

Functional Connectivity during Surround Suppression in Macaque Area V4

Theodoros P. Zanos, Patrick J Mineault, Jachin A. Monteon and Christopher C. Pack

Abstract—Surround suppression is a common feature of sensory neurons. For neurons of the visual cortex, it occurs when a visual stimulus extends beyond a neuron's classical receptive field, reducing the neuron's firing rate. While several studies have been attributing the suppression effect on horizontal, long-range lateral or feedback connections, the underlying circuitry for surround modulation remain unidentified. Since most of these models have been relying on single neuron recordings, the contribution of lateral connections can only be suggested from the surround field properties. A more straightforward approach would be to detect these connections and their dynamics using simultaneous recordings from multiple neurons in one or more visual areas. We have developed a method for estimating these connections and we analyzed data obtained from 100-electrode Utah arrays chronically implanted into area V4 of the macaque monkey. Using a method based on the nonlinear Volterra modeling approach, we computed estimates of the strength and statistical reliability of connections among neurons, including nonlinear interactions and excitatory and inhibitory connections. Our results thus far reveal a pattern of connectivity within V4 that conforms to the results of previous anatomical work: Excitatory connections are far more common than inhibitory connections (~65%), stronger connections are found among neurons that are physically near one another, and connections are stronger among neurons with similar receptive field properties. However, this connectivity is capable of reorganizing on short time scales according to the stimulus: Stimuli that evoke strong suppression at the single-unit level introduce stronger inhibition among V4 neurons, identifying recurrent

connectivity as the source of the suppression. Overall, these results provide insight into the dynamic nature of neuronal organization within V4 and its contribution to surround suppression.

I. INTRODUCTION

Much of the input to a cortical neuron originates from within the cortex, and corticocortical connections are of two main types. Inter-areal connections link distinct cortical areas, either by feedforward or feedback projections, while intra-areal connections involve neurons within the same cortical area. Most of our understanding of sensory systems is based on models that rely heavily on inter-areal connectivity, as in the standard hierarchical models of visual processing. However, intra-areal connections tend to be far more common in cortical neurons, and their function is poorly understood.

One common property among visual sensory neurons, that has been attributed frequently to horizontal intra-areal connections, is surround suppression, also known as size tuning. Surround suppression, found initially in the retina [1], has since been found and studied extensively in all subsequent visual areas, such as the LGN [2], cortical areas V1 [3] and V2 [4]. Studies have also attributed properties of later visual processing area MT to surround suppression in V1 [5]. Originally suggested by anatomical evidence in V1 [6], the circuitry underlying surround suppression has been thought to be horizontal or long-range lateral connections. Most models of the neuronal organization giving rise to surround suppression have since been based on single unit recording and the properties of the surround [7-8].

The advances in electrophysiological recordings have provided the possibility of an alternate approach to unveil the circuitry behind surround suppression. Simultaneous recordings from multiple neurons from the same area provide the capability of studying their correlations and relating them to the dynamics of size tuning. We have developed a method for estimating these causal connections [9] and relating them to a variety of contexts, like surround suppression. To this end we have analyzed data obtained from 100-electrode Utah arrays chronically implanted into area V4 of the macaque monkey [10]. Area V4 contains a retinotopic representation of visual space, and individual neurons in this area are selective for complex stimulus features related to the

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T. P. Zanos is with the Montreal Neurological Institute, Department of Neurology and Neurosurgery, McGill University, Montreal, QC H3A 2B4 Canada (514-625-9213; fax: 514-398-5871; e-mail: theodoros.zanos@mcgill.ca).

P. J. Mineault, J. A. Monteon and C. C. Pack are with the Montreal Neurological Institute, Department of Neurology and Neurosurgery, McGill University, Montreal, QC H3A 2B4 Canada (e-mail: patrick.mineault@gmail.com, jachin@neuralbiology.com, christopher.pack@mcgill.ca).

