Local Sensitivity to Stimulus Orientation and Spatial Frequency within the Receptive Fields of Neurons in Visual Area 2 (V2) of Macaque Monkeys

Running head: Receptive-field Structure of Macaque V2 Neurons

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Abstract

We used dynamic dense noise stimuli and local spectral reverse correlation methods to reveal the local sensitivities of neurons in visual area 2 (V2) of macaque monkeys to orientation and spatial frequency within their receptive fields. This minimized the potentially confounding assumptions that are inherent in stimulus selections. The majority of neurons exhibited a relatively high degree of homogeneity for the preferred orientations and spatial frequencies in the spatial matrix of facilitatory subfields. However, about 20% of all neurons showed maximum orientation differences between neighboring subfields that were greater than 25°. The neurons preferring horizontal or vertical orientations showed less inhomogeneity in space than the neurons preferring oblique orientations. Over 50% of all units also exhibited suppressive profiles and those were more heterogeneous than facilitatory profiles. The preferred orientation and spatial frequency of suppressive profiles differed substantially from those of facilitatory profiles and the neurons with suppressive subfields had greater orientation selectivity than those without suppressive subfields. The peak suppression occurred with longer delays than the peak facilitation. These results suggest that the receptive field profiles of the majority of V2 neurons reflect the orderly convergence of V1 inputs over space, but that a subset of V2 neurons exhibit more complex response profiles having both suppressive and facilitatory subfields. These V2 neurons with heterogeneous subfield profiles could play an important role in the initial processing of complex stimulus features.

Keywords: Local spectral reverse correlation, RF subfields, Extrastriate visual neurons, Primates
Introduction

The perception of global form depends on multiple stages of cortical processing (e.g., Geisler et al, 2001; Tanaka 1996; Orban, 2008; Rust and Stoker, 2010; Willmore et al, 2010; El-Shamayleh and Movshon, 2011). The small receptive fields of V1 neurons are sensitive to stimulus orientation, spatial/temporal frequency, and contrast and thus, considered to encode local stimulus features or attributes of visual scenes (i.e., initial filtering stage). There is a considerable debate in the literature concerning exactly where and how local stimulus features are compared and pooled (second-stage processing).

One idea regarding the second stage processing is that the complex networks of V1 neurons play a critical role (Lamme, 1995; Lamme et al, 2000; Lee et al, 2002; Sigman et al, 2001; Li et al, 2002; 2004; 2006; Sceniak et al, 2001; Smith et al, 2007; Shapley, 2007; Jehee et al, 2007; Graf et al, 2008; Levi, 2007).

Neurons in the extrastriate visual areas, with increasingly larger RF centers and more complex response properties, are thought to support a variety of global perceptual phenomena (see reviews by Ghose and Maunsell, 1999; Roe et al, 2007; Orban, 2008; El-Shamayleh and Movshon, 2011). In this scheme, multiple inputs from V1 neurons tuned to various local stimulus features (e.g., orientation) converge on V2 neurons (also from V2 onto V4, and so on), and as a result, many of these ‘intermediate’ extrastriate neurons acquire ‘new’ sensitivities. For instance, a considerable proportion of V2 (Kobatake and Tanaka, 1994; Hegde and Van Essen, 2000; Mahon and De Valois, 2001; Ito and Komatsu, 2004; Bakin et al, 2000; Zhou et al, 2000; Marcus and Van Essen, 2002; Anzai et al, 2007; Huang et al, 2008; Schmid et al, 2009; Willmore et al, 2010) and V4 (Gallant et al, 1993; 1996; Pasupathy and Conner, 1999; 2001; 2002) neurons become sensitive to corners or angled contours that make up a part of a global
shape by efficiently linking local feature information (but see Hegde and Van Essen, 2007; El-Shamayleh and Movshon, 2011).

To uncover neuron’s local sensitivities to stimulus orientation, most of the previous V2 studies used spatially restricted grating stimuli at various locations within their receptive fields (RFs) or a finite set of complex stimuli. Because of the relatively high spiking threshold and large nonlinearities of extrastriate neurons, mapping their receptive fields using a part of optimal stimuli, e.g., a small bar or a restricted patch of grating, often failed to activate these neurons (Tanaka et al, 1991; Pasupathy and Connor, 2001; Ito and Komatsu, 2004). An effective approach to overcome this difficulty is to quantitatively analyze the spatial profiles of neuron’s receptive fields without depending on a finite set of luminance-defined stimuli. In this study, therefore, we applied dynamic dense white-noise stimuli, which stimulated large visual areas over the receptive field and a local spectral reverse correlation analysis (LSRC) to reveal the local ‘subfield’ sensitivities within the receptive fields of macaque V2 neurons (Nishimoto et al, 2006). The LSRC is based on spectral analyses in a two-dimensional spatial frequency domain for spatially localized areas within and around the receptive fields. It is an objective, quantitative method for measuring the response profiles containing local variations of orientation and spatial frequency tuning properties in neurons with substantial non-linearity. The LSRC method is especially suitable to study the receptive field spatial structure in a subset of V2 neurons that may be sensitive to complex visual features because such V2 neurons are thought to receive inhomogeneous inputs from the earlier stages of cortical processing (e.g., Ito and Komatsu, 2004; Nishimoto et al, 2006; Anzai et al, 2007).

Materials and Methods
Recordings were made in five adult macaque monkeys (*Macaca mulatta*) weighing between 4.0 to 6.0 Kg. All experimental and animal care procedures were in compliance with the Guiding Principles for Research Involving Animals and were approved by the Institutional Animal Care and Use Committee of the University of Houston.

**Surgical preparation**

The surgical preparation and the recording and stimulation methods have been described in detail elsewhere (Maruko et al, 2008). Briefly, monkeys were initially anesthetized with an intramuscular injection of ketamine hydrochloride (15-20 mg/kg) and acepromazine maleate (0.15-0.2 mg/kg). A cannula was placed in a superficial vein to facilitate the continuous infusion of Propofol (4 mg/kg/hr) and sufentanyl citrate (0.05 µg/kg/hr). A tracheotomy was performed to allow artificial respiration. The subjects were then secured in a stereotaxic instrument. A small craniotomy and durotomy were made over the lunate sulcus to expose a small area for electrode insertion. The well covering the exposed dura and brain surface were filled with warm agar and closed with melted wax. After all surgical procedures were completed, the animals were paralyzed by an intravenous injection of vecuronium bromide (Norcuron; 0.1 mg/kg/hr), and artificially ventilated with a mixture of 59% N₂O, 39% O₂, and 2% CO₂. Core body temperature was kept at 37.6 °C by a warming pad. Cycloplegia was produced by a topical instillation of 1% atropine, and the animals’ corneas were protected with rigid gas-permeable, extended-wear contact lenses. Retinoscopy was used to determine the contact lens parameters required to focus the eyes on the stimulus screens.

**Recording and visual stimulation**
Visual stimuli were displayed on a cathode ray tube display (VRG) with ultra-short persistence (frame rate = 140Hz, 800x600 pixels). The viewing distance was set to 114 cm at which the display subtended 20° (horizontal) x 15° (vertical). Tungsten-in-glass microelectrodes (Merril and Ainsworth, 1972; Fredric-Haer, Maine) were used to record multi-unit or single-unit activity from which activity from single cortical neurons were isolated by using spike-sorting software. Action potentials were extracellularly recorded and amplified and digitized at 25 KHz and stored to disk on a computer running the TDT (Tucker-Davis Technology, Fl) data acquisition components of our workstation.

For each isolated neuron, the receptive fields for both eyes were mapped on the tangent screen and its ocular dominance was initially determined using handheld stimuli. The mapped receptive fields were projected on the monitor screen by using a pair of gimbaled mirrors, and the responses of each neuron to a variety of stimuli were closely examined quantitatively as follows.

