

A SPATIOTEMPORAL FREQUENCY PERSPECTIVE ON THE COLUMNAR
ORGANIZATION OF POPULATION ACTIVITY IN VISUAL CORTEX

by

Amit Basole

Department of Neurobiology

Duke University

Date: _____

Approved:

David Fitzpatrick, Advisor

Dissertation submitted in partial fulfillment of
the requirements for the degree of Doctor
of Philosophy in the Department of
Neurobiology in the Graduate School
of Duke University
2005

ABSTRACT

The present study takes a spatiotemporal filtering perspective on one of the most prominent organizational principles of population activity in visual cortex, viz. columns or feature maps. Functional maps have been demonstrated in V1 for stimulus position, orientation, direction of motion and spatial frequency, as well as for ocular dominance, although not all maps are present in all species examined. The existence of such maps and the observed topological relationships between them has led to the proposal that they could serve as the basis for a spatial feature code. In this scheme, a specific combination of stimulus features would elicit a pattern of population activity that is predicted from the intersections of the independent feature maps. However, several properties of neural receptive fields in primary visual cortex make this scenario unlikely. While neural responses to stimulus position, orientation and eye of stimulation are indeed independent of each other, the same is not the case for orientation, direction of motion and spatial frequency. Spatiotemporal frequency theory that models neurons not as feature detectors but as frequency filters having bandpass properties in the two spatial and the temporal dimension, predicts several critical interdependencies between the neural selectivity for these three features. Here we demonstrate for the first time, using optical imaging of intrinsic signals, the population level consequences of spatiotemporal filtering that force us to revise our current notions of what is mapped in primary visual cortex. We also construct a simple receptive field model to show that such filtering can indeed account for the neural behavior we observe. Finally, we investigate the related question of the mapping of spatial frequency preference and show that this map, at least in the ferret, is dependent upon the maps of orientation and visual space. Thus the body of work presented in this thesis, taken together, argues against the view of V1 as consisting of several overlapping feature maps (of orientation, direction and spatial/temporal frequency) and in favor of preferred position in 3D frequency space being the most prominent functional receptive field property mapped in primary visual cortex.

To,

Ramchandra Hari Sahasrabudhey

(1917-2002)

Everything passes away - suffering, pain, blood, hunger and pestilence. The sword will pass away too, but the stars will remain when the shadows of our presence and our deeds have vanished from the earth. There is no man who does not know that. Why, then, will we not turn our eyes towards the stars? Why?

-Mikhail Bulgakov, The White Guard

**sab kahan; kuch lala-o-gul mein numayaan ho gaiin
khak mein kya suratein hongiin ke pinhaan ho gain**

**But a few do the tulip and the rose reveal
What faces of beauty must the dust conceal!**

-Asadullah Khan "Ghalib"

Chapter One: Introduction

Overview

The columnar organization of neural activity is one of the most prominent features of the visual cortex. From the classical orientation columns of V1 and the direction columns of MT to more tenuous “object columns” in inferotemporal cortex, columnar organization seems to be a recurring principle of cortical circuitry. While they are easy to demonstrate in the form of feature maps (which are basically a set of columns), particularly with the advent of *in vivo* imaging techniques such as optical imaging of intrinsic signals, the biological function of a column is still far from settled. This thesis concerns itself largely with functional columns in V1 and V2 (areas 17 and 18) of ferret visual cortex. In general terms, we will explore the consequences of adopting a spatiotemporal frequency space approach to interpreting neural activity, for feature maps in V1. We will attempt to show that spatial coding schemes that use multiple feature maps as their substrate will fail when one considers the true nature of the V1 map. This is due to the fact that many different combinations of stimulus features give rise to very similar columnar patterns of activity. This is expected if what a V1 neuron responds to are not particular stimulus features but those aspects of local spatiotemporal image structure that match its receptive field structure. Population activity in V1 then results from a map of receptive field position in spatiotemporal frequency space instead of from a set of overlapping maps of different stimulus features such as orientation or spatial frequency. The introductory chapter begins with a brief overview of the “neuron doctrine,” the preeminent unifying idea in modern neuroscience. We then go on to review the history of cortical columns in general and visual feature maps in particular. Next, a spatial coding scheme based on feature maps is articulated and potential problems with it are discussed. We end with an account of spatiotemporal filtering in visual cortex and its implications for cortical feature maps.

The neuron doctrine in modern neuroscience

Overwhelming evidence has accumulated since antiquity that an animal’s brain is essential for its behavior and for the successful propagation of its genes (but see Lorber, 1981). While it would be vain to pinpoint an exact time for the birth of modern neuroscience, the hundred year period from the later-half of the 19th century to the first-half of the 20th century saw several important advances that defined the shape it would take. Following an

early false start in the form of the phrenology school of Gall and others, area-level cytoarchitectonic studies of cortex, neuron-level anatomical studies of Golgi, Cajal, Sherrington and others and finally electrophysiological recordings (both cortical evoked potentials by Canton and spike recordings from peripheral neurons by Adrian and others) all saw the light of day in this brief period (Adrian, 1946; Finger, 1994). Ramon y Cajal's extension of the cell theory of Schleiden and Schwann to the brain, at the end of the 19th century (Shepherd, 1991), can be considered the beginning of an era in modern neuroscience. The forceful articulation by Cajal (and others of the so-called "neuron doctrine" school of thought), of the idea that the neuron constitutes an important, if not the fundamental functional unit of brain function undergirds all of modern neurophysiology and neuroanatomy.

Frogs and grandmothers

The functional analog of Cajal's essentially structural idea was articulated famously by Horace Barlow (Barlow, 1953; Barlow, 1972) and by Lettvin and colleagues (Lettvin et al., 1968) who spoke of "bug detectors" in the frog retina. The notion that the activity (spike discharge) of a single neuron is related directly to perception of a specific aspect of the outside world is now a commonly held belief among neuroscientists, even if not all will go the full extent of affirming their faith in the infamous "grandmother cell," the mythical neuron at the top of the neural totem pole that is sensitive to a complex organization of features (such as the face of one's grandmother). However, the discovery of neurons selective for complex visual objects (such as faces and fire extinguishers) in inferotemporal cortex (Gross et al., 1972; Tsunoda et al., 2001) make the grandmother-selective neuron seem like not such an outlandish idea after all. Although, exactly how a neuron selective for a complex object could subservise perception of that object is still unclear, the link between neural selectivity and perception (Barlow's 4th and 5th dogmas, see Barlow, 1972) has been most convincingly demonstrated for the middle temporal area (MT) in primates. But before we discuss that, the particular types of feature selectivity discovered in visual cortex need to be examined.

Receptive fields

In relating the activity of single neurons to perception, the neural receptive field is an important concept. Hartline (1940) first spoke of a neural receptive field as being that area of visual space where an increase in brightness elicited increased spike discharge from the retinal ganglion cells he was recording from. However,

the spatial aspect of a receptive field is only its most obvious feature. Since the early days of physiological recordings, much attention has been focused on an analysis of the receptive field properties of neurons starting at the periphery of the visual system (Barlow, 1953; Hartline and Ratliff, 1957; Kuffler, 1953). The reason for such efforts is that a characterization of the input-output transform of a neuron is believed to be the key to understanding visual processing. In line with this project and closely following Mountcastle's pioneering efforts in somatosensory cortex (Mountcastle, 1957; Powell and Mountcastle, 1959), Hubel and Wiesel greatly advanced our understanding of the transforms performed by neurons in primary visual cortex (Hubel and Wiesel, 1962; Hubel and Wiesel, 1965; Hubel and Wiesel, 1968). One significant discovery to result from this work was the phenomenon of orientation selectivity. Neurons in visual cortex responded differentially to bars of light depending upon the spatial orientation of the bar. **Figure 1.1a** (top) shows a typical orientation tuning curve obtained from an extracellular recording in ferret V1. As can be seen the neuron has a preferred orientation (i.e. the orientation in response to which it fires the most number of spikes) and an orientation bandwidth (i.e. the width of the tuning curve). Further work by Hubel, Wiesel and other investigators showed that cortical neurons responded selectively to many aspects of the visual stimulus including its direction and speed of motion, its spatial frequency (i.e. the size and spatial detail of a pattern), its contrast and in a few cases its color as well (Livingstone and Hubel, 1984). Example direction and spatial frequency tuning curves from the ferret are shown in **Figure 1.1a** (middle and bottom panels).

