

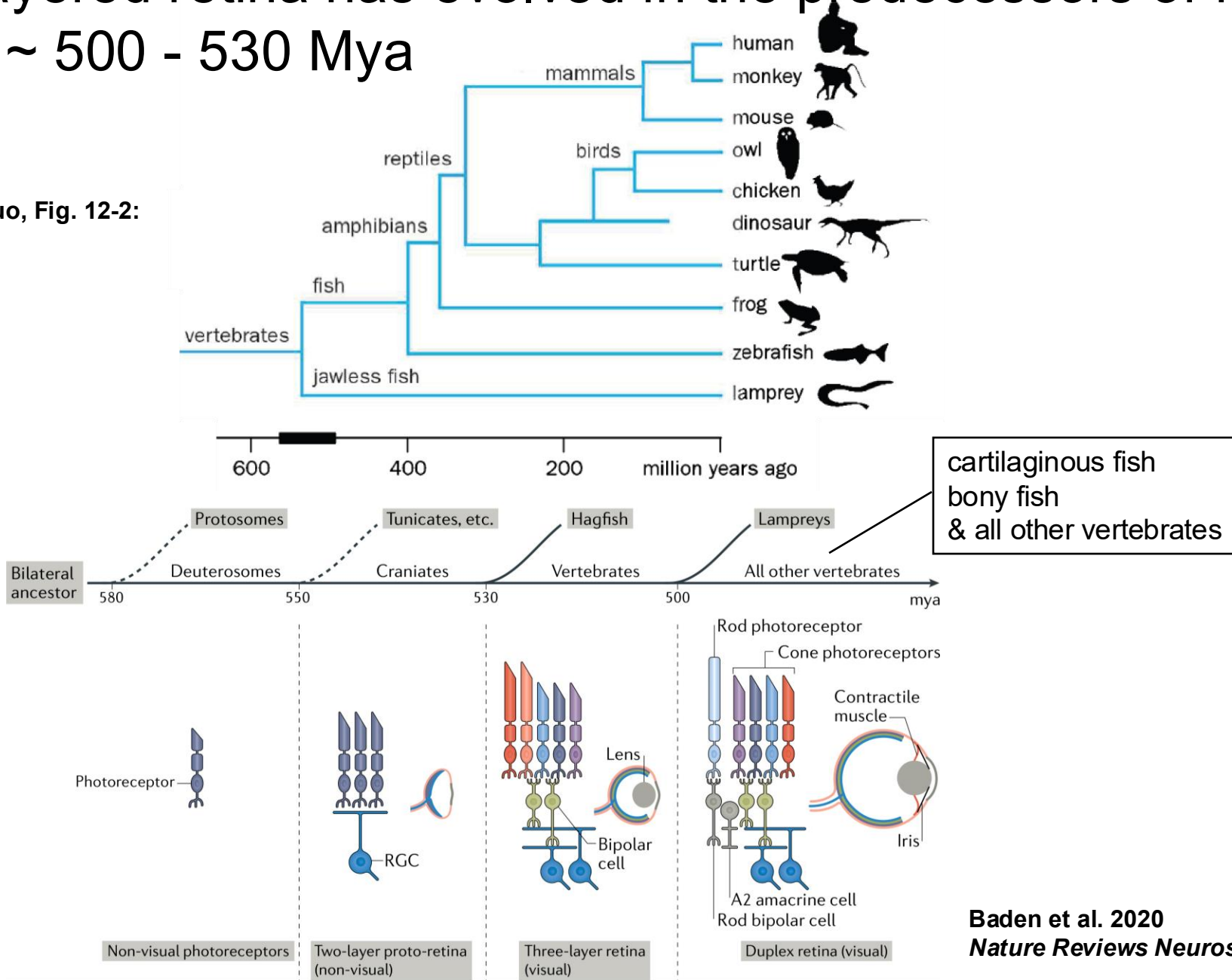


Vision part 2 - system & circuits

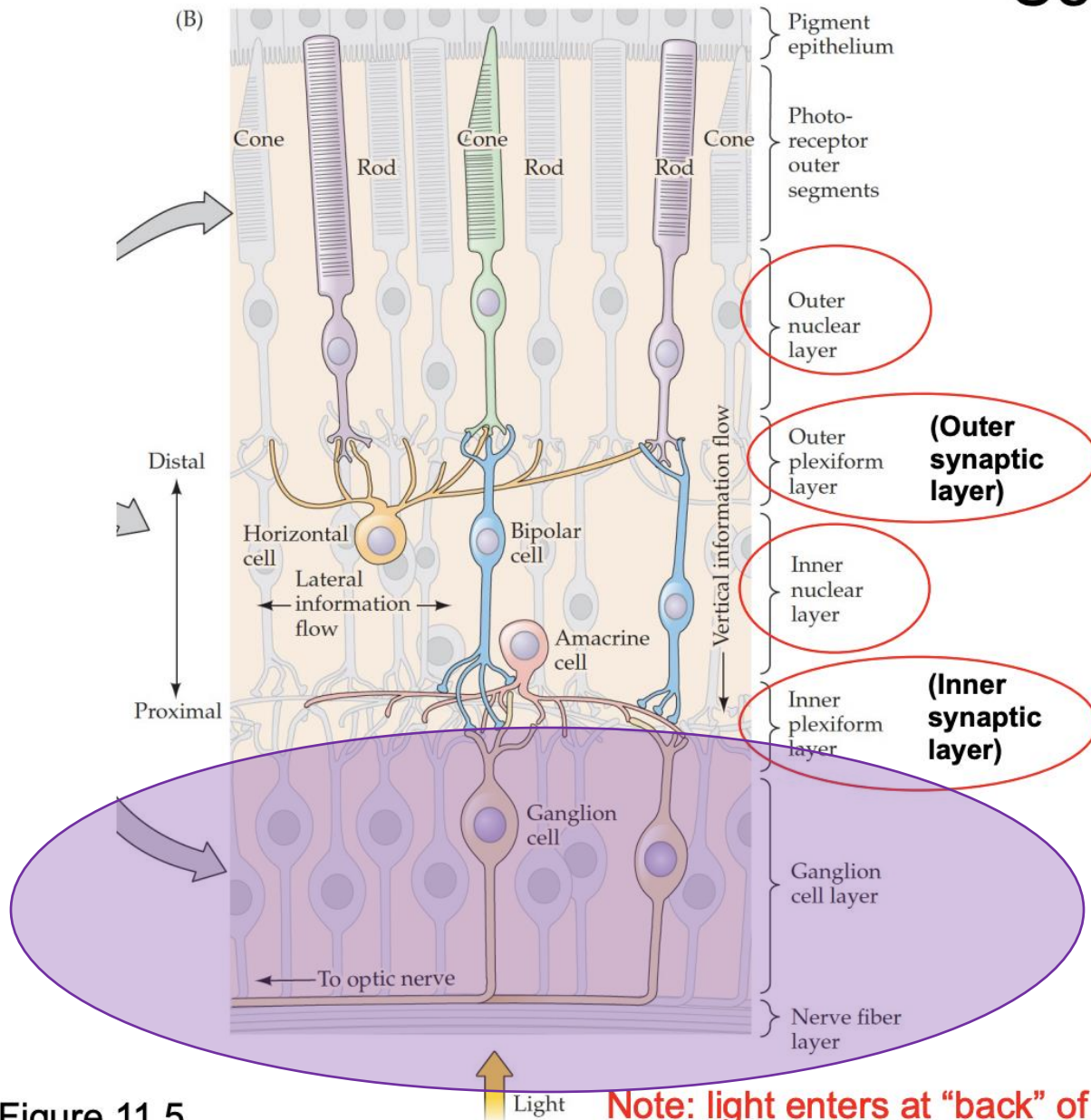
Mackenzie Mathis, PhD

The three-layered retina has evolved in the predecessors of fish & all other vertebrates ~ 500 - 530 Mya

Luo, Fig. 12-2:



Cell-specific layers in the retina



5 classes of neurons:

Photoreceptors

Bipolar cells

Ganglion cells

Horizontal cells

Amacrine cells

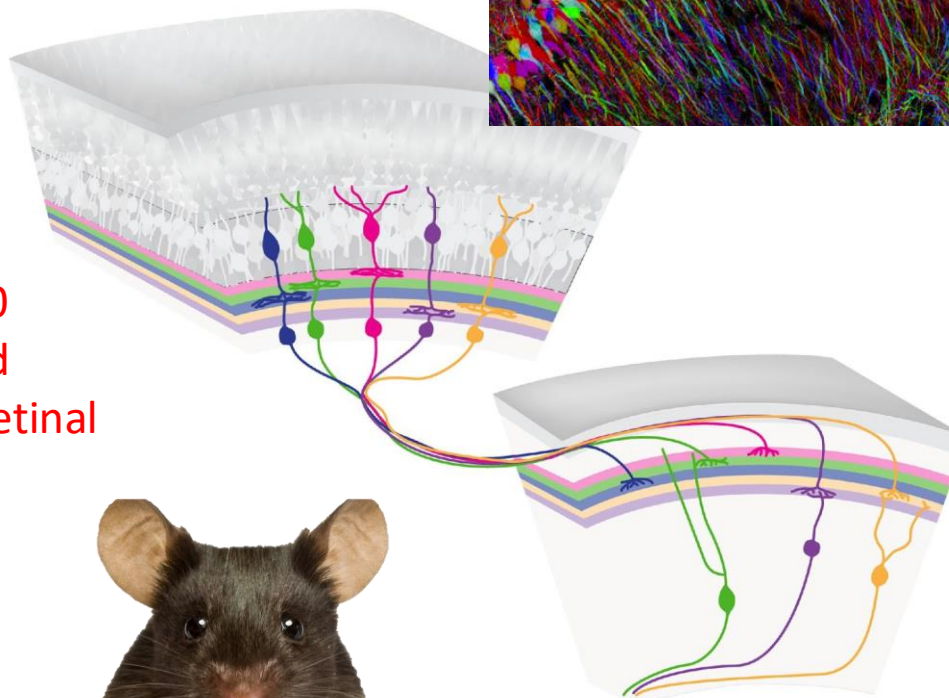
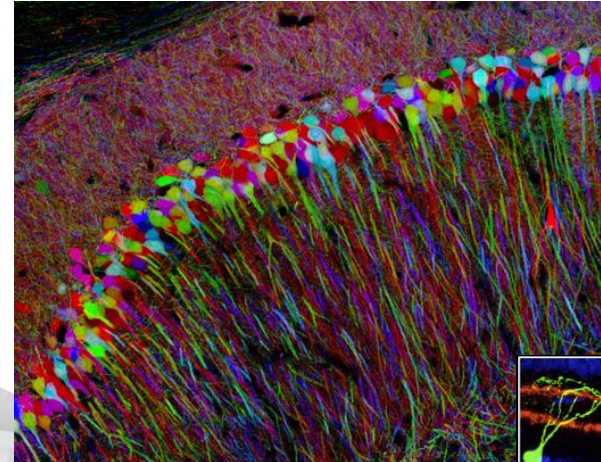
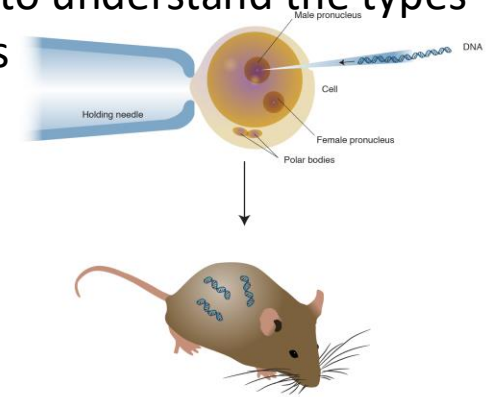
Purves, Figure 11.5

Note: light enters at "back" of pathway to enable photoreceptor-pigment ep. contact

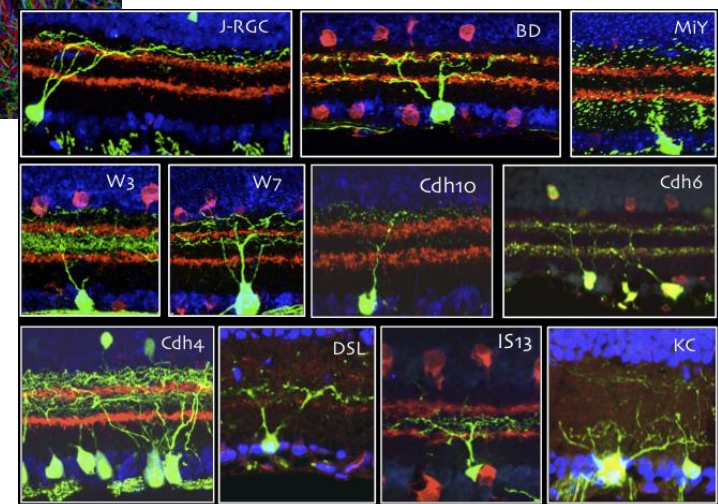
Functionally Distinct Types of Retinal Ganglion Cells

Reading the text on this page requires a high-resolution sampling of the retinal image, whereas regulating circadian rhythms and adjusting the pupil accordingly require only a measure of the overall changes in light levels, and little or no information about the features of the image.

Transgenic mice have been critical to understand the types of RGCs

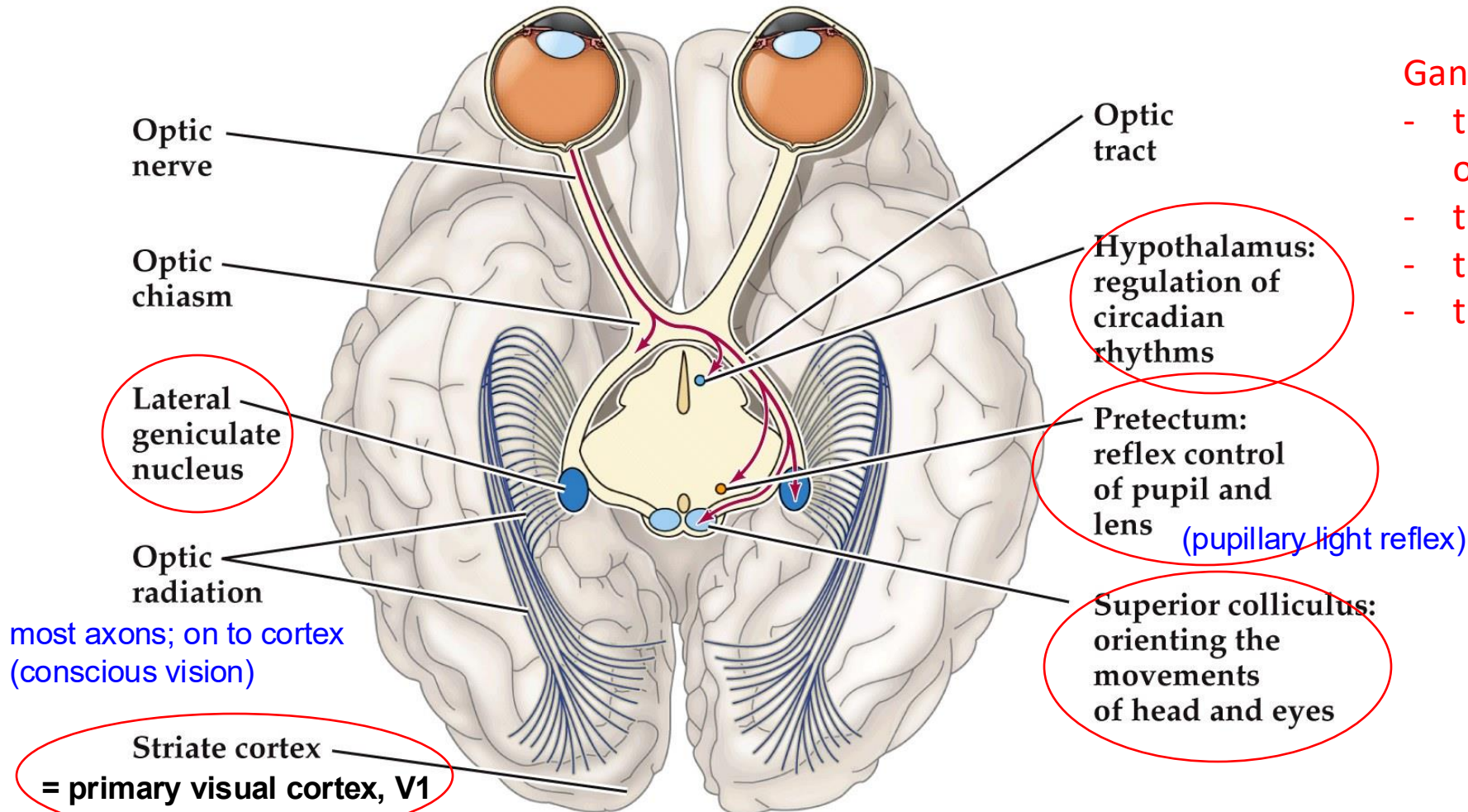


there are at least 30 morphologically and physiologically distinct retinal ganglion cell types



Prof. Josh Sanes

Central projections of retinal ganglion cells



Ganglion cell axons terminate in:

- the lateral geniculate nucleus of the thalamus → cortex
- the superior colliculus
- the pretectum
- the hypothalamus

40% of axons project to the same side, 60% cross the optic chiasm

- Optic nerve: axons of retinal ganglion cells, RGCs (which release *glutamate*)
- in some cases, different RGCs project to different brain areas
- some RGCs can also send axons to 2 brain areas

Different projections of retinal ganglion cells:

- 1) to **visual thalamus**, lateral geniculate nucleus (LGN)
 - and from LGN to **primary visual cortex (V1)**

=> => **voluntary behavior, navigation, conscious perception of vis. stimuli**

- 2) to **superior colliculus** (in the midbrain)
 - orienting head movements (primates)
 - creating another visual map

=> => **fast defensive - approach - orienting "ballistic" responses**

- 3) to **pretectum** (in the midbrain)
 -

=> => **control of pupil width & lens accommodation**

- 4) to the **hypothalamus** (in the diencephalon - interbrain)
 - (this projection by RGCs with an intrinsic light response)

=> => **stabilization of intrinsic circadian rhythm to day/night rhythm**

Central projections of retinal ganglion cells

Ganglion cell axons terminate in:

- the lateral geniculate nucleus of the thalamus
- the superior colliculus
- **the pretectum**
- **the hypothalamus**

Pretectum

Regulation of pupillary light reflex

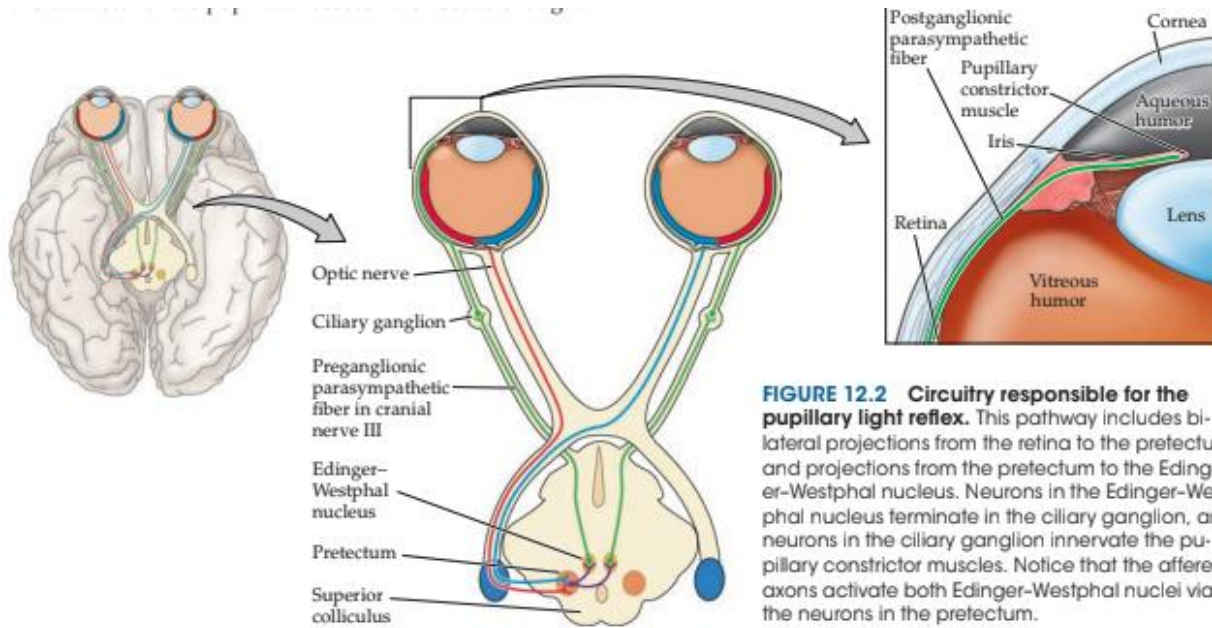
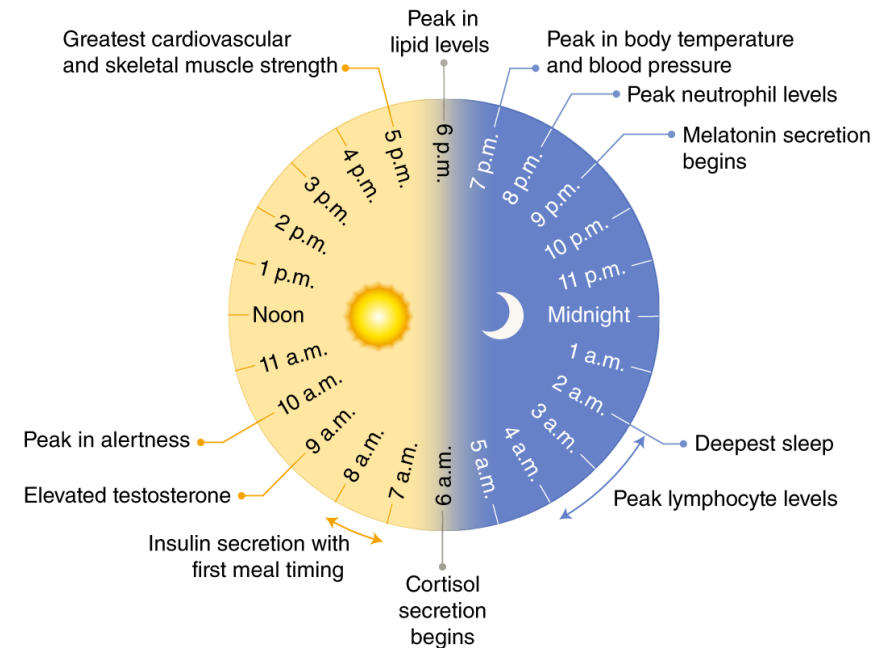


FIGURE 12.2 Circuitry responsible for the pupillary light reflex. This pathway includes bilateral projections from the retina to the pretectum and projections from the pretectum to the Edinger-Westphal nucleus. Neurons in the Edinger-Westphal nucleus terminate in the ciliary ganglion, and neurons in the ciliary ganglion innervate the pupillary constrictor muscles. Notice that the afferent axons activate both Edinger-Westphal nuclei via the neurons in the pretectum.