*Measurement with sine wave gratings.* For drifting gratings, a neuron's responses were sampled at a rate of 140 Hz (7.14 msec bin widths) and compiled into peristimulus time histograms (PSTHs) that were equal in duration to, and synchronized with, the temporal cycle of the grating. For sine-wave gratings, the amplitude and phase of the temporal response components in the PSTHs were determined by Fourier analysis. The stimuli were presented multiple times in a randomly ordered sequence for relatively short periods (e.g., 3.22 sec). During a given experiment, the re-randomized stimulus presentations were repeated 3 to 6 times producing PSTHs for each stimulus that represent the neuron's response to 30-60 stimulus grating cycles. One or two blank stimuli (i.e., zero contrast control) were included in each repeat of the re-randomized sequence to provide a measure of the neuron's maintained firing rate.

Responses to sine wave gratings (Contrast = 80%, Temporal Frequency = 3.0 Hz) were measured to characterize the monocular receptive field properties. Sine wave
gratings were presented randomly to either the left or the right eye for a given presentation. The orientation tuning functions were initially obtained using the qualitatively determined optimal spatial frequency for each neuron. This was followed by acquisition of the spatial frequency tuning functions at the neuron’s preferred orientation and the preferred direction of drift. The preferred orientation and orientation bandwidth for each receptive field were determined by fitting the orientation tuning functions with wrapped Gaussian functions (Swindale, 1998):

\[ G(\theta) = m_1 \sum \exp\left[-(\theta-m_2+180n)^2/(2m_3^2)\right] \]

where  \( \theta \) = orientation,  \( m_1 \) = response amplitude,  \( m_2 \) = preferred orientation, and  \( m_3 \) = standard deviation of the Gaussian function. Orientation bias was calculated by using the vector summation methods (Levick and Thibos, 1982; Smith et al, 1990). Briefly, the response of a given neuron to a given orientation is expressed as the following complex number:

\[ R = r \exp(j2\theta). \]

The response amplitude for a grating of orientation  \( \theta \) is described by a vector with a length of  \( r \) at an angle coordinate of  \( 2\theta \), where  \( j \) is the square root of -1. The orientation bias is expressed as the mean response vector for a series of equally spaced stimulus orientations:  \( R_{\text{mean}} = \Sigma R/N \), where  \( N \) = number of orientations. The mean response vector was then normalized with respect to the average amplitude of the vectors for all orientations, i.e.,  \( \Sigma r/N \). A normalized phasor for all stimulus orientations was computed by the following formula:

\[ B = b \exp(j2\theta_0) = \Sigma R/\Sigma r, \]

where  \( \Sigma R \) is the vector sum for all 12 orientations and  \( \Sigma r \) is the scalar sum of the amplitudes of all of the response vectors. The normalized phasor  \( b \) represents
orientation bias, which varied between 0 (no orientation bias) and 1.0 (responsive to only 1.0 (responsive to only one orientation). The term $2\theta_p$ signifies the angular coordinates of the resultant vector and the angle $\theta_p$ is the preferred stimulus orientation of the unit. The above normalization procedure minimizes the sensitivity of the measure to the responsiveness of the neuron (Thibos and Levick, 1985).

To determine each cell's preferred spatial frequency, the spatial frequency response data were fitted with Gaussian functions (DeAngelis et al., 1993):

$$G(f) = m_1 \exp \left[ -\frac{(f-f_0)^2}{2s^2} \right]$$

where $f =$ spatial frequency, $m_1 =$ response amplitude, $f_0 =$ preferred spatial frequency, and $s =$ standard deviation of the Gaussian function. Finally, size tuning functions were obtained for the receptive fields of each V2 neuron. We determined the receptive field center and surround of a given neuron and the strength of surround suppression by measuring area-summation functions with drifting high-contrast (80%) sinusoidal gratings that were optimized for the orientation, spatial frequency, and temporal frequency of the receptive field center (Zhang et al., 2005). The receptive field center size was determined by searching for the smallest center stimulus diameter at which neuronal discharges reached 95% of the peak firing rate.

**Local Spectral Reverse Correlation (LSRC) Method.** The details of visual stimulation and data analysis for the LSRC method have been described previously by Nishimoto et al. (2006). Briefly, the experiment control functions and the stimulus generations were performed using custom-written software on two Windows personal computers (Komputer, Houston, TX). For each cell, we presented a dynamic two-dimensional noise array. The area covered by the noise array was three times larger than the classical receptive fields in width and height (typical ranges were from 1x1° to 12x12°). The noise array consisted of 51x51 elements, in which the luminance of each element was bright
(99 cd/m²), dark (1 cd/m²), or equal to the mean luminance of the display (50 cd/m²). The noise array was redrawn with a new noise pattern every 28 ms (four video frames). Typically, 15 blocks of the noise arrays (a total of 62565 frames) were presented to obtain a sufficient number of spikes for data analysis.

To obtain two-dimensional frequency tuning functions for spatially localized areas, we calculated local spectral reverse correlations (LSRC). Specifically, we calculated the spike-triggered average of the amplitude spectra of a given subfield of the noise array to obtain a two-dimensional frequency tuning function for the given subfield (Fig 1A). The subfields were windowed by a two-dimensional Gaussian function, and the frequency spectra were calculated by the standard fast Fourier transform algorithm with zero padding (Press et al., 1992). The center of the window was stepped typically by one standard deviation (SD) of the Gaussian function. By interpreting the two-dimensional frequency tuning as a polar coordinate representation, we obtained a joint spatial frequency and orientation profile. The distance from the origin to the peak of the excitation indicated the optimal spatial frequency for the local subfield of the receptive field. The angle perpendicular to the line connecting the origin and the excitation peak (with the horizontal axis) depicted the optimal orientation for the local subfield. By systematically changing positions of the subfield for calculating the spectra, we obtained a matrix of subfields in which each element of the matrix contained the two dimensional frequency tuning functions (Figs 1A & 1B). Therefore, the final matrix describes the tuning profile of the neuron as a function of position (x, y) as well as spatial frequency and orientation in a joint manner. We optimized the number of position/spacing for each unit depending on the spatial frequency tuning of the unit; for neurons with band pass profile in their SF tuning functions, the analysis window covered at least a half of the period of the optimal spatial frequency within 1 SD of the Gaussian. In rare cases where
neurons had a low-pass SF tuning, we used the SD value corresponding to one-fifth of the mapped area.

We have calculated spike-triggered averages of stimulus local spectra for correlation delays from 0 to 150 ms in 15 ms steps. Then, the optimal correlation delay was determined as the delay for which the signal amplitude was maximal. Typical correlation delays varied from 45 to 90 ms. The average number of spikes for our population of neurons was 16136 spikes per recording. The minimum and maximum were 1574 and 77271 spikes, respectively.

To evaluate the significance of the spike-triggered signals, we calculated the average and SD (noise level) of signals using shuffled correlations. We obtained the shuffled correlations by calculating cross correlations between spike trains and shifted (unpaired) stimulus blocks. The mean and SD of the shuffled correlations were then used to normalize the original spike-triggered signals into z-score representations. To reduce the computational burden, we assumed that the noise level was identical for a sequence of random patterns for any given subfield and spatial frequency. Therefore, for each neuron, we calculated a set of mean and SD values of the shuffled correlations and used it to normalize all spike-triggered signals for the neuron.

Z-scores were used to represent the response strength in these spectral receptive field profiles, taking variability and statistical significance of responses into account. Z-scores were sometimes negative, which was interpreted as a reduction of activities below the baseline level. The statistical significance of signals was examined by the z-score, corrected for multiple comparisons by the Bonferroni’s method (Fig1B, right). The degree of freedom for the Bonferroni’s correction was set to the number of subfields multiplied by the number of noise elements within ±1 SD of the analyzing Gaussian window. Black curves in the LSRC plot indicate contours for $p = 0.05$. 
Anatomical methods.

