What We Know and Don't Know about Biological Vision

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for Theoretical Neuroscience

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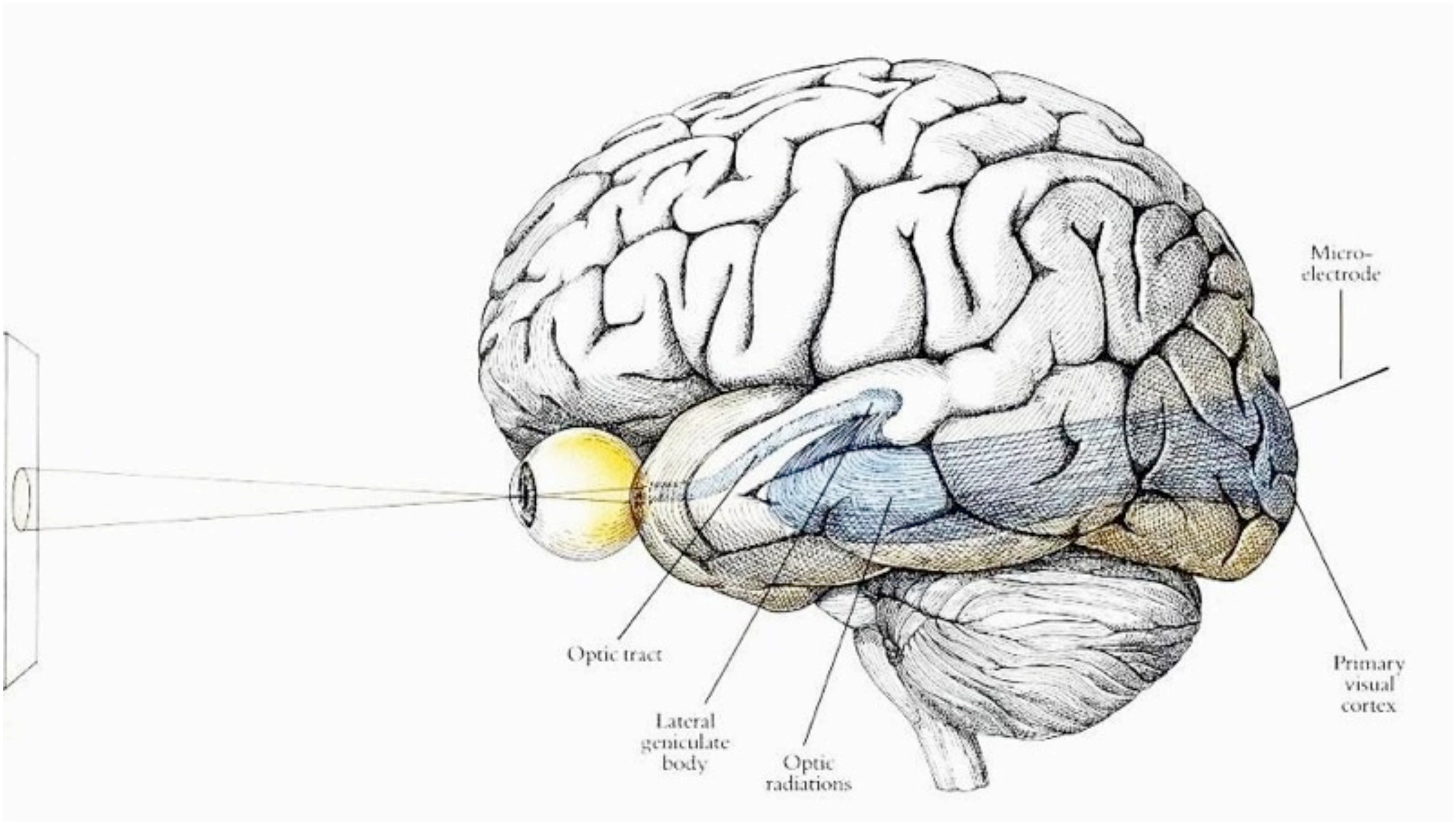
Biological vision

- Most of what is going on we don't understand.

- From what little we do understand, we see impressive information processing strategies and coding principles at work.

- Biology is highly complex, but not impenetrable, and it has much to teach us about how to build perceptual systems.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Optic tract
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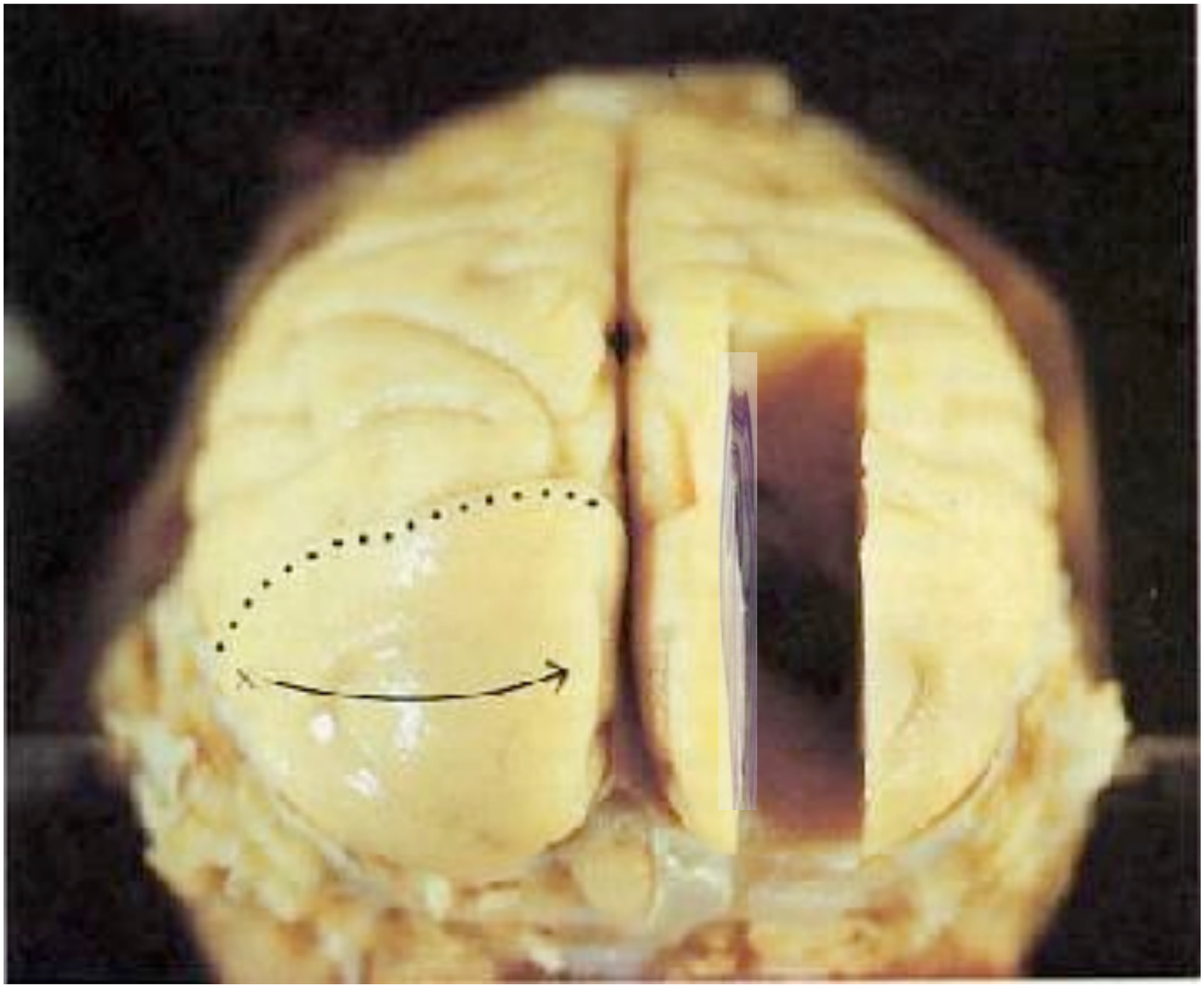
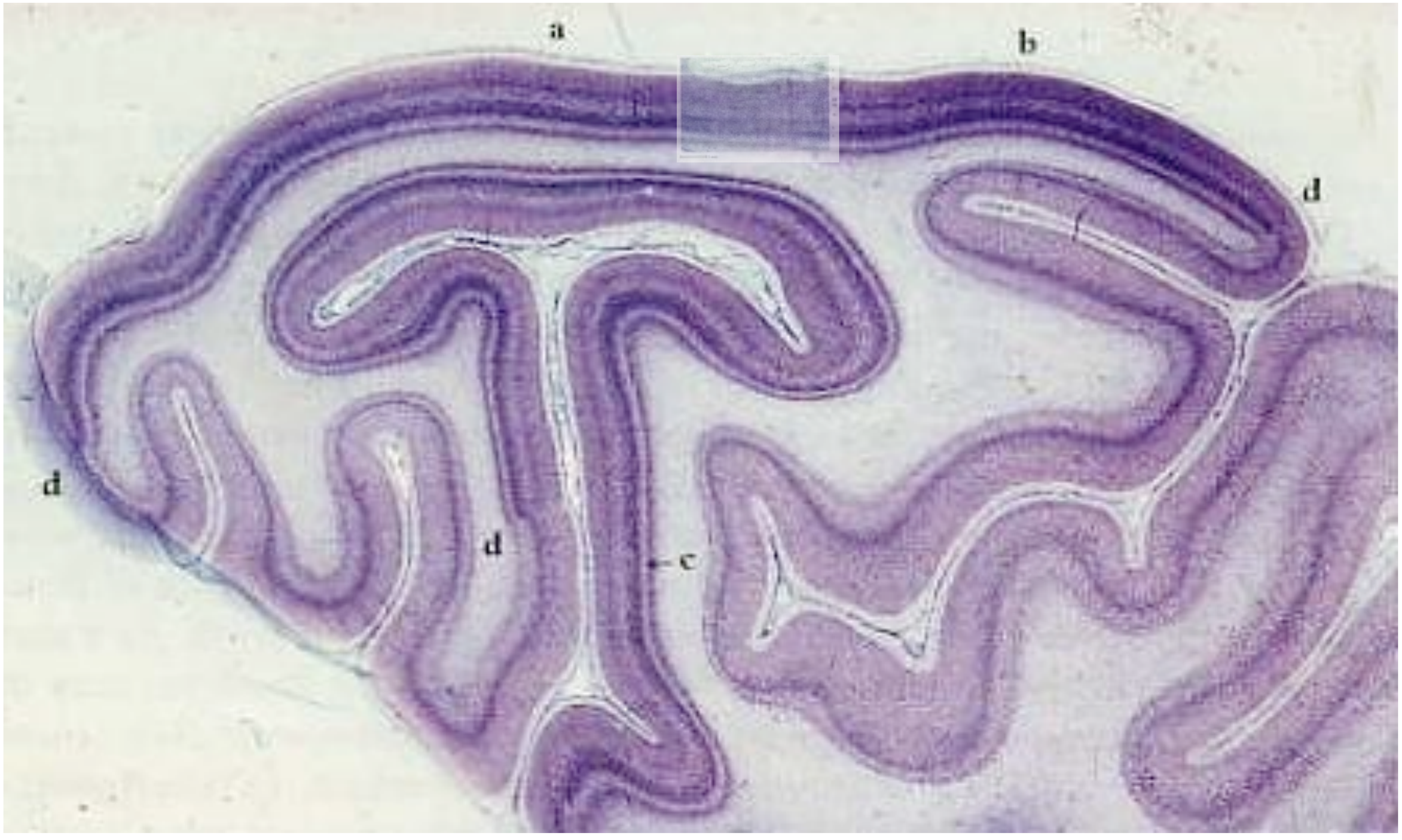
Primary
visual
cortex

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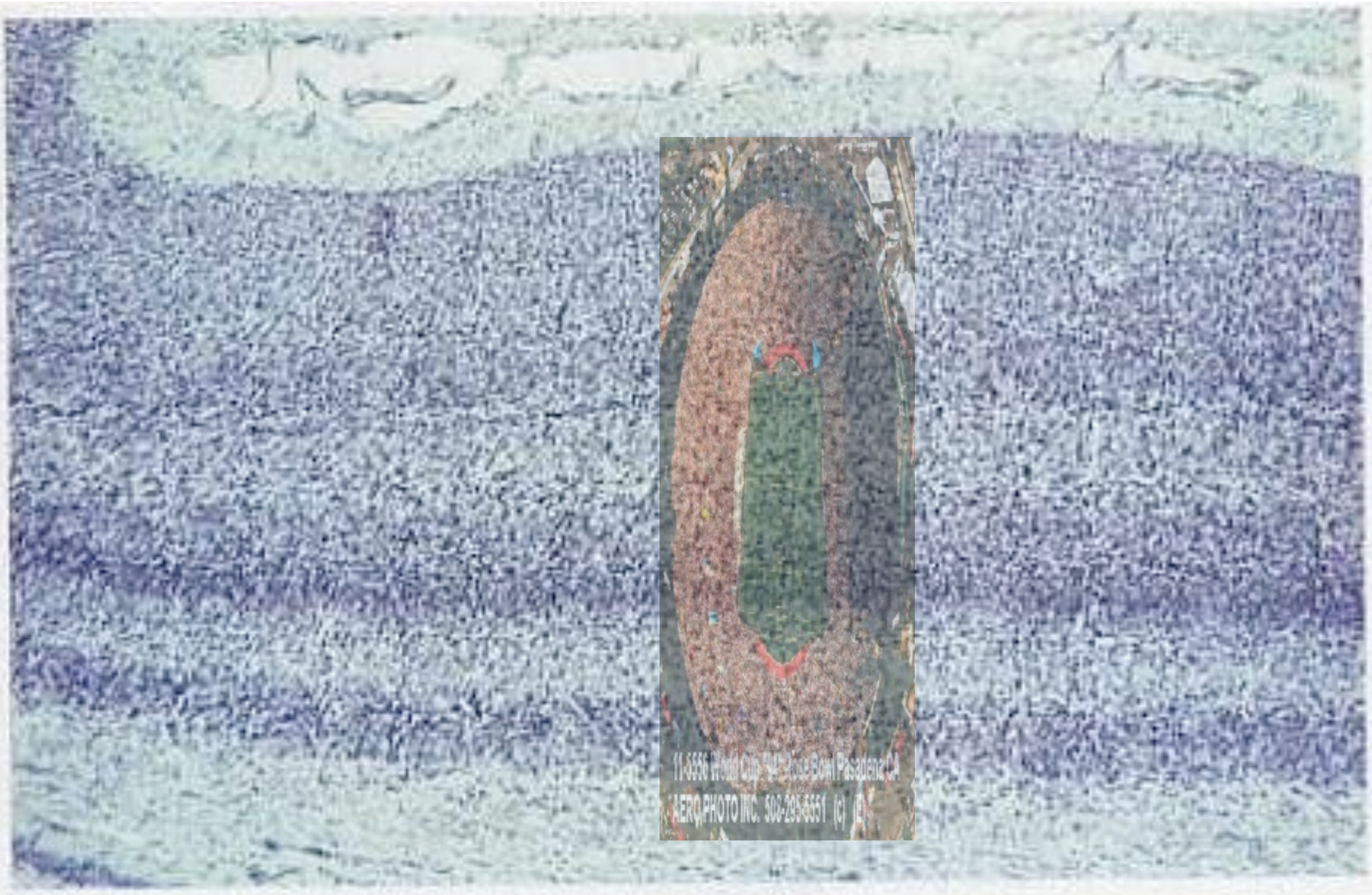
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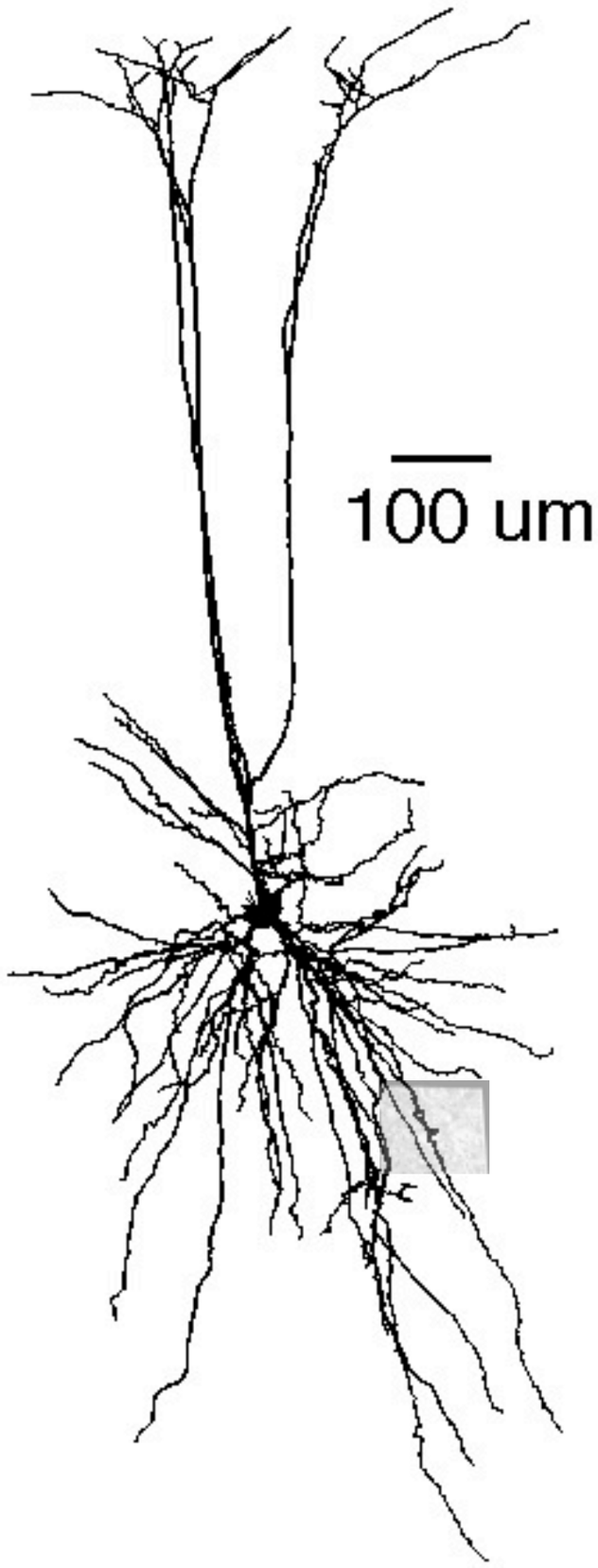
11-5556 World Cup '94" Rose Bowl Pasadena CA
AERO PHOTO INC. 508-295-5551 (c) (E)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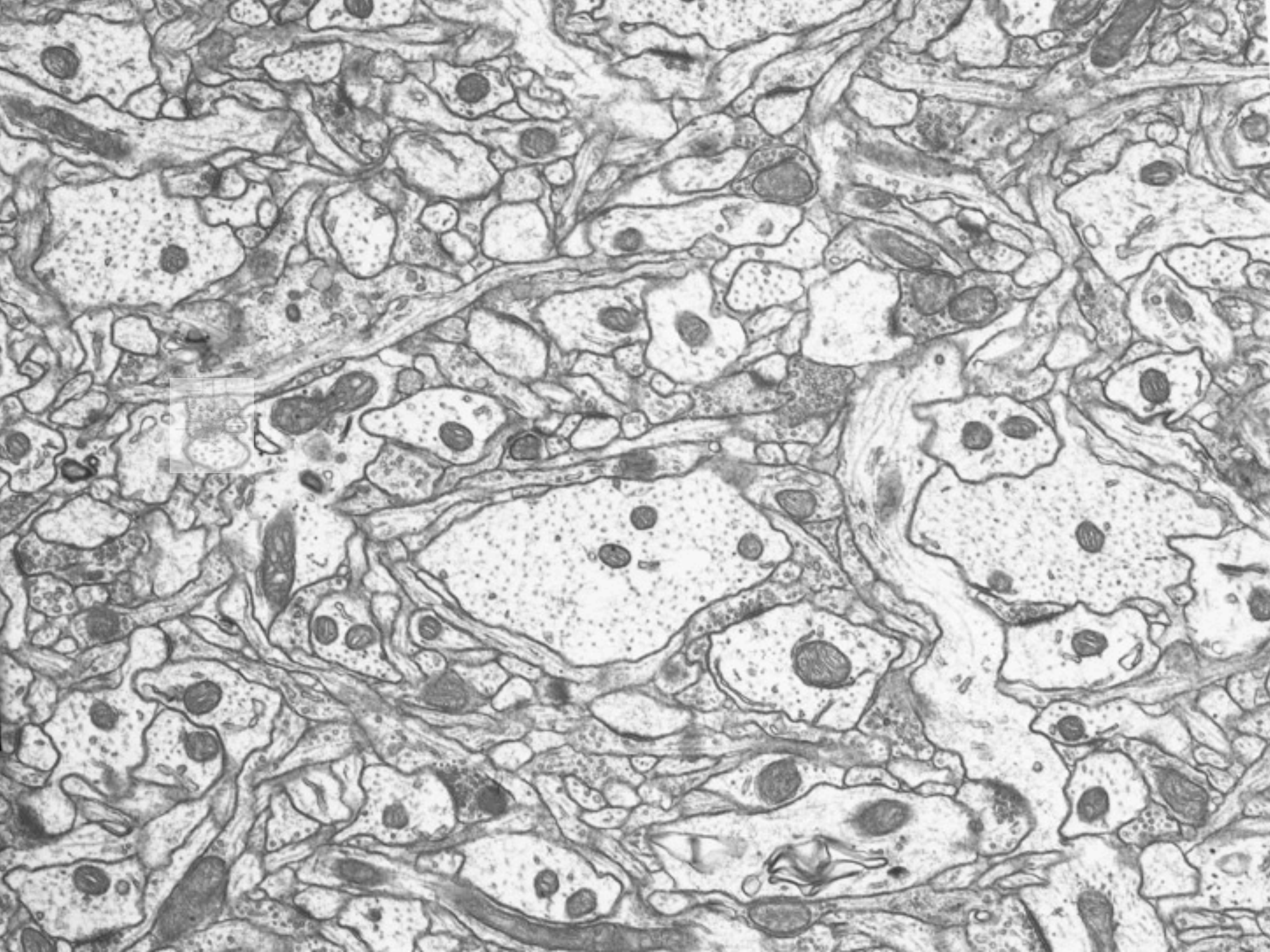
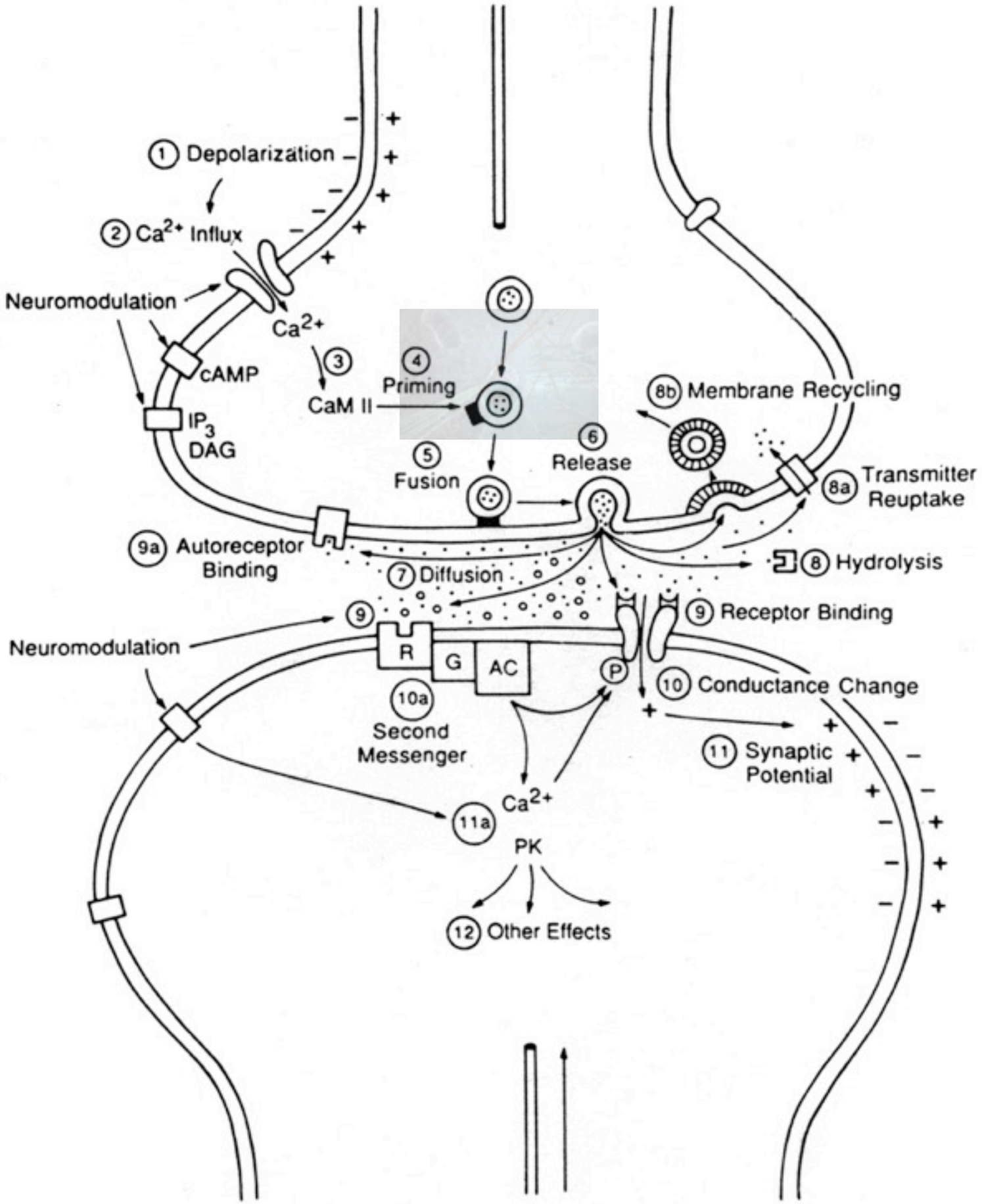
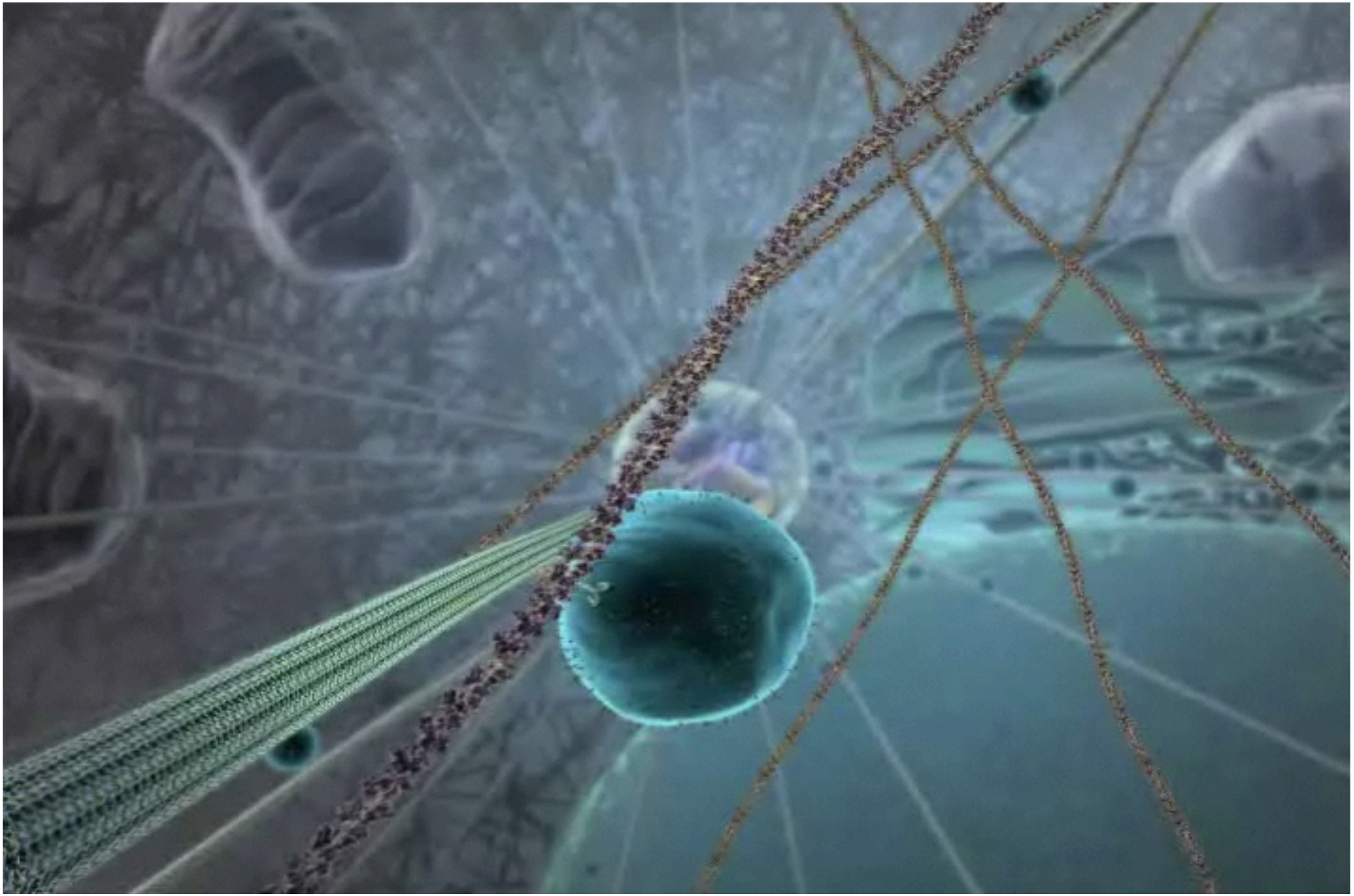


