization of suppression in receptive fields of neurons in cat striate cortex. *Journal of Neurophysiology*, 68, 144–163.
- Douglas, R. J. & Martin, K. A. C. (1991). A functional microcircuit for cat visual cortex. *Journal of Physiology, London*, 440, 735–769.
- Douglas, R. J., Martin, K. A. C. & Whitteridge, D. (1989). A canonical microcircuit for neocortex. *Neural Computation*, 1, 480–488.
- Enroth-Cugell, C. & Robson, J. G. (1966). The contrast sensitivity of retinal ganglion cells of the cat. *Journal of Physiology, London*, 187, 517–552.
- Gilbert, C. D. & Kelly, J. P. (1975). The projections of cells in different layers of the cat's visual cortex. *Journal of Comparative Neurology*, 163, 81–106.
- Gilinsky, A. S. & Doherty, R. S. (1969). Interocular transfer of orientational effects. *Science*, 164, 454–455.
- Guillery, R. W. (1966). A study of Golgi preparations from the dorsal lateral geniculate nucleus of the adult cat. *Journal of Comparative Neurology*, 128, 21–50.
- von Helmholtz, H. (1910). *Handbuch der physiologischen Optik* (3rd edn, Vol. 3). Hamburg: Verlag Leopold Voss.
- Hubel, D. H. & Wiesel, T. N. (1962). Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *Journal of Physiology, London*, 160, 106–154.
- Hubel, D. H. & Wiesel, T. N. (1974). Sequence regularity and geometry of orientation columns in the monkey striate cortex. *Journal of Comparative Neurology*, 158, 267–293.
- Kato, H., Bishop, P. O. & Orban, G. A. (1981). Binocular interaction on monocularly discharged lateral geniculate and striate neurons in the cat. *Journal of Neurophysiology*, 46, 932–951.
- Kisvárdy, Z. F., & Eysel, U. T. (1993). Functional and structural topography of horizontal inhibitory connections in cat visual cortex. *European Journal of Neuroscience*, 5, 1558–1572.
- Kisvárdy, Z. F., Martin, K. A. C., Freund, T. F., Maglóczy, Z., Whitteridge, D. & Somogyi, P. (1986). Synaptic targets of HRP-filled layer III pyramidal cells in the cat striate cortex. *Experimental Brain Research*, 64, 541–552.
- Lehky, S. R. (1988). An astable multivibrator model of binocular rivalry. *Perception*, 17, 215–228.
- Lehky, S. R. & Blake, R. (1991). Organization of binocular pathways, modeling and data related to rivalry. *Neural Computation*, 3, 44–53.
- Lehky, S. R. & Maunsell, J. H. R. (1993). No binocular rivalry in LGN of alert macaque. *Society for Neuroscience Abstracts*, 19, 525.
- Lehmkuhle, S. W. & Fox, R. (1975). Effect of binocular rivalry suppression on the motion aftereffect. *Vision Research*, 15, 855–859.
- Levitt, W. (1965). *On binocular rivalry*. Institute of Perception, Soesterberg, The Netherlands.
- Liu, L., Tyler, C. W. & Schor, C. (1992). Failure of rivalry at low contrast: Evidence of a suprathreshold binocular summation. *Vision Research*, 32, 1471–1479.
- Livingstone, M. S. & Hubel, D. H. (1988). Segregation of form, color, movement and depth: Anatomy, physiology, and perception. *Science*, 240, 740–749.
- Logothetis, N. K. & Schall, J. D. (1989a). Neuronal correlates of subjective visual perception. *Science*, 245, 761–763.
- Logothetis, N. K. & Schall, J. D. (1989b). Neuronal activity related to motion perception in the middle temporal area (MT) of the macaque. In Lam, D. M. K. & Gilbert, C. D. (Eds), *Proceedings of the Retina Research Foundation, Vol. 2: Neural mechanisms of visual perception* (pp. 199–222). Texas: Portfolio.
- Matsuoka, K. (1984). The dynamic model of binocular rivalry. *Biological Cybernetics*, 49, 201–208.
- Mitchell, D. E., Reardon, J., Muir, D. W. (1975). Interocular transfer of the motion after-effect in normal and stereoblind observers. *Experimental Brain Research*, 22, 163–173.
