Visuotopic organization of monkey V1

Tootell, Silverman, Switkes and DeValois, 1982
**Figure 25-10** Receptive field size, eccentricity, retinotopic organization, and magnification factor. The color code refers to position in visual space or on the retina.

A. The distance of a receptive field from the fovea is referred to as the eccentricity of the receptive field.

B. Receptive field size varies with distance from the fovea. The smallest fields lie in the center of gaze, the fovea, where the visual resolution is highest; fields become progressively larger with distance from the fovea.

C. The amount of cortical area dedicated to inputs from within each degree of visual space, known as the magnification factor, also varies with eccentricity. The central part of the visual field commands the largest area of cortex. For example, in area V1 more area is dedicated to the central 10° of visual space than to all the rest. The map of V1 shows the cortical sheet unfolded.
Precise visuotopic organization of monkey V1

Adams and Horton, 2003
Laminar organization and information flow in the striate cortex

A Inputs from lateral geniculate nucleus

B Resident cells

C Information flow

To other (extrastriate) cortical areas (e.g. V2, 3, 4, 5, MT)

To subcortical areas:
- to superior colliculus, pulvinar, pons
- to LGN, claustrum

From LGN

Layers:

1
2 Blob
3
4A
4B
4Cα
4Cβ
5
6
Orientation selectivity in V1

Hubel & Wiesel (1962, 1968)
**Figure 25–13** A cortical computational module. A chunk of cortical tissue roughly 1 mm in diameter contains an orientation hypercolumn (a full cycle of orientation columns), one cycle of left- and right-eye ocular-dominance columns, and blobs and interblobs. This module would presumably contain all of the functional and anatomical cell types of primary visual cortex, and would be repeated hundreds of times to cover the visual field. (Adapted, with permission, from Hubel 1988.)
<table>
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<th>NM1</th>
<th>NM2</th>
<th>NM3</th>
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Figure 25–11 (Opposite) Functional architecture of the primary visual cortex. (Images from M. Kinoshita and A. Das, reproduced with permission.)

A. The surface of the primary visual cortex is functionally organized in a map of the visual field. The elevations and azimuths of visual space are organized in a regular grid that is distorted because of variation in the magnification factor (see Figure 25–10). The grid is visible here in the dark stripes (visualized with intrinsic-signal optical imaging), which reflect the pattern of neurons that responded to a series of vertical candy stripes. Within this surface map one finds repeated superimposed cycles of functionally specific columns of cells, as illustrated in B, C, and D.

B. The dark and light stripes represent the surface view of the left and right ocular dominance columns. These stripes intersect the border between areas V1 and V2, the representation of the vertical meridian, at right angles.

C. Some columns contain cells with similar selectivity for the orientation of stimuli. The different colors indicate the orientation preference of the columns. The orientation columns in surface view are best described as pinwheels surrounding singularities of sudden changes in orientation (the center of the pinwheel). The scale bar represents 1 mm. (Surface image of orientation columns on the left reproduced, with permission, from G. Blasdel.)

D. Patterns of blobs in V1 and stripes in V2 represent other modules of functional organization. These patterns are visualized with cytochrome oxidase.
Hubel and Wiesel, 1962

Simple cortical cell

LGN cells
Orientation selectivity in V1 is robust to cooling of cortex
Retinal Ganglion Cell Mosaic

Ganglion cell mosaic
X-off cells

Ganglion cell mosaic
X-on cells

Lateral Geniculate
Nucleus

Probability of connection

Synaptic strength

Ringach, 2004
Ganglion cell mosaic
X-off cells

Ganglion cell mosaic
X-on cells

Lateral Geniculate Nucleus

Probability of connection

Synaptic strength

Ringach, 2004
Receptive Field Organization
[Reverse Correlation Analysis]
Tuning for orientation

Complex Cell
Simple cells

Complex cells

Movshon, Thompson and Tolhurst, 1978
Dichotomy of simple and complex cells

Skottun, D. Valo, Grosof, Movshon, Albrecht & Bonds, 1991

Skottun et al., 1991

Complex

Simple

Cat

Monkey

F1/F0

Skottun et al., 1991
Single trials | Average firing and Vm | Cycle average | Nonlinearity

- Single trials: Graphs showing neuronal activity over time.
- Average firing and Vm: Graphs illustrating firing rate and membrane potential over time.
- Cycle average: Graphs summarizing cycle-averaged data.
- Nonlinearity: Scatter plots showing firing rate versus membrane potential, with labeled slopes ($\rho$).