From feature selectivity to perception via population codes

A simple (and tempting) interpretation of orientation or direction selectivity is that these properties encode the perception of orientation or motion direction in the world. Such an interpretation is indeed widely endorsed and a large number of experiments and computational models have been devoted to elaborating upon this theme. However, it is also obvious from visual inspection of the tuning curves shown in **Figure 1.1a** that an individual neuron responds to a broad range of orientations or spatial frequencies. This observation argues against the straightforward notion that each neuron may subserve the detection of a given orientation or for that matter any other feature. Indeed it was the physicist Thomas Young who noticed early on that since there were an infinite number of possible stimuli (in his case color or wavelength of cone excitation) it would be rather uneconomical (not to say impossible) for the nervous system to have a separate receptor dedicated to the detection of each stimulus (the so-called labeled-line hypothesis of coding). On the other hand, he argued

for color, the existence of just three broadly tuned receptors would be adequate provided (and this is the key insight) one were to consider the activation of a given receptor *with reference to* the activity of the other two (Young, 1802). Such a system would today be called a “population code” or a “distributed code.” That broad neural tuning functions require some sort of distributed coding scheme has been appreciated independently by many authors working in different sensory systems (see Erickson, 2001 for a comparative review). A relevant thought from Hartline (1940) is worth quoting because it prefigures several of the ideas that we now consider commonplace and that have been most convincingly demonstrated by optical imaging of intrinsic signals, a technique extensively employed in the present study. Hartline says with regard to position coding by the retina:

“It is evident that illumination of a given element of area on the retina results in a specific pattern of activity in a specific group of optic nerve fibres. The particular fibres involved, and the distribution of activity among them are characteristic of the location on the retina of the particular element of area illuminated. Corresponding to different points on the retina are different patterns of nerve activity; *even two closely adjacent points do not produce quite the same distribution of activity, although they may excite many fibres in common*” (Hartline, 1940, quoted in Erickson, 2001, italics mine).

This basic idea has now been extended in generalized formal models for many different sensory, motor and even cognitive applications (Deneve et al., 1999).

The next step, from population codes to perception has also been attempted albeit these are still early days. In a comprehensive article Parker and Newsome (1998) review various forms of experimental evidence in many different sensory systems that try to establish the link between sensory perception and the activity of neurons in the sensory cortices. The lines of evidence presented are of the following types:

1. The sensitivity of the neuron to a particular parameter matches well with the organism’s sensitivity, i.e. the neurometric function and the psychometric function are comparable.
2. Signal detection theory approaches can be applied to neural data to show that an ideal observer could discriminate between two alternatives based on the differences in neural activity and neural discrimination thresholds thus measured, match psychophysical ones.
3. Simultaneous acquisition of neural and psychophysical data shows that under identical conditions both performances can be comparable and that on a trial-by-trial basis errors in neural discrimination are reflected in the organism’s decisions
4. Electrical microstimulation shows that artificially increased activity levels in a population of neurons with a particular preference affects the organism’s performance by biasing its decisions in the manner predicted by the

stimulation

All the above criteria have been met and the connection between a neural receptive field property and perception most clearly demonstrated, in the primate visual area MT for the perception of direction of motion (Britten et al., 1992; Newsome and Pare, 1988; Salzman et al., 1990; Salzman et al., 1992; Shadlen et al., 1996). However almost everywhere else in the visual system and elsewhere in the brain this connection remains problematic and the link from neural activity to perception is far from clear. Experiments described in thesis further complicate straightforward interpretations of neural activity as conveying information about specific features of the visual world, at least for early visual cortex.

Coding with Columns

Along with selectivity to stimulus features, described in the previous section, we will be equally concerned with a particular spatial organization of feature selective responses found in mammalian cerebral cortex. This organization is the cortical column, arguably the most salient feature of the cerebral cortex, discovered first by Mountcastle in primate somatosensory cortex and soon after by Hubel and Wiesel in cat and primate visual cortex (Hubel and Wiesel, 1977; Mountcastle, 1957).

A computational unit of cortical function?

Although cortical anatomists had noticed something akin to a columnar organization of cells normal to the pial surface as early as the 1920s, Lorente de No in 1949 was one of the first to explicitly talk about a cortex “composed of an enormous number of elementary units” (quoted in Mountcastle, 2003). The functional proof of this concept came in the form of Mountcastle’s observations in his seminal study on the somatosensory system of the cat. He recorded from a series of neurons in a vertical penetration (normal to the pial surface) and found that these neurons shared several of their receptive field properties (e.g. they were activated by the same class of peripheral receptors) (Mountcastle, 1957). Extending Mountcastle’s work to the visual system, Hubel and Wiesel noted that neighboring neurons in cat and monkey striate cortex were responsive to stimulation in largely overlapping parts of visual space and were also tuned to similar orientations. Moreover the preferred orientation and the preferred position in space changed smoothly if one recorded a sequence of neurons in a tangential (as parallel to the pial surface as possible) penetration through cortex. This led them to propose

that the visual cortex consisted of sets of such “orientation columns” (which in their scheme is the amount of cortical space it takes to change the preferred orientation by 10° , which amounts to $\sim 50 \mu\text{m}$) (Hubel and Wiesel, 1977). Over the years many other stimulus features have been added to the list of columns and elaborate spatial coding schemes have been proposed taking inspiration from Hubel and Wiesel’s original observations. These are discussed in the next section.

While the foregoing picture of the cortical column is correct in its broad outlines, there are several problems too. Firstly, the anatomical features of a column are not as easy to find as the physiology might suggest. In fact Mountcastle’s initial discovery was received with doubt precisely because anatomical features to delineate a column were hard to find (Mountcastle, 2003). That said there are still many features of local and long-distance intracortical circuitry that seem to obey some sort of columnar rule (Bosking et al., 1997; Gilbert and Wiesel, 1989; Kisvarday et al., 1997; Lund et al., 2003). Perhaps it is more accurate to say that many properties that obey such rules are not strictly columnar in that they do not occur in all cortical layers. Thus at the functional level, receptive field properties do not stay strictly constant in the vertical dimension. For example, neurons in layer 4c of the primate are poorly tuned for orientation, while those in layer 2/3 are well-tuned (Blasdel and Fitzpatrick, 1984) and neurons in layer 4b are well-tuned for direction while those in layer 2/3 are not (Hawken et al., 1988). Secondly, the functional extent of a column may itself vary based on the type of technique used to measure it as well as the choice of stimulus. For example, in the original scheme proposed by Hubel and Wiesel an orientation column was the amount of cortical space required to change the preferred orientation by 10° ($\sim 50 \mu\text{m}$). With modern imaging techniques it is possible to show that even a single orientation can activate a cortical area as broad as $200\text{-}300 \mu\text{m}$ (Blasdel, 1992; Bonhoeffer and Grinvald, 1991). This is presumably a function of the orientation tuning width, which can be up to 45° (half-width at half-height). As a corollary, stimuli that evoke more broadly tuned responses will result in a broader “columnar” activity pattern. These facts may argue against the monolithic nature of a column, however they do not rule out the possibility that different components of a column (e.g. different lamina) function together to perform the same computations everywhere. The observation that one can induce orientation modules in auditory cortex by routing retinal inputs to it (Sharma et al., 2000) does suggest some kind of equivalence of general function between varied sensory cortices. At the theoretical level the idea of cortex as a generic model-builder that performs the same computations everywhere has been articulated by (Barlow, 1985). Whatever form this

computation may take (and it is far from clear at this point), experiments presented here argue that it is unlikely to be the detection of a single orientation or any other such simple feature.

Optical imaging and the 2D columnar organization of feature selectivity

Although extracellular single unit recording had revealed the phenomenon of feature selectivity and even given us some understanding of its organization in visual cortex, the technique was incapable of addressing the issue of two-dimensional organization. The 2D patterns of ocular dominance columns could be demonstrated by injection of tracers such as tritiated proline into the eye however a property such as orientation selectivity which is essentially a functional aspect of neural organization could not be similarly tackled. The advent of 2-deoxy glucose (2DG) labeling revealed for the first time the actual nature of orientation columns. Using a full-field grating of one orientation Hubel et al. (1978) demonstrated that orientation columns in macaque striate cortex were more complex than the originally conceived “slabs” that would run orthogonal to the ocular dominance columns (i.e. the ice-cube model in Hubel and Wiesel, 1977). Although 2DG labeling is an activity-based technique (it labels metabolically active neural populations) it has the serious limitation that the experimenter can only measure the cortical response to one stimulus before the animal has to be sacrificed for autoradiography. It was optical imaging of intrinsic signals that first offered a powerful new way of visualizing the patterns of activity evoked by many orientations within the same piece of cortex. Intrinsic signal imaging is an *in vivo* technique that relies on the fact that increases in neural activity cause an increased metabolic demand in the active tissue (in this it is similar to 2-DG labeling) which in turn causes changes in the tissue reflectance under red illumination (>600 nm). The changes in reflectance have been mainly attributed to changes in the ratio of oxy to deoxy hemoglobin as well as less well-defined changes in the way light is scattered by active neural tissue (Bonhoeffer and Grinvald, 1996; Frostig et al., 1990; Malonek et al., 1997). This technique revealed a prominent attribute of the functional architecture of primary visual cortex in the form of “feature maps.” A feature map is the result of a systematic 2D organization of neurons in which neighboring neurons are similarly tuned to a stimulus property (i.e. fire more action potentials in response to a stimulus with say the same orientation or spatial frequency). Such maps have now been demonstrated in areas V1 and V2 of cats, ferrets and primates for ocular dominance and for stimulus position, orientation, direction of motion and spatial frequency (Blasdel and Salama, 1986; Bonhoeffer and Grinvald, 1991; Everson et al., 1998; Hubel and Wiesel, 1977; Hubener et al., 1997; Issa et al., 2000; Shmuel and Grinvald, 1996; Weliky et al.,

1996; Rao et al., 1997; White et al., 2001; White et al., 1999). The first feature maps to be demonstrated with optical imaging were the maps of ocular dominance and orientation (Blasdel and Salama, 1986; Grinvald et al., 1986). Subsequent to these initial discoveries, several studies in the early 1990s established the key aspects of organization of the orientation map such as pinwheels (around which orientation preference goes the full circle) and saddle points where orientation preference changes only slowly (Bartfeld and Grinvald, 1992; Blasdel, 1992; Bonhoeffer and Grinvald, 1991).

