A shrewd insight for vision

Farran Briggs and **W Martin Usrey**

Center for Neuroscience, University of California, Davis, California 95616, USA. e-mail:
wmusrey@ucdavis.edu

Abstract

The circuitry responsible for generating orientation-specific responses in primary visual cortex
remains controversial. A new study identifies an anatomical substrate for orientation selectivity
and suggests the mechanism may be conserved across species.

For over 40 years, scientists have hotly debated how orientation tuning emerges in the visual
system. One reason for such intense scrutiny is that this work provides insight into the
general question of how structure underlies function in the brain. As with other emergent
properties of cortical neurons, identifying the circuitry responsible for orientation tuning has
proven extremely difficult. This difficulty is partly due to the complexity of intracortical
connections, along with the strong possibility that more than one mechanism may be at play.
Hubel and Wiesel suggested that orientation tuning results from an anatomically precise
organization of feedforward projections from the lateral geniculate nucleus (LGN) of the
thalamus to layer 4 of visual cortex[1]. In contrast, alternative models assert that feedforward
projections lack sufficient strength and precision to support orientation tuning; these models
emphasize the role of intracortical mechanisms in amplifying and sharpening orientation
tuning[2–5]. In this issue, Mooser, Bosking and Fitzpatrick[6] identify an elegant anatomical
substrate that may support orientation tuning in the tree shrew. This substrate shares features
with both types of models—feedforward and intracortical—and could serve to establish a
fundamental principle governing connections within the cerebral cortex.

'Orientation tuning' refers to the observation that cortical neurons respond strongly to
stimuli presented at a particular orientation and less to stimuli presented at other
orientations. In the visual system of the cat, where this property has been studied most
extensively, orientation-tuned neurons are present at the first stage of cortical processing—
layer 4. Individual layer 4 neurons in cat have receptive fields that are elongated along the
axis of preferred orientation[1], whereas LGN inputs have circular receptive fields and lack
orientation tuning[7]. Based on these differences, Hubel and Wiesel proposed a
straightforward model for the generation of orientation tuning[1]. In this model, orientation-
tuned neurons in layer 4 receive convergent input from several LGN neurons whose
individual receptive fields are displaced along a line of visual space. The combined input
from the ensemble of LGN neurons establishes an elongated receptive field that, together
with mechanisms of summation and threshold, confers orientation tuning on the cortical
neuron.

Although the cat has served as a model animal for studies of the visual system, there are
important species-specific differences in the functional organization of the visual pathway.

In particular, although orientation tuning is a prominent feature of layer 4 neurons in cat visual cortex, neurons in layer 4 of many primates and insectivores lack orientation tuning, which instead emerges one or two synapses after the geniculocortical synapse. Thus, input from the LGN to layer 4 cannot be directly responsible for the establishment of orientation tuning, as it is in the cat8–13. Instead, orientation tuning must rely on intracortical mechanisms. Can the Hubel and Wiesel model work given the organization of the primate and insectivore visual systems? The new paper from Mooser *et al.*6 demonstrates that the intracortical, feedforward projections from layer 4 to 2/3 in the tree shrew are organized in a fashion similar in spirit to the geniculocortical connections in the Hubel and Wiesel model. Thus, there appears to be a generalized and conserved mechanism contributing to the generation of orientation tuning across species.

The tree shrew is a small, diurnal insectivore from Southeast Asia. Once considered a primate, these animals have a highly developed visual system packaged in a relatively small brain. These features, along with a lack of ocular dominance columns and an extremely precise retinotopic map across the visual cortex with very little distortion, make the tree shrew an ideal animal for studying structure–function relationships in the cortex14.

To examine the organization of layer 4 connections to layers 2/3, where orientation tuning emerges in the tree shrew, Mooser and colleagues made small injections of dye into the middle of layer 4 and compared the distribution of labeled boutons in layers 2/3 to the map of orientation preference, as determined with optical imaging techniques.

Although all local orientation columns received input from the labeled layer 4 projections, Mooser *et al.*6 noticed an organization to the projections whereby boutons clustered in orientation columns whose orientation preference matched the retinotopic displacement of the boutons from their injection site. From the perspective of a single, unoriented layer 4 neuron, synapses are made with a variety of layer 2/3 neurons with overlapping receptive fields and differing orientation preferences. From the perspective of a single layer 2/3 neuron, inputs come from multiple layer 4 neurons with receptive fields displaced along a line of visual space (Fig. 1).

Although the results of Mooser *et al.*6 indicate that intracortical, feedforward projections from layer 4 neurons establish a substrate for orientation tuning, additional cortical mechanisms, both excitatory and inhibitory, are almost certainly involved in the refinement and maintenance of orientation tuning4,5,13. In particular, previous work from the authors' laboratory has shown that layer 2/3 neurons in the tree shrew give rise to long-distance, patchy, horizontal projections15. These horizontal projections not only link neurons with similar orientation preferences, but also extend anisotropically across the cortex, linking neurons along a retinotopic axis that matches the orientation preference of the projecting neuron15. Thus, although feedforward connections from layer 4 to 2/3 are involved in the emergence of orientation, it is important to keep in mind that this pathway is not operating in isolation, but rather represents one component of a larger machine.

By combining clever thinking with stateof-the-art techniques and an excellent animal model, Mooser *et al.*6 have significantly advanced our progress in the ongoing quest to understand

structure–function relationships in the cortex. The finding that a common rule applies to feedforward connections and the emergence of orientation tuning in both the shrew and the cat strongly suggest that a similar plan may exist in other species.

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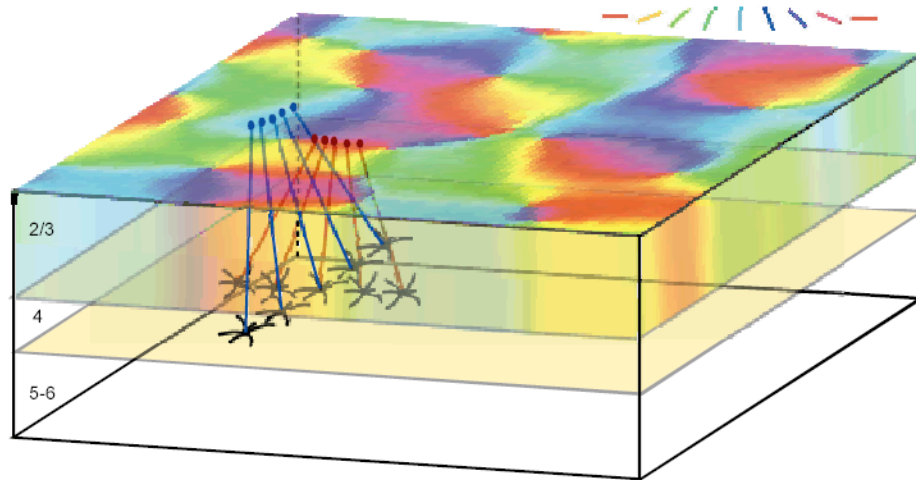15. Bosking WH, Zhang Y, Schofield B, Fitzpatrick D. J Neurosci. 1997; 17:2112–2127. [PubMed: 9045738]

Figure 1.

Schematic diagram illustrating cortical circuits reported by Mooser *et al.*6. The orientation map in cortical layer 2/3 is constructed by combining optical imaging responses to stimuli presented at various orientations, coded in different colors (upper right). Anatomical tracing experiments suggest that orientation tuning in layer 2/3 could arise from input from a group of layer 4 neurons whose receptive fields and cell bodies are arranged in a line (adapted from ref. 15).