The Special Senses

READ tonic, phasic adaption in Chpt. 13. Know all bold-faced terms.

I. Vision and the Eye

- What is vision? The perception of information received by special cells called PHOTORECEPTORS. The stimulus is light energy. In other words, vision is the perception of light energy. The EYE is a special organ that allows us to receive light energy, focus it, and transduce it into an action potential. So let’s talk about some characteristics of light:

A) CHARACTERISTICS OF LIGHT

1. light = movement of photons = an energy; therefor, it can cause CHANGE (or WORK).

   *what we call “Light” is a small section of a continuous energy spectrum called the VISIBLE SPECTRUM

   *the eye, or more importantly, the photoreceptors, are designed to detect this narrow range; that is why you cannot “see” infrared, microwaves, etc. although the difference is only the strength of the energy. Notice that light is middle of the scale. You have other receptors for detecting OTHER PARTS OF THE SPECTRUM (heat, for example, is energy just a little more energetic that the color “RED”. UV = “ultraviolet” = what causes damage to skin tissue if exposed to high doses for long time.

2. Light is FAST. Photons travel at 186,322 miles per second in a vacuum. In fact, it is the fastest movement in the universe. The eye will have several adaptations to slow it down.

   *To put things in perspective, sound travels at about 750 miles/hour (“mach 1”). It would take sound about 4.5 hours to travel across the U.S. (3,500 miles), while it takes light 0.02 seconds.
3. Light travels straight, but in waves just like water in an ocean.

*light (as does all energy) travels in WAVES. Analogous to water waves. Can describe these waves (as you can waves in water) by their HEIGHT, LENGTH and FREQUENCY (how close are they to each other?).

*low wave height = long wave length = lower power.

*Higher wave height (= short length) = higher frequency (closer together); and since it is the movement of particles called photons, higher frequency = higher power (or ability to do work).

NOTE: “colors” are different wavelengths in the visible spectrum.

*since light travels straight in waves, it undergoes “reflection” .... it bounces at a predictable angle:

Light waves follow the "law of wave reflection."

B) VISION BASICS

1. Vision is the reception of light reflected off of other objects into the eye, where it is then transduced by photoreceptors. This forms an IMAGE. But obviously, sight is more than the mere presence or absence of light ..... our nervous system uses this information to tell us about size, shape and movement. In order to do this, we must be able to perceive the “edge” or “boundary” of what we are seeing ..... in other words, we must be able to FOCUS (= distinguish a line).
2. Light bounces off of a subject towards the eyeball. This light pattern enters the eye, where the lens focuses the light onto the photoreceptive layer (the **Retina**). **Notice:** the retina is just one thin layer of cells .... it is like a movie on a screen.

   * Due to the way that lenses focus light, the image is “flipped”; the brain “un-flips” the image.

   ![Image of eye with light bouncing off retina](image)

3. Of course, the above example is overly simplistic ..... in reality, light bouncing off of several images at the same time are entering the eyeball. This sets up a **Visual Field**. Notice .... as you “see”, there is one object on which you are focused ... this image is sent to an area of dense cells called the **Macula Lutea**. The rest of the image is out of focus:

   * ACUITY is the ability of the eye to focus on the image.

   ![Diagram of visual field](image)

   * Any light hitting the optic disk IS NOT PERCEIVED! But wait! There is no “blind spot” in your field of vision, is there? You brain learned a long time ago that this spot is not “real”, and “fills in the spot” with colors from the surrounding region for a “best fit”. To prove the existence of the blind spot:
*Notice: Vision is 2-dimensional .... just like a movie on a picture screen!! But your vision is in 3 dimensions, isn't it? No ... this is an optical illusion, caused by the fact that you have 2 eyes, each of which is seeing the image at a slightly different angle.

* The 2 fovea are 5-7.5 cm apart, and the nose and eye socket block the view of the opposite side. Also, your brain learns to interpret “up” as “back”. This is termed DEPTH PERCEPTION.

** NOTICE ... the eyes are receiving information from the opposite side of the room ..... the images are “switched” at the optic chiasma!!

** Also notice: as the subject gets closer to the eye, the image on the retina gets bigger (that is, more receptor cells are activated)! This is interpreted as movement towards the observer.

4. There are 2 types of photoreceptors: RODS (black & white; very light sensitive, allowing us to see in lightly-light rooms) and CONES (color vision; give us a sharper, clearer vision). Sit outside at sunset, and you can tell when you vision shifts from cone-based to rod-based.

