

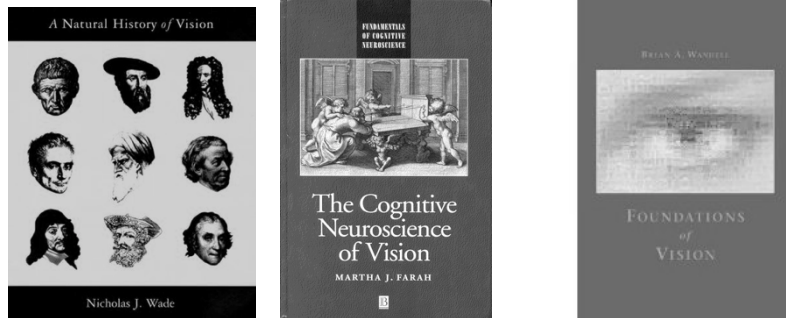
Biological Vision

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Outlines

- How do we see: some historical theories of vision
- Biological vision: theories and results from psychology and cognitive neuroscience of vision.

Sources



- N. Wade "A Natural History of Vision" MIT press 1999
- Martha J. Farah "The Cognitive Neuroscience of Vision" Blackwell 2000
- Brian Wandell, Sinauer "Foundations of Vision", Associates, Sunderland MA, 1995

How do we see - Historical view

- Understanding Vision requires:
 - Understanding the physics of light and its interaction with objects
 - Understanding optics
 - Understanding how our brain works
- Two historical opposing views of vision
 - Extramission
 - Intromission

How do we see - Historical view

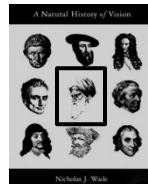
- Extramission theories of vision (Euclid, Plato,...)
 - eye emits rays, and a person perceives the objects struck by these rays
 - Plato (350 B.C.) - from our eyes flows a light similar to the light of the sun
 - How that interact with luminance sources like, sun, etc ?
 - Ptolemy (ca. 90 -- ca. 168 AD): visual flux for our eyes + external light, study of refraction
 - “Therefore, when these three conditions concur, sight occurs, and the cause of sight is threefold: the light of the innate heat passing through the eyes, which is the principal cause, the exterior light kindred to our own light, which both acts and assists, and the light that flows from visible bodies, flame or color; without these the proposed effect [vision] cannot occur.” [Chalcidius (ca. 300), middle ages].

How do we see - Historical view

- Extramission theories faced many difficulties
 - why do we see faraway objects instantaneously when we open our eyes?
 - the visual spirit that leaves the eyes is exceptionally swift
 - why don't the vision systems of different people looking at the same object interfere with each other?
 - they just don't
 - what if the eyes are closed when the visual spirit returns?
 - the soul has things timed perfectly - this never happens
 - Other non-material theories (spiritual, the “evil eye”)

How do we see - Historical view

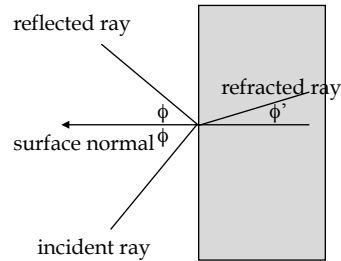
- Intromission theories of vision (Aristotle, Democritus, ...)
 - Atomists: objects create “material images” (copies) that are transported through the atmosphere and enter the eye (Aristotle 330 B.C.)
 - but how do the material images of large objects enter the eye?
 - why don't the material images of different objects interfere?
 - “light” travels from an object to the observer's eye, that's why we see reflection in the eye pupil!



- Abu Ali al-Hassan ibn al-Hasan ibn al-Haytham (965-1040)
 - mercifully shortened to Alhazen
 - greatest optical scientist of the middle ages,
 - revolutionized the theory of optics “*Book of Optics*” (7 volumes, translated to Latin in 1270)
 - Light is a physical phenomenon (independent of vision)
 - Light radiates from self luminous bodies: sun, moon, light
 - Lights travel in straight lines
 - Concept of medium: transparent and opaque.
 - Light is refracted between two transparent medium
 - When light hits an object it irradiates in all directions.
 - pointillist theory of vision - we see a collection of points on the surfaces of objects
 - geometric theory to explain the 1-1 correspondence between the world and the image formed in our eyes

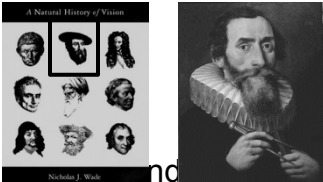
Lens and image formation

- Ray of light leaves the light source, and travels along a straight line
- Light hits an object and is
 - reflected and/or
 - refracted
- If the object is our lens, then the useful light for imaging is the refracted light



Ptolemy, Alhazen and refraction

- The phenomena of refraction was known to Ptolemy
- Alhazen's problem - since light from a surface point reaches the entire surface of the eye, how is it that we see only a single image of a point?
 - he assumed that only the ray that enters perpendicular to the eye affects vision
 - the other rays are more refracted, and therefore "weakened"
 - but in fact, the optical properties of the lens combine all of these rays into a single "focused" point under favorable conditions

