

Visual Object Recognition

Computational Models and Neurophysiological Mechanisms

Neurobiology 230. Harvard College/GSAS 78454

Class 1 [09/02/2020]. Introduction to Vision

Class 2 [09/14/2020]. Natural image statistics and the retina

Class 3 [09/21/2020]. The Phenomenology of Vision

Class 4 [09/28/2020]. Learning from Lesions

Class 5 [10/05/2020]. Primary Visual Cortex

October 12th: University Holiday

Class 6 [10/19/2020]. Adventures into *terra incognita*

Class 7 [10/26/2020]. From the Highest Echelons of Visual Processing to Cognition

Class 8 [11/02/2020]. First Steps into in silico vision

Class 9 [11/09/2020]. Teaching Computers how to see

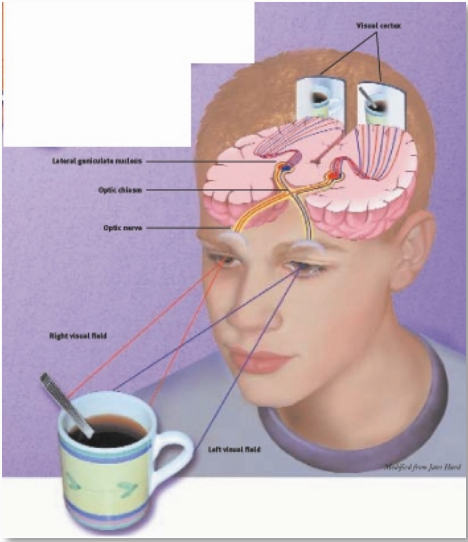
Class 10 [11/16/2020]. Computer Vision

Class 11 [11/23/2020]. Connecting Vision to the rest of Cognition

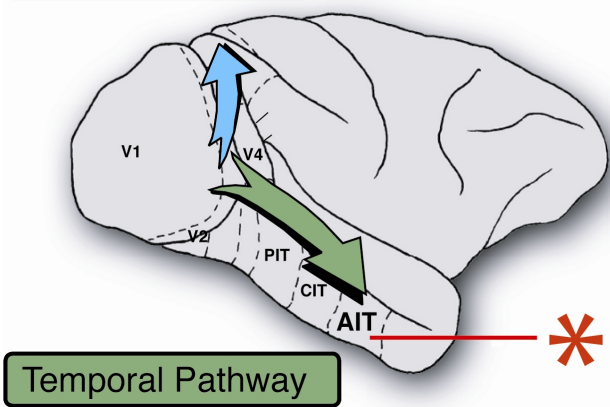
Class 12 [11/30/2020]. Visual Consciousness

FINAL EXAM, PAPER DUE 12/14/2020. No extensions.

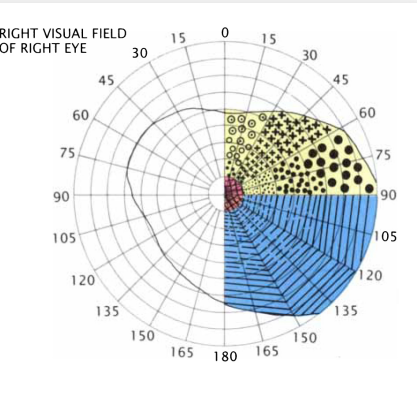
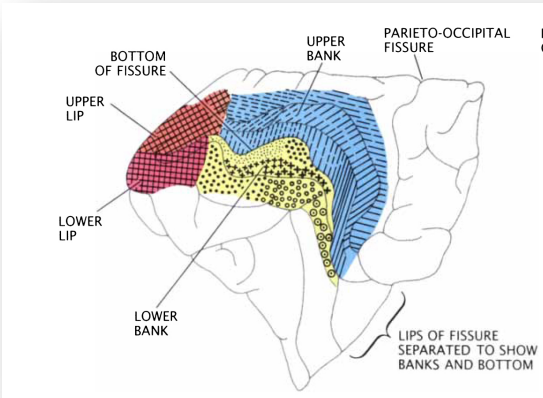
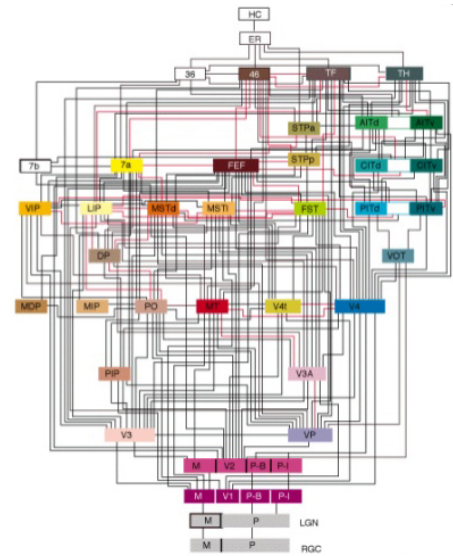
Quick recap



Parietal Pathway

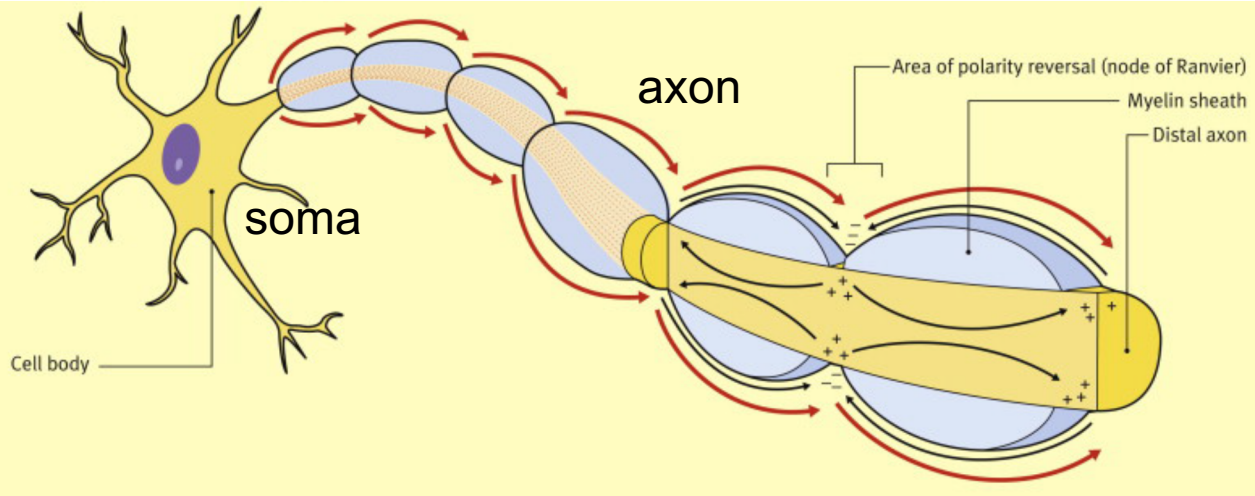


Temporal Pathway



Basic Neuroscience

dendrites



soma

axon

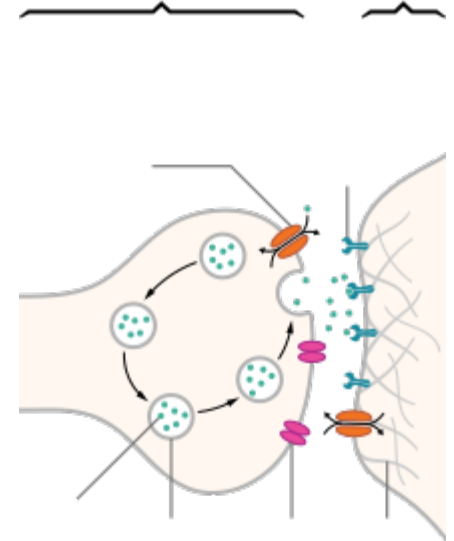
Area of polarity reversal (node of Ranvier)

