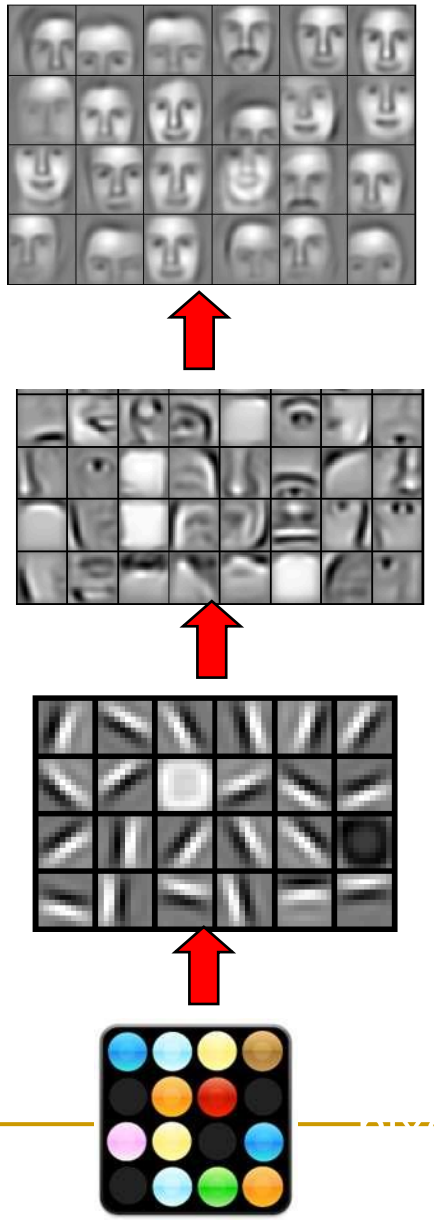
The Visual System: Retina-LGN-V1-V2-V3-V4-V5

How does a CNN learn to recognize faces?

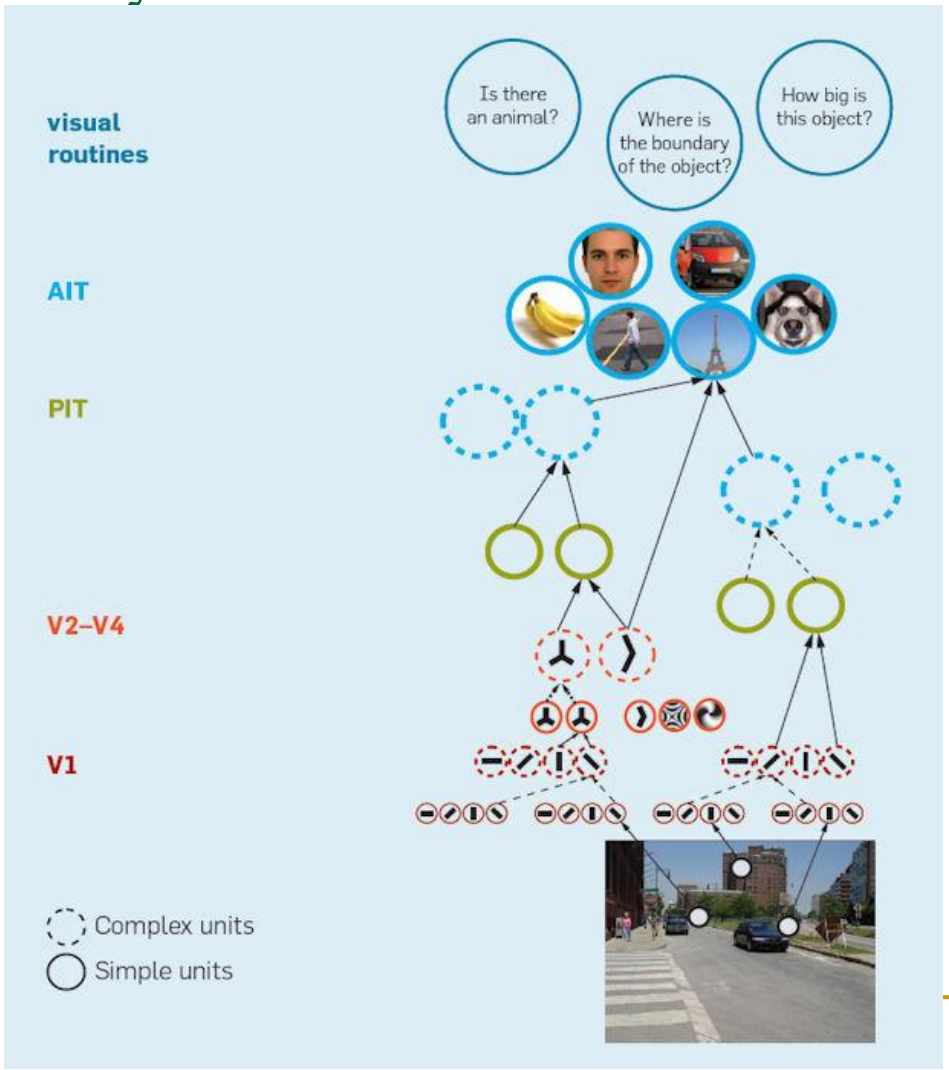


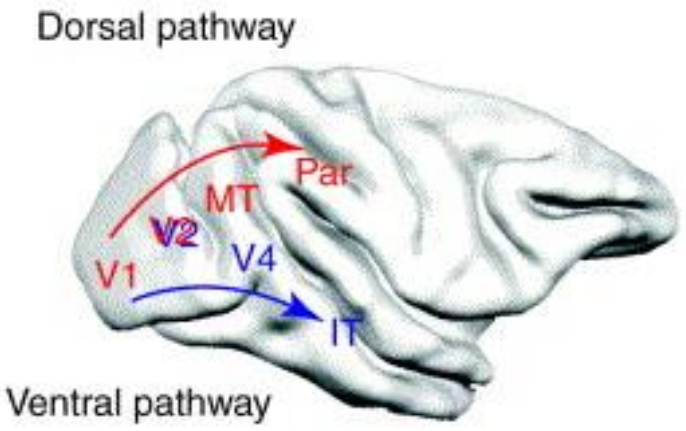
Last layer learns nearly the entire face

Middle layer learns parts of the face

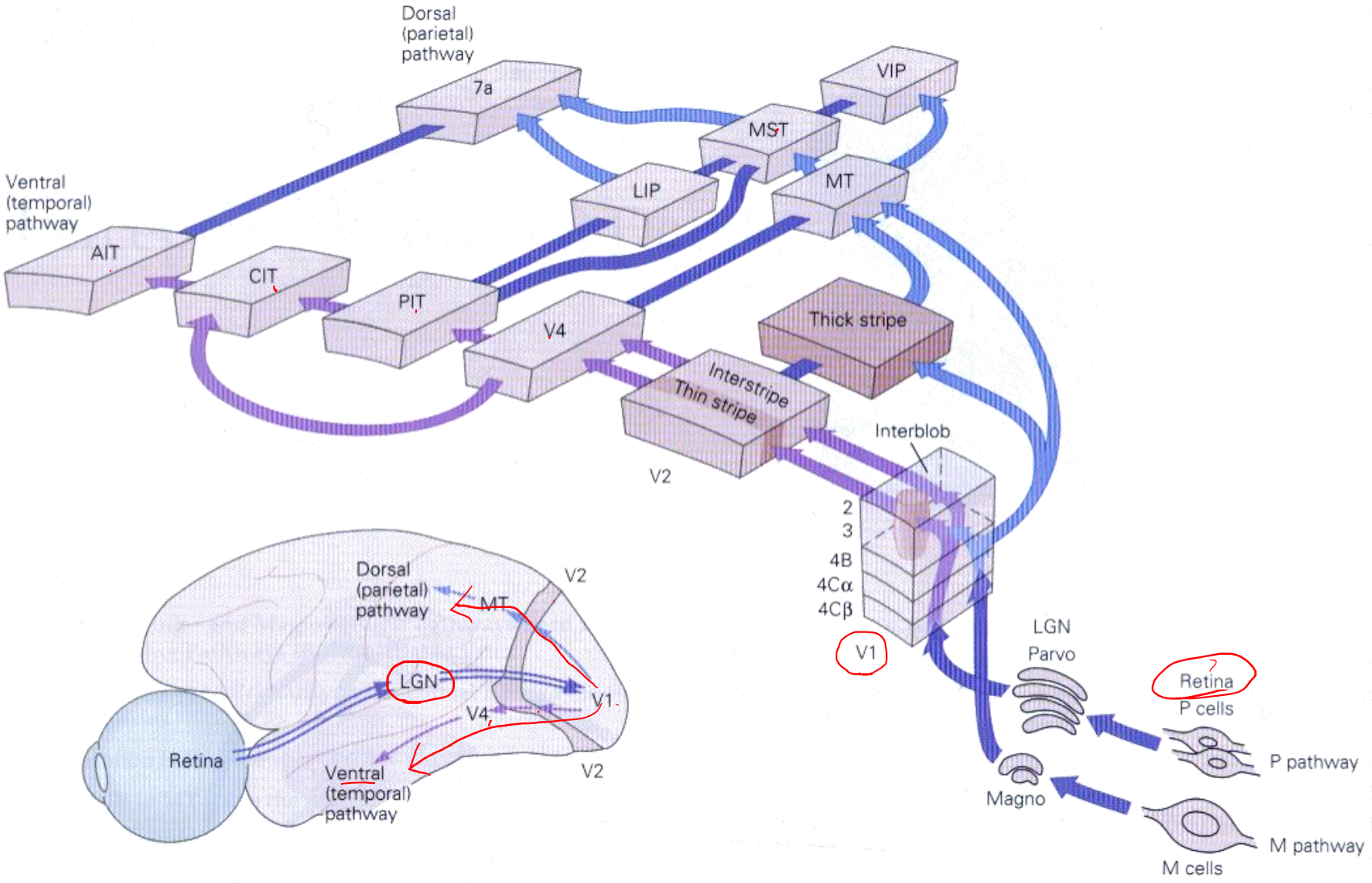
Lowest layer learns edges

Hierarchical organization in the visual system



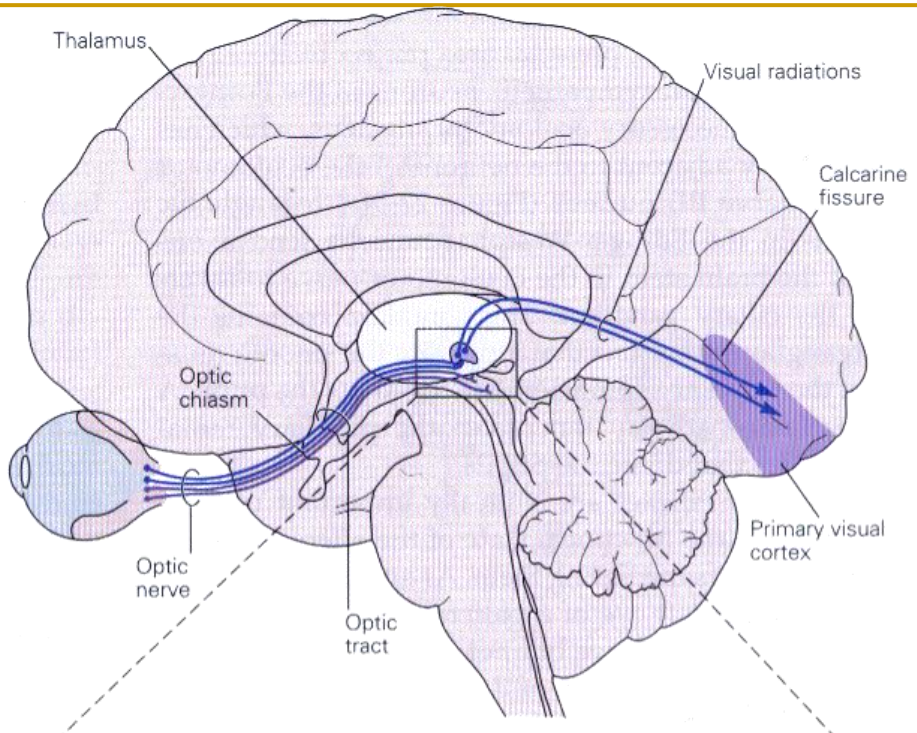


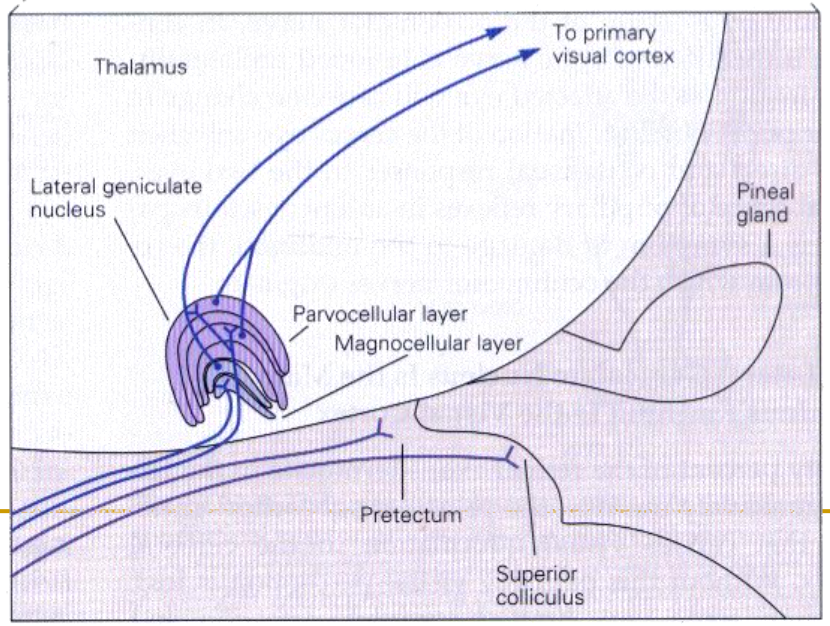
LET'S LEARN ABOUT THE VISUAL SYSTEM…


Dorsal
(parietal)
pathway
7a
VIP
MST
LIP
MT
Ventral
(temporal)
pathway
AIT
CIT
PIT
V4
Thick stripe
Interstripe
Thin stripe
V2
Interblob
2
3
4B
4Cα
4Cβ
V1
LGN
Parvo
Retina
P cells
P pathway
Magno
M pathway
M cells
Dorsal
(parietal)
pathway
MT
V2
LGN
V1
V4
Retina
Ventral
(temporal)
pathway
V2

Visual Areas

- Area 7a
- LGN: lateral geniculate nucleus
- V1: striate cortex
- AIT: anterior inferior temporal area
- CIT: central inferior temporal area
- LIP: lateral intraparietal area
- MST: medial superior temporal area
- MT: middle temporal area
- PIT: posterior inferior temporal area
- VIP: ventral intraparietal area



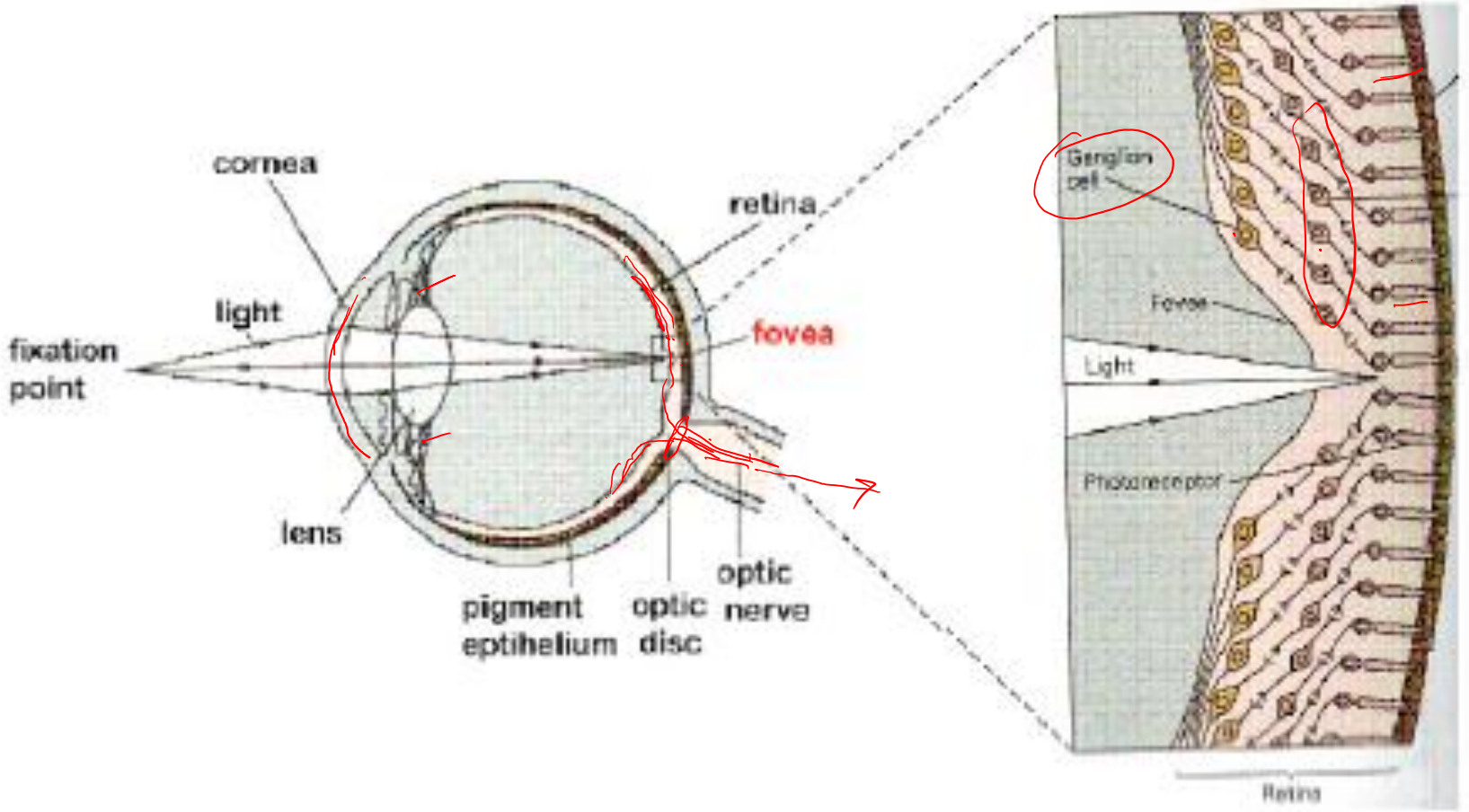


http://www.inma.ucl.ac.be/EYELAB/neurophysio/light_perception/LGN.html

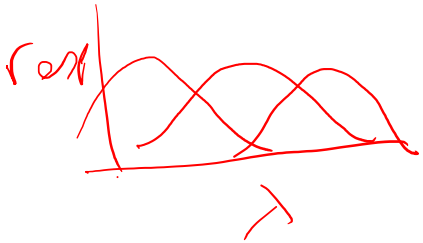
The Fovea

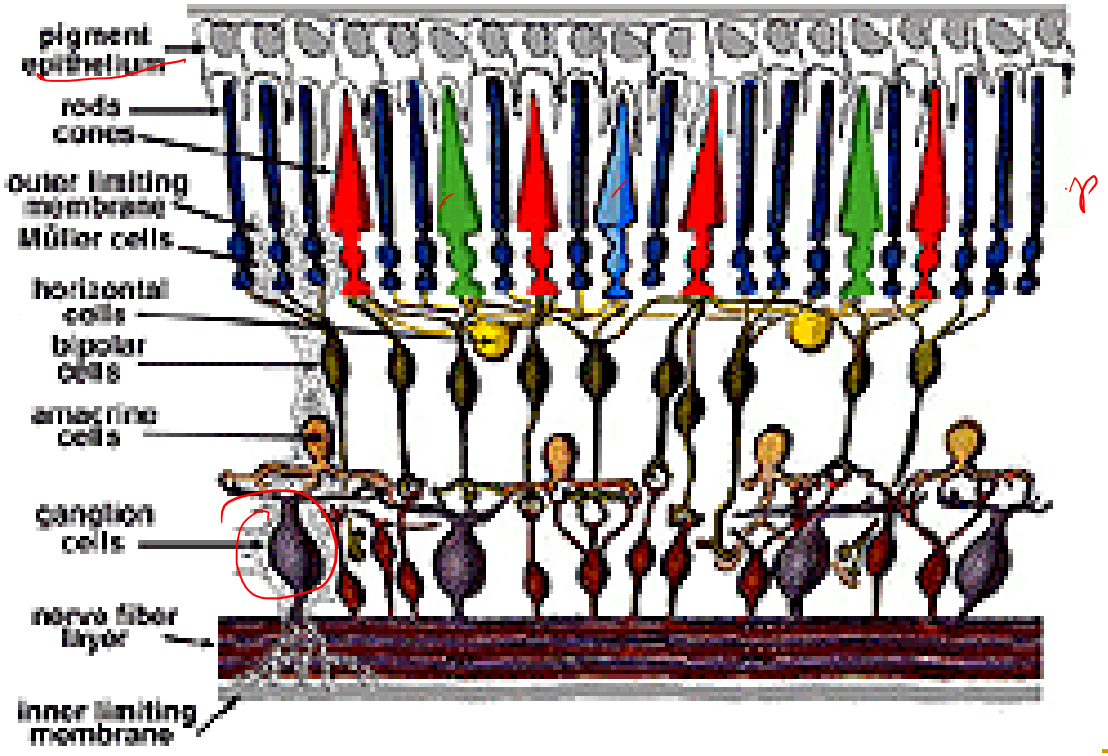
- Packed with cones - high density of sensors, divergent connections
- Minimal light scattering (depleted of other cell types)

