Sensory Systems and Perception: Vision

Week 5

Martin Schrimpf

Slide credit: structure and content adapted from
EPFL BIO-311 (P. Ramdya) and MIT 9.017 (R. Desimone)

Learning Objectives – Week 5

Describe the key components involved in vision.

Know what V1 responds to and the Hubel & Wiesel experiments.

Explain receptive fields.

Understand how a Gabor model relates to early vision.

Explain the visual hierarchy.

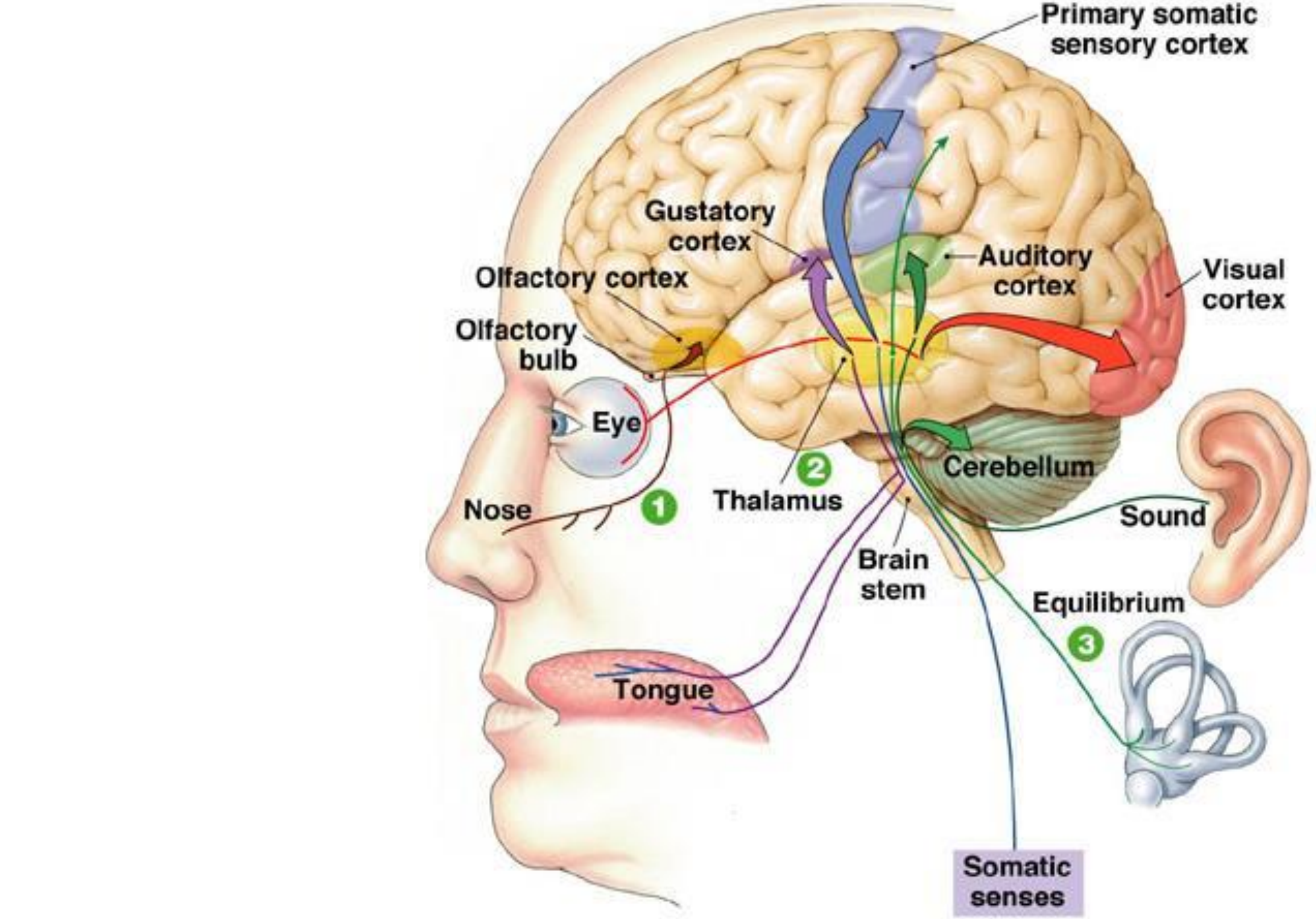
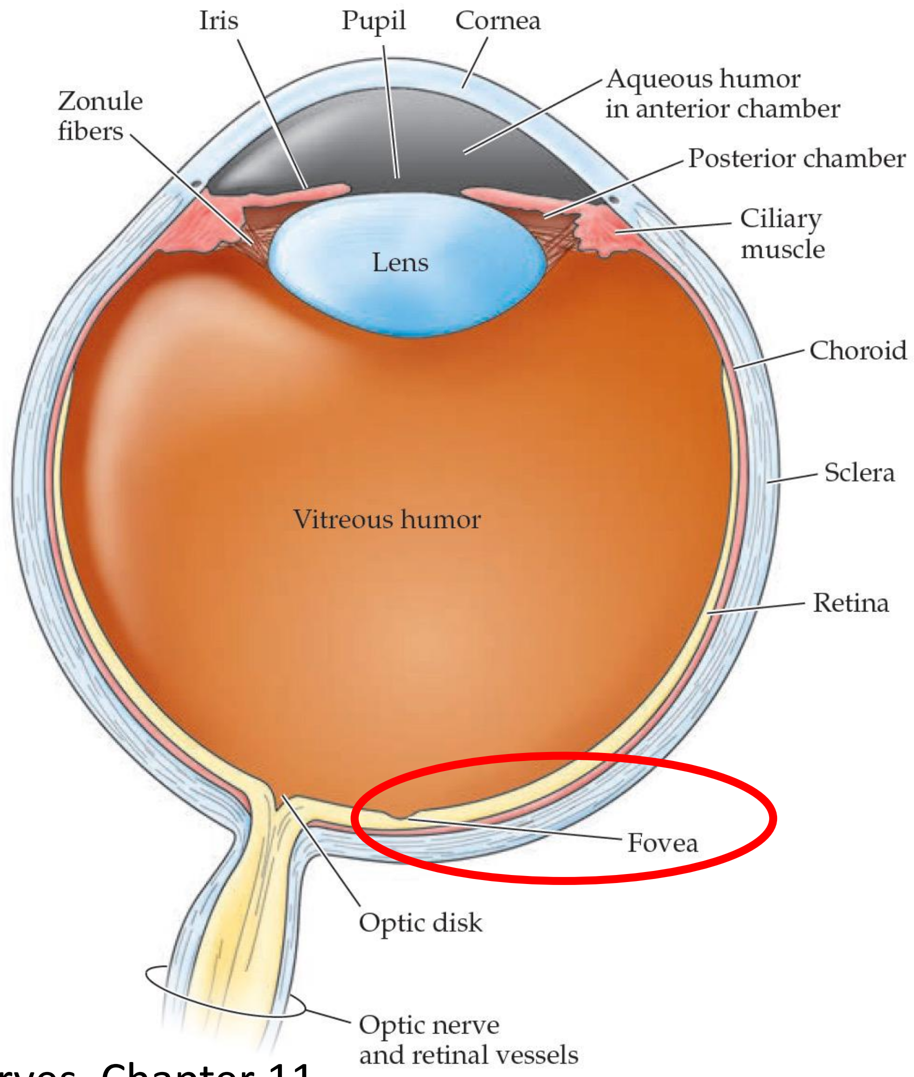
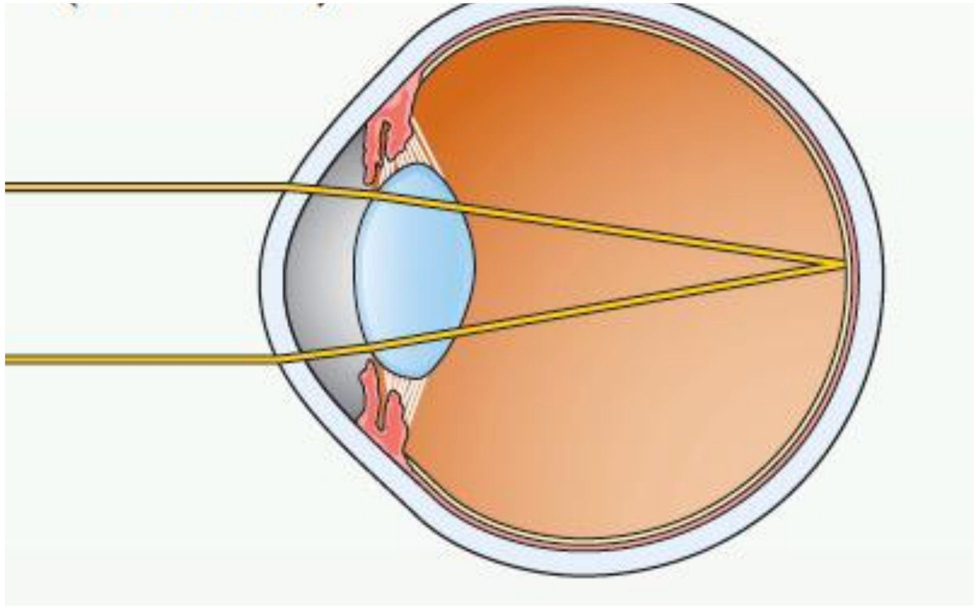


Fig. 10-4

Courtesy of Bob Desimone's class MIT 9.017

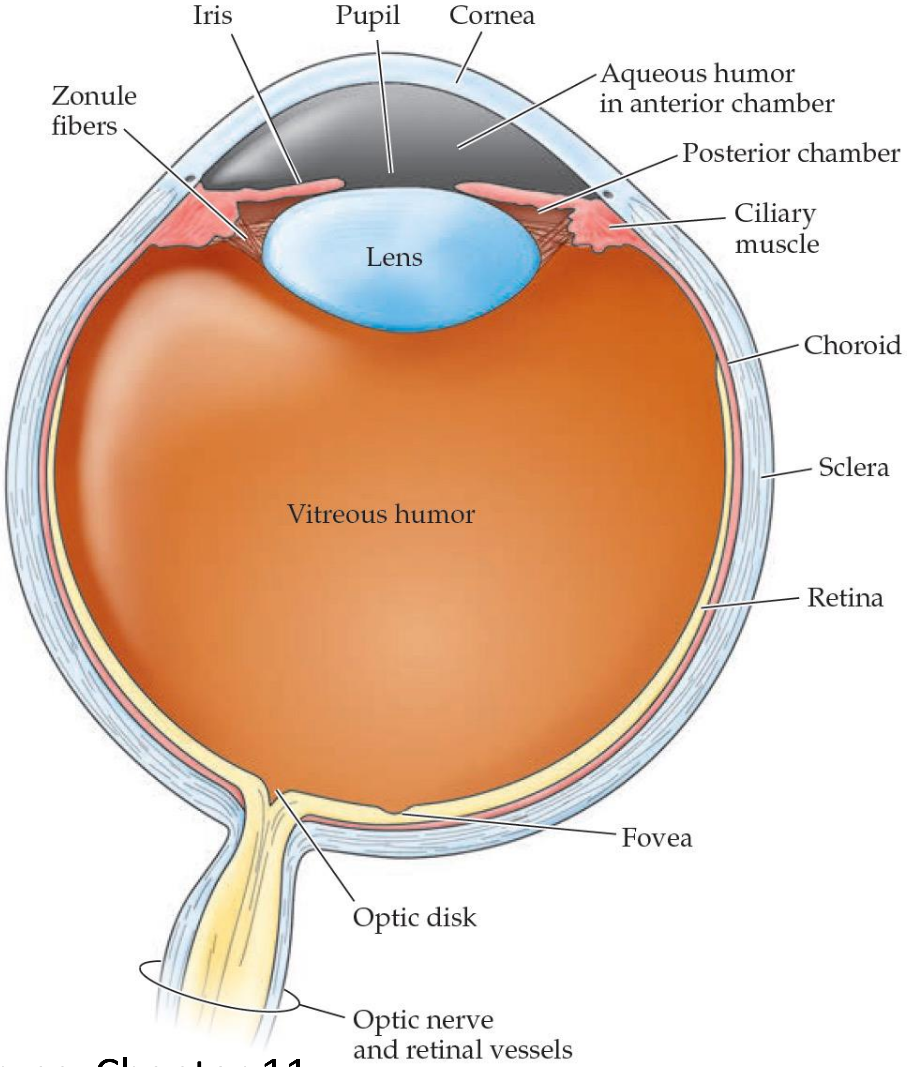
Retina

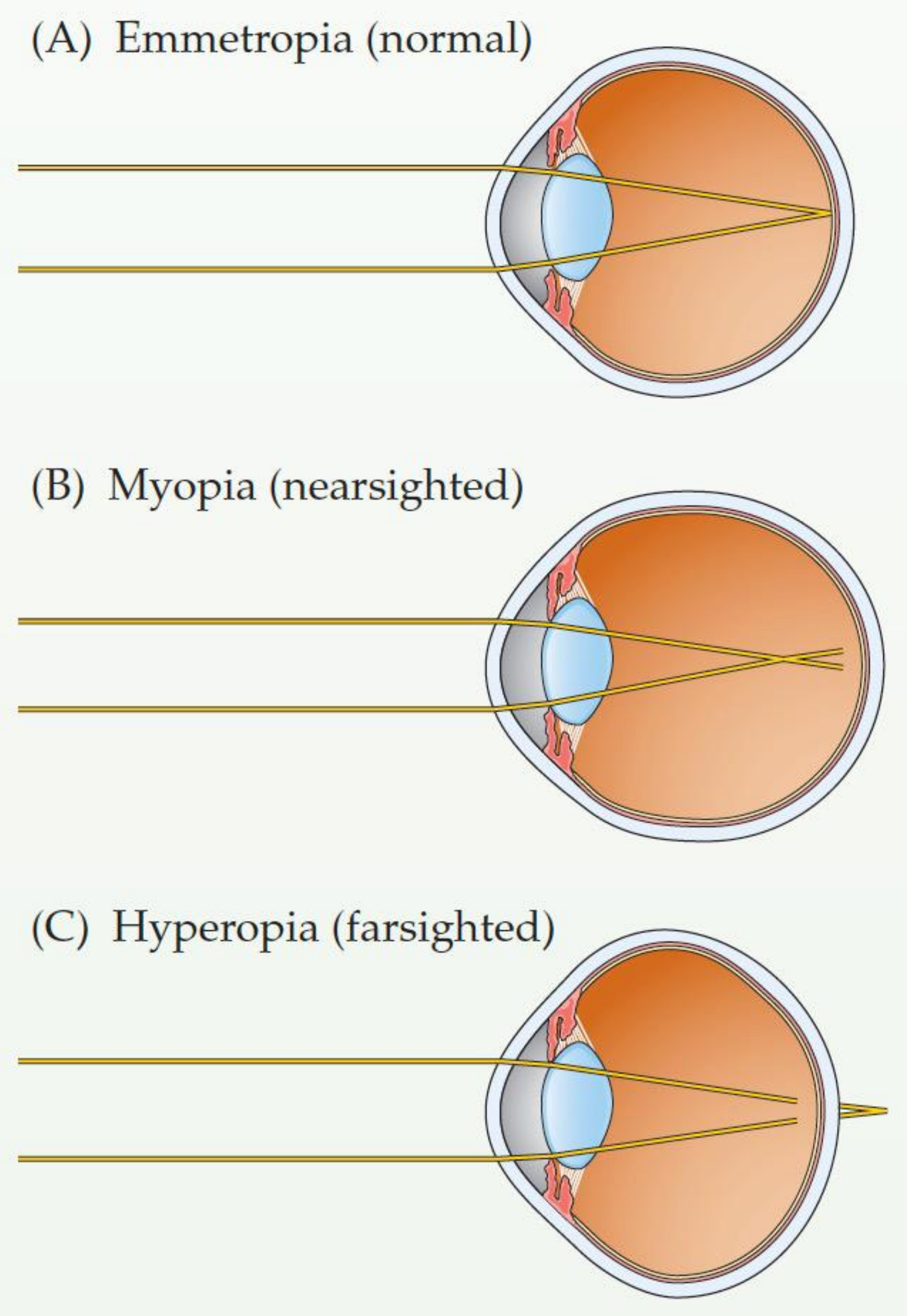




Purves, Chapter 11

Retina





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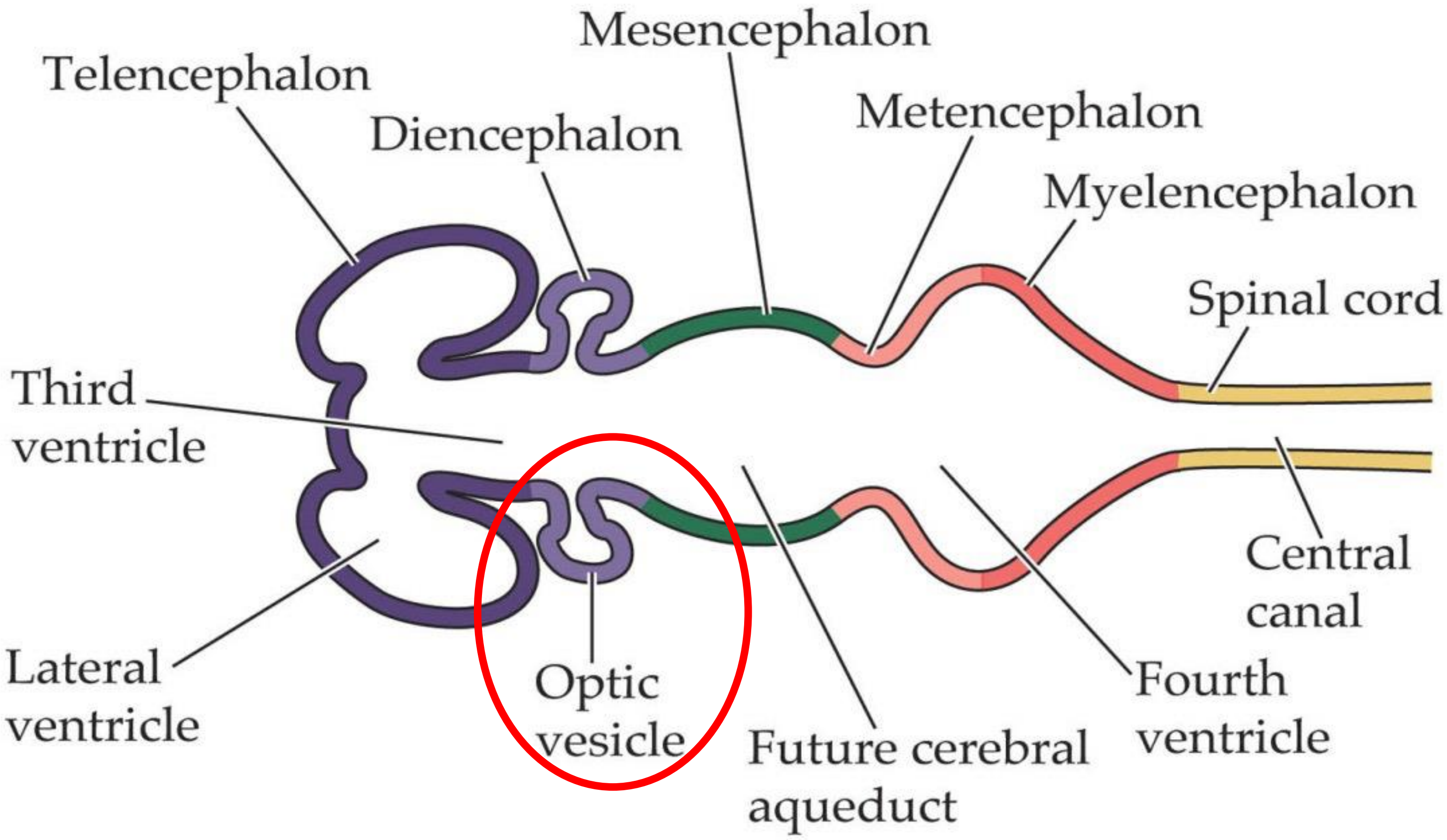
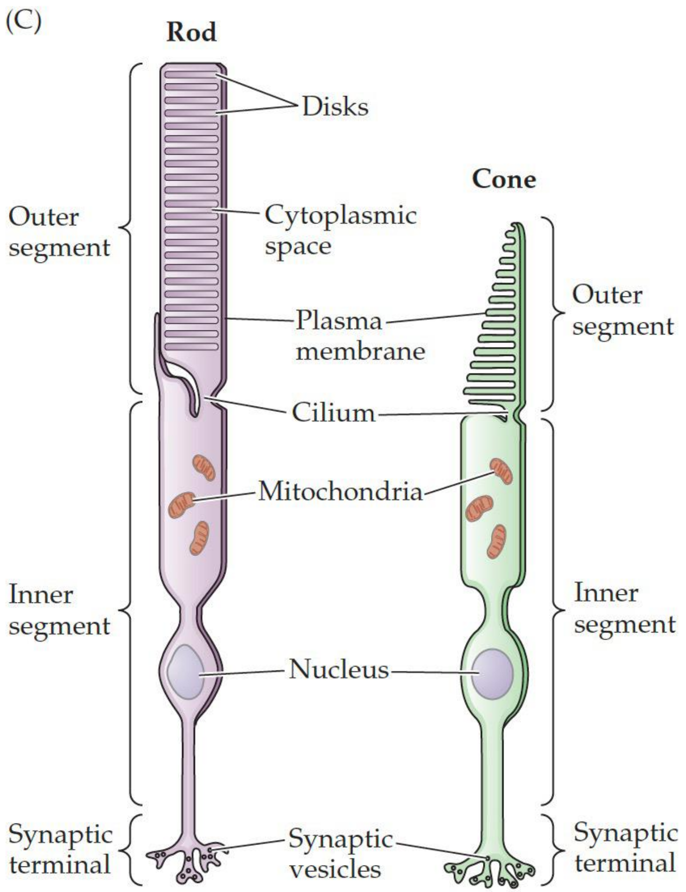
Retina is part of central nervous system



