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INTRODUCTION

As you stand looking at this poster imagine the enormous task your retina and visual brain need to accomplish! There are 100 million receptors in your retina that are constantly being bombarded by photons of light. These light signals are translated into electrical impulses in the retina. The retina and brain need to translate all of these signals into useful information. How does your visual brain do all of this in less than a second? You not only recognize colors and shapes, but also words and faces. The world seems stable but you are in constant motion, moving your head while you talk, your eyes while you read, or look around, and your feet to keep you balanced. You integrate what you see with what you hear and where people and objects are in space.

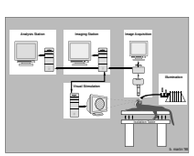
The overall goal of this research is to unravel the mysteries of visual signal processing by the brain. Specifically, we are interested in understanding how the visual thalamus and cortex interact to construct our perceptual world.

On this poster we provide several current examples of ongoing or past lab projects. In (**A**) (below) we use optical imaging of intrinsic signals to ask how feature maps are organized in primary visual cortex (V1) and one higher visual area, the middle temporal (MT) visual area. In (**B**) (right) we investigate whether sound can influence our perception of light at the earliest processing station in the brain, the lateral geniculate nucleus. In (**C**) we investigate a controversial hypothesis about the role of the visual thalamus in cortical visual processing. In (**D**) (far right) we provide evidence that the visual cortex is organized to facilitate perceptual skills. Finally, in (**E**), we show that coincident spikes can influence the transmission of sensory information between cortical neuron populations.

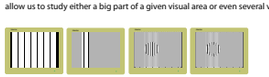
Details concerning these projects, our recent papers and the lab community can be found on our website listed above.

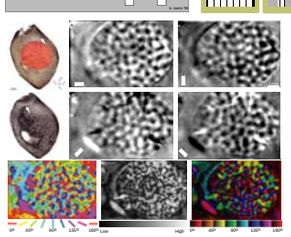
A. How are feature maps organized in visual cortex?

Our goal in this project is to determine functional organization of visual cortex. The visual system of primates has been the most intensely studied sensory system, given its major importance to humans and other primates. Of special importance are studies that compare the anatomical and functional organization of visual cortex across various primate species, since persistent similarities across species can add to our understanding of common underlying priciples of the visual system. We used a new technique, optical imaging of intrinsic signals, to examine the functional organization of primary visual cortex (V1) in distant primate relatives of humans, bush babies (*Otolemur garnetti*) and owl monkeys (*Aotus trivirgatus*). Until recently, the most commonly used technique to study the functional organization of the primate brain was recording from individual neurons (by means of electrophysiology). While this method is a powerful study tool, allowing the recording of the responses of individual cells with very fine temporal resolution, it is not very effective in creating overall functional maps of entire cortical areas, such as V1. By contrast, optical imaging can be used to map the functional organization of large regions of visual cortex simultaneously at fairly high resolution.



Side panel depicts our experimental setup. Animal is placed on the isolation table to eliminate vibration artifacts. Animals observe stimuli on the monitor, while the CCD camera acquires images of the brain illuminated with red light. Active regions of the brain consume oxygen, which changes the ratio of oxy- to deoxy-hemoglobin, resulting in more light being absorbed. Acquired data is transmitted to a computer where preliminary analysis is done. Further analysis is done off-line. Bottom panels depict the stimuli that were used in this study. Most cells in the primary visual cortex and several higher visual areas are very sensitive to moving gratings of different orientations. Confining such gratings to an area allows us to probe functional properties of confined parts of visual cortex, while full screen stimuli allow us to study either a big part of a given visual area or even several visual areas simultaneously.

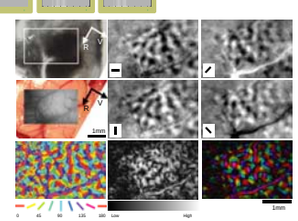




Funcitonal maps of area V1 in bush baby. Top left panel depicts alignment of the digital image with the vasculature obtained during the experiment on the first histological section. The white outline (white arrow) depicts the imaged area with the area of exposed brain shown as a circular outline in the center.

Four images shown at the right depict V1 responses (left to right, top to bottom) to 0, 90, 45, and 135 degree oriented full screen gratings.

These images were used to create the color coded orientation map seen in the bottom left panel, the magnitude map (bottom center) and the combined map (bottom right). Center left image depicts the correspondence between the imaged area and the cytochrome oxydase (CO) stained sections. These two panels were used to confirm that the data was acquired from area V1, which in bush babies has intense CO blob staining.



Functional maps of area MT in owl monkey. Top left, Myelin stained section showing heavy myelination in and around the middle temporal visual area (MT). White rectangle represents the studied area. R-rostral; V-ventral. Middle left, green light reference image of the cortical surface showing vascular pattern used to align optical images with histological sections. Reference image is aligned with color photo of the cortical surface.

Differential images of orientation preference (four top right), with the orientation preference of the darker patches indicated at the lower left corner of each panel.

Bottom left, orientation preference map obtained by vector summation of differential maps with color key shown below. Bottom middle, magnitude map showing strength of activation across MT, with key shown below. Bottom right, polar map showing both orientaion preference and magnitude of activation.