Figure 1.1b shows examples of feature maps obtained by measuring the optical response to full-field gratings that differ in one of the three parameters. Here the color of a pixel denotes its orientation, direction or spatial frequency preference. It is obvious that neighboring pixels share stimulus preferences, as Hubel and Wiesel had first noted in their extracellular recordings. As a consequence of the presence of a feature map, the presentation of a particular stimulus orientation, for example, results in a cortical activation pattern that can be well-predicted based on the knowledge of the topology of the orientation map (which provides the center-of-mass of the activity pattern) and the tuning width of individual neurons (which provides the spread of activity around its center-of-mass). This aspect of cortical organization (first demonstrated by 2DG but most convincingly shown by optical imaging of intrinsic signals) has led some to propose that feature maps could serve as bases for a spatial code wherein the spatial pattern of cortical activity resulting from a stimulus would encode information about particular stimulus features. The idea at its core is the same as the population coding schemes discussed earlier, but in addition it has a spatial dimension that abstract population coding schemes lack.

The multiple-maps hypothesis, map relationships and the idea of “coverage”

The concept of coverage draws inspiration from the views of cortical function alluded to earlier, which hold that the same basic computational function is performed by cortex in an iterative fashion everywhere, while the inputs and outputs change. Central to this notion is the existence of a piece of “cortical machinery” devoted to processing information from a small part of the world. This basic machinery is thought to be replicated so as to cover all parts of the visual field. “Coverage” thus refers to the act of covering all parts of the visual field with machinery for processing all aspects of the visual scene (orientation, direction, spatial frequency etc). It was once again Hubel and Wiesel, who first asked a simple question starting this line of inquiry. They pondered “what happens to the position of receptive fields in the visual field as an electrode moving

horizontally through the cortex traverses a hypercolumn” (a unit of cortex required to accommodate neurons with orientation preferences spanning the entire 180° range)? They pointed out that it would “make no sense at all if movement through one orientation hypercolumn were associated with a movement through the visual field that was large compared to aggregate field size” because that would mean that there were “holes” in the cortical representation of orientation (Hubel and Wiesel, 1977). Furthermore, in their “ice-cube” model of visual cortex, out of similar coverage considerations, Hubel and Wiesel also proposed that ocular dominance bands should intersect orientation slabs at some consistent angle. In accordance with this prediction, iso-orientation lines have been shown to run orthogonal to ocular dominance boundaries while orientation pinwheels are centered along the midline of ocular dominance columns in cat and monkey (Bartfeld and Grinvald, 1992; Blasdel et al., 1995; Hubener et al., 1997). Surprisingly, the relationship between the maps of visual space and orientation has been somewhat more controversial. An early report argued that the mapping of visual space in the cat was not smooth (as had been thought) and that orientation rate-of-change (ROC) was positively correlated with ROC in the visual space map (for e.g. near pinwheels where orientation ROC is highest, neighboring neurons were seen to have spatially non-overlapping receptive fields) (Das and Gilbert, 1997). The implication of this finding is that there are “holes” in the cortical mapping of orientation such that all orientations are not in fact covered for all parts of visual space. Later findings have shown that this is, in fact, not the case in both cats (Buzas et al., 2003) and tree shrews (Bosking et al., 2002).

Although Hubel and Wiesel’s original model was limited to the three maps of orientation, ocular dominance and visual space (and wisely so, for good evidence exists to suggest that these receptive field properties are independent of each other, as required for the coverage idea to work), the idea has since been extended to the mapping of the three receptive field properties that will be of main concern to us viz. orientation, direction of motion and spatial frequency. Orderly relationships between these three (and possibly even more) overlapping feature maps are thought to ensure that all combinations of stimulus features are represented uniformly across the visual field (Issa et al., 2000; Swindale, 2000; Swindale et al., 2000). Many studies have been devoted to delineating the topological relationships between these feature maps. Thus orientation domains are thought to be divided into two direction domains of opposite directions orthogonal to that orientation (Shmuel and Grinvald, 1996; Weliky et al., 1996) and possibly into several spatial frequency sub-domains that code for a gradient of spatial frequencies from low to high. Moreover, high spatial frequency zones are thought to coincide with orientation pinwheel centers (Issa et al., 2000). The spatial organization

of spatial frequency preference, however, has proved to be much more controversial than that of orientation preference and these relationships are not as robust as those found between the orientation map and maps of visual space and ocular dominance. We take up the issue of spatial frequency maps in more detail in Chapter Four.

Furthermore, in the foregoing framework, a specific combination of stimulus features (e.g. a vertical stimulus of high spatial frequency moving to the right) is represented by a pattern of population activity that corresponds to appropriate intersecting regions of different feature maps and this pattern of activity uniquely signifies the presence of a specific combination of stimulus features. This hypothesis, here referred to as the “multiple-maps hypothesis” is illustrated schematically in **Figure 1.2**. To quote Swindale (2000):

“In addition to topographic map of the retina, mammalian visual cortex contains superimposed, orderly periodic maps of features such as orientation, eye dominance, direction of motion and spatial frequency. There is evidence that these maps are overlaid so as to ensure that all combinations of the different parameters are represented as uniformly as possible across visual space.”

However, as we shall see, this whole scheme is problematic for anything beyond Hubel and Wiesel’s original combination of orientation, ocular dominance and visual space mapping. In particular for the relationships between orientation, direction and spatial frequency this idea has appeared to be sustainable not because these feature are truly independent in the neural response but largely because of the choice of stimuli employed in studying feature maps.

The aperture problem and limitations of full-field grating stimuli

To date, the multiple-maps hypothesis has been based on the analysis of cortical responses to drifting gratings wherein the range of motion and spatial frequency cues is limited to those that vary along an axis orthogonal to the grating’s orientation. This limitation is a consequence of the so-called “aperture problem” (Wallach, 1935; English translation by Wuerger et al., 1996). As shown in **Figure 1.3** the veridical direction of motion of a line segment translating behind an aperture is ambiguous. Its apparent motion is determined by the geometry of the aperture and the direction of motion of its end-points or “terminators.” Thus for a circular aperture, though the motion of a line always appears to be orthogonal to its orientation, the direction of perceived motion is in fact consistent with any of an infinite number of veridical directions (**Fig. 1.3a**). Similarly, in the well-known “Barber-Pole Illusion” a line segment translating behind a rectangular aperture

appears to move either in the up-down axis or the left-right axis depending on the orientation of the rectangle (**Fig. 1.3b**, for more compelling demonstrations of this effect see <http://www.purveslab.net/>). Since full-field gratings which extend beyond the limits of the stimulus field (monitor) can be considered as infinite line segments, their motion is constrained along an axis orthogonal to their orientation. Moreover the spatial frequency of a grating (or an infinitely long line segment) is also defined only along an axis orthogonal to its orientation by virtue of the fact that the luminance modulation along the axis parallel to the line orientation is zero (**Fig. 1.3c**, in this and all such subsequent images, the x and y axes correspond to spatial frequency along the x and y dimensions and the color scale encodes magnitude of power at a given frequency.). Hence it is not possible, with grating stimuli, to examine two dimensional interactions between motion, orientation and spatial frequency that are common in real world situations.

At this point one may wonder why gratings became the stimulus of choice for studying functional maps. As described below, the use of sine wave gratings in revealing maps of orientation, direction and spatial frequency was a natural extension of their use in describing receptive field properties, where they played a pivotal role in challenging the feature detector view of cortical receptive field organization. It is thus one of the ironies of scientific inquiry that grating stimuli have been used to construct the multiple maps hypothesis even by investigators whose work at the single unit level challenged the feature detector hypothesis.

How to think about V1 neurons: Edge detectors or Fourier analyzers

In order to appreciate the use of sine wave gratings to characterize visual responses some background is required on current receptive field models of visual cortical neurons. Revolutionary though they were in advancing our understanding of visual cortical processing, the Hubel-Wiesel experiments offered an ultimately restrictive view of neural receptive field properties. In their model, neurons in V1 were primarily considered orientation or edge detectors. Using simple stimuli such as flashed and moving bars of light, they classified neurons in primary visual cortex into several subtypes and classes. One enduring dichotomy on which much attention has been focused is that between simple cells and complex cells. Simple cells have receptive fields that can be divided into spatially distinct excitatory and inhibitory subdivisions (the so-called “on” and “off” subfields), while complex cells usually show overlapping on and off responses all over the receptive field. Moreover, simple cells seem to sum inputs from different parts of the receptive field in a more-or-less linear

fashion while complex cells are obviously non-linear in their responses (Movshon et al., 1978a; Movshon et al., 1978c).

