Neurobiology HMS 230
Harvard/GSAS 78454

Visual Object Recognition

Primary Visual Cortex

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Visual system

Anatomy

Physiology

Functional organization

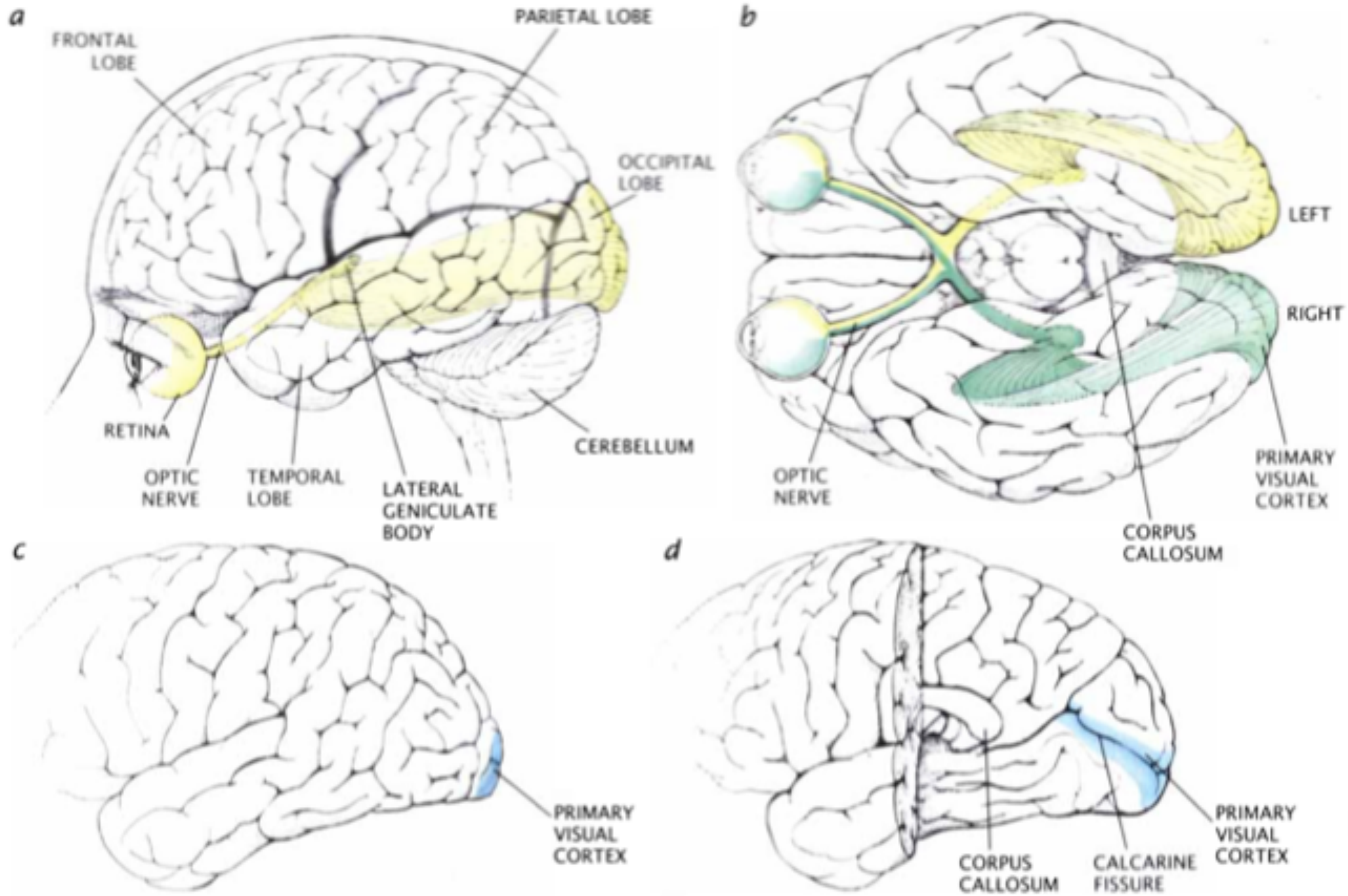
Receptive field models

Neural populations

Neural Correlates of Behavior

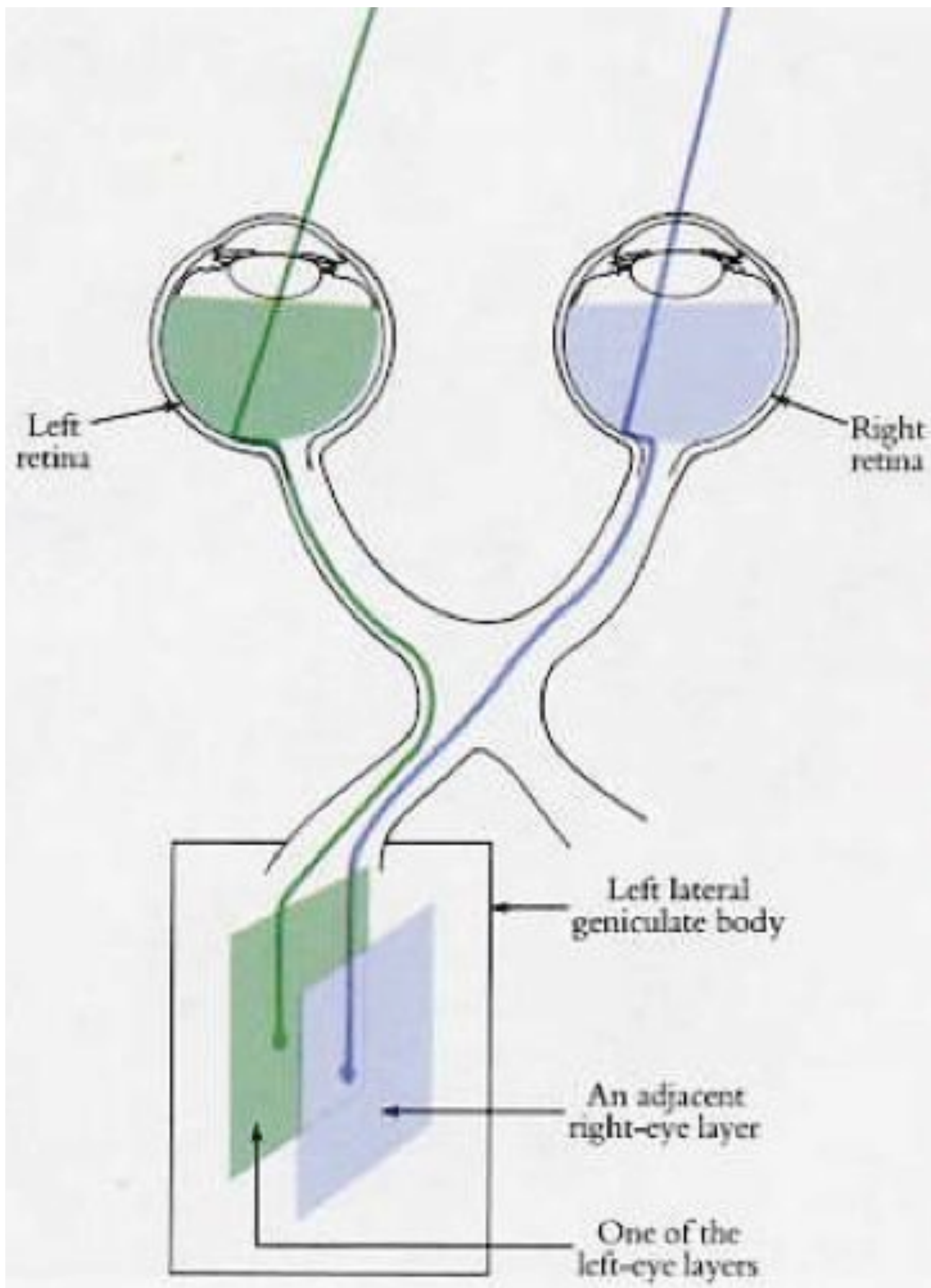
The Unknown

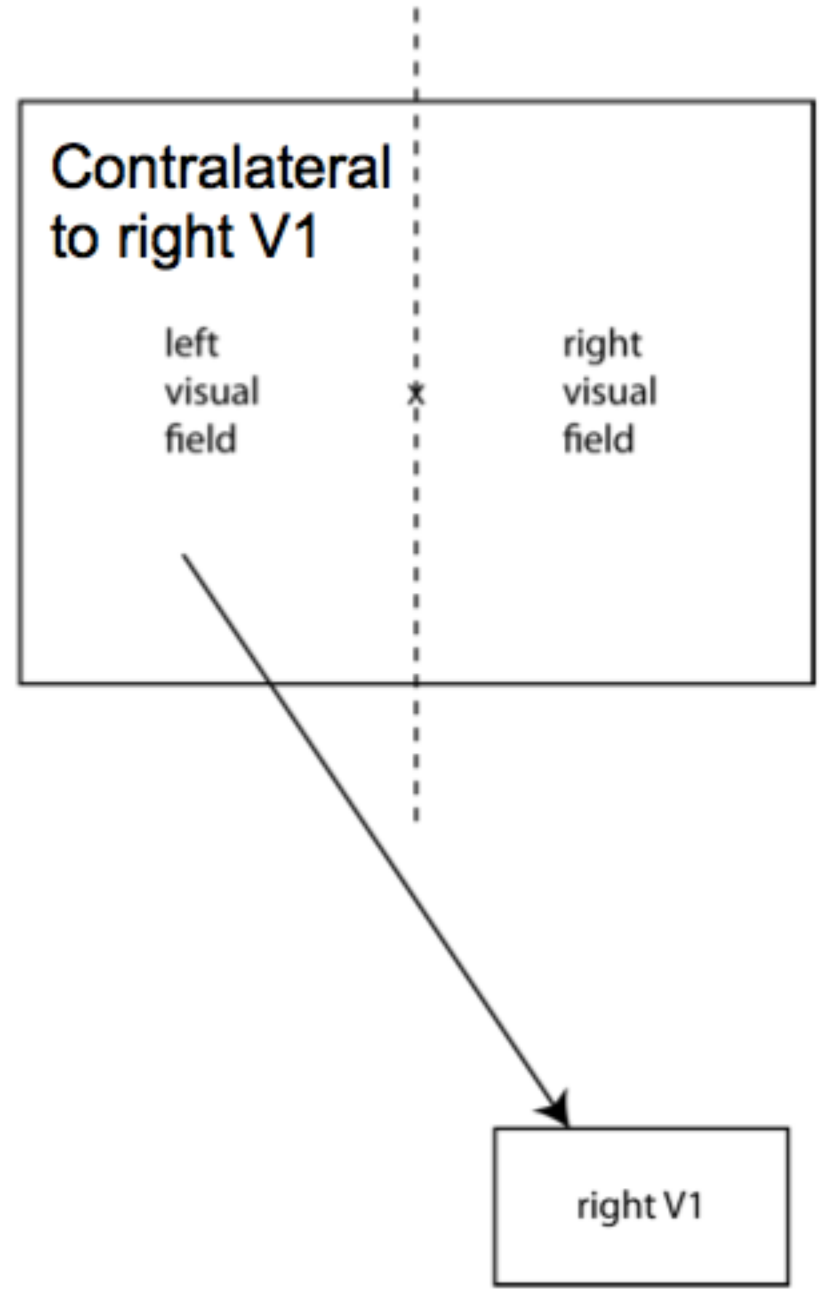
From the retina to the cortex



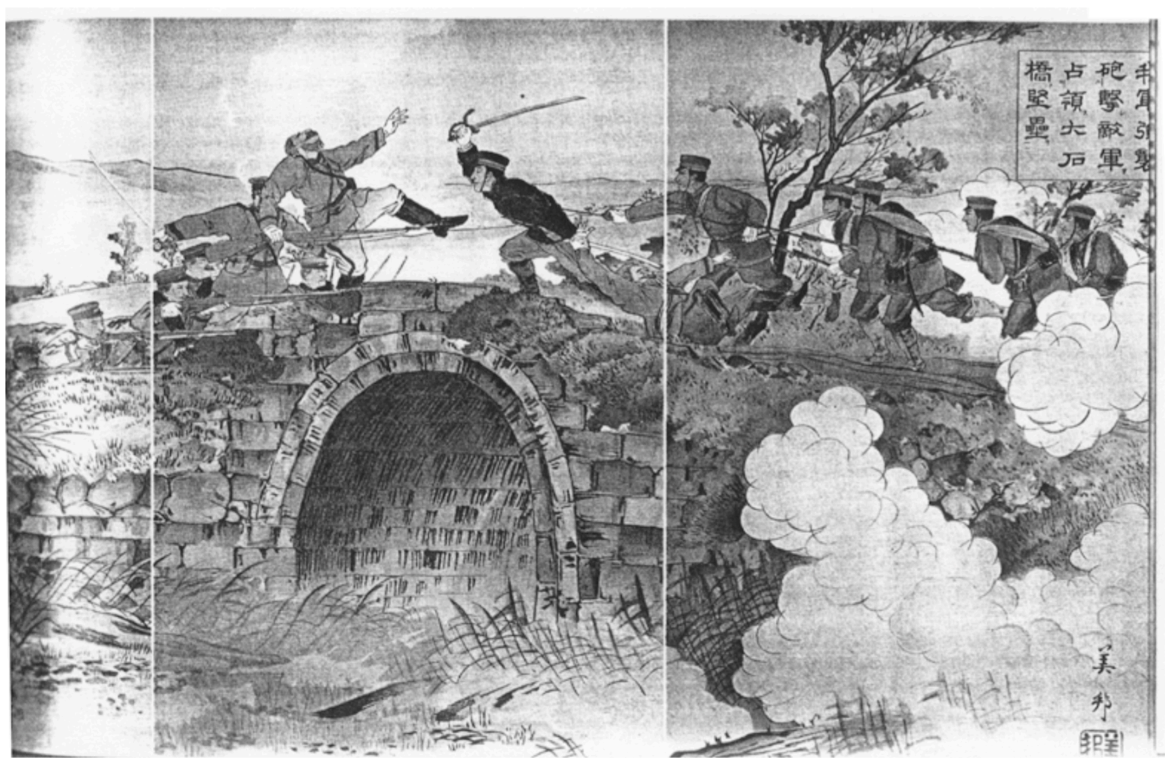
Glickstein M. *Sci. Am.* 1988

Each hemisphere of the brain represents its contralateral visual field





Studies of cerebral lesions revealed topographic visual deficits



Russo-Japanese War of 1904–5

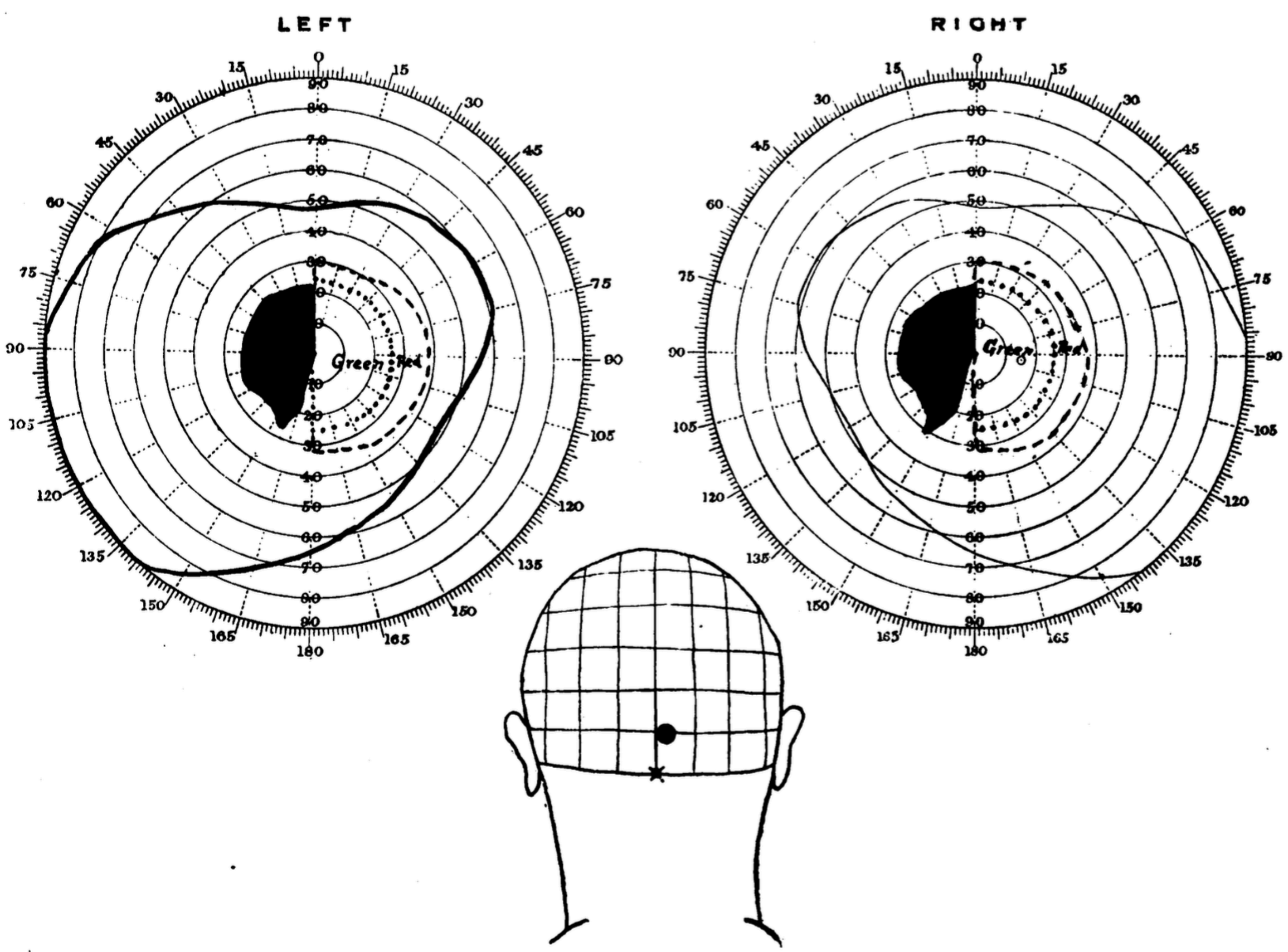


FIG. 1.