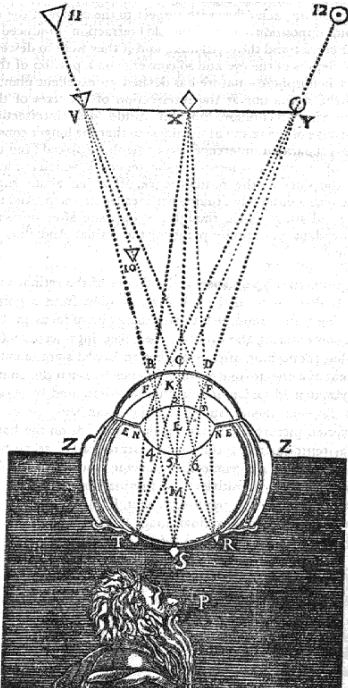


- Johannes Kepler (1571-1630)
- Founder of modern theories about light
 - Light has the property of flowing or being emitted by its source towards a distance place
 - From any point the flow of light takes place according to an infinite number of straight line.
 - Light itself is capable of advancing to the infinite
 - The lines of these emissions are straight and are called rays.

Kepler's retinal theory

Even though light rays from "many" surface points hit the same point on the lens, they approach the lens from different directions.

Therefore, they are refracted in different directions - separated by the lens



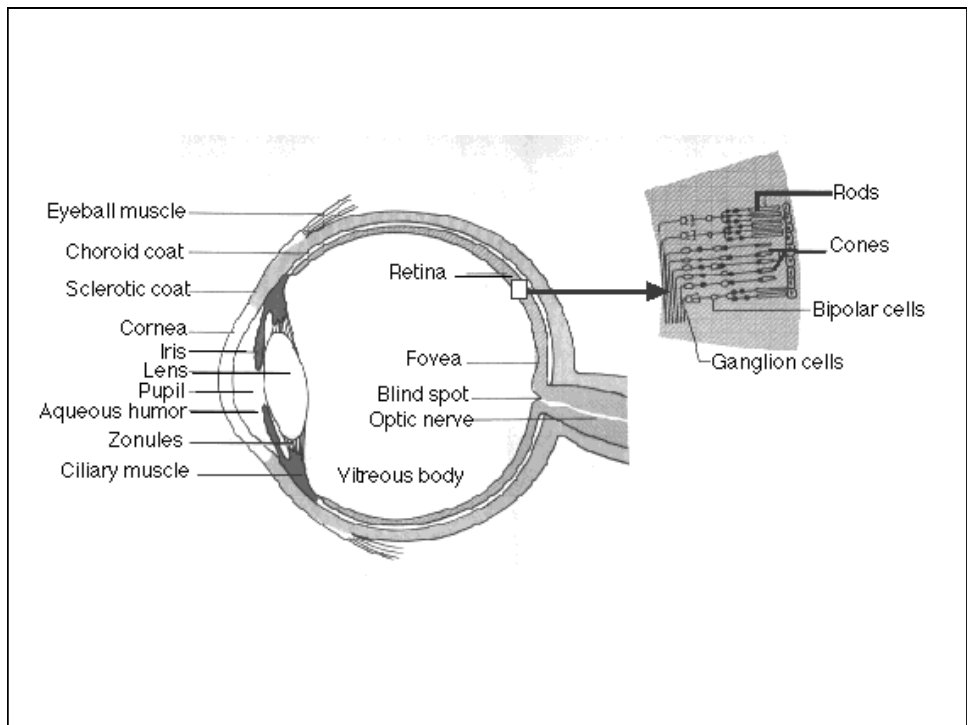
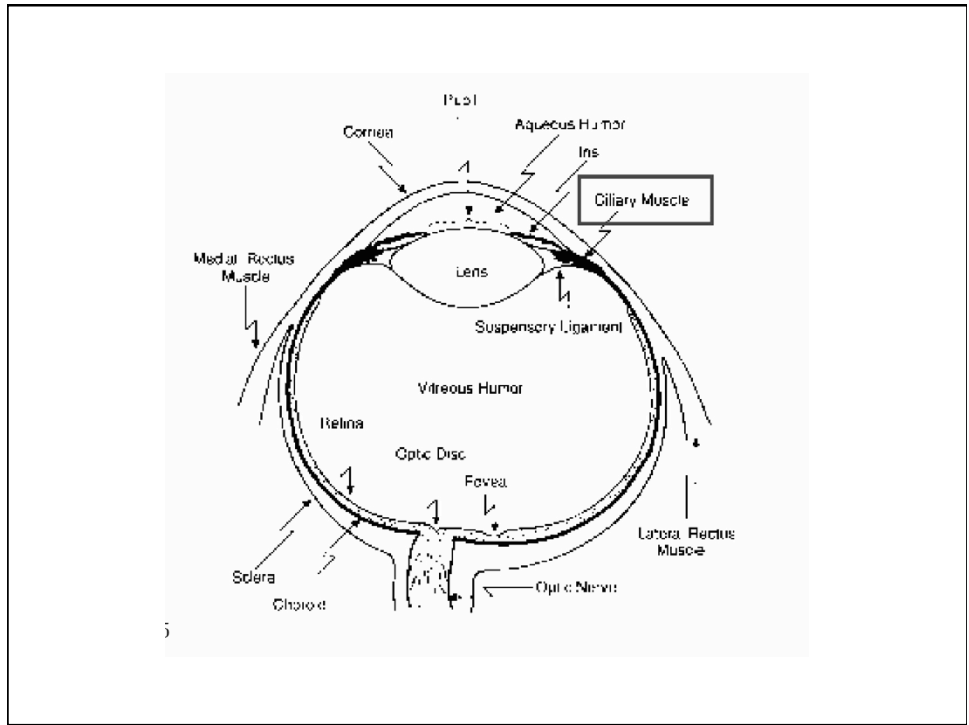
Modern theories of Vision