NEUROSCIENCE, Third Edition, Figure 21.5 (Part 3)

Photoreceptor cells: rods and cones



Rods:
- Low spatial resolution
- High light sensitivity

Cones:
- High acuity (spatial resolution)
- Less light sensitive

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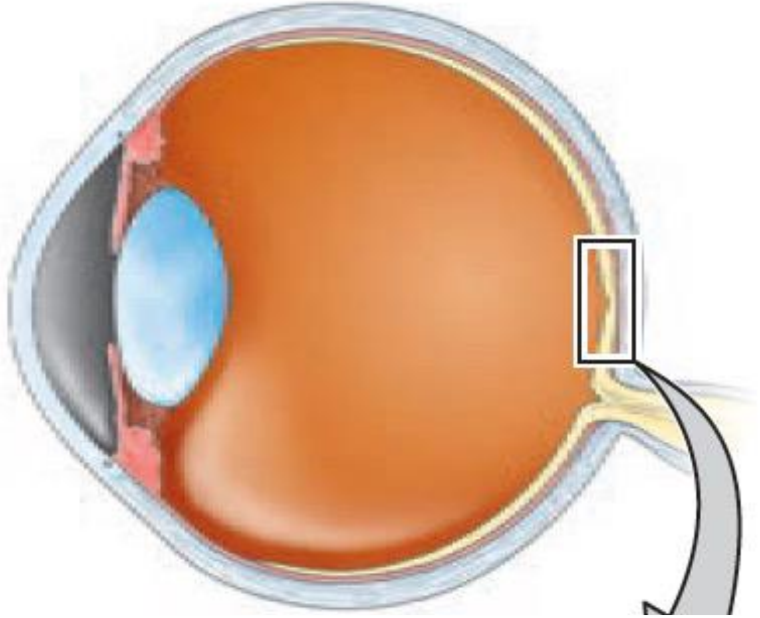
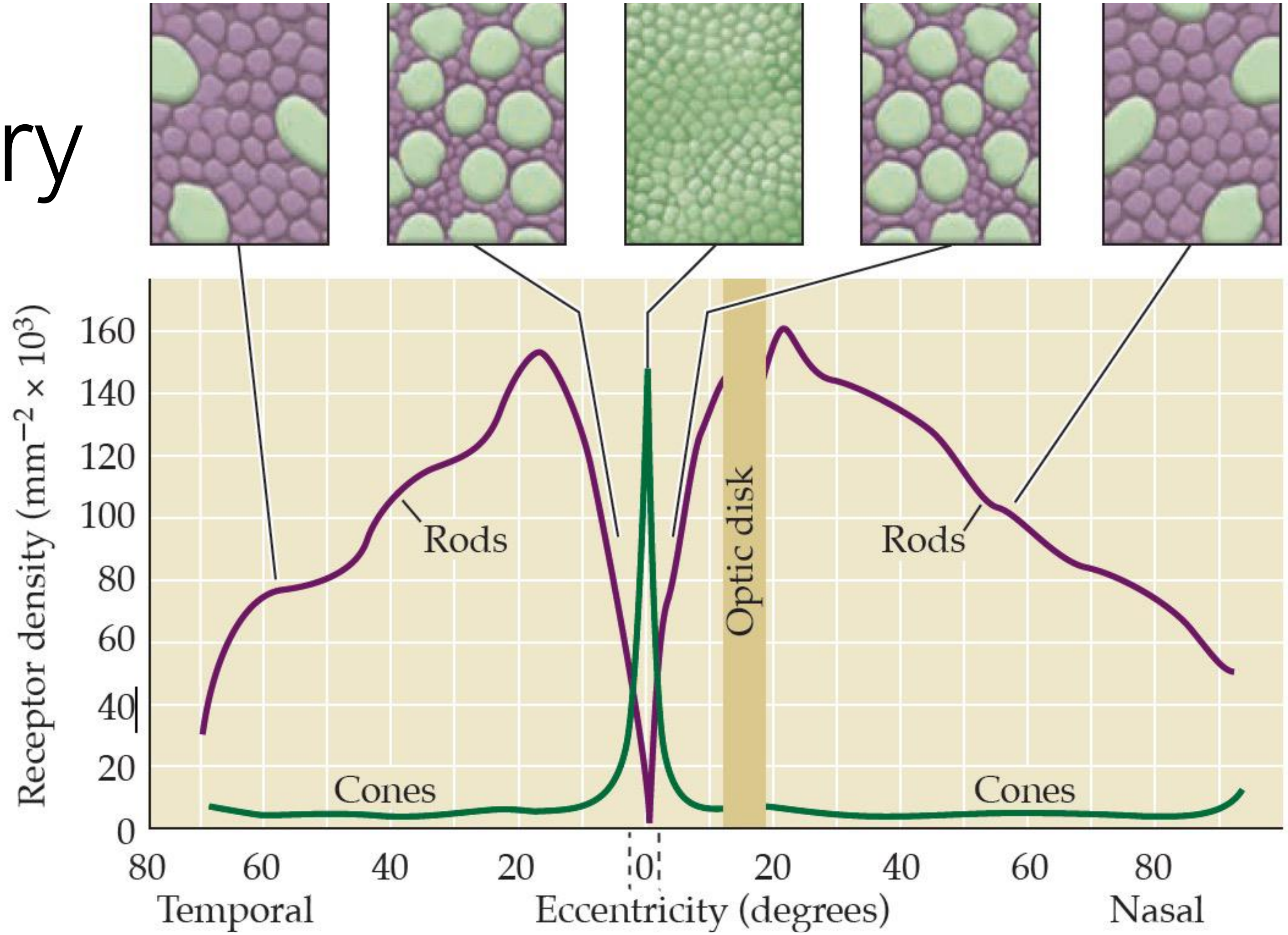
Fovea vs periphery





Fovea: high density of cones → better resolution

Periphery: rods > cones → worse resolution, better night vision

Optic disk: optic nerve to LGN → blindspot

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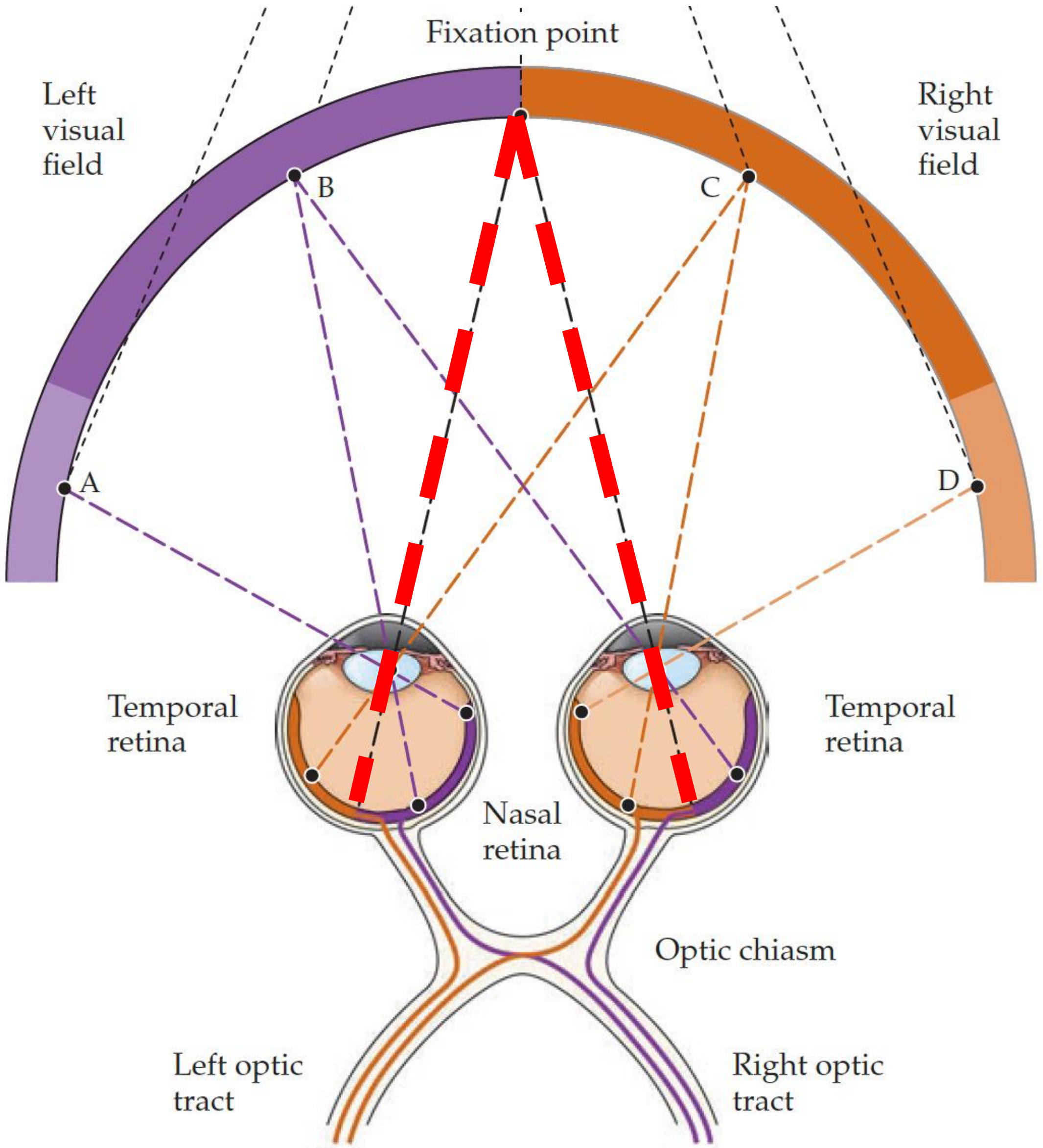
Fixation point falls on the fovea



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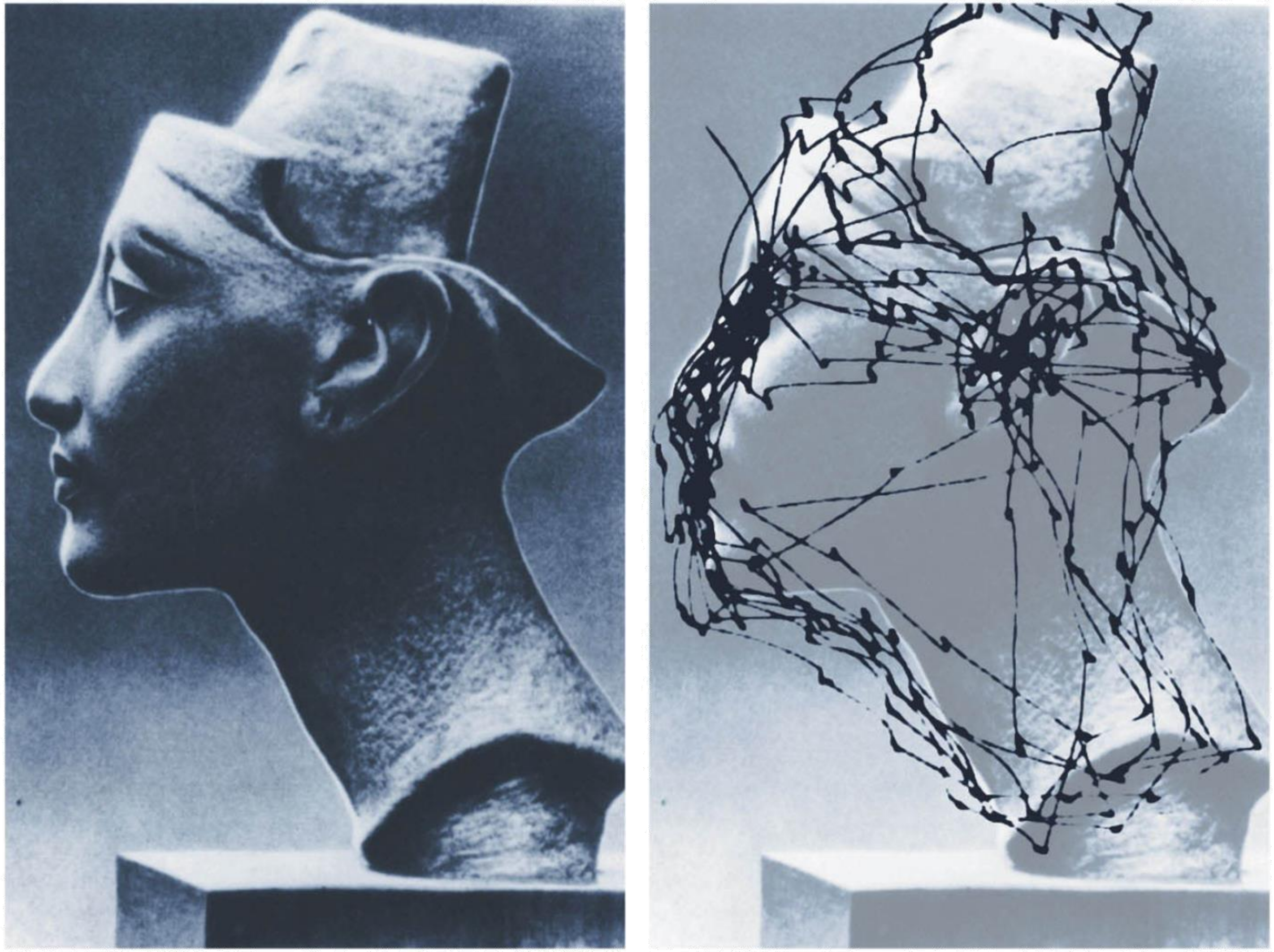
Foveation via saccades



To sample many parts of image at high resolution:

→Saccade to new point

→That part of the image can now be processed with high resolution (fovea)

→Repeat

NEUROSCIENCE, Third Edition, **Figure 19.1**

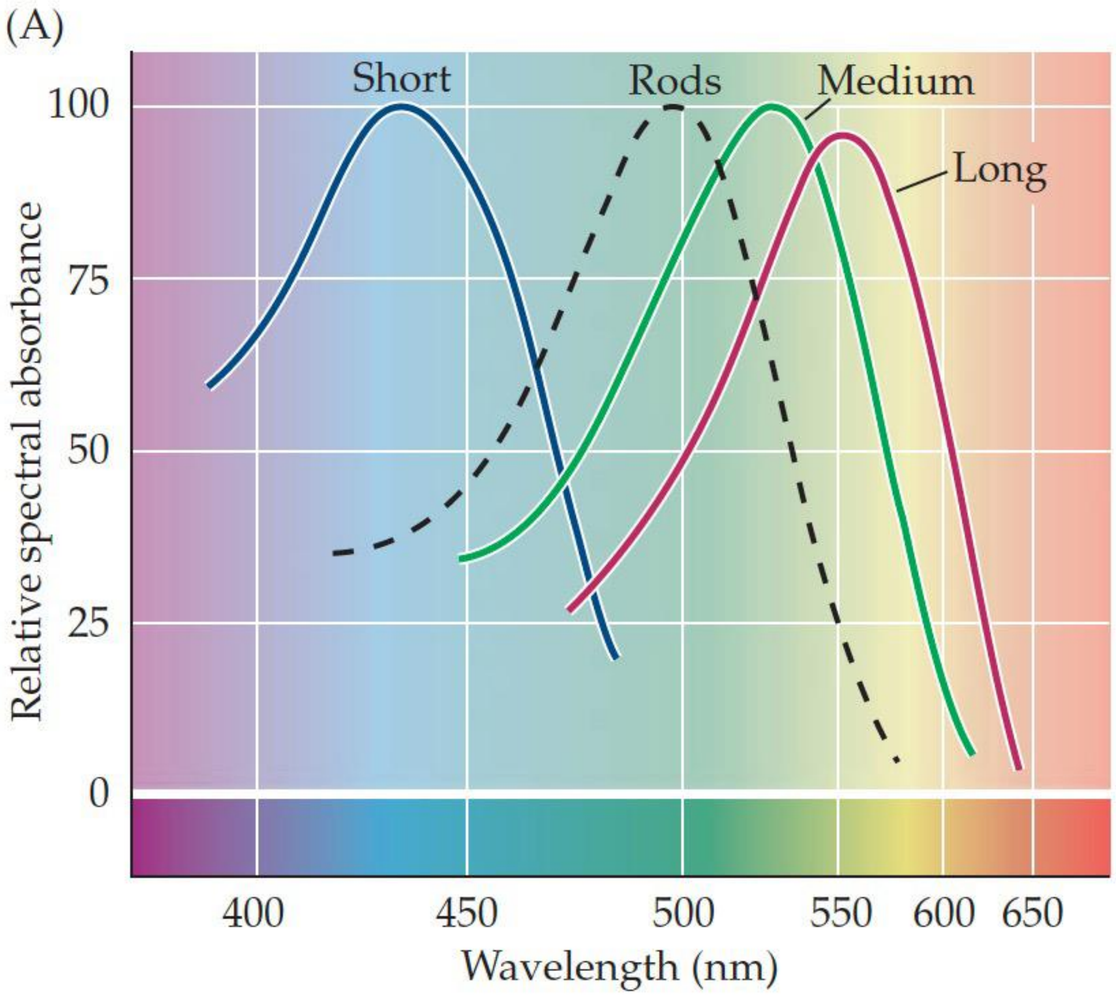
Blind spot

A demonstration of the blind spot:

Courtesy of Pavan Ramdya's class EPFL BIO-311

- Fixate on the cross (+) with your left eye (having your right eye closed)
- Move the image backward / forward around ~20 cm from the eye
- The circle should disappear (its image is on the blind spot!)
- The line will appear continuous (the image of the break is on the blind spot!)

Color vision is realized by 3 types of cones with different spectral sensitivities



S-cones M-cones L-cones

Identify specific colors via combination of cone activity.

~No color vision in periphery!

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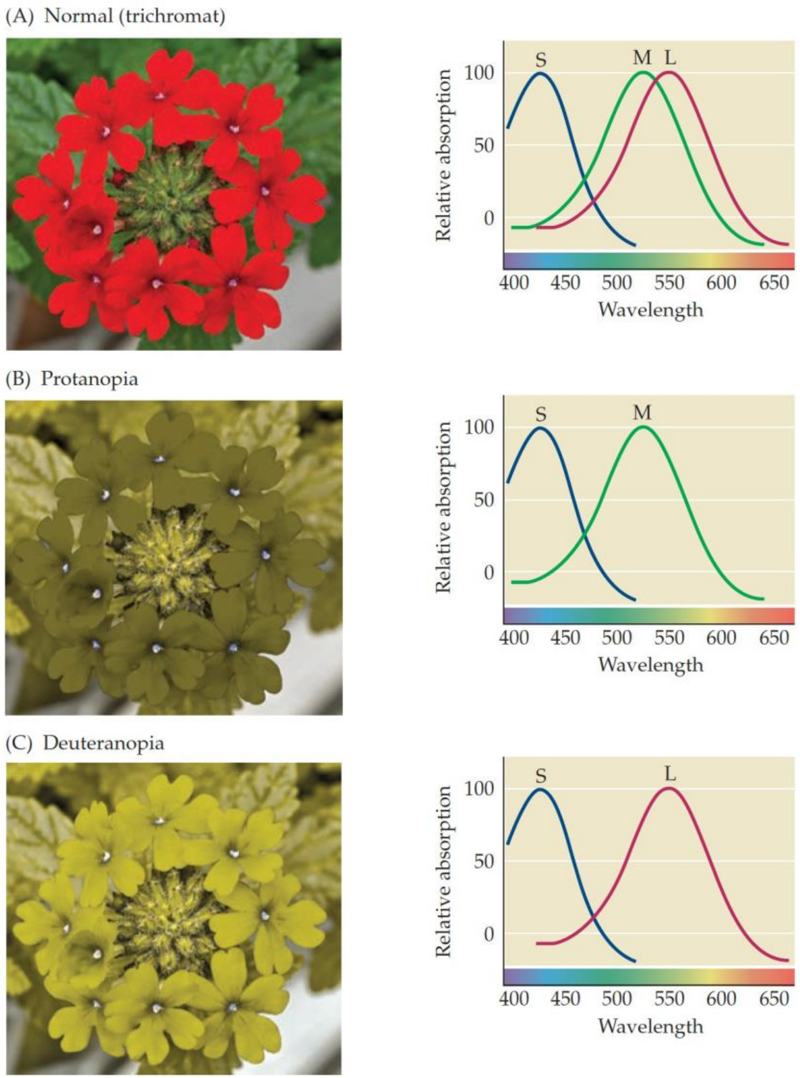
Color blindness (dichromacy)



Neurotypical

Loss of L-Cones → Red-Green color blind

Loss of M-Cones → Red-Green color blind

Also: Tritanopia. Loss of S-Cones → Blue-Yellow (rare)

