

## Visual Perception (Schwartz)

3 classic experimental approaches are used to study visual perception:

1. Anatomic - determine structures involved
2. Neurophysiologic - determine functions/processing of individual components.
3. Psychophysical - treat the visual system as a black box; specific input is presented to the system and the output is determined. From the input/output relationship, the operational characteristics of the system are determined.

New experimental approach:

Brain imaging: observe the metabolic activity of the brain while a subject performs a specified task.

The clinical application of the material presented rests largely on psychophysical procedures (because it is noninvasive).

### **Very Basic Ocular Anatomy:**

3 ocular layers: sclera, uvea, and retina

At birth, the average eye has an axial length of 17 mm

Adult: 25.4 mm ( 1 inch)

**Outermost layer: sclera** - consists largely of collagen. Provides support and protection for the internal elements of the eye.

**Middle: uvea** - highly vascularized; plays a large role in providing nutrition to the various elements of the eye. The uvea is divided into 3 components:

1. Iris - controls diameter of the pupil; helps regulate the amount of light entering eye.
2. Ciliary body - 2 functions
  - \*accommodation
  - \*aqueous humor production
3. Choroid - provides blood to the outermost aspects of the retina

**Innermost layer: retina** - 0.02 mm thick. Neural component involved in light capture and image analysis/transfer.

### **Ocular Anatomy From Anterior to Posterior:**

Most anterior aspect of the eye: **cornea** - five layered transparent tissue. Provides approx. 2/3 of the refractive power of the eye. Cornea's power is approx. 40 D where the eye's total power is about 60 D.

**Aqueous humor** is contained within the **anterior** and **posterior chambers** of the eye. The anterior chamber is bounded by the posterior surface of the cornea and the anterior surfaces of the iris and lens. The posterior chamber is bounded by the posterior surface of the iris and the anterior surface of the vitreous humor. Aqueous humor drains out of the eye through the **canal of Schlemm**. Aqueous humor exerts a pressure, called IOP of about 16 mmHg that helps maintain the structural integrity of the eye.

Posterior to the iris: **crystalline lens**. Provides about 1/3 of refractive power of the eye (about 20 D). When viewing near objects the power increases (accommodation). Accommodation occurs when the ciliary muscle constricts. This releases tension on the **lens zonules**. Crystalline lens becomes less transparent with age, apparently due to the destructive oxidative effects of free radicals. This leads to cataract formation.

Vitreous humor makes up the bulk of the eye volume. Consists largely of collagen and hyaluronic acid and has a gel like structure. Provides structural and nutritive support for the retina in addition to creating a dioptrically critical space.

### **Basic Retinal Anatomy:**

The retina is a multilayered neural tissue that begins the process of actively analyzing the image that falls upon it. The retina does not transmit point by point information that falls on it. It makes decisions about which information is important, and transmits that info., and disregards unimportant info. This hypothesis is nicely illustrated by studying the visual systems of lower animals. Lower animals have smaller brains and more visual processing takes place at the retina.

The same is true of the mammalian retina: **color, motion, and contrast information are analyzed by the retina** and transmitted as a complex signal to higher centers in the brain.

Retinal Layers:

The photoreceptors (rods and cones) respond to light and transform this radiant energy into electrical activity. This electrical activity is transmitted to retinal bipolar cells and then to retinal ganglion cells. The retinal ganglion cells have long axons which leave the eye and synapse in the dorsal lateral geniculate nucleus, a midbrain structure.

**This photoreceptor --> bipolar cell --> ganglion cell** arrangement reflects the **feed-forward** or **centripetal** nature of retinal organization. In addition to this feed forward arrangement, there are lateral connections within the retina. These provide for the lateral, or horizontal, transmission of retinal info. **Horizontal and amacrine cells are involved in this lateral integration of retinal information.**

In addition to the feed forward nature of the retina and the lateral interactions, there is also a **feedback transmission of information**. This is referred to as the **centrifugal pathway**, where info is transmitted from the ganglion cell back toward the photoreceptors by **interplexiform cells**.

Light must pass thru the inner layers of the retina before it is absorbed by the photoreceptors, which are on the outer layers of the retina. The inner retinal layers are somewhat transparent and are laterally displaced near the fovea so the inner layers do not distort or degrade vision.

**The outermost layer of the retina is the RPE.** This tissue provides a critical role in providing nutritional support for the photoreceptors. The RPE continuously phagocytizes the continuously produced outer segments of the photoreceptors. In addition, the RPE absorbs light photons not absorbed by the photoreceptors, which reduces light scatter.

**Inner to the RPE is the photoreceptors.** Photoreceptors manifest a very high level of metabolic activity; among the highest in the body. It is for this reason they are located in the outer retina close to the choroidal blood supply.

2 categories of photoreceptors:

1. Rods - night vision
2. Cones - daytime vision

Outermost aspect of the photoreceptor is the outer segment. This contains the photopigment that absorbs light and converts this radiant energy into electrical activity. The outer segments form a distinct retinal layer. The next retinal layer consists of the inner segments of the photoreceptors. This layer contains many of the organelles of these cells, excluding their nuclei.

A thin structural layer called the outer limiting membrane separates the inner segments of the photoreceptors from their nuclei. The photoreceptor nuclei form a distinct layer called the outer nuclear layer (ONL).

The first synapses within the retina occur within the outer plexiform layer (OPL). This layer consists of the dendrites of the bipolar and horizontal cells and the synapses these cells make with the photoreceptors.

Inner to the OPL is the inner nuclear layer (INL). This layer consists of the cell bodies of the bipolar, horizontal, and amacrine cells.

The second stage of synapses within the visual system occurs within the inner plexiform layer (IPL). Contained within this layer are the various synapses among the bipolar, amacrine, and ganglion cells.

The innermost cell body layer of the retina is the ganglion cell layer. There are two major classes of ganglion cells. The smaller midget or parvo cells (P), cells comprise about 80 percent of the ganglion cells and the larger parasol or magno (M) cells about 10 percent of the ganglion cells.

The axons of the ganglion cell constitute the next layer, which is referred to as the nerve fiber layer.

The innermost retinal layer is the internal limiting membrane. This membrane acts as an interface between the retina and the vitreous humor.

Summary of retinal layers (outermost to innermost):

1. RPE
2. Photoreceptors: outer segment: rhodopsin pigment  
inner segment: organelles but not nuclei
3. OLM: separates inner segments from nuclei
4. ONL: photoreceptor nuclei
5. OPL: first synapses in retina - dendrites of bipolar and horizontal cells.
6. INL: cell bodies of the bipolar, amacrine, and horizontal cells.
7. IPL: second synapses: bipolar, amacrine, and ganglion cells.
8. Ganglion cell layer - M & P cells
9. Nerve fiber layer
10. ILM

Key feature of retinal organization is lateral interaction. Horizontal and amacrine cells integrate info. laterally w/in the retina. These lateral interactions allow for the processing of visual info across space.

There is significant convergence of info w/in the retina. Implied by fact that there are more photoreceptors than ganglion cells. Approximately 100 million photoreceptors and only 1 million ganglion cells. Shows that info is processed as it is transmitted. Some info is highlighted and encoded while other info is lost.

Fovea: subtends a visual angle of about 1.2 degrees. Rods are absent. Maximal density of cones. Neural elements are pushed aside to allow light to fall directly on the photopigment containing outer segments. Avascular to prevent light scatter. Metabolic nourishment is from choroid.

Surrounding the fovea is the macula lutea which contains yellow pigment to absorb blue light.

Postretinal pathways:

At the optic chiasm, ganglion cell fibers from the nasal retina of each eye cross over to join the temporal fibers of the fellow eye to form the optic tract. Fibers constituting the left optic tract carry info about the right visual field and vice versa. Primary target of the optic tract is the dLGN - a thalamic nucleus. Layers 2, 3, and 5 receive input from the ipsilateral eye. Layers 1, 4, and 6 receive input from the contralateral eye.

The dLGN is composed of two distinct regions: the dorsal four layers are the parvo layers. Larger neurons, make up the magno layers. Axons from the p-cells synapse on p-cells in the dLGN forming the parvo pathway. M-cells from the retina also synapse onto m-cells in the dLGN forming the magno pathway. These 2 paths are referred to as parallel paths because they apparently process different aspects of the visual image that falls on the retina. The parvo path encodes detail and color. The magno path encodes fast movement.

The cells of the dLGN send most of their axons to the cerebral cortex, the most highly evolved portion of the brain. This structure consists of 2 hemispheres that are connected by the corpus collosum. The cortical area in which most dLGN axons synapse is the striate visual cortex. This region is also referred to as visual area 1 (V1), primary visual cortex, and Brodmann's area 17. The striate cortex is dominated by foveal input, a phenomenon referred to as the cortical magnification of foveal vision.

Cells in the striate cortex send many of their axons to nearby visual cortical areas, which are collectively called the extrastriate visual cortex. From here, axons are sent to a great diversity of higher cortical areas. These higher cortical areas are involved in the integration of visual info with memory and other sensory modalities. The striate cortex also sends a major projection back to the dLGN. This feedback loop can be considered analogous to the retinal centrifugal pathway. The organization of the cortex is somewhat opposite that of the retina: there is a divergence of info.

The pathway from the retina to the dLGN to striate visual cortex is referred to as the retinocortical pathway (great majority of retinal ganglion cells). Smaller percentage of ganglion cells contribute the retinotectal pathway. Ganglion cells in this pathway synapse in the midbrain's superior colliculus (or tectum), bypassing the dLGN. The tectum apparently does not project to the cortex. This pathway appears to be important for encoding eye movements.

### **Electromagnetic spectrum**

Visible light = 380 - 700 nm.

Wavelength and frequency are inverseley proportional:  $V = c/h$  ( $h$  is lambda or wavelength).  $V$  is frequency

Dual nature of light: wave and quantal nature (quanta = discrete packets of energy or photons). The amount of energy in a quantum of light is given by the following relationship:  $E = hv$

$E$  = energy per quantum.  $H$  = planck's constant ( $6.626 \times 10^{-37}$ )  $v$  = frequency

$$E = hc / h$$

These relationships show that quanta of short wavelenghts have more energy than do quanta of longer wavelenghts. Important b/c high energy quanta (shorter wavelenght light like UV) produces more tissue damage.

Cornea absorbs much of the very short wavelength UV C radiation. Consequently, excess ocular exposure to UV C, as with skiing, can lead to solar keratitis. Crystalline lens absorbs UV A and UV B.

### **Duplex Nature of the Retina**

The human visual system has an operational range on the order of 10 log units.

The pupil's role in determining light adaptation:

Suppose we go from bright conditions with a pupil diameter of 3 mm, to dark conditions with a pupil diameter of 9 mm. Use  $A = \pi(r)^2$

$$3 \text{ mm pupil: } A = 3.14 (1.5)(1.5) = 2.25 (\pi)$$

$$9 \text{ mm pupil: } A = 3.14 (4.5)(4.5) = 20.25(\pi)$$

$$\text{Ratio of } A_d / A_b = 9.0 \text{ or about } 1 \text{ log unit}$$

This 1 log unit accounts for a very small portion of adaptation, b/c the visual system adapts over a 10 log unit range. **The remaining adaptation** is largely due to the existence and properties of 2 classes of retinal photoreceptors: **rods and cones**.