Myelin sheath

Distal axon

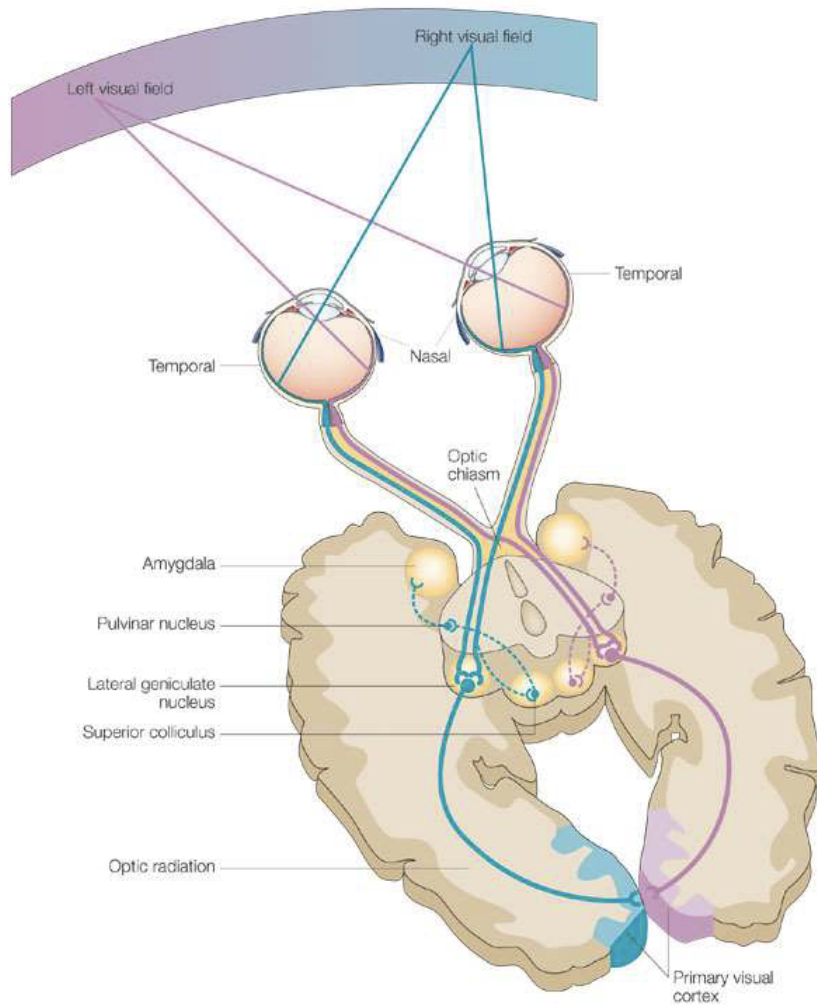
Pre-synaptic

Post-synaptic

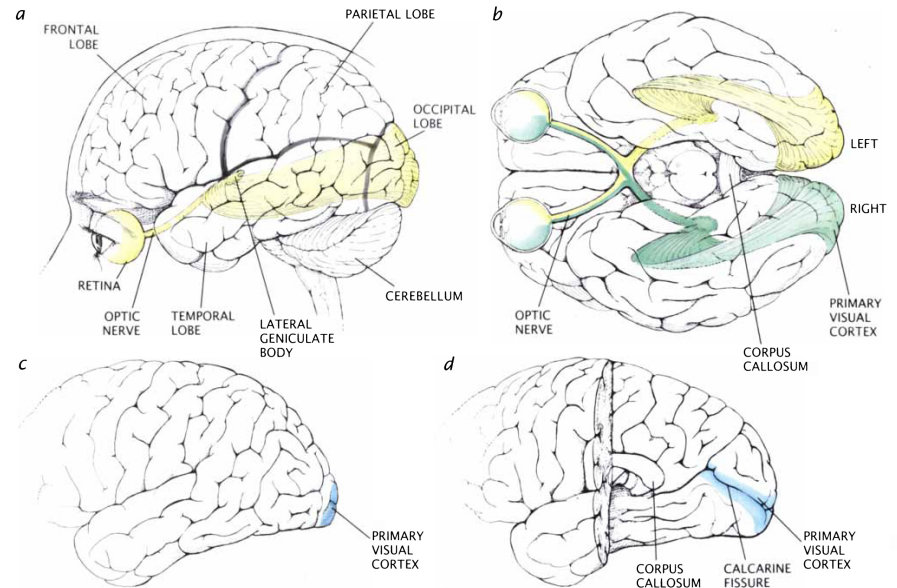


Voltage changes inside the neuron
Voltage changes in the extracellular space

From the retina to cortex

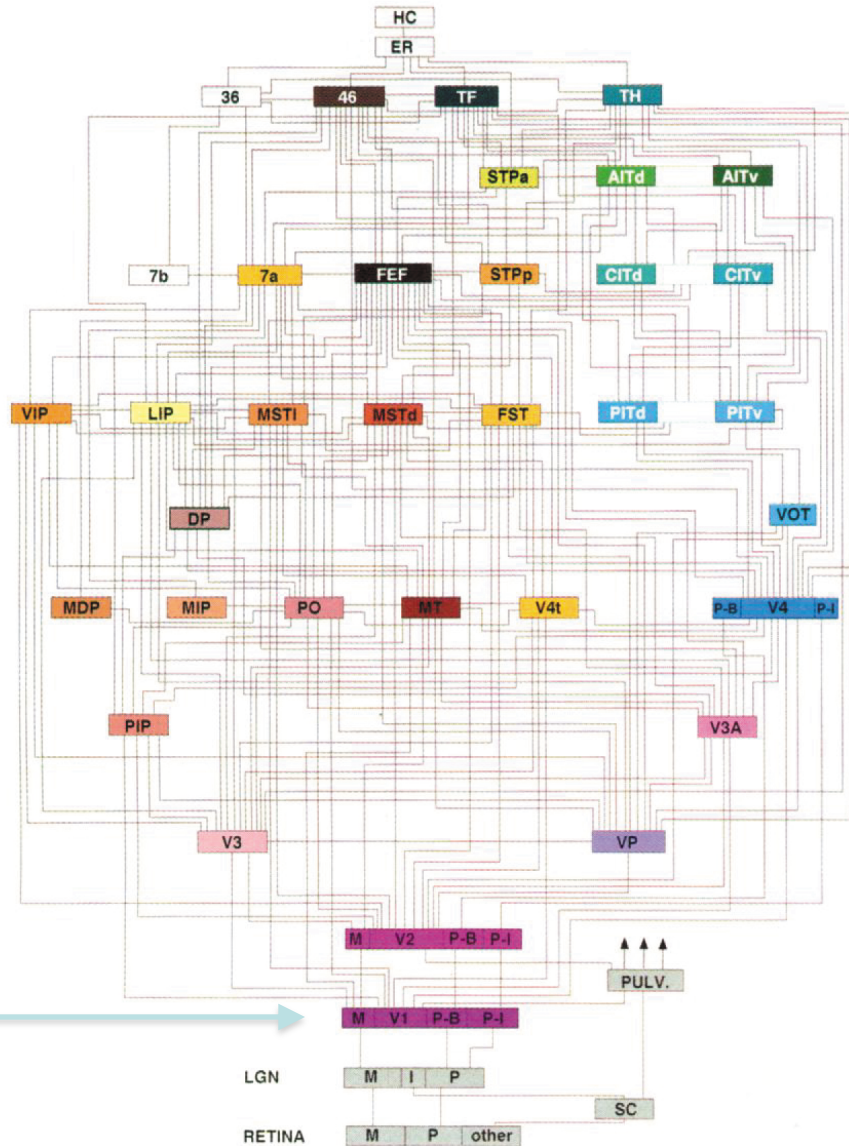


Nature Reviews | Neuroscience



Glickstein, M. (1988). The discovery of the visual cortex. Scientific American

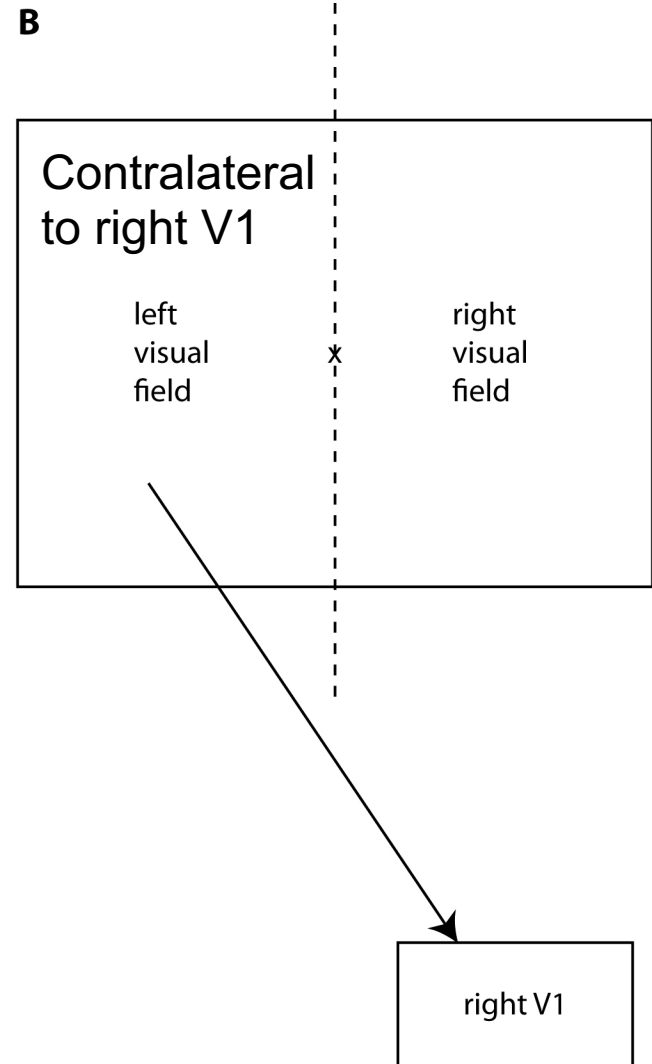
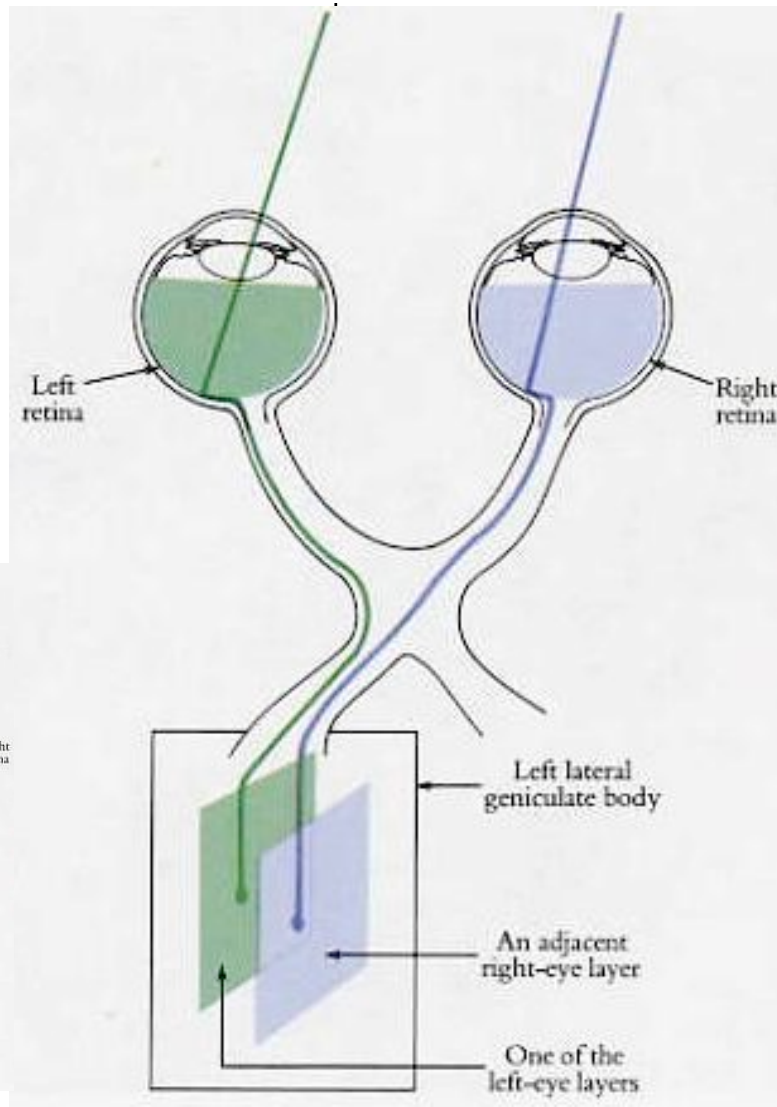
Visual system circuitry



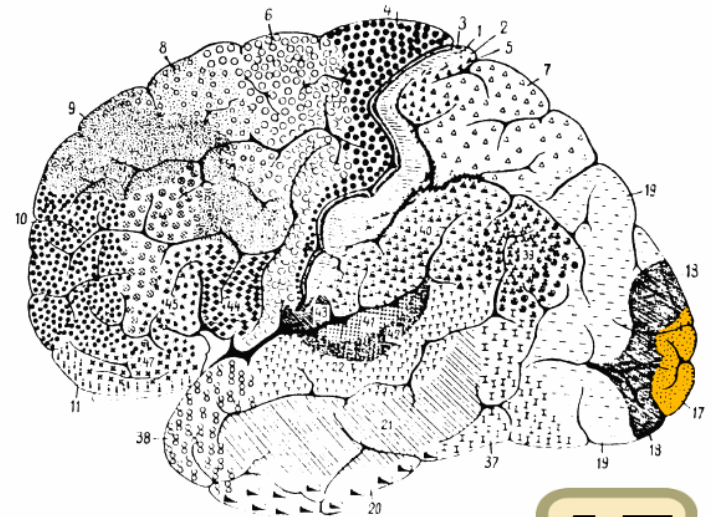
You are here



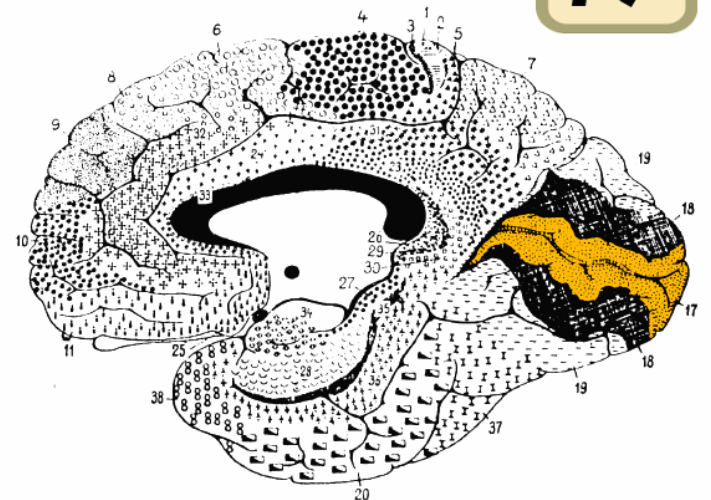
V1 in each hemisphere represents the *contralateral* visual field