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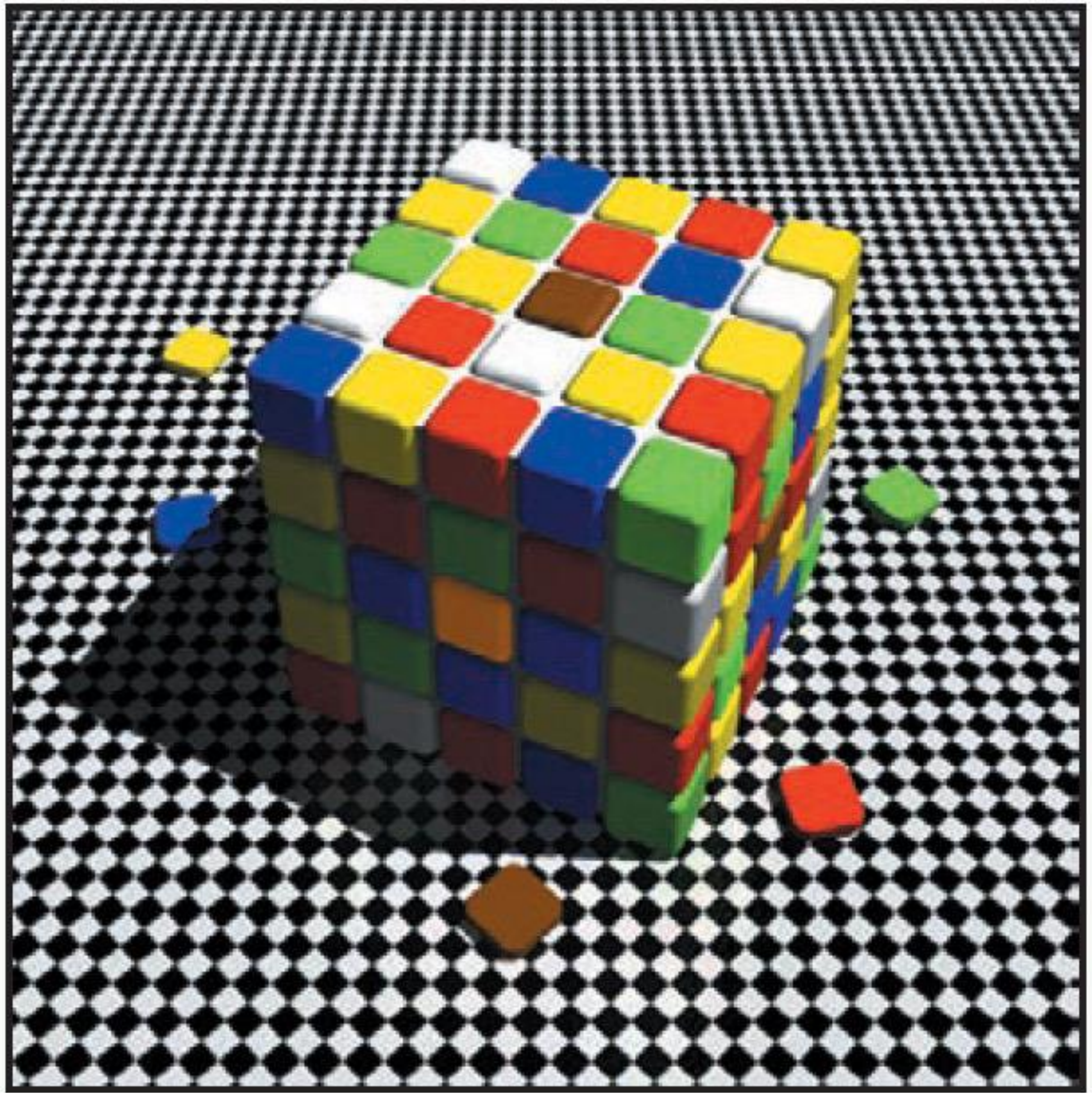
Visual Context

What is the color of the middle squares?



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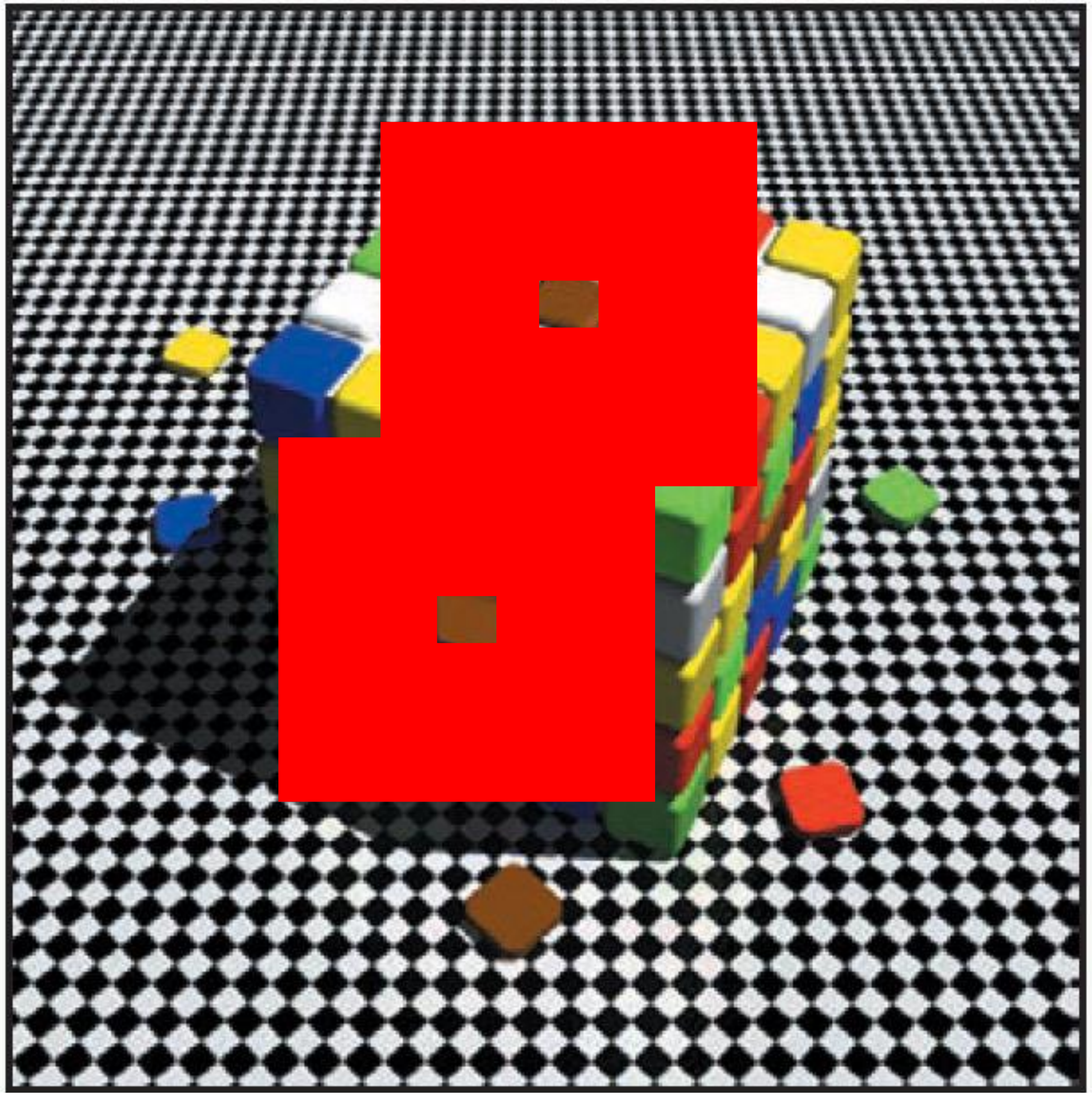
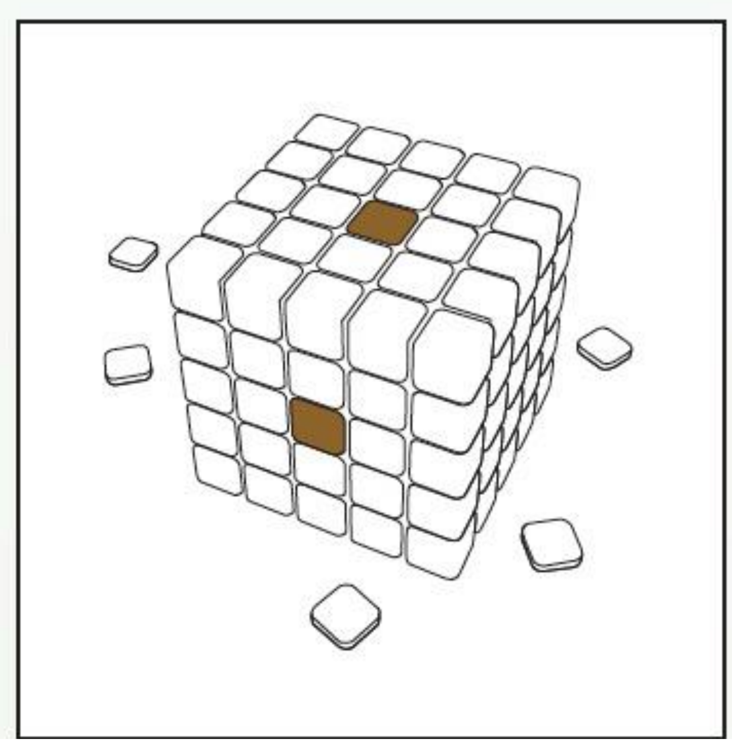
Visual Context

What is the color of the middle squares?





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The dress

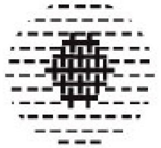
Blue and black?

or

White and gold?

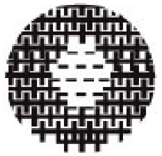
https://en.wikipedia.org/wiki/The_dress#/media/File:The_dress_blueblackwhitegold.jpg

A simple form of context in retinal ganglion cells: ON- and OFF-center



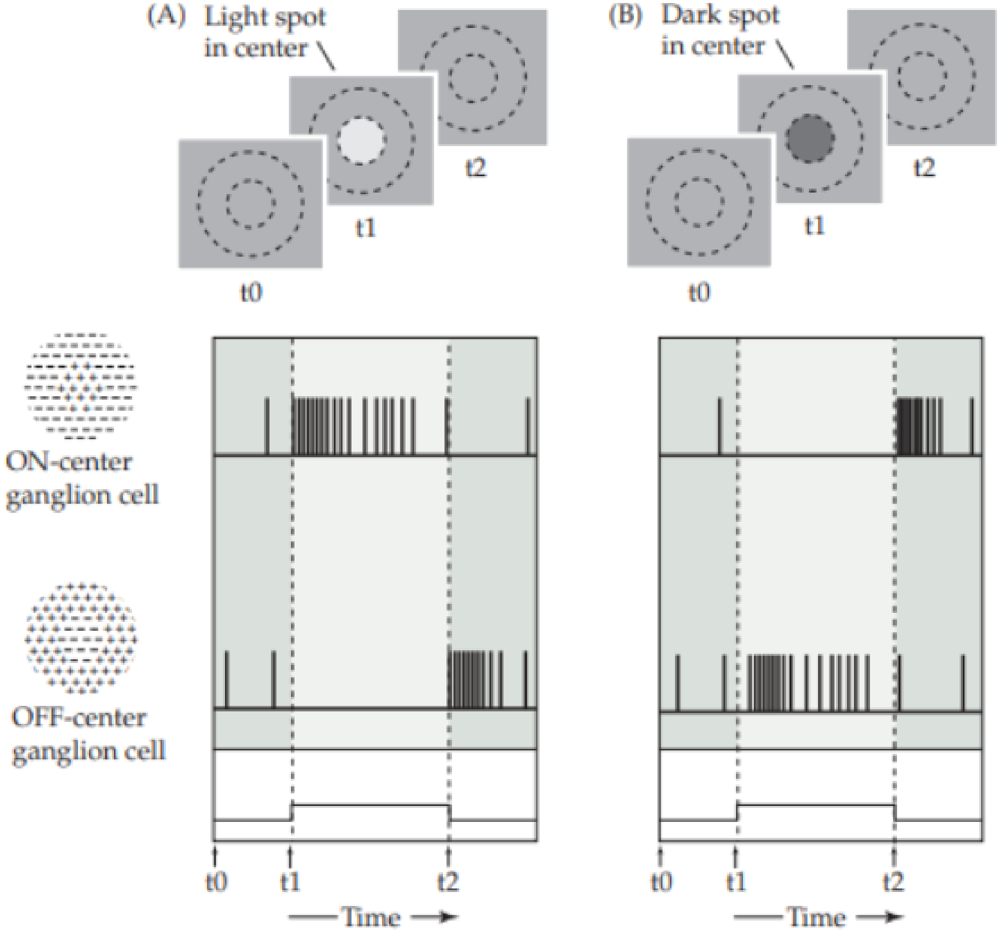
On-center ganglion cell

"ON-center":
↑ AP- frequency
in the center of the receptive field (RF)



Off-center ganglion cell

"OFF center"
↓ AP-frequency
in the center of the RF



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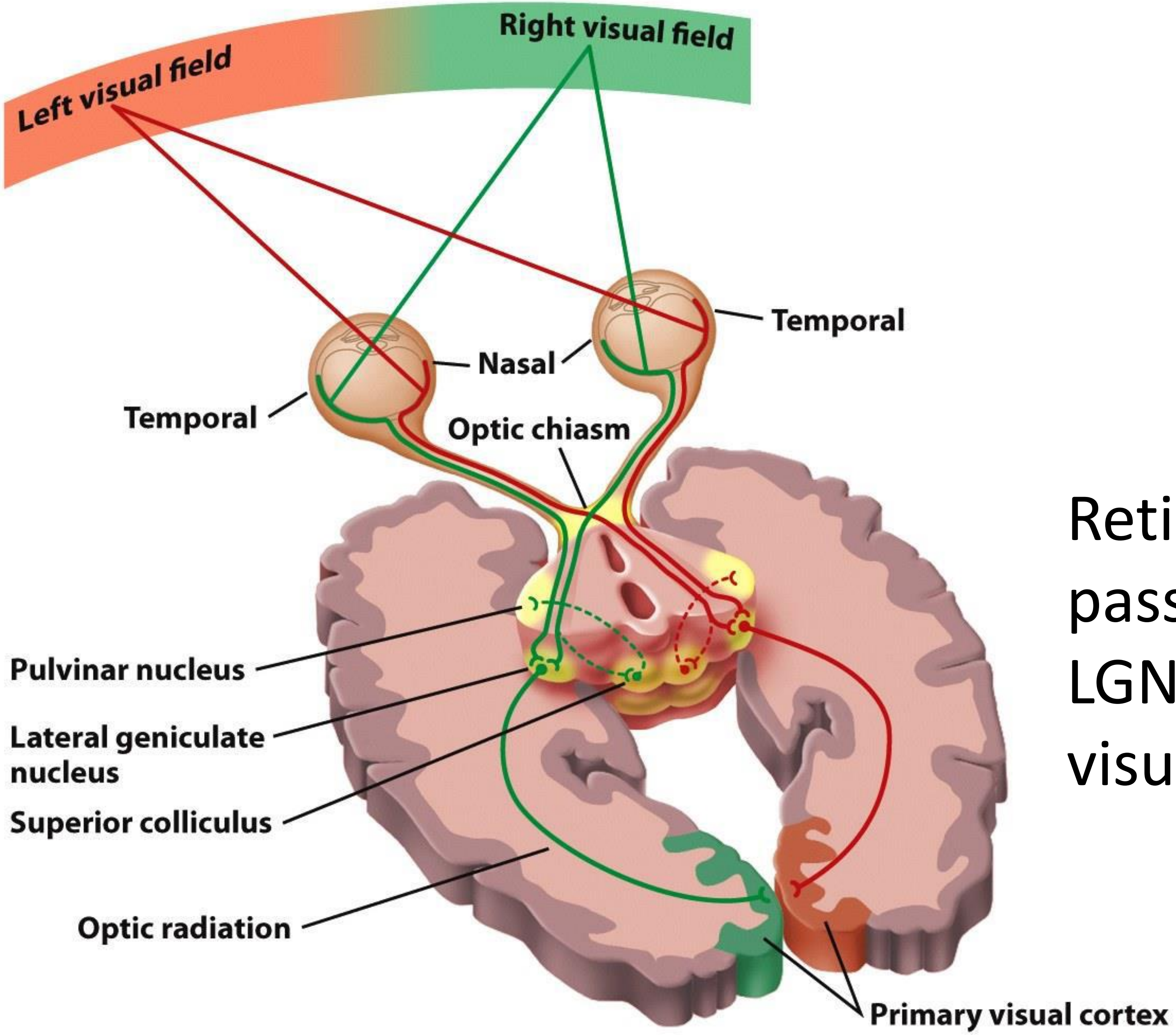
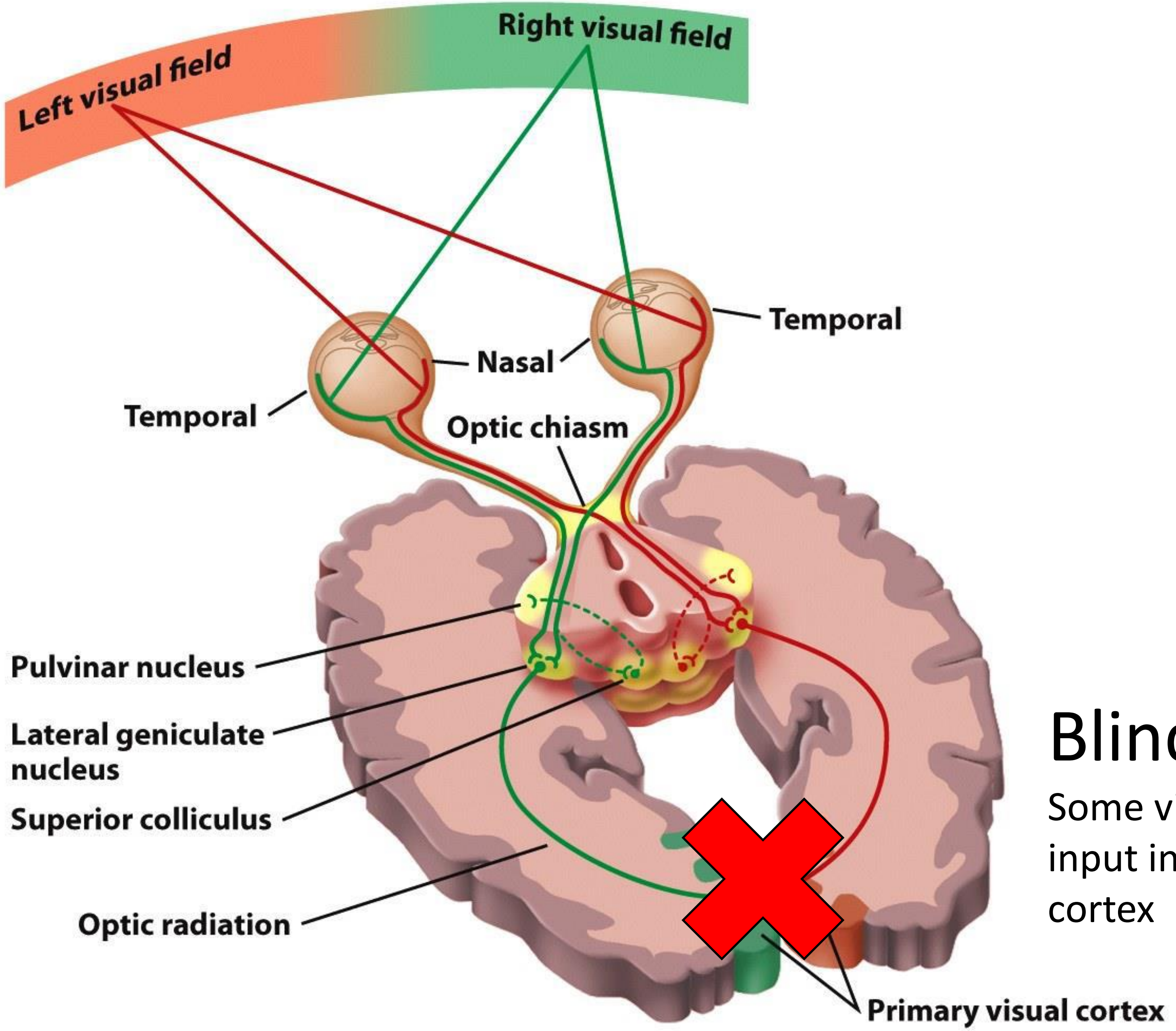


Retinal input passes through LGN into primary visual cortex

Courtesy of Bob Desimone's class MIT 9.017

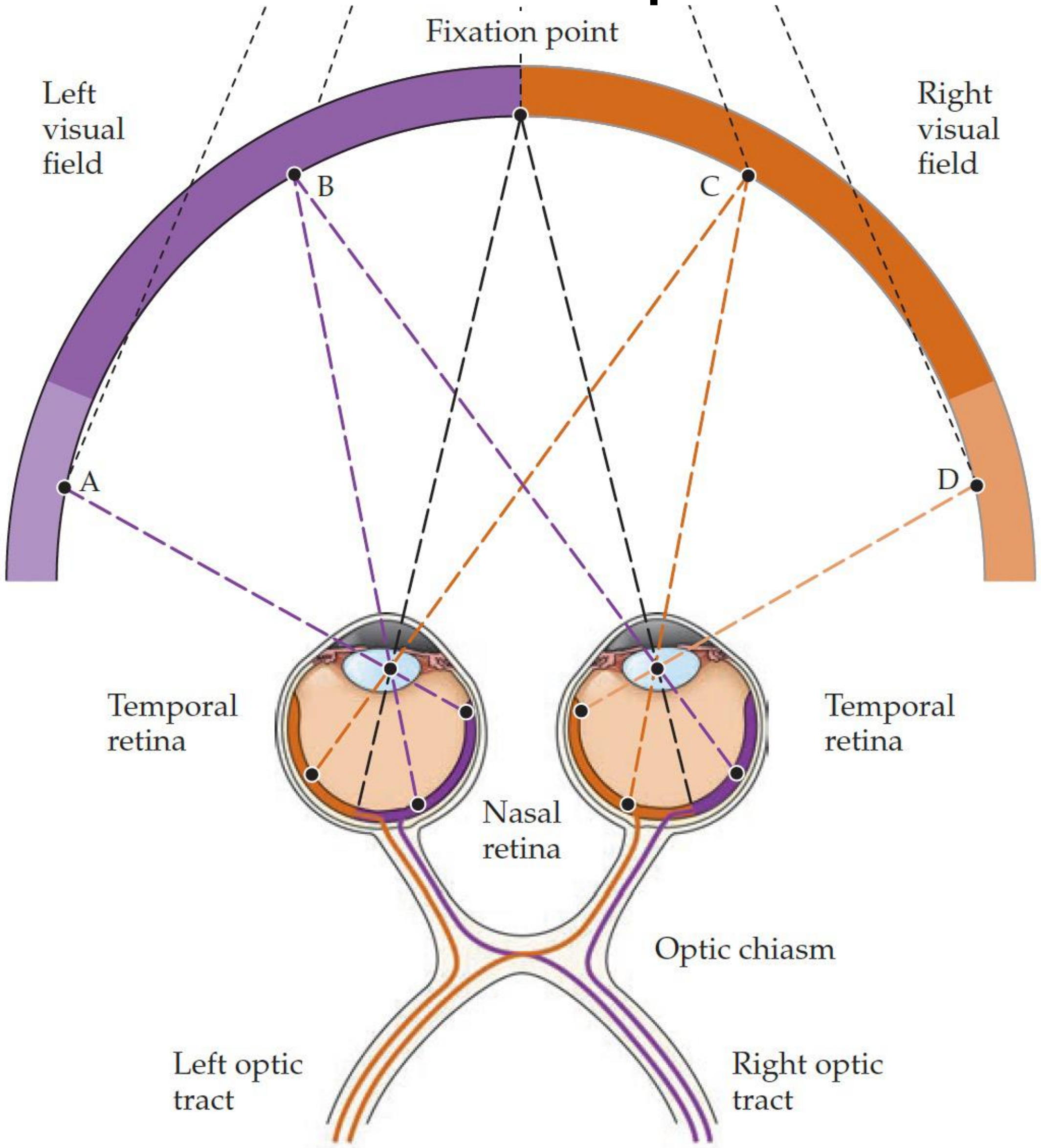


Blindsight?