## Basic distinctions between scotopic and photopic vision

Scotopic = occurs under dim lighting. Poor VA (20/200). Absence of color vision. Due to rods.

Photopic = occurs under bright lighting. Poor sensitivity to dim lights. Good VA (20/20). And color vision. Due to cones.

This is the duplex nature of the retina: 2 different classes of photoreceptors that operate under different conditions.

Mesopic conditions: both rods and cones contribute to vision. Under twilight conditions.

Differences between rods and cones:

Rods: outer segment is rod-shaped. Free floating photopigment disks. Synaptic endings have a roundish **spherule**.

Cones: outer segment is cone-shaped. Disks are attached to outer segment. Synaptic endings have a flat **pedicle**.

(remember that outer segment disks are phagocytized by the RPE).

Rod disks are produced, shed, and metabolized at the rate of 10% per day. Happens mostly during the day. Cone disks tend to be shed at night.

Without the phagocytizing of outer segments, metabolic waste builds up which damages rods and cones.

Photopigments in rods and cones:

Rods: rhodopsin (visual purple). About  $10^{15}$  molecules of rhodopsin per eye. About 120 million rods. Each molecule of rhodopsin is capable of capturing 1 photon of light. Peak sensitivity for rhodopsin is **507 nm (highest probability of absorption, and appear brightest)**. The absorption of only one photon of light will bleach a molecule of rhodopsin. Probability that a bleached molecule of rhodopsin will revert back to a non-bleached state over a five minute period is 50%. Half life for regeneration of rhodopsin is 5 minutes.

Compare the effects of 1000 quanta of 507 nm and 1000 quanta of 580 nm. Assume that the rhodopsin absorption curve gives a probability of 0.20 that a quantum of 507 nm will be absorbed, and a probability of 0.10 that a quantum of 580 nm will be absorbed. The 507 nm will bleach 200 rhodopsin molecules ( $0.20 \times 1000 = 200$ ). 580 nm will bleach 100 molecules. If the intensity of the 580 nm light was doubled to 2000 quanta, it now would produce the same number of absorptions as does the 1000 quanta of 507 nm. Thus producing the same effect, making it impossible to distinguish between the 2 stimuli based on the number of quantal absorptions. This is referred to as the **principle of univariance**. **Univariance occurs b/c once a quantum of light is absorbed, all info about wavelength is lost.**

Scotopic spectral sensitivity of a person: scotopic spectral sensitivity curve is the same as the rhodopsin absorption spectrum. Shows that the human scotopic spectral sensitivity function is determined by the absorption spectrum of rhodopsin.

Cone photopigments: unlike rods, human cones do not all contain the same photopigment. There are 3 fundamental cone photopigments, with each cone containing only 1 type of photopigment. 3 photopigments are **erythrolabe, chlorolabe, and cyanolabe**.

Erythrolabe: long-wavelength cones (L-cones)

Chlorolabe: middle-wavelength cones (M-cones)

Cyanolabe: short-wavelength cones (S-cones)

Only takes about 1.5 minutes for 50% of the cone photopigment to recover following bleaching.

Photopic spectral sensitivity:

Determined under daytime conditions. Photopic sensitivity is a fn of wavelength. **555 nm** is the peak of sensitivity (and appear brightest). Curve only due to M and L cones. S cones apparently do not contribute to photopic spectral sensitivity.

#### Photochromatic interval:

Plot photopic and scotopic curves on same graph. **Difference in sensitivity between scotopic and photopic systems, for a given wavelength, is referred to as the photochromatic interval.** Scotopic system is more sensitive than the photopic system at all wavelengths, except in the long wavelength region of the spectrum. In this area, the photochromatic interval is approximately zero and rods and cones are almost equally sensitive.

#### Purkinje Shift:

The scotopic and photopic spectral sensitivity curves are based on threshold data. They can be used to predict the relative brightness of stimuli that are above threshold - suprathreshold stimuli.

The change in peak sensitivity from scotopic (507 nm) to photopic (555 nm) is the basis for the Purkinje shift. Purkinje noted that as illumination increases, longer wavelengths appear relatively brighter. This is consistent with a shift from rod-mediated vision, with a peak sensitivity of 507 nm, to cone-mediated vision, where the peak sensitivity is 555 nm.

#### Retinal distribution of photoreceptors:

Rods are densest 20 degrees from the fovea (150,000 rods/mm<sup>2</sup>). Cones (M & L) are densest in the fovea (150,000 cones/mm<sup>2</sup>). But there are still cones present all the way out to the peripheral retina. Only about 4% of all cones are in the fovea.

S-cones show a different distribution. Considerably less numerous, and none are in the fovea. Peak density is just outside the fovea. Accounts for the inability to see very small blue objects when they are foveally fixated. The ratio of L cones to M cones is 2:1. Total number of cones is about 6 million (120 million rods).

#### Dark adaptation:

After exposure to an adapting light, rods and cones recover sensitivity at different rates.

Dark adaptation curve important features: most obvious is that over a period of about 35 minutes, threshold improves by about 5 log units (after 35 minutes in the dark, the person is 100,000 times more light sensitive). Another imp. feature of the curve is the division in its two sections. First section shows a rapid reduction in threshold up to about 5 minutes, where the curve plateaus. This portion of the dark adaptation curve represents cone thresholds. At about 10 minutes, there is an abrupt change in the slope of the curve. This break in the curve referred to as the **rod-cone break**, is followed by a slow reduction in threshold out to about 35 minutes. This portion of the curve represents detection by the rods.

Difference between the two threshold lines (about 3 log units) represents the difference in cone and rod thresholds (photochromatic interval).

The recovery in sensitivity that occurs during dark adaptation is related to the regeneration of photoreceptor photopigments. But photopigment regeneration does not fully explain dark adaptation.

#### Effects of stimulus wavelength

Dark adaptation curve is made using 420 nm light. If use 650 nm light, rod portion is missing. Explained by looking at the photochromatic interval. At 650 nm the interval is zero. Scotopic and photopic systems are equally sensitive, so there is no rod-cone break.

### Physiologic Basis of Dark Adaptation:

**Photochemical explanation:** solely dependent on regeneration of photopigment. Regeneration of photopigment increases probability of quantal absorption and so threshold is reduced. But if you bleach 50% of the rhodopsin it should double the threshold. But in reality it increases the threshold by  $10^{10}$ . So other factors clearly play a role. Likely that postreceptor and receptor factors likely contribute.

### Light adaptation

Studied using an **increment threshold procedure**. Threshold determined by presenting a light on a background light. Light presented on background is of increment  $\Delta I$ . After threshold determined, background intensity is increased and threshold remeasured. Scotopic portion is parts 1 - 4. Section 1 is due to neural noise present in extreme darkness (light seen is so called dark light). Section 2: slope of 1/2. Follows DeVries-Rose Law ( $\Delta I = I_b^{1/2}$ ). Due to fluctuations in background light. Section 3: slope is 1. 4 log unit range. Weber's Law is followed. Shows that as the background is increased, the increment intensity must be increased such that the ratio of the increment intensity to the background intensity remains constant. Weber's fraction here is 0.14 (if background has 100 units of intensity, the increment must have an intensity of 14).

**Saying that the visual system follows Weber's law is the same as saying that the threshold contrast remains constant as the illumination changes.**

Section 4: rods are fully saturated. Occurs when 10 percent of rhodopsin is bleached. Results in a closure of sodium channels located in the rod outer segment. Reduces flow of sodium into the outer segment and leads to rod hyperpolarization.

Photopic portion (section 5): slope of 1 indicates that Weber's law is followed. Photopic weber's fraction is 0.015, showing that the photopic system is more sensitive to contrast than the scotopic system. Cones do not show a saturation effect.

### Spatial Resolution and Spatial Summation:

Visual resolution is superior under photopic conditions, we are more sensitive under scotopic conditions. Rods are connected in a manner to sum up info over space. Produces great sensitivity, but poor resolution. Cones have connections that maximize resolution at the expense of sensitivity.

Many more rods are connected to a ganglion cell than compared to cones. Show that rods sum up info over space = spatial summation (scotopic system).

But, it is important to know that less than 20 percent of the quanta incident on the retina are absorbed by rhodopsin (due to reflections and preabsorption by other elements).

Ricco's Law = up to 10 minutes arc, the critical diameter, the scotopic system manifests total spatial summation. ( $IA = K$ ). I = stim intensity. A = stimulus area K = constant

### Temporal Resolution and Temporal Summation:

**Scotopic system** sums up info over time to a greater extent than the photopic system. **Greater temporal summation.**

**Photopic system = better temporal resolution** (can distinguish two separate flashes of light better than the scotopic system).

Two subthreshold flashes of light to scotopic system will be summed up and subject will see 1 flash of light.

**Scotopic temporal summation period is 100 msec.**

**Photopic temporal summation period is 10 msec - 50 msec.**

Summary: scotopic system has good spatial and temporal summation, while the photopic system has better spatial and temporal resolution.

**Bloch's law: temporal equivalent to Ricco's law (It = K)**

**(think bloch as a block of time)**

Critical duration = duration at which there is temporal summation.

Stiles Crawford Effect of the First Kind:

Angle at which light rays are incident on rods is relatively insignificant.  
Angle is significant for cones.

**Stiles-Crawford Effect (first kind)= Rays that strike cones perpendicular to there surface are perceived as brighter.**

(2nd kind = change in hue and saturation of monochromatic light as the point of entry into the pupil is changed.)

1st kind again:

Probably due to waveguide properties of the cones. Quantum of light is similar in size to a cone. Makes angle of entry into the funnel shaped cone critical. Normally cones point toward the center of the pupil. Cones are mobile and can orient themselves to light.

Clinical considerations:

Hill of vision: sensitivity is greatest in fovea and falls off toward periphery (for photopic conditions). Used with age-matched norms for VF testing.

Dark adaptation: imp in diagnosis of RP.

Summary of Features of the Scotopic and Photopic Systems:

<u>Property</u>	Scotopic	Photopic
Receptor	Rods	Cones
Outer segment morphology	Sep. Disks	Disks are infoldings of membrane
Weber's fraction	0.14	0.015
Photopigments & peak abs	Rhodopsin (507 nm)	Erythrolabe (565 nm) Chlorolabe (535 nm) Cyanolabe (430 nm)
Maximal sensitivity of system	507 nm	555 nm
Chromatic Discrimination	colorblind	color discrimination
Sensitivity	dim lights	bright lights
Spatial resolution	20/200	20/20
Spatial summation	excellent	poor
Temporal resolution	poor (20 Hz)	excellent (70 Hz)
Temporal summation	excellent	poor
Contrast sensitivity	low	high
Stiles-Crawford Effect	minimal	yes

Self assesment questions

1. Rod monochromat eyes are missing most of their cones; vision is dominated by rods. A. Describe the symptoms you expect a patient who is a rod monochromat to manifest. B. What color sunglasses would you recommend for a patient who is a rod monochromat?