Anatomy of a synapse

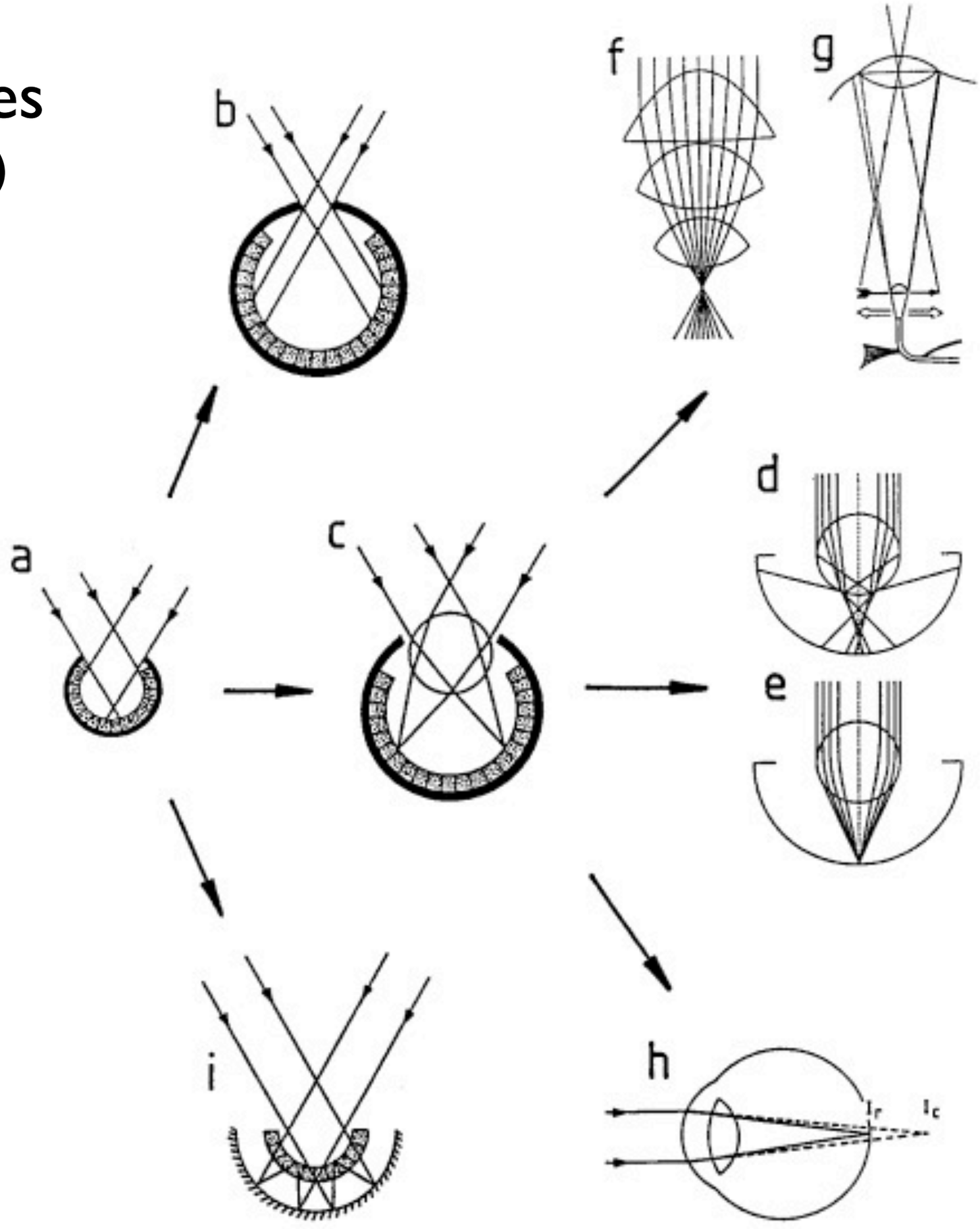


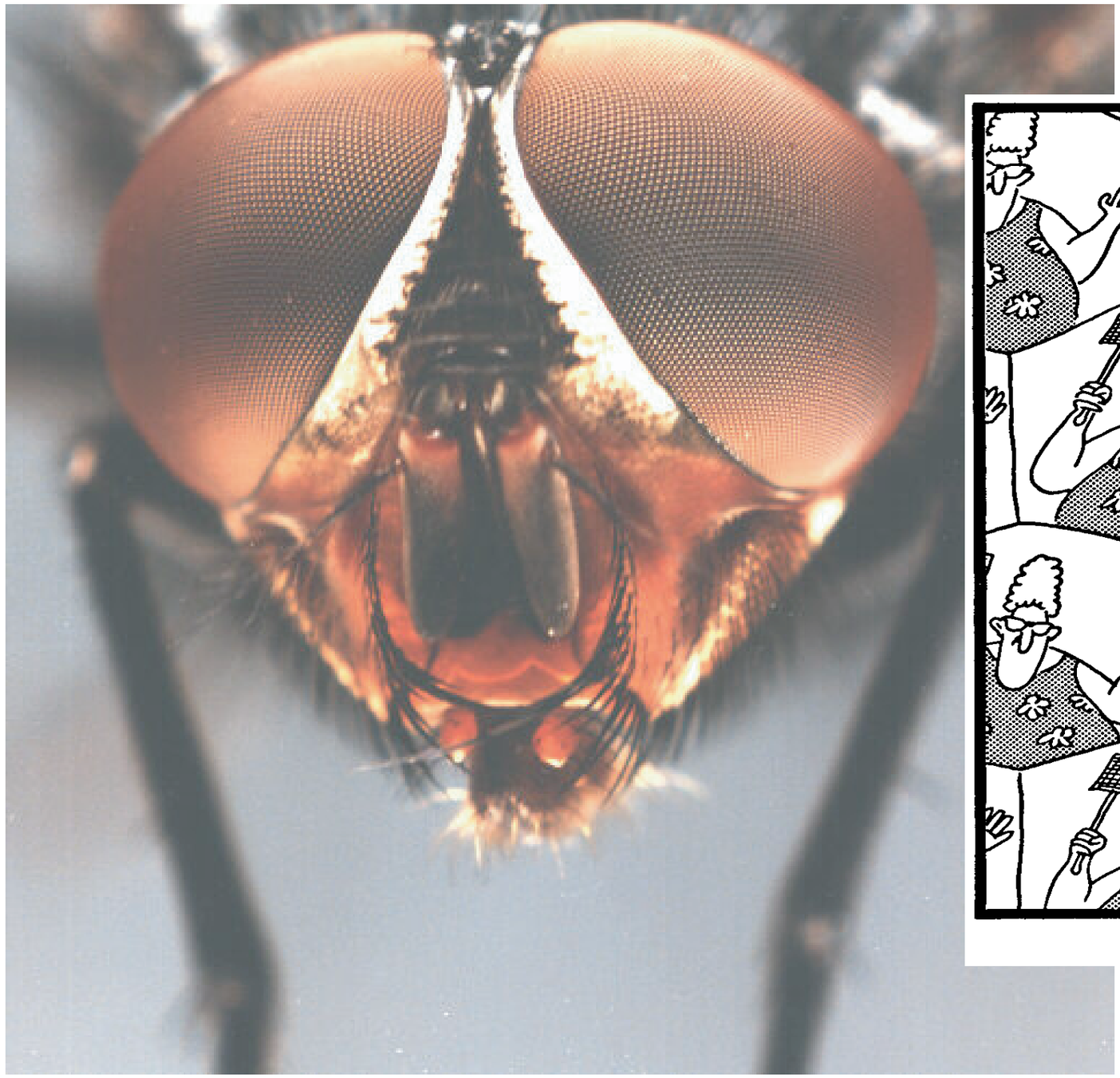
Inner life of the cell

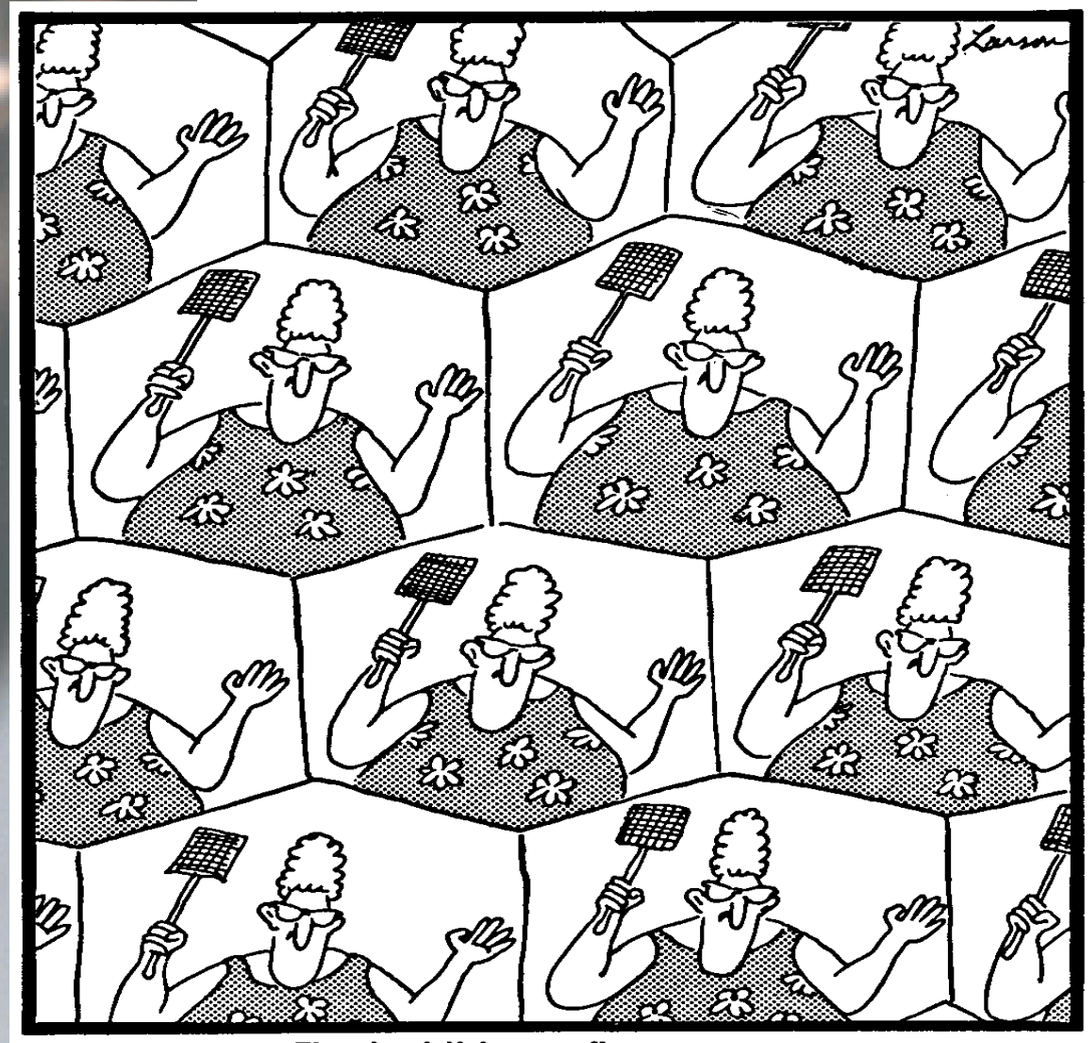


The evolution of eyes

Land & Fernald (1992)



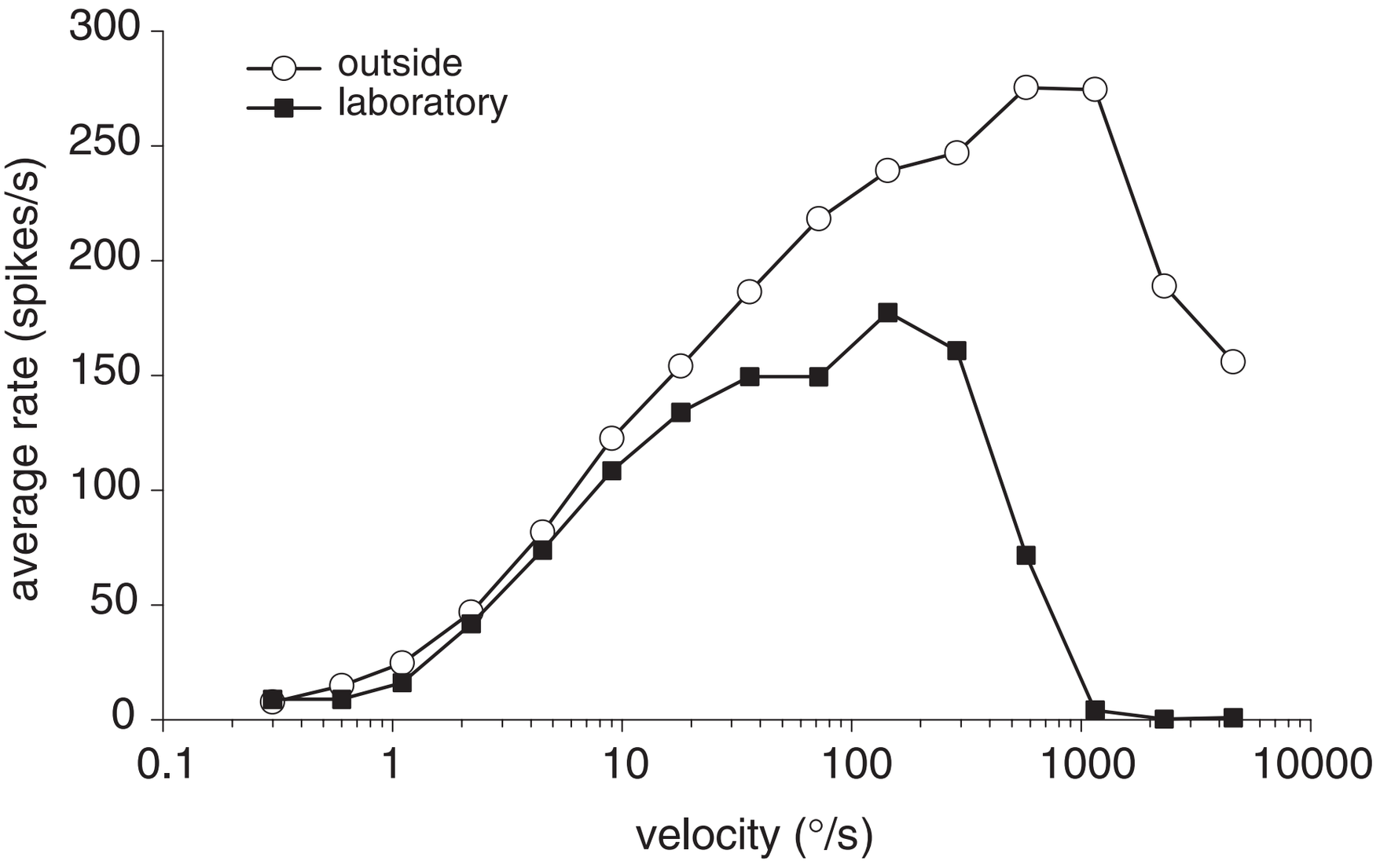




The last thing a fly ever sees

Fly H1 neuron - dynamic range of speed sensitivity

Lewen, Bialek & de Ruyter van Steveninck (2001)



Land & Collett (1973)

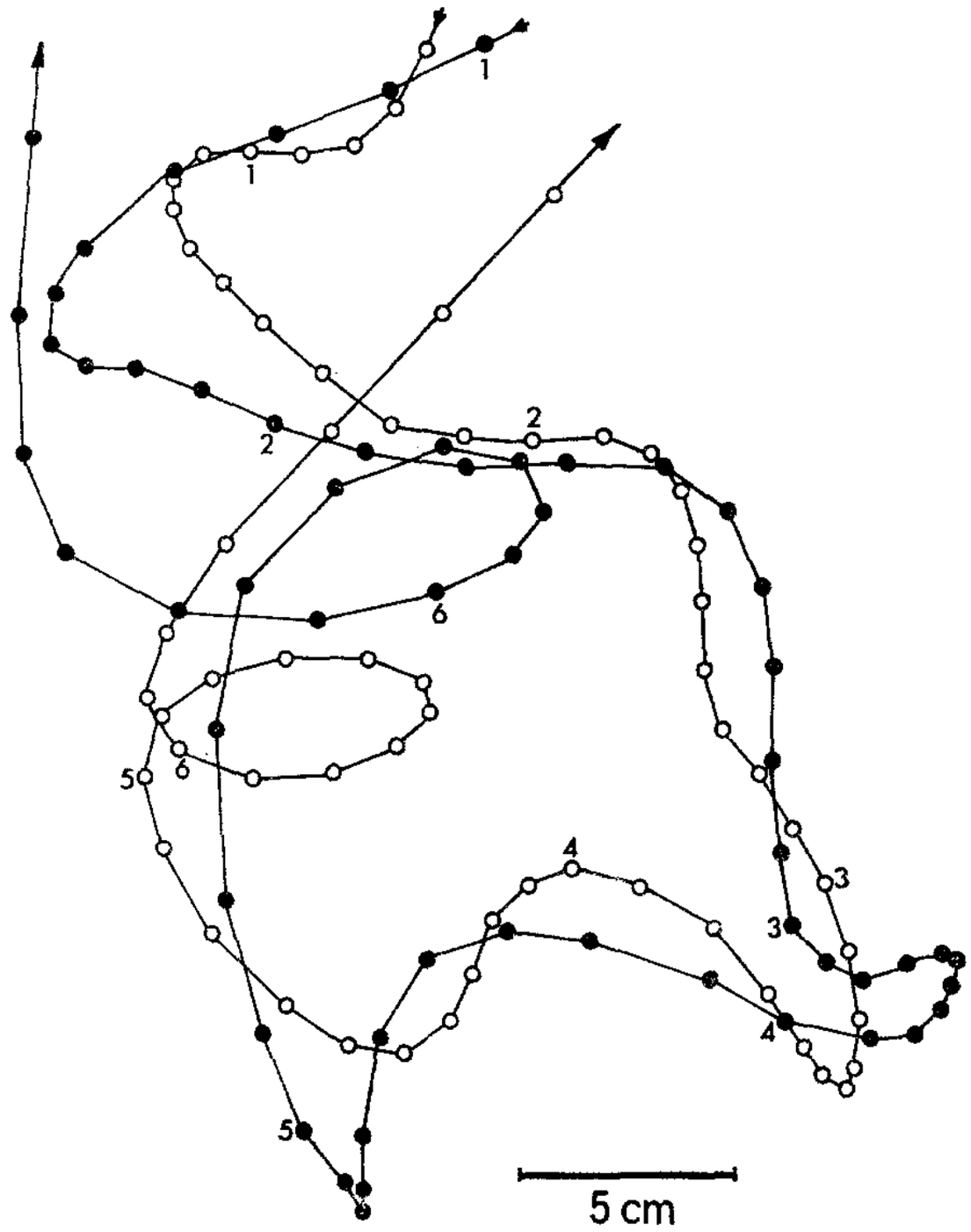
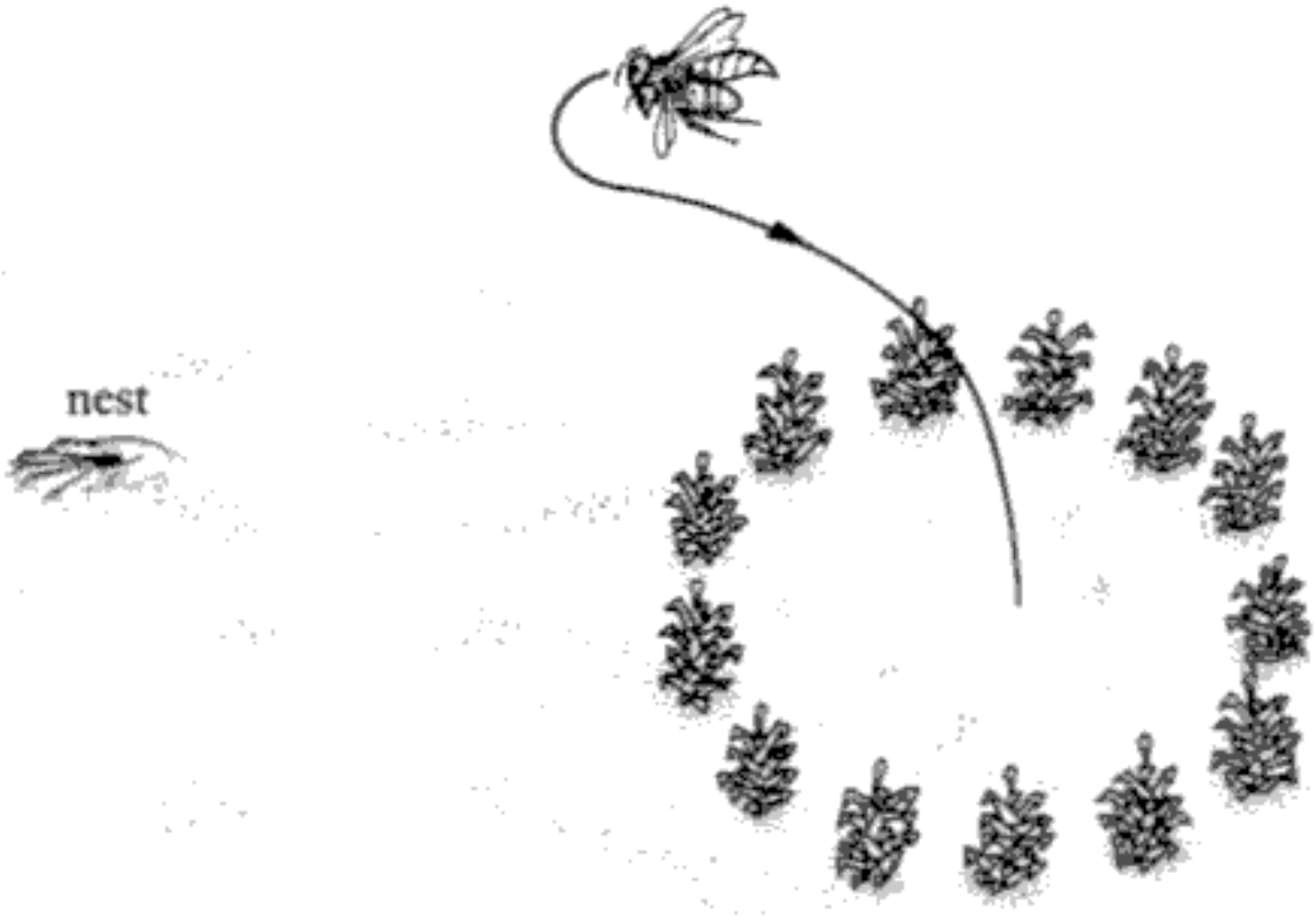
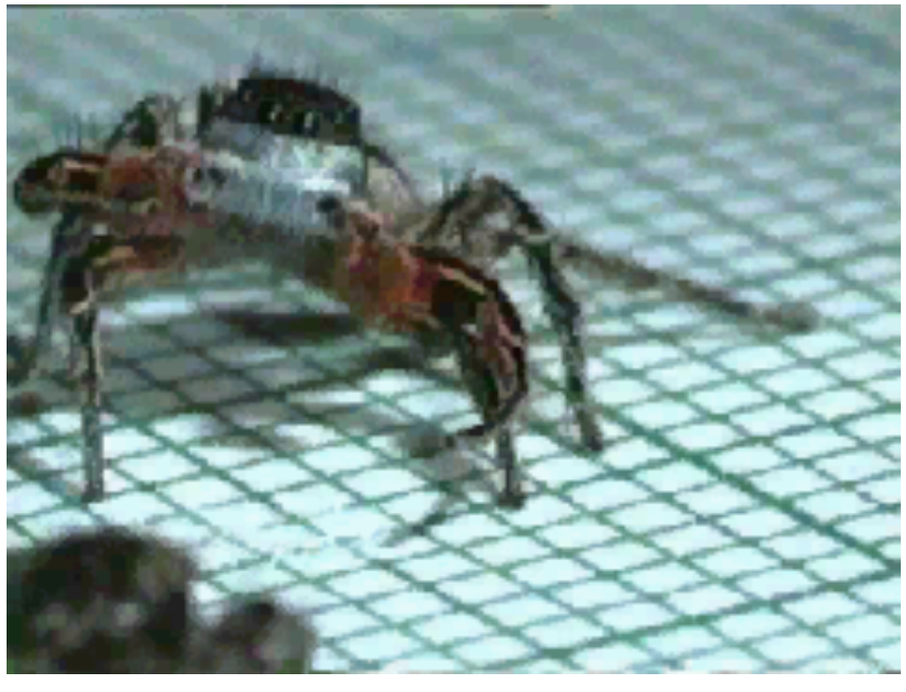


Fig. 4. Flight paths of chasing (●) and leading (○) flies during the longest recorded chase. Points at 20 ms intervals. Corresponding instants on the two paths numbered at 200 ms intervals

Philanthus triangulum
(sand wasp)



