Early Visual Processing: Receptive Fields & Retinal Processing
(Chapter 2, part 2)

Lecture 5

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Sensation & Perception
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normal eye - accommodation

far away object

(min) Good

(max)

(courtesy ben backus)
normal eye - accommodation

far away object

near object

(min) Good

(max) Good

(courtesy ben backus)
myopic (near-sighted) eye

- lens too powerful

- far away object
  - min
  - max
  - can’t get far objects in focus
myopic (near-sighted) eye

- lens too powerful

![Diagram of myopic eye](image)

- far away object
  - min: can’t get far objects in focus
  - max: can’t get far objects in focus

- near object
  - Good
hyperopic (farsighted) eye

- lens not powerful enough

far away object

min

max

Good
hyperopic (farsighted) eye

- lens not powerful enough

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<tr>
<th>far away object</th>
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<th>max</th>
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The precipitous drop in amplitude of accommodation with age

![Graph showing the precipitous drop in amplitude of accommodation with age.](graph.png)

- Different studies
- Amount of accommodation required to focus at 15 cm.
- Amount of accommodation required to focus at 40 cm.
• **Astigmatism**: visual defect caused by the unequal curving of one or more of the refractive surfaces of the eye, usually the cornea

![Spherical shape](image1) (A)  

![Shape with more curvature along vertical than horizontal](image2) (B)  

spherical shape  

(“no astigmatism”)  

shape w/ more curvature along vertical than horizontal
• **Astigmatism**: visual defect caused by the unequal curving of one or more of the refractive surfaces of the eye, usually the cornea

• if you have an astigmatism, some lines will be blurrier
Summary

• light, electromagnetic spectrum, visible spectrum

• light as a wave / particle

• pinhole cameras, lenses, image formation, blur, diffraction, optics of the eye

• anatomy of the eye (cornea, pupil, iris, aqueous, ciliary muscle, lens, vitreous, fovea, retina, and who could forget the Zonules of Zinn!)

• accommodation, emmetropia, refractive errors (hyperopia, myopia, astigmatism)
Camera analogy for the eye

• **Aperture** (F-stop) = **Iris/pupil**. Regulates the amount of light coming into the eye

• **Focus** = **Lens**.
  Changes shape to change focus

• **Film** = **Retina**.
  Records the image
the retina
(“smart” film in your camera)
What does the retina do?

1. Transduction
   • Conversion of energy from one form to another (i.e., “light” into “electrical energy”)

2. Processing
   • Amplification of very weak signals (1-2 photons can be detected!)
   • Compression of image into more compact form so that information can be efficiently sent to the brain
     optic nerve = “bottleneck”
     analogy: jpeg compression of images
photoreceptors

? 100

ganglion cells
Basic anatomy: photomicrograph of the retina

- Sclera
- Pigment epithelium
- Photoreceptor layer
- External limiting membrane
- Outer nuclear layer
- Outer plexiform layer
- Inner nuclear layer
- Bipolar cell
- Amacrine cells
- Ganglion cell layer
- Ganglion cell axon
- Nerve fiber layer
- Inner limiting membrane

Layers:
- Outer segments
- Inner segments
- Photoreceptor nuclei
- Photoreceptor axons (Henle’s fiber layer)
- Outer synaptic layer
- Horizontal cells
- Amacrine cells

Light
What’s crazy about this is that the light has to pass through all the other junk in our eye before getting to photoreceptors!

**Cephalopods** (squid, octopus): did it right.
- photoreceptors in innermost layer, no blind spot!

**Debate:**
1. accident of evolution?
   OR
2. better to have photoreceptors near blood supply?
- retina
- cone
- bipolar cell
- retinal ganglion cell
- RPE (retinal pigment epithelium)
- optic nerve
- optic disc (blind spot)
blind spot demo

(a)

F

(b)

F
**phototransduction:** converting light to electrical signals

**rods**
- respond in low light (“scotopic”)
- only one kind: don’t process color
- 90M in humans

**cones**
- respond in daylight (“photopic”)
- 3 different kinds: responsible for color processing
- 4-5M in humans
**phototransduction**: converting light to electrical signals

**outer segments**

- packed with discs
- discs have **opsins** (proteins that change shape when they absorb a photon - amazing!)