A frequency space challenge to edge-detection

Through the 1970s the Hubel-Wiesel view was challenged and the model of V1 receptive fields made more sophisticated, by the work of several investigators (De Valois et al., 1979; Movshon, 1975; Movshon et al., 1978a; Movshon et al., 1978b; Movshon et al., 1978c; Hammond and MacKay, 1977). The idea of using sine-wave gratings, linear systems theory and Fourier analysis to understand neural response dates back to the pioneering studies of Enroth-Cugell and colleagues (Campbell et al., 1969). Since those early days, many studies have been devoted to developing a comprehensive linear filtering model for cortical simple cells (Carandini et al., 1999; De Valois et al., 1979; De Valois and De Valois, 1988; Jones and Palmer, 1987a; McLean and Palmer, 1989; Movshon et al., 1978b; Simoncelli and Heeger, 1998; Skottun et al., 1994). At the core of these efforts lies the idea that simple cells respond (to varying degrees of approximation) by performing a weighted integration of luminance within the receptive field over local space and recent time. We now describe two applications of linear systems theory to understanding the behavior of cortical neurons.

Movshon et al. (1978c), showed that for simple cells in cat striate cortex, the spatial frequency tuning function and the spatial impulse response (also called the line-weighting function because it is determined by measuring the response of the cell to thin lines positioned at different places within the receptive field) were related to each other via the Fourier transform. More specifically one could predict the shape of the line-weighting function (or the spatial profile of activation) from the inverse Fourier transform of the spatial frequency tuning curve. This brings out the equivalence between the space domain organization of the receptive field (revealed by its line-weighting function) and its frequency domain organization (revealed by its spatial frequency tuning curve). This finding has since been replicated by several authors (Andrews and Pollen, 1979; Glezer et al., 1982; Kulikowski and Bishop, 1981) and extended into the time domain by DeAngelis et al. (1993) who show that, for layer 4 simple cells, receptive field maps obtained by reverse correlation techniques can well predict the spatial *and* temporal frequency tuning measured by sine-wave gratings. Such equivalence between the two domains is characteristic of a linear neuron (or linear system). We will exploit this linearity in Chapter Three when we present a space domain receptive field model and demonstrate that its behavior is equivalent to two frequency domain models of our data published by Mante and Carandini (2005) and Baker

and Issa (2005).

Our second example is a much cited experiment by De Valois et al. (1979) that attempts to settle the question of whether V1 neurons (in the cat) function as edge detectors or frequency filters. Using sine-wave gratings and checkerboard stimuli DeValois et al showed that the responses of V1 neurons (simple and complex) were correctly predicted by the orientation and spatial frequency of the Fourier components and not the orientation of the edges present in the stimulus (but see MacKay, 1981) for an alternative explanation). Thus a neuron would respond equivalently to checkerboards of many different orientations as long as the Fourier fundamental in the checkerboard was oriented at the same angle. This experiment is possible because, unlike a square or sine wave grating, a checkerboard can possess power in the frequency domain at orientations other than the orientation of the edges of its elements (because of the presence of corners in the pattern).

Spatiotemporal frequency filters

The two examples cited above showed that a simple edge-detection framework was inadequate to describe the behavior of V1 neurons. This work has since been extended and formalized. Many investigators have shown that neural responses in V1 and V2 can be modeled as the output of a quasi-linear (“quasi” because strict linearity is not possible for reasons such as the presence of a spike threshold and other non-linearities discussed later), band-pass filters, sensitive to a range of spatial frequencies along two spatial dimensions as well as to a range of temporal frequencies (De Valois et al., 1979; De Valois and De Valois, 1988; Movshon et al., 1978b; Movshon et al., 1978c; Skottun et al., 1994; DeAngelis et al., 1993; Jones and Palmer, 1987a). In this conception, each neuron has a receptive field in three-dimensional frequency space, the shape of which is determined by the tuning function of the neuron along each of the three dimensions. **Figure 1.4a** adapted from Mante and Carandini, schematically depicts such a receptive field (Mante and Carandini, 2005). This work and its relation to the present study are recounted in the Discussion section of Chapter Three. **Figure 1.4b** shows a slice of the same receptive field in the two spatial dimensions (collapsing across the temporal frequency axis) and schematically demonstrates the preferred orientation of such a neuron based on its preferred 2D spatial frequency. That such a neuron would behave in an orientation selective fashion and that its orientation selectivity (as measured by single bars, for example) is a consequence of its tuning in frequency space was demonstrated by DeValois et al. (1979). The foregoing discussion applies most immediately to simple cells. Complex cells are similar to simple cells in having selectivity for orientation in space-time (see red arrow

in **Fig. 1.4a**) resulting from the position of their receptive field in frequency space. However, unlike simple cells, their responses are phase independent (i.e. independent of the precise location of the stimulus within the receptive field). The phase independence is usually modeled as resulting from a combination of two or more phase dependent (simple-cell like) subunits that are squared and summed. These subunits are in quadrature i.e. 90° out-of-phase with one another (Adelson and Bergen, 1985). There is indeed some evidence that complex cell receptive fields are built out of a number of linear simple-cell like subunits (e.g. Martinez and Alonso, 2001), although this idea is by no means universally accepted (Fregnac, 1996; Martin and Whitteridge, 1984). For our purposes, the distinction between simple and complex cells is not as important as the similarities, the key similarity being that they are both selective for spatiotemporally oriented stimulus energy.

Consequences for cortical functional architecture

It now remains to list a few consequences of spatiotemporal filtering for tuning to stimulus features. Then the challenge to the multiple map framework discussed earlier, will be obvious. It has been shown that preferred orientation depends on the spatial frequency content of a stimulus (De Valois et al., 1979), preferred direction depends upon its speed (Hammond and Reck, 1980), and the preferred spatial frequency can vary with orientation (Webster and De Valois, 1985). These observations are consistent with the main assumptions of spatiotemporal filtering but they raise problems for the multiple-maps hypothesis since they imply that orientation, direction and spatial frequency selectivity are dependent upon one another. While these ideas are not new, their implications for population codes based on multiple maps have not been appreciated. If a neuron acts as a multidimensional filter, its output will be related to its input by a convolution integral (in case of linear filters). Such a neuron is not expected to faithfully encode a particular feature such as orientation or spatial frequency independent of changes in other features. Even for neurons that display obvious non-linearities (e.g. complex cells) the response is determined by a combination of features that contribute to the energy (i.e. the power at different frequencies) of the stimulus. Since this neuron responds not just to a particular spatial pattern (such as an oriented line) but to a range of spatial and temporal frequencies, it seems likely that its measured orientation preference will not be constant but instead will change with the frequency content of the stimulus. Thus the above described line of empirical research also leads us to question the multiple-maps hypothesis couched as it is in terms of independent orientation, direction and spatial frequency maps. Adopting

a spatiotemporal filtering framework, such as the one outlined above thus forces us to revise our notions of what is mapped in primary visual cortex. The remainder of this thesis is dedicated to articulating this viewpoint with the help of empirical data from the ferret.

Aim and scope of the present study

With specialization comes modesty of endeavor. And hence, the scope of the present study is considerably less grand than the preceding introduction may suggest. The following is a brief outline of the work presented in Chapters Two, Three and Four. In Chapter Two we present evidence that “orientation maps” in ferret V1 and V2 are better thought of as maps of receptive field position in spatiotemporal frequency space (henceforth preferred position in frequency space). This study was published in 2003 under the title “Mapping multiple features in the population response of visual cortex” (Basole et al., 2003). Chapter Three describes a computational receptive field model that attempts to explain the results of Basole et al in the spatiotemporal frequency framework. Chapter Four considers the question of spatial frequency maps and whether preferred spatial frequency is mapped independent of other features, in visual cortex. Chapter Five concludes the thesis with a general discussion of the results.

Figure 1.1: Tuning curves and preference maps in visual cortex

a. Extracellularly recorded tuning curves for bar orientation (top), direction of motion (middle) and spatial frequency of a sine-wave grating (bottom, on \log_2 scale). Each point is average number of spikes/trials \pm s.e.m.
b. Preference maps for orientation (top), direction (middle) and spatial frequency (bottom) obtained with optical imaging of intrinsic signals. Keys on right of each image show the color code for each variable. The spatial frequency map is from Issa et al. (2000) (copyright 2000 by the Society for Neuroscience).

Figure 1.2: The multiple map hypothesis

Top: An optical image showing orientation domains (black) activated by the presentation of a horizontal grating. Superimposed on the orientation domains are arrows indicating the preferred direction of motion. Each orientation domain is divided into direction domains preferring opposite directions of motion. Bottom: Each direction domain is further sub-divided into high and low spatial frequency preferring sub-domains.

Figure 1.3: The aperture problem

a. An infinite line segment translating behind a circular aperture. The perceived direction of motion (red arrow) is orthogonal to the line orientation and is consistent with an infinite number of veridical directions (some of which are shown as black arrows). **b.** The “barber-pole” constitutes a single line or a grating translating behind a rectangular aperture. The perceived direction of motion of the line is determined by the geometry of the aperture. **c.** An infinite line segment in the space (left) and frequency (right) domains. The frequency domain representation of the 2D image shows power only at an orientation orthogonal to the orientation of line segment in space. The axes for the 2D power spectrum are spatial frequency along the x axis (SF_x) and spatial frequency along the y axis (SF_y). The origin of the plot is at the center of the image and the spectrum is symmetrical about the origin (out of convention). Amount of power (normalized to the maximum value) is represented by the pseudocolor scale with larger values being shown as hotter colors.