- A. Photophobia, squinting, poor daytime vision, reduced VA (20/200), nystagmus, poor fixation
- B. Red sunglasses b/c long wavelength light is less effective at bleaching rhodopsin

2. Stimuli of 507 and 555 nm are placed side by side. These stimuli are bright and are detected by the photopic system. An observer is asked to adjust the intensities of the stimuli so that they are equally bright. The intensities of the two stimuli are reduced by the same amount such that they are detected by the scotopic system. Under these scotopic conditions, which stimulus appears brightest?

- A. 507 nm b/c scotopic peak sensitivity is at 507 nm.

3. Name the wavelength that is most effective at bleaching rhodopsin.

507 nm b/c that is the peak sensitivity.

4. Refer to figure 3-10. A. After 20 min of dark adaptation, what is the color of the 610 nm stimulus at threshold. B. Answer the same question for the 465 nm stimulus.

- A. Red (still mediated by cones)
- B. No color b/c it is mediated by scotopic system

5. Refer to figure 3-10. A. After 1 hour of dark adaptation, what is the difference in sensitivity between the rods and cones for a stimulus of 465 nm? B. Answer the same question for the 610 nm stimulus.

- A. About 4 log units (photochromatic interval)
- B. About 0.5 log units (photochromatic interval)

6. The cones are exposed to a bright light source that bleaches much of their photopigment. After 3 minutes in the dark, what percentage of the bleached cone photopigment has recovered? B. What percentage of the rod photopigment have recovered at the rod-cone break for a 610 nm stimulus.

- A. After 1.5 minutes 50% of the bleached photopigment has regenerated and 50% remains bleached. Over the next 1.5 minutes 50% of the remaining bleached pigment regenerates ( $0.5 \times 0.5 = .25$ ). So the total is 75%.
- B. The rod cone break occurs at about 35 minutes. The half-life for rho regeneration is about 5 minutes. Therefore, after about 5 minutes, 50% of the rho has regenerated. And after 10 min, 75% has regenerated. Carrying this out to 35 minutes means that about 99.25% of the rho has regenerated.

7. Refer to figure 3-8. A. What is the rod threshold after about 11 minutes of dark adaptation for a large 420 nm stimulus? B. For the same 420 nm stimulus, what is the cone threshold after 20 min of dark adaptation? C. What is the photochromatic interval for 420 nm?

- A. 6 relative log units
- B. About 3.75 relative log units
- C. About 3 log units

8. 2 patches of light are adjacent to each other. The conditions are scotopic. One patch emits light of 507 nm and the other emits light of 620 nm. Both patches produce 40 quanta of light. Which patch is brighter? B. A patch of 507 nm and a patch of 620 nm each bleach 30 rhodopsin molecules. Which patch is brighter?

- A. 507 nm is brighter.
- B. Both are the same b/c they both bleach the same # of rho molecules.

## **Photometry**

**Radiometry = measurement of the power produced by a source of electromagnetic radiation.**

**Photometry = effect this radiation has on the visual system.**

Photopic luminosity curve = shows luminous efficiency as a fcn of wavelength. Has a form that is very similar to the photopic spectral sensitivity curve. Basically, the photopic luminosity fcn shows how efficient we are at detecting different wavelengths of light.

**Lumen = basic unit of photometry. A measure of luminous power (compared to a watt which is a unit of radiant power).**

680 lumens / watt @ 555nm.

Wavelengths other than 555nm are less efficient and yield fewer lumens per watt.

Calculating total luminous power:

600 nm light. Radiant power is 10 watts. The luminous efficiency off the curve at 650 nm is 0.62.

$(0.62)(680 \text{ lumens / watt})(10 \text{ W}) = 4216 \text{ lumens}$

But in comparison to 400 nm of light with 10 W, the total lumens here is about zero b/c the luminous efficiency at 400 nm is zero.

**Abney's Law of Additivity:**

To calculate the total luminous power of light that is not monochromatic (not just one wavelength), you figure out the luminous power from each wavelength and then add these values together.

**This works b/c the photometric system is additive, and this property is referred to as Abney's Law of Additivity.**

**Luminous intensity:**

Luminous power is a nondirectional measure. It is useful for expressing the total light power produced by a light source in all directions. Luminous intensity refers to the number of lumens produced in a given direction by a point source of light. Units are lumens per steradian. One lumen per steradian = one candela. A steradian is a solid angle. It is a conic section of a sphere.  $\text{Steradian (w)} = A/r^2$ . A is surface area of sphere. r is radius.

Given the intensity of a point source, the total number of lumens produced by this source may be calculated if the source is uniform in its output. This calculation is based on the fact that a light source with an intensity of 1 cd, which has equal output in all directions, produces a total power of  $4(\pi)$  lumens.

**Luminance:**

Luminance is similar to luminous intensity, except that it refers to an extended source, which is a large source like a wall. **Luminance is basically the brightness of a surface. Common units are candelas / square meter and foot-lamberts.**

Just as the brightness of a surface does not change with viewing distance, luminance does not change with viewing distance. As the viewing distance increases, the projected surface area decreases at the same rate as does the number of candelas contained within the projected surface. This results in a constant ratio of candelas to projected surface area and therefore, the luminance remains constant.

**Illuminance:**

Refers to the luminous power that falls on a surface. Units are lumens / square meter (lux) and lumens / square foot (foot-candles). Think of illuminance as being analogous to rain. The greater the density of rain drops (lumens) the harder it is raining (the greater the illuminance). Illuminance is unrelated to the surface upon which it is falling.

Summary of this:

**Luminous power** = total light power produced by a source. Units are lumens.

**Luminous intensity** = light power produced in a solid angle by a point source. Units are lumens / steradian or candelas. 1 lumen / steradian = 1 candela.

**Luminance** = luminous intensity per unit projected area of an extended source (wall). Units are **candelas / square meter** or foot-lamberts.

**Illuminance** = luminous power falling on a surface. Units are **lumens / square meter (lux)** or lumens / square foot.

### **Cosine diffusers:**

A cosine surface shows the same luminance regardless of the angle at which its luminance is measured. Cosine surfaces are also referred to as Lambert surfaces, perfectly diffusing surfaces, or matte surfaces. **Remember, a cosine surface has the same luminance regardless of viewing angle.**

$L = rE$        $L$  = luminance     $r$  = reflectance factor (0 to 1)     $E$  = illumination in foot-candles

### **Inverse Square Law:**

As a surface is moved away from a point source, the # of lumens falling on the surface decreases with the square of the distance.

$E = I / d^2$      $E$  = illumination falling on the surface.     $I$  = intensity of the point source.  
 $d$  = distance from the point source to the surface.

### **Retinal Illumination:**

Takes into account the area of the pupil.

$T = LA$        $T$  = retinal illumination in trolands     $L$  = luminance of the surface that is viewed  
 $A$  = pupil area

### **Scotopic Units:**

So far our discussion of photometry has concerned photopic vision. Now lets talk about scotopic units. The basic unit is the scotopic lumen. Have to look at the scotopic luminosity fxn. **The peak is at 507 nm. There are 1700 scotopic lumens / W at 507 nm.**

Use the following proportionality to figure it out:

Luminous efficiency of 555 nm/680 scotopic lumens = luminous efficiency of 507 nm / X

$0.4 / 680 = 0.2 / X$        $X = 1700$

Scotopic lumens can be confusing. It is important to keep in mind that by definition there are **680 scotopic lumens per watt at 555 nm**, and **555 nm is the peak of the photopic luminosity fxn**. The **peak of the scotopic fxn is at 507 nm**.

### **Derivation of the Photopic luminosity fxn:**

So far we have assumed that this fcn is related to brightness. This is true, but is not the whole story.

If the photopic luminosity fcn truly represents brightness, you could perform a direct brightness matching procedure. But this is hard to do b/c a person has to match the brightness of different wavelengths (colors). Person must ignore the color differences, and this is really hard to do.

Solution: **Use heterochromatic flicker photometry (HFP).**

In this procedure, person views two monochromatic stimuli that are alternated back and forth. The observer's task is to adjust the brightness until no flicker is seen.

If you use red and green as the 2 monochromatic colors and alternate them at 15 cycles per second, a person will see an orange color that is flickering. The person's job is to then adjust the brightness of the red and green colors until the flicker is minimized. This is then repeated across the spectrum.

Can also use **minimally distinct border method (MDB)**. Here the person views two monochromatic wavelengths side by side such that a border is seen where they meet. Person then adjusts the brightness until the appearance of the border is reduced. When repeated across the spectrum, a photopic luminosity fcn is obtained. As with HFP, MDB produces highly reliable results.

**The results of HFP and MDB follow Abney's Law of additivity. Direct brightness matching procedures do not.**

**Specification of light sources:**

2 categories = incandescent and luminescent.

Incandescent = generates light by being heated

Luminescent = generates light by excitation of gas molecules which then release light when they return to their unexcited state. Common example is the fluorescent tube.

Incandescent = has more long-wavelength light.

Luminescent = more spikes across the spectrum and more low wavelength light.

**Blackbody radiators and color temperature:**

Blackbody radiator = theoretical source. A perfect radiator of electromagnetic energy.

Convenient feature of a blackbody radiator is that its spectral output is totally defined by its temperature.

**Wein's displacement law:** peak wavelength proportional to  $1/T$   
(shows relationship between spectral output and temperature)  
**(as temperature increases, peak wavelength decreases)**

**Stefan-Boltzman Law:** Total power proportional to  $T^4$

**Color temperature:** temperature in degrees Kelvin of the blackbody radiator with an output that most closely matches your light of interest.

So if you compare a 2000 K and a 10,000 K light, the 2000K light will appear more yellow-white while the 10,000 K light will appear more blue-white (higher temperature has more short wavelengths in it).

**Color temperature is only used for incandescent sources.**

**Flourescent (luminescent) sources use correlated color temperature.** This depends on the nature of the phosphor used to coat the bulb.

## Standard Illuminants:

Illuminant A = represents an incandescent bulb

Illuminant B & C = represent sources with higher blue concentrations. Illuminant C is used for color vision tests.

## Filters:

Colored filters: absorbs some of the wavelengths that are incident on it and transmits other wavelengths.

**Narrow band filter:** passes only a **narrow spectrum of light**. **Specified by the location of their peak and their half-height bandwidth. Smaller the half-height bandwidth, the more selective the filter.**

Example: if the percent transmission of a filter is 60% at a peak wavelength of 550, you go to the 30% transmission mark (half-height or 1/2 of 60%) and the range of wavelengths passed is from 528 to 552 nm.  $552 - 528 = 24$  nm. 24 nm is the half-height bandwidth. (see page 84 for picture).

**Interference filters:** often have very small half-height bandwidths. **Can be thought of as only passing 1 wavelength.** Are essentially monochromatic.

**Broad-band filters:** transmit a broad range of wavelengths.

**Long-pass filters:** transmit long wavelengths, but not short.

## Subtractive and additive Color mixtures:

**subtractive color mixture:** two colored filters in a row. **Only the light that is common to the two filters is transmitted (light represented by the overlap of the two transmission curves).** Called subtractive color mixture b/c the 2 filters transmit less light than either filter alone. When you **mix paints** together you are making a subtractive color mixture.