B. What does the visual thalamus contribute?

Our primary research goal is to understand more fully the functional role of the visual thalamus in human vision. We combine the precision of single unit electrophysiology with the power and freedom of an awake behaving animal preparation. We work with various species of macaque monkeys (indiginous to Asia and Northern Africa) because they have visual systems designed in a very similar way to humans, and equally important, they are intelligent enough to learn very complicated visuomotor tasks.

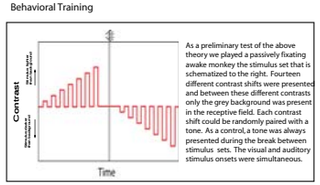
Behavioral Training

Before recording from single neurons, monkeys are trained to perform a series of tasks like the one shown at left. Here the monkey was required to fixate on the fixation spot (*) until a colored stimulus was presented on screen (■). In this task, shifting gaze to the stimulus elicited reward (fruit juice).

Tasks vary in complexity. The visually guided saccade task shown at left represents one of the first and most basic tasks the moneys learn.

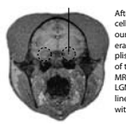
Another topic of interest is the way that sensory signals from the different sensory modalities interact. Our lab hypothesizes that the LGN may be an early sight where auditory and somatosensorysignals might influence the predominately visual information that is processed and relayed by the LGN.

Behavioral Training

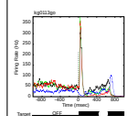


As a preliminary test of the above theory we played a passively fixating awake monkey the stimulus set that is schematized to the right. Fourteen different contrast shifts were presented and between these different contrasts only the grey background was present in the receptive field. Each contrast shift could be randomly paired with a tone. As a control, a tone was always presented during the break between stimulus sets. The visual and auditory stimulus onsets were simultaneous.

Electrophysiological Recordings

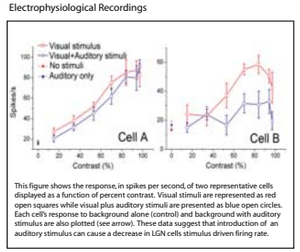


After behavioral training, recording from cells can begin. The first step is to locate our thalamic nucleus of interest, the lateral geniculate nucleus (LGN). We accomplish this via MRI and a stereotaxic atlas of the monkey brain. At left is a coronal MRI image showing the location of both LGN (circled in black). The vertical black line represents our recording electrode with its tip positioned within the left LGN.



Many LGN cells are color selective. This figure is a peri-stimulus time histogram (PSTH) showing the average response of a single LGN cell to presentations of colored stimuli inside its receptive field (RF) center. This cell increased its firing rate when red, green, and white stimuli were flashed in its RF (red trace, green trace, and black trace respectively) and decreased its firing rate when a blue stimulus was flashed in its RF (blue trace). This cell would be classified as a Blue OFF/Yellow ON color opponent cell.

Electrophysiological Recordings



This figure shows the response, in spikes per second, of two representative cells displayed as a function of percent contrast. Visual stimuli are represented as red open squares while visual plus auditory stimuli are presented as blue open circles. Each cell's response to background alone (control) and background with auditory stimulus are also plotted (see arrow). These data suggest that introduction of an auditory stimulus can cause a decrease in LGN cells stimulus driven firing rate.

C. What does the Pulvinar contribute?

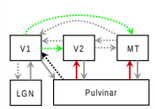


Figure 1

In this project we test the controversial hypothesis that all thalamic nuclei contain some cell groups that act as drivers (send the main message) and some that act as modulators for multiple cortical areas, thus mediating the generation of an array of diverse cortical functions. In the traditional view the thalamus acts as a passive relay to cortex and all subsequent processing of significance is done in the cortex. Our hypothesis is that the thalamus is not simply a passive relay to cortex. Instead, just as primary visual cortex (V1) depends on lateral geniculate nucleus (LGN), the secondary visual area (V2) and the middle temporal visual area (MT) depend on a combination of dedicated pathways through the thalamus (e.g., pulvinar) and direct feedforward connections from V1. This hypothesis is illustrated schematically in **Figure 1**. This arrangement allows new properties to emerge at both the thalamic and cortical levels through dynamic loops. Tests of this hypothesis involve both anatomical labeling of thalamic and cortical pathways and recording from pulvinar or cortex while manipulating alternative inputs through neural blockade or stimulation.

An example of one possible anatomical result that would partially support our hypothesis is shown in **Figure 2** where the driving input axons from pulvinar have larger boutons located closer to the cell body (red) and the modulatory axons from V1 have smaller boutons located farther from the cell body (green).

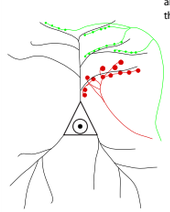


Figure 2

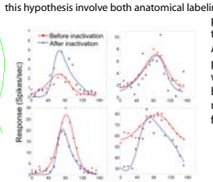
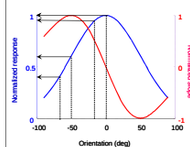


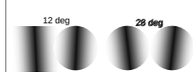
Figure 3

Figure 3. Responses of 4 V1 neurons before and after blocking the retinotopically matched region of the pulvinar. These results show that V1 responses do not change drastically when the pulvinar is inactivated, confirming our hypothesis that the feedback from the pulvinar to V1 is not necessary for "driving" V1 responses.