Three main streams contribute to our understanding of vision:

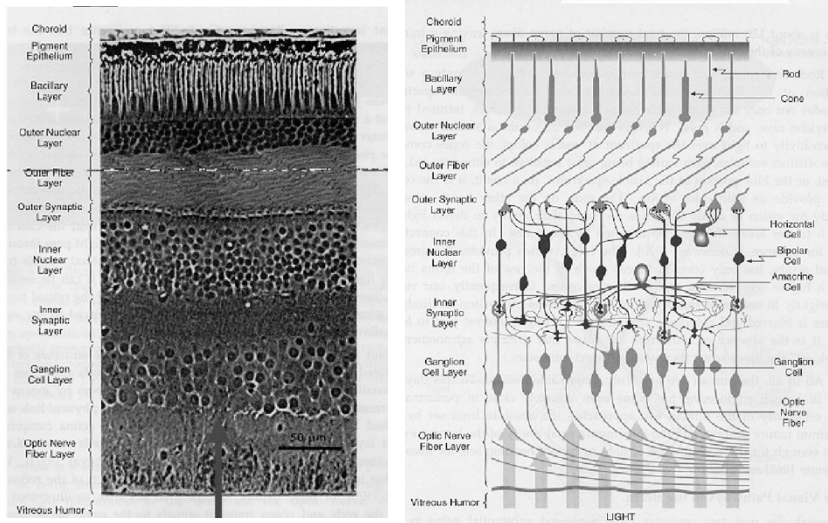
- Psychology of perception: functionalities
- Neurophysiology: explanations
- Computational vision: more problems

Biological Vision

- Early vision:
Parallelism. Multiplexing. Partitioning.
- High-level vision:
Modularity.



Retina



Retina

Three layers of cells:

- Receptor cells
- Collector cells
- Retinal ganglion cells

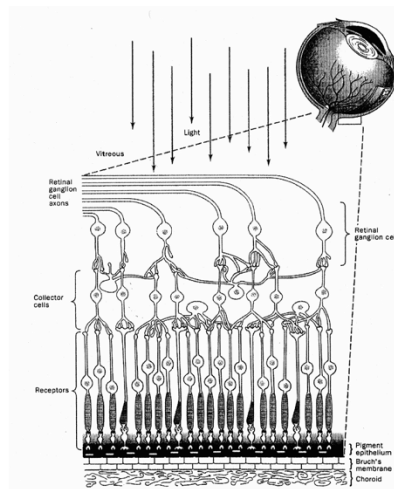


Figure 1.1 Cross-section through the retina, showing three functionally distinct layers of cells: receptor cells, collector cells, and ganglion cells. From R. S. S. and R. Blake, Perception, New York, McGraw-Hill, 1994.

Photoreceptor mosaics

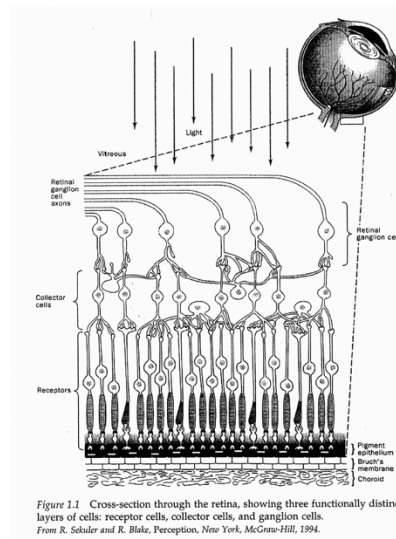
- The retina is covered with a mosaic of photoreceptors
- Two different types of photoreceptors
- rods - approximately 100,000,000
- cones - approximately 5,000,000
- Rods
 - sensitive to low levels of light: scotopic light levels
- Cones
 - sensitive to higher levels of light: photopic light levels
- Mesopic light levels - both rods and cones active
- Difference in conversion to receptor cells.