Additive color mixture: light from two sources is added together. Contains more light than that emitted by either of the two filters alone. Done when you **shine 2 lights onto a screen (tvs and movie screens).**

## Neutral density filters:

Flat transmission curve. Minimize color distortion. Transmit all wavelengths equally.

$$OD = \log (1/T)$$

**Advantage of specifying optical density in log units is that these values are then additive. If we place a 1 log filter and a 2 log filter back to back, the combination is a 3 log filter (OD = 3).**

Summary: Radiometry refers to the power produced by electromagnetic sources. It does not take into account the visibility of these sources. Photometry does. This is done through the photopic luminosity fxn. Photopic luminosity fxn provides the basis for an additive photometric system.

The spectral distribution of a light source can be given by specifying the source's color temperature or correlated color temperature.

## Self-Assessment Questions:

1. A light source and filter combination produces 1000 lumens. The filter is monochromatic with peak transmission at 600 nm. How many watts are transmitted by the filter?

There are 680 lumens / W at 555 nm. So at 600 nm the luminous efficiency is 0.62

Formula:

**(# watts) x visual efficiency x 680 = lumens**

$$(\# \text{ watts}) \times 0.62 \times 680 = 1000 \text{ lumens}$$

$$\# \text{ watts} = 2.37 \text{ W}$$

2. A source produces 10 W at 500 nm, 5 W at 550 nm, and 20 W at 650 nm. How many lumens are produced?

$$(\# \text{ watts}) \times \text{vis. effic.} \times 680 = \text{lumens}$$

$$(10 \text{ W}) \times 0.35 \times 680 = 2380$$

$$(5 \text{ W}) \times 1.00 \times 680 = 3400$$

$$(20 \text{ W}) \times 0.10 \times 680 = 1360$$

$$\text{Total} = 7140 \text{ lumens}$$

3. For the data in question 2, give the number of scotopic lumens produced.

There are 680 scotopic lumens / W at 555 nm. The number of scotopic lumens per watt at other wavelengths is determined by a proportionality factor.

$$500 \text{ nm: } (10\text{W}) \times 1.0/0.4 \times 680 = 17,000$$

$$550 \text{ nm: } (5\text{W}) \times 0.50/0.4 \times 680 = 4250$$

$$650 \text{ nm: } (20\text{W}) \times 0 \times 680 = 0$$

$$\text{Total} = 21,250 \text{ scotopic lumens}$$

4. An illuminance probe is used to measure the illuminance in a classroom. The reading obtained is 70 foot-candles. The probe measures 3 x 3 cm. How many lumens are incident on the surface of the probe?

Area of the probe is  $0.0097 \text{ ft}^2$ . Therefore,

$$70 \text{ lumens} / \text{ft}^2 \times 0.0097 \text{ ft}^2 = 0.67 \text{ lumens}$$

5. A device measures irradiance. You would like to convert this device into an illuminance probe. How do you do this?

Place a filter with the transmission characteristics of the  $V(\lambda)$  function (luminosity fcn) in front of the probe. The device would then need to be calibrated.

6. A point source has an intensity of 100 cd. What illumination does it produce at a distance of 2 ft? Give your answer in both foot-candles and lux ( $\text{lumens}/\text{m}^2$ ). Assume there are 10 lux per foot-candle.

$$E = I / d^2$$

$$E = 100 \text{ lumens} / 2 \text{ ft}^2 = 25 \text{ lumen} / \text{ft}^2 \text{ or } 25 \text{ foot-candles.}$$

$$\text{Convert to lux: } 25 \text{ foot-candles} \times 10 \text{ lux} / \text{foot-candle} = 250 \text{ lux}$$

7. A point source of 50 cd is 1 ft from a sheet of paper. Another point source at 3 ft from this same piece of paper illuminates the paper equal to the first source. What is the intensity of the point source?

$$E_1 = E_2$$

$$I_1 / d_1^2 = I_2 / d_2^2$$

$$50 \text{ cd} / 1 \text{ ft}^2 = x / 3 \text{ ft}^2$$

$$X = 450 \text{ cd}$$

8. A neutral density filter absorbs 75 percent of the light incident on it. What is the OD of the filter?

$$\begin{aligned} \text{OD} &= \log(1/T) \\ \text{OD} &= \log(1/.25) \\ \text{OD} &= \log 4 \\ \text{OD} &= 0.60 \end{aligned}$$

9. A neutral density filter is combined with a 1.0 neutral density filter.
- How much light (as a percentage) does the combination transmit?
  - How much is absorbed?

A.

$$\begin{aligned} \text{OD} &= \log(1/T) \\ 1.5 &= \log(1/T) \\ 1/T &= 10^{1.5} \\ T &= 0.032 \end{aligned}$$

Percent transmitted = 3.2 %

B. 96.8% is absorbed

10. A matte surface with a reflectance factor of 0.7 has a luminance of 50 foot-lamberts. What is the illuminance falling on the surface?

$$\begin{aligned} L &= rE \\ 50 &= 0.7 \times E \\ E &= 71.43 \text{ foot-candles} \end{aligned}$$

11. By use of the inverse square law and an illuminance device, the intensity of a point source is determined to be 25 cd. Assume this uniform point source produces the same amount of light in all directions. How many total lumens does it produce?

$$25 \text{ cd} \times 4\pi \text{ lumens / cd} = 314 \text{ lumens}$$

12. A light source is located 3 ft from a matte surface. The illumination falling onto the surface is 100 lux. The luminance factor of this surface, at an angle of 30 degrees, is 5 foot-lamberts. What is the reflectance factor of this surface?

Convert 100 lumens / m<sup>2</sup> to foot-candles:

$$100 \text{ lumens / m}^2 \times (1 \text{ foot-candle/ } 10 \text{ lumens/m}^2) = 10 \text{ foot-candles}$$

$$\begin{aligned} L &= rE \\ 5 &= r(10) \\ r &= 0.5 \end{aligned}$$

### **Color Vision**

Trichromatic Theory: condition where given four or more wavelengths, divided into two patches, the individual is able to adjust the relative intensities of these wavelengths such that the two patches appear identical. The two patches appear identical b/c they result in the same number of quantal absorptions by each of the three photopigments. They are metamers.

Monochromacy: person has only 1 photopigment and has no color discrimination.

Univariance: once a quantum of light has been absorbed, all info regarding its wavelength is lost.

Monochromat shown two patches of light can distinguish between the 2 based on brightness. But if we make the number of quantal absorptions the same between the two patches, the person will not be able to distinguish the

two. Person is therefore unable to distinguish objects on the basis of wavelength alone.

Dichromacy: person has 2 photopigments (M & L), which peak at different wavelengths and which overlap through much of the spectrum. Person can match a light of 1 wavelength to a patch of light made up of 2 wavelengths. Person can therefore become confused by lights made up of 3 wavelengths.

Metamers: two stimuli that appear identical but are physically different.

**Grassman's Laws (of metamers):** describe the general characteristics of trichromatic vision.

1) **Additive Property:** when the same radiation is added in an identical manner to 2 metamers, they remain metamers.

2) **Scalar property:** if the intensity of 2 metamers are increased (or decreased) by the same amount, they remain metamers.

3) **Associative property:** a match will be maintained if one metamer is substituted for another metamer.

### **Absorption Spectra of the Cone Photopigments:**

Retinal densitometry: dim light is cast onto the retina. Some light is reflected back and the amount of reflected light is measured. The amount reflected is less than the amount incident because of retinal absorption. If this is repeated across the spectrum, it is possible to obtain absorption spectra for the retinal photoreceptors. But, it is necessary to examine retinal areas that have only one type of cone. This is done by projecting the light into the fovea of a red-green dichromat (missing either the M or the L cone). As the fovea does not have S-cones, the foveas of these folks have only 1 photopigment. Retinal densitometry is not sensitive enough to allow determination of the photopigment absorption characteristics in the tails of the curves. This is an important consideration b/c the tails of the photopigment spectra are critical for predicting color matching data.

**Microspectrophotometry:** retinal tissue is back-illuminated with monochromatic light. The light beam is directed toward a single cone. The difference between the amount of light transmitted through the cone is determined. This is repeated across the spectrum.

### **The molecular genetics of cone photopigments:**

Each molecule of cone photopigment consists of the **chromophore** and an **opsin**. The chromophore, which is identical for all cone photopigments, is **retinal**, an aldehyde derivative of retinol (vitamin A). The opsin determines the absorption characteristics. Each class of cones has a different opsin.

The genes for the cone photopigments are homologous to the rhodopsin gene, suggesting that all four genes evolved from the same ancestor.

The M & L cones show a 98 percent homology. The S-cone photopigment gene is only 40 % homologous, showing that it evolved at a different time.

### **Color Labels:**

**Color is typically specified along 3 perceptual dimensions: hue, saturation, and brightness.**

Hue: perception most closely associated with wavelength.

Saturation (and Desaturation): desaturated color appears as if it is mixed with white. Pastels are examples. Saturated colors appear to be full of color.

Saturation is wavelength dependent. For example, 570 nm appears less saturated than other wavelengths.



Color opponent neurons tell us that the receptor info is coded in an opponent fashion at postreceptoral levels.

### **Parvo and Magno Pathways:**

Parvo: color opponent  
Magno: noncolor opponent

### **Munsell Color Appearance System:**

Allows us to describe colors with a great detail of specificity. Specifies colors along 3 physical dimensions: hue, chroma, and value.

**Hue:** related to **wavelength**

**Chroma:** kind of like colorimetric purity and is **related to saturation** of the color

**Value:** **refers to the reflectance** of the sample and is **related to brightness**.

### **The CIE Color Specification System:**

Describes a color by specifying the mixture of 3 primary colors required to match a given color sample. The CIE primaries are not real primaries they are imaginary.

**R, G, B System:** match a color by mixing necessary amounts of R, G, B

When done across the spectrum, you get the **color matching fxns**. The quantity of each primary required for a match is referred to as the **tristimulus value**. Problem is that sometimes a negative amount of color is needed for a match.

**CIE system was created to overcome the problem of having negative values.**

The R,G, B color matching fxns are mathematically transformed into color matching fxns for the 3 imaginary primaries called X,Y,Z. All wavelengths can be matched with positive quantities of these primaries; it is not necessary to have negative quantities.

**CIE chromaticity diagram shows the relative amounts of the imaginary primaries required to match any real color.**

**Tristimulus values** are given by **uppercase** letters, whereas the **chromaticity coordinates** on the CIE diagram are given **lowercase** letters.

$$x = X / X + Y + Z \quad y = Y / X + Y + Z \quad z = Z / X + Y + Z$$

**Sum of the chromaticity coordinates must equal 1.**

Basic attributes of the CIE Chromaticity Diagram:

All physically realizable colors are contained inside the diagram.  
Imaginary primaries fall outside the diagram as they are not physically realizable.  
Spectral hues (monochromatic hues) are arranged along the arc of the perimeter.  
**Arc** is referred to as the **spectral locus**.  
Nonspectral purples fall along the straight line connecting 400 and 700 nm.

Calculations:

Color mixtures can be calculated by joining together with a line the colors to be mixed. The resultant mixture falls at the midpoint of this line (if equal quantities are mixed).  
If we then connect the midpoint of the line with point W (white), these two lines will intersect at a point on the arc = **dominant wavelength** of the mixture.



As the stimulus intensity increases, the red-green channel remains "neutralized" and there is no change in hue.

