

*Dr. Salmon's*  
**National Boards Part 1 Review**

July 20, 2000

This review is designed to help you quickly and efficiently review Vision Science II (monocular vision) and Vision Science IV (binocular vision) in preparation for Part 1 of the National Boards. It follows the official NBEO outline ([http://www.optometry.org/part\\_1.htm](http://www.optometry.org/part_1.htm)).

Relevant outline headings are followed by references and a summary of that topic. Subjects taught in Vision Science II and IV make up about 12% of the entire test, the largest single topical section. You should also read the entire book by Schwartz (Visual Perception), and practice as many review questions, from the review book and my old tests, as possible.

-- Dr. Salmon

**3. Ocular Physiology/Neurophysiology (p. 26)**

*K. Retina*

**6. Photoreceptor electrophysiology (membrane potentials, dark current, role of sodium, calcium, etc.)**

Schwartz Ch.. 12, p. 278-281, Fig. 12-8; Adler's Ch.. 14, Fig. 14-12, 14-14

Photoreceptors maintain a slight negative electrical charge of about -50 mV in the dark. This is caused by active transport of cations such as sodium and calcium from within to outside the cell. Sodium (Na<sup>+</sup>) tries to re-enter the outer segment by passive diffusion, but sodium channels limit sodium inflow. The result is the -50 mV net negative charge. The flow of sodium and other cations into and out of the cell while it is in the dark is referred to as the **dark current** (Fig. 14-12). The dark current is blocked following exposure to light and the cell hyperpolarizes.

Light is absorbed by rhodopsin in the rod outer segment, and this sets off a biochemical cascade known as **phototransduction**, which converts absorbed light into an electrical signal. A key event during phototransduction is closing of the **sodium channels in the outer segment**. This prevents Na<sup>+</sup> from entering and the negative charge increases to about -70 mV. This **hyperpolarization** is the electrical signal that is passed on to the bipolar cells.

Note that photoreceptors do not produce action potentials but rather **graded potentials**. The degree of hyperpolarization depends on how much light is absorbed. When about **10% of the rhodopsin** in the outer segment is bleached by light, the sodium channels are completely closed and the photoreceptor is maximally hyperpolarized. In effect, rods are saturated after 10% of the rhodopsin is bleached.

**7. Retinal neurotransmitters**

Schwartz Ch.. 12, p. 281-3, Fig. 12-10

The neurotransmitter **glutamate** enables the photoreceptor to communicate with the bipolar cells. It is continuously being released by the photoreceptor, but when it hyperpolarizes, glutamate production is reduced. Depending on the type of bipolar cell, the reduction in glutamate can cause a different response. For on-center bipolar cells, the decrease in glutamate is excitatory. For off-center bipolar cells, the decrease in glutamate is inhibitory.

**8. Function of bipolar, horizontal, amacrine, and ganglion cells (receptive fields)**

Schwartz Ch.. 12, p. 281-285, **Fig. 12-7\***

Bipolar cells have center-surround receptive fields (**spatial antagonism**). Some are on-center/off-surround; others are off-center/on-surround. When excited, bipolar cells hyperpolarize. When inhibited they depolarize. They respond with graded potentials.

Horizontal cells receive input from a large number of photoreceptors and contribute to spatial summation. They also have graded potentials and hyperpolarize in response to light. Receptive fields are not center/surround type.

Amacrine cell receptive fields have center/surround organization and respond with **action potentials**.

Ganglion cells have center/surround receptive fields of two types: on-center/off-surround or off-center/on-surround. They respond with **action potentials**. Even in the dark, ganglion cells have a baseline level of electrical firing referred to as the **spontaneous activity** or **maintained discharge** of the cell. Stimulation of the ganglion cell causes an increase in the rate of firing. Inhibition causes the rate of firing to decrease below the maintained discharge frequency. The center/surround organization makes ganglion cells more sensitive to changes in **spatial contrast** than to diffuse illumination.

9. *Retinal neural mechanisms of color vision (spatial, temporal and chromatic)*

Schwartz Ch. 5, p. 114-120, Ch.. 3, p 33-35; Adler's Ch.. 22, p. 714-716; VSII Lectures 18, 19

Wavelength discrimination is possible because of our **trichromatic** visual system that consists of three cones types, each with a different photopigment. Each pigment has a different absorption spectrum for light. See **Schwartz Fig. 5-6**.

Cone type	Photopigment	Peak sensitivity (nm)	Range (nm)
S	cyanolabe	430	~400 - 500+
M	chlorolabe	535	~400 - 680+
L	erythrolabe	565	~400 - 700+

Recent research has indicated that our visual system seems to make use of the trichromatic theory at the receptor level, but higher up (at the horizontal cell level in the retina) the neural processing uses **opponent color channels**.

- \* A red-green opponent channel which can signal either red or green, but never both at the same time.
- \* A blue-yellow opponent channel which can signal either blue or yellow but never both at the same time.

**Fig. 5-18** illustrates how the trichromatic cone system and the higher color opponent neurons may be connected. This is just one theory.

- \* The M and L cones provide input into a R-G color opponent channel.
- \* They may also combine to provide input to a B-Y opponent channel which receives signals from the S cones. The theory states that color opponent channels carry color, but not brightness information. A separate non-opponent channel is proposed which codes brightness information. It receives input from both the M and L cones. Some neurons may have receptive fields that show **double opponency**. For example, the neuron is stimulated by red / inhibited by green in the center of the circular receptive field, but in the surrounding annular region it is inhibited by red / stimulated by green. In these neurons, stimulation causes an increased rate of firing, inhibition decreases the rate of neuronal firing.

It appears that the **parvo cellular system** is primarily involved in color vision, while the

magnocellular system is not. The parvo cellular system is dominated by foveal input and is carries high spatial frequency (fine detail) and low temporal frequency information.

L. Visual pathway

2. Receptive fields of cells in the lateral geniculate body (relationship to color vision, binocularity, space perception, etc.)

Schwartz Fig. 13-1, 14-6; Adler’s Ch... 23, p. 742-743, Fig. 2317; VSIV Lectures 2, 29, 32

The receptive fields of the LGN neurons are very similar to those of their corresponding ganglion cells. That is, they are annular with on-center/off-surround or off-center/on-surround organization. Although the LGN receives input from both eyes, the signal from the eyes are not combined in individual neurons, but input from the right and left retinas are segregated into different layers. Binocular visual processing, therefore, does yet occur at the LGN level—the LGN neurons are still monocular.

Table 29-1 below (from Adler’s Fig. 24-18), summarizes different visual functions associated with these pathways. The division into these main pathways is based on work with monkey and some psychophysical studies with humans, and much of it is still theoretical.

Table 29-1. Major pathways within the visual system.

Pathway	Perception	Stereopsis	Oculomotor
Magno	Motion, flicker, transient luminance	40-36000”, coarse, motion	Initiate pursuit & vergence
Parvo	High spatial frequency, color	2-1200”, fine, static	Maintain vergence

3. Function of the visual cortex

Schwartz Ch.. 14, 15; Adlers Ch.. 23, p. 743-759; VSIV Lectures 3, 29, 30

The majority of LGN fibers synapse in the primary visual cortex, which extends from the occipital pole, and internally above and below the calcarine fissure (Adler’s Fig. 23-6). The cerebral cortex is arranged in six layers (**Adler’s Fig. 23-13**), from the surface (layer I) toward the internal white matter (layer VI). **Layer IV** (4) receives input from the LGN fibers and is subdivided into layers IVB, IVC-alpha, IVC-beta.

**Table 32-1.** Major neurons and connections in the parvo and magnocellular pathways. Bold type indicates levels at which binocular neurons may be found.

Major Pathway	Retinal Ganglion cells	LGN layers	V1 first connection	<b>V1 higher connections</b>	<b>V2</b>	<b>Higher centers</b>
parvo	cells	Dorsal 4	Layer IVC	<b>Layers II, III</b>	<b>Interstripe thin strip</b>	<b>V4</b>
magno	cells	Ventral 2	Layer IVC	<b>Layer IVB</b>	<b>Thick strip</b>	<b>V3, MT</b>

Fig. 23-12 shows an easily visible line (stripe) within the visual cortex, called the **stria of Gennari**. Because of this stria which is visible in the primary visual cortex, the primary visual cortex is also called the striate cortex. It is also labeled Brodmann area 17 or area V1 (visual area 1).

Surrounding cortical regions are named V2, V3, V4, etc.

Table 32-1 summarizes the course of the major pathways. In the mature human visual systems, individual neurons are monocular up to the first connection in area V1. In the higher level connections in V1 and beyond, binocular neurons may be found. This is denoted by the bold print in the right part of Table 32-1. Also see **Adler's Fig. 23-22**.

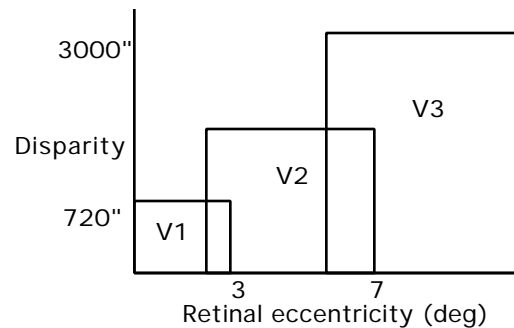
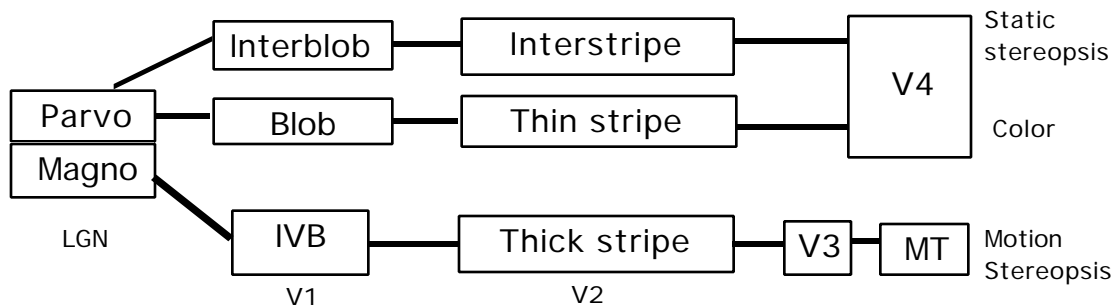


Figure 29-1. Higher order neurons.