Primary visual cortex in Brodmann's map

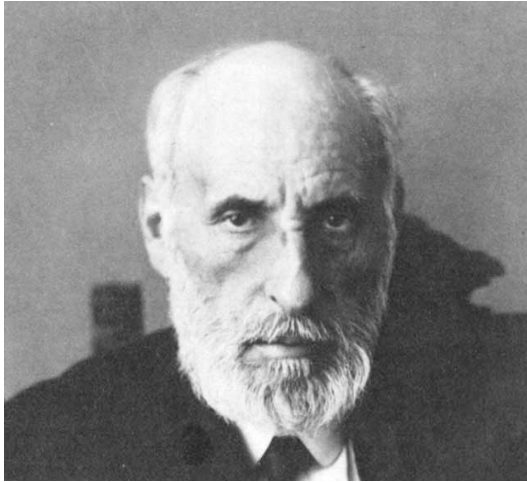


17

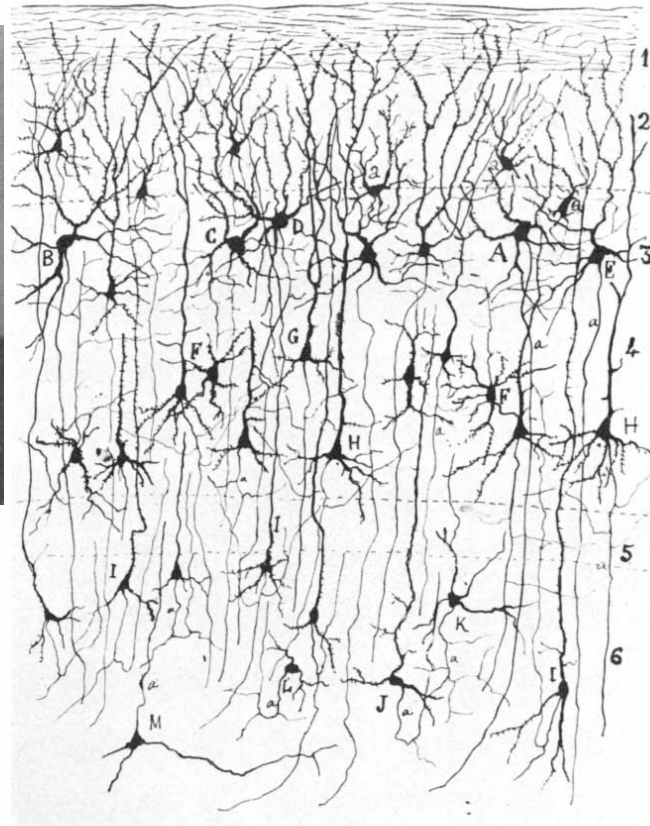


Brain shown from the side, facing left.
Above: view from outside, below: cut
through the middle. Orange = Brodmann
area 17 (primary visual cortex)

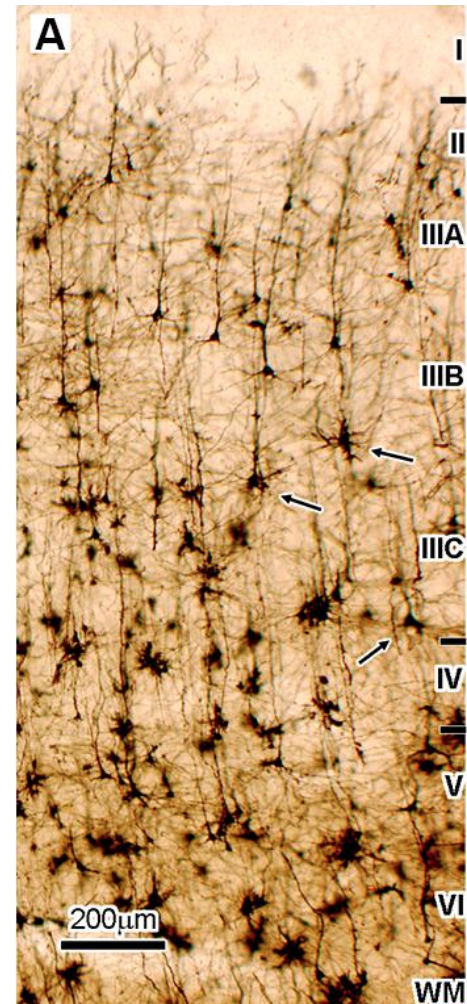
The complex circuitry of cortex as drawn by Ramon y Cajal



Ramon y Cajal
[1852-1934]



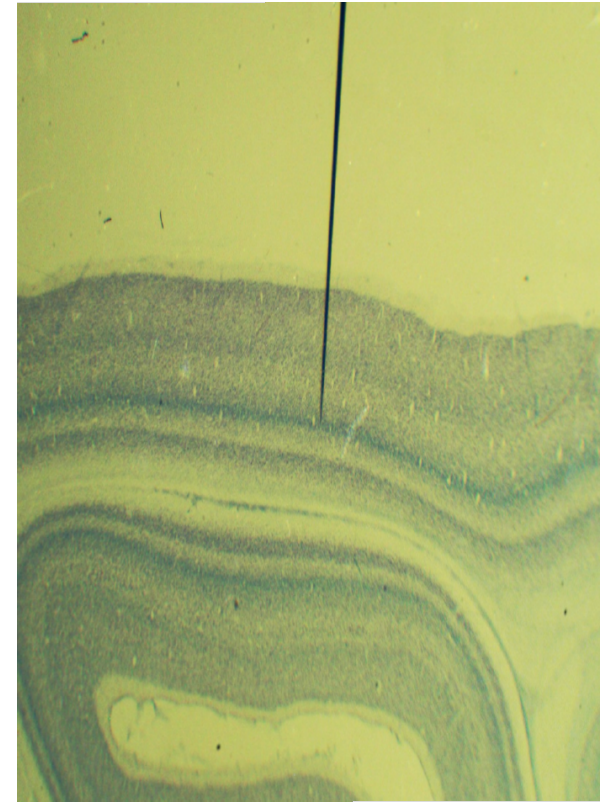
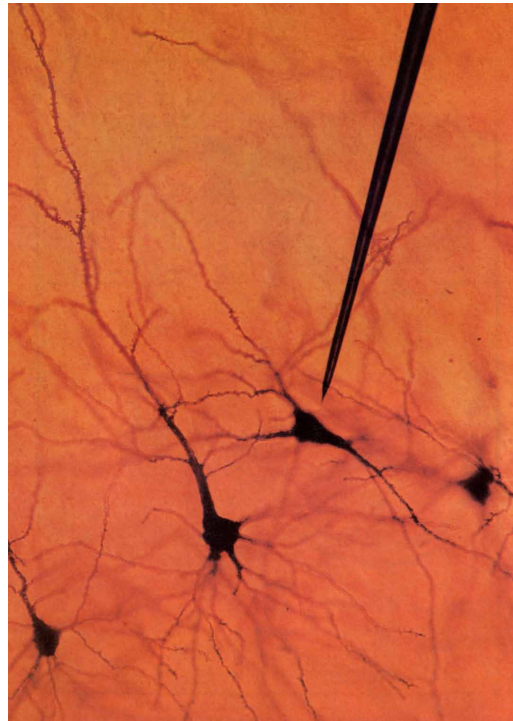
GOLGI-STAINED NERVE TISSUE from the visual cortex of a rat was sketched by Cajal in 1888. The numbers along the right-hand margin identify cellular layers; the capital letters label individual neurons. One of Cajal's most important contributions to neurobiology was to establish the neuron as a discrete, well-defined cell rather than as part of a continuous network.



The gold standard to examine neuronal activity: microelectrode recordings

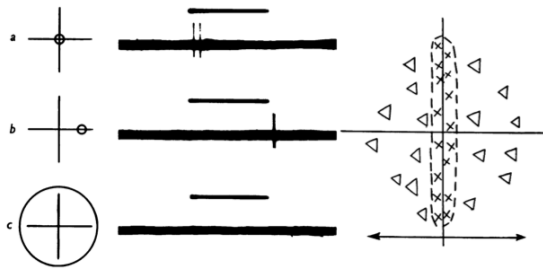
Edgar Adrian 1926

Neuronal resolution
Sub-millisecond temporal resolution
Direct examination of action potentials



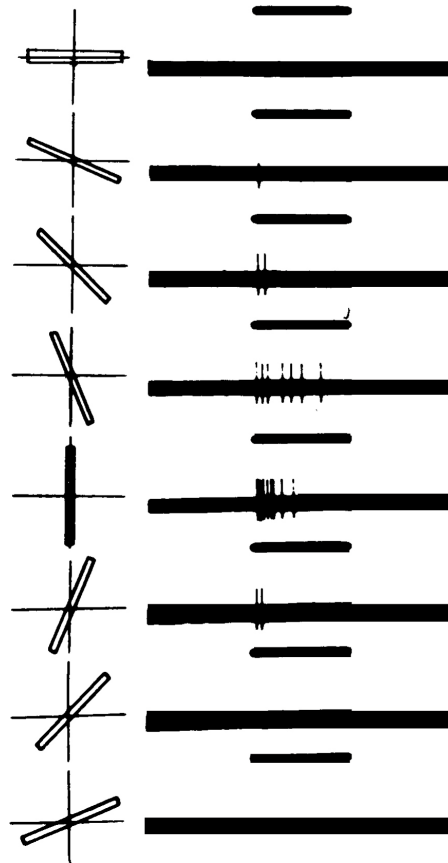
Hubel, D. (1979). The Visual Brain.
SCIENTIFIC AMERICAN 241, 45-53.