### **Anomalies of Color Vision:**

About 4.5% of the population has color vision defects.

**Acquired defects** are less common than **hereditary defects**. Acquired defects are usually secondary to disease.

Color deficiencies can be divided into two general categories:

1. Dichromacy - missing 1 of the 3 photopigments
2. Anomalous trichromacy - absorption spectra of 1 of the pigments is displaced.

Dichromats:

**Deuteranope:** missing chlorolabe (**M cone**)

**Protanope:** missing erythrolabe (**L cone**)

**Tritanope:** missing cyanolabe (**S cone**)

The missing pigment is replaced by another photopigment - referred to as the **replacement model of dichromacy** (b/c they do have normal VA so they do not have a decreased number of cones).

Deuteranomalous trichromat: M-cone displaced toward longer wavelength

Protanomalous trichromat: L-cone displaced toward middle wavelength

Terms protan, deutan, and tritan refer to the affected photopigment.

Protans and deutans tend to confuse red and green; usually inherited.

Tritans confuse blues and yellows; usually acquired.

Dichromats manifest luminance fns that differ from the normal photopic luminosity fxn.

Protanopes show a luminance curve displaced toward shorter wavelengths.

Deuteranopes show a luminance curve displaced toward longer wavelengths.

The photopic luminosity fxn is presumably due to the addition of the M & L cone inputs so it makes sense that dichromacy will cause the fxn to be displaced.

**Deuteranopes show less of a shift toward longer wavelengths than do protanopes who have a more pronounced shift toward shorter wavelengths = means that L cones have more input into the luminosity fxn than do the M cones.**

Protanopes have trouble seeing long wavelengths = red

Deuteranopes have trouble with medium wavelengths = green

Wavelength Discrimination:

Above 545 nm, both protanopes and deuteranopes are not able to discriminate between stimuli on the basis of wavelength differences alone. Basically they are monochromats above 545 nm. They make differences on brightness.

### **Confusion lines:**

Each set of confusion lines originate from a copunctal point. All colors falling on a confusion line are indistinguishable to the dichromat.

Deuteranopes and protanopes share a confusion line that is tangential to the right side of the CIE diagram.

## Saturation:

Dichromatic neutral points: wavelengths that appear white to a dichromat. 498 nm for deuteranope and 492 for a protanope. See page 148 and 149 in Schwartz.

## Hereditary Color Vision Anomalies:

Vast majority of red-green defects are inherited in a sex-linked, X-linked recessive manner. Tritan defects are inherited in an autosomal dominant manner.

Prevalence of R-G defects in men is about 8% and only 0.4% in women. Color deficient boy always receives the gene from the mom.

It should be assumed that blue-yellow defects are acquired b/c they are rare = so until proven otherwise assume blue-yellow defects are acquired.

## Summary of distinctions between hereditary and acquired defects:

<u>Hereditary</u>	<u>Acquired</u>
typically R-G	Often B-Y
More in males	equally prevalent in males and females
Same in each eye	often asymmetry between the two eyes
Color naming errors rare	recent history of color naming errors
Defect is stable w/ time	unstable and changes w/ time
Easily classified	classification not straightforward
Not assoc. w/ disease	assoc. w/ disease or toxicity

\*important to perform color vision tests monocularly

**Kollner's Rule = outer retinal disease and media changes will produce B-Y defects. Inner retina, optic nerve, visual pathways, or visual cortex will be R-G**

## Achromatopsias:

Patient behaves as a monochromat and often has nystagmus, photophobia, and reduced VA

Most common is rod monochromacy. Patients may have M & L cones but in decreased numbers. Inherited in an autosomal recessive manner.

Blue cone monochromacy: only have rods and S-cones. Inherited in an X-linked recessive manner.

Cone monochromacy: VA is normal, yet the patient behaves as a monochromat.

## Chromatopsias:

Represent a distortion of color vision. Frequently follows CAT extraction. Patient has been accustomed to looking thru a yellow filter that filters blue light. After removal, patient is now exposed to more blue light and it results in a perception of blueness (cyanopsia).

-----

Desaturated D-15 test is useful for detecting minor changes often found in the early stages of disease like glaucoma.

**Nagel anomaloscope** allows the complete diagnosis of red-green defects. It is the only clinical instrument that can be used to differentiate dichromacy from anomalous trichromacy.

Patient views a bipartite field which is composed of an upper mixture field and a lower test field. Mixture field is of green and red. Test field is yellow. Normal trichromats adjust the top field to a value of about 45 and the lower field (the brightness) to a value of about 17.

Deuteranopes vs. Protanopes on the anomaloscope:

Deuteranopes will match any mixture field setting with a test field setting of about 17. This occurs b/c the luminosity fcn of a deuteranope is similar to that of a normal subject. Since the luminance of the mixture field is designed to remain constant, deuteranope can adjust the top field to any setting and it will match the bottom.

Protanope has a luminosity fcn that is different from that of a normal person. Protanopes luminosity fcn is displaced toward shorter wavelengths. Protanopes will adjust the radiance of the test field. 670 nm (red) appears dim whereas 546 appears bright.

Lighting conditions for color vision testing:

Need a MacBeth Lamp or standard illuminant c glasses.

Self-Assessment Questions:

1. A color defective patient is unable to read the numbers given in a pseudoisochromatic plate test A. Will he be able to read these numbers when viewing thru a red filter? B. Explain.

A. Typically yes.

B. By wearing a filter, the patient has formed a subtractive color mixture with the plate and eliminated the metamerism of the plate.

2. A normal trichromat matches the mixture fields in the Nagel anomaloscope. A. Will the two fields appear matched when they are viewed through a red filter? B. Describe the appearance of the mixture and test fields when viewed through this red filter.

A. No

B. Top mixture field appears red and the bottom test field appears black. The red filter transmits only the longer wavelengths that emerge from the anomaloscope (subtractive mixture). Consequently, for the top mixture field, only red is transmitted. For the bottom test field, little or no light is transmitted.

3. A normal trichromat matches the mixture and test fields in the anomaloscope. He or she then observes a large, bright red, adapting light for several minutes. Following this red adaptation, he observes the original match. A. Does the match between the mixture and test field still hold? B. Describe the appearance of the mixture and test fields.

A. Yes.

B. Both the mixture and test field appear green. Exposure of the eye to a red light produces a disproportionate bleaching of erythrolabe. The result is that subsequently viewed objects appear relatively more green. This is true for the mixture and test fields which initially appeared yellow. They remain metamers, but now appear green.

4. A rod monochromat is tested on an anomaloscope. A. Describe the test field settings that are expected to match 546 and 670 nm.

670 is matched by a very dim yellow test field, whereas 546 is matched by a relatively bright test field. The scotopic spectral sensitivity curve peaks at 507 nm, so 546 is brighter than 670.

**Spatial Vision:**

Spatial vision = perception of borders, lines, and edges.

Study spatial vision with sine wave gratings.

Need to specify 4 aspects of a grating:

1. **Frequency** (high spatial frequency = lots of tightly packed bars)
2. **Contrast** (contrast =  $\frac{\Delta I}{I_{ave}}$ )  $\Delta I$  = diff. in luminance between peak and avg. luminance
3. **Phase** (refers to the position of 1 grating with another - their peaks and troughs)
4. **Orientation** (refers to the angle made by a grating with respect to a reference angle)

Fourier analysis = can use sine waves to reconstruct any spatial stimulus (like a picture)

**Optical defocus results in a reduction of image quality at primarily high spatial frequencies.**

Human Contrast Sensitivity Fxn:

The grating appears to emerge out of the background. This border represents the contrast threshold for this grating. Human CSF is a band-pass fxn; it shows a distinct peak sensitivity and a decreasing sensitivity on either side of the peak. **Typical CSF peaks about 4 cycles/degree.**

**High-frequency cutoff:** reveals that there is a finite limit to the visual system's **ability to resolve detail**. Typically at **60 cycles/degree**. **Equivalent to VA. Due to packing density of retinal photoreceptors = called Nyquist theorem.**

Limitation of typical acuity charts: only a small portion of a person's CSF is measured.

The CSF in uncorrected refractive errors: reduction in high-frequency cutoff.

**Low-frequency dropoff:** due to **lateral inhibition in the retina**. Have to think of center-surround. Light falling on center excites, while light falling on surround inhibits. Cell is maximally activated when a bright light falls on the center and a dark light falls on the surround. When bright light (bar) falls on the surround = get inhibition.

**The visual system acts as a Fourier analyzer.**

**Mach bands:** demonstrate the usefulness of considering the visual system as a Fourier analyzer. Person views a stimulus that gradually gets darker = they perceive bands that are actually not present in the stimulus. The gradual transition between the bright and dark regions consists of low spatial frequencies. As the CSF manifests low sensitivity to low frequencies, these low frequencies are not perceived. The result is a relative enhancement of high spatial frequencies. This relative enhancement of high spatial frequencies results in the perception of enhanced boundaries (Mach Bands).

Contact lens patients and cataract patients can complain of poor vision despite seeing 20/20. Cataracts act as a diffuser that results in a decrease in contrast across all frequencies. CL's can cause edema that causes light scatter that also effects contrast. So these people can complain of poor vision despite seeing 20/20.

**Resolution acuity:** involves distinguishing a pattern (grating) from a uniform patch of light of equal luminance. For normal young adults the high frequency cut-off is typically 40-60 cycles/degree.

**Recognition acuity:** example is **Snellen acuity**. Person must be familiar with alphabet.

**Hyperacuity:** depends on visual systems ability to **sense direction** (like tilt). Very resilient to refractive errors unlike resolution acuity.

Self-Assessment Questions:

1. Determine the predicted high-frequency CSF cutoff, in cycles/degree, for the following VA's. A. 20/15 B. 20/80. C. 20/150

A. 20/15 --- MAR = 0.75' arc = each bar subtends 0.75' arc. So therefore a dark bar and a light bar subtend 1.50' arc. Convert this to cycles/degree.

$$1 \text{ cycle}/1.5' \text{ arc} = 60' \text{ arc}/1 \text{ deg}$$

40 cycles/degree

B. 20/80 ---- MAR = 4' arc ---- so 2 bars subtend 8'arc.

$$1 \text{ cycle}/ 8'\text{arc} = 60'\text{arc}/1 \text{ degree}$$

7.5 cycles/degree

C. 4.0 cycles/degree

2. A VA task is performed with a Snellen chart at 20 ft. Calculate the expected Snellen fractions for patients with the following high spatial frequency cutoffs. A. 5 cycles/degree B. 20 cycles/degree C. 60 cycles/degree

A. The cutoff was 5 cycles / degree. If the grating has 5 cycles in one degree, then each cycle must subtend 1/5 of a degree. Each cycle is composed of a dark bar and a light bar. The bars themselves represent the detail of the grating. Therefore, the detail is 1/2 of one cycle or  $1/2(1/5) = 1/10$  degree. This is the MAR in degrees. We must convert this MAR to minutes of arc.

$$1/10 \text{ degree} \times 60' \text{ arc}/1 \text{ degree} = 6' \text{ arc. Snellen fraction is therefore } 20/120$$

B. 20/30

C. 20/10

3. A patient has a Snellen fraction of 20/80. What would you predict the Snellen fraction to be when acuity is measured at 10ft?