Figure 1.4: Receptive fields in spatiotemporal frequency space

a. The figure shows two spheres of the receptive field (corresponding to the neural response to opposite directions of motion). The three axes are ω_x – spatial frequency along the x dimension, ω_y – spatial frequency along the y dimension and ω_t – temporal frequency. The shape of the sphere is a result of its tuning function along each of the three dimensions and its position determined the preferred orientation in space-time (red arrow) of the receptive field (adapted from an earlier version of Mante and Carandini (2005)). **b.** A 2D projection of the right quadrant of the plot in a, collapsing across the temporal frequency axis. The receptive field is now a circle and the slope of the line from the origin to the center of the circle is the preferred orientation (in space only) of this neuron.

WORK CITED

- Adelson, E. H., and Bergen, J. R. (1985). Spatiotemporal energy models for the perception of motion. *J Opt Soc Am A* 2, 284-299.
- Adelson, E. H., and Movshon, J. A. (1982). Phenomenal coherence of moving visual patterns. *Nature* 300, 523-525.
- Adrian, E. D. (1946). *The Physical Background of Perception* (London, Oxford University Press).
- Albus, K. (1975). A quantitative study of the projection area of the central and the paracentral visual field in area 17 of the cat. II. The spatial organization of the orientation domain. *Exp Brain Res* 24, 181-202.
- Amthor, F. R., and Grzywacz, N. M. (1993). Inhibition in ON-OFF directionally selective ganglion cells of the rabbit retina. *J Neurophysiol* 69, 2174-2187.
- Andrews, B. W., and Pollen, D. A. (1979). Relationship between spatial frequency selectivity and receptive field profile of simple cells. *J Physiol* 287, 163-176.
- Appelle, S. (1972). Perception and discrimination as a function of stimulus orientation: the “oblique effect” in man and animals. *Psychol Bull* 78, 266-278.
- Attneave, F. (1954). Some informational aspects of visual perception. *Psychol Rev* 61, 183-193.
- Baker, G. E., Thompson, I. D., Krug, K., Smyth, D., and Tolhurst, D. J. (1998). Spatial-frequency tuning and geniculocortical projections in the visual cortex (areas 17 and 18) of the pigmented ferret. *Eur J Neurosci* 10, 2657-2668.
- Baker, T. I., and Issa, N. P. (2005). Cortical maps of separable tuning properties predict population responses to complex visual stimuli. *J Neurophysiol*. 94, 775-787.
- Barlow, H. (2001). Redundancy reduction revisited. *Network* 12, 241-253.
- Barlow, H. B. (1953). Summation and inhibition in the frog's retina. *J Physiol* 119, 69-88.
- Barlow, H. B. (1972). Single units and sensation: a neuron doctrine for perceptual psychology? *Perception* 1, 371-394.
- Barlow, H. B. (1985). Cerebral cortex as model builder. In *Models of the visual cortex*, D. Rose, and V. G. Dobson, eds. (New York, John Wiley and Sons), pp. 37-46.
- Barlow, H. B., and Levick, W. R. (1965). The mechanism of directionally selective units in rabbit's retina. *J Physiol* 178, 477- 504.

- Bartfeld, E., and Grinvald, A. (1992). Relationships between orientation-preference pinwheels, cytochrome oxidase blobs, and ocular-dominance columns in primate striate cortex. *Proc Natl Acad Sci U S A* 89, 11905-11909.
- Basole, A., White, L. E., and Fitzpatrick, D. (2003). Mapping multiple features in the population response of visual cortex. *Nature* 423, 986-990.
- Bauer, J. A., Jr., Owens, D. A., Thomas, J., and Held, R. (1979). Monkeys show an oblique effect. *Perception* 8, 247-253.
- Bauer, R., and Jordan, W. (1993). Different anisotropies for texture and grating stimuli in the visual map of cat striate cortex. *Vision Res* 33, 1447-1450.
- Bell, A. J., and Sejnowski, T. J. (1997). The “independent components” of natural scenes are edge filters. *Vision Res* 37, 3327-3338.
- Berkeley, G. (1709/1975). Philosophical works including works on vision (London, Everyman/J.M.Dent).
- Blakemore, C., and Campbell, F. W. (1969). On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. *J Physiol* 203, 237-260.
- Blasdel, G., Obermayer, K., and Kiorpes, L. (1995). Organization of ocular dominance and orientation columns in the striate cortex of neonatal macaque monkeys. *Vis Neurosci* 12, 589-603.
- Blasdel, G. G. (1992). Differential imaging of ocular dominance and orientation selectivity in monkey striate cortex. *J Neurosci* 12, 3115-3138.
- Blasdel, G. G., and Fitzpatrick, D. (1984). Physiological organization of layer 4 in macaque striate cortex. *J Neurosci* 4, 880-895.
- Blasdel, G. G., and Salama, G. (1986). Voltage-sensitive dyes reveal a modular organization in monkey striate cortex. *Nature* 321, 579-585.
- Bonhoeffer, T., and Grinvald, A. (1991). Iso-orientation domains in cat visual cortex are arranged in pinwheel-like patterns. *Nature* 353, 429-431.
- Bonhoeffer, T., and Grinvald, A. (1996). Optical Imaging of Intrinsic Signals. In *Brain Mapping: The Methods*, A. W. Toga, and J. C. Mazziotta, eds. (New York, Academic), pp. 55-97.
- Borg-Graham, L. J., Monier, C., and Fregnac, Y. (1998). Visual input evokes transient and strong shunting inhibition in visual cortical neurons. *Nature* 393, 369-373.
- Born, R. T., and Tootell, R. B. (1991). Spatial frequency tuning of single units in macaque supragranular striate cortex. *Proc Natl Acad Sci U S A* 88, 7066-7070.
- Bosking, W. H., Crowley, J. C., and Fitzpatrick, D. (2002). Spatial coding of position and orientation in primary visual cortex. *Nat Neurosci* 5, 874-882.

- Bosking, W. H., Zhang, Y., Schofield, B., and Fitzpatrick, D. (1997). Orientation selectivity and the arrangement of horizontal connections in tree shrew striate cortex. *J Neurosci* *17*, 2112-2127.
- Bridge, H., Cumming, B. G., and Parker, A. J. (2001). Modeling V1 neuronal responses to orientation disparity. *Vis Neurosci* *18*, 879-891.
- Britten, K. H., Shadlen, M. N., Newsome, W. T., and Movshon, J. A. (1992). The analysis of visual motion: a comparison of neuronal and psychophysical performance. *J Neurosci* *12*, 4745-4765.
- Burr, D. C., and Ross, J. (2002). Direct evidence that “speedlines” influence motion mechanisms. *J Neurosci* *22*, 8661-8664.
- Buzas, P., Volgushev, M., Eysel, U. T., and Kisvarday, Z. F. (2003). Independence of visuotopic representation and orientation map in the visual cortex of the cat. *Eur J Neurosci* *18*, 957-968.
- Campbell, F. W., Cooper, G. F., and Enroth-Cugell, C. (1969). The spatial selectivity of the visual cells of the cat. *J Physiol* *203*, 223-235.
- Carandini, M., and Ferster, D. (1997). A tonic hyperpolarization underlying contrast adaptation in cat visual cortex. *Science* *276*, 949-952.
- Carandini, M., Heeger, D. J., and Movshon, J. A. (1997). Linearity and normalization in simple cells of the macaque primary visual cortex. *Journal of Neuroscience* *17*, 8621-8644.
- Carandini, M., Heeger, D. J., and Movshon, J. A. (1999). Linearity and gain control in V1 simple cells. In *Cerebral Cortex*, P. S. Ulinski, ed. (New York, Kluwer Academic/Plenum), pp. 401-443.
- Caywood, M. S., Willmore, B., and Tolhurst, D. J. (2004). Independent components of color natural scenes resemble V1 neurons in their spatial and color tuning. *J Neurophysiol* *91*, 2859-2873.
- Chapman, B., and Bonhoeffer, T. (1998). Overrepresentation of horizontal and vertical orientation preferences in developing ferret area 17. *Proc Natl Acad Sci U S A* *95*, 2609-2614.
- Chapman, B., Zahs, K. R., and Stryker, M. P. (1991). Relation of cortical cell orientation selectivity to alignment of receptive fields of the geniculocortical afferents that arborize within a single orientation column in ferret visual cortex. *J Neurosci* *11*, 1347-1358.
- Chavane, F., Monier, C., Bringuier, V., Baudot, P., Borg-Graham, L., Lorenceau, J., and Fregnac, Y. (2000). The visual cortical association field: a Gestalt concept or a psychophysiological entity? *J Physiol Paris* *94*, 333-342.
- Coppola, D. M., Purves, H. R., McCoy, A. N., and Purves, D. (1998a). The distribution of oriented contours in the real world. *Proc Natl Acad Sci U S A* *95*, 4002-4006.
- Coppola, D. M., White, L. E., Fitzpatrick, D., and Purves, D. (1998b). Unequal representation of cardinal and oblique contours in ferret visual cortex. *Proc Natl Acad Sci U S A* *95*, 2621-2623.

