Early and Intermediate Visual System

NEU/MOL 502A: **From Molecules to Systems to Behavior**

Overview

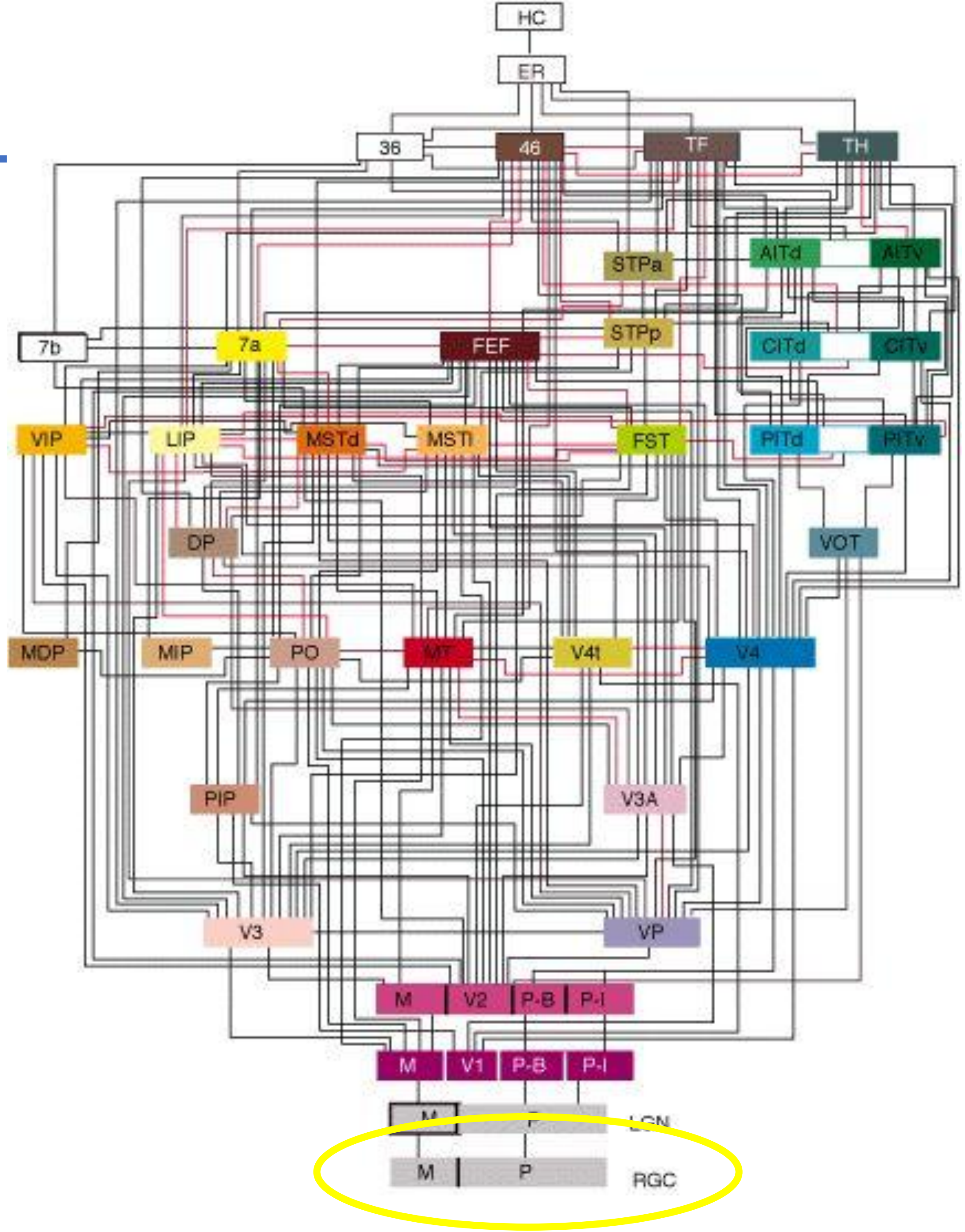
- Retina and Thalamus
- Moving up the cortical hierarchy
- Beginning to Parse Objects: How to distinguish figure and ground?

The Visual Hierarchy

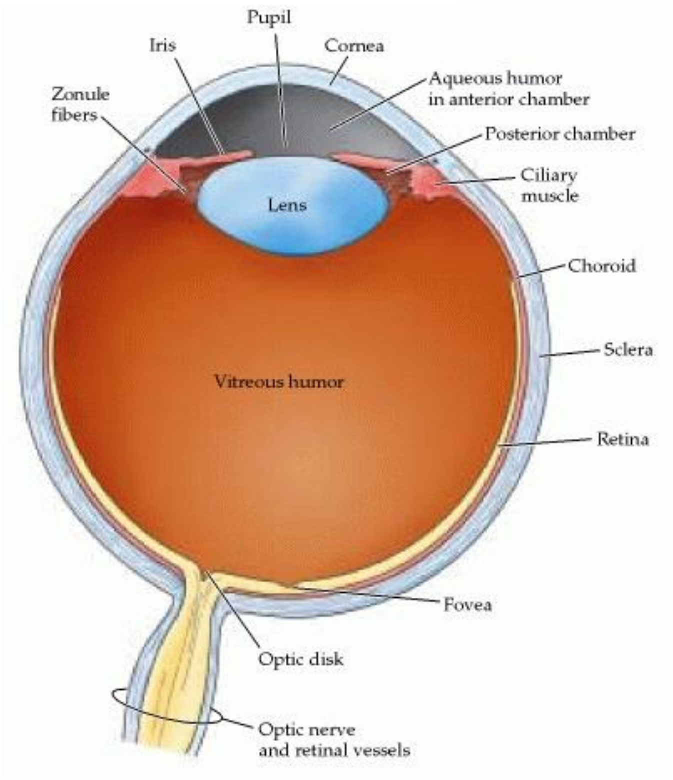
The ‘subway map’ of the visual brain.

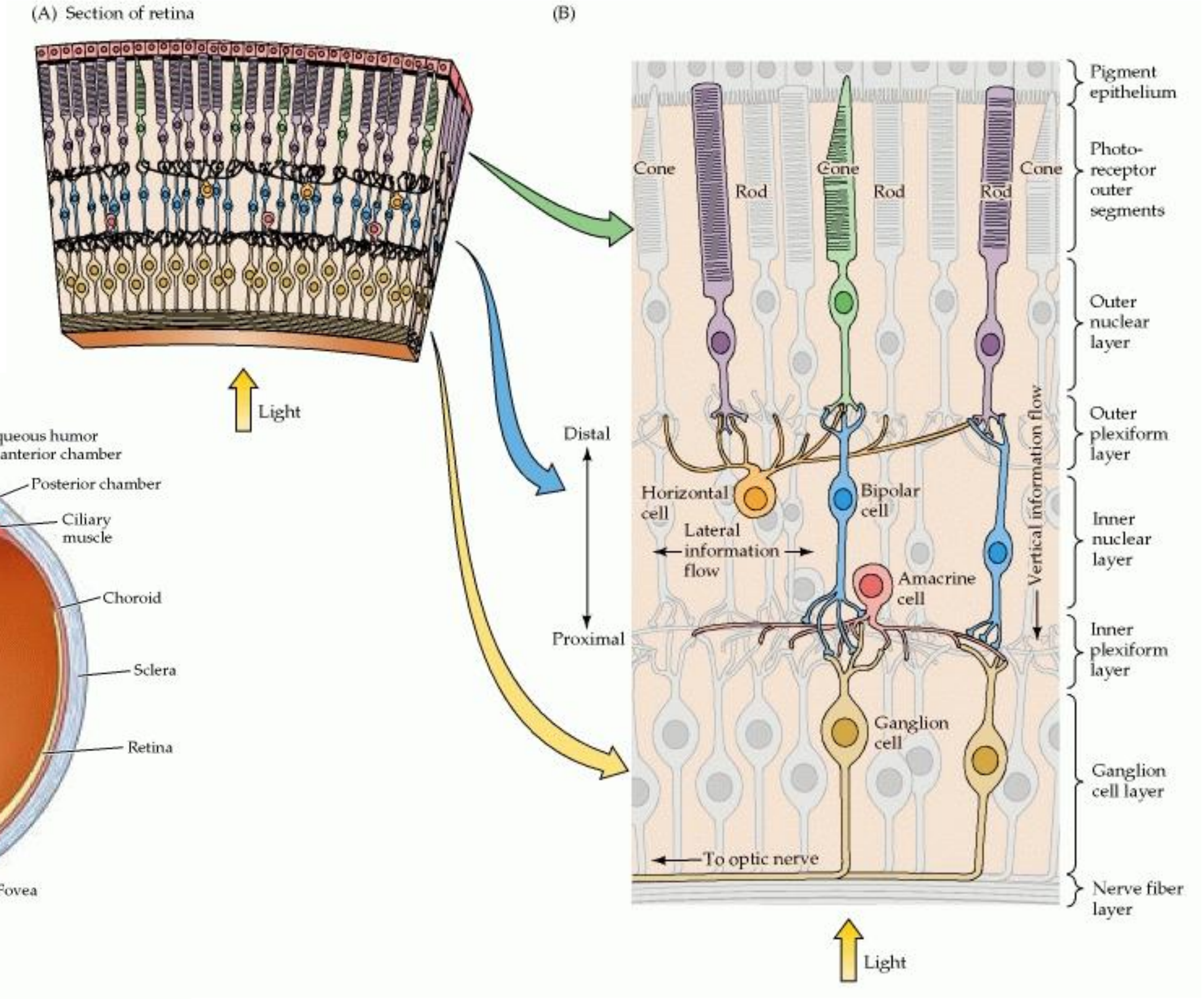
Often misinterpreted to mean unidirectional connections – almost all of these connections are **bidirectional**.

NOTE: Even LGN receives more inputs from V1 than from the retina!



Anatomy of the Eye

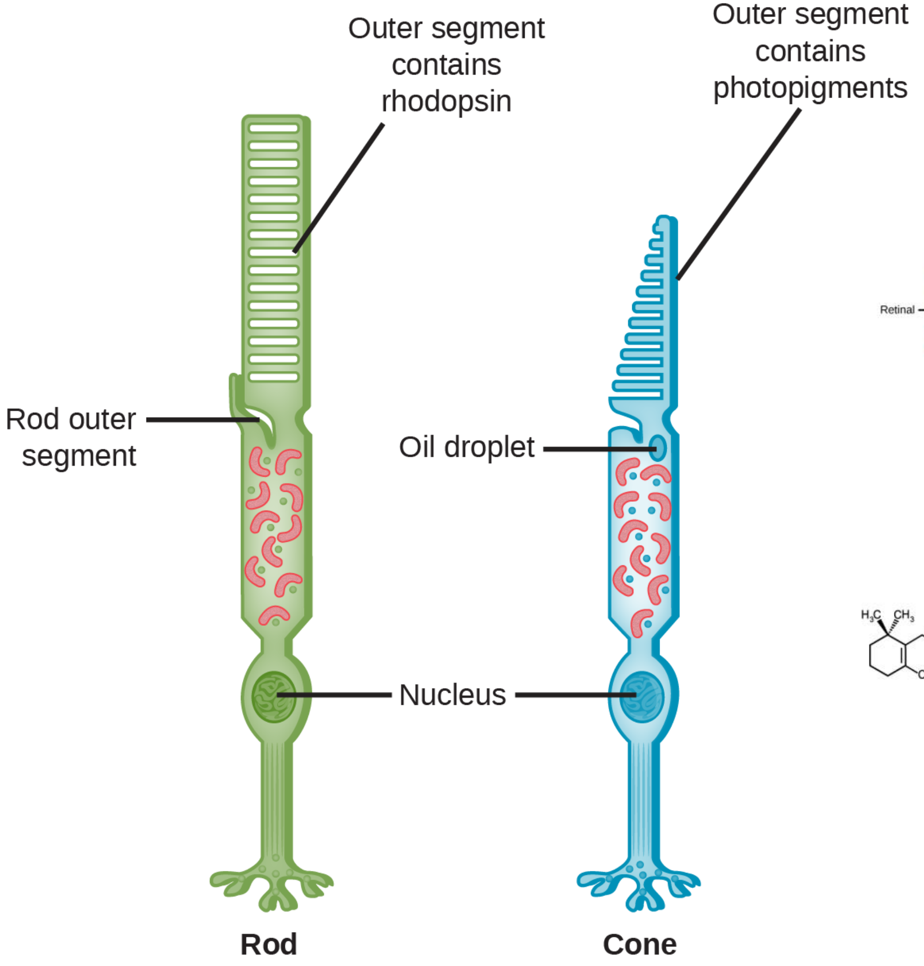


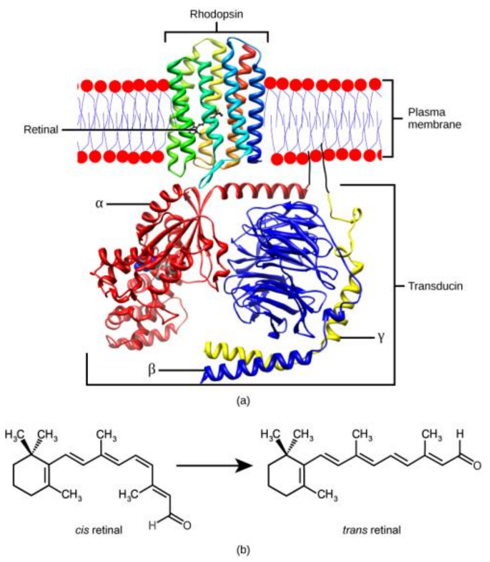


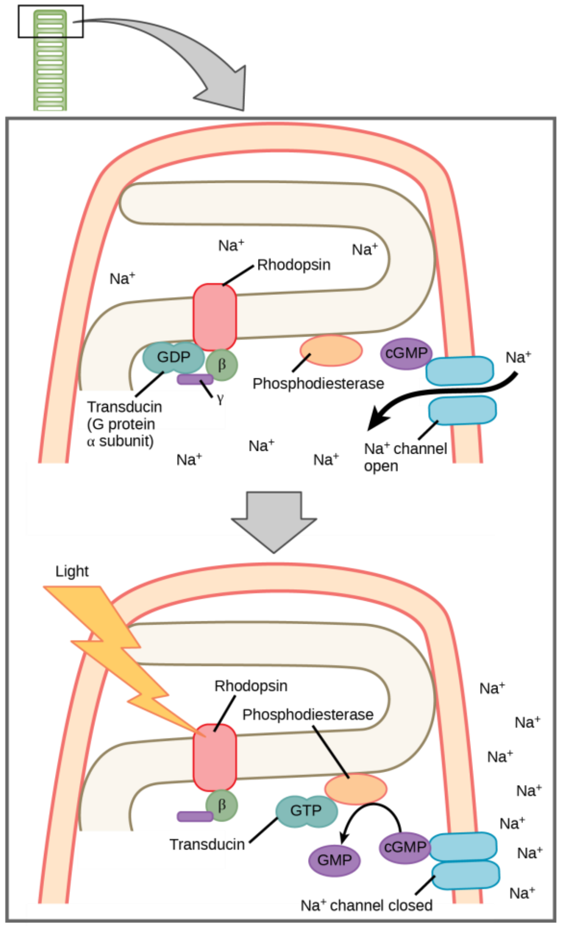
Photoreceptors: Rods and Cones

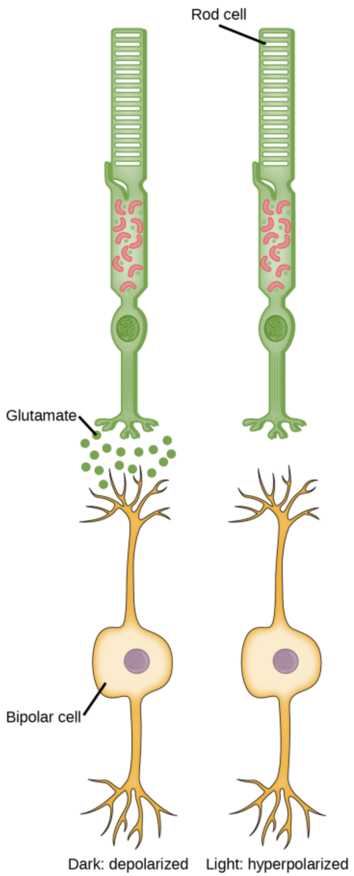
Your eye has two classes of photoreceptors: rods and cones.

Both work in roughly the same way: light causes a conformational change in a membrane-bound G-coupled protein which closes Na+ channels, **hyperpolarizing** the rod/cone and **stopping** the release of Glutamate.



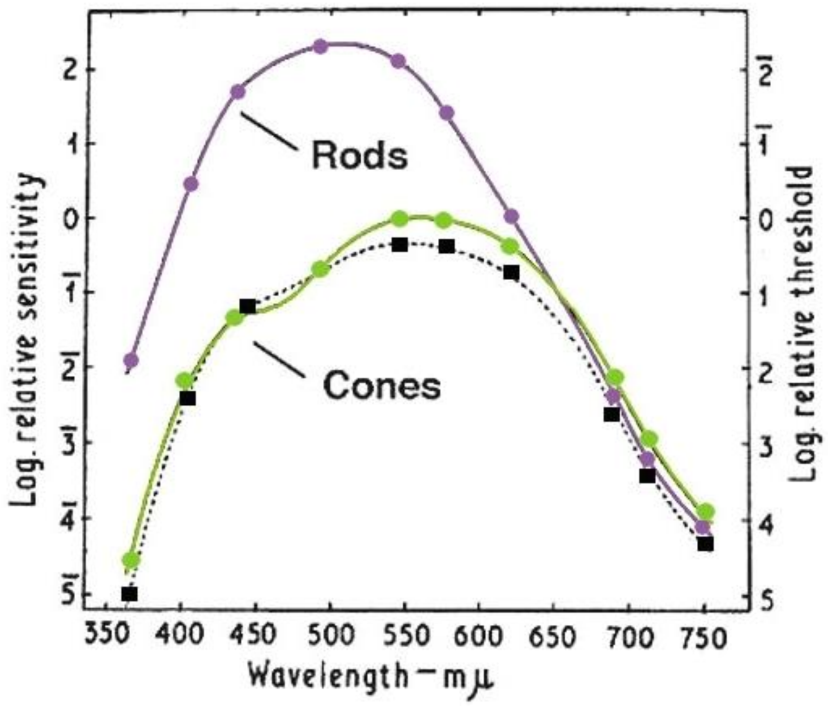


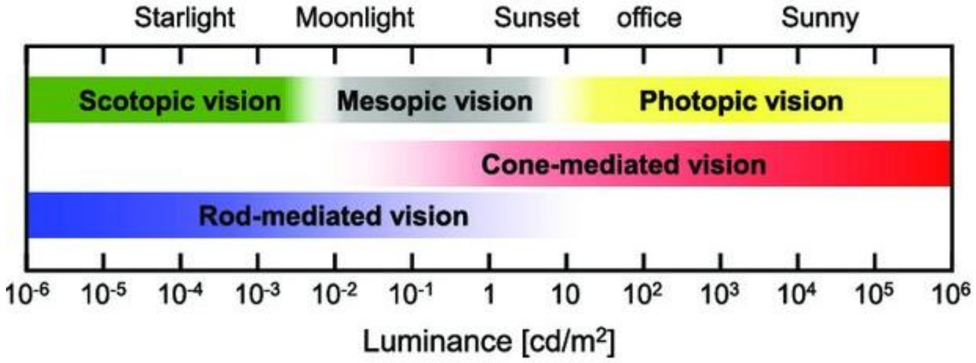




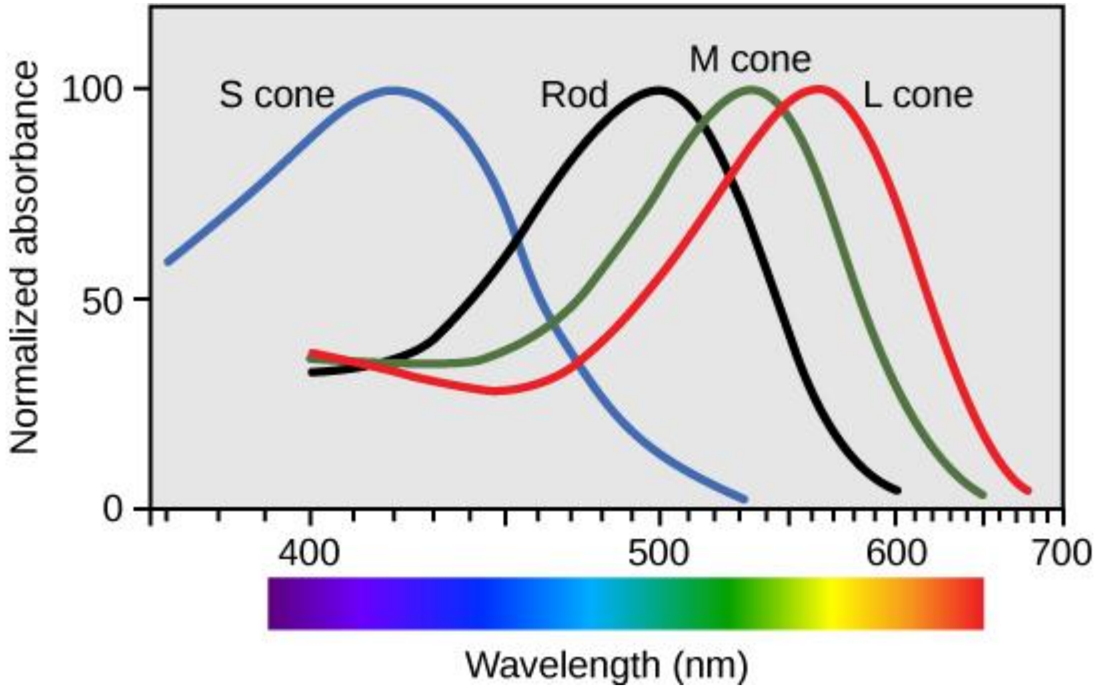
Photoreceptors: Rods and Cones are Tuned Differently

Rods are much more sensitive to light than cones.



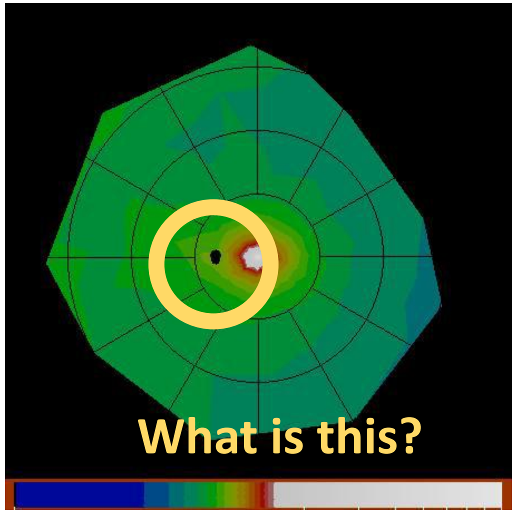


All four photoreceptors have different responses to wavelengths.