=> High acuity (high resolution) vision



Retinal Layers

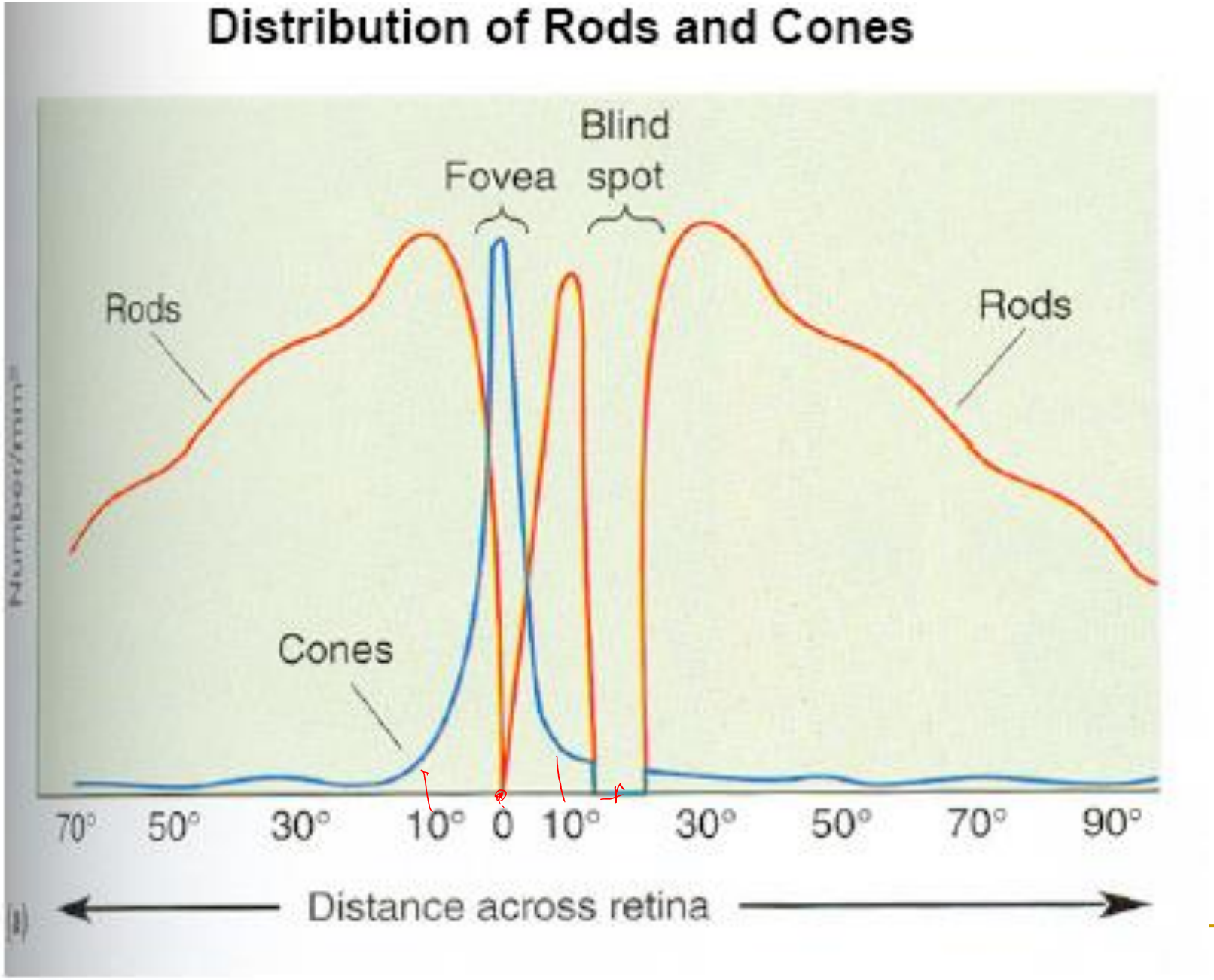




Transducers: Rods and Cones

- Convert light into electrical energy.
- In one eye:
  - 120 million rods
  - 7 million cones
- **Fovea**: a central region with a high density of cones. It has no rods.
- **Cones**: color sensitive (R, G & B)
- **Rods**: not color sensitive

Distribution of Rods and Cones



Fixation point

Binocular zone

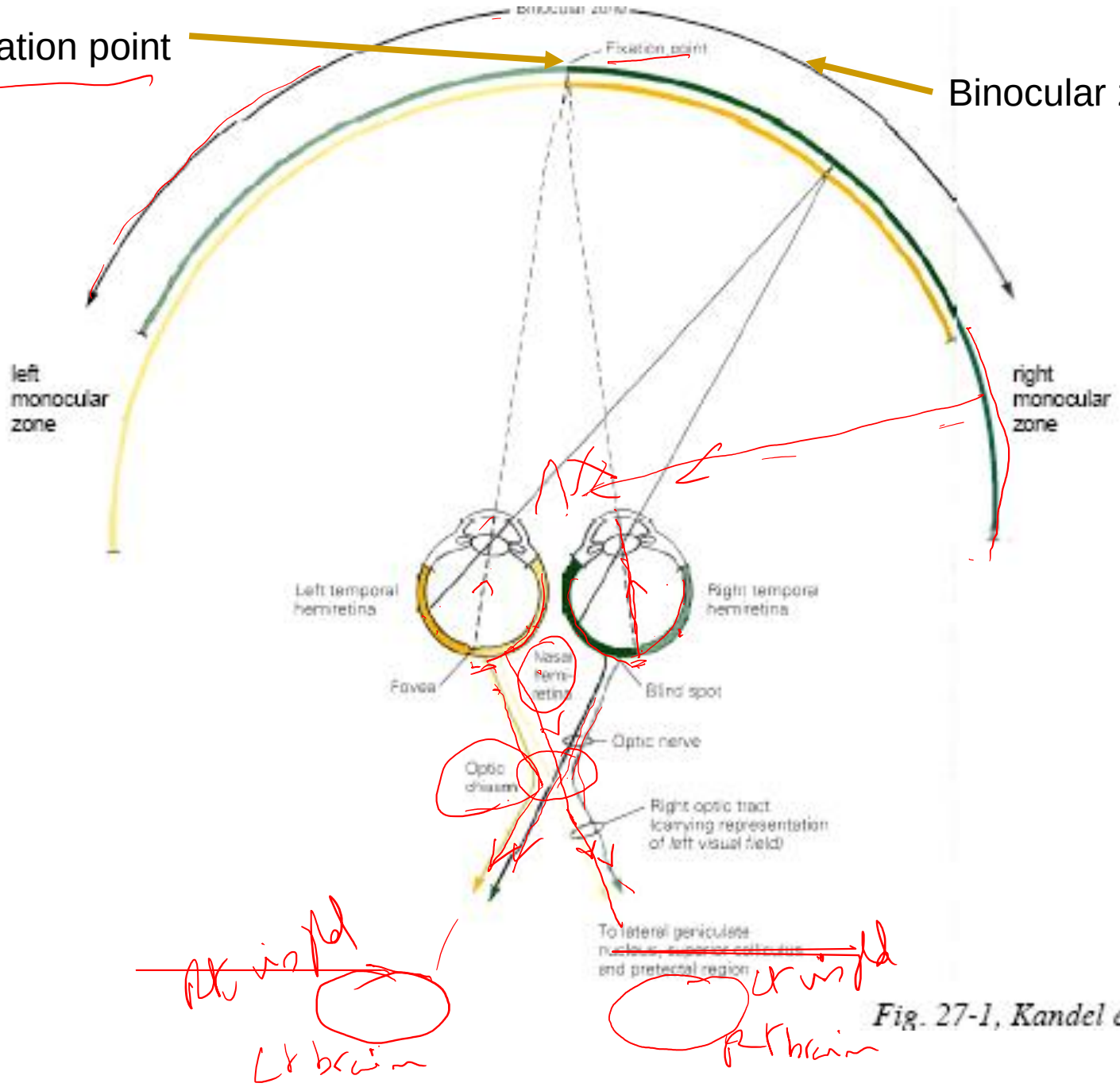
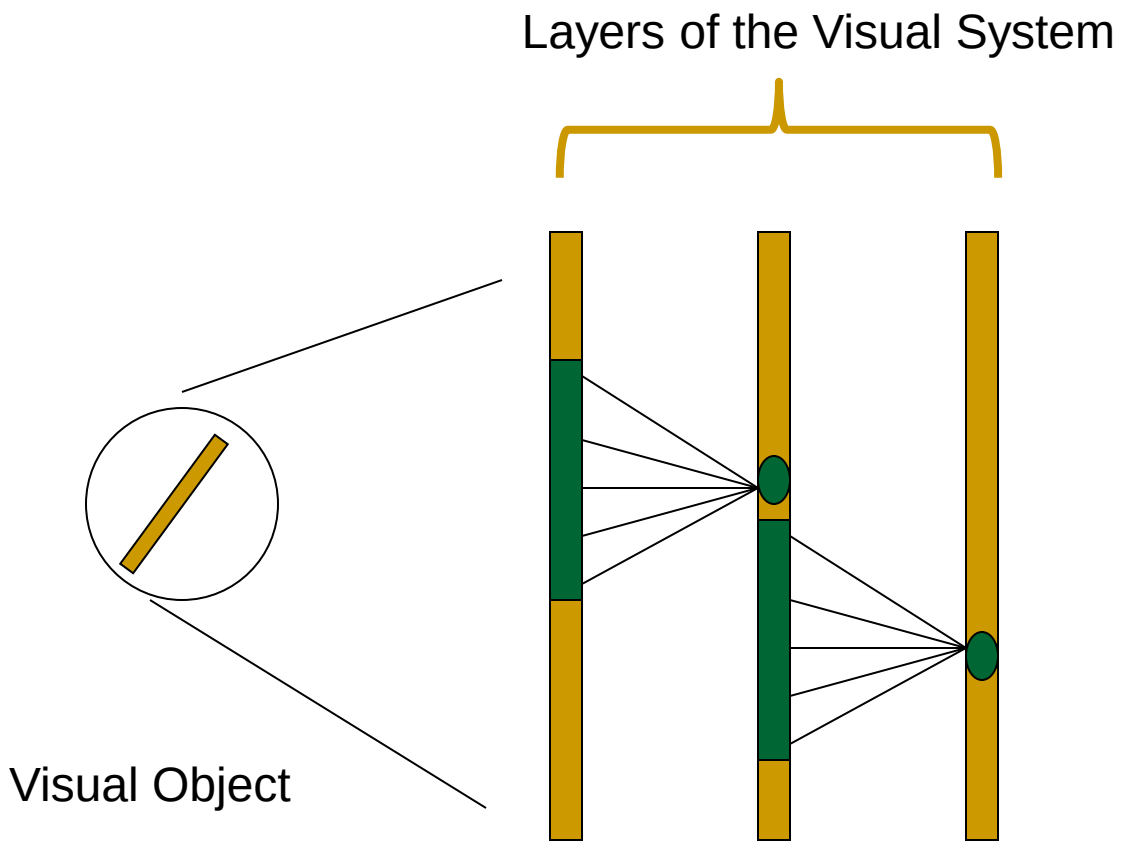


Fig. 27-1, Kandel et al., 4th edition

The Notion of a Receptive Field



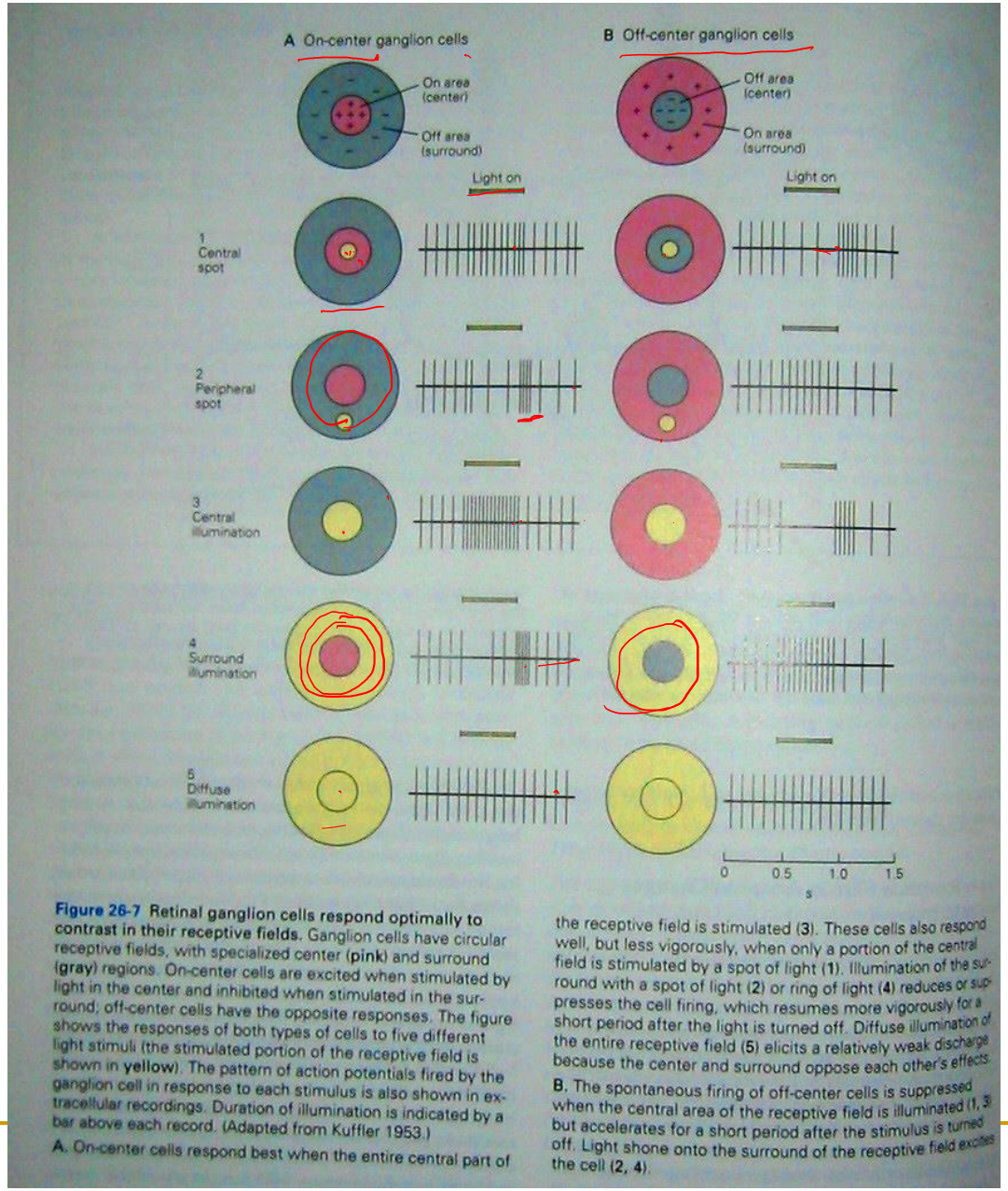


Figure 26-7 Retinal ganglion cells respond optimally to contrast in their receptive fields. Ganglion cells have circular receptive fields, with specialized center (**pink**) and surround (**gray**) regions. On-center cells are excited when stimulated by light in the center and inhibited when stimulated in the surround; off-center cells have the opposite responses. The figure shows the responses of both types of cells to five different light stimuli (the stimulated portion of the receptive field is shown in **yellow**). The pattern of action potentials fired by the ganglion cell in response to each stimulus is also shown in extracellular recordings. Duration of illumination is indicated by a bar above each record. (Adapted from Kuffler 1953.)