Holmes G. *Br. J. Ophthalmol.* 1918

Acuity is much higher at the fovea

Fixate here

x

TRY READING THIS [44]

Retinal photoreceptor density [36]

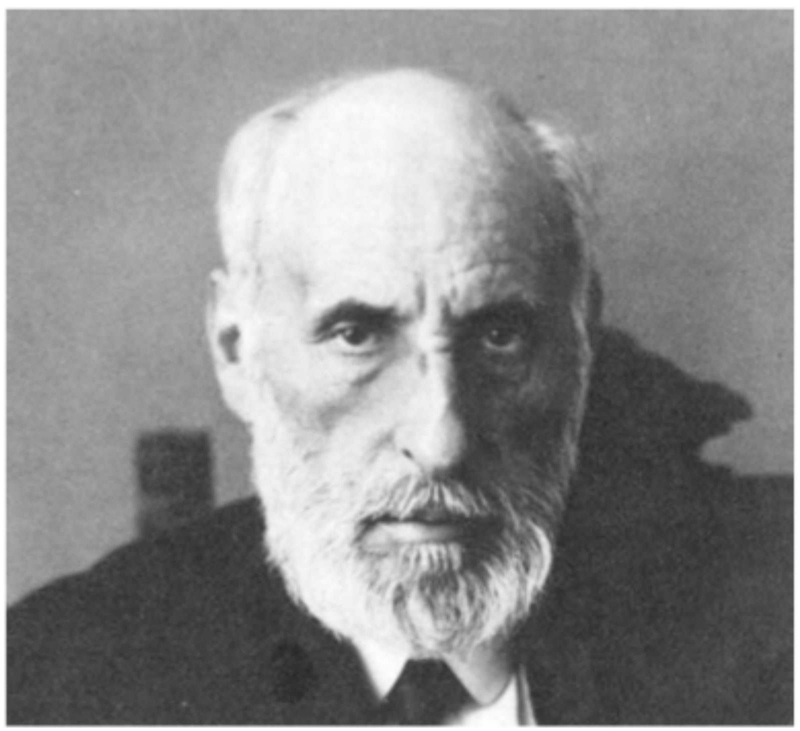
Cortical magnification factor [28]

Why is it that we do not see things upside down? [20]

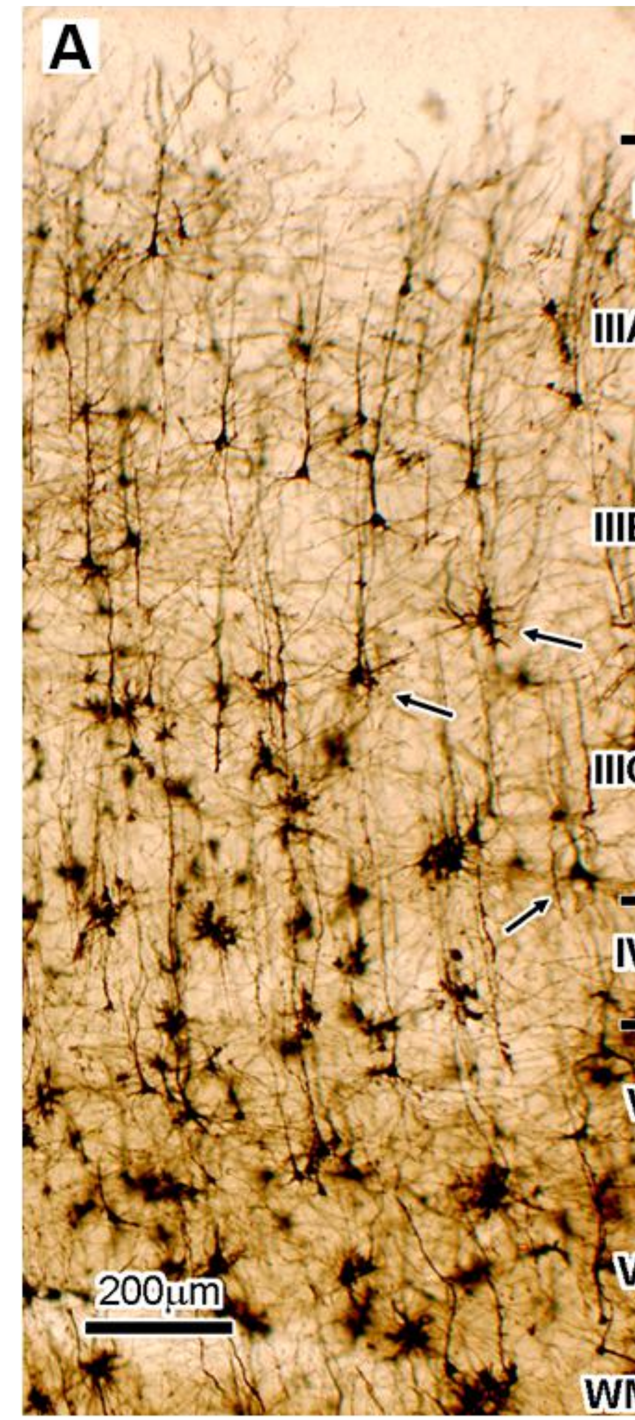
Or the split between the two hemifields? [12]

And do not forget about the importance of crowding! [8]

The complex circuitry of cortex as drawn by Ramon y Cajal

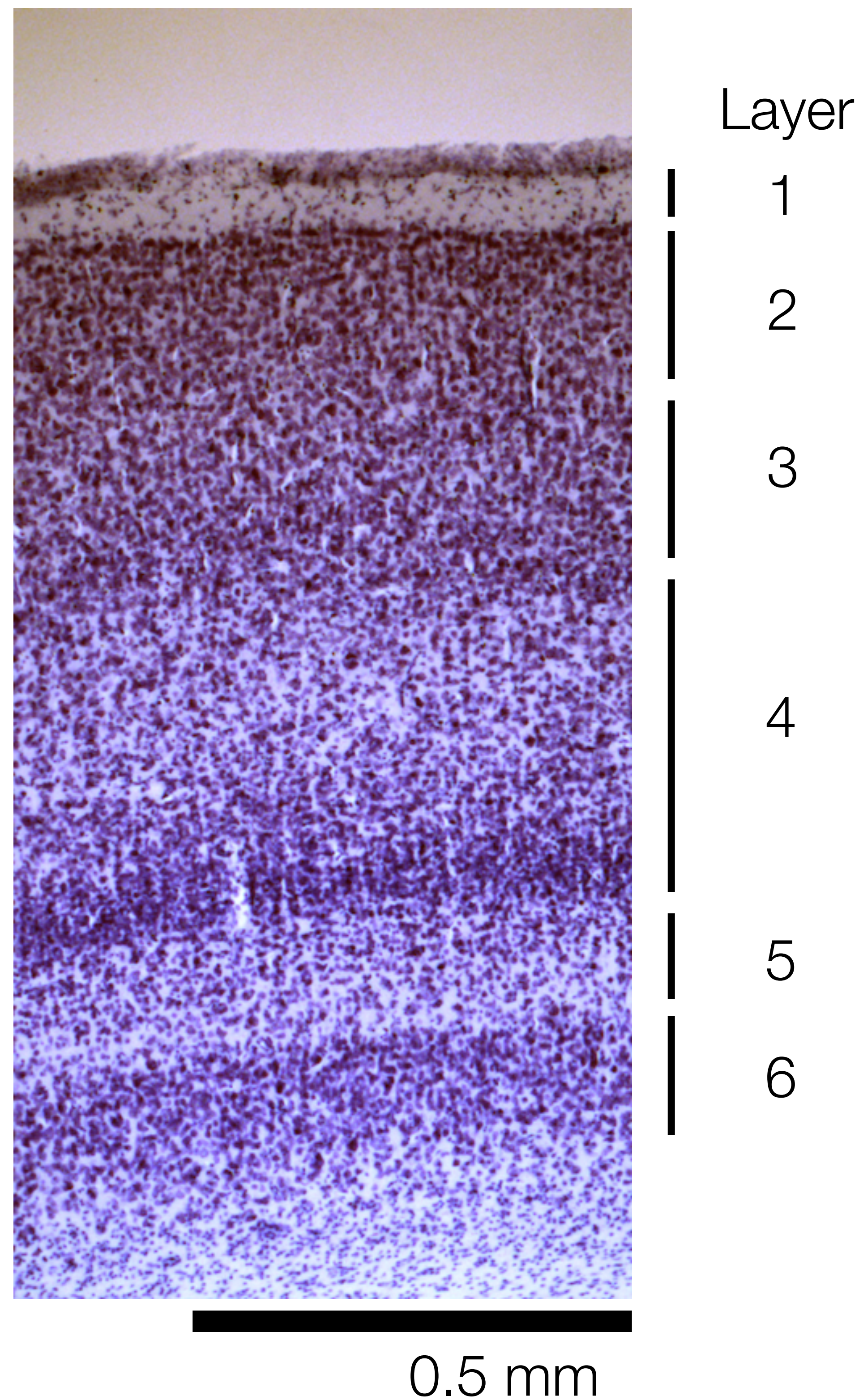


GOLGI-STAINED NERVE TISSUE from the visual cortex of a rat was sketched by Cajal in 1888. The numbers along the right-hand margin identify cellular layers; the capital letters label individual neurons. One of Cajal's most important contributions to neurobiology was to establish the neuron as a discrete,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

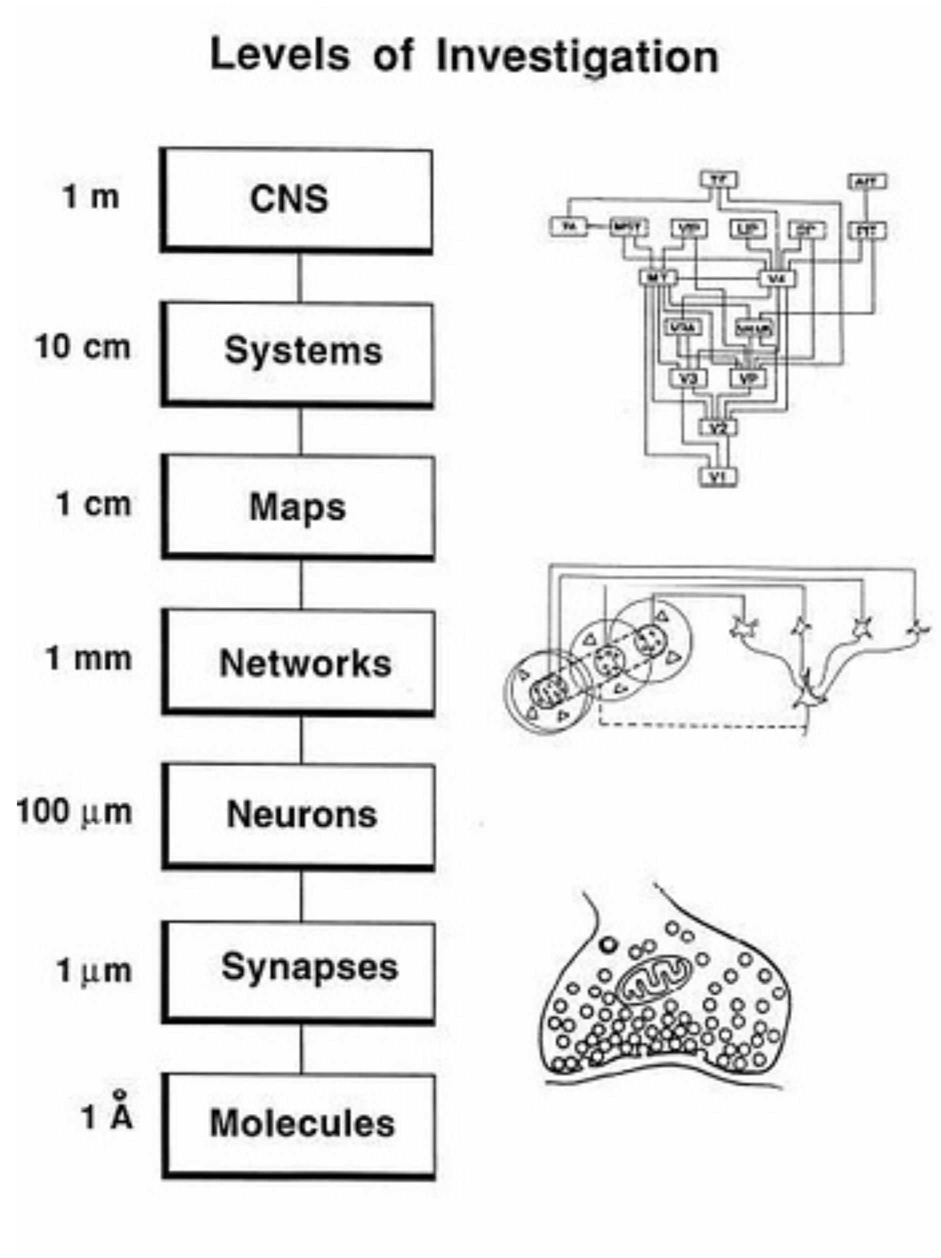


Džaja et al., *Front. Neuroanat.*, 2014

The six layers of the “striate” cortex (V1)



Scales of the nervous system



Churchland & Sejnowski, 1992

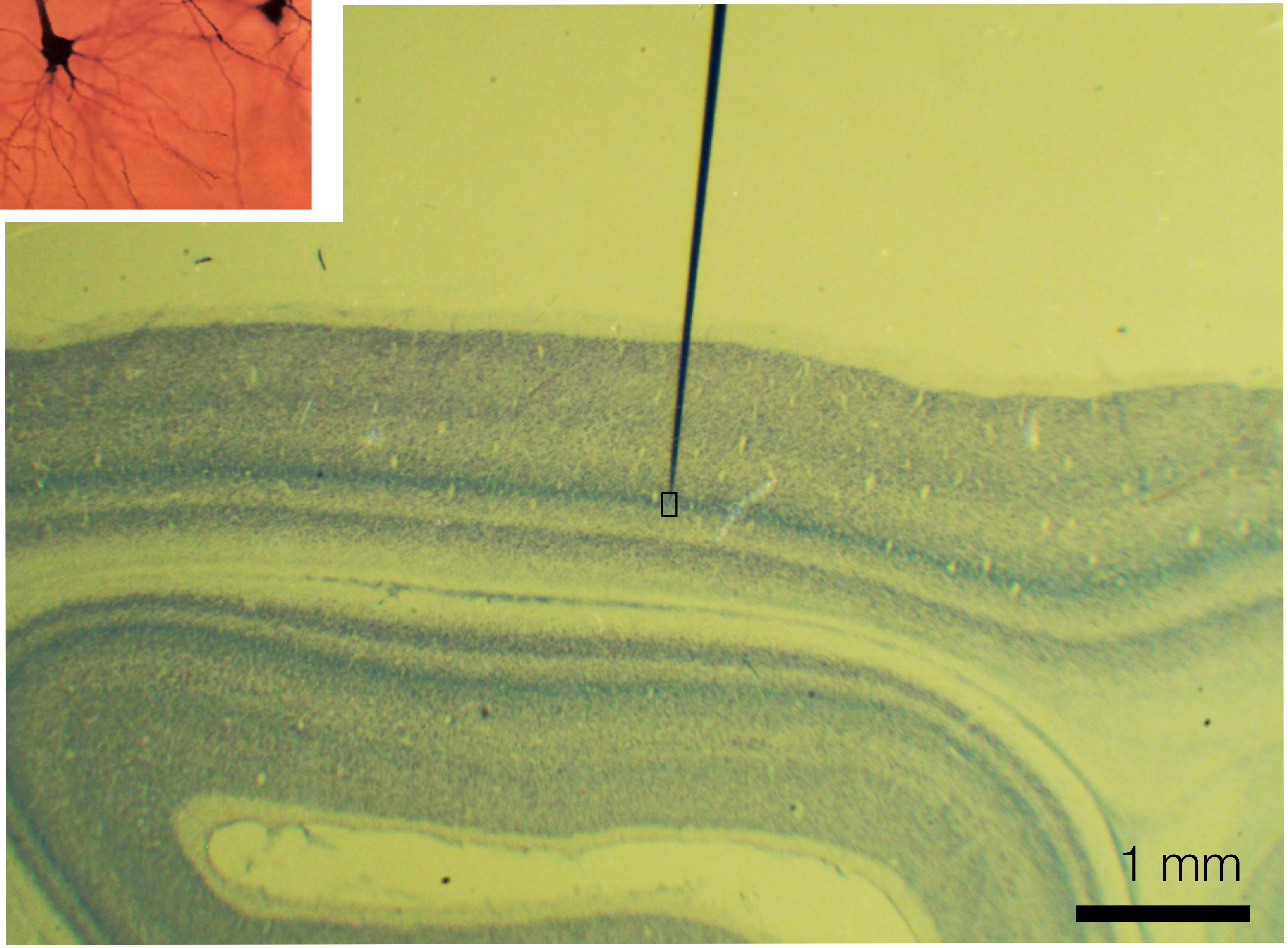
The gold standard to examine neuronal activity: microelectrode recordings

Physiology

Edgar Adrian 1926

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

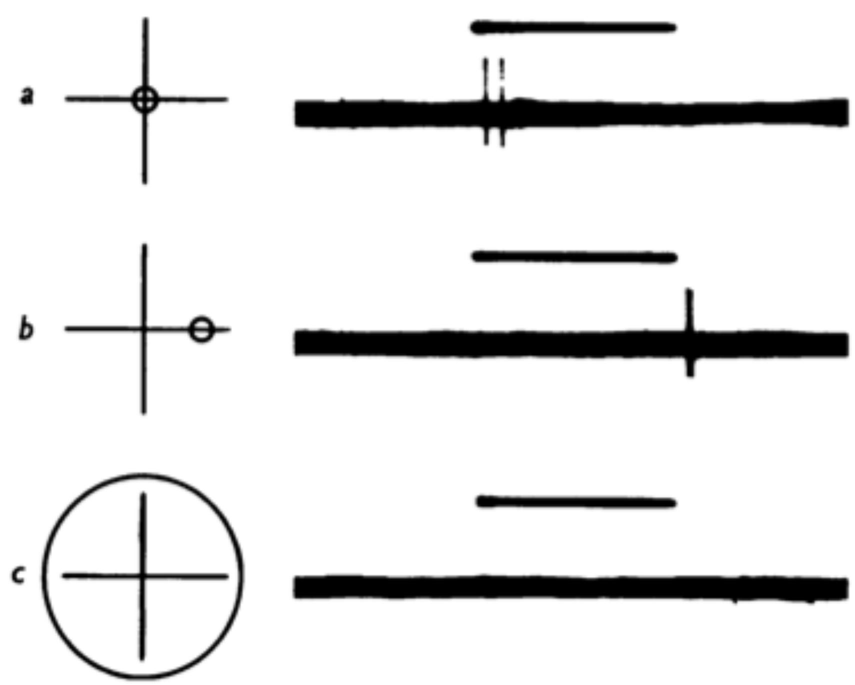
Hubel, D. (1979). The Visual Brain. SCIENTIFIC AMERICAN 241, 45-53.