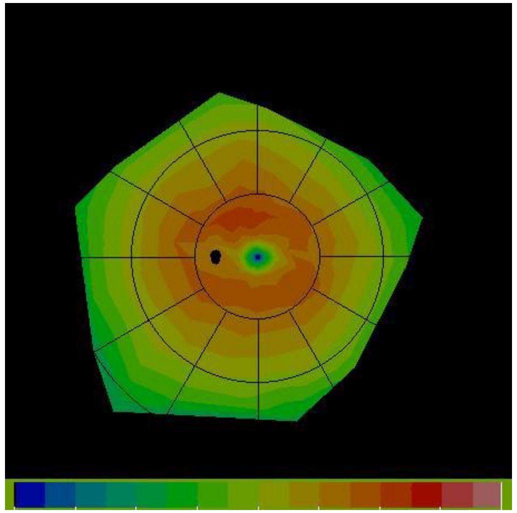


Photoreceptors: Distribution of Rods and Cones

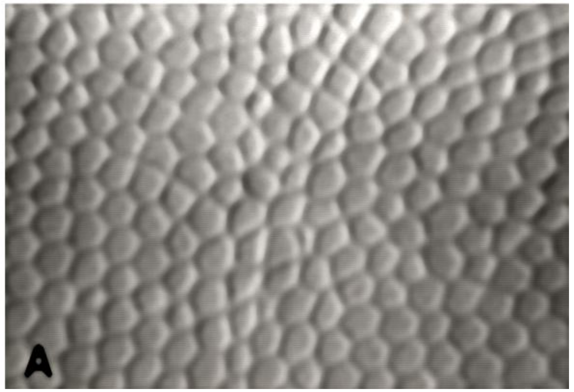
Distribution of Cones

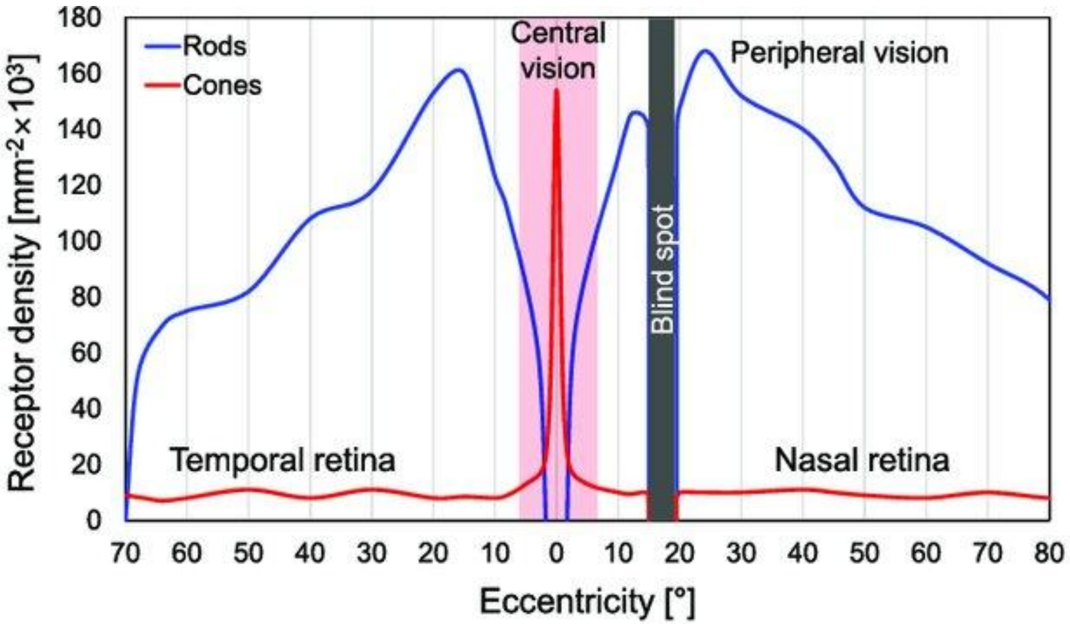


Distribution of Rods

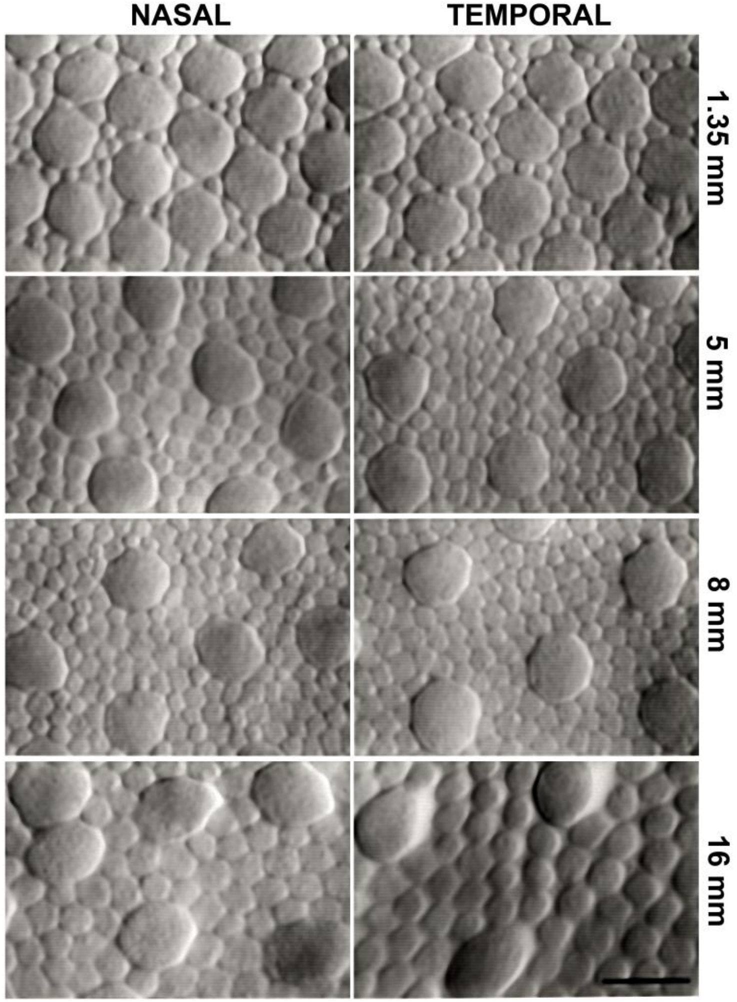


Fovea



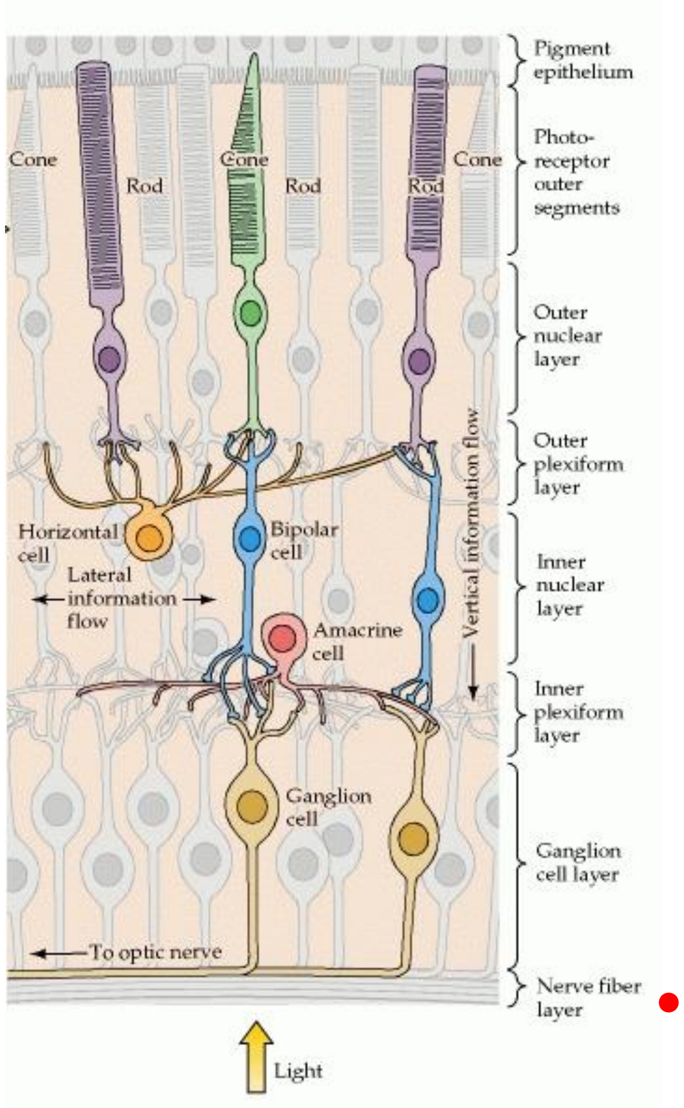


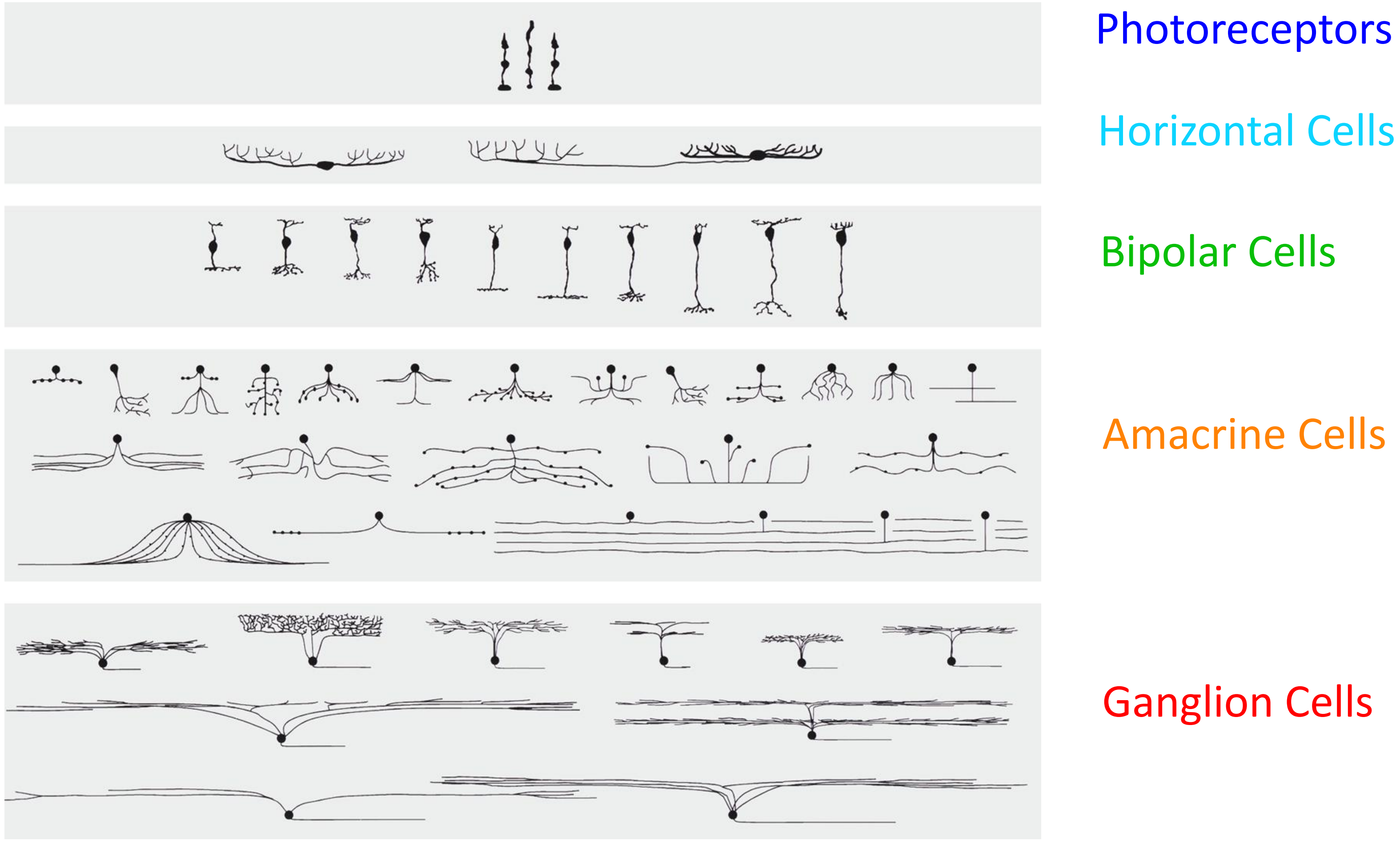
Periphery



Visual Responses in the Retina

Signals propagate through several layers of neurons in the retina. Canonically, these have identified three stages, each with lateral connections.



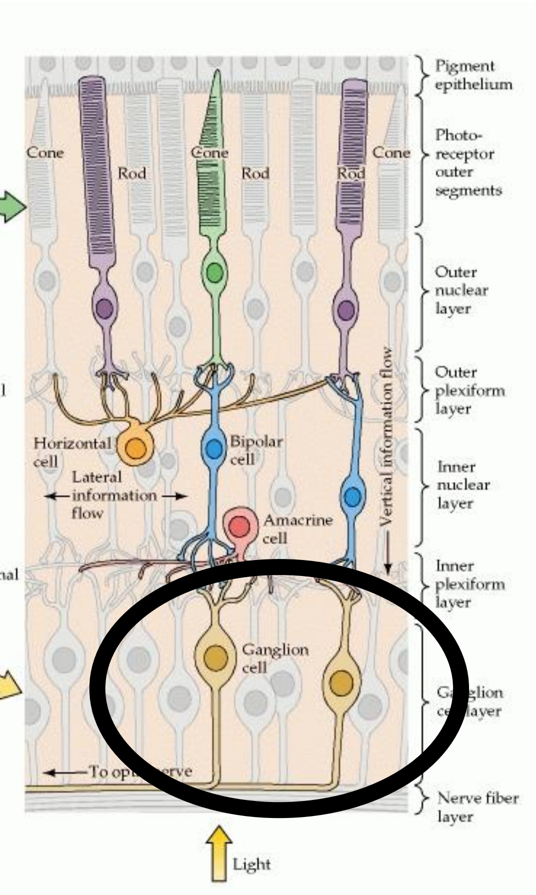


- Current estimate: 50-100 cell types in the retinal microcircuit

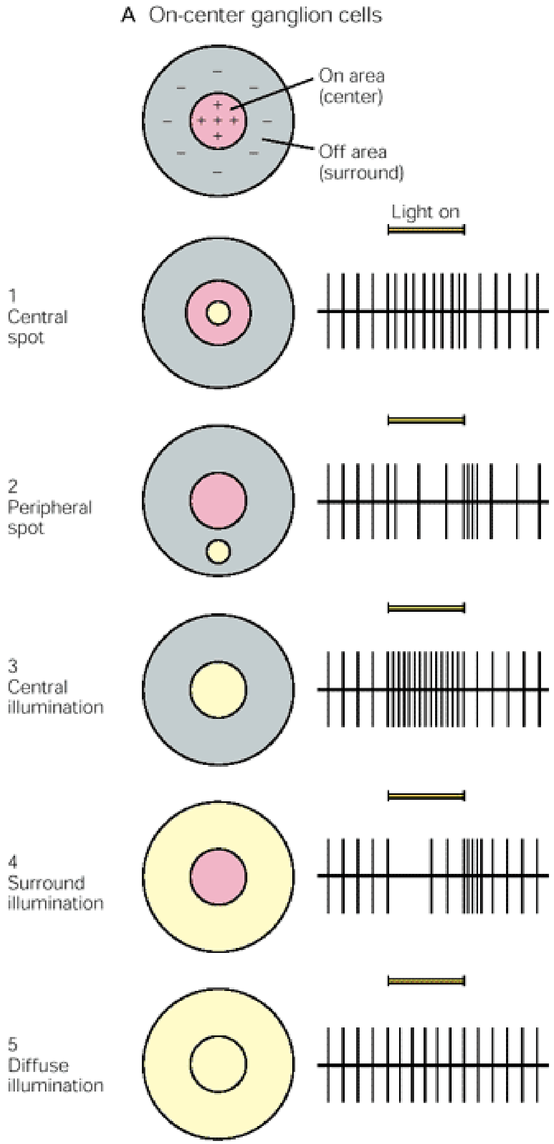
*** What is all this complex circuitry for?

(Masland)

Visual Responses in the Retina



What about the outputs?



What is the purpose of calculating the contrast?

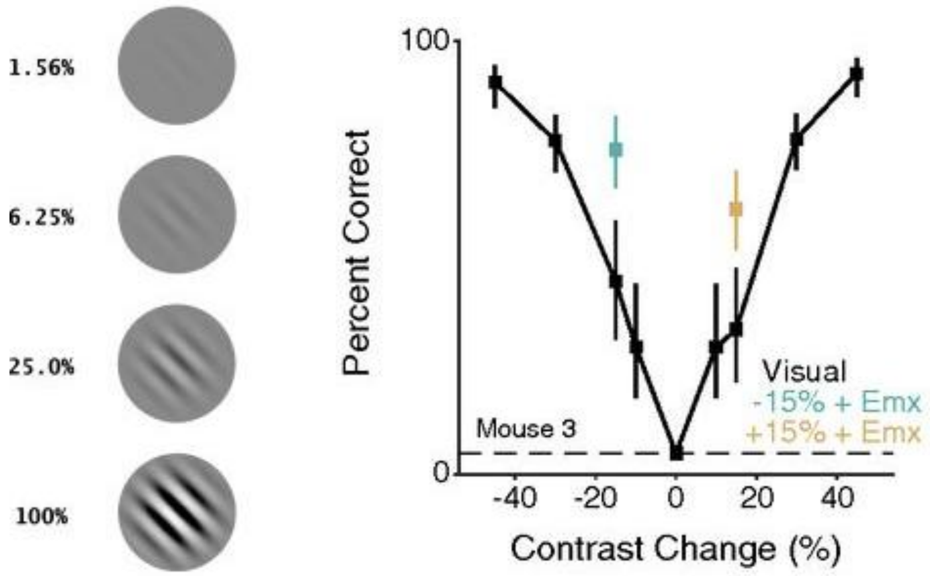
- Overcomes the limited firing rate range of neurons, allowing for high acuity no matter the ambient light levels.
- Reduces the number of neurons and spikes needed to convey visual information.

Why have both ON-center and OFF-center ganglion cells?

- Speeds response to either increases or decreases in light

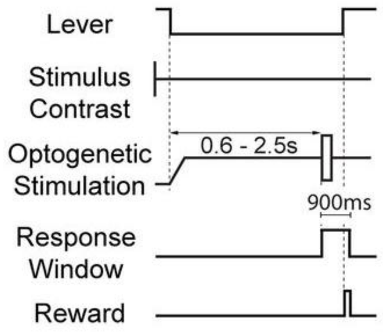
Detecting changes in firing rate of neurons

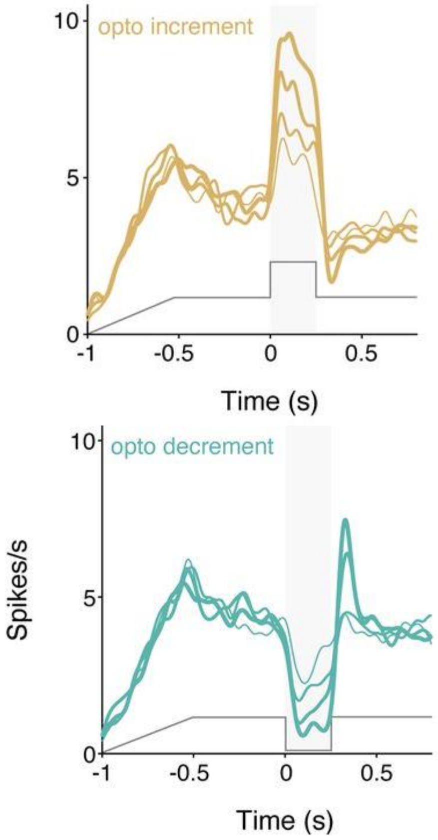
Mice were trained to detect an increment OR a decrement in the contrast of a stimulus.



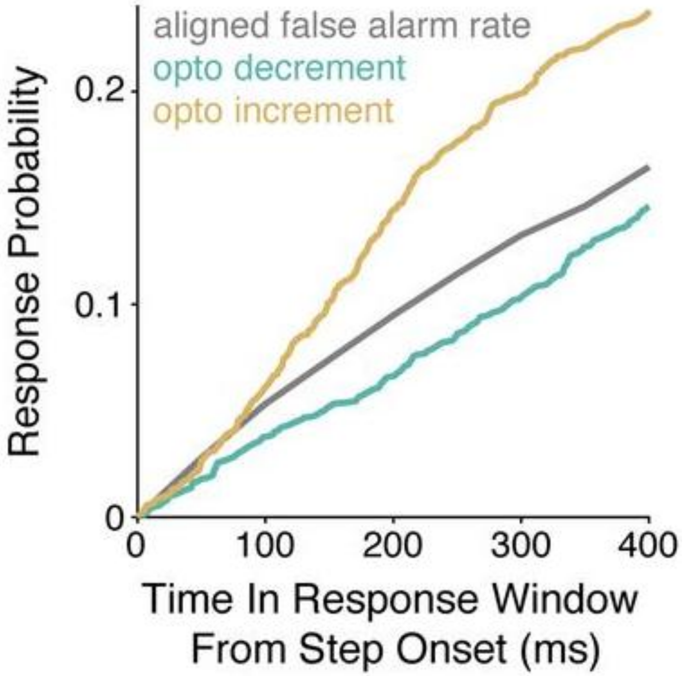
Typically, an increase in contrast is associated with an increase in neural response.

Yet, *adding* spikes with optogenetics improves mouse performance on detecting either an increase or a decrease.





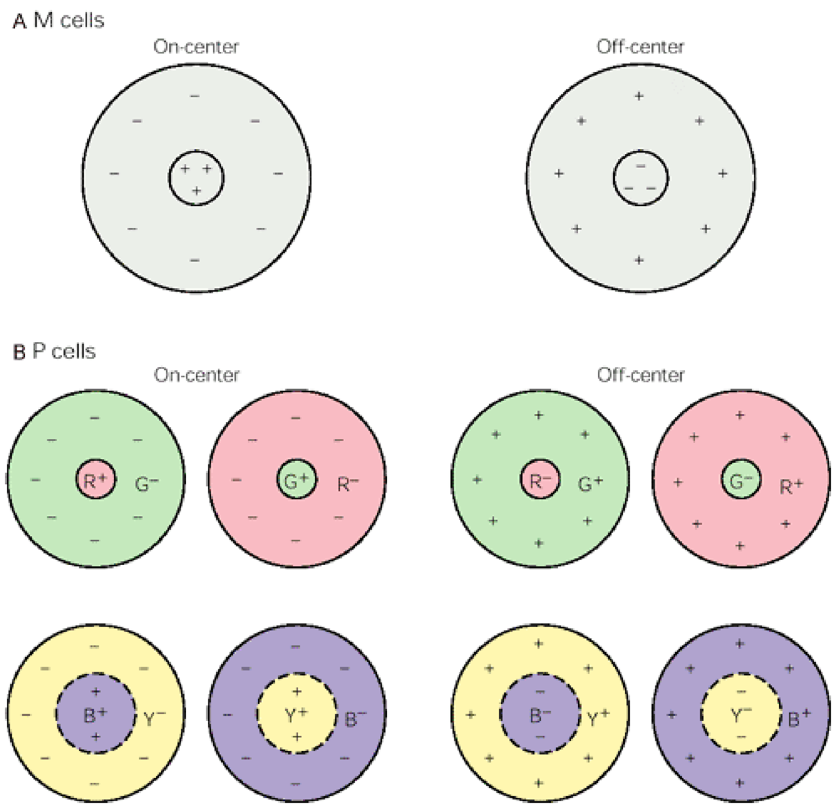
Optogenetics could be used to induce the percept of a change in a stimulus. This works well for increases in neural activity but fails for decreases.

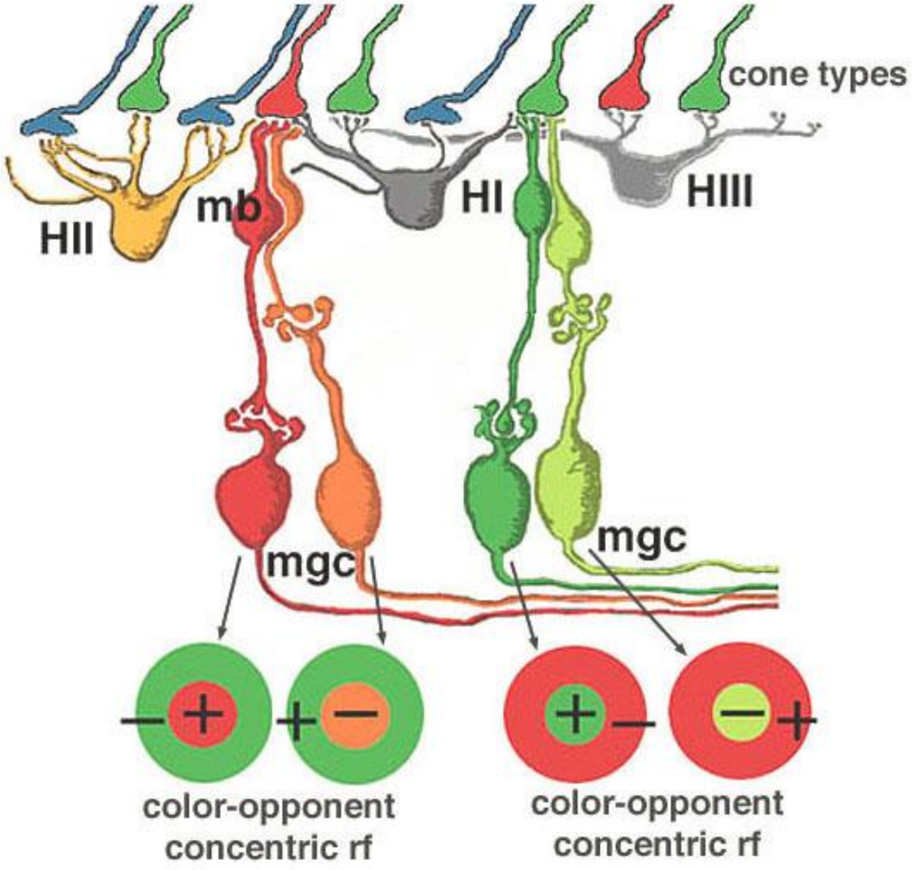


RNNs trained to *save spikes* do the same thing.