To identify recording sites, small electrolytic lesions were produced at several locations along the electrode track by passing current through the electrode (5µA for < 5 sec, electrode tip negative). At the end of the recording experiments, an overdose of sodium pentobarbital (100 mg/kg) was administered intravenously to induce a deep level of anesthesia and the animals were euthanized. The animals were perfused through the heart with an aldehyde fixative (2% paraformaldehyde and 0.5% glutaraldehyde in 0.1 M phosphate buffer, ph = 7.4). The brains were removed immediately, and kept overnight in fixative with 20% sucrose. The tissues were cut in 40 µm sections on a freezing microtome in the tangential, frontal, or sagittal plane. The sections were used to confirm that we recorded from comparable sites in different animals.

Results

We quantitatively analyzed the responses of 149 V2 neurons. In each unit, we initially measured the orientation, spatial frequency, and size tuning functions using sine wave gratings. Using the optimal parameters obtained in these experiments we performed the LSRC analysis of the neuron using the dynamic dense noise stimuli.

Local spectral selectivity maps with facilitatory profiles

High homogeneity of facilitatory profiles. According to the previous studies using spatially restricted grating stimuli, a V2 neuron containing the small 'sub-regions' within its receptive field that are different in preferred orientations could encode angles embedded in complex stimuli, e.g., ‘position-specific’ curvature neurons (Anzai et al,
With the LSRC method we looked for the spatial matrix of subfields that would fulfill this requirement. The majority of V2 neurons in this study exhibited homogeneous matrices of facilitatory subfields. Figure 2 illustrates the responses of a typical V2 neuron to grating stimuli (2A-2C) and dynamic dense noise stimuli (Figs 2D-2F). In response to grating stimuli, this neuron showed the typical orientation tuning properties having its preferred orientation at 84.2 degrees and orientation bias of 0.54 (Fig 2A). The unit was tuned to relatively high spatial frequencies, having the preferred spatial frequency at 1.81 cy/d and the high-frequency cut-off at 12.8 cy/d (Fig 2B). The receptive field center size of this unit was 1.4 deg estimated from its size tuning function (Fig 2C). Figure 2D shows the spatial matrix of subfields with facilitatory profiles (two-dimensional spatial frequency tuning) for this unit obtained by changing iteratively the center position of the Gaussian window. The detail profile of the most responsive subfield (with the maximum z-score) is illustrated in Fig 2E. The schematic diagram, showing the preferred orientation (bar angle) and spatial frequencies (width), and the maximum z-scores (saturation) of the subfields, is illustrated in Fig 2F. The preferred orientations of facilitatory subfields within the matrix were similar to the preferred orientation of the unit measured with sine wave gratings (compare Fig 2A with 2E & 2F). The preferred spatial frequency of the subfields was also similar between subfields, and was similar to the preferred spatial frequency of the unit determined by grating stimuli (compare 2B with 2E). The spatial extent (spatial matrix) of facilitatory subfields was confined within the receptive field center of this neuron determined from the neuron’s area summation function (compare Fig 2C with 2D), and the strength of activation (z-scores) was highest near the center of the subfield matrix (saturation of each bar in Fig 2F).

A subset of V2 neurons showed far more complex receptive field spatial profiles (Fig 3). The spatial matrix of subfields for the unit in Fig 3D showed highly inhomogeneous
local sensitivities to stimulus orientations and spatial frequencies within its receptive
field. The preferred orientation of the subfield with the maximum z-score was 0 degree
and the preferred spatial frequency was 1.3 cy/deg. More importantly, the maximum
orientation difference between a pair of subfields for this neuron was 83 degrees, nearly
orthogonal to each other (Fig 3E). In response to grating stimuli, this V2 neuron had a
relatively broad orientation tuning, having the preferred orientation at 48.0 degrees (Fig
3A). The preferred spatial frequency was 1.95 cy/d (Fig 3B) and its receptive field center
size was 1.8 deg in diameter (Fig 3C). In contrast to the unit in Fig 2, the preferred
orientation and spatial frequency of the subfield with the maximum z-score were
substantially different from the neuron’s responses to gratings. Therefore, we measured
the weighted sum of the subfield preferred orientations and spatial frequencies to
determine if the weighted sum can correlate better with the preferred orientation and
spatial frequency measured with gratings. We calculated the weighted sum of the
subfield’s preferred orientations by a vector summation method; we determined a vector
for each subfield using its z-score (value) and orientation (direction) and summing all
vectors across subfields gave the ‘weighted’ preferred orientation for the unit. The
weighted sum of the preferred spatial frequencies of subfields was calculated by initially
multiplying the preferred spatial frequency of each subfield with its z-score and then,
summed across the matrix of the unit. We divided this sum by the sum of z-scores. The
weighted sum of the preferred orientations and spatial frequencies of the subfields for
this neuron was 41.0 deg and 1.48 cy/deg, respectively, both of which were very similar
to the preferred orientation and spatial frequency of the unit measured with gratings.
Finally, the schematic diagrams of subfield matrices in Fig 3F and 3G illustrate additional
eamples of the units exhibiting a broad range of preferred orientations and spatial
frequencies among their facilitatory subfields.
Distribution of the orientation and spatial frequency differences. To quantify the degree of homogeneity in the matrix of subfields, we first analyzed the local variations in optimal orientation and spatial frequency between subfields with facilitatory profiles by calculating the largest difference between any pair of subfields (149 pairs in 149 units) (Nishimoto et al, 2006)(Fig 4). Figure 4A plots the orientation difference as a function of the spatial frequency difference for each comparison. The majority of neurons had relatively small variations in both orientation and spatial frequency. For example, 61% of all pairs showed the orientation differences that were smaller than 20 degrees (Fig 4B) whereas 74 % of all neurons had the spatial frequency differences less than 0.5 octaves (Fig 4C). If we compare the largest differences for all neighboring pairs, the differences between pairs of subfields were similar but slightly smaller (Fig 4D and 4E). Although the facilitatory subfields in the majority of V2 neurons showed a relatively high homogeneity, over 20% of all neurons showed substantial inhomogeneities in their response profiles; the maximum orientation differences between neighboring facilitatory subfields were greater than 25°, and a small subset of neurons (5%) showed the orientation difference greater than 60 degrees (e.g., Figs 3, 4B and 4D). These neurons could potentially show a higher sensitivity to angled or curved luminance elements in complex visual stimuli.

The finer details of the relationship between neighboring subfields for a given receptive field, hence an analysis of its finer receptive field spatial structure, can be obtained by comparing the preferred orientation and spatial frequency of all possible neighboring pairs of subfields within a single matrix (Fig 5). The overwhelming majority of the pairs showed the orientation difference between neighboring subfields that were smaller than 10 degrees and the spatial frequency difference less than 0.5 octaves (Fig 5A). This result suggests that the receptive fields of most V2 neurons are made up of remarkably homogeneous V1 inputs. Interestingly, if the maximum difference in the preferred orientation between any pair of subfields for a given neuron was greater than
30 degrees, the rest of subfield pairs for the same neuron also had greater orientation
differences, i.e., showed a more inhomogeneous subfield matrix (compare Fig 5B with
Fig 5D). The spatial frequency differences were unaffected by this analysis (compare Fig
5C with Fig 5E).