Scotopic 10^{-2} to 10^{-6} cd/m², Mesopic 10^{-2} to 1 cd/m², Photopic 1- to 10^6 cd/m²

Pooling (conversion) of the output of receptor cells:

Rods: several rods connects to each collector cell

Cons: limited pooling to collector cells



Duplex retina

- Trade off: Sensitivity to light vs. spatial resolution.
- Two parallel systems:
 - One that favor sensitivity to light (Rods)
 - One that favor resolution (Cons)

Duplex Retina

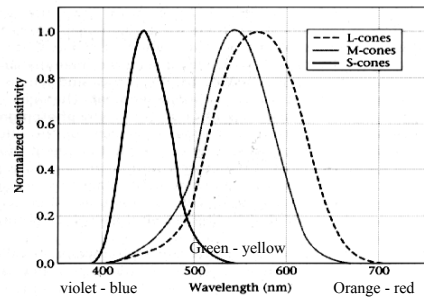
Trade off: Sensitivity to light vs. spatial resolution

- Rods:
 - high sensitivity (sensitive to low levels of light: scotopic light levels)
 - extensive convergence onto collector & ganglion cells
 - ⇒ low resolution image of the world that persists even in low illumination condition
- Cones:
 - sensitive to higher levels of light: photopic light levels
 - much limited convergence
 - ⇒ High resolution image of the world in good illumination.

Cones and color

- Three different types of cones
 - they differ in their sensitivity to different wavelengths of light (blue-violet, green, yellow-red)

3.3 SPECTRAL SENSITIVITIES OF THE L-, M-, AND S-CONES in the human eye. The measurements are based on a light source at the cornea, so that the wavelength loss due to the cornea, lens, and other inert pigments of the eye plays a role in determining the sensitivity. Source: Stockman and MacLeod, 1993.

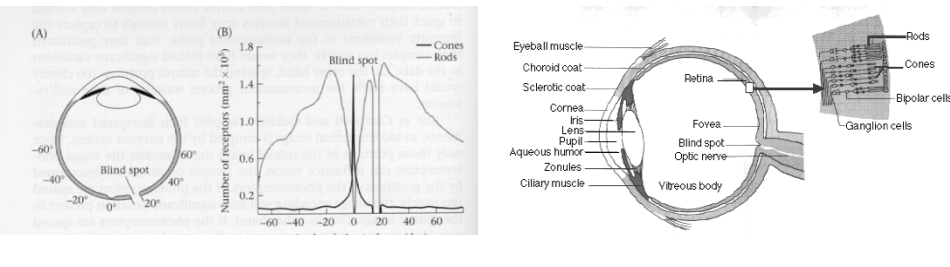


Cons and Color

- Example of a distributed representation
- Three different photopigments which absorb different wavelengths of light to different degrees.
- Recall: Cons traded resolution for sensitivity (inactive in low light)
 - ⇒ color blindness in low illumination

Photoreceptor mosaics

- Fovea is area of highest concentration of photoreceptors
- fovea contains no rods, just cones
- approximately 50,000 cones in the fovea
- cannot see dim light sources (like stars) when we look straight at them!

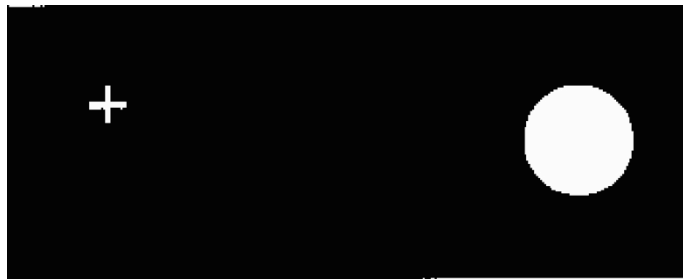
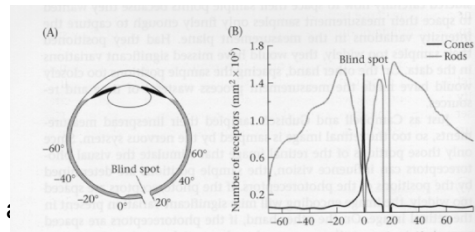


Cones, CCD's and space

- How much of the world does a cone see?
 - measured in terms of visual angle
 - the eye lens collects light over a total field of view of about 100°
 - each cone collects light over a visual angle of about 1.47×10^{-4} degrees, which is about 30 seconds of visual angle
- TV camera photoreceptor mosaics
 - nearly square mosaic of approximately 800X640 elements for complete field of view
- How much of the world does a single camera CCD see
 - example: 50° lens
 - 50/500 gives about 10^{-1} degrees per CCD

Blind spot

- Close left eye
- Look steadily at white cross
- Move head slowly toward and :
- At a particular head position the white disk completely disappears from view



Retina

Three layers of cells:

- Receptor cells
- Collector cells
- Retinal ganglion cells

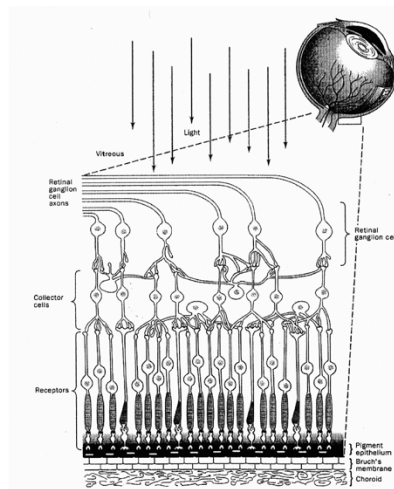
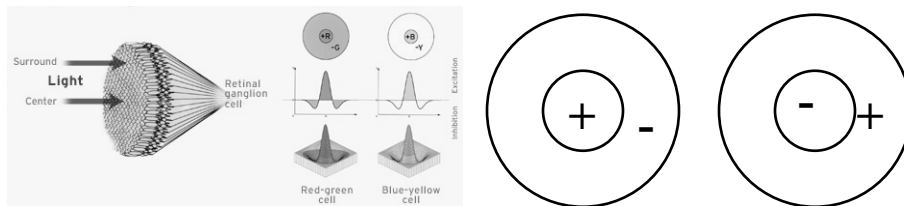