Neurophysiological recordings from primary visual cortex



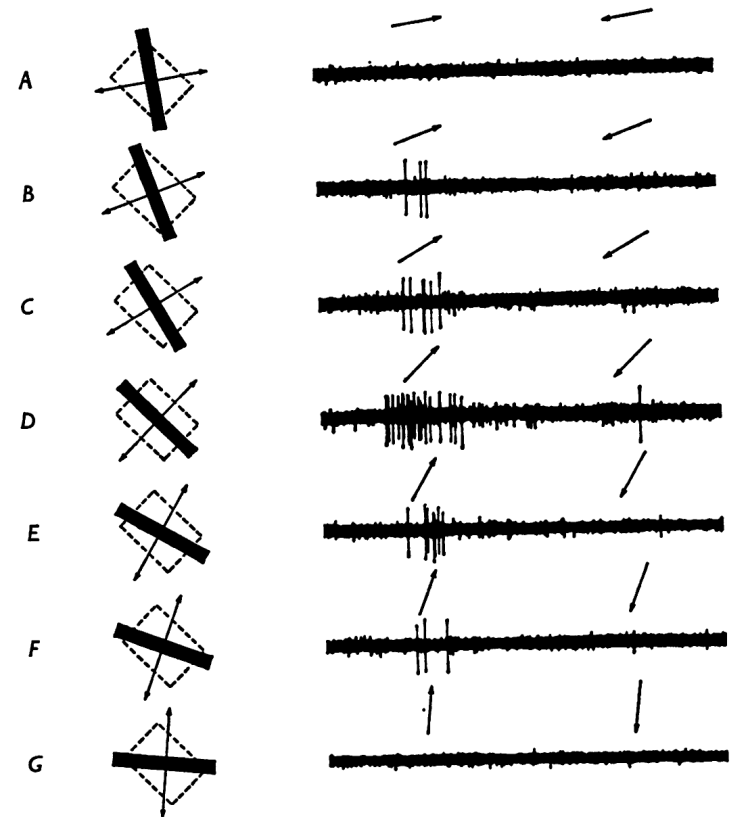
Hubel & Wiesel
J. Physiol. 1959

Orientation selectivity



Hubel – Nobel Lecture

Direction selectivity



Hubel and Wiesel 1968

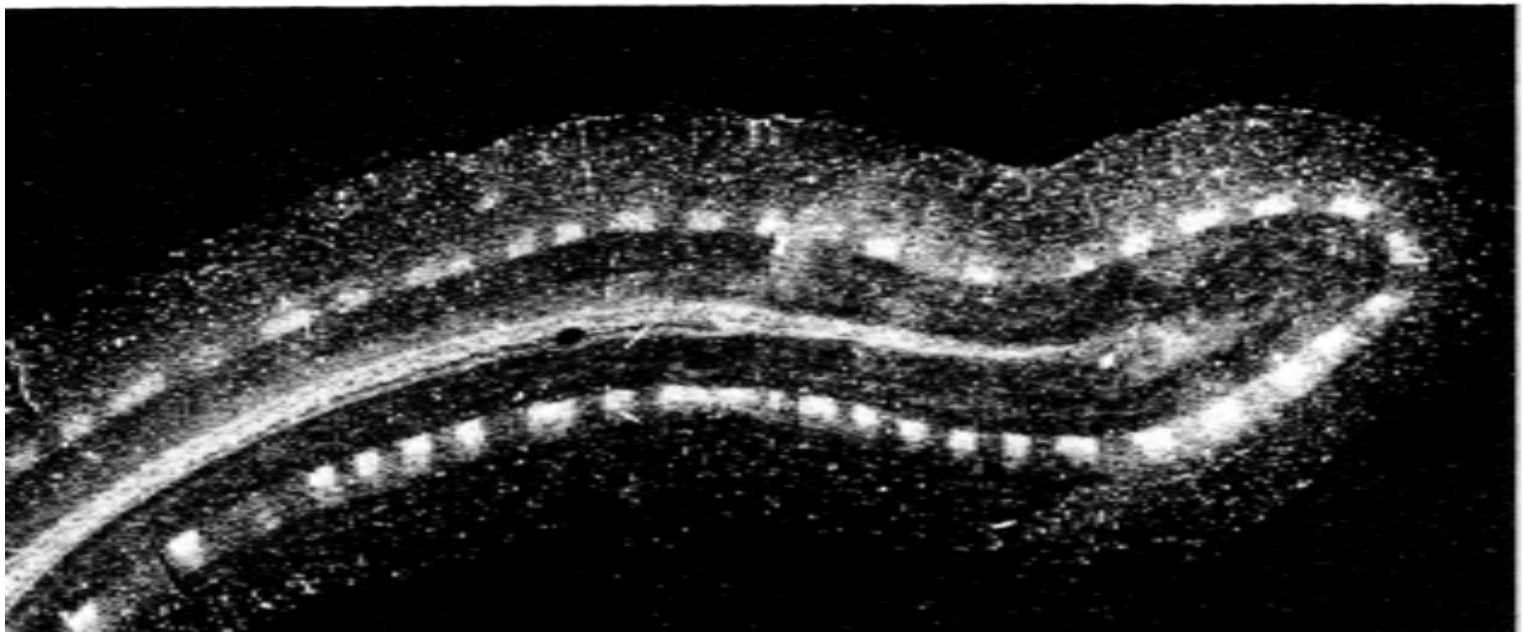
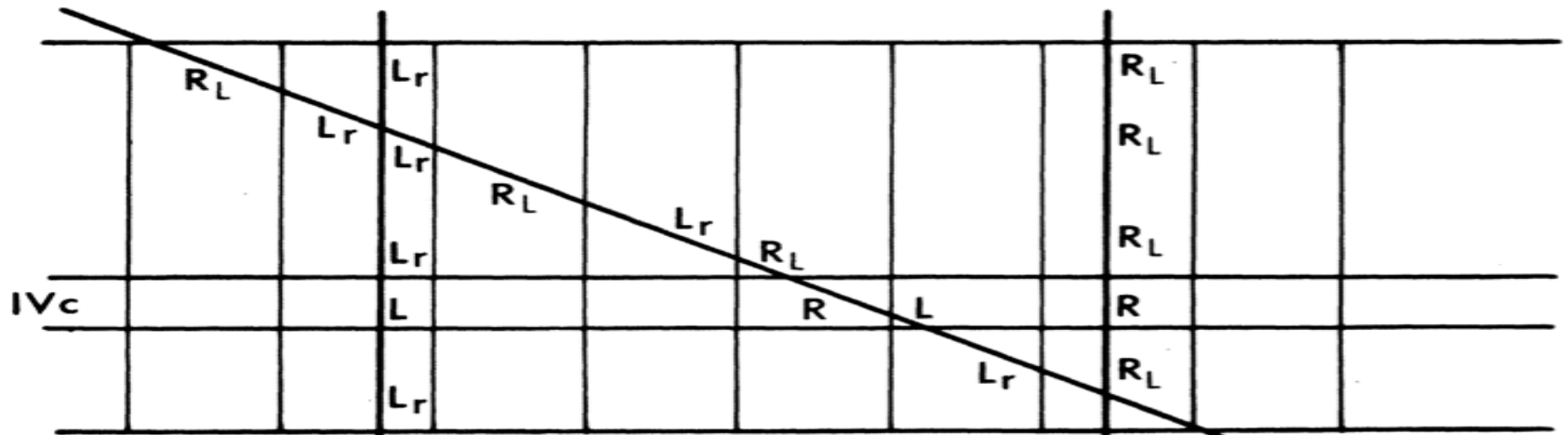
Simple Cells Video (Hubel and Wiesel)

<http://www.youtube.com/watch?v=8VdFf3egwfg>

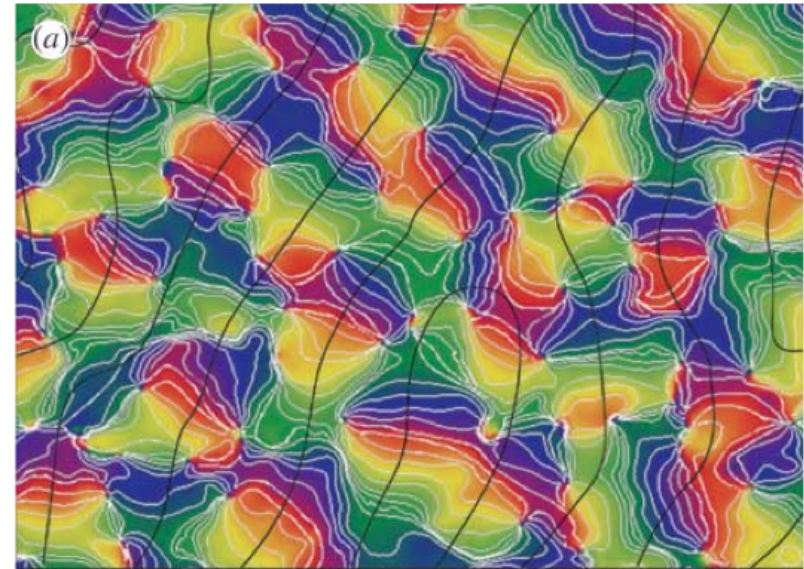
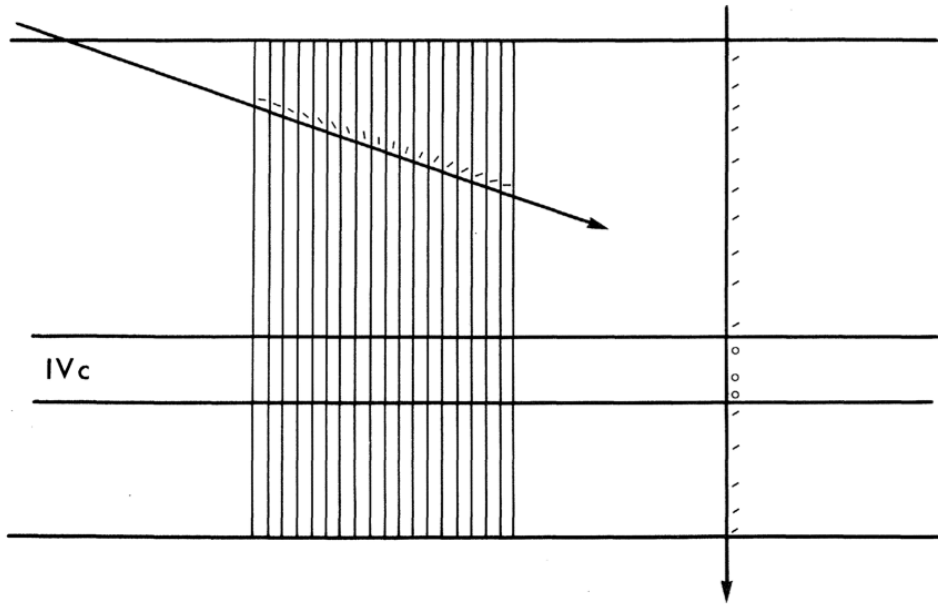