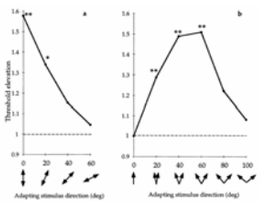
D. Is the visual cortex organized to facilitate perceptual skills?

In primates, neurons in the primary visual cortex are grouped together by their response properties and organized in orderly maps across the cortical surface. This systematic arrangement is thought to facilitate averaging within groups of similarly tuned neurons, minimize connection length, and ensure uninterrupted functionality over visual space. Optical imaging has shown systematic maps of activation domains, i.e., regions of cortex that are most responsive to a given stimulus feature, for many stimulus properties such as orientation, ocular dominance and spatial frequency in many species (see Section A).

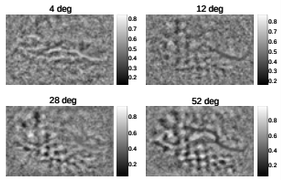




But maximum responsivity to a feature is associated with the detection of the feature while the discrimination of two similar features has been shown to depend on change in responsivity. Thus the location of the peak of the tuning curve determines what feature will be best ***detected*** by the neuron while the location of the steepest gradient of the tuning curve determines what features will be best ***discriminated*** by the neuron. Since primates excel at discrimination tasks as well as at detection, we asked whether the organization and read-out of information for both tasks follow the same principles. If this were true, then neurons must be grouped together into orderly maps according to the changes in responses they produce for small changes in feature values (fine discrimination).



To test this hypothesis, we performed optical imaging of intrinsic cortical signals from the primary visual cortex of the anesthetized, paralyzed bush baby for fine orientation discrimination. Sine wave gratings at the behaviourally optimal spatial and temporal frequencies were presented at increments and decrements of 2°, 4°, 8°, and 14° from the vertical orientation. Using receiver operating characteristic (ROC) curve analysis, we computed the probability with which the changes in reflectance value at a pixel could correctly predict the orientation of the stimulus shown to the animal. These discrimination probabilities were found to be organized in an orderly map of distinct domains, much the same way that orientation domains were organized across this cortical surface. For small orientation differences of about 4-8°, the peaks of these domains reached discrimination probabilities of 0.9 to 1.0. We suggest that functional maps for fine discrimination of features exist and that these maps are organized largely by the same principles followed for the organization of maps of feature selectivity.



E. How do cells communicate in visual cortex?

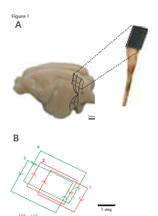


Figure 1
Examining the role of coincident spikes in neuronal activation in bush baby areas V1, V2 and V3. (**A**) Our animal model was ideal because the 100-electrode array we used had the capability of recording from many different neurons in retinotopically matching regions of V1, V2 and V3 of the bush baby. (**B**) V1 and V2 neuron receptive fields with similar orientation preference. (**C**) Because we recorded from so many different neurons, we were able to examine spike time correlations among pairs with both cells in the same area (intra-areal) and pairs with both neurons in different areas (inter-areal). Correlations among both these types of pairs were similar, although the inter-areal pair peaks were generally delayed several milliseconds.

Our lab has recently begun investigating neural coding in the primate visual system using a 100-electrode array. We have been the first to do large-scale recordings of single unit data from retinotopically-matching regions of V1, V2 and V3 in a primate (Figure 1A). Because the connectivity of these regions has been extensively studied, we have been able to examine the role of spiking properties on downstream spike activation. Specifically, in a recent study we examined the role of coincident spikes and spike counts on spike activation in higher area neurons. We found that both coincident spikes and spike counts are highly correlated with spiking activity in higher area neurons, however, whereas spike counts were correlated over longer time scales, coincident spikes are correlated with higher responses over shorter scales. For the coincident spikes we found that the strength of correlations measured between two neurons in a lower area (intra-areal pairs) is significantly related to the correlations measured between these neurons and their potential downstream targets (inter-areal pairs, Figure 1B). This could imply that during epochs where there is maximum coincidence among lower area neurons, these are also the epochs where these neurons are driving their downstream targets most efficiently. This was the first study that demonstrated that coincident spikes among cortico-cortical connections may have a significant impact on spiking properties.

We have also recently begun investigating the impact of local feedback connections from area MT on synchronizing spikes in visual area V1. Although the properties of single neurons were not affected, we find that in the absence of MT feedback there is a decreased probability of detecting coincident V1 spikes, and the amplitudes of the peaks are lower (**Fig 2**). These data suggest that feedback from area MT may have a role in coordinating population activity in lower visual areas.

Figure 2
Effect of blocking area MT on V1 spike time correlations. These spike time correlograms illustrate a common trend. Spike time correlations were significantly reduced after MT block.