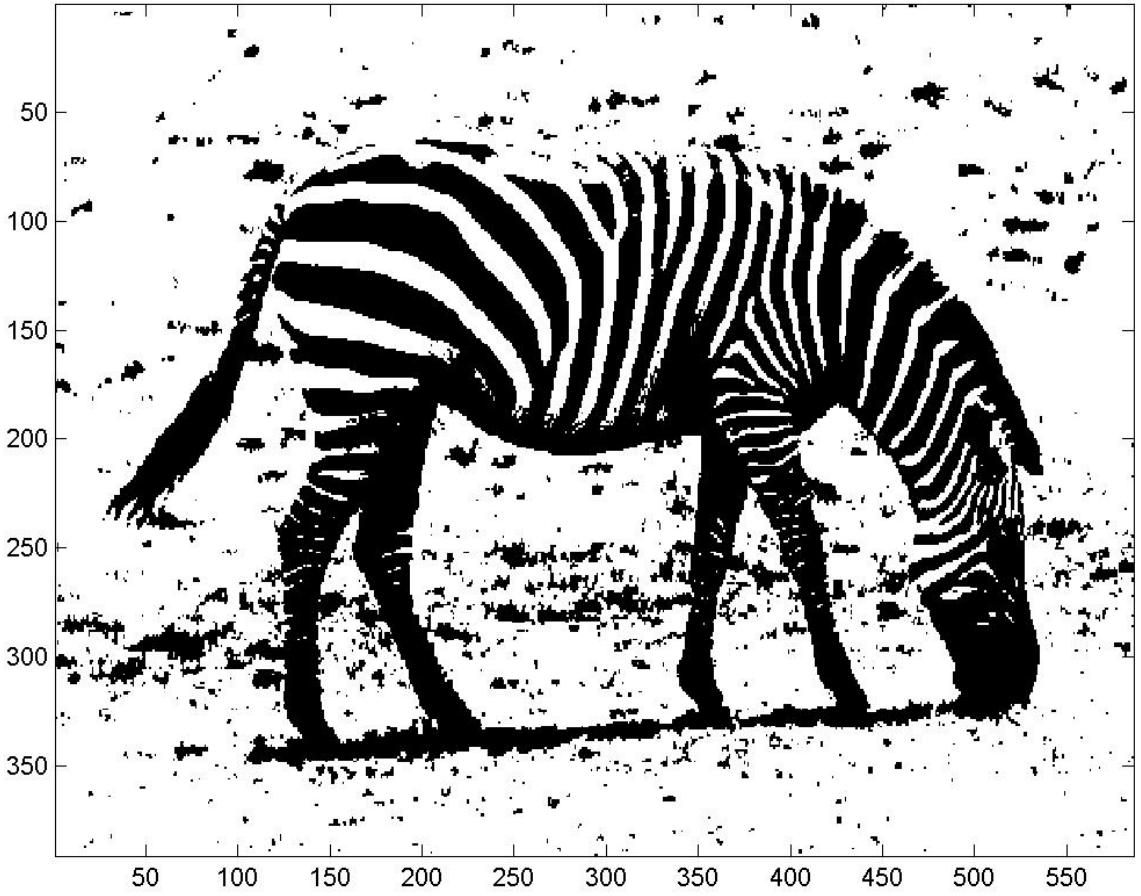
A. On-center cells respond best when the entire central part of the receptive field is stimulated (**3**). These cells also respond well, but less vigorously, when only a portion of the central field is stimulated by a spot of light (**1**). Illumination of the surround with a spot of light (**2**) or ring of light (**4**) reduces or suppresses the cell firing, which resumes more vigorously for a short period after the light is turned off. Diffuse illumination of the entire receptive field (**5**) elicits a relatively weak discharge because the center and surround oppose each other's effects.

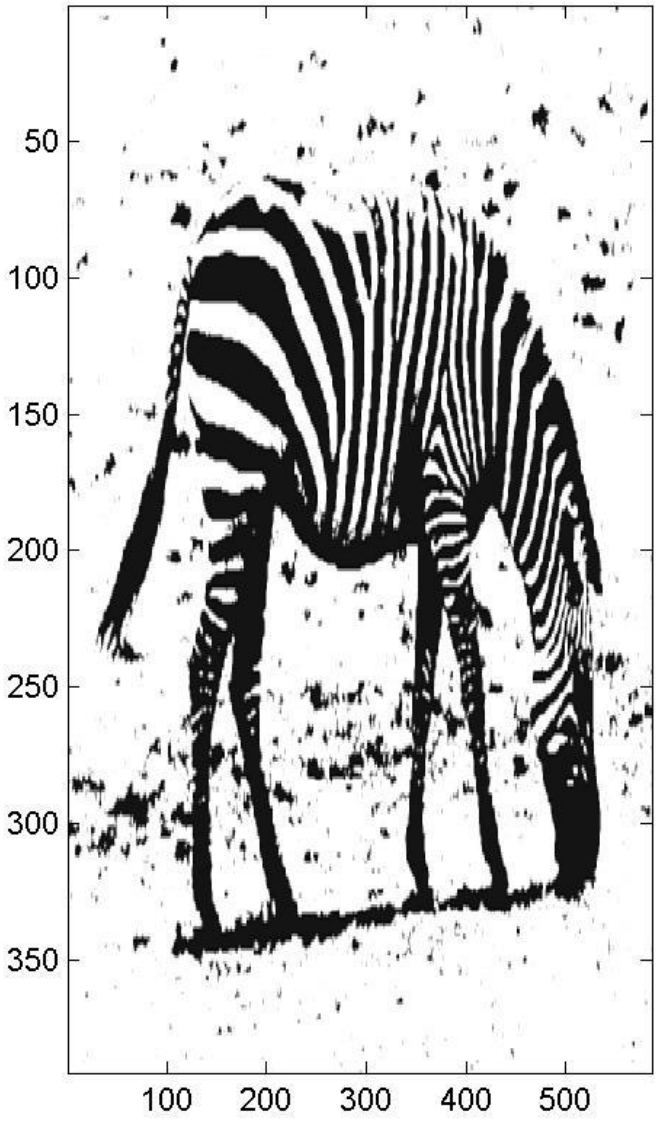
B. The spontaneous firing of off-center cells is suppressed when the central area of the receptive field is illuminated (**1, 3**) but accelerates for a short period after the stimulus is turned off. Light shone onto the surround of the receptive field excites the cell (**2, 4**).

What do the Ganglion Cells do?

- Response of the ganglion cell layer as a convolution with a center-surround kernel
- Evaluate Response for various kernel parameters

Original Image

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100
150
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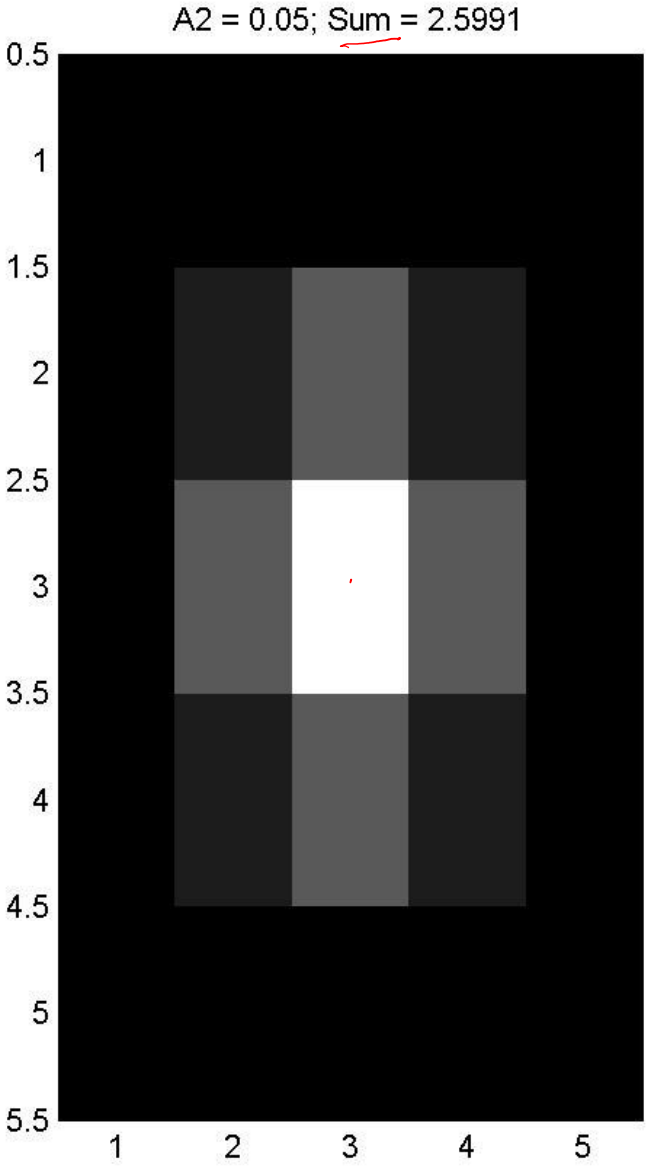
500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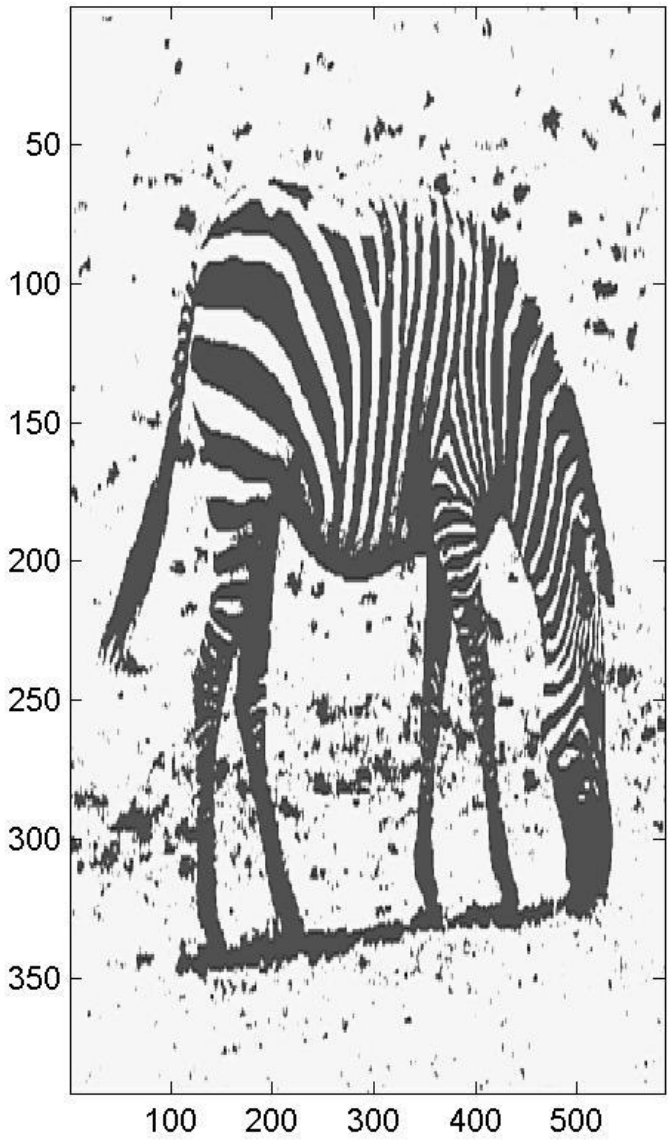
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
1
2
3
4
5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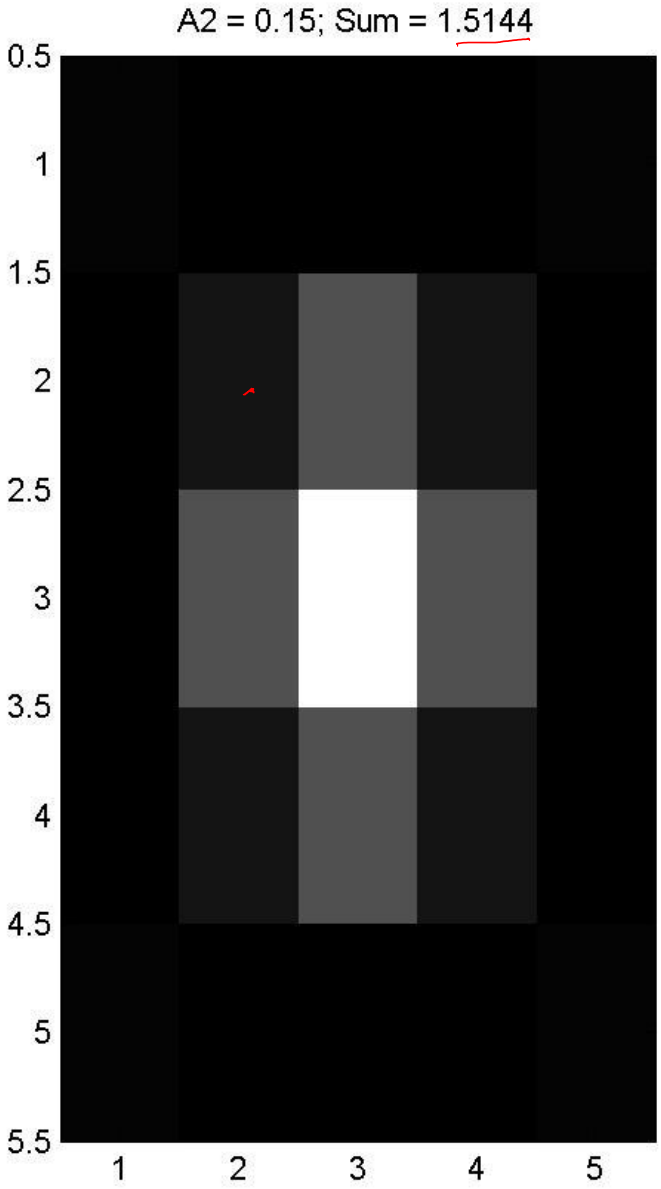
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2.5
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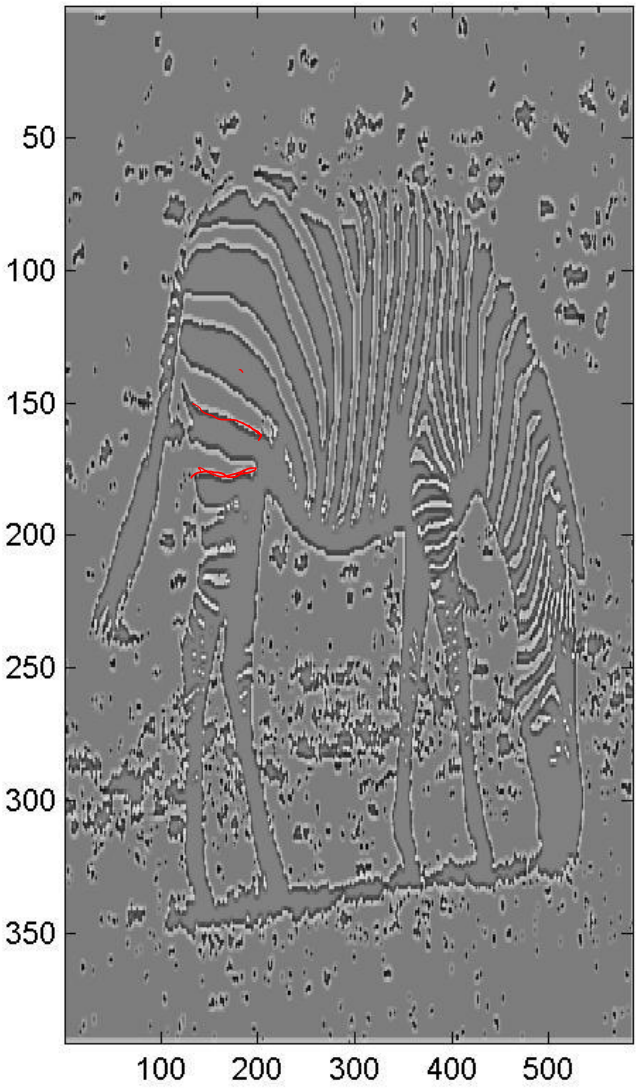
3.5
4
4.5
5
5.5
1
2
3
4
5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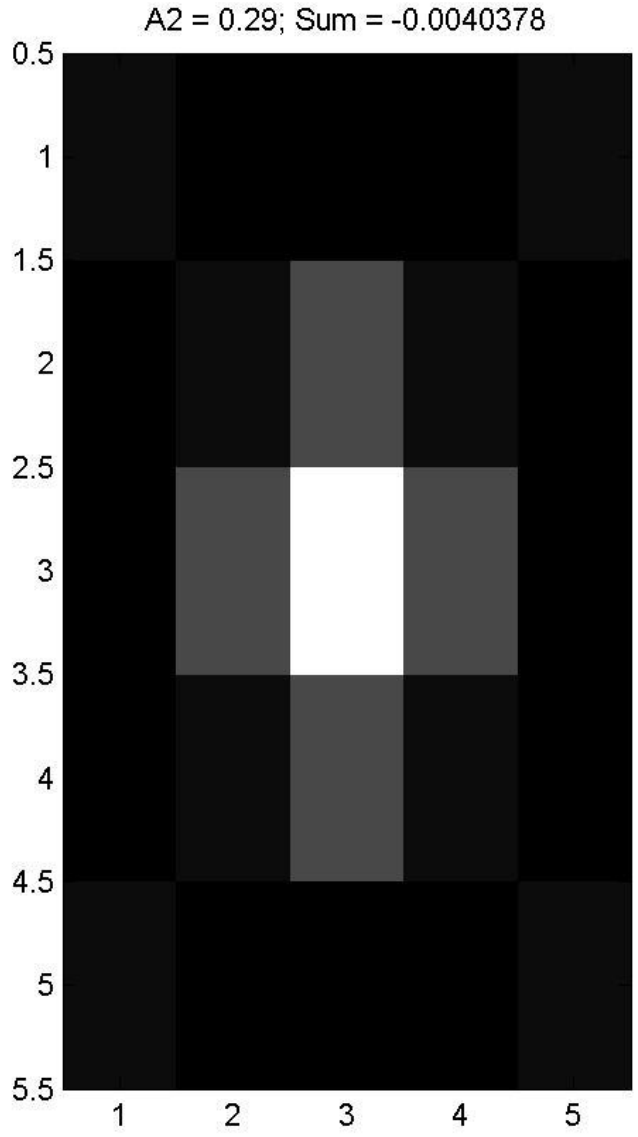
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4.5
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150
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250
300
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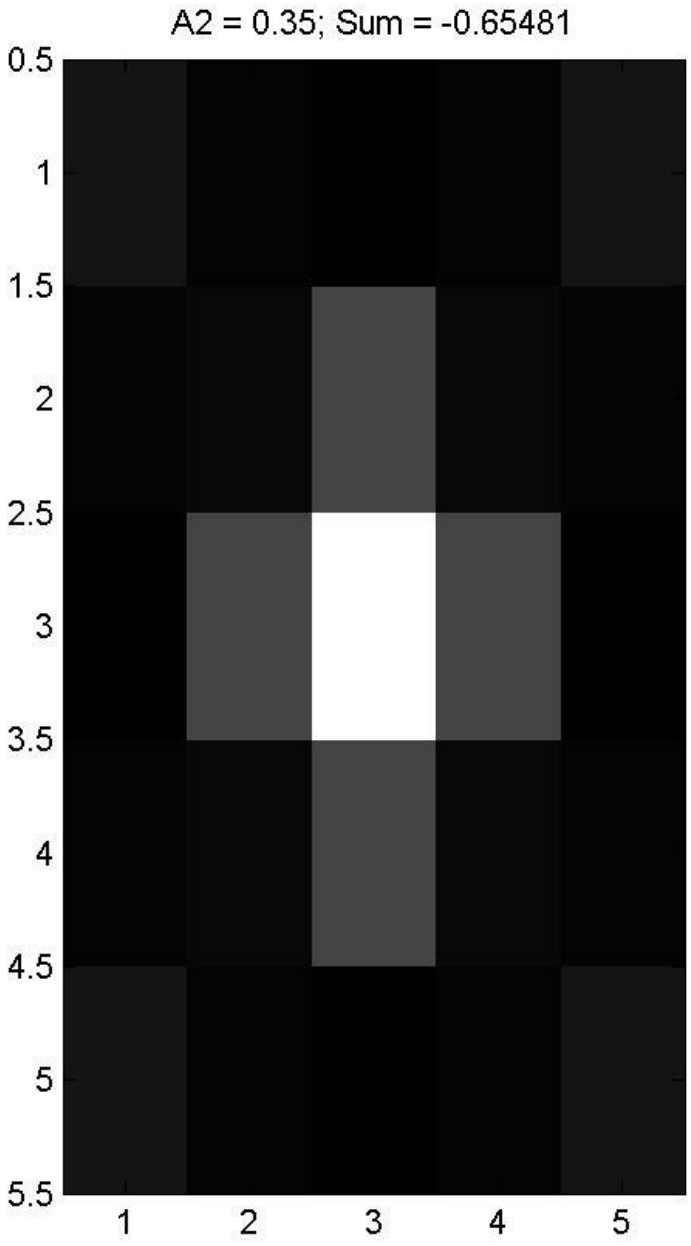
100
200
300
400
500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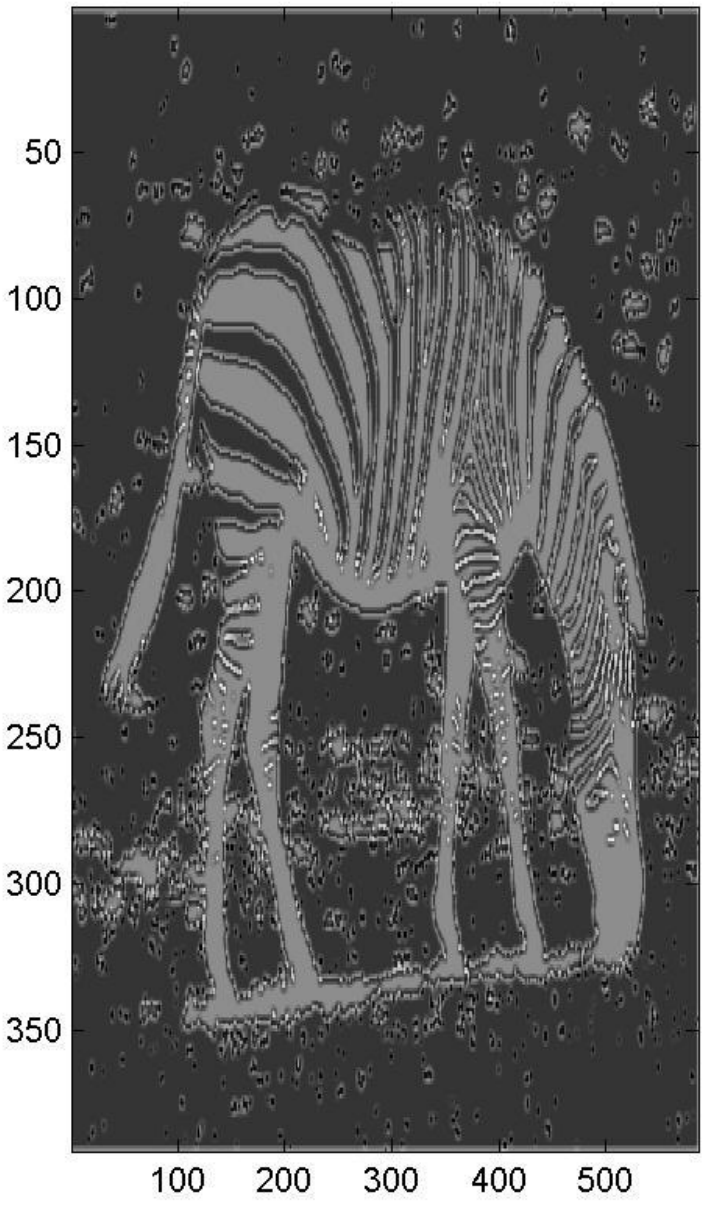
1.5
2
2.5
3
3.5
4
4.5
5
5.5
1
2
3
4
5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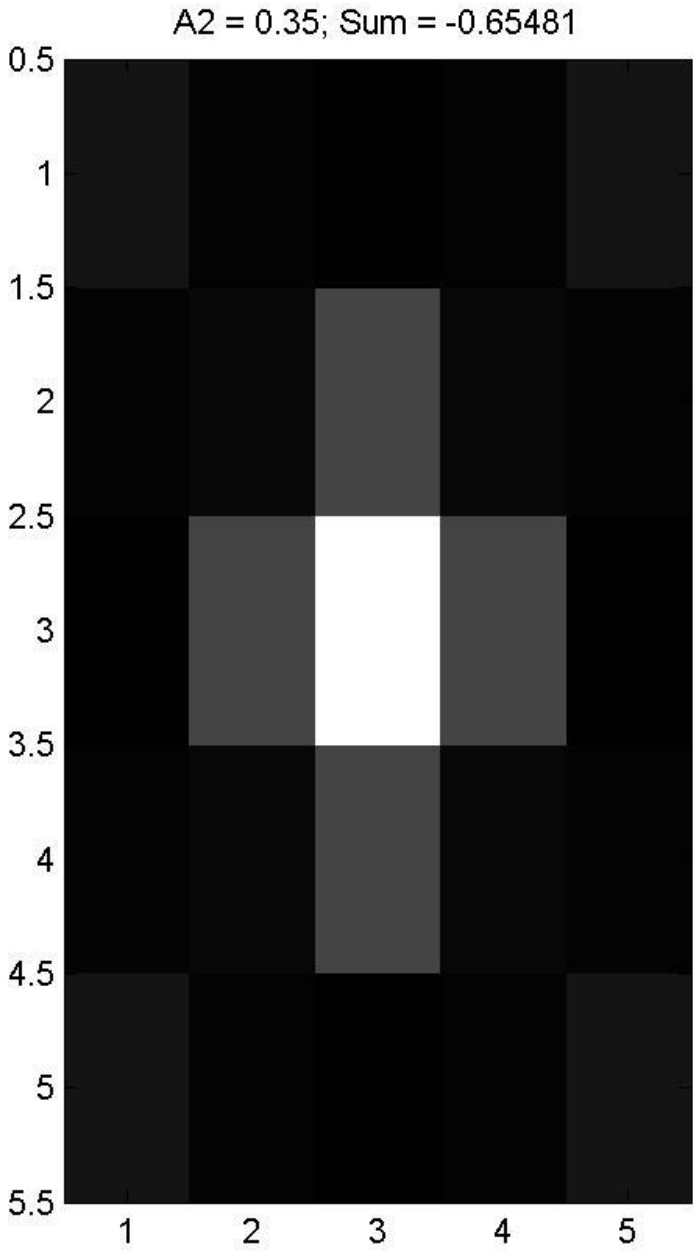
A2 = 0.35; Sum = -0.65481
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
1
2
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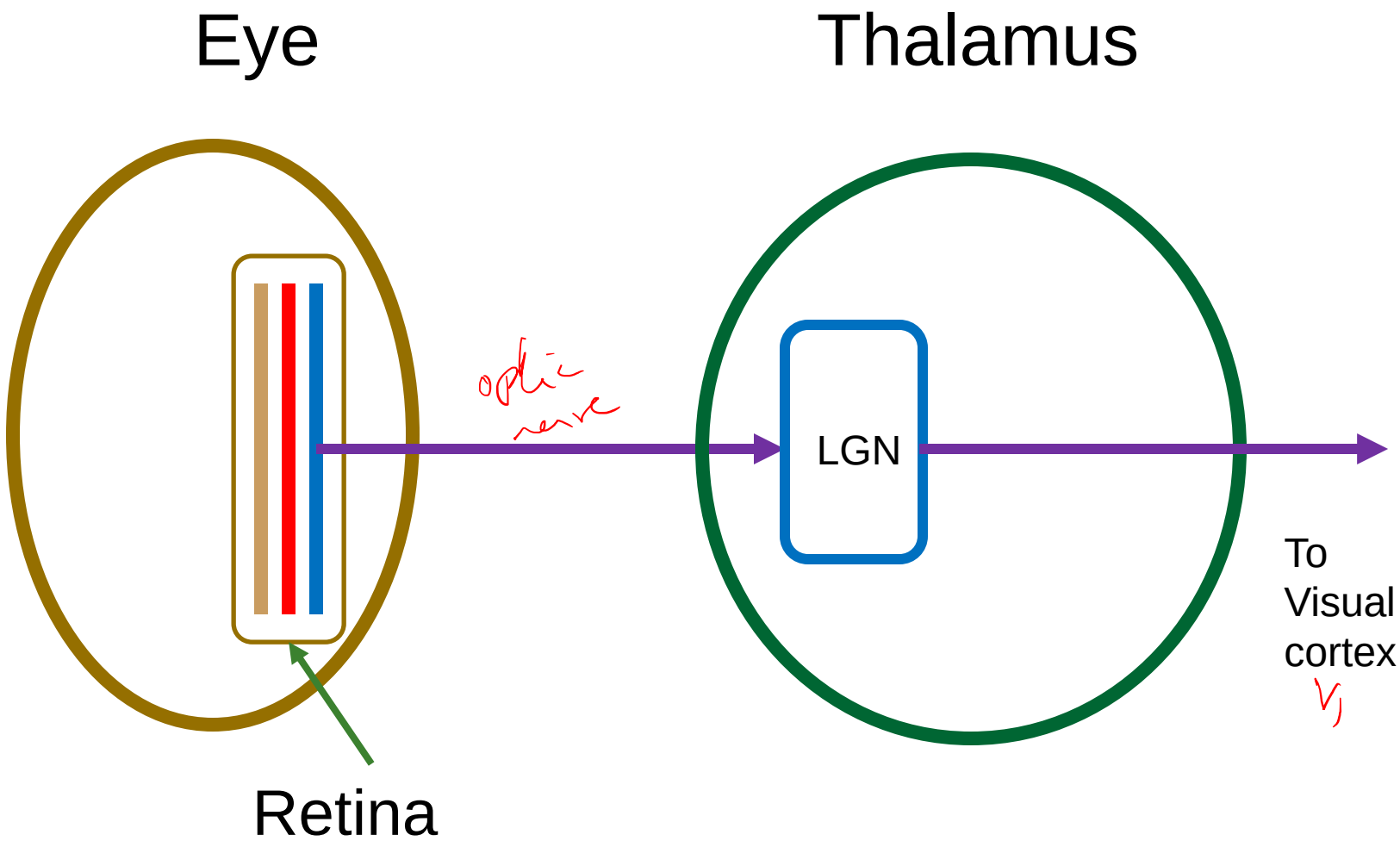
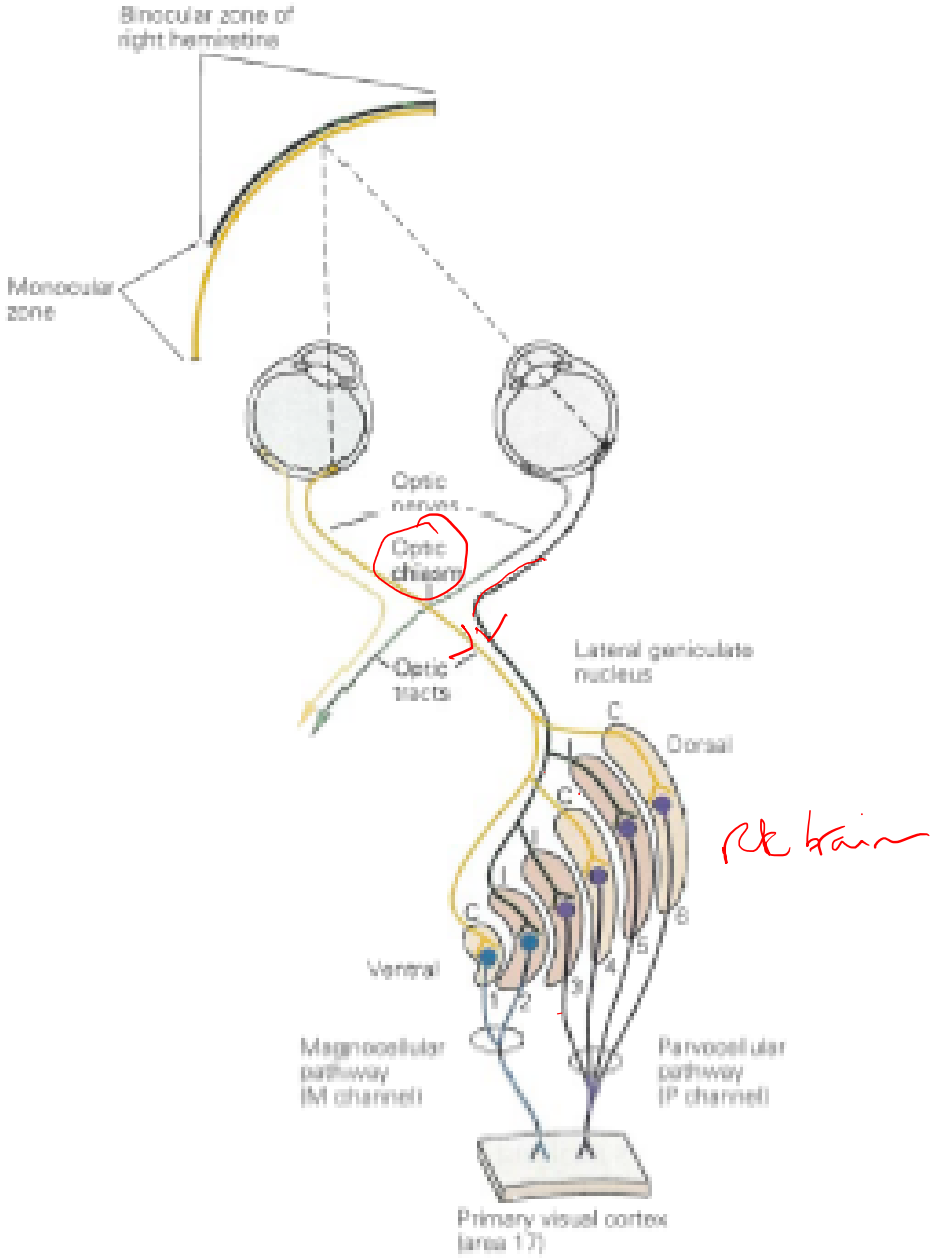
4
5