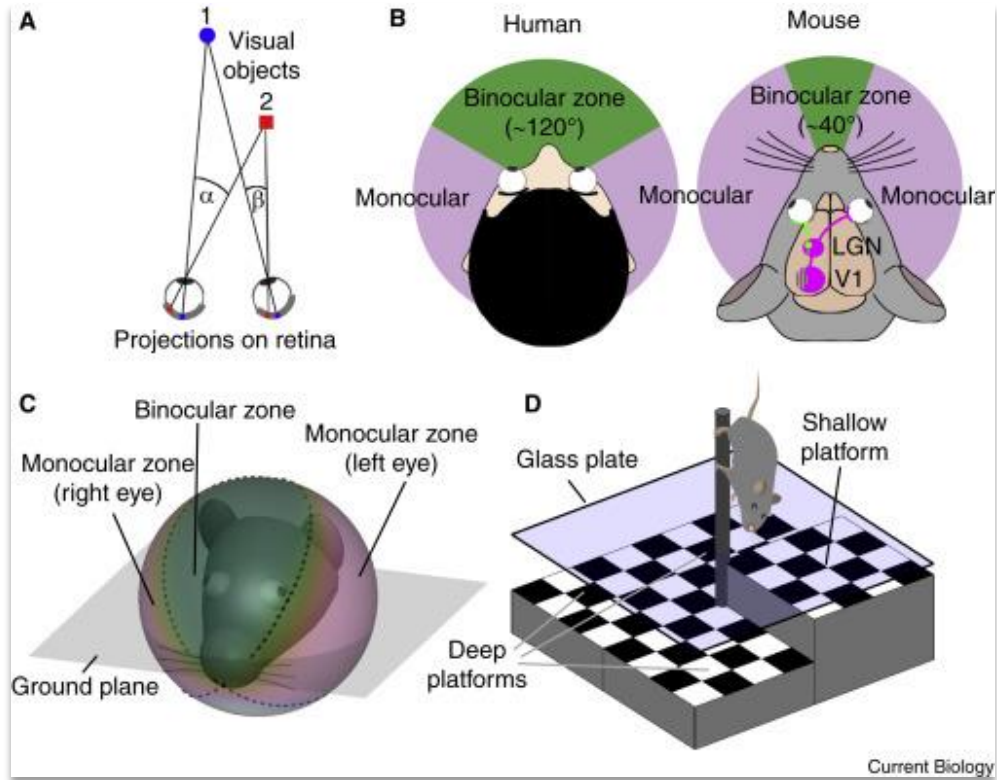
Hypothalamus

Regulation of circadian rhythms



*will we not discuss this further

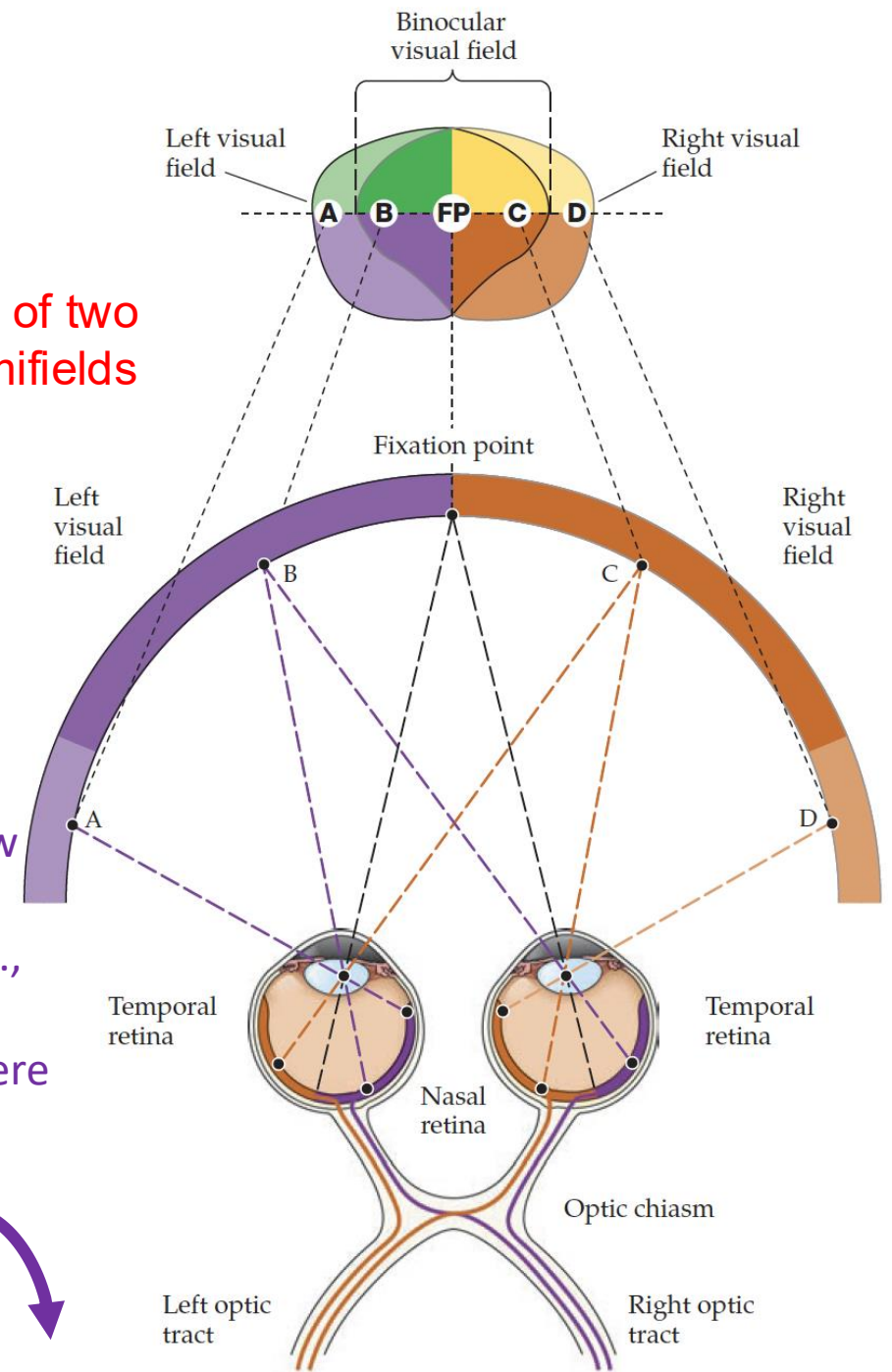
Binocular vision in humans:



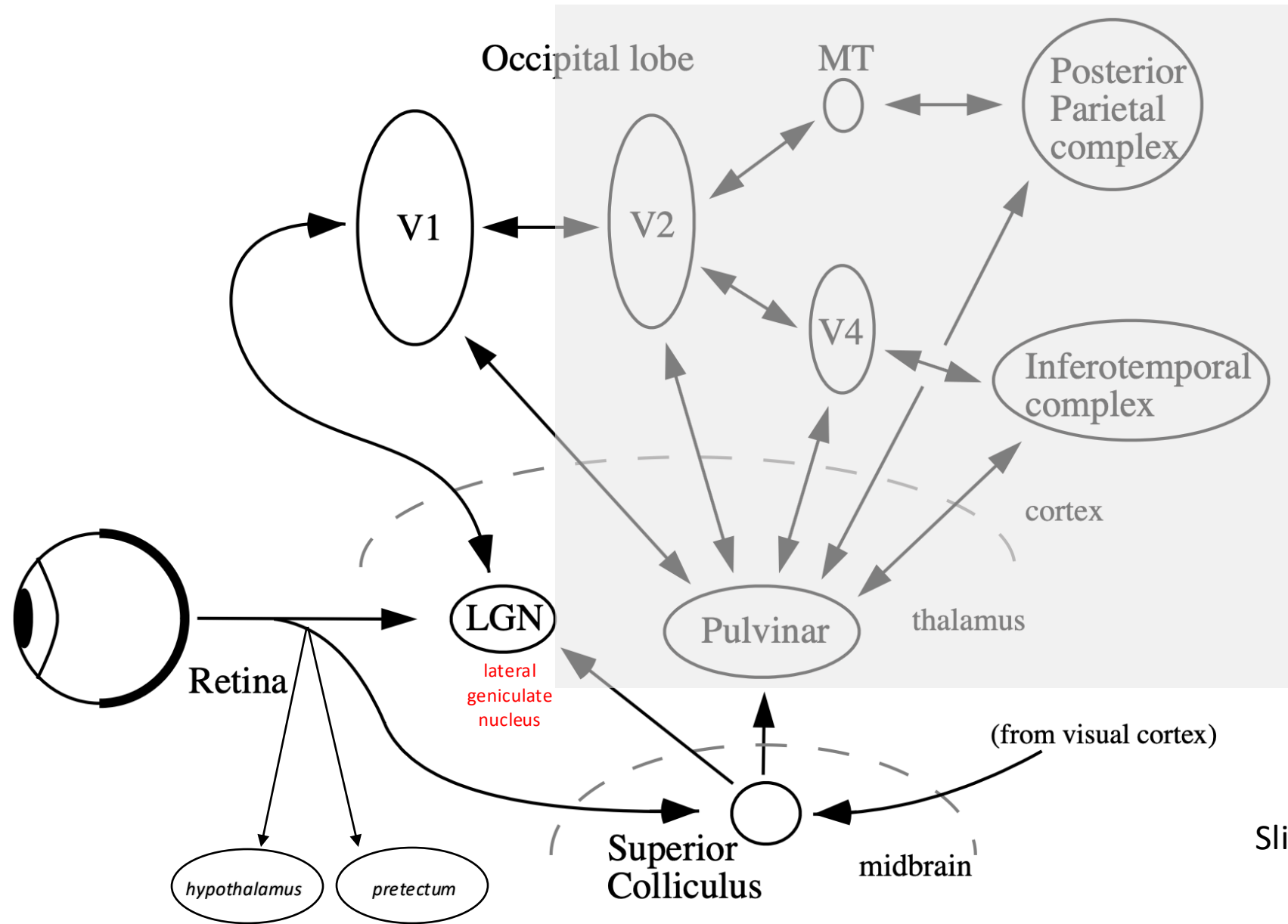
[JasperPoort¹²](#) [Arne F.Meyer³⁴](#)

binocular field consists of two symmetrical visual hemifields (left and right).

peripheral view is strictly monocular; i.e., left projects to right hemisphere

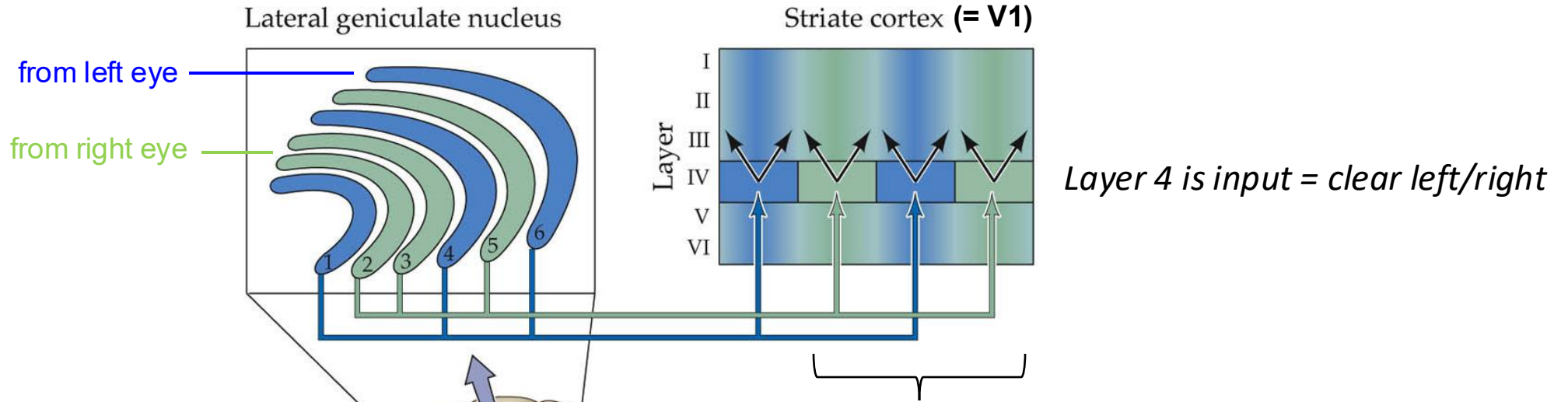


Visual information processing pathways

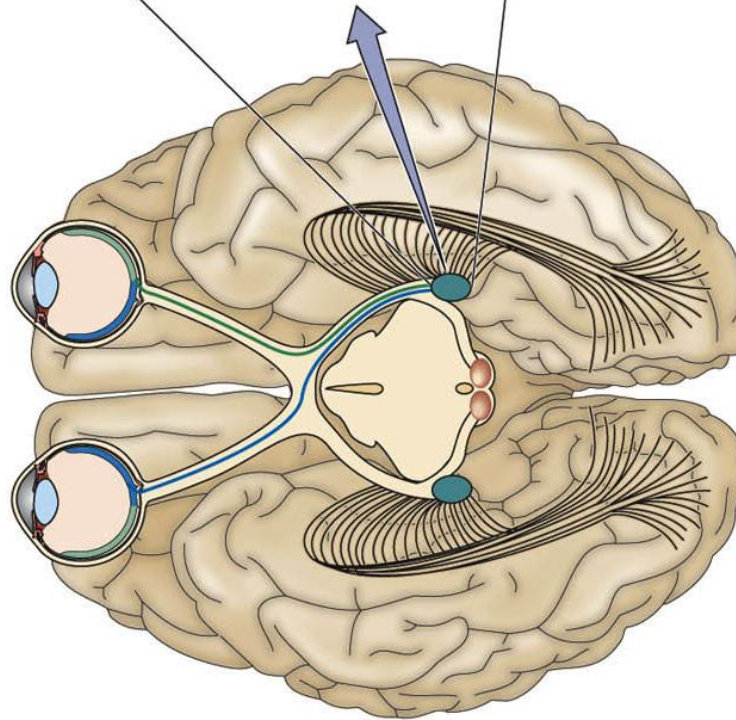


Slide adapted courtesy of Prof. Bruno Olshausen

How the LGN projects to the ipsilateral V1



As a general rule, information from the left half of the visual world, whether it originates from the left or right eye, is represented in the right half of the brain, and vice versa.



ocular dominance columns,
~ 1 mm wide

-The information from the 2 eyes
comes close in V1

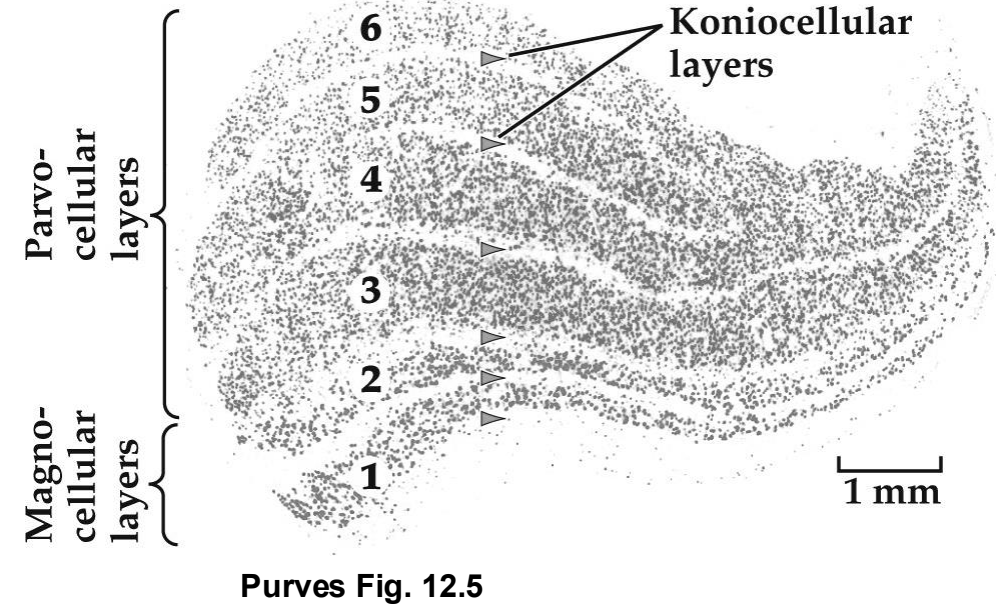
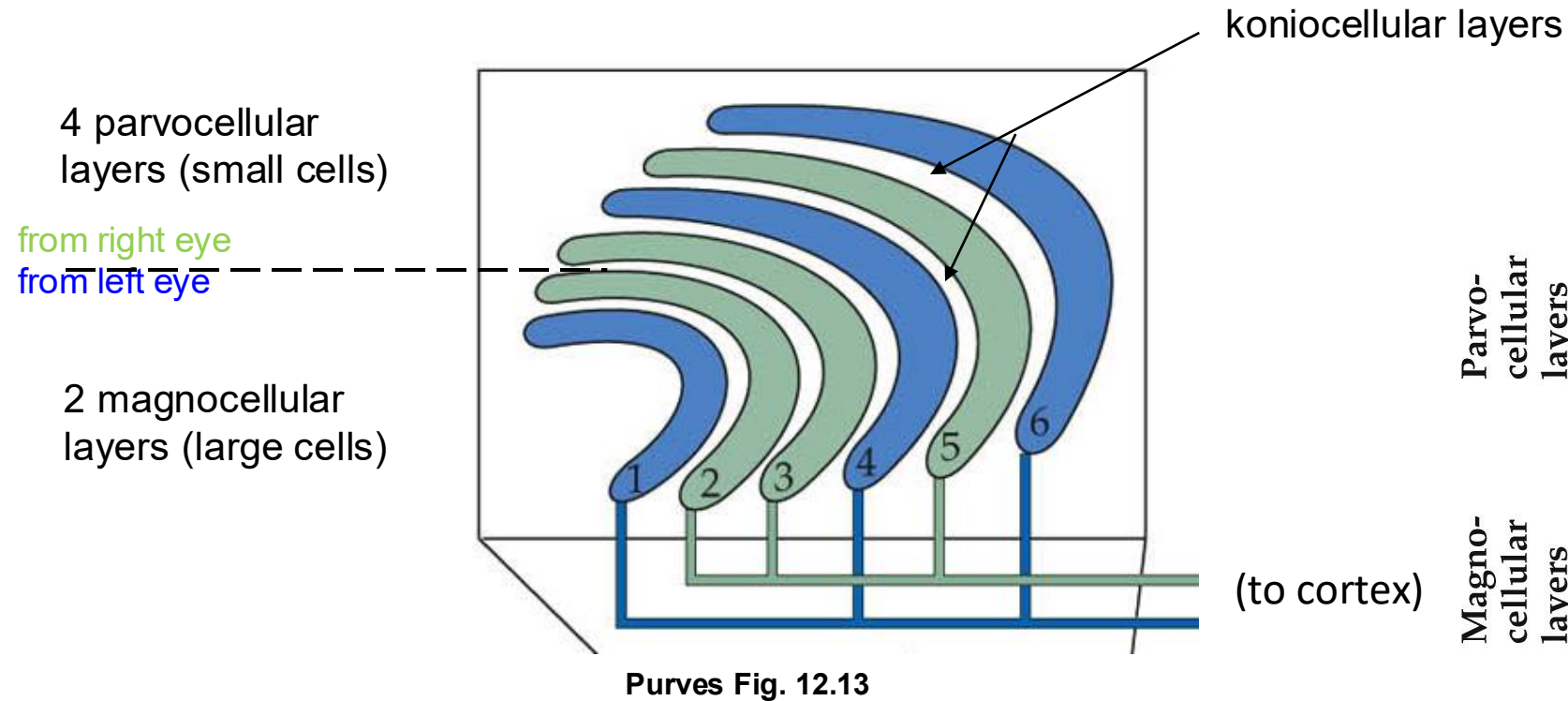
- many V1 neurons respond to stimuli
from both eyes (binocular)

definition:

ipsilateral: on same brain side

contralateral: ≠

Histological organization of the visual thalamus (= LGN) in primates / humans

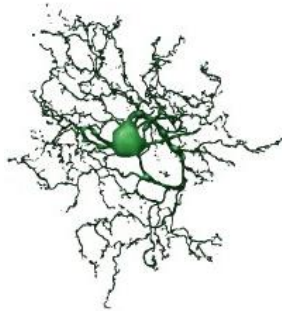


- neurons in LGN : same receptive field as RGCs
- (small circle-like center & ring-like surround; antagonistic)

3 cells types, 3 layer types:

P cells have smaller cell bodies and dendritic fields. They supply the parvocellular layers of the lateral geniculate nucleus.

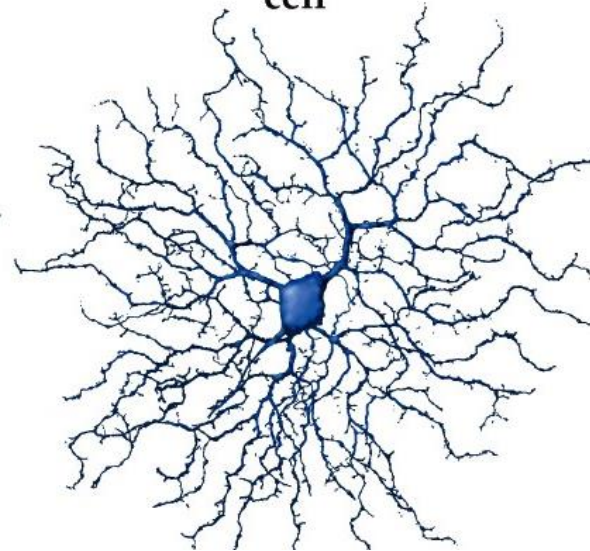
P ganglion cell



- inputs from relatively few rods and cones
- slow **conduction velocity**
- respond to changes in color
- respond only weakly to changes in contrast

M cells have large-diameter cell bodies and large dendritic fields.