#### 4. Receptive field properties (single cell properties)

Schwartz Ch.. 12, p. 272-277, 281-285, **Fig. 12-7**, Fig 12-4, 12-5, 12-6; Adlers Ch.. 23, p. 747-750  
 Whereas ganglion cell and LGN receptive fields are circular, those for the initial neurons in the visual cortex are **linear**, and they respond best to elongated forms such as bars or edges. The neurons which responded in this way were called **simple cells**. Figure 14-4 in Schwartz illustrates features of simple cell receptive fields. They are elongated, have surrounding spatially antagonistic regions and are optimally stimulated by bars which have a particular orientation. The linear receptive fields of the simple cells are probably built by the combined input of several LGN cells which had circular fields, as illustrated in **Adler's Figure 23-20** and **Schwartz Figure 14-6**.

Other visual cortex neurons have more complex receptive fields which appear to be built up from input received from simple cells. They are referred to as **complex cells**. Complex cells are also stimulated best by elongated stimuli in the visual field, but in addition they specialize in detecting edges which are moving in a particular direction. The visual systems processes images in a **hierarchical** fashion, with neurons responding to more basic stimuli feeding information into higher order neurons which respond to increasingly complex images.

#### 5. Physiology of binocular vision

VSIV Lecture 29; Adlers Ch.. 24, p. 786-798

Neurons in the visual cortex that receive input from both eyes support binocular vision. **Schwartz Fig. 14-10** shows that, while the eyes are fixated on a certain point, the corresponding receptive fields in the two eye, which stimulate a particular binocular neuron, do not appear to coincide. Note, however, that at some point in space, the two receptive fields do superimpose. In this way, you can see that a specific amount of **disparity** will optimally stimulate the binocular neuron; this structure allows certain neurons to encode a particular amount of disparity and a specific stereoscopic perception of distance.

Four types of parvo pathway binocular neurons within V1 of the monkey seems to be involved in **fine-static stereopsis**. They respond most strongly to objects located on or very near the fixation point (small binocular disparity). The response of the four cells types are shown in **Adler's Fig. 24-21**. The neurons have been labeled, "tuned near" (TN), "tuned far" (TF), "tuned zero" (T0) and "tuned inhibitory" (TI).

Two types of magno pathway binocular neurons within V1 of the monkey seems to be involved in **coarse-motion stereopsis**. They respond most strongly to large binocular disparities and have been labeled, near (NE) neurons, and far (FA) neurons. The response of these two cells types are shown in **Adler's Fig. 24-22**.

#### 8. Gross electrical potentials

- a. EOG
- b. ERG
- c. VEP (VER)

Schwartz Ch.. 16; Adler's Ch.. 21; VSII Lecture 22, Labs 11, 12

The **EOG (electrooculogram)** measures the difference in electrical charge between the front and back of the **whole eye**. Electrodes are attached near the inner and outer canthus and the patient looks right and left while the electrical potential is recorded over about 30 minutes. The electrical potential (difference) is minimal (**dark trough**) after about 8 minutes of dark adaptation. This may be related to RPE function. It reaches a maximum (**light rise**) after about 10 minutes of light adaptation. The extreme values are recorded and the **Arden ratio**.

Arden ration = light rise / dark trough

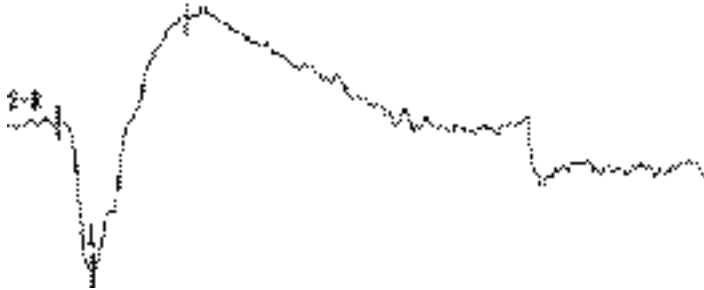
Values below 165-180% are considered abnormal.

EOG is not used much but may help to detect certain retinal diseases such as patterned RPE anomalies, fundus flavimaculatus (Stargardt's disease), advanced drusen, or vitteliform dystrophy (Best's disease).

The **electroretinogram (ERG)** measures the retina's electrical response to a light stimulus. The **standard ERG** floods the **entire retina** with single or multiple flashes and is most useful for detecting diseases of the **peripheral retina**, such as **retinitis pigmentosa**. **Since the fovea occupies a very small area of the retina, it contributes little to the standard ERG**. The typical ERG flash response is shown below. The **a-wave** is associated with the photoreceptors. The **b-wave** comes from the Müller (neuroglial) cells. Another subtle feature of the b-wave, called the "oscillatory potentials" is used to diagnose retinal ischemia as in diabetic retinopathy. The response to a flicker is a repeating series of waves. By adjusting stimulus conditions, it is possible to isolate the response of rod or cones. Besides the standard flash ERG, the pattern or focal ERGs are available to evaluate other retinal functions.

A decreased amplitude or delayed b wave **implicit time** can indicate some retina disease such as retinitis pigmentosa (RP).

- \* To **isolate rods**: dark adapt subject, use dim, short wavelength light (505 nm).
  - \* To **isolate cones**: light adapt, use bright, longer wavelength light (555 nm), flicker ~30 Hz.
- With flicker above 20 Hz rod responses disappear.



The **VER** (**VEP**, **VECP**) tests the electrical response of the primary visual cortex to a visual stimulus. Since most of area V1, especially the part near the occipital pole, is dominated by foveal input, this tests V1's response to foveal stimulation. Any anomaly between the fovea and visual cortex can interfere with the VER. The VER will tell you if the visual system between the retina and V1 is OK. For example, this could help you diagnose **retrobulbar optic neuritis**, the disease in which “the doctor sees nothing and the patient sees nothing.” It can be useful in supporting a diagnosis of **malinger**. It can detect an anomaly between the fovea and V1, but it cannot localize the defect.

The basic VER plot is easy to interpret. Normally you expect to see the peak of a large positive wave (the **P<sub>100</sub> wave**) at 100 ± 10 msec. More than this is abnormal.

The **steady state VEP** uses a checkerboard pattern to **test visual acuity** or contrast sensitivity in patients who cannot communicate.

#### 4. Visual Optics

G. Radiation and the eye

##### 1. Radiometry

Schwartz Ch.. 4; Adler's Ch.. 13; VSII Lectures 2,3, Lab 2, Environmental Lecture 1, p. 1-2

##### 1. Radiometry (radiant intensity, radiance, irradiance)

The basic unit of **energy** is the **joule**. Power is defined as energy per unit time. The basic unit is the **watt**.

$$1 \text{ watt} = 1 \text{ joule} / 1 \text{ second}$$

A light bulb which puts out 60 watts of **radiant power** produces 60 joules of energy each second. If it's left on for 10 seconds it produces 600 joules of energy.

A **point source** of light emits radiant energy in all directions. If it was at the center of a sphere, it's energy or power would be evenly distributed within the sphere. The amount of power contained within a defined cone-shaped volume is termed the **radiant intensity**. The more power in the cone, the greater its radiant intensity. The unit for cone volume (solid angle) is the steradian, which is somewhat like the 3-D version of a radian.

$$\text{Steradians} = \text{Area at cone opening} / (\text{cone length})^2$$

For example an ice cream cone with an opening 6.75” in diameter and 6” long has a solid angle of about 1 steradian. (Big ice cream cone!)

Radiant intensity is used with point sources and is expressed in **watts/steradian**.

For an **extended source** which has a surface area measured in m<sup>2</sup>, the light emitted in a particular direction produced is called its **radiance**. Radiance is expressed as **radians/steradian/m<sup>2</sup>**.

The amount of light falling on a surface is the **irradiance**. Irradiance is expressed as **watts/m<sup>2</sup>**.

This table shows that there is a parallel between radiometric and photometric units. Photometry is concerned with how bright a light looks and that depends both on the radiant power and the wavelength of the light.

Radiometry	Description	Unit	Photometry	Unit
energy		joule		
power	energy/time	watt (joule/sec)	luminous power	lumen
intensity	point source output	watt/steradian	luminous intensity	lumen/steradian (candela)
radiance	extended source output	watt/steradian/m <sup>2</sup>	luminance	lumen/steradian/m <sup>2</sup> (nit)
irradiance	falling on a surface	watt/m <sup>2</sup>	illuminance	Lumen/m <sup>2</sup> (lux)

Also see Schwartz **Fig 4-4**.

2. *Photometry (luminosity function, Lambertian surfaces—cosine laws)*

The eye is sensitive to radiant energy between about 380 and 700+ nm. Within that range, the luminous efficiency of a wavelength (how bright it looks) is plotted on the **V(λ) curve**. This is also called the **photopic luminosity function** for cone vision. The relative brightness of each wavelength is slightly different for rods and luminous efficient plotted as function of wavelength for cones is called the **scotopic luminosity function** or the **V'(λ) curve**. Both curves are bell-shaped. The V( ) curve peaks at about **555 nm** (peak cone sensitivity). V( 555) = 1.0. The V'( ) curve is shifted toward shorter wavelengths and peaks at about **507 nm** (peak rod sensitivity). V'( 507) = 1.0. See Schwarz **Fig. 4-9**.

Whereas radiant power is just a function of how much energy is present, **luminous power** indicates how bright it looks. 10 watts at 555 nm is much brighter than 10 watts at 400 nm. Even though the radiant power is the same, the luminous power at 400 nm is less. Luminous power is just the radiant power multiplied by the luminous efficiency of the eye at that wavelength. A scaling factor of 685 converts it to **lumens**.

$$\text{lumens} = V(\lambda) \cdot \text{watts} \cdot 685 \quad (\text{Schwartz rounds to 680, Adler's says 685})$$

Note that this is for photopic lumens. At the peak of the V'( 507) there are 1700 **scotopic lumens**. I works out that for the V'( 507) function, V'( 555) = 0.4 = 680 lumens.