Relationships between LSRC subfield responses and responses to gratings. The
preferred orientation and spatial frequency of the subfield for a given V2 neuron did not
substantially differ from the preferred orientation and spatial frequency for the same
neuron determined with grating stimuli (Fig 6). We calculated the weighted sum of the
preferred orientations and spatial frequencies of subfields using the method described
above. The correlation for the preferred orientation between the two measurements was
relatively strong ($r = 0.95$, $p < 0.01$), and except for a few units, the data points rarely fell
out of the 95% confidence interval for the fitted regression line (Fig 6A). The similar
correlation for the preferred spatial frequency was weaker ($r = 0.45$, $p < 0.01$)(Fig 6B).
Nevertheless, these data support the idea that to a first approximation, the neuron’s
preferred orientation and spatial frequency are primarily determined by a weighted sum
of the local sensitivities (subfields) for stimulus orientation and spatial frequency within
the receptive field central regions (e.g., Anzai et al, 2007).

Orientation anisotropy of subfields. We next analyzed all possible pairs of subfields
along each of the 4 major axes of the spatial matrix, i.e., vertical, horizontal, and two
oblique orientations (Fig 7). We classified each unit according to its preferred orientation
into one of the 4 major primary orientation categories ($\pm 22.5$ degrees)(Fig 7A). Then, we
determined the largest orientation and spatial frequency differences between adjacent
subfields for the unit. This analysis was designed to reveal any consistent
inhomogeneity of the subfield map in the 4 primary orientations (anisotropy). The most
important finding was that the receptive fields of those units preferring vertical or
horizontal orientation (‘cardinal’ orientations) had significantly smaller orientation or
spatial frequency differences between subfields than units preferring oblique orientations
(Wilcoxon rank-sum test. p < 0.001 for orientation, p < 0.001 for spatial frequency)(Figs
7B and 7C). This result suggests that the overall sensitivity of V2 neurons could be
potentially higher for vertically or horizontally oriented contour stimuli than for obliquely
oriented contours, i.e., the “oblique effects” (Li et al, 2003; Girshick et al, 2011). Also the
result suggests that besides a higher prevalence of V1 neurons preferring the cardinal
orientations (De Valois et al, 1982; Chapman and Bonhoeffer, 1998; see Li et al, 2003
for a comprehensive review), there appears to be a novel cortical mechanism underlying
the oblique effects. More specifically, the convergence of V1 inputs is more orderly in
those V2 neurons preferring the vertical or horizontal orientation than those tuned to
oblique orientations.

Local spectral selectivity maps with suppressive profiles

Contrary to the striate cortex of cats (Nishimoto et al, 2006), the majority of V2 neurons
in macaque monkeys had suppressive response profiles along with facilitatory profiles
(Fig 8). Figure 8A shows a typical spatial matrix of a V2 neuron containing both
suppressive (blue) and facilitatory (red) profiles. The preferred orientations of 12
facilitatory subfields of this neuron were very similar with one exception in a peripheral
location (Fig 8A and 8C). The preferred orientations of three suppressive profiles
substantially differed from those for facilitatory profiles; in two cases the relationship
between facilitatory and suppressive profiles were nearly orthogonal and in the subfield
with the maximum z-score, the orientation difference was 52 degrees (Fig 8B and 8C).
However, there were two suppressive subfields that showed orientation preference
similar to those for facilitatory subfields (Fig 8A and 8C). The preferred spatial frequency
for the suppressive profile with the maximum z-score for this neuron (2.8 c/d) was higher
than that of the corresponding facilitatory profile (1.1 c/d)(Fig 8B). Fifty five percent of
149 V2 neurons that we examined contained suppressive profiles (Fig 8D). However, for
a given neuron the number of suppressive profiles was smaller than the number of
facilitatory profiles (see below)(Fig 8E).

One of the more important differences between the suppressive and facilitatory
profiles was that the homogeneity of the suppressive subfields was substantially lower
than that for the facilitatory subfields (Fig 9). The spectral maps of Figures 9A and 9B
illustrate the two additional examples of V2 neurons that exhibited complex spatial
profiles of suppression. The suppressive subfields of the unit in Figure 9A showed the
widely different preferred orientations and spatial frequencies while the spatial profiles of
its facilitatory subfields were quite homogeneous. In contrast, the unit in Figure 9B
showed the heterogeneous spatial profiles in both suppressive and facilitatory subfields.
Comparisons of 264 neighboring pairs revealed a wide range of orientation
differences among suppressive subfields (Fig 9C). The median orientation difference
was 11.7 deg (Fig 9D) compared to 2.73 deg for facilitatory profiles (Fig 5B) and this
difference was statistically significant (Wilcoxon rank-sum test, p < 0.001). As with
facilitatory profiles, there was substantial variations in the preferred spatial frequency of
suppressive profiles, and the spatial frequency differences for the suppressive profiles
were significantly greater than those for the facilitatory profiles (compare Fig 9E with Fig
5C)(Wilcoxon rank-sum test, p = 0.035). In a related matter, the homogeneity along the 4
major orientation axes for suppressive subfields showed similar anisotropy to those for
facilitatory subfields; smaller differences for the vertical and horizontal orientations.
However, this difference was not statistically significant (Wilcoxon rank-sum test, p =
0.12 for orientation, and p = 0.21 for spatial frequency)(compare Fig 10 with Fig 6).

**Relationships between suppressive and facilitatory profiles**
Activation strengths (Z-max values). What are the relationships between the facilitatory and suppressive profiles in those individual subfields having both profiles? Figure 11A plots the Z-max value (defined as the highest z-score for a given neuron) and the preferred orientation of the facilitatory (red) and suppressive (blue) profiles that had the highest plus or minus z-scores, respectively. The Z-max values for facilitatory profiles were always higher than those for paired suppressive profiles. However, the subfields with higher Z-max values for facilitatory profiles also had tendency to show higher Z-max values for suppressive profiles (higher negative z-scores) ($r = 0.59$, $p < 0.001$). The frequency histograms in Fig 11B shows that over 80% of the subfields with both profiles had Z-max values for their suppressive profiles that were less than one-half of Z-max values for their facilitatory profiles.

Orientation and spatial frequency differences between facilitation and suppression. Another clear and potentially more significant relationship in Fig 11A was that in a relatively large percentage of subfields, the preferred orientation of the suppressive profile was very different from that for the facilitatory profile. Over 30% of all subfields showed orientation differences between 80 and 90 degrees and a little over 70% had orientation differences greater than 50 degrees (Fig 11C). These relationships between facilitatory and suppressive subfield profiles in the majority of V2 neurons resemble classical cross-orientation suppression in V1 neurons (e.g., Morrone et al, 1987; Bonds, 1989; 1991; Allison et al, 2001; DeAngelis et al, 1992; Heeger 1992; Somers et al, 1995; Ringach et al, 2002; Kimura and Ohzawa, 2009; Malone and Ringach, 2008; Willmore et al, 2010). However, it should be noted that about 10% had similar preferred orientations and nearly 20% showed mildly different orientation differences (less than 50 degrees)(see below for the discussion on the interpretation of suppressive vs. facilitatory profiles). The homogeneity of facilitatory subfields in those units having suppressive
subfields was not significantly different from that in those units without suppressive subfields; the median orientation differences were 18.4° for the units without suppression and 14.7° for with suppression (Wilcoxon rank-sum test, p = 0.48).

With respect to the spatial frequency differences between the suppressive and facilitatory profiles, the preferred spatial frequencies of suppressive profiles were substantially higher than those of facilitatory profiles in the great majority of subfields. For example, 70% of the subfields with both profiles had suppressive profiles that had higher preferred spatial frequencies than their paired facilitatory profiles (Fig 11D). This relationship is more clearly seen in the figure where the orientation differences between the suppressive profiles and facilitatory profiles are plotted as a function the spatial frequency differences (Fig 11E). A significant proportion of the subfields (88%) showed relatively higher spatial frequencies for suppressive profiles; only 10 subfields exhibited facilitatory profiles that showed substantially higher spatial frequencies than their suppressive profiles. This result in V2 neurons substantially differs from the ‘delayed’ suppression in V1 neurons “that are centered at low spatial frequencies” (Malone and Ringach, 2008).