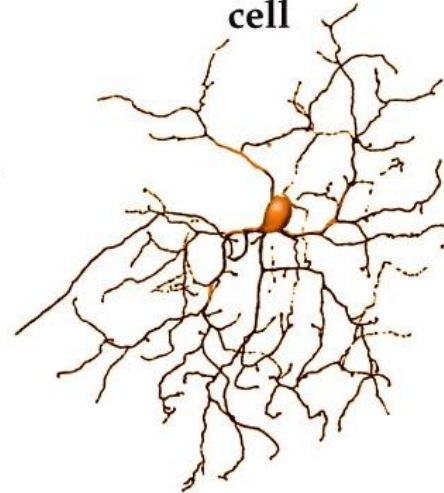
M ganglion cell



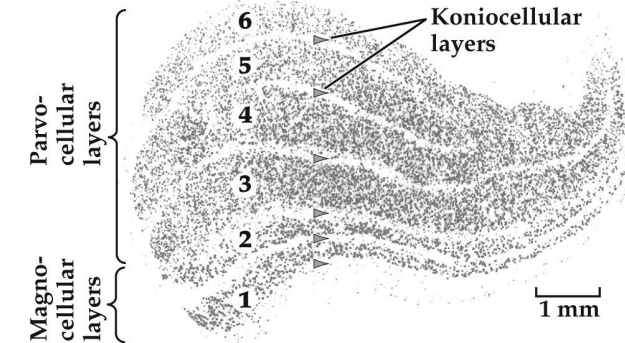
- inputs from relatively many rods and cones.
- fast conduction velocity
- respond to low-contrast stimuli
- not very sensitive to changes in color.

K cells have small cell bodies and intermediate-sized dendritic fields. They supply the koniocellular layers of the lateral geniculate nucleus

K ganglion cell



- Newly discovered, only 10%
- inputs (intermediate) from rods and cones.
- Likely involved in color
- Large receptive field

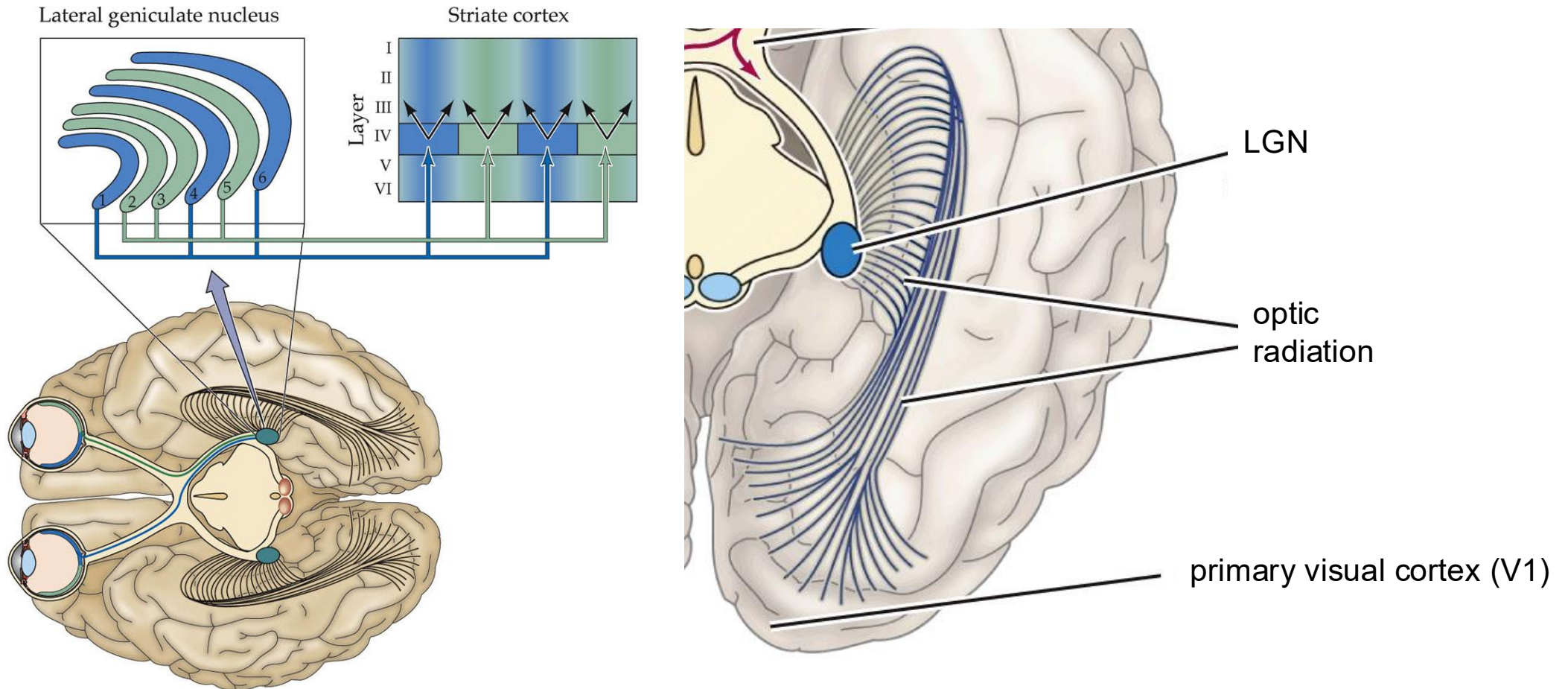


Purves Fig. 12.5

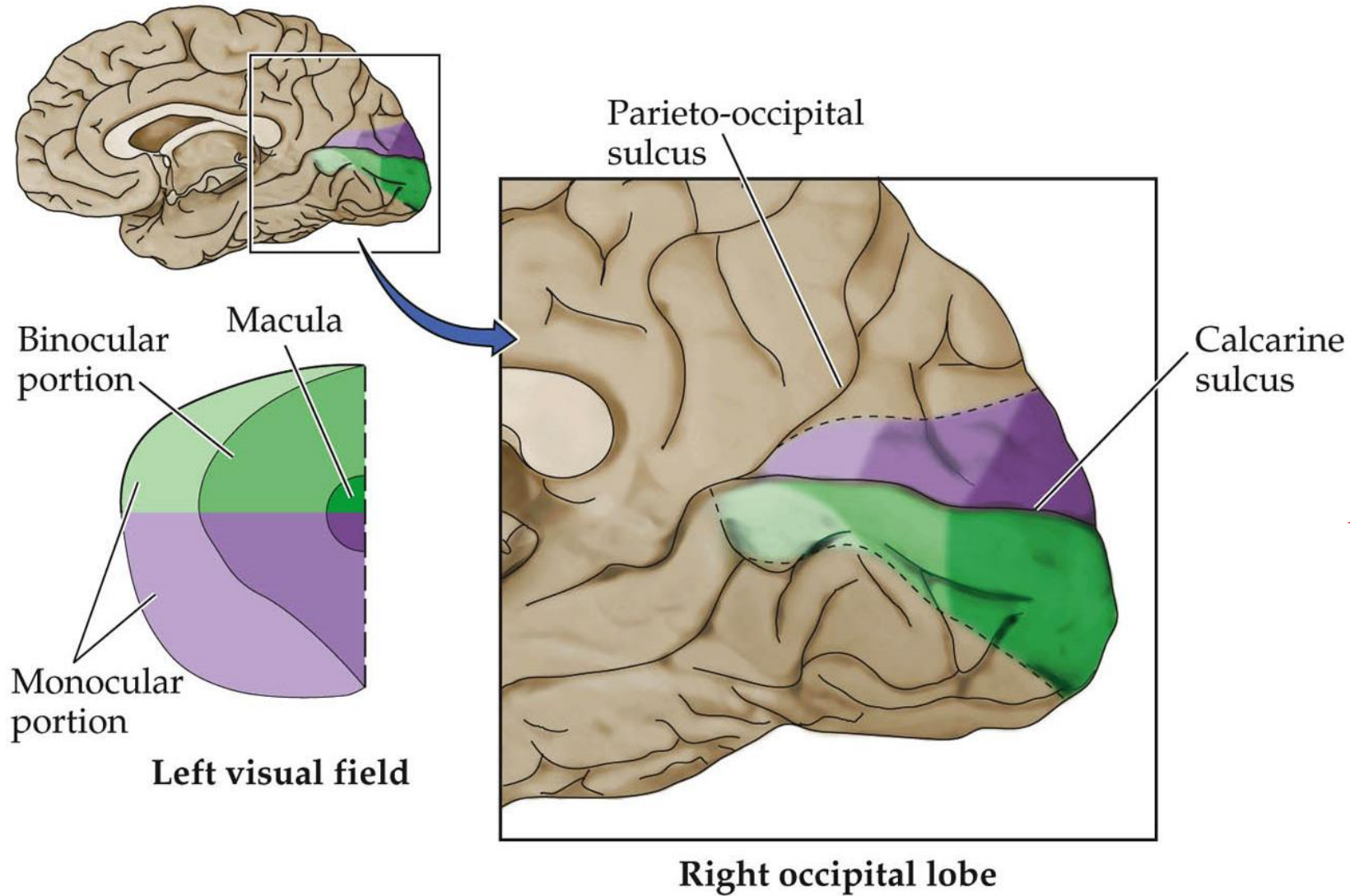
Illustration of broad classes of RGCs in primates

The LGN sends its axons through the optic radiation to the primary visual cortex

(LGN axons release *glutamate*)



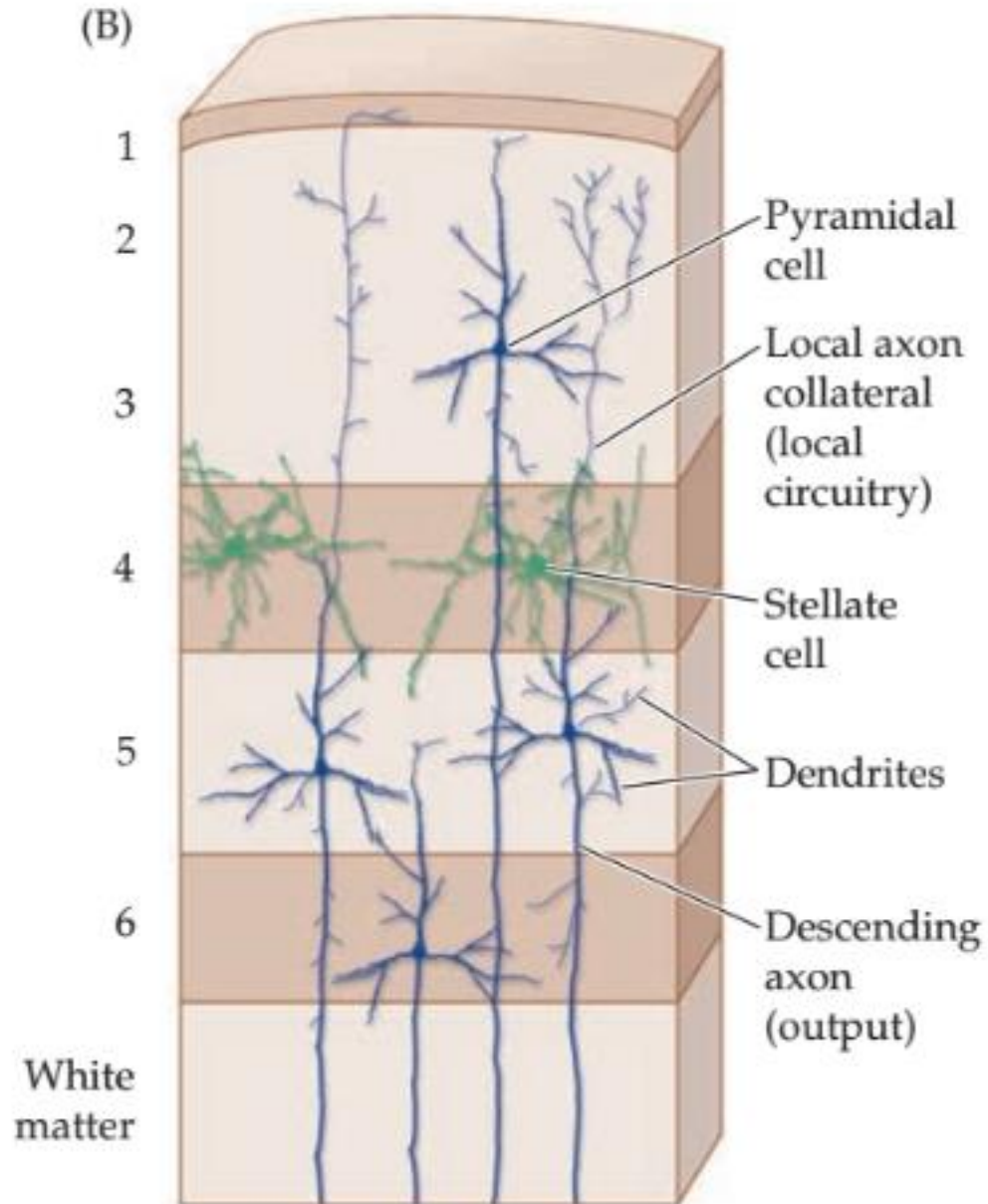
Visuotopic organization of the primary visual cortex (V1)



Also known as “striate cortex” and Brodmann's area 17

As in the somatosensory system, the amount of cortical area devoted to each unit of area of the sensory surface is not uniform, but reflects the density of receptors and sensory axons that supply the peripheral region.

Organization of the 6-layer cortex

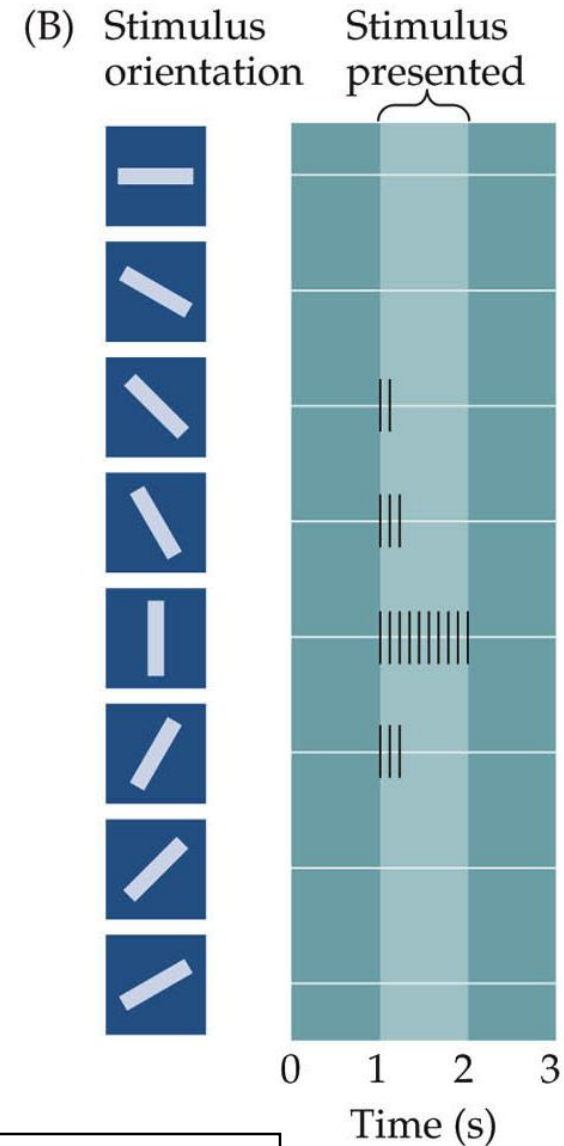
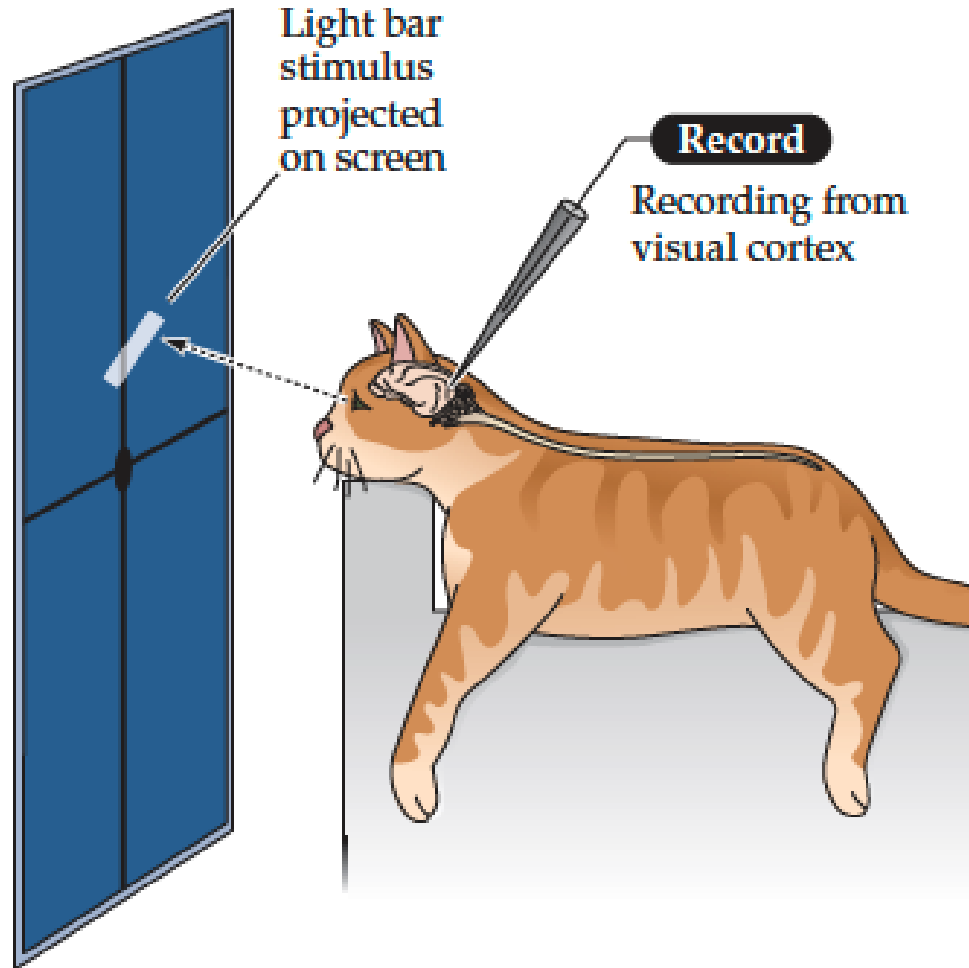


- **inputs from LGN: to Layer 4**, and "patchy" to L2/3, L1
- in-between layer connections: **L4 → L2/3**
L2/3 → L5
- outputs:
 - **L2/L3 "ascending"** ; "associational"; that is to higher cortical areas (e.g., V2)
 - **L5 "descending"** to superior colliculus (!)
 - **L6 "cortico-thalamic"** back to visual thalamus

2 broad classes of neurons:

- Spiny (pyramidal & stellate) GLUT
- Aspinous (smooth). GABA

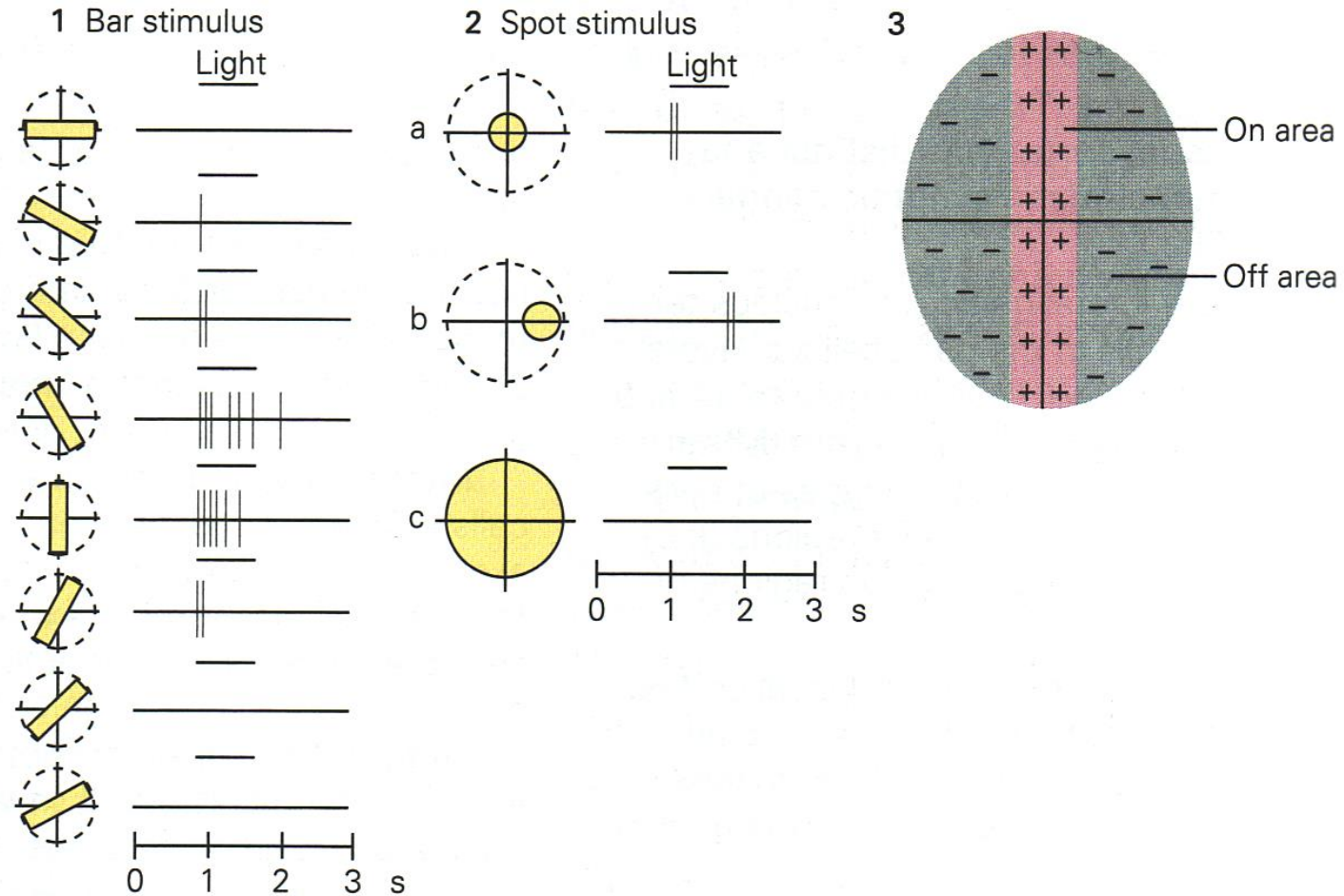
Organization of receptive field of neurons in the primary visual cortex