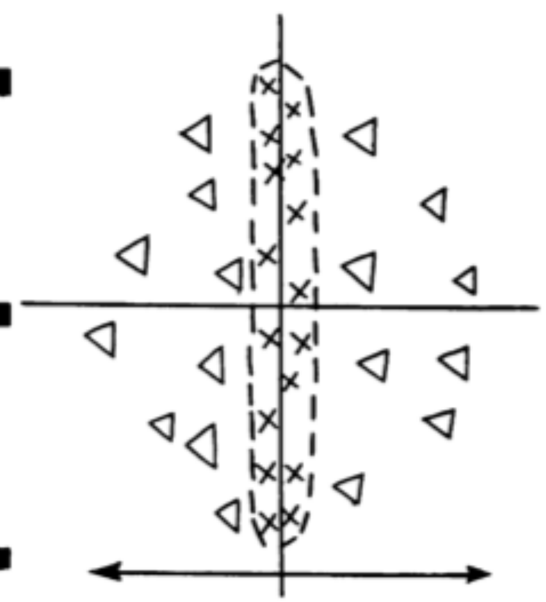


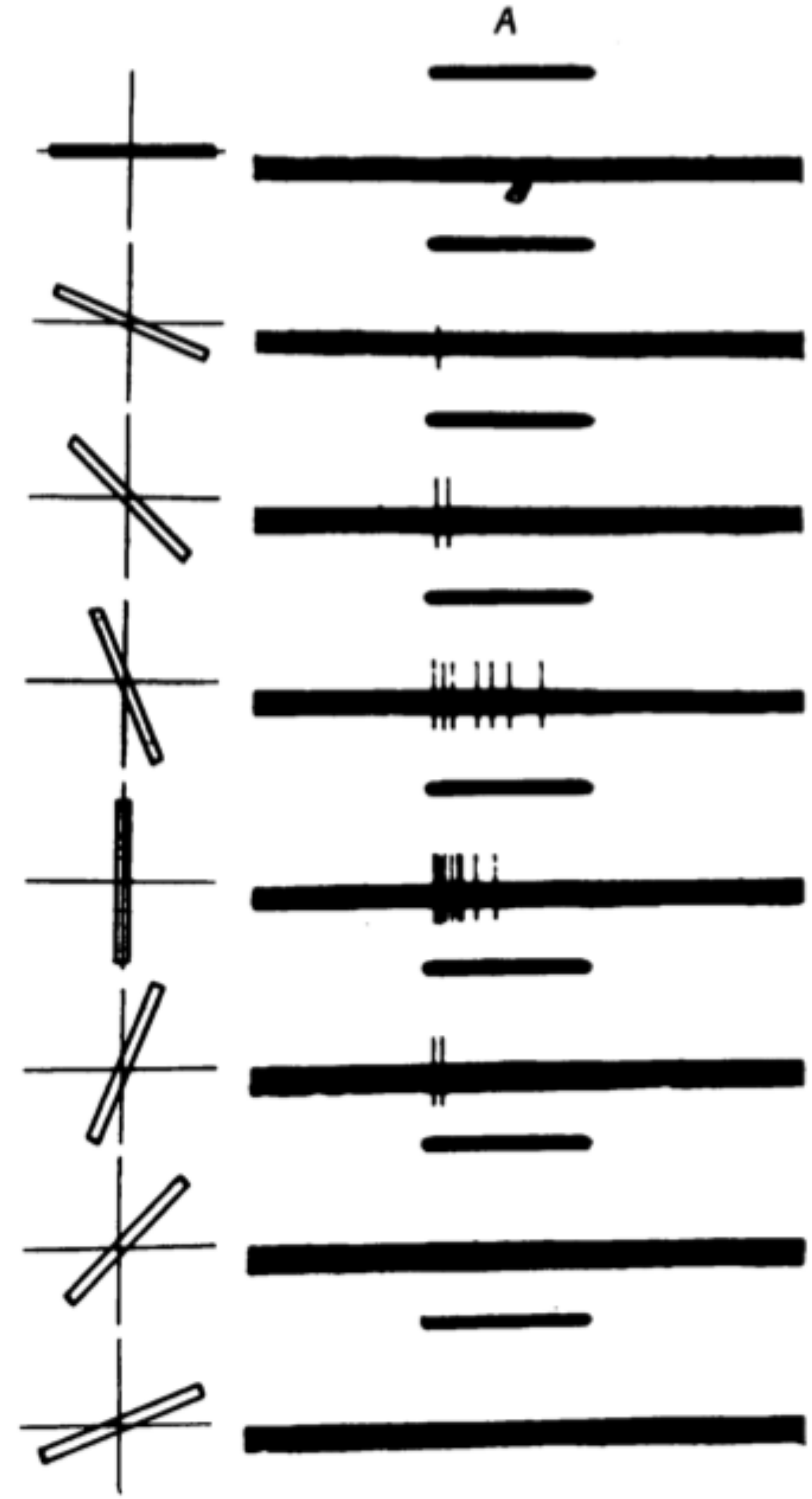
Livingstone, *Neuron*, 2013

Neurophysiological recordings from V1

Orientation selectivity of simple fields

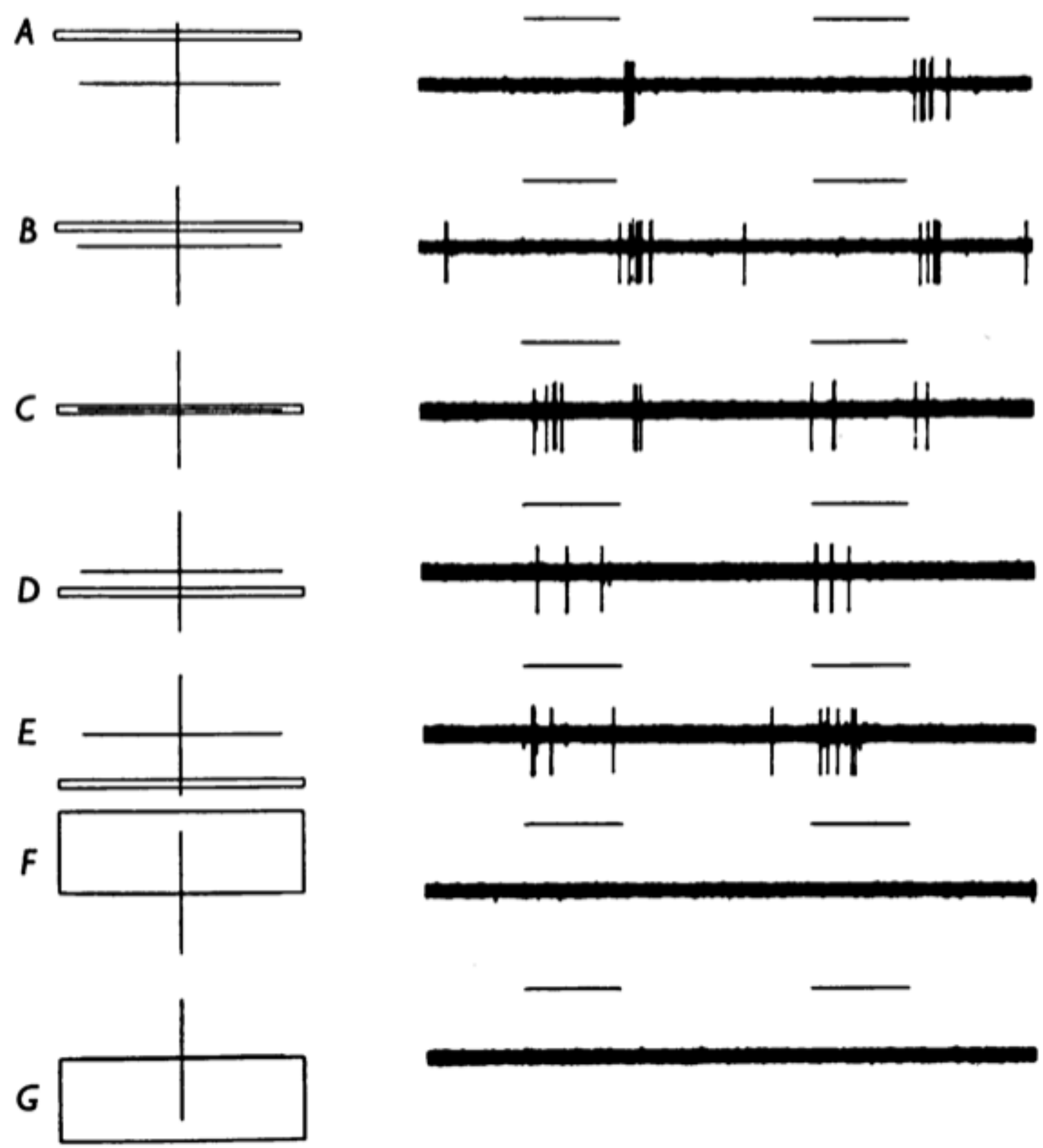






Hubel & Wiesel, *J. Physiol.*, 1959

Selectivity and tolerance of complex fields

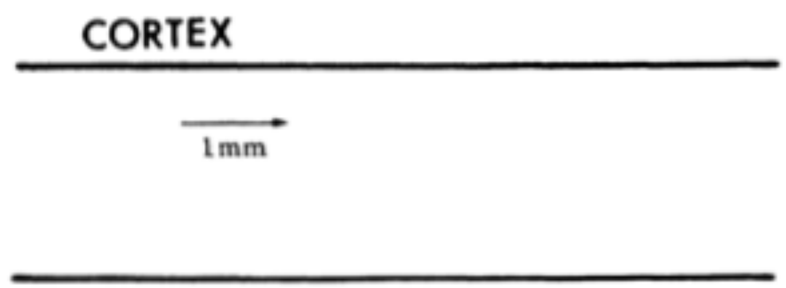


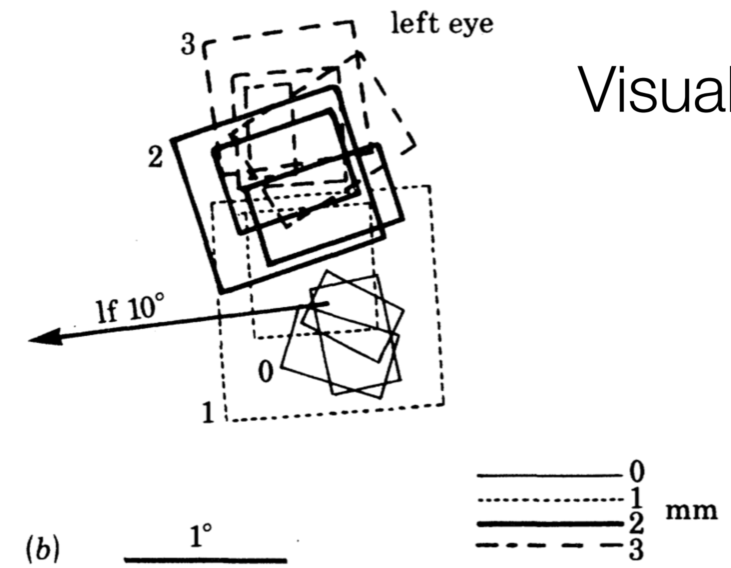
Hubel & Wiesel, *J. Physiol.*, 1962

Hubel and Wiesel mapping V1 neurons

www.youtube.com/watch?v=8VdFf3egwfg

Retinotopical map in the cortex





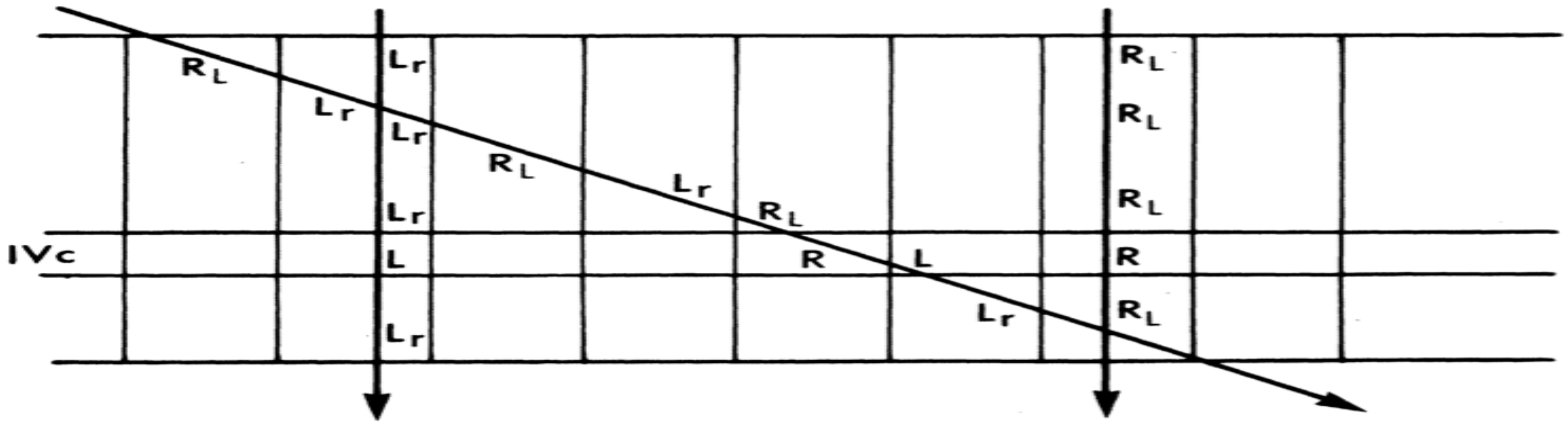
Visual field

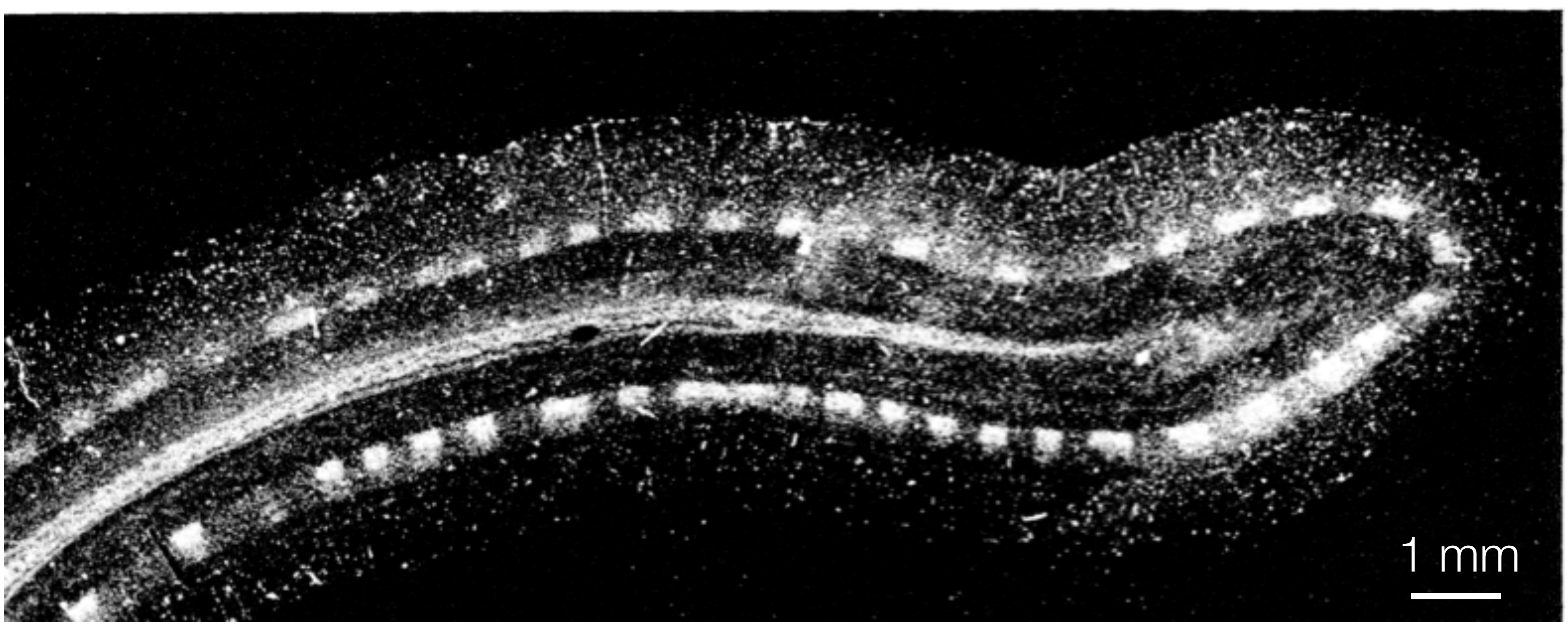
Visual field

Eccentricity

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

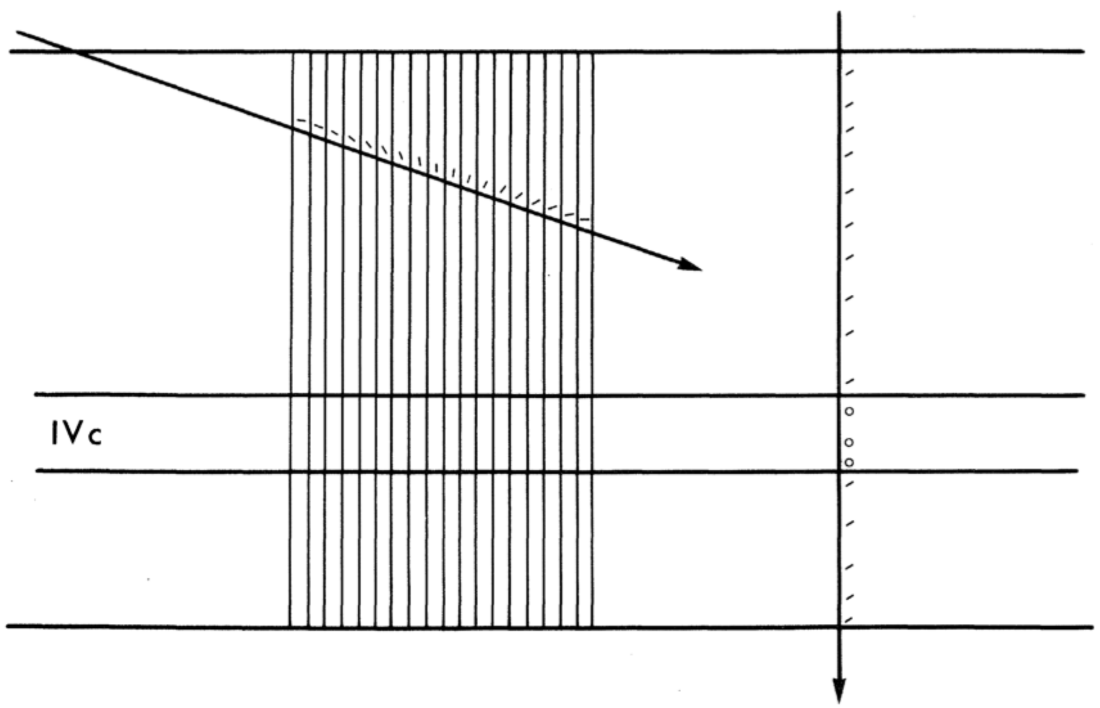
Ocular dominance columns