**Timing of peak facilitatory and suppressive responses.** Another important relationship between the facilitatory and suppressive profiles of subfields was in their dynamics; specifically, the timing (correlation delays) of the peak responses between the two profiles was quite different. To quantify this relationship, we measured the z-max value for the facilitatory and suppressive profile at all correlation delays between 30 msec and 150 msec in 15 msec steps. Then we looked for the correlation delay at which the highest z-score was located for facilitatory and suppressive profiles. Each neuron had a different pattern of correlation delays. For example, the neuron in Fig 12A did not show any difference in correlation delays between facilitatory and suppressive profiles (45 msec). The neuron in Fig 12B had a substantially longer delay for the suppressive
profiles (40-45 msec) although its facilitatory profiles were still present at the maximal delay for the suppressive profiles. The neuron in Fig 12C was unique in that at the optimal delay for the facilitatory profiles (60 msec), it did not exhibit a suppressive profile. Moreover, at the optimal delay for the suppressive profiles (105 msec), the unit showed no facilitatory profile.

Figure 12D shows the distribution of the optimal delay differences between the subfield profiles (facilitatory – suppressive). The most notable result was that the correlation delay for the Z-max value ('latency') for suppressive profiles was considerably longer than that for facilitatory profiles. Specifically, the majority of units (67%) with both subfield profiles had longer correlation delays for suppressive profiles than for facilitatory profiles (the median difference was 21 msec). In only 3 % of all neurons, the delay was shorter for the suppressive profiles; 33% had nearly equal optimal correlation delays for both subfield profiles. Note that we calculated spike-triggered averages of stimulus local spectra for correlation delays from 0 to 150 ms in 15 ms steps, and then, the optimal correlation delay was determined as the delay for which the signal amplitude was maximal (maximal z-score)(Nishimoto et al, 2006). This means that the ‘actual’ timing between the two profiles in each unit could be off by ± 7.5 msec (see below for more discussion on the interpretation of the correlation delays between facilitatory and suppressive profiles).

Relationships between subfield suppression and RF properties determined with gratings

The source of suppressive profiles of V2 subfields in not known. We examined whether those neurons having strong surround suppression as revealed by grating stimuli showed a more robust group of subfields with suppressive profiles (Fig 13). V2 neurons
without measurable surround suppression had a nearly equal percentage of suppressive subfields to those that failed to show surround suppression (Fig 13A) (Chi-square test, p > 0.6). Moreover, the suppression index (the strength of surround suppression) for a given neuron obtained from its area summation function had little consistent relationship to its suppressive Z-max value (Fig 13B) or to the ratio of suppressive to facilitatory subfields (Fig 13C). These results suggest that the source of suppressive profiles may not be entirely explained by the mechanisms supporting RF surround suppression in V2 neurons.

The local inhibitory connections in macaque V1 are known to sharpen neuron’s orientation selectivity (Ringach et al, 2002; Ringach, 2007). We have examined whether V2 neurons with suppressive subfields show sharper orientation tuning when measured with grating stimuli (Fig 14A). Those V2 neurons that contained suppressive profiles in their subfields had significantly better orientation selectivity, i.e., exhibiting higher orientation biases to grating stimuli (Wilcoxon rank-sum test, p < 0.05). Finally, the spatial frequency tuning of V1 neurons is also influenced by local inhibitory connections, which mainly affect the low spatial frequency range (Ringach et al, 2002). We examined whether similar relationships are present in macaque V2. Unlike the orientation selectivity of V2 neurons in this study and what is expected from the previous results in V1, the spatial frequency tuning characteristics of macaque V2 neurons that had subfields with suppressive profiles were not different from those neurons without suppressive subfields (Fig 14B) (Wilcoxon rank-sum test, p > 0.6).

Discussion

Several new results emerged from this study. The spatial matrix of subfields with facilitatory profiles of macaque V2 neurons had relatively high homogeneity although a
subset of neurons exhibited notable inhomogeneity. Over 50% of V2 receptive-fields had subfields with suppressive profiles that differed widely in preferred orientation and spatial frequency from those for facilitatory profiles. The neurons preferring horizontal or vertical orientations showed less inhomogeneity in space than the neurons preferring oblique orientations. V2 neurons having suppressive profiles were more selective to stimulus orientations than those without suppressive subfields. The preferred spatial frequency of suppressive profiles was generally higher than that for facilitatory profiles, and the suppression tended to occur with longer delays than the facilitation.

**Methodological considerations**

_Sensitivity of the LSRC analysis._ A potential limitation of LSRC could be how high-density one can make for the subfield matrix. The window size depends on the spatial frequency tuning of a unit and the sigma of the Gaussian window used for computing the spectrum at each window location. If the window size is too small, we could not acquire proper response profiles for low spatial frequency spectra whereas if the window size is too large, we would lose spatial resolution (Nishimoto et al, 2006). The advantage of using LSRC is that we can choose the position, size and steps of the Gaussian window after recording in order to calculate the optimal values for each unit. Therefore, we carefully optimized the number of position/spacing for each unit depending on the spatial frequency tuning of the unit (see the methods). A previous study that characterized the receptive field structure of V2 neurons set the number and location of stimulus patches (hence ‘subfields’) within a given receptive field during recording, and therefore, could not be varied or optimized during the data analysis (Anzai et al, 2007). The average density of the subfield matrix in our study, e.g., the window size and subfield separation, is estimated to be comparable or better than the grid resolution used in Anzai et al.
Overall, the sensitivity of the LSRC method should be greater than previous studies of V2 receptive field profiles (e.g., Ito and Komatsu, 2004; Anzai et al, 2007; see below).

Another analysis tool we considered to reveal subfields was the spike-triggered covariance (STC) technique (Touryan et al, 2002; Rust et al, 2005). There are two main reasons why we employed LSRC for our study rather than STC. First, although both STC and LSRC use white noise stimuli and are capable of revealing filtering profiles of a neuron, the LSRC is more efficient because it requires far less spikes. STC needs far more spikes to obtain reasonable signals because it belongs to a class of second-order approximations. On the other hand, LSRC is essentially a first-order approximation of filtering properties and hence requires far less spikes (Nishimoto et al, 2006). In other words, if you need a reasonable number of sample units from each subject, LSRC is a better choice. Secondly, STC assumes that the receptive fields can be characterized using a small number of discrete orthogonal bases, while LSRC does not have that kind of assumptions and tries characterizing the receptive fields in a rather continuous manner. For our purpose of testing potential (continuous) curvature selectivity, the LSRC method is more advantageous.

Interpretation of the spectral maps with suppressive profiles. The LSRC calculates the net sum of facilitation and suppression for each frequency and therefore, can only visualize whichever is stronger (Nishimoto et al, 2006). The interpretation of the relationship between suppressive and facilitatory profiles in terms of the cortical mechanisms generating the suppression is not unambiguous. For instance, the preferred orientations of suppressive profiles relative to that of the facilitatory profiles in the same matrix of a unit (Fig 8) may be interpreted as: 1) the suppressive effects exist for all orientations of the frequency range overlapped to the facilitatory one or 2) they exist just for orientations nearly orthogonal to the optimal orientation for facilitatory profiles. These
possibilities cannot be distinguished by the LSRC method. Similarly, the delay in appearance of suppressive profiles (Fig 12) may reflect: 1) the delayed onset of the suppressive effects, or 2) suppressive effects “decay more slowly”. The LSRC analysis cannot distinguish the two possibilities. Either of these issues (‘masking effects’ in preferred orientations or delays) is not a problem unique to the LSRC analysis, but is a general problem of the extracellular recording. However, it is important to keep in mind that the ‘summed’ information is represented in spiking output of neurons and thus, is transmitted to the next neurons in the cascade of cortical processing. The data on suppression (e.g., Figs 11 and 12) are, therefore, very informative with respect to how V2 neurons process information over space and time by spiking activity.