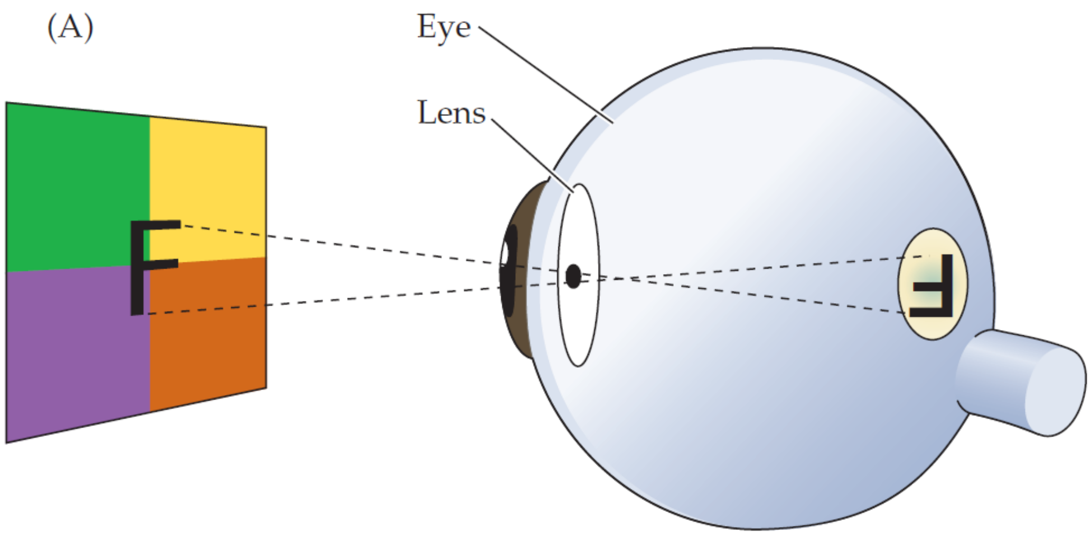
Some visual function without input into primary visual cortex

Courtesy of Bob Desimone's class MIT 9.017

Contralateral processing along optic chiasm



Visual input is inverted – but your brain takes care of that



- Each eye perceives left **and** right visual field
- **Left** optic tract propagates only **right** visual field
- **Right** optic tract propagates only **left** visual field
- Contralateral processing: each hemisphere processes sensory input from the opposite side of the body

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NB: contralateral processing and split-brain patients

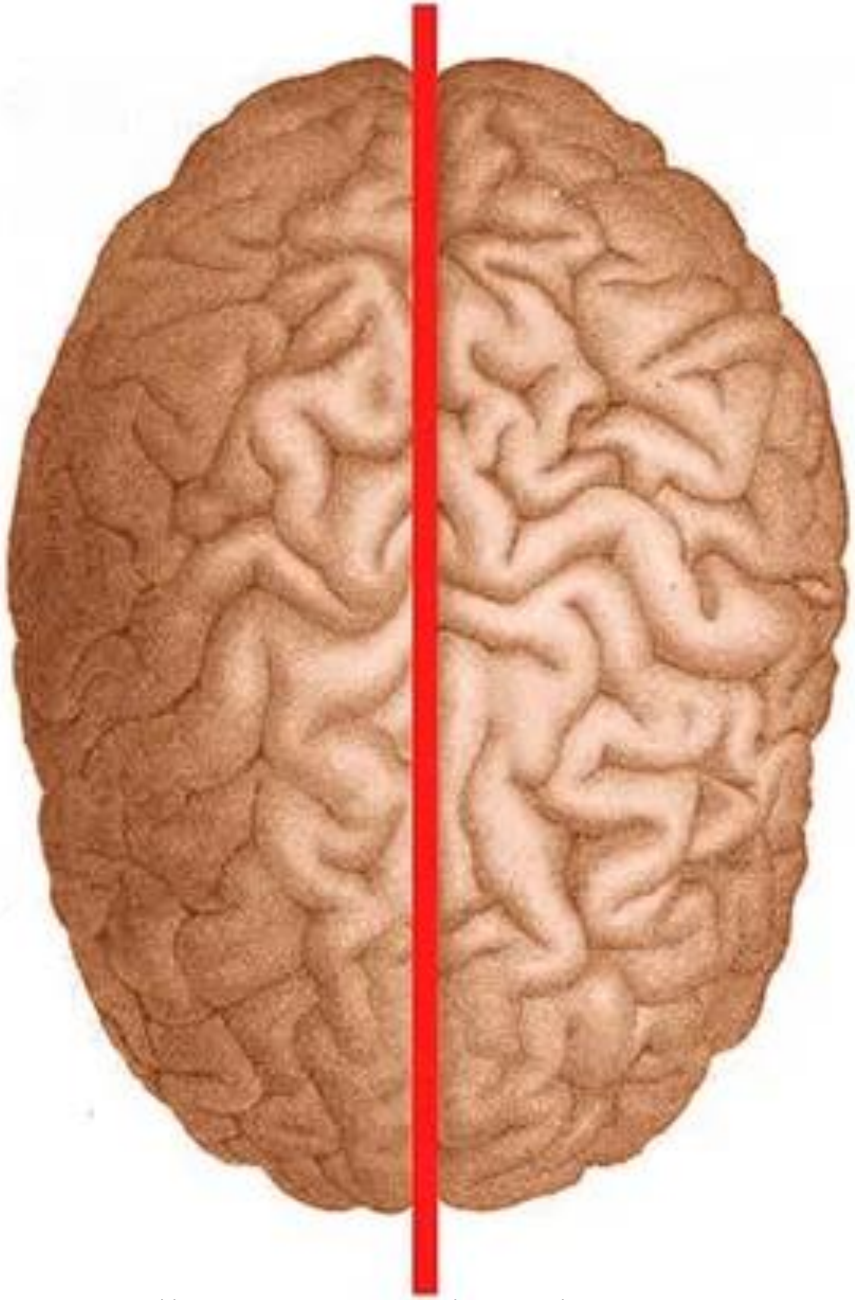
Two hemispheres are connected via corpus callosum.

Severe this connection as a last resort to treat epilepsy.

Effect in some patients: **alien-hand syndrome**, e.g.

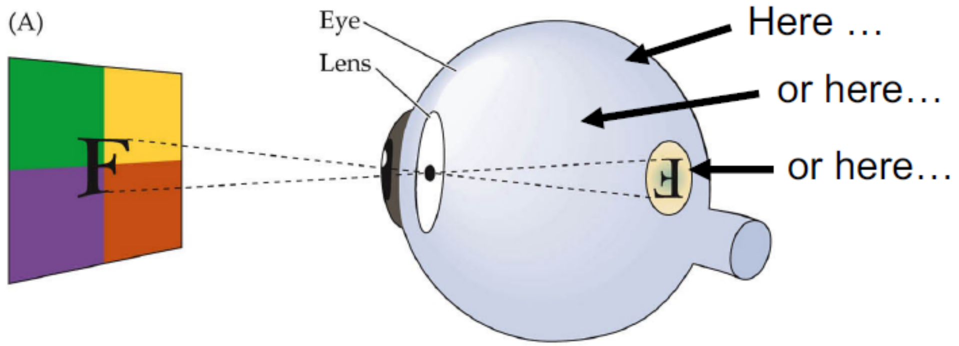
- Ask patient to pick up glass (language ~ left hemisphere)
- Right hand will attempt to pick up glass (LH → right side of body)
- Left hand will interfere (left side of body → RH → did not receive language input)

Seen as evidence for dual consciousness after corpus callosotomy.



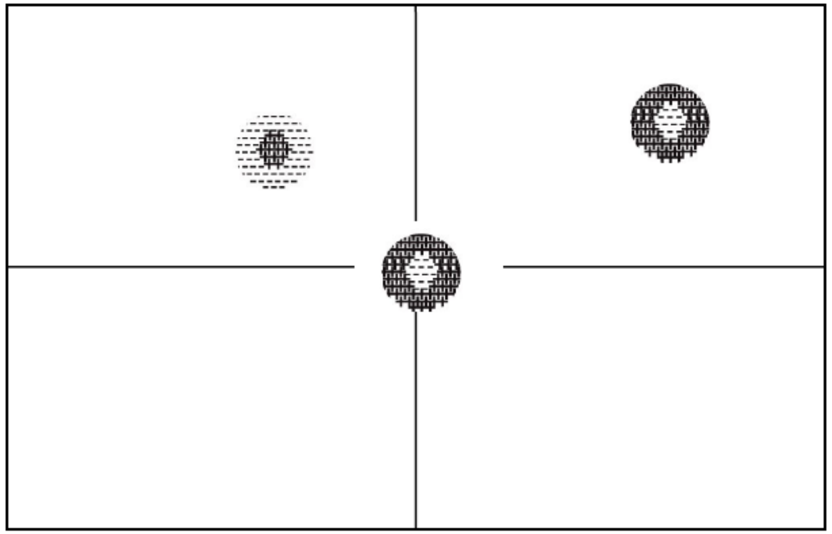
https://www.britannica.com/science/split-brain-syndrome

Receptive fields



For each neuron: the part of the visual field for which it is most sensitive

Field of view:



If you record from a retinal ganglion cell (RGC).
They fire APs with generally two types of responses:

On-center ganglion cell

"ON-center":
↑ AP- frequency
in the center of the receptive field (RF)

Off-center ganglion cell

"OFF center"
↓ AP-frequency
in the center of the RF

Courtesy of Pavan Ramdya’s class EPFL BIO-311

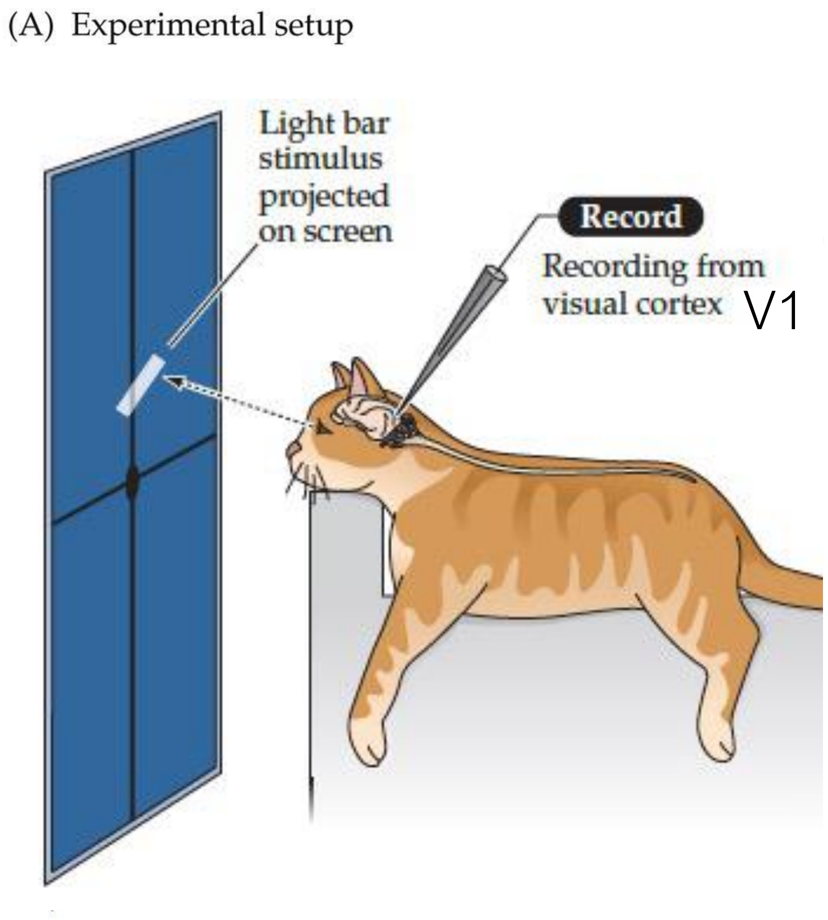
V1

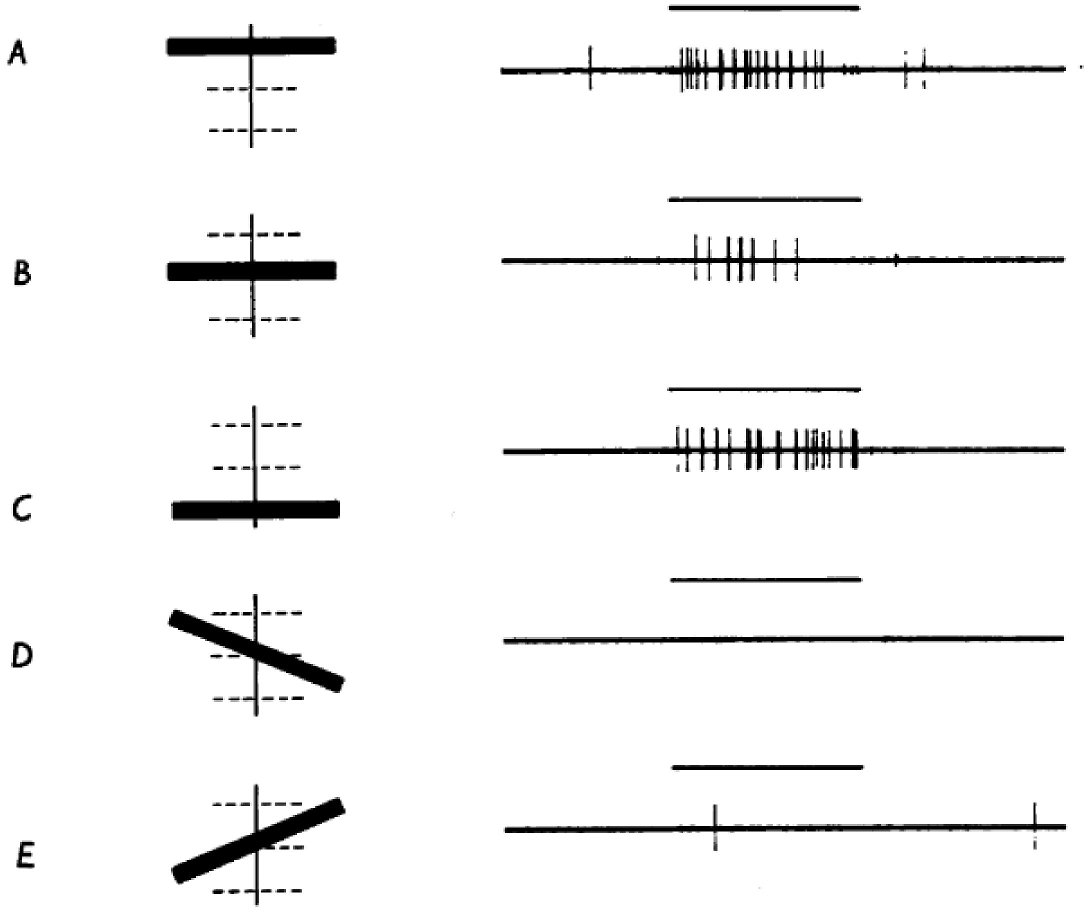
Receptive fields: ~1° visual angle.

Textbook function: edge detection.

Hubel and Wiesel 1962

Nobel Prize 1981





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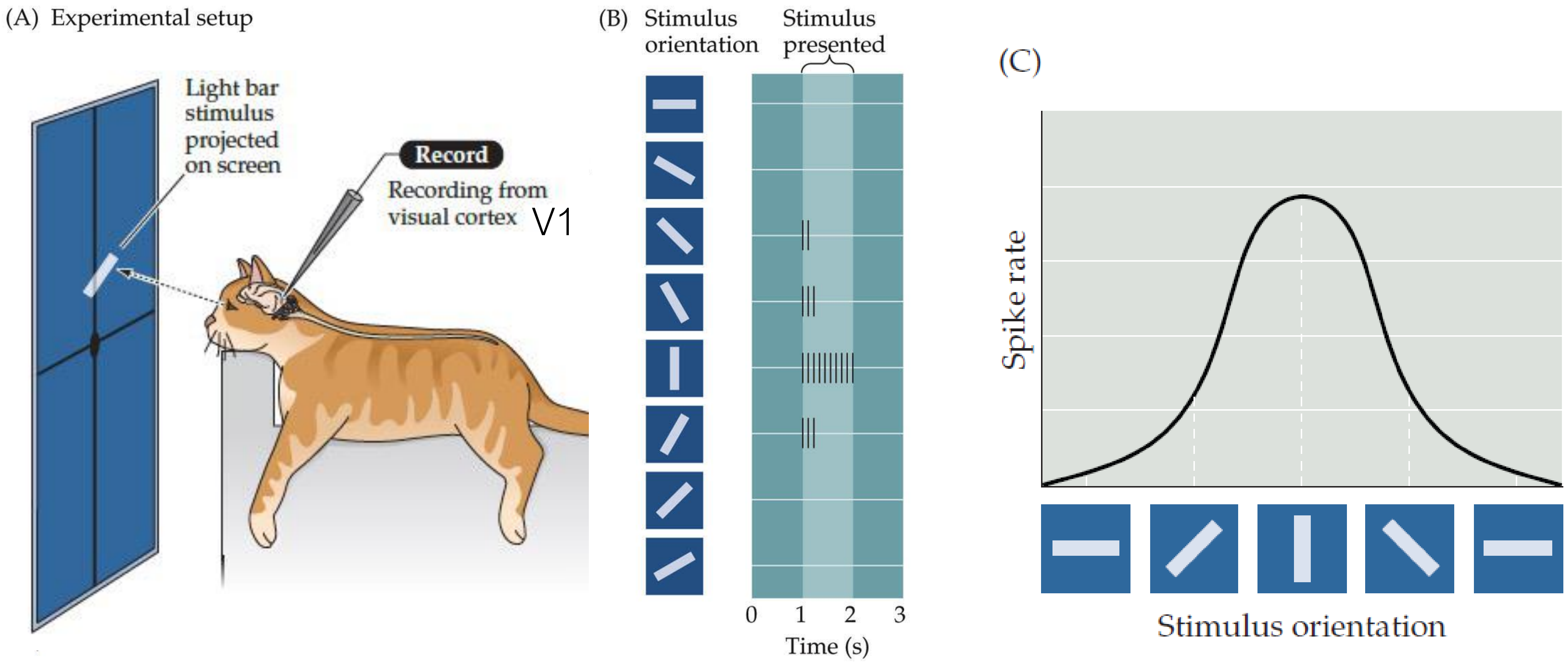

NEUROSCIENCE, Third Edition, Figure 11.9 © 2004 Sinauer Associates, Inc.

V1

Receptive fields: ~1° visual angle.