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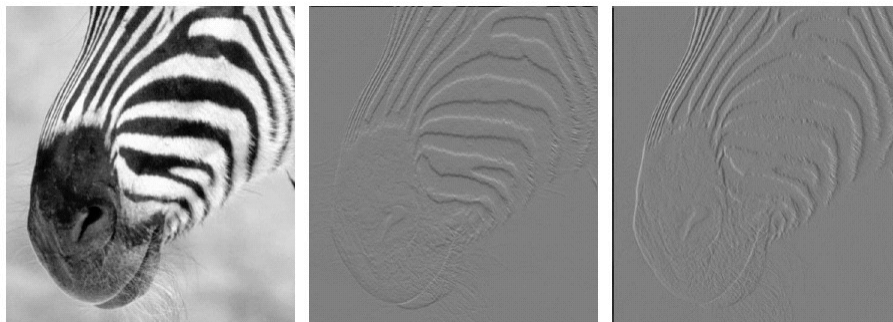
Retinal Ganglion cells

- First stage of visual processing
- Function: Absolute levels of illumination is replaced by a retinotopic map of “differences”
- How: center-surrounding organization of their receptive fields:
 - on-center (off-surrounding) cells
 - off-center (on-surrounding) cells

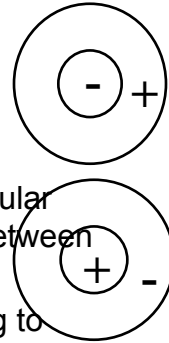


Retinal Ganglion cells

- How a spatial difference image might look like ?



Retinal Ganglion cells

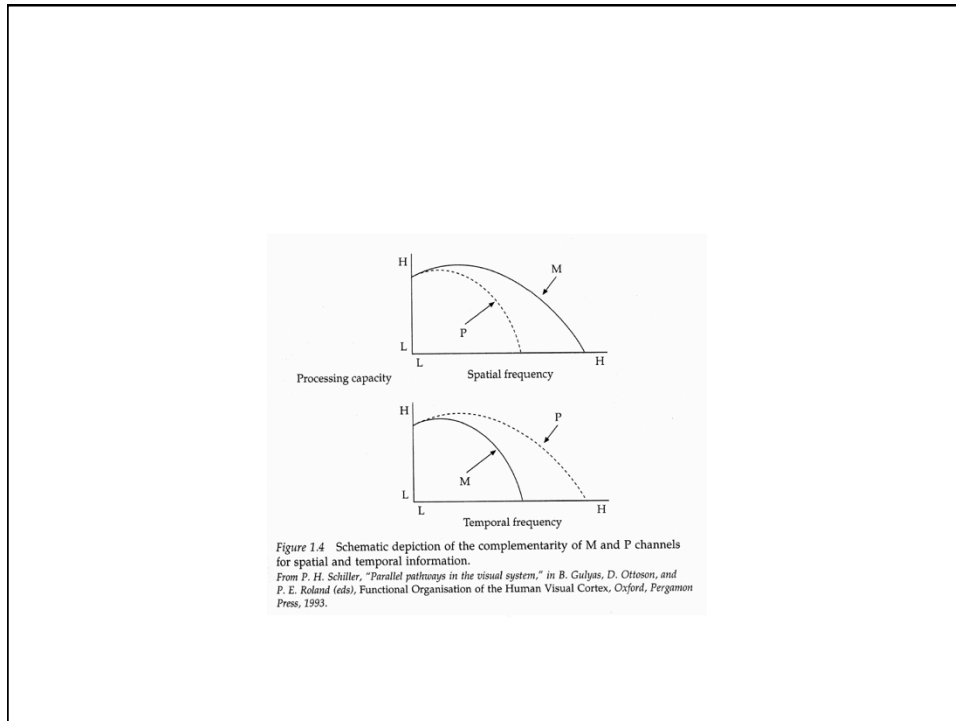


- Why: objects are not associated with any particular brightness, but with differences in brightness between themselves and the background.
- The differences can be amplified without having to represent the enormous range of values that would result from the amplification of absolute values.
- \Rightarrow groundwork for perception of objects.