- Moore, R. J., Spear, P. D., Kim, C. B. Y. & Xue, J. T. (1992). Binocular processing in the cat's dorsal lateral geniculate nucleus. III. Spatial frequency, orientation, and direction sensitivity of nondominant-eye influences. *Experimental Brain Research*, 89, 588–598.
- Morrone, M. C., Burr, D. C. & Speed, H. D. (1987). Cross-orientation inhibition in cat is GABA mediated. *Experimental Brain Research*, 67, 635–644.
- Mueller, T. J. (1990). A physiological model of binocular rivalry. *Visual Neuroscience*, 4, 63–74.
- Mueller, T. J. & Blake, R. (1989). A fresh look at the temporal dynamics of binocular rivalry. *Biological Cybernetics*, 61, 223–232.
- Nelson, J. I., Kato, H. & Bishop, P. O. (1977). Discrimination of orientation and position disparities by binocularly activated neurons in cat striate cortex. *Journal of Neurophysiology*, 40, 260–283.
- Nicoll, A. & Blakemore, C. (1993). Patterns of local connectivity in the neocortex. *Neural Computation*, 5, 665–680.
- Ohzawa, I. & Freeman, R. D. (1986a). The binocular organization of simple cells in the cat's visual cortex. *Journal of Neurophysiology*, 56, 221–242.
- Ohzawa, I. & Freeman, R. D. (1986b). The binocular organization of complex cells in the cat's visual cortex. *Journal of Neurophysiology*, 56, 243–259.
- Ohzawa, I., Sclar, G. & Freeman, R. D. (1985). Contrast gain control in the cat's visual system. *Journal of Neurophysiology*, 54, 651–667.
- O'Shea, R. P. & Crassini, B. (1981). Interocular transfer of the motion after-effect is not reduced by binocular rivalry. *Vision Research*, 21, 801–804.
- Schmielau, F. & Singer, W. (1977). The role of visual cortex for binocular interactions in the cat lateral geniculate nucleus. *Brain Research*, 120, 354–361.
- Sengpiel, F. & Blakemore, C. (1993). Neurons in cat area 17 exhibit bistable response gain during binocular stimulation. *Society for Neuroscience Abstracts*, 19, 628.
- Sengpiel, F. & Blakemore, C. (1994). Interocular control of neuronal responsiveness in cat visual cortex. *Nature*, 368, 847–850.
- Sengpiel, F., Harrad, R. A. & Blakemore, C. (1992). Responses of cells in the cat's LGN and area 17 to rivalrous stimuli. *Society for Neuroscience Abstracts*, 18, 295.
- Shou, T. & Leventhal, A. G. (1989). Organized arrangement of orientation-sensitive relay cells in the cat's dorsal lateral geniculate nucleus. *Journal of Neuroscience*, 9, 4287–4302.
- Tsumoto, T., Legendy, C. R. & Creutzfeldt, O. D. (1978). Functional organization of the corticofugal system from visual cortex to lateral geniculate nucleus in the cat. *Experimental Brain Research*, 32, 345–364.
- Van Essen, D. C. & Maunsell, J. H. R. (1983). Hierarchical organization and functional streams in the visual cortex. *Trends in Neuroscience*, 6, 370–375.

- Varela, F. J. & Singer, W. (1987). Neuronal dynamics in the visual corticothalamic pathway revealed through binocular rivalry. *Experimental Brain Research*, 66, 10–20.
- Vidyasagar, T. R. & Urbas, J. V. (1982). Orientation sensitivity of cat LGNd neurones with and without inputs from visual cortical areas 17 and 18. *Experimental Brain Research*, 46, 157–169.
- Wolfe, J. M. (1983). Influence of spatial frequency, luminance, and duration on binocular rivalry and abnormal fusion of briefly presented dichoptic stimuli. *Perception*, 12, 447–456.
- Xue, J. T., Ramoa, A. S., Carney, T. & Freeman, R. D. (1987). Binocular interaction in the dorsal lateral geniculate nucleus of the cat. *Experimental Brain Research*, 68, 305–310.
- Yang, Y., Rose, D. & Blake, R. (1992). On the variety of percepts associated with dichoptic viewing of dissimilar monocular stimuli. *Perception*, 21, 47–62.

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