* there are no rods in the macula lutea. The highest concentration of cones occur in the center, known as the fovea or FOVEA CENTRALIS ..... site of sharpest vision.

** this is why, at night, it is hard to stare at a dim object (like a star) and see it .. it is easier to see it if you look slightly to one side.

** COLOR VISION: cones receive color, which are different wavelengths of visible light. The different cones are excited by different wavelengths. However, it would be impossible for there to be a different photoreceptor for each possible wavelength (i.e., color)....there are an endless number, as there are an infinite number of possible “shades” .... you literally would not have room on the retina for one cell for each possible color!

Instead, have three “colors”: Red/Green/Blue. By mixing different proportions of these three, one can get all the possible colors.

** COLOR BLINDNESS: One or more classes of cones are non-functional. Genes for red & green cones are on the X chromosome; therefor it is a “sex-linked” trait, and males get it more than females.
- males only have one "X" chromosome, so a mistake on this chromosome is always exhibited. Females have 2 "X" chromosomes, so a defect on one is made up for by the other chromosome. In order for the female to get the disorder, she must have 2 "bad" chromosomes, which is MUCH rarer.

- NOTICE: the test uses "points" of color; the brain will "fill them in" with the nearest color, just as it did with the blind spot. Or, it will see the "other colors present", and they will see something completely different (perhaps another number).

C) REFRACTION

- RECALL: “In Focus” means the rays of light hit the photosensitive layer in such a way that they “line up” ... so a line can be distinguished.

- Physics of light moving: light is bent (“REFRACTED”) when it moves between areas or mediums of differing densities. To see this, stick a pencil in a glass of water. It “bends” .... the light is traveling at a different speed in the water!
-Within you eye, most refraction happens in the anterior chamber (due to the aqueous humor) and the lens.

*where these lines intersect is the FOCAL POINT.

Acuity depends on the ability of the lens to get the focal point on the macula lutea.

*NOTE: anything that does not hit the macula lutea will not be in focus! Lack of acuity!

- SO: the ability to focus depends on the lens’s ability to refract properly. The ability of any lens to refract properly depend on 2 factors:

1. Distance of the object from the lens. 
   *in this example, moving the image closer will put the focal point on the macula lutea.

2. Shape of the lens. Rounder shortens the focal distance; flatter lengthens it. So, I could also move the focal point to the macula lutea by flattening the lens!

* You eye changes the focal length by changing the shape of the lens ... keeping focal length constant is called ACCOMMODATION. The suspensory ligaments do this. Under normal conditions ("EMMETROPIA"), a person focuses on a line that is about 5" long from 20 feet away. To test: ability to distinguish arabic letters. If the patient can see at 20 feet what a "normal" person can see, they have "20/20". Maybe they can see the same letters at a farther distance (say, they can see the letters at 30 feet = better than normal = "30/20"). If their vision is less than normal, they have to stand closer (say, for example, they have to stand 10 feet away to see the line that a normal person can see from 20 feet away = 10/20).

- Abnormal conditions:

1. **Myopia**. Elongated eye. Focal point within posterior cavity. Person self-corrects the condition by moving the object closer ("near-sightedness").

2. **Hyperopia**. Narrowed eye. Focal point at imaginary point behind retina. Person self-corrects by keeping the object at a greater distance ("far-sightedness").

3. **Presbyopia**. Special case of hyperopia, where lens loses elasticity.
4. **Astigmatism.** Due to small imperfections in cornea/lens (facets), there are multiple focal points.

5. **Legally Blind.** Visual acuity falls below 20/200.

**E) PHOTORECEPTION**

- The neural tunic consists of a thin INNER pigmented layer and a thick neural retina. The pigmented layer absorbs light, passes it to the neural layer, which contain photoreceptors. The pigmented layer also stores vitamin A, which will be used later by the photoreceptors. **NOTICE:** light must pass through the neural layer before it is absorb by the pigmented layer. Why? unknown, possibly “evolutionary baggage”.

- Photoreceptors depend on diffusion of nutrients and wastes; in the case of a detached retina (separation of the 2 layers), they die.

  * **Visual pigments** are the light-absorbing molecules that mediate vision.

Four kinds of light-sensitive receptors are found in the retina:

1. rods

2. three kinds of **cones**, each “tuned” to absorb light from a portion of the spectrum of visible light
   a. cones that absorb long-wavelength light (red)
   b. cones that absorb middle-wavelength light (green)
   c. cones that absorb short-wavelength light (blue)

- Each type of receptor has its own special pigment for absorbing light. Each consists of:
  a. transmembrane protein called **opsin** coupled to the prosthetic group retinal. Retinal is a derivative of vitamin A (which explains why night blindness is one sign of vitamin A deficiency) and is used by all four types of receptors. The amino acid sequence of each of the four types of opsin are similar, but the small differences account for their differences in absorption spectrum.