Priebe, Mechler, Carandini and Ferster, 2004
Figure 2

**a**

Firing rate (spk/s) as a function of membrane potential (mV). The graph shows the transition from resting state \( V_{rest} \) to threshold \( V_{th} \) with a dashed line indicating the firing rate.

**b**

Trace diagrams illustrating the effects of frequency (FR) and voltage \( V_m \) on membrane response.

**c**

Distribution of firing rate ratios \( R_1/R_0 \) for different power modulations \( p \) ranging from 2 to 5.

**d**

Frequency distribution against \( V_1/V_0 \), showing the effect of varying voltage ratios on frequency response.

**e**

Graph showing the relationship between voltage \( V_1 \) and frequency, illustrating the transformation curve for membrane potential with an orange trace and other models.

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Priebe, Mechler, Carandini and Ferster, 2004
Priebe, Mechler, Carandini and Ferster, 2004
Spatial contrast sensitivity
Population representation – spatial frequency

DeValois, Albrecht and Thorell, 1982
Population representation – orientation and spatial frequency

DeValois, Albrecht and Thorell, 1982
Spatial frequency tuning and bandwidth

Simple cell A16L7

8.3 degrees

270°

90°

30 impulses/sec

0.78 octaves

Response [impulses/sec]

0.3

0.1

1.0

10.0

Spacial frequency [c/deg]
Spatial frequency tuning and bandwidth

Simple cell A15L6

Response [impulses/sec]

Spatial frequency [c/deg]
Spatial frequency tuning and bandwidth

Complex cell A8L5

19.8 degrees

40 impulses/sec 180°

300.0

30.0

3.0

0.3 0.1 1.0 10.0

Spatial frequency [c/deg]

Response [impulses/sec]
Spatial frequency tuning and bandwidth

Simple cell A14L4

20.9 degrees

35 impulses/sec

2.08 octaves

Response [impulses/sec]

0.3 0.1 1.0 10.0

Spatial frequency [cycles/deg]
Spatial frequency tuning and bandwidth

Complex cell A14L5

34.0 degrees

2.30 octaves

Response [impulses/sec]

50 impulses/sec 180°

Spatial frequency [c/deg]
Population representation – orientation and spatial frequency

DeValois, Albrecht & Thorell, 1982
Is that \textit{IT}?
Simple cortical cell

LGN cells

Hubel and Wiesel, 1962
Intracortical Lateral Inhibition

Feed-forward Excitation from LGN relay cells

Preferred stimulus

Null stimulus

Response

Orientation

Excitation

Inhibition

Spiking

$V_m$

$V_{rest}$

$V_{th}$

$V_m$

$V_{rest}$

Priebe and Ferster, 2008
Intracellular measurement of tuning
Orientation tuning of excitation and inhibition

Anderson, Carandini & Ferster, 2000
Is that *IT*?
DeAngelis, Ohzawa & Freeman, 1995
A

Spatial Frequency, SF [cyc/deg]

Null

Temporal Frequency, TF [Hz]

Null

0.14

0.18

0.23

0.3

0.38

0.49

0.62

0.8

15.0

12.0

8.0

4.0

2.0

1.0

0.5

0.25

DeAngelis, Ohzawa & Freeman, 1995

B

TF

SF

0

33

0

-33

0

0.8

X [deg]

0

9

C

Response [spikes/s]

50

40

30

20

10

0

0.1

SF [cyc/deg]