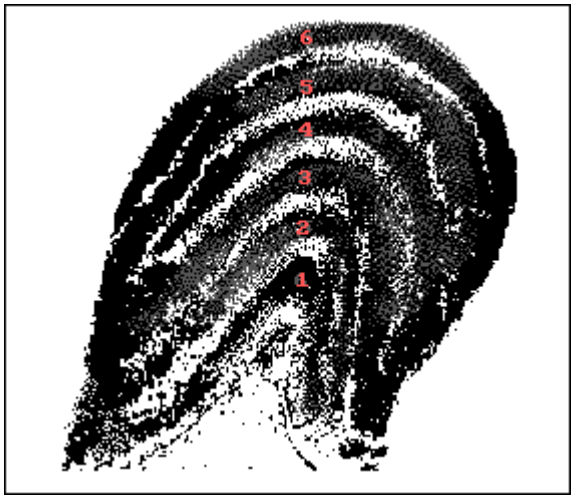

Eye
Thalamus
optic nerve
LGN
To Visual cortex
V1
Retina

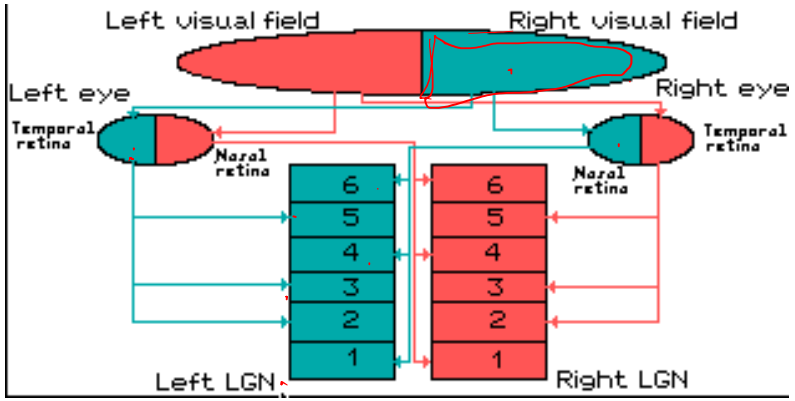
Segregation of Inputs into the LGN

- **Magnocellular pathway**
  Layers 1 & 2
- **Parvocellular pathway**
  Layers 3 - 6
- **Contralateral input**
  Layers 1, 4, 6
- **Ipsilateral input**
  Layers 2, 3, 5
- Point-to-point topography of visual field is preserved between retina and LGN



Inputs to LGN





- 1-2: Magnocellular layers; M ganglion cells project here.
- 3-6: parvocellular layers; P ganglion cells project here.
- Individual layer in LGN receives input from one eye only
- Fibers from contralateral nasal hemiretina project to layers 1, 4, 6
- Fibers from ipsilateral temporal hemiretina project to layers 2, 3, 5
- Each layer contains the representation of the contralateral hemifield
- Greater representation to Fovea than periphery
  - Nearly half the LGN cell mass represents the fovea and surrounding region
  - Magnification factor

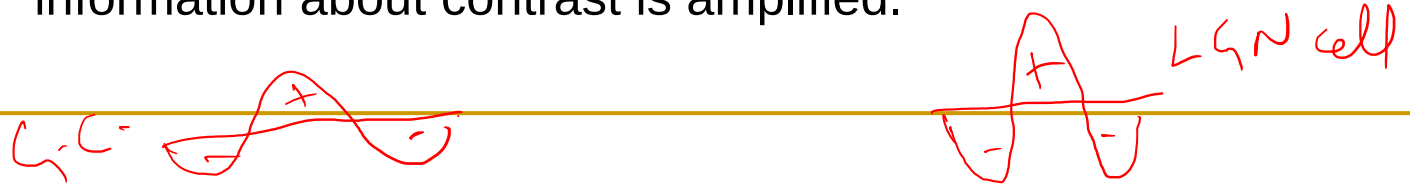
http://www.lifesci.sussex.ac.uk/home/George_Mather/Linked%20Pages/Physiol/LGN.html

Receptive Fields of LGN cells

- LGN cells have circular, center-surround receptive fields -- similar to those of retinal ganglion cells (1^{o} dia)

- Like ganglion cells, both types of RFs (ON-Ctr/OFF-Surr & OFF-Ctr/ON-Surr) are present
- However, there is some segregation of the two types of RFs
  - magnocellular layers (1 and 2) each contain a mixture of cells with ON/OFF and OFF/ON receptive fields,
  - each of the parvocellular layers (3-6) contains only one or the other type of receptive field (two layers contain only ON/OFF and two contain only OFF/ON).

- The surrounds of LGN receptive fields also have stronger influences than ganglion cell surrounds. This means that the surrounds in LGN receptive fields are weighted more heavily, and, consequently, information about contrast is amplified.