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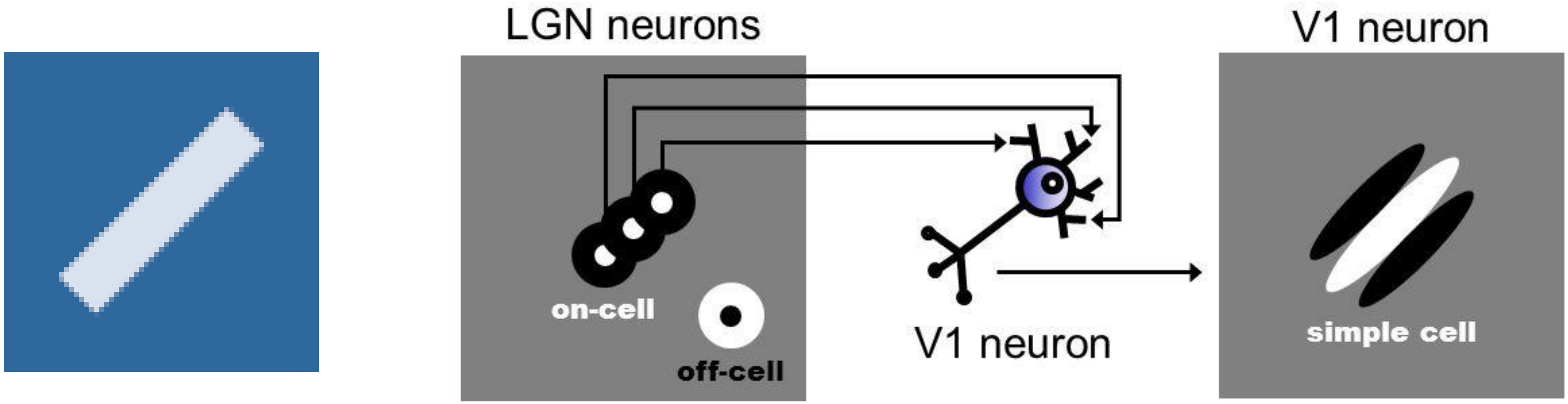

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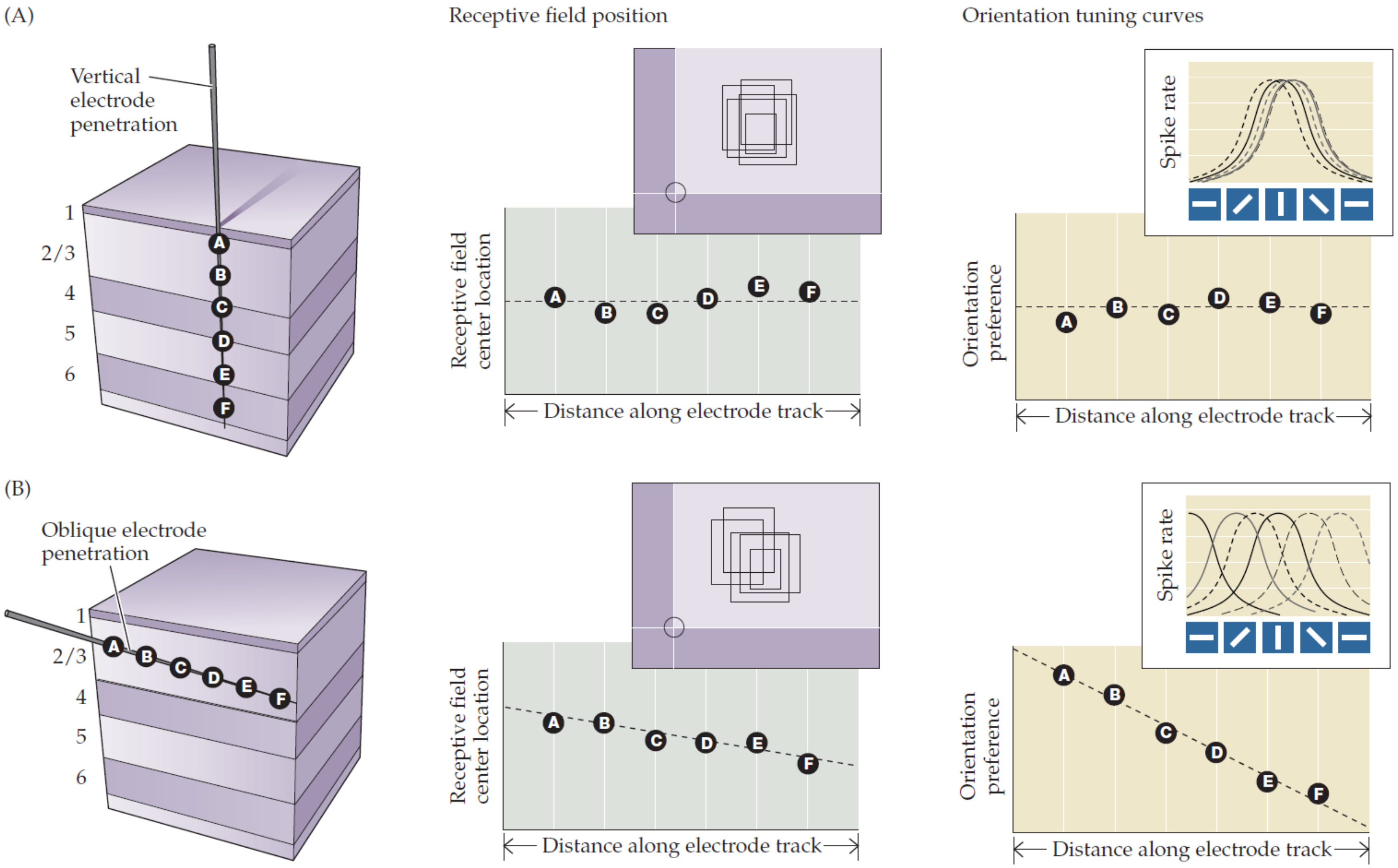
V1 columnar organization



Layers in cortical micro-circuit typically have highly similar receptive fields
→ **Organized in columns**

Adjacent columns typically have adjacent receptive fields
→ **Organized in maps**

Courtesy of Pavan Ramdya's class EPFL BIO-311; Purves, chapter 11

V1 columnar organization: pinwheels

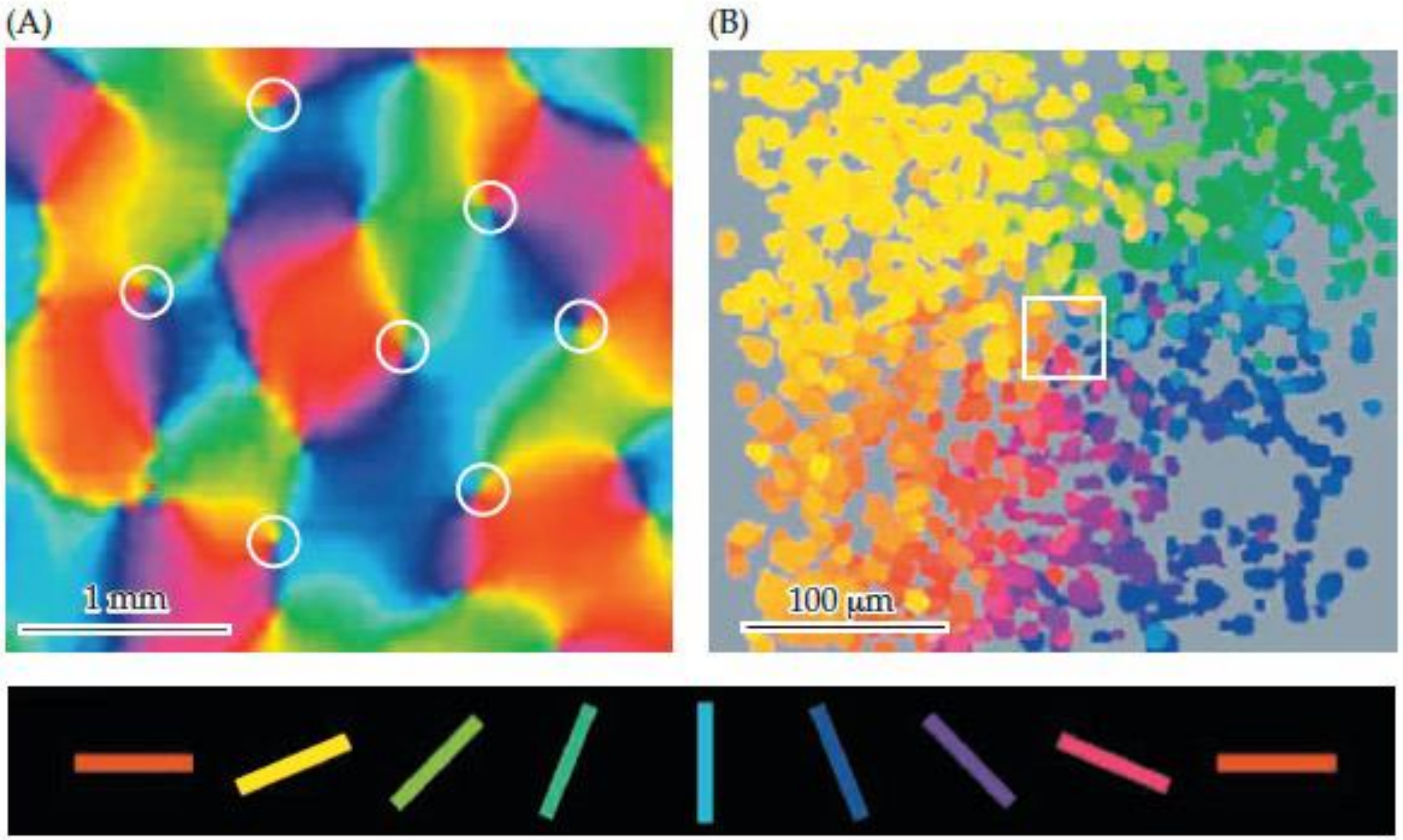


FIGURE 12.10 Functional imaging reveals orderly mapping of orientation preference in the primary visual cortex.

Nearby V1 neurons tend to respond to similarly oriented bars, organized in a pinwheel structure

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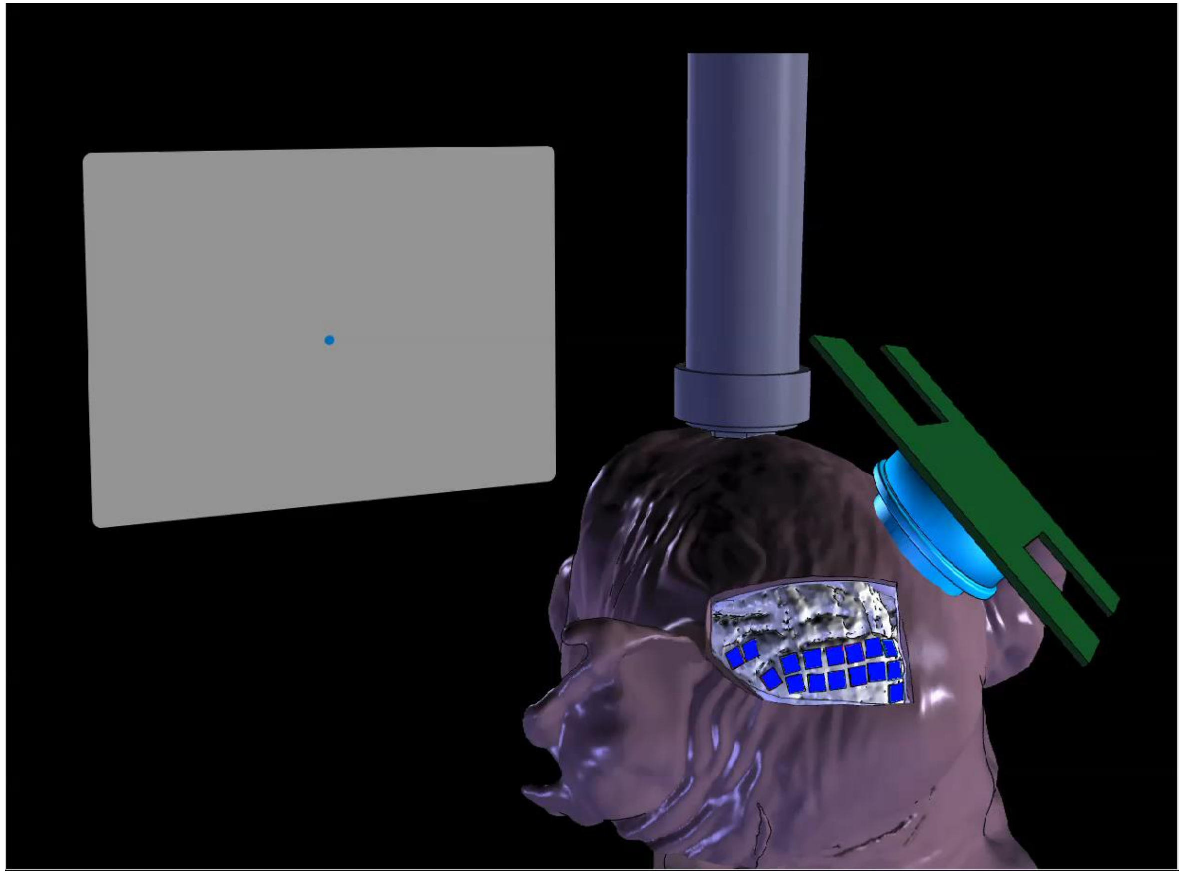
V1 retinotopy

Mapping of visual input from retina to neurons

In V1: relatively well-preserved spatial organization of inputs.

Wandell et al. 2007

V1 retinotopy allows "painting on cortex" with electrical micro-stimulation



Chen et al. 2020

Beauchamp et al. 2020

Fernández et al. 2021

Computational model of V1: Gabor filters

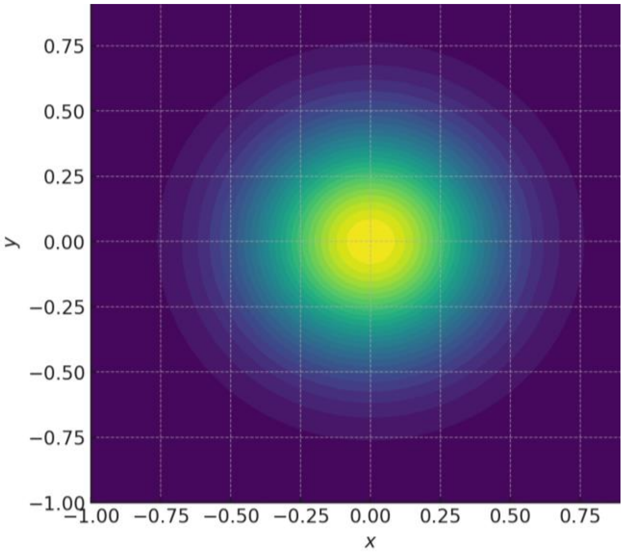
We can approximate the spatial receptive field of a simple cell with the Gabor function:

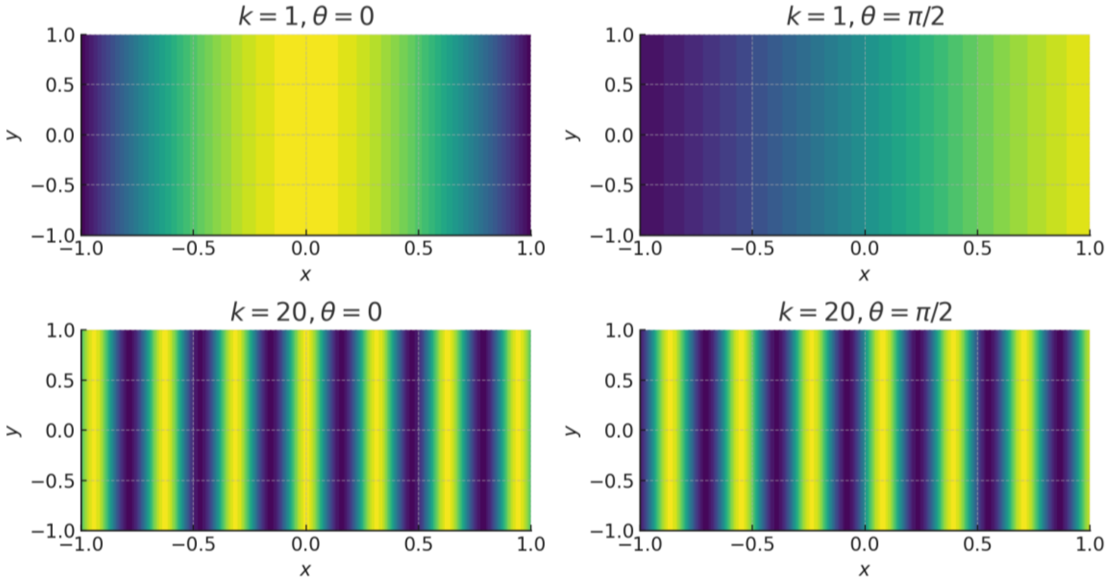
$$f(x, y) = \frac{1}{2\pi\sigma_x\sigma_y} \cdot \exp\left(-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right) \cdot \cos(kx - \varphi)$$

no rotation with this formulation, need x+y dependency

spatial phase

receptive field location

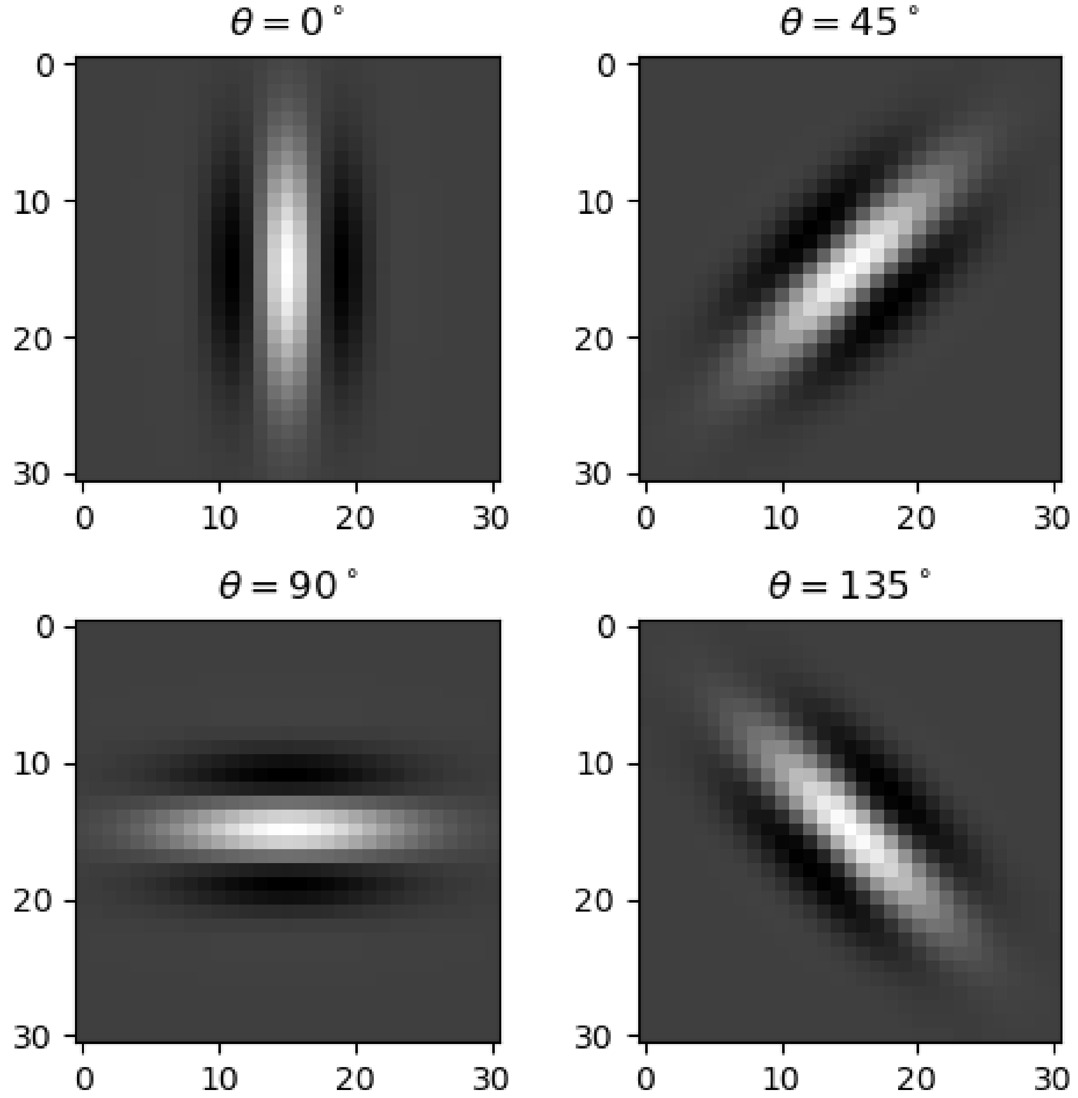




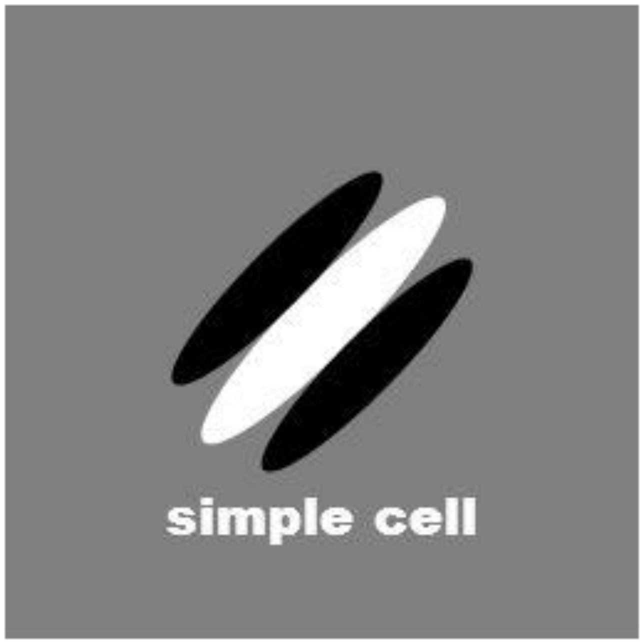
with:

- σ_x, σ_y determine the spatial receptive field in x and y direction, respectively
- k is the preferred spatial frequency (i.e. the spacing of light/dark bars)
- φ is the preferred spatial phase

Gabor model: example filters



V1 neuron



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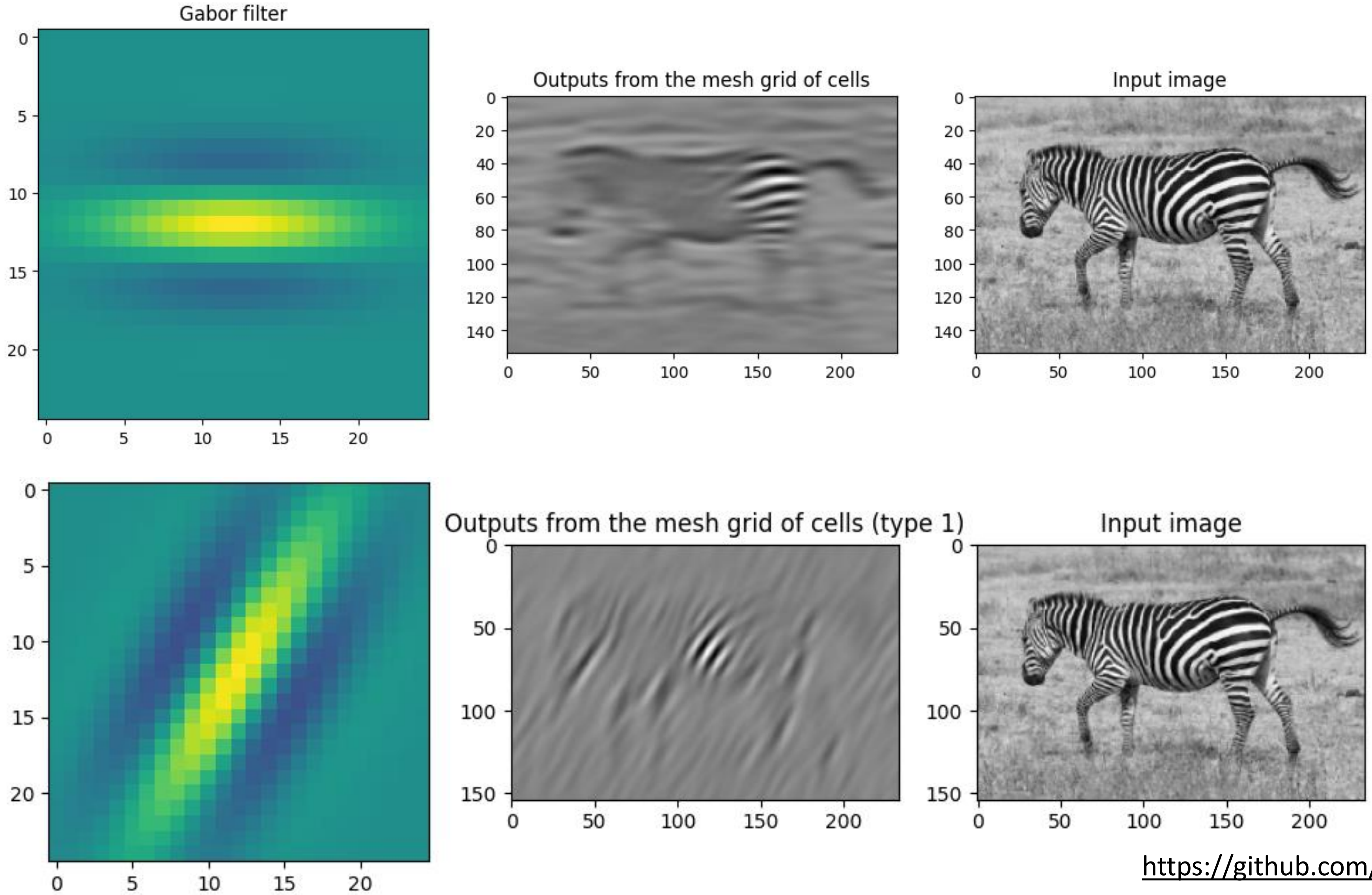
Gabor model: example filters applied



https://github.com/epflneuroailab/bioeng-310

Visual hierarchy

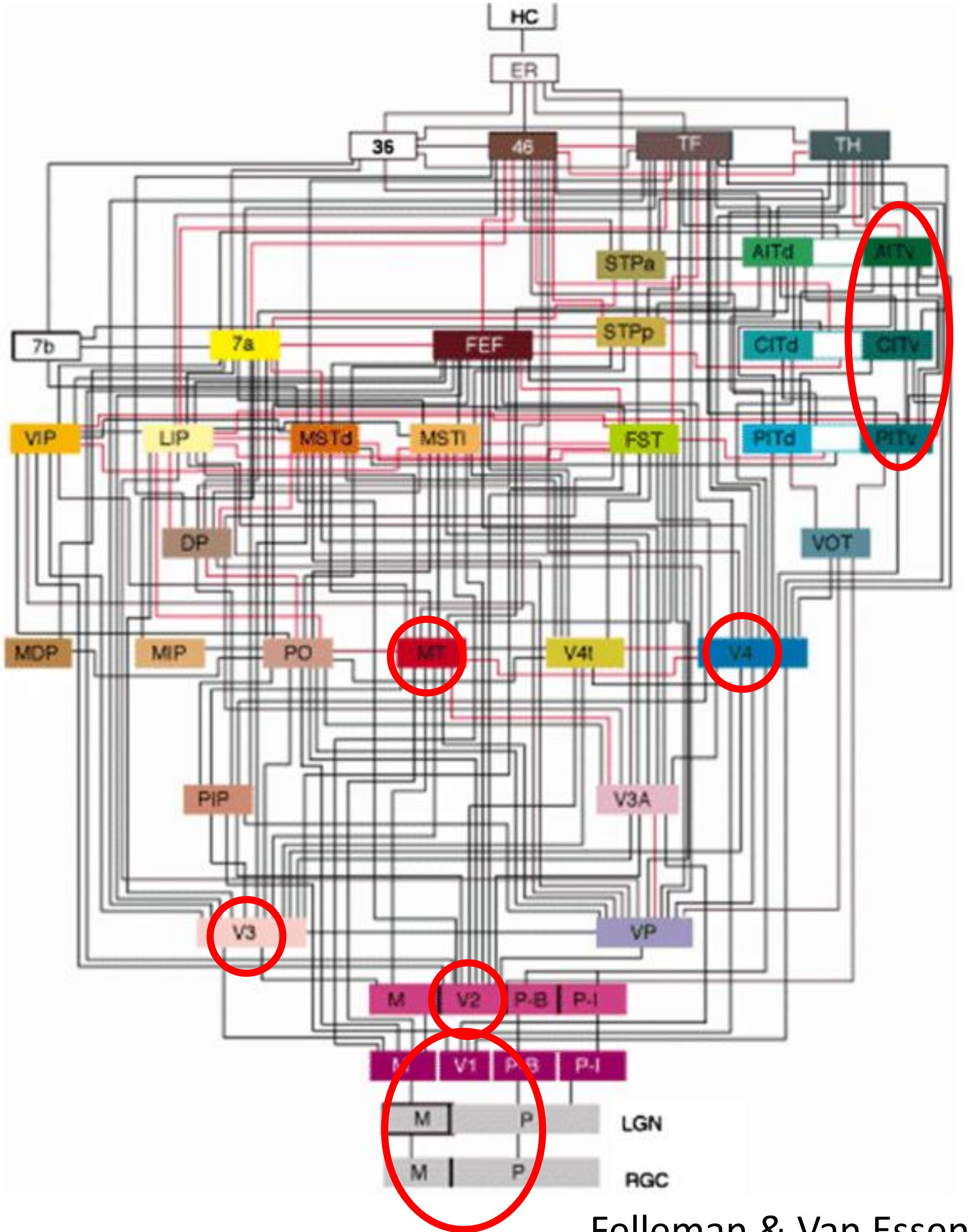
<u>Subcortical structures</u>

- Inputs from retinal ganglion cells (RGC)
- Project to lateral geniculate nucleus (LGN)

<u>Cortex</u>

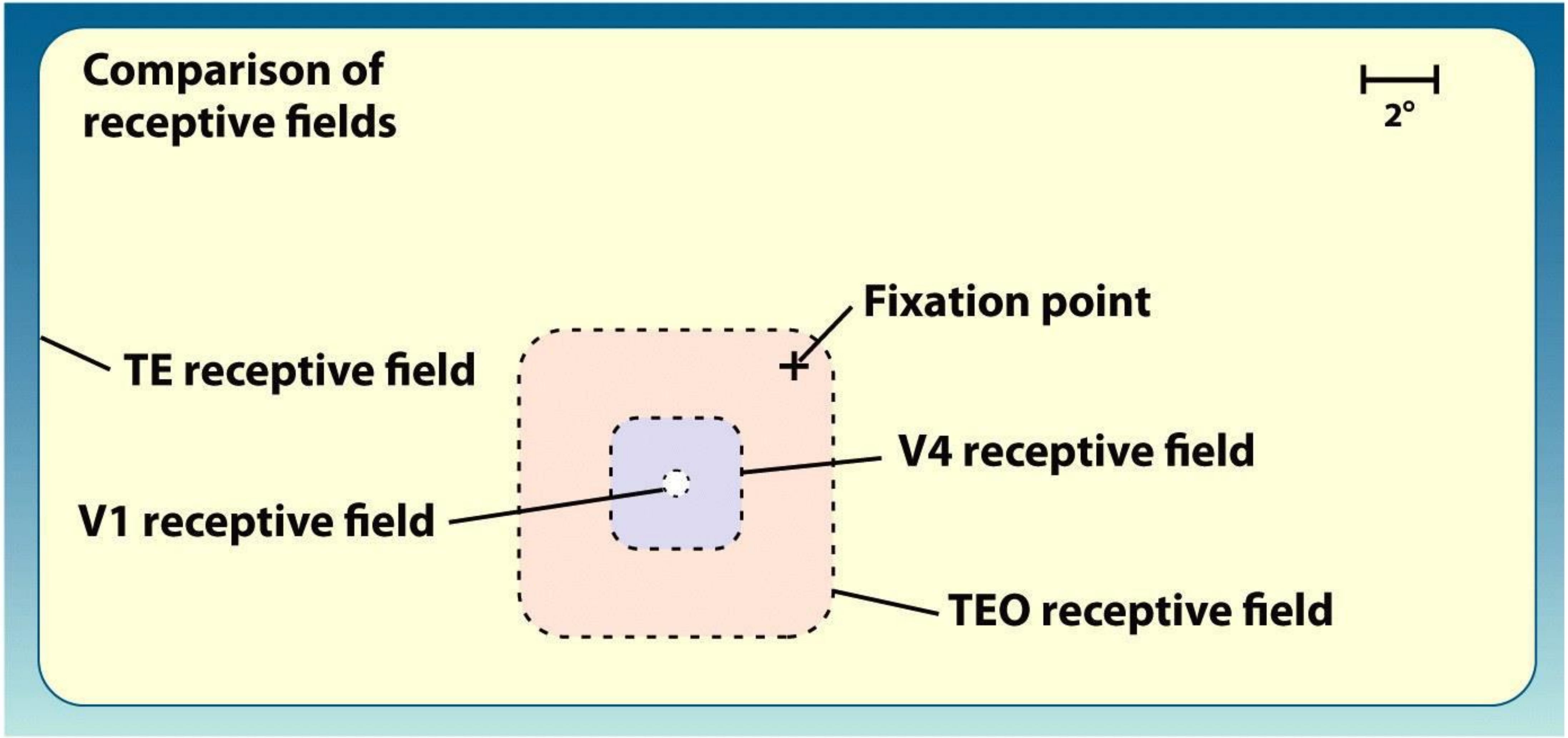
- To V1
- Dorsal stream
  - V3
  - MT (V5)
- Ventral stream
  - V2
  - V4
  - IT (TEO)

...and to a whole lot of other areas!



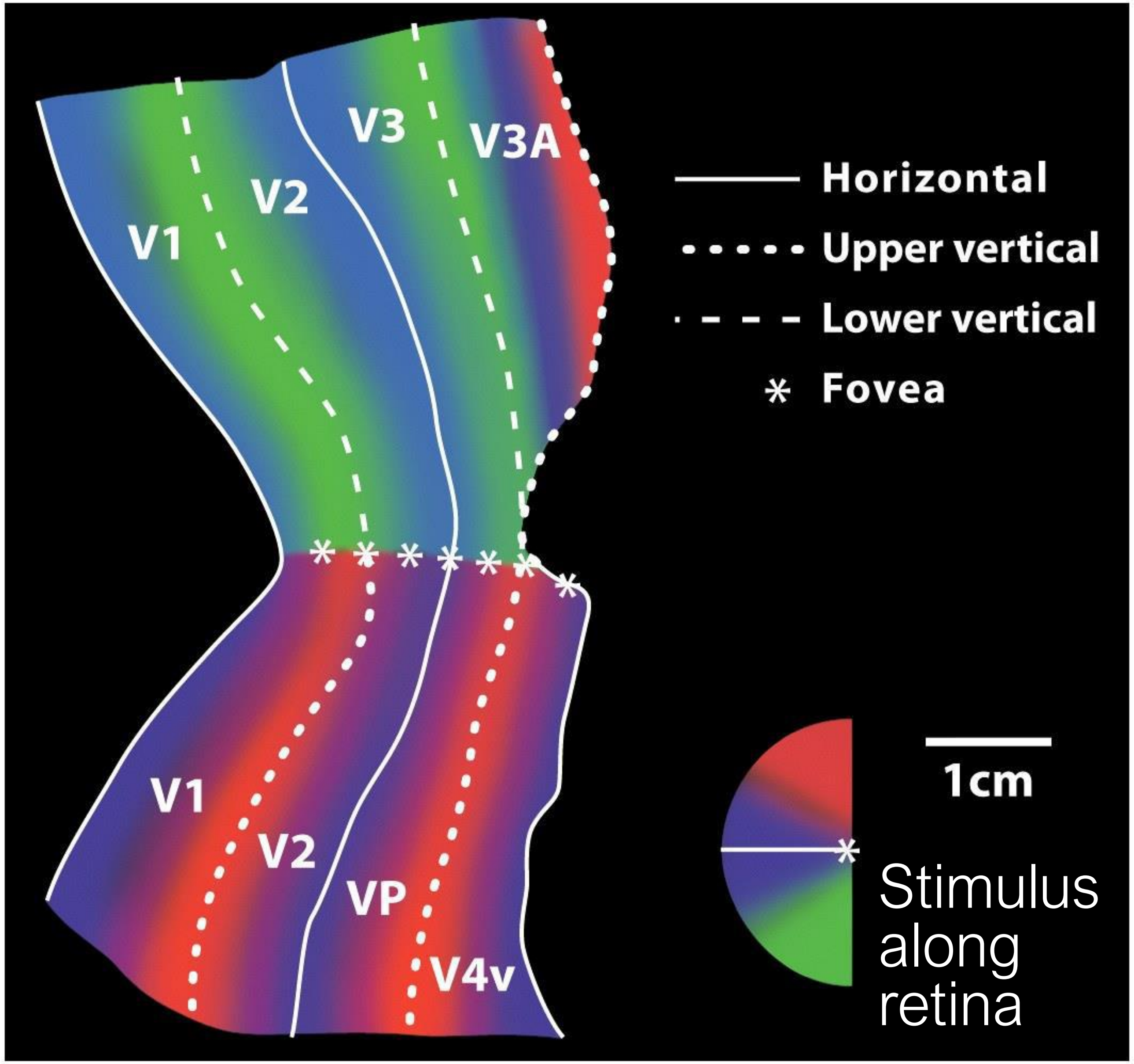
Felleman & Van Essen 1991

Beyond V1: receptive field sizes increase along the visual hierarchy



Courtesy of Bob Desimone's class MIT 9.017

Retinotopy

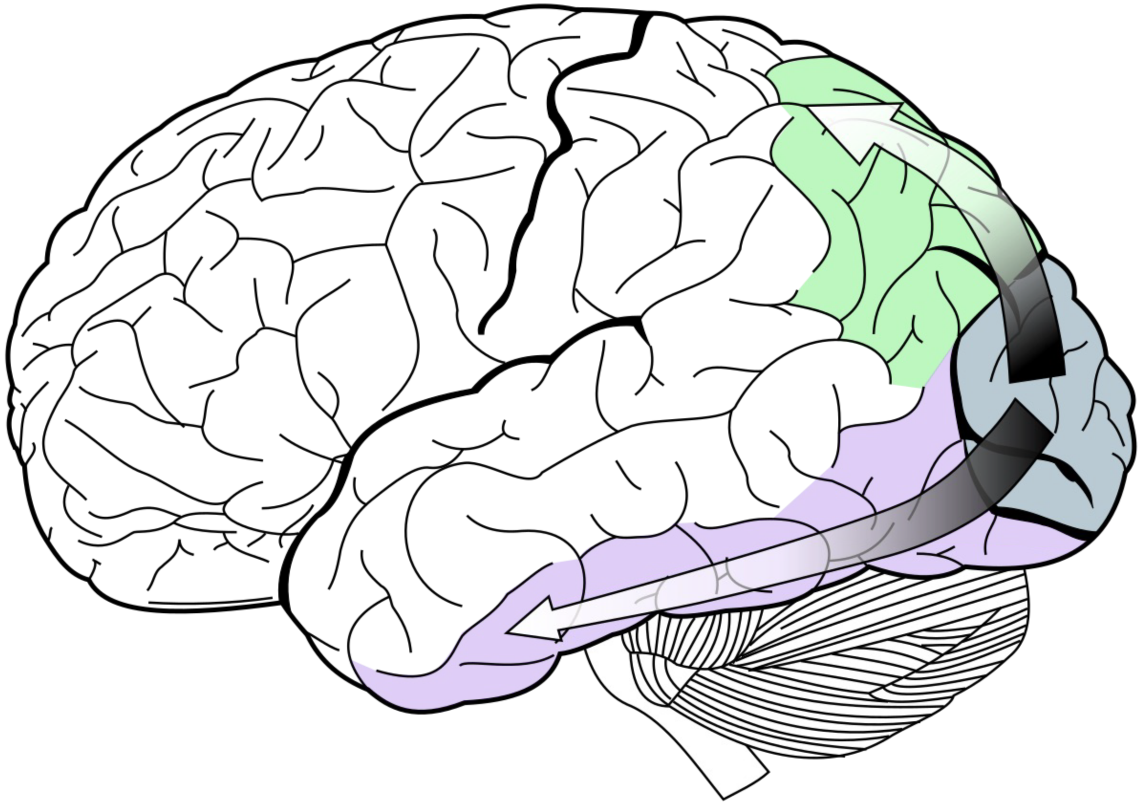


Mapping of visual input from retina to neurons

- Foveal input processed centrally
- Peripheral input along edges to subsequent areas

Courtesy of Bob Desimone's class MIT 9.017

Two-streams hypothesis



Dorsal pathway:
spatial vision
“where?”

Ventral pathway:
object recognition
“what?”