**Joint information of preferred orientation and spatial frequency of subfields.** One of the advantages of using LSRC is that it is capable of revealing the response profiles that were not detectable with simple luminance stimuli such as small gratings optimized for unit’s spatial frequency (e.g., Anzai et al, 2007) or angled luminance bars (e.g., Ito and Komatsu, 2004). Each subfield in our LSRC analysis contains information about its preferred orientation but also its preferred spatial frequency that may differ substantially from other subfields. In this regard, two new observations are notable: 1) the correlation between the preferred orientation of subfields and the preferred orientation measured with gratings was tighter than the correlation for the preferred spatial frequency (Fig 6), and 2) in V2 neurons having both suppressive and facilitatory profiles, the preferred spatial frequencies of suppressive profiles were substantially higher than those of facilitatory profiles in the great majority of subfields (Fig 11D). These results are consistent with the recent idea that “the suppressive mechanisms in V2 are tuned for specific spatial features present in natural images” that contain a wide range of orientation and spatial frequency information (Willmore et al, 2010). This sort of ‘tuned’
suppression is rare in the striate cortex (Nishimoto et al, 2006; Willmore et al, 2010; also see below for more discussion).

Comparisons to previous studies

Proportions of V2 units that may show a higher sensitivity to ‘complex stimuli’. A little over 20% of all V2 neurons in this study showed maximum orientation differences between neighboring subfields that were greater than 25° (Fig 4). These neurons could potentially exhibit higher sensitivities to local line components embedded in small restricted areas of complex stimuli that differ in orientations as reported in the previous studies (e.g., Ito and Komatsu, 2004; Anzai et al, 2007). However, we found only 5% of units that had the largest orientation differences between a pair of subfields greater than 60 degrees compared to nearly 30% of the samples in the study of Anzai et al. This difference could not be attributed to the sensitivity of our LSRC method because LSRC, which simultaneously stimulates the area three times larger than the unit’s receptive field center, should more easily overcome both the high threshold for spiking and relatively large nonlinearities of V2 neurons than stimulating a small part of receptive fields with a patch of grating flashed for 40 msec as in the study of Anzai et al. Considering the comparable sample size and cell type in the two studies (136 complex cells in Anzai et al and 149 complex cells in our study), differences in sampling methods, e.g., variations in recording sites with respect to cortical layers and/or cytochrome oxidase stripes, may have, at least in part, contributed to the differing results. Stimulus-dependent non-linearity or adaptation effects (David et al, 2004; Felsen et al, 2005; Sharpee et al, 2006) could also have contributed to the apparent differences. Regardless, it is important to emphasize that 60-70% (Anzai et al, 2007) and 80% (this study) of V2 neurons had
facilitatory ‘subfields’ that had similar preferred orientations throughout the receptive fields.

Response profiles. Direct comparisons of the detail response profiles of V2 neurons between this study and the previous studies are difficult, if not impossible, because the methodology (stimuli and/or computation, anesthetized or awake animals) is quite different between the studies and also the detail description of response profiles are lacking in some of the previous studies. For instance, Willmore et al (2010) presented natural images as stimuli and used to regularize regressions to reveal response profiles. They concluded that V2 has more tuned suppressions than V1, but they did not provide extensive descriptions or figures of actual receptive field profiles. In the study of Anzai et al (2007), small circular gratings of various orientations were rapidly presented at one or two of the 19 locations over the area slightly bigger than the unit’s classical receptive field. As mentioned earlier, the overall stimulus energy at any moment is relatively weak, and, therefore, it is difficult to directly compare their results with the response profiles that are obtained using broadband stimuli (e.g., natural images or white noise). In the study of Ito and Komatsu (2004), the “angle stimuli” were a combination of two straight lines that formed angles at the center of the receptive field and extended out into the receptive field surround. Although about 25% of V2 units responded quite selectively to a particular angle, there is no actual description of the response profiles within the receptive fields to explain such selectivity.

Surround effects. The increased sensitivities of V2 neurons to angled or curved contours may be explained by their receptive field surround mechanisms that can pool local feature information over a larger range of space (e.g., Hubel and Wiesel, 1965; Das and Gilbert, 1999). We found no direct link between surround suppression index obtained by annular surround stimuli and the prevalence or the strength of suppressive subfields (Fig 13). However, unlike the surround effect measured with annular surround
stimuli (suppression index), we previously found that spatially restricted surround
stimulations of V2 neurons can enhance or suppress center responses depending on the
orientation, contrast, and/or location of spatially restricted surround stimuli (Zhang et al,
2008). Similar asymmetries in surround effects have been described for neurons of cat
area 17 (DeAngelis et al, 1994; Walker et al, 1999: Tanaka and Ohzawa, 2009; Kimura
and Ohzawa, 2009) and monkey V1 (Cavanaugh et al, 2002a) although these effects
were all suppressive in nature (but see Tanaka and Ohzawa, 2009). This sort of local
differences in the center-surround interactions previously observed in macaque V2 and
in cat area 17 (Tanaka and Ohzawa, 2009) may be an additional mechanism for pooling
local feature information over an extended range of space that would enable a V2
neuron to encode ‘angles’ between neighboring stimulus elements. El-Shamayleh and
Movshon (2011) recently proposed a potential involvement of ‘inhomogeneous’ surround
suppression in encoding texture-defined form by extrastriate neurons.

V2 versus V1. There is no comparable study of the RF spatial structure of V2
neurons using the LSRC analysis for macaque V1. The original LSRC study by
Comparisons of the population summary of cat area 17 neurons (their Fig 6) with the
present results from macaque V2 (Fig 4) show that our V2 spectral maps of subfields are
less homogeneous than those in cat area 17. In cat area 17, only 7% of units, compared
to 40% of macaque V2 neurons in this study, showed the maximum orientation
differences between any pair of subfields that were greater than 20° (Fig 4B). Moreover
the maximal spatial frequency difference between a pair of any subfields of neurons in
cat area 17 was far smaller than that for V2 units in our monkeys. Incidentally, the study
in cats reported that there was no significant difference between area 17 and 18 with
respect to the receptive field homogeneity. However, since area 18 in cats receives
direct Y-cell inputs from the LGN, the comparison of macaque V2 with feline area 18
with respect to the response characteristics of subunits or filter properties here may not be appropriate.

Another important difference between the two studies of the subfields is that in cat area 17 (and 18), only 10 out of 193 cells (5.2%) had suppressive profiles whereas in macaque V2, over 50% of 149 neurons had suppressive profiles. These differences between V2 and V1, if the species difference can be ignored, suggest that the spatial structural organization of V2 receptive fields, revealed by the LSRC method, is more complex than that of V1 neurons. Importantly the proportion of V2 neurons that showed suppression in this study was similar to the percentage of V2 neurons having ‘tuned’ suppression in previous studies (slightly over 50%) (Schmid et al, 2009; Willmore et al, 2010).

It was proposed that the presence of ‘tuned’ suppression in receptive fields plays a critical role in the emergence of selectivity in V2 neurons for complex stimulus features that is not extensively present in V1 neurons (Willmore et al, 2010). Our results on suppressive profiles (Figs 9 and 11) are generally in agreement with the conclusion of their study. We also found that suppressive profiles cover a broad range of preferred orientations and spatial frequencies within a single receptive field. This heterogeneous array of suppressive profiles of a V2 unit could interact with its facilitatory profiles that show high homogeneity, thus altering their preferred orientations of the spiking output signals from these ‘homogeneous’ facilitatory subfields. Consequently the spatial response profile of the neuron determined by spiking output signals could become more heterogeneous.