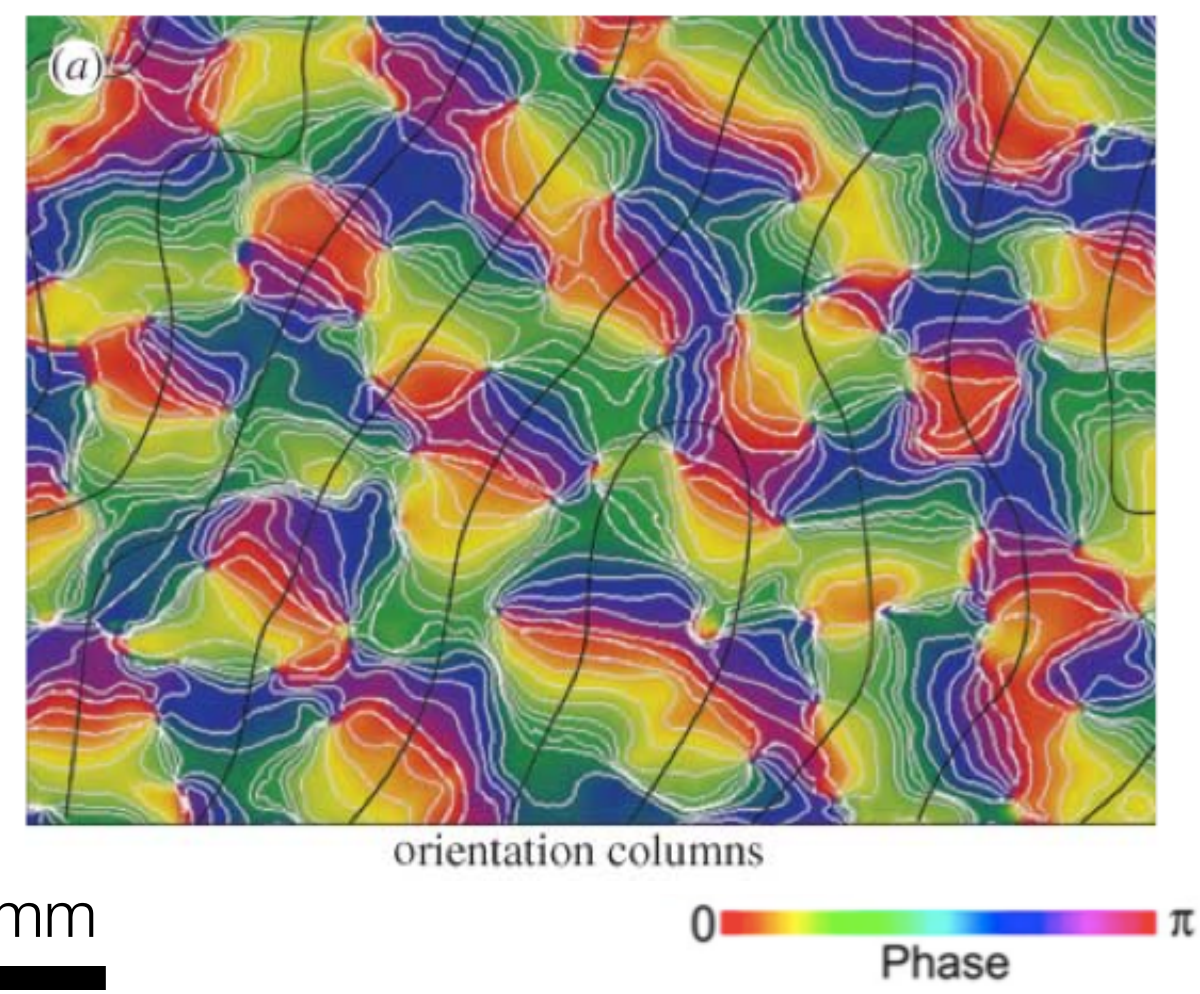


Hubel & Wiesel, *Proc. R. Soc. Lond. B*, 1977

Visual orientation columns



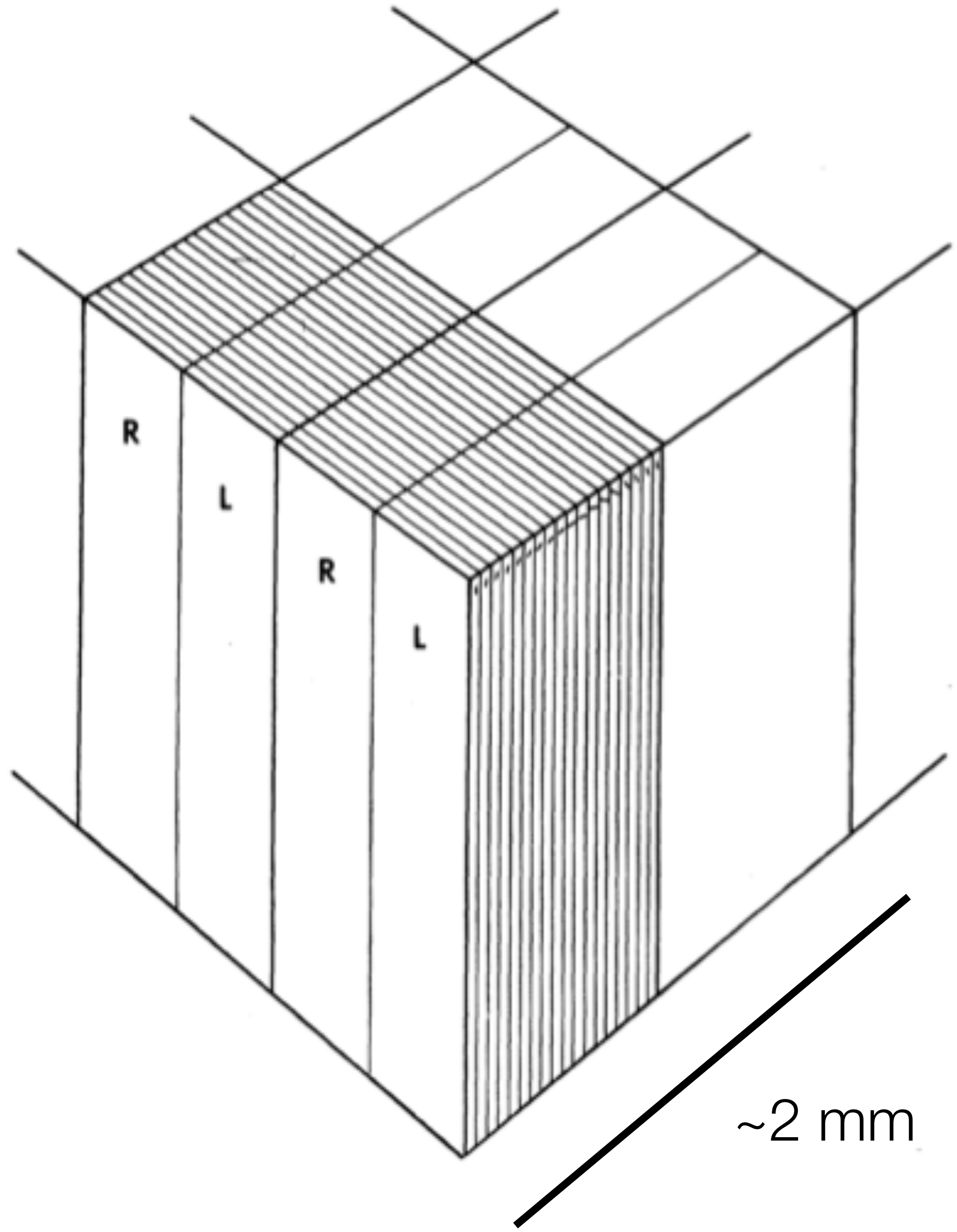
1 mm



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

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

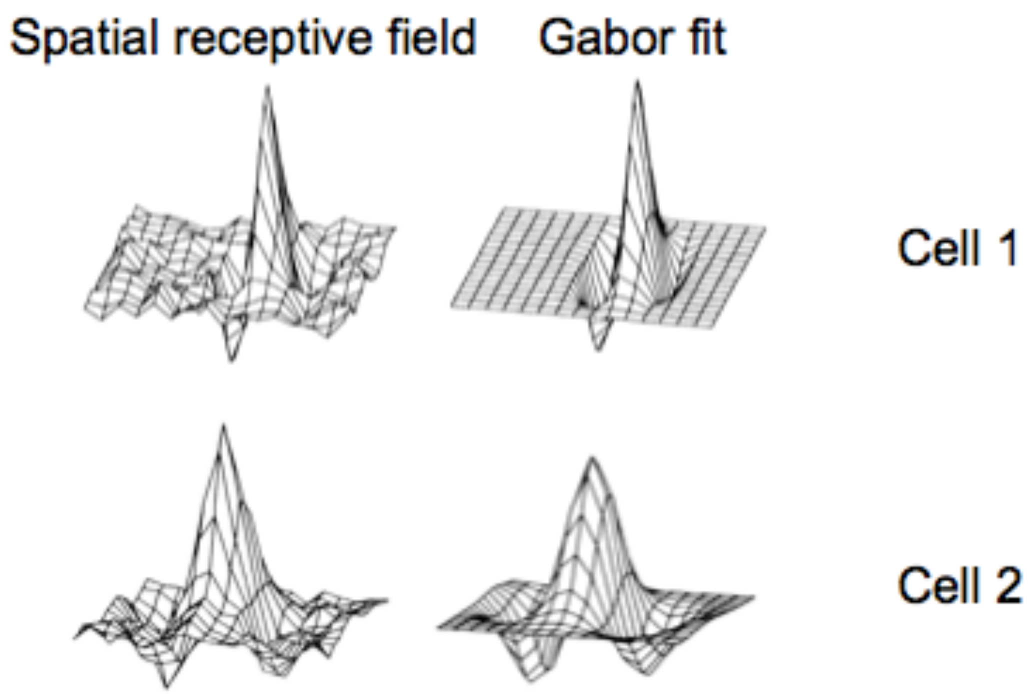
Putting it all together: the “hypercolumn”



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

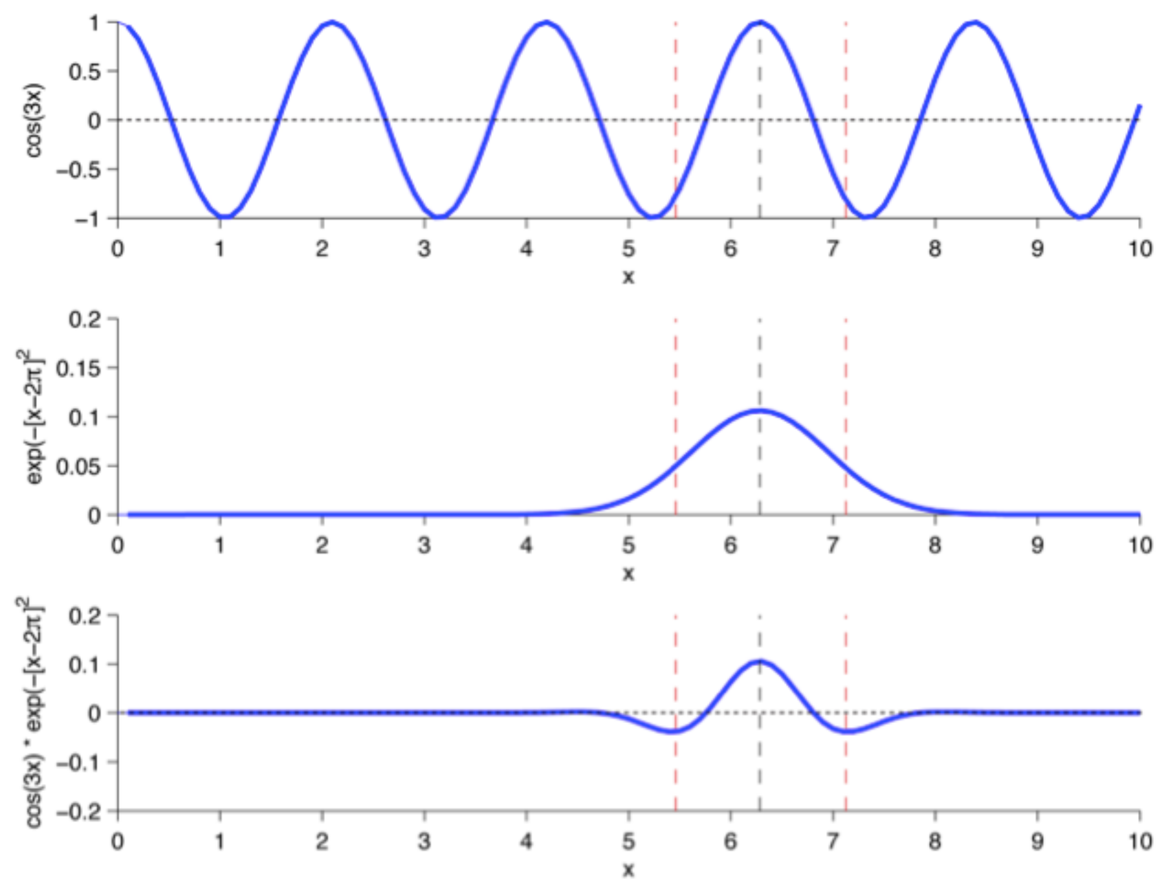
Different primary visual cortex neurons show a variety of interests

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



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 : MATLAB

An easy way to write computer code

- http://www.mathworks.com/index.html
- "High-level" computer programming language
- Quite powerful!