Visual ventral stream

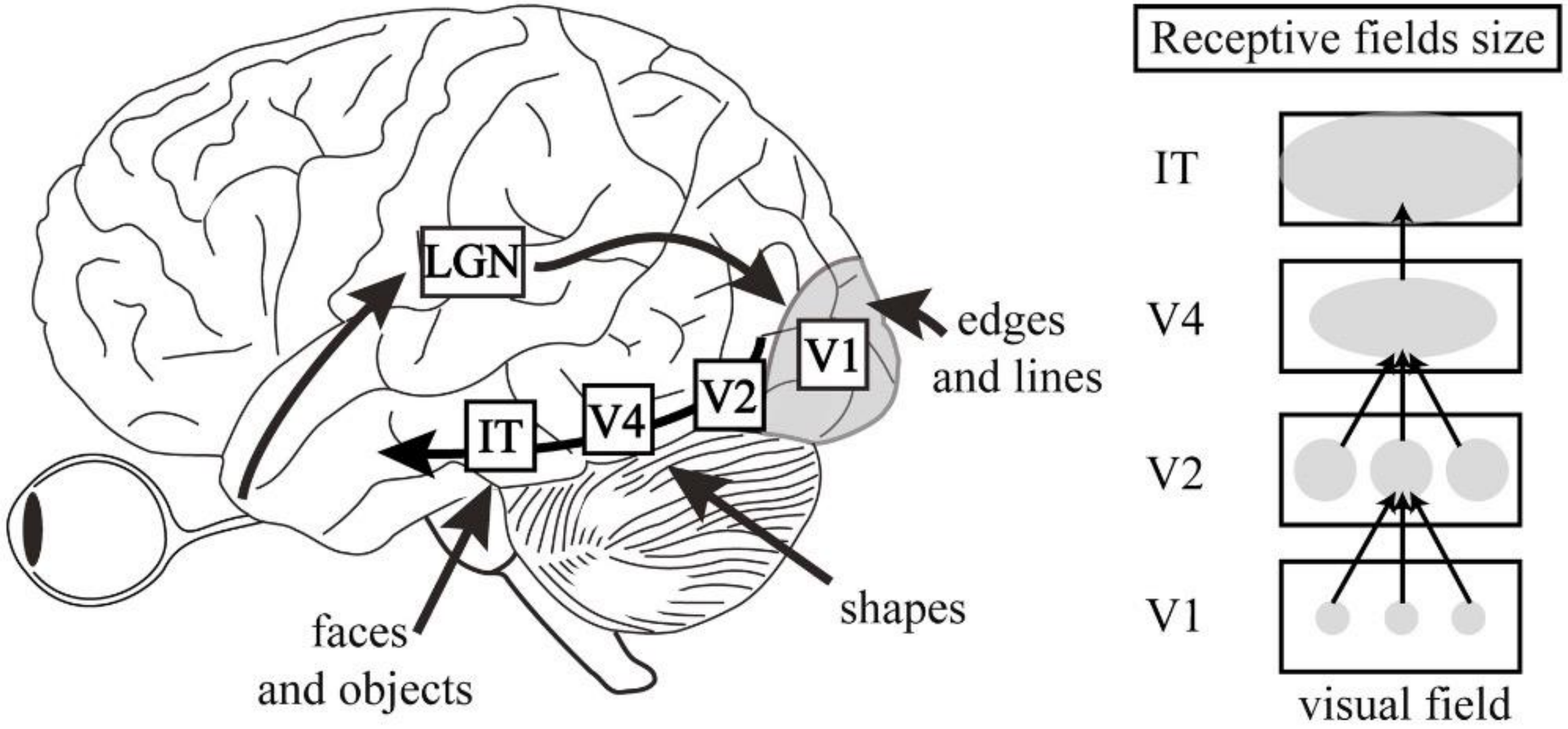


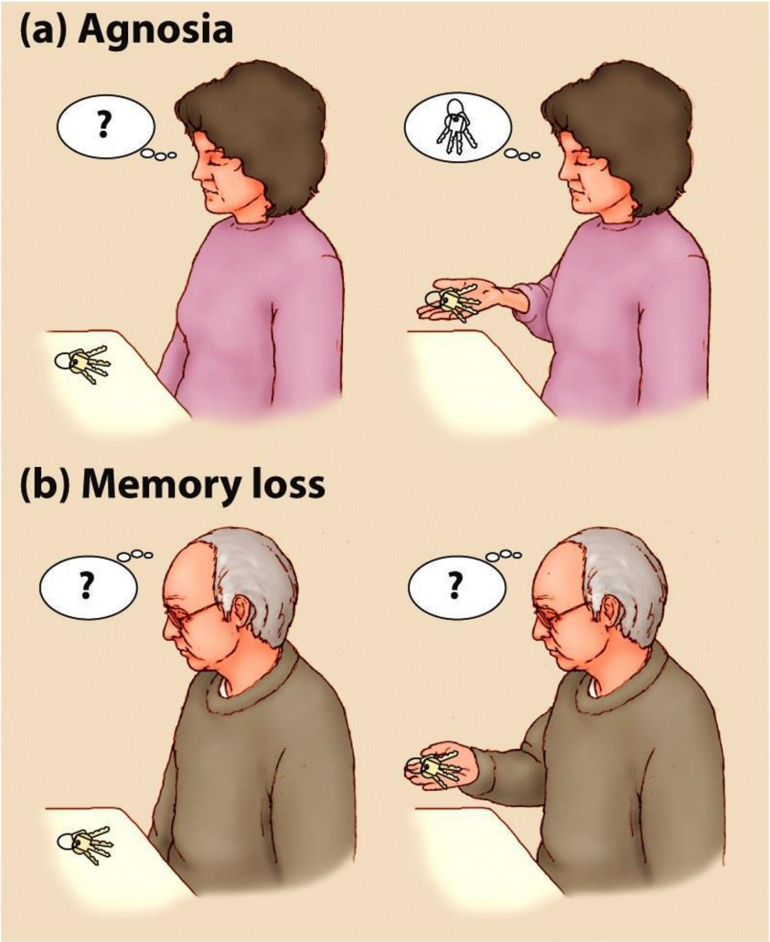
Figure from Herzog & Clarke 2014

Visual agnosia: Inability to recognize objects despite normal vision

To diagnose an agnosic disorder, it is essential to rule out general memory problems.

(a) The patient with agnosia is unable to recognize the keys by vision alone but immediately recognizes them when she picks them up.

(b) The patient with a memory disorder is unable to recognize the keys even when he picks them up.



Courtesy of Bob Desimone's class MIT 9.017

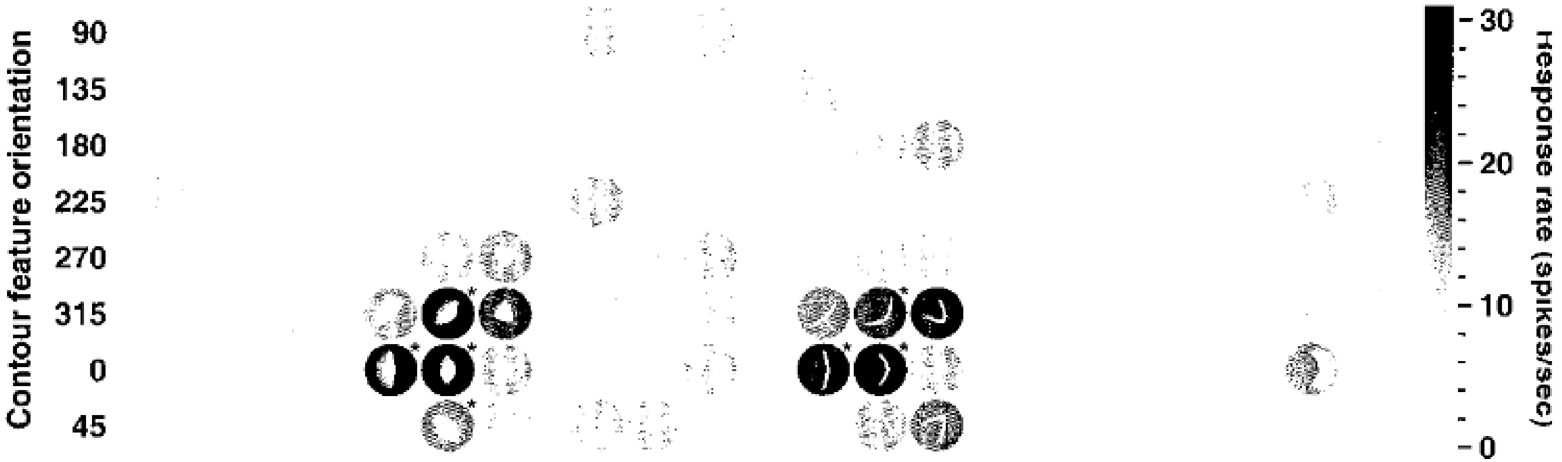
Ventral stream: V2, V4

V2

- RF size: ~1.4°
- Function: ~combined edges

V4

- RF size: ~5°
- Function: ~curvatures

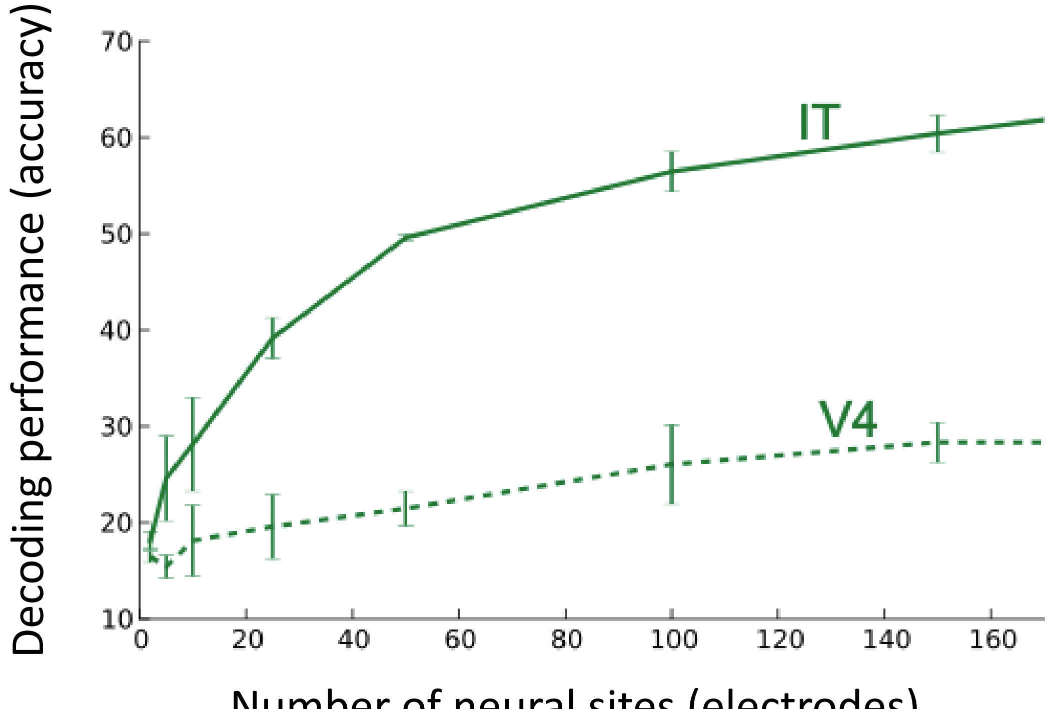


Pasupathy & Connor 1999

Ventral stream: IT

- RF size: ~12°
- Function: objects
- Directly supports object recognition (correlational and causal evidence)

IT linearly provides object category



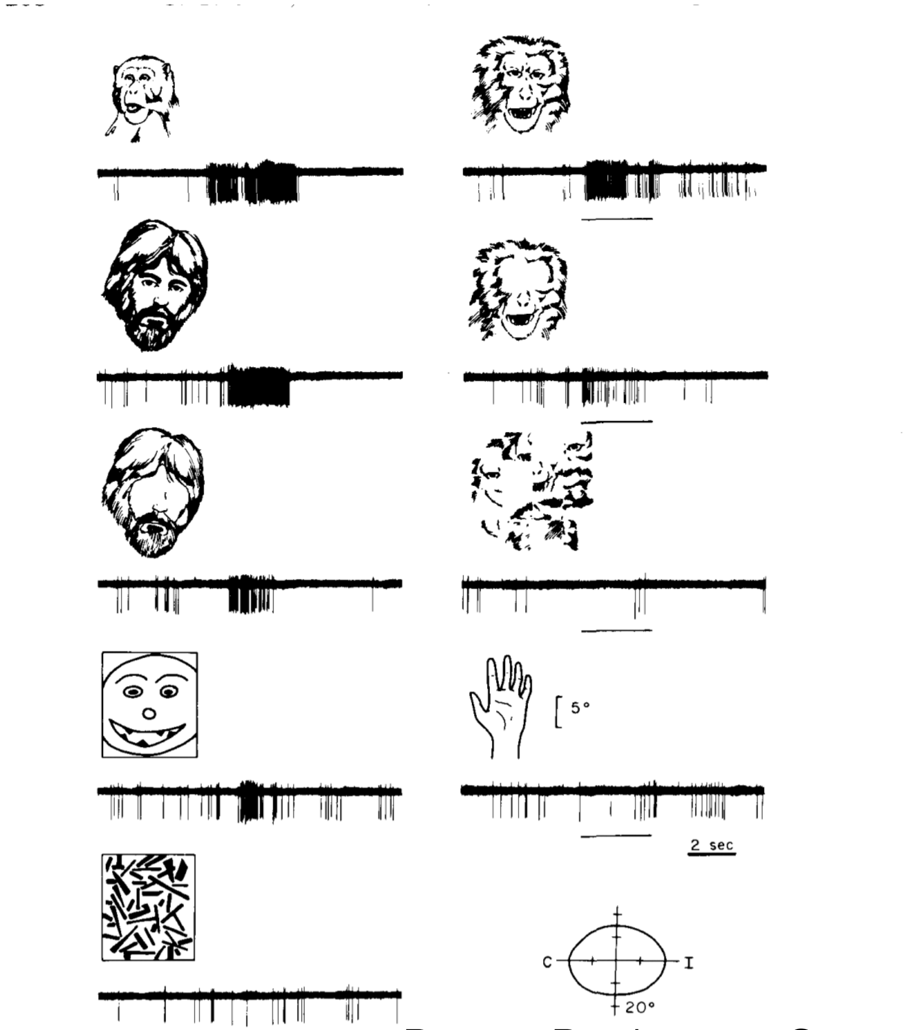
Majaj & Hong et al., JNeuroSci 2015
Hong & Yamins et al., NatNeuro 2016

Ventral stream: IT Face cells

Kavli Prize in Neuroscience 2024

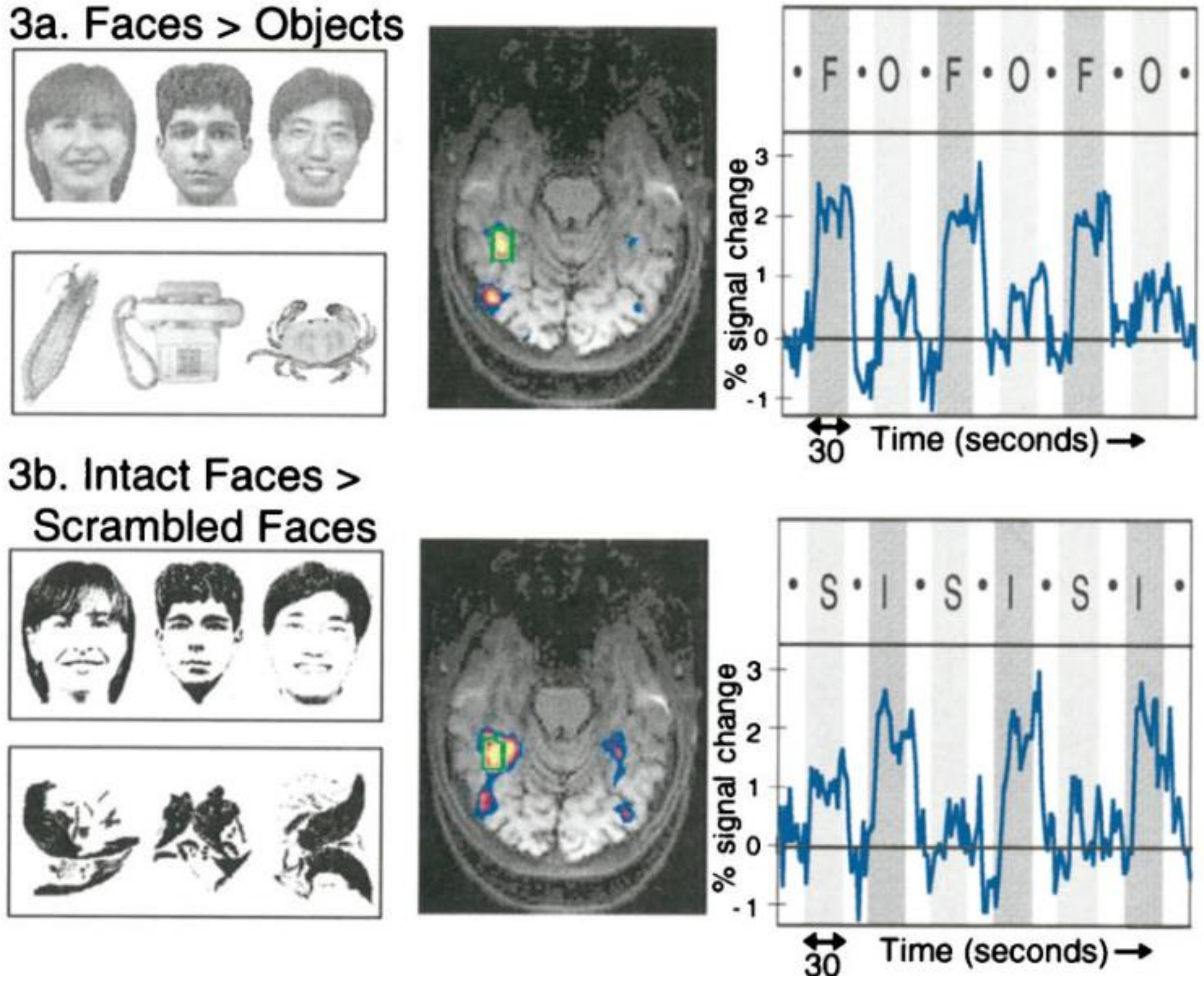
Nancy Kanwisher will visit EPFL on April 4!

Single neuron preference for faces



Bruce, Desimone, Gross 1981

Face patches



Kanwisher et al. 1997

Stimulating face-selective sites distorts face perception

https://www.youtube.com/watch?v=O7AQ8NjSnTo

Parvizi et al. 2012

Stimulating face-selective sites *induces* face perception

Stim. Elec. 181-182	*…just for the very first second… I saw an eye, an eye, and a mouth.*	*How do I explain this? Just like the previous one, I see an eye, an eye, and a mouth, sideways.*	*Your face completely changed…I don't know what's going on. Your eyes change.*	*Hm. Am I just imagining things? Can you do it again?… OK, just as I thought, I see a face.*
Stim. Elec. 177-178	*The left side of the box looks like a rainbow.*	*If I look at the ball, the rainbow is there, wider than before, and blinking.*	*If I look at the face, this side looks like a rainbow and glowing.*	*It's kind of the same, this half is colorful.*

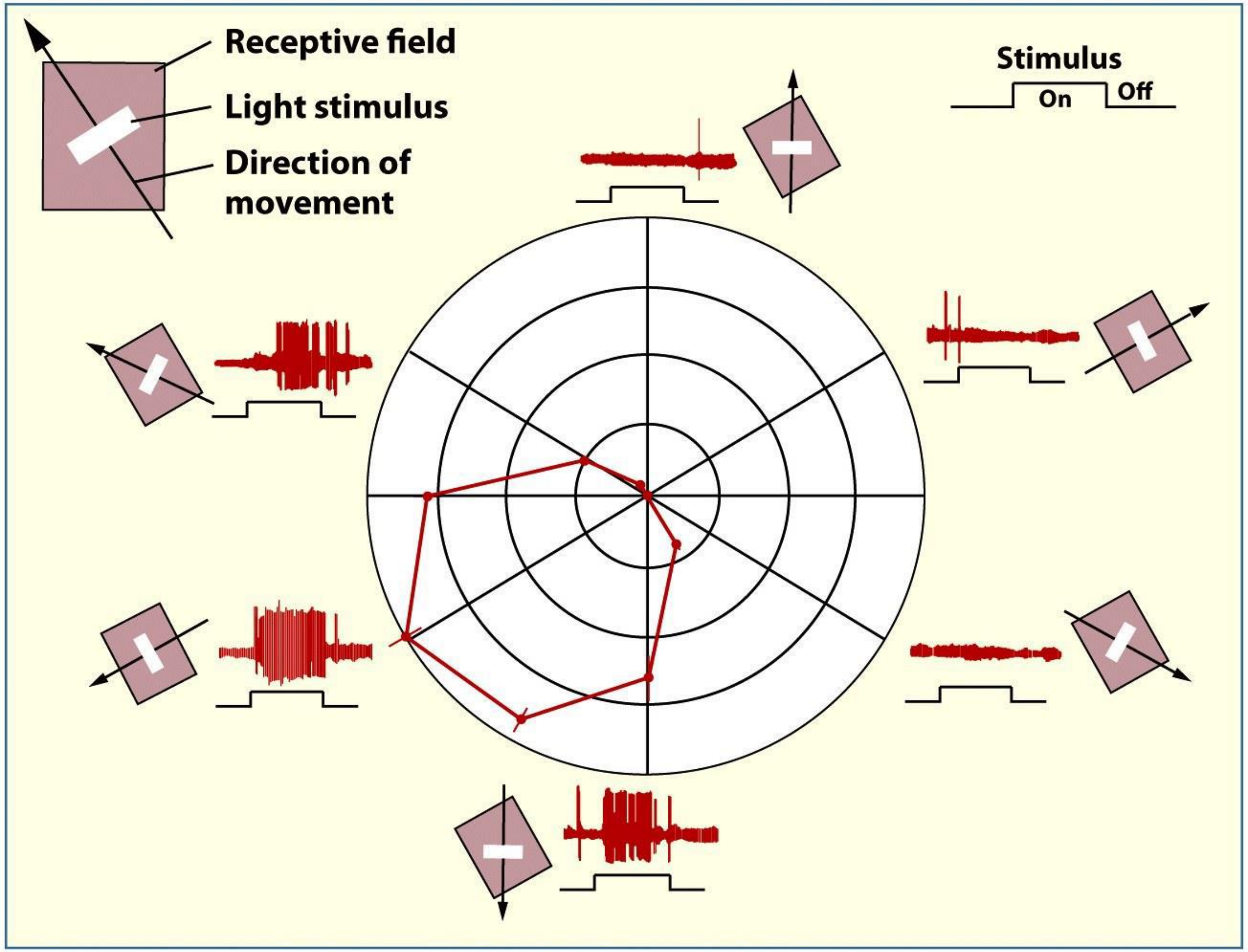
Fig. 3. Transcript excerpts from patient's report during electrical stimulation of electrodes 181–182 (FFA) and 177–178 (color-preferring site) while viewing a box, a ball, the experimenter's face, or a kanji character. For full transcript see *Transcript of Entire Stimulation Session*; for excerpted videos see Movies S1 and S2

Schalk et al. 2017

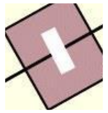
Dorsal stream: MT

- Highly selective for motion direction and speed
- Invariant to object form or texture
- Thought to underlie motion recognition