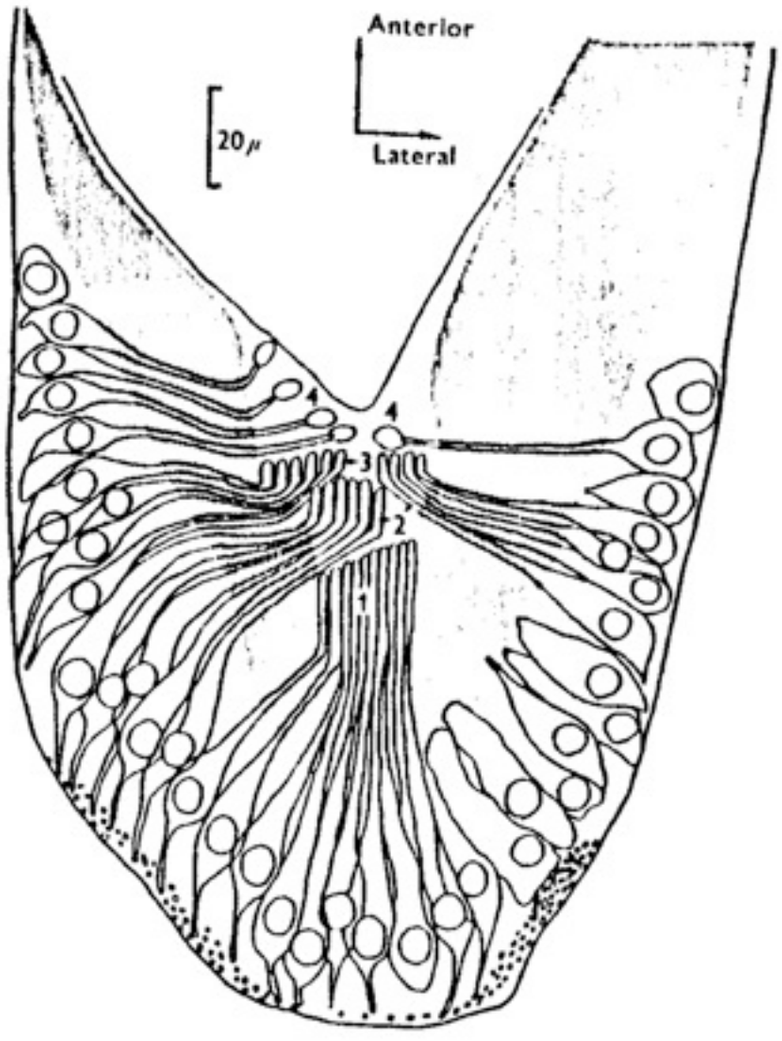
Jumping spiders



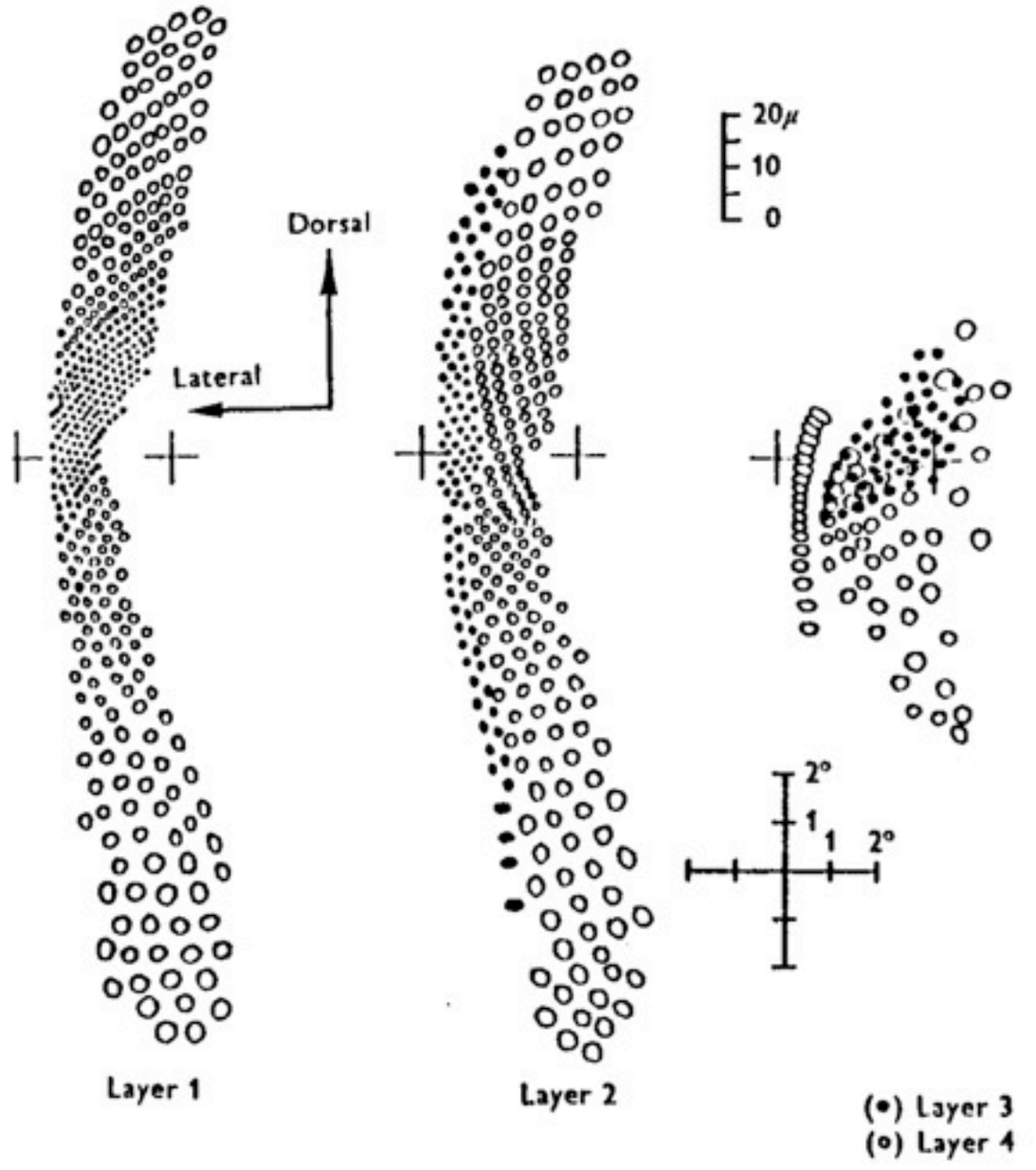
Jumping spider visual system

Jumping spider retina

horizontal section



photoreceptor array

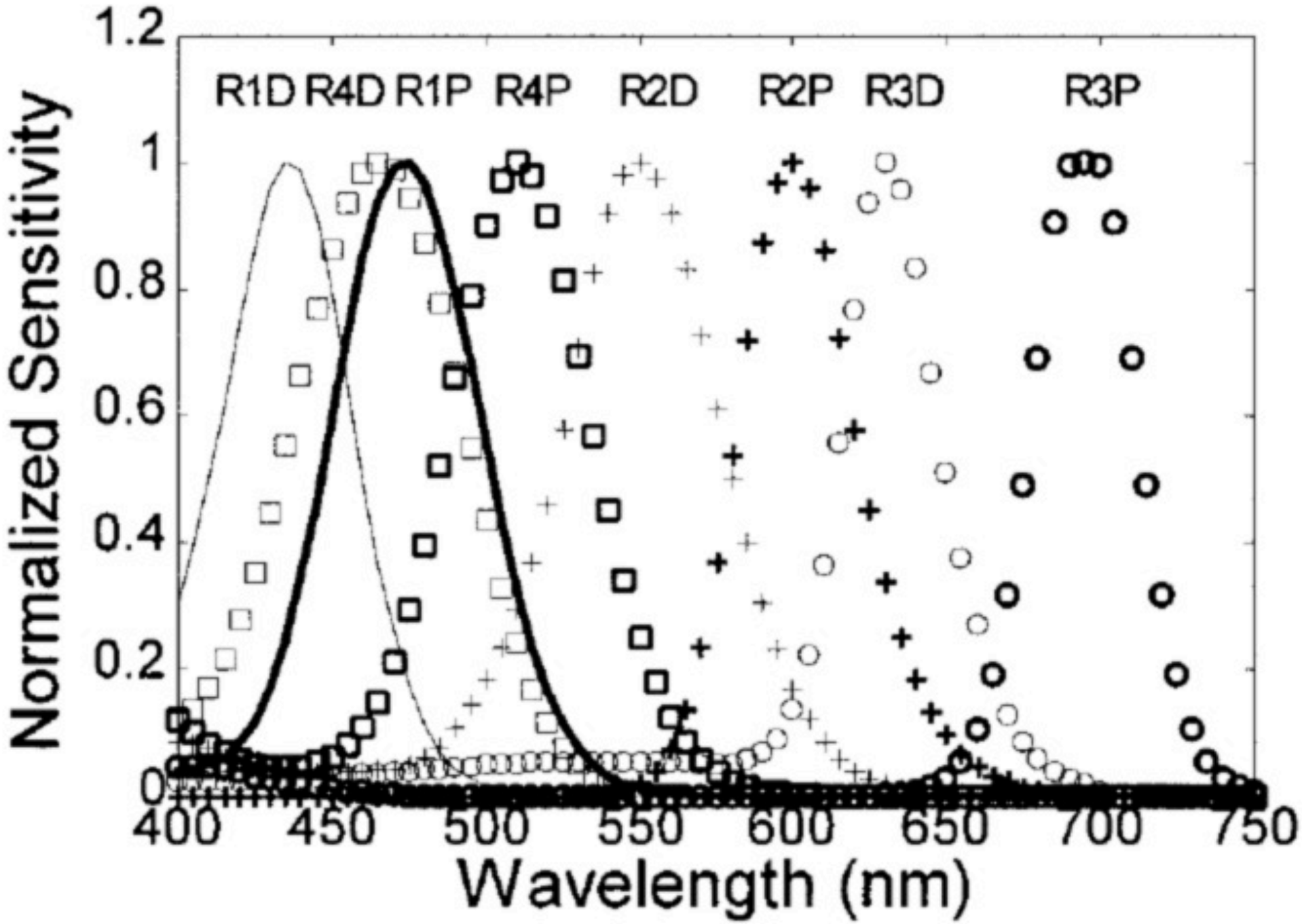


Jumping spiders do object recognition

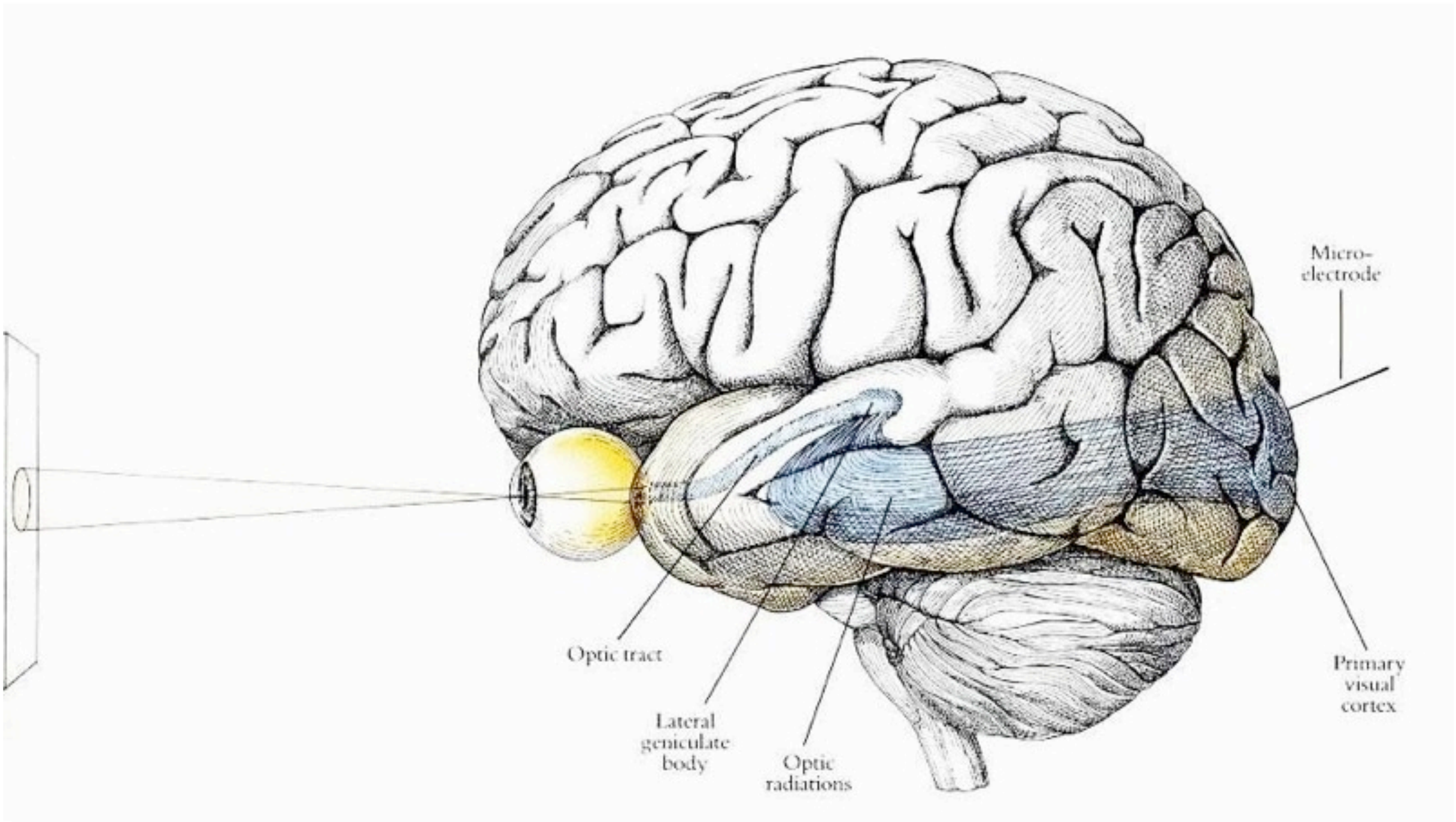
Text-fig. 12. Stimuli found by Drees to evoke courtship (*a*) and prey capture (*b*) in male jumping spiders (*Epiblemum scenicum*). The numbers beneath each figure in (*a*) are the percentage of trials on which courtship was evoked. After Drees (1952).

Mantis shrimp

Mantis shrimp - photoreceptor spectral sensitivities



Dung beetles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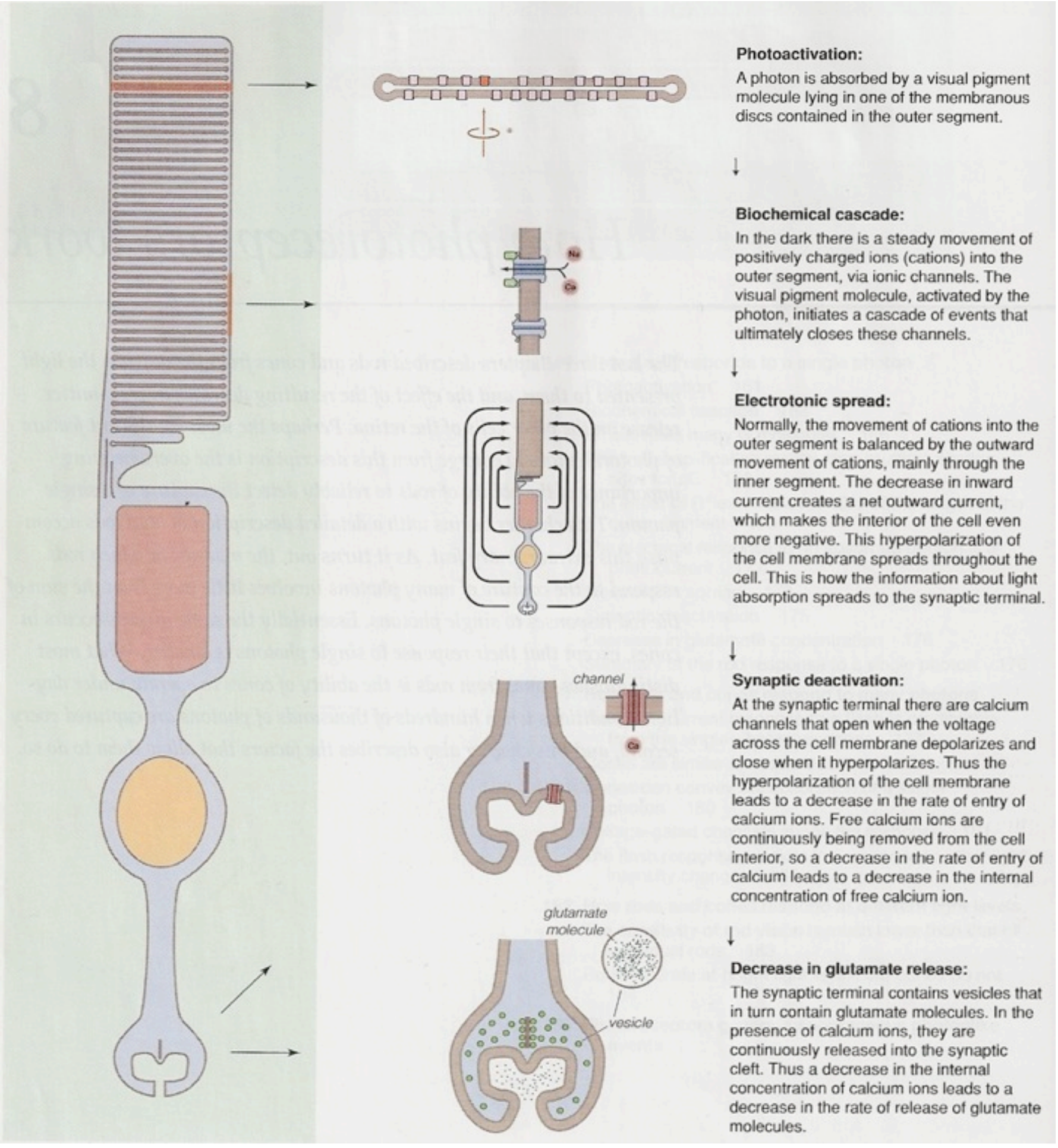


Photoactivation:

A photon is absorbed by a visual pigment molecule lying in one of the membranous discs contained in the outer segment.

Biochemical cascade:

In the dark there is a steady movement of positively charged ions (cations) into the outer segment, via ionic channels. The visual pigment molecule, activated by the photon, initiates a cascade of events that ultimately closes these channels.

Electrotonic spread:

Normally, the movement of cations into the outer segment is balanced by the outward movement of cations, mainly through the inner segment. The decrease in inward current creates a net outward current, which makes the interior of the cell even more negative. This hyperpolarization of the cell membrane spreads throughout the cell. This is how the information about light absorption spreads to the synaptic terminal.

Synaptic deactivation:

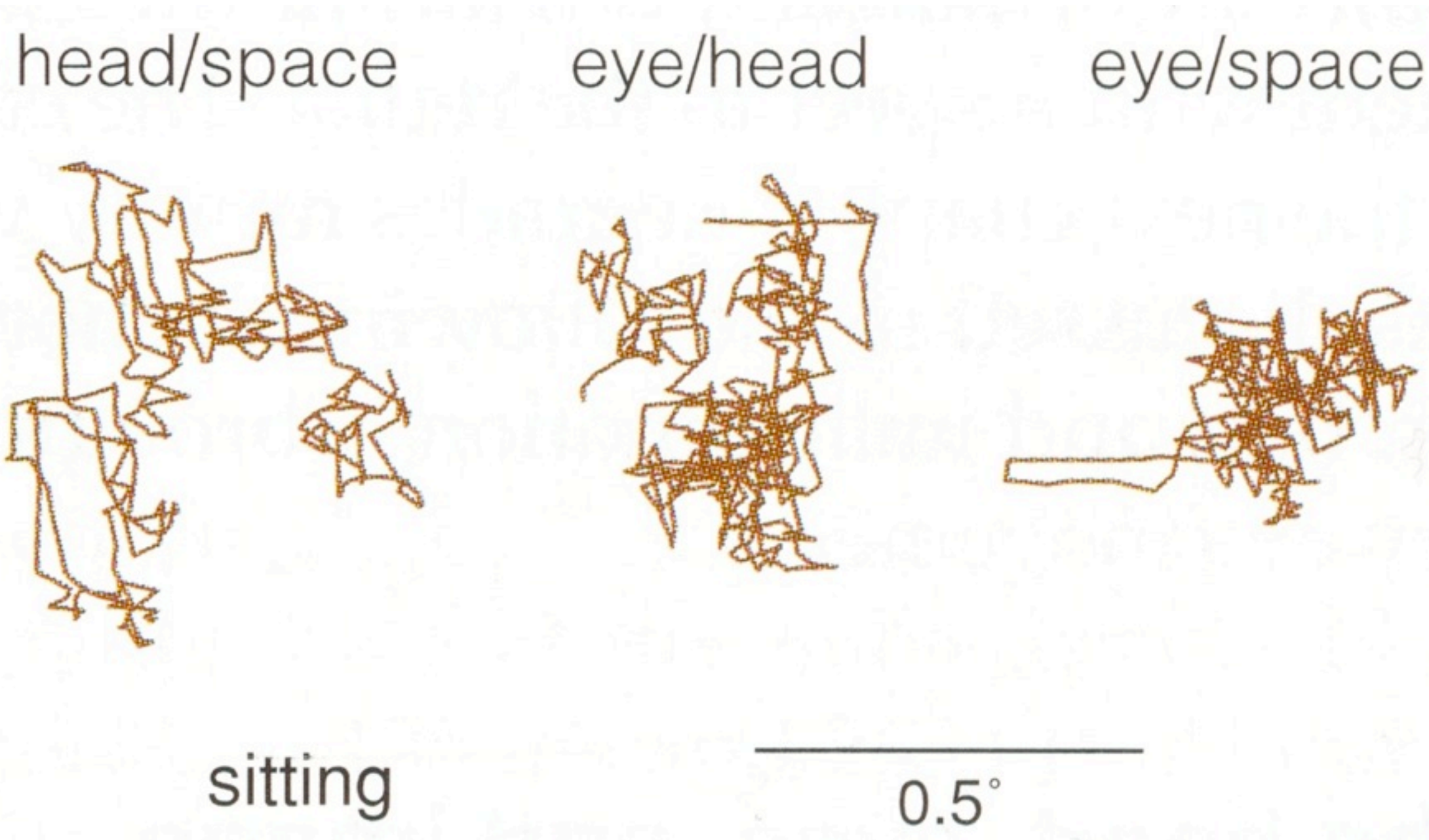
At the synaptic terminal there are calcium channels that open when the voltage across the cell membrane depolarizes and close when it hyperpolarizes. Thus the hyperpolarization of the cell membrane leads to a decrease in the rate of entry of calcium ions. Free calcium ions are continuously being removed from the cell interior, so a decrease in the rate of entry of calcium leads to a decrease in the internal concentration of free calcium ion.

Decrease in glutamate release:

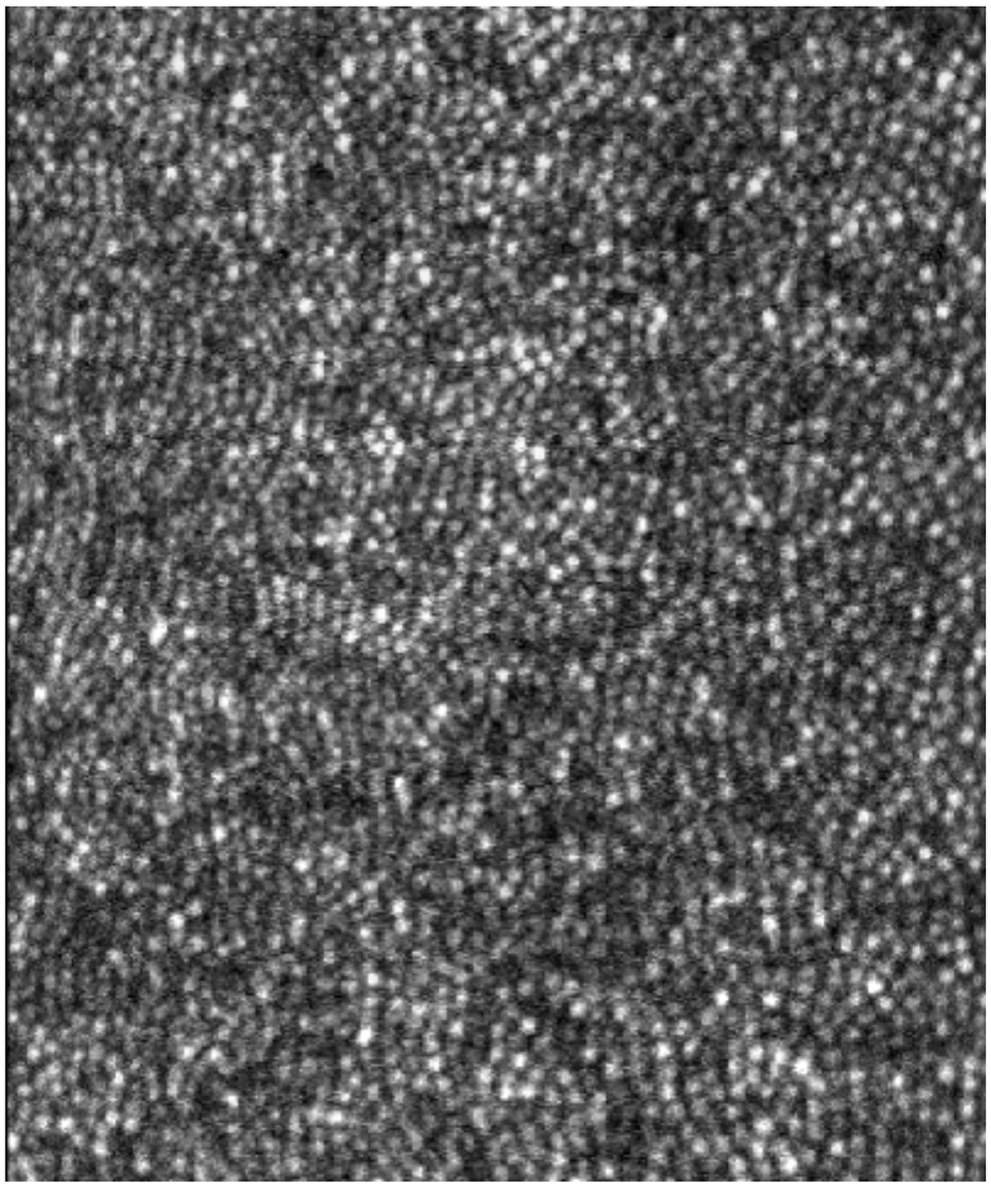
The synaptic terminal contains vesicles that in turn contain glutamate molecules. In the presence of calcium ions, they are continuously released into the synaptic cleft. Thus a decrease in the internal concentration of calcium ions leads to a decrease in the rate of release of glutamate molecules.

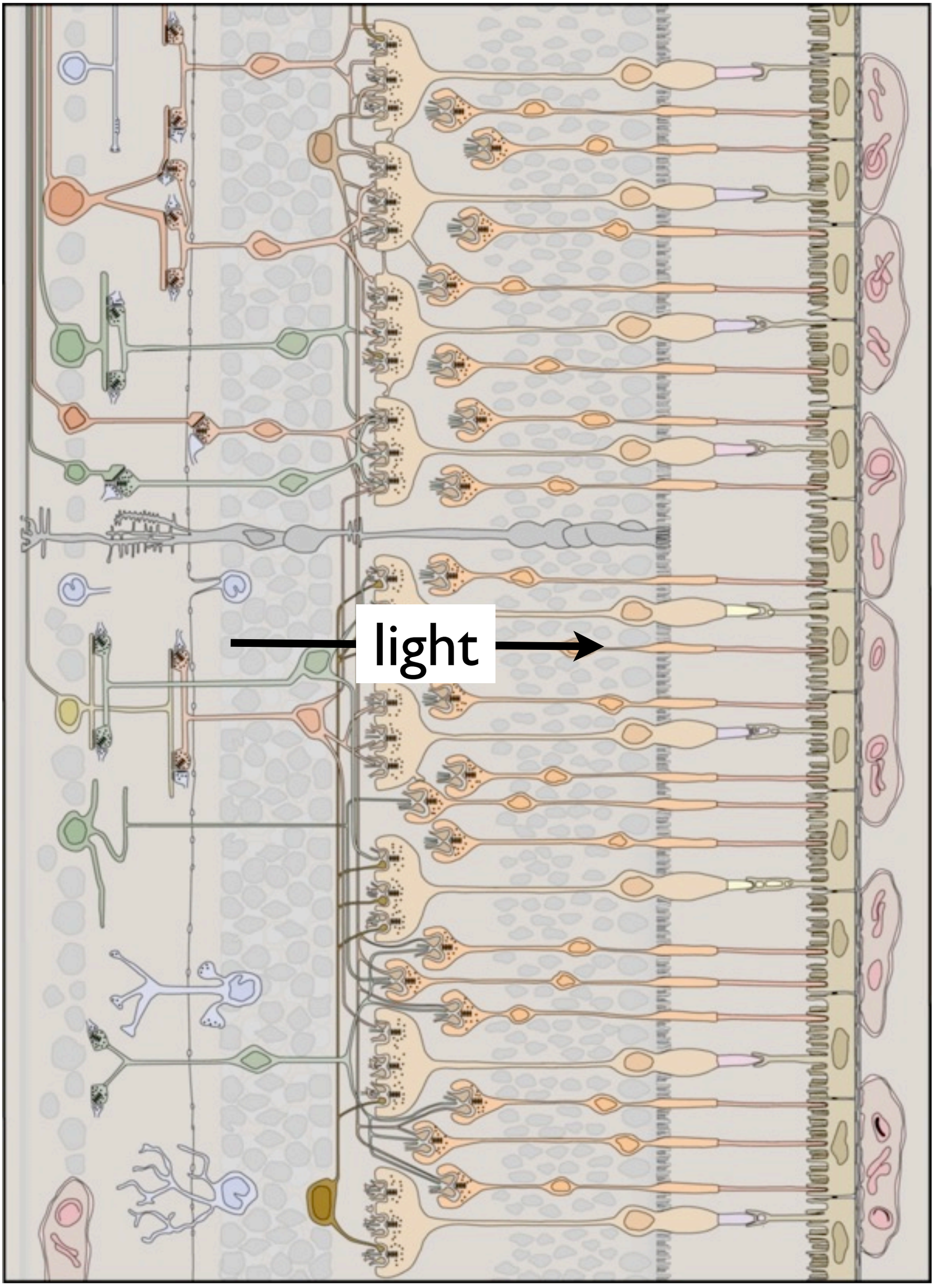
Steps in *phototransduction*

Fixational eye movements

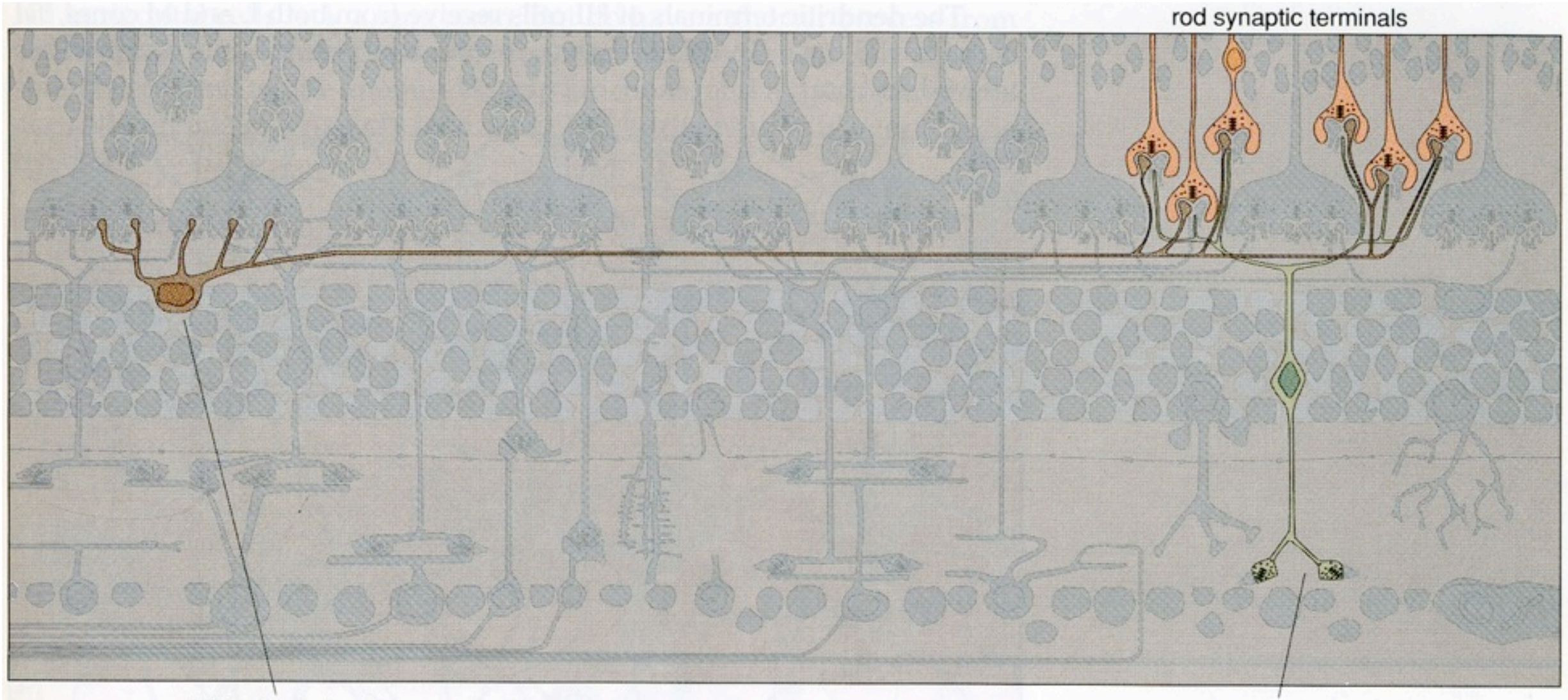


Human fixational eye movements
(Austin Roorda, UCB)