Retinal Ganglion cells

Another partition:

- M and P cells:
- Feeds into the M and P channels (magnocellular and parvocellular layers in LGN)
- Tradeoff: temporal vs. spatial resolution



Retinal Ganglion cells

- Tradeoff: temporal vs. spatial resolution
- M cells: input from large number of photoreceptors \Rightarrow good light sensitivity, good temporal resolution (can sample easily from large input), low spatial resolution.
- P cells: input from small number of photoreceptors \Rightarrow good spatial resolution, poor temporal resolution.
- M cells are larger, faster nerve conduction velocities, responses are more transient.
- P cells show color sensitivity, M cells don't.

M cells: Temporal resolution, fast

\Rightarrow motion perception, sudden stimulus.

P cells: Spatial resolution + color

\Rightarrow Color, texture, patterns (major role in object perception).

- Bundle of axons leaving the eye: optic nerve
- Split into a number of pathways
- Retinotopy organization

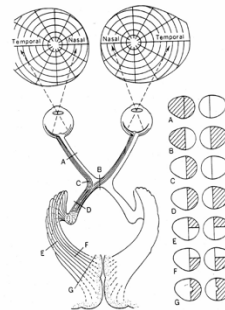
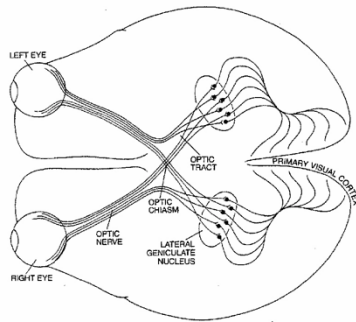


Figure 1.6 Correspondences between location of lesion within the visual system and pattern of visual field defects.
From J. Hamann, A Textbook of Surgery, Springfield, IL, Charles C. Thomas, 1945.

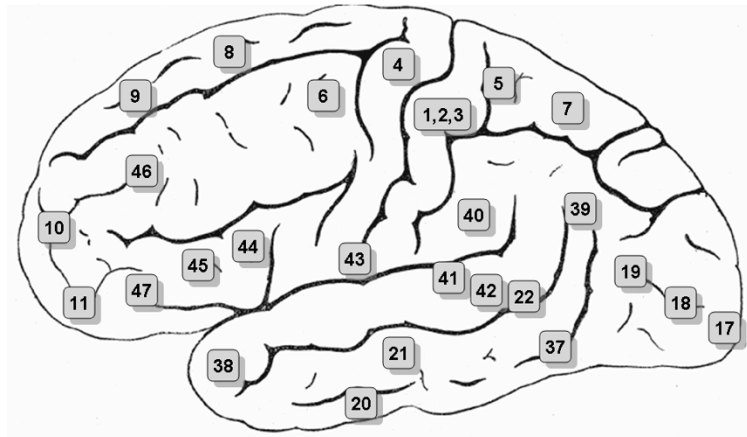
The lateral geniculate nucleus (LGN):

- One LGN in each cerebral hemisphere
- Magnocellular layers (two) : feed from M-cells
 - Best temporal resolution
- Parvocellular layers (four) : feed from P-cells
 - Best spatial resolution, wavelength sensitivity
- Another example of division of labor and multiplexing
- Neurons in all layers show center-surrounding organization
- Retinotopy: all layers keep retinotopic organization of the image
- Feed back from visual cortex
- What is LGN for ? Gate or Amplify visual input, attention ?



The primary visual cortex

- Also known as area 17, Striate cortex, V1
- David H. Hubel & Torsten N. Wiesel : Nobel prize
- Three types of cells (1962):
- Center-surrounding
- Simple cells:
 - Like center-surrounding with elongated excitatory and inhibitory regions.
 - edges at particular location and orientation.
- Complex cells:
 - more abstract type of visual information. Partially independent of location within the visual field.

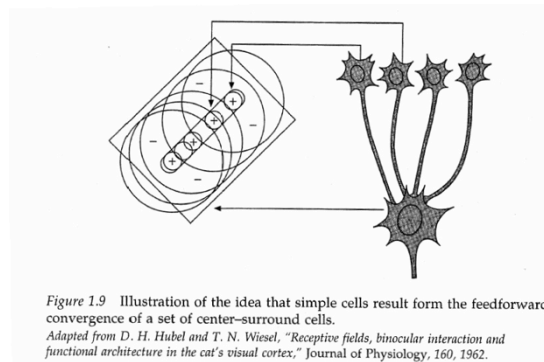
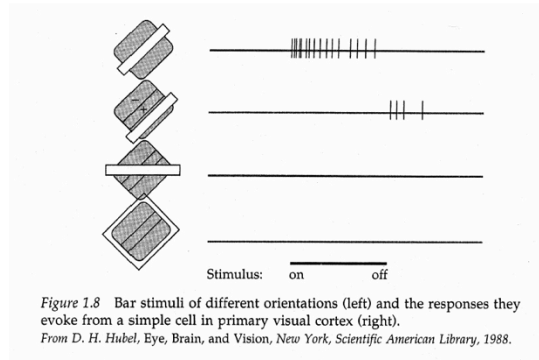


Brodman numbering



- David H. Hubel & Torsten N. Wiesel : Nobel prize
 - Discovering of simple and complex cells, their functions and anatomical organization
 - Pioneering the technique for single cell recording in cortex

- Simple cells:
 - Like center-surrounding with elongated excitatory and inhibitory regions.
 - edges at particular location and orientation.