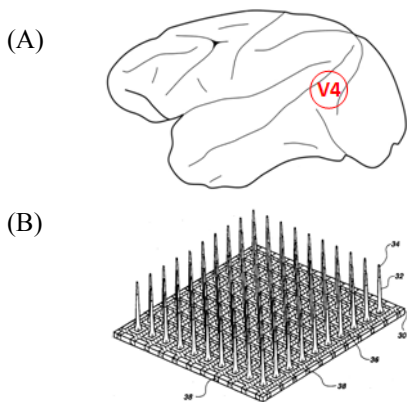


Fig. 1. (A) Sketch of a macaque brain and the position of the visual area V4. (B) Sketch of the Utah microelectrode array implanted [Maynard et al. 1997]

perception of object shape [11]. Based on our recordings we are able to estimate the interactions or functional connectivity among V4 neurons, using a method based on the nonlinear Volterra modeling approach.

II. METHODS

A. Electrophysiological recordings

A rhesus macaque monkey took part in the experiments. The macaque underwent a sterile surgical procedure to implant a headpost and a chronic microelectrode array [10] (Fig. 1B) on area V4 (Fig. 1A). After recovery, the monkey was seated comfortably in a primate chair (Crist Instruments) and trained to fixate a small spot on a computer monitor in return for a liquid reward. Eye position was monitored at 200 Hz with an infrared camera (SR Research) and required to be within 3° of the fixation point for the reward to be dispensed. Recordings were obtained from well-isolated single units in area V4, identified based on anatomical magnetic resonance imaging scans and the physiological properties of the neurons [11]. All aspects of the experiments were approved by the Animal Care Committee of the Montreal Neurological Institute and were conducted in compliance with regulations established by the Canadian Council of Animal Care.

Electrophysiological signals were recorded with a standard data acquisition system (Plexon Multichannel Acquisition Processor [MAP] System). Spike detection and sorting based on the high-pass filtered wideband signal were performed off-line using established methods [12].

B. Procedure and visual stimuli

During the experiment, the animal acquired fixation, while the stimuli appeared randomly in one of 9 possible positions of a 3×3 grid (4° separation between positions) that covered the visual space of all neuron's receptive fields. Stimuli

appeared every 250msec and remained visible for 200msec. Stimulus size was sampled in 2° steps with a minimum patch radius of 2° and a maximum of 10° . Grating orientation was sampled in 45° steps, resulting in 4 different orientations. Stimuli were displayed at 85 Hz at a resolution of $1,920 \times 1,200$ pixels and the viewing area subtended $70 \times 42^\circ$ of visual angle at a distance of 42 cm. Stimuli consisted of sinusoidal gratings of optimal spatiotemporal frequency displayed on a gray background (luminance of 70.3 cd/m^2). The stimuli presentation was repeated four times in blockwise random order.

C. Surround Suppression

Quantification of the amount of surround suppression for each neuron was performed by calculating the suppression index [13], for its preferred orientation, using the following equation:

$$SI = \frac{R_{\max} - R_{\text{largest}}}{R_{\max}}$$

where R_{\max} is the maximum response of the neuron and R_{largest} is the response of the neuron for the largest stimulus radius (10°).

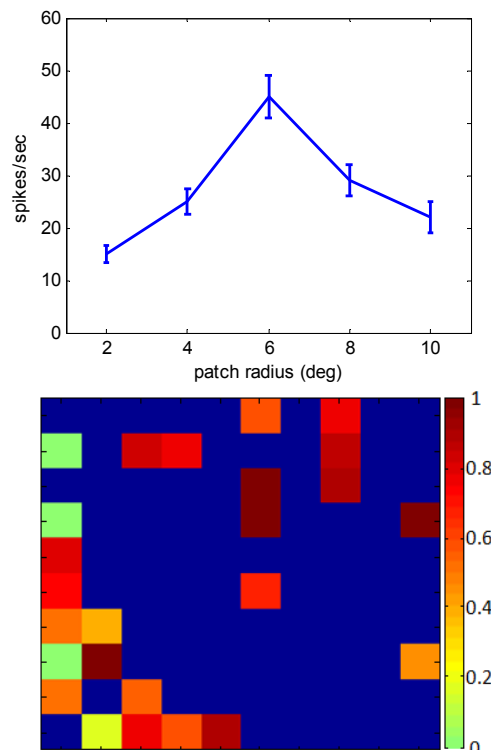


Fig. 2. Upper panel shows an illustrative example of the surround suppressed response of a neuron to its preferred orientation for various stimulus sizes. Lower panel shows the layout of the Suppression Indexes (SI) on the corresponding locations of the Utah Array. Note that dark blue color denotes the absence of a neuron in that location.