- different opsins sensitive to different wavelengths of light
- **rhodopsin**: opsin in rods
- **photopigment**: general term for molecules that are photosensitive (like opsins)
dark current

- In the dark, membrane channels in rods and cones are open by default (unusual!)
- current flows in continuously
- membrane is **depolarized** (less negative)

- neurotransmitter is released at a high rate
to bipolar cells
transduction & signal amplification

- photon is absorbed by an opsin
- channels close (dark current turns off)
- membrane becomes more polarized (more negative)

- neurotransmitter is released at a lower rate
to bipolar cells
transduction & signal amplification

inner segments

machinery for amplifying signals from outer segment

neurotransmitter release

graded potential (not spikes!)

to bipolar cells
Photoreceptors: not evenly distributed across the retina

- fovea: mostly cones
- periphery: mostly rods

Q: what are the implications of this?
• not much color vision in the periphery
• highest sensitivity to dim lights: 5° eccentricity
**visual angle**: size an object takes up on your retina (in degrees)

Vision scientists measure the size of visual stimuli by **how large an image appears on the retina** rather than by **how large the object is**.
Retinal Information Processing: Kuffler’s experiments

“ON” Cell

(a) ON-center ganglion cell

Spot in center

Response

Light on

Spot in surround

Response
Retinal Information Processing: Kuffler's experiments

“OFF” Cell

(b) OFF-center ganglion cell

Spot in center

Spot in surround

Response

Light on
Receptive field: “what makes a neuron fire”

- weighting function that the neuron uses to add up its inputs

Response to a dim light

1×(+5) + 1×(-4) = +1 spikes

“center” weight

“surround” weight

Light level
Receptive field: “what makes a neuron fire”

- weighting function that the neuron uses to add up its inputs

Response to a spot of light

\[
1 \times (+5) + 0 \times (-4) = +5 \text{ spikes}
\]

“center” weight  \quad “surround” weight

patch of bright light
Mach Bands

Each stripe has constant luminance ("light level")
Response to a bright light

2 \times (+5) + 2 \times (-4) = +2 \text{ spikes}

“center” weight

“surround” weight

higher light level
Response to an edge

2\times(+5) + 2\times(-3) + 1\times(-1) = +3 \text{ spikes}
Mach Band response

\[ 2 \times (+5) + 2 \times (-3) + 1 \times (-1) = +3 \text{ spikes} \]

“center” weight

“surround” weight
Mach Band response

edges are where light difference is greatest

2\times(+5) + 2\times(-3) + 1\times(-1) = +3 \text{ spikes}

“center” weight

“surround” weight
Also explains:

Lightness illusion
ON and OFF retinal ganglion cells’ dendrites arborize ("extend") in different layers:

Parvocellular
("small", feed pathway processing shape, color)

Magnocellular
("big", feed pathway processing motion)
“Channels” in visual processing

Incoming Light

- **ON, M-cells** (light stuff, big, moving)
- **OFF, M-cells** (dark stuff, big, moving)
- **ON, P-cells** (light, fine shape / color)
- **OFF, P-cells** (dark, fine shape / color)

The Retina

Optic Nerve

the brain
Luminance adaptation

remarkable things about the human visual system:
• incredible range of luminance levels to which we can adapt
  (six orders of magnitude, or 1 million times difference)

Two mechanisms for **luminance adaptation**
(adaptation to levels of dark and light):
(1) Pupil dilation
(2) Photoreceptors and their photopigment levels

the more light, the more photopigment gets “used up”,
→ less available photopigment,
→ retina becomes less sensitive
The possible range of pupil sizes in bright illumination versus dark

(a) Bright illumination

(b) Dark

2-mm pupil

8-mm pupil

• 16 times more light entering the eye
Luminance adaptation
- adaptation to light and dark

• It turns out: we’re pretty bad at estimating the overall light level.

• All we really need (from an evolutionary standpoint), is to be able to recognize objects regardless of the light level.

• This can be done using light differences, also known as “contrast”.

**Contrast** = difference in light level, divided by overall light level

\[ C = \frac{\Delta I}{I} \]

(Think back to Weber’s law!)
Luminance adaptation

Contast is (roughly) what retinal neurons compute, taking the difference between light in the center and surround!

\[ \Delta I = (5 \cdot I_{ctr}) - (4 \cdot I_{surround}) \]

**Contrast** = difference in light level, divided by overall light level

\[ C = \frac{\Delta I}{I} \]

(Think back to Weber’s law!)

• from an “image compression” standpoint, it’s better to just send information about local differences in light
transduction: changing energy from one state to another

Retina: photoreceptors, opsins, chromophores, dark current, bipolar cells, retinal ganglion cells.

“backward” design of the retina

rods, cones; their relative concentrations in the eye

Blind spot & “filling in”

Receptive field

ON / OFF, M / P channels in retina

contrast, Mach band illusion

Light adaptation: pupil dilation and photopigment cycling