The primary visual cortex

- Feed forward sequence or hierarchy of visual processing
Center-surrounding → Simple → Complex
- Cells' responses become increasingly specific w.r.t the form of the stimulus (ex. oriented edges or bars)
- Increasingly general w.r.t viewing conditions (from just one location to a range of locations)
- These dual-trends are essential for object recognition
- can respond to specific form (like familiar face) generalized over changes in size, orientation, view point
- More recent research: lateral interaction plays important role (Gilbert 1992)

- spatial arrangement of cells

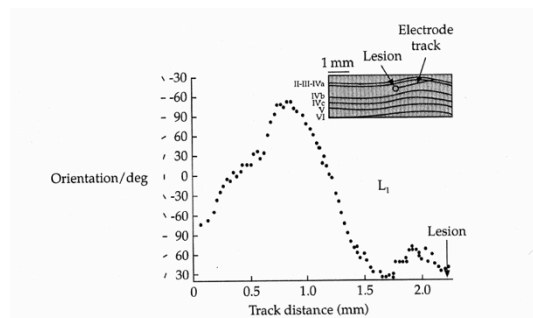


Figure 1.10 The orderly progression of orientation preference as a function of electrode position during an oblique penetration of primary visual cortex. From R. C. Reid, "Vision," in M. J. Zigmond, F. E. Bloom, S. C. Landis, J. L. Roberts, and L. R. Squire (eds), *Fundamental Neuroscience*, San Diego, Academic Press, 1999.

- Organization and orientation selectivity (why and how?):
- spatial arrangement of cells for minimizing the distance between neurons representing similar stimulus along three different stimulus dimensions:
 - Eye of origin
 - Orientation
 - Retinotopic location
- Hebb rule : neurons that fire together wire together.

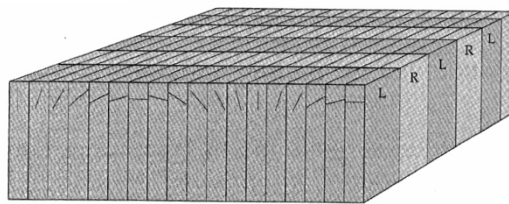


Figure 1.11 Idealized depiction of the organization of orientation selectivity and ocular dominance in primary visual cortex.
Adapted from D. H. Hubel and T. N. Wiesel, "Receptive fields, binocular interaction and functional architecture in the cat's visual cortex," *Journal of Physiology*, 160, 1962.

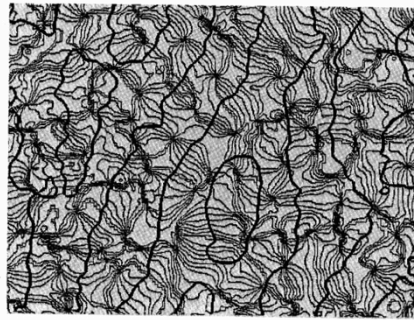


Figure 1.12 Reconstruction of the actual relations between orientation columns (gray) and ocular dominance columns (black) in primary visual cortex.
 From K. Obermayer and G. G. Blasdel, "Geometry of orientation and ocular dominance columns in monkey striate cortex," *Journal of Neuroscience*, 13, 1993.