Outputs from LGN

- M-pathways
  - Initial analysis of movement
  - Projections from M cells to V1
- P-pathways
  - Fine structure and color vision
  - Projections from P cells to V1
- Only 10-20% of inputs to LGN cells are from retina; the rest are from cortex (and retinal formation etc)

Function of LGN

- enhances information about contrast
- organizes information (e.g., eye of origin, colour, motion, form)
- modulates levels of processing with arousal (via the reticular activating system)
- receives feedback from higher areas (V1)

Reconstruction of Natural Scenes from Ensemble Responses in the Lateral Geniculate Nucleus

(Stanley, Li & Dan, 1999 – *J. Neuroscience*)

- Natural scenes were reconstructed from 177 LGN cells
- Quality of reconstruction at a given point:
  - depends on the number of cells
  - saturates at 6-8 pairs (ON/OFF) of cells

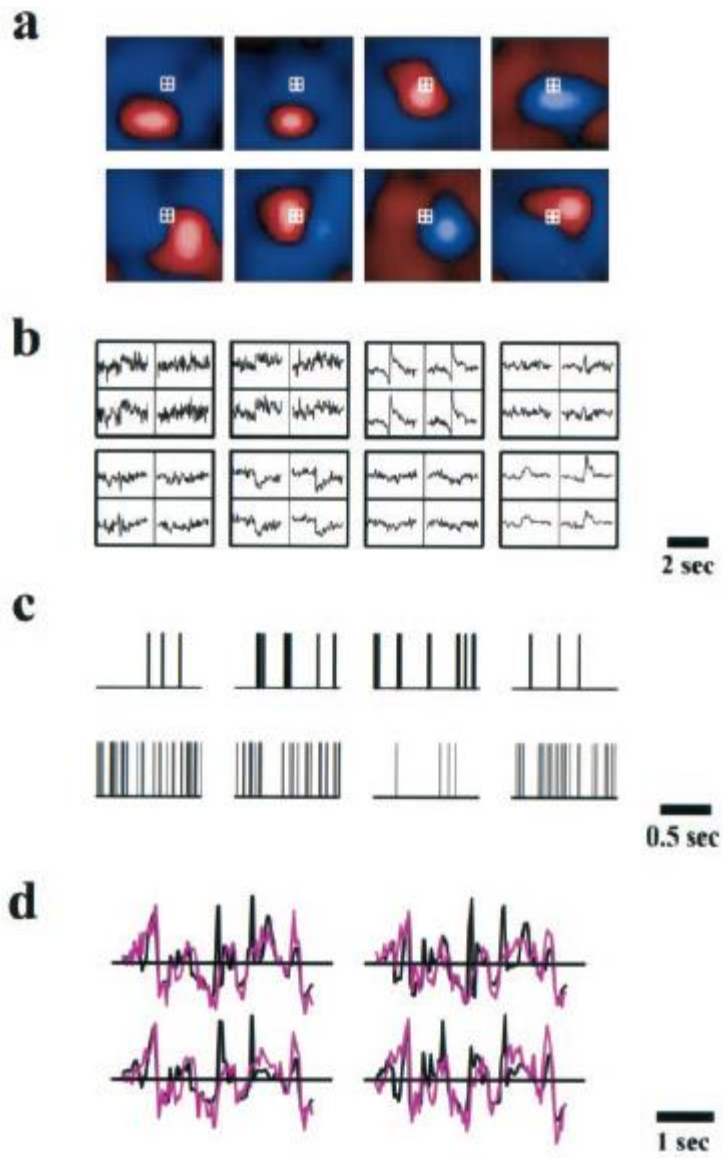


Figure 1. The procedure for reconstructing visual stimuli from the responses of multiple neurons. *a*, Receptive fields of eight neurons recorded simultaneously with multielectrodes. These receptive fields were mapped with white-noise stimuli and the reverse correlation method (Sutter, 1987; Reid et al., 1997). *Red*, On responses. *Blue*, Off responses. The brightest colors correspond to the strongest responses. The area shown is 3.6 × 3.6°. The responses of these cells were used to reconstruct visual inputs at the four pixels (0.2°/pixel) outlined with the *white squares*. *b*, Linear filters for input reconstruction. The eight blocks correspond to the eight cells shown in *a*. Shown in each block are the four filters from that cell to the four pixels outlined in *a*. They represent the linear estimates of the input signals at these pixels immediately preceding and following a spike of that cell. Each filter is 3.1-sec-long, with 1.55 sec before and 1.55 sec after the spike. *c*, Spike trains of the eight neurons in response to movie stimuli. *d*, The actual (*black*) and the reconstructed (*magenta*) movie signals at the four pixels outlined in *a*. Unlike white noise, natural visual signals exhibit more low-frequency, slow variations than high-frequency, fast variations. Such temporal features are well captured by the reconstruction.

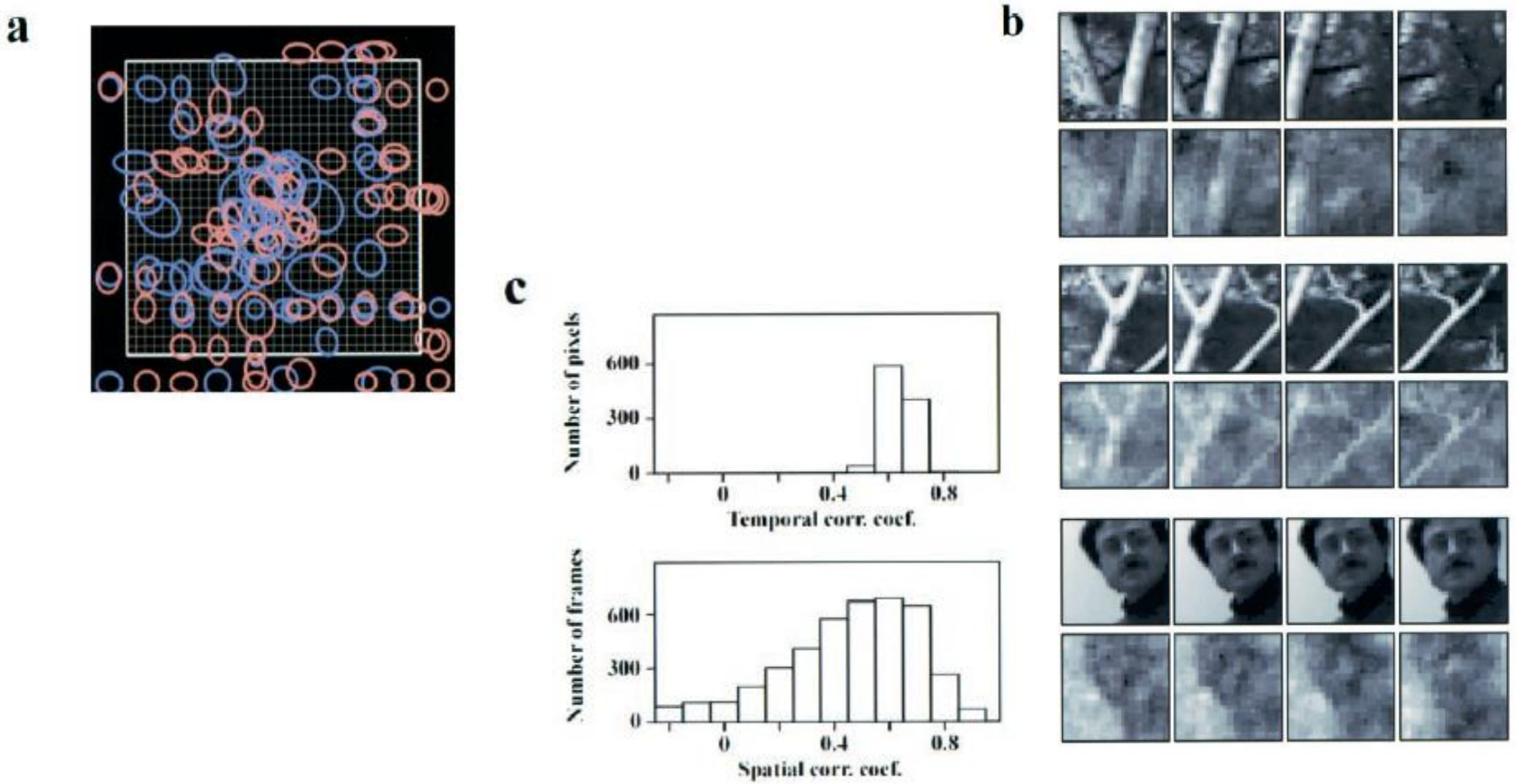
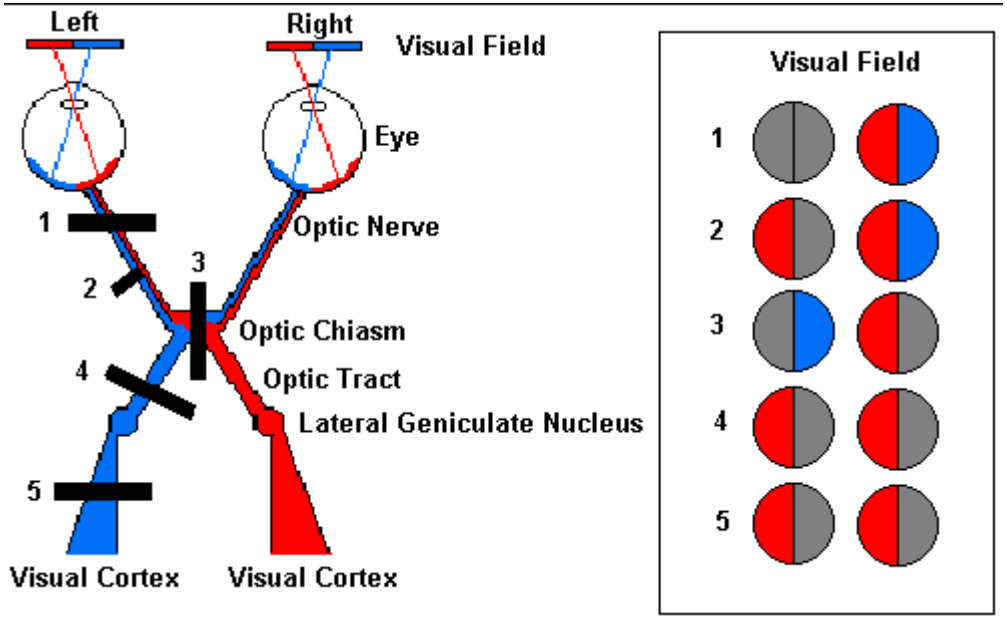


Figure 2. Reconstruction of natural scenes from the responses of a population of neurons. *a*, Receptive fields of 177 cells used in the reconstruction. Each receptive field was fitted with a two-dimensional Gaussian function. Each ellipse represents the contour at one SD from the center of the Gaussian fit. Note that the actual receptive fields (including surround) are considerably larger than these ellipses. *Red,* On center. *Blue,* Off center. An area of 32 × 32 pixels (0.2°/pixel) where movie signals were reconstructed is outlined in *white*. The *grid* inside the *white square* delineates the pixels. *b,* Comparison between the actual and the reconstructed images in an area of 6.4 × 6.4° (*a*, *white square*). Each panel shows four consecutive frames (interframe interval, 31.1 msec) of the actual (*top*) and the reconstructed (*bottom*) movies. *Top panel,* Scenes in the woods, with two trunks of trees as the most prominent objects. *Middle panel,* Scenes in the woods, with smaller tree branches. *Bottom panel,* A face at slightly different displacements on the screen. *c*, Quantitative comparison between the reconstructed and the actual movie signals. *Top,* Histogram of temporal correlation coefficients between the actual and the reconstructed signals (both as functions of time) at each pixel. The histogram was generated from 1024 (32 × 32) pixels in the *white square*. *Bottom,* Histogram of spatial correlation coefficients between the actual and the reconstructed signals (both as functions of spatial position) at each frame. The histogram was generated from 4096 frames (512 frames per movie; 8 movies).



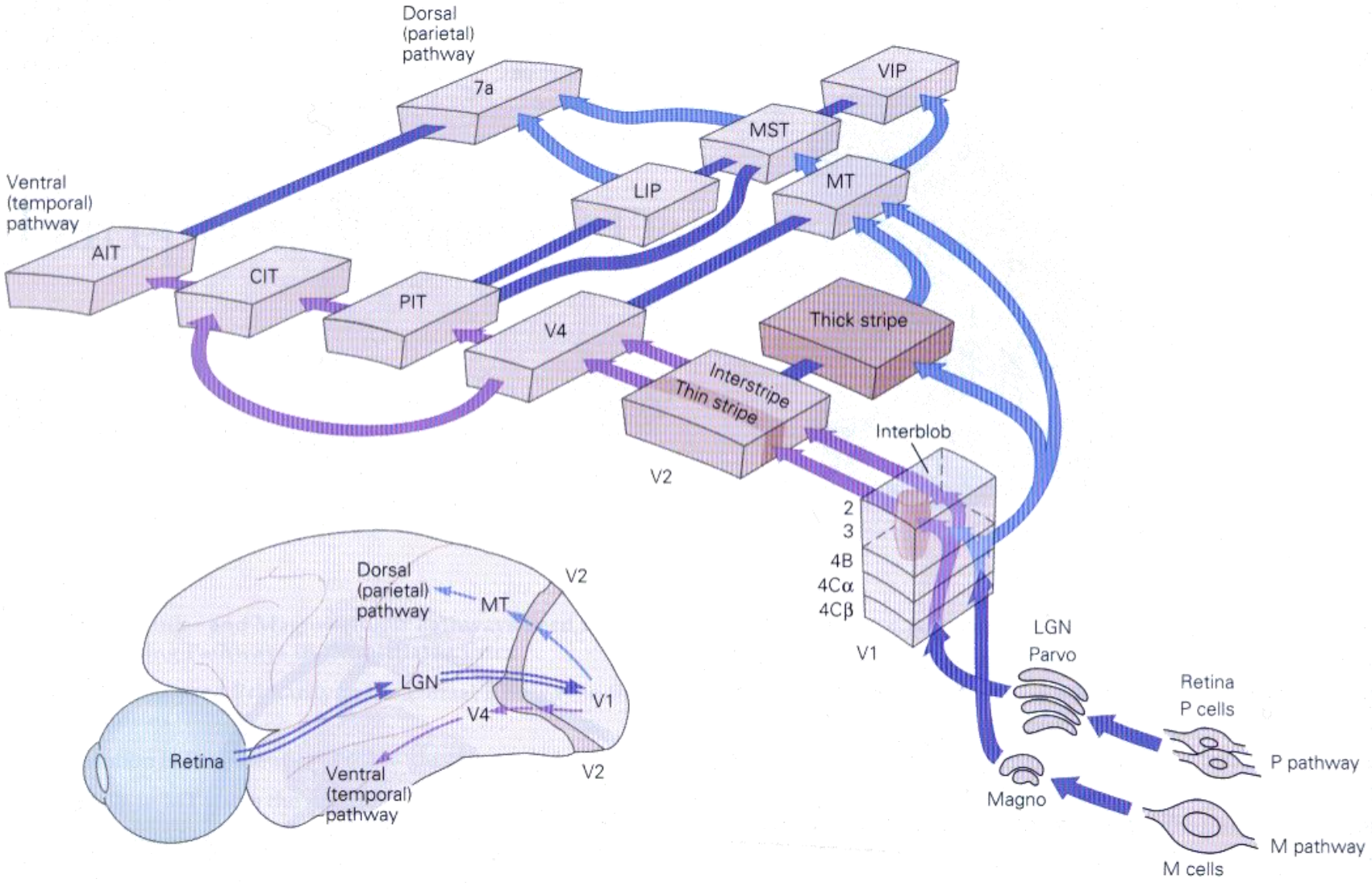
Damage at site #1: this would be like losing sight in the left eye.
The entire left optic nerve would be cut and there would be a total loss of vision from the left eye.

Damage at site #2: partial damage to the left optic nerve.
Here, information from the nasal visual field of the left eye (temporal part of the left retina) is lost.

Damage at site #3: the optic chiasm would be damaged.
In this case, the temporal (lateral) portions of the visual field would be lost.
The crossing fibers are cut in this example.

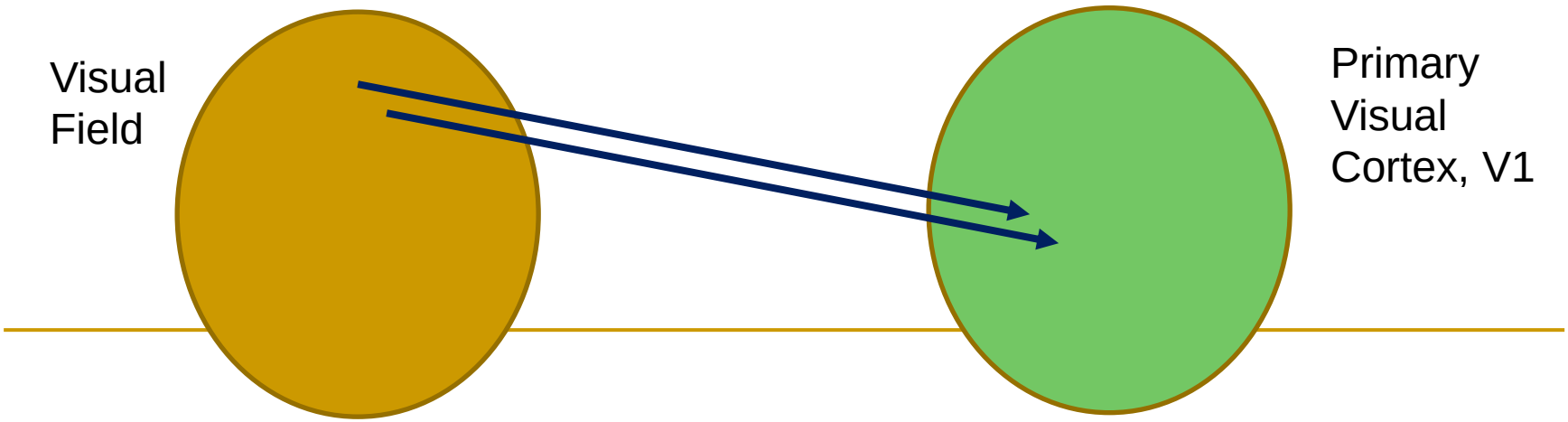
Damage at site #4 and #5: damage to the optic tract (#4) or the fiber tract from the LGN to the cortex (#5) can cause identical visual loss.
In this case, loss of vision of the right side.