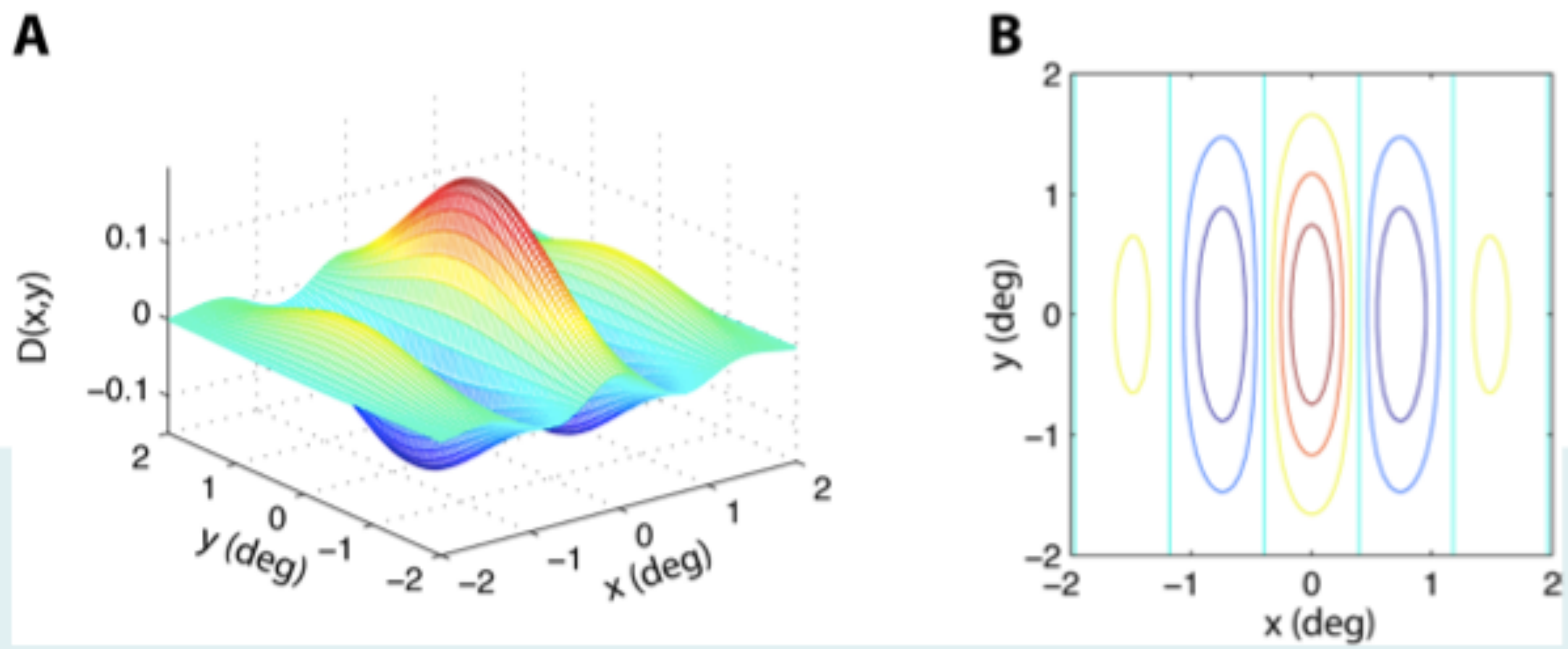
```
theta_rad=(2*pi/360)*theta;                          % theta angle in radians
x=(-2*sigma_x):bin:(2*sigma_x);nx=length(x);         % define x axis
y=(-2*sigma_y):bin:(2*sigma_y);ny=length(y);         % define y axis

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 : MATLAB

An easy way to make plots

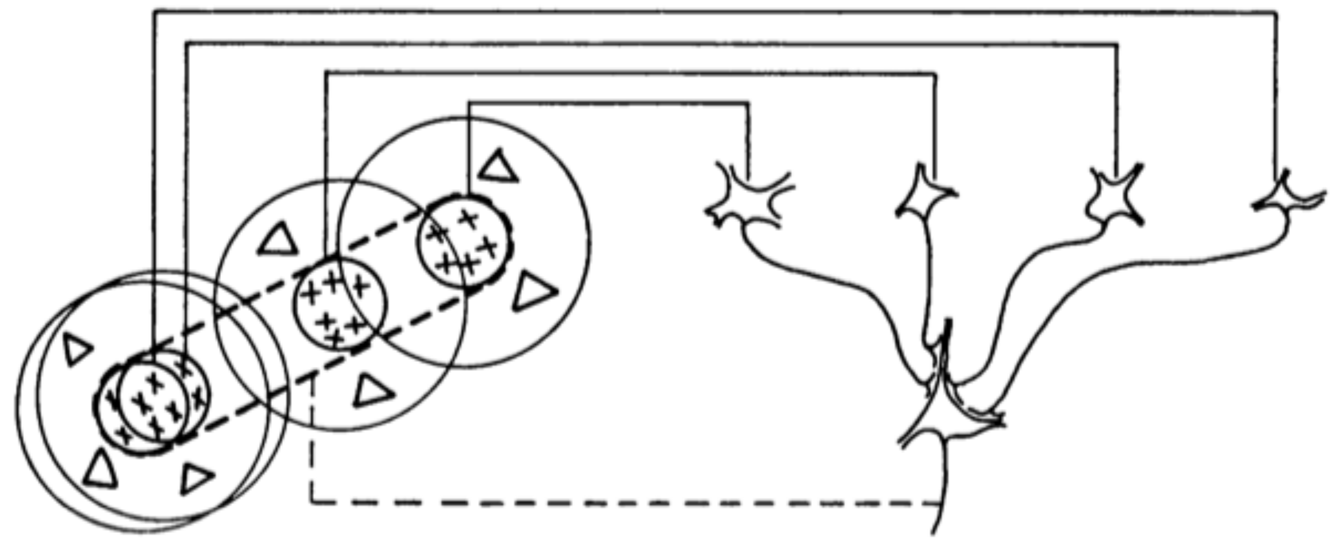


$$D(x,y) = \frac{1}{2\pi\sigma_x\sigma_y}\exp\left[-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}\right]\cos(kx-\phi)$$

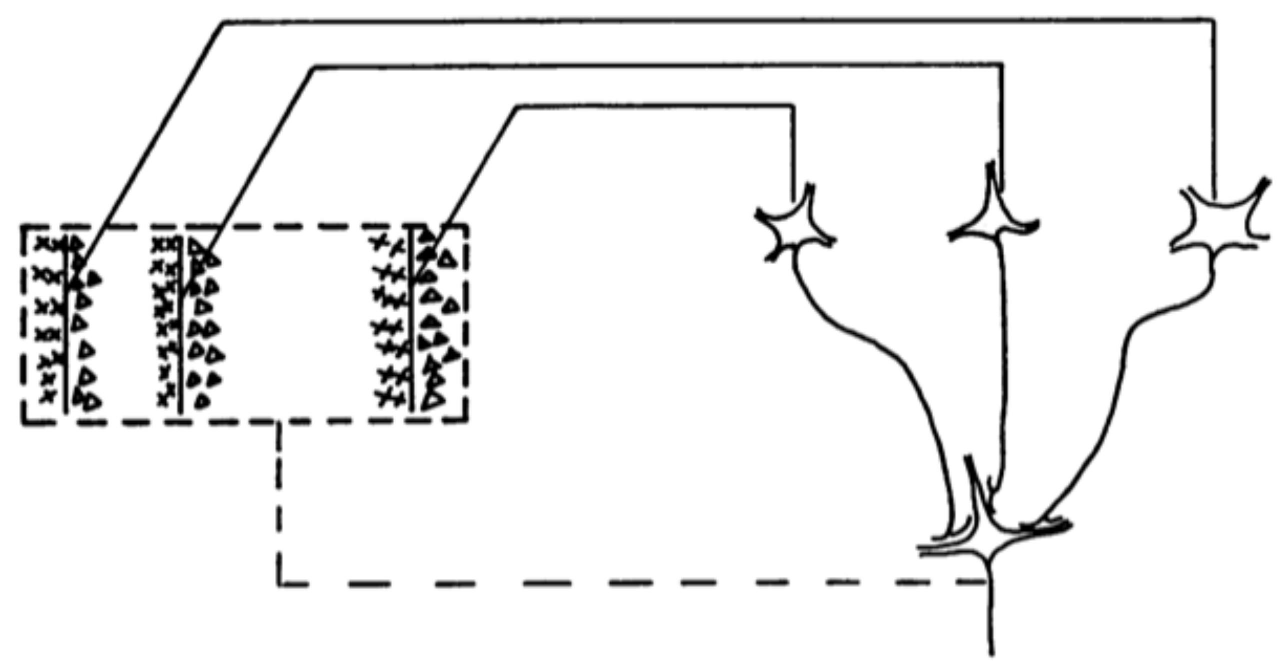
```
sigma_x=1;
sigma_y=1;
bin=0.05;
k=1/0.25;
theta=0;
i=0;
phi=0;
[Ds,x,y]=mygabor1(sigma_x,sigma_y,k,phi,theta,bin);
subplot(2,2,1);
mesh(x,y,Ds');
axis([min(x) max(x) min(y) max(y) min(Ds(:)) max(Ds(:))]);
subplot(2,2,2);
contour(x,y,Ds');
axis square;
```

Stimulus “selectivity” and “tolerance”

Orientation selectivity of a simple cell:
boolean ‘AND’ operation over circular ON fields with *different positions*



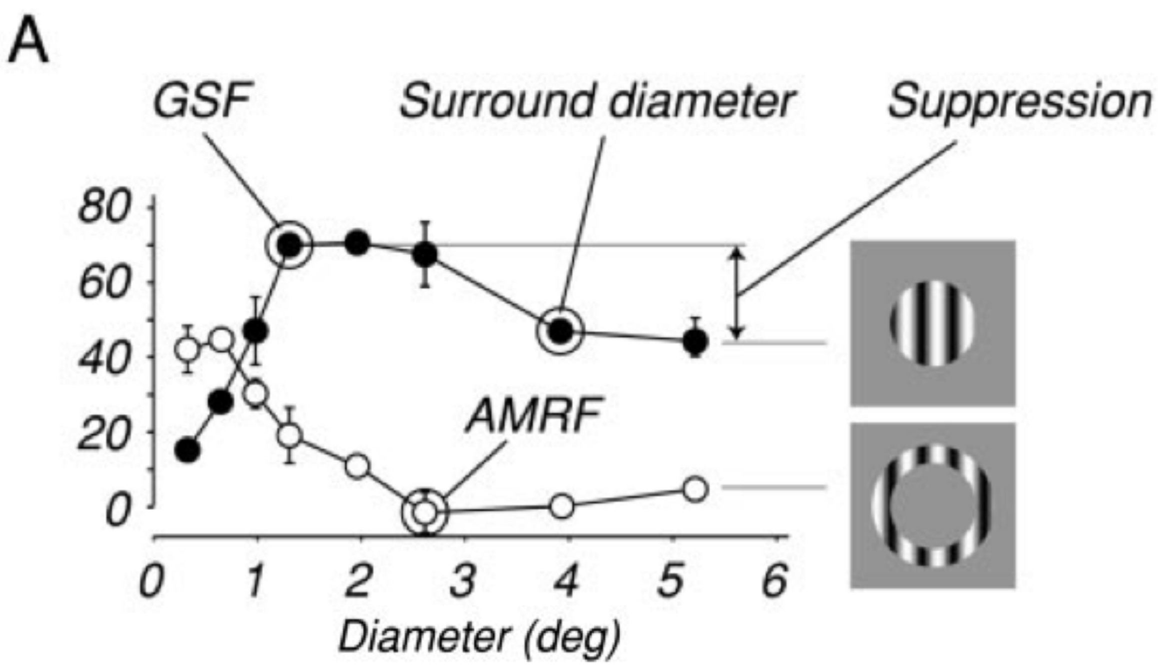
Position tolerance of a complex cell:
boolean ‘OR’ operation over simple fields with *same orientation preference*



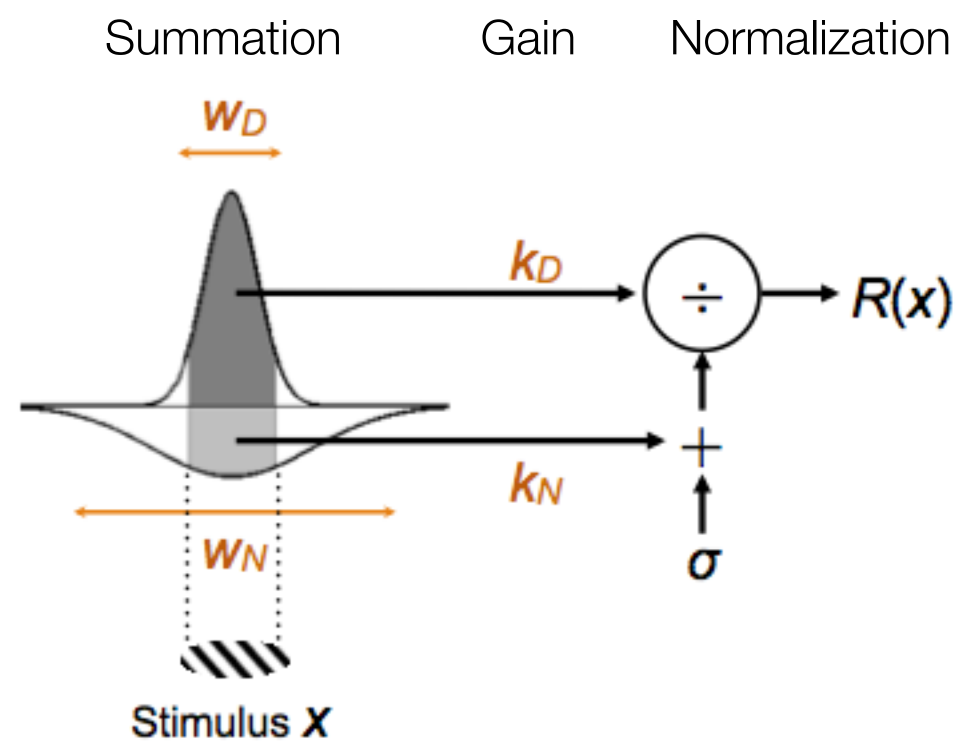
Hubel & Wiesel, *J. Physiol.*, 1962

Question: The circuits are identical to each other, so why is one ‘AND’ and the other ‘OR’?

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



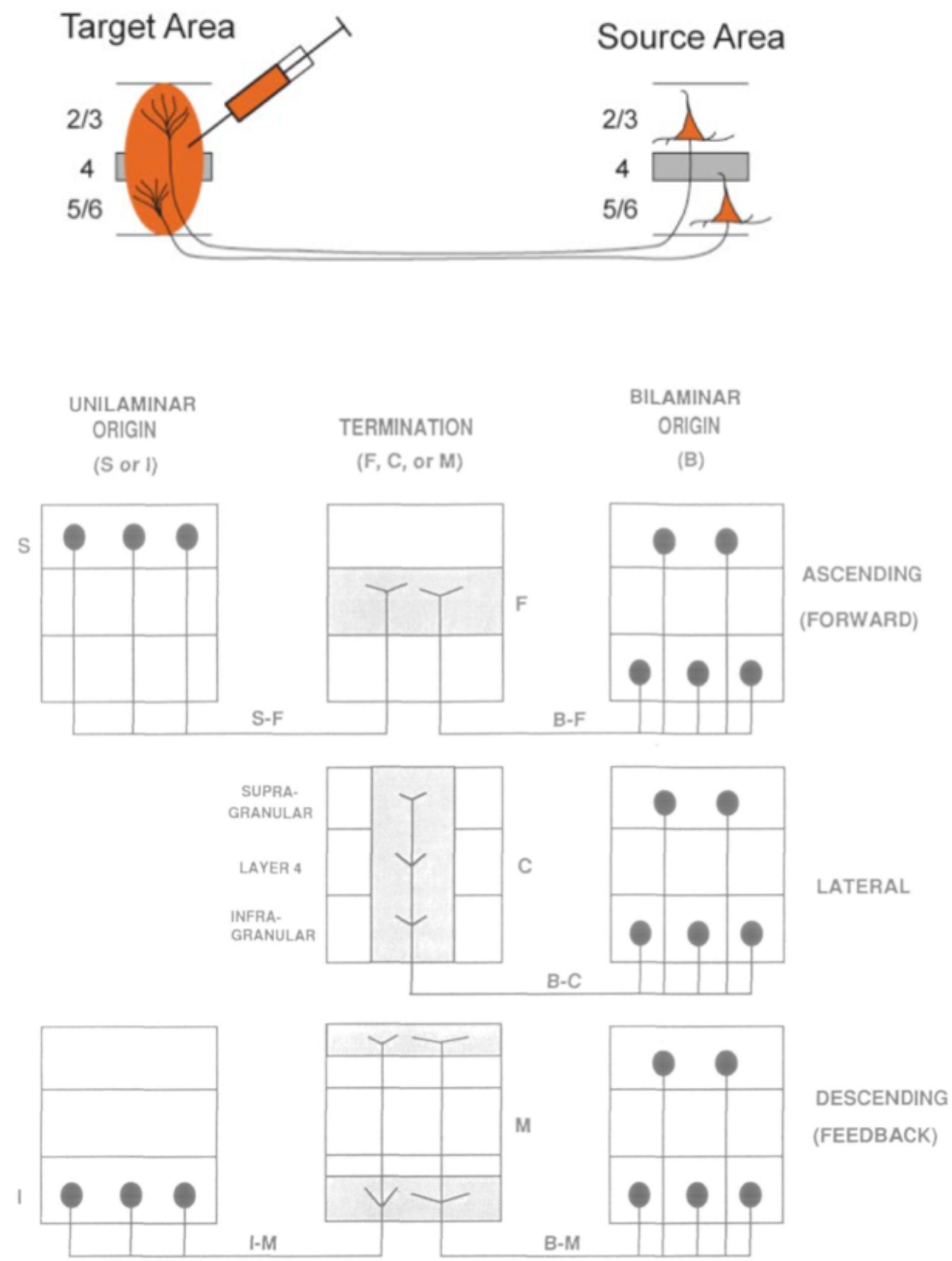
Cavanaugh et al., *J. Neurophysiol.*, 2002



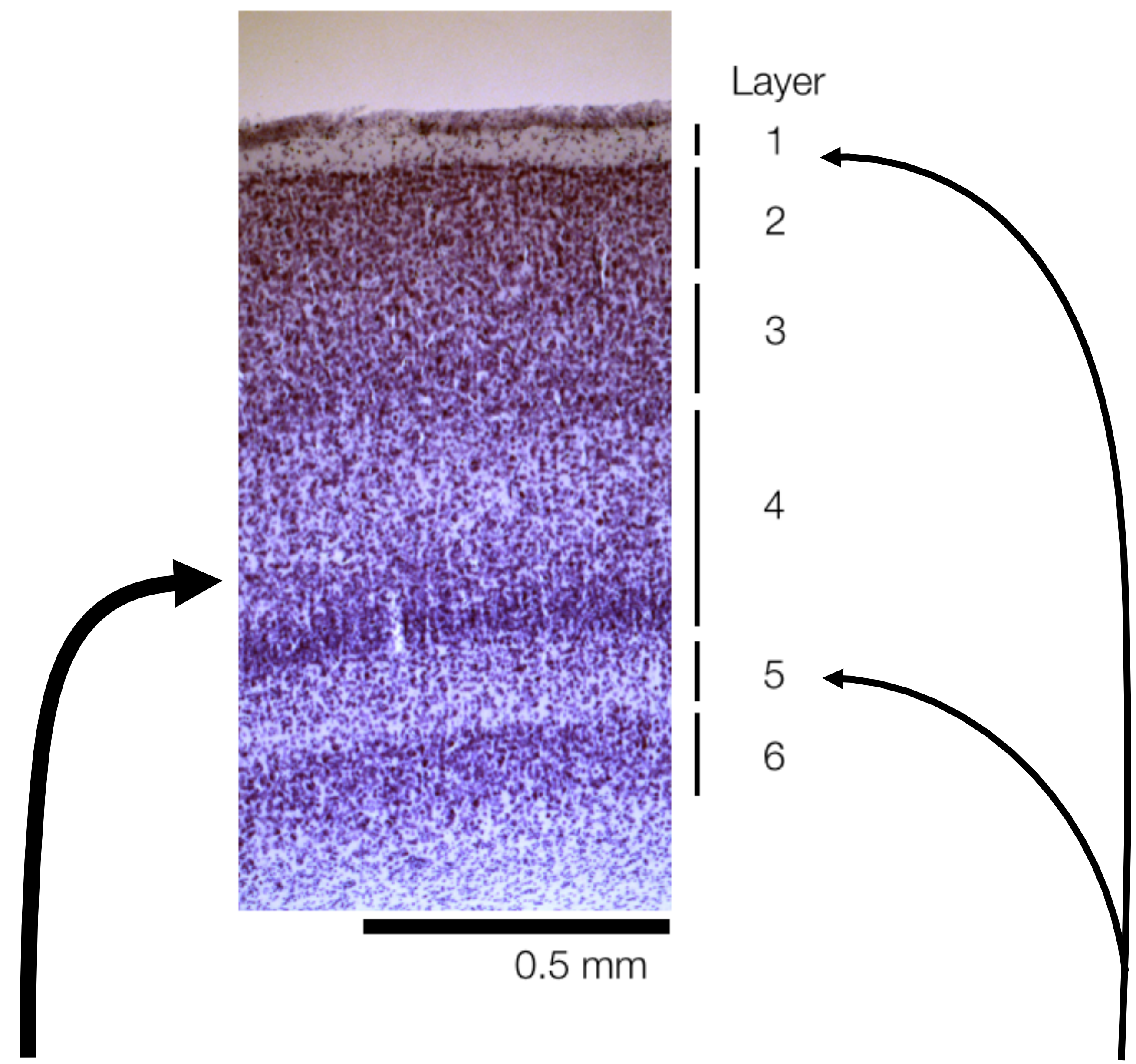
$$R_{\mathrm{ROG}}(x) = R_0 + \frac{k_D\,[w_D\,\mathrm{erf}(x/2w_D)]^2}{\sigma + k_N\,[w_N\,\mathrm{erf}(x/2w_N)]^2}$$