If the light source has multiple wavelengths, just compute the lumens for each wavelength separately and add them up for the total luminous power of the source. The additivity of luminous power at each wavelength is called **Abney's law of additivity**.

**Luminous intensity** - light produced by a point source. Unit is the candela.

$$1 \text{ candela} = 1 \text{ lumen} / 1 \text{ steradian}$$

**Luminance** - perceived brightness of an extended source. Unit is the nit.

$$1 \text{ nit} = 1 \text{ candela} / 1 \text{ m}^2$$

Other units for luminance which you might run into are:

$$1 \text{ apostilb} = (\text{candela} / \text{m}^2) \cdot (1/ \quad) = (1/ \quad) \text{ nits}$$

$$1 \text{ footlambert} = (\text{candela} / \text{ft}^2) \cdot (1/ \quad)$$

These two are specifically used with **Lambertian surfaces**, which will be discussed later.

**Illuminance** - amount of light falling on a surface. Unit is the lux.

$$1 \text{ lux} = 1 \text{ lumen} / \text{m}^2$$

Another unit you might see is the foot-lambert.

$$1 \text{ foot-lambert} = 1 \text{ lumen} / \text{ft}^2$$

Other units for luminance and illuminance are in Schwartz Table 4-1.

The illuminance (light falling on a surface) is inversely proportional to the distance (**inverse square law**). If you double the distance, you reduce the illuminance on the surface by (1/2<sup>2</sup>) or by (1/4). If the surface is tilted with respect to the light source, the illuminance on the surface is proportional to the cosine of the tilt angle. This is one of the **cosine laws**.

A matte surface which reflects light evenly in all directions, like white piece of paper, is called a **Lambertian surface**, or a **perfect diffuser**. The opposite extreme is a surface which reflect light in only one direction - a **specular reflector** such as a piece of polished chrome.

The other cosine law relates the illumination of (light falling on) a Lambertian surface with the resulting luminance (light reflected off).

$$\text{If you shine } 1 \text{ lumen/m}^2 \text{ on you get } (1/ \quad) \text{ lumens/steradian/m}^2 \text{ off,}$$

$$\text{or, } 1 \text{ lux on } \longrightarrow (1/ \quad) \text{ nits off}$$

The unit is called the **apostilb** and was designed to simplify computation of luminance for Lambertian surfaces. An apostilb is just a small nit. To be precise,

$$1 \text{ apostilb} = (1/ \quad) \text{ nits}$$

$$\text{or } 1 \text{ nit} = \quad \text{ apostilbs.}$$

Then, if for example, you are measuring the illuminance of the perimeter light source and you want

to see how much luminance will be coming off toward the patient you can use the cosine rule:

1 lux on → 1 apostilb off

Or, if you want the luminance to be 30 apostilbs, you should adjust the brightness of the light until the measured illuminance is 30 lux. These calculations assume that the Lambertian surface is 100% white, that is, it reflects 100% of the light off. If the surface reflects less than 100%, for example a 50% gray surface, the luminance of the surface will also be reduce by that factor.

For people who prefer English units we have the parallel relationships:

illumination = 1 foot-candle = 1 lumen/ft<sup>2</sup>

luminance = (1/ ) candela/ft<sup>2</sup>

1 foot-candle on → (1/ ) candela/ft<sup>2</sup> off

or 1 foot-candle on → 1 foot-lambert off

Remember, foot-lamberts are for luminance off a Lambertian surface.

Illuminance is for light shining on a surface. It has two main units:

lux

footcandles

Luminance is for the light coming off. The basic unit is the nit. But for Lambertian surfaces two other luminance units are:

apostilb

footlambert.

There are many more units for luminance. See Schwartz Table 4-2.

### 3. Spectral transmission of the ocular media

Environmental Lecture 1; Adler's Fig. 13-6, 13-7

Cornea strongly absorbs UV-C (man-made sources only) and short wavelength UV-B. From UV-B and into A the cornea starts to transmit more. It transmits visible light and near IR, but absorbs IR-C. The conjunctiva is very similar to the cornea.

Then lens absorbs most of the UV-B and A which gets through the cornea and begins to transmit UV-A. It transmits visible light (unless there's a cataract) and absorbs IR-A and B.

The ocular media absorb light more strongly in the shorter (blue) wavelengths, mainly due to the lenses stronger absorption for short wavelengths. The yellow pigment in the macula (xanthophyll) absorbs blue light also. Absorption by the retinal receptors is closely related to the V( ) curve.

### 4. Retinal illuminance

VS II Lectures 2,3; Both Schwartz and Adlers only briefly mention trolands.

The unit for retinal illuminance is the **troland**. For an light source with a certain amount of luminance in nits (candela/m<sup>2</sup>), the retinal illuminance it produces does not change with distance! Therefore, if you look at an object, it does not become dimmer as it gets further away, despite the fact that, according to the inverse square law, the illuminance reaching your eye decreases. This is because the illuminance decreases as the square of the distance but the size of the retinal image also decreases as the square of the distance - so they balance off and the retinal illuminance does not

change with object distance.

The retinal illuminance decreases in direct proportion to the **area** of the pupil. The troland therefore is proportional to the object luminance and pupil area (not diameter).

$$1 \text{ troland} = 1 \text{ nit} \cdot (\text{pupil area in mm}^2)$$

5. *Affects of incoherent radiation (e.g. Infrared, visible, ultraviolet) on tissue.*

- a. *Mechanism of damage*
- b. *Wavelength, energy levels, thresholds for reactions*
- c. *Protective measures*

Environmental Lecture 1; Borish Ch.. 24, p. 949-953

Damage to ocular tissues by any radiation depends on its absorption at that tissue. (See notes above on ocular transmission.) Shorter wavelengths primarily cause **photochemical** damage; longer wavelength mainly cause **thermal** damage. The main threat to ocular health is from UV radiation. Shorter wavelengths are more damaging since they contain more energy per photon. **UV-C** cannot penetrate the earth's atmosphere, so it's not a natural hazard, but certain man-made sources such as arc welding can produce UV-C and damage the eye.

**UV-C and B** can cause **corneal** and **conjunctival** damage. Examples: photokeratitis, pingueculae, pterygia. **UV-B** may be a primary cause of cortical, anterior subcapsular, possibly posterior subcapsular **cataract**, but not nuclear. UV exposure from the superior temporal field tend to concentrate energy to the inferior nasal conjunctiva and lens, so pinguecula, pterygia and cortical cataracts tend to form there. UV-A is strongly absorbed by the lens but it is not thought to cause cataracts. UV damage is cumulative. It may contribute to **ARMD**.

UV protection:

- 1) Sunglasses with **polycarb** or CR-39 lenses. CR-39 is OK but its UV protection is enhanced by a UV-400 dye. General purpose glasses should be neutral gray with ~15% transmission for visible light. UV-A should be <1%, UV-B should be <0.2%
- 2) Sunglasses should have **side shields** or wrap-around protection.
- 3) Wear a brimmed **hat** also.
- 4) Minimize outdoor exposure during mid-day.

Natural **IR** radiation is essentially not a risk for ocular health since it is easily absorbed by the clouds and its energy is low. Many made sources can be dangerous. Example - **glass blower's cataract**.

Table 24-12 from Dr. Pitt's chapter in Borish's Clinical Refraction

Structure	Action spectrum	Most sensitive l	UV damage threshold
cornea	200-320	270	0.05 J/cm <sup>2</sup>
conjunctiva	270-310	270	0.0025 J/cm <sup>2</sup>
uvea	295-310	305	0.015 J/cm <sup>2</sup>
lens	295-320	300	0.15 J/cm <sup>2</sup>
retina	310-380	325	0.21 J/cm <sup>2</sup>

6. *Effects of coherent radiation (lasers) on ocular tissue*

- a. Mechanism of damage
- b. Wavelength, energy levels, thresholds for reactions
- c. Ophthalmic applications (argon, excimer, YAG, helium-neon, krypton, holmium.)
- d. Protective measures

Environmental Lecture 1; Borish Ch.. 24

Primary damage mechanisms:

- 1) **Photochemical** / photoablation / vaporize. Short wavelength UV with higher energy. **Excimer** laser for PRK.
- 2) **Thermal** / photocoagulation / cook. Visible wavelengths absorbed by ocular pigments. **Argon, krypton** lasers for PRP, ALT, etc.
- 3) **Ionizing** / photodisruption / explode. Long wavelength IR. **Nd:YAG** laser in capsulotomy. The **holmium** (2000 nm) is also an IR laser and has been used to blast holes in the sclera for extreme glaucoma.

The **helium-neon** (633 nm red) laser is commonly used in research, optics laboratories, surveying, laser pointers, etc.

**Table 4.** Laser classification

Class	Description	Maximum power	Comment
I	exempt	< 0.38 μW or enclosed	No eye hazard
II	low power	< 1 mW	Safe within blink reflex time (0.25 sec)
IIIa	medium power	< 5 mW	1 sec macular burn threshold for monkeys (Lappin, 1970)
IIIb	medium power	< 500 mW	No skin burn for < 1 sec No hazard for diffuse reflections
IV	high power		Potential fire hazard

**Table 5.** ANSI Z-136.1 exposure limits for visible light.

Wavelength (nm)	Exposure time (sec)	Maximum permissible exposure
400 to 700	$10^{-9}$ to $18 \times 10^{-6}$	$0.5 \times 10^{-3}$ mJ/cm <sup>2</sup>
400 to 700	$18 \times 10^{-6}$ to 10	$1.8t^{0.75}$ mJ/cm <sup>2</sup>
550 to 700	10 to 452	$1.8t^{0.75}$ mJ/cm <sup>2</sup>
550 to 700	452 to $10^4$	175.79 mJ/cm <sup>2</sup>
400 to 700	$10^4$ to $3 \times 10^4$	$17.58 \times 10^{-3}$ mW/cm <sup>2</sup>

Laser exposure limits to prevent accidental retinal damage can be computed from **ANSI Z-136.1** Formulae used to compute the maximum permissible exposure (MPE) vary depending on the wavelength and exposure time. If the laser output power exceeds the MPE, the person must be protected.