Ocular dominance columns

Hubel & Wiesel, Proc. R. Soc. Lond. B, 1977



Visual orientation columns



orientation columns

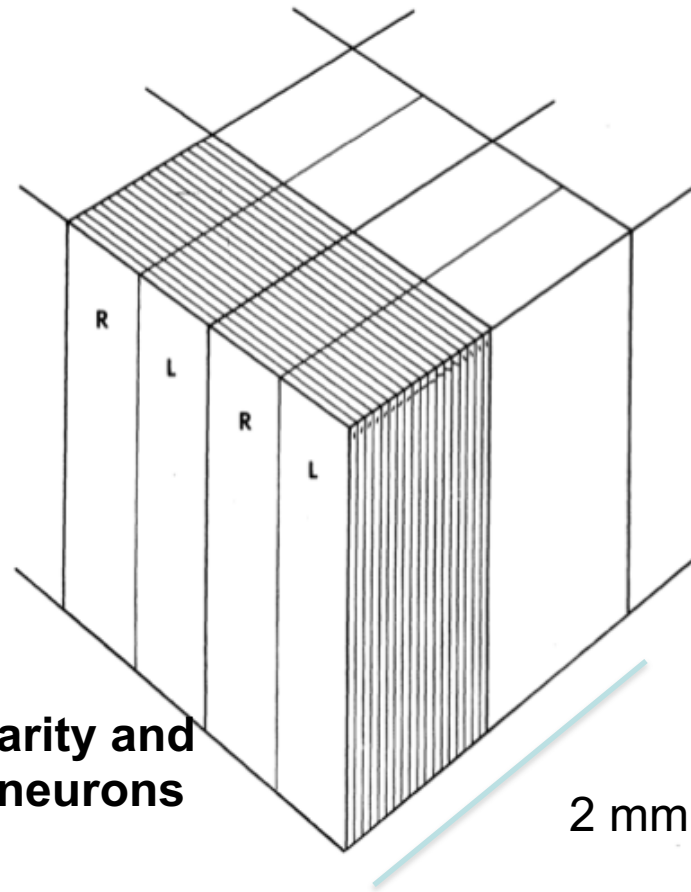
Hubel & Wiesel, Proc. R. Soc. Lond. B, 1977

Horton & Adams, Phil. Trans. R. Soc. B, 2005

Different primary visual cortex neurons show a variety of interests

- Orientation selectivity
- Direction selectivity
- Speed selectivity
- Typically monotonic response with contrast
- Spatial frequency preferences
- Color

Putting it all* together: the “hypercolumn”

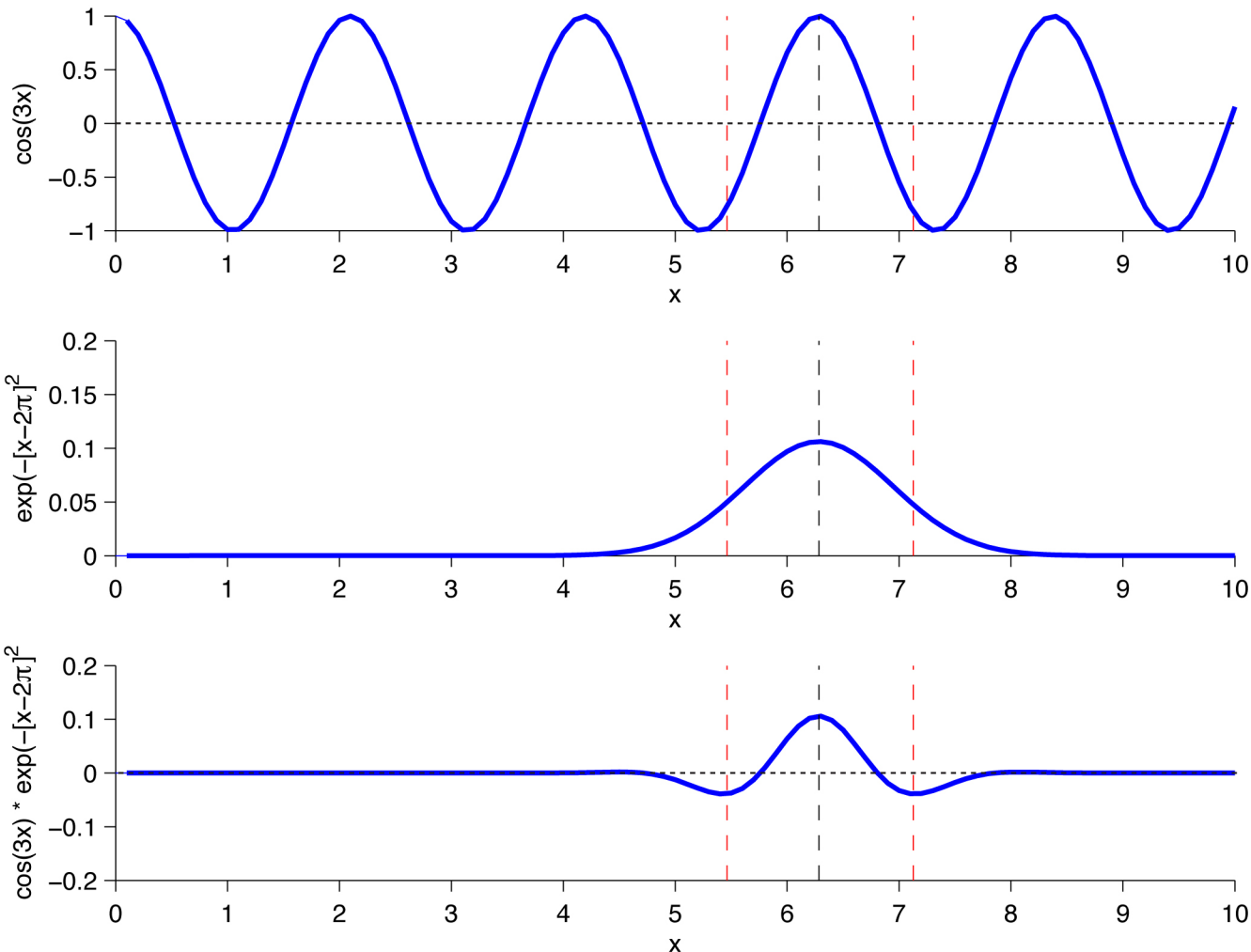


***all is more than ocularity and orientation. Many V1 neurons are also selective for:**

- Direction & speed**
- Depth**
- Color**

Hubel & Wiesel, Proc. R. Soc. Lond. B, 1977

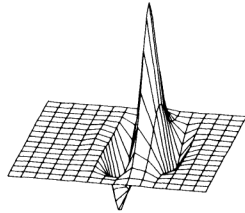
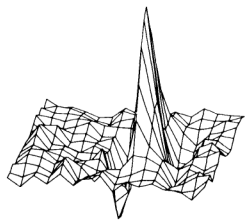
Interlude 1: Multiplying a cosyne and a Gaussian function



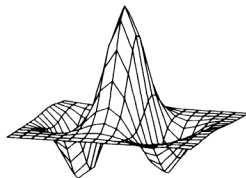
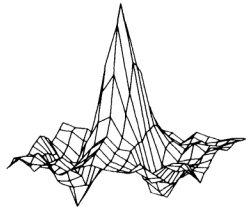
Receptive fields for simple cells in V1

Spatial receptive field

Gabor fit



Cell 1



Cell 2

Gabor function

$$D(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} \exp\left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right] \cos(kx - \phi)$$

Spatial receptive field

Cat primary visual cortex (area 17)

Jones and Palmer 1987

Interlude 2: MATLAB (or Python)

An easy way to write computer code

- <http://www.mathworks.com/index.html>
- “High-level” computer programming language
- Quite powerful!

```
theta_rad=(2*pi/360)*theta;  
x=(-2*sigma_x):bin:(2*sigma_x);nx=length(x);  
y=(-2*sigma_y):bin:(2*sigma_y);ny=length(y);
```

% theta angle in radians

% define x axis

% define y axis

```
factor1=1/(2*pi*sigma_x*sigma_y);
```

```
for i=1:nx
```

```
    for j=1:ny
```

```
        curr_x=x(i)*cos(theta_rad)+y(j)*sin(theta_rad);
```

```
        curr_y=y(j)*cos(theta_rad)-x(i)*sin(theta_rad);
```

```
        factor2=exp(-curr_x^2/(2*sigma_x^2)-curr_y^2/(2*sigma_y^2));
```

```
        factor3=cos(k*curr_x-phi);
```

```
        Ds(i,j)=factor1*factor2*factor3;
```

```
    end
```

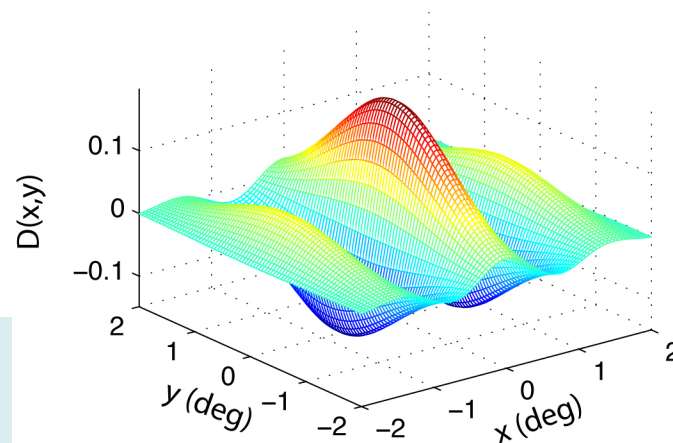
```
end
```

$$D(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} \exp\left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right] \cos(kx - \phi)$$

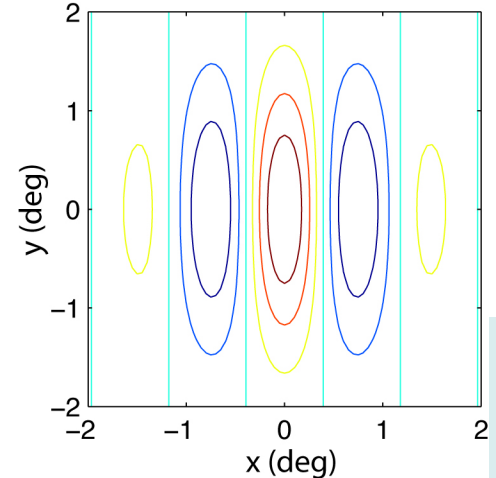
Interlude 2: MATLAB (or Python)