Example for a V1 neuron with a "simple" (bar-like) receptive field



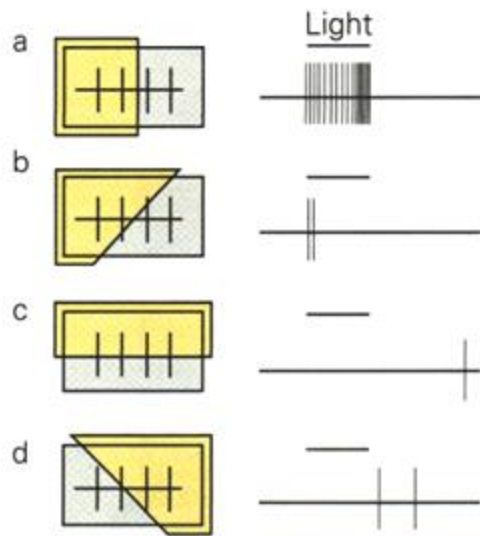
V1 simple cell



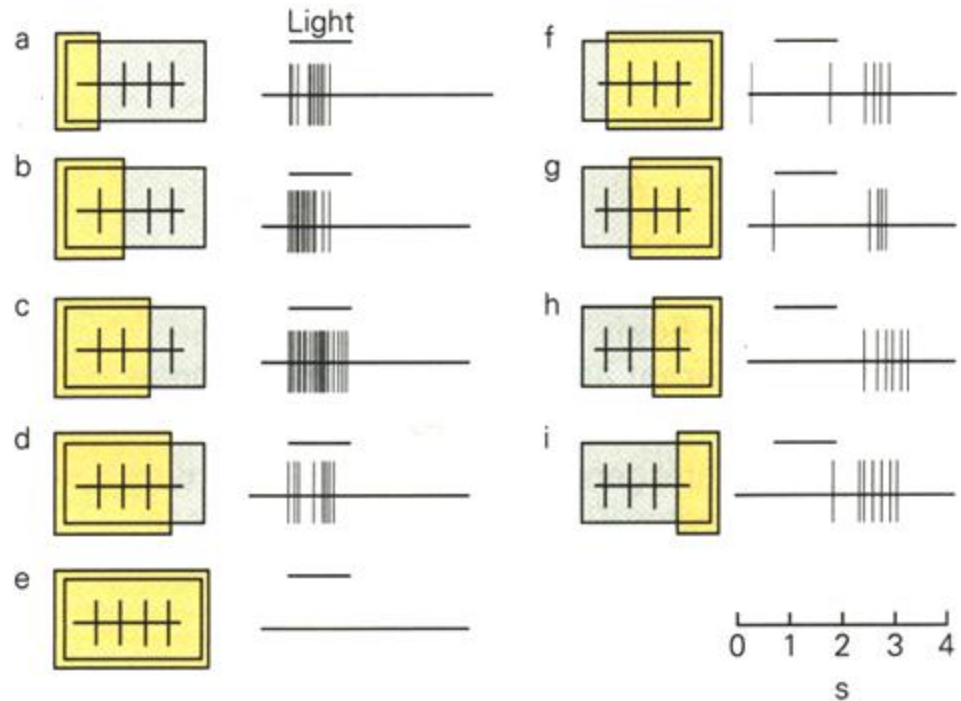
- Orientation specificity!

V1 complex cell

A₁ Response to orientation of stimulus



A₂ Response to position of stimulus



- Orientation specificity!
- Less sensitive to exact locations

"Simple cells"

- bar-like receptive field. Optimally tuned for the direction / or movement of the bar

"Complex cells"

- more complex RF structure

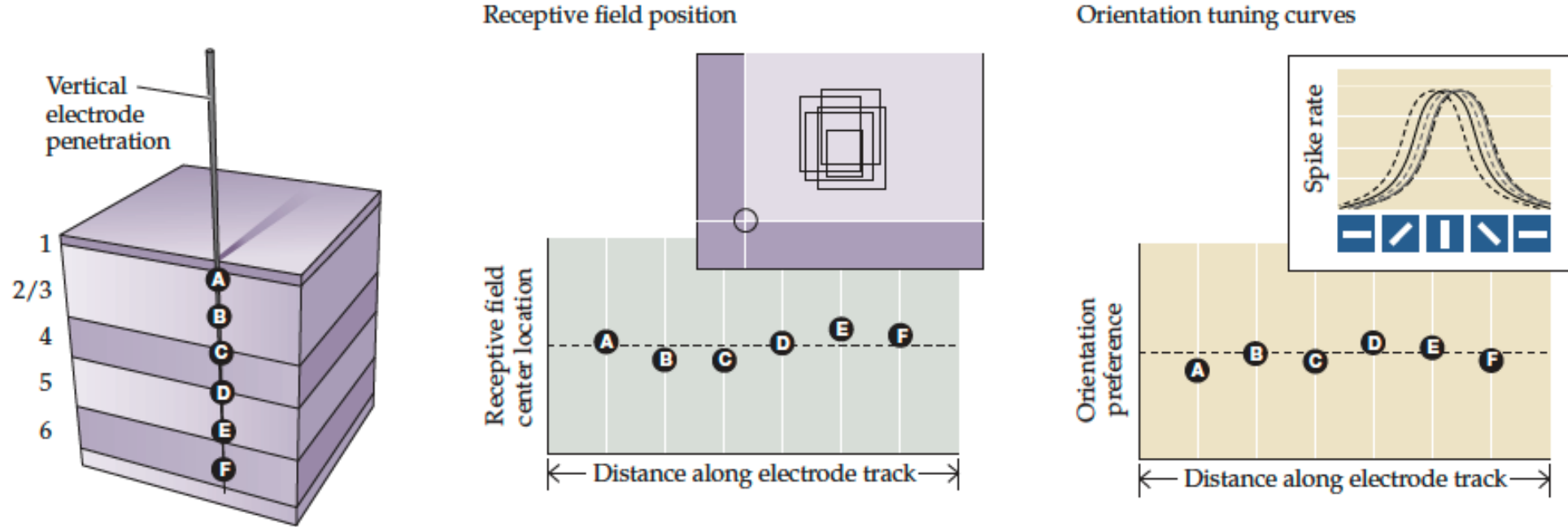


FIGURE 12.9

- Only 10% of cells are sensitive to color

- Neurons along radial axis of the cortex have receptive fields that are centered on the same region of visual space and exhibit similar orientation preferences.

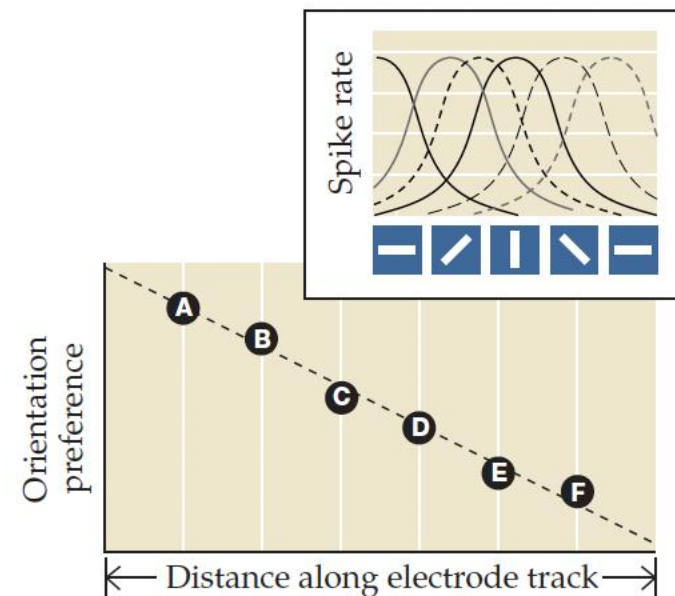
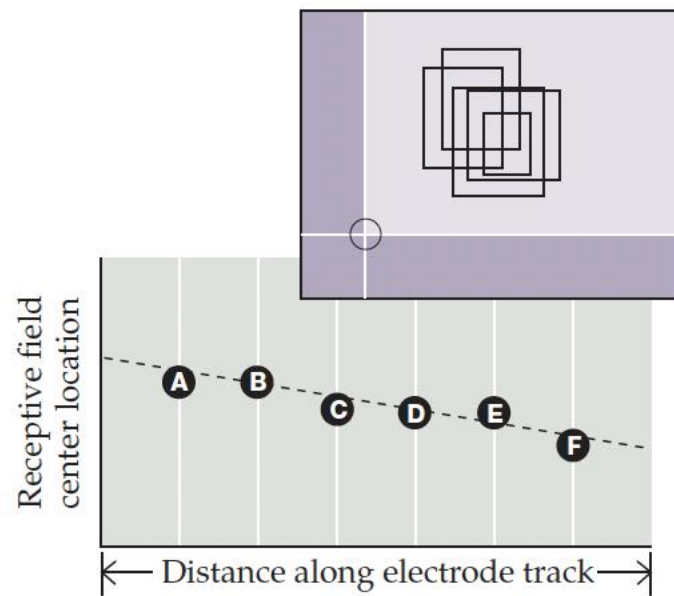
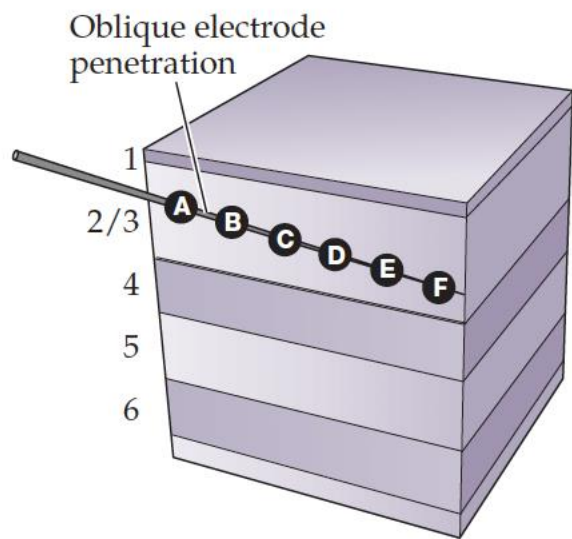
"Simple cells"

- bar-like receptive field. Optimally tuned for the direction / or movement of the bar

"Complex cells"

- more complex RF structure

(B)



Organization of “pin wheels” in the primary visual cortex

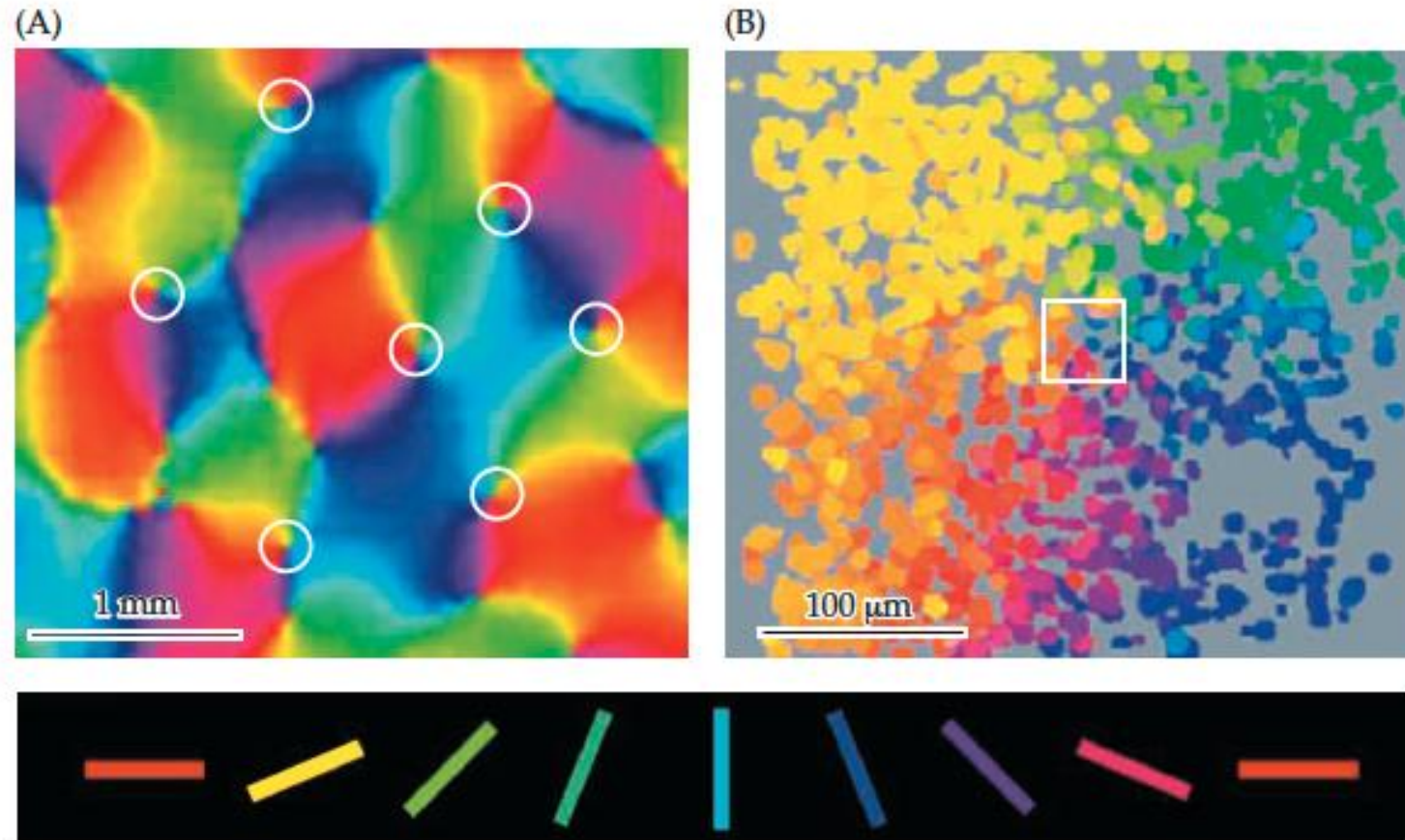
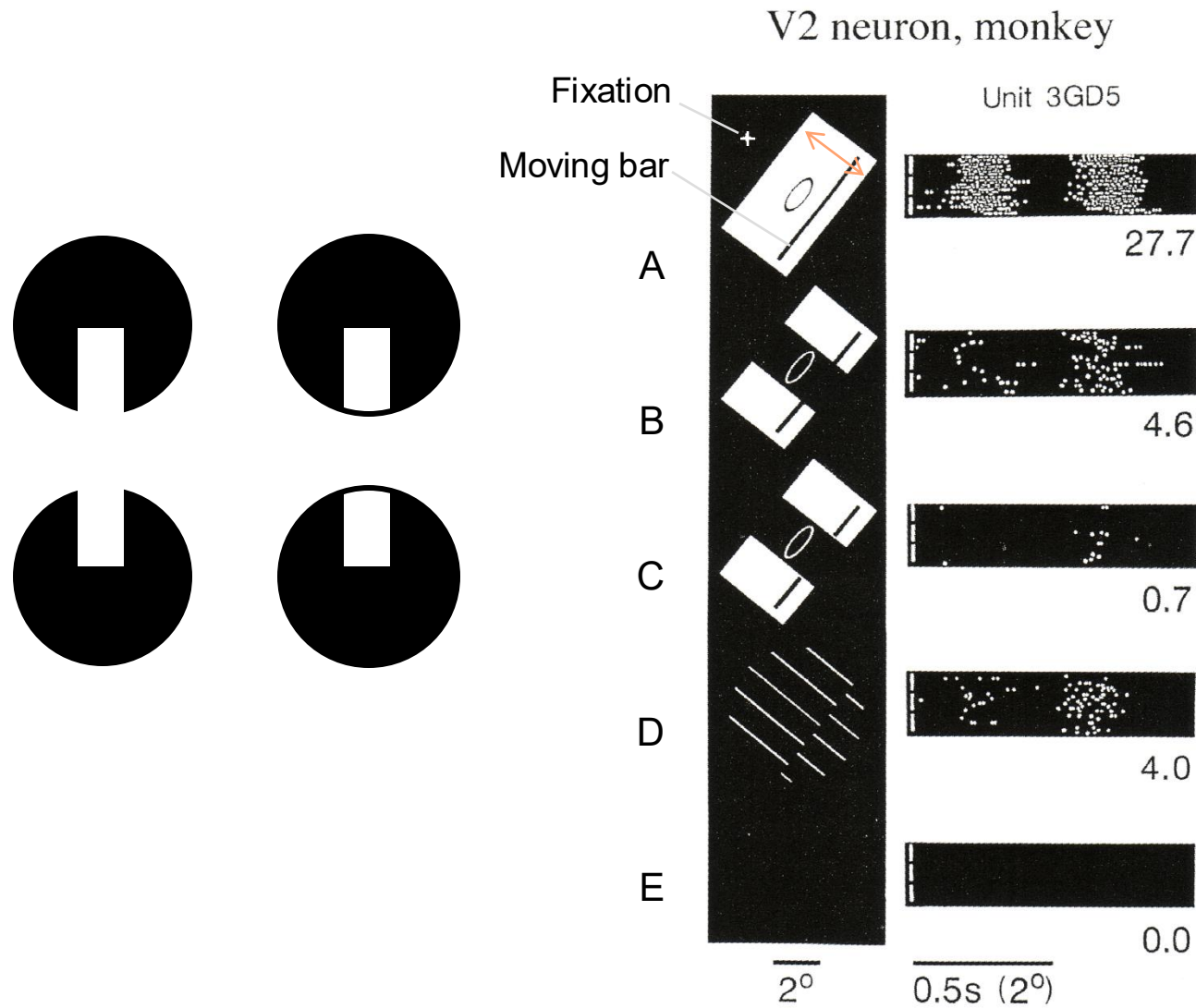


FIGURE 12.10 Functional imaging reveals orderly mapping of orientation preference in the primary visual cortex.

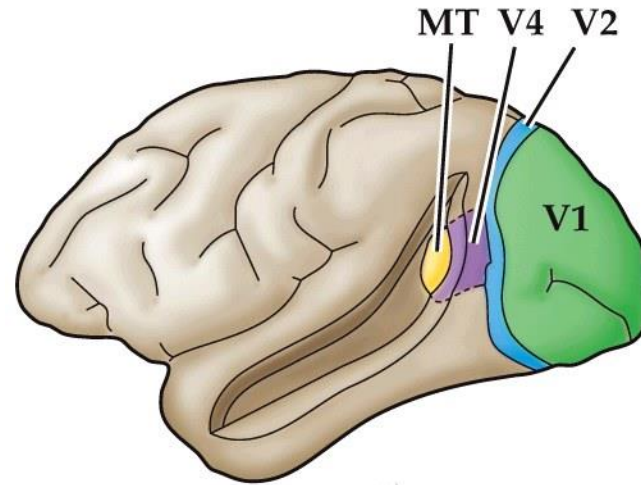
V2 neurons respond to “subjective contours”



(Peterhans & von der Heydt, 1991)

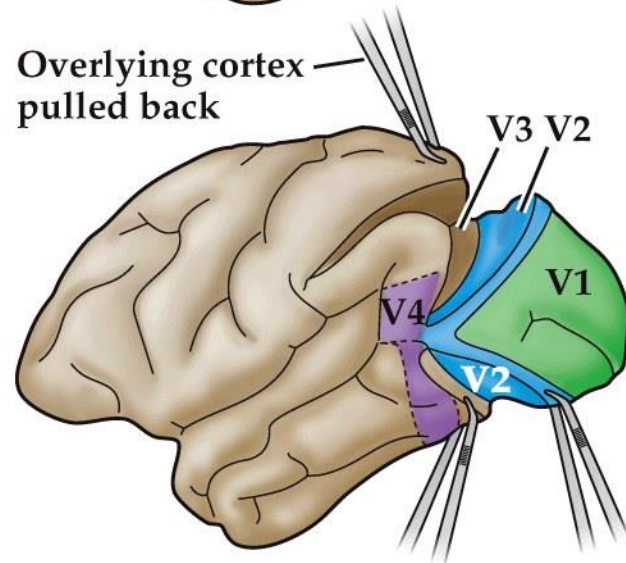
break

Beyond V1: Visual brain areas of cortex (in the rhesus macaque*)