Protective measures

- 1) Warning signs
- 2) Prevent entry or exposure
- 3) Laser safety goggle designed for the specific wavelength of the laser and with sufficient optical density at that wavelength to reduce the laser power to below the MPE.

## 5. Visual Perception

### A. Color Perception

1. Chromatic discrimination (hue and saturation) for normal and defective color vision.
2. Color mixture and appearance

Schwartz Ch.. 5

**Metamer** - a pair of stimuli (patches of light) which appear to be the same color, but they are actually composed of different wavelengths.

**Monochromacy** - no color discrimination (color blind) based on wavelength. If you show them two patches, each with a different wavelength, you can fool them into thinking they are the same color by adjusting brightness. **(Can make metamer out of 2 wavelengths)**

**Dichromacy** - some color discrimination. Given the monochromat's challenge (2 wavelengths in 2 patches), they can always tell the two patches apart based on color. If however, you add the correct amount of a third wavelength to one of the patches, you can fool the dichromat into thinking that the two patches are the same color. **(Requires at least 3 wavelengths to create metamers.)** See Figure 5-5.

**Trichomacy** - Metamers for a dichromats (3 wavelengths, 2 patches) will not fool a trichromat. They have better color discrimination than a dichromat, so those stimuli will never look the same no matter how you adjust the intensities of the 3 wavelengths. But they can be fooled into thinking 2 different patches are the same color (are metamers) if you mix 4 wavelengths in the right way. **(Requires at least 4 wavelengths to create metamers.)**

Name	Number of photopigments	Minimum number of wavelengths for metamerism
monochromat	1	2
dichromat	2	3
trichromat	3	4

**Grassman's laws** describe some principles about metamers. If you add another wavelength to a pair of metamers they are still metamers (additive property). If you multiply the intensity of the metamers by the same amount, they remain metamers (scalar property). If a third patch of light matches one patch of a metameric pair, it will also match the other patch; metamers can be substituted (associative property).

Color is not synonymous with wavelength, though they are closely related. Color is a complex concept which is described by the three variables of hue, saturation, and brightness.

**Hue** is the aspect of color which is most closely correlated with wavelength. For example, shorter wavelengths have blue hues, longer wavelengths have red hues. In some situations the hue of a

wavelength may change depending on its luminance. This is the **Bezold-Brücke phenomenon (Fig. 5-14)**. Figure 5-14 shows **hue contour lines**. As you increase luminance of monochromatic target, you must shift its wavelength as shown in the chart, to keep the hue the same. The hue contour line represents one unchanging hue. The hue remains the same, but the wavelength associated with that hue shifts slightly, except for 3 wavelengths (**478, 503 and 578 nm**). These are called the **invariant points, invariant wavelengths or unique hues**. The wavelength associated with these hues remains the same at all luminance levels.

**Saturation** describes how rich or pure a color appears. Crimson is a more saturated red hue, while pink could be a desaturated version of the same hue. Given one hue (one wavelength), you can desaturate or dilute it by adding white light. **Colorimetric purity** is a number, between 0 and 1.0, which describes a color's saturation. 1.0 means it's colorimetrically pure (no white added). Lower numbers indicate that the color is desaturated.

Given a light patch for every hue of the spectrum, even if they all have a colorimetric purity of 1.0, some hues appear to be more saturated than others. The hue associated with **570 nm** is the least saturated hue. **Abney's phenomenon** is the change in hue which accompanies the change in saturation.

**Brightness**, which is closely related to luminance but not exactly equivalent. Because the eye is more sensitive to certain wavelengths than others, as shown by the  $V(\lambda)$  curve, brightness also varies as a function of wavelength.

**Wavelength discrimination** is best at about **495 and 590 nm**. This is displayed in the "W curve" for wavelength discrimination (See **Fig. 5-13**).

### 3. Color contrast, constancy, and adaptation.

**Color contrast** is the visual illusion in which a gray or white spot will appear to take on a color which is the complement of color in its surrounding field. For example, place light gray spot in a green field and it will look reddish. Place the same spot on a red field and it will look greenish. Evidence of complex neural interactions in the retina, such as the opponent and double opponent systems.

**Color constancy or hue constancy**, The hue of an object appears to remain the same even if it is illuminated by lights which have a different spectral balances. A blue cloth looks the same when illuminated by either incandescent (greater red content) or fluorescent (greater blue content). Under some conditions color constancy breaks down.

**Chromatic adaptation**. Adapt the retina to one hue, then look at a white page and you will see an after-image with the complementary hue. This is caused by neural adaptation of the photoreceptors to the first hue. Example: stare at a green, black and yellow American flag, then look at a white page and see a red, white and blue after image.

### 4. Color specification and colorimetry (CIE)

Schwartz Ch.. 5 p 121-132; VSII Lab 9, Lecture 19

The **Munsell** color-order system organizes colors in a cylinder and any color can be located using three variables, hue, chroma, and value. **Hue** (0-100) varies around the circumference from red to yellow to green to blue to purple. **Value** (0-10) varies from top to bottom and indicates lightness. In center of the column, 0 is pure black and 10 pure white. **Chroma** (1-14+) varies from center to

periphery corresponds with saturation. See figure 5-18.

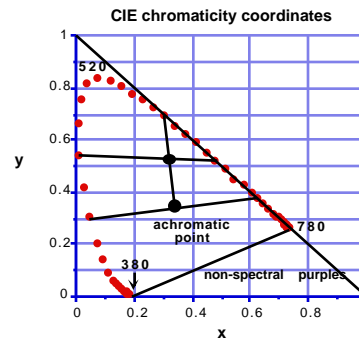
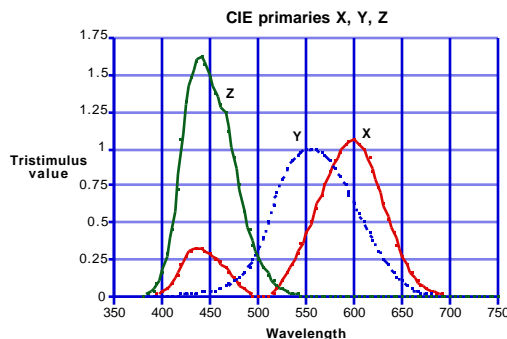
The **CIE color specification system** uses a mixture of three primary hues, X, Y, Z to specify any other hue. X, Y, and Z are three imaginary hues which were developed for convenience. In order to make any hue, mix appropriate amounts of X, Y, and Z. The amount of each primary is its **tristimulus values**. The tristimulus values of X, Y, and Z plotted as a function of wavelength are shown in the Figure 1 below. Note that the plot of the tristimulus values for Y is the same as the V(l) curve. For any wavelength, relative contribution of X to the sum of (X+Y+Z) at that wavelength is **chromaticity coordinate x**. Similarly chromaticity coordinates **y** and **z** may be computed for each wavelength.

$$x = X / (X + Y + Z)$$

$$y = Y / (X + Y + Z)$$

$$z = Z / (X + Y + Z)$$

Therefore, for any wavelength  $x + y + z = 1.0$ . You make plot the x versus y chromaticity coordinate for each wavelength and the result is the **CIE chromaticity diagram** (Figure 2, below). Any hue can be specified by it's x and y coordinate and the z value, which is not shown, can be computed from:  $z = 1 - (x + y)$ . All physically possible hue of the spectrum are represented by a point on the arc. The line joining the extremes of the arc represent the “non spectral purples” since purple is not a color in the natural spectrum but a mixture of violet and red. White is at the center and has coordinates  $x = 0.33, y = 0.33, z = 0.33$ .



The CIE chromaticity diagram can be used to:

Compute the result of **mixing two hues**. (See Schwartz **Fig 5-23, 24**)

- \* Connect the hues with a line
- \* Shift a dot on that line toward the stronger component so that the segments reflect the proportion of the hues in the mixture. If equal amounts of the two hues are mixed, the dot will be midway between them.
- \* Draw a line from white, through the dot to the arc. The point where it intersects the arc is the **dominant wavelength** of the mixture.
- \* The **excitation purity** is the distance from the **achromatic point** (white at  $x = 0.33, y = 0.33$ ) to the dot on the mixture line / distance from the achromatic point to the dominant wavelength. Max is 1.0.

Find the **complementary color** of a certain hue. When mixed they form white. Just draw a line to the other side of the arc, passing through the achromatic point. Non-spectral purples are specified by their complement.

5. *Spectral sensitivity of normal and defective color vision*  
Schwartz Ch.. 6;VSII Lectures 20, 21

	Red deficient	Green deficient	Blue deficient
Dichromat	protanope	deuteranope	tritanope
Male prevalence	1%	1%	<0.005%
Anomalous trichromat	protanomalous	deuteranomalous	tritanomalous
Male prevalence	1%	5%	<0.005%
Etiology	hereditary	hereditary	acquired
Normal peak sensitivity	565	535	430
Anomalous absorption spectrum shifted	To lower l	To higher l	

**Chromatic spectral sensitivity** - How sensitive is the eye for detecting a faint colored patch and detecting its color, against a white background? Normals show three peaks: at ~ 440, 520, 620 nm. Dichromats will be missing a peak.