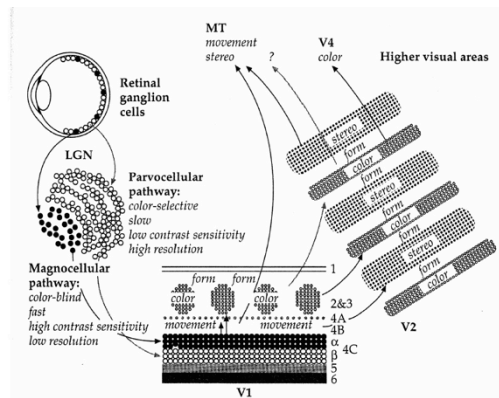
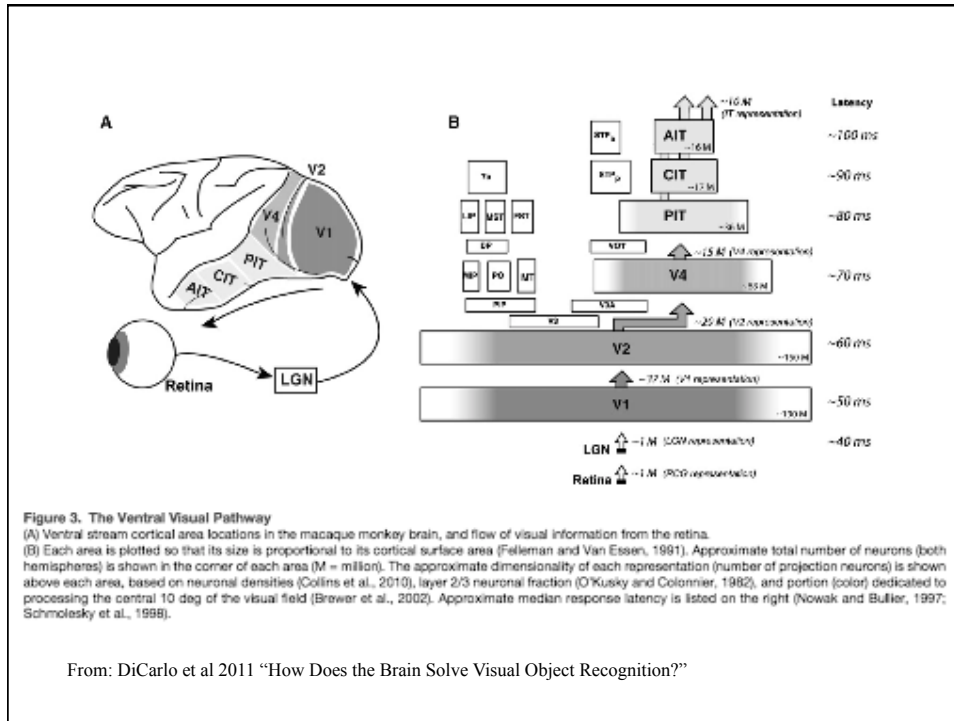
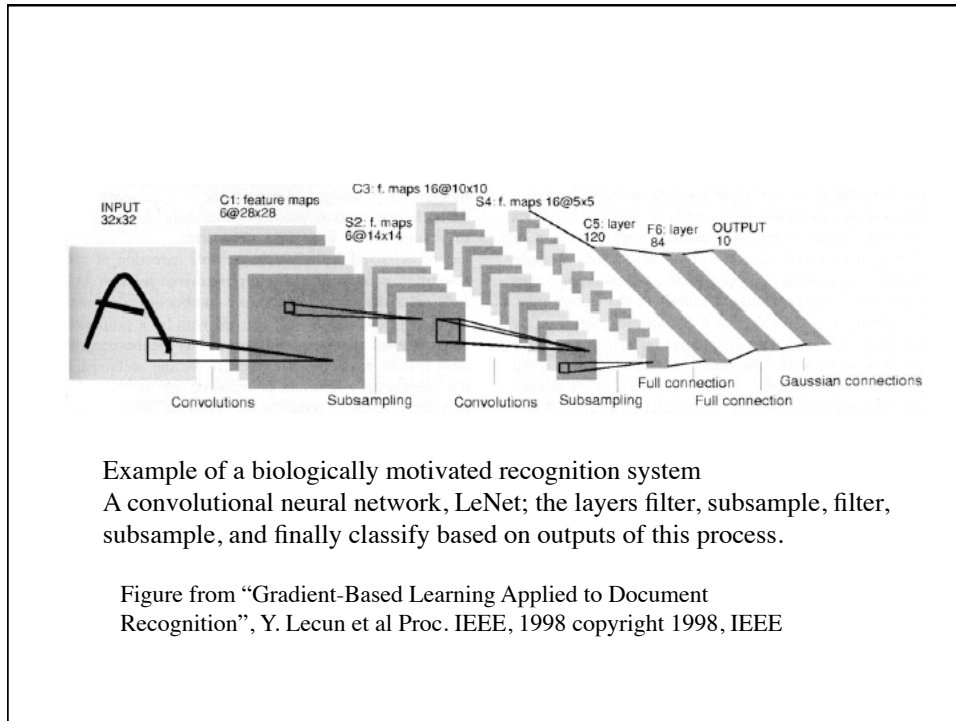


Figure 1.15 Original version of Livingstone and Hubel's hypothesis, according to which anatomically and physiologically defined subdivisions of the visual system formed independent streams of processing from the retina through extrastriate cortex, with each stream responsible for distinct perceptual functions.
 From M. S. Livingstone and D. H. Hubel, "Segregation of form, color, movement, and depth: anatomy, physiology, and perception," *Science*, 240, 1988. Copyright 1988 American Association for the Advancement of Science.



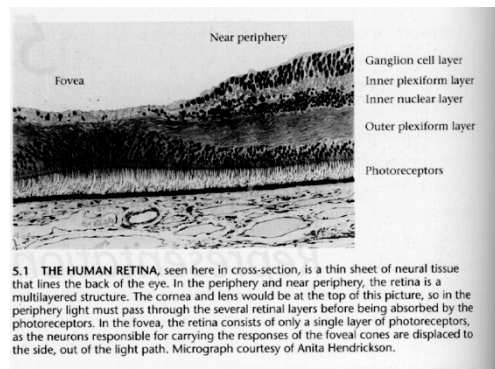
Modern theories of vision

- Reconstructionist: Marr
 - Internal reconstruction of the 3D world as the central representation.
- Hierarchy of feature detectors: Edelman
 - “Bug detector” in the frog retina (Lettvin 1959)



The human eye

- Limitations of human vision
 - Blood vessels and other cells in front of photoreceptors
 - shadows cast on photoreceptors
 - non-uniform brightness



The human eye

- Limitations of human vision
 - the image is upside-down!
 - high resolution vision only in the fovea
 - only one small fovea in man
 - other animals (birds, cheetas) have different foveal organizations
 - blind spot