Dorsal stream: MT motion preference



single-neuron direction tuning

Same bar orientation  evokes different responses depending on movement

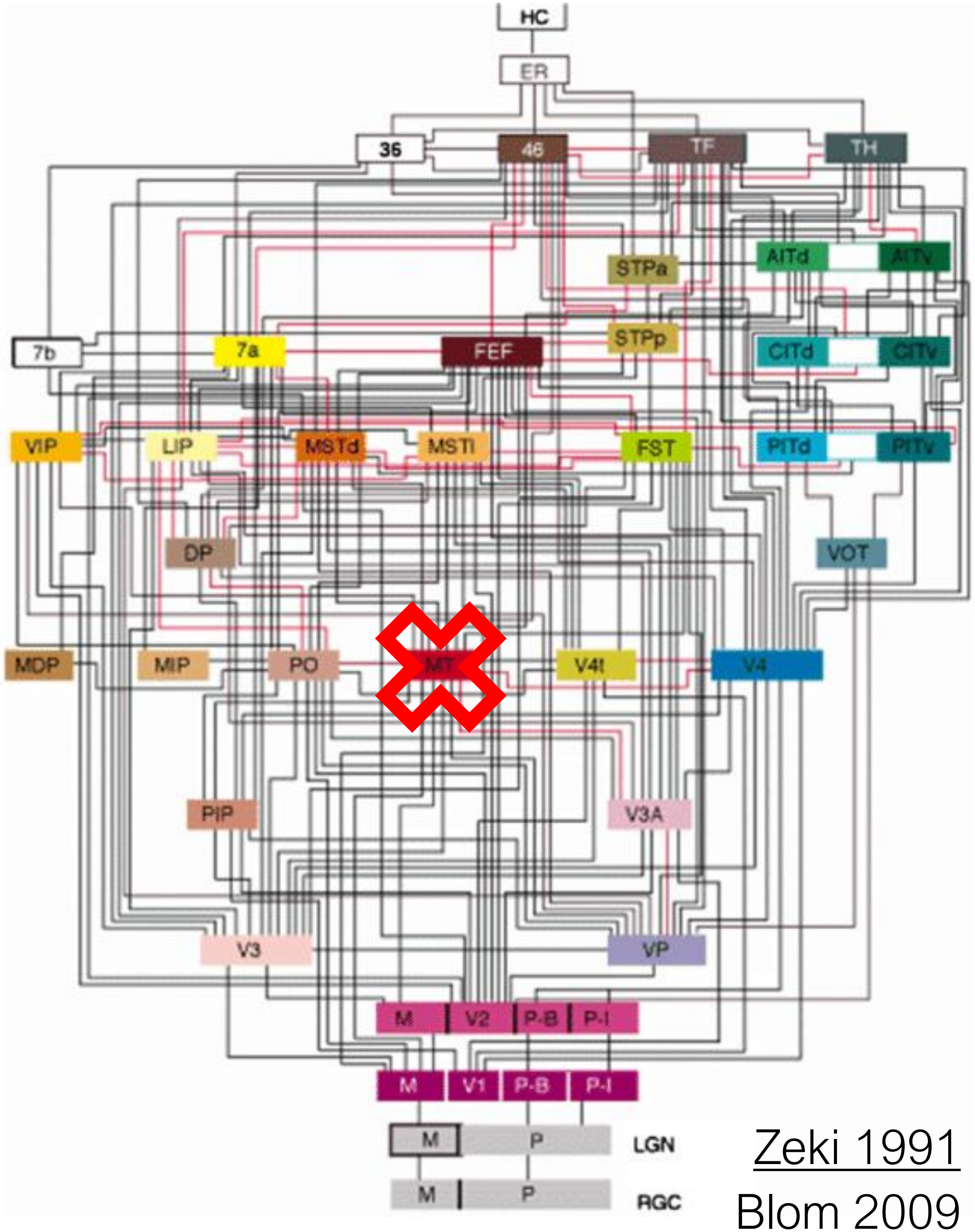
Courtesy of Bob Desimone's class MIT 9.017

Akinetopsia

Damage to MT (middle temporal visual area, also called V5)

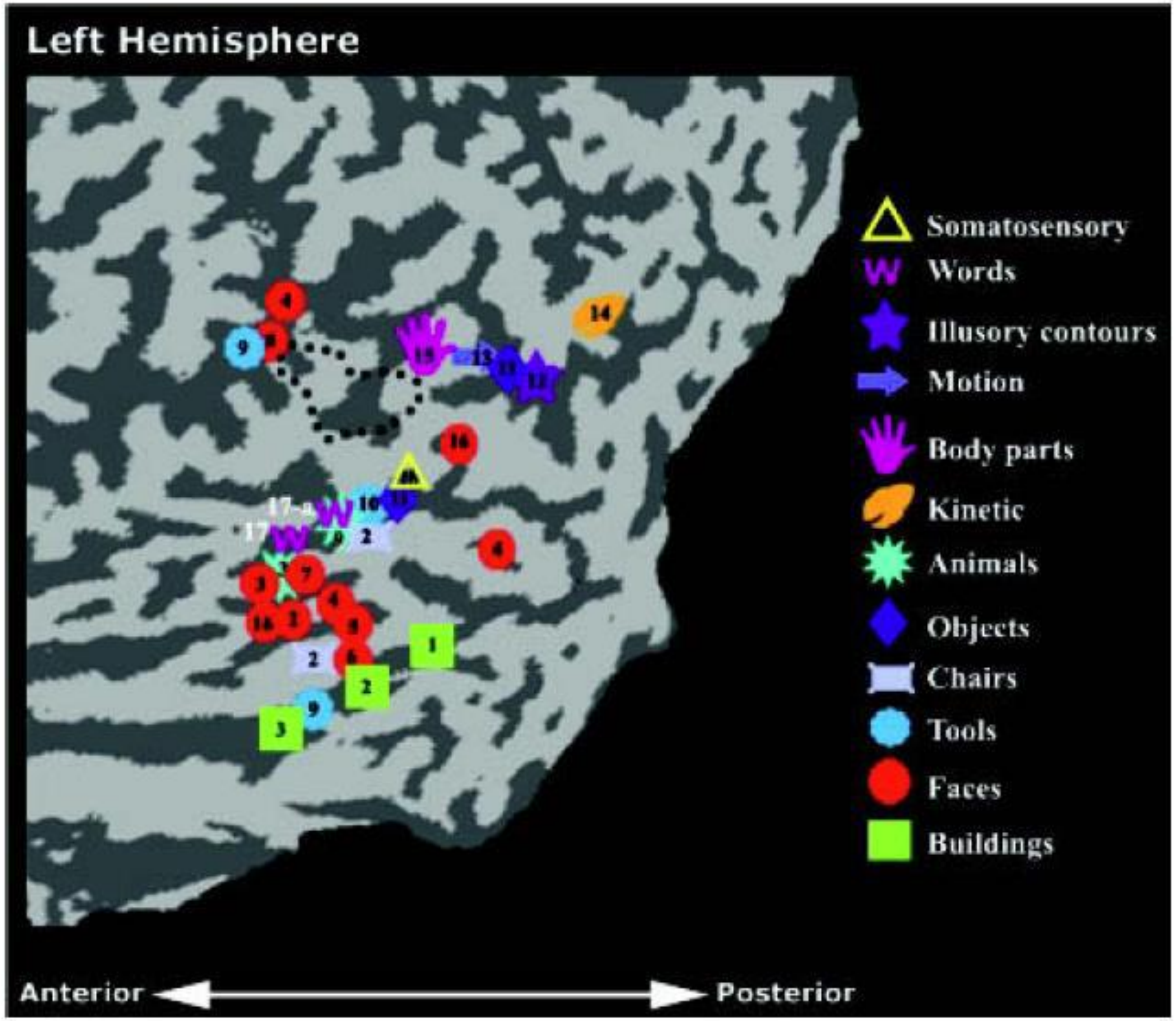
→inability to perceive motion

→but: intact ability to perceive stationary objects



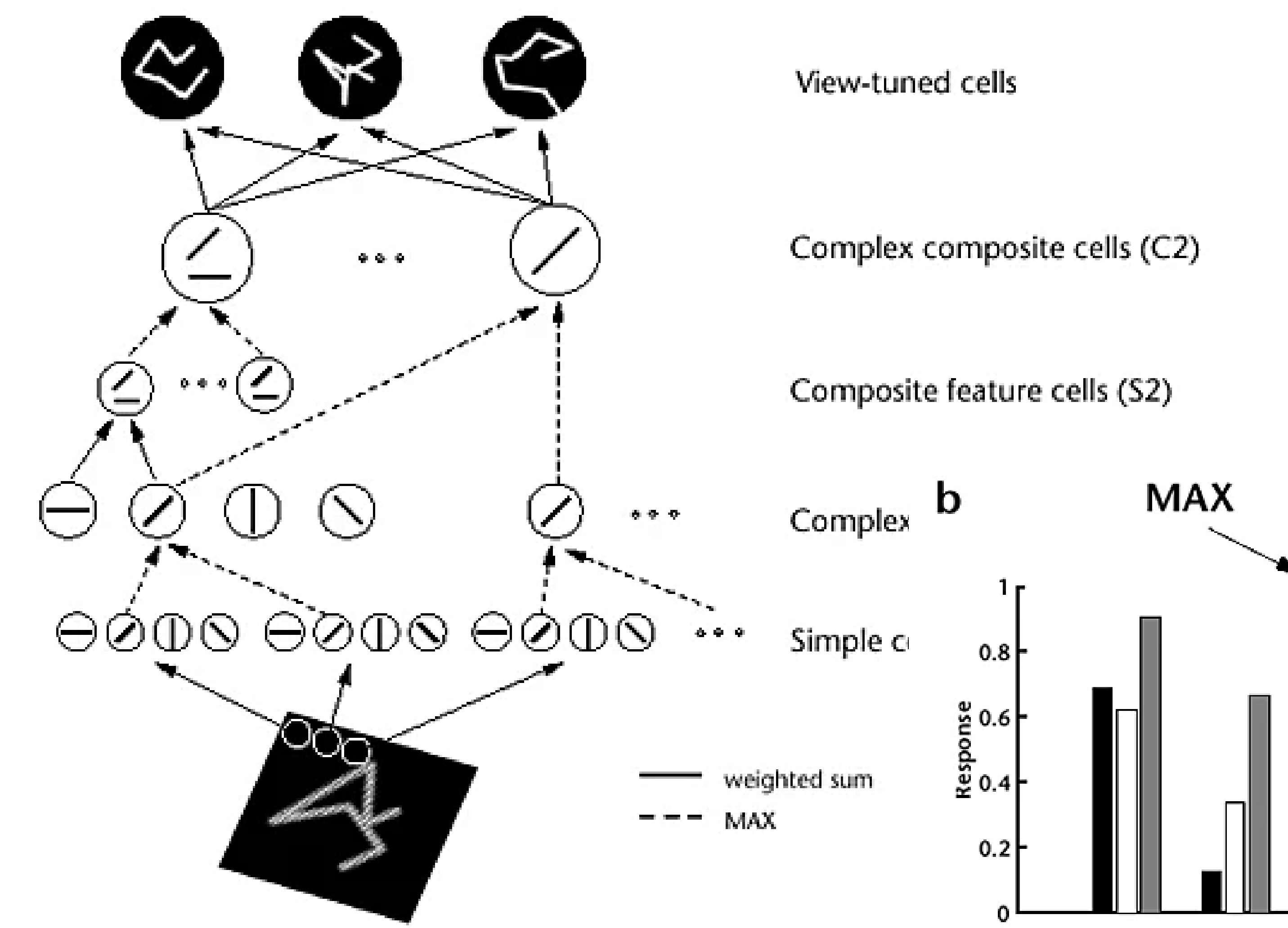
Zeki 1991
Blom 2009

Swiss army knife of visual areas



Grill-Spector et al. 2004

Computational Models of Vision: HMAX

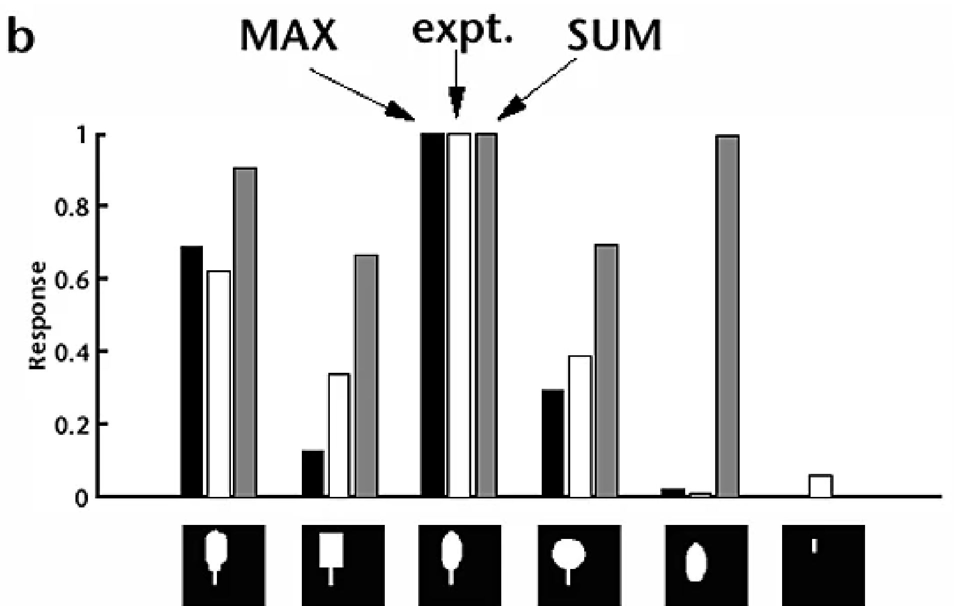


Hierarchical feedforward architecture

Simple cells: linear operations

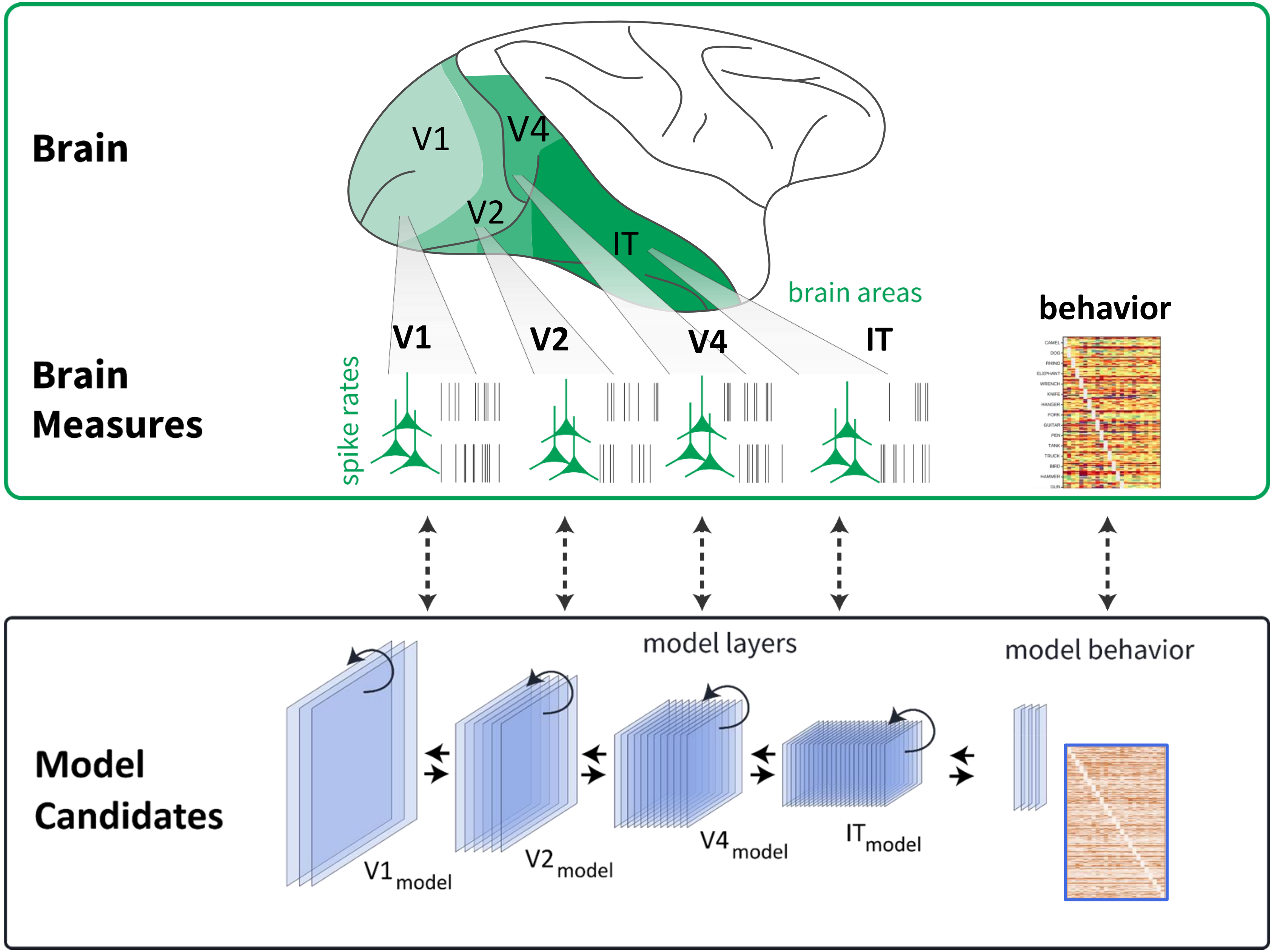
Complex cells: nonlinear pooling (max-pool)

Replicates higher-order effects in IT



senhuber & Poggio 1999

Computational Models of Vision: Deep Nets



Schrimpf et al. 2020

Vision conditions

Achromatopsia: see world devoid of color

Synesthesia: associate letters with numbers

Prosopagnosia: inability to recognize faces

Prosopagnosia

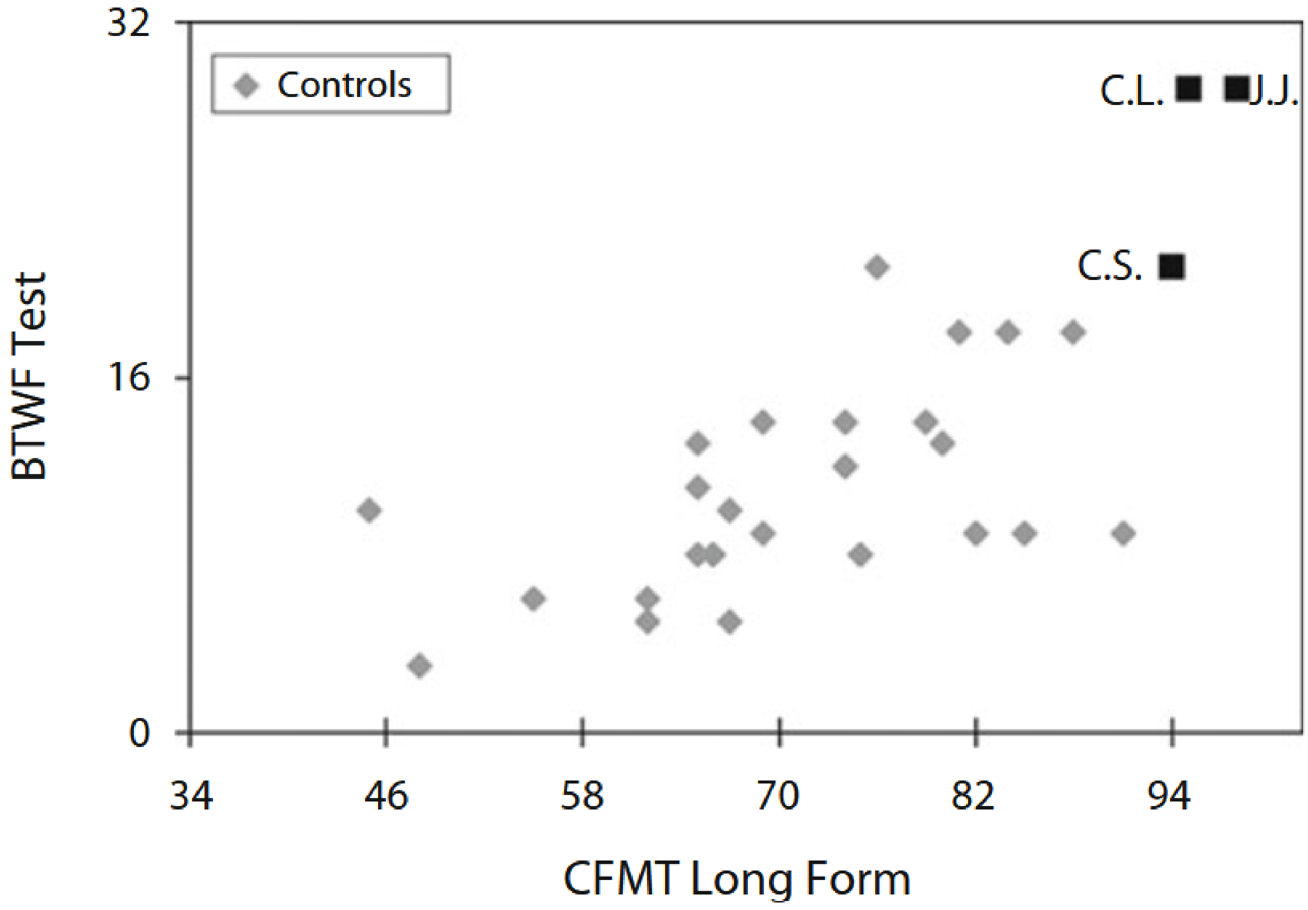
Which is easier?

Which is easier?

Neurotypical individuals find it easier to recognize faces in their usual orientation. People with prosopagnosia have no difference in performance.

Super-recognizers

- Extraordinary face recognition ability
- Opposite of prosopagnosia
- Improved face matching performance compared to average population



Russel et al. 2009

Questions

- Name three structures involved in vision in the brain
- What is a receptive field?
- What types of stimuli do neurons in V1 respond to?
- How does the Gabor model relate to V1?
- What two pathways does V1 feed into and what are thought to be their key functions?
- How are IT and MT different from one another?