Nassi et al., *Front. Syst. Neurosci.*, 2014

Function through connectivity



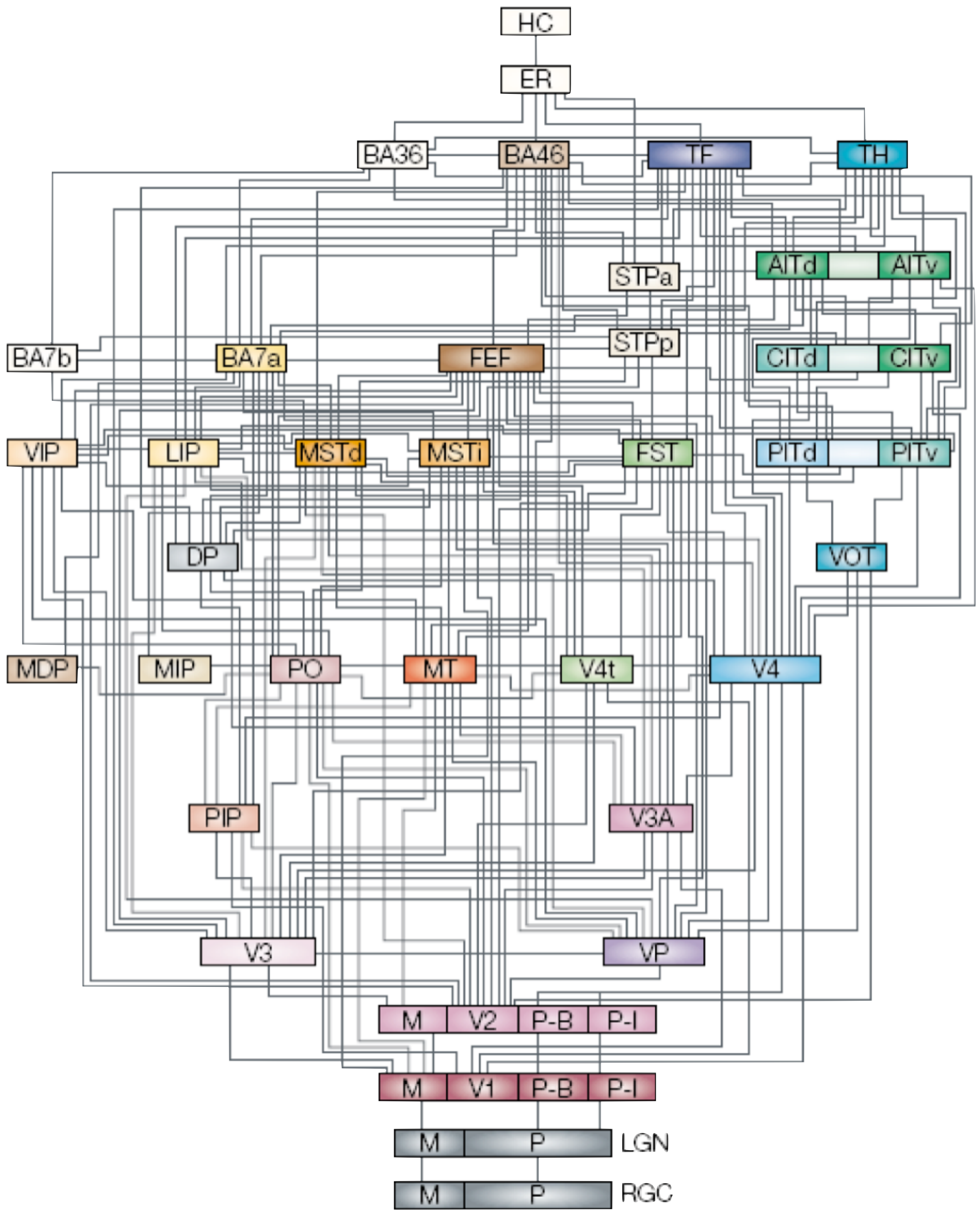
Maunsell & Van Essen, *J. Neurosci.*, 1983



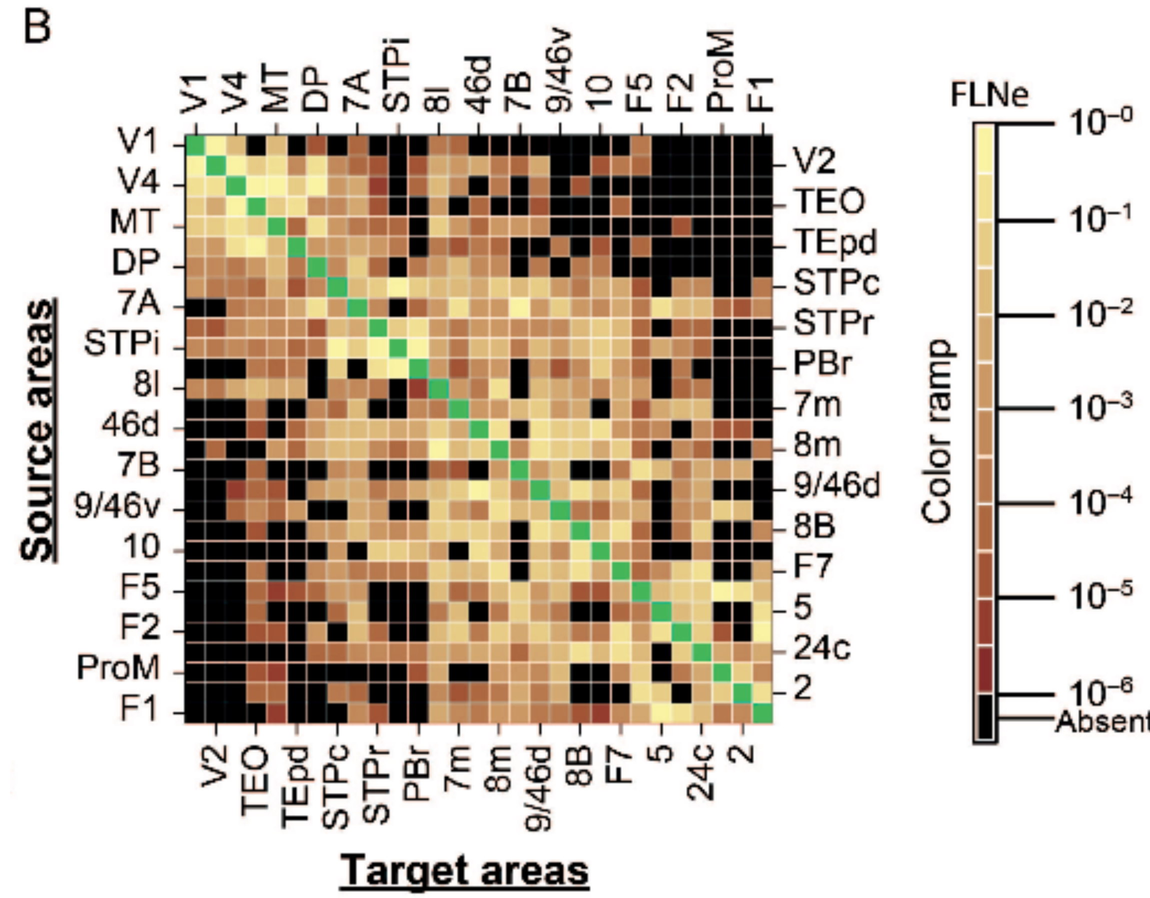
Forward input from LGN

Feedback from V2

Visual cortex is hierarchically organized



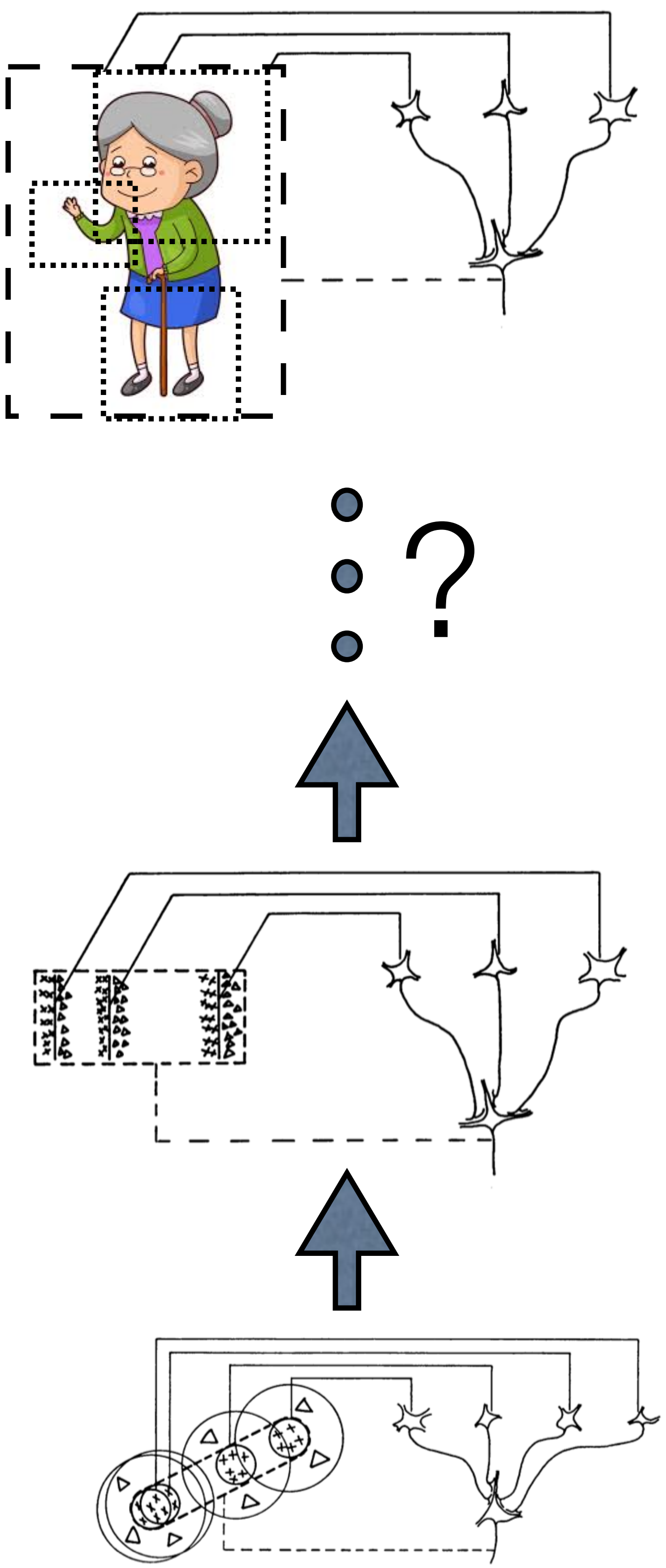
Felleman & Van Essen, *Cereb. Cortex*, 1991

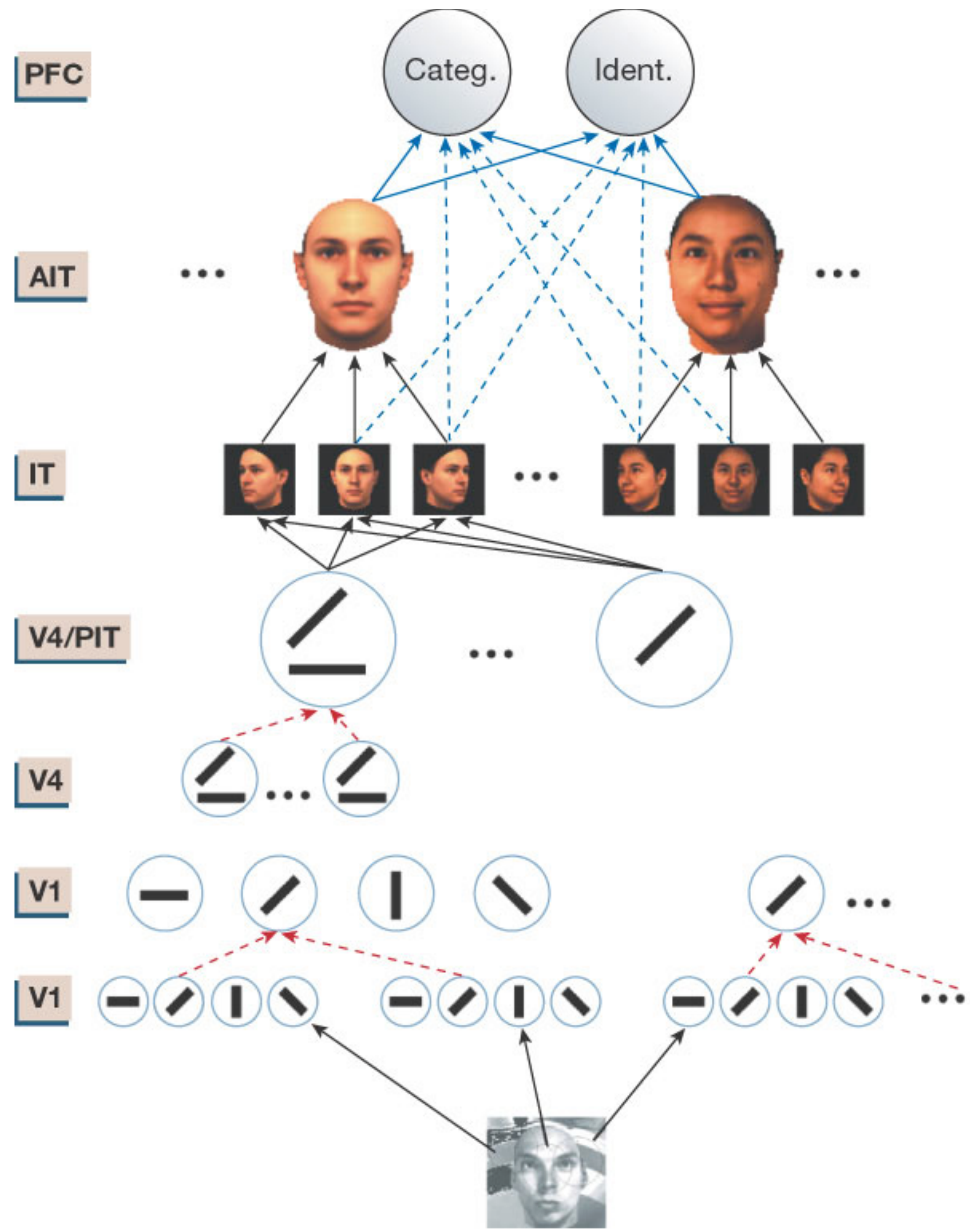


Markov et al., *Cereb. Cortex*, 2014

Symmetry about the diagonal indicates mutual connections between areas

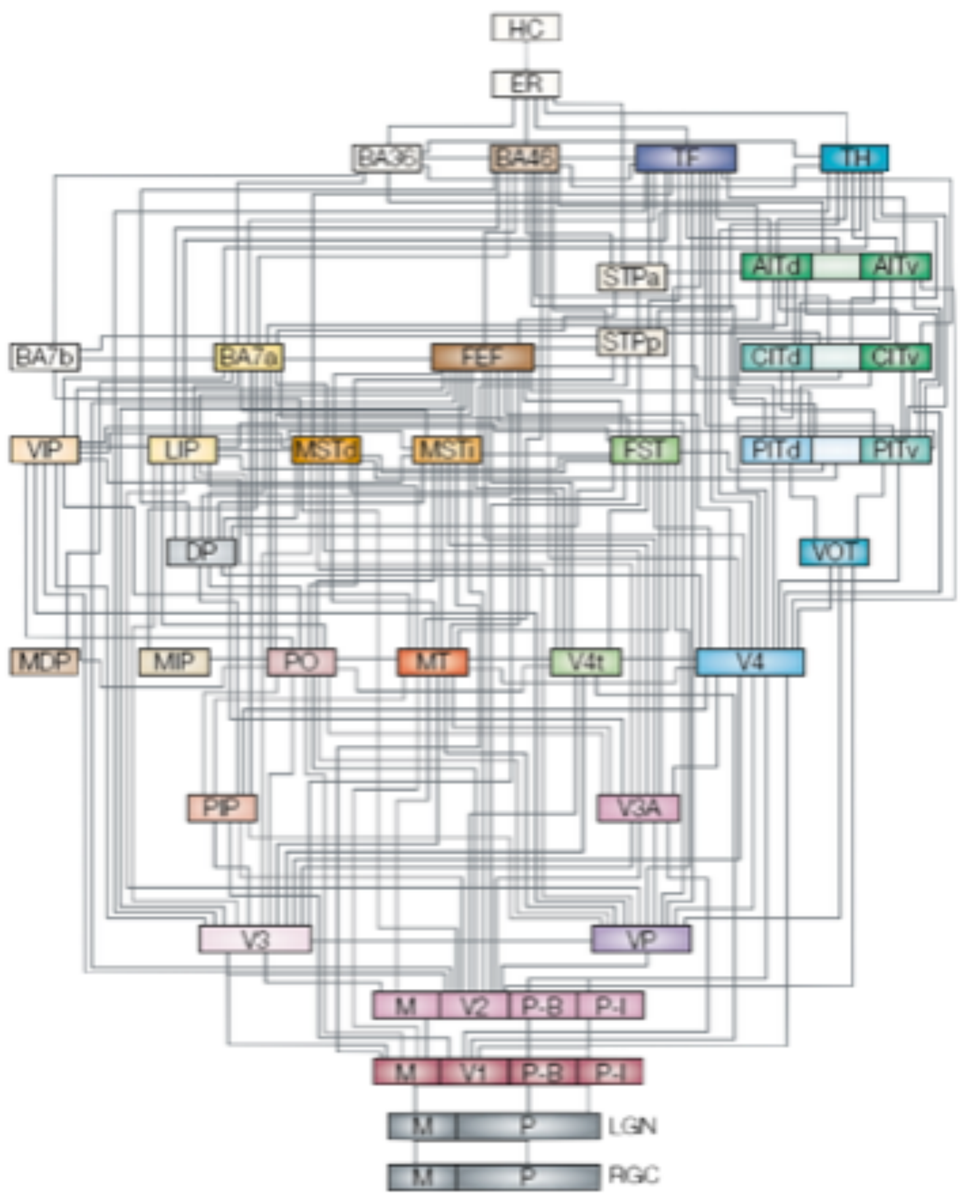
Object recognition (for another day)

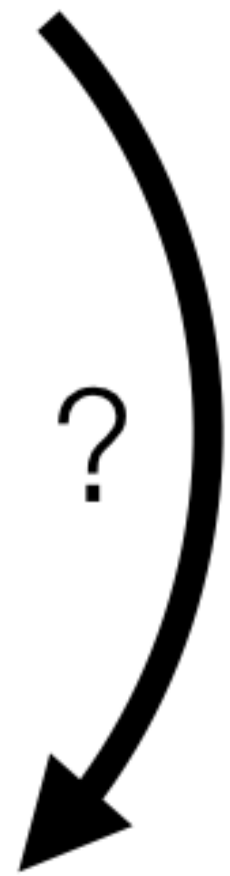


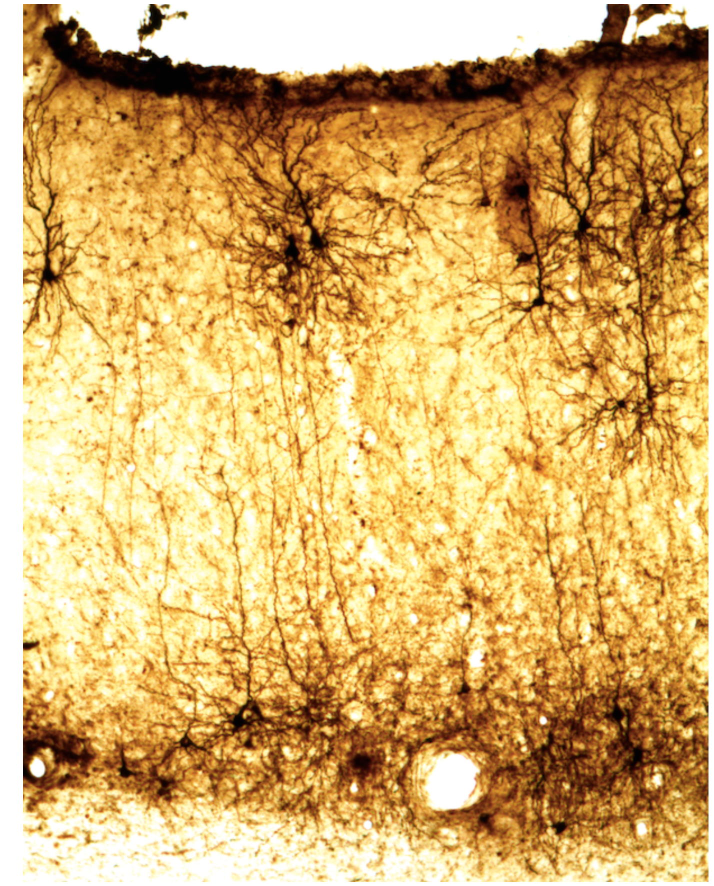


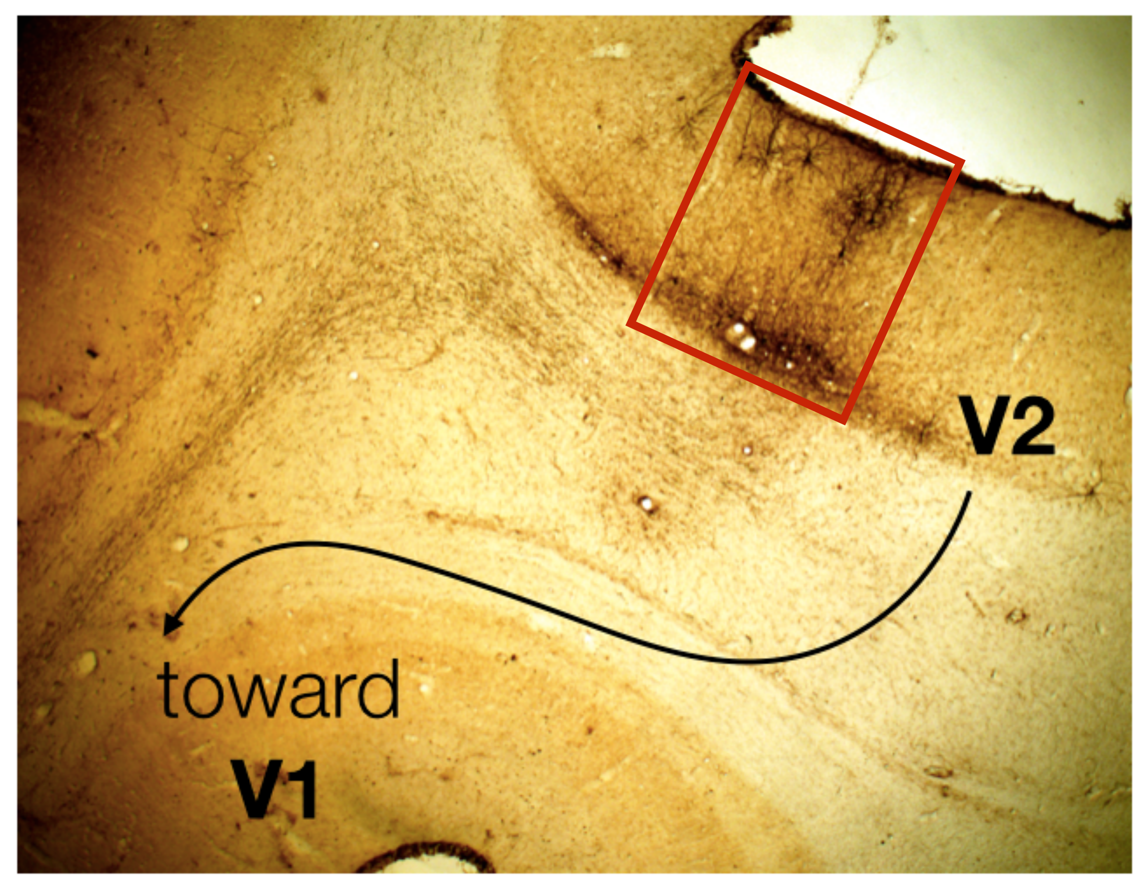
Poggio & Bizzi, *Nature*, 2004

Role of cortico-cortical feedback



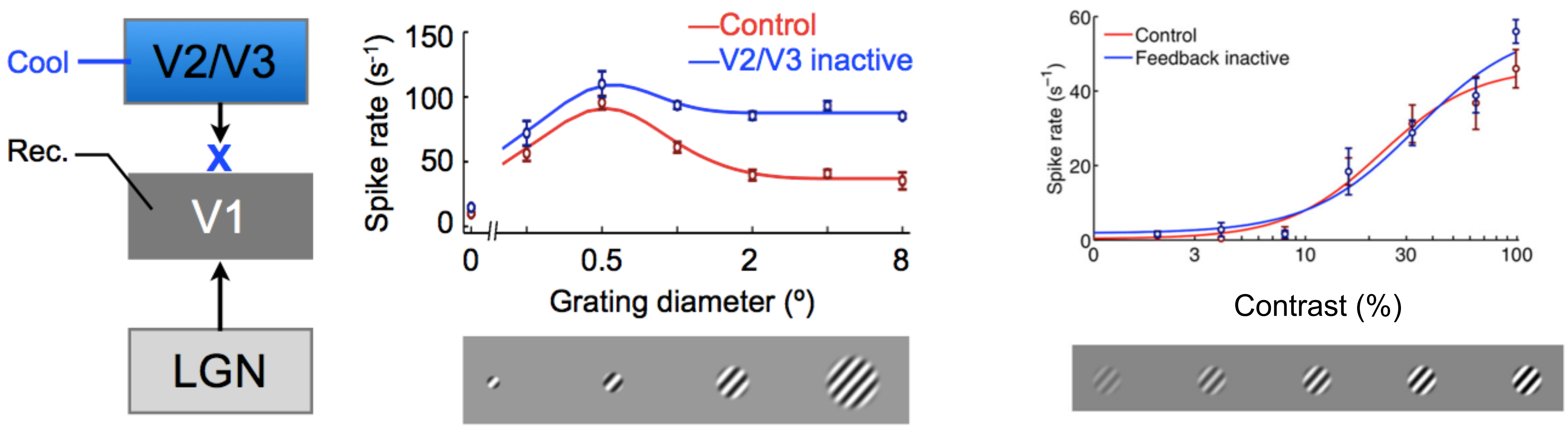






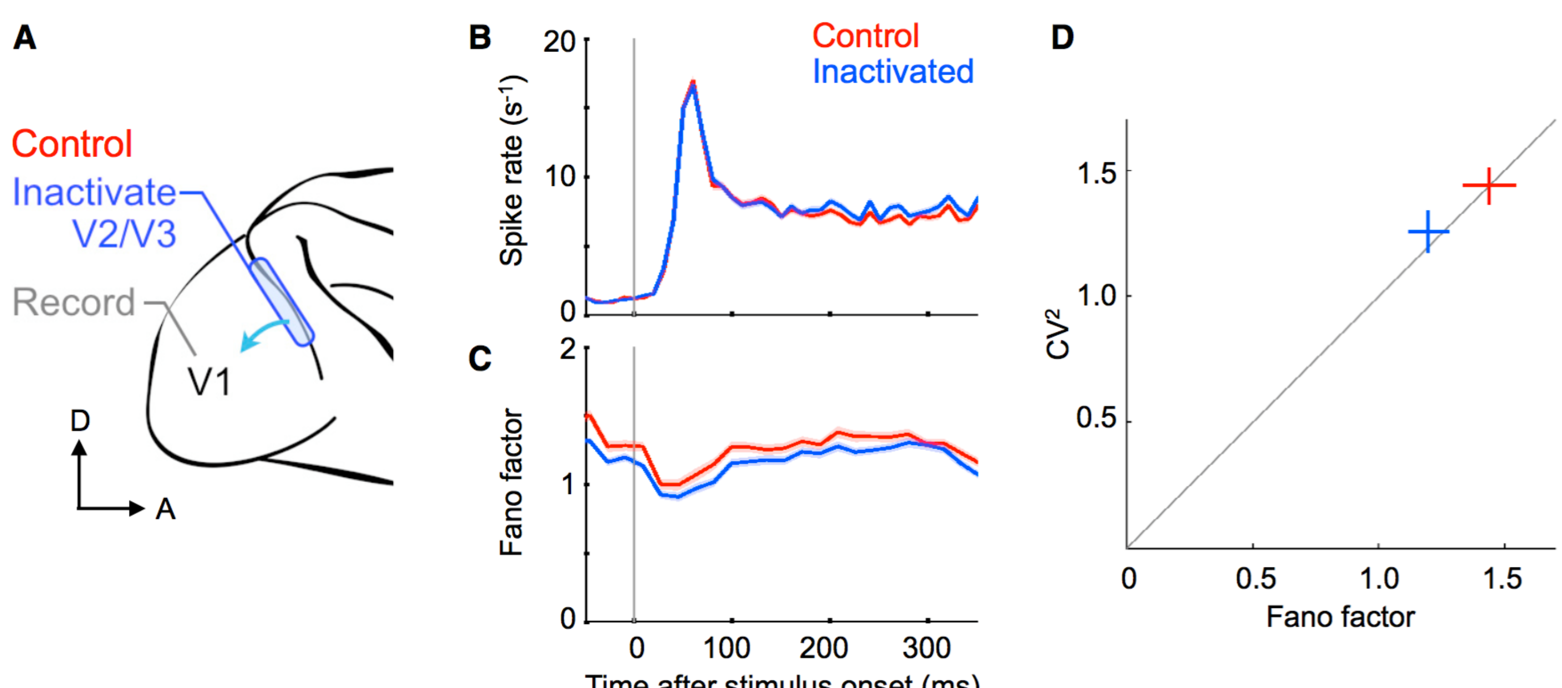
Effects of feedback inactivation in V1

Cortical feedback provides surround suppression to V1 neurons



Nassi et al., *Front. Syst. Neurosci.*, 2014

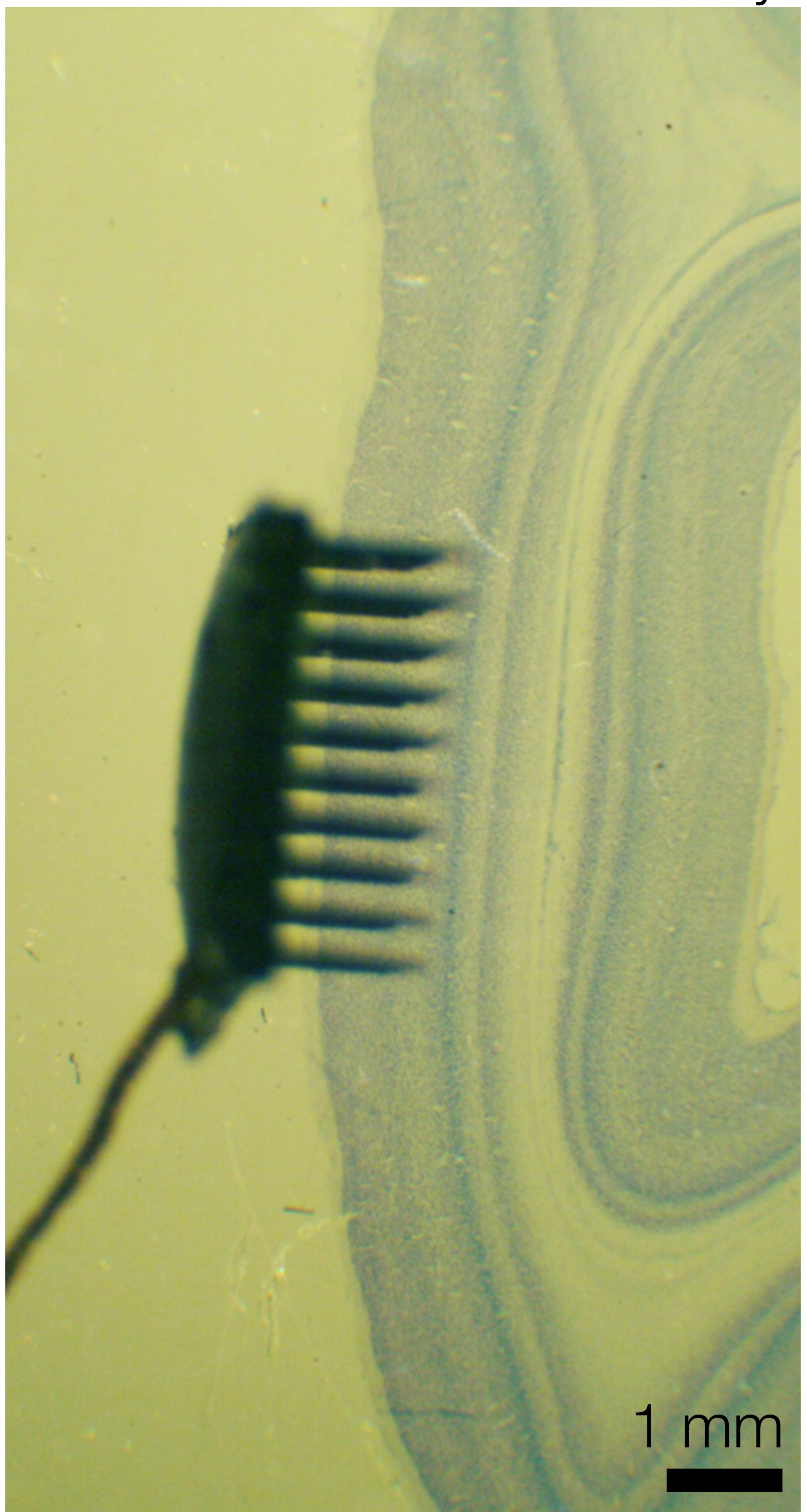
Cortical feedback increases trial-by-trial and spike train variability of V1 neurons

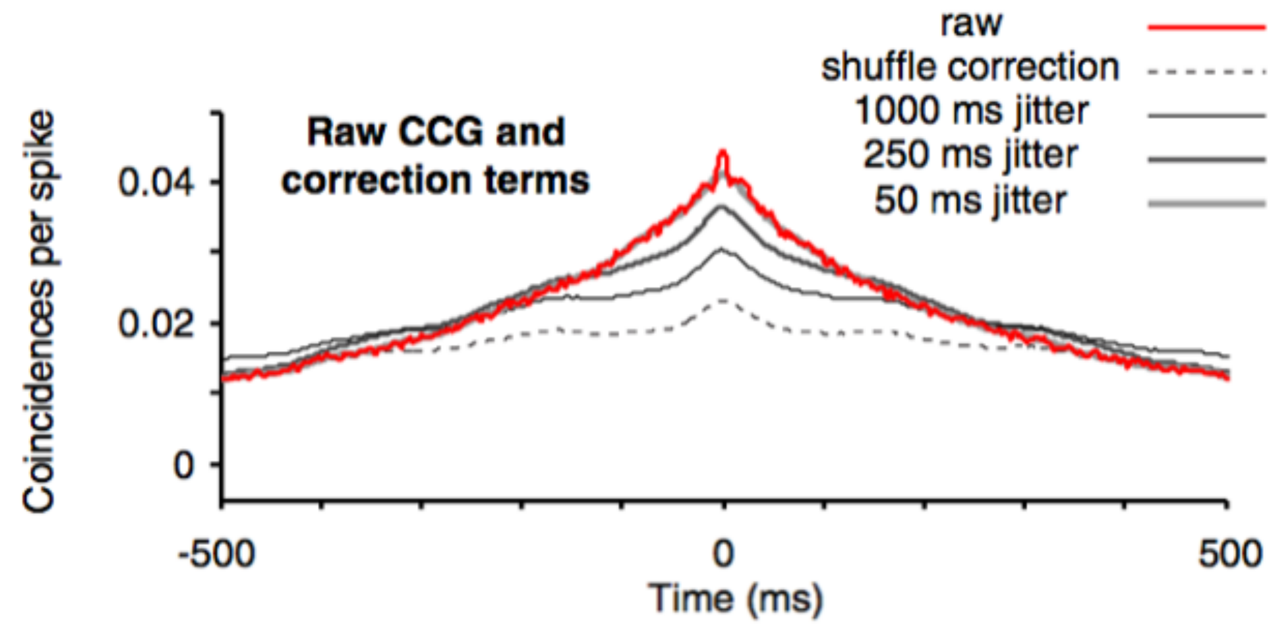


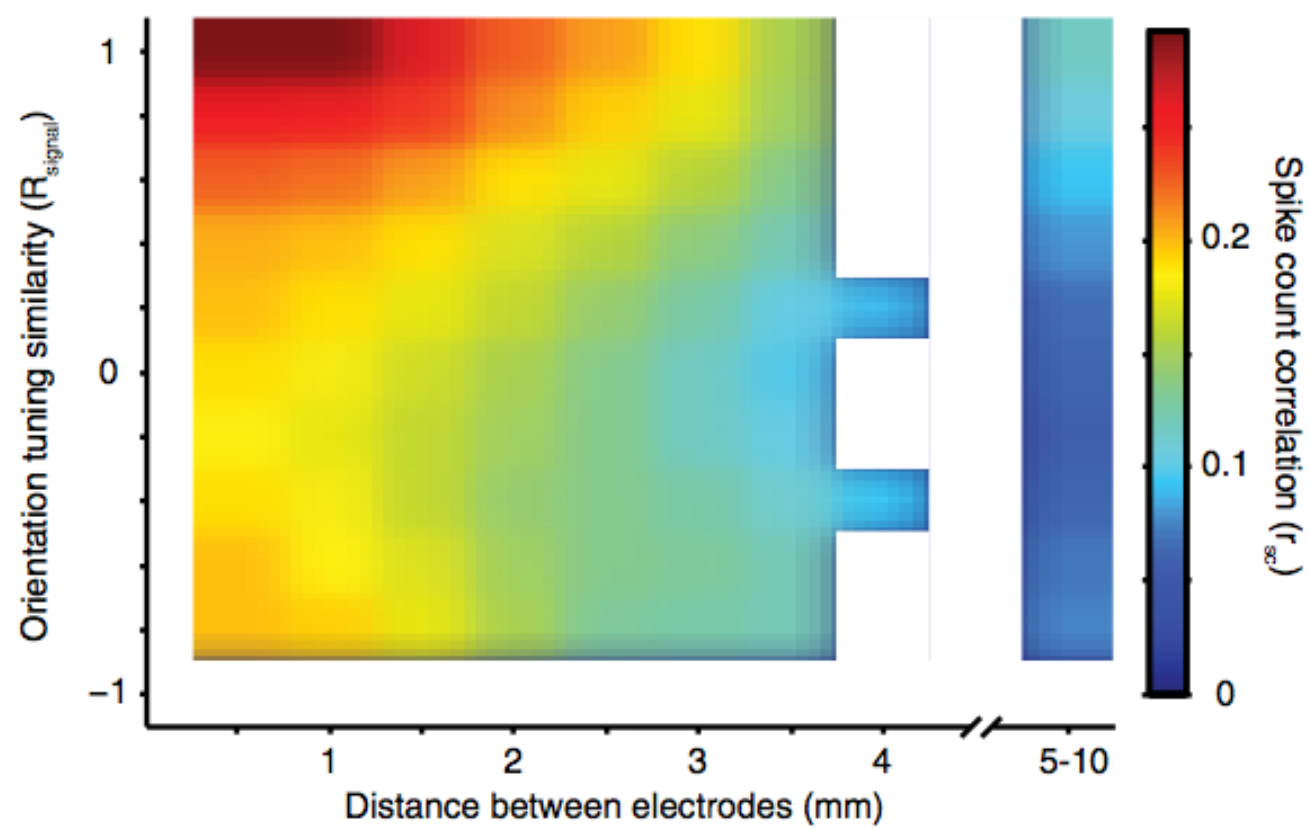
Gómez-Laberge et al., *Neuron*, 2016

Neural variability: consequence of correlated activity?

10 x 10 multi-electrode array





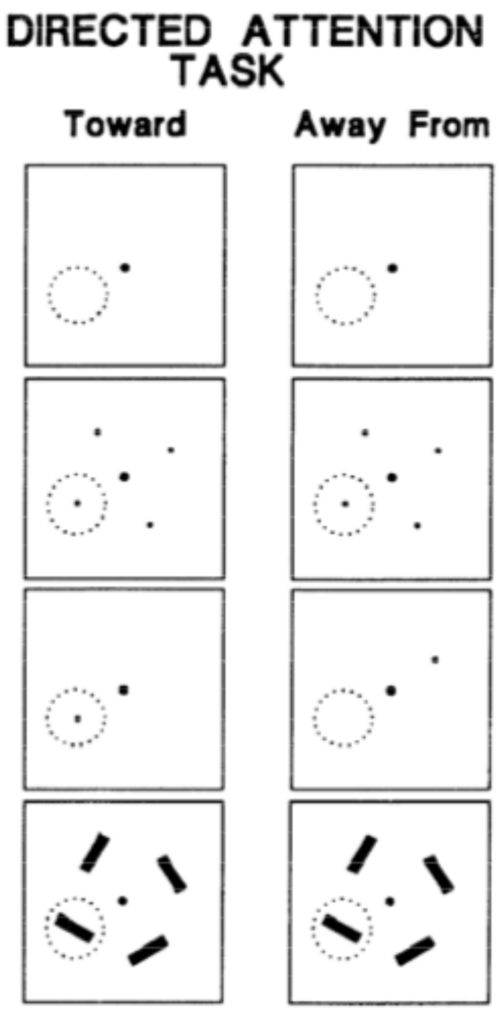


Smith & Kohn, *J. Neurosci.*, 2008

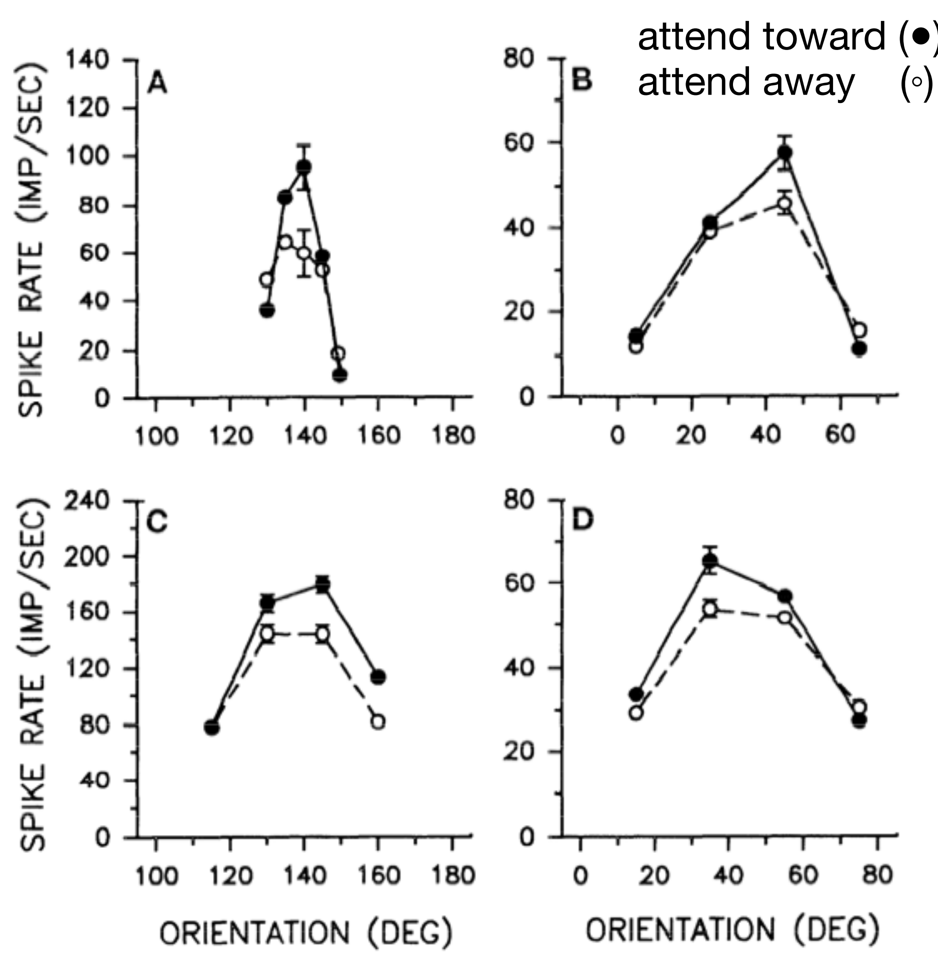
Spatial attention

Neural Correlates of Behavior

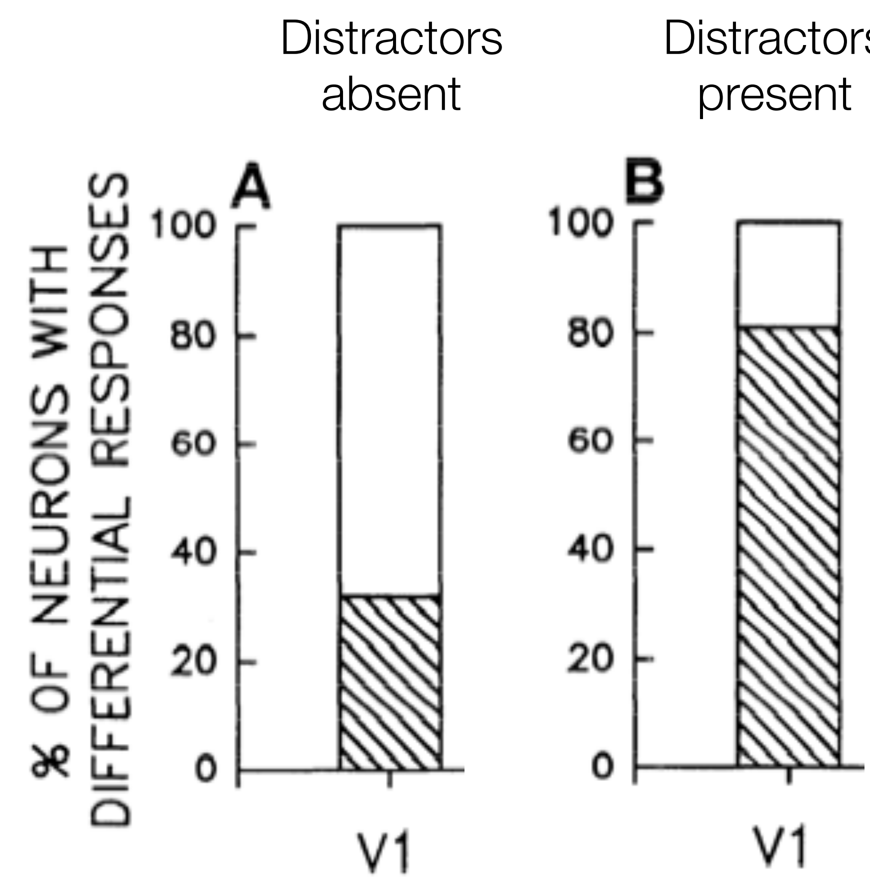
Orientation discrimination task by 'button press'