- Dan, Y., Atick, J. J., and Reid, R. C. (1996). Efficient coding of natural scenes in the lateral geniculate nucleus: experimental test of a computational theory. *J Neurosci* *16*, 3351-3362.
- Das, A., and Gilbert, C. D. (1997). Distortions of visuotopic map match orientation singularities in primary visual cortex. *Nature* *387*, 594-598.
- Daugman, J. G. (1985). Uncertainty relation for resolution in space, spatial frequency, and orientation optimized by two-dimensional visual cortical filters. *J Opt Soc Am A* *2*, 1160-1169.
- David, S. V., Vinje, W. E., and Gallant, J. L. (2004). Natural stimulus statistics alter the receptive field structure of v1 neurons. *J Neurosci* *24*, 6991-7006.
- De Valois, K. K., De Valois, R. L., and Yund, E. W. (1979). Responses of striate cortex cells to grating and checkerboard patterns. *J Physiol* *291*, 483-505.
- De Valois, R. L., and De Valois, K. K. (1988). *Spatial Vision* (New York, Oxford University Press).
- DeAngelis, G. C., Ghose, G. M., Ohzawa, I., and Freeman, R. D. (1999). Functional micro-organization of primary visual cortex: receptive field analysis of nearby neurons. *J Neurosci* *19*, 4046-4064.
- DeAngelis, G. C., Ohzawa, I., and Freeman, R. D. (1993). Spatiotemporal organization of simple-cell receptive fields in the cat's striate cortex. II. Linearity of temporal and spatial summation. *Journal of Neurophysiology* *69*, 1118-1135.
- Deneve, S., Latham, P. E., and Pouget, A. (1999). Reading population codes: a neural implementation of ideal observers. *Nat Neurosci* *2*, 740-745.
- Derrington, A. M., and Fuchs, A. F. (1979). Spatial and temporal properties of X and Y cells in the cat lateral geniculate nucleus. *J Physiol* *293*, 347-364.
- Erickson, R. P. (2001). The evolution and implications of population and modular neural coding ideas. *Prog Brain Res* *130*, 9-29.
- Everson, R. M., Prashanth, A. K., Gabbay, M., Knight, B. W., Sirovich, L., and Kaplan, E. (1998). Representation of spatial frequency and orientation in the visual cortex. *Proc Natl Acad Sci U S A* *95*, 8334-8338.
- Finger, S. (1994). *Origins of Neuroscience* (New York, Oxford University Press).
- Fitzpatrick, D. (2000). Cortical imaging: capturing the moment. *Curr Biol* *10*, R187-190.
- Fregnac, Y. (1996). Dynamics of functional connectivity in visual cortical networks: an overview. *J Physiol Paris* *90*, 113-139.
- Frostig, R. D., Lieke, E. E., Ts'o, D. Y., and Grinvald, A. (1990). Cortical functional architecture and local coupling between neuronal activity and the microcirculation revealed by in vivo high-resolution optical imaging of intrinsic signals. *Proc Natl Acad Sci U S A* *87*, 6082-6086.

- Furmanski, C. S., and Engel, S. A. (2000). An oblique effect in human primary visual cortex. *Nat Neurosci* 3, 535-536.
- Gabbiani, F., Krapp, H. G., Hatsopoulos, N., Mo, C. H., Koch, C., and Laurent, G. (2004). Multiplication and stimulus invariance in a looming-sensitive neuron. *J Physiol Paris* 98, 19-34.
- Gabbiani, F., Krapp, H. G., Koch, C., and Laurent, G. (2002). Multiplicative computation in a visual neuron sensitive to looming. *Nature* 420, 320-324.
- Gabor, D. (1946). Theory of communication. *JIEE Lond* 93, 429-457.
- Geisler, W. S. (1999). Motion streaks provide a spatial code for motion direction. *Nature* 400, 65-69.
- Geisler, W. S., Albrecht, D. G., Crane, A. M., and Stern, L. (2001). Motion direction signals in the primary visual cortex of cat and monkey. *Vis Neurosci* 18, 501-516.
- Gilbert, C. D. (1977). Laminar differences in receptive field properties of cells in cat primary visual cortex. *J Physiol* 268, 391-421.
- Gilbert, C. D., and Wiesel, T. N. (1989). Columnar specificity of intrinsic horizontal and corticocortical connections in cat visual cortex. *J Neurosci* 9, 2432-2442.
- Gizzi, M. S. y., Katz, E., Schumer, R. A., and Movshon, J. A. (1990). Selectivity for orientation and direction of motion of single neurons in cat striate and extrastriate visual cortex. *Journal of Neurophysiology* 63, 1529-1543.
- Glezer, V. D., Tsherbach, T. A., Gauselman, V. E., and Bondarko, V. M. (1982). Spatio-temporal organization of receptive fields of the cat striate cortex. The receptive fields as the grating filters. *Biol Cybern* 43, 35-49.
- Graham, N., and Nachmias, J. (1971). Detection of grating patterns containing two spatial frequencies: a comparison of single-channel and multiple-channels models. *Vision Res* 11, 251-259.
- Grinvald, A., Lieke, E., Frostig, R. D., Gilbert, C. D., and Wiesel, T. N. (1986). Functional architecture of cortex revealed by optical imaging of intrinsic signals. *Nature* 324, 361-364.
- Gross, C. G., Rocha-Miranda, C. E., and Bender, D. B. (1972). Visual properties of neurons in inferotemporal cortex of the Macaque. *J Neurophysiol* 35, 96-111.
- Hammond, P., and MacKay, D. M. (1977). Differential responsiveness of simple and complex cells in cat striate cortex to visual texture. *Exp Brain Res* 30, 275-296.
- Hammond, P., and Reck, J. (1980). Influence of velocity on directional tuning of complex cells in cat striate cortex for texture motion. *Neuroscience Letters* 19.
- Hammond, P., and Smith, A. T. (1983). Directional tuning interactions between moving oriented and textured stimuli in complex cells of feline striate cortex. *J Physiol* 342, 35-49.
- Hansen, B. C., and Essock, E. A. (2004). A horizontal bias in human visual processing of orientation and its

correspondence to the structural components of natural scenes. *J Vis* 4, 1044-1060.

Hansen, B. C., Essock, E. A., Zheng, Y., and DeFord, J. K. (2003). Perceptual anisotropies in visual processing and their relation to natural image statistics. *Network* 14, 501-526.

Hartline, H. K. (1940). The receptive field of the optic nerve fibers. *American Journal of Physiology* 130, 690-699.

Hartline, H. K., and Ratliff, F. (1957). Inhibitory interaction of receptor units in the eye of *Limulus*. *J Gen Physiol* 40, 357-376.

Hawken, M. J., Parker, A. J., and Lund, J. S. (1988). Laminar organization and contrast sensitivity of direction-selective cells in the striate cortex of the Old World monkey. *J Neurosci* 8, 3541-3548.

Henderson, Z., Finlay, B. L., and Wikler, K. C. (1988). Development of ganglion cell topography in ferret retina. *J Neurosci* 8, 1194-1205.

Hubel, D. H., and Wiesel, T. N. (1962). Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *J Physiol* 160, 106-154.

Hubel, D. H., and Wiesel, T. N. (1965). Receptive Fields and Functional Architecture in Two Nonstriate Visual Areas (18 and 19) of the Cat. *J Neurophysiol* 28, 229-289.

Hubel, D. H., and Wiesel, T. N. (1968). Receptive fields and functional architecture of monkey striate cortex. *J Physiol* 195, 215-243.

Hubel, D. H., and Wiesel, T. N. (1977). Ferrier lecture. Functional architecture of macaque monkey visual cortex. *Proc R Soc Lond B Biol Sci* 198, 1-59.

Hubel, D. H., Wiesel, T. N., and Stryker, M. P. (1978). Anatomical demonstration of orientation columns in macaque monkey. *J Comp Neurol* 177, 361-380.

Hubener, M., Shoham, D., Grinvald, A., and Bonhoeffer, T. (1997). Spatial relationships among three columnar systems in cat area 17. *J Neurosci* 17, 9270-9284.

Issa, N. P., Trepel, C., and Stryker, M. P. (2000). Spatial frequency maps in cat visual cortex. *J Neurosci* 20, 8504-8514.

Jagadeesh, B. y., Wheat, H. S., and Ferster, D. (1993). Linearity of summation of synaptic potentials underlying direction selectivity in simple cells of the cat visual cortex. *Science* 262, 1901-1904.

Jones, J. P., and Palmer, L. A. (1987a). An evaluation of the two-dimensional Gabor filter model of simple receptive fields in cat striate cortex. *J Neurophysiol* 58, 1233-1258.

Jones, J. P., and Palmer, L. A. (1987b). The two-dimensional spatial structure of simple receptive fields in cat striate cortex. *J Neurophysiol* 58, 1187-1211.

