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

Lecture 5

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Sensation & Perception
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Summary of last time:

• 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
- Inner plexiform layer
- Ganglion cell layer
- Nerve fiber layer
- Inner limiting membrane

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

Light

Scale: 50 μm
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
inner
outer
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

• neurotransmitter is released at a lower rate
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?
Photoreceptors: not evenly distributed across the retina

- 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)

“Rule of thumb”

2 deg

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.
Recording from retina in a dish!

Data: Chichilnisky Lab, The Salk Institute
Responses to Moving Bar: #1

Frechette et al, 2005
Responses to Moving Bar

Frechette et al, 2005
Retinal Information Processing: Kuffler’s experiments

“ON” Cell

(a) ON-center ganglion cell

Spot in center

Light on

Response

Spot in surround

Response
“OFF” Cell

Retinal Information Processing: Kuffler’s experiments
Kuffler: mapped out the **receptive fields** of individual retinal ganglion cells in the cat

- **ON-center ganglion cells**
  - excited by light that falls on their center and inhibited by light that falls in their surround

- **OFF-center ganglion cells**
  - inhibited when light falls in their center and excited when light falls in their surround
Receptive field: “what makes a neuron fire”

• weighting function that the neuron uses to add up its inputs”

Response to a dim light

patch of light

light level

1×(+5) + 1×(-4) = +1 spikes

“center” weight

“surround” weight
**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
- “surround” weight
Mach Bands

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

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

higher light level

“center” weight

“surround” weight
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×(+5) + 2×(-3) + 1×(-1) = +3 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
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
- 2-mm pupil

(b) Dark
- 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”.

\[ \text{Contrast} = \frac{\Delta I}{I} \]

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

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

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

\textbf{Contrast} = difference in light level, divided by overall light level

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

(Think back to Weber’s law!)

\[ \text{from an “image compression” standpoint, it’s better to just send information about local differences in light} \]
summary

• 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