Cone et al, 2020

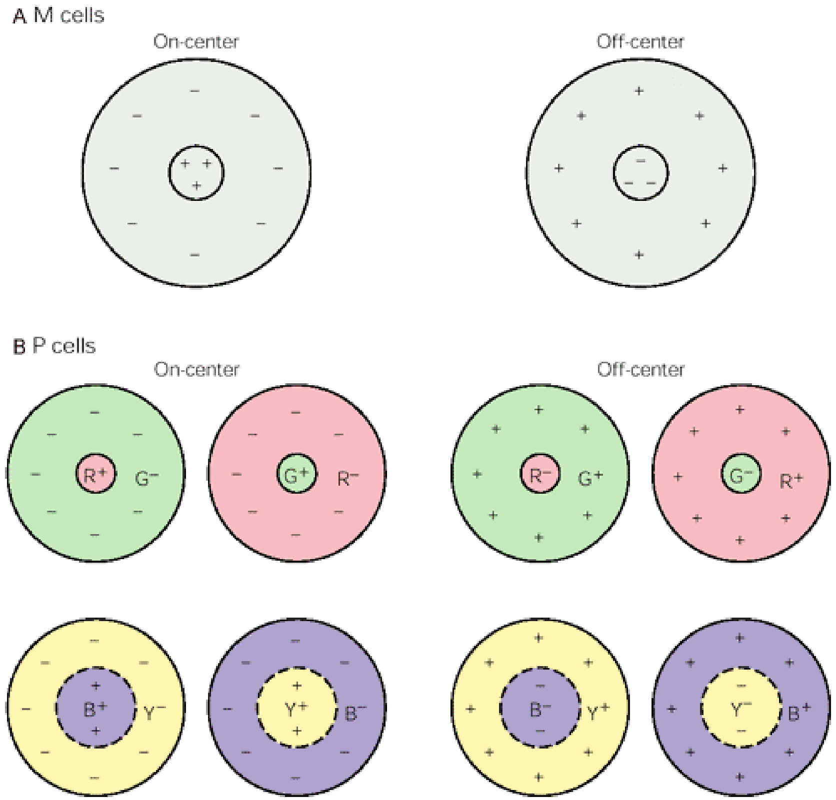
Building Color Opponency in the Brain



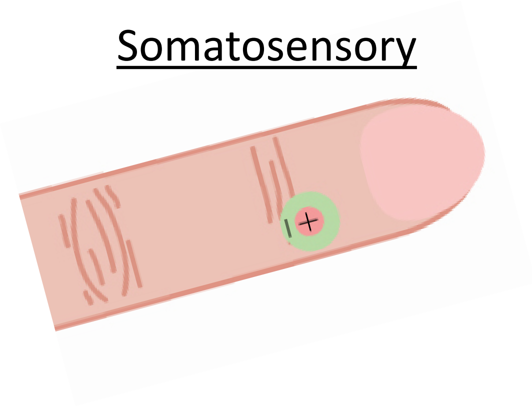


Opponency in all sensory systems…

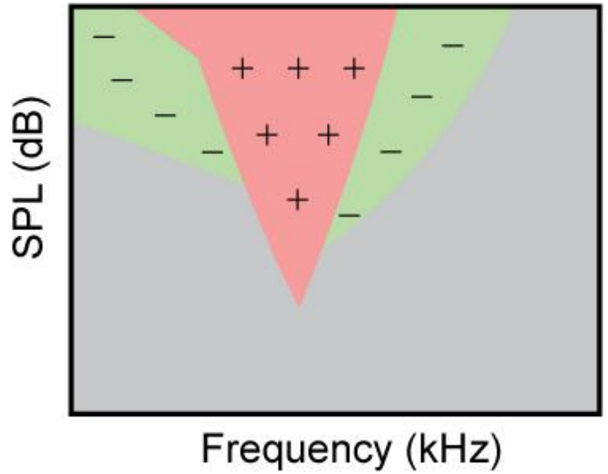
Visual



Somatosensory

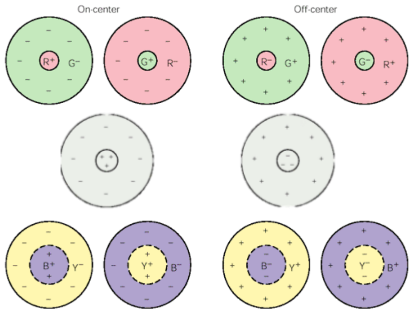


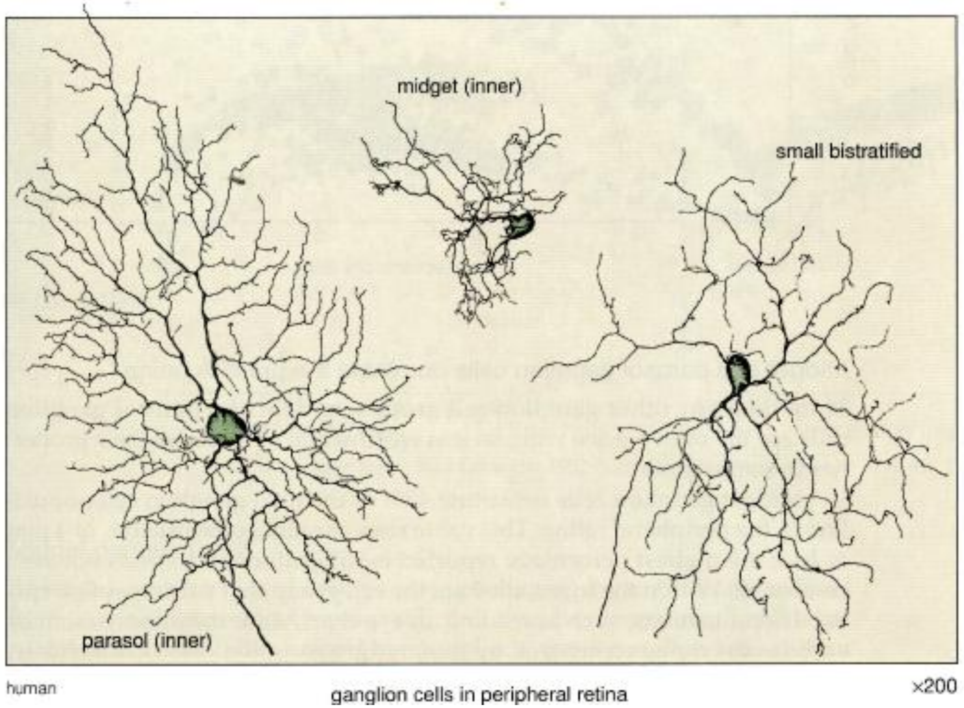
Auditory

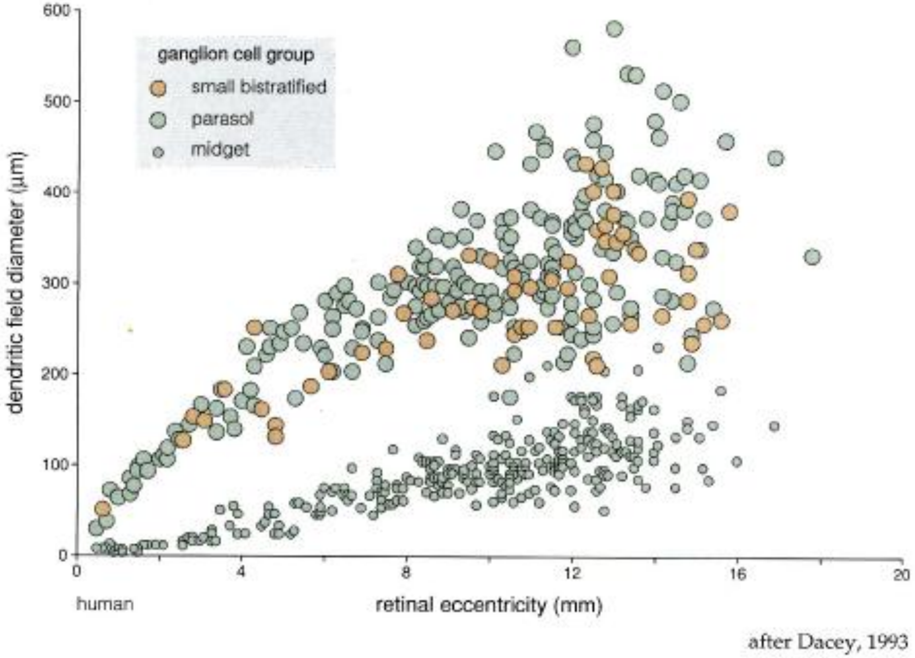


Three of the Major Retinal Ganglion Cell Types

• Midget (ON, OFF)	700,000 cells	smallest RF	red-green
• Parasol (ON, OFF)	100,000 cells	fastest spikes	no color
• Small bistratified	50,000 cells	blue ON	blue-yellow







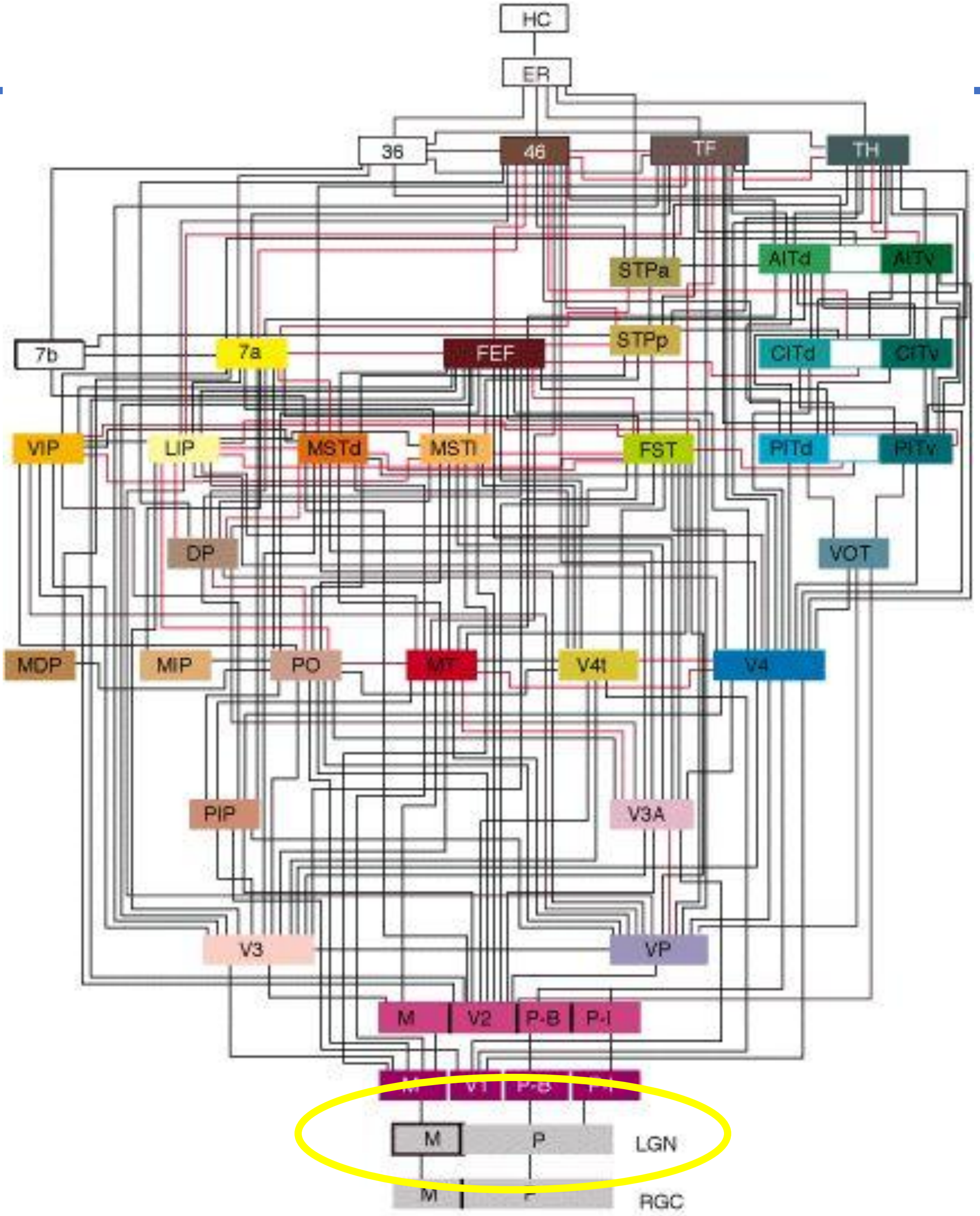
- Fovea: highest cell density — midget cell connects to 1 cone!
- Periphery: specializes in motion processing — less spatial resolution

The Visual Heirarchy

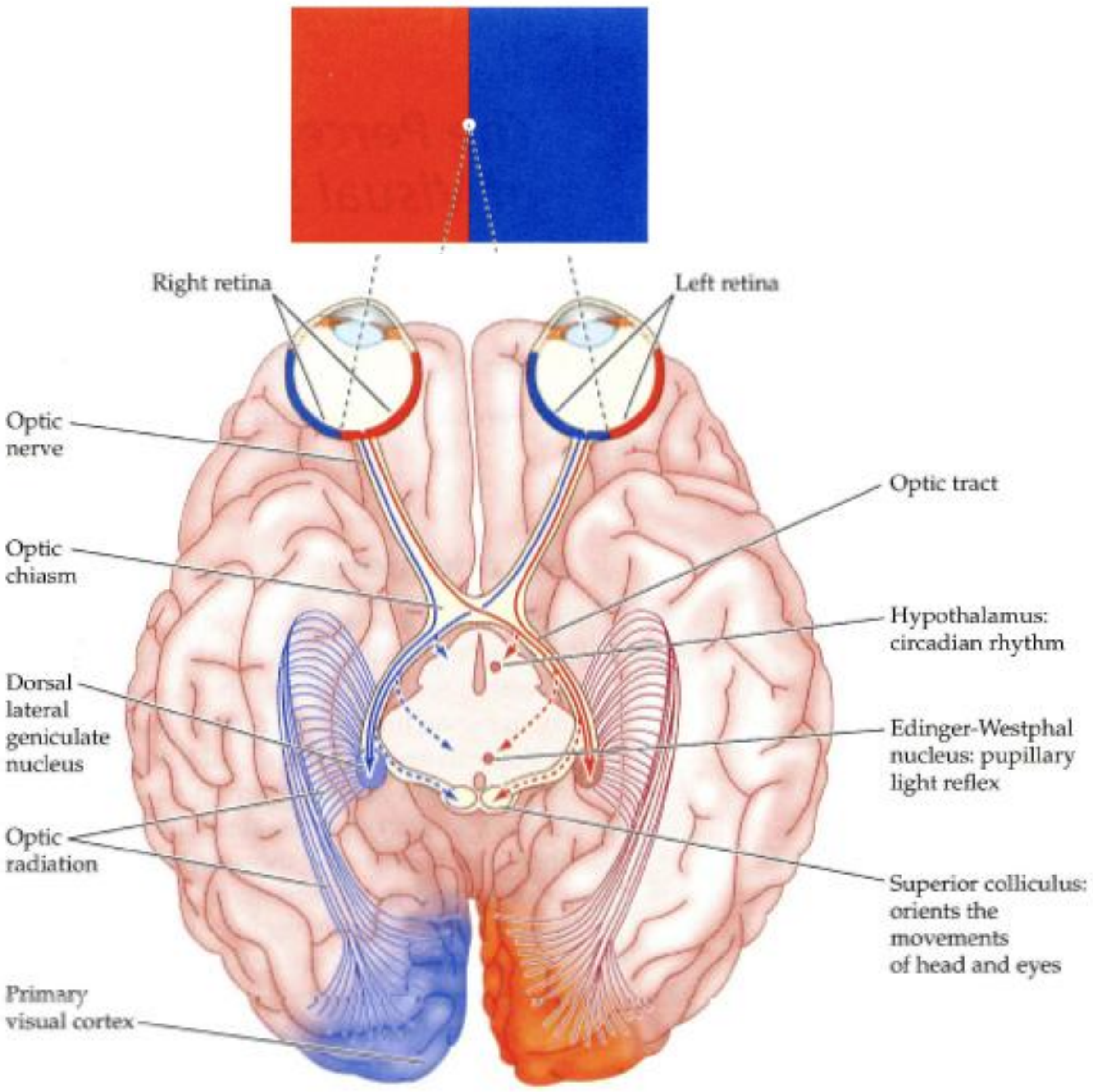
The 'subway map' of the visual brain.

Often misinterpreted to mean unidirectional connections – almost all of these connections are **bidirectional**.

NOTE: Even LGN receives more inputs from V1 than from the retina!

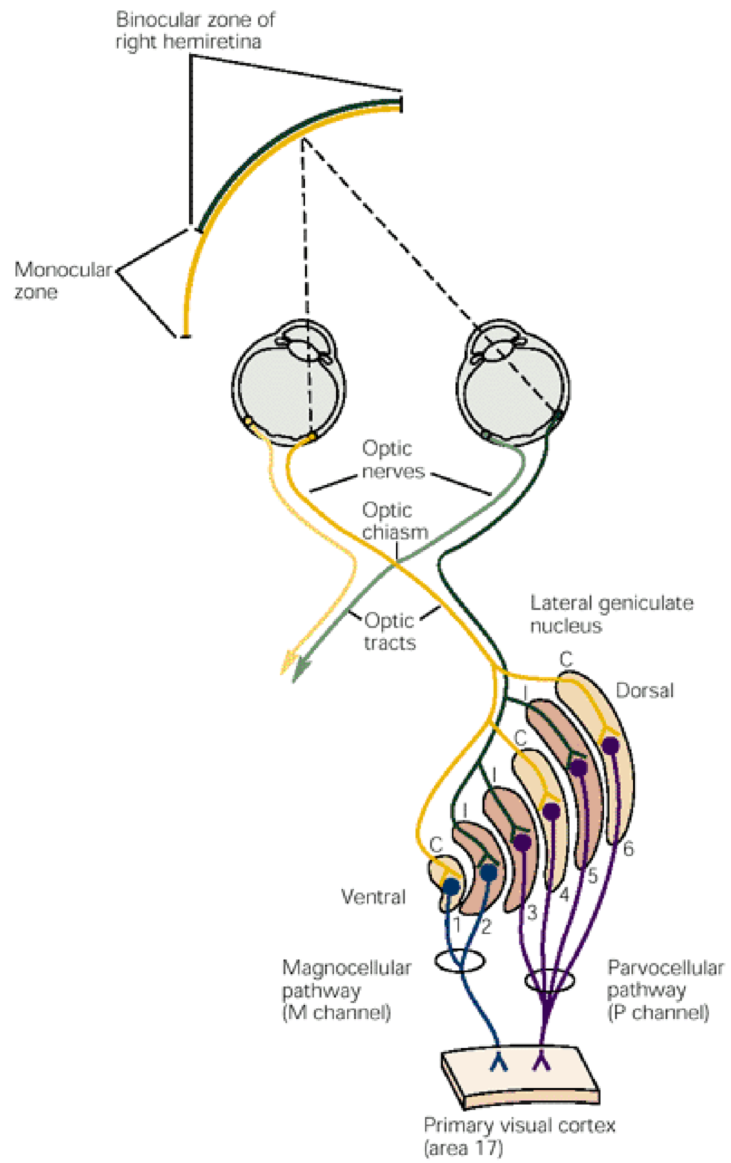


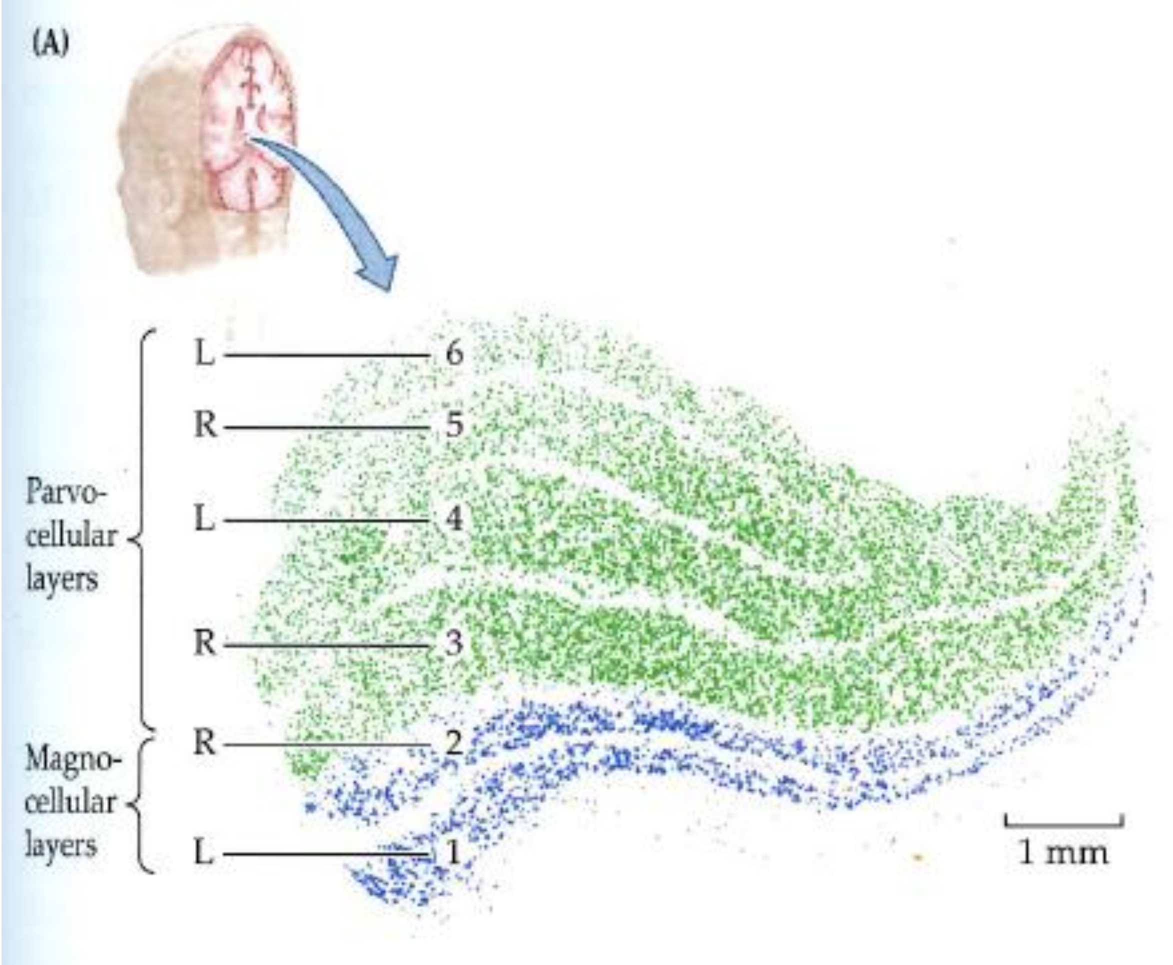
Projections from Retina into Thalamus



Organization of LGN

- Parvocellular: 4 layers — midget ganglion cells
- Magnocellular: 2 layers — parasol ganglion cells
- Koniocellular: in between — all other cell types