10/40.

4. A patient shows a high-frequency CSF cutoff of 30 cycles/degree when tested at 20 ft. A. What is the expected high-frequency cutoff in cycles/degree when the procedure is repeated at 10 ft?

A. This measurement represents an MAR of 1' arc. This MAR does not change with distance. The size of the stimulus (grating acuity bars or acuity letters) required to produce this MAR will change, but the MAR remains constant. Consequently, the patient's high-frequency cutoff will be 30 cycles/degree at both 20 feet and 10 feet.

5. You measure a patient's VA with a projected Snellen chart. In a dark room the acuity is 20/20. A. What happens to the measured VA when you turn on the overhead room lights?. B. Why?

The measured acuity is expected to be less than 20/20.

The overhead lights decrease the amount of contrast of the letters of the projected chart. This results in a reduction in the CSF high-frequency cutoff leading to a reduction in measured VA.

### **Temporal Aspects of Vision:**

Spatial vision = analysis of changes in luminance across space.

Temporal vision = analysis of changes in luminance over time.

**An example of temporal vision would be detecting flicker. Temporal vision is closely related to the**

## **ability to perceive motion.**

### Depth of modulation

The visibility of a temporally modulated stimulus is related to its depth of modulation. A light source that is modulated at a low depth appears steady; no flicker.

### Temporal frequency

Low temporal frequency = flickers slowly

High temporal frequency = flickers fast

As the temporal frequency is increased, a frequency is reached at which flicker can no longer be resolved = called **critical flicker fusion frequency (CFF)**

CFF is analogous to spatial resolution acuity

As the frequency of a spatial grating is increased, it appears to consist of increasingly thin bars. At the high spatial frequency cutoff, the bars are not resolvable = the stimulus appears as a uniform gray surface. Likewise, as the frequency of a temporally modulated stimulus is increased, the flicker appears more rapid. A frequency is eventually reached where the stimulus appears steady. Temporal frequency is given in Hz. One hertz = 1 cyc/sec.

Spatial vision is characterized by the CSF

**Temporal vision is characterized by the temporal modulation transfer fcn (TMTF).**

### Reduction in Sensitivity for Low Temporal Frequencies

Very gradual or slow changes in illumination are not seen.

The inability to perceive **stabilized retinal images** is a manifestation of the visual system's reduced sensitivity to low temporal frequencies. Consider the retinal blood vessels that lie on top of the photoreceptors. Relative to the retina, these vessels are stabilized; they move as the eye moves and manifests a temporal frequency of zero. Only when a moving light is shined into the eye, which casts moving shadows is it possible to see our own retinal vessels. This retinal vasculature is referred to as the **Purkinje tree**.

**Troxler phenomenon:** disappearance of low temporal frequency stimuli.

The high-frequency cutoff of the TMTF is due to neural limitations in coding high temporal frequency info. Eventually, a frequency is reached that cannot be resolved b/c of limitations in the speed of the neural response.

The low-frequency cutoff is due to time lags inherent in lateral inhibitory interactions within the retina. Low temporal frequency stimuli maximize these inhibitory interactions with a resultant reduction in sensitivity.

Critical Flicker Fusion Frequency (CFF):

The critical flicker fusion frequency is the highest or lowest temporal frequency that can be resolved at a given percentage of modulation.

### Effect of Illumination on the CFF:

Increasing background illumination has different effects on relative sensitivity for low and high temporal frequencies.

Low temporal frequencies: increasing background illumination has no effect

High temporal frequencies: increasing background illumination causes a relative increase in sensitivity.

**Ferry-Porter Law:** high frequency CFF increases approx. with the log of the retinal illumination.

(due to general speeding up of retinal processes that occurs at increasing levels of light adaptation).

Effect of Stimulus Size on the CFF:

**Granit-Harper Law:** CFF increases with the log of the stimulus area (flicker is more likely to be seen if the stimulus is large).

Consistent with the observation that the peripheral retina is better at detecting movement and flicker than is the central retina. The physiologic pathway that accounts for the high temporal resolution of the peripheral retina is most likely the magno pathway.

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**Broca-Sulzer Effect:** suprathreshold flashes of light with a duration on the order of 50 - 100 msec appear brighter than stimuli of either shorter or longer durations.

Not due to action potential profile of a ganglion cell.

Actually not sure what the Broca-Sulzer effect is due to.

**Brucke-Bartley Effect** (brightness enhancement): a light presented at approx. 10 Hz, which is seen as flickering, appears brighter than a steady light of the same average luminance.

**Talbot-Plateau law:** brightness of a temporally modulated stimulus, when fused, is equal to the brightness of a steady light with the same time-averaged luminance. For this law to apply, the stimulus must be presented at a rate beyond the CFF (no flicker can be seen by subject).

Masking:

Masking involves the use of one stimulus, the mask, to reduce the visibility of another stimulus, the target.

Masking phenomena provide info regarding both spatial and temporal processing of visual info.

**Simultaneous masking:** both the mask and the target are present at the same time. Example is the use of spatial gratings of a given frequency (the mask) to interfere with the detection of spatial gratings of a similar frequency (target). Since both frequencies share the same spatial frequency channels, there is a reduction in the visibility of the target gratings. More pronounced in amblyopes. Consequently, the VA is better when viewing a single letter than when viewing a line of letters --- called the **crowding phenomenon**.

**Backward masking:** target precedes the mask. Typically occurs when the mask is substantially brighter than the target. Because it is brighter, the mask is transferred along the neural path at a rapid rate. This enables it to surpass the preceding target and interfere with its detection.

**Forward masking:** mask precedes the target.

Metacontrast:

Form of backward masking where the mask and the target are spatially adjacent. The visibility of a briefly presented target is reduced by the subsequent presentation of a spatially adjacent mask. Due to lateral processing within the retina and the magno pathway.

Paracontrast:

Form of forward masking where the target and mask are spatially adjacent. A mask reduces the visibility of a

subsequently presented, spatially adjacent target.

Self-Assessment Questions:

1. A square wave stimulus has a frequency of 20 Hz. Calculate in msec, the duration of the on phase of each cycle.

20 Hz = 20 cycles / sec. Each cycle is 1/20th of a second or 0.05 second. One half of a cycle is the on-phase; its duration is  $1/2 \times 1/20 = 0.025$  sec. This is 25 msec.

2. A stimulus is on for 20 msec. This stimulus is presented continuously. Calculate its temporal frequency in Hz.

A total cycle is 40 msec, or 1 cycle/ 40 msec. Convert to Hz:  $1 \text{ cyc} / 40 \text{ msec} \times 1000 \text{ ms} / \text{s} = 25 \text{ cycles} / \text{s} = 25 \text{ Hz}$

3. Figure 8-8 shows that relative sensitivity, at low temporal frequencies, remains constant as the background illumination increases. Is this a manifestation of Weber's Law?

The percentage modulation remains constant at low frequencies as level is increased. Because the amplitude remains a constant fraction of the background illumination (level), Weber's law is followed.

### **Motion Perception:**

Changes in the spatial distribution of light, over time, can lead to the perception of motion.

**Apparent or illusory motion:** perception of motion that is not real motion.

**Stroboscopic motion** or the **phi phenomenon**: using flashes of light to create the illusion of motion (1st order phenomenon). Various sensations of movement are produced by different intervals between 2 flashes of light. An interval of **60 msec** produces **realistic movement (optimum or beta movement)**. An interval of less than 30 msec produces no sensation of movement. Durations of **60 - 200 msec** produce a **partial illusion of movement (pure or phi movement)**.

**First order stimuli for motion:** linear exchange of light for dark.

**Second order or global motion:** more complex stimuli

Random Dot Kinematograms:

Used to study global (2nd order) motion perception. **Coherence threshold** = smallest coherence that results in the perception of motion in a given direction.

Minimum displacement threshold: minimum distance that dots must move in a given direction to perceive motion. Also have maximum displacement threshold.

Perception of motion occurs in higher level motion centers in the cortex.

Motion is processed along a Specialized Pathway:

From the retina to the striate cortex, motion info is processed primarily along the magno pathway. Motion info is disseminated from the striate cortex to Visual Area 5 (V5, middle temporal area). This cortical pathway from the striate cortex to V5 and then to the prefrontal cortex is called the parietal pathway (dorsal processing stream, where system).

Luminance is a stronger stimulus for motion than color:

Due to magno pathway

### Spatial resolution is affected by stimulus movement:

As stimulus velocity increases, resolution acuity remains relatively constant until about 60-80 degrees/second. Due to our inability to accurately follow the stimulus while tracking (smooth pursuits).

### The world is not smeared by saccadic eye movements:

Due to saccadic suppression of the magno pathway.

### **Depth Perception:**

Not only a binocular phenomenon.

Monocular depth cues play a large role in depth perception.

### **Monocular Depth Cues:**

Pictorial depth cues, motion parallax, and accommodation

**Pictorial depth cues:** size, linear perspective, texture, interposition, clarity, lighting, shadow.

size: larger objects are closer

Relative size: view several objects with sizes that can be compared

Familiar size: view objects of known size it is easier to judge distance.

Linear perspective: related to relative size. Convergence of parallel lines as get farther away.

Texture: related to relative size. Smaller, more densely packed objects appear farther away.

Interposition: occurs when one object blocks the view of another.

Clarity: essential form of interposition. Near objects appear clearer.

Lighting and shadow: shadow is interpreted as falling behind the object; so depth is created

**Motion parallax: kinetic monocular depth** produced by the relative motion of two or more objects. Near objects have against motion, and distant objects have with motion.

**Accommodation:** during accomm, the dioptric power of the lens increases. The signal for accomm contains info regarding the distance of viewed objects, but the extent to which this info is used for determination of depth is not known.

### **Binocular Depth Cues:**

Stereopsis: when someone is asked to fixate on a near object, the images of the object fall on the two foveas. The two foveas correspond to the same direction in space and are referred to as **corresponding points**. If another object's light rays fall on the retina nasal to the two foveas, the distance between the corresponding points (the foveas and the nasal retinas) is referred to as the **retinal disparity**. Retinal disparity provides info that allows the visual system to judge the distance of objects.

Uncrossed retinal disparity: retinal images fall nasal to the corresponding points (foveas). Objects are perceived as farther away.

Crossed retinal disparity: retinal images fall temporal to the foveas. Objects are perceived as closer than the fixated object.

**The perception of the depth that is produced by binocular retinal disparity is referred to as stereopsis.**

**Stereopsis is important for providing finely tuned depth perception at near distances (arms length).**

Binocular disparity produces stereopsis only if the retinal disparity is not too great. If the retinal disparity is not too great, the retinal images are fused with a resultant sensation of depth--stereopsis. **The area of the retina that corresponds to this area of binocular fusion is referred to as Panum's fusional area.** If the retinal disparity is too great, binocular fusion does not occur. The images fall on retinal positions that signal grossly different directions, resulting in **physiologic diplopia.**

Images falling on the two foveas signal the same direction (i.e. They are corresponding points). In fact, each retinal point has a corresponding point in the other eye, and each of these pairs of corresponding points signal the same distance. **Plotting these corresponding points (for a given fixation distance) results in a curved plane referred to as the horopter.** All points on the horopter stimulate corresponding retinal points and are perceived as being at the same distance (the horopter is curved because of the curvature of the retina).