**Luminance spectral sensitivity** - Detecting a light against a dark background - the photopic  $V(\lambda)$  curve peak is normally at 555 nm. In absence of erythrolabe (protanopia) the  $V(\lambda)$  will be displaced toward shorter wavelengths. Since they have reduced sensitivity to longer wavelengths, it's harder for them to see red objects compared to normals. They will be blind objects greater than 660 nm, the end of the chlorolabe curve. Deuteranopes don't show much change in their  $V(\lambda)$  function, perhaps because the M-cones don't contribute much to it. Protanomalous patients show a similar trend as protanopes. Deuteranomalous patients have normal  $V(\lambda)$  curves. (Fig. 6-3)

**Wavelength discrimination** - How well can they tell one hue from another nearby one? Protanopes and deuteranopes are essentially monochromatic above 545 nm, so they have no wavelength discrimination in that range. In the shorter wavelengths where they have and overlap with blue cones, wavelength discrimination is nearly normal. Tritanopes show normal wavelength discrimination at longer wavelengths, but poorer at short wavelengths.

**Color confusion lines** are drawn on the CIE chromaticity diagram and indicate hues which are indistinguishable to patients with color anomalies. See Fig. 6-6. The lines converge to a **copunctal point**. This also shows that above 545 nm deuteranopes and protanopes have no color discrimination. The confuse red and green so are called "red-green" anomalous. Tritanopes have color confusion lines running from 400 to 570 and confuse blue & yellow, hence the designation, "blue-yellow" anomaly.

**Saturation as a function of wavelength**. Normally 570 nm yellow is seen as the most desaturated color. For deuteranopes and protanopes, all colors are more desaturated than for normals for most of the spectrum. At their **neutral points**, those wavelengths are indistinguishable from white (See Fig. 6-7, 6-8). For deuteranopes, it's at 498 nm; for protanopes, it's at 492 nm.

Can also find these on the color confusion lines which pass through white (See **Fig 6-6**). Anomalous trichromats do not have neutral points, but their spectral saturation perception is reduced compared to normals.

6. *Mechanism of color deficiencies*

Schwartz Ch. 6, p 153-158

**8% of men, 0.4% of women** have color vision anomalies. Most red-green defects are **X-linked recessive**, therefore men are more affected. A male with the affected gene (**XY**) will be affected. A female may be a carrier if she is heterozygous (**XX**), and will manifest the condition only if she is homozygous (**XX**). See Fig. 6-9.

**Acquired color defects** may be red-green or blue-yellow. But hereditary red-green defects are common enough that most of those you see will be hereditary. Blue-yellow hereditary defects are so rare that if you see one, you should assume it's acquired. See **Table 6-3**.

**Köllner's Rule (Law)** - Diseases of the **outer** retina (outer plexiform layer, receptors, RPE) cause **blue-yellow** defects. **Inner** retina (ganglion cell layer, optic nerve) and visual pathways cause **red-green** defects. The blue-yellow channels may be more susceptible in certain diseases and with progression they may change to red-green. See Table 6-4.

**Chromatopsia** - altered color sense but not due to the usual color vision anomalies. Examples - post cataract (**cyanopsia**), since the cataract absorbs blue so strongly and the person adapts to a low blue visual environment. It may be a side effect of certain medications.

You should completely understand the Nagel **anomaloscope** (Schwartz p. 163-168, **\*\*Fig. 6-16** and VSII Lecture 21).

Hereditary	Acquired
99% red-green	blue-yellow or red-green
96% males	male or female
color naming errors rare	recent history of color naming error
stable with time	variable with time
easily diagnosed & classified	difficult to diagnose & classify by tests
no associated disease	associated disease
same binocularly	may be monocular or asymmetric

B. *Space Perception*

Schwartz Ch. 10, VSIV Lecture 15, 16, 17, 18, 19, 4, Lab 4, 1

1. *Direction and depth discrimination (monocular and binocular cues, oculocentric and egocentric localization)*

The visual perception of three-dimensional space can be organized into **absolute** and **relative depth perception**. They have the following characteristics:

Absolute depth perception is sometimes referred to as "distance perception"

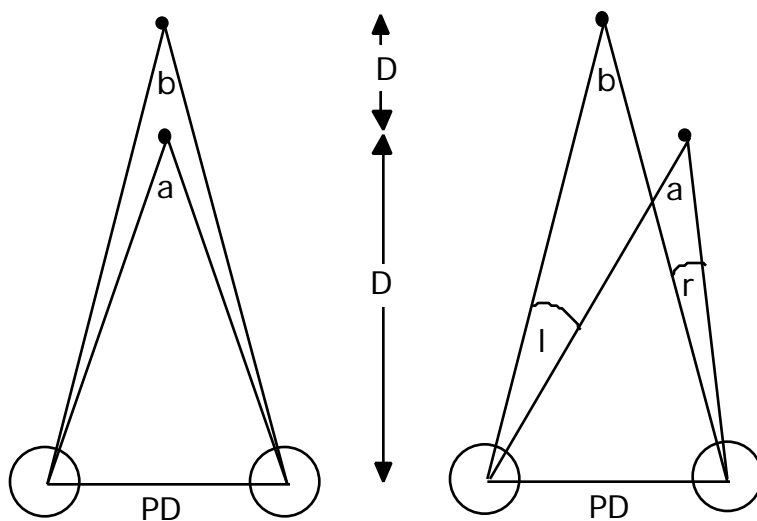
- \* estimates physical distance from observer to object
- \* For example, "He hit the golf ball about 200 yards."
- \* primarily judged based on monocular cues

Relative depth perception is also called “depth perception”

- \* estimate of the relative position between objects
- \* For example, “The golf ball is on this side of the hole.”
- \* Based on monocular cues + stereopsis, though stereopsis is less important beyond arm’s length.

Visual cues which help us judge distance and depth may also be divided into **monocular and binocular depth cues**. Monocular depth cues include size, linear perspective, texture, interposition, clarity, lighting and shadow, and motion parallax.

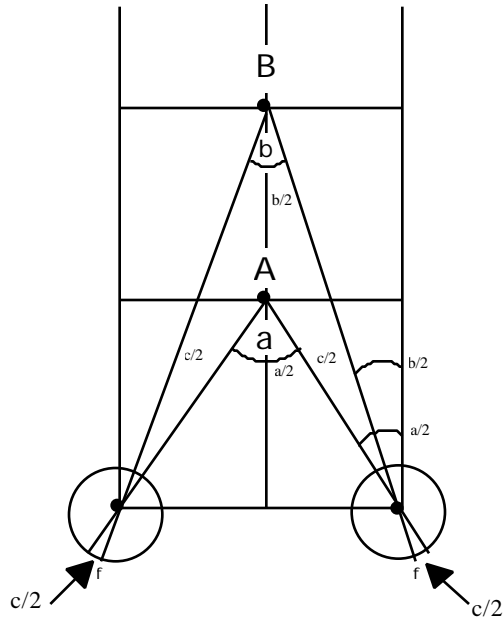
**Stereopsis** is a uniquely binocular phenomenon that gives us a sense of relative depth, based on geometric disparity in object space, which give rise to **retinal disparity**. The retinal disparity is caused by the fact that the two eyes view objects from different vantage points. This is known as **binocular parallax**.



For long distances (D) or small D values, such as when measuring the stereo acuity threshold at 40 cm or more, the geometric disparity ( ) in radians can be closely approximated by:

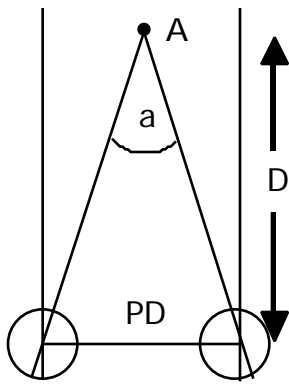
$$= \frac{PD(D)}{D^2}$$

To express the geometric disparity in arc seconds, multiply by 206,265. Note that may be computed either as the difference between angles a and b or between r and l. The next figure shows that the geometric disparity in object space is equal to the retinal disparity. Retinal disparity is the sum of the two binocular parallax angles (c/2 + c/2).



$$c/2 + c/2 = c = a - b$$

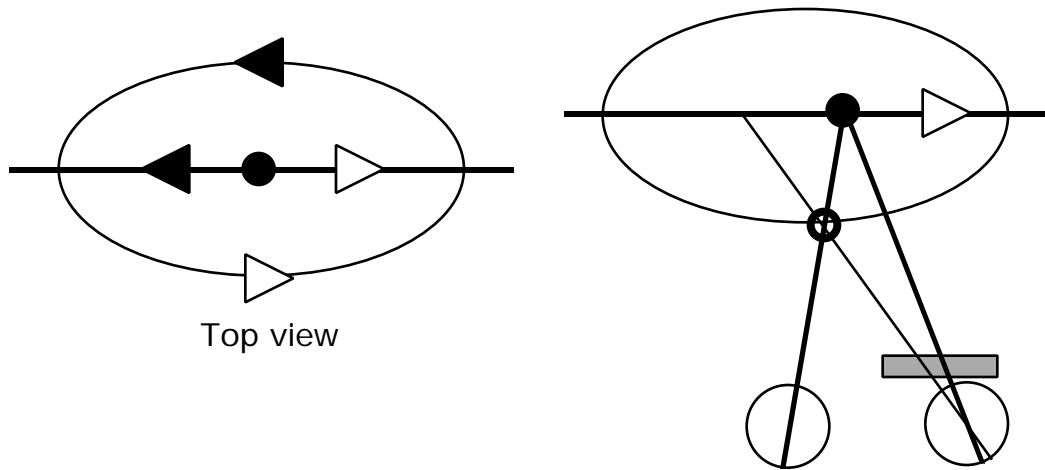
The minimum angular disparity required to perceive relative depth between two objects using stereopsis is the **stereoacuity threshold**. Under ideal conditions, it is **2-10 arc seconds**. Given a certain stereoacuity threshold, you can compute the greatest distance that an object can be located and be distinguished as closer than infinity by stereopsis:



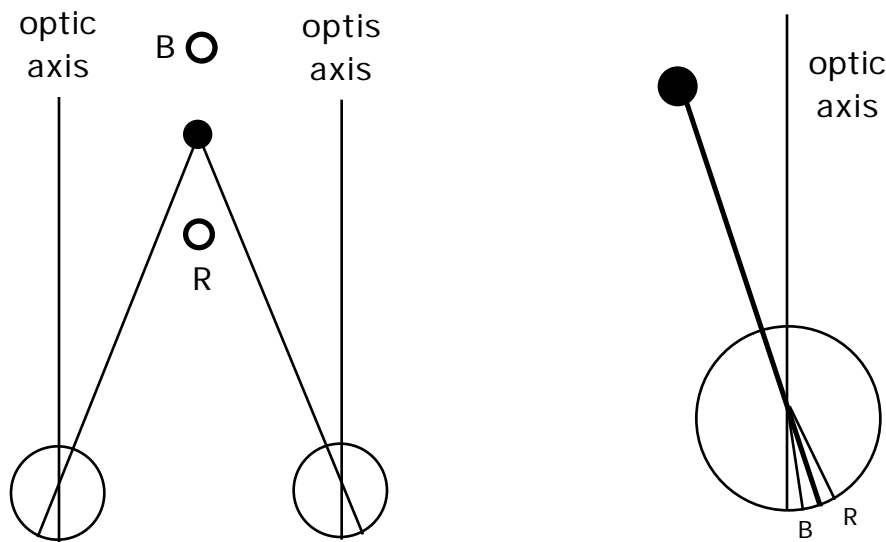
In radians,

$$\text{angle}_a = \frac{PD}{D} \text{ therefore } D = \frac{PD}{\text{angle}_a}$$

If the PD = 0.064 m and angle a is 20 arc seconds ( $9.696 \times 10^{-5}$  radians), distance D is equal to 660 meters.