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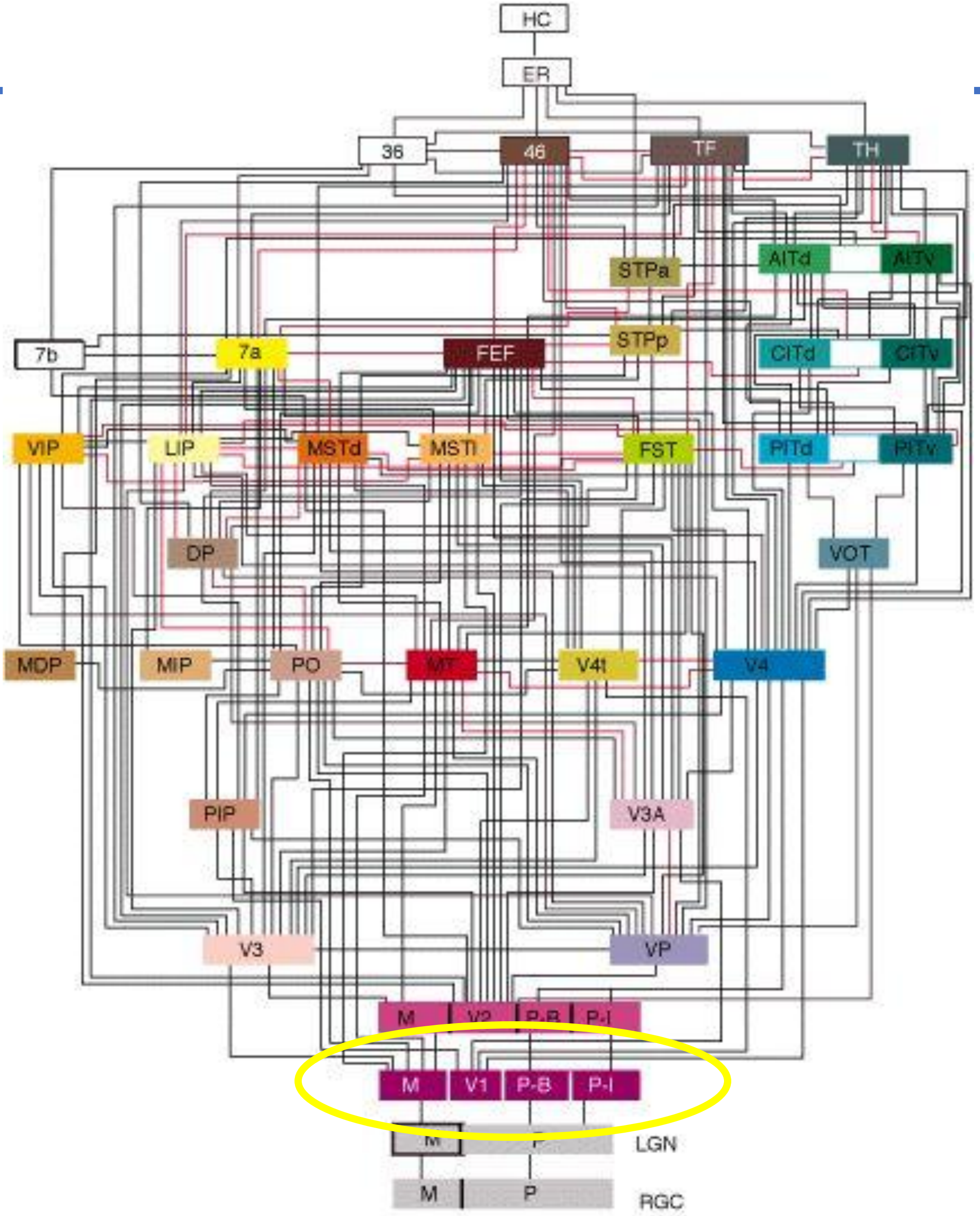
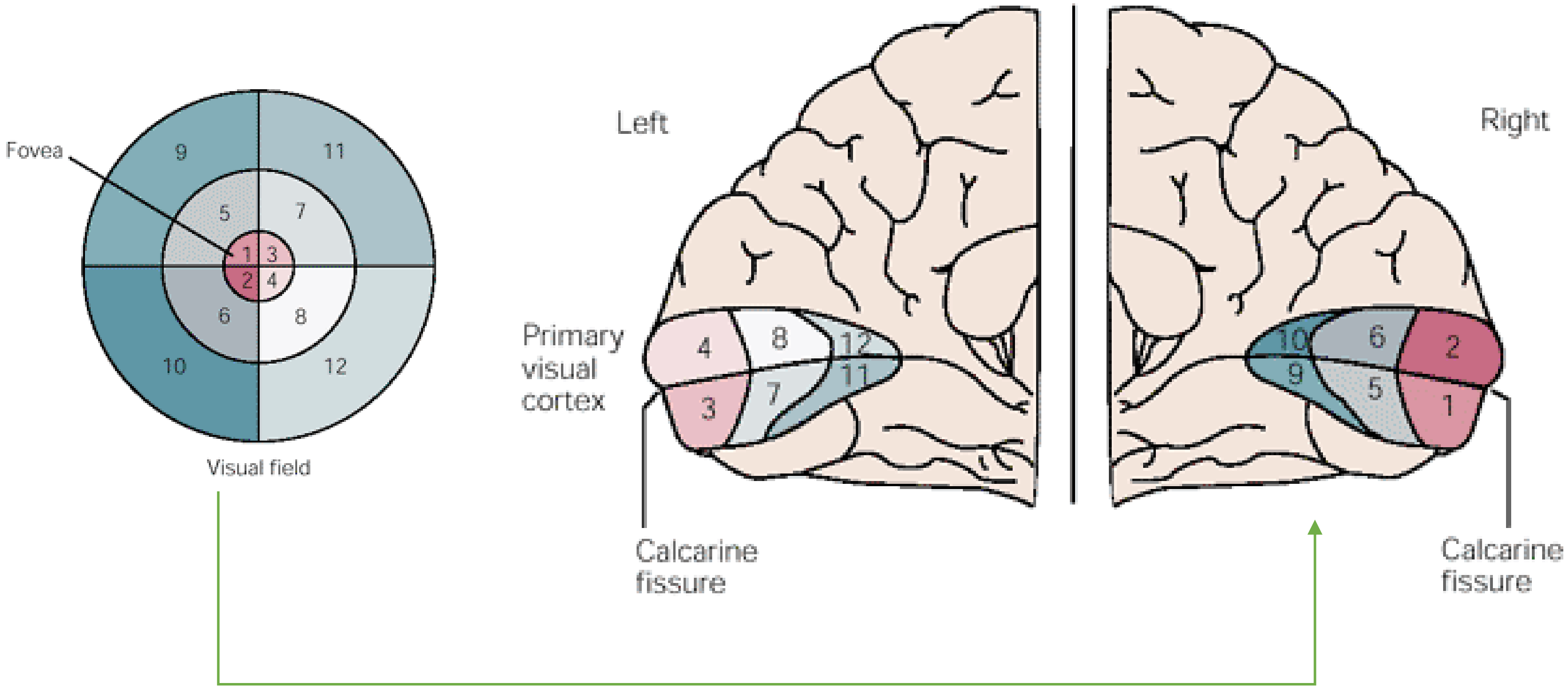
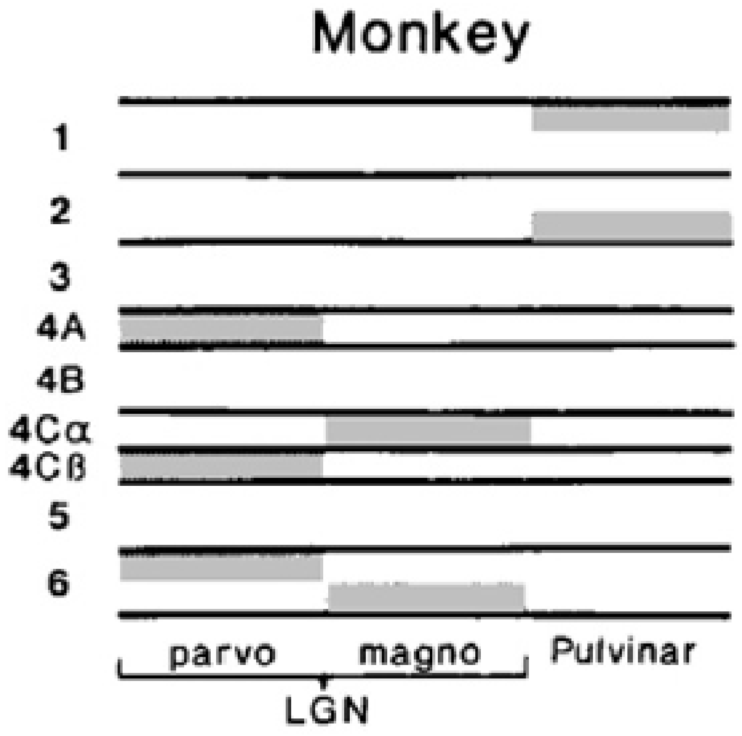


LGN Projects into Primary Visual Cortex

Unlike the retina, the cortex no longer has to deal with a direct spatial mapping – it can expand those regions of greatest interest. This leads to **cortical magnification**.



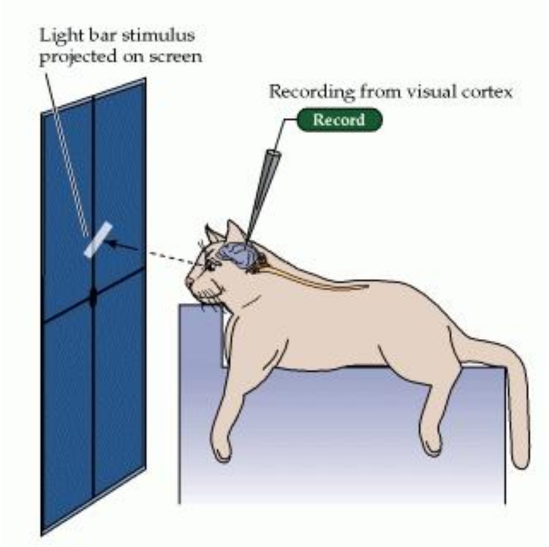
Remember, projections cross the midline.



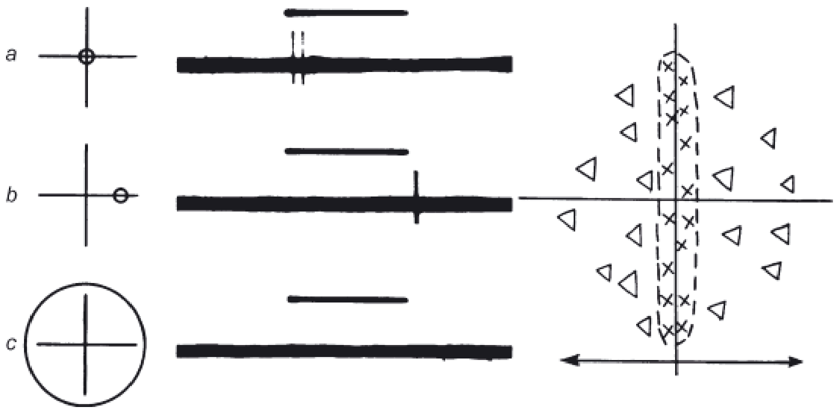
Inputs from LGN to V1 largely target layer 4. However, the exact layer depends on the cell type. This leads to a separation between parvo and magno inputs.

Neural Receptive Fields in V1

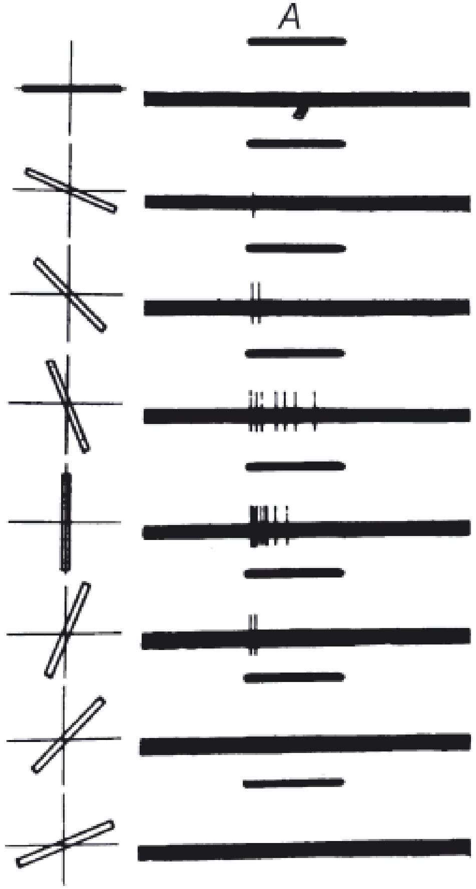
<u>Experimental Setup</u>



Mapping a Receptive Field (RF) by hand:

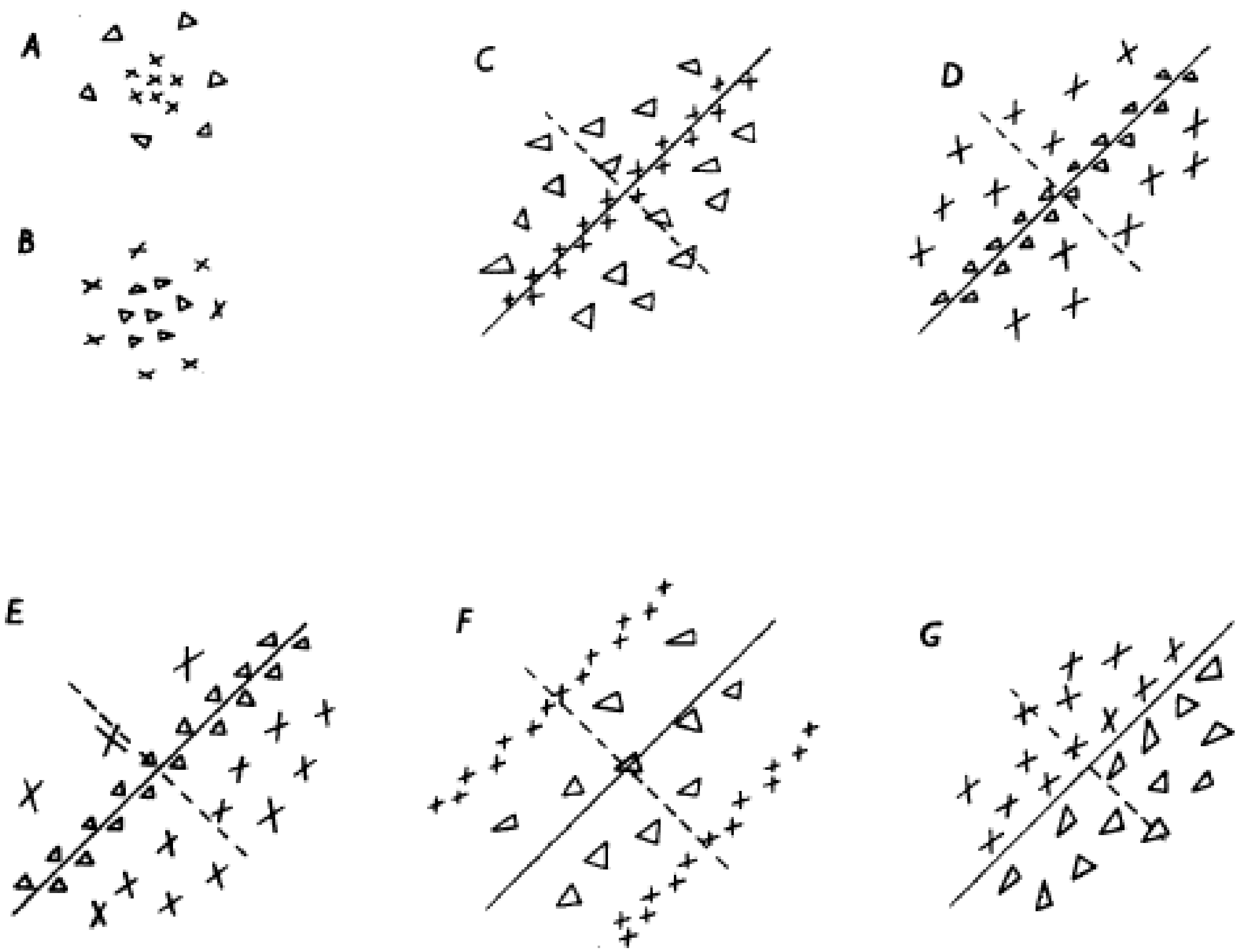


<u>Orientation Selectivity of a 'Simple' Cell</u>



LGN and V1 Simple Cells

LGN



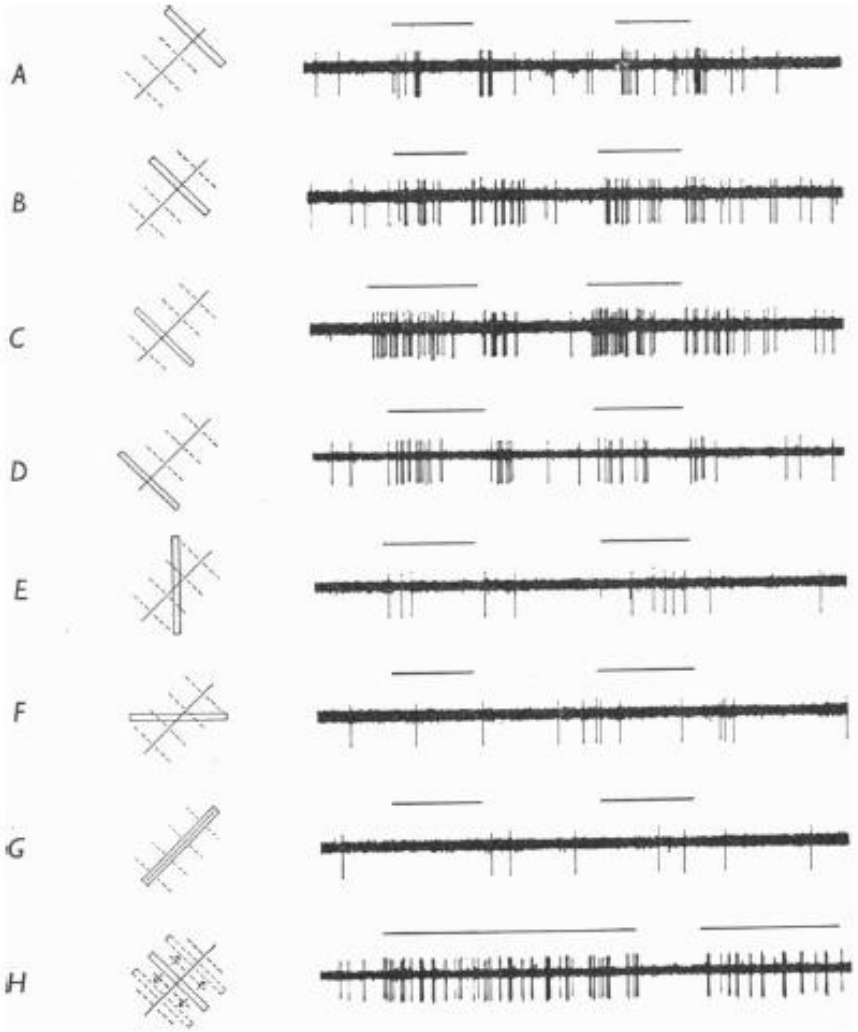
ON response

OFF response

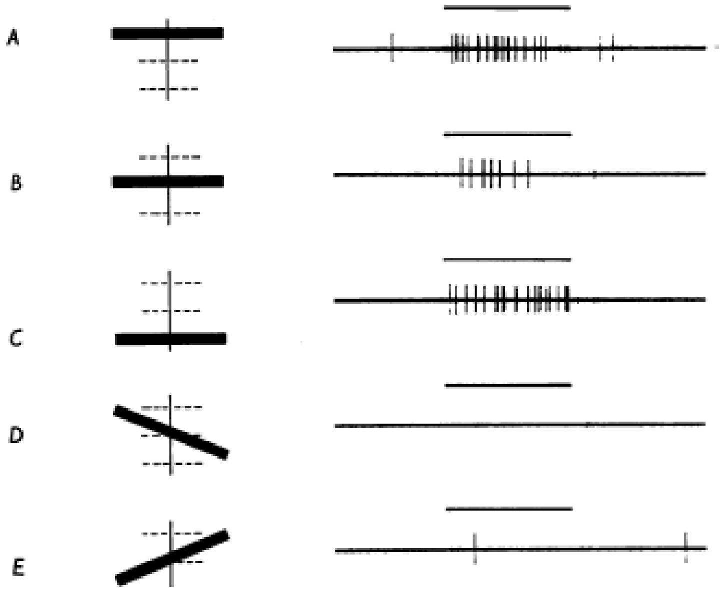
Hubel & Wiesel 1962

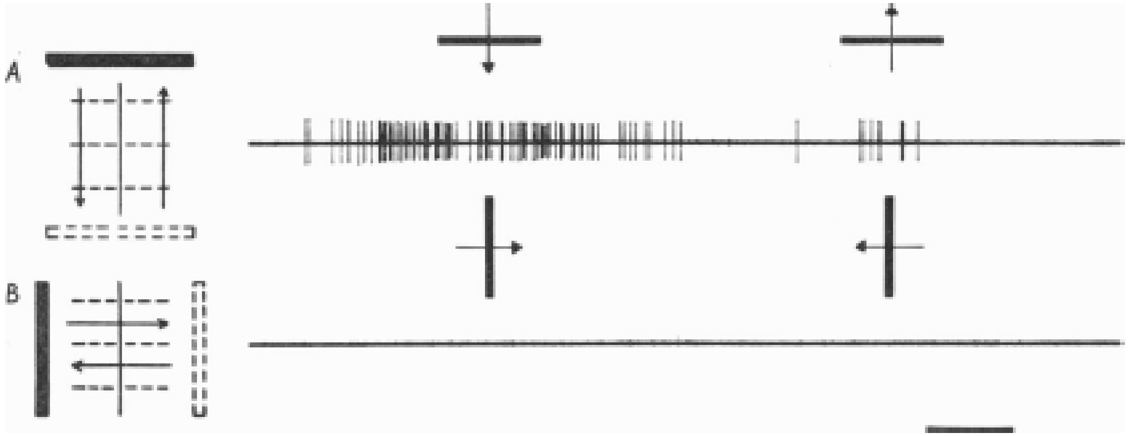
V1 Complex Cells

Translational invariance with orientation selectivity



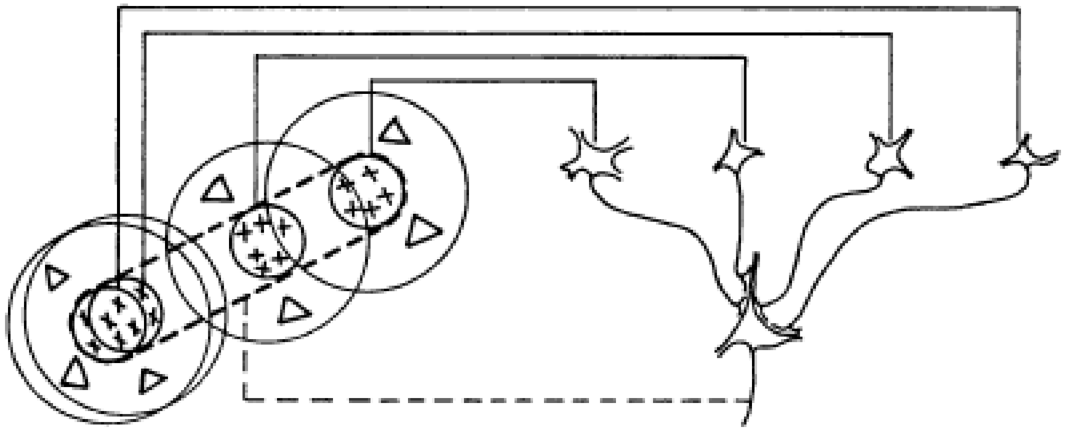
Translational invariance, plus directional selectivity