Objects that fall relatively close to the horopter are fused. For these stimuli, the retinal disparity falls within Panum's fusional area and the result is stereopsis.

### **Visual illusions:**

Erroneous perceptions.

**Size constancy:** visual system compensates for differences in retinal image size by taking into account the relative distance of an object. When judgments of distance are erroneous, such as occurs when viewing a flat picture, size constancy may fail. The result is a type of illusion called a **size illusion.**

Corridor illusion: size constancy fails because monocular depth cues provide incorrect info regarding the relative distances of circles. (illusion is of same sized circles on a railroad like track extending into the distance).

Moon illusion: moon appears larger when on the horizon. From background info like trees that cause the moon to be perceived as closer (and larger) than when it is directly overhead in the sky.

**Muller-Lyer Illusion:** thought to result from the lines mimicking the corner of a room. The line that appears as an outgoing corner is judged as farther away than the line that appears as an ingoing corner. The more "distantly" perceived line is perceived as longer.

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Highly developed stereoacuity is dependent upon a normal complement of binocular neurons in the visual cortex. For these cortical neurons to be present, the visual system must have been exposed to a normal visual environment during development.

### **Psychophysical Methodology:**

Psychophysical experiments and psychophysically based clinical procedures frequently involve the determination of a threshold.

Hypothetical ideal observer manifests a perfect threshold. Above threshold, observer always sees it. Below, never sees it.

Real observer: as the intensity of a stimulus is increased, the probability of seeing the stimulus increases.

**Threshold is defined as the intensity that results in detection of the stimulus on one half of the presentations.**

Threshold is variable b/c neural noise is preset in the system. And b/c motivation, attention, and fatigue also affect performance.

Method of Ascending Limits: at 1st the stimulus is not visible. Stimulus is presented at increasing levels of

intensity until it is first seen.

Adv: quick, does not affect retinal adaptation.

Disadv: observer can anticipate when they should start seeing the stimulus based on previous trials.

Method of Descending Limits: stimulus starts as clearly visible and then goes down in intensity until it is no longer seen.

Disadv: suffers from observer anticipation.

Staircase Method: combination of two above. Threshold is frequently defined as having occurred after 3-4 reversals.

Adv: quick, and reliable.

Method of Constant Stimuli: stimulus visibility is varied from presentation to presentation in a random fashion. Designed to maintain observer expectations b/c it is random.

Disadv: time consuming.

Method of Clinical Adj: participants themselves adjust the stimulus intensity until the stimulus is barely visible. Relatively quick.

Disadv: suffers from participants own criterion for what they think is threshold.

Forced Choice Method: all the previous experiments suffer from variability in the threshold criteria used by observers. Some have a strict criterion - don't answer until they are sure they see it. Being a strict observer results in low sensitivity. Lax criterion results in high sensitivity - lower threshold.

If have two possible windows where the stimulus can be in, and have the subject say which window they see the stimulus - the lowest percentage correct will be 50%. This is where the person is just guessing. Threshold is taken as halfway between lowest score and perfect score - 75%. If have 4 windows: lowest score is 25% and highest is 100%. Threshold is at 62.5% correct.

Forced choice methodology results in lower thresholds than other procedures.

Signal Detection Theory: formally addresses the role that attention, decision criteria, and internal neural noise play in the determination of threshold.

Key element of model: neural noise is randomly distributed over time. The larger the stimulus, the easier it is for the participant to distinguish the signal plus noise from the noise alone. See page 257.  $d'$  is the detectability or a measure of the strength of the stimulus. Detectability refers to the difference between the means of the N and N + S distributions. With a very large  $d'$ , there is no overlap of the distributions; therefore, there is no uncertainty regarding whether a stimulus is present or not.

Effect of Subject Criterion: signal detection theory allows us to predict the effect of the observer's criterion on the detection of a stimulus. Lax criterion: results in more false positives. High number of hits and few misses. False positive: when only noise is present and the subject reports seeing the stimulus if the level of activation is above the criterion level.

Strict criterion: results in lower hits but less false positives.

Receiver Operating Characteristic Curve (ROC): plot of various effects of criteria and levels of detectability. For a ROC curve, the probability of a hit is plotted against the probability of a false positive.

When  $d' = 0$  it is a straight line fcn. Probability of a hit equals probability of a false positive.

$d'$  is infinity = observer always sees the stimulus and there are no false positives.

Weber's Law:  $\Delta I = KI(\text{background})$

Visual system detects stimuli in the context of their background. Brightness of a stimulus depends on its background - referred to as simultaneous contrast. Weber's law tells us that the contrast of the stimulus, not the luminance of the stimulus - is the key factor in predicting its appearance.

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Growth in magnitude of a sensation follows a power relationship, not a logarithmic relationship. Shows there is a saturation of sensation as stimulus intensity increases.

Self-Assessment Questions:

1. A. For a 3-alternative forced choice experiment, what is the percentage correct used to determine the threshold? B. Answer the same question for a five-choice experiment.

A. Minimal correct: 33.3% Maximal correct: 100 percent. Threshold is halfway between 33.3% and 100%. Threshold is 66.5%

### **Functional Retinal Physiology:**

Extracellular recording: microelectrode is placed in close proximity to the neuron and records action potentials generated by a neuron.

Intracellular recording: microelectrode pierces the membrane of the neuron and records the membrane potential. Necessary for neurons that do not generate action potentials (such as several classes of retinal cells). Instead they generate graded potentials.

Receptive Fields of Ganglion Cells:

Microelectrode is placed in close proximity to a single ganglion cell. A spot of light is directed onto various areas of the screen, and an area is found that elicits a response from this ganglion cell. The area in space that influences the activity of this single cell is referred to as the receptive field of the cell.

Even when the light is not shining on the cell's receptive field, the cell spontaneously generates action potentials (called spontaneous activity or maintained discharge). A stimulus positioned within a neuron's receptive field can either increase or decrease the discharge rate of the neuron. Small light in the center of the field causes an increase in the frequency. The light positioned in the surround of the receptive field causes a decrease in the frequency of the action potentials. This is called center-surround organization.

They manifest what is referred to as spatial antagonism or lateral inhibition. This means that light falling on one part of the cell's receptive field has the opposite effect of light falling elsewhere.

The greater the area of the excitatory center that is covered, the more vigorous the response. Once the stimulus is larger than the field's receptive center, it encroaches on the antagonistic surround. The result is a decrease in the cell's response rate.

Retinal ganglion cells are designed to detect one of the most critical features of our visual world: spatial contrast (not diffuse illumination).

Photoreceptors along with several classes of retinal neurons, do not generate action potentials. They generate graded or slow potentials.

### **Photoreceptors**

cells are slightly depolarized relative to a typical neuron. When exposed to light they hyperpolarize instead of depolarizing like most neurons. The degree of hyperpolarization that a photoreceptor undergoes is related to the intensity of the stimulus. This is one reason that the potentials produced by photoreceptors are referred to as

graded potentials.

**Dark current** of photoreceptors: in the dark, sodium ions flow into the rod outer segment through pores, producing a slight depolarization.

The absorption of light by rhodopsin initiates a series of events that result in the blockage of the sodium pores and the resultant hyperpolarization of the outer segment.

**Only amacrine and ganglion cells generate action potentials. All other retinal neurons generate graded potentials.**

Rhodopsin consists of two portions: opsin and a chromophore. Opsin is a visually inert chain of amino acids that is interlaced into the disk membranes of the rod outer segment. The chromophore consists of retinal, an altered form of retinol (vitamin A). In normal circumstances, retinal is in the 11-cis state. There is a bend at carbon number 11 of the molecule. Absorption of a quantum of light transforms the retinal molecule to the all trans isomer. Subsequently, the protein transducin activates the protein phosphodiesterase (PDE). PDE breaks down cyclic GMP into ordinary GMP. A decrease in cGMP levels leads to the closing of the Na<sup>+</sup> channels of the rod outer segment. This results in hyperpolarization.

When only about 10% of a rod's rhodopsin is bleached, a critical number of Na<sup>+</sup> channels are closed. Consequently, further bleaching of rhodopsin does not result in further hyperpolarization.

**Horizontal Cells:** a large number of photoreceptors synapse with a widely dispersed dendritic tree of a single horizontal cell. Light falling on any of these photoreceptors can affect the neural activity of the horizontal cell. Consequently, horizontal cells manifest substantial spatial summation. Horizontal cells also show a graded hyperpolarization like photoreceptors. Therefore, the synapses between the 2 are referred to as **sign conserving synapses**.

**Bipolar Cells:** first retinal cells to display spatial antagonism. There are on-center bipolar cells, which tend to form a specialized synapse, referred to as a **triad**, at their synapse with photoreceptors. At this specialized synapse, a bipolar cell and two horizontal cells form an invagination within the photoreceptor. Also have off-center bipolar cells which have conventional flat synapses. **Glutamate** is the reason some bipolar cells have off-center and others have on center. For on-center cells, glutamate is inhibitory. For off-center, glutamate is excitatory. Glutamate is continually released in the dark.

Amacrine cells: first retinal neurons to display action potentials.

Ganglion cells: like bipolar and amacrine cells, ganglion cells show spatial antagonism. Ganglion cells have action potentials b/c they must traverse a long distance. Action potentials do not decay like graded potentials. Foveal ganglion cells have a very small receptive field centers. As few as one cone may contribute to the receptive field center of a foveal ganglion cell, resulting in a high degree of spatial resolution.

Ganglion cells are either magno or parvo. Magno cells have a much more extensive dendritic tree. As a consequence, magno neurons have larger receptive fields than parvo neurons.

### **Parallel Processing:**

The axons of most retinal ganglion cells synapse on the neurons that constitute the dLGN. The dLGN then sends its neurons to the visual cortex.

dLGN has two distinct regions:

1. Two most ventral layers consist of large neurons referred to as magno cells.
2. Dorsal four layers consist of small neurons called the parvo cells.

Parvo cells: sensitive to color. Not sensitive to fast movement.

Magno cells: sensitive to movement but not color.

The division of the visual system into parvo and magno pathways is most apparent at the level of the dLGN; however, this division is also found in the retina and, to a lesser extent, in the striate cortex and higher cortical areas.

**Feature detection** is a manifestation of **parallel processing**; specific aspects of visual information are processed along specialized visual pathways or channels.

Parvo cells: show color opponency

Magno cells: show little or no color opponency

Characteristics of parvo and magno cells:

	Parvo	Magno
Color coding	color opponent	weak or no color opponency
Temporal responsiveness	sustained	transient
Speed of transmission	slow	fast
Spatial linearity	linear	linear or nonlinear
Retinal distribution	central	peripheral
Spatial sensitivity	high frequencies	extrafoveal
Response to increasing contrast	weak	saturates
Cortical projection (V1)	4A, 4CB	4Ca

### **The Striate Cortex:**

The most highly evolved portion of the human brain is the cortex.

The first stage of cortical processing of visual info occurs in the striate cortex, the primary target site for projections from the dLGN.

Cortex tissue consists of superficial gray matter (cell bodies) and underlying white matter (myelinated axons).