V1 cell tuning curves measured during attention task



Attentional effects in 94 V1 cells



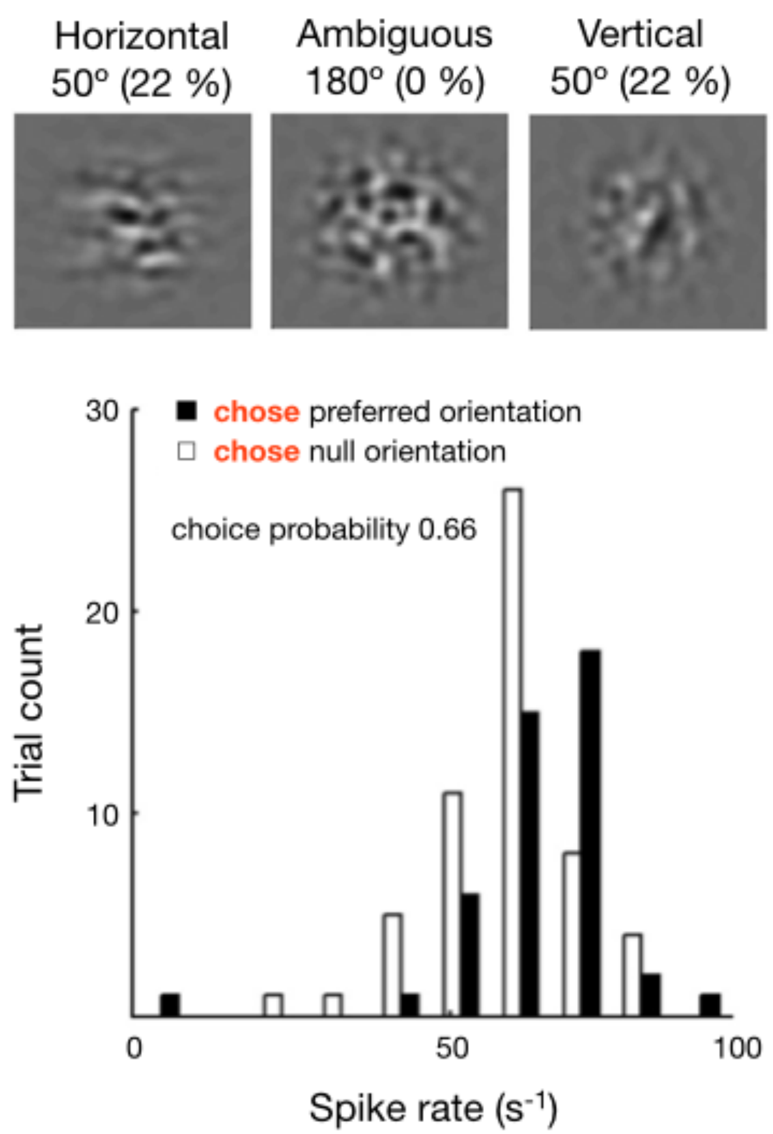
Motter, *J. Neurophysiol.*, 1993

Decision-related activity

The Emergence of a Neurobiology of Perception

The ready ability to record neuronal activity in alert nonhuman primates has allowed one of the most notable achievements of modern neuroscience: the establishment of direct links between the behavior of single neurons and that of the whole organism (e.g., Mountcastle et al. 1972, Newsome et al. 1989; see also Barlow 1972).

Albright & Stoner, *Annu. Rev. Neurosci.*, 2002



Nienborg & Cumming, J. *Neurosci.*, 2014

A cell's CP is largely influenced by its correlation with its neighbors:

$$CP_k \approx \frac{1}{2} + \frac{\sqrt{2}}{\pi} \frac{(\mathbf{C}\boldsymbol{\beta})_k}{\sqrt{C_{kk}\boldsymbol{\beta}^{\mathrm{T}}\mathbf{C}\boldsymbol{\beta}}}$$

Haefner et al., *Nat. Neurosci.*, 2013

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

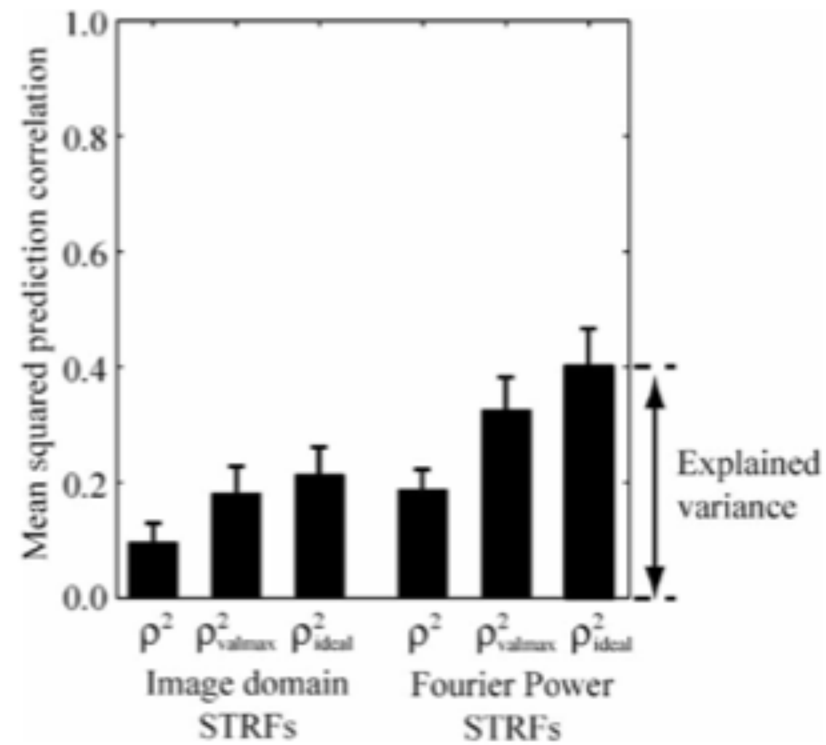


Figure 8. Summary of the effect of finite sampling on predictions. Each bar indicates mean squared predictio correlation for the 49 neurons with greater than 2000 stimulus-response samples (error bars indicate standard error). Data for image domain STRFs are shown at left, and for Fourier power STRFs at right. ρ^2 indicates the mea squared prediction correlation actually measured for the STRFs. ρ^2_{valmax} indicates mean prediction after correctin for finite sampling of validation data. ρ^2_{ideal} indicates the mean prediction after correcting for finite sampling o 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 respons variance in V1. The remaining portion of the response results from nonlinear response properties (‘unexplaine variance’) not included in the Fourier power model.