Ringach and his colleagues showed a relatively high prevalence of response suppression in V1 neurons that had different dynamics than response enhancement, with the emergence of suppression being relatively delayed (Ringach et al, 2002; Malone and Ringach, 2008). We also found longer delays to peak responses in subfields
of V2 neurons with suppressive profiles relative to those in facilitatory profiles (Fig 12).

As mentioned above, the LSRC analysis does not detect suppression ‘masked’ by
stronger facilitation. However, our LSRC analysis revealed V2 representation that is
transmitted to the next neuron and we compared the delay time between the facilitatory
and suppressive subfields at the respective maximum activation. Our results are also
consistent with the earlier observations made in macaque V2 using a different analysis
method (Schmid et al, 2009).

The orientation and spatial frequency tuning functions of V1 neurons were sharper in
those units suppressed by non-optimal stimuli (e.g., Ringach et al, 2002). We also found
that those V2 neurons with suppressive profiles exhibited better orientation selectivity
(orientation bias) than those without suppressive profiles (Fig 14A). Why do V2 neurons
with suppressive subfields show better orientation selectivity than those without? One
possibility is that signals from V1 are better tuned; V1 neurons with the presence of
suppression mechanism exclusively converge onto a single V2 neuron and therefore,
exhibit sharper tuning (Ringach et al, 2002; Malone and Ringach, 2008; but see
Willmore et al, 2010). Alternatively, the intrinsic local inhibitory network can improve the
orientation selectivity of a V2 neuron by suppressing responses to non-preferred
orientation (i.e., similar to cross-orientation suppression). Also V2 neurons with greater
orientation selectivity may result from a more orderly spatio-temporal convergence of V1
inputs that may depend on the presence of suppressive mechanisms than more broadly
tuned neurons. Obviously these are not mutually exclusive and likely to combine with
different weights as suggested for V1 by Malone and Ringach (2008).

In a related matter, the cortical circuits generating the suppressive profiles of V2
neurons are difficult to isolate. In V1, suppression within a receptive field presumably
originates from one or more of three known sources; feed-forward inhibitory input (e.g.,
Priebe and Ferster, 2006; Freeman et al, 2002; Carandini et al, 2002), local intracortical
inhibitory circuits underlying ‘cross-orientation suppression’ (e.g., Albrecht and Geisler, 1991; Carandini et al, 1997; Heeger 1992; DeAngelis et al, 1992; Kimura and Ohzawa, 2008; Morrone et al, 1982; Williams and Shapley, 2007) and long-range intrinsic or feedback connections (Angelucci et al, 2002; Cavanaugh et al, 2002a;b; Ichida et al, 2007; Rust et al, 2005; Sceniak et al, 2001). Similar patterns of input for V2 neurons could exist; feed forward inhibition that is a part of converging V1 inputs, local and long-range inhibitory network within V2, and feedback connections from higher-order visual areas. Again, these possibilities are not mutually exclusive.

**Conclusions**

The receptive fields of the majority of V2 neurons are made up of remarkably homogeneous V1 inputs while a subset of V2 neurons exhibit relatively complex response profiles. More than one half of V2 neurons contain heterogeneous suppressive subfields, and we speculate that such suppression plays an important role in the initial processing of complex stimulus features (Anzai et al, 2007; Willmore et al, 2010). Our results give new evidence for the view (e.g., Rust and Stocker, 2005; Willmore et al, 2010; El-Shamayleh and Movshon, 2011) that the complex features of visual scenes are “gradually”, instead of “abruptly”, processed in the multiple and successive stages along the hierarchy of extrastral visual areas (also see Kobatake and Tanaka, 1994; Hedges and Van Essen, 2007; Yamane et al, 2008; Willmore et al, 2010). The present results caution against placing too much emphasis on a single extrastriate visual area like V2 as a ‘site’ where ‘encoding’ of complex stimulus features takes place.

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References


Li W, and Gilbert CD. Global contour saliency and local colinear interactions. *J*


Nishimoto S, Ishida T, and Ohzawa I. Receptive field properties of neurons in the early visual cortex revealed by local spectral reverse correlation. *J Neurosci* 26: 3269-3280


Sceniak MP, Hawken MJ, and Shapley R. Visual spatial characterization of macaque


Figure legends
Figure 1. Schematic diagram of the LSRC analysis (see the methods for details). A. The visual stimuli and analysis procedure used to derive LSRC maps. We calculated a cross correlation between the spike train and the amplitude spectra of Gaussian-windowed stimuli to obtain a two-dimensional frequency tuning function for the given subfield. B. An example of spike-triggered average of local spectra (local spectral selectivity map or subfield). The x- and y-axes show vertical and horizontal spatial frequency in cycle/degree (c/d). The facilitations and suppressions are indicated by red and blue, respectively. Asterisks show the location of the highest and lowest z-scores that correspond to the frequency of the maximum facilitation and suppression, respectively. The scale bar with z-scores is illustrated on the right. The distance from the origin to the peak of the excitation indicated the optimal spatial frequency for the local subfield of the receptive field. The angle perpendicular to the line connecting the origin and the excitation peak (with the horizontal axis) depicted the optimal orientation for the local subfield (curved arrow).

Figure 2. A spatial matrix of subfields with facilitatory profiles in a V2 neuron that exhibited spatial homogeneity of orientation and spatial frequency within its receptive field. A-C. Selectivity to the orientation (A), spatial frequency (B) and size (C) measured using sinusoidal grating stimuli (temporal frequency = 3.1 Hz; Contrast 80%). D. Spatial matrix of subfields with facilitatory profiles (two-dimensional spatial frequency tuning) obtained by changing iteratively the center position of the Gaussian window shown in Fig 1. E. Detail profile of the subfield with the maximum z-score. F. Schematic diagram showing the preferred orientation (bar angle) and spatial frequencies (width), and the maximum z-scores (saturation) of the subfields illustrated in D. c/d, cycle per degree; deg, degree.
**Figure 3.** Spatial matrix of subfields with facilitatory profiles in a V2 neuron that exhibited substantial inhomogeneity of orientation tuning within its receptive field. **A-C.** Selectivity to the orientation (A), spatial frequency (B) and size (C) measured using sinusoidal grating stimuli (temporal frequency = 3.1 Hz; Contrast 80%). **D.** Spatial matrix of subfields with facilitatory profiles of the unit. **E.** Schematic diagram showing the preferred orientation (bar angle) and spatial frequencies (width), and the maximum z-scores (saturation) of the subfields illustrated in D. **F.** Schematic diagrams of the facilitatory subfields in two additional V2 neurons that showed relatively high spatial inhomogeneity.

**Figure 4.** Spatial homogeneity of local spectral selectivity maps with facilitatory profiles across the receptive fields. **A.** The maximum orientation differences between a pair of subfields within each neuron are on the x-axis and spatial frequency (SF) differences are on the y-axis. **B.** Histogram illustrating the distribution of the maximum orientation differences (149 pairs). **C.** Distribution of the maximum spatial frequency differences (149 pairs). **D.** Distribution of the maximum orientation differences between neighboring pairs of subfields (149 pairs). **E.** Distribution of the maximum spatial frequency differences between neighboring pairs of subfields (149 pairs). Filled triangles indicate median values and open triangles indicate means (±se).