An easy way to make plots

A



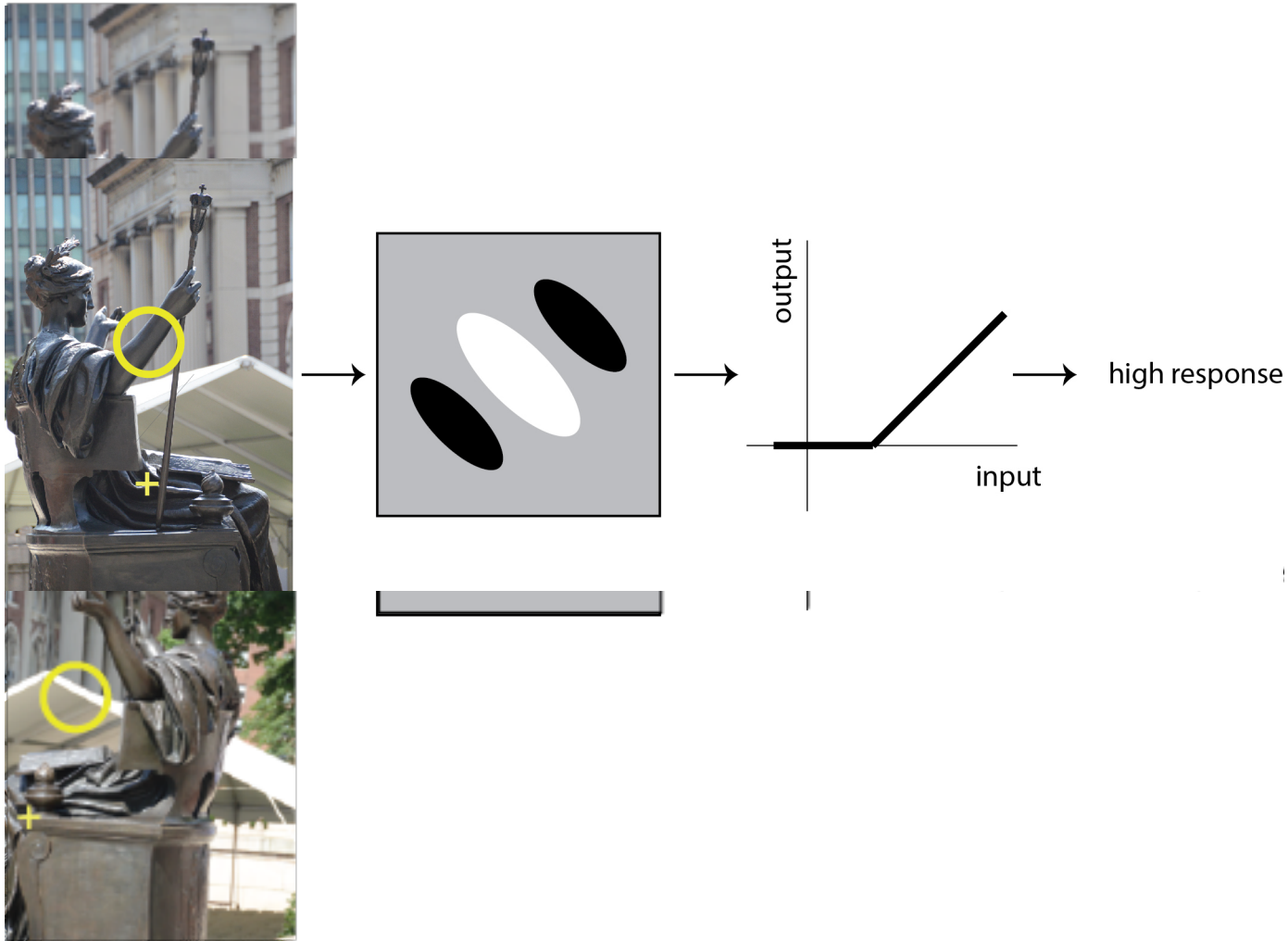
B



```
sigma_x=1;  
sigma_y=1;  
bin=0.05;  
k=1/0.25;  
theta=0;  
i=0;  
phi=0;  
[Ds,x,y]=mygabor1(sigma_x,sigma_y,k,phi,theta,bin);  
subplot(2,2,1);  
mesh(x,y,Ds');  
axis([min(x) max(x) min(y) max(y) min(Ds(:)) max(Ds(:))]);  
subplot(2,2,2);  
contour(x,y,Ds');  
axis square;
```

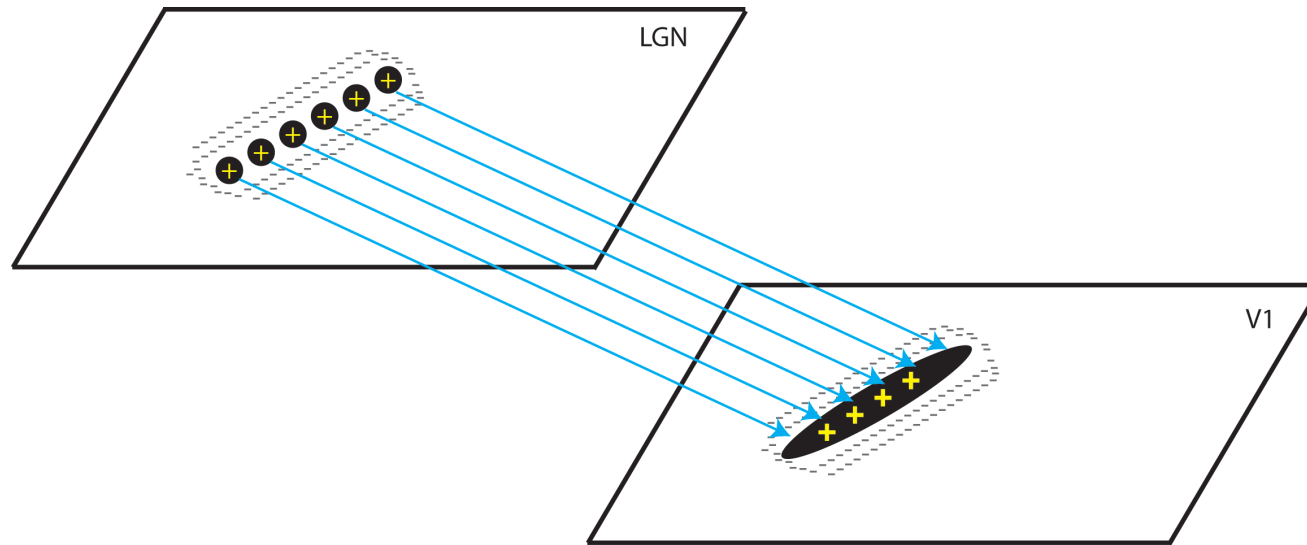
$$D(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} \exp\left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right] \cos(kx - \phi)$$

Unit computations in deep convolutional network models



Movshon 1978, Carandini 2006

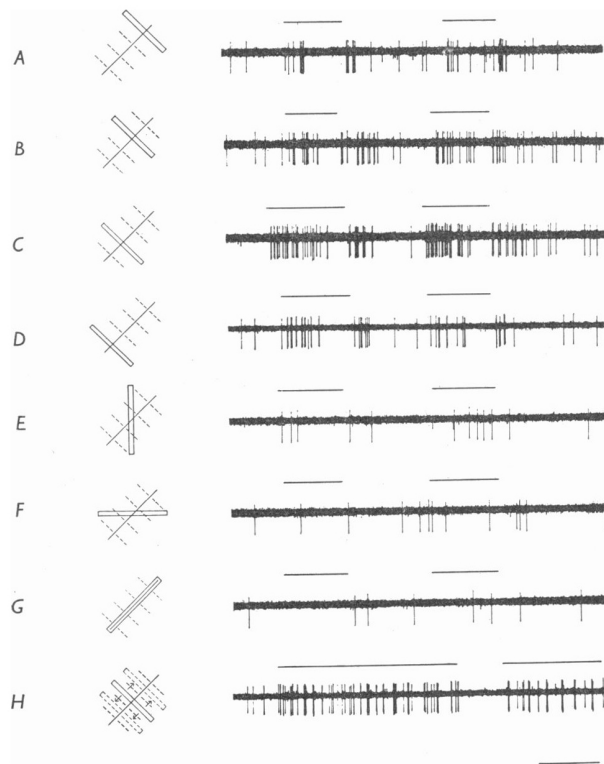
A model for orientation tuning in simple cells



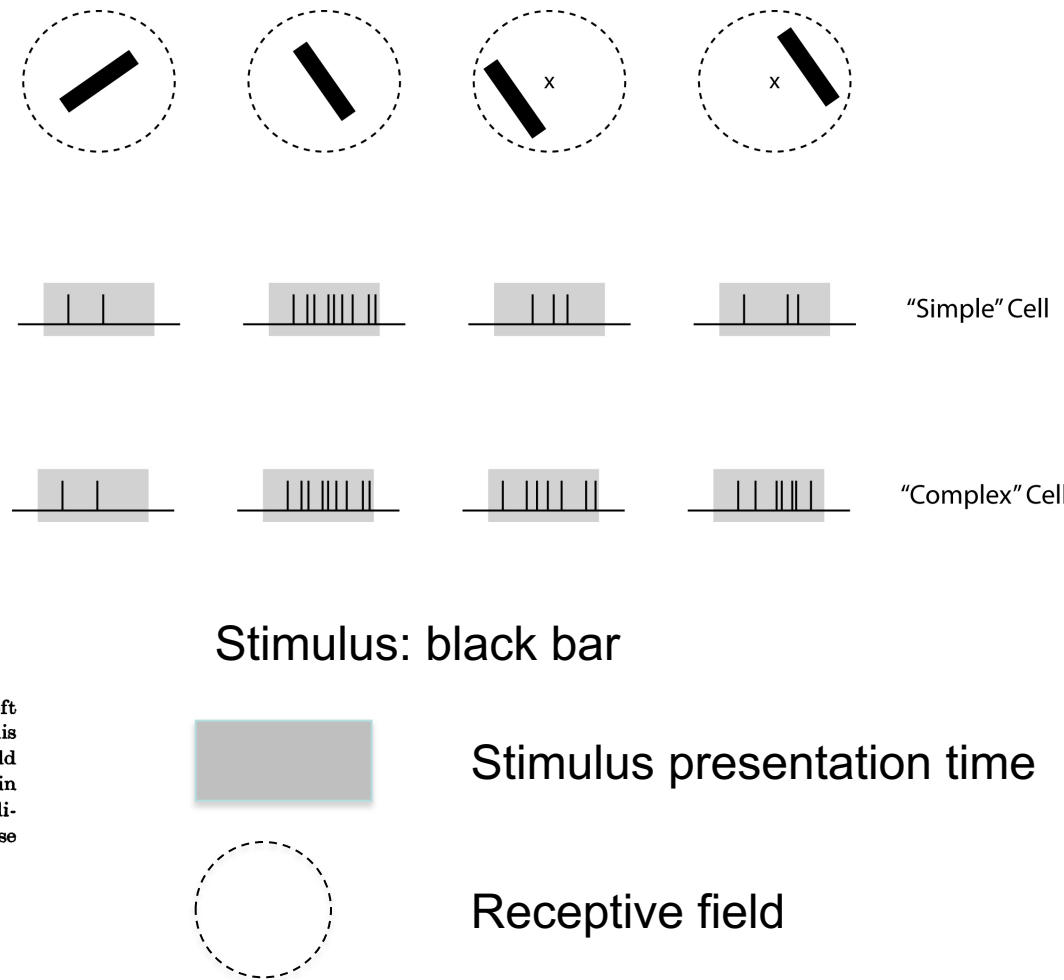
A feed-forward model for orientation selectivity in V1
(by no means the only model)

Wandell (1995), Foundations of Vision. Sinauer Books
Dayan and Abbott. (2001) Theoretical Neuroscience. The MIT Press