0.1

1

2

0

10

20

30

40

50

0.1

1

10

20

DeAngelis, Ohzawa & Freeman, 1995
Is that *IT*?
The linear model of simple cells

Carandini, Heeger and Movshon, 1997
Contrast normalization

Carandini, Heeger and Movshon, 1997
The linear model of simple cells

The normalization model of simple cells

Carandini, Heeger and Movshon, 1997
Contrast normalization

Carandini, Heeger and Movshon, 1997
Contrast normalization

Carandini, Heeger and Movshon, 1997
**Contrast normalization**

**A** Orientation (deg)

-45  -15

Contrast

- 0.12
- 0.25
- 0.5
- 1

Time (ms)

0  154

197

**B** Response (spikes/s)

Contrast (0.1 0.3 1)

**C** Phase (deg)

Contrast (20 spikes/s)

**D**

Carandini, Heeger and Movshon, 1997
Contrast normalization

A  Spatial frequency (c/deg)
   1.1  1.4

Contrast
   0.25  0.5  1

B  Response (spikes/s)

C  Phase (deg)

D  10 spikes/s

Carandini, Heeger and Movshon, 1997
Contrast-invariant tuning

Movshon; Finn, Priebe & Ferster, 2008
Cross-orientation suppression

Carandini, Heeger and Movshon, 1997
The linear model of simple cells

The normalization model of simple cells

RC circuit implementation

Carandini, Heeger and Movshon, 1997
Proposed mechanisms of normalization

Feedforward

Recurrent

RC network

Synaptic depression

Noise

Carandini & Heeger, 2012
Cross-orientation suppression at the input to V1

Relay-cell Responses

Simple cell Input
Cross-orientation suppression is enhanced by threshold

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</tbody>
</table>

David Ferster and Nicholas Priebe
Is that IT?

The linear model of simple cells

The normalization model of simple cells

RC circuit implementation
Figure 25-16 Long-range horizontal connections in each layer of the visual cortex integrate information from different parts of the visual field.

A. The axons of pyramidal cells extend for many millimeters parallel to the cortical surface. Axon collaterals form connections with other pyramidal cells as well as with inhibitory interneurons. This arrangement enables neurons to integrate information over large parts of the visual field. An important characteristic of these connections is their relationship to the functional columns. The axon collaterals are found in clusters (arrows) at distances greater than 0.5 mm from the cell body. (Reproduced, with permission, from Gilbert and Wiesel 1983.)

B. Horizontal connections link columns of cells with similar orientation specificity.

C. The pattern of horizontal connections is visualized by injecting an adenoviral vector containing the gene encoding green fluorescent protein into one orientation column and superimposing the labeled image (black) on an optically imaged map of the orientation columns in the vicinity of the injection. (Scale: diameter of white circle is 1 mm.) (Reproduced, with permission, from Stettler et al. 2002.)
Figure 12. Physiological Data Using a Complex Background Stimulus

(A) Depictions of the stimuli used in this set of experiments. In addition to normal target/flank combinations, four new stimuli were introduced in which the target was placed within a background of pseudorandomly oriented line segments.

(B–E) The response patterns of 4 cells to the various stimuli. Each data bar represents the response to the corresponding stimulus depicted in (A), as labeled. When placed within the noisy background, the response of cells to the target often declined substantially (C–E). As surround elements were rotated to become colinear with the target, however, much of this inhibition was eliminated and, in some instances, increased beyond the response to the central bar stimulus.
Circuit implementations of common neural computations

Response (imp/sec)

Grating patch diameter (deg)

Optimal diameter

Surround diameter

Suppression

Monkey

CRF

Surround

$k_c$

$k_s$

CRF

Surround

Cavanaugh et al., 2002
GSF = 1.7 deg
Center = 4.2 deg
Surround = 9.8 deg
MRF = 0.8 deg

Cavanaugh, Bair and Movshon, 2002
Figure 12. Physiological Data Using a Complex Background Stimulus

(A) Depictions of the stimuli used in this set of experiments. In addition to normal target/flank combinations, four new stimuli were introduced in which the target was placed within a background of pseudorandomly oriented line segments.

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The linear model of simple cells

Retinal image → Firing rate

The normalization model of simple cells

Retinal image → Firing rate

Other cortical cells

RC circuit implementation

Retinal image → Firing rate

Other cortical cells

Is that IT?