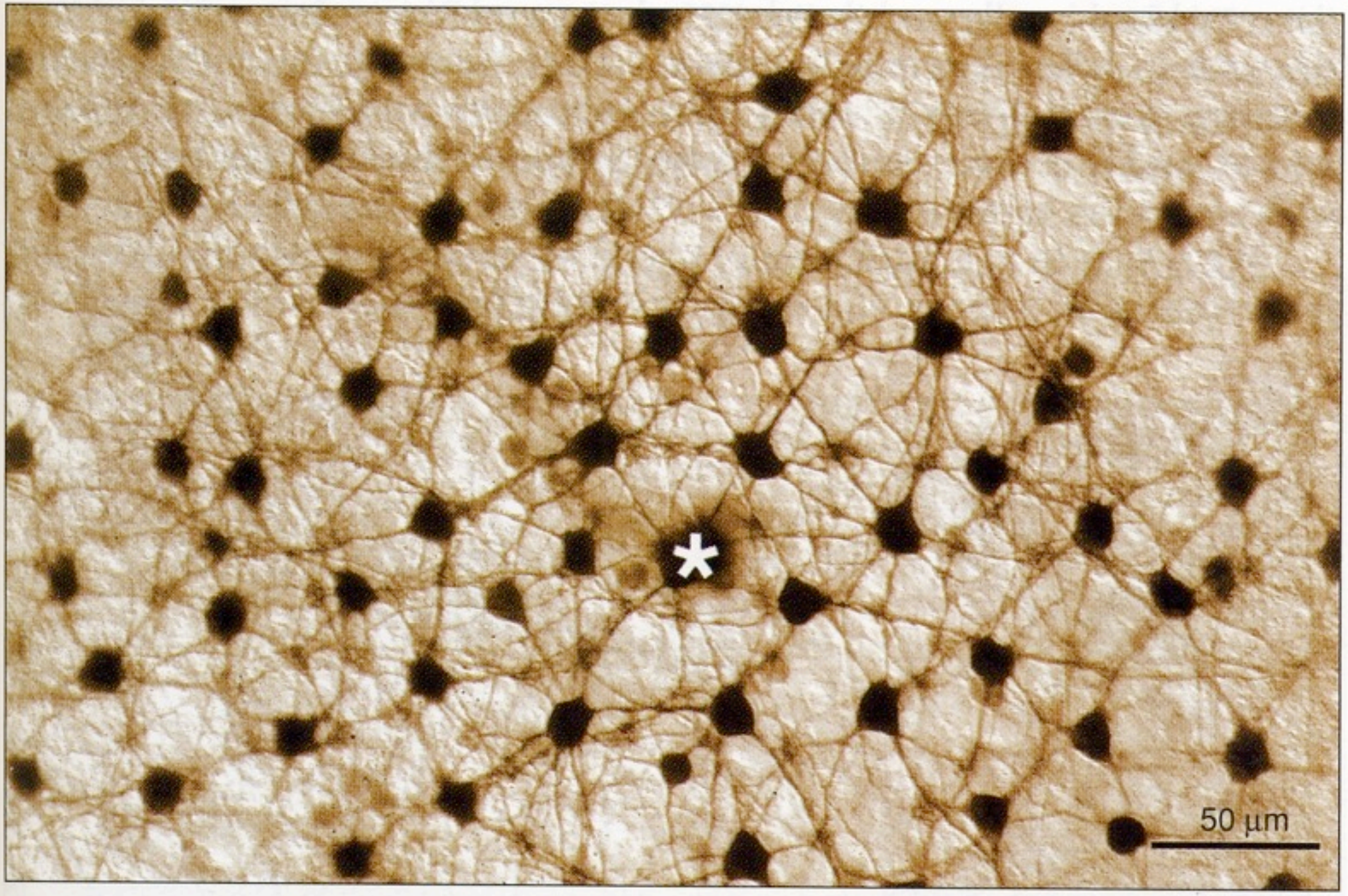



light

HI horizontal cell



HI horizontal cells connected via gap junctions

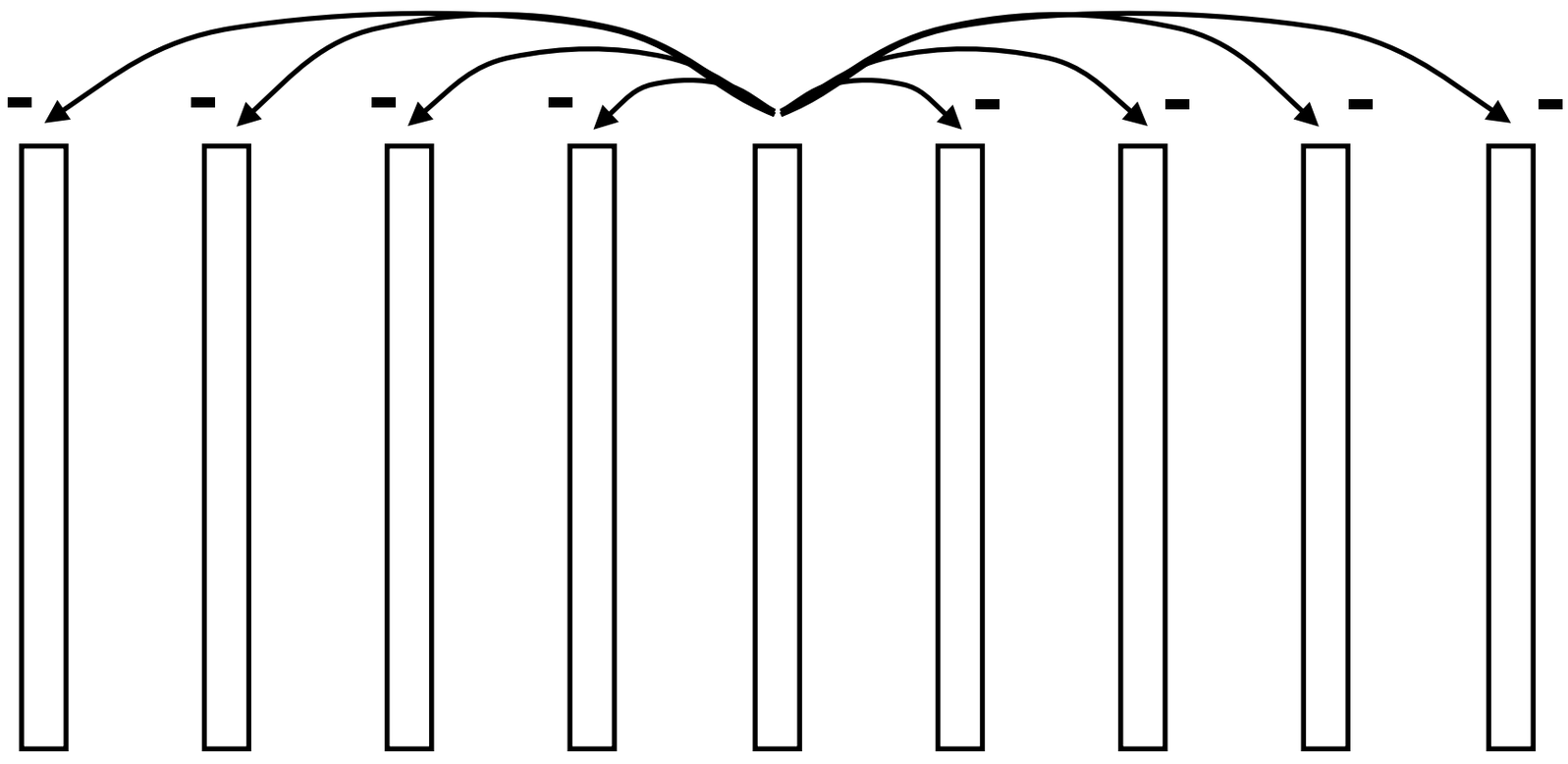


HI horizontal cells labeled following injection of one HI cell (*) ×300

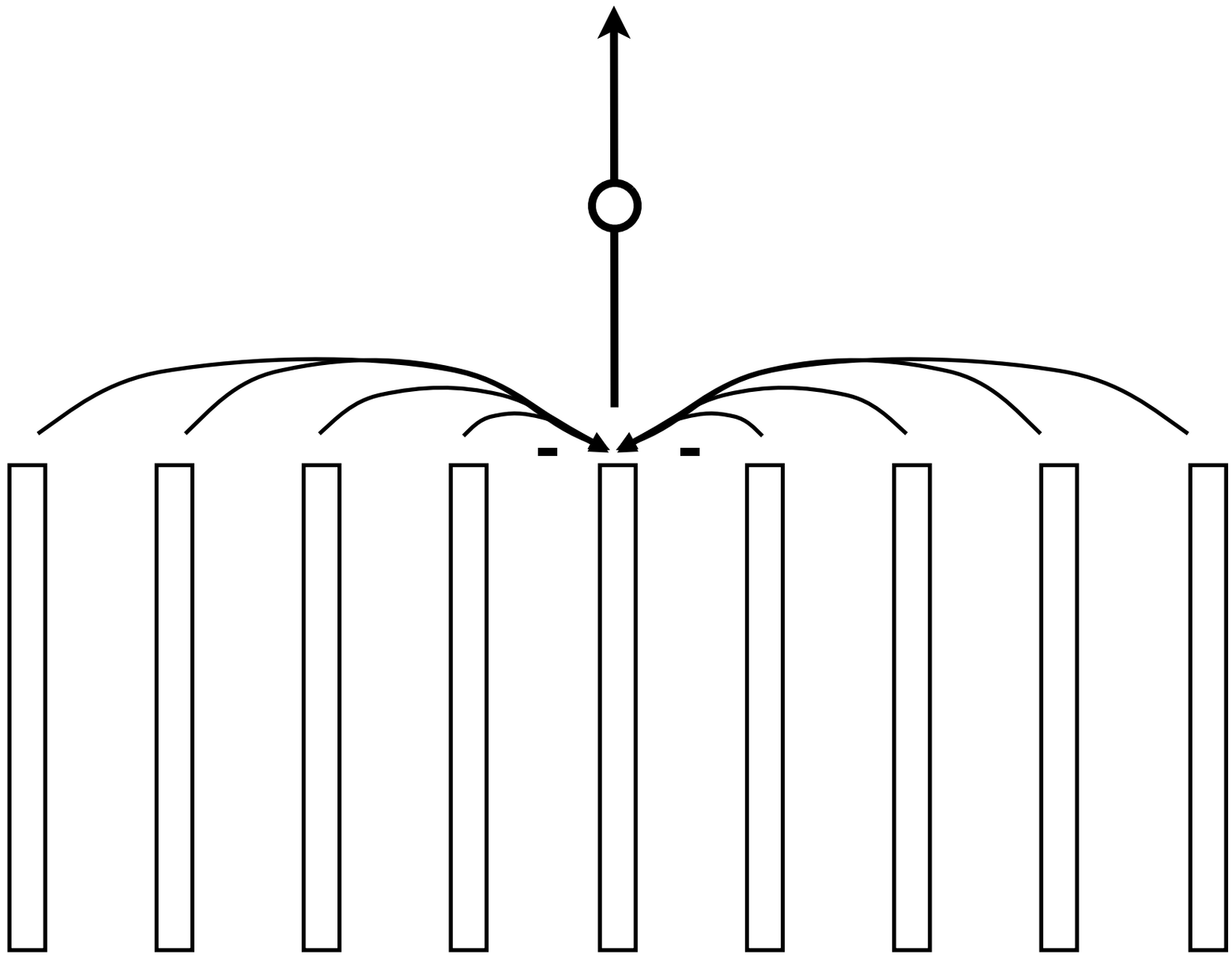
after Dacey, Lee, and Stafford, 1996

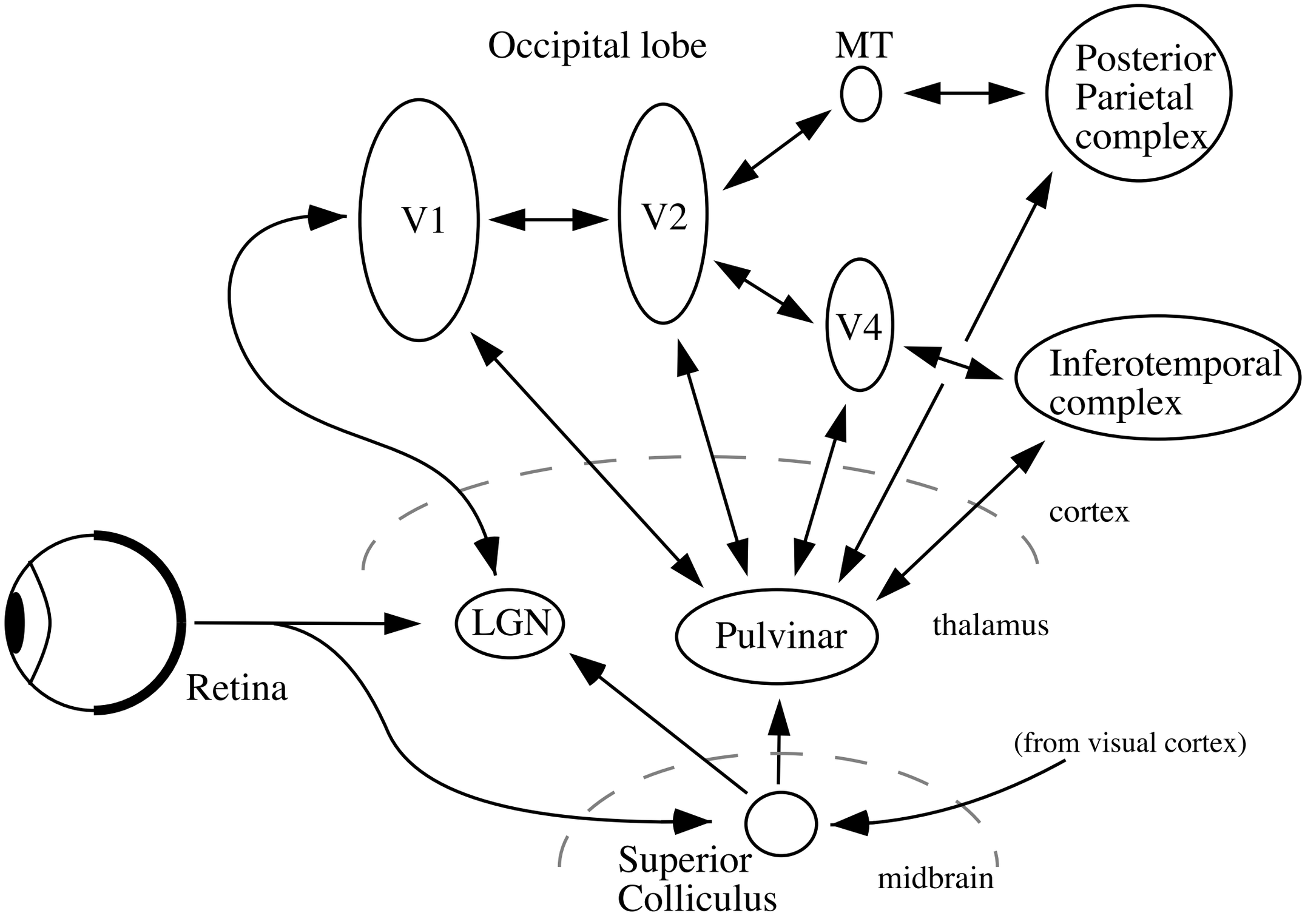
Lateral inhibition:

activation of one photoreceptor inhibits neighboring photoreceptors

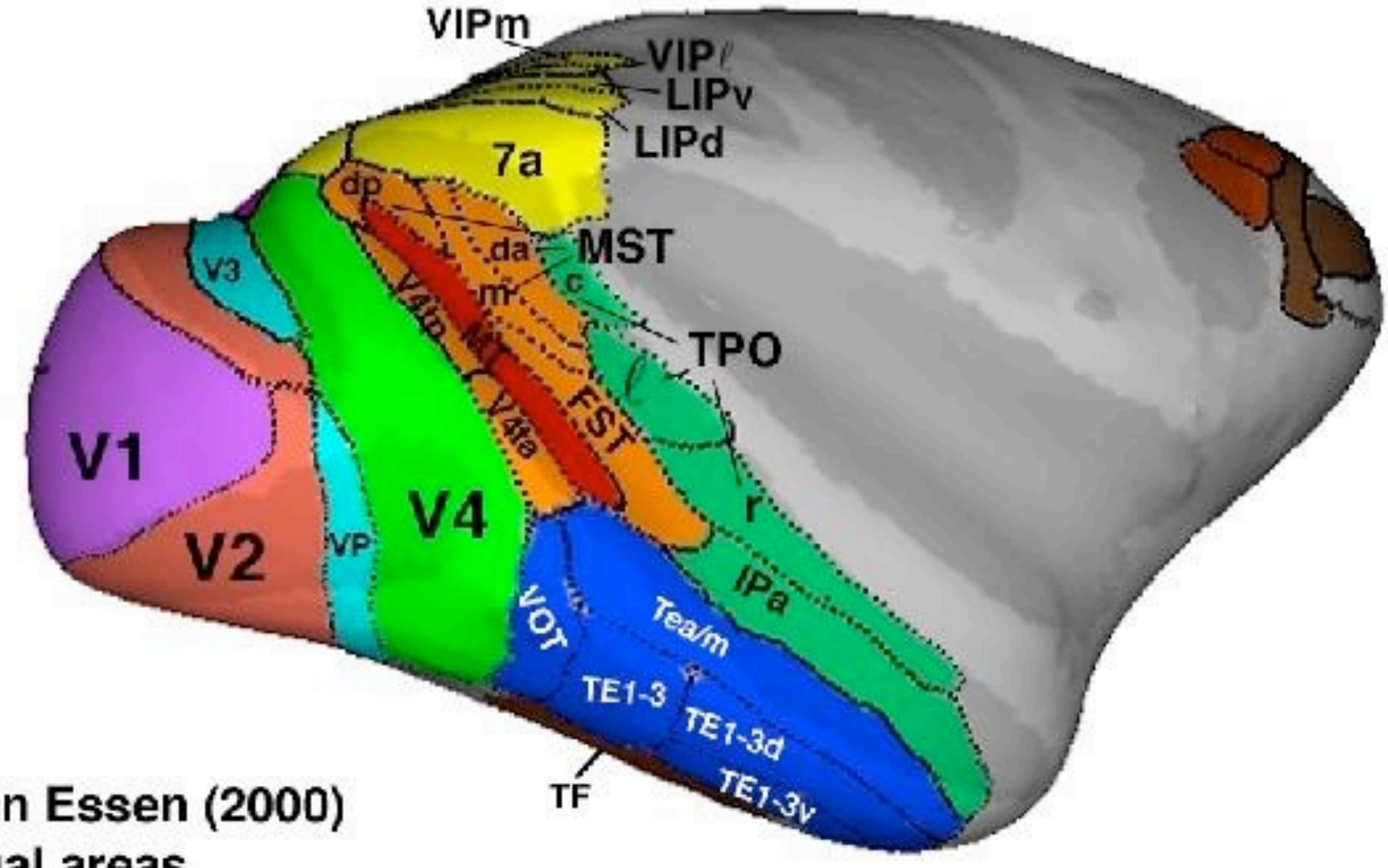


Bipolar cells read out differences between one photoreceptor's activity and its neighbors as computed by horizontal cell network

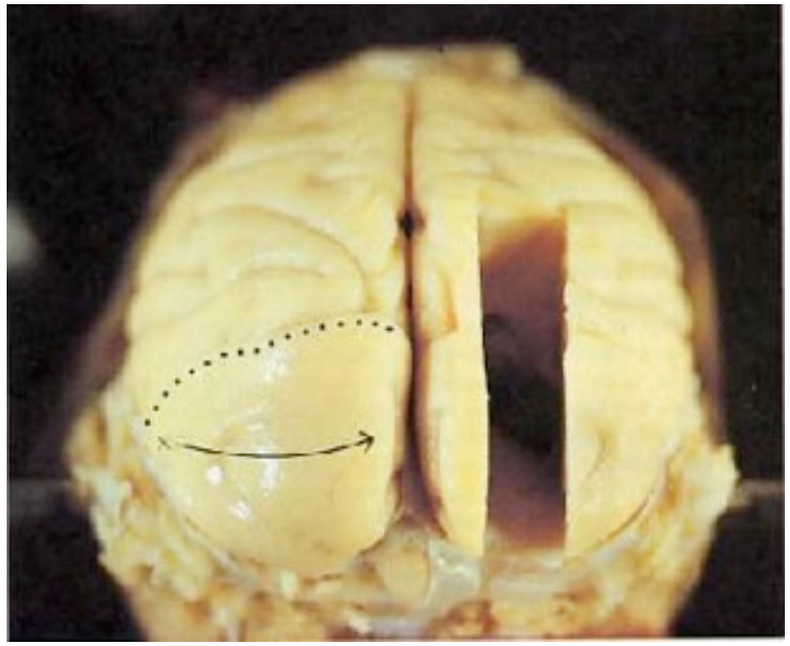


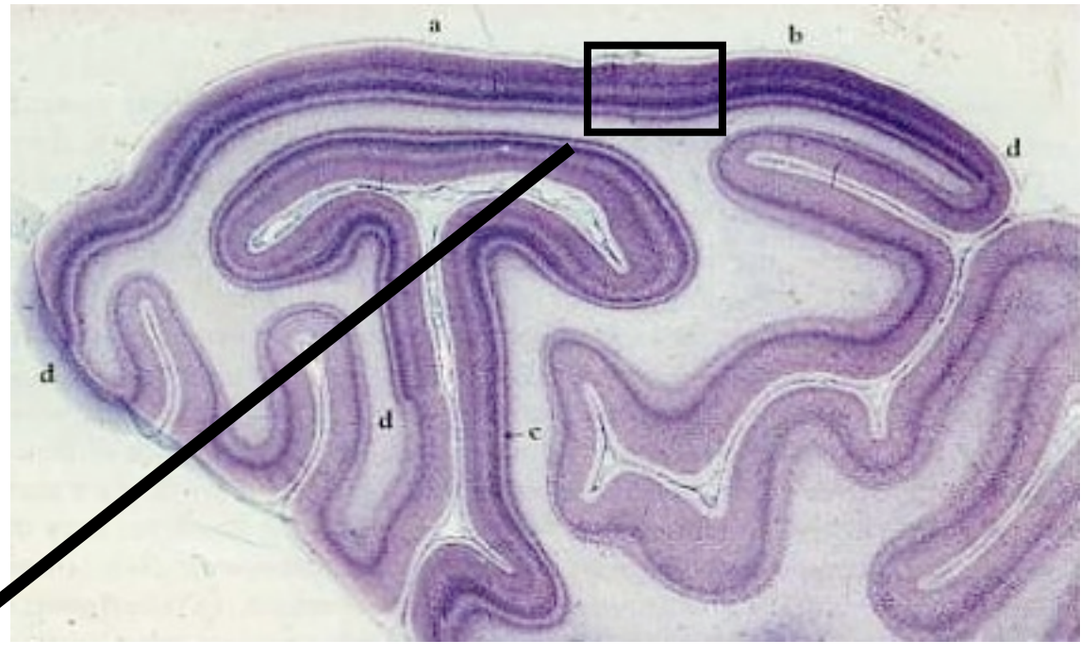

Occipital lobe
MT
Posterior
Parietal
complex
V1
V2
V4
Inferotemporal
complex
cortex
LGN
Pulvinar
thalamus
Retina
(from visual cortex)
Superior
Colliculus
midbrain

Primate visual cortex

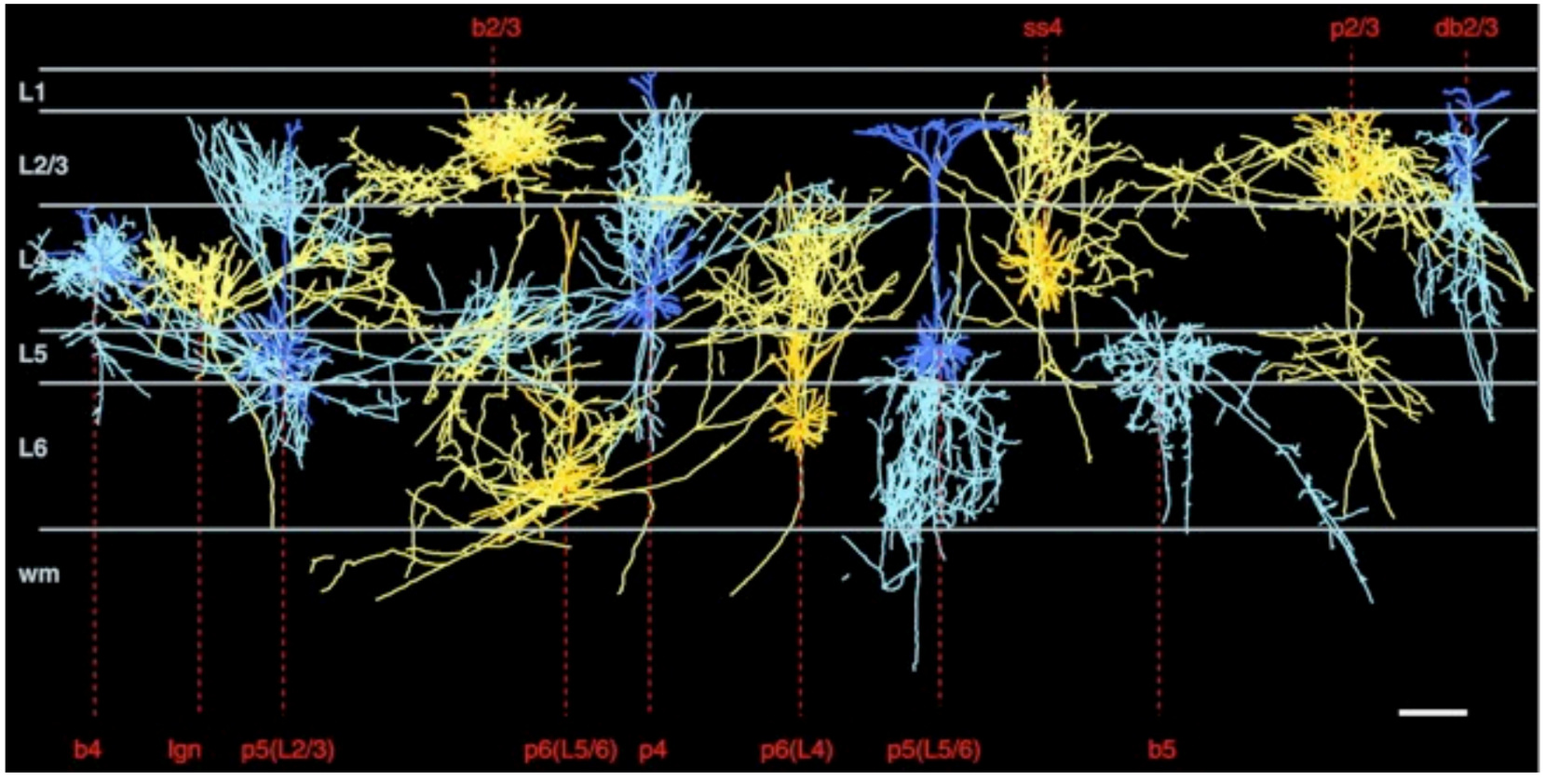


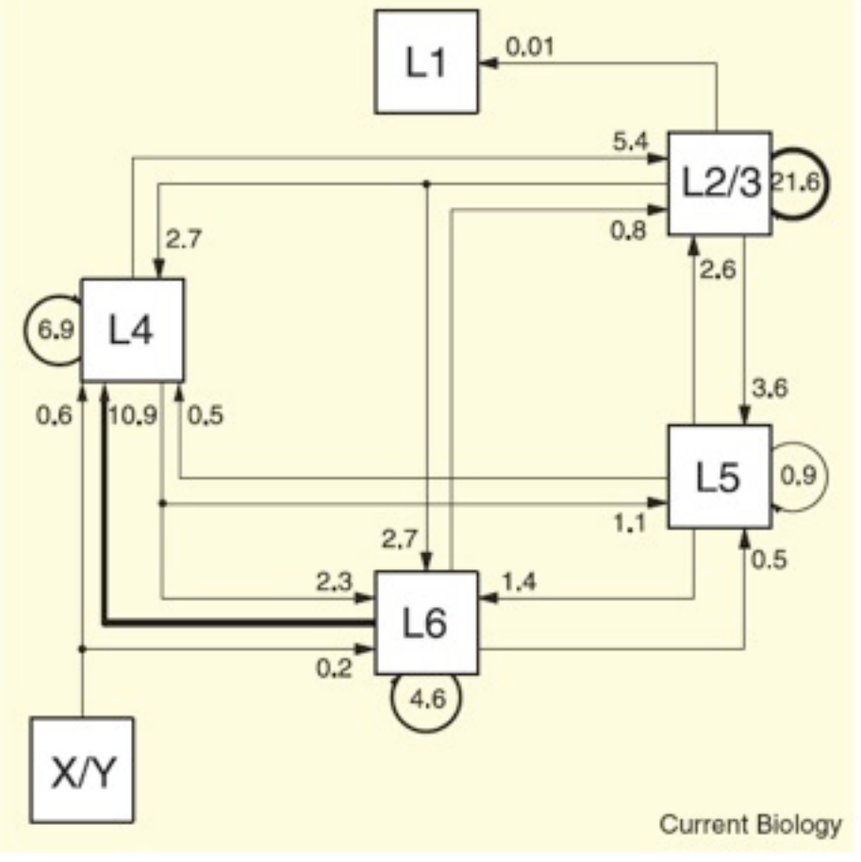
Lewis & Van Essen (2000)
Visual areas



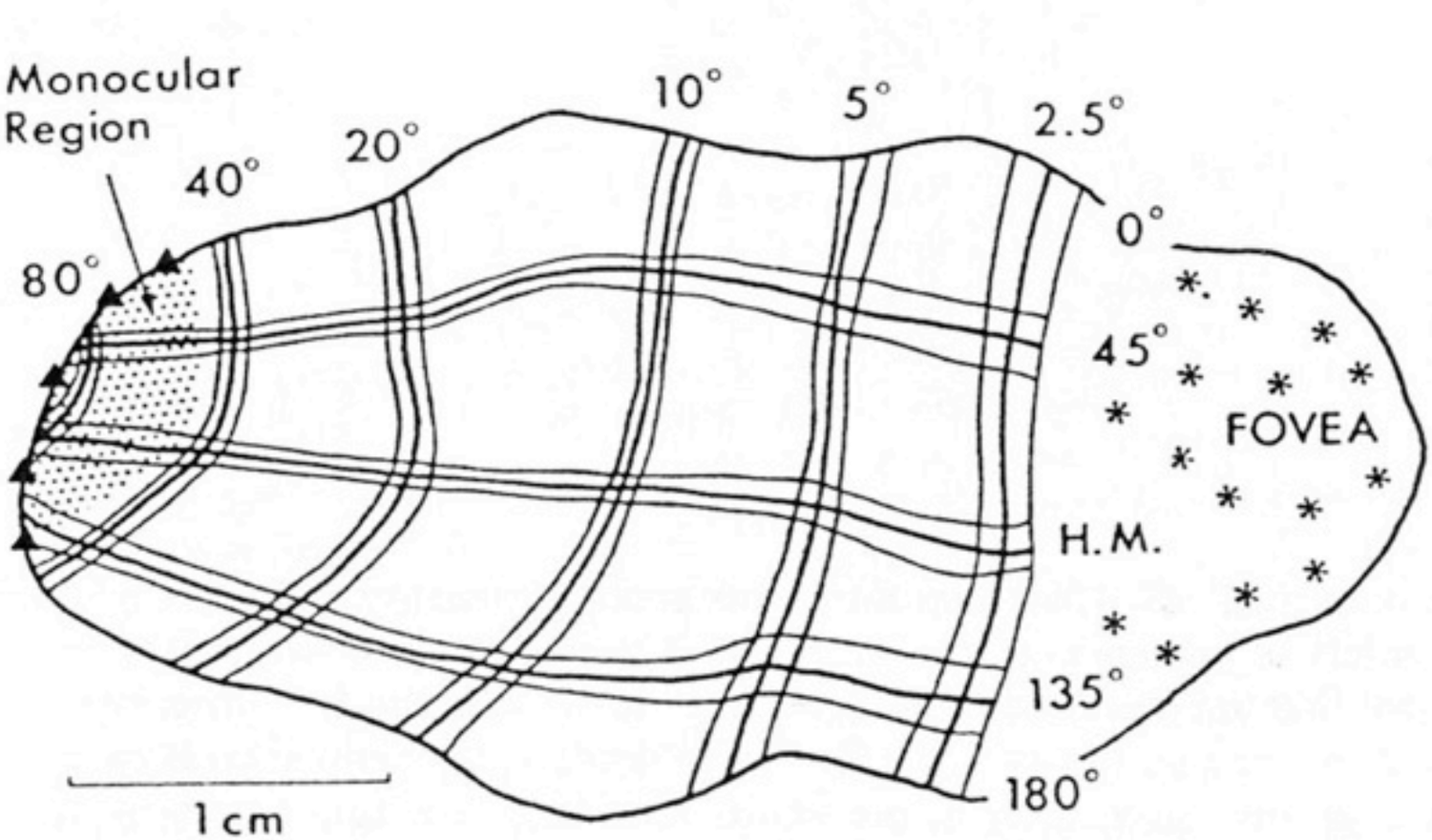


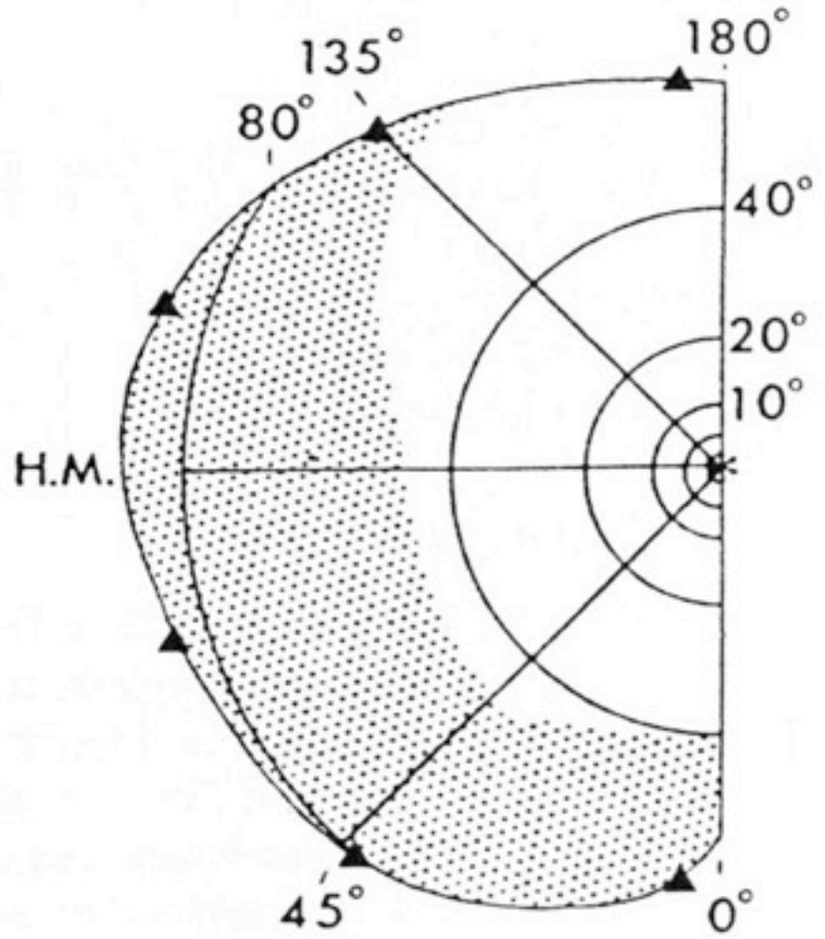
‘canononical microcircuit’