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

Carandini et al J. Neurosci. 2005

Further reading

- Wandell B. Foundations of Vision. Sinauer Books1995.
- Dayan and Abbott. Theoretical Neuroscience. MIT Press 2001.

Papers cited in these slides (not exhaustive list):

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3. Hubel DH, Wiesel TN (1977) Functional architectureof macaque monkey visual cortex. Proc R Soc Lond B 198:1–59.
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8. Felleman DJ, van Essen DC (1991) Distributed hierarchical processing in the primate cerebral cortex. Cereb Cortex 1:1–47.
9. Markov NT et al. (2014) A weighted and directed interareal connectivity matrix for macaque cerebral cortex. Cereb Cortex 24:17–36.
10. Poggio T and Bizzi E. (2004) Generalization in vision and motor control. Nature 431:768–774.
11. Gómez-Laberge C, Smolyanskaya A, Nassi JJ, Kreiman G, Born RT (2016) Bottom-up and top-down input augment the variability of cortical neurons. Neuron 91:540–547.
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Reading assignment

There are two generic overarching themes that need to be included in your write-up:

(1) Write a critical comment on the paper.
   What was right?
   What was wrong?
   Is the interpretation justified?
   Is the math correct?
   Are all the controls there?
   Are there any confounding factors?

(2) What would be a good follow up study based on this paper?