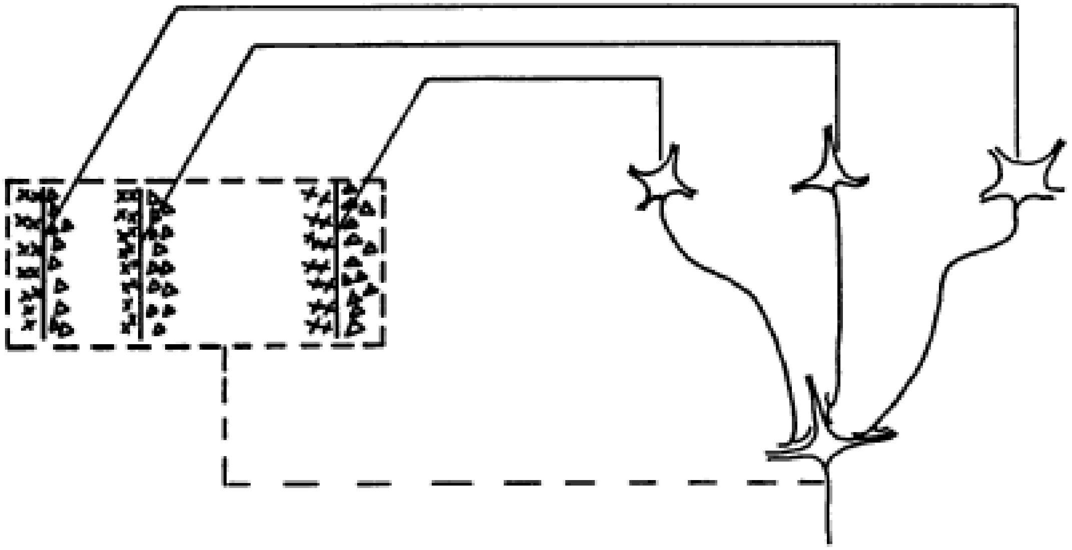


Models of V1 Responses

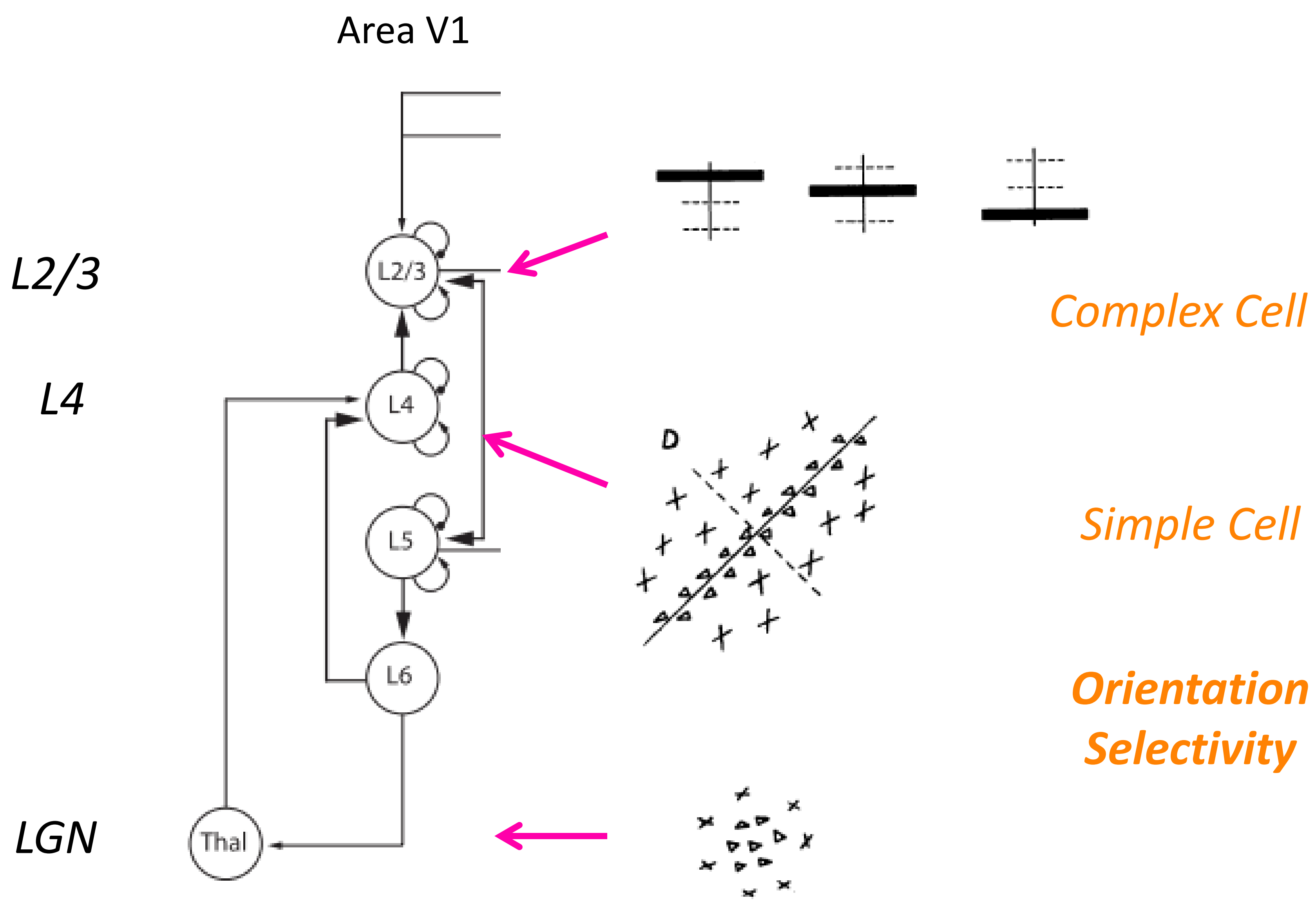
- LGN ➔ Simple Cell



- Simple Cell ➔ Complex Cell



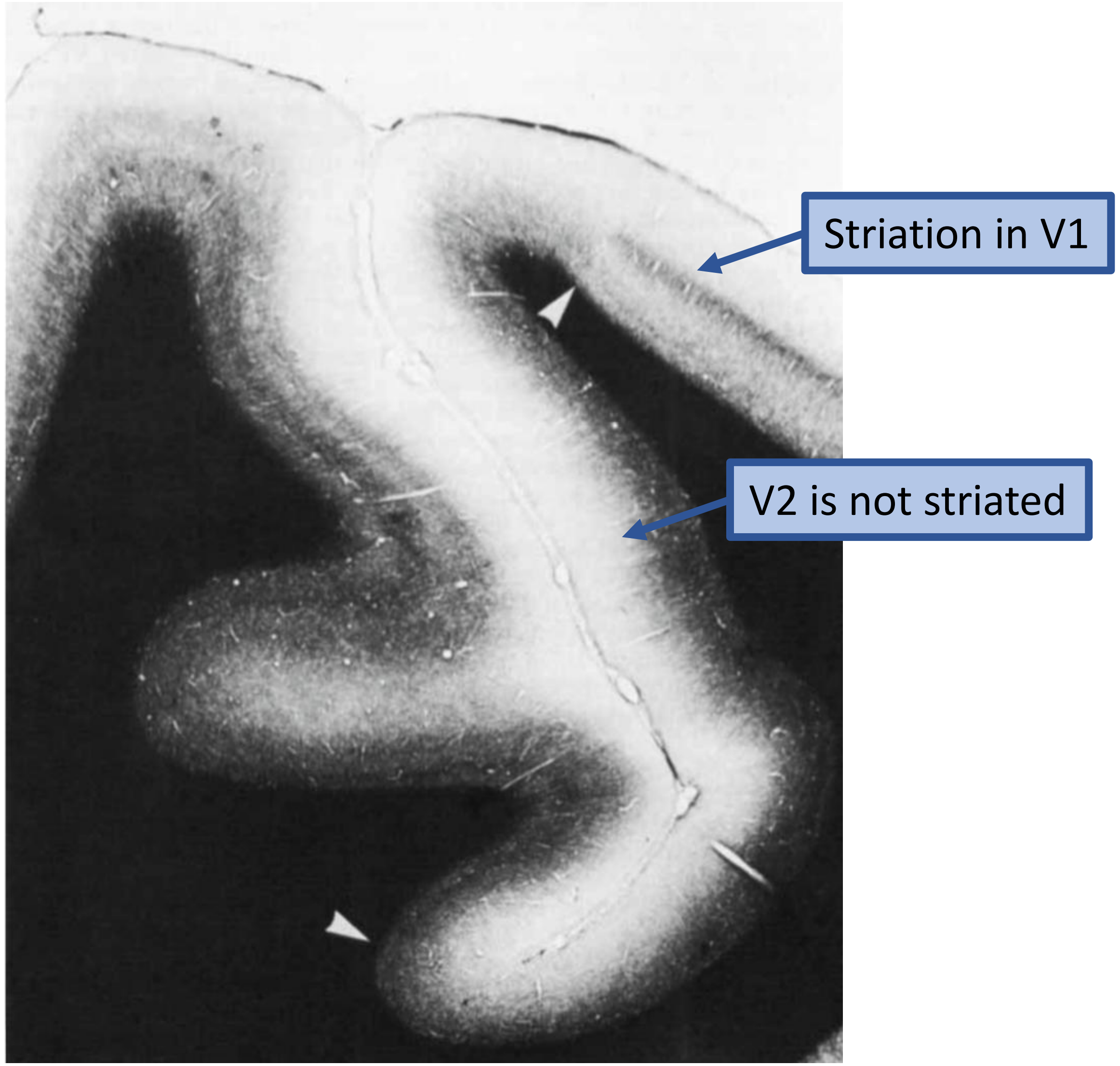
Organization across cortical layers



Hubel & Wiesel, *J. Physiol.* 1962

Cortical Hierarchy

Anatomical distinctions between regions

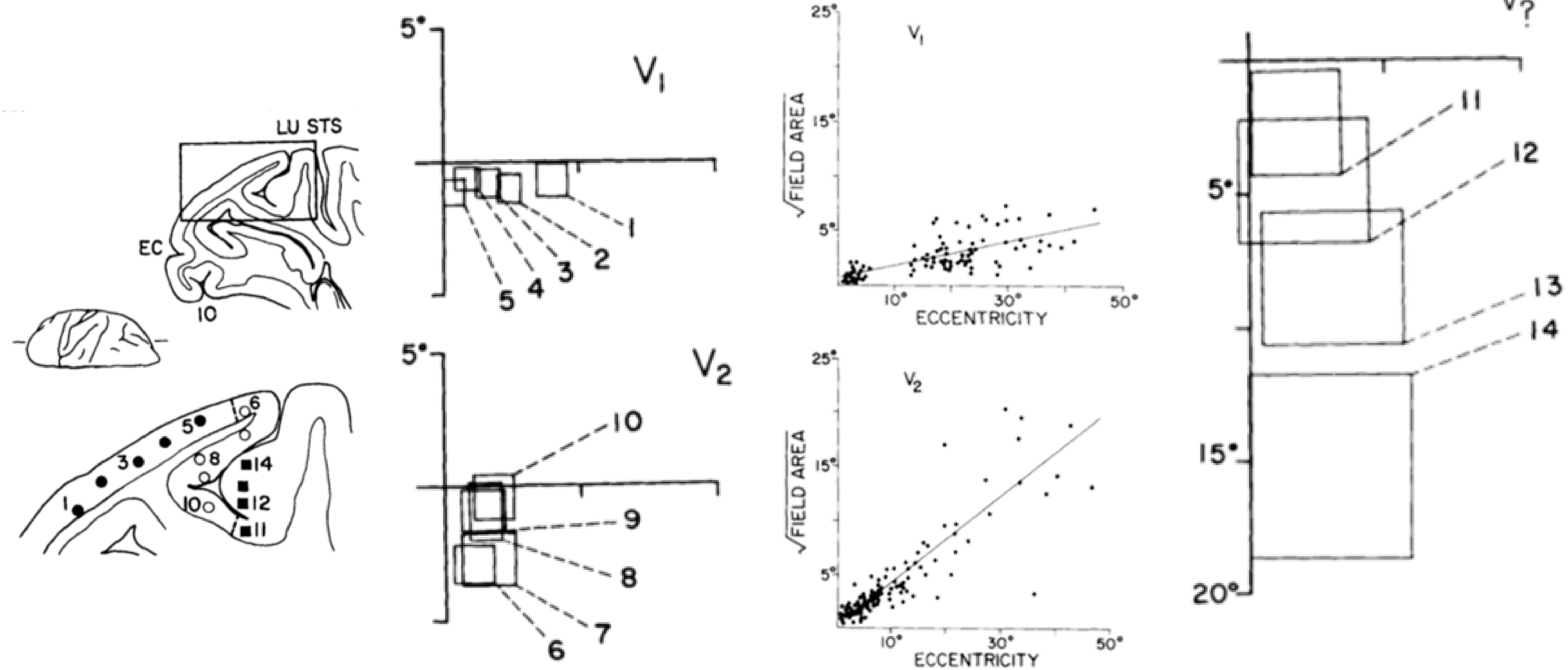


Brain regions were initially differentiated based on cytoarchitectonic markers.

Distinction between striate and extra-striate cortex is obvious. However, distinguishing between many other extra-striate regions is difficult based on anatomy alone.

Gattass, Gross, Sandell *J Comp Neuro* 1981

Receptive Fields Increase Along Cortical Hierarchy



Gattass, Gross, Sandell *J Comp Neuro* 1981

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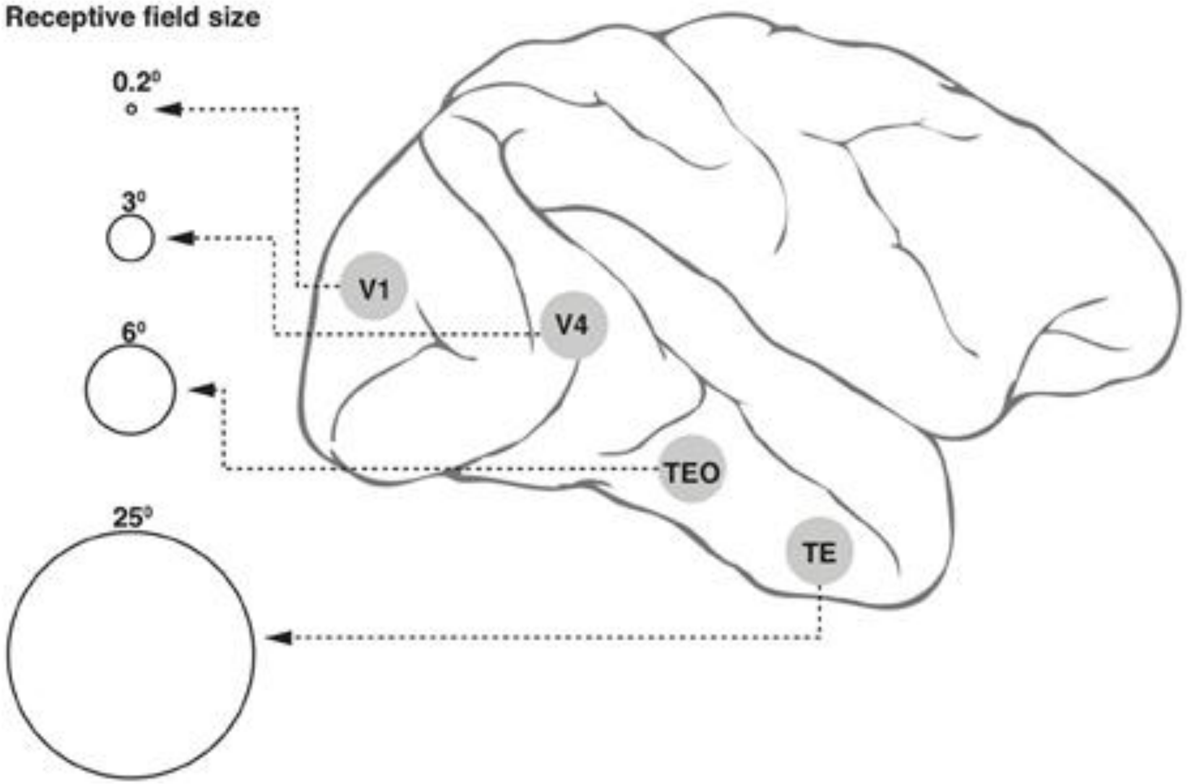
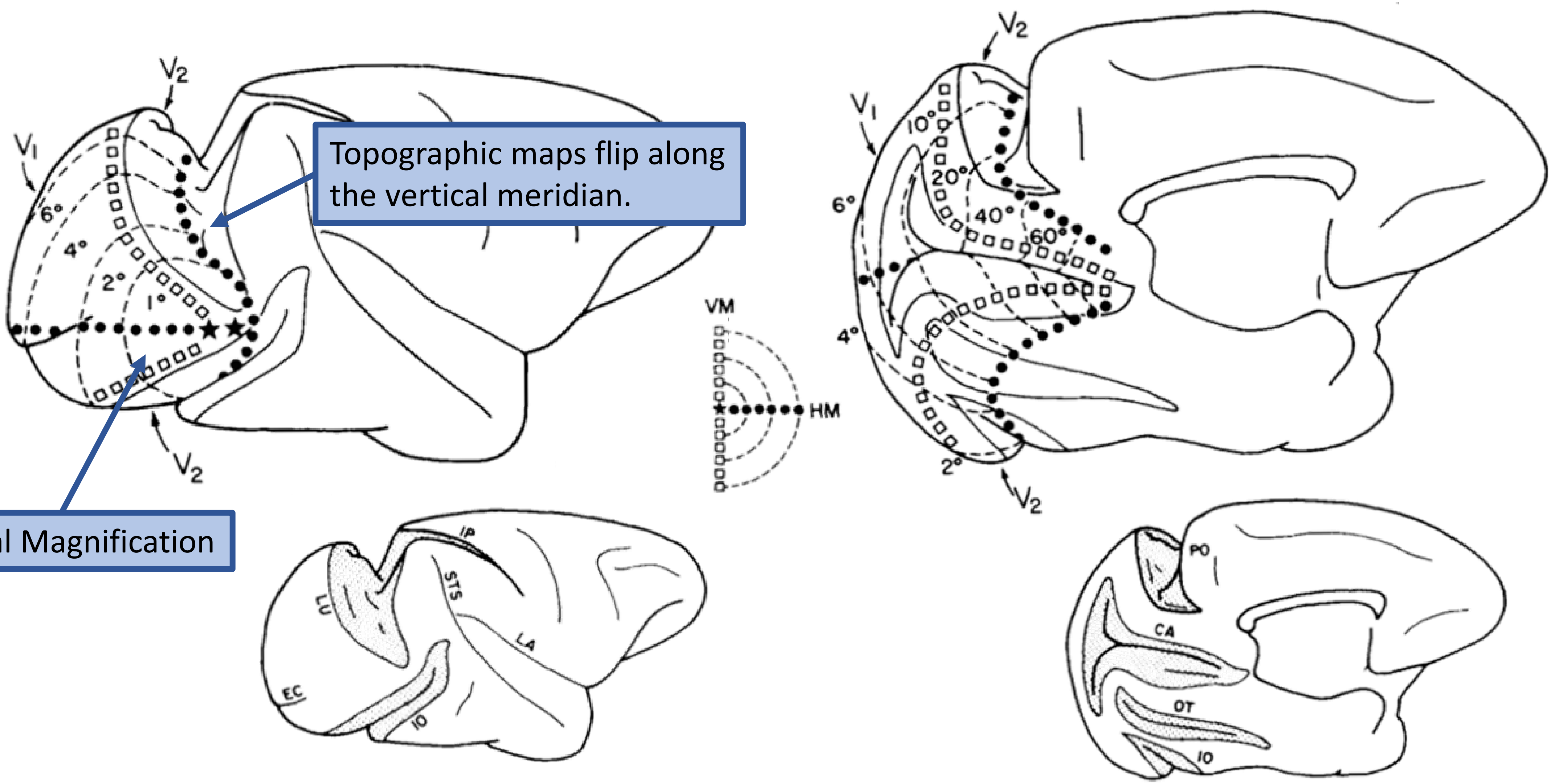


V2 Anatomy and Topography



Topographic maps flip along the vertical meridian.

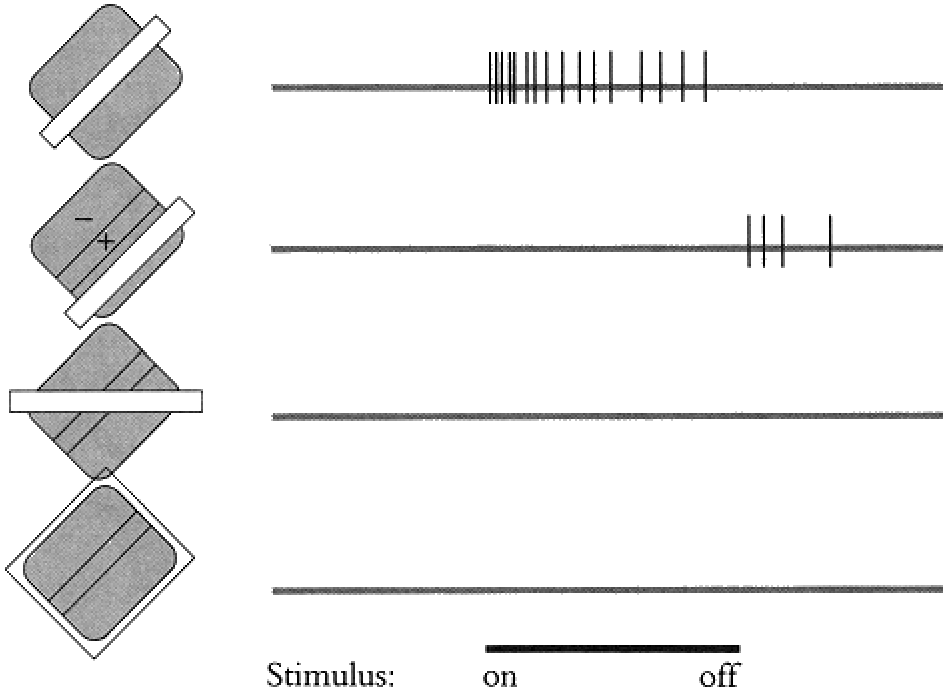
Cortical Magnification

Gattass, Gross, Sandell *J Comp Neuro* 1981

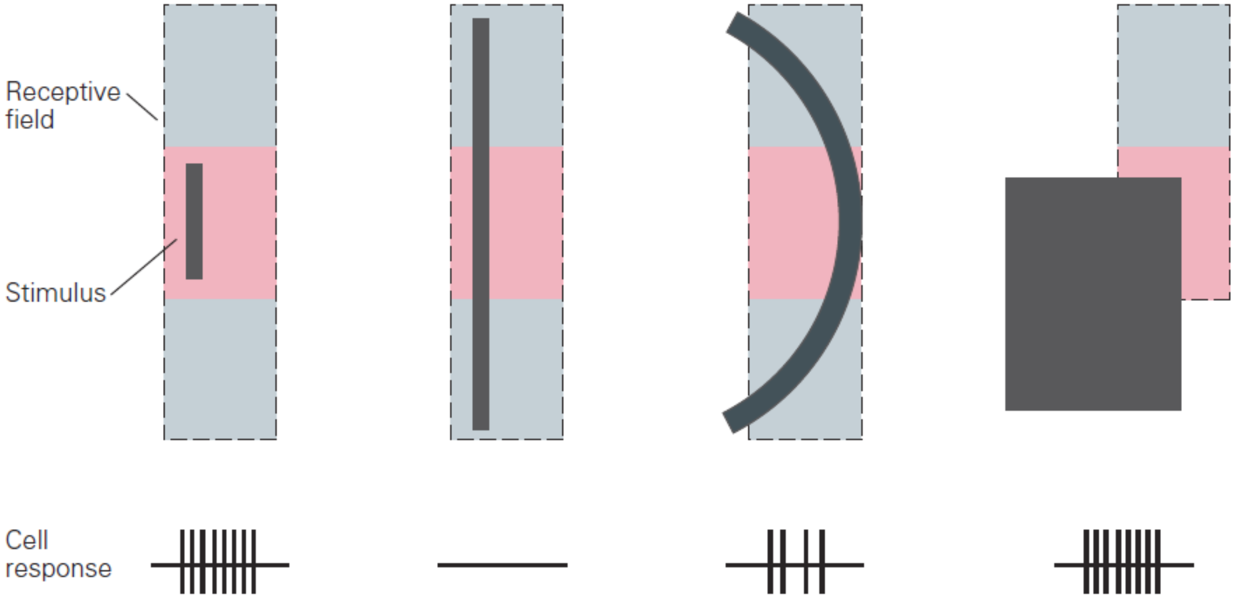
V1 to IT: Visual complexity increases along hierarchy

Neurons in V1 respond to 'simple' visual properties, such as orientation, spatial frequency, and motion.

V1: Simple cells respond to oriented bars

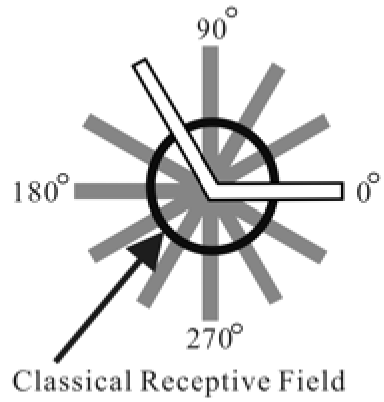


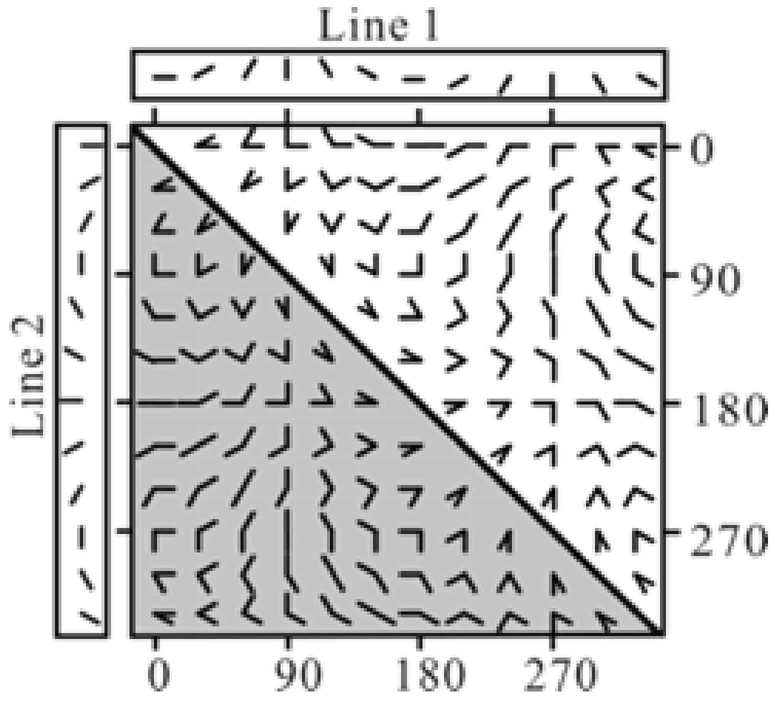
'End-stop' cells respond to oriented bars with a specific length

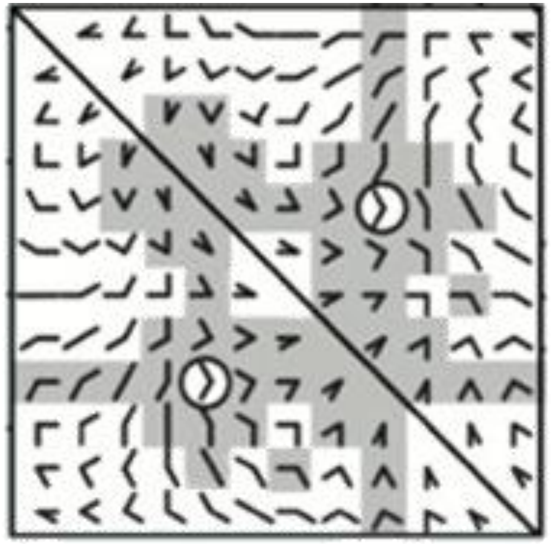


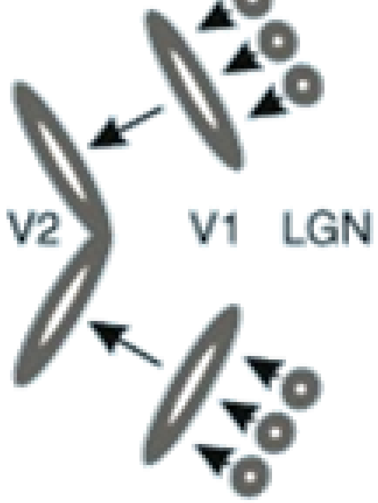
V2: Conjunction of Lines

<u>V2 neurons begin to respond to object parts, such as corners</u>



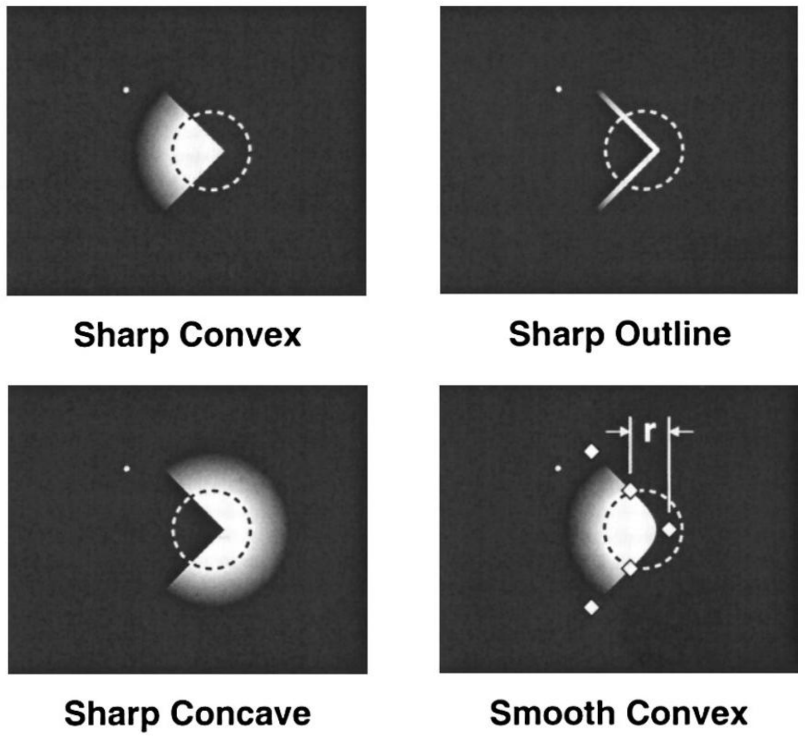


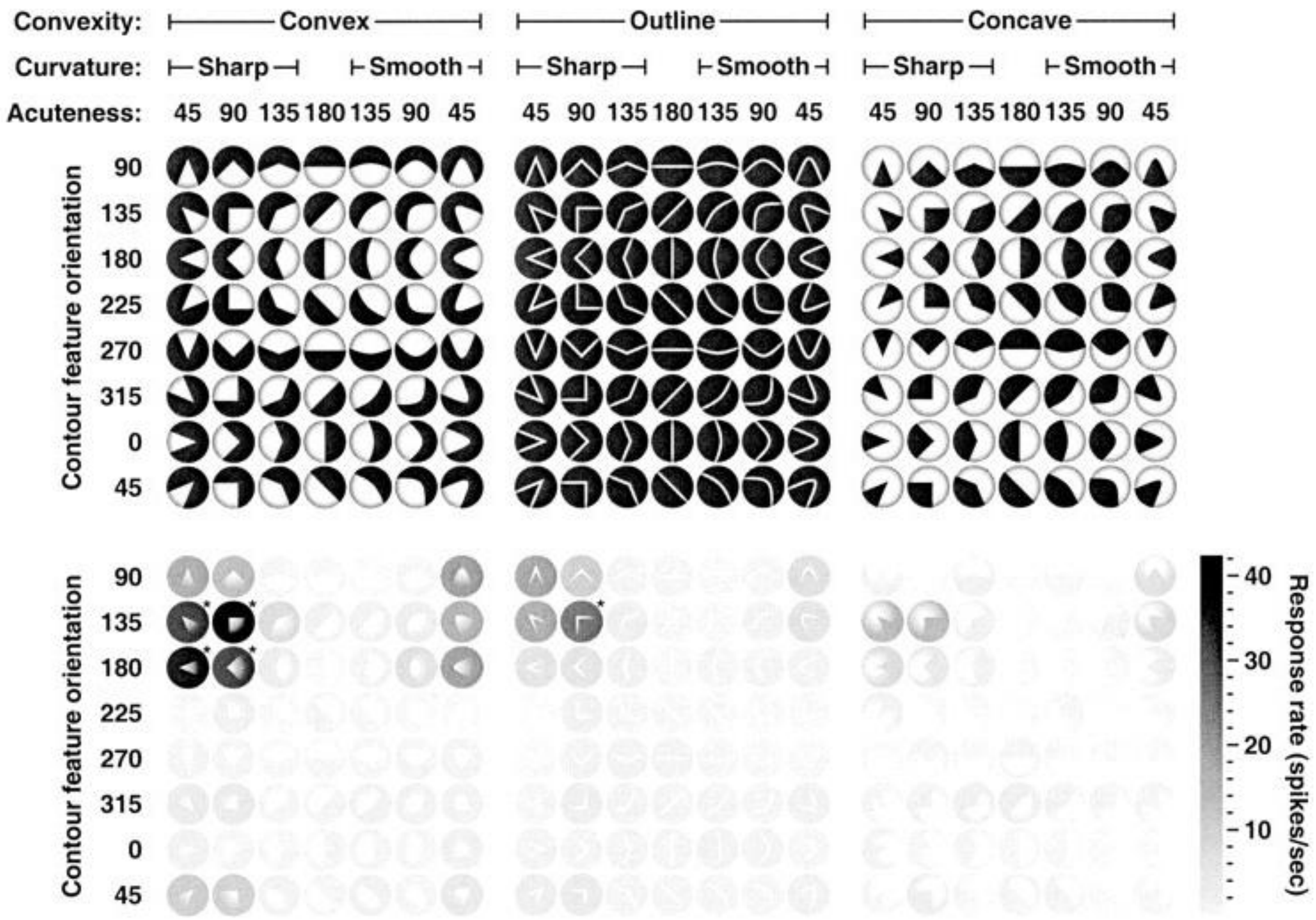




V4: Increasing complexity and invariance

V4 neurons show greater complexity than V2 as well as growing invariance to contrast and translation.