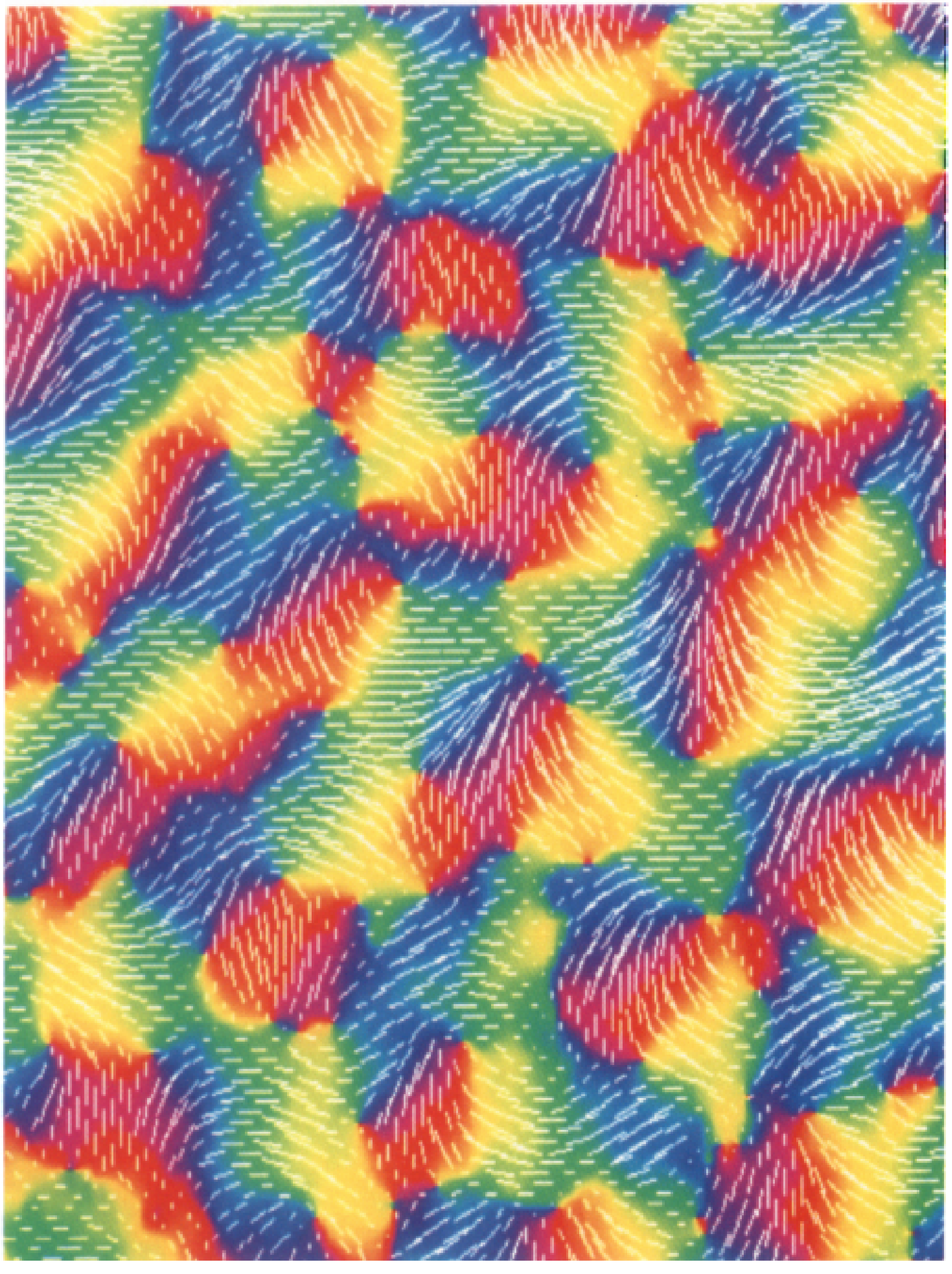


V1 - topographic representation

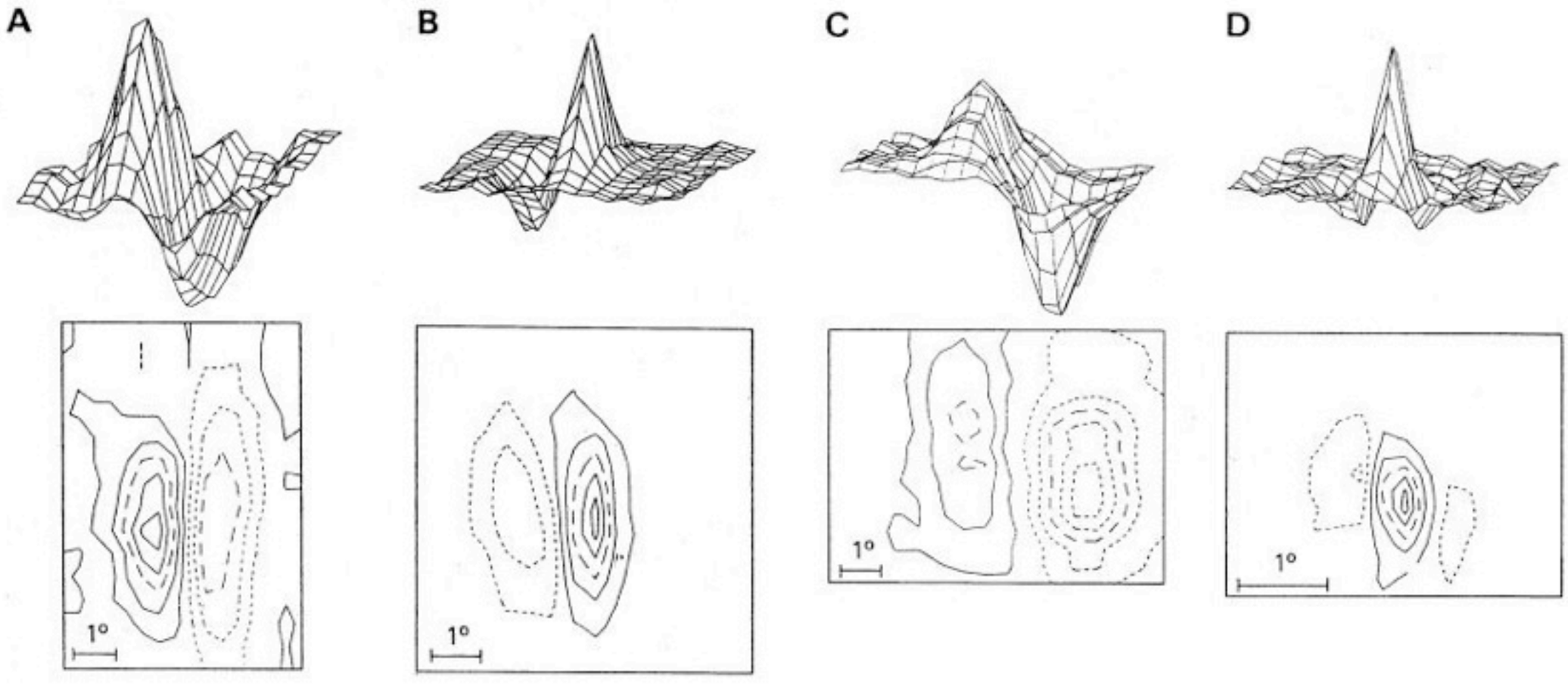




Orientation columns

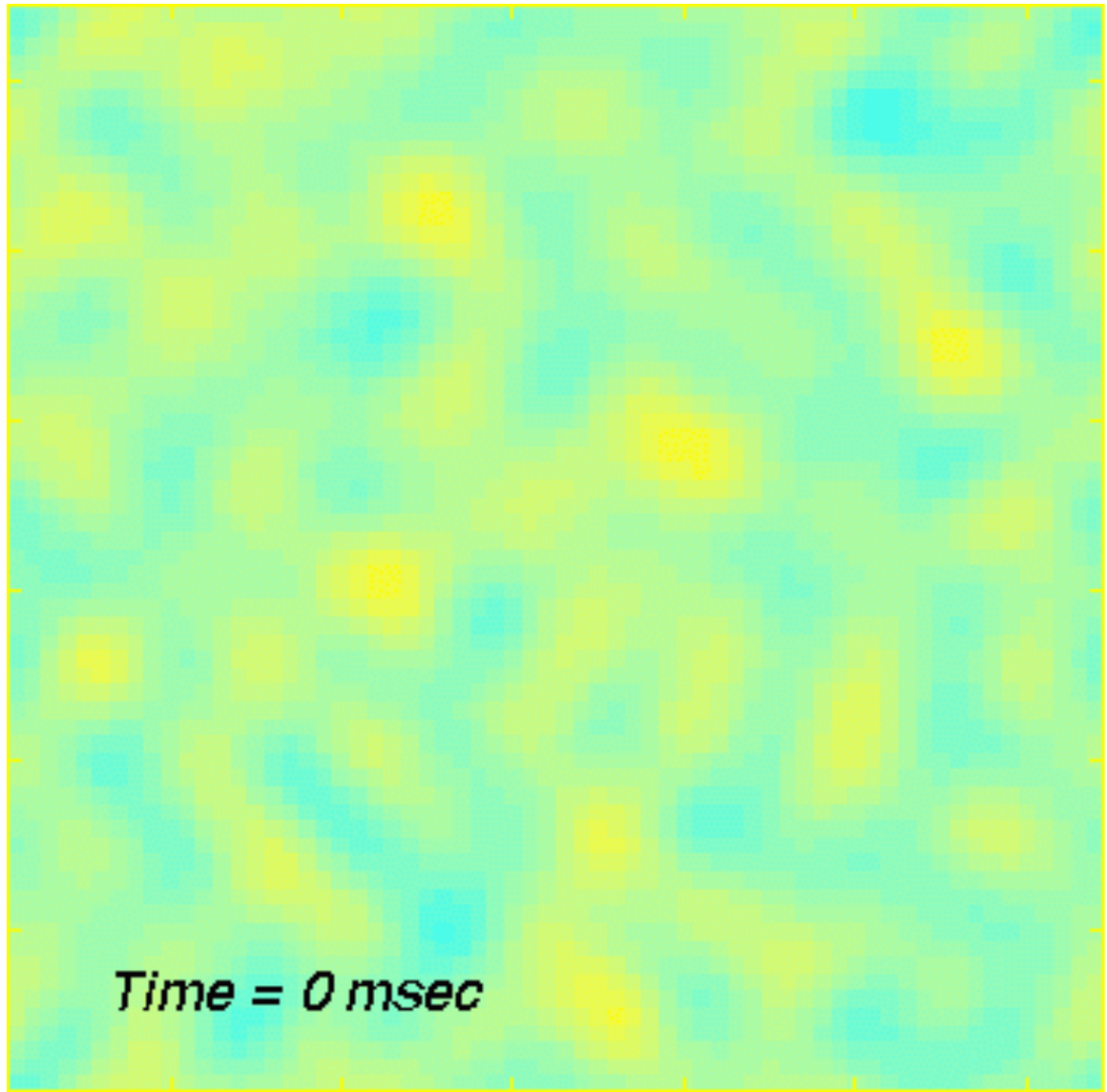


V1 receptive fields - ‘simple cells’

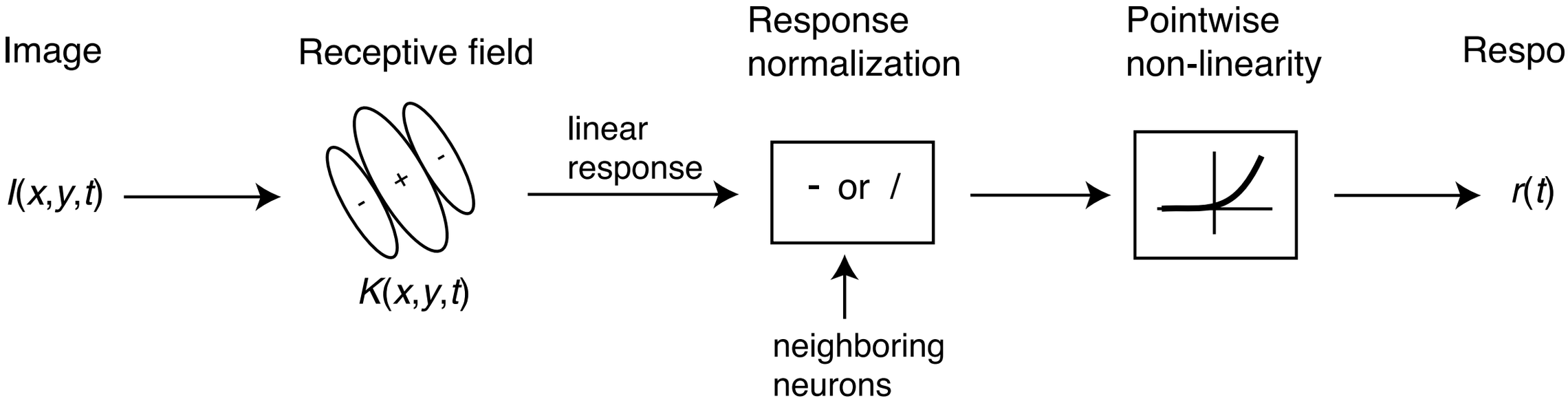


Jones & Palmer (1987)

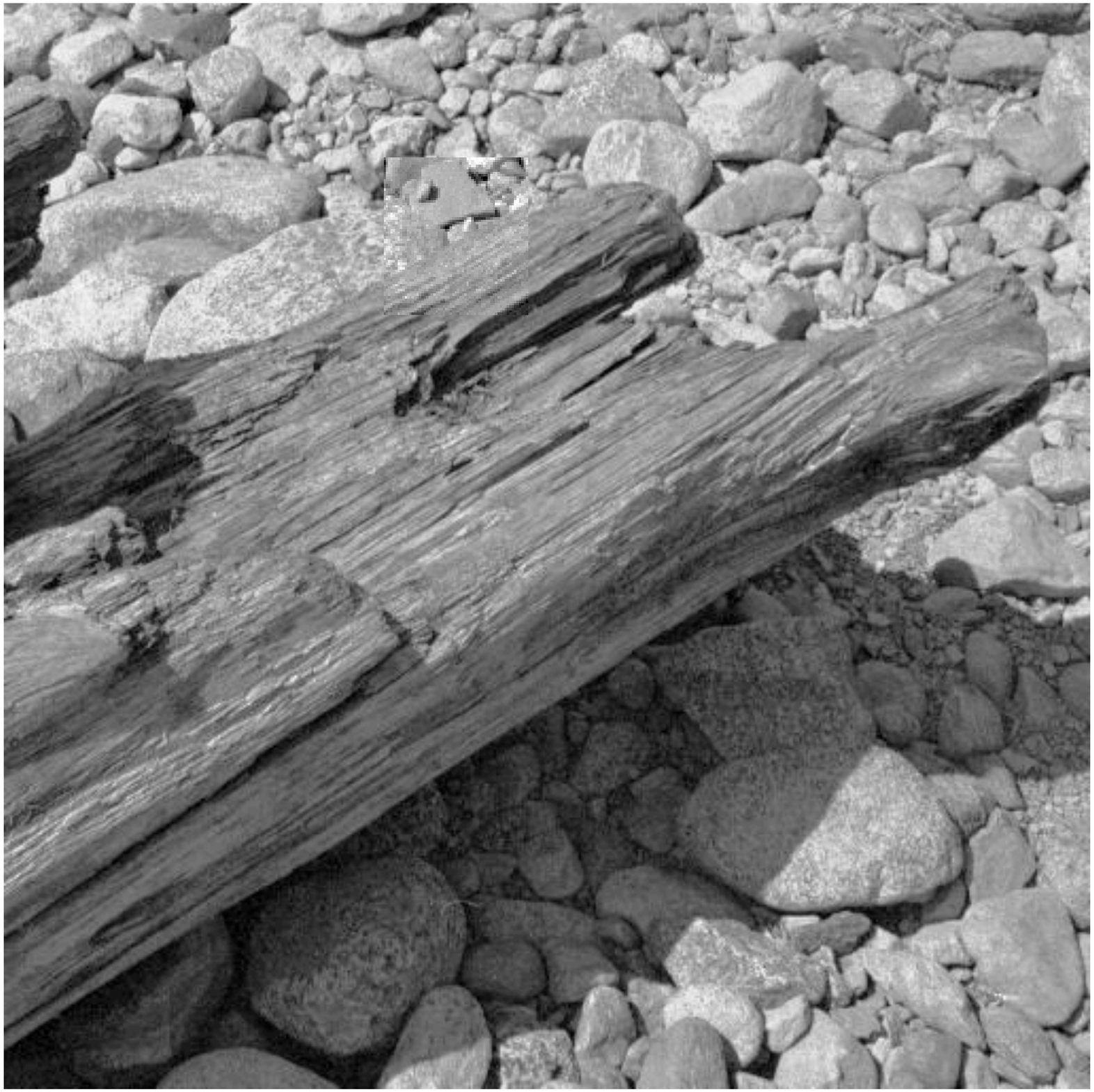
V1 space-time receptive field
(Courtesy of Dario Ringach, UCLA)



The "standard model" of V1



How would a population of such neurons represent a natural image?



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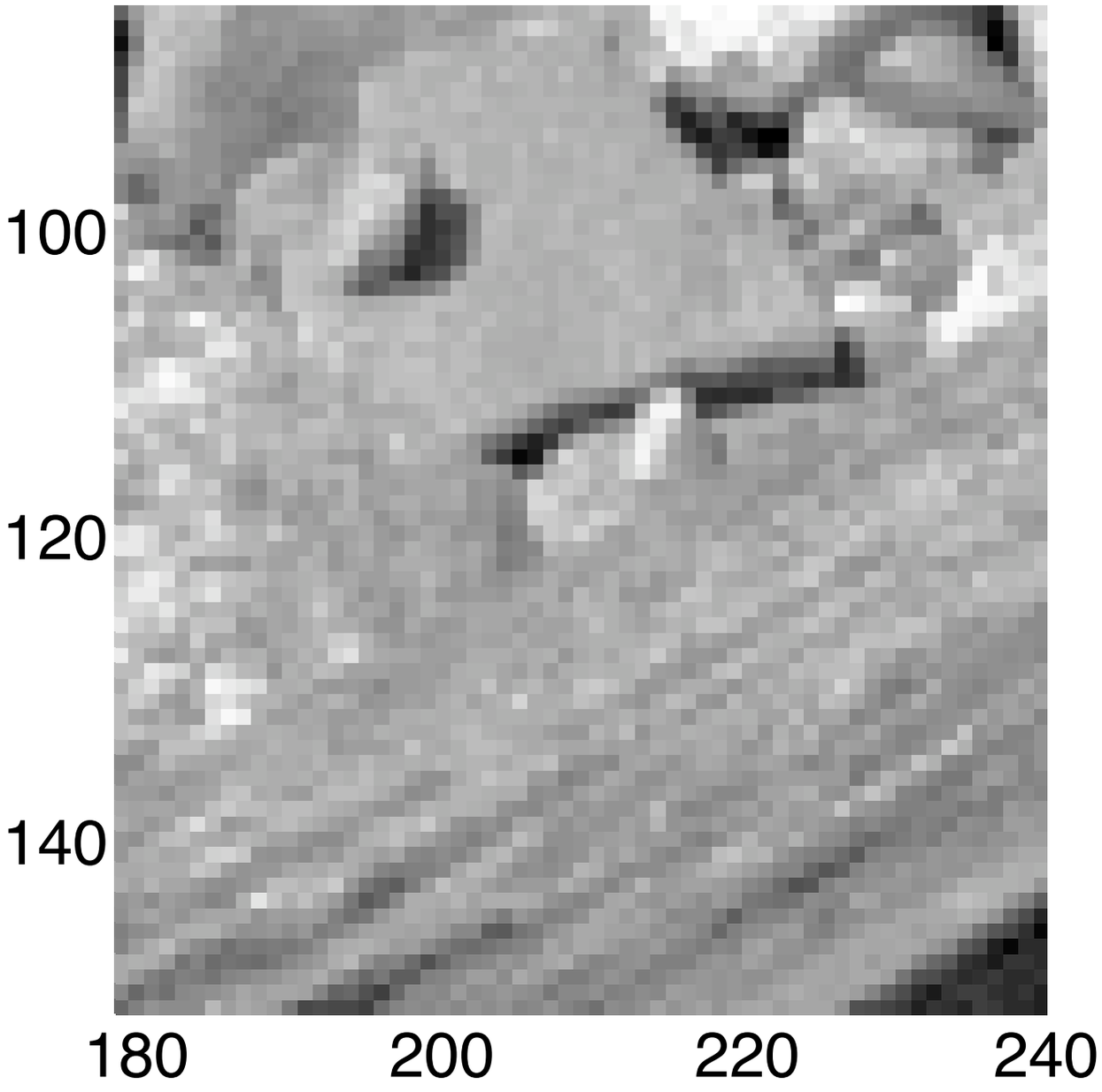
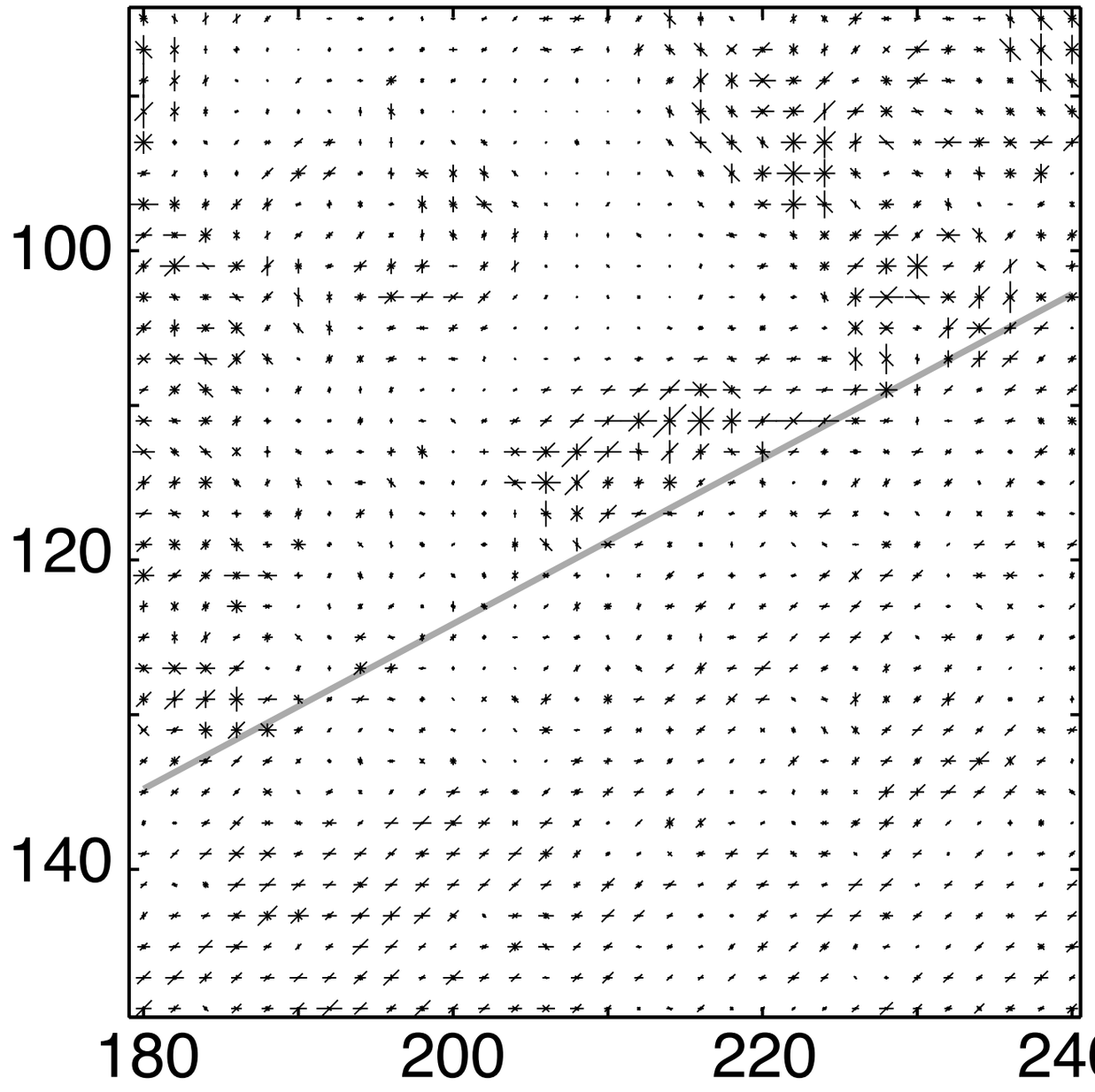
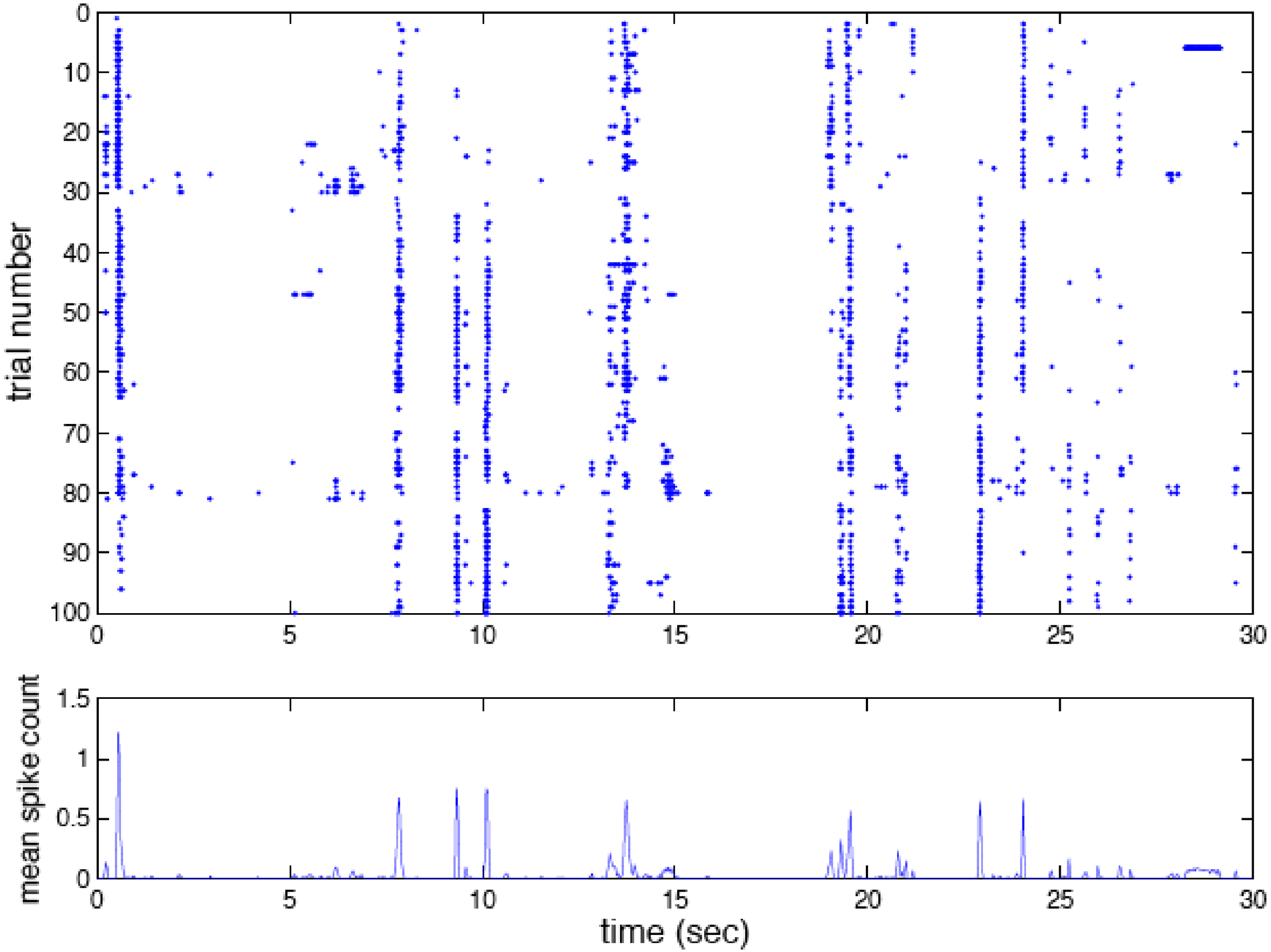


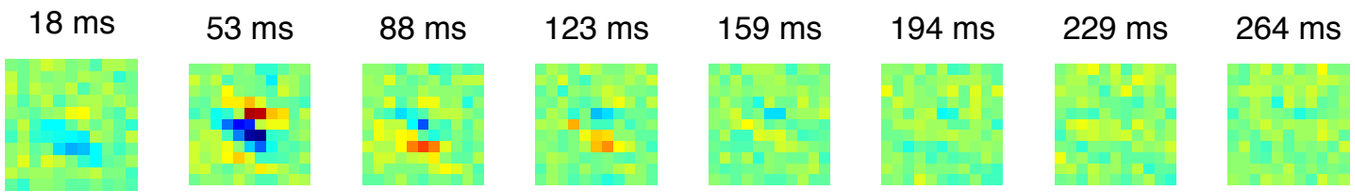


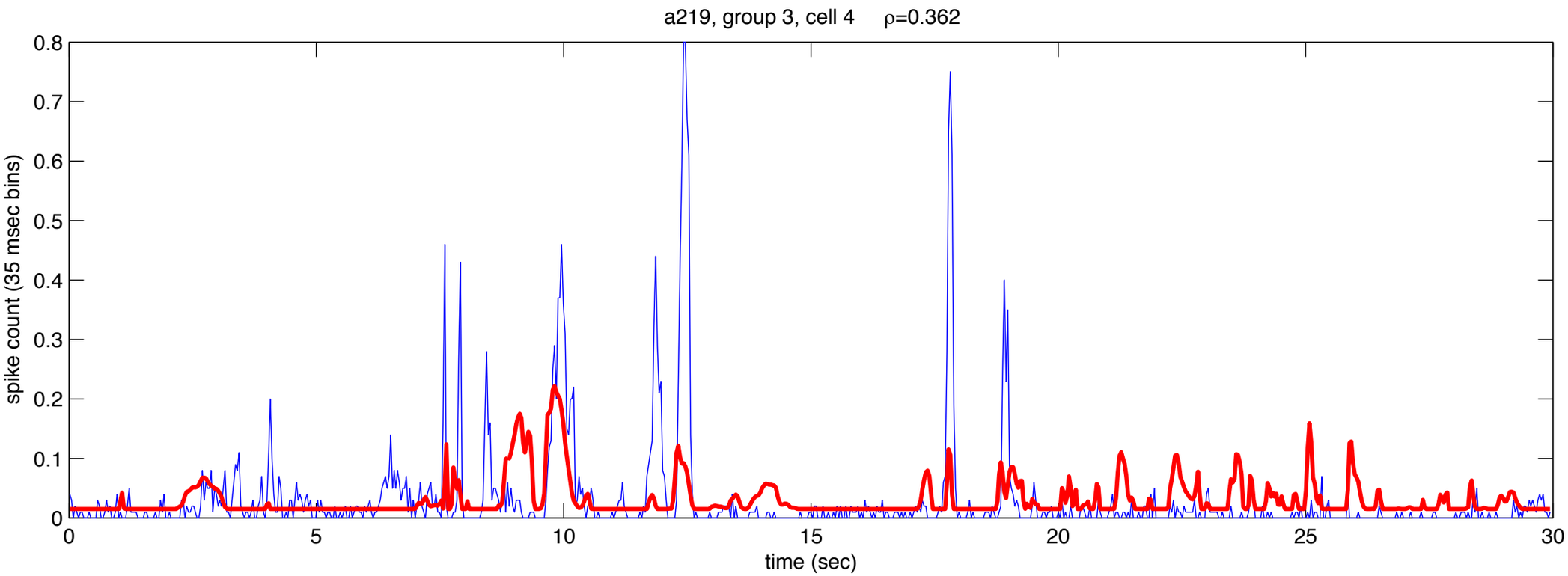
Cat V1 - natural movies (J. Baker, S.C. Yen, C.M. Gray, MSU Bozeman)



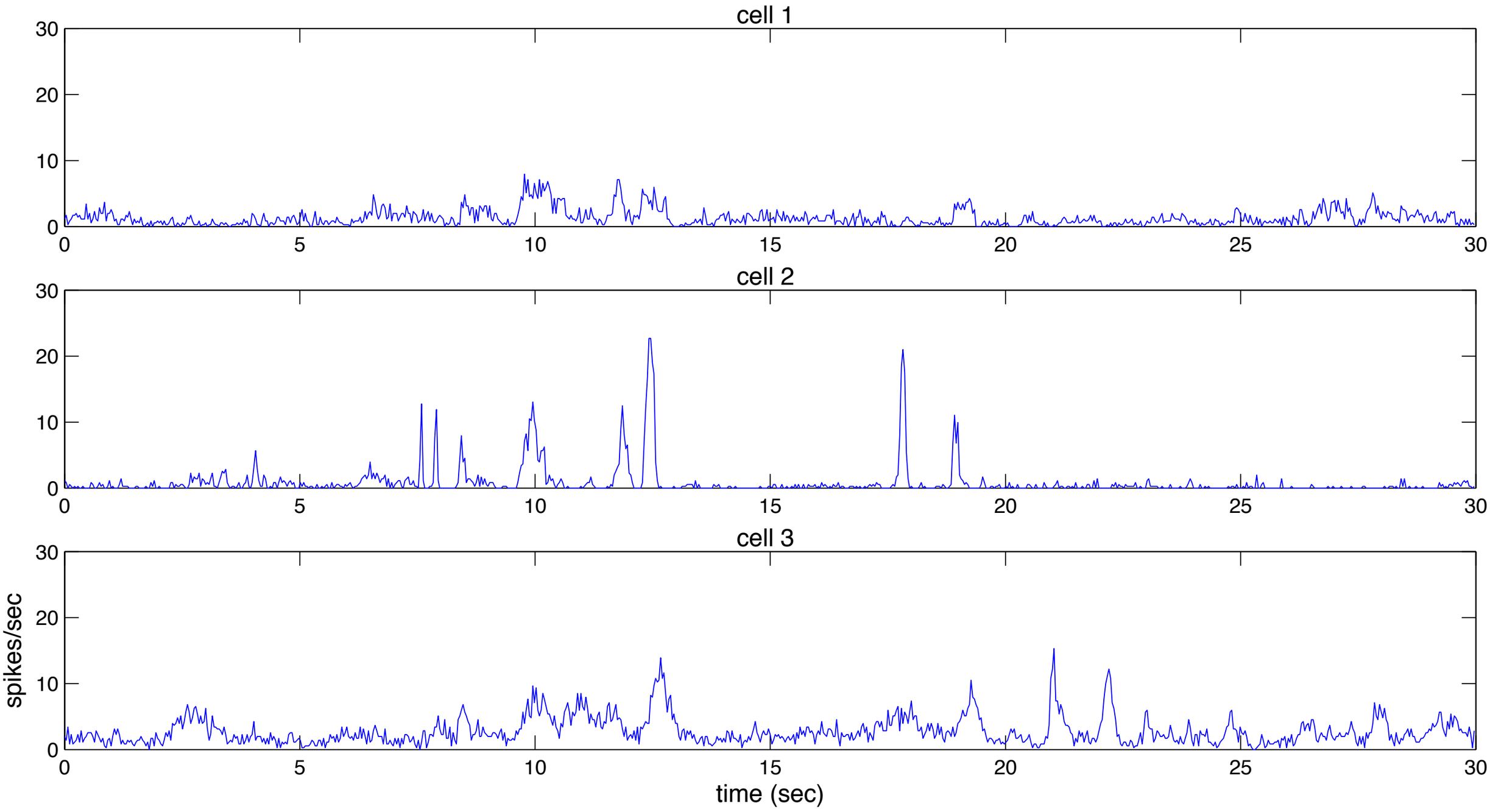
Responses of V1 neurons are not well predicted by RF models

receptive field:

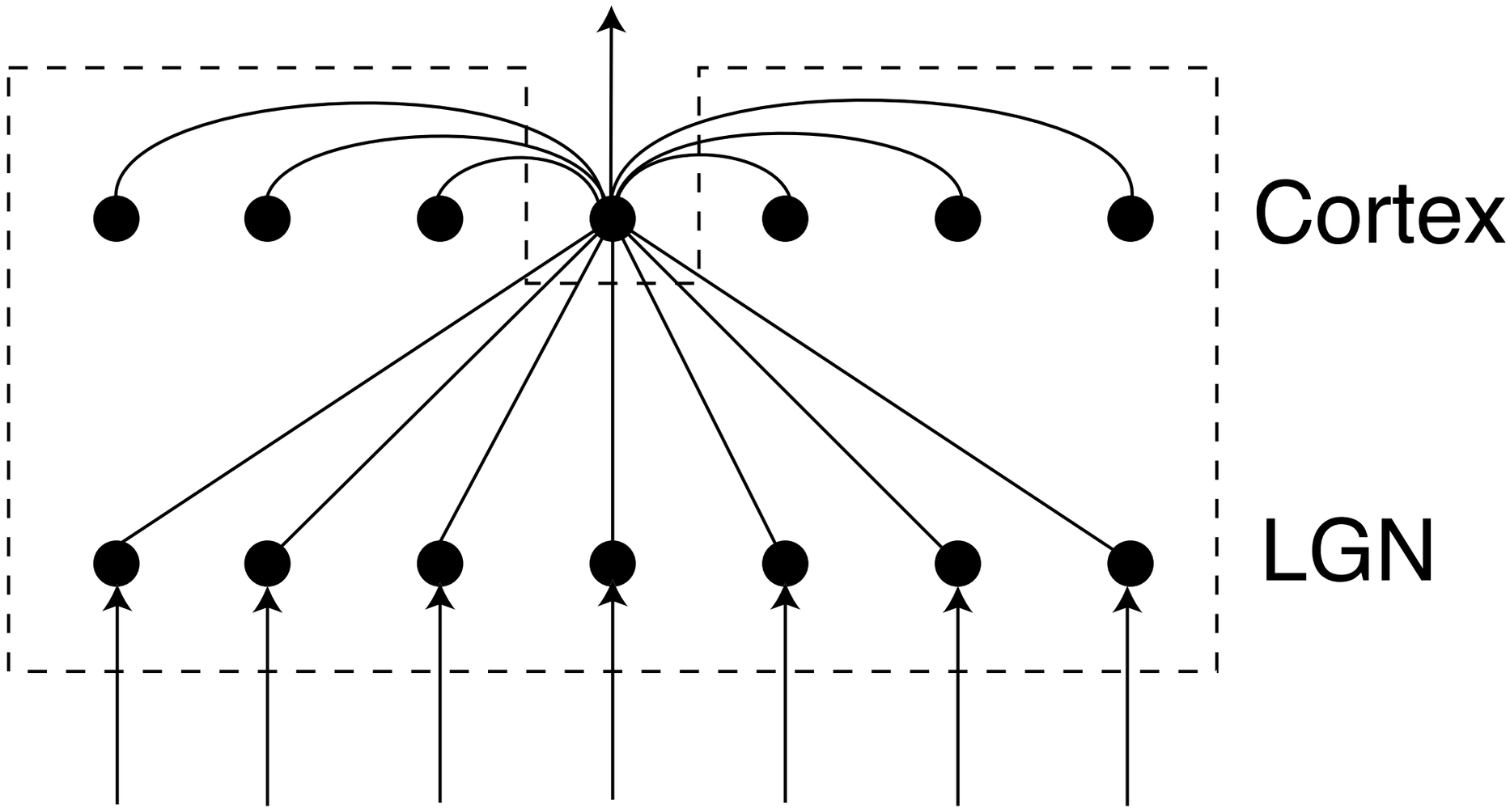




Responses of neighboring cells are heterogeneous

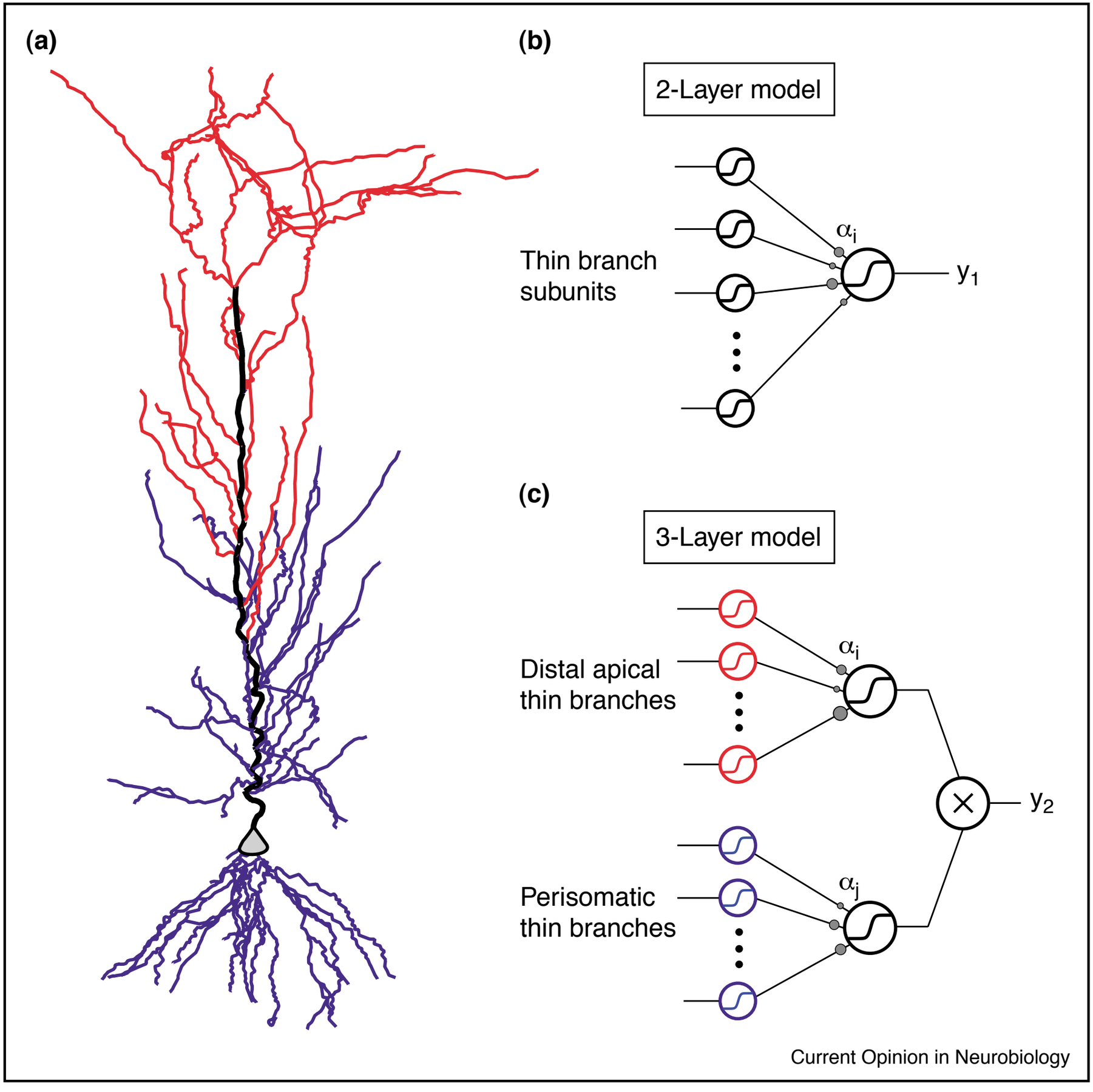


Single unit recording is blind to neuronal interactions



...their (neurons') apparently erratic behavior was caused by our ignorance, not the neuron's incompetence. -- H.B. Barlow (1972)

Hausser & Mel (2003)

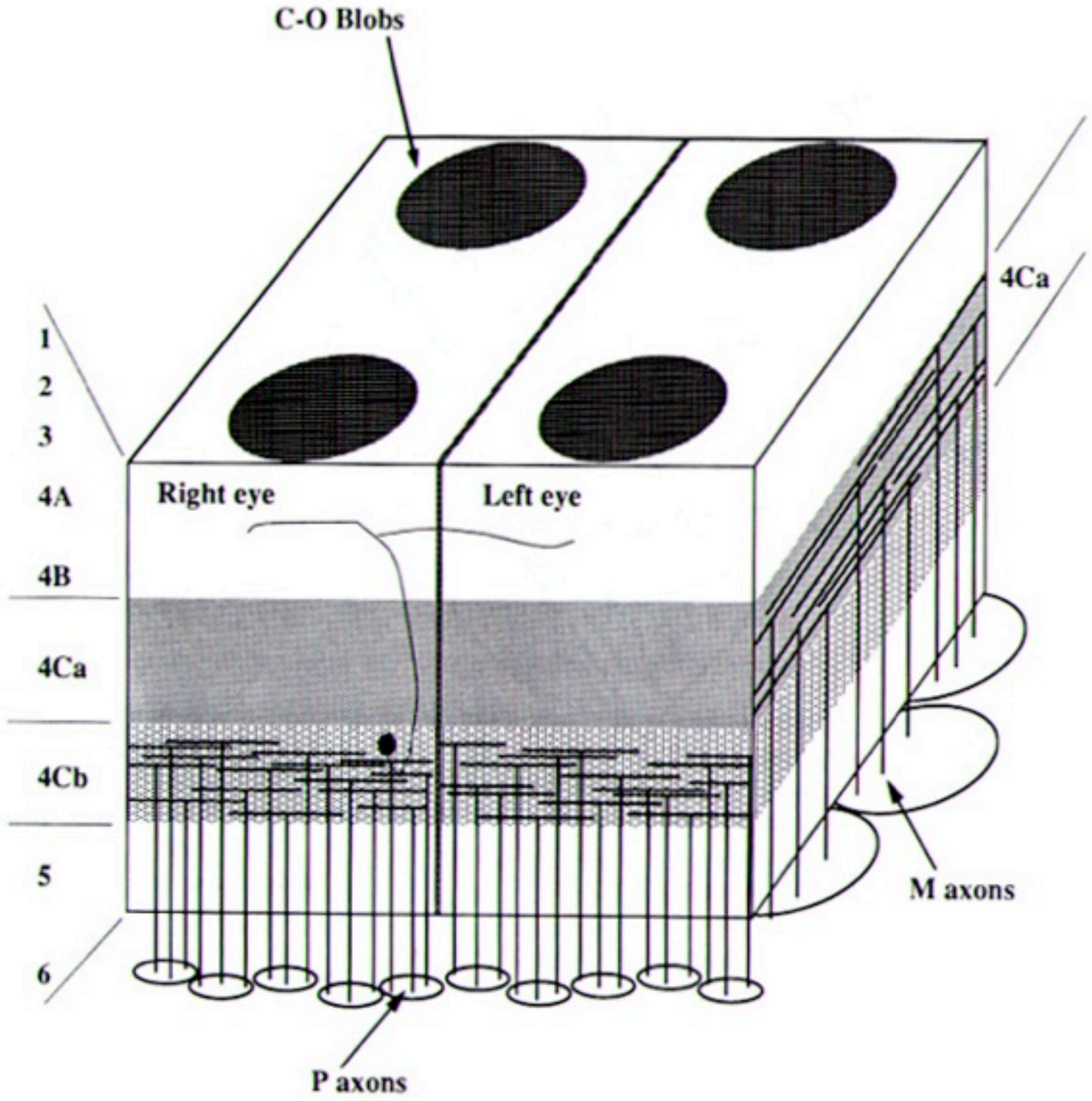


Five problems with the current view of V1

- Biased sampling (single unit recording)
- Biased stimuli (bars, spots, gratings)
- Biased theories (data-driven vs. functional theories)
- Interdependence and context (effect of intra-cortical inputs)
- Ecological deviance

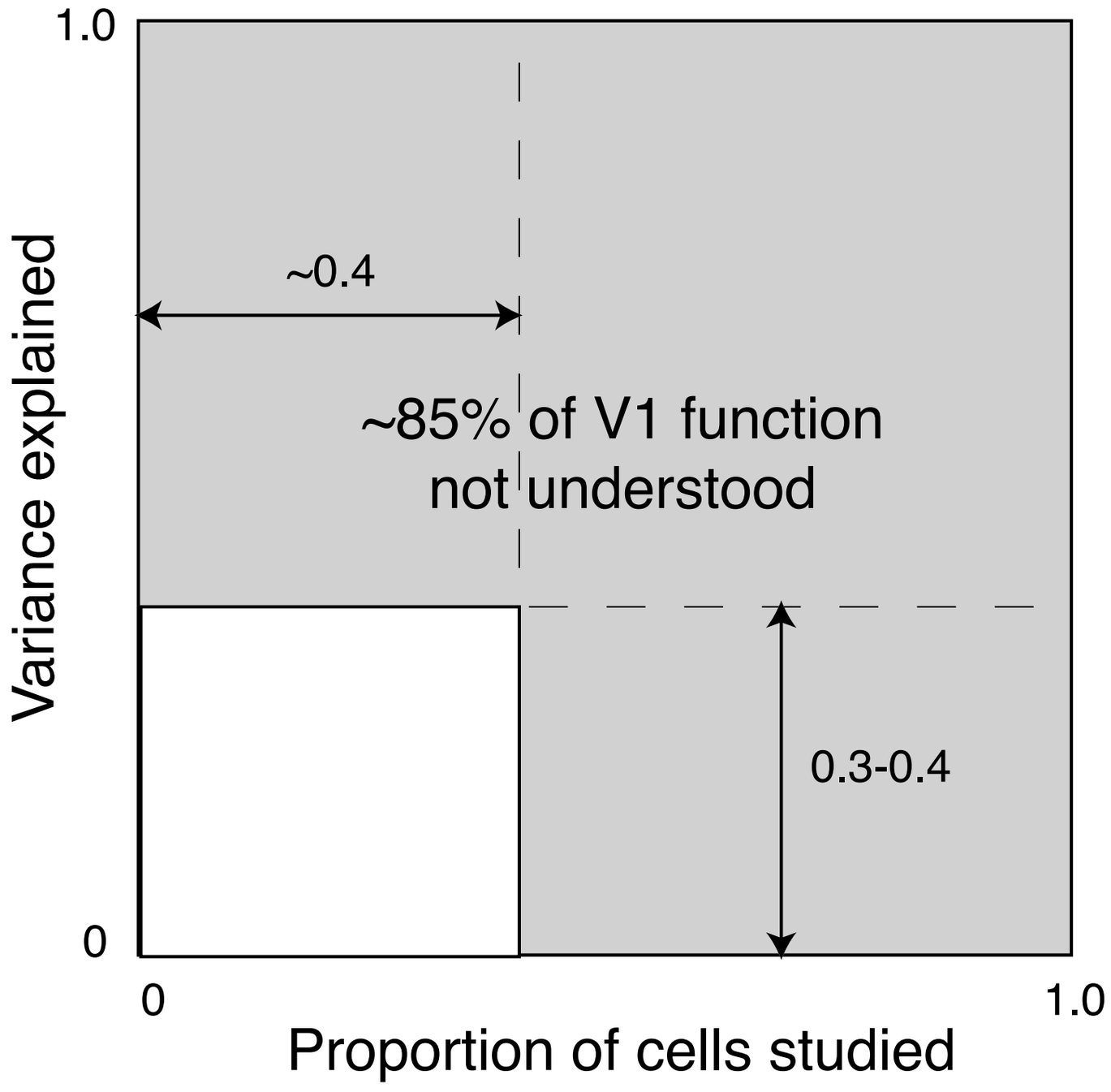
See: Olshausen BA, Field DJ (2005) How close are we to understanding V1? *Neural Computation, 17*, 1665-1699.

1 mm^2 of cortex analyzes ca. 14 x 14 array of retinal sample nodes and contains 100,000 neurons



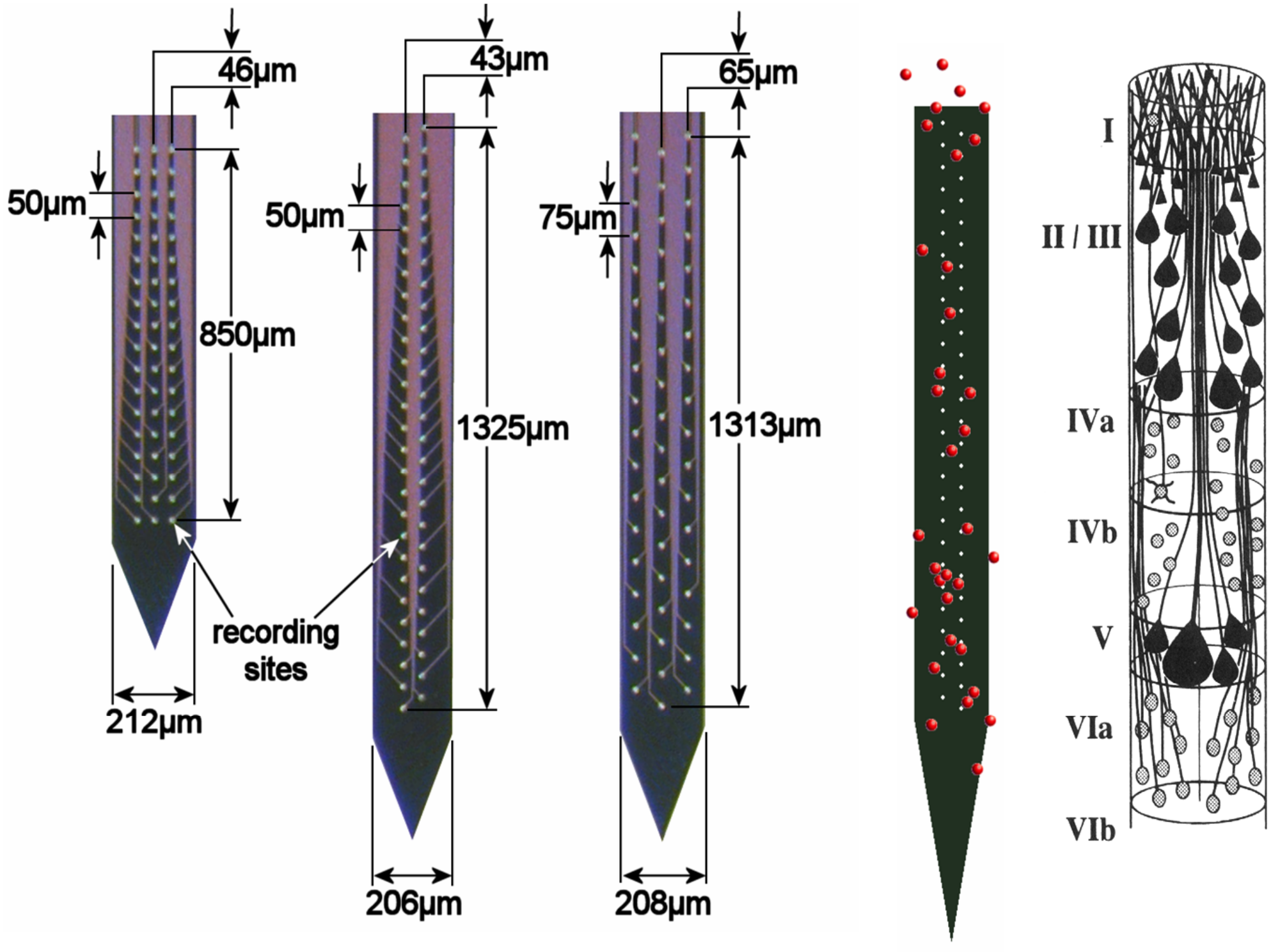
11-5556 World Cup "94" Rose Bowl Pasadena CA
AERO PHOTO INC. 508-295-5551 (c) (E)

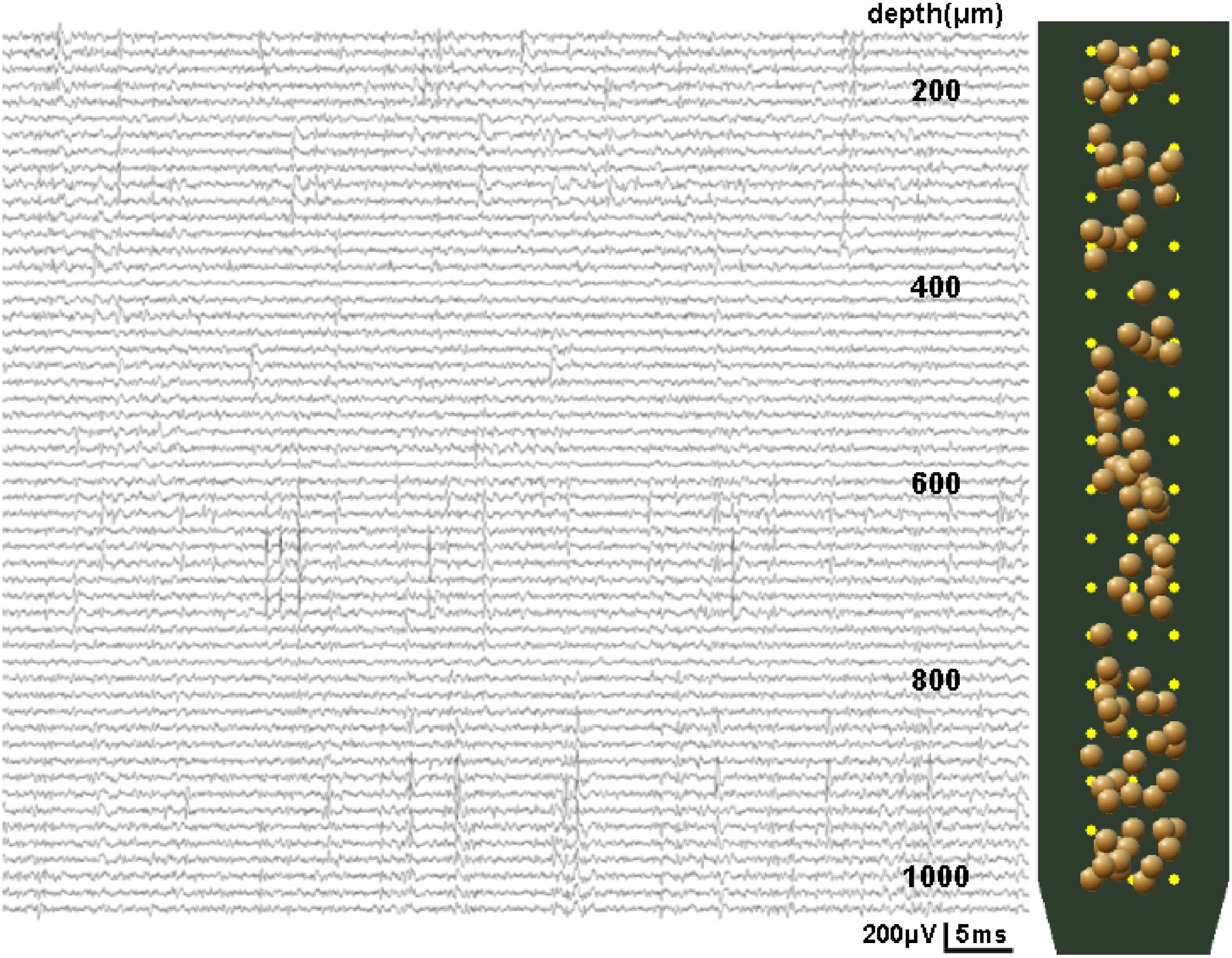
What is the other 85% doing?

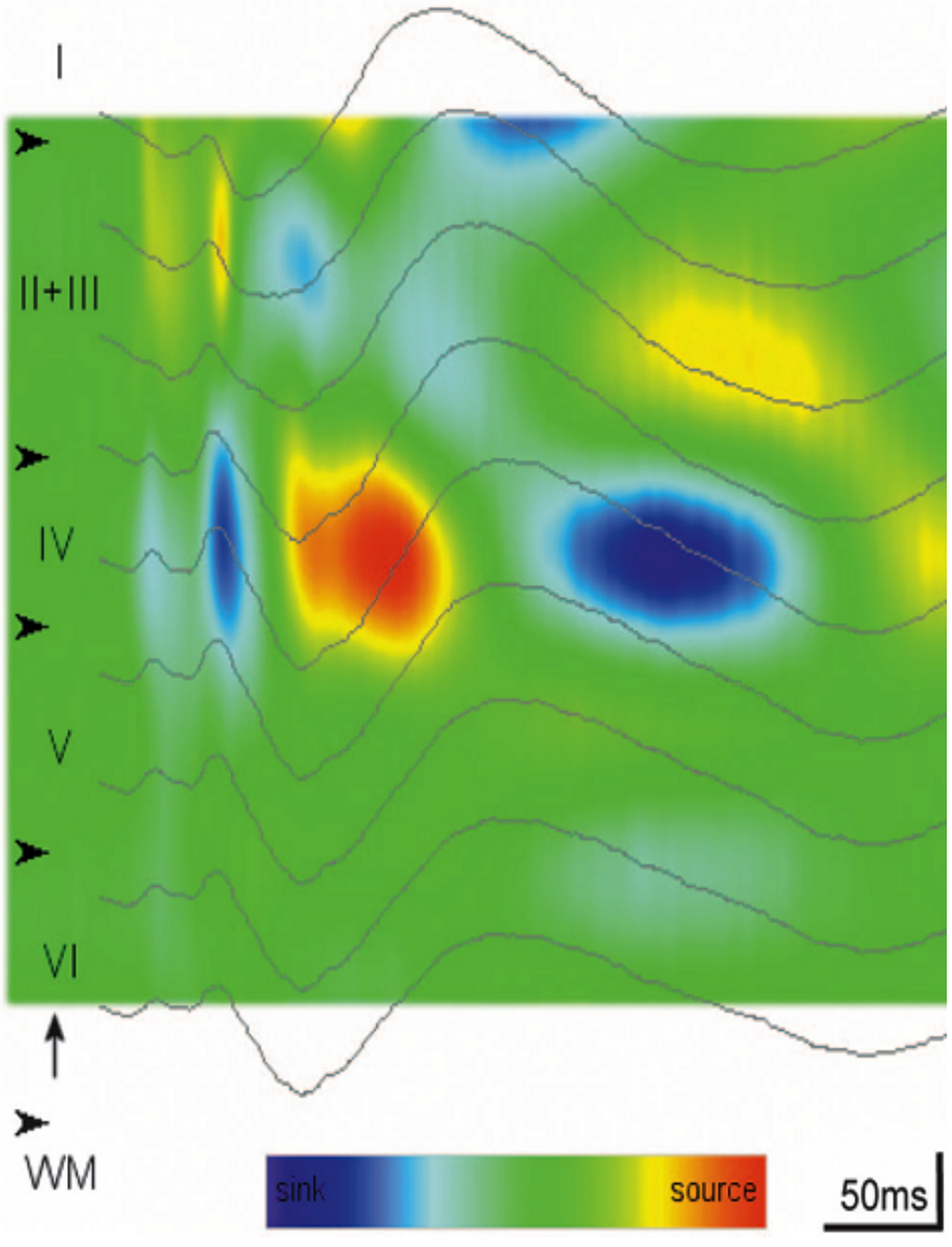


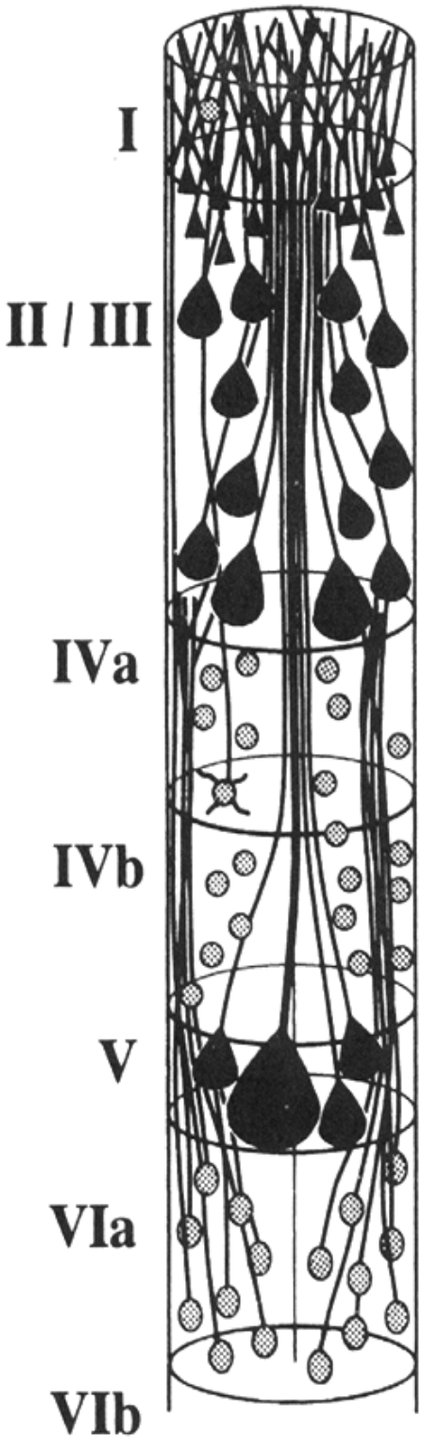
There’s hope.

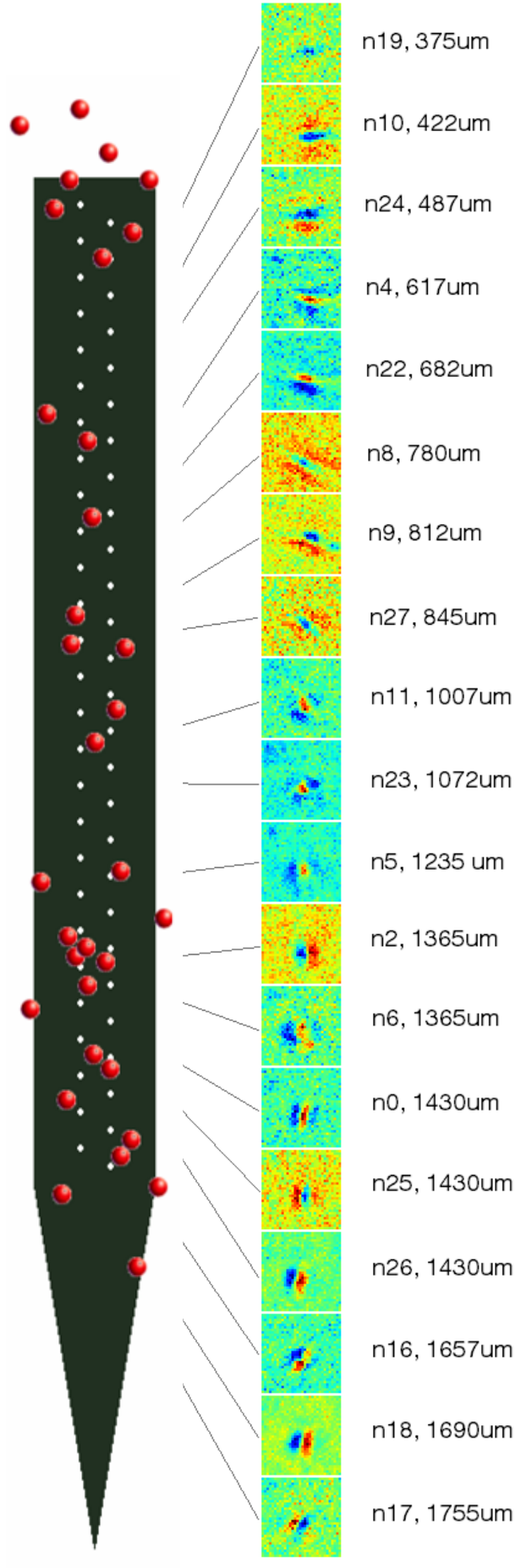
Silicon polytrodes




depth(μm)
200
400
600
800
1000
200μV
5ms


I
II+III
IV
V
VI
WM
sink
source
50ms


I
II / III
IVa
IVb
V
VIa
VIb

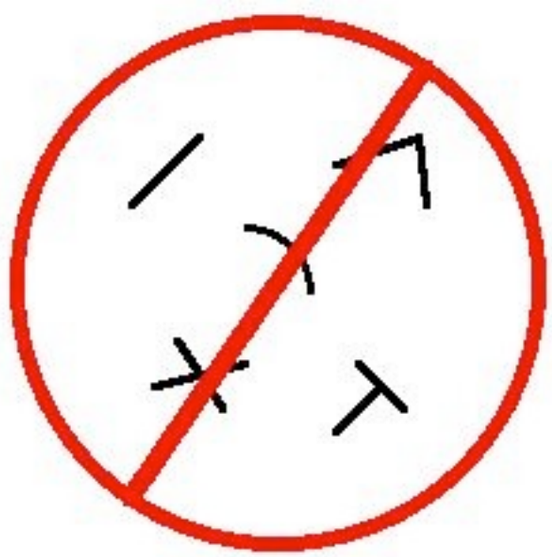

n19, 375um
n10, 422um
n24, 487um
n4, 617um
n22, 682um
n8, 780um
n9, 812um
n27, 845um
n11, 1007um
n23, 1072um
n5, 1235 um
n2, 1365um
n6, 1365um
n0, 1430um
n25, 1430um
n26, 1430um
n16, 1657um
n18, 1690um
n17, 1755um

What should we look for?

Surface perception

Visual representations are 3D, not 2D

Nakayama K, He ZJ, and Shimojo S. (1995) Visual surface representation: a critical link between lower-level and higher level vision. In: S.M. Kosslyn and D.N. Osherson, Eds, *An Invitation to Cognitive Science*. MIT Press, pp. 1-70.



Images vs. surfaces

One of the most striking things about our visual experience is how dramatically it differs from our retinal image.

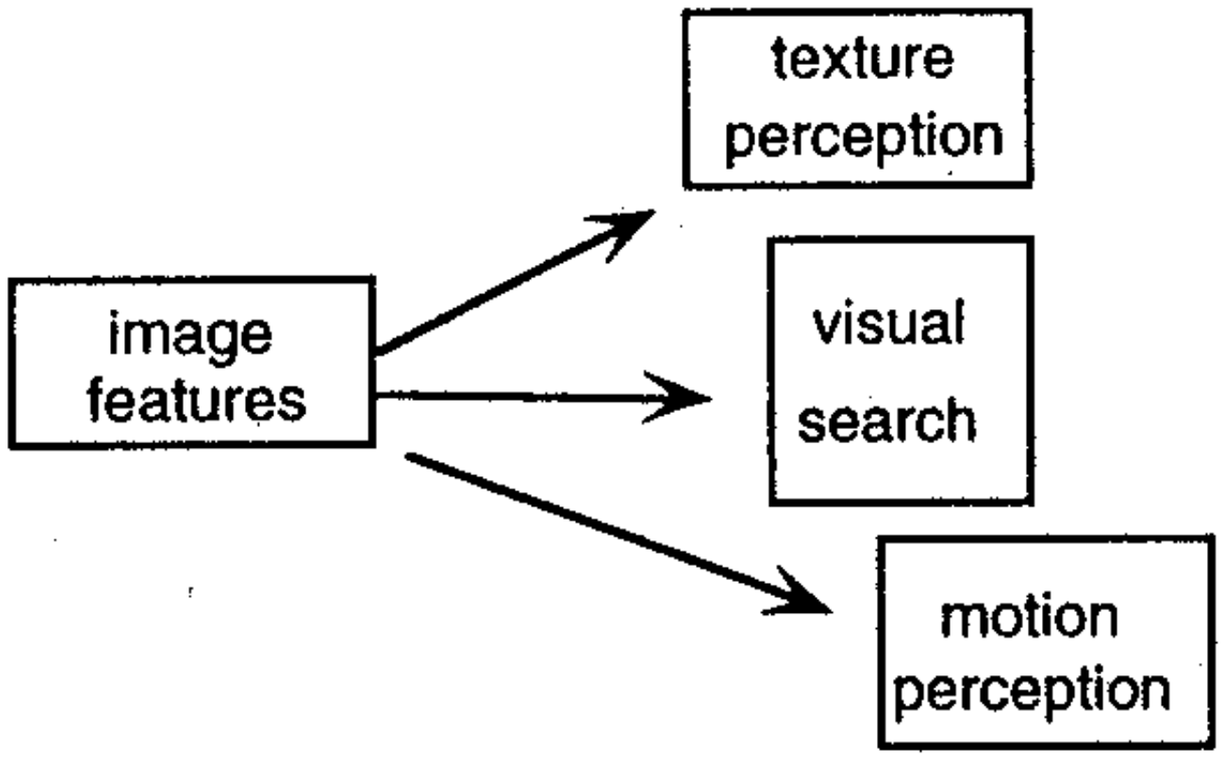
...

Our perception is closely tied to surfaces and objects in the real world; it does not seem tightly tied to our retinal images.

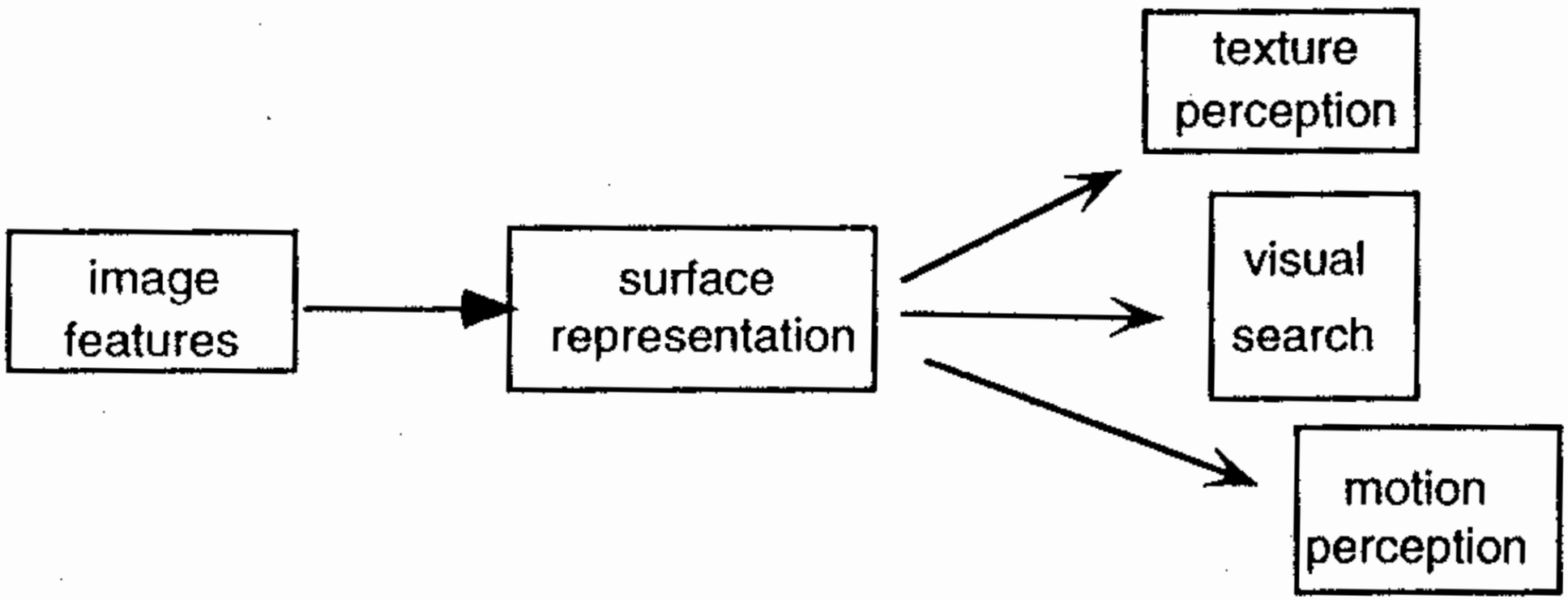
...

Our view is that higher functions require, as an input, a data format that explicitly represents the world as a set of surfaces.

The traditional view of visual processing



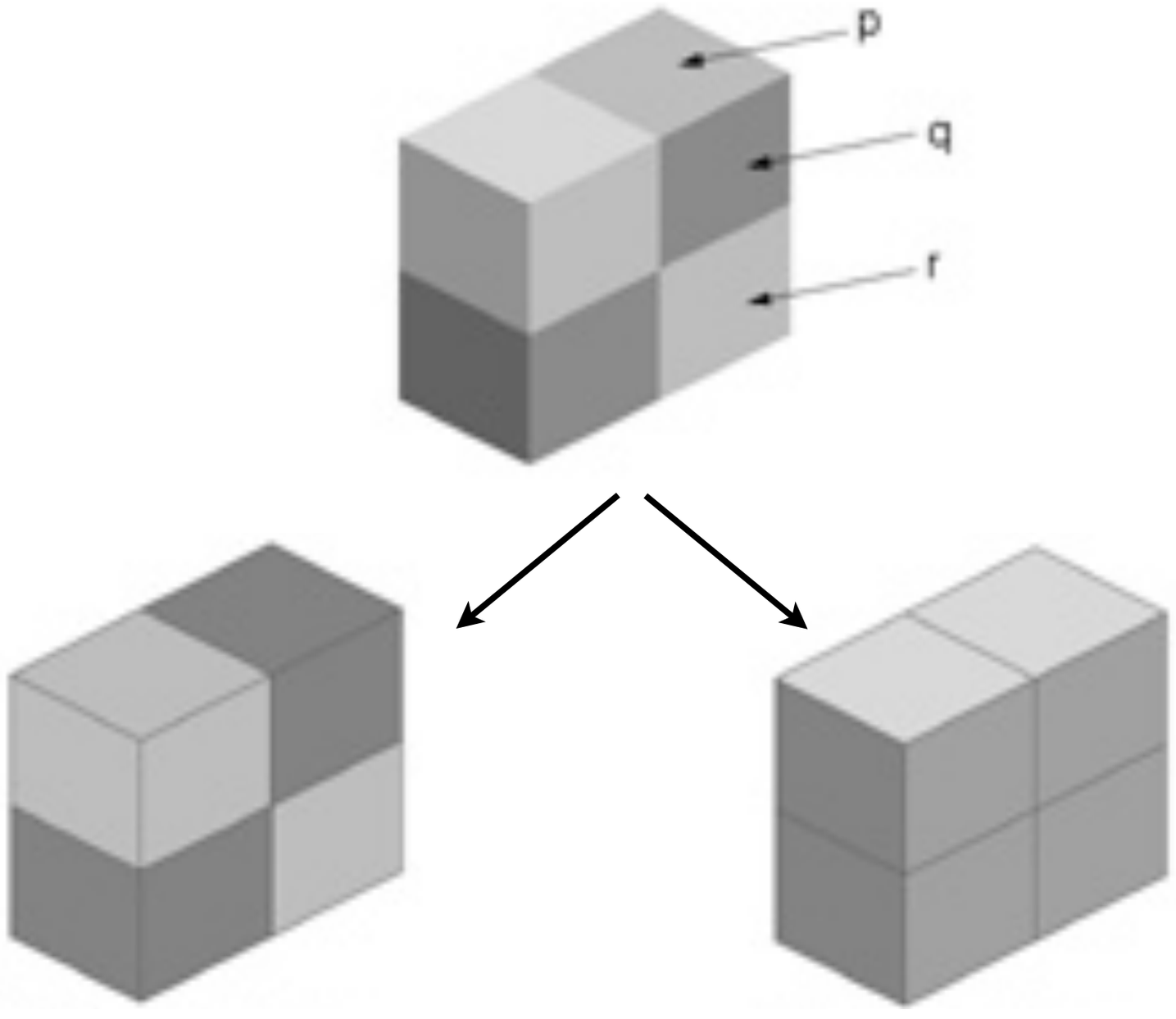
The new view of visual processing



How do you interpret an edge?

How do you interpret an edge?

An edge can mean different things



Object recognition depends on scene context

Object recognition depends on scene context

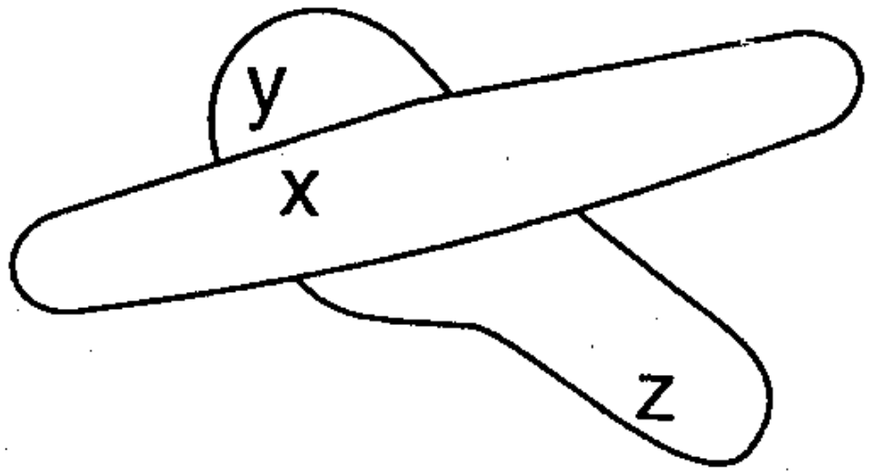
Object recognition depends on scene context

Rules of occlusion

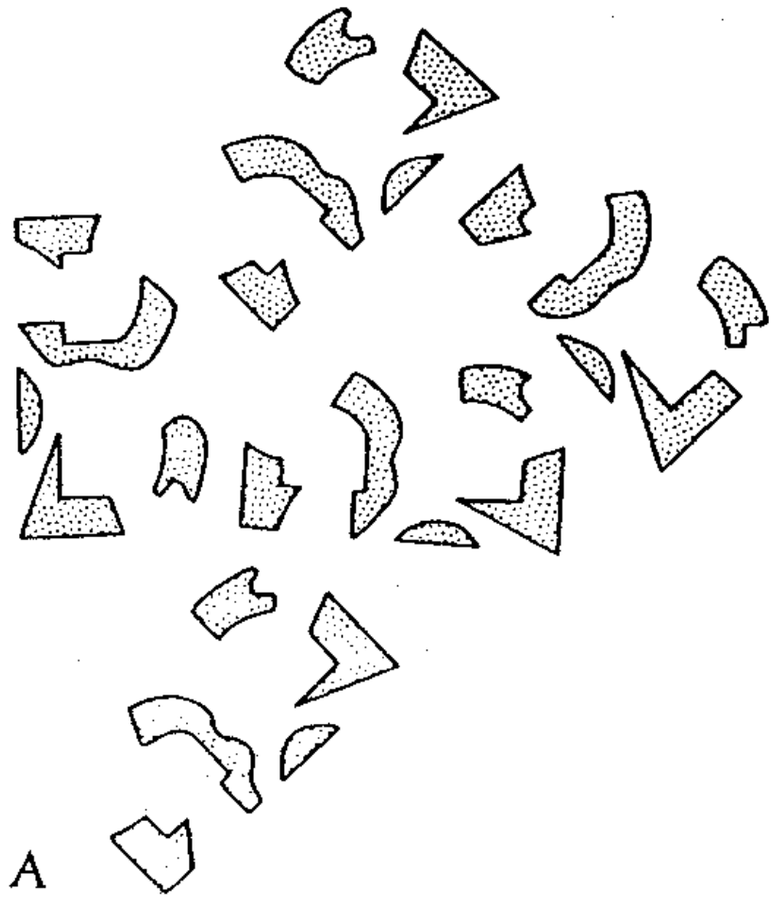
• When image regions corresponding to different surfaces meet, only one region can "own" the border between them.

• Under conditions of surface opacity, a border is owned by the region that is coded as being in front.

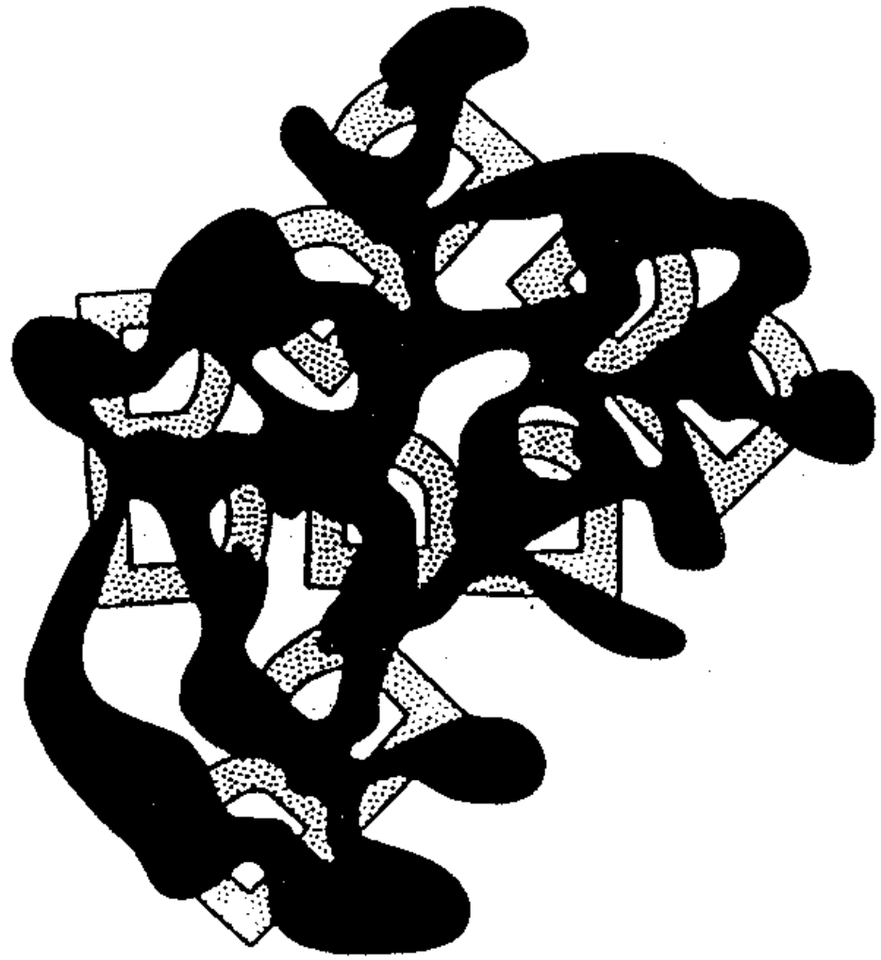
• A region that does not own a border is effectively unbounded. Unbounded regions can connect to other unbounded regions to form larger surfaces completing behind.



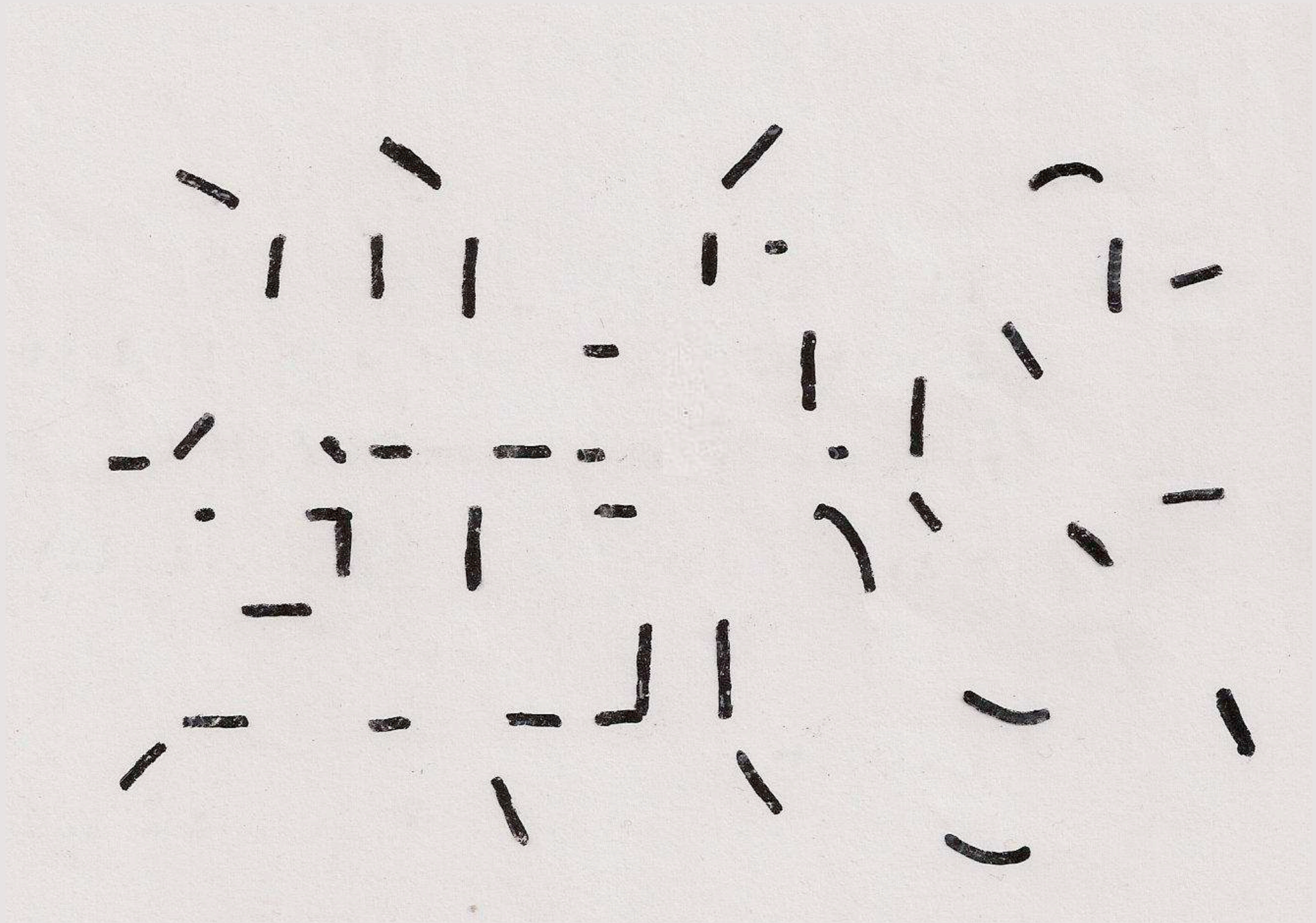
Bregman B's

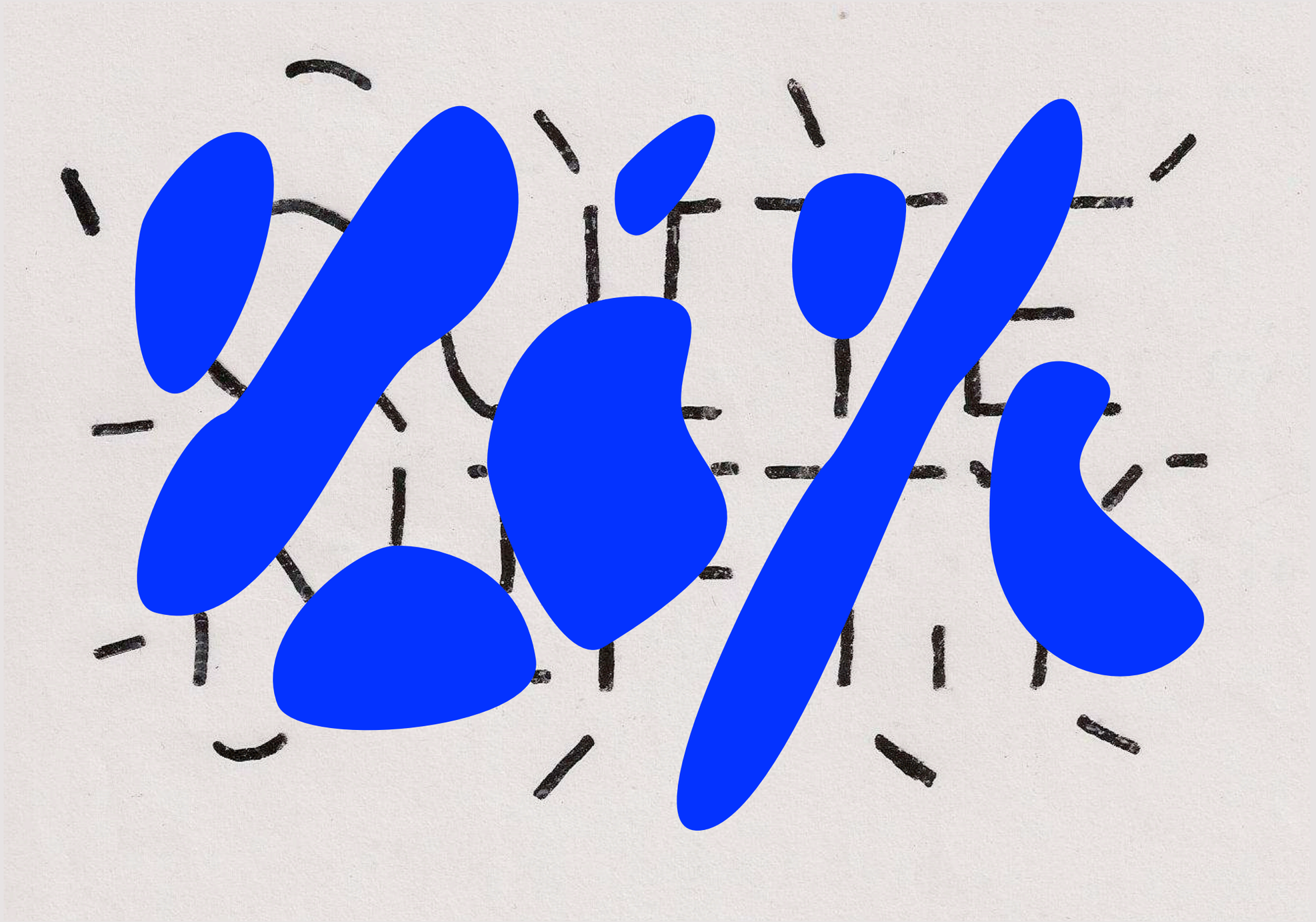


A



B





Do oriented filters make it any easier to resolve figure-ground?

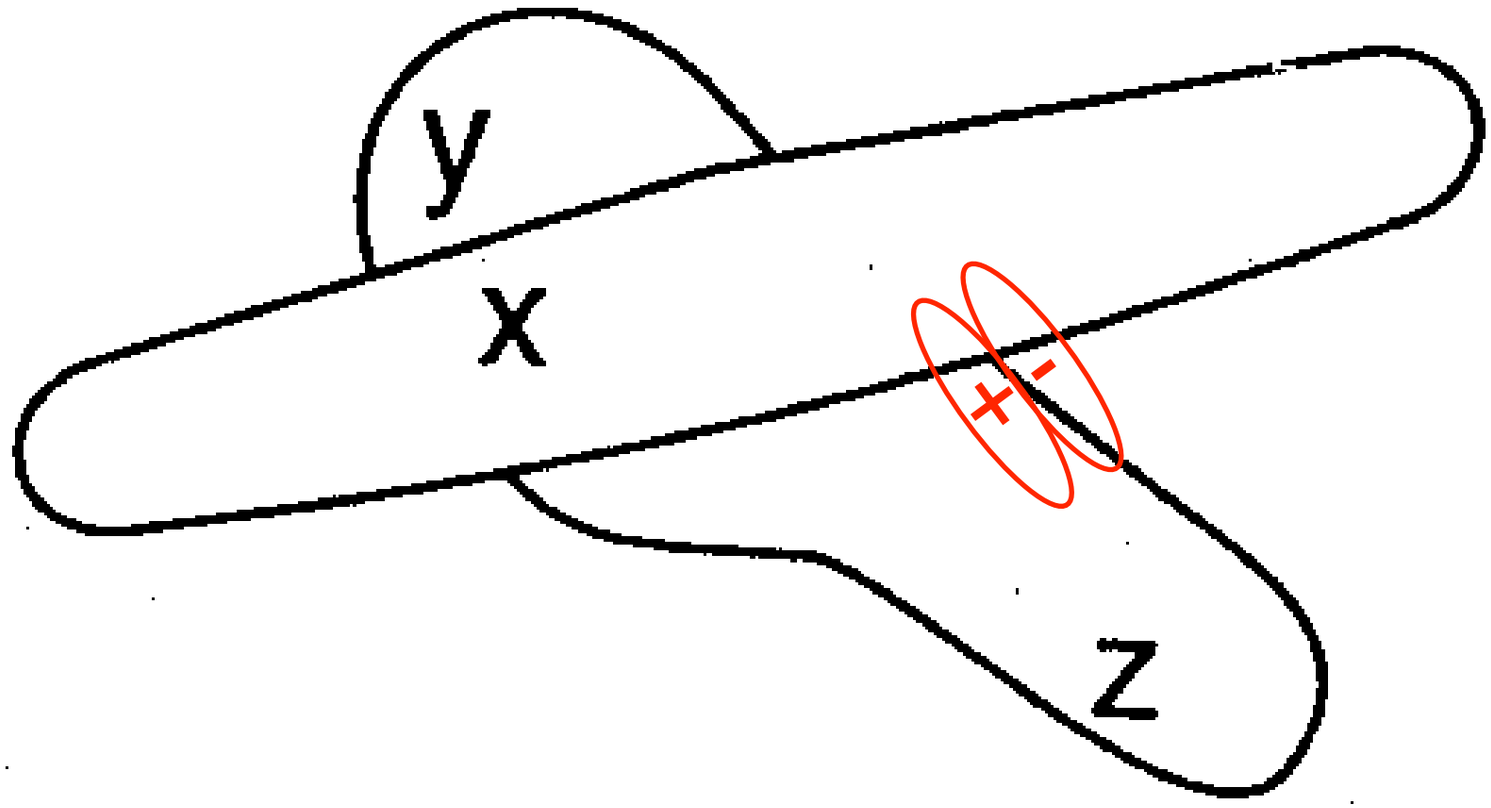
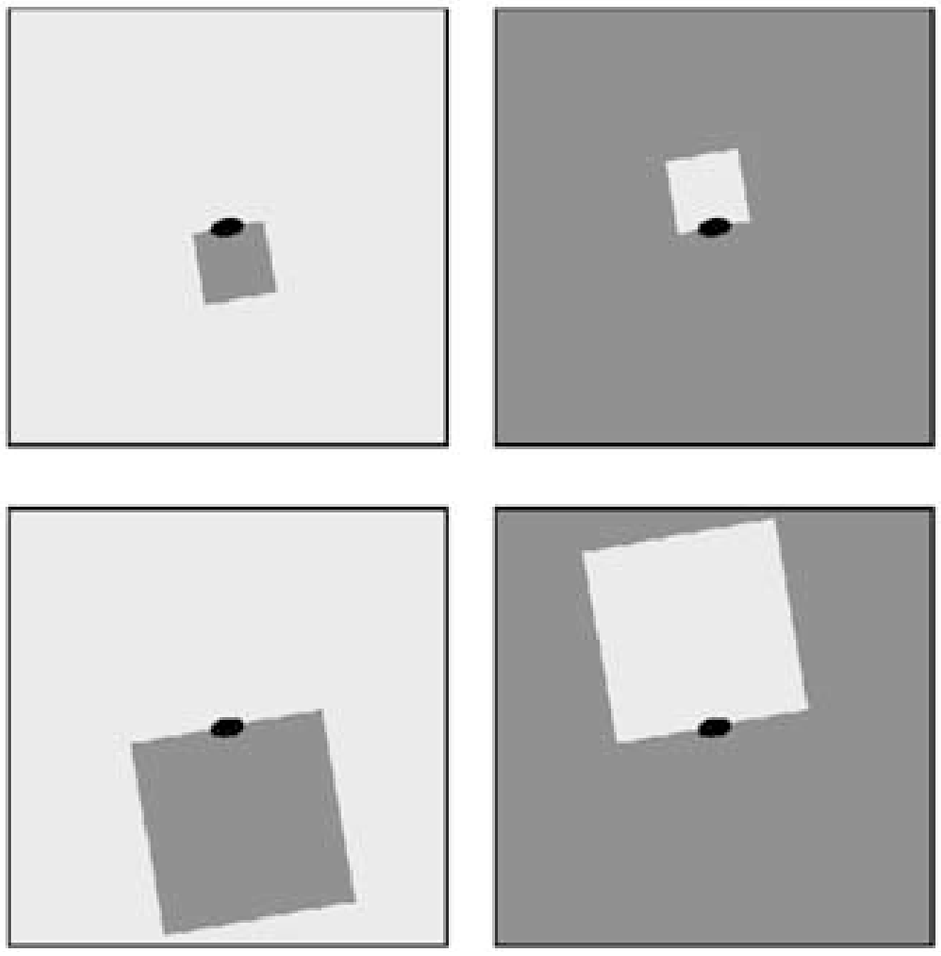
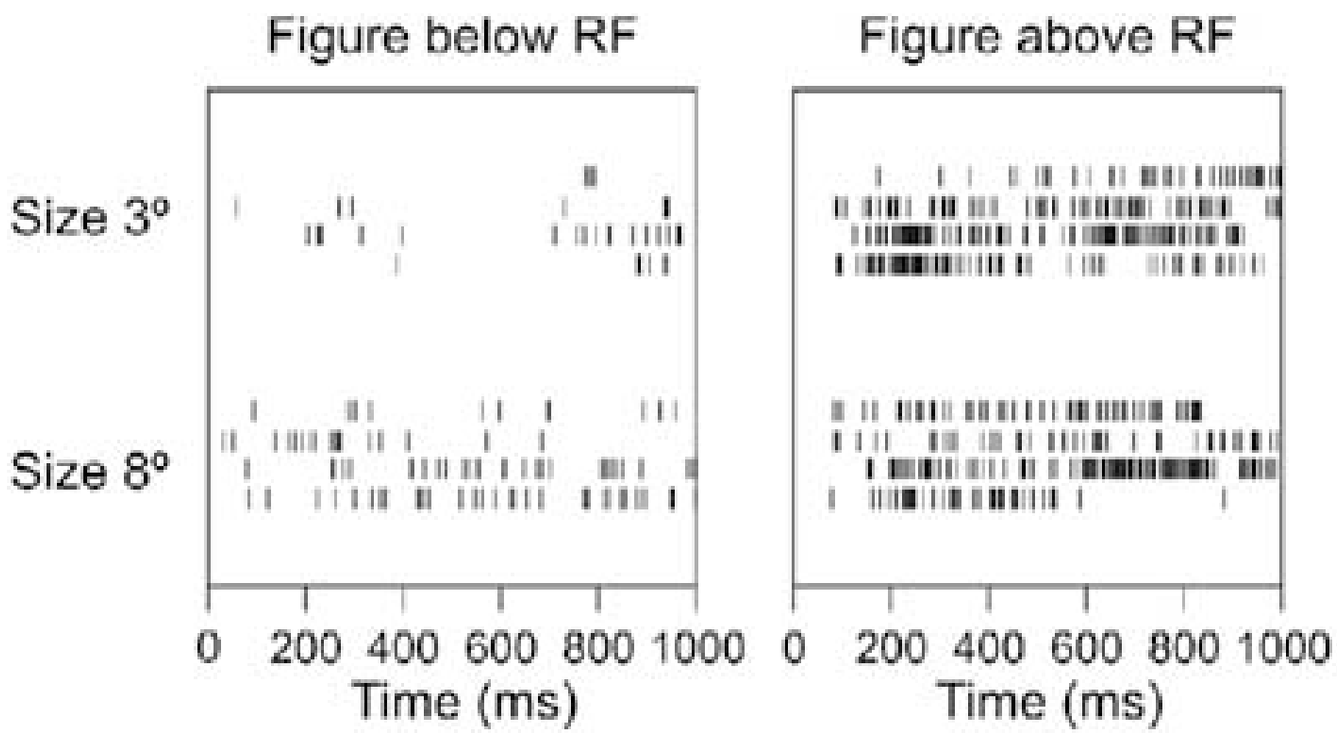


image segmentation ≠ figure-ground

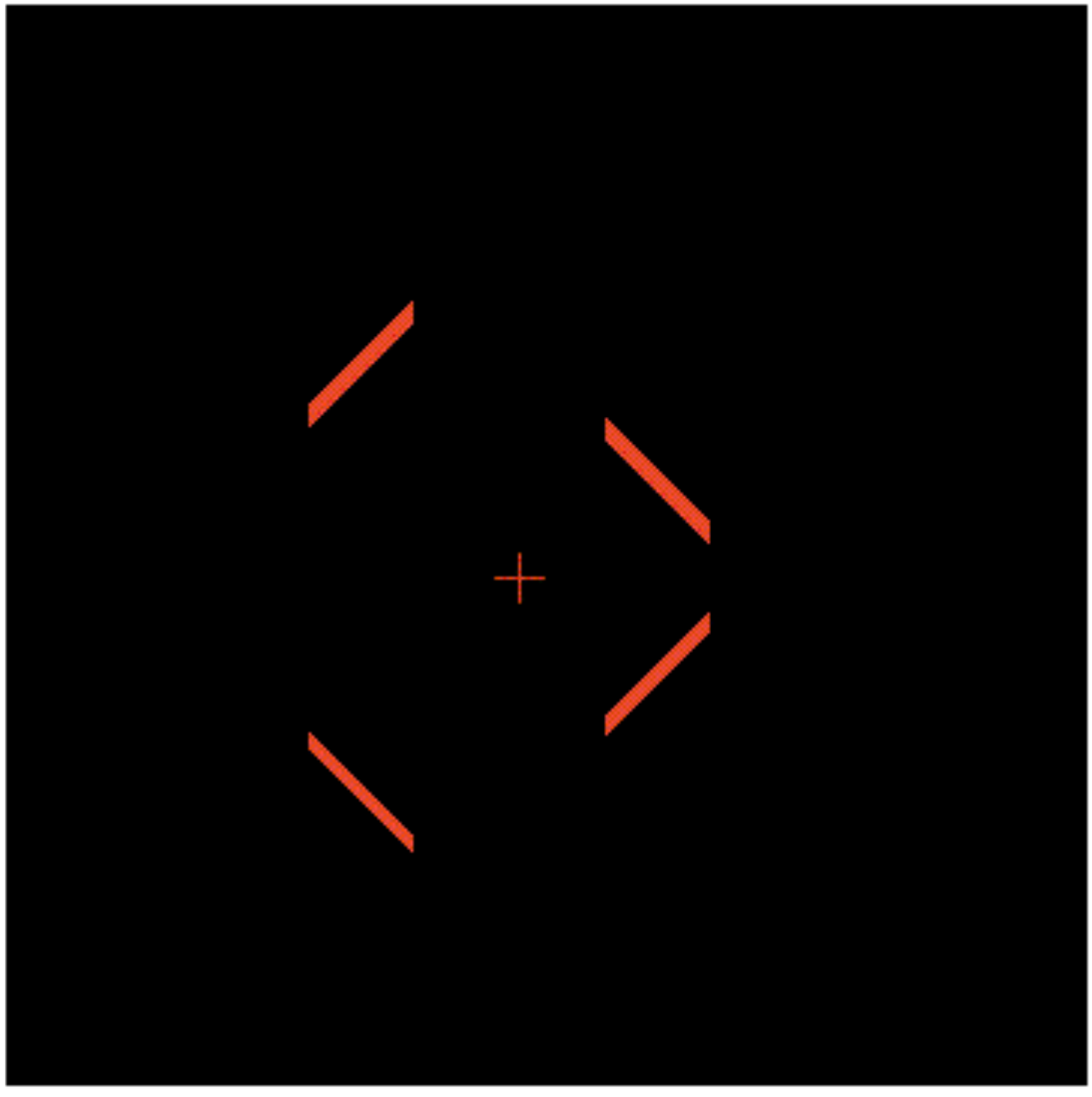
Neurons in V2 (and even some in V1) code for border ownership as well as orientation





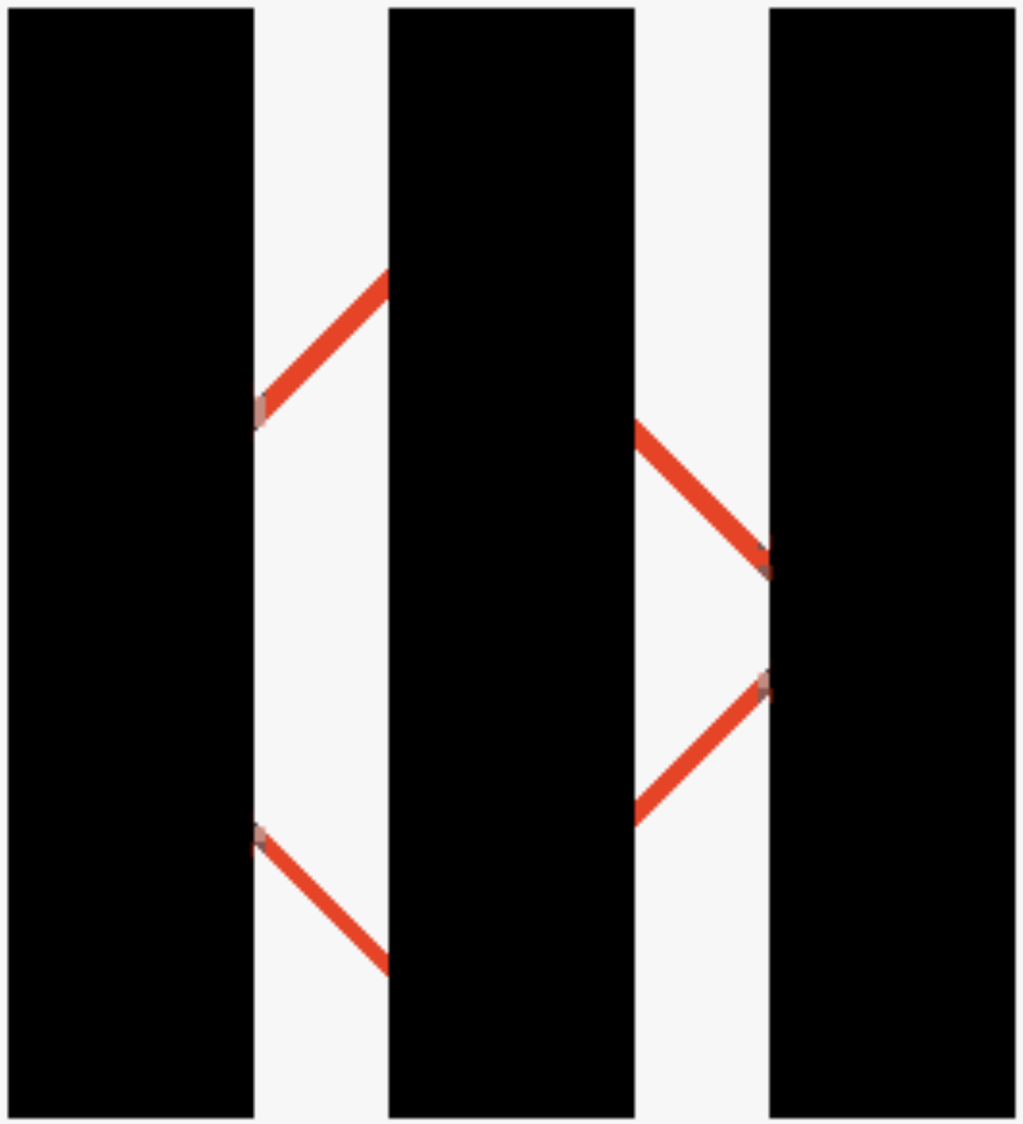
What do you see?

How do neurons in V1 encode this?

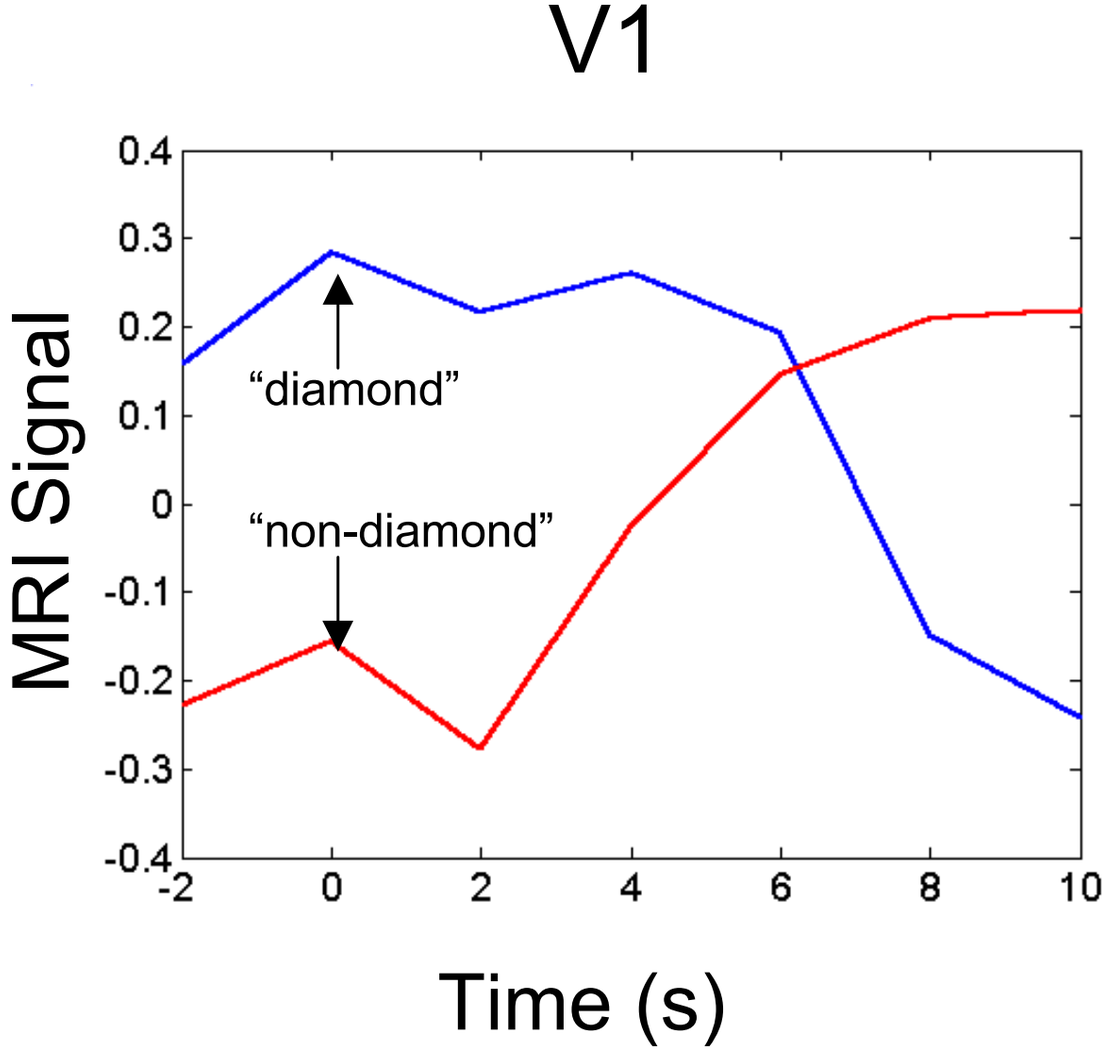


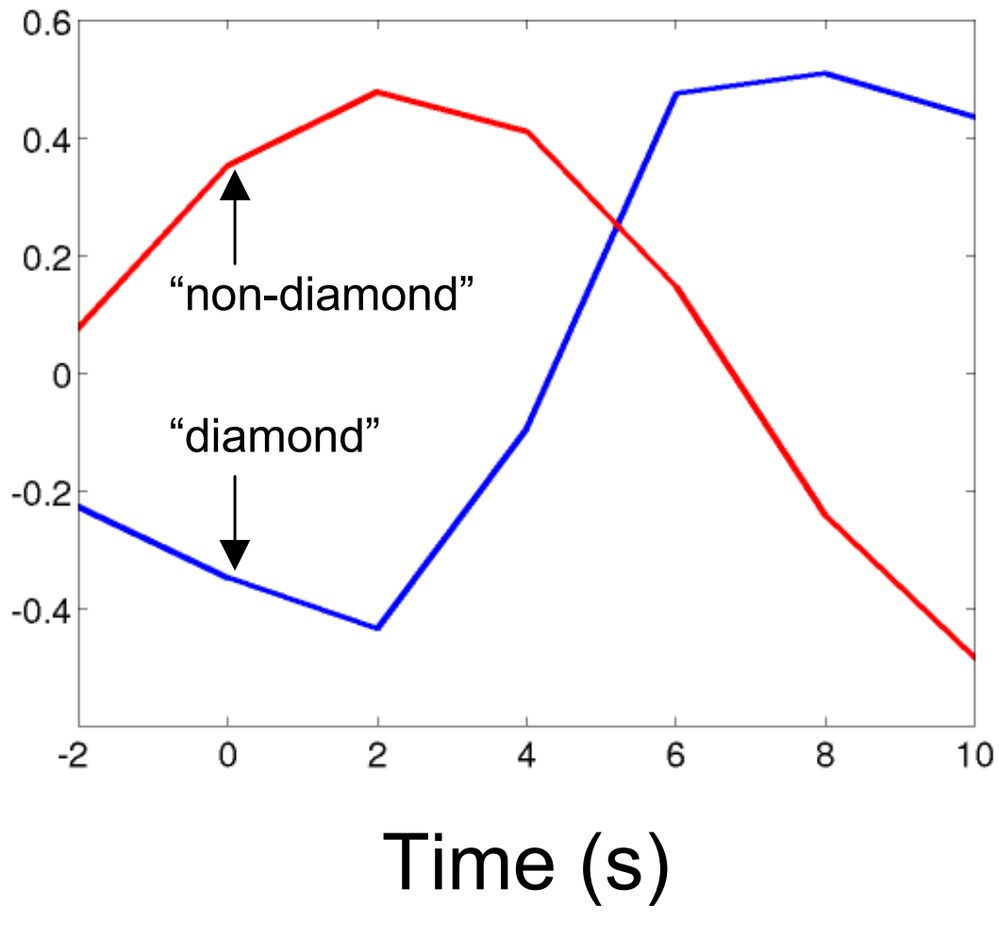
Murray, Kersten, Schrater, Olshausen, Woods, *PNAS* 2002.

(easy version)



BOLD signal in V1 and LOC





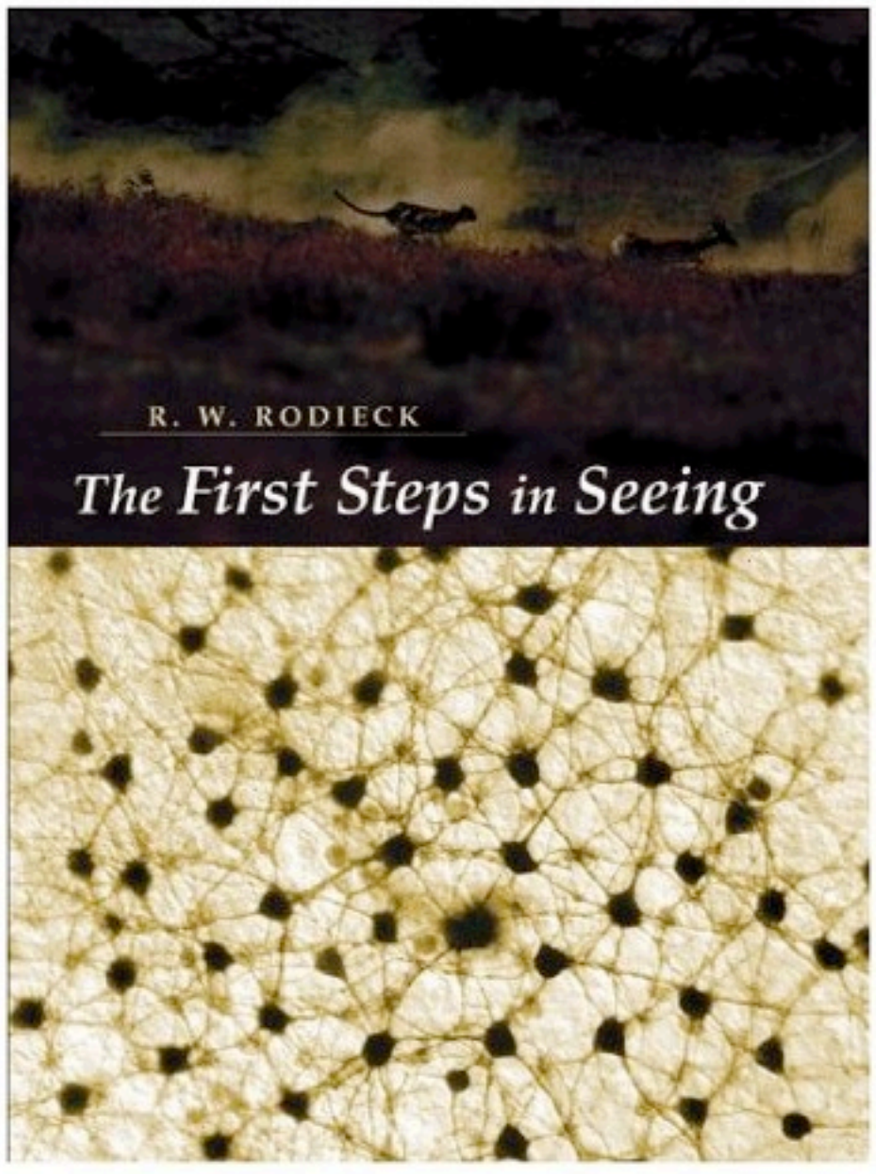
Open questions

- How do visual neurons respond to object borders vs. reflectance changes in natural images?

- How is border ownership computed? How do neurons encoding border ownership interact?

- Is amodal completion represented implicitly or explicitly?

Further information



Van Essen DC, Anderson CH (1995) Information Processing Strategies and Pathways in the Primate Visual System In: *An Introduction to Neural and Electronic Networks*, 2nd ed., Academic Press, Zornetzer et al., eds., pp. 45-76

Olshausen BA, Field DJ (2005) How close are we to understanding V1? *Neural Computation, 17*, 1665-1699.