In the **Pulfrich effect**, if an ND filter is placed over the right eye, the pendulum will appear to swinging in a oval, rather than straight, swinging pattern due to the delayed neural signal for the covered eye. Though both eyes are fixating the pendulum, the left eye processes the image for where the pendulum is now, but the right eye processes the signal for where the pendulum was a moment before. In effect, it is as if the right eye still sees the pendulum as slightly to the left. This sets up a retinal disparity in the two images, which are fused. Based on the disparity information, the apparent location of the object is slightly nearer to the observer (circle) than the actual location of the pendulum.



**Chromostereopsis** is another illusory stereoscopic perception, which is based on chromatic aberration within the eye. If the optic axis and visual axis in each eye do not coincide, the retinal image formed by red and blue light to fall on slightly different retinal locations. In the figure above, the greater refraction of blue light causes its image to fall on more nasal retinal locations, while the red image falls on more temporal locations. This disparity between the images in the two eyes gives rise to a stereoscopic perception such that the red object will appear closer, and the blue object will appear further away. Some people perceive the opposite relationship—blue objects appear closer and red objects appear further away. Presumably, this is caused by having the opposite relationship

between the visual and optic axes.

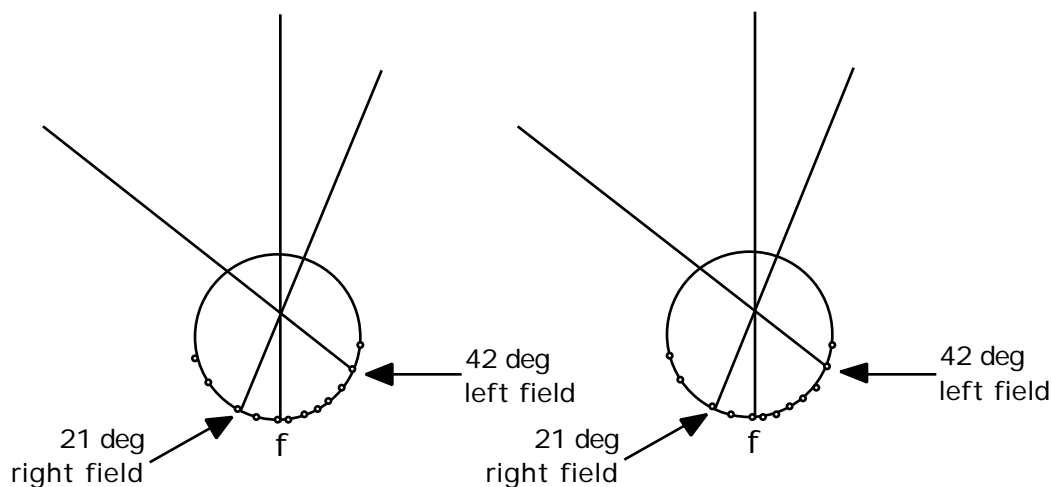
If we isolate vision from the rest of the senses, the reference point for normal binocular vision is a point in the head. In vision science this is called **egocentric localization**. Our brain combines the input from the two eyes, and it is as if we see things from a single eye (**cyclopean eye**) that is located at the **egocenter**, midway between the two eyes. The brain receives input from the two eyes and computes the egocentric direction of an object based on:

- 1) The retinal direction or **local sign** of the object's image in each eye relative to the fovea. Direction relative to the fovea of one eye is called, **oculocentric localization**.
- 2) The eye's orientation. The brain may receive direction of gaze information from proprioception within the extraocular muscles and from the oculomotor neurons which drive the muscles.

2. *Characteristics of sensory fusion (binocular interactions including summation, binocular suppression and rivalry; corresponding points including horopter criteria).*

VSIV Lectures 7, 8, 9, 20, 21

Hering's law of identical visual directions says that for every visual line in one eye, there is a corresponding visual line in the other eye which has the same visual direction. It follows then that, for every retinal point in one eye, there is a point in the other eye's retina which has the same visual direction. The pair of points in the two retinas which have the same oculocentric visual direction are known as **corresponding points**.



**Figure 3.** Corresponding points have the same oculocentric visual directions.

The **horopter** (horizon of vision) is the set of points in space that stimulate corresponding points in the two retinas. When a person is fixating an object, the horopter is an arc in the horizontal plane, which passes through the fixation point. Each fixation distance has a horopter associated with it. Based on the definitions for corresponding points and the horopter, each point on the horopter has the same oculocentric visual direction in both eyes. The two images (on each retina) of any object located on the horopter have **zero retinal disparity**. Based on certain assumptions, we can draw a theoretical horopter, which passes through the fixation point and the nodal points of the two eyes. This theoretical horopter is called the **Vieth-Müller circle**. For greater fixation distances, the Vieth-Müller circle becomes larger and the curvature of the theoretical horopter flattens. The V-M

circle assumes that both retinas are circular in cross-section, the corresponding points are evenly and symmetrically distributed (nasal & temporal) in both eyes, and that the eye has a single nodal point.

Object located on the horopter are binocularly fused because the images fall on corresponding retinal points. Objects located a little nearer or farther than the fixation point, theoretically are off the horopter and therefore stimulate non-corresponding points, yet they can still be fused binocularly. This is because they fall within a zone surrounding the horopter called **Panum's space**, in which binocular fusion is still possible. If an object is moved far enough away from the horopter, while the person is still fixed on the fixation point, the retinal disparity will become large enough that the person will perceive diplopia for that object. At that point, the object has exceeded the bounds of Panum's space. On the retina, the small area surrounding a corresponding point, on which an image may fall and still be fused, in spite of a small amount of disparity, is called **Panum's area**. For images outside of Panum's area, they are seen diplopic.

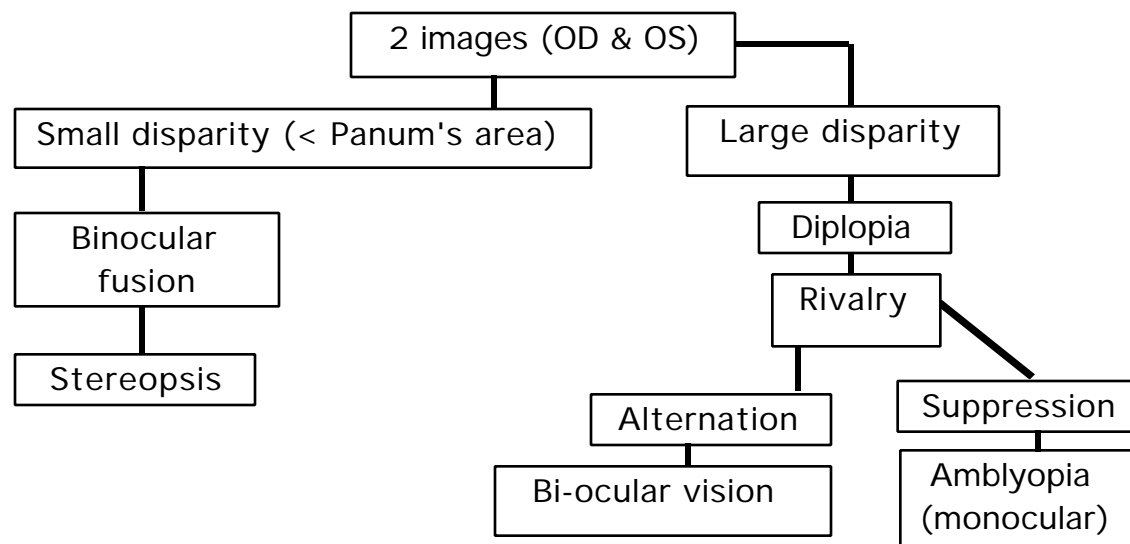
The **empirical horopter** is that which is measured on real human subjects. One technique measures the apparent fronto-parallel plane (AFPP) of the subject, but this and other empirical horopters often do not match the V-M circle for that fixation distance. The difference between the empirical and theoretical (V-M circle) horopters is called the **Hering-Hillebrand deviation**. The AFPP horopter is usually curved toward the subject for near fixation distances, but flattens and actually curves away from the subject for longer fixation distances. The distance at which the AFPP horopter becomes flat is the **abathic distance**. The **nonius horopter** is considered the most accurate technique for measuring the empirical horopter because it actually measures the visual direction in the two eyes. The Hering-Hillebrand deviation indicates that some of the assumptions inherent in the V-M circle are not correct.