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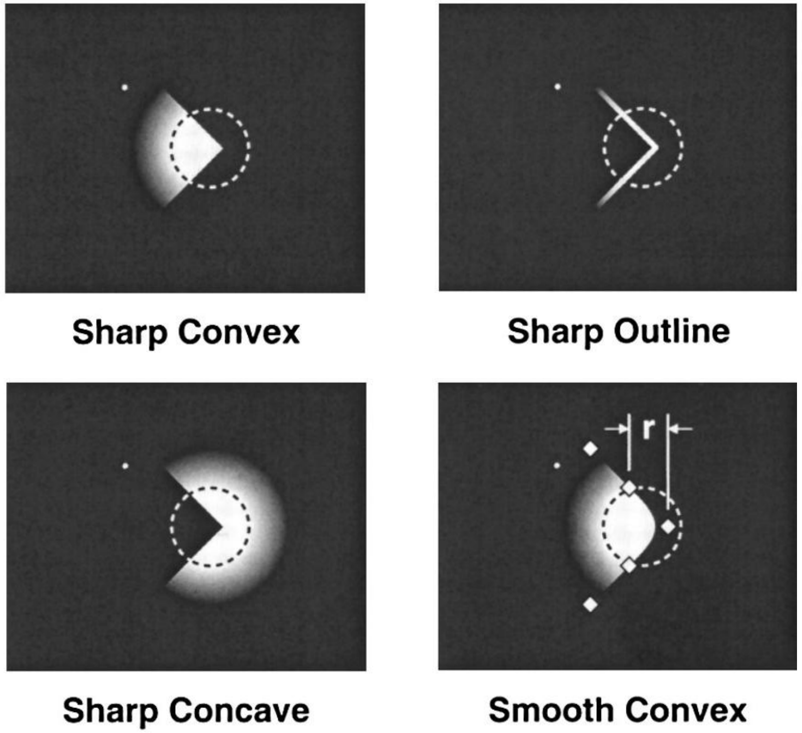

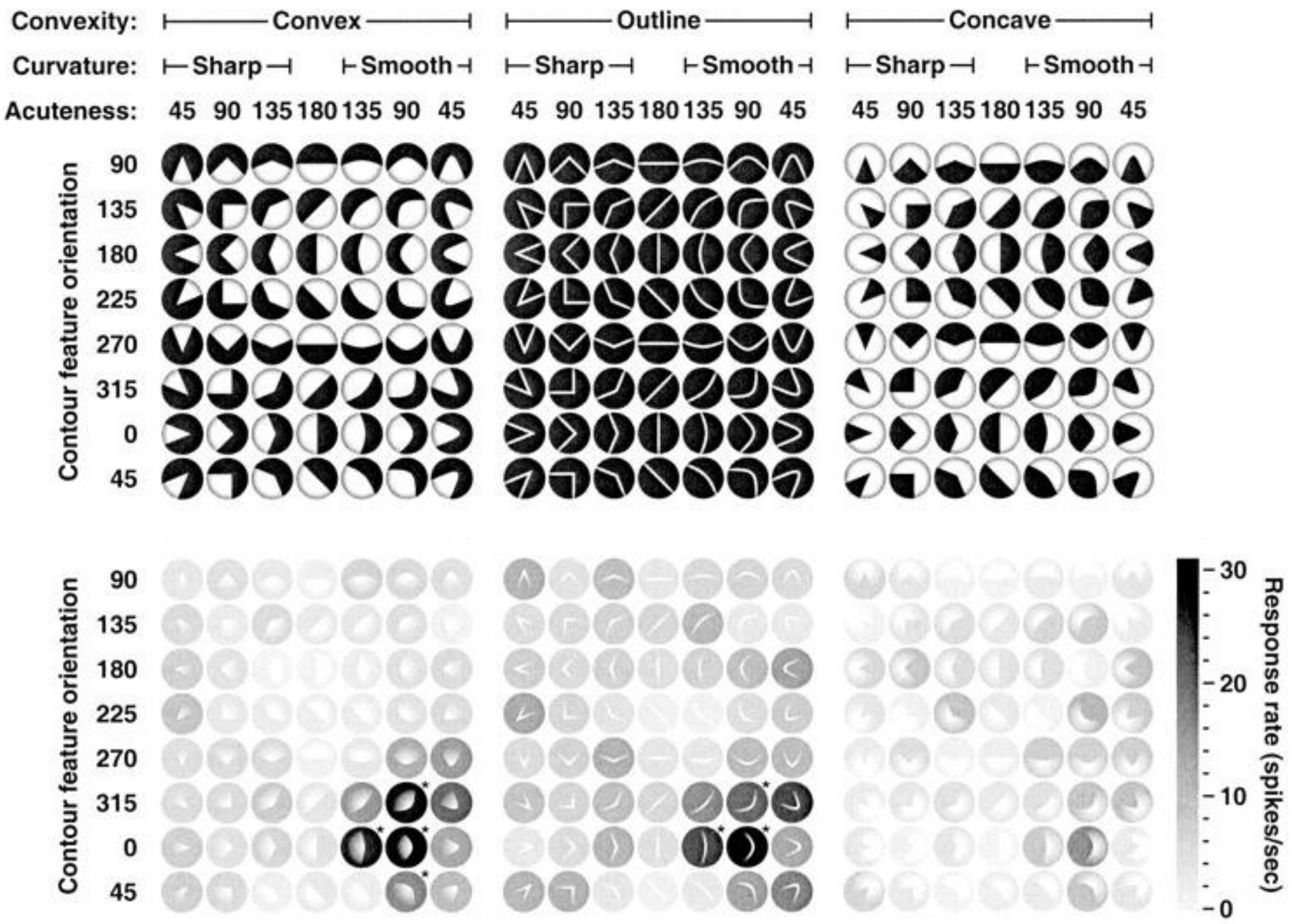

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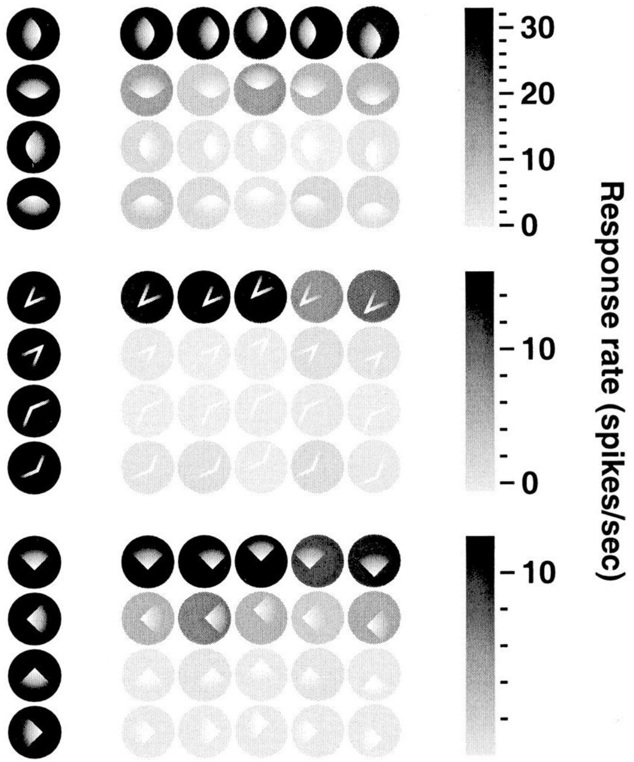
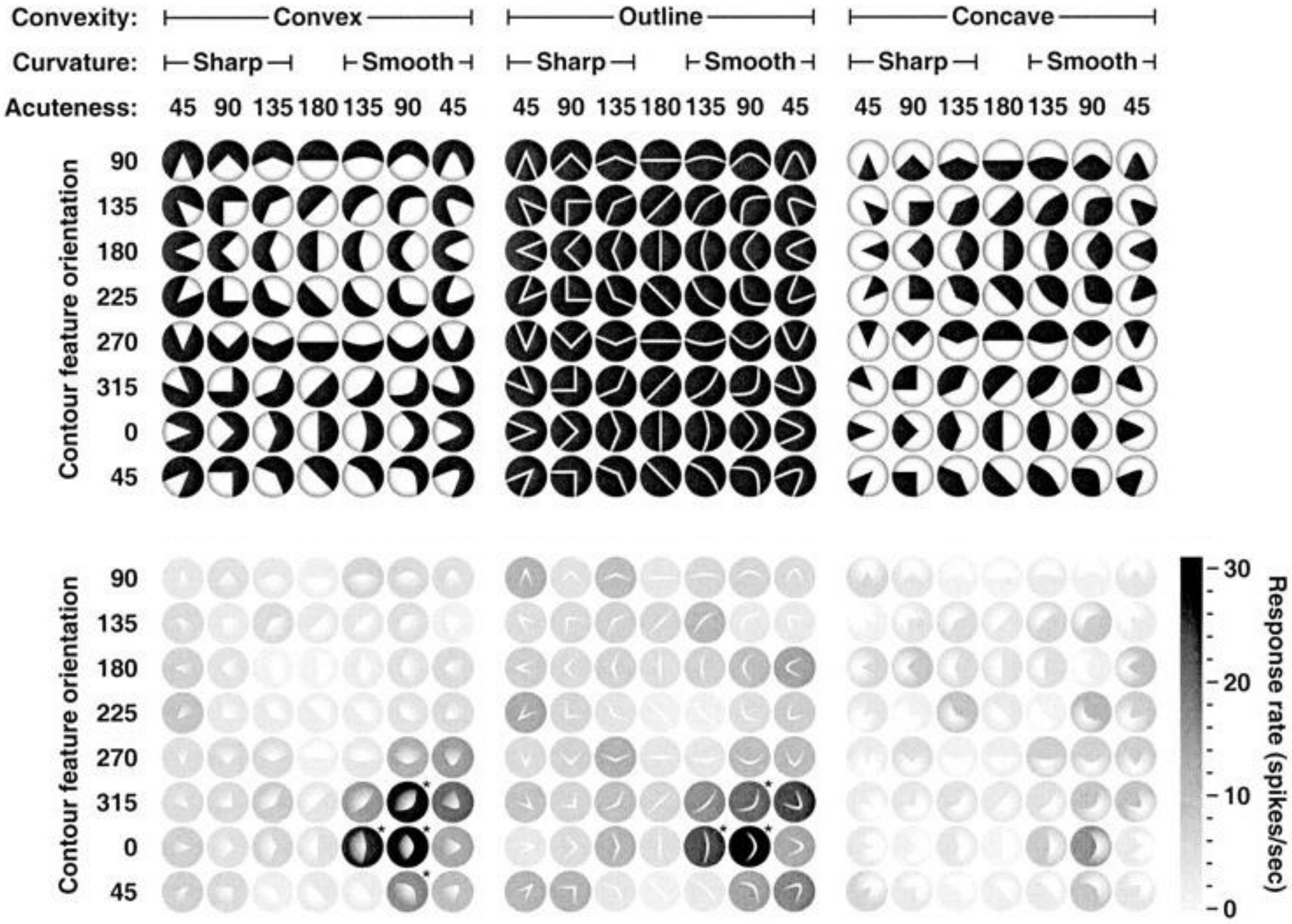
Spatial Invariance within RF

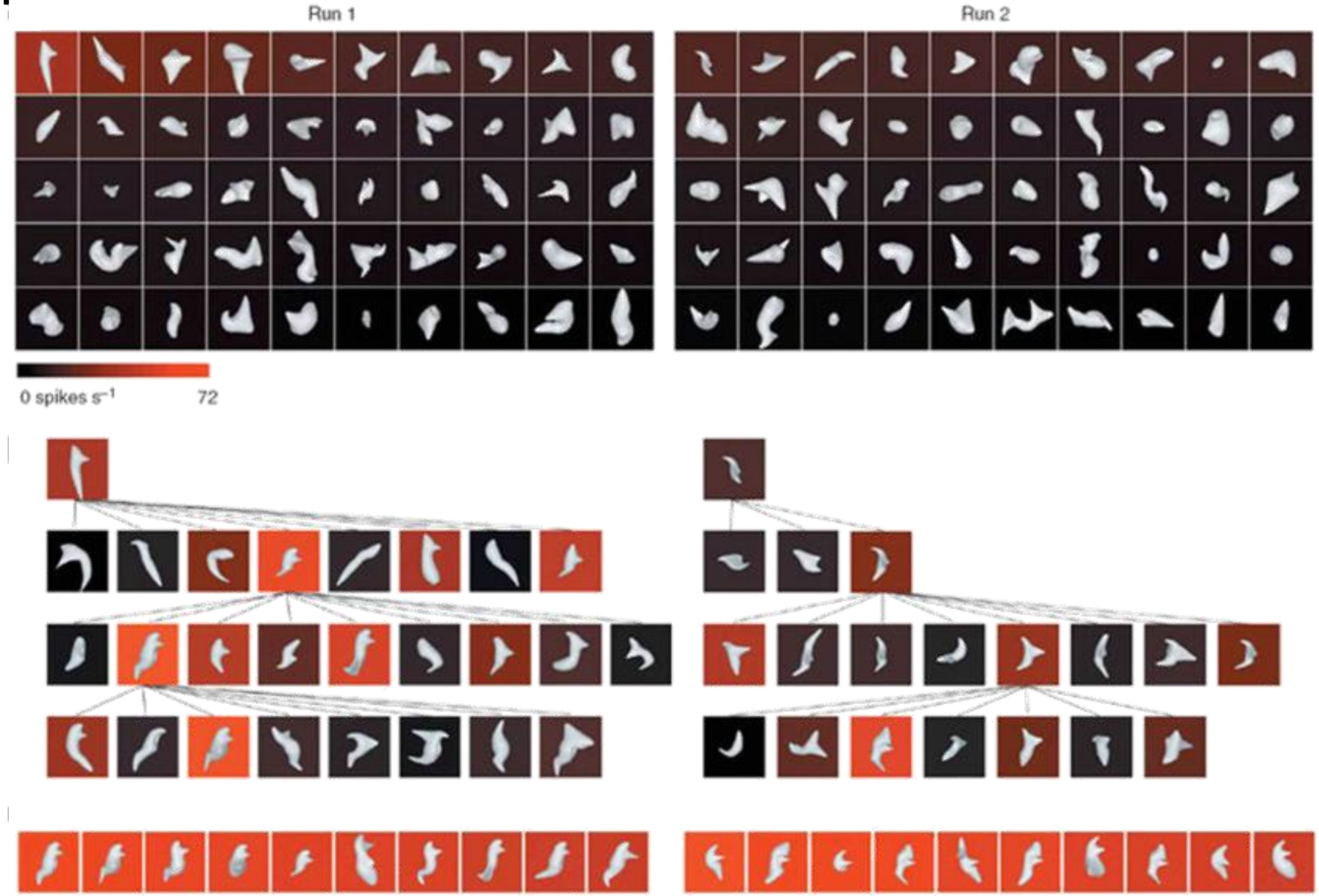




Posterior IT Responds to Combinations of Surfaces

How do you find the response properties of neurons that respond to increasingly complex stimuli?

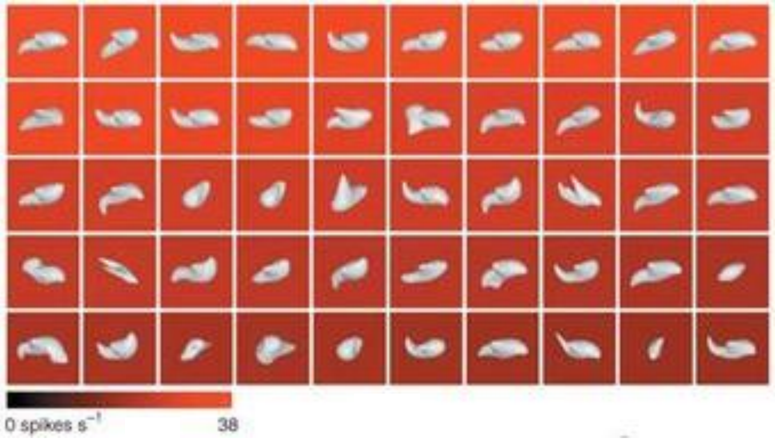
Learn it!



Yamane et al, *Nat Neuro* 2008

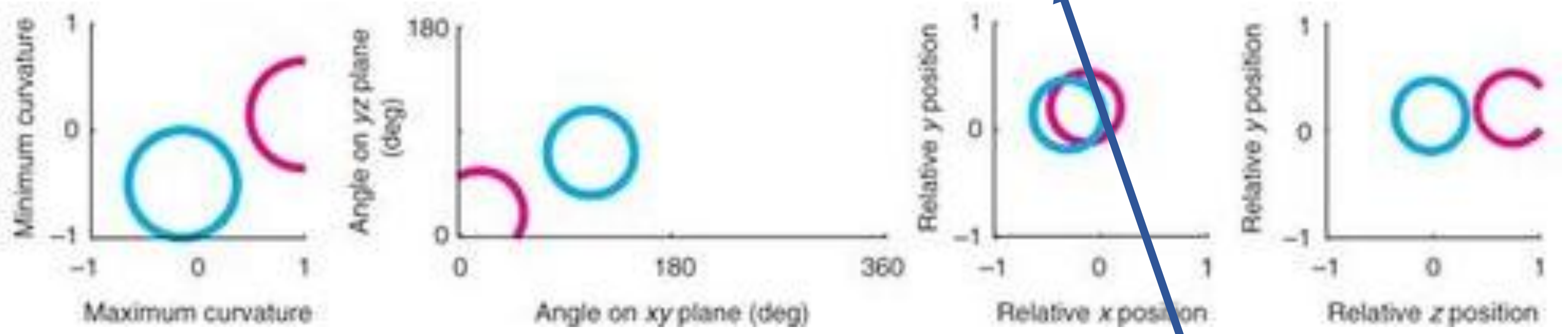
Posterior IT Responds to Combinations of Surfaces

Repeated runs finds a neuron responds to similar shapes (it is 'tuned')



Model fits suggest that posterior IT neurons respond to surface fragments.

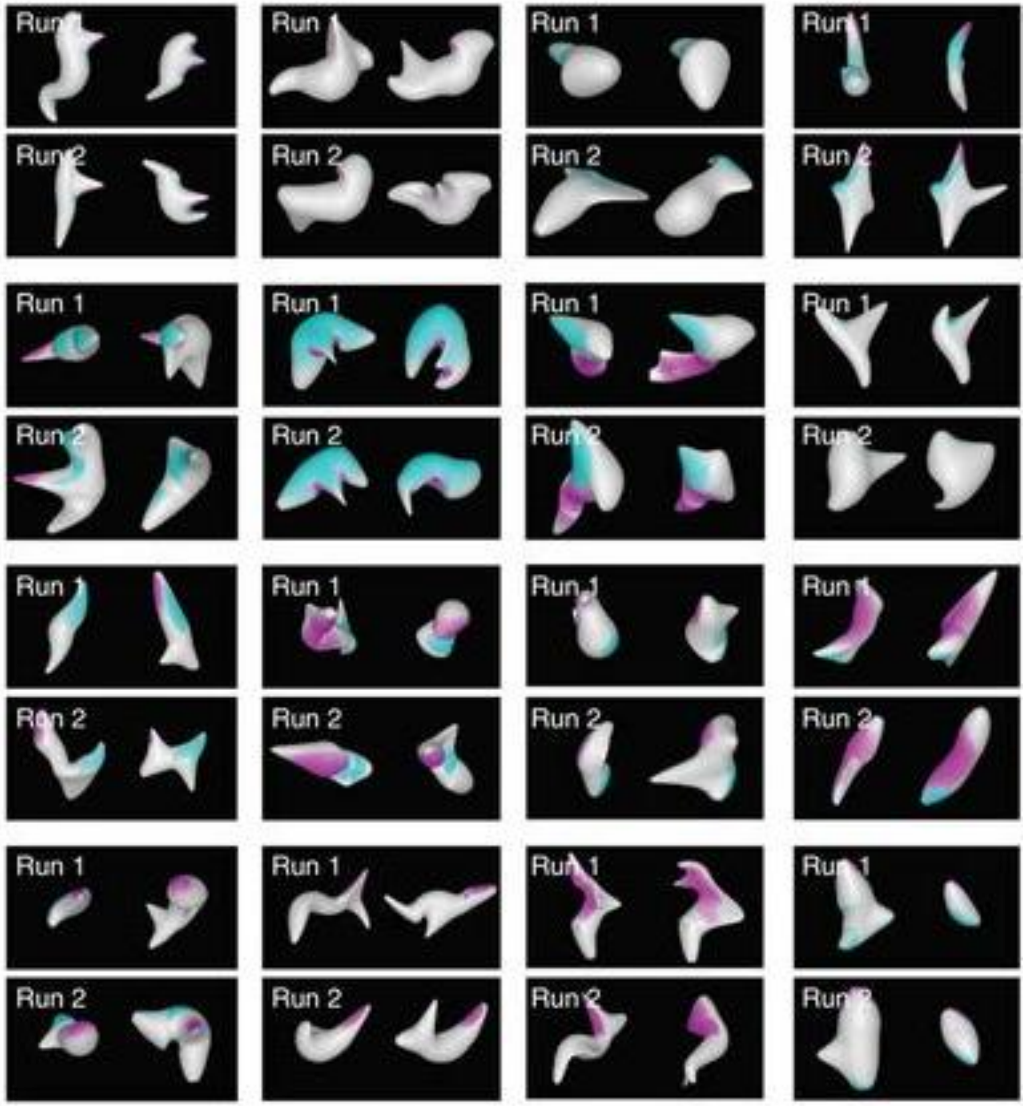
Response = 0.4A + 0.0B + 49.0AB + 0.0



Note: most of activity is explained by the non-linear term (conjunction of surfaces)

Yamane et al, *Nat Neuro* 2008

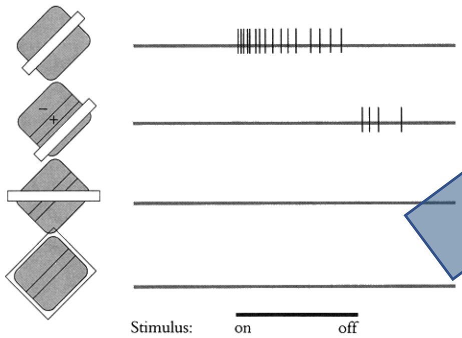
Posterior IT Responds to Combinations of Surfaces



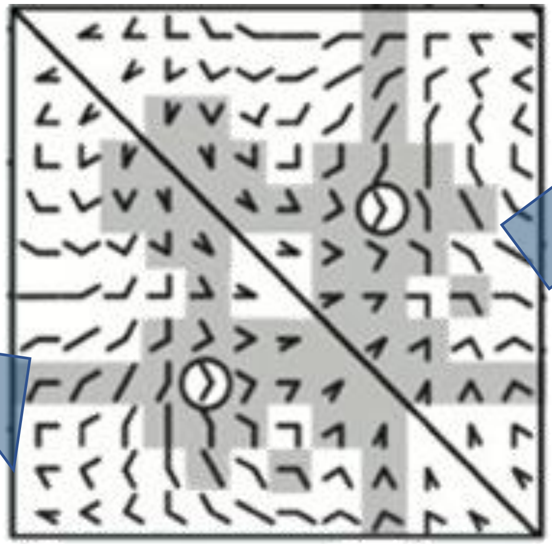
Yamane et al, *Nat Neuro* 2008

Visual complexity increases along cortical hierarchy

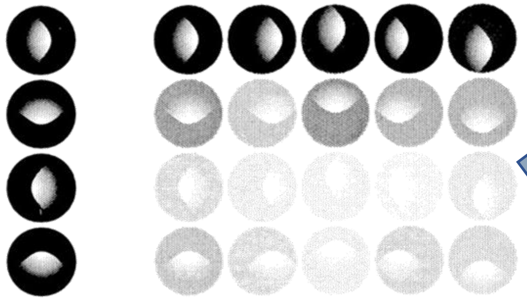
V1: Orientation, Spatial Frequency, Motion Direction



V2 neurons begin to respond to object parts, such as corners

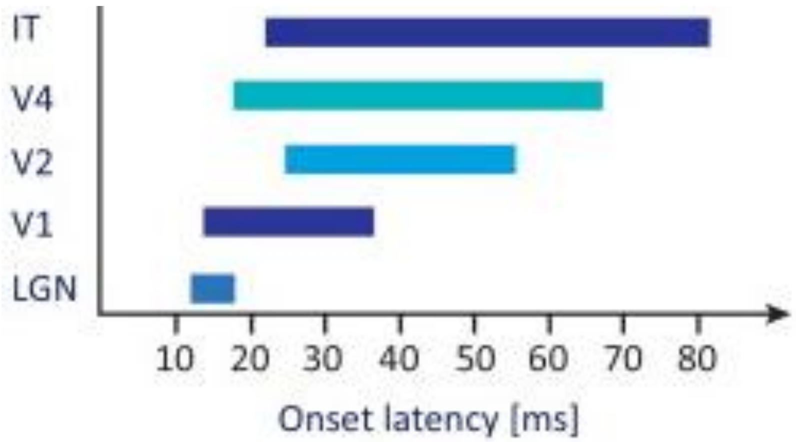


V4 neurons are invariant to translation and contrast inversion



Posterior IT neurons respond to surface parts of objects

Onset times increase along hierarchy



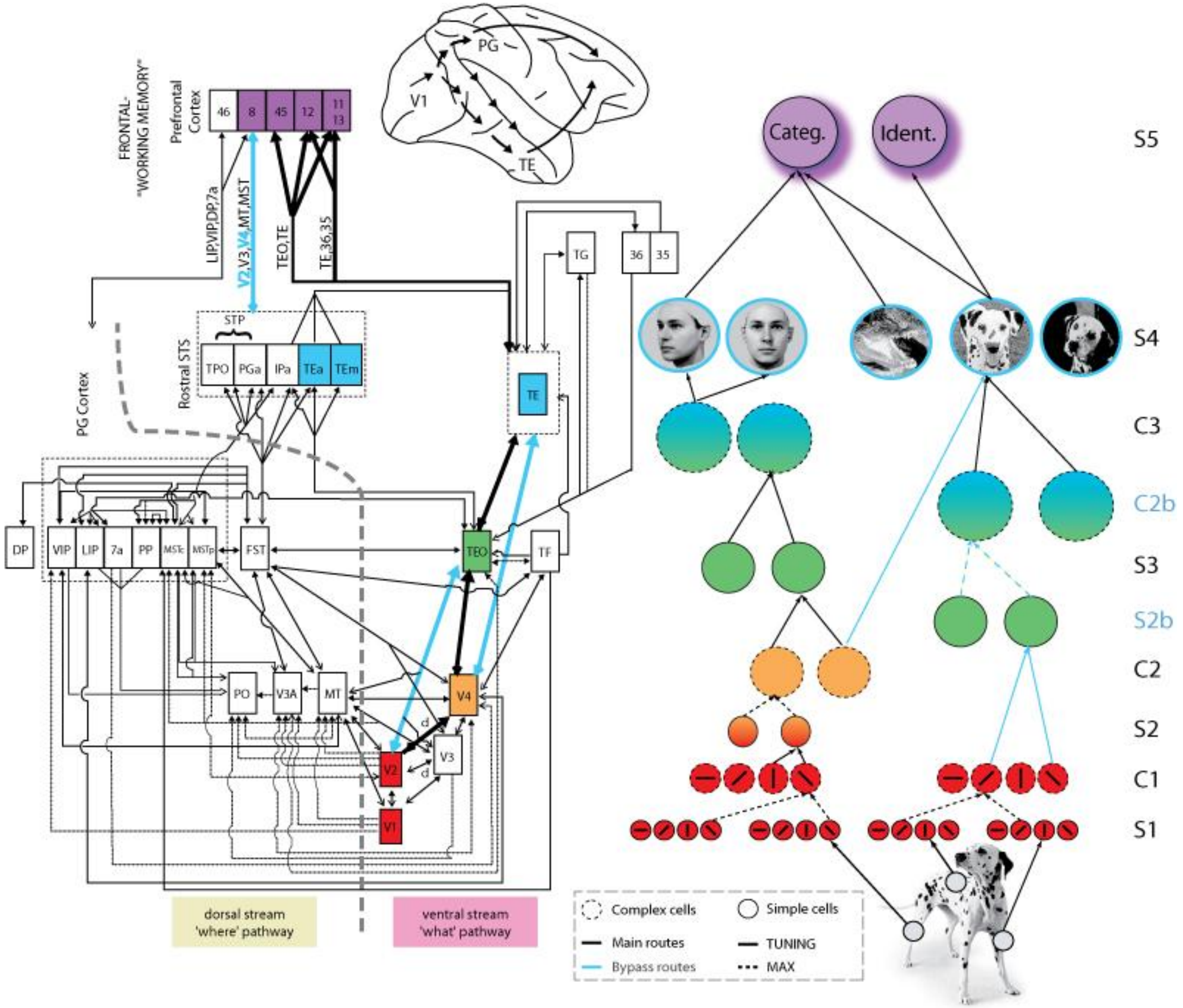
Building Models of the Visual System

Construct hierarchy models that attempt to mimic the hierarchy used by the brain.

Increasing complexity of representations along hierarchy is matched by increased spatial receptive fields.

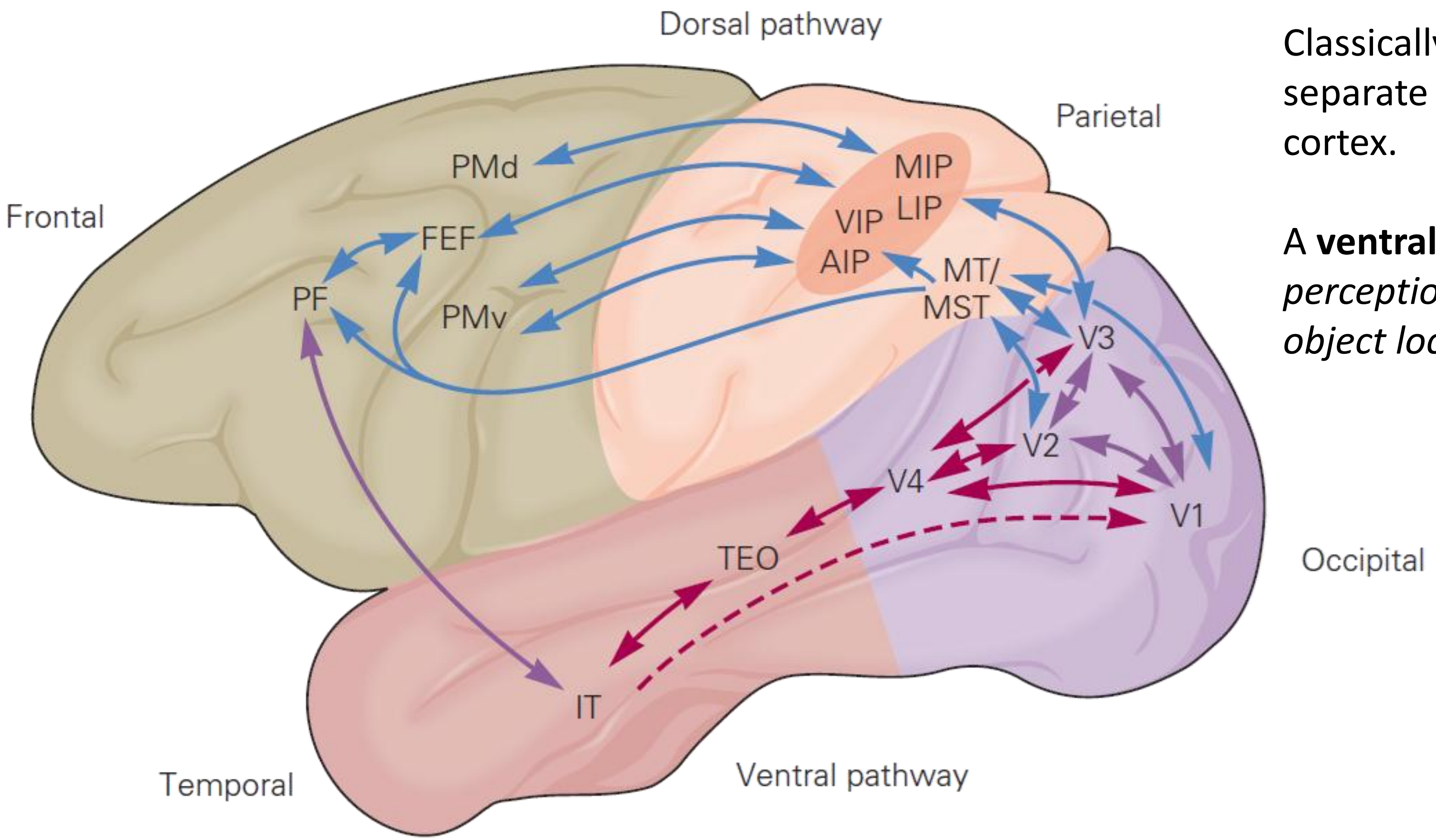
Alternating layers of average (e.g. simple cells) followed by winner-take-all (e.g. complex cells).

This performs surprisingly well – one of the best computer vision algorithms we have to date…



Gabriel Kreiman (2008) Biological object recognition. Scholarpedia, 3(6):2667.

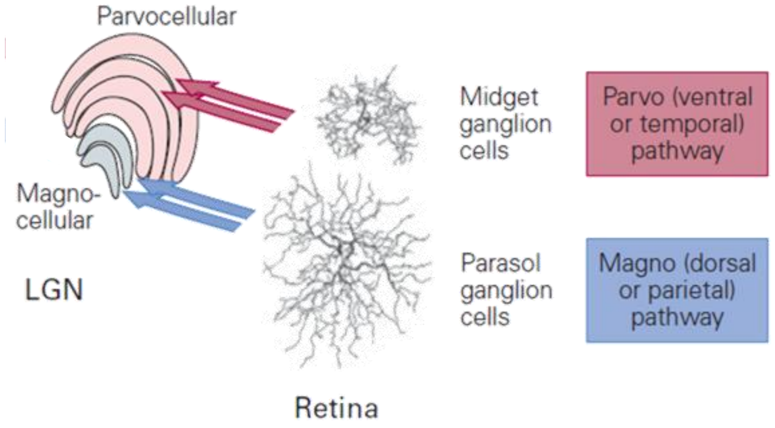
Cortical Hierarchy



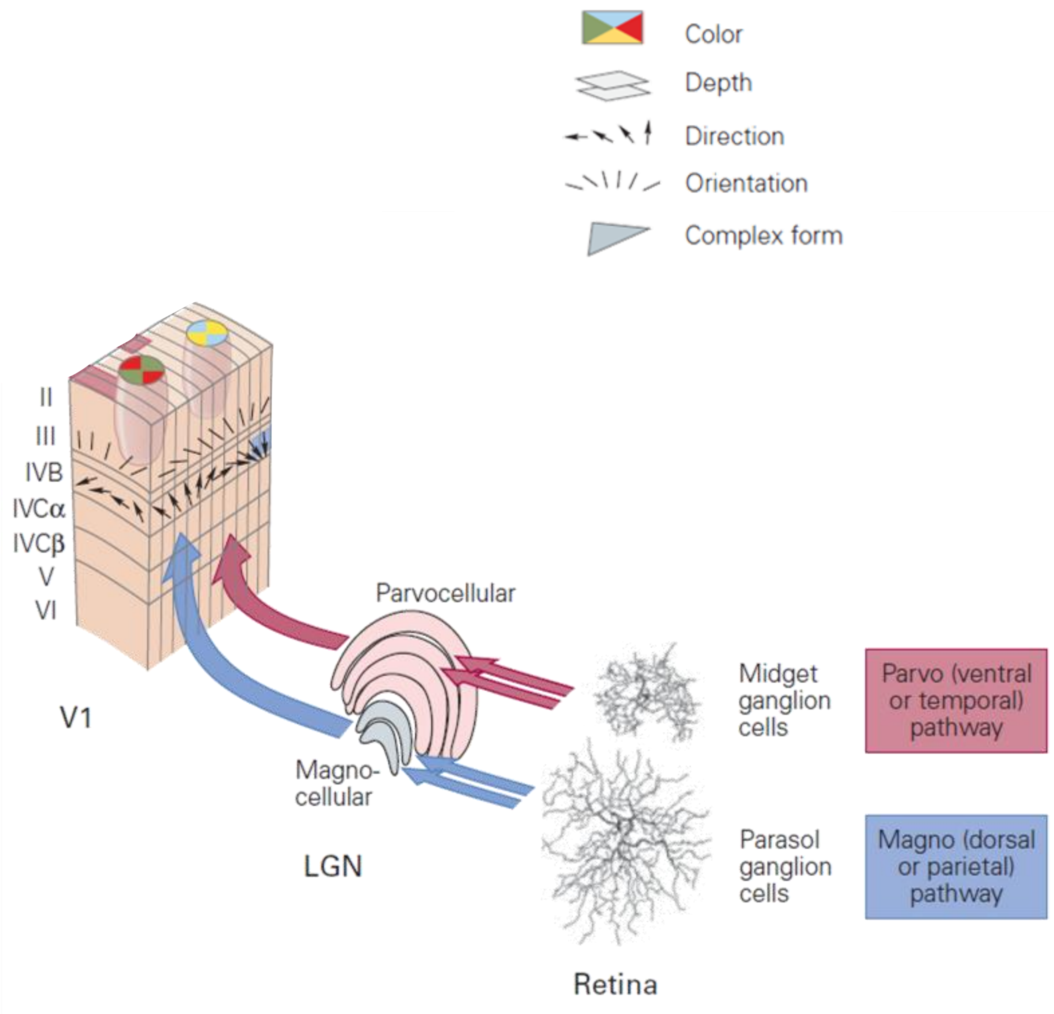
Classically, neuroscientists have defined two separate 'streams' of processing in visual cortex.

A **ventral pathway** that does *object perception* and a **dorsal pathway** that does *object localization*.

Anatomical and Physiological Evidence for Separate Pathways



Anatomical and Physiological Evidence for Separate Pathways



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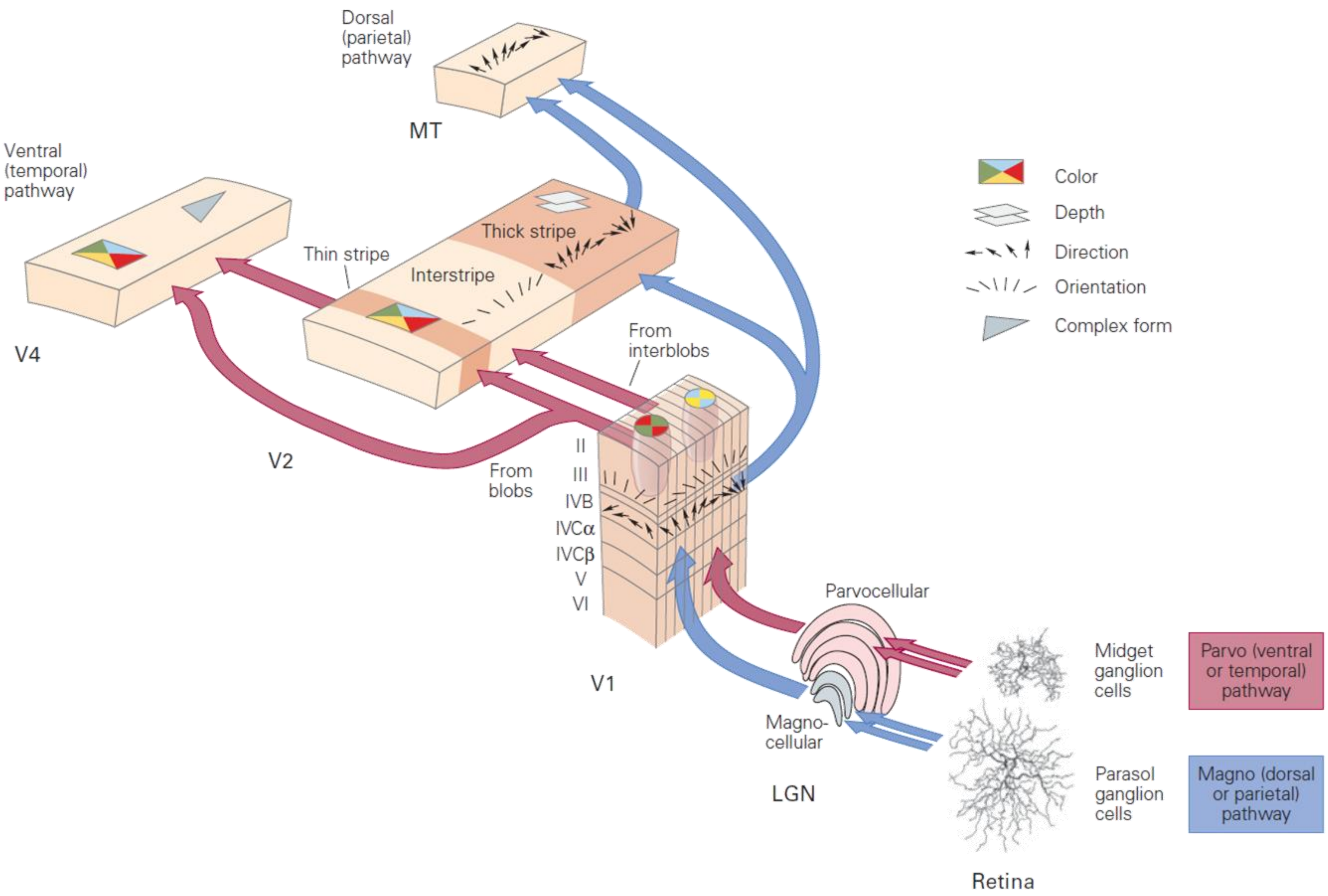
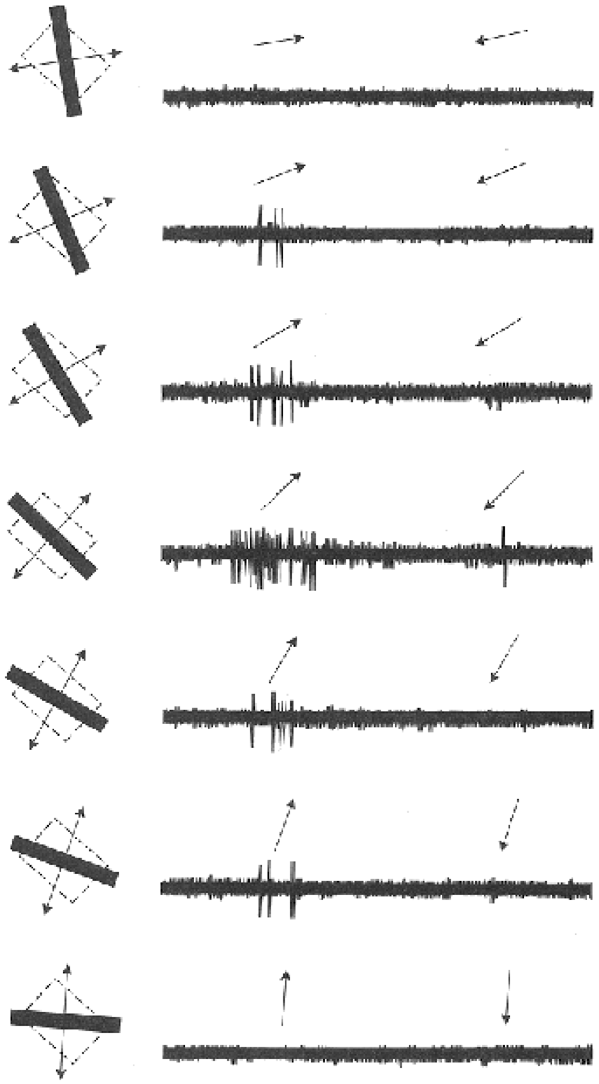


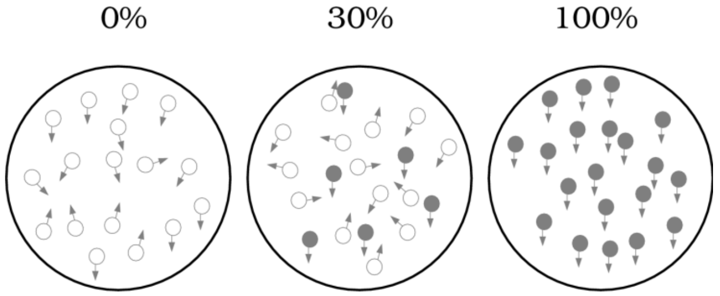
Motion Perception

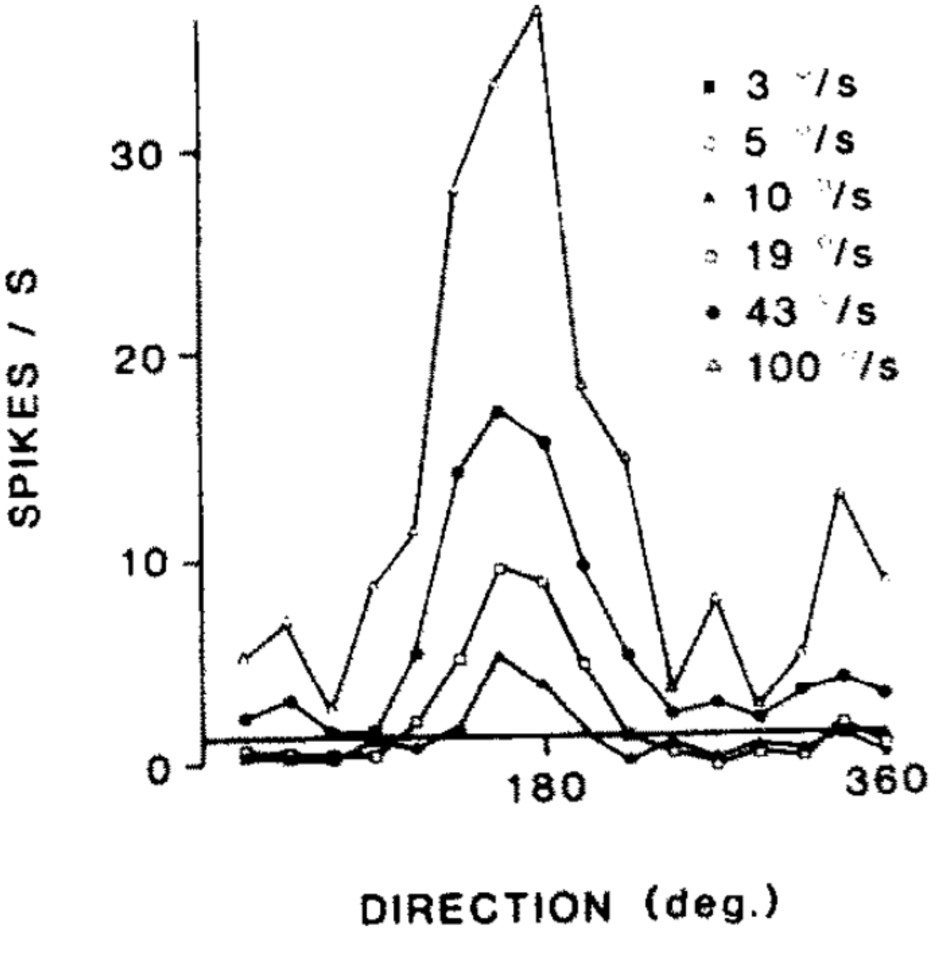
Area MT: Perceiving motion

Motion perception begins in V1:



Similar selectivity is seen in area MT:

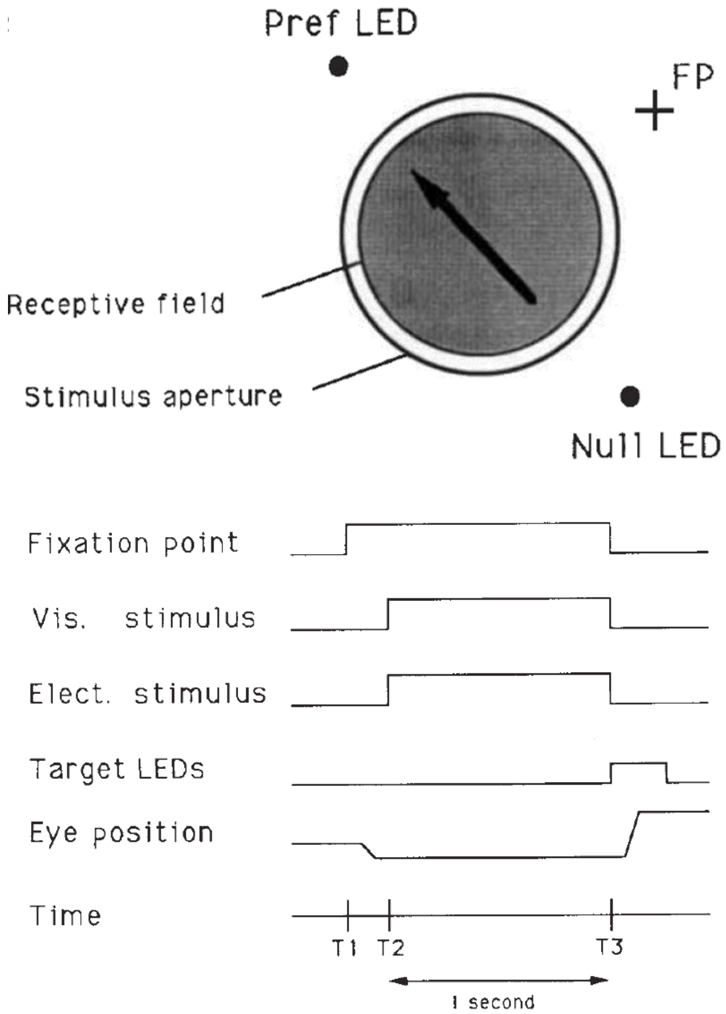


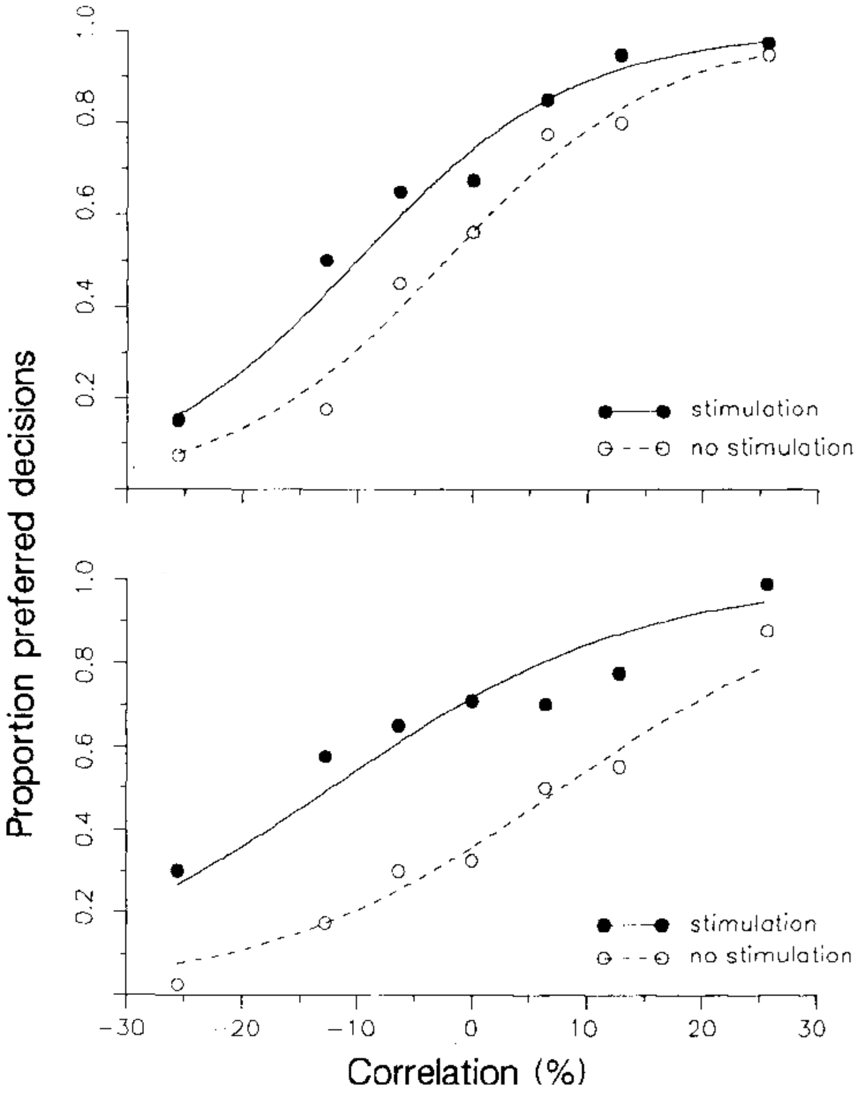


Duffy and Wurtz, *J Neurosci* 1991

Area MT: Stimulating MT induces motion perception

Electrical stimulation biases perception, as if there is an additional stimulus in the neuron's preferred direction.

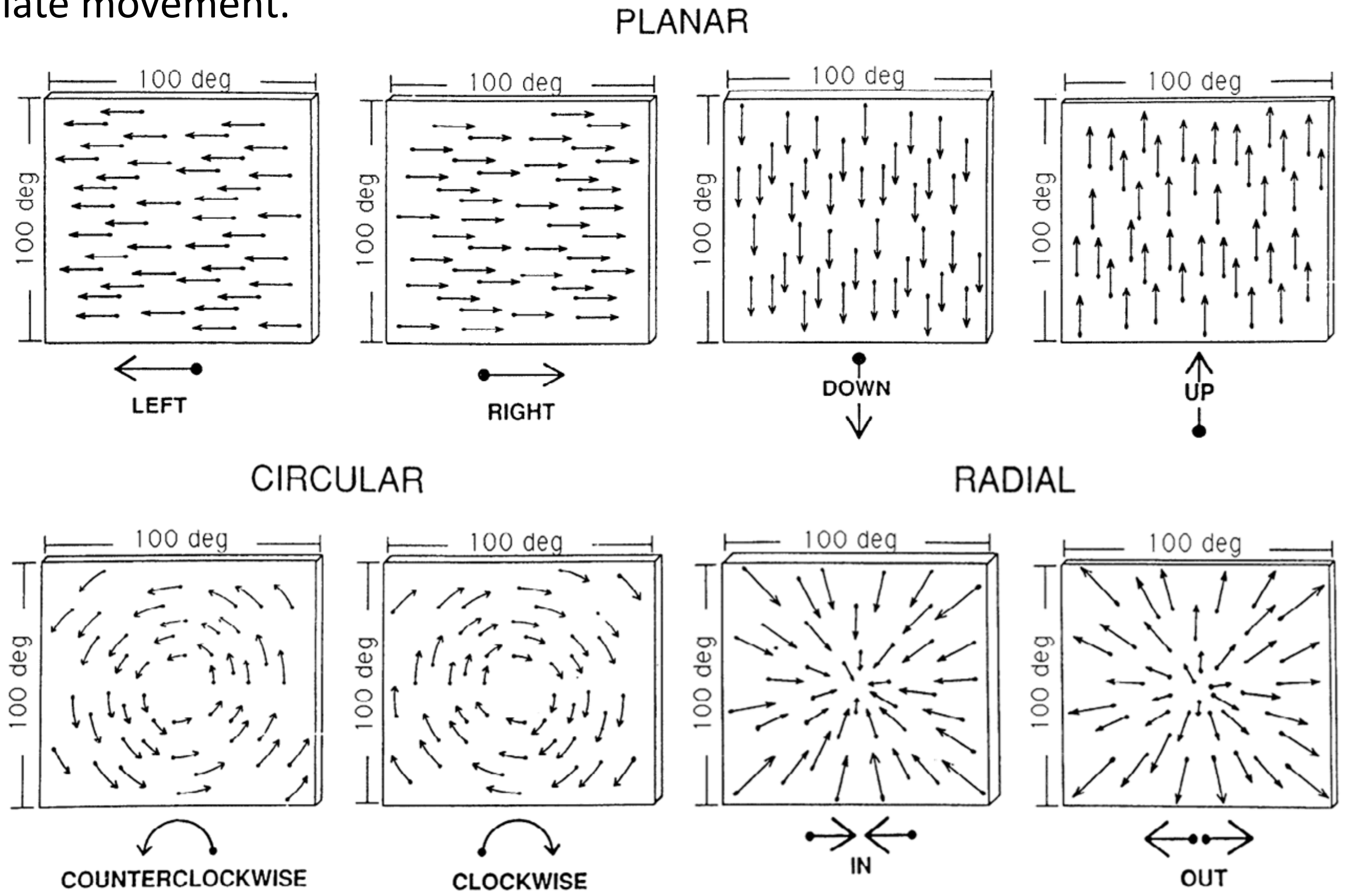




Salzman et al, *Nature* 1985

Perceiving Flow Fields

It is important to perceive movement that extends across the entire visual field, as it can provide information about heading direction. In addition, it is necessary to subtract the global motion from any local movement signal in order to accurately calculate movement.



Duffy and Wurtz, *J Neurosci* 1991

Perceiving Flow Fields

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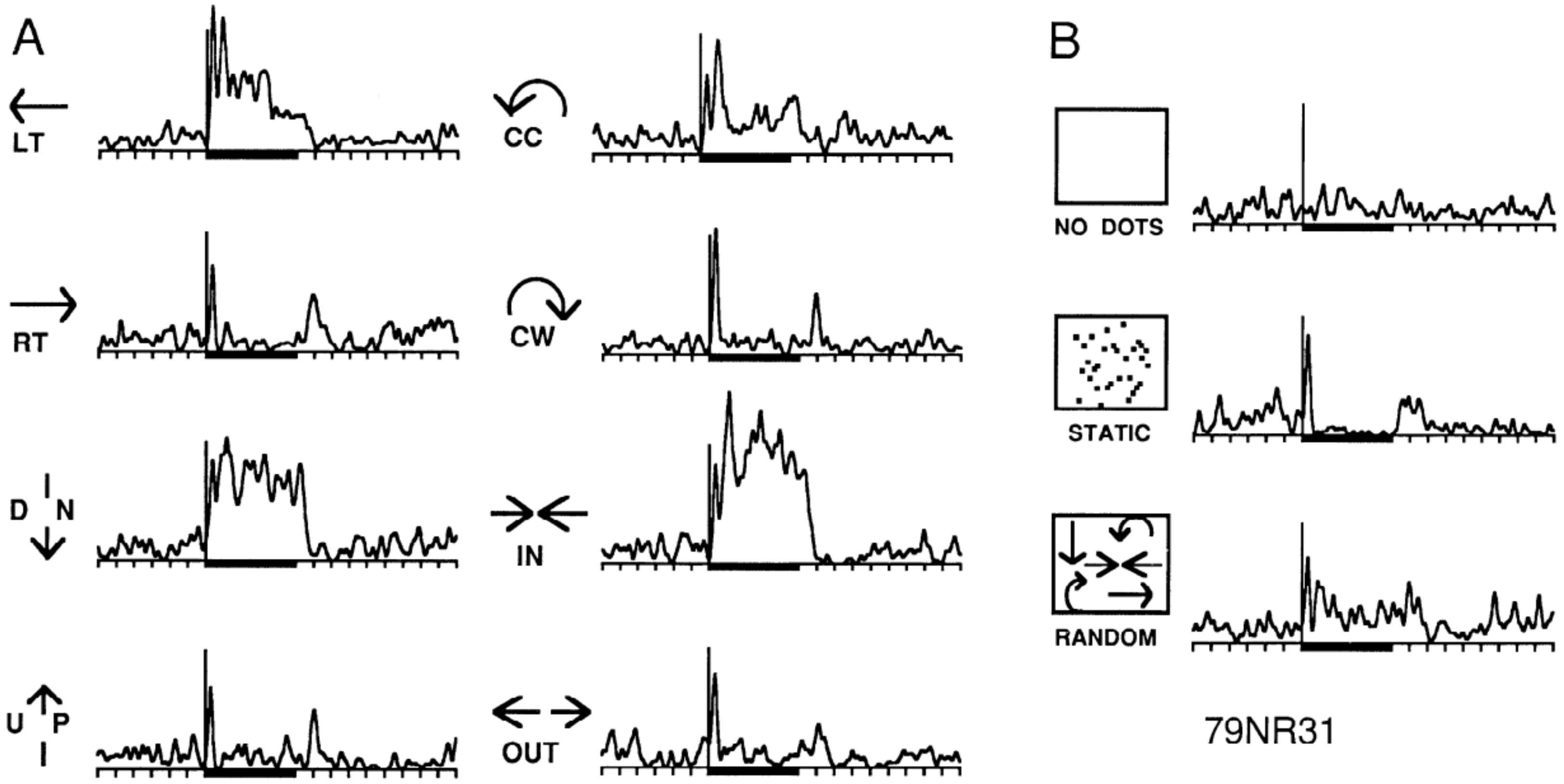
<u>MST neurons represent full-field movement.</u>



Duffy and Wurtz, *J Neurosci* 1991

Perceiving Flow Fields

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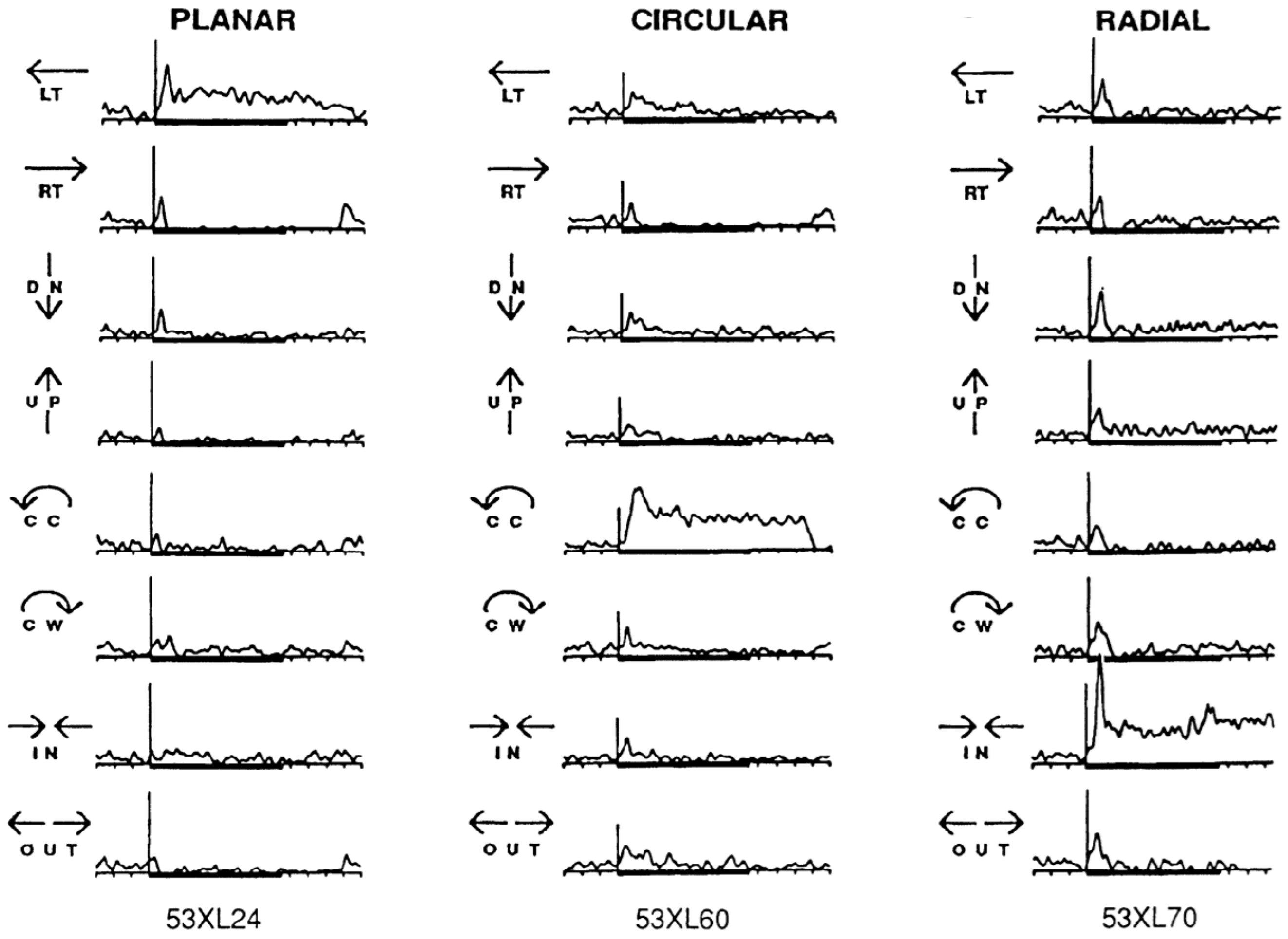


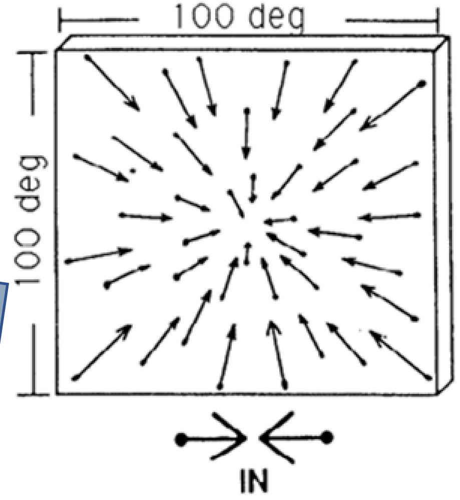
MST neurons represent large field movement of many different kinds.

As with MT, microstimulation can bias monkey's perceived heading direction.

Duffy and Wurtz, *J Neurosci* 1991; Britten and Van Wezel, *Nat Neuro* 1999

Visual complexity increases along cortical hierarchy

MST responds to full-field movement



MT neurons respond to object motion

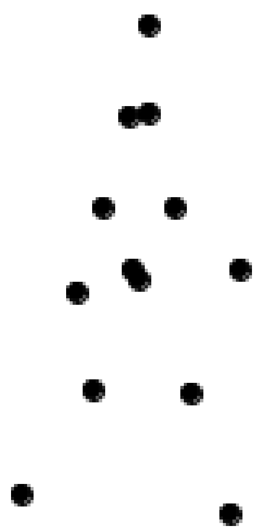
V1: Orientation, Spatial Frequency, Motion Direction

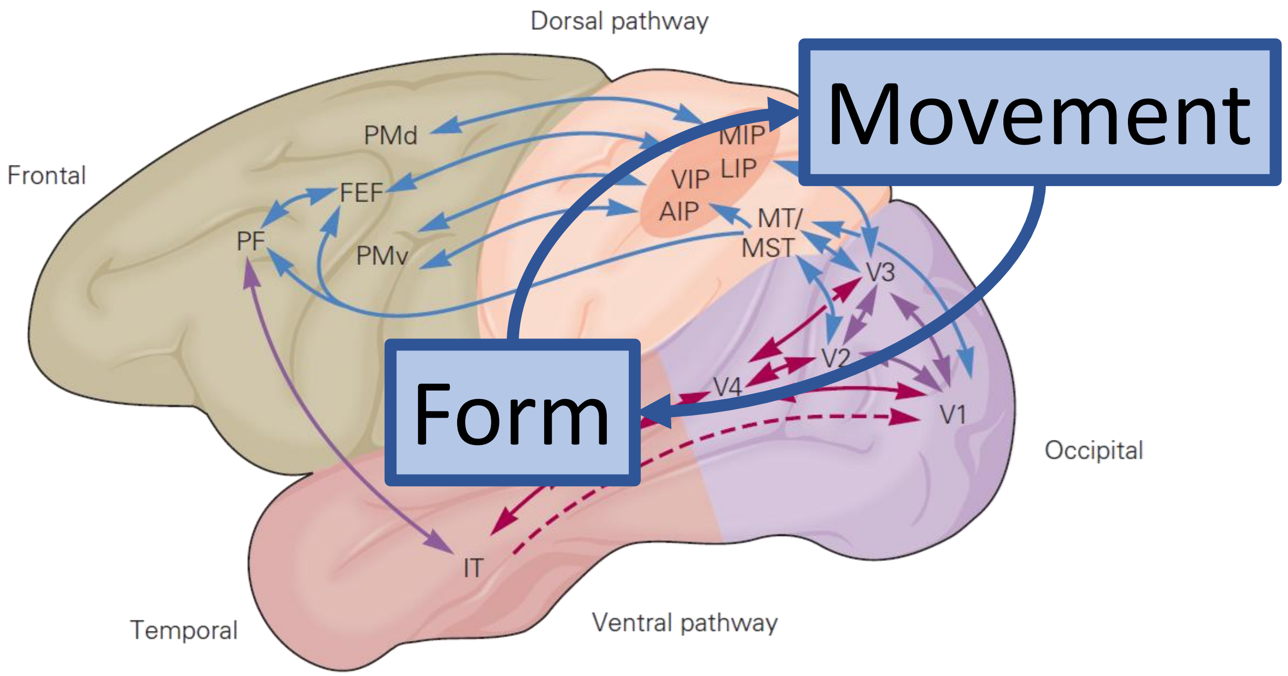
NOTE: MT doesn't require V1; lesioning V1 preserves motion selectivity in MT (most likely due to projections from SC)

Rodman et al, *J Neurosci* 1989

Interactions between Motion and Objects

Movement helps define objects while object information helps constrain movement.





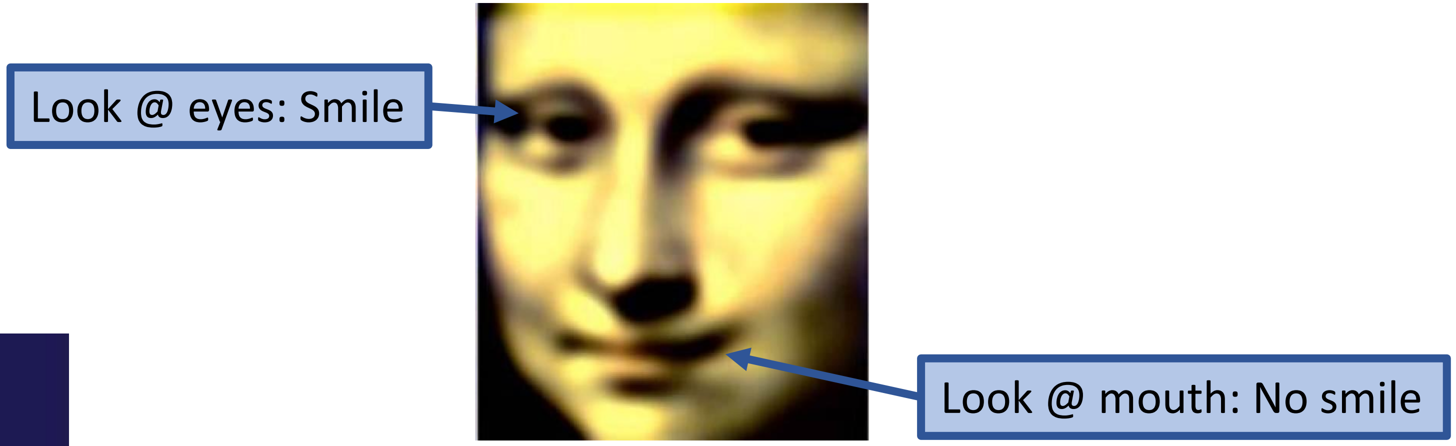
If true, then how is information shared? How separate are the two streams?

www.georgemather.com

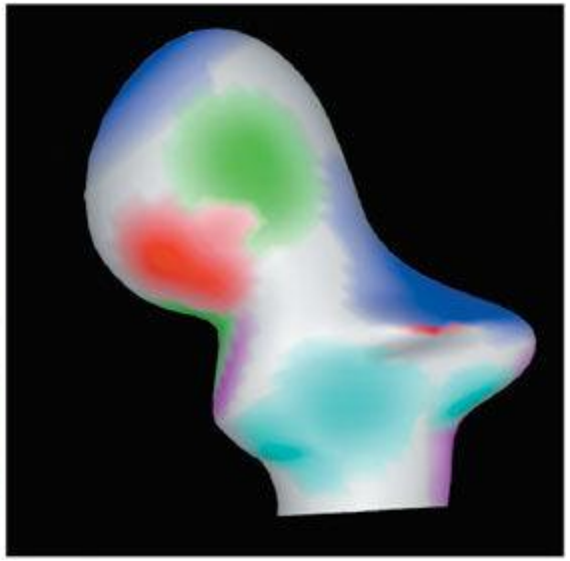
Visual Perception and Art

Picasso uses water color effect.

Matisse relies on figure/ground segregation.



Spatial frequency effects perception of Mona Lisa's smile.



Abstract art intuitively uses the 'bases' of object perception.