- The retina also contains a complex array of interneurons: **bipolar cells** and **ganglion cells** that together form a path from the rods and cones to the brain.

  * Ganglion cells are always active. Even in the dark they generate trains of action potentials and conduct them back to the brain along the **optic nerve** (“dark current”). Vision is based on the modulation of these nerve impulses by the rods and cones (and a complicated series of horizontal and amacrine cells that we shall not go into here). There is not the direct relationship between visual stimulus and an action potential that is found in the senses of hearing, taste, and smell. In fact, action potentials are not even generated in the rods and cones.

- **OVERVIEW of Photoreception:** In darkness, rods and cones (photocells) inhibit the bipolar cells, which stop the ganglion cells from firing.

  * Reception of a photon hyperpolarizes the photocells, which removes the inhibition on the bipolar cells (and therefor the ganglion cells). Information on the arrival of light is sent, via the optic nerve, cross at the optic chiasma, processed by the lateral geniculate nuclei, and sent to the visual cortex and the reflex centers of the brain stem.

  **Rod Vision: an example:**

-Rhodopsin is the light-absorbing pigment of the rods. It is incorporated in the membranes of disks that are neatly stacked (some 2000 of them) in the outer portion of the rod.
* Although the disks are initially formed from the plasma membrane, they become separated from it. Thus signals generated in the disks must be transmitted by a chemical mediator (a "second messenger" called cyclic GMP [cGMP]) to alter the potential of the plasma membrane of the rod.

* Rhodopsin consists of an opsin of 348 amino acids coupled to retinal.
  1. The opsin has 7 segments of alpha helix that pass back and forth through the lipid bilayer of the disk membrane.
  2. Retinal consists of a system of alternating single and double bonds. When light (that is, a photon) is absorbed by retinal, the molecule straightens out (forming what is called the all- trans isomer).

- This physical change in retinal triggers the following chain of events culminating in a change in the pattern of impulses sent back along the optic nerve.
  1. Formation of all- trans retinal activates its opsin; we now have an “activated rhodopsin”.
  2. Activated rhodopsin, in turn, activates many molecules of a protein called transducin.

Transducin activates an enzyme that breaks down cyclic GMP. (GMP is the guanine-containing cousin of AMP.)
  * The drop in cGMP closes Na⁺ channels in the plasma membrane of the rod causing an increase in its membrane potential from -40 to as much as -80 mV (= hyperpolarization!!!).

This slows the release of a neurotransmitter at the synapse of the rod. However, because this transmitter is inhibitory, the effect is a “double-negative” one, i.e. positive.

- Interneurons (bipolar cells) are relieved of their normal inhibition. This, in turn, relieves the inhibition of the spontaneous firing of the ganglion cells to which they are connected.

So ..... the retina is not simply a sheet of photocells, but a tiny brain center that carries out complex information processing before sending signals back along the optic nerve. This processing is very complex; for example, as many as 1,000 rods may pass information (via their bipolar cells to a single ganglion cell. In fact, ganglion cells pick up information that light has arrive to a REGION instead of to a single spot on the retina). This processing, along with the inhibition/excitation provided by the horizontal cells, is called CONVERGENCE. The retina really is part of the brain and grows out from it during embryonic development.

*NIGHT BLINDNESS: visual pigments are synthesized from vitamin A, which can be synthesized from CAROTENE (an orange pigment in vegetables such as carrots). You have a reserve for several months. If dietary sources are inadequate, amount of pigment declines. Day vision is affected, but usually unnoticed at first, since there is still enough light to activate the photocells. At night, dim light is not enough to activate the photocells.

READ: section on "Light and Dark Adaptation"

E) CLINICAL PROBLEMS OF THE EYE AND VISION

-Know these terms:

sty
corneal transplants
detached retina
diabetic retinopathy
cataracts
glaucoma
II. Equilibrium and Hearing

- Both controlled by the **INNER EAR**. Both done via **HAIR CELLS**. 2 major senses; both separated ... in this respect, the inner ear is two (at least) separate organs.

- **HEARING**: The detection of sound waves, which are mechanical force in the air.

- **EQUILIBRIUM**: Position in space. Important for body to be aware, in order to maintain homeostasis. Three aspects: up vs. down (gravity), front and back (acceleration), rotation. Body uses position of head to determine position of body.