D. Volterra Functional Connectivity

The response of neurons whose receptive fields were overlapping with the stimulus position, was used to assign the 200msec time epoch corresponding to each stimulus presentation into two groups. When the response of the neuron was below its maximum value while the stimulus radius was larger than the radius evoking the maximum response, the corresponding time epoch was considered as "surround suppression active". All these epochs were subsequently concatenated and this dataset was used to calculate the functional connectivity maps during surround suppression. Naturally, the rest of the time epochs were concatenated to calculate the functional connectivity maps without surround suppression.

In order to calculate the functional connectivity for these two neuronal states, we used the Volterra Functional Connectivity method [9, 14], a method based on the nonlinear dynamic Volterra modeling approach [15]. The method provides estimates of the strength and statistical reliability of connections among neurons, including nonlinear interactions and excitatory and inhibitory connections. Briefly, the method utilizes an array of Multiple Input/Single Output (MISO) modules, which contain a set of Volterra kernels. The statistical significance of each estimated module is established using the Mann-Whitney two-sample statistic [16] and the null hypothesis of a "random predictor". The theta value of this statistical test can also be used to denote the strength of the connection, while the mean value of the Volterra kernels output from each input can define whether a connection is excitatory (greater than zero) or inhibitory (lower than zero). The complete mathematical framework, algorithmic steps as well as illustrative examples of the method used can be found in [9].

III. RESULTS

Calculating size tuning curves for the preferred orientations of all neurons (an example of a size tuning curve for one of the neurons recorded is shown in Fig 2a) allowed us to calculate the suppression index (SI). The resulting index, plotted at the corresponding electrode position of each neuron is shown in Fig. 2b. It is evident from the figure that two groups of neurons can be distinguished both for their spatial location, as well as the strength of their surround suppression. The lower left part of the array appears to capture neurons which have low or zero values of SI, while the upper and right of the array captures neurons with strong amounts of surround suppression.

As described earlier, we also divided our recordings into two different data sets, one where surround suppression is active, meaning one or more neurons' response is being

suppressed by a visual stimulus that extends to its surround, and one where visual stimuli limit their radii to the receptive fields of the neurons recorded. We applied the VFC algorithm to both and the results are shown in Figures 3 and 4.

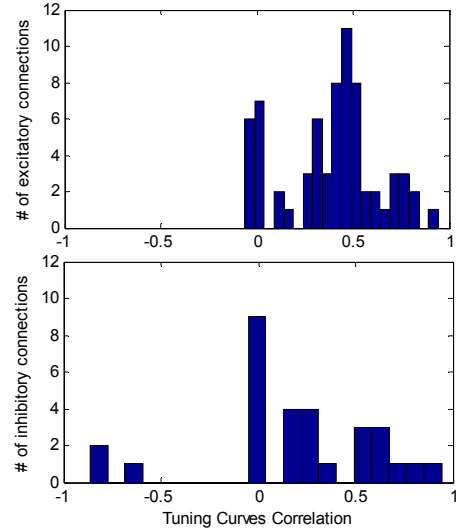


Fig. 3. Histograms of excitatory and inhibitory connections for different tuning curves correlations. Correlations of tuning curves are based on both the receptive field positions as well as their orientation preference.