Not only may the images in the two eyes fall on slightly disparate retinal points, but they may also be slightly different from each other in terms of their shapes, due to binocular parallax. Occasionally the images that fall on roughly corresponding points may be quite different from each other and the eyes may have difficulty fusing them. If there is a competition between the two eyes, and the simultaneous perception of different foveal images is called, **confusion**. The competition between the two ocular images in the binocular visual system is known as **rivalry**. Reading defines this as, "the periodic or intermittent extinction of brightness, color, or contour from the perception of one eye as a result of stimulation of the other eye." In some cases the visual system avoids confusion by suppressing one image or parts of one image. Reading defines **suppression** as, "the failure of one of the two monocular visual systems to perceive a normally visible object in all or part of the visual field."

Suppression is an important clinical problem in children with **strabismus**. One eye is deviated, causing the two eyes to receive different images. The initial perception will be diplopia and **confusion**. The visual system will not tolerate this for long. The normal solution to the rivalry between the two ocular images is that one usually wins out and the other is suppressed. Usually, the eye with the larger refractive error, or poorer quality retinal image is suppressed. If suppression continues for a long time in a young child with a developing visual system, this can become permanent. This can hinder the normal development of vision in that eye and lead to **amblyopia**, in which the eye never develops normal visual acuity.

In some cases, in spite of strabismus, image quality between the two eyes is nearly equal and the visual system may not give preference to one eye or the other. In this case, the visual system may solve the rivalry problem by **alternately suppressing** the two eyes. Children who develop **alternation** usually do not become amblyopia; each eye develops normal visual acuity. However,

since the visual system does not learn to fuse the two images, binocular visual functions such as stereopsis, never develops.



Suppression can be complicated, depending on the nature of the stimulus presented to each eye and the way the images are processed by the visual system. In general, the following trends are expected:

- \* Bright features tend to suppress darker features
- \* High contrast features tend to suppress low contrast features
- \* Clear images tend to suppress blurry images
- \* Foveal images tend to suppress peripheral images
- \* Moving images tend to suppress stationary images

Sometimes if the eyes try to fuse black and white images which are negatives of each other, the eyes may perceive binocular **luster**. When two different colors are presented to each eye, the result may be **binocular color fusion**, in which the color appears to be a mix of the monocular hues. This delicate percept may be difficult to maintain, and the binocular image may alternate between the two original colors, or portions of the binocular image may contain a mixed color, while other portions may contain one color or the other.

Stereopsis is not the only benefit of binocular vision. We also discussed how much larger the binocular visual field is than the monocular fields. In addition, some visual stimuli are easier to see with two eyes than with one eye. This indicates **binocular summation** of the input from the two eye. For example, dim lights are easier to detect with two eyes than one. In this task the improvement is simply due to **probability summation** — the improved probability of detection from having two rather than one detector. If binocular function improves beyond that expected from probability summation, it may be due to physiological mechanisms which enhance the binocular perception. Above threshold, lights generally appear to be slightly brighter when seen by two eyes rather than one.

In some conditions, the brightness of a light seen binocularly is actually lower than if it is seen monocularly. If a neutral density filter is placed over one eye, while the other eye views a bright

light directly, the binocular perception of brightness is less than the brightness seen by the unfiltered eye. This is called, **Fechner's paradox**, and it suggests that the binocular perception is a sort of average between the two monocular perceptions.

The visual system seems to respond more quickly to stimuli which are presented binocularly than monocularly. For a flickering light, the highest flicker frequency which can be detected (CFF) is greater for binocular than monocular viewing if the lights presented to the two eyes are in phase. If they are out of phase with respect to each other, the binocular CFF is actually smaller than the monocular CFF. This also indicates a summation or interaction with the input from the two eyes.

Condition	Typical Photopic CFF
Binocular - OD, OS flicker in phase	45
Binocular - OD, OS flicker out of phase	30
Monocular	40

**Table 2.** CFF under binocular and monocular conditions.

Both visual acuity and contrast sensitivity are slightly better with binocular viewing, probably due to both statistical and physiological summation. Generally, you would expect binocular visual acuity to be about one line better than monocular acuity in a clinical setting.

### 3. Development of sensory fusion and binocular vision

VSIV Lecture 30, 31, 32

At birth, LGN afferents that synapse into layer IVC of area V1 make broad connections, and there is much overlap between axons carrying right eye and left eye information (**Adler's Fig. 24-47**). As the visual system matures, the extent of axonal branching begins to shrink so that neurons in layer IVC segregate into right and left ocular dominance regions. During the first few months of life, distinct, well segregated **ocular dominance columns** develop within the primary visual cortex (V1). In cases of monocular visual deprivation, dominance columns corresponding with the seeing eye expand, while the columns associated with the deprived eye shrink. Binocular neurons are first found at the next synaptic level (layer II and III for the parvo system, layer IVB for the magno system). Disparity sensitive neurons are located at this level and they receive input from layer IVC neurons located in both the right and left eye ocular dominance columns.

The development of normal binocular processing depends on the quality of binocular input that these neurons receive during the **critical (or sensitive) period**. It is as if neurons from layer IVC are competing for the attention of the next higher level binocular neurons. Monocular deprivation reduces the size of a ocular dominance column, and this presumably weakens input from that eye into the binocular neuron in layers II, III, IVB (second synaptic level in V1).

Quoting again from Bishop (Adler's 8th ed., p. 672):

Many of the diverse effects of visual deprivation can be linked together by the idea that during the sensitive period the afferent paths from the two eyes compete for control over the cortical cells.

Although the actual mechanism of this binocular competition is still unknown, it is proposed that ... [axons] ... compete with each other for synaptic sites on binocular cortical neurons.

In order to develop normal binocular vision, the visual system must receive good quality, corresponding retinal images during the critical period. If the quality of either image is poor, this

will lead to **amblyopia**. If the images are both of good quality, but are non-corresponding (for example, due to strabismus), then visual acuity may develop normally, but binocular fusion will not develop normally.

A prerequisite for sensory fusion is **motor fusion**. As previously shown in **Adler's Fig. 24-44**, newborns normally have unstable ocular alignment, and intermittent strabismus is common. The majority of babies in this age range have an intermittent exotropia; some vary between intermittent exo and eso deviations; a small number tend to show occasional esotropia only. By about 6 months of age, the majority of these infants were fixating normally. This variable, intermittent and temporary strabismus is part of normal binocular development for most babies.

While **visual acuity** slowly develops, reaching adult levels by about age 3 or 4, **stereopsis** develops much more quickly. By three months of age, when the majority of infants are developing normal motor fusion most of the time, the normal infant should already be able to superimpose images (second degree fusion). Between about age 3-5 months there is a **rapid development of stereopsis**, so by about 6 months of age, the infant should be capable of nearly adult levels of stereopsis (60 arc seconds).

Magnocellular neurons seem to develop sooner than parvocellular neurons, and these are the ones which are associated with low spatial frequencies and motion. At first the oculomotor system shows a preference for pursuit movements for targets which are moving nasally (temporal to nasal).

The **critical period** in humans appears to be divided into two phases.

- Infantile phase - birth to about 8 months of age
- Post-infantile phase - from about 8 months to 9 years of age

During the initial infantile phase visual functions appear to develop very rapidly but during the post-infantile phase the rate of development slows. During the infantile phase, visual acuity improves quickly and stereopsis develops during this time. Anatomic studies confirm this time of rapid growth, as shown in **Adler's Fig. 24-48**. The top graphs shows the steep increase in cerebral cortex volume and the density of synapses per cubic mm during the first 10 months of life. Within these two phases, the magno and parvo cellular systems appear to mature at different rates. Rapid growth in the magno system begins sooner and proceeds more quickly than the parvo system.

As would be expected from animal studies, earlier diagnosis and treatment for monocular deprivation within the critical period improves the prognosis for recovery of normal visual acuity and binocular vision. For example, an infant born with cataracts should have surgery and be corrected as soon as possible to allow their visual system to mature normally. In the case of strabismus with amblyopia, treatment options include spectacle correction of any refractive error, strabismus surgery, monocular occlusion of the non-amblyopic eye and vision training. If treatments is delayed until late in the critical period, the likelihood of developing normal vision becomes increasingly remote.

#### *4. Disturbances of perceived direction and distance (aniseikonia and amblyopia)*

VSIV Lectures 27, 28, 35; Borish Ch.. 5

Aniseikonia is a difference in image size between the two eyes, and the most common cause is **anisometropia**, or unequal refractive errors. Actual retinal image size depends on the person refractive error as well as the type of correction they are using. Perceived image size depends on additional factors, such as the distribution of local signs across the retina, as well as processing in the visual system. This shows that the problem of aniseikonia is more complex than simply a

difference in spectacle powers. **Spectacle magnification, retinal image size, local sign distribution, neural processing and adaptation all can affect the perception.**

Classically, aniseikonia has been studied by altering the spectacle magnification before one eye, then analyzing the distortion in space perception. The types of space distortions have been divided into three categories:

- 1) Geometric effect
- 2) Induced effect
- 3) Oblique effect

The **geometric effect** is the binocular distortion caused by magnification in the horizontal plane and is represented by Figure 5-18 in Borish. As shown in that figure, horizontal magnification of the right eye image causes the true fronto-parallel plane appear to be tilted away from the right eye. If the magnifying lens were placed over the left eye, the plane would appear to be tilted in the opposite direction

The **induced effect** describes the binocular distortion caused by magnification in the vertical plane. A lens which causes a vertical (only) magnification in front of the right eye, has the same effect as a horizontal magnifying lens over the left eye.

An overall magnification (includes equal horizontal and vertical) magnification before one eye, will cause both a geometric effect and induced effect. Since these effects are opposite, they tend to cancel each other out, and the net result may be less perceived aniseikonia than would be expected from the magnification alone.

The oblique effect refers to meridional magnification before both eyes. For example, a meridional magnification at 135 degree OD and 45 degrees OS. The oblique effect is illustrated by Figure 5-20 and 5-21 in Borish for a meridional magnifying lens at 45 degrees before OD and at 135 degrees before OS. The checkerboard appears to tilt away at the top and toward the observer at the bottom.