Primary Visual Cortex
V1-Striate Cortex


Dorsal
(parietal)
pathway
7a
VIP
MST
LIP
MT
Ventral
(temporal)
pathway
AIT
CIT
PIT
V4
Thick stripe
Interstripe
Thin stripe
V2
Interblob
2
3
4B
4Cα
4Cβ
V1
LGN
Parvo
Retina
P cells
P pathway
Magno
M pathway
M cells
Dorsal
(parietal)
pathway
MT
V2
LGN
V1
V4
Retina
Ventral
(temporal)
pathway
V2

V1

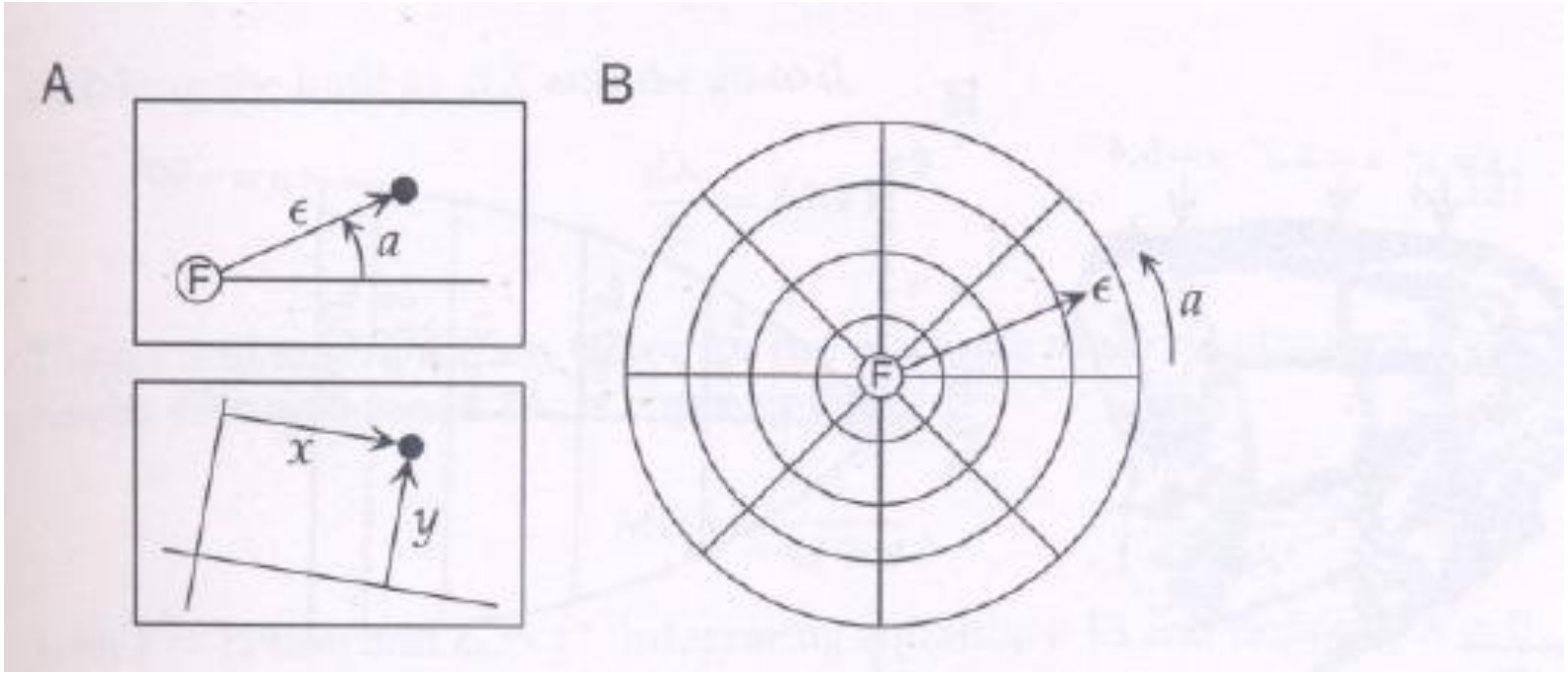
- First stopover of visual information in cortex
- Retinotopic map:
  - Retinal information is mapped onto V1 such that nearby points in the visual field are mapped onto nearby neurons in V1



Visual Field

- Consider the visual field as a sphere with the viewer at the center
- “North pole” of the sphere is the fixation point; this point is mapped onto fovea
- Latitude is called “eccentricity”, ε $(0–70^{o})$
- Longitude is called “azimuth,” a (-90^{o} to 90^{o})

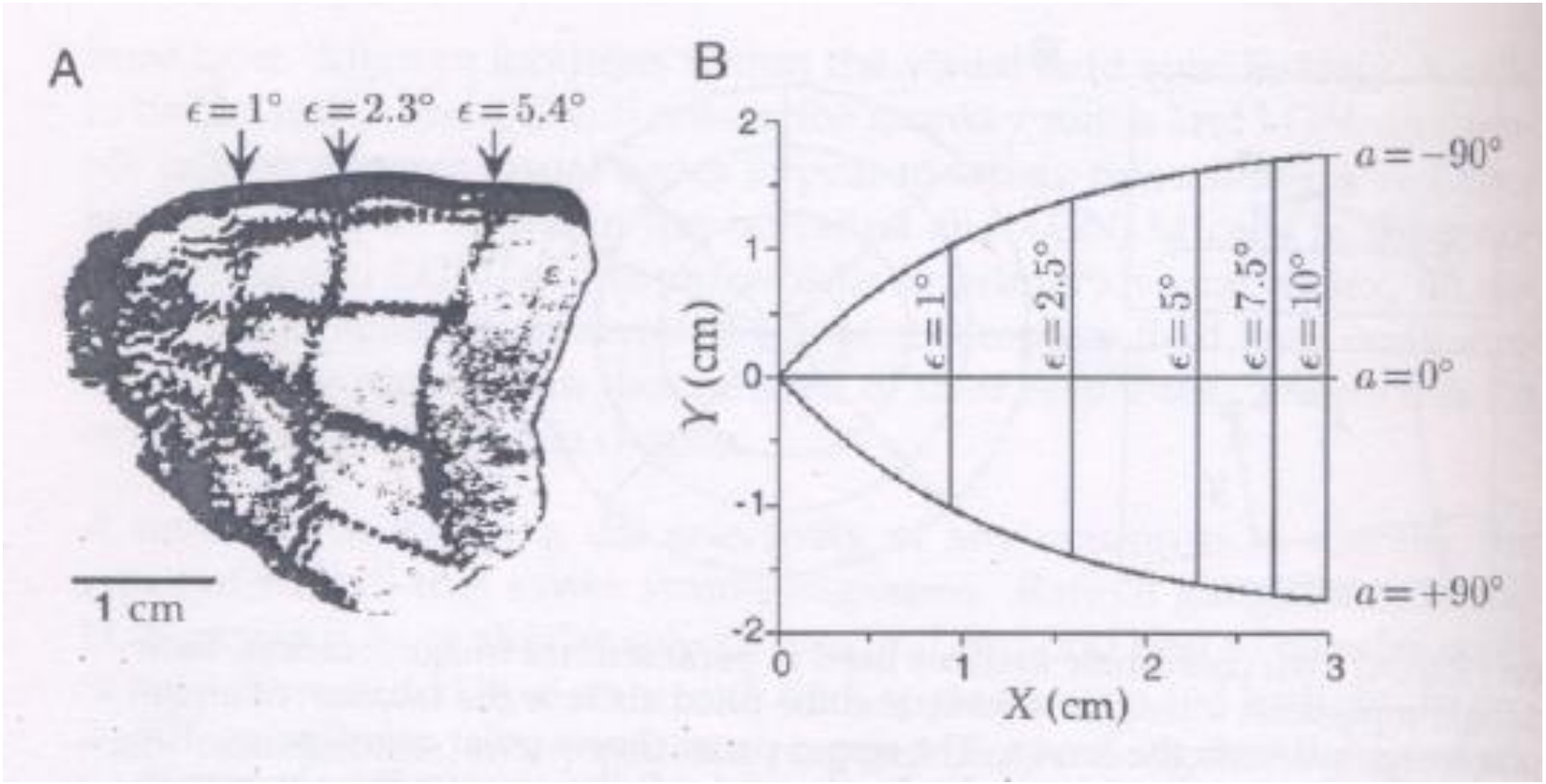
Visual field



Experiment to find Retinotopic Map

- “Bull’s-eye” pattern is displayed on a screen
- Pattern of activity in V1 is imaged by using a radioactive glucose; imaging reveals which neurons are active (taking up glucose)
- Experiment performed on monkey

Retinotopic Map



Retinotopic Map Features

- Vertical lines correspond to circles in the image
- Roughly horizontal lines correspond to radial lines
- Fovea is represented at the leftmost pole
- Azimuthal angles are positive in lower half, and negative in the upper half

Responses of neurons in V1

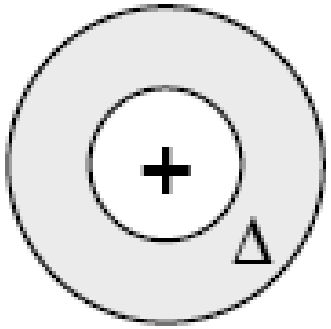
- Work of Hubel & Wiesel at Harvard in ’60s.
  - Neurons in V1 respond to oriented bars and edges and not to spots.
  - Some neurons also respond to moving bars.
  - Different neurons respond to different orientations.Within a dia of 1mm, all orientations are represented.

Simple and Complex Cells

- Simple cells: respond to an oriented line present in the center of their RF
- Complex cells: respond to an oriented line present almost anywhere in their RF
- End-stopping: some cells respond best when the line is not too long.

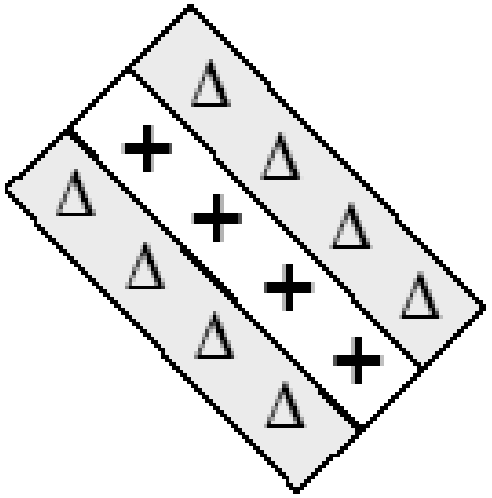
Transformation of Receptive Field Properties from LGN to Primary Visual Cortex

LGN Neuron



Circular Receptive Field
(e.g., on-center, off-surround)

"Simple Cell" in Cortex



Rectangular Receptive Field
(e.g., on-center, off-flanks)

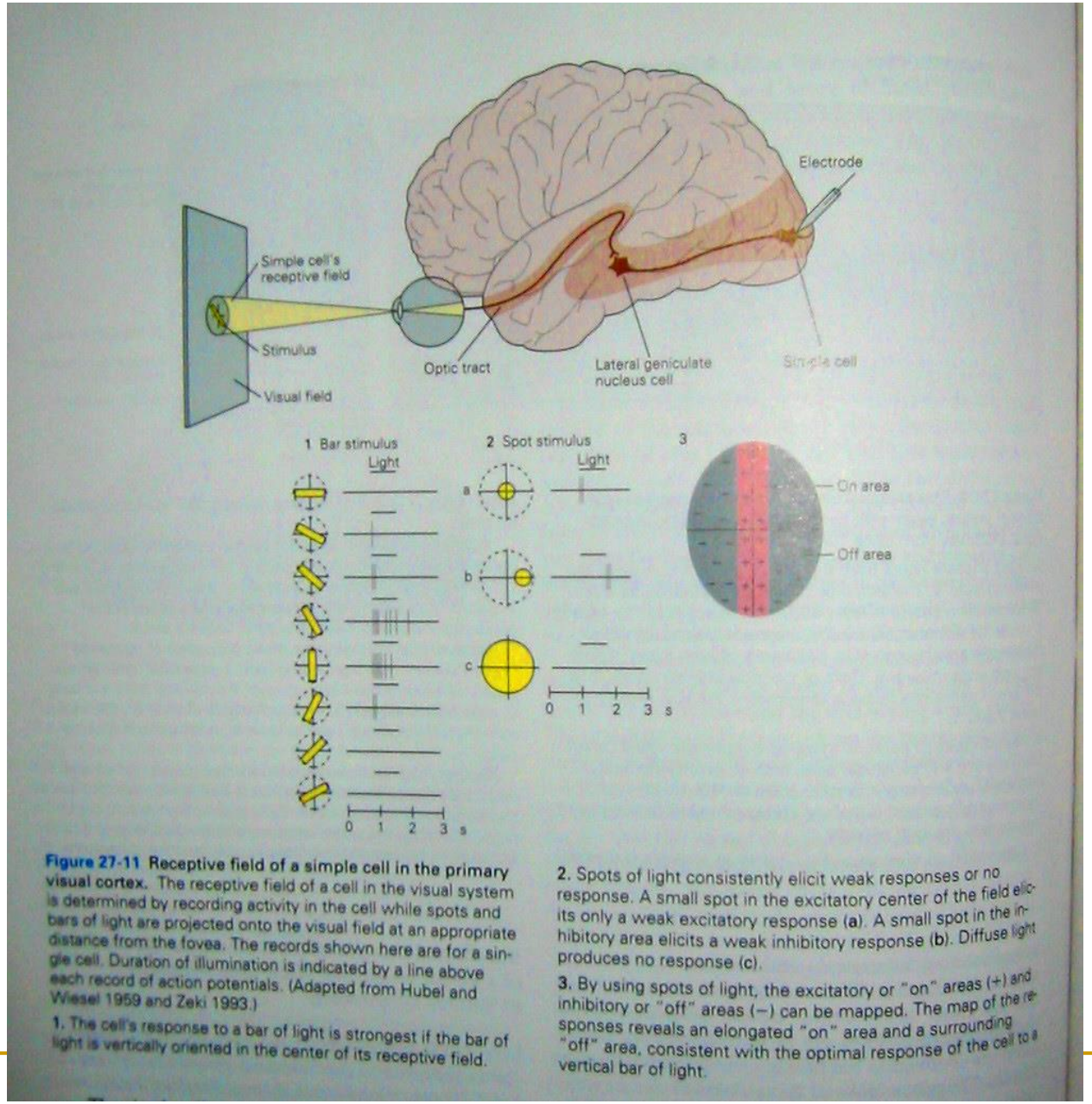


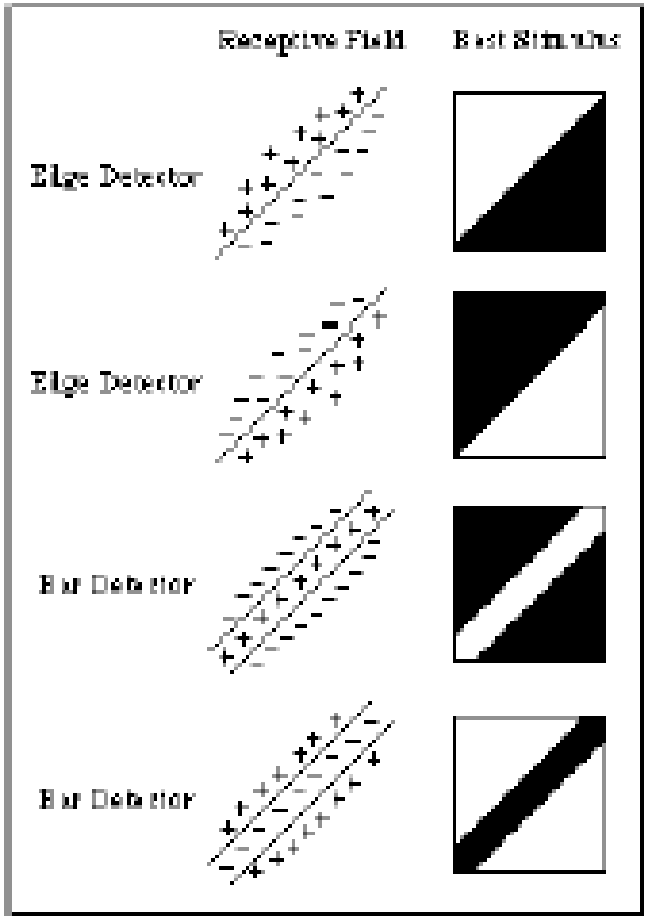
Figure 27-11 Receptive field of a simple cell in the primary visual cortex. The receptive field of a cell in the visual system is determined by recording activity in the cell while spots and bars of light are projected onto the visual field at an appropriate distance from the fovea. The records shown here are for a single cell. Duration of illumination is indicated by a line above each record of action potentials. (Adapted from Hubel and Wiesel 1959 and Zeki 1993.)

1. The cell's response to a bar of light is strongest if the bar of light is vertically oriented in the center of its receptive field.

2. Spots of light consistently elicit weak responses or no response. A small spot in the excitatory center of the field elicits only a weak excitatory response (**a**). A small spot in the inhibitory area elicits a weak inhibitory response (**b**). Diffuse light produces no response (**c**).

3. By using spots of light, the excitatory or "on" areas (+) and inhibitory or "off" areas (−) can be mapped. The map of the responses reveals an elongated "on" area and a surrounding "off" area, consistent with the optimal response of the cell to a vertical bar of light.

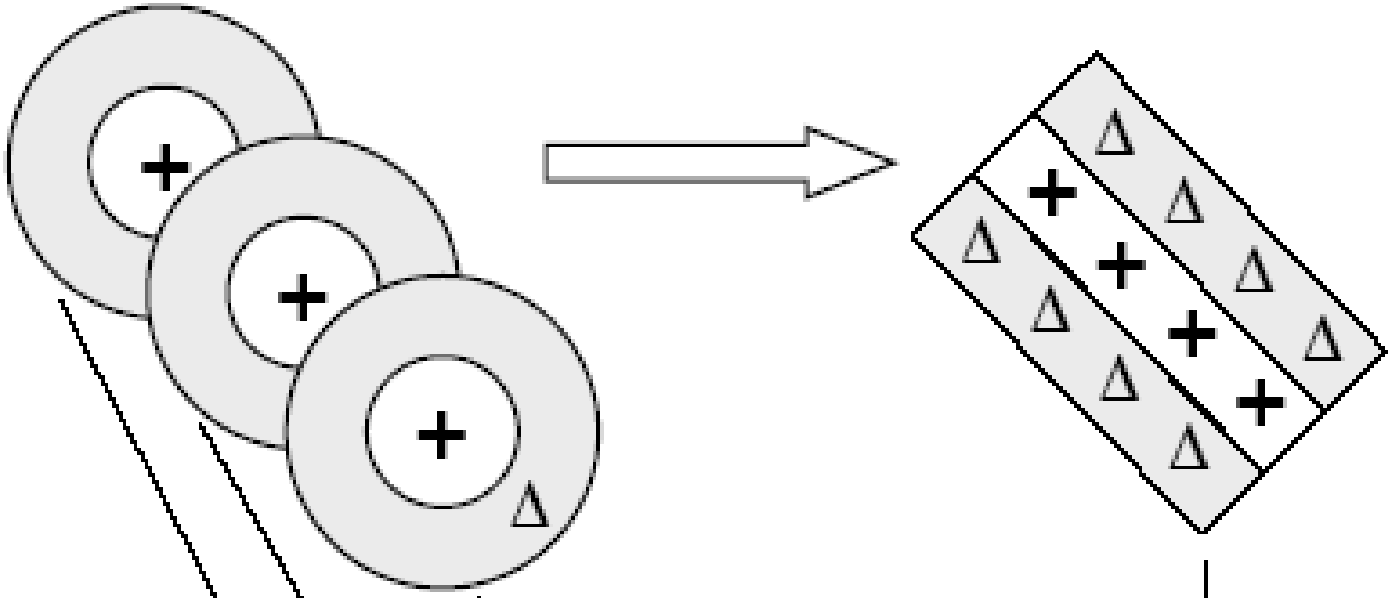
Examples of Simple Cell Receptive Fields