Jones, J. P., Stepnoski, A., and Palmer, L. A. (1987). The two-dimensional spectral structure of simple receptive fields in cat striate cortex. *J Neurophysiol* 58, 1212-1232.

- Keil, M. S., and Cristobal, G. (2000). Separating the chaff from the wheat: possible origins of the oblique effect. *J Opt Soc Am A Opt Image Sci Vis* 17, 697-710.
- Kersten, D. (1999). High-Level Vision as Statistical Inference. In *The New Cognitive Neurosciences*, M. S. Gazzaniga, ed. (Cambridge, MIT Press).
- Kisvarday, Z. F., Toth, E., Rausch, M., and Eysel, U. T. (1997). Orientation-specific relationship between populations of excitatory and inhibitory lateral connections in the visual cortex of the cat. *Cereb Cortex* 7, 605-618.
- Kuffler, S. W. (1953). Discharge patterns and functional organization of mammalian retina. *J Neurophysiol* 16, 37-68.
- Kulikowski, J. J., and Bishop, P. O. (1981). Linear analysis of the responses of simple cells in the cat visual cortex. *Exp Brain Res* 44, 386-400.
- Law, M. I., Zaksas, K. R., and Stryker, M. P. (1988). Organization of primary visual cortex (area 17) in the ferret. *J Comp Neurol* 278, 157-180.
- Lee, T. W., Wachtler, T., and Sejnowski, T. J. (2002). Color opponency is an efficient representation of spectral properties in natural scenes. *Vision Res* 42, 2095-2103.
- Lettvin, J. Y., Maturana, H. R., McCulloch, W. S., and Pitts, W. H. (1968). What the frog's eye tells the frog's brain. In *The Mind: Biological approaches to its functions*, W. C. Corning, and M. Balaban, eds., pp. 233-258.
- Leventhal, A. G., and Hirsch, H. V. (1977). Effects of early experience upon orientation sensitivity and binocularity of neurons in visual cortex of cats. *Proc Natl Acad Sci U S A* 74, 1272-1276.
- Li, B., Peterson, M. R., and Freeman, R. D. (2003). Oblique effect: a neural basis in the visual cortex. *J Neurophysiol* 90, 204-217.
- Livingstone, M. S., and Hubel, D. H. (1984). Anatomy and physiology of a color system in the primate visual cortex. *J Neurosci* 4, 309-356.
- Livingstone, M. S. y. (1998). Mechanisms of direction selectivity in macaque V1. *Neuron* 20, 509-526.
- Lorber, J. (1981). Is your brain really necessary? *Nurs Mirror* 152, 29-30.
- Lorenceanu, J., Shiffrar, M., Wells, N., and Castet, E. (1993). Different motion sensitive units are involved in recovering the direction of moving lines. *Vision Res* 33, 1207-1217.
- Lund, J. S., Angelucci, A., and Bressloff, P. C. (2003). Anatomical substrates for functional columns in macaque monkey primary visual cortex. *Cereb Cortex* 13, 15-24.
- MacKay, D. M. (1981). Strife over visual cortical function. *Nature* 289, 117-118.
- Maffei, L., and Fiorentini, A. (1973). The visual cortex as a spatial frequency analyser. *Vision Res* 13, 1255-

1267.

Maffei, L., and Fiorentini, A. (1977). Spatial frequency rows in the striate visual cortex. *Vision Res* 17, 257-264.

Maldonado, P. E., Godecke, I., Gray, C. M., and Bonhoeffer, T. (1997). Orientation selectivity in pinwheel centers in cat striate cortex. *Science* 276, 1551-1555.

Malonek, D., Dirnagl, U., Lindauer, U., Yamada, K., Kanno, I., and Grinvald, A. (1997). Vascular imprints of neuronal activity: relationships between the dynamics of cortical blood flow, oxygenation, and volume changes following sensory stimulation. *Proc Natl Acad Sci U S A* 94, 14826-14831.

Mansfield, R. J., and Ronner, S. F. (1978). Orientation anisotropy in monkey visual cortex. *Brain Res* 149, 229-234.

Mante, V., and Carandini, M. (2005). Mapping of stimulus energy in primary visual cortex. *J Neurophysiol.* 94, 788-798.

Marr, D. (1982). *Vision* (San Francisco, W.H. Freeman and Company).

Martin, K. A., and Whitteridge, D. (1984). Form, function and intracortical projections of spiny neurones in the striate visual cortex of the cat. *J Physiol* 353, 463-504.

Martinez, L. M., and Alonso, J. M. (2001). Construction of complex receptive fields in cat primary visual cortex. *Neuron* 32, 515-525.

Masson, G. S., Rybarczyk, Y., Castet, E., and Mestre, D. R. (2000). Temporal dynamics of motion integration for the initiation of tracking eye movements at ultra-short latencies. *Vis Neurosci* 17, 753-767.

McLean, J., and Palmer, L. A. (1989). Contribution of linear spatiotemporal receptive field structure to velocity selectivity of simple cells in area 17 of cat. *Vision Research* 29, 675-679.

Mooser, F., Bosking, W. H., and Fitzpatrick, D. (2004). A morphological basis for orientation tuning in primary visual cortex. *Nat Neurosci* 7, 872-879.

Mountcastle, V. B. (1957). Modality and topographic properties of single neurons of cat's somatic sensory cortex. *J Neurophysiol* 20, 408-434.

Mountcastle, V. B. (2003). Introduction. *Computation in cortical columns. Cereb Cortex* 13, 2-4.

Movshon, J. A. (1975). The velocity tuning of single units in cat striate cortex. *Journal of Physiology* 249, 445-468.

Movshon, J. A., and Newsome, W. T. (1996). Visual response properties of striate cortical neurons projecting to area MT in macaque monkeys. *Journal of Neuroscience* 16, 7733-7741.

Movshon, J. A., Thompson, I. D., and Tolhurst, D. J. (1978a). Receptive field organization of complex cells in the cat's striate cortex. *Journal of Physiology* 283, 79-99.

- Movshon, J. A., Thompson, I. D., and Tolhurst, D. J. (1978b). Spatial and temporal contrast sensitivity of neurones in areas 17 and 18 of the cat's visual cortex. *Journal of Physiology* 283, 101-120.
- Movshon, J. A., Thompson, I. D., and Tolhurst, D. J. (1978c). Spatial summation in the receptive fields of simple cells in the cat's striate cortex. *Journal of Physiology* 283, 53-77.
- Muller, T., Stetter, M., Hubener, M., Sengpiel, F., Bonhoeffer, T., Godecke, I., Chapman, B., Lowel, S., and Obermayer, K. (2000). An analysis of orientation and ocular dominance patterns in the visual cortex of cats and ferrets. *Neural Comput* 12, 2573-2595.
- Newsome, W. T., and Pare, E. B. (1988). A selective impairment of motion perception following lesions of the middle temporal visual area (MT). *J Neurosci* 8, 2201-2211.
- Nundy, S. (2004) The perception of brightness and orientation in relation to the success or failure of visually-guided behavior, PhD thesis, Duke University, Durham.
- Olshausen, B. A., and Field, D. J. (1997). Sparse coding with an overcomplete basis set: a strategy employed by V1? *Vision Res* 37, 3311-3325.
- Pack, C. C., Berezovskii, V. K., and Born, R. T. (2001). Dynamic properties of neurons in cortical area MT in alert and anaesthetized macaque monkeys. *Nature* 414, 905-908.
- Pack, C. C., and Born, R. T. (2001). Temporal dynamics of a neural solution to the aperture problem in visual area MT of macaque brain. *Nature* 409, 1040-1042.
- Pack, C. C., Gartland, A. J., and Born, R. T. (2004). Integration of Contour and Terminator Signals in Visual Area MT of Alert Macaque. *J Neurosci* 24, 3268-3280.
- Pack, C. C., Livingstone, M. S., Duffy, K. R., and Born, R. T. (2003). End-stopping and the aperture problem: two-dimensional motion signals in macaque V1. *Neuron* 39, 671-680.
- Parker, A. J., and Newsome, W. T. (1998). Sense and the single neuron: probing the physiology of perception. *Annu Rev Neurosci* 21, 227-277.
- Pettigrew, J. D., Nikara, T., and Bishop, P. O. (1968). Responses to moving slits by single units in cat striate cortex. *Exp Brain Res* 6, 373-390.
- Powell, T. P., and Mountcastle, V. B. (1959). Some aspects of the functional organization of the cortex of the postcentral gyrus of the monkey: a correlation of findings obtained in a single unit analysis with cytoarchitecture. *Bull Johns Hopkins Hosp* 105, 133-162.
- Purves, D., and Lotto, B. (2003). *Why We See What We Do* (Sunderland, MA, Sinauer Associates).
- Rao, S. C., Toth, L. J., and Sur, M. (1997). Optically imaged maps of orientation preference in primary visual cortex of cats and ferrets. *J Comp Neurol* 387, 358-370.
- Richmond, B. J., Optican, L. M., and Spitzer, H. (1990). Temporal encoding of two-dimensional patterns by single units in primate primary visual cortex. I. Stimulus-response relations. *J Neurophysiol* 64, 351-369.