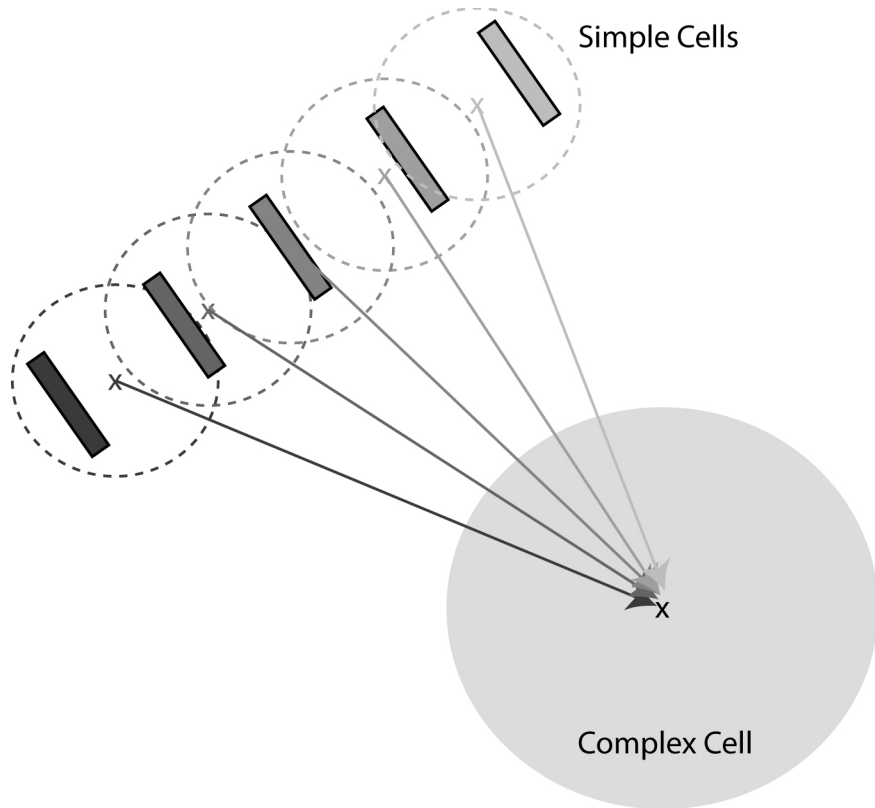
Complex cells show position tolerance



Text-fig. 4. Responses of a cell with a complex field to stimulation of the left (contralateral) eye with a slit $\frac{1}{8} \times 2\frac{1}{2}^\circ$. Receptive field was in the area centralis and was about $2 \times 3^\circ$ in size. A-D, $\frac{1}{8}^\circ$ wide slit oriented parallel to receptive field axis. E-G, slit oriented at 45 and 90° to receptive-field axis. H, slit oriented as in A-D, is on throughout the record and is moved rapidly from side to side where indicated by upper beam. Responses from left eye slightly more marked than those from right (Group 3, see Part II). Time 1 sec.



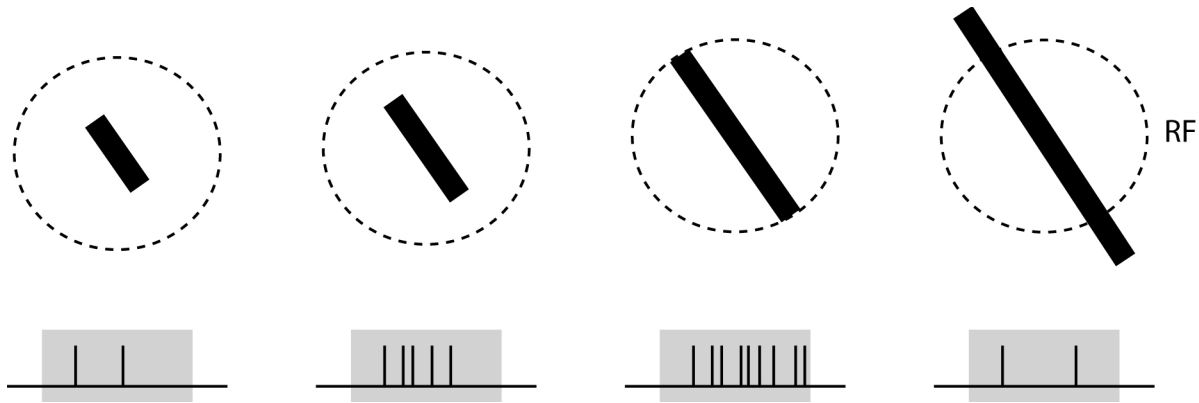
A model to describe tolerance in complex cells



A feed-forward model
describing the responses of
complex cells arising from
non-linear (e.g. OR) adding
of inputs from multiple simple
cells

(by no means the only model)

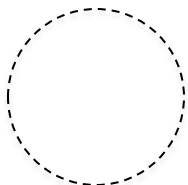
End stopping



Stimulus: bar with preferred orientation

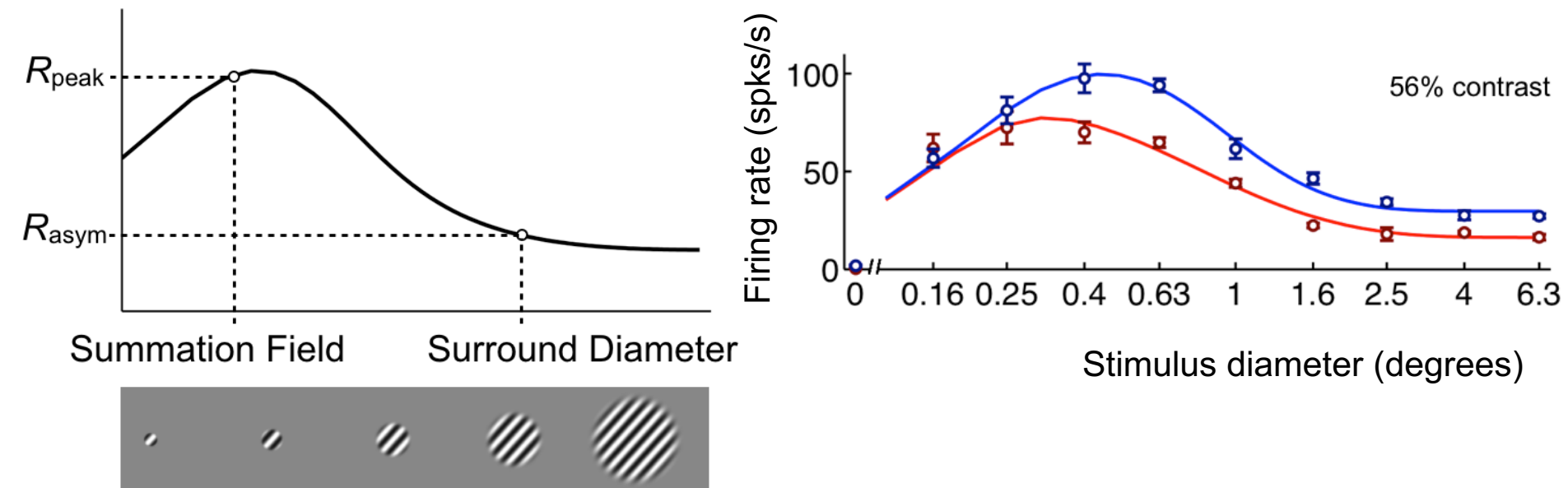


Stimulus presentation time



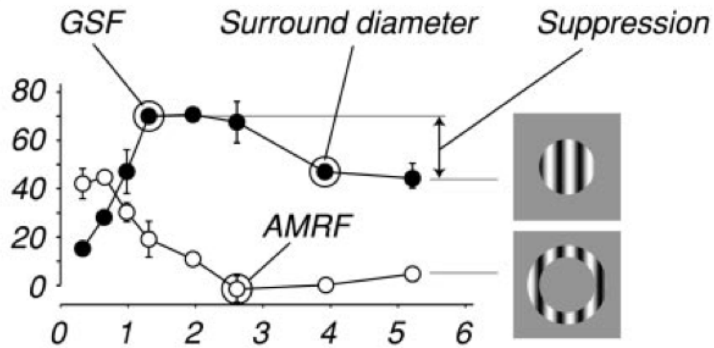
Receptive field

More is not necessarily better: the surround can inhibit the responses of neurons in V1

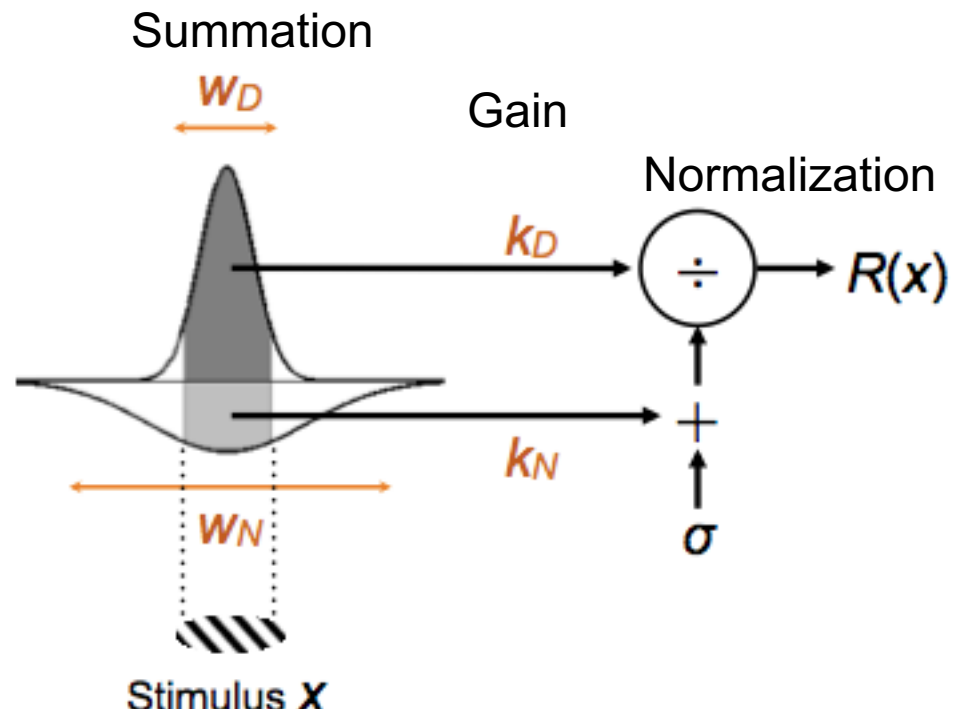


More is not necessarily better: the surround can inhibit the responses of neurons in V1