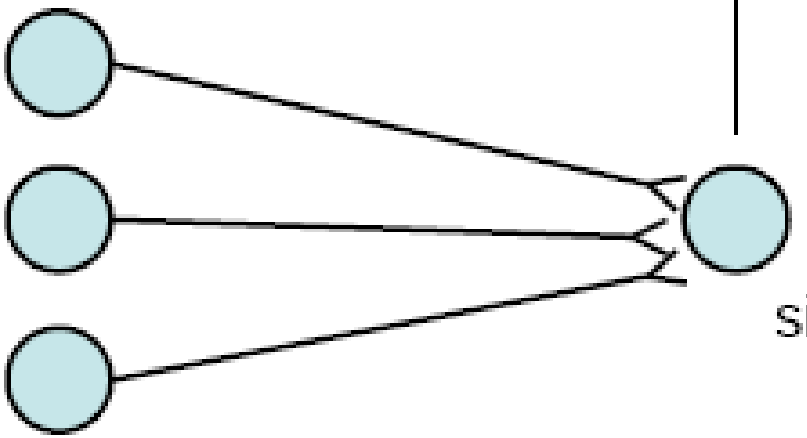


http://www.cquest.utoronto.ca/psych/psy2808/ch4/orientSelec.html

Simple cells can be used to detect edges and contours

Hypothetical Wiring Diagram for Generating a Simple Cell Receptive Field

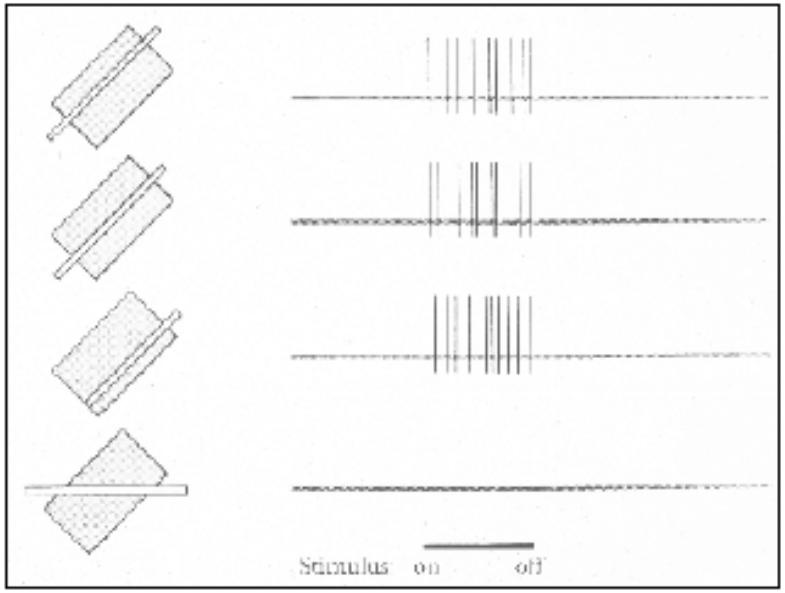




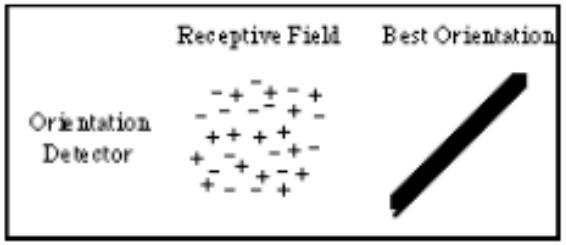
3 cells with circular receptive fields

simple cell

Complex Cell Receptive Field Properties



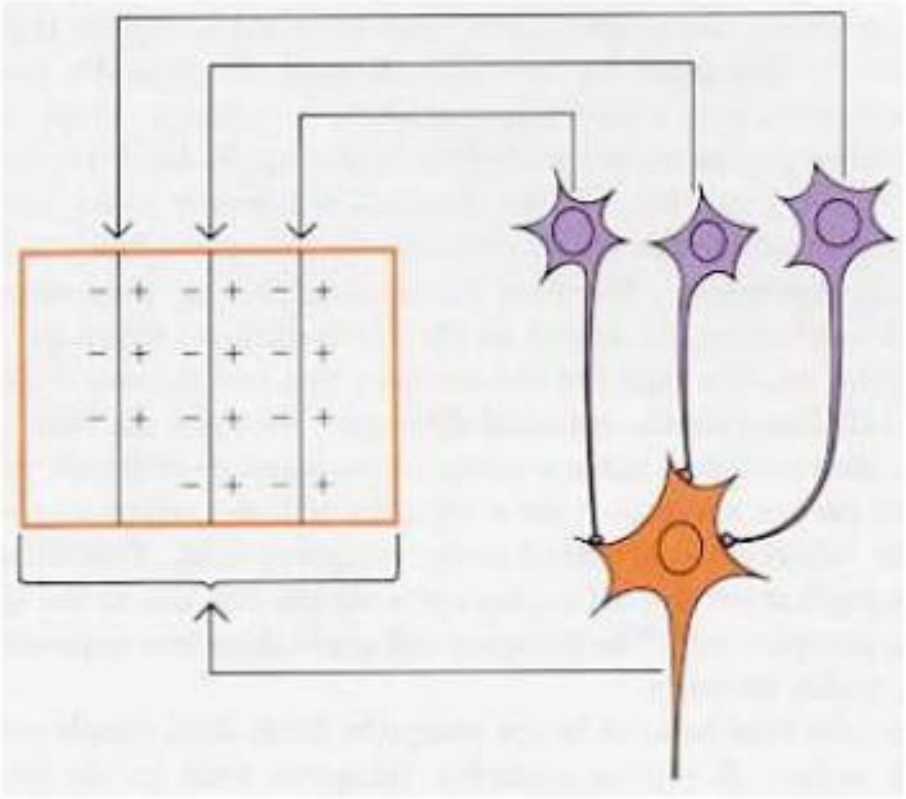
http://www-psych.stanford.edu/~lera/psych115s/notes/lecture3/figures.html



http://www.cquest.utoronto.ca/psych/psy280f/ch4/orientSelec.html

- "On" and "off" regions throughout receptive field
- Orientation selective

Hypothetical Wiring Diagram for Generating a Complex Cell's Receptive Field



http://neuro.med.harvard.edu/site/dh/b18.htm

Construction of complex cell receptive field via input from multiple simple cells

Schematic of Orientation Selectivity in the Primary Visual Cortex

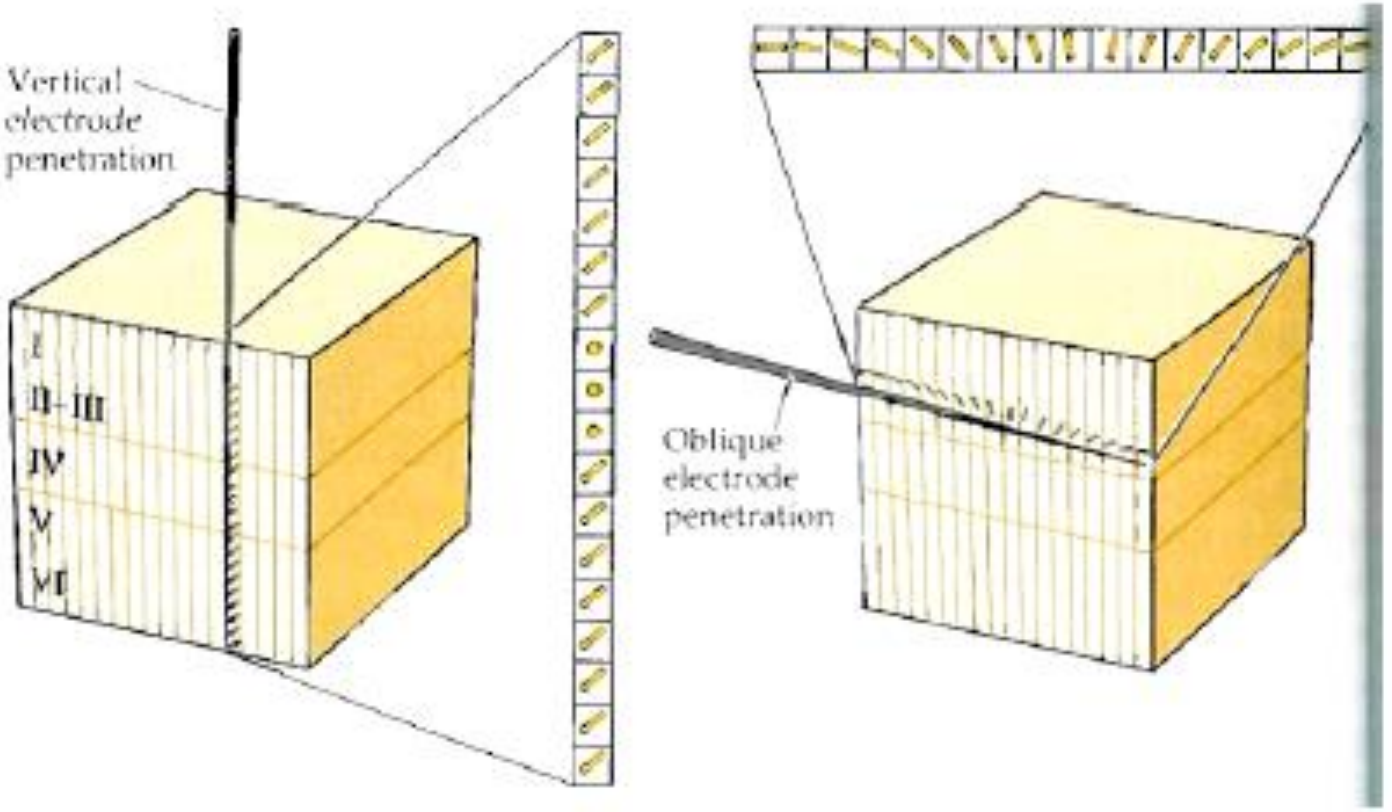
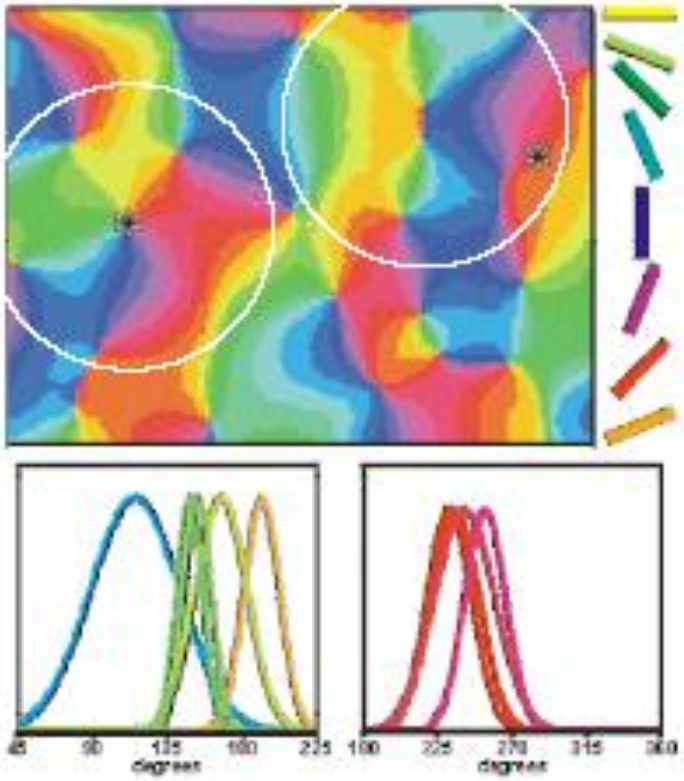


Fig. 11.12, Purves et al., Neuroscience, 3rd edition

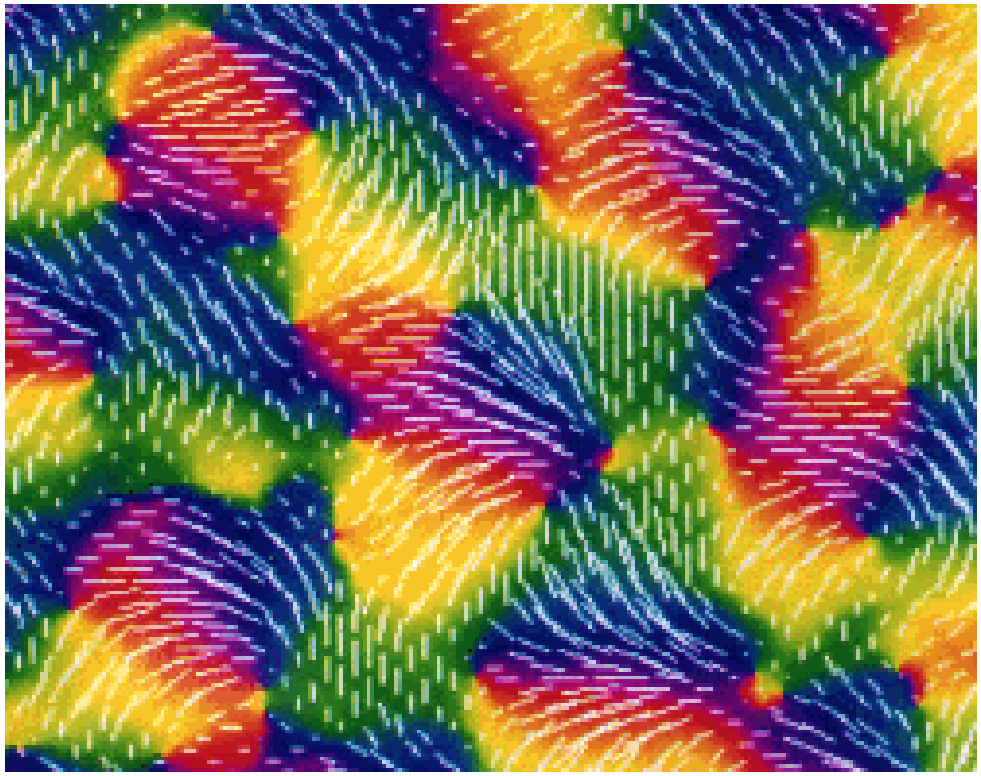
- Oblique/tangential penetration reveals progressive change in orientation selectivity
- Vertical penetration reveals columnar organization of orientation selectivity

Pinwheel Arrangement of Orientation Columns Revealed by Optical Imaging of Intrinsic Signals



http://www.neuro.mpg.de/ research/csn/pinwheel/

Orientation Columns



Schematic of Ocular Dominance Columns

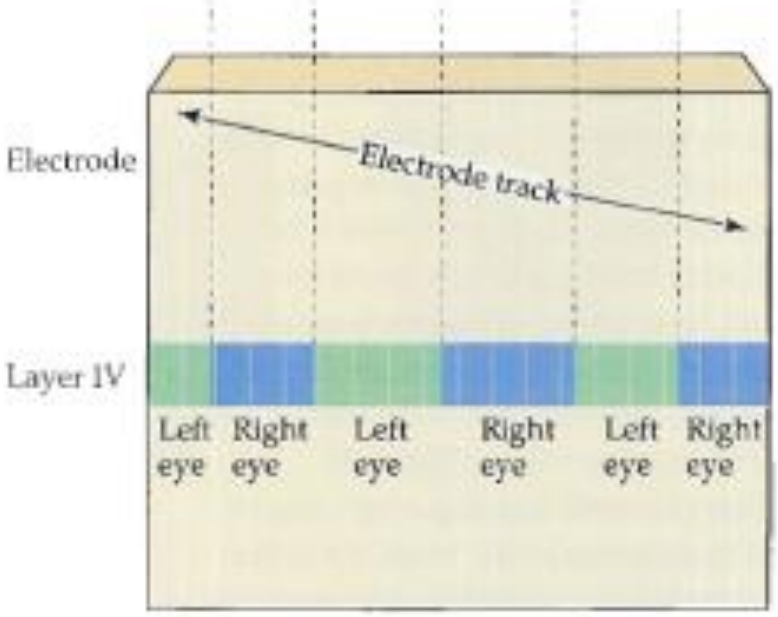


Fig. 11.13, Purves et al., Neuroscience, 3rd edition

- Alternating columns of cells showing preferential responses to right eye or left eye input
  - Monocular cells in layer 4
  - Binocular cells are found in other layers

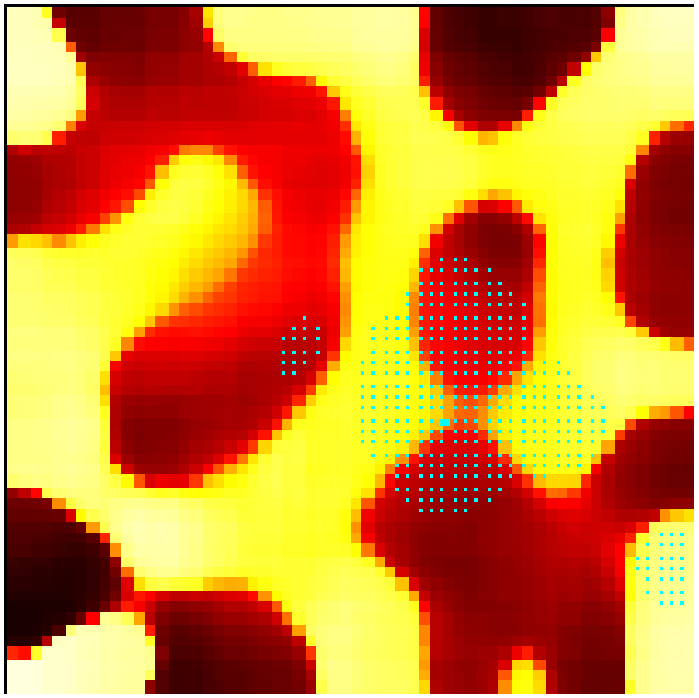
Ocular Dominance Columns in Primary Visual Cortex Revealed by Trans-Synaptic Labeling

- Injection of ^{3}H amino acid tracer into one eye
- Tracer is transferred trans-synaptically from retina to LGN to cortex
- Autoradiography of flattened cortical sheet reveals interdigitating regions of left eye vs. right eye inputs

Autoradiogram of V1

www.utoronto.ca/psy260sh/ PSY_Lecture_4_jpgs.html

Ocular Dominance Columns in Simulations



Orientation sensitivity AND Ocular Dominance

Properties of OrientationMaps:

- The maps of O.S. and O.D. are highly repetitive
- Orientation changes continuously as a function of cortical location except at isolated points.
- Orientation changes by 180 deg around singularities
- Both types of singularities appear in equal numbers
- There exist line-like regions (fractures), across which orientation preferences change rapidly with distance.
- (Obermeyer, Blasdel & Schulten 1992)

Orientation sensitivity AND Ocular Dominance

- Properties of Ocular Dominance Maps
  - Ocular dominance changes continuously as a function of cortical location.
  - The ocular dominance pattern is locally organized into parallel strips, which sometimes branch and terminate.
  - **Iso-orientation slabs often cross the borders of ocular dominance bands at approximately right angles.**
  - **The singularities tend to align with the center of the ocular dominance bands.**

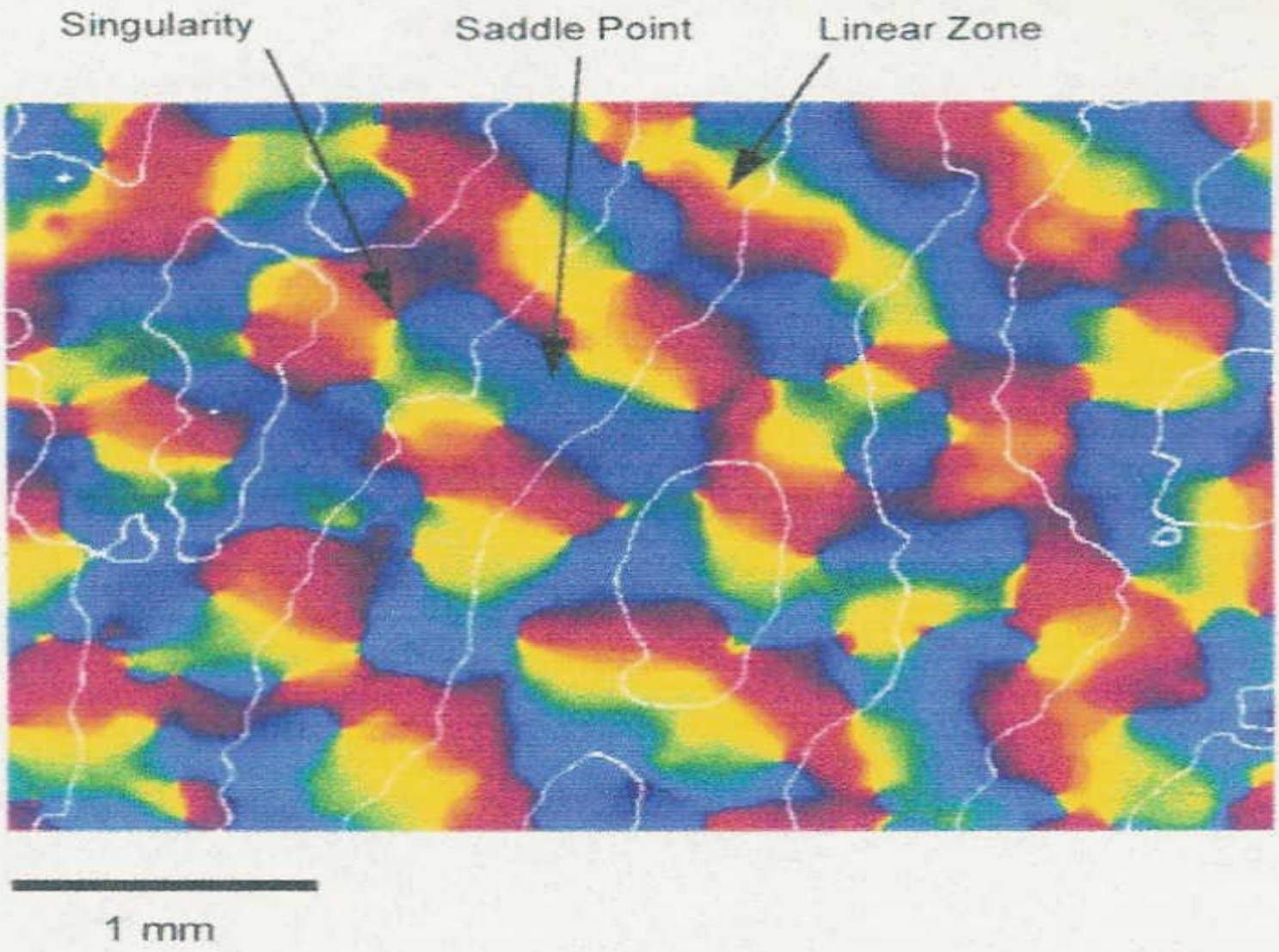


Figure 3. Composite figure showing the arrangement of orientation domains (a single colour represents a unique range of orientation preferences) and their relationship with ocular dominance column boundaries (white lines). The images were obtained by optical recording in macaque monkey striate cortex. Note that the iso-orientation domains tend to intersect ocular dominance column borders at right angles. (Figure supplied by K Obermayer, from data presented in Blasdel (1992b).)