A., and Bialek, W. (1995). Naturalistic stimuli increase the rate and efficiency of information transmission by primary auditory afferents. *Proc Biol Sci* 262, 259-265.

Saarinen, J., and Levi, D. M. (1995). Orientation anisotropy in vernier acuity. *Vision Res* 35, 2449-2461.

Sachs, M. B., Nachmias, J., and Robson, J. G. (1971). Spatial-frequency channels in human vision. *J Opt Soc Am* 61, 1176-1186.

Salzman, C. D., Britten, K. H., and Newsome, W. T. (1990). Cortical microstimulation influences perceptual judgements of motion direction. *Nature* 346, 174-177.

Salzman, C. D., Murasugi, C. M., Britten, K. H., and Newsome, W. T. (1992). Microstimulation in visual area MT: effects on direction discrimination performance. *J Neurosci* 12, 2331-2355.

Saul, A. B., and Humphrey, A. L. (1990). Spatial and temporal response properties of lagged and nonlagged cells in cat lateral geniculate nucleus. *J Neurophysiol* 64, 206-224.

Sengpiel, F., Stawinski, P., and Bonhoeffer, T. (1999). Influence of experience on orientation maps in cat visual cortex. *Nat Neurosci* 2, 727-732.

Shadlen, M. N., Britten, K. H., Newsome, W. T., and Movshon, J. A. (1996). A computational analysis of the relationship between neuronal and behavioral responses to visual motion. *J Neurosci* 16, 1486-1510.

Sharma, J., Angelucci, A., and Sur, M. (2000). Induction of visual orientation modules in auditory cortex. *Nature* 404, 841-847.

Shepherd, G. M. (1991). *Foundations of the neuron doctrine* (New York, Oxford University Press).

Shmuel, A., and Grinvald, A. (1996). Functional organization for direction of motion and its relationship to orientation maps in cat area 18. *J Neurosci* 16, 6945-6964.

Shoham, D., Glaser, D. E., Arieli, A., Kenet, T., Wijnbergen, C., Toledo, Y., Hildesheim, R., and Grinvald, A. (1999). Imaging cortical dynamics at high spatial and temporal resolution with novel blue voltage-sensitive dyes. *Neuron* 24, 791-802.

Shoham, D., Hubener, M., Schulze, S., Grinvald, A., and Bonhoeffer, T. (1997). Spatio-temporal frequency domains and their relation to cytochrome oxidase staining in cat visual cortex. *Nature* 385, 529-533.

Silverman, M. S., Grosz, D. H., De Valois, R. L., and Elfar, S. D. (1989). Spatial-frequency organization in primate striate cortex. *Proc Natl Acad Sci U S A* 86, 711-715.

Simoncelli, E. P., and Heeger, D. J. (1998). A model of neuronal responses in visual area MT. *Vision Res* 38, 743-761.

Simoncelli, E. P., and Olshausen, B. A. (2001). Natural image statistics and neural representation. *Annu Rev Neurosci* 24, 1193-1216.

- Sirovich, L., and Uglesich, R. (2004). The organization of orientation and spatial frequency in primary visual cortex. *Proc Natl Acad Sci U S A* 101, 16941-16946.
- Skottun, B. C., Zhang, J., and Grosof, D. (1994). On the directional selectivity of cells in the visual cortex to drifting dot patterns. *Visual Neuroscience* 11, 885- 897.
- So, Y. T., and Shapley, R. (1981). Spatial tuning of cells in and around lateral geniculate nucleus of the cat: X and Y relay cells and perigeniculate interneurons. *J Neurophysiol* 45, 107-120.
- Somers, D. C., Nelson, S. B., and Sur, M. (1995). An emergent model of orientation selectivity in cat visual cortical simple cells. *J Neurosci* 15, 5448-5465.
- Swindale, N. V. (2000). How many maps are there in visual cortex? *Cereb Cortex* 10, 633-643.
- Swindale, N. V., Shoham, D., Grinvald, A., Bonhoeffer, T., and Hubener, M. (2000). Visual cortex maps are optimized for uniform coverage. *Nat Neurosci* 3, 822-826.
- Switkes, E., Mayer, M. J., and Sloan, J. A. (1978). Spatial frequency analysis of the visual environment: anisotropy and the carpentered environment hypothesis. *Vision Res* 18, 1393-1399.
- Tolhurst, D. J., and Thompson, I. D. (1982). Organization of neurones preferring similar spatial frequencies in cat striate cortex. *Exp Brain Res* 48, 217-227.
- Tootell, R. B., Silverman, M. S., and De Valois, R. L. (1981). Spatial frequency columns in primary visual cortex. *Science* 214, 813-815.
- Tootell, R. B., Silverman, M. S., Hamilton, S. L., Switkes, E., and De Valois, R. L. (1988). Functional anatomy of macaque striate cortex. V. Spatial frequency. *J Neurosci* 8, 1610-1624.
- Tsodyks, M., Kenet, T., Grinvald, A., and Arieli, A. (1999). Linking spontaneous activity of single cortical neurons and the underlying functional architecture. *Science* 286, 1943-1946.
- Tsunoda, K., Yamane, Y., Nishizaki, M., and Tanifuji, M. (2001). Complex objects are represented in macaque inferotemporal cortex by the combination of feature columns. *Nat Neurosci* 4, 832-838.
- Tusa, R. J., Palmer, L. A., and Rosenquist, A. C. (1978). The retinotopic organization of area 17 (striate cortex) in the cat. *J Comp Neurol* 177, 213-235.
- Usrey, W. M., Sceniak, M. P., and Chapman, B. (2003). Receptive fields and response properties of neurons in layer 4 of ferret visual cortex. *J Neurophysiol* 89, 1003-1015.
- van Gelder, T. (1995). What might cognition be if not computation. *The Journal of Philosophy* 92, 345-381.
- Vitek, D. J., Schall, J. D., and Leventhal, A. G. (1985). Morphology, central projections, and dendritic field orientation of retinal ganglion cells in the ferret. *J Comp Neurol* 241, 1-11.
- Walker, G. A., Ohzawa, I., and Freeman, R. D. (2000). Suppression outside the classical cortical receptive field. *Vis Neurosci* 17, 369-379.

- Wallach, H. (1935). Uber visuell wahrgenommene Bewegungrichtung. *Psychologische Forschung* 20, 325-380.
- Wang, G., Ding, S., and Yunokuchi, K. (2003a). Difference in the representation of cardinal and oblique contours in cat visual cortex. *Neurosci Lett* 338, 77-81.
- Wang, G., Ding, S., and Yunokuchi, K. (2003b). Representation of cardinal contour overlaps less with representation of nearby angles in cat visual cortex. *J Neurophysiol* 90, 3912-3920.
- Watson, A. B., and Ahumada, A. J. (1983). A look at motion in the frequency domain. NASA Technical Memorandum TM-84352.
- Webster, M. A., and De Valois, R. L. (1985). Relationship between spatial-frequency and orientation tuning of striate-cortex cells. *J Opt Soc Am A* 2, 1124-1132.
- Weliky, M., Bosking, W. H., and Fitzpatrick, D. (1996). A systematic map of direction preference in primary visual cortex. *Nature* 379, 725- 728.
- White, L. E., Bosking, W. H., Williams, S. M., and Fitzpatrick, D. (1999). Maps of central visual space in ferret V1 and V2 lack matching inputs from the two eyes. *J Neurosci* 19, 7089-7099.
- White, L. E., Coppola, D. M., and Fitzpatrick, D. (2001). The contribution of sensory experience to the maturation of orientation selectivity in ferret visual cortex. *Nature* 411, 1049-1052.
- Wilson, H. R., Loffler, G., Wilkinson, F., and Thistlethwaite, W. A. (2001). An inverse oblique effect in human vision. *Vision Res* 41, 1749-1753.
- Wingate, R. J., Fitzgibbon, T., and Thompson, I. D. (1992). Lucifer yellow, retrograde tracers, and fractal analysis characterise adult ferret retinal ganglion cells. *J Comp Neurol* 323, 449-474.
- Wuerger, S., Shapley, R., and Rubin, N. (1996). "On the visually perceived direction of motion" by Hans Wallach, 60 yers later. *Perception* 25, 1317-1367.
- Yang, Z., Shimpi, A., and Purves, D. (2001). A wholly empirical explanation of perceived motion. *Proc Natl Acad Sci U S A* 98, 5252-5257.
- Yo, C., and Wilson, H. R. (1992). Perceived direction of moving two-dimensional patterns depends on duration, contrast and eccentricity. *Vision Res* 32, 135-147.
- Young, T. (1802). On the theory of light and colors. *Philos Trans R Soc Lond*, 12.
- Yu, H. B., and Shou, T. D. (2000a). [The oblique effect revealed by optical imaging in primary visual cortex of cats]. *Sheng Li Xue Bao* 52, 431-434.
- Yu, H. B., and Shou, T. D. (2000b). [Spatial frequency tuning characteristics of cat primary visual cortex at different topological locations by optical imaging]. *Sheng Li Xue Bao* 52, 411-415.