V2, V3, V4:
secondary to tertiary visual cortices

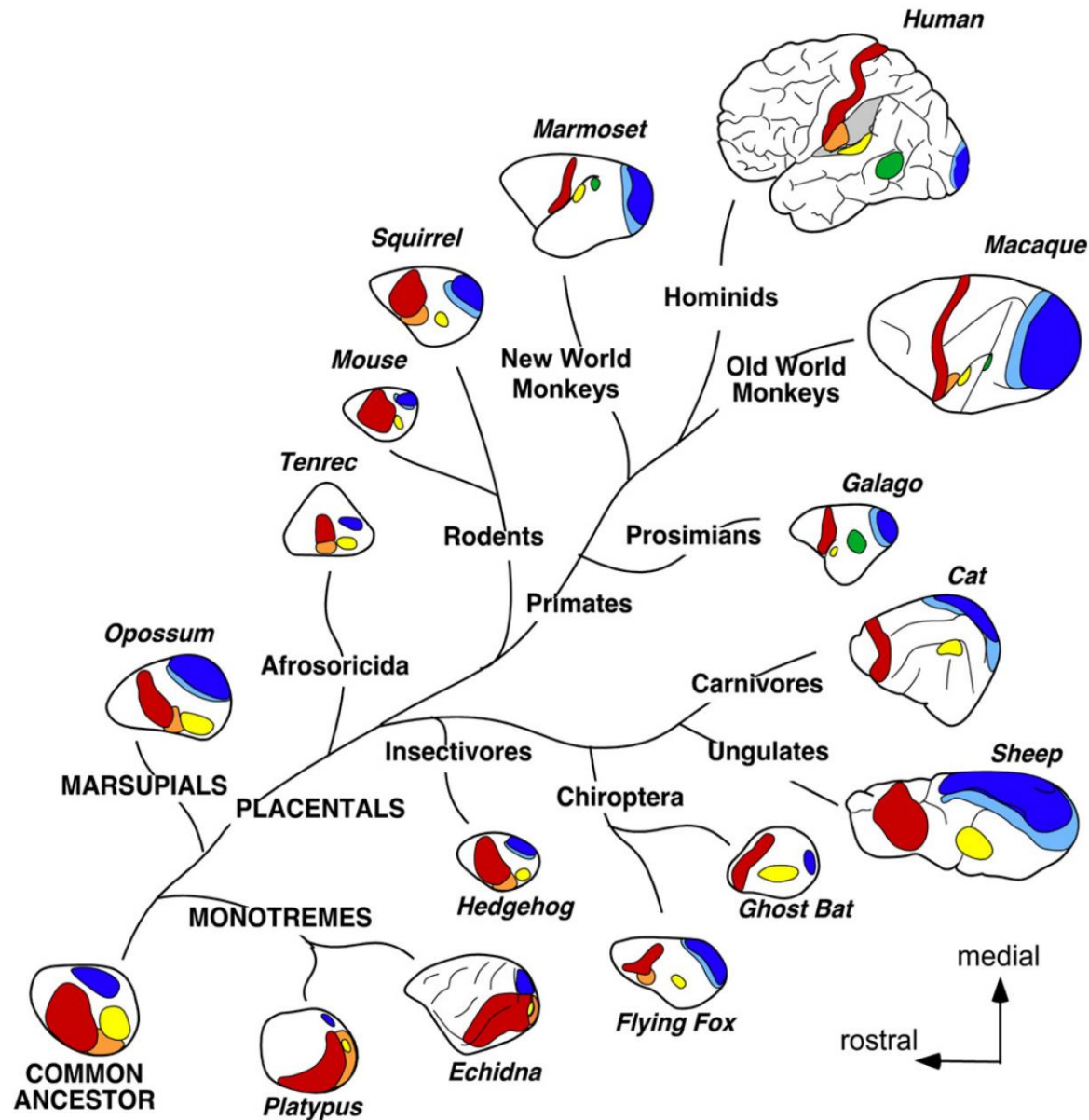
MT:
medial temporal area



dorsal
↑

←
rostral
(towards face)

*Sensory cortical areas across mammalian species in a clade-like plot



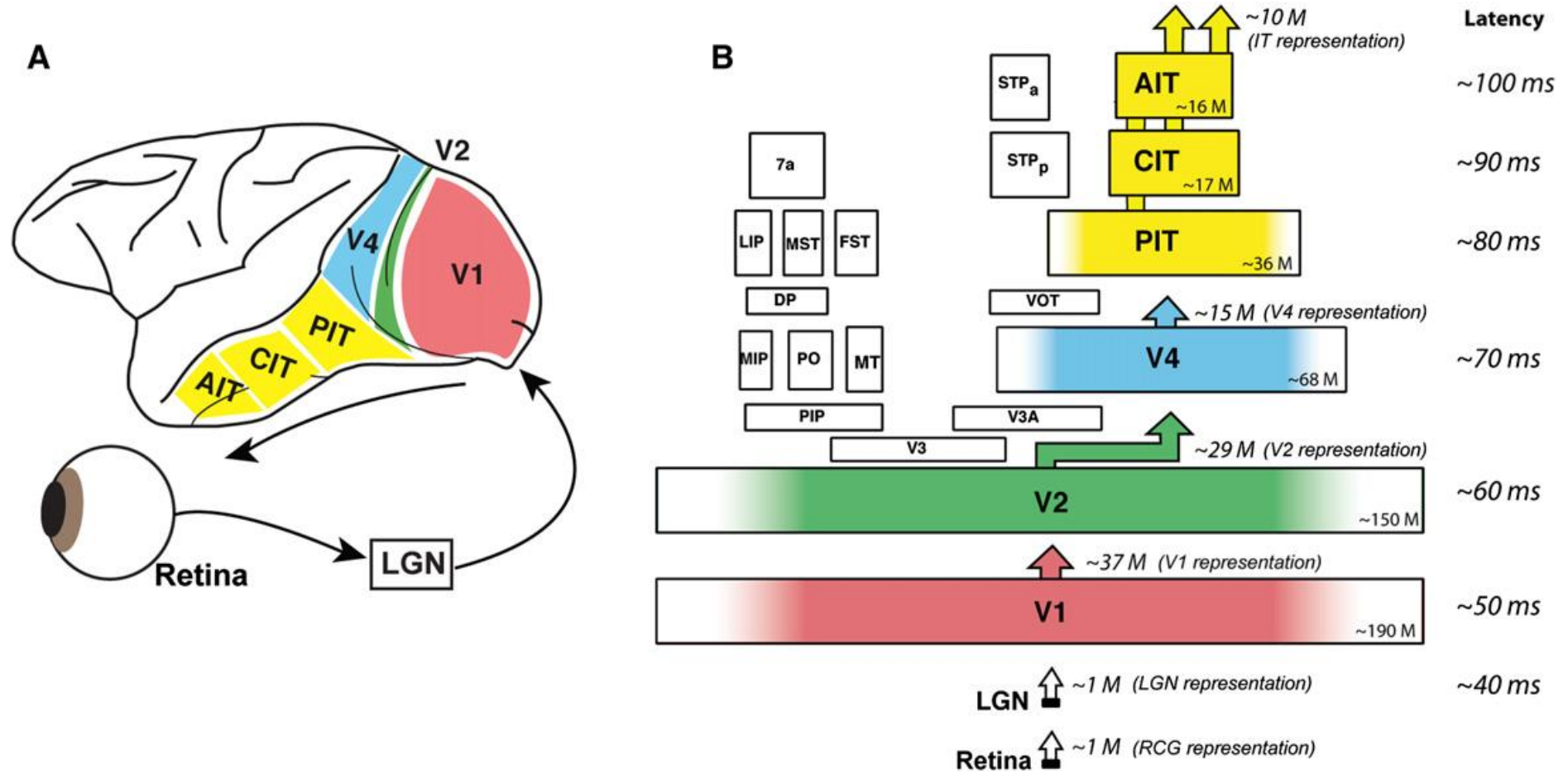
- Primary visual area (V1)
- Second visual area (V2)
- Primary auditory area (A1)
- Primary somatosensory area (S1)
- Second somatosensory area (S2)
- Middle temporal visual area (MT)

- white: either motor areas
(located frontally)

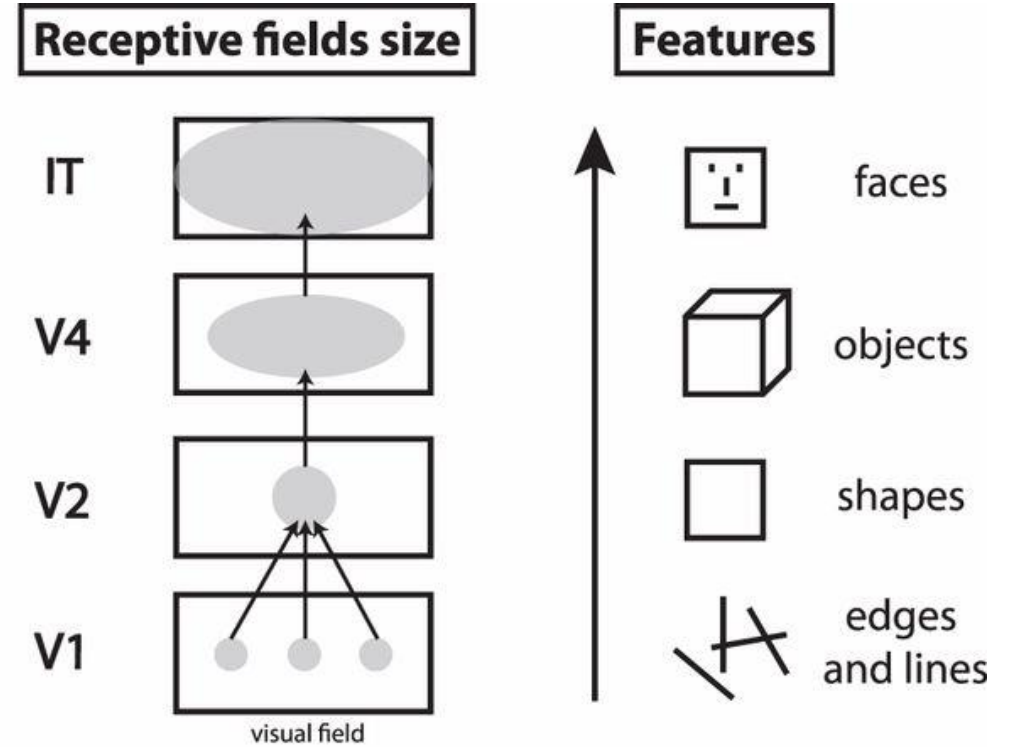
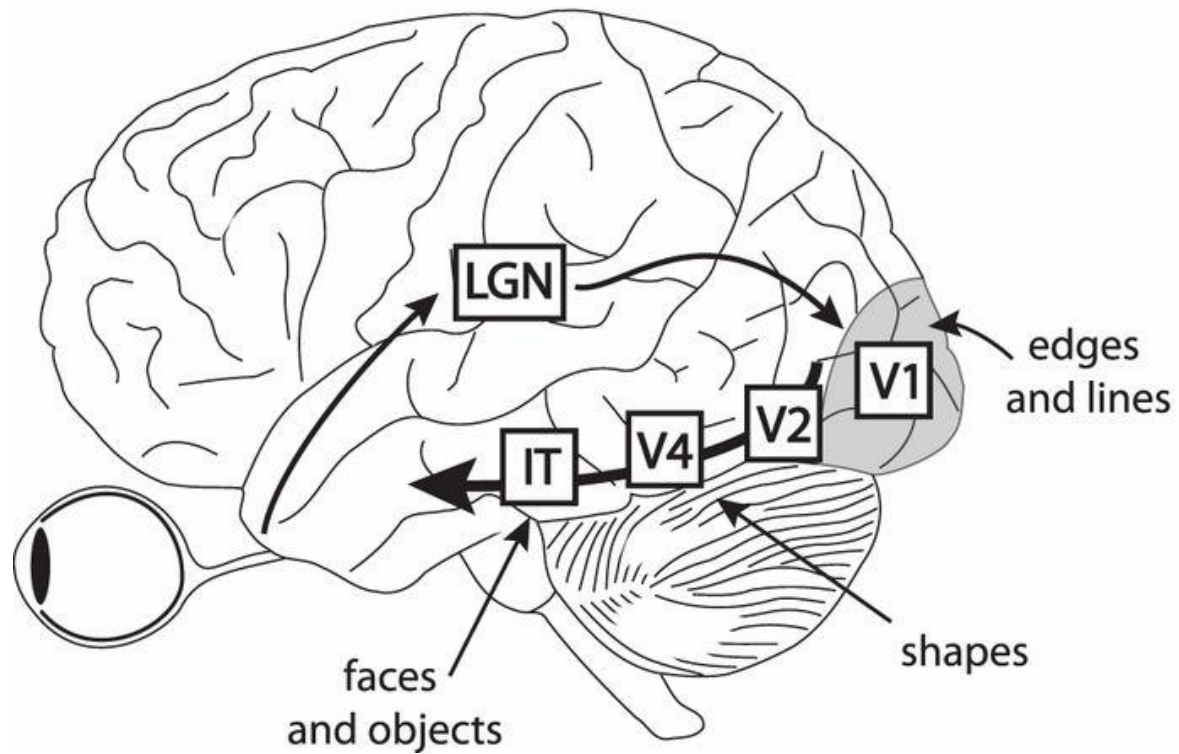
OR higher association areas

- In "higher" mammals (e.g.
primates) more cortical space
devoted to associational
areas

Beyond V1: Visual brain areas of cortex (in the rhesus macaque*)

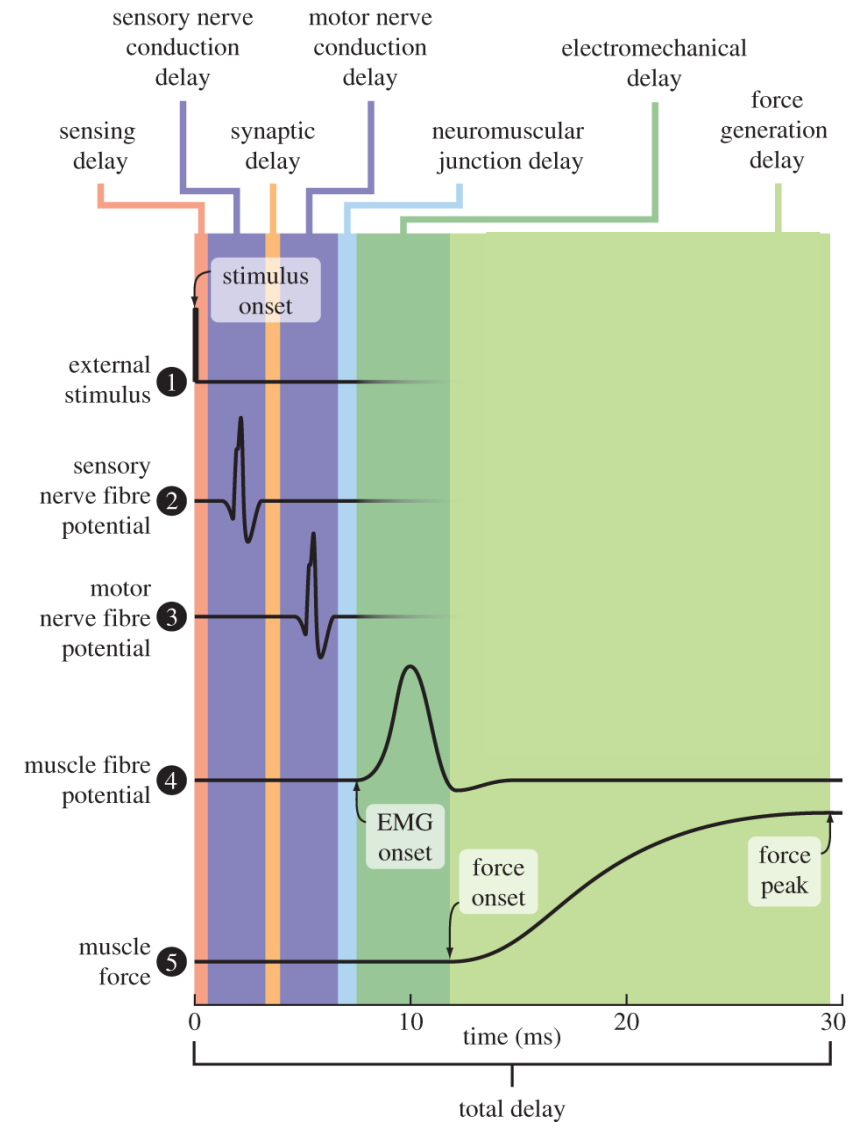
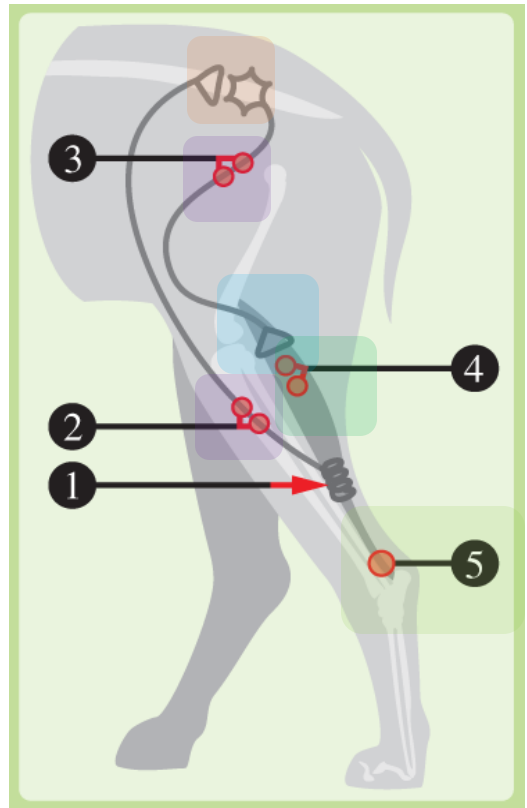
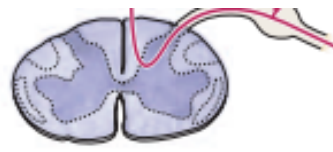


Hierarchical visual processing



- V1 neurons are most sensitive to low-level features, such as edges and lines.
- In higher visual areas, like V4 and IT, receptive fields are larger, and neurons are sensitive to complex features, such as shapes and objects.
- Responses of high-level neurons are fully determined by the neural firing of lower-level neurons. For example, the neural firing to a square is determined by the neural firing for two vertical and two horizontal lines.

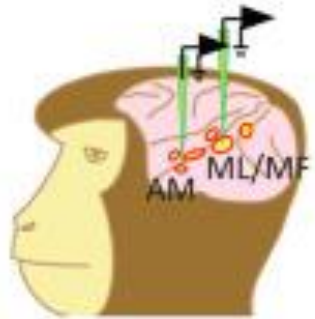
Reminder: the stretch reflex: how long does it take to act?



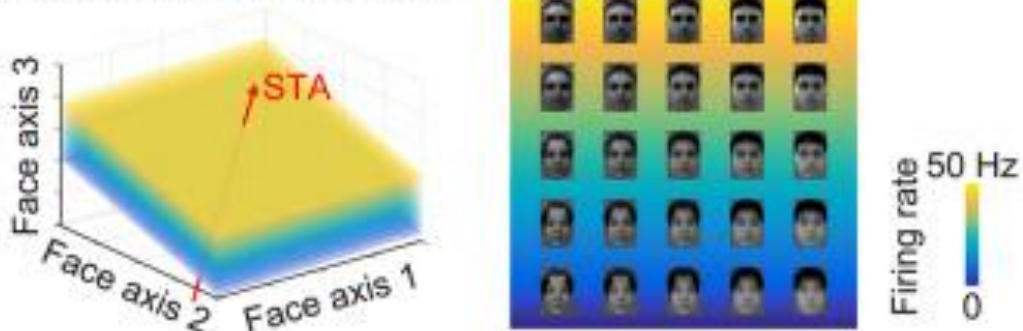
Adapted from Scaling of sensorimotor delays in terrestrial mammals. DOI: (10.1098/rspb.2018.0613)

Beyond V1: face patch neurons in inferotemporal (IT) cortex

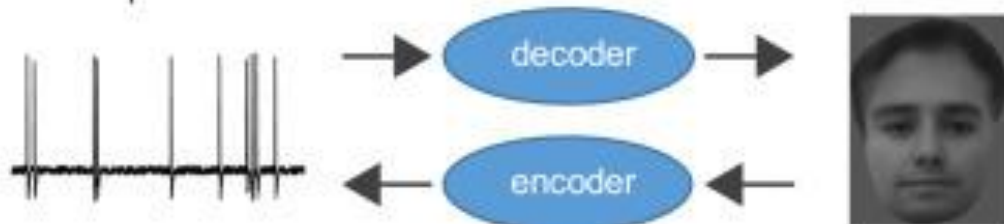
1. We recorded responses to parameterized faces from macaque face patches



2. We found that single cells are tuned to single face axes, and are blind to changes orthogonal to this axis



3. We found that an axis model allows precise encoding and decoding of neural responses



The Code for Facial Identity in the Primate Brain

Le Chang^{1,*} and Doris Y. Tsao^{1,2,3,*}

¹Division of Biology and Biological Engineering, Computation and Neural Systems, Caltech, Pasadena, CA 91125, USA

²Howard Hughes Medical Institute, Pasadena, CA 91125, USA

³Lead Contact

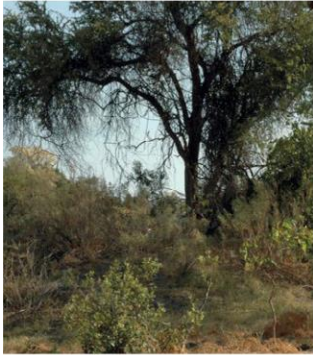
*Correspondence: lechang@caltech.edu (L.C.), dortsao@caltech.edu (D.Y.T.)