By analyzing the "surround suppression inactive" dataset, the organization of the neuronal circuit we reveal is consistent with previous anatomic work. On average, 65% of the connections are excitatory and 35% are marked as inhibitory (Fig. 4, upper panel). The connections also have non-linear components, as an average of 18% of them would not get detected using simpler linear approaches. Also, the connection strength is correlated with the physical distance of the neurons ($r = 0.46$, $p < 0.01$). Finally, neurons that have similar orientation tuning properties tend to share stronger excitatory connections while neurons having inhibitory connections have anti-preferred or orthogonal preferred orientations (Fig.3).

However, when analyzing the "surround suppression active" dataset, the organization of these horizontal connections significantly changes. As shown in the lower panel of Fig. 4, a large amount of inhibitory connections emerges when surround suppression is active, as plotted by the blue colored arrows. On average, 48% of the connections are excitatory, while 52% are now inhibitory. Non-linearity is once again significant, with 20% of the connections being detected because of their non-linear components. It should also be noted that 74% of the inhibitory connections appear only when surround suppression is active and are not present otherwise, either as inhibitory or excitatory. Finally, 35% of the excitatory connections that are "active" without surround suppression, disappear during surround suppression.

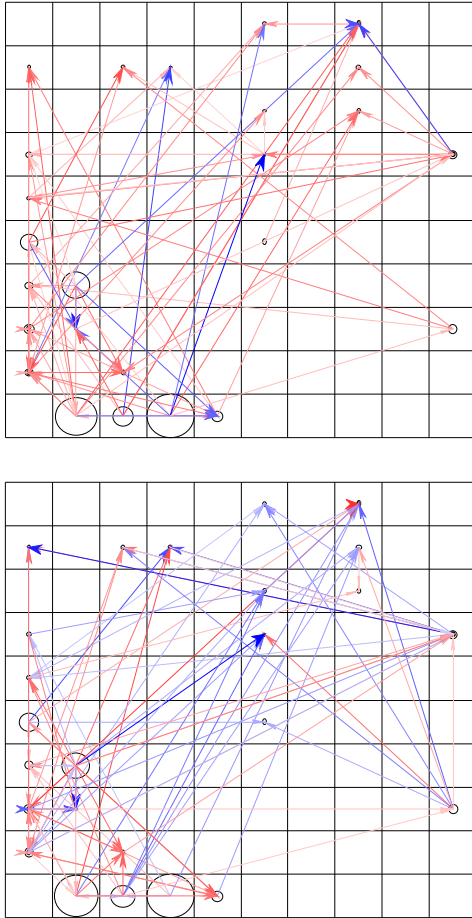


Fig. 4. Functional connectivity maps with all neurons in their respective positions on the Utah array, for the two datasets: Surround Suppression Inactive (upper panel) and Surround Suppression Active (lower panel). Red arrows denotes excitatory connections and blue arrows inhibitory. The strength of each connection is represented by the opaqueness of each arrow. The neuron's normalized response (to the highest firing neuron) is also plotted as the radius of each circle.

IV. DISCUSSION

Applying the Volterra Functional Connectivity on multi-electrode data, we identified dynamic changes in the functional organization of area V4 of the macaque cortex, when surround suppression is activated. The results suggest that neurons from the same area that are not significantly suppressed, contribute with inhibitory connections to the surround suppressed neurons. These connections become "active" only when a visual stimulus extends beyond the classical receptive field of the neurons and at the same time, several excitatory connections disappear. This suggests that the underlying circuit related to surround suppression is not the same with the organization of V4 neurons when surround suppression is not active and remains dormant until the surround of the cells gets activated by large enough stimuli.

It should be noted here that the results of functional connectivity methods are not equivalent to anatomical connections, but, as a data-true method, they rely on the neurons' recorded activity. Sampling of only a subset of neurons, as well as sampling from one specific area are known limiting factors. However, functional connections can reveal general properties of lateral interactions, inter-neuronal correlations critical for population coding, as well as dynamics of information flow in neuronal networks.

We propose an alternate approach to reveal the underlying networks responsible for a common feature of sensory neurons, surround suppression. Initial results showcase the potential of this approach, which combined with existing models can advance our understanding of the function of intra-areal connections.

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