Another principle of space distortion is that the side that is tilted away from the observer appears larger. This is based on the principle of size constancy. Even though stereoscopic disparity creates the illusion that part of the surface is tilted away, the angular size of the object is nearly the same. For a more distant object to have the same angular size as a nearer object, it must be larger. This is the same logic used to explain the moon illusion. This was illustrated in Borish Figure 5-21.

Based on **Knapp's law**, certain types of anisometropia are better corrected by contact lenses, while others are better corrected by spectacles. Knapp's law says that a **refractive anisometropia** should be corrected by contact lenses (in the corneal plane), but an **axial anisometropia** should be corrected by spectacles, to minimize aniseikonia. In clinical practice, Knapp's law is not so important because it's hard to know for sure whether a person's aniseikonia is refractive or axial and it does not take into account other factors which can affect perceived image size (distribution of retinal receptors, neural processing, adaptation, etc.).

An instrument which has been designed to measure perceived aniseikonia is the **Space Eikonometer**. It subjectively measures aniseikonia based on the patient's perceived distortion of a standard target.

Patients with **amblyopia** have a reduction in **contrast sensitivity**, usually in the high, but not low

spatial frequencies. Interestingly, this is true only for central vision. Peripheral visual acuity and contrast sensitivity beyond 10 degrees of eccentricity is normal in amblyopes.

Amblyopes also have poorer than normal **vernier acuity**. In a vernier task, the subject must judge whether two lines are aligned or offset with respect to each other (Fig. 35-1). In normal patients vernier thresholds are much smaller (2-10 arc seconds) than you would predict based on foveal cone diameter, therefore this is called a **hyperacuity task**.

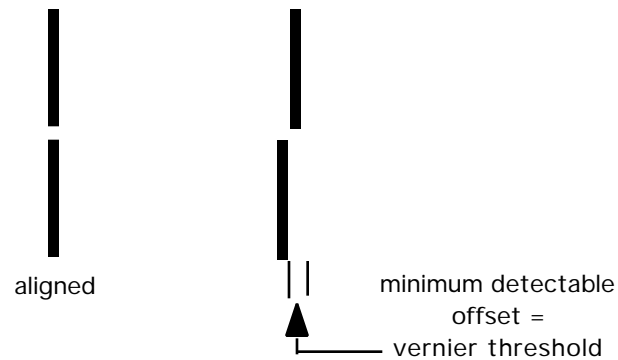


Figure 35-3. The vernier acuity test determines the minimum detectable offset of two lines, or other similar task.

People with amblyopia experience the **crowding effect**, which is described as difficulty reading a letter when it is surrounded by other letters or contours. For this reason, when testing visual acuity on amblyopes, you may measure a better visual acuity using isolated letters than if you use a single line or the entire chart. Also, when reading a row of letters, amblyopes can usually read the first and last letters more easily than the middle letters.

In persons with normal binocularity, pupils are about 30% smaller with binocular viewing than with monocular viewing. This is an indication of summation of the input from the two eyes. In amblyopia, this effect is less pronounced, indicating a less complete summation of luminance input from the two eyes. The reduced summation is thought to be at the cortical level and not in the retina.

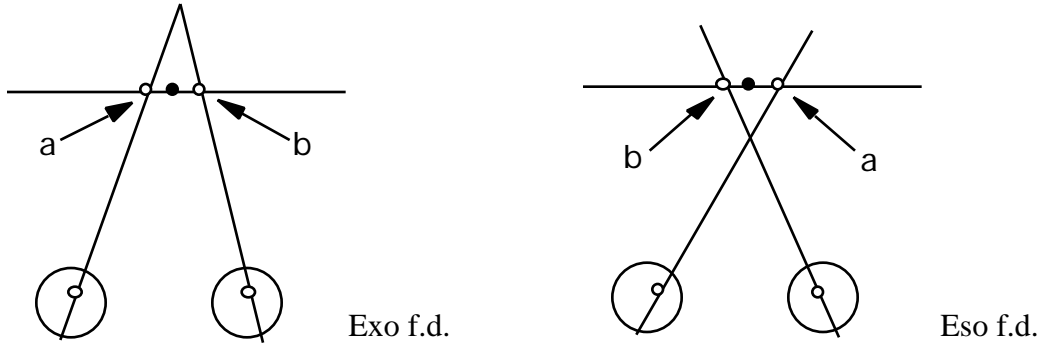
Patients with amblyopia are able to appreciate the **Pulfrich effect** without using an ND filter. It appears that electrical signals are conducted at a slightly slower velocity in the geniculate or cortical neurons associated with the amblyopic eye.

5. *Sensory-motor interactions (fixation disparity, past pointing, visually guided behavior, body posture and perceived orientation, and self-motion)*

VSIV Lectures 10, 11, 12, 13, 39, Lab 3; Review book

A residual misalignment with bifoveal fixation is called **fixation disparity**. Since it is possible to fuse images that fall within Panum's area, it is not absolutely necessary for both foveas to point exactly at the fixation point in order to achieve binocular fusion. In fact, a small amount of fixation disparity may be beneficial.

If the person attempts to fixate a point located 40 cm from the egocenter, the visual axes may actually be converging on a point slightly beyond to the intended fixation point. For example, at 40.5 cm. This is an example of **exo fixation disparity** (left figure below).



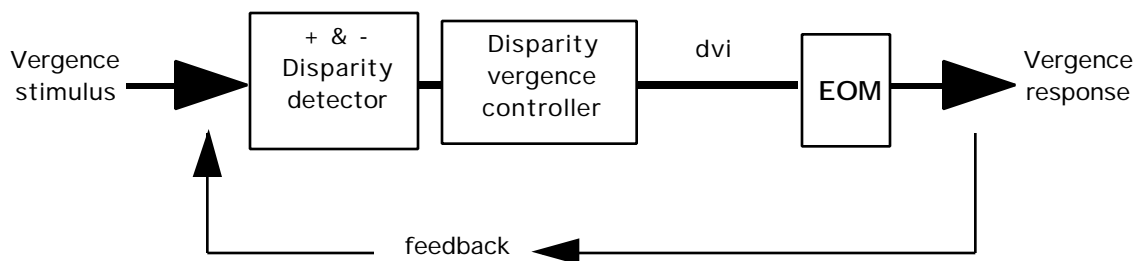
In **eso fixation disparity**, the eyes are slightly over-converged. The over-convergence is small enough that the images are binocularly fused, but each eye's visual axis is pointing to a point nearer than the intended fixation point. This is illustrated by the right figure above.

These three ocular misalignments are fundamentally different in their definitions and characteristics.

- \* **Fixation disparity** is a very small deviation of the visual axes during normal binocular fusion. The misalignment is so small that the fixated object is still seen as fused. Specially designed testing equipment is required to measure fixation disparities.
- \* **Heterophoria** may be thought of as the rest position that the eyes turn to when binocular fusion is interrupted. In order to detect and measure a heterophoria, normal binocular vision is interrupted using prisms (Von Graefe test), alternate occlusion (cover test), or by other means. During normal binocular fusion, the phoria is compensated and is not apparent.
- \* **Heterotropia**, or strabismus, is a deviation of the visual axes which exceeds Panum's area, therefore, binocular fusion is not possible. When the person with strabismus attempts to view an object with both eyes, the strabismic eye deviates. If the good eye is covered, however, the strabismic eye will usually correctly fixate the object. A person with strabismus is limited to monocular vision with the good eye, or they may alternate between the eyes.

**Table 1.** Three ocular misalignments.

Name	Size	Binoc fusion possible?	Test condition
Fixation disparity	$< 5'$ ( $\sim 0.15^\circ$ )	yes	binocular
Heterophoria	$< 10'$	yes	monocular
Heterotropia	Up to $30'$ +	no	binocular



**Figure 1.** Disparity vergence system considered in isolation from other components.

When shifting attention from a distant to near fixation point, a convergence demand or stimulus to vergence is created. The presence of a positive disparity (crossed disparity) is detected by special mechanisms, which inform the disparity vergence controller. The controller estimates the required magnitude of convergence and issues an innervation for a initial coarse vergence movement, which reduces the disparity. Proximal vergence and accommodative convergence may be at work here. Shortly after, the controller issues an innervation for a fine motor response, which will adjust the disparity to approach zero. It continues to operate to maintain a sustained level of vergence. Keep in mind that **disparity vergence** requires some disparity to continue working. What happens then, if the mechanism perfectly aligns the visual axes on the fixation point? The vergence demand will become zero and the stimulus to maintain the correct vergence will be lost. Without disparity vergence, the eyes would quickly swing back toward their position of rest; but then disparity would increase and they would have to swing back toward fixation. Saladin explains how fixation disparity helps to maintain a stable alignment (Borish, p. 748-749).

One would think that, in a manner similar to that of the accommodative system, the disparity vergence control mechanism would direct the innervational pattern until the desired vergence level is reached and the controller no longer had an error signal. At first thought, this null situation would seem appropriate if the vergence level is at some rest position, but if this point were actually reached, the system would become unstable because it would have no input. It would fluctuate back and forth within a disparity deadspace (a few minutes of arc, depending on the stimulus configuration, and roughly equivalent to Panum's area) in which no error signal was generated. Instead of going to the null point (the center of the deadspace), however, the system goes to one side of the deadspace and thereby leaves a small directionally specific error. ... The amount of disparity left to provide the necessary steady-state or maintenance innervation is known clinically as *fixation disparity*.

Generally the disparity vergence endpoint for exophoria patients is just beyond fixation, but within Panum's space. That is, you expect to see a slight exo fixation disparity with exophoric patients. This leaves a small amount of positive disparity that stimulates a continuing fine fusional convergence. In the case of esophoria, the eye tend to favor an over convergent posture relative to the fixation point. During binocular fusion, fine disparity vergence reduces this, but not perfectly. Usually a small amount of residual negative, or eso fixation disparity is left and this helps to stimulate a steady divergent response.

One way to study the disparity vergence system is to see how fixation disparity changes when different amounts of BI or BO prism are introduced before the eyes. Ogle investigated different subjects and classified them into four types of responses, which are plotted as the forced vergence / disparity function. See **Figure 20-27** from Borish or your notes for illustrