

# Medical Neuroscience | Tutorial Notes

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## Visual System: The Eye

### MAP TO NEUROSCIENCE CORE CONCEPTS<sup>1</sup>

- NCC1. The brain is the body's most complex organ.
- NCC3. Genetically determined circuits are the foundation of the nervous system.
- NCC7. The human brain endows us with a natural curiosity to understand how the world works.

### LEARNING OBJECTIVES

After study of the assigned learning materials, the student will:

1. Describe the factors and neural mechanisms that account for the focusing of an image on the retina.
2. Identify the five neuronal cell types of the retina and state the roles of each in retinal processing.
3. Characterize the molecular processes that underlie phototransduction.
4. Discuss the responses of retinal ganglion cells to the onset and offset of light and the relevance their receptive fields for the detection of light and shadow.

### TUTORIAL OUTLINE

- I. Review the gross anatomy of the human eye (see [Figure 11.1](#)<sup>2</sup>)
- II. Formation of optical images
  - A. refraction: “bending” of light that occurs at the interface of different optical media
    1. most (~80%) of refraction occurs as light passes through the cornea
    2. sharp focusing of images at variable distances from the eye requires an adjustable **lens**, by a process called **accommodation**
  - B. accommodation
    1. dynamic changes in the refractive power of the lens
      - a. when the lens is flat ... least refractive power (far vision)
      - b. when lens is rounded ... most refractive power (near vision)
    2. control of lens shape (see [Figure 11.2](#))

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<sup>1</sup> Visit [BrainFacts.org](https://www.brainfacts.org) for Neuroscience Core Concepts (©2012 Society for Neuroscience ) that offer fundamental principles about the brain and nervous system, the most complex living structure known in the universe.

<sup>2</sup> Figure references to Purves et al., *Neuroscience*, 5<sup>th</sup> Ed., Sinauer Assoc., Inc., 2012. [[click here](#)]

- a. lens is an elastic structure that tends to round up
- b. the lens is attached to the circular **ciliary muscle** by an array of **zonule fibers**; the resting tension exerted by the zonule fibers is sufficient to pull the lens into a flattened position
- c. to focus on a near object, the lens must become more rounded, which is accomplished by the contraction of the ciliary muscle
  - (i) contraction of the circular ciliary muscle brings the attachment points of the zonule fibers closer to the lens
  - (ii) this relieves tension on the lens and the lens's intrinsic elasticity allows it to round up
- 3. adjustments of pupil size also contribute to focusing of images on the retina
  - a. because optical aberrations are greatest as light passes through the edges of the lens, the pupil minimizes these errors by restricting the passage of light to the center of the lens
  - b. a very small pupil severely limits the amount of light entering the eye, which may be detrimental under conditions of dim illumination
  - c. the neural control over pupil size (see **Figure 12.2**) provides for a optimization of these two competing considerations under varying conditions of illumination

### III. Inner layer of the eye

- A. comprises two tissues derived from the developing diencephalon (see **Figure 11.4**)
  - 1. neural retina (see below)
  - 2. pigment epithelium (see **Figure 11.6**)
    - a. tissue containing the pigment, melanin (albino individuals lack this pigment and are highly "light sensitive")
    - b. reduces the back scattering of light
    - c. absorbs photoreceptor disk membrane and recycles photopigment
    - d. photoreceptors become dysfunctional and eventually nonfunctional if separated from the pigmented epithelium (e.g., retinal detachment)
- B. basic wiring diagram of the retina (see **Figure 11.5**)
  - 1. five neuronal cell types stacked into five histological layers of alternating cell bodies and neuropil (cellular processes and synapses)
    - a. direct flow of information mediated by a three-neuron chain:
      - (i) **photoreceptors**: main sensory transducers in retina; two basic types: rods and cones (generate graded potentials)
      - (ii) **bipolar cells**: interneurons between photoreceptor and ganglion cells (generate graded potentials)

- (iii) **ganglion cells**: integrates electrical activity from bipolar (and amacrine) cells and gives rise to axons that form the optic nerve; only cell class in retina that fires action potentials
  - b. lateral interactions mediated by two cell types:
    - (i) **horizontal cells**: mediate lateral interactions between photoreceptors and bipolar cells
    - (ii) **amacrine cells**: mediate lateral interactions between bipolar cells, other amacrine cells and ganglion cells
- 2. in addition, there is specialized type of glial cell (called the Müller cell) that helps to maintain the ionic environment across the retina
- 3. light path: *through the retinal layers!*

#### IV. Phototransduction

- A. in the dark, photoreceptors are **depolarized** (to about -40 mV) and are continuously releasing their neurotransmitter, which is glutamate
  - 1. **cation-selective ion channels** in the outer segments of the photoreceptors are gated by cytoplasmic **cGMP** (see [Figure 11.8](#))
  - 2. in the dark, cGMP levels are high and cations flow into the outer segments (called the “dark current”), keeping the cell in a depolarized state
- B. effects of light
  - 1. photopigments
    - a. in the membranous disks of the outer segments there are a variety of photopigment molecules that consist of two subunits:
      - (i) a light-absorbing component, **11-*cis* retinal**
      - (ii) any one of a number of **opsin** proteins that fine-tune the molecular absorption of 11-*cis* retinal
    - b. the best known photopigment is **rhodopsin**, the pigment of rods
    - c. cones have one of three photopigments that are sensitive to short, medium or long wavelengths of light (see [Figure 11.14](#))
  - 2. when light strikes the outer segments, photoreceptors **hyperpolarize** (to about -65 mV) and release much less glutamate (see [Figure 11.8-11.10](#))
    - a. absorption of a photon of light by rhodopsin leads to a conformation change and the activation of a G-protein, called **transducin**
    - b. transducin activates a **phosphodiesterase** that hydrolyzes cGMP
    - c. cGMP concentrations in the outer segment fall and the cation-selective channels close, which leads to hyperpolarization
  - 3. amplification: this complex second messenger cascade allows for great amplification of the initial event

V. Rods and Cones (see [Figure 11.11-11.13](#))

- A. **rods:** very low spatial resolution, but extremely sensitive to light
  - 1. large outer segments in a rod-like shape maximizes the amount of photopigment that can be contained and made available for transduction
  - 2. greater molecular amplification in transduction cascade; sensitive to 1 photon (cones typically require about 100 photons to become activated)
  - 3. predominant type of photoreceptor across the retina, except for the fovea
  - 4. convergence pattern: the ratio of rods to ganglion cells is relatively high (signals derived from many rods converge onto the same ganglion cell)
- B. **cones:** very high spatial resolution, but relatively insensitive to light
  - 1. different cones with different absorption spectra make color vision possible
  - 2. convergence pattern: the ratio of cones to ganglion cells is very low, approaching 1 to 1 in the **fovea** (= “pit”), a specialized part of the retina where cones are very dense and visual acuity is greatest
- C. rods and cones make different contributions to visual activity
  - 1. **scotopic vision:** very low levels of illumination when only rods are activated
  - 2. **mesopic vision:** low levels of illumination (e.g., under moonlight) when both rods and cones are activated
  - 3. **photopic vision:** moderate and high levels of illumination when rods are saturated and only cones are activated

## VI. Ganglion cell receptive fields

- A. **receptive field** (in the visual system): region of visual space (or region of the retina) that when illuminated or darkened elicits a response in a visual sensory neuron
- B. center-surround structure of ganglion cell receptive fields (see [Figure 11.17](#))
  - 1. center: small circular region
    - a. **ON center:** ganglion cell increases its firing rate when light falls on the center of the its receptive field
    - b. **OFF center:** ganglion cell decreases its firing rate when light falls on the center of its receptive field
  - 2. surround: larger annulus surrounding the receptive field center
    - a. surround antagonizes the center
      - (i) ON center cells have **OFF surrounds**
      - (ii) OFF center cells have **ON surrounds**
    - c. **OFF surround:** firing rate decreases when light falls on the surround
    - d. **ON surround:** firing rate increases when light falls on the surround
  - 3. center/surround design allows for increased sensitivity to **luminance contrast**, such as the edge of shadow (see [Figure 11.19](#))

- C. retinal circuitry underlying ganglion cell receptive fields
1. receptive field structure is generated in the outer plexiform layer, by the interactions of photoreceptors, bipolar cells and horizontal cells
  2. two physiological classes of bipolar cells define the center response type of ganglion cells (see [Figure 11.18](#))
    - a. **ON center** bipolar cells **hyperpolarize** in response to the glutamate released by photoreceptors, due to the activation of metabotropic receptors and their related second-messenger systems
    - b. **OFF center** bipolar cells **depolarize** in response to glutamate released by photoreceptors, due to activation of AMPA receptors
    - c. bipolar cells respond with graded potentials, not action potentials
      - (i) they release more neurotransmitter when depolarized
      - (ii) they release less neurotransmitter when hyperpolarized

So now consider what happens when light strikes the center of a ganglion cell's receptive field center. Be prepared to explain why **ON-center ganglion cells increase their activity** and **OFF-center ganglion cells decrease their activity** in terms of the neurophysiology of bipolar cells in the middle of the retina.
  3. lateral interactions mediated by horizontal cells account for center-surround antagonism

### LEARNING OBJECTIVES

- Q1. In order to properly **fixate** nearby, stationary visual targets and **focus** their images on the retina, each of the following actions listed below usually occurs, EXCEPT for one. Identify the action that IS NOT part of the normal response to visual fixation.
- A. the shape of the lens in each eye is altered
  - B. vergence eye movements (convergence or divergence)
  - C. the firing rate of brainstem neurons that govern iris constrictor muscles is altered
  - D. the shape of the cornea in each eye is altered
  - E. the diameter of the pupils is altered
- Q2. Which of the following natural stimulus configurations provides the BEST stimulus for an **OFF-center ganglion cell**?
- A. uniform illumination across the entire receptive field
  - B. the edge of a shadow that falls across the border between the center and surround of the receptive field, with the center region in shadow
  - C. a small spot of light that falls within the surround region
  - D. the edge of a shadow that falls across the border between the center and surround of the receptive field, with the center region illuminated
  - E. uniform shadow across the entire receptive field