**Figure 5.** Spatial homogeneity of local spectral selectivity maps with facilitatory profiles across the receptive fields. **A.** The orientation differences between all pairs of neighboring subfields for all 149 units are shown on the x-axis and spatial frequency differences are on the y-axis. Filled circles indicate the subfield pairs of the unit where the maximum differences were greater than 30 degrees in preferred orientations. **B.** Distribution of the orientation differences between all pairs of neighboring subfields for 149 units in which the maximum orientation difference for each unit was less than 30
degrees. C. Distribution of the orientation differences between all pairs of neighboring subfields for 149 units in which the maximum orientation difference for each unit was equal to or greater than 30 degrees. D. Distribution of the spatial frequency differences between all pairs of neighboring subfields for 149 units in which the maximum orientation difference for each unit was less than 30 degrees. E. Distribution of the spatial frequency differences between all pairs of neighboring subfields for 149 units in which the maximum orientation difference in each unit was equal to or greater than 30 degrees. Filled triangles indicate median values and open triangles indicate means (±se).

**Figure 6.** Comparisons of the preferred orientation and spatial frequency measured with drifting gratings and the LSRC method. A. Preferred orientation of subfields measured with the weighted sum of all subfields in a given unit vs. the preferred orientation measured with gratings. B. Preferred spatial frequency of subfields with the weighted sum of all subfields in a given unit vs. the preferred spatial frequency measured with gratings. Dotted lines above and below the unity line represent the 95% confidence interval of the fitted regression line.

**Figure 7.** Spatial homogeneity of subfields with facilitatory profiles along 4 major orientation axes. A. Analysis method for a representative V2 neuron. The preferred orientation and spatial frequency of subfields are illustrated with short bars and the preferred orientation of the unit determined with grating stimuli is shown with a thin line. B. Statistics of the orientation difference in each major axis. White circle and vertical bars represent the mean ± standard errors. Each box represents the three-quartile range with each horizontal bar representing a quartile value. C. Statistics of the spatial frequency difference in each major axis.
Figure 8. A representative V2 neuron having subfields with both facilitatory and suppressive profiles. A. Representative spatial matrix of subfields with both profiles. B. Detailed profile of the subfield with the maximum z-scores. Location of the highest and lowest z-scores is indicated with asterisks. C. Schematic diagram of the preferred orientations (bar angles) and spatial frequencies (widths) of subfields with the facilitatory (red) and suppressive (blue) profiles. D. Proportion of V2 neurons having subfields with facilitatory profiles alone (left) or with both facilitatory and suppressive profiles (right). E. Proportion of V2 neurons having different percentages of subfields with suppressive profiles relative to those without. Filled triangles indicate median values and open triangles indicate means (±se).

Figure 9. Spatial inhomogeneity of local spectral selectivity maps for suppressive profiles. A. An example of the V2 neuron having subfields with homogeneous facilitatory profiles and the inhomogeneous suppressive profiles. B. An example of the V2 neuron having subfields with both inhomogeneous facilitatory and suppressive profiles. C. Orientation differences vs. spatial frequency differences for all possible pairs of suppressive subfields. Orientation differences are on the x-axis and spatial frequency differences are on the y-axis. D. Distribution of the orientation differences among subfields. E. Distribution of spatial frequency differences. Filled triangles indicate median values and open triangles indicate means (±se).

Figure 10. Spatial homogeneity of subfields with suppressive profiles along 4 major orientation axes. A. Analysis method for a representative V2 neuron. Orientation and spatial frequency of subfields are illustrated with short bars and the preferred orientation
of the neuron determined with grating stimuli is shown with a thin line. **B.** Statistics of the
orientation difference in each major axis. White circle and vertical bars represent the
mean ± standard errors. Each box represents the three-quartile range with each
horizontal bar representing a quartile value. **C.** Statistics of the spatial frequency
difference in each major axis.

**Figure 11.** Relationships between the suppressive profiles and the facilitatory profiles of
subfields for individual V2 neurons. **A.** Differences in z-max values. For each neuron, x-
value represents the z-score from the subfield with the maximum suppressive strength
and y-value represents the z-score from the subfield with the maximum facilitatory
strength. Red bars represent the optimal orientation for the facilitatory profile and blue
bars represent the orientation of the suppressive profiles. The dashed line represents
the z-score for suppressive profiles that was statistically significant (p <0.05). **B.**
Distribution of the ratios of maximum suppressive z-scores over maximum facilitatory z-
scores. **C.** Distribution of differences in the preferred orientation of subfields between
facilitatory and suppressive profiles. **D.** Distributions of the preferred spatial frequency
differences. **E.** Scatter plot illustrating the distribution of the differences between the
suppressive profiles and facilitatory profiles of subfields in individual neurons (i.e., a joint
plot of information shown in the panels C and D). Each circle represents a single V2
neuron. Y-axis values represent the differences in orientations and x-axis values
represent the differences in spatial frequencies. Filled triangles indicate median values
and open triangles indicate means (±se).

**Figure 12.** Differences in correlation delays (‘latency’) between the facilitatory and
suppressive subfields. **A-C.** Examples of correlation delays. The z-max values at
different delays for facilitatory (circles) and suppressive (squares) profiles. Filled data point signifies $z$-max values that are significant. Arrows indicate the ‘latency’ at which the peak response occurred for facilitatory and suppressive profile, respectively. **D.** Distribution of the differences in correlation delays (‘latency) between facilitatory and suppressive subfields. Triangle signifies median value and circle the mean. Filled triangles indicate median values and open triangles indicate means ($\pm$ se).

**Figure 13.** Relationships between receptive-field surround suppression and subfields with suppressive profiles. **A.** The proportion of units without surround suppression and having subfields with or without suppressive profiles. **B.** Scatter plot relating suppression index of a neuron as a function of its $z$-max value of suppressive subfields. **C.** Scatter plots relating suppression index of a neuron as a function of its number of suppressive profiles relative to facilitatory profiles.

**Figure 14.** Relationships between suppressive subfields and orientation and spatial frequency tuning. **A.** Distribution of orientation bias of neurons with suppressive subfields (open bars) and without (filled bars). Median values are shown on top. **B.** Distribution of spatial frequency low pass index of neurons with suppressive subfields (open bars) and without (filled bars). Spatial frequency low pass index was calculated by the following formula: \( \text{SF low pass index} = \frac{R_0}{R_{\text{Peak}}} \), where \( R_0 \) is the response at the lowest SF tested, \( R_{\text{Peak}} \) is the response at the optimal SF (Ringach et al, 2002). Median values are shown on top.
Figure 1

A

Stimuli (2D noise)

Local stimuli

Local spectra

Spike train

Time (ms)

B

Spatial Frequency X (c/d)

Spatial Frequency Y (c/d)

374.029.11112 OR: 135 (deg) SF: 1.2 (c/d)

Z-score

-15 -10 -5 0 5 10 15
Figure 3

A

B

C

D

E

F

G
Figure 4
Figure 5
Figure 6

A

Grating Orientation (deg) vs. LSRC Orientation (deg)

- r = 0.95
- p < 0.01

B

Grating Spatial Frequency (c/d) vs. LSRC Spatial Frequency (c/d)

- r = 0.45
- p < 0.01
Figure 7
Figure 8
Figure 9

A

374.043.11112  Zmax: 19.98

2.8
2.0
1.2
0.3
-1.4
-2.2

Center Position X (deg)

B

386.048.11112  Zmax: 15.01

1.6
1.3
1.0
0.7
0.4
0.1

Center Position Y (deg)

C

≥1.5

SF Difference (octave)

D

N=264 (pairs)

E

N=264 (pairs)
Figure 10
Figure 11
Figure 12

A

B

C

D

n=78
Figure 13

A

Proportion of units without surround suppression (%)

Without

With

n=14

n=18

Subfields showing suppressive profile

B

Suppression Index

n=78

Z_{max_{suppression}}

C

Suppression Index

n=78

Number of suppressive profiles / number of facilitatory profiles (%)
Figure 14

A

Proportion of Units (%) vs Orientation Bias

B

Proportion of Units (%) vs Spatial Frequency Low Pass Index

with suppression

without suppression