**A) HEARING AND SOUND.**

- **SOUND**: pressure waves conducted through a medium. Travels in waves (“cycles”). Hertz = cycles/second = frequency. Pitch = sensitivity to frequency; high frequency for a human is 15,000 - 20,000 Hz. Low frequency = 100 Hz or less (lowest is about 20 Hz within children).

- “Decibels” is intensity (volume); interpreted as loudness. Resonance is when an object vibrates at the same frequency as sound due to the waves striking.

  *Sound waves (air waves) are very weak, and they dissipates rapidly. Therefore, the ear must have several adaptions that direct and amplify the sound waves in order to discriminate.

**B) MECHANICS OF HEARING.**
- The ear is divided into 3 anatomical regions, most of which is encased in bone (which has good resonance):

1. External or outer ear: collects & directs sound waves, transferring them to the tympanic membrane, which vibrates as the waves strikes it. This amplifies the sound.
* Know where to find these:

Pinnae (auricle), external auditory canal, temporal bone.

* Cerumen (ear wax), secreted by ceruminous glands, slows the growth of microorganisms/infection.

* Water can become trapped in the canal near the tympanum, leading to "swimmer’s ear".

2. The middle ear: the vibrating tympanum then transfers the vibrations to three bones called the AUDITORY OSSICLES. Notice that the ossicles gradually get narrower, thereby amplifying the vibration even more:

- The auditory (eustachian, pharyngotympanic) tube helps dissipate the vibrations down into the nasopharynx, equalizing pressure.

3. The vibrations of the oval window transfer the sound waves to the fluid-filled cochlea (part of the INNER EAR responsible for HEARING ... sound detection).

* Water is incompressible (if you push on one part, the water bulges somewhere else). Therefore, water is a good medium to transfer sound waves.

* To see how this works, let’s build a device that will detect sound:
*NOTE: the sensors furthest down the tube will detect long waves (low pitched waves); the sensors closest up the tube will detect short waves (high pitched sound). The longer I make the tube, the more sounds (waves) the system can discriminate! Intensity of sound is determined by the number of cells activated in a region.

-I can make this system even more sensitive by adding a mechanism that amplifies the waves in the liquid.

- Now that I have made it more sensitive to vibration, I want to make it even more efficient at dissipating vibrations in the fluid. I can do that by extending the length of the tube. In order to conserve space, I’ll wrap the tube back onto itself:

-And now, let’s make the system more sensitive by lengthening the entire system. In order to make it fit, I’ll “wrap it up” like a hose. Now we have a structure called the COCHLEA. The sensory apparatus inside the Cochlear Duct is the ORGAN OF CORTI.

*PERILYMPH: fluid inside scala vestibuli & tympani; inside the cochlear duct is ENDOLYMPH.

*know: bony labyrinth, basilar & tectorial membrane, hair cell, supporting cells, kinocilia, stereocilia cochlear nerve.


C) EQUILIBRIUM.

- Anterior region of inner ear is the VESTIBULAR COMPLEX.

1. Utricle & Saccule: Position with respect to gravity (up vs down) & acceleration. Chambers within the vestibule. Filled with endolymph produced in the cochlear duct. Drained into the subdural space; excessive endolymph end up in general circulation.
*suspended in the endolymph are **OTOLITHS** ... calcium carbonate crystals. Hair cells are found in clusters along the wall called **MACULAE**. Tilting of the head distorts the kinocilia as the otoliths are shifted in the endolymph. You brain integrates this information & visual information to distinguish acceleration vs. tilting.

** Motion Sickness: seems to be central processor receives conflicting information (eyes say “not moving”, labyrinthine receptors report movement. Below deck on a boat, reading in a car/airplane). Watching the horizon seems to help. Dramamine and other drugs appear to depress activity at vestibular nuclei.

** Space Sickness: lack of gravity causes lack of input, leads to nausea.

2. Semicircular ducts (canals). Respond to rotation of head. This gives placement in 3-D space. Notice the three ducts outline the axes of 3-D space (length, width, height). Ducts are filled with endolymph. Each duct has an expanded region with receptor cells (AMPULLAE). Cilia of hair cells are embedded in a gelatinous structure called the CUPULA. Rotation causes the endolymph to shift within the duct, pushing the receptor cilia.

C) CLINICAL CONDITIONS ...... Know these terms:

- Otitis media
- Motion sickness
- Conductive deafness
- Nerve deafness
- Aminoglycide antibiotics diffuse into endolymph, killing hair cells.
- Nystagmus