<http://dx.doi.org/10.1016/j.cell.2017.05.011>

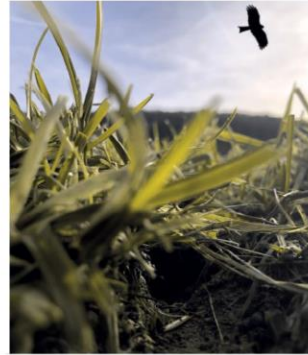
- Facial images can be linearly reconstructed using responses of ~200 face cells

Across species, there are evolutionarily-driven diffs to the visual pathway

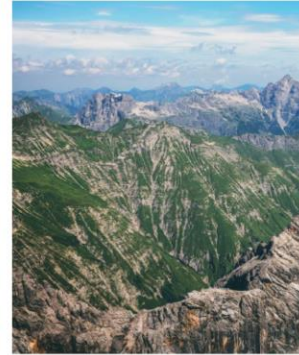
a
Primate



b
Mouse

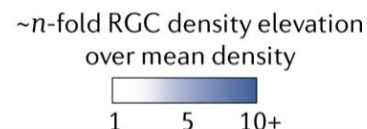
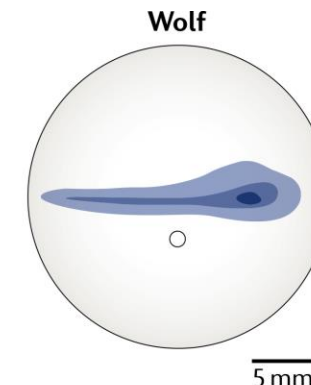
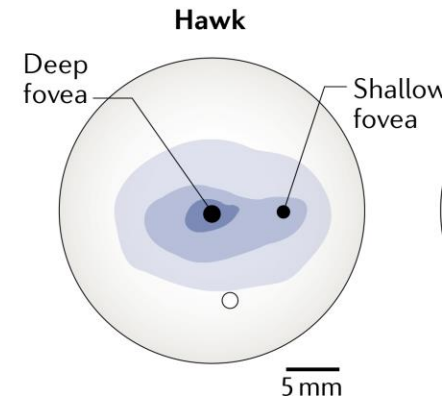
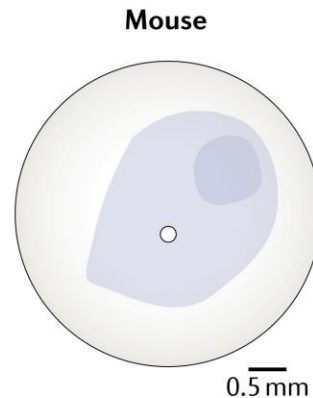
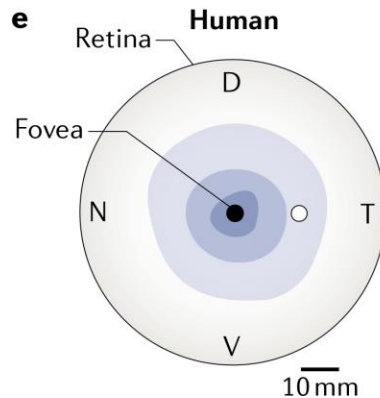


c
Hawk



Across vertebrates species, retina organization is different according to the requirement of the ecological niche

Baden et al. 2020 Nat. Reviews:
"Understanding the retinal basis of vision across species"



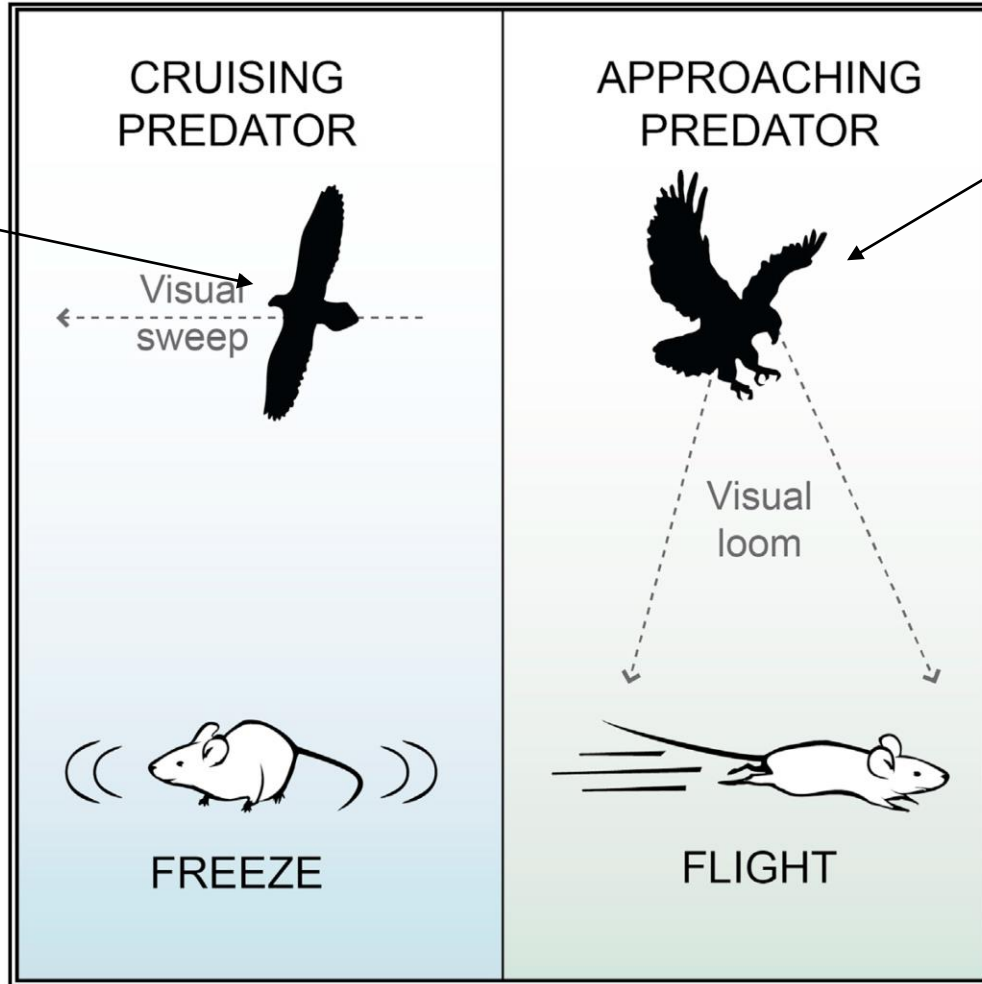
Also differences in central pathways:

- in primates > 80% of RGCs in *retinogeniculate* pathway
- in most other mammals and vertebrate > 80% in *retinotectal* pathway!

Prey / predator relations as a drive for evolution

Example: hawk (predator) and mouse (prey)

Buzzard:
- high visual acuity
- motion detection!

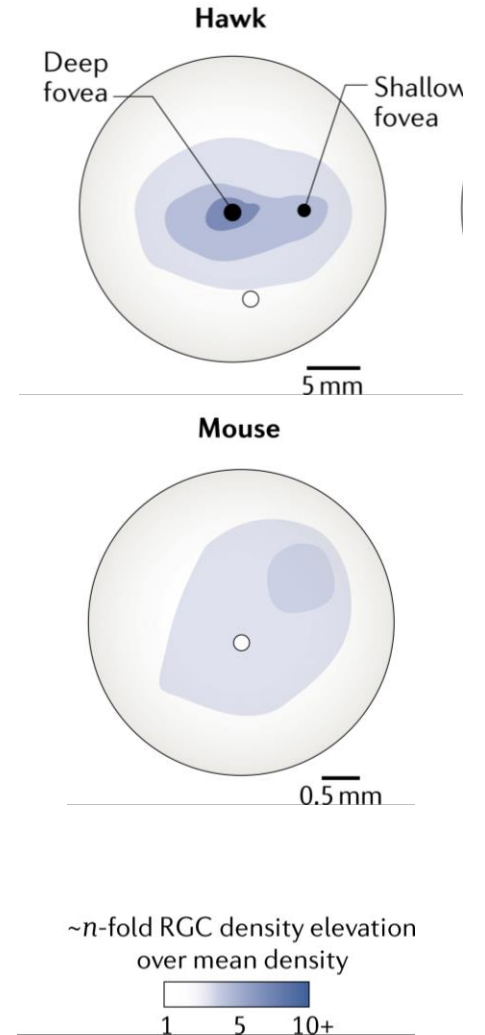


- Freeze (to avoid motion detection!)

- Flight / escape (when predator comes close)

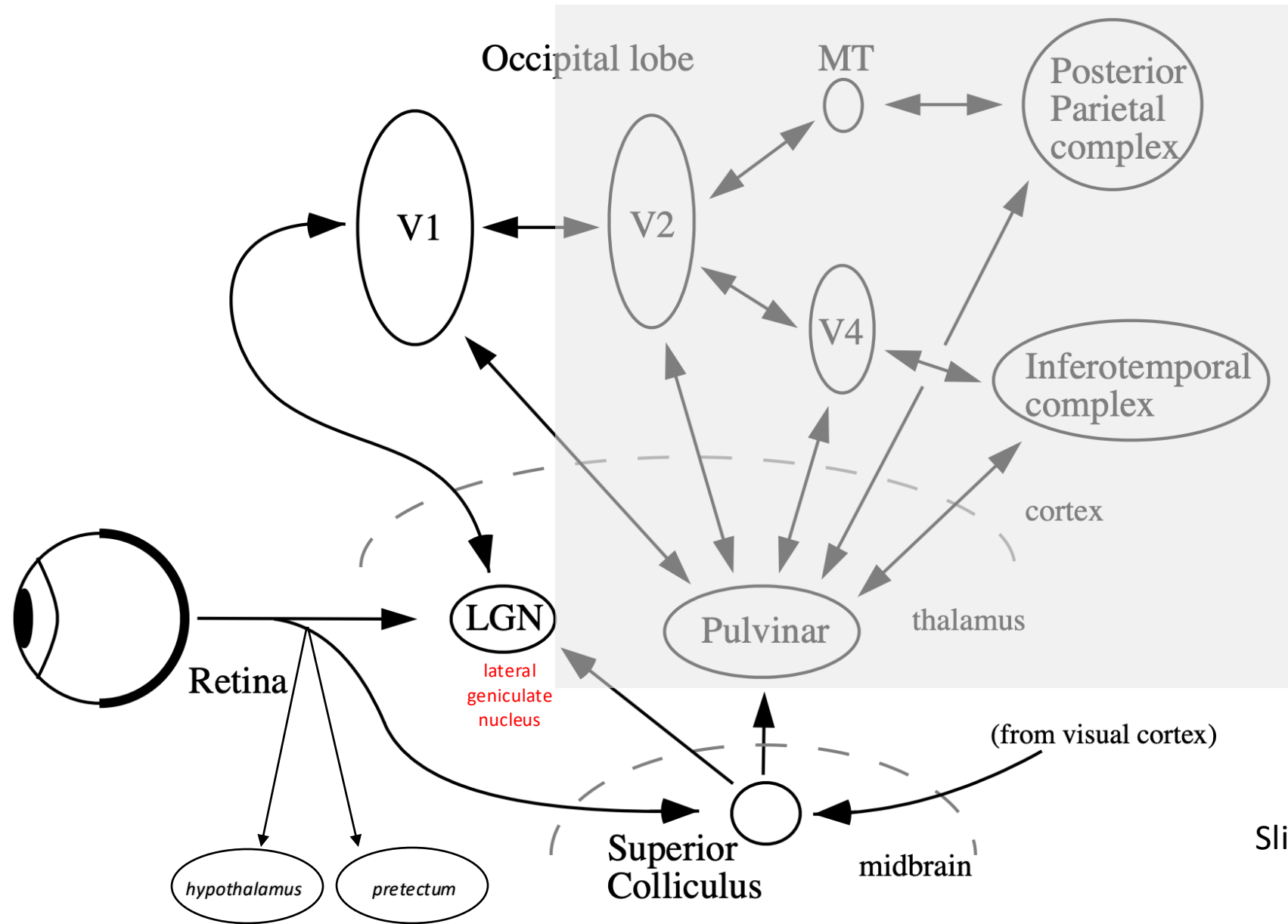
Buzzard:
- Hunting behavior

Mouse:
- appropriate defense behavior
(depending on visual input information!)

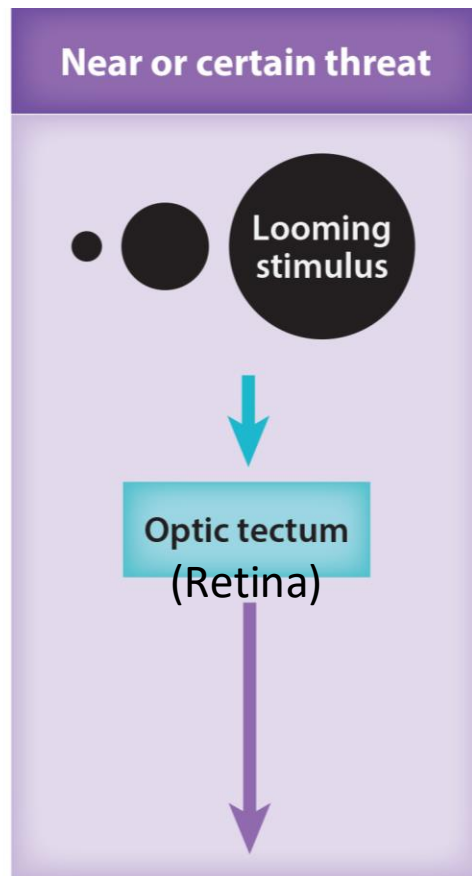


from: De Franceschi et al.
2016, Curr. Biology

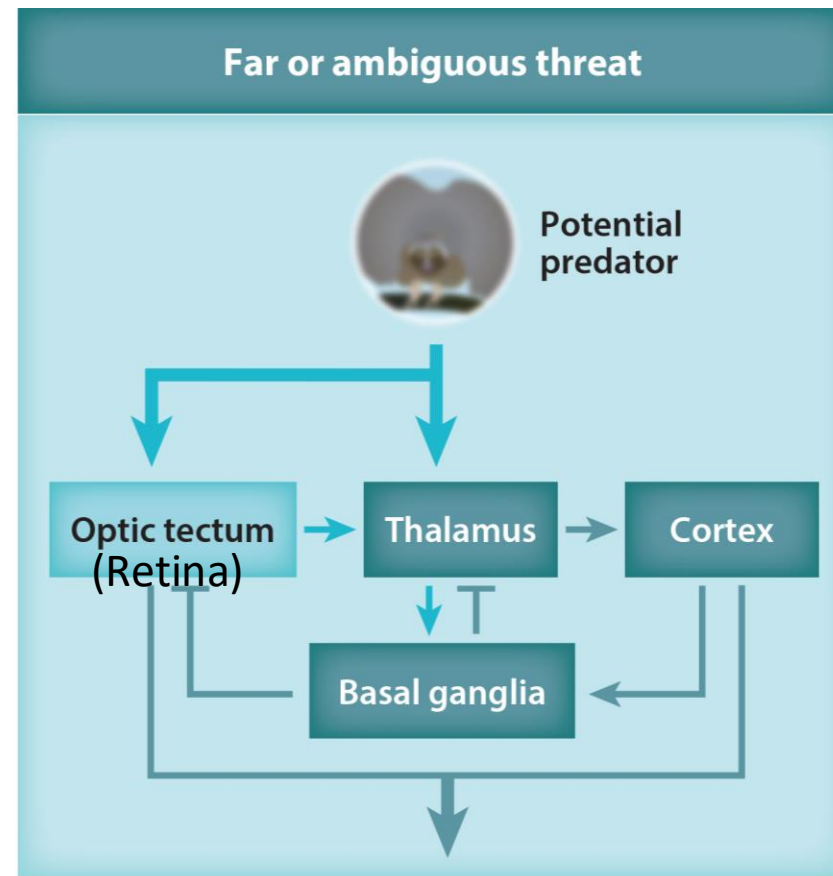
Visual information processing pathways



Slide adapted courtesy of Prof. Bruno Olshausen



Escape execution
(midbrain/hindbrain/spinal cord)



further evaluation (forebrain)
later, execution of appropriate behavior

- a **Looming stimulus** signals **impending collision**

- requires **immediate, "ballistic"** response:
(retina → sup. Colliculus) → midbrain / hindbrain motor areas
(motor areas: see later units!)

Escape behavior in the lab



Mouse

Expanding spots



Ultrasonic sweeps

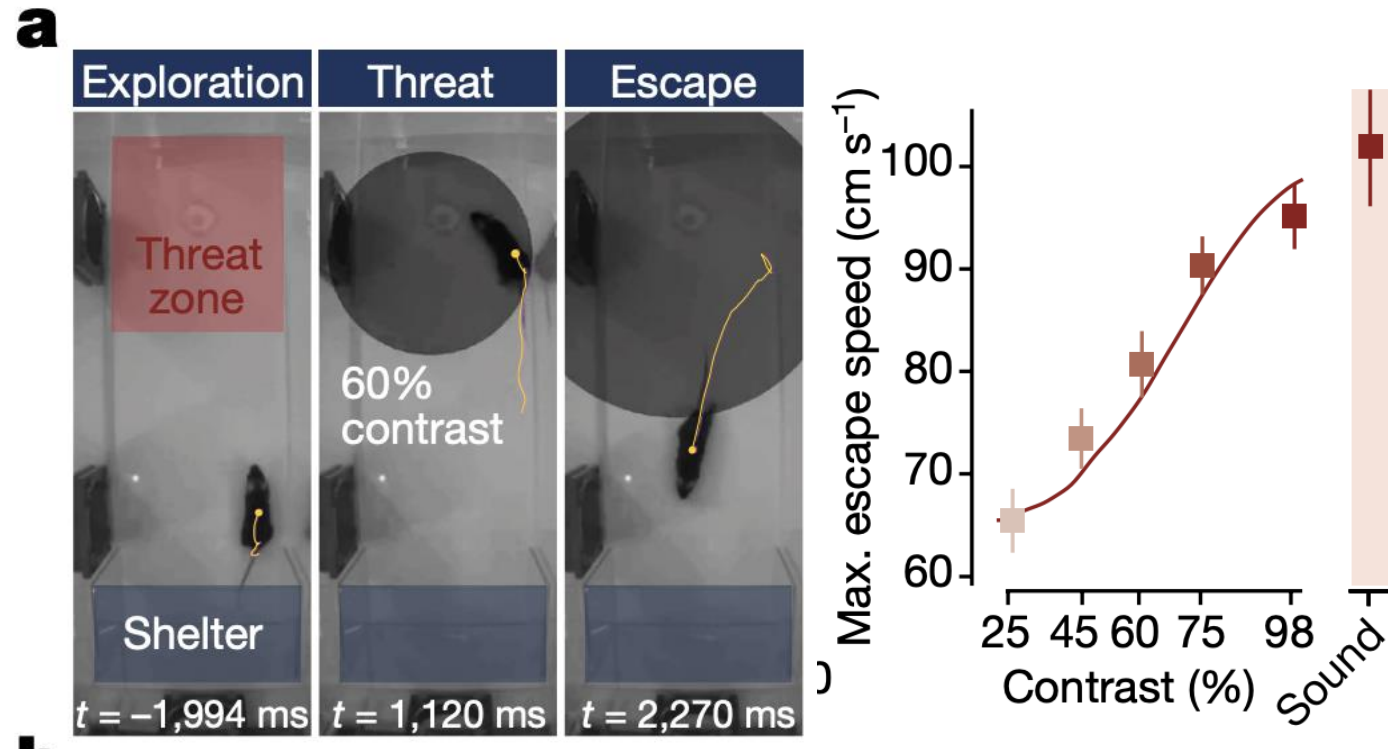


Innate threats

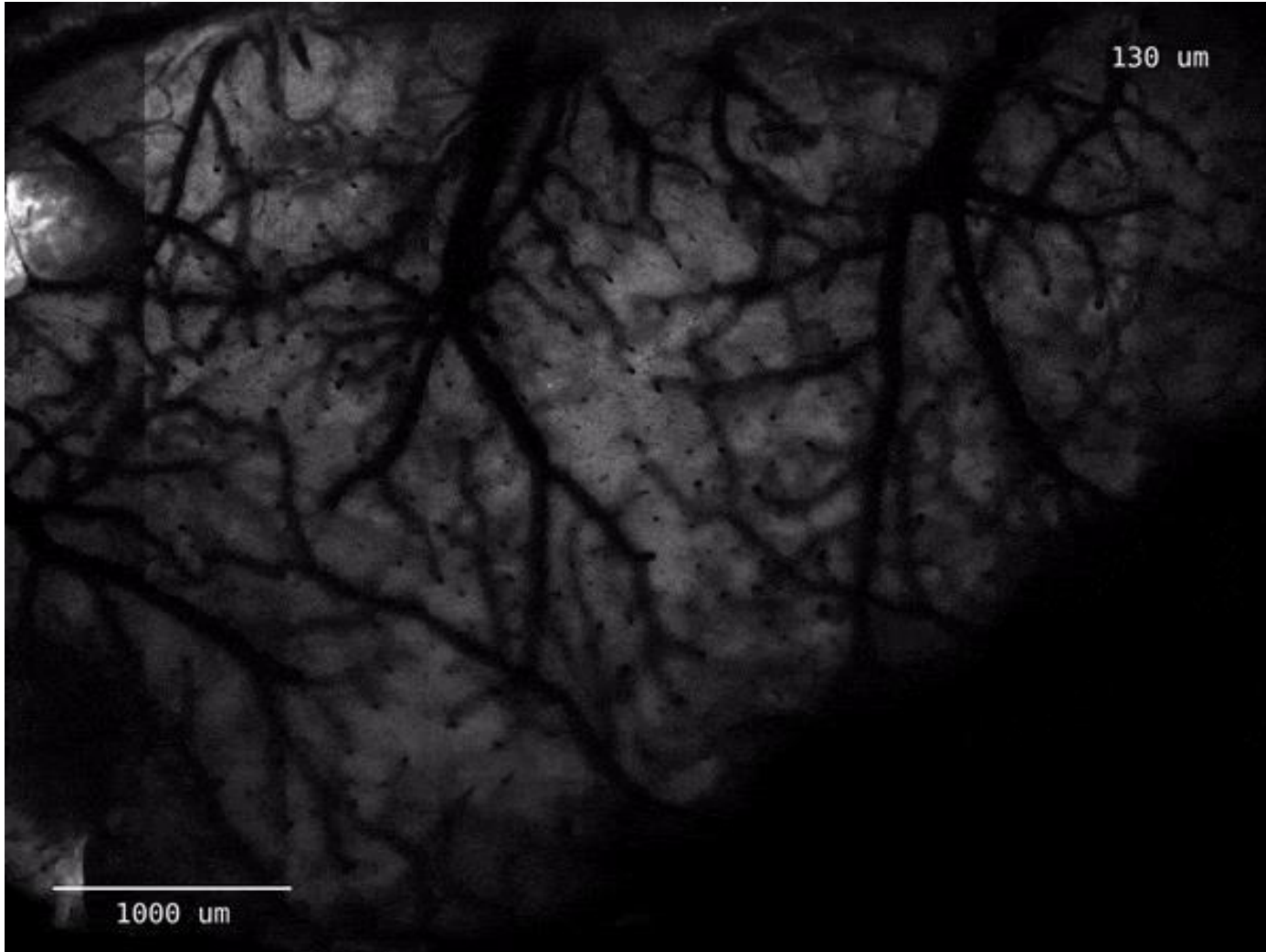


A synaptic threshold mechanism for computing escape decisions

Dominic A. Evans^{1,2,3}, A. Vanessa Stempel^{1,2,3}, Ruben Vale^{1,2}, Sabine Ruehle^{1,2}, Yaara Lefler^{1,2} & Tiago Branco^{1,2*}

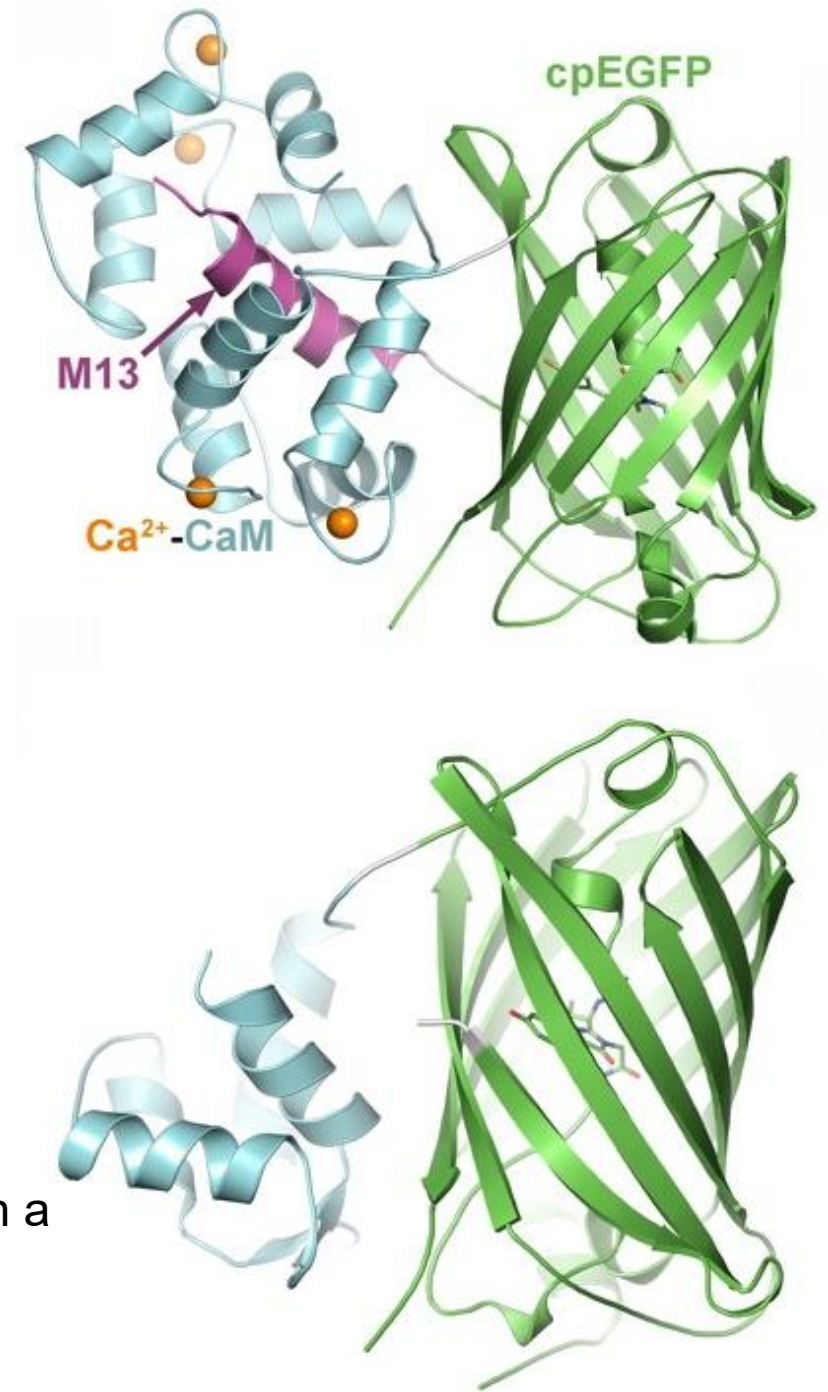


*GCaMP imaging

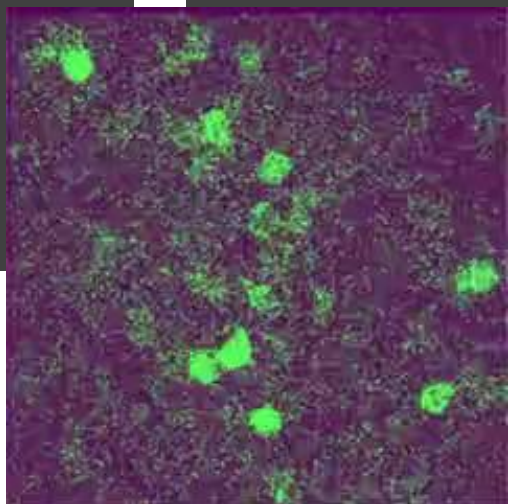
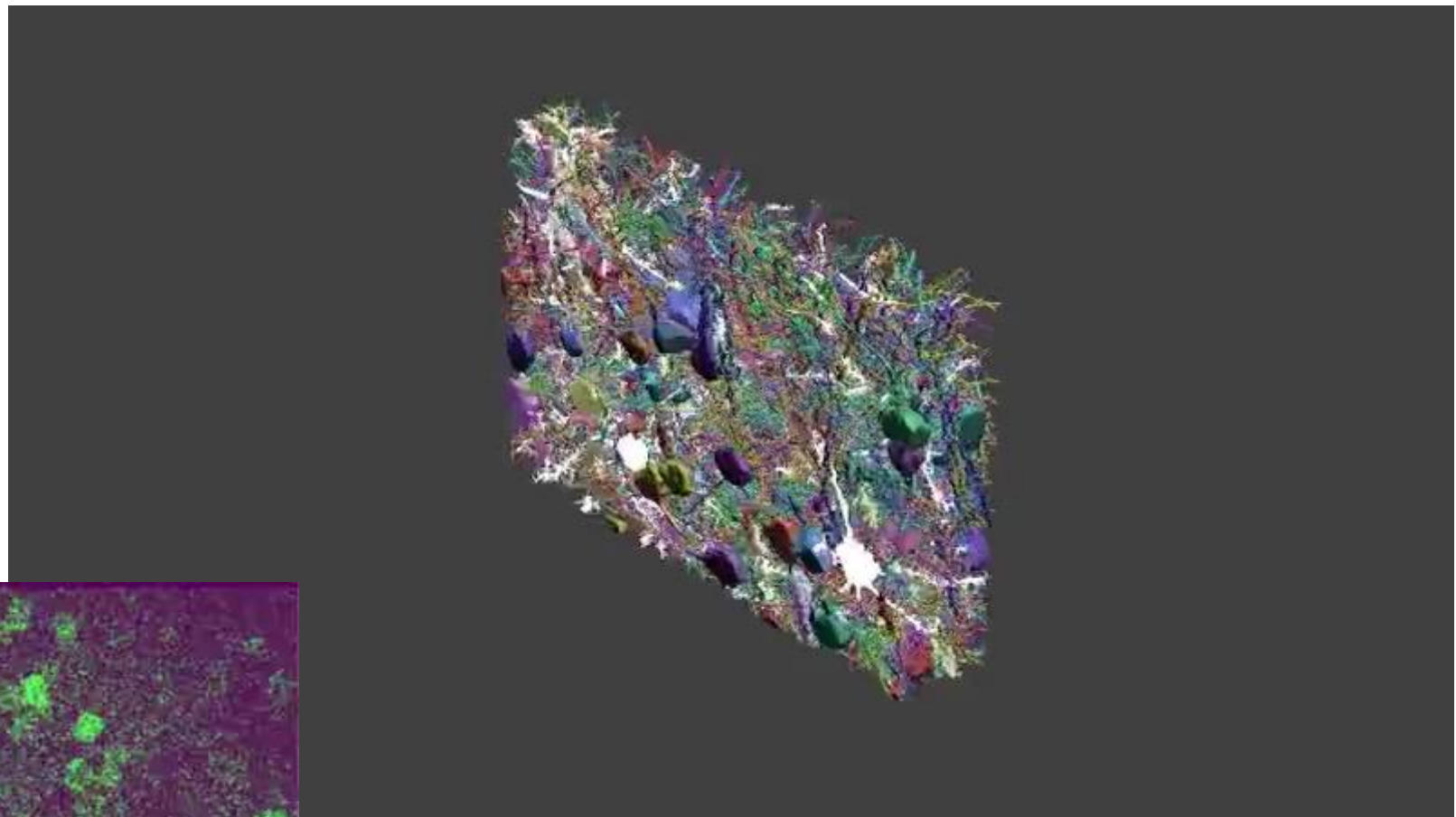
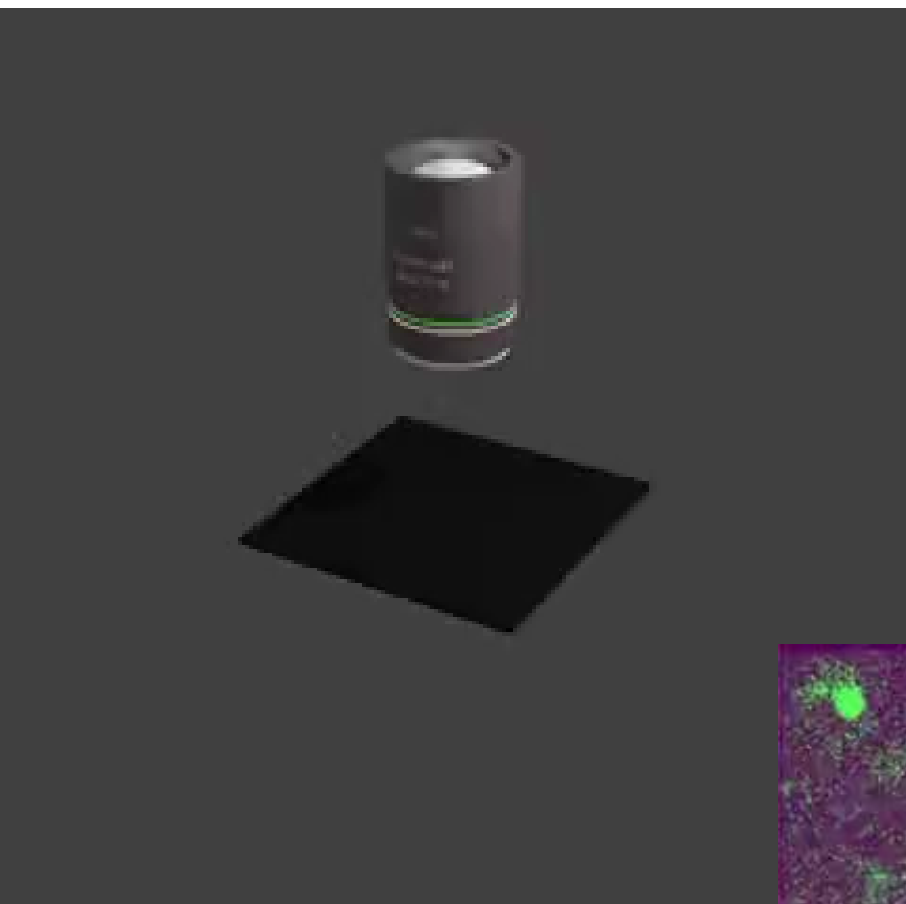


Sofroniew et al 2016 eLife

When bound to Ca^{2+} , GCaMP fluoresces green with a peak excitation wavelength of 480 nm and a peak emission wavelength of 510 nm

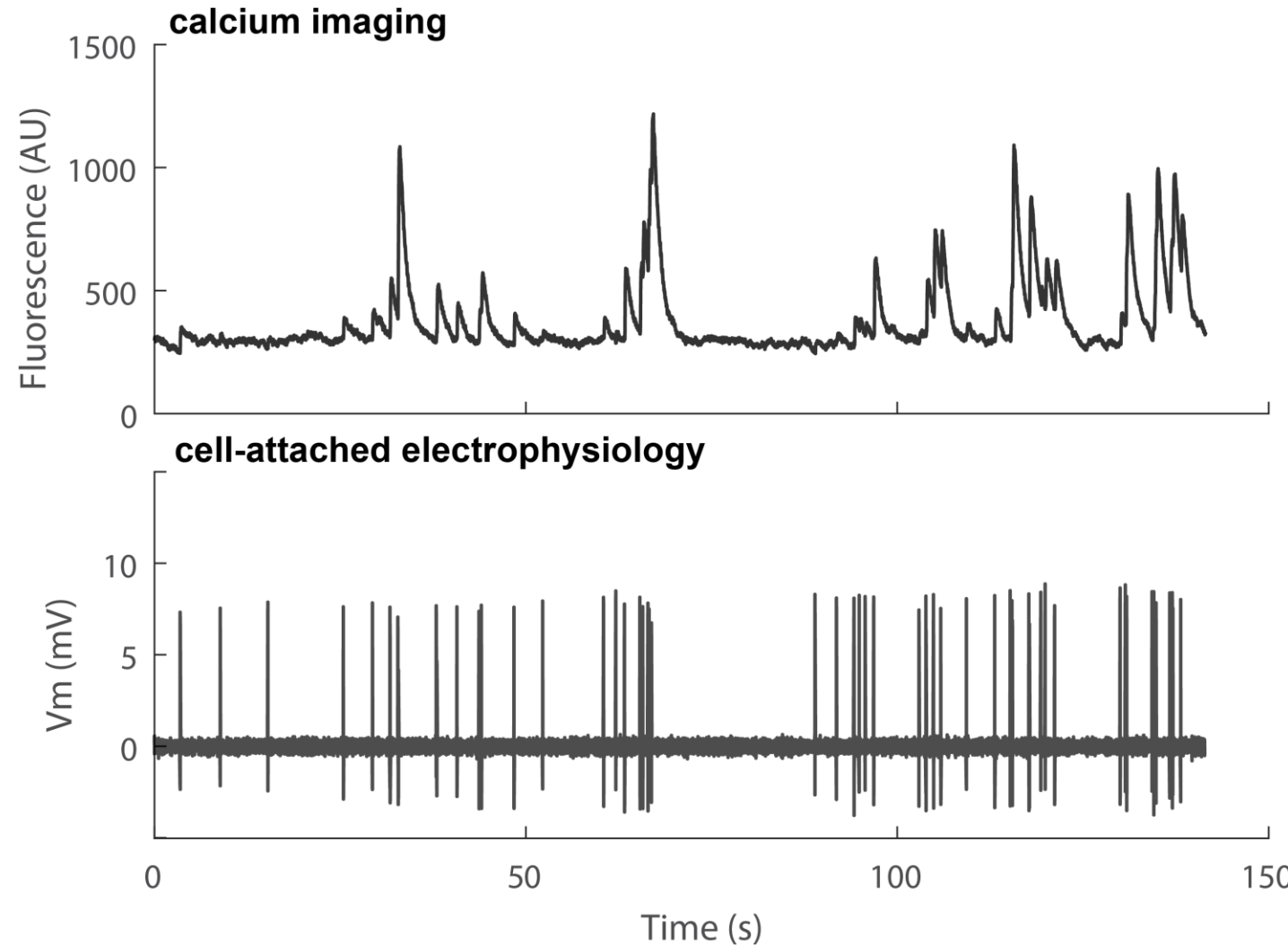
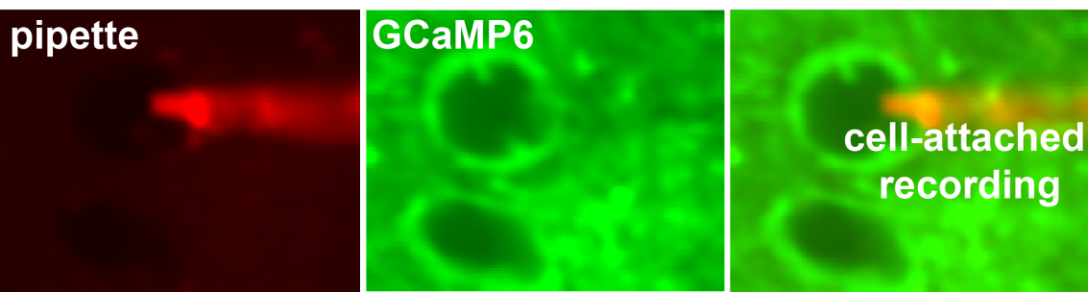
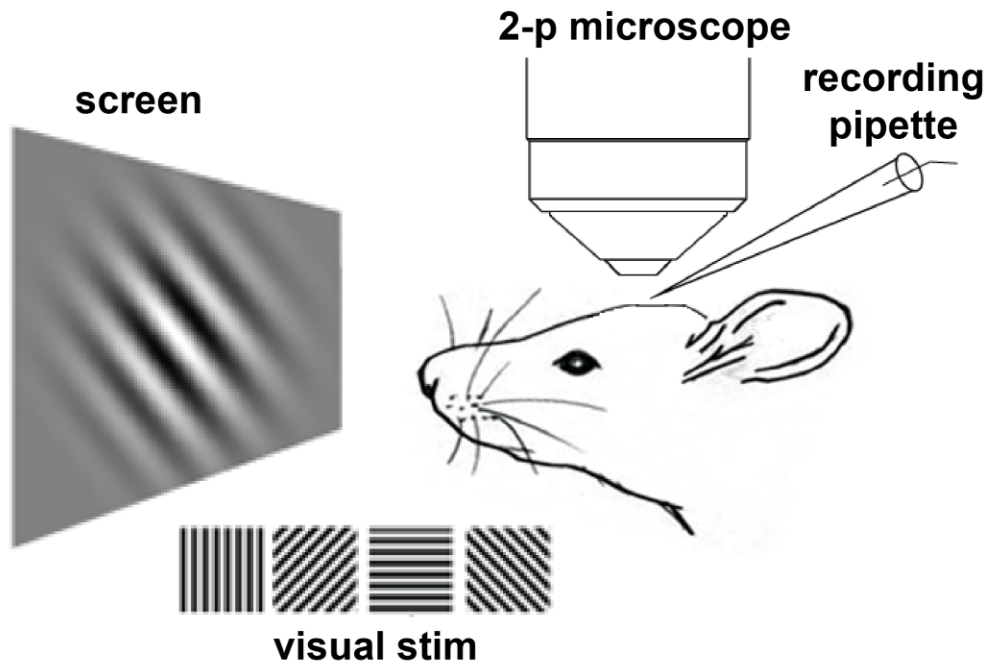


GCaMP imaging in mice



Courtesy of Prof. Andreas Tolias

GCaMP imaging in mice



JOINTLY RECORDED NEURONS AT MULTIPLE LEVELS OF MAGNIFICATION.

The dataset consists of 91 neurons from 4 transgenic mouse lines for which calcium imaging was performed at high optical zoom focused on individual cells. A subset (37) of these neurons were additionally imaged at a lower zoom factor, i.e. one at which the responses of many neurons can be characterized in parallel. The dataset is described in Huang, Knoblich et al., *Relationship between spiking activity and simultaneously recorded fluorescence signals in transgenic mice expressing GCaMP6*.



Visual Behavior - 2P

Transgenic Mice

Surgery

ISI Mapping

Behavior

In Vivo Physiology

Perfusion

Ex Vivo Imaging

Data Processing

Web Product



Change Detection



Single-plane 2P



2P Serial Tomography



Habituation



Multi-plane 2P



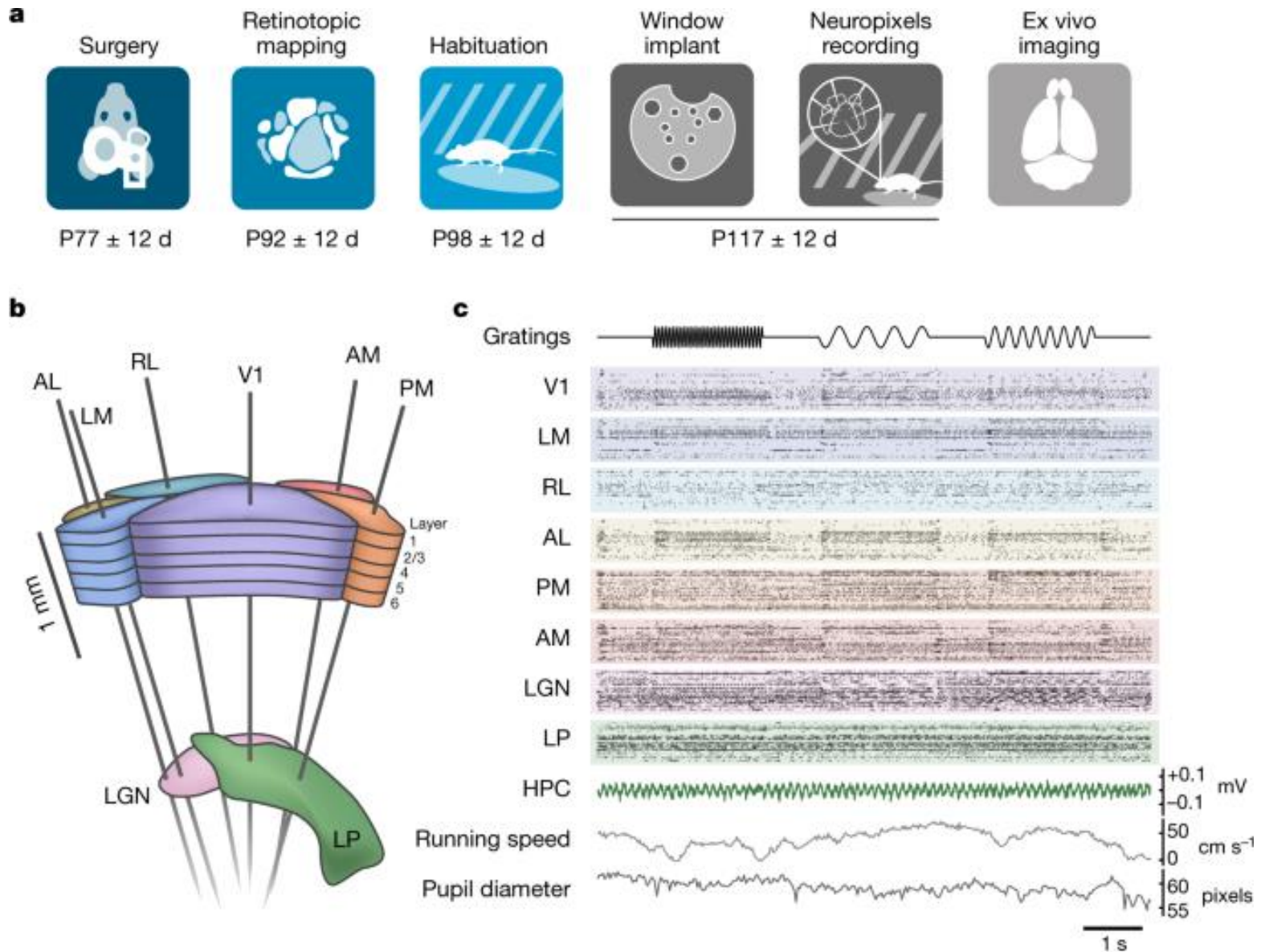
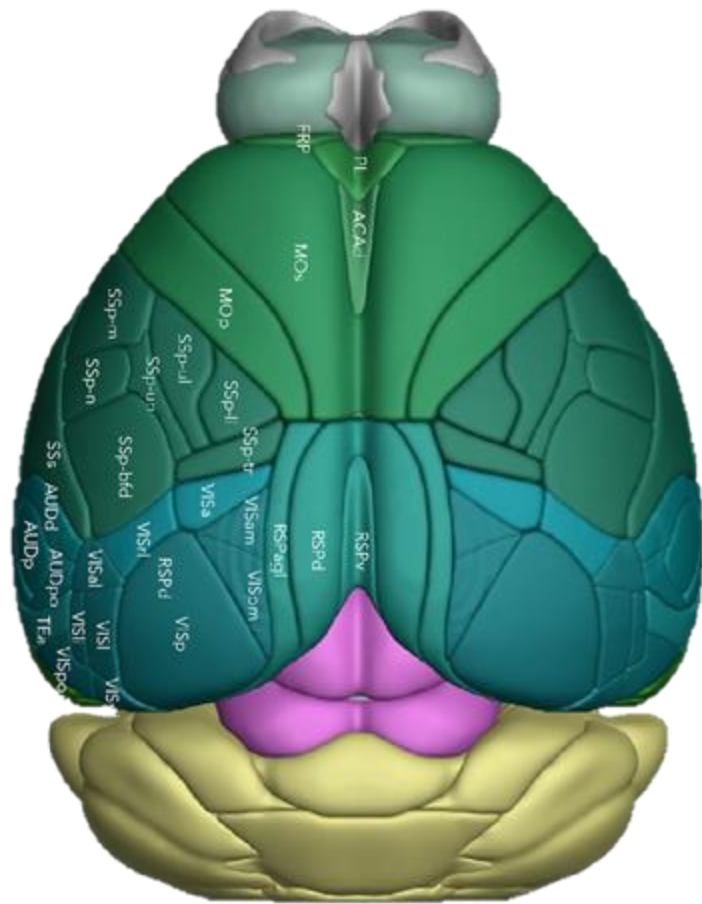
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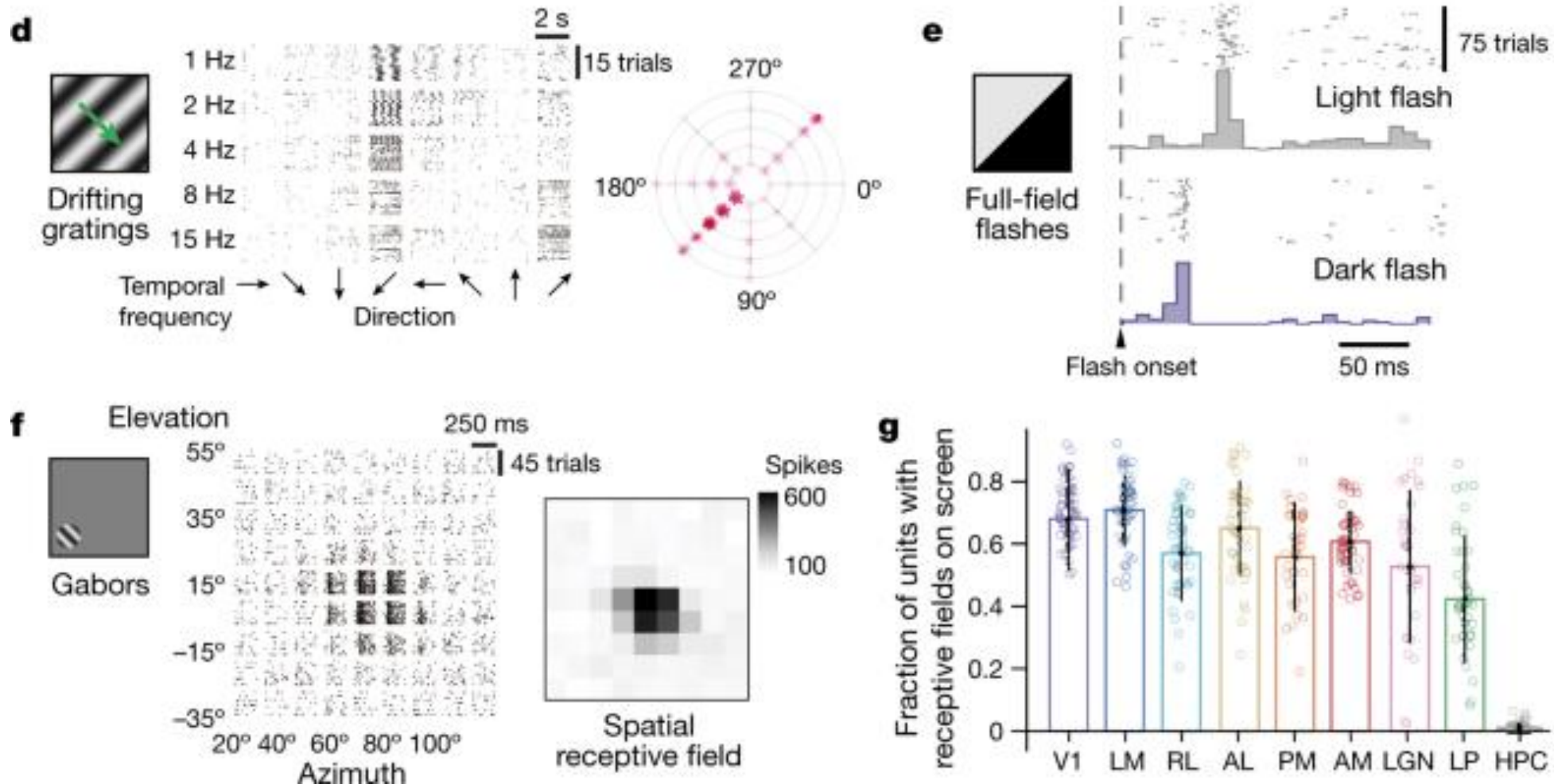
Neuropixels



Survey of spiking in the mouse visual system reveals functional hierarchy

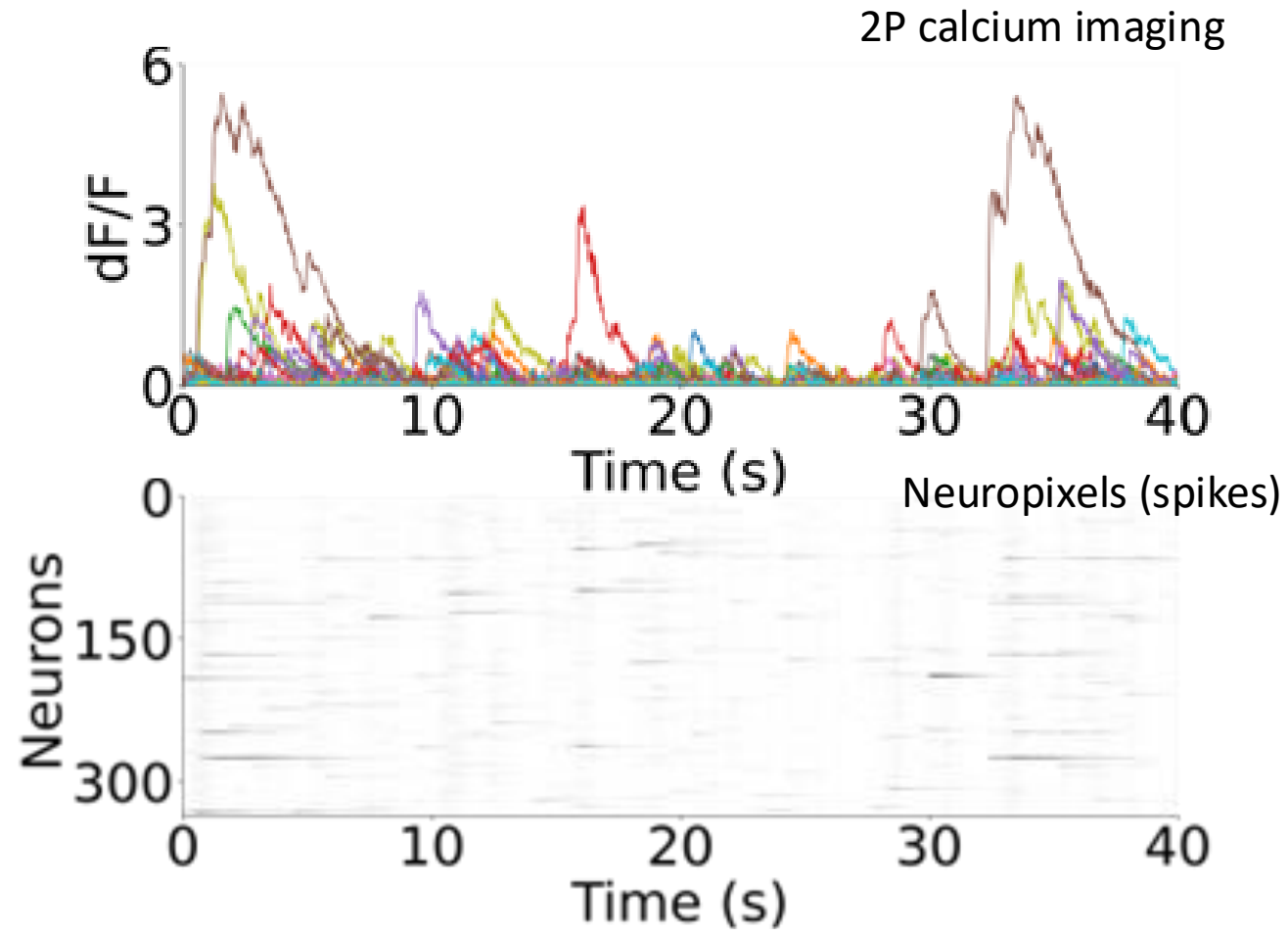
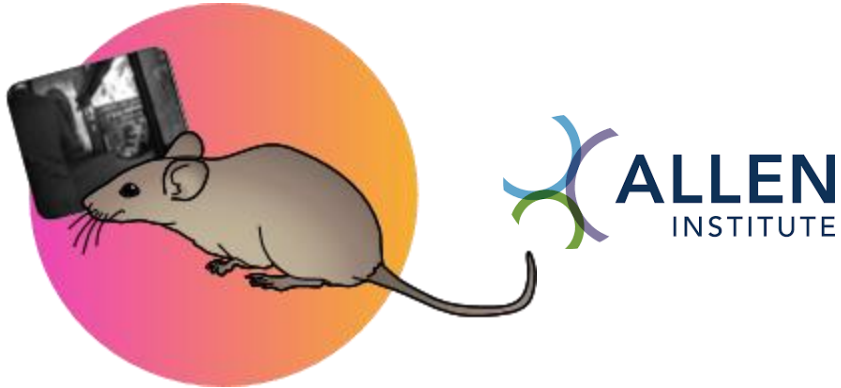


Survey of spiking in the mouse visual system reveals functional hierarchy



What type of cells would respond to this grating?

Encoding & Decoding models for Vision: what information is “encoded” in V1, and what information can we “decode?”



Data: de Vries et al. (2020)
Deitch, Rubin, and Ziv (2021)
Siegle et al. (2021)

Self-supervised encoder models

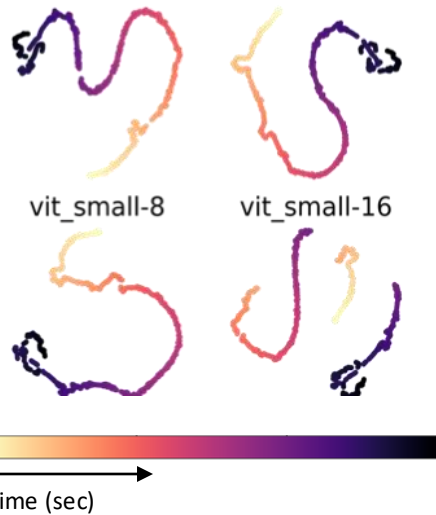
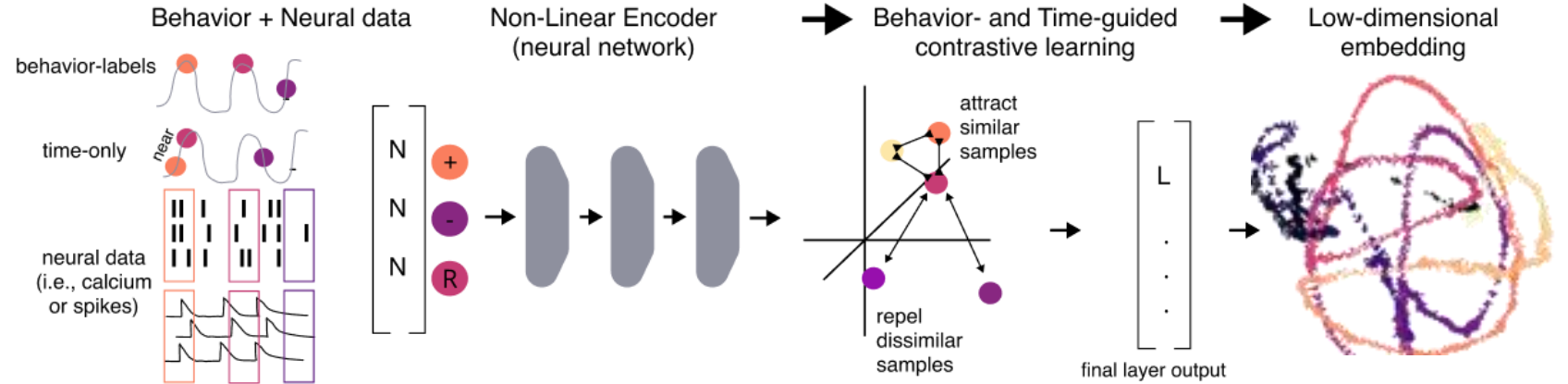


Pre-trained DINO

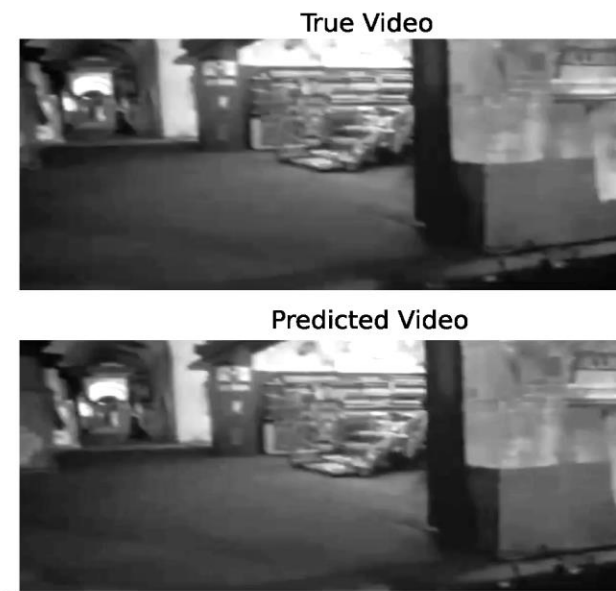
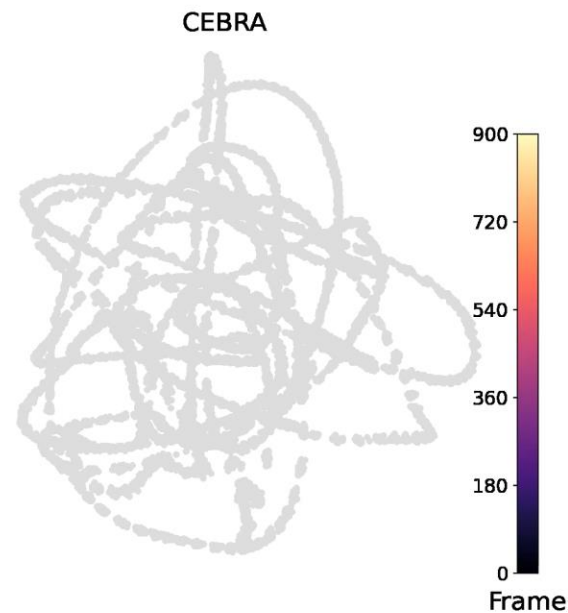
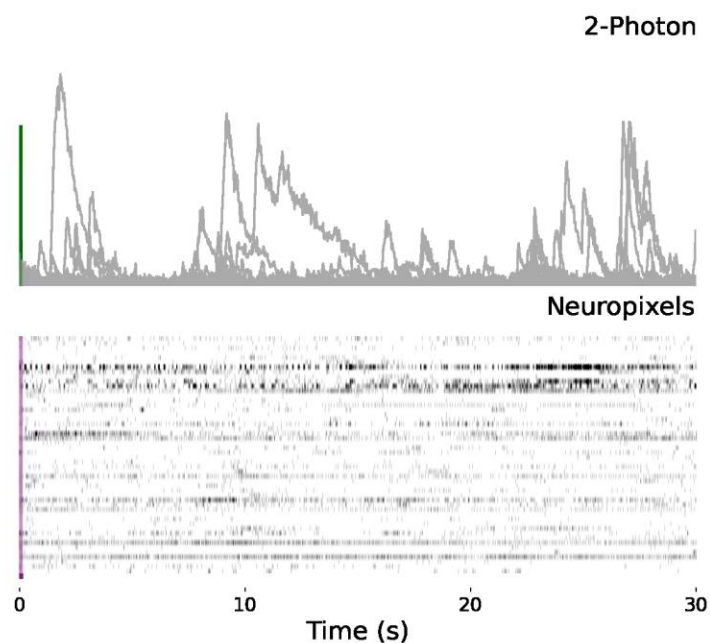


Caron et al 2021 arxiv

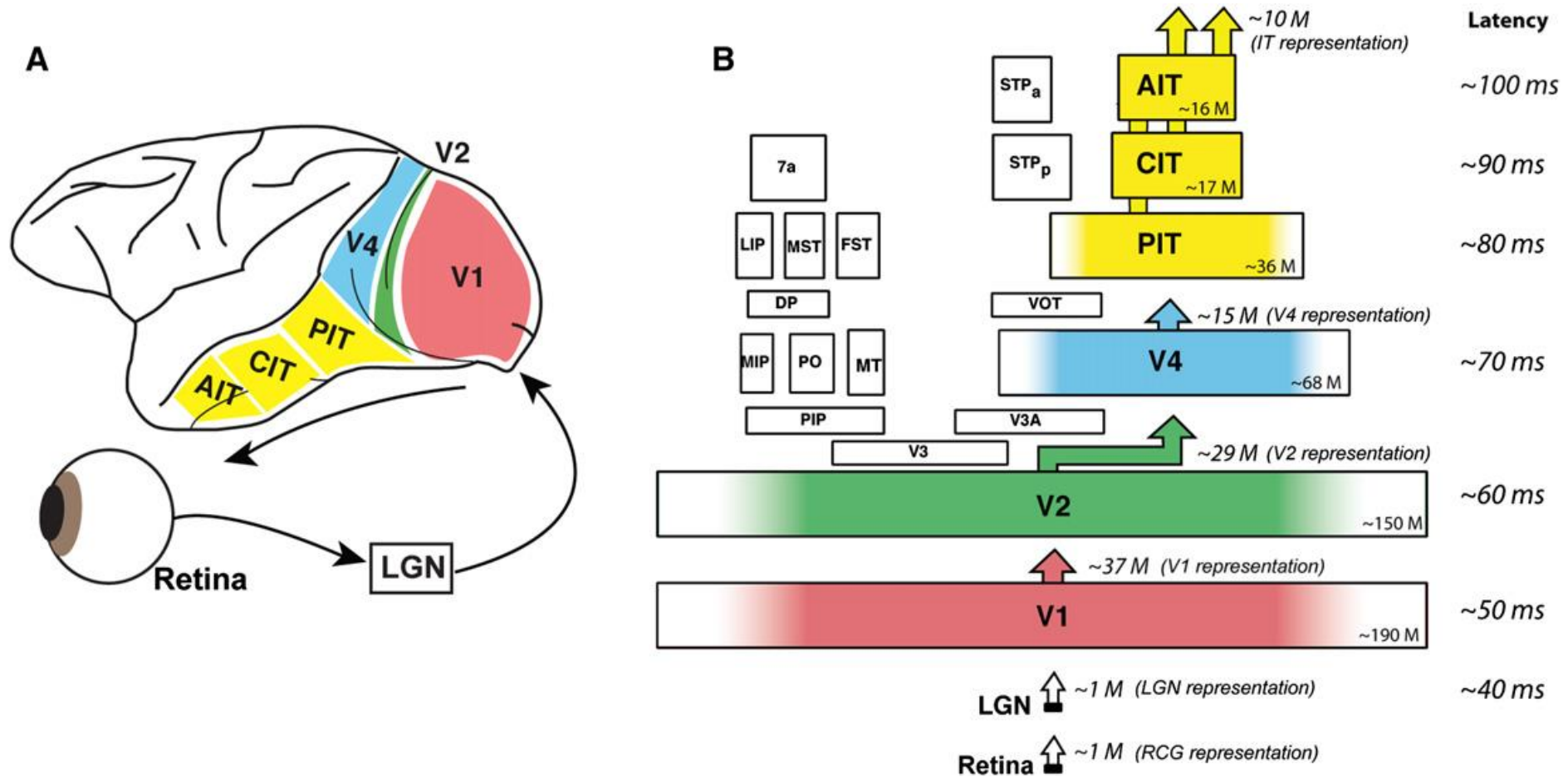
Emerging Properties in Self-Supervised Vision Transformers



Decoding from primary visual cortex of mice



Visual brain areas of cortex in the rhesus macaque



Summary

Important concepts and keywords

- Be able to describe the pathway of information flow from retina to higher visual areas of cortex (V1 -> V2, etc).
 - There are 4 projection pathways, you should know them!
- Describe what cell types are in the LGN, and how they process information (contra, ipsi)
- What is the relation from LGN to primary visual cortex (where does it project? What layer?)
- What are the 6 layers of visual cortex? (is this layering in all cortex?)
- What is a receptive field?
- Describe simple and complex cells
- How does ecological niche and evolution shape vision
- What are some of the modern tools we use to study active vision? (GCAMP imaging, computer vision, clever behavioural paradigms)