The cortex consists of four lobes:

1. Frontal
2. Parietal
3. Temporal
4. Occipital - contains striate cortex

Striate cortex: named b/c has a dense plexus of geniculate axons that forms a distinctive striae, referred to as the **line of Gennari**, in layer 4B. Striate cortex is commonly referred to as primary visual cortex, visual area 1, V1, and Brodmann's area 17.

Striate cortex projects to the extrastriate cortex, the region of visual cortex that is not distinguished by the line of Gennari. Among the extrastriate areas that we will refer to are visual area 2 (V2), V4, inferotemporal cortex (IT), and V5, also referred to as middle temporal cortex or MT.

In general, info travels along two pathways, the **temporal and parietal pathways**.

Temporal pathway (ventral processing stream): what system. Receives predominant input from parvo system.

Parietal pathway (dorsal processing stream): where system. Receives predominant input from magno system.

The two systems are not independent and there is considerable communication between the two.

**Simple cells:**

Most sensitive to a bar of light of specific orientation. Different cells are sensitive to different orientations. The receptive fields of these cells are divided into antagonistic excitatory and inhibitory regions. Suggested that the simple receptive fields are formed from the addition of dLGN nucleus receptive fields that lie along a straight line.

The buildup of more complicated receptive field arrangements (simple cells) from less complicated arrangements (concentric dLGN cells) is referred to as **serial or hierarchical processing**. This is the same process that occurs in the retina. The receptive fields of distal retinal elements (photoreceptors, horizontal, bipolar cells, and amacrine cells) are combined to form the receptive fields of ganglion cells.

### **Complex cells:**

Also respond best to a bar of elongated light of a specific orientation. But they differ from simple cells in several ways. For simple cells, stimulus position within the receptive field is critical. With complex cells, the stimulus can be positioned anywhere within the neuron's receptive field.

Many are characterized by direction selectivity; they are sensitive to a stimulus moving in a specific direction. A stimulus moving in the opposite direction, even if of the proper orientation, does not elicit a response.

The receptive fields of complex cells cannot be divided into discrete excitatory and inhibitory regions. The manner in which simple cells combine to produce a complex cell receptive field is not understood.

### **Striate Cortical Architecture:**

Many cortical neurons are binocular: they receive input from both eyes. Binocular cortical cells may mediate stereopsis. The receptive fields of many binocular cells do not overlap; this permits the coding of disparity b/c the receptive fields do overlap at a critical distance from the eyes. A stimulus located at this distance maximally activates the neuron b/c the inputs from the two eyes are summed. As a result, the stimulus distance is encoded. This presumably provides the physiologic basis for stereopsis.

Although the majority of cortical neurons are binocular, most cortical cells are dominated by one eye or the other. Stimulation of the so-called dominant eye causes a stronger response than stimulation of the other eye. In the striate cortex, ocular dominance is laid out in a regular pattern of alternating R and L ocular dominance columns.

Neurons at a certain depth all respond to the same orientation of bars of light. Above this location, all the cells across the column respond to different orientations of light. Shows that the striate cortex is organized into orientation slabs and ocular dominance slabs.

A complete set of ocular dominance columns (both eyes) and orientation columns (all orientations) form a hypercolumn. Each hypercolumn has dimensions of approximately 1 x 1 mm.

**Blobs:** in the striate cortex and are rich with concentrically organized, double-color opponent neurons. Blobs are connected in an organized manner to certain stripes in V2; this constitutes a continuation of the color-sensitive parvo pathway.

The superficial region of the striate cortex between blobs, the interblob region, also appears to be a portion of the parvo pathway. The magno pathway apparently bypasses the blob and interblob regions of the striate cortex by synapsing within deeper layers of the striate cortex.

The parvo blob and interblob pathways and the magno pathway send organized projections to the stripes in visual area 2, and these stripes project to the higher cortical centers. The blob and interblob system apparently projects to V4, a color area, whereas the magno pathway projects to V5 (middle temporal cortex), a motion area.

Blindsight: patient's striate cortex is totally destroyed but can still see a little. Because the patient still has the subcortical pathways, such as the retinotectal pathway. The retina sends a projection to the superior colliculus, which is referred to as the retinotectal pathway. This pathway is important for coding eye movements.

## **Information Streams and Extrastriate Processing:**

Extrastriate cortex: does more processing beyond what the striate cortex does to create the rich world we perceive.

Beyond the striate cortex there is a great divergence of info.

**Retinotopic map:** region of the brain that contains a map of the visual field. As of now, we know of at least 20 distinct areas.

V4: cells have chromatic sensitivity - color perception.

Inferotemporal cortex (IT): respond to complex forms - form perception

\*both the V4 and IT are part of the ventral processing stream.

V5 (middle temporal cortex): component of dorsal processing stream. Encodes motion.

Use functional MRIs and PET scanning to monitor brain activity while person is performing a specific task.

V5 is active while a person views a moving object and while they are experiencing motion aftereffects (person adapts to an object moving in a particular direction for couple minutes and then looks at stationary surroundings; surroundings appear to move opposite to direction of adapting stimulus).

Lesions in the striate cortex produce scotomas.

Lesions in the extra striate cortex produce inability to recognize objects (**visual agnosia**).

Lesions in the dorsal processing stream can lead to **visual neglect**. For instance, a patient with a lesion located in the left parietal area may shave only the left side of his face and ignore the right side. The neglect is apparently accentuated when a patient is presented visual objects in both the affected and nonaffected regions of his or her visual field. It is for this reason that clinicians, when performing a confrontation visual field test, sometimes present objects to both the patient's left and right visual fields. Presentation of an object in the normal visual field extinguishes visualization of the object in the field affected by the parietal lesion, thereby facilitating detection of the abnormality.

Prefrontal cortex: integrates dorsal and ventral processing streams and combines it with memory (cognition).

Binocular rivalry: alternating perception of nonfusible images (viewing oppositely slanting lines by the left and right eyes).

Binocular rivalry and ambiguous figures are sometimes said to be manifestations of **bottom-up** visual attention. The untrained observer presumably does not choose which perception he or she experiences.

## **Gross Electrical Potentials:**

Gross electrical potentials represent the summed electrical activity of a large number of neurons.

**Electrooculogram (EOG):** think of the eye as a battery. The front of the eye has a + charge relative to the back of the eye.

Dark adapted EOG is most likely from the RPE. The increased value of the EOG under light adapted conditions appears to be due to rod activity.

**Electroretinogram (ERG):** retinal potential elicited by a brief flash of light. It is believed that the standard ERG is derived largely from the outer retina.

**ERP:** due to outer segments of photoreceptors, primarily cones.

**a-wave:** photoreceptors

**b-wave:** muller cells

**c-wave:** RPE?

### **Effect of contrast on the amplitude of VEPs:**

If a patterned stimulus used to elicit a steady-state VEP is of high contrast, the amplitude of the VEP is larger than if the stimulus is of low contrast.

This correlation of VEP amplitude and stimulus contrast has been used as a basis to assess contrast sensitivity and visual acuity.

The contrast sensitivity and VA of malingers, hysterics, the mentally retarded, infants, and other noncooperative patients can be objectively assessed using VEPs.

### **Importance of the fovea in visually evoked potentials:**

The vast majority of the striate cortex is devoted to analyzing foveal vision. Because of this **cortical magnification of foveal vision**, the VEP is largely a foveal phenomenon. Approximately 2/3 of the VEP is due to foveal and macular input.

Amblyopia causes an abnormal VEP but normal EOGs, ERGs, and focal PERGs.

### **Development and Maturation of Vision:**

The human visual system is not fully developed at birth; rather it matures over the first several years of life.

Deprivation Studies:

Most neurons in the visual cortex receive input from both eyes; they are binocular. Most binocular cortical cells do not, however, receive equal input from the two eyes.

Ocular dominance histogram:

Cells in categories 1 and 7 are monocular; category 1 cells receive input from only the contralateral eye, whereas category 7 cells receive input from only the ipsilateral eye. Neurons in category 4 are binocular and receive equal input from both eyes. Cells in the remaining categories are binocular, but dominated by one of the eyes. Neurons in categories 2 and 3 are dominated by the contralateral eye, and those in categories 5 and 6 are dominated by the ipsilateral eye.

Visual deprivation (occlude 1 eye during development): virtually all cells are monocular.

The period during which the visual system can be influenced by environmental manipulation is referred to as the **critical or sensitive period**.

The human visual system is most sensitive to environmental manipulation during the first 2 years of life, with the human critical period over by about 7-9 years of age.

### **Amblyopia:**

Reduction in vision secondary to monocular deprivation during the critical period is referred to as amblyopia. Amblyopia is a condition that reflects abnormal cortical development, not an abnormality of the eye itself.

**A diagnosis of amblyopia should be made only if one of the following factors is present:**

- 1. Occlusion - monocular congenital cataract, monocular lid ptosis, etc.**
- 2. Anisometropia - unequal refractive error (mostly hyperopic)**
- 3. Strabismus - constant unilateral eye turn. Patient suppresses turned eye which leads to amblyopia. They suppress the turned eye to avoid double vision.**

**\*constant strabismus leads to amblyopia; alternating or nonconstant strabismus does not**

\*tilt aftereffect: mediated by the binocular cortical neurons. If no such neurons are present, then interocular transfer does not happen. Tilt aftereffect is done by having the subject stare at a group of tilted lines (monocularly) for a couple minutes. Then person opens other eye and closes off first eye while looking at a group of vertical lines. Normal person should see the vertical lines tilting to the opposite direction as the first group of lines.

\*it is probably best to consider prescribing lenses for young, school-aged children if the astigmatism shows no signs of resolving and is at least 2.00 D (to avoid meridional amblyopia).

OKN: moving grating produces an involuntary nystagmus - called optokinetic nystagmus. OKN is presumably dependent on the ability to resolve the grating. If the grating cannot be resolved, the OKN response is presumably not elicited.

Contrast sensitivity: CSF shifts to the right as infants mature - showing that contrast sensitivity improves as infants mature. CSF probably reaches adult levels by about 6 months of age.

Stereopsis: few infants manifest stereopsis prior to 3 months of age. But it has a rapid onset between 3 and 6 months of age.

Whereas spatial vision (grating and vernier acuity) does not reach adult levels until 3-5 years of age, the critical flicker fusion frequency is 40 Hz at 1 month of age and reaches adult levels of about 55 Hz by 3 months.

Scotopic sensitivity: scotopic sensitivity function is adult-like at 1 month. Not surprising since the shape is due to absorption characteristics of rhodopsin and does not depend on postreceptoral processing of info. The absolute sensitivity of the scotopic system (peak of 507 nm) reaches adult levels at 6 months of age.

Color vision: rudimentary R-G discrimination arises at 2 months of age. Adult levels by 1 year.

Vernier acuity is the last to be adult like (3-5 years).

Vision in old folks:

Contrast sensitivity: reduced in elderly. Due to several factors:

\* Senile miosis (small pupils): causes a reduction in retinal illumination. CATs also cause it, aging of neural elements.

Small pupil does increase a person's depth of field.

It is very important to stress to old people to use more light while doing near work b/c reduction in retinal illumination is a primary factor in reduction of visual function in the elderly.