Introduction to Neuroscience: Visual Processing by the Retina

Morgan and Wong [http://webvision.med.utah.edu], 2007

Ramon Y Cajal, 1900
Visual processing starts in the retina, and travels through the optic nerve to the brain.
The human Eye

http://webvision.med.utah.edu/
An introduction to the cell types of the retina

[Diagram showing cellular layers of the retina, including layers such as choroid, pigment epithelium, outer segments, inner segments, outer nuclear layer (ONL), outer plexiform layer (OPL), inner nuclear layer (INL), inner plexiform layer (IPL), ganglion cell layer (GCL), optic fiber layer (OFL), photoreceptor, horizontal cell, bipolar cell, and amacrine cell.]
Each class is composed of multiple subtypes
Retinal neurons stratify in specific laminas of the plexiform layers.
Photoreceptors: Rods and Cones

Rods: dim night vision.
Cones: bright day light vision & color vision
Distribution of Rods and Cones in human retina

Curcio et al., 1990
Fovea

0.3 mm diameter
Ophthalmic view of the retina

Human retina

fovea

optic nerve
How photoreceptors work?
Phototransduction

Rhodopsin + light $\rightarrow$ metarhodopsin II
Metarhodopsin II activates transducin
Transducin activates PDE
cGMP levels decrease
Na&Ca channels close
Photoreceptor hyperpolarizes
Amplifying the visual signal

Rieke & Baylor, 1998
Recovery

Guanylate cyclase synthesizes cGMP from GTP
Calcium inhibits GC
Upon closure of channels, Ca concentration decreases

Rieke & Baylor, 1998
The rhodopsin cycle

- Rhodopsin
- Opsin
- All-trans retinal
- 11-cis retinal
- All-trans Vitamin A
- 11-cis Vitamin A

Rods

Pigment epithelium
The dark current

Purves et al., 2001
Rods detect single photons

Rieke & Baylor, 1998
Cones mediate color vision

Color vision is based on two or more receptors

- Red (L)
- Green (M)
- Blue (S)

“As it is almost impossible to conceive each sensitive point of the retina to contain an infinite number of particles..., it becomes necessary to suppose the number limited, for instance to the three principal colors.”
Thomas Young, 1802

Purves 2001
Monochromatic vision at night

Cone vision (day)

Rod vision (night)

Some animals normally have monochromatic vision:
Color blindness
Visual adaptation

• Light intensities range across 9 orders of magnitude.
  – A piece of white paper can be 1,000,000,000 times brighter in outdoor sunlight than in a moonless night.
  – If we were sensitive to this whole range all the time, there wouldn’t be able to discriminate lightness levels in a typical scene.
  – The visual system solves this problem by restricting the ‘dynamic range’ of its response to match the current overall or ‘ambient’ light level.
Visual adaptation

• Already at the retina!
  – Pupil’s diameter: 2-8 mm.
  – Rods and cones – two visual systems.
  – Both rods and cones adapt – becomes less sensitive as light levels increase.

Craik & Vernon, 1941:
Pressure blind experiments.
Psychophysical Measurement of Light/Dark Adaptation
Light and dark adaptation

Weber contrast: \[ C = \frac{L_{\text{object}} - L_{\text{background}}}{L_{\text{background}}} \]
Light and dark adaptation
Bipolar Cells

Adapted from Morgan and Wong http://webvision.med.utah.edu
And from Euler et al. 2014 Nature reviews Neuroscience
Ribbon synapse

- Rapid neurotransmitter release.
- Precise and sustained, and graded release.
- The synaptic ribbon releases 100s-1000s vesicles per second.
- Each pre-synaptic cell has 10-100 ribbons.
- Requires a large pool of readily releasable vesicles.
On- and Off-bipolar cells
Straight through retinal pathway

Fig. 6. Schematic drawing of the cone bipolar subtypes and their connections with ganglion cell subtypes in sublaminas a and b.
Horizontal Cells

Fig. 17. Two types of horizontal cells in the feline retina. A. HA with a dendritic spread of about 250 μm x 250 μm has no axon and its dendrites contact only cone photoreceptors. B. HB has a smaller dendritic field than HA (about 150 μm x 150 μm) but an elaborately branched axon terminal system (a.t.). The dendrites of HB contacts only cones, while the axon terminal contacts only rods. From Fisher & Boycott, 1974.
Retinal ganglion cells are sensitive to contrasts in light rather than absolute intensity.

Retinal neurons signal relative intensity of stimulation
Midget ganglion cells

cone types

Color opponent ganglion cells

red ON/green OFF, red OFF/green ON

green ON/red OFF, green OFF/red ON

blue ON/yellow OFF
Convergence and acuity

- Small dendritic arbors
- Small receptive fields
- ~80% of ganglion cell
- Chromatic
- Form and color
- Fine details

- Large dendritic arbors
- Large receptive fields
- ~10% of ganglion cells
- Non-chromatic
- Gross features of stimulus
- Movement
Magno and Parvo pathways
Retinal ganglion cells

What defines a neuron subtype in the retina?
- Morphology (including input & output)
- Physiology (=light responses)
- Form mosaic/tile the retina
Mosaic organization

- Cover the entire visual field
- Exclusion zone for same cell type

Spacing within types
Spacing between types

Density (cells/mm²)

Distance from reference cell

Starburst (n=12)
A2 to Horizontal (n=5)
Amacrine Cells

- GABA
- Glycine
- Dopamine
- acetylectholine
Direction selective retinal ganglion cell has preferred and null directions

Rivlin-Etzion et al.
On-Off Direction Selective Ganglion Cells

Rivlin-Etzion et al., J Neurosci, 2011
Computation of motion direction is both pre- and post-synaptic.
Starburst amacrine cells co-stratify with direction selective ganglion cells.
Local computations in starburst amacrine cells

Euler & Denk, 2002

Brigmann & Denk 2011
Directional responses are mediated by asymmetric inhibition

Photoreceptors

Bipolar cells

Direction selective ganglion cell

OFF starburst amacrine cell

ON starburst amacrine cell

Demb, Neuron 2007
The visual image is not stable on the retina

saccades
Some computations performed by RGCs

- Texture motion: RGCs that respond to high spatial frequencies moving in all directions.
- Object motion-sensitive (OMS) ganglion cells fire only when a local patch on the receptive field center moves with a trajectory different from the background.
- Approaching motion.
- Prediction of location of a moving object.
- Omitted stimulus response: after exposure to a periodic stimulus, if one stimulus is omitted, some neurons generate a pulse of activity at the time corresponding to the missing stimulus.
- Saccadic suppression.
Switching circuits

- On-RGCs change to Off-RGCs.
- Pattern adaptation.
- Contrast adaptation.
- Change in spatial encoding.
On-Off DSGCs reverse their directional preference upon visual stimulation

Rivlin-Etzion et al., Neuron 2012
All amacrine cells
Intrinsic photosensitive RGCs (ipRGCs)

- Express the visual pigment melanopsin
- Mice, rats, cats, monkeys, human
- Light responses develop slowly
- Sustained depolarization to light
- Slow recovery
- Project to the suprachiasmatic nucleus – controls the circadian clock
- Projects to the pretectal nucleus, which controls the pupillary light reflex

Berson, 2002
Visual acuity

- The human visual system is capable of acuity of 1 min of arc or 60 cycles/degree of visual angle.
- One degree of visual angle is thought to cover approximately 280-300 μm of retinal distance.
Retina: advantages

• Sensory “simple” system, but performs complex computations.
• Organized structure: Cell bodies are separated from processes.
• Full control on its input.
• Approachable for recordings/imaging.
• Similar anatomical arrangement in all mammals.
Retinal development
Retinal waves