A



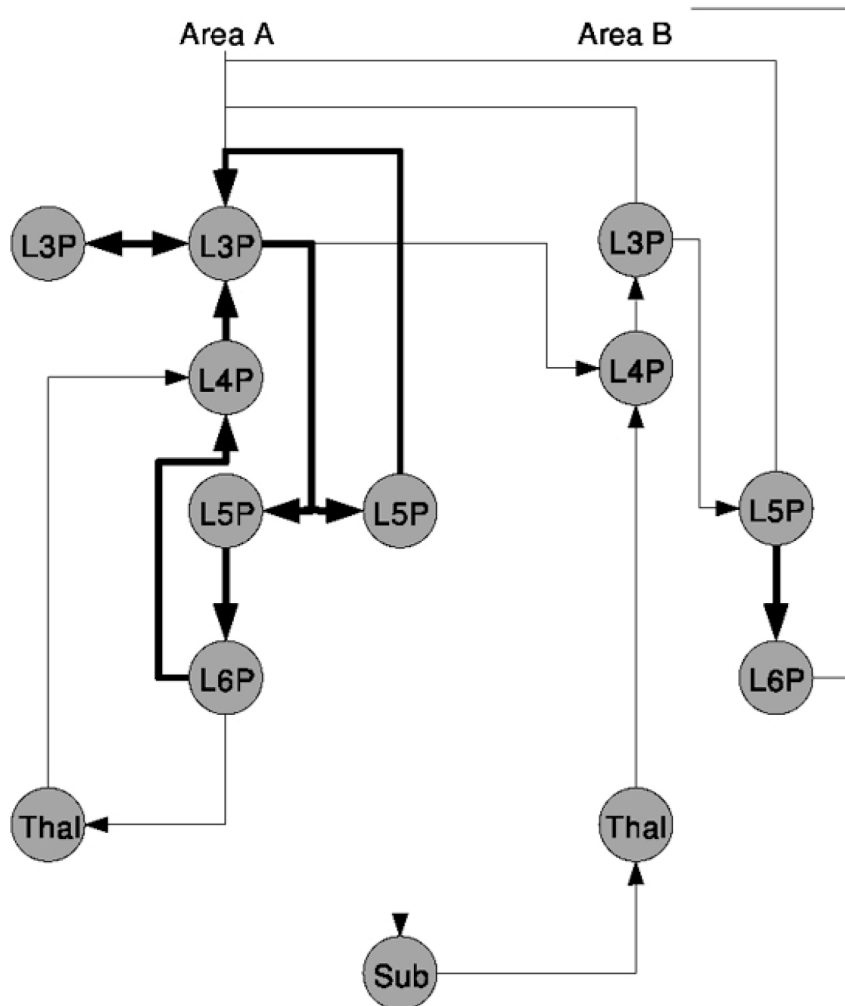
Cavanaugh et al J.
Neurophys 2002



$$R_{\text{ROG}}(x) = R_0 + \frac{k_D [w_D \text{erf}(x/2w_D)]^2}{\sigma + k_N [w_N \text{erf}(x/2w_N)]^2}$$

Nassi et al Front. Syst. Neurosci. 2014

“Canonical” microcircuits in neocortex



Felleman and Van Essen 1991
Douglas and Martin 2004

Edges can take us a long way towards object recognition



1.9% of pixels > 0



MATLAB:

`I: image`

`I_edges = edge(I);`

Different methods:

Sobel, Prewitt, Roberts,
Laplacian of Gaussian,
Canny

(determining how the
gradients of I are
computed)



2.9% of pixels > 0



Note: this is a major
oversimplification. The output
of V1 does not simply
represent the image edges

Do we know what the early visual system does?

Up to 85% of “V1 function” has yet to be accounted for (Olshausen and Field 2005)

- Biased sampling of neurons
- Biased stimuli
- Biased theories
- Contextual effects
- Internal connections and feedback
- Joint activity

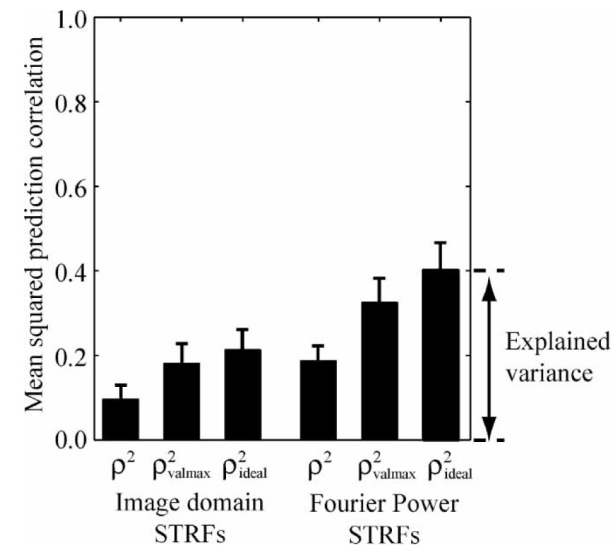
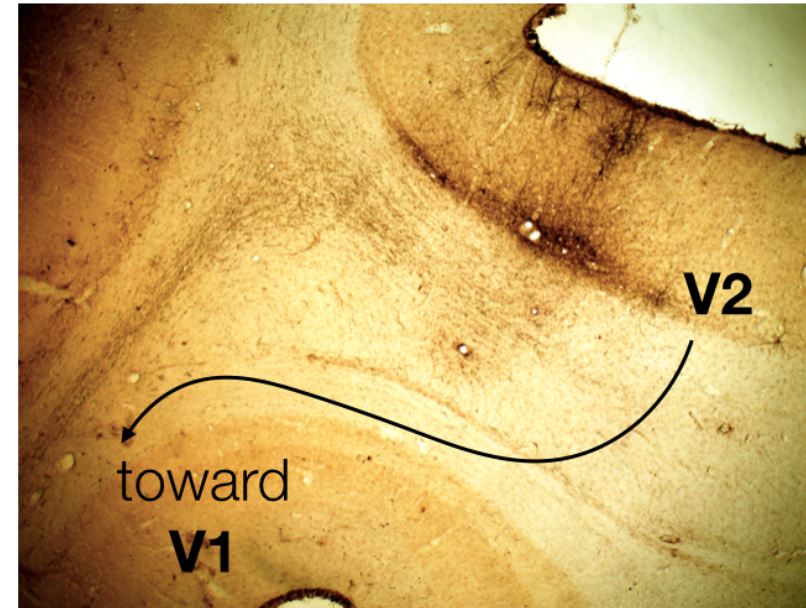
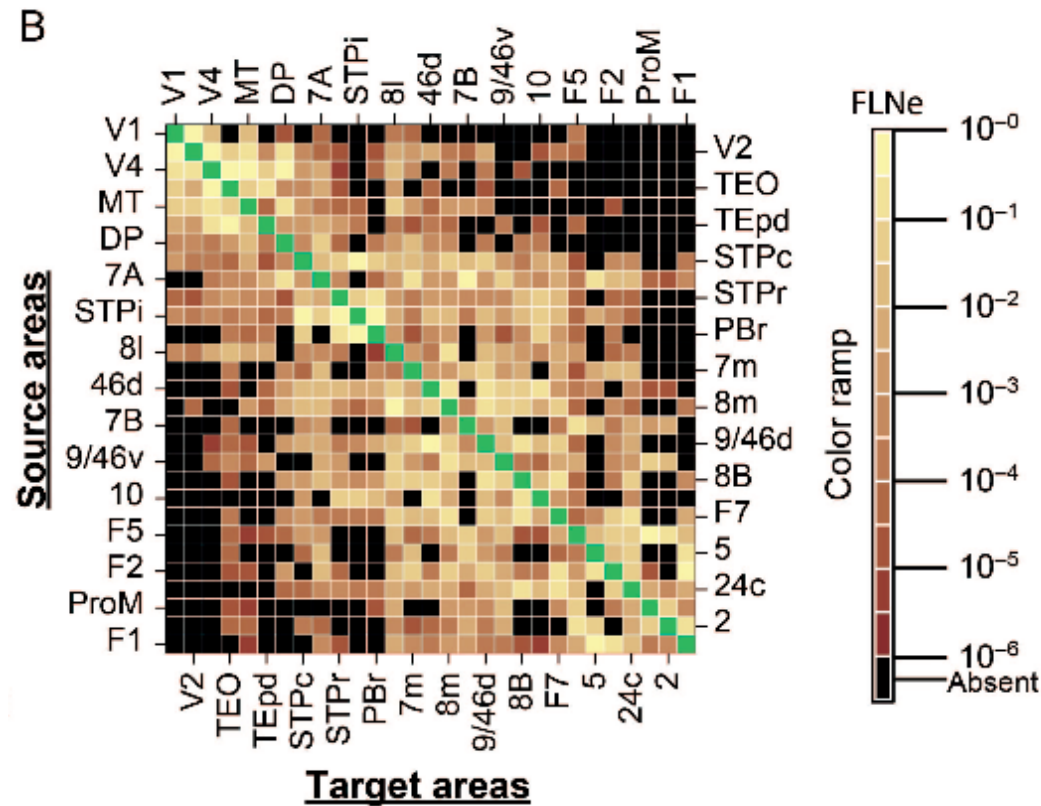


Figure 8. Summary of the effect of finite sampling on predictions. Each bar indicates mean squared prediction correlation for the 49 neurons with greater than 2000 stimulus-response samples (error bars indicate standard error). Data for image domain STRFs are shown at left, and for Fourier power STRFs at right. ρ^2 indicates the mean squared prediction correlation actually measured for the STRFs. ρ^2_{valmax} indicates mean prediction after correcting for finite sampling of validation data. ρ^2_{ideal} indicates the mean prediction after correcting for finite sampling of both estimation and validation data. Fourier power STRFs perform consistently better than image domain STRFs. After correcting for sampling limitations, Fourier power STRFs can account for an average of 40% of the response variance in V1. The remaining portion of the response results from nonlinear response properties ('unexplained variance') not included in the Fourier power model.

David and Gallant, J.L. Network (2005)

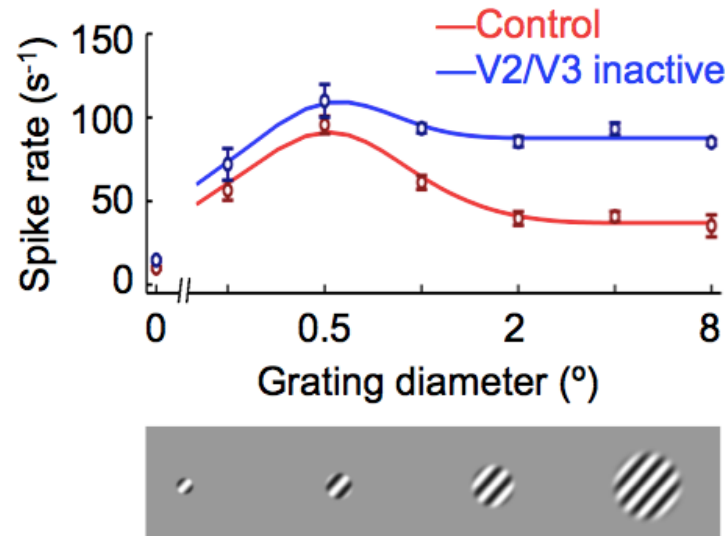
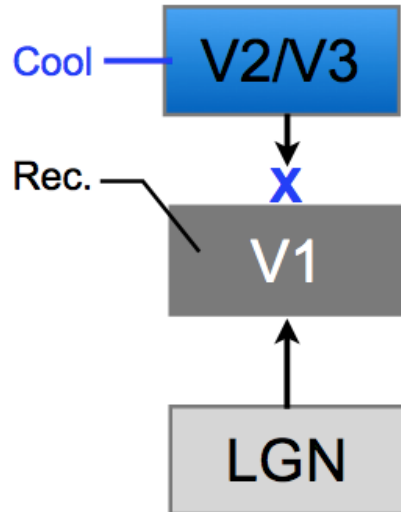
There are more top-down connections than bottom-up ones



Markov et al.

Cerebral Cortex 2014

Inactivating feedback to V1 leads to less surround suppression



Cited works

- Carandini, M., Demb, J. B., Mante, V., Tolhurst, D. J., Dan, Y., Olshausen, B. A., Gallant, J. L., & Rust, N. C. (2005). Do we know what the early visual system does?. *The Journal of neuroscience*, 25(46), 10577-10597.
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- Yacoub, E., Harel, N., & Uğurbil, K. (2008). High-field fMRI unveils orientation columns in humans. *Proceedings of the National Academy of Sciences*, 105(30), 10607-10612.