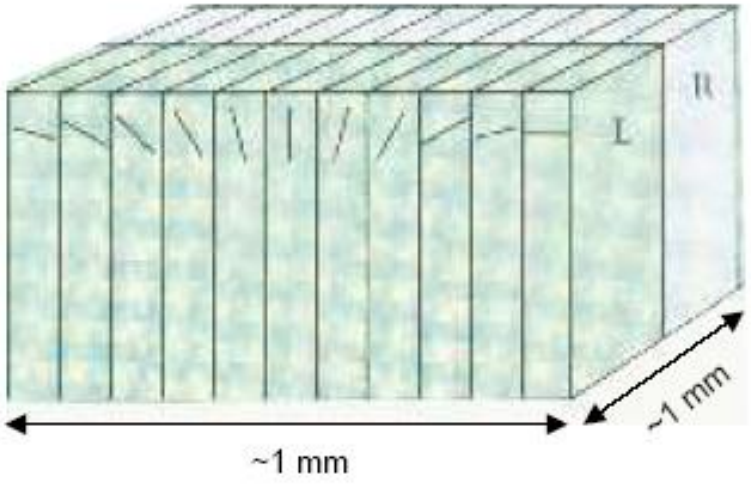
Blobs

- Peg-shaped regions of cells
- In layers 2 and 3 of V1
- These cells respond to color, not orientation
- About 0.2 mm dia

Hypercolumn

- Smallest unit in V1 necessary to analyze all aspects of a region of visual field.
- Area = 1 sqmm
- Complete set of orientation columns (180^{o})
- Inputs from both eyes.
- Several blobs

Schematic of a Cortical Hypercolumn: A Unit of Information



http://www-psych.stanford.edu/~lera/psych115s/notes/lecture3/figures.html

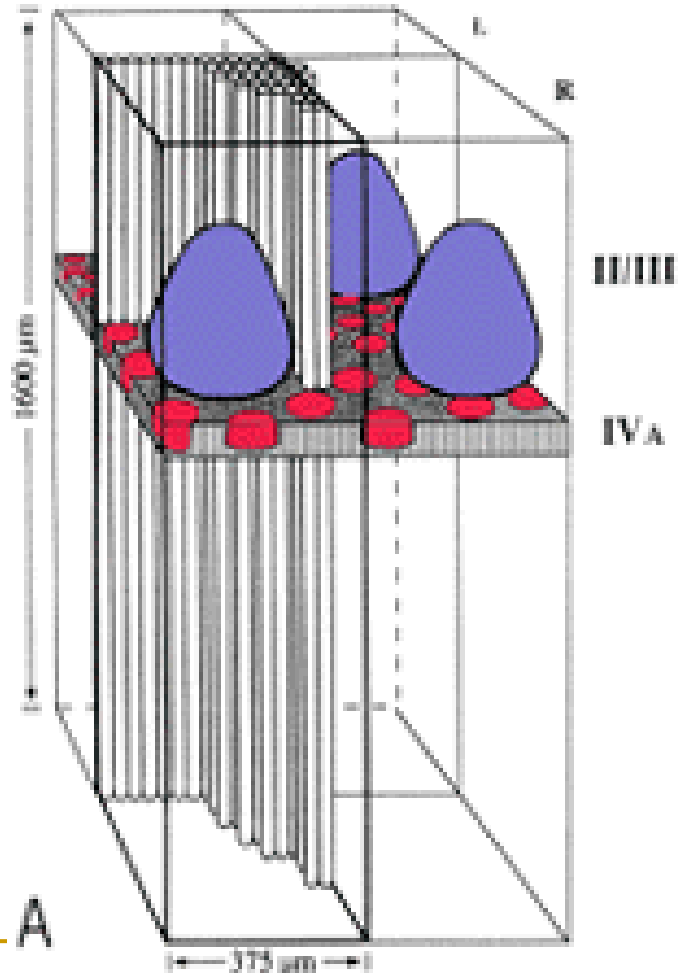
Each column
= 30 – 100 μm

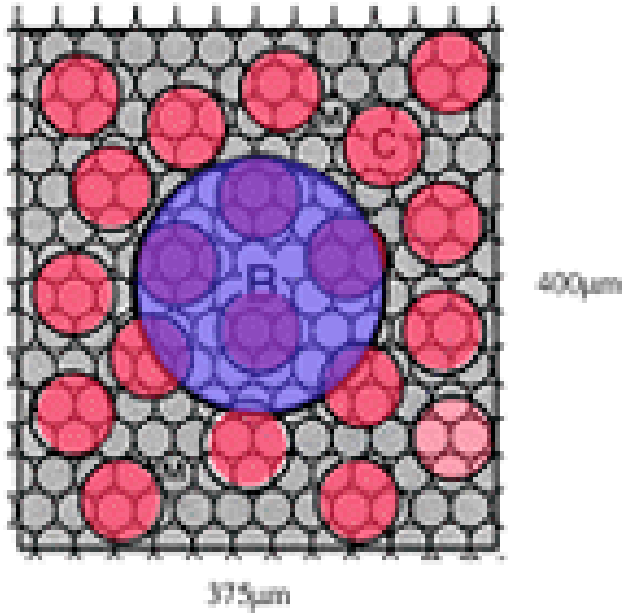
~1 mm x ~1 mm

180° orientation

one L + R pair

Hypercolumns

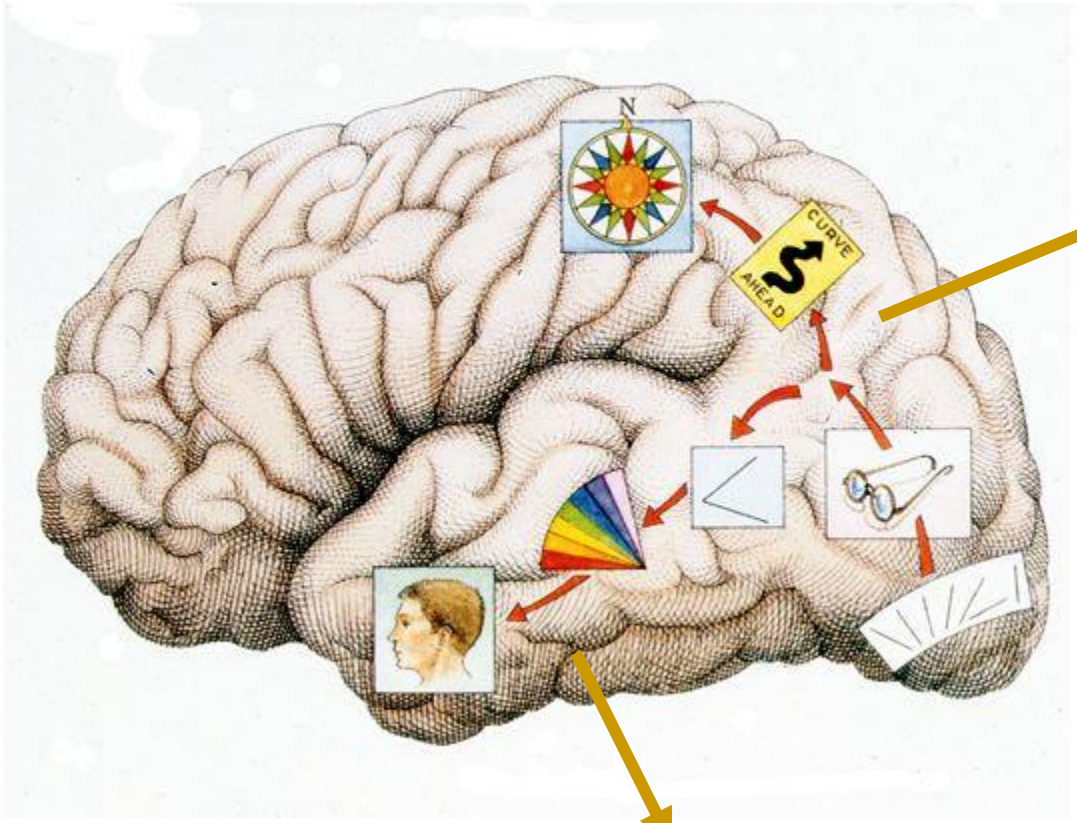




Horizontal connections among hypercolumns

- Axon collaterals of pyramidal cells in layers 3 and 5 run long distances parallel with layers
- They give rise to clusters of axon terminals at regular intervals that approximate the width of hypercolumn

What and where pathways



Where (dorsal) pathway

What (ventral) pathway

Other visual areas

- One in area 17 – V1 (striate cortex)
- Two in area 18 – V2, V3
- Three in area 19 – V3a, V4, V5 (Middle Temporal area)
- Parietal cortex – V5a (Medial Superior Temporal area)

Functions of visual areas

- V1 – primary visual analysis
- V2 – more visual analysis
- V3 – dynamic form
- V4 – color and form
- V5 - motion

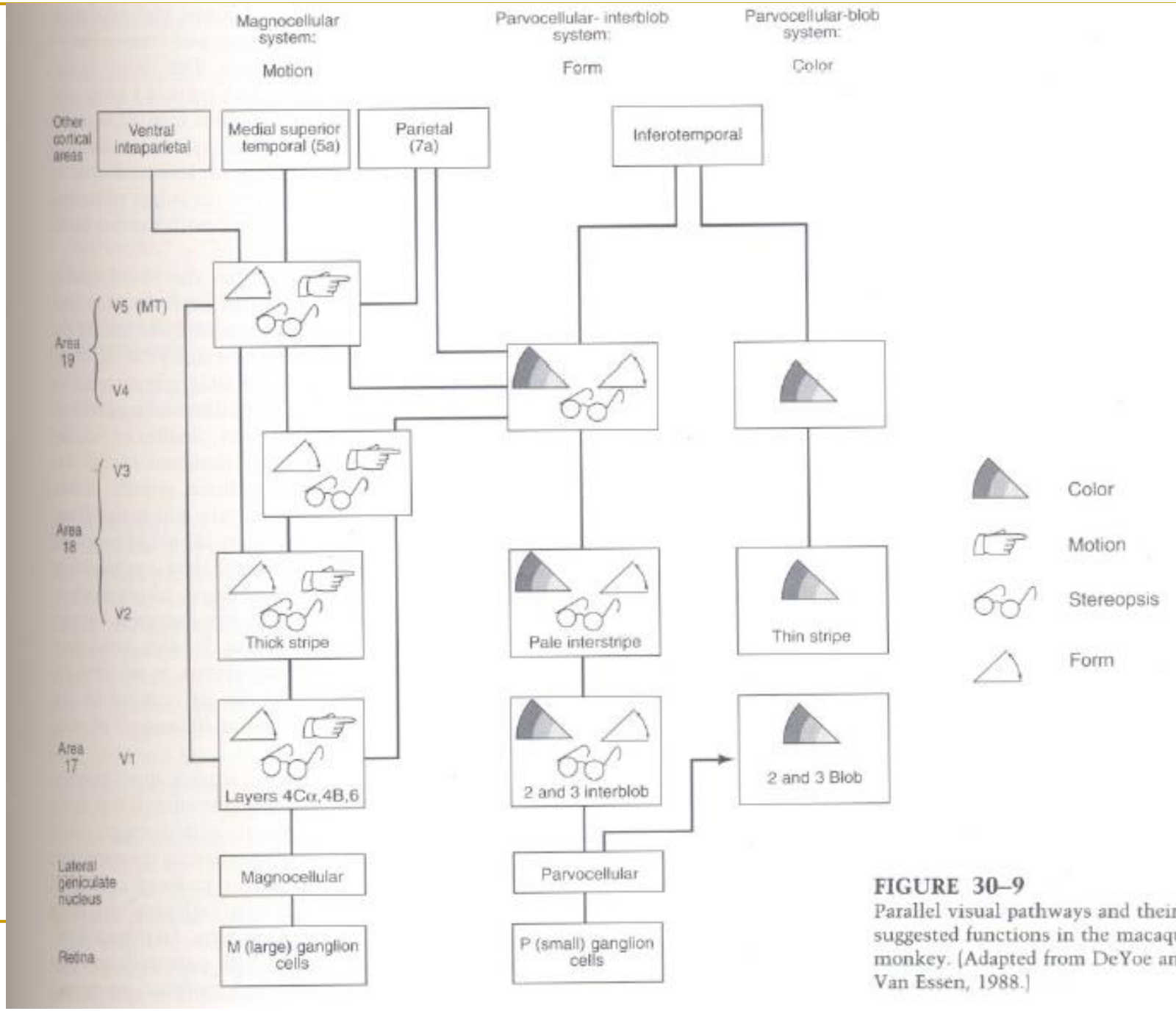


FIGURE 30–9
Parallel visual pathways and their suggested functions in the macaque monkey. [Adapted from DeYoe and Van Essen, 1988.]

Dorsal ("Where") Pathway

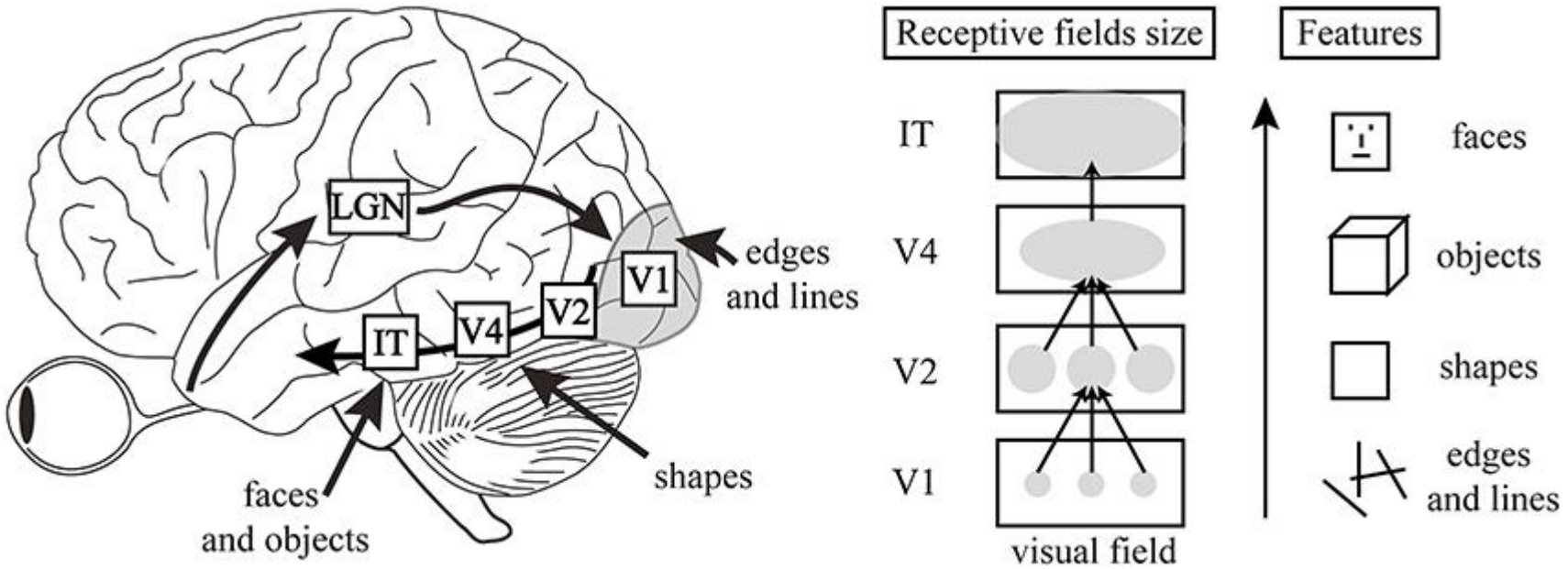
- Also called "how" pathway – connects visual input to motor output
- Starts with visual function in occipital lobe and ends in spatial awareness in posterior parietal cortex (PPC)
- PPC is involved in: "the perception and interpretation of spatial relationships, accurate body image"

Damage to Where Pathway

- Simultanagnosia: patients see one object at a time and cannot see several objects as parts of a whole
- Optic Ataxia: inability to use visuo-spatial information to guide arm movements
- Hemineglect: patient is unaware of the left half of the visual world
- Akinetopsia: inability to perceive motion
- Apraxia: inability to produce complex and volitional movements

What (ventral) pathway

- Object recognition and form representation
- Recognition of complex visual objects. Particular emphasis on faces.
- Has strong connections to medial temporal lobe (which has hippocampus, which in turn is responsible for declarative memory)
- Damage to this pathway can cause inability to recognize faces - prosopagnosia



https://neurdiness.wordpress.com/2018/05/17/deep-convolutional-neural-networks-as-models-of-the-visual-system-qa/

Convolutional Neural Networks as a Model of the Visual System: Past, Present, and Future

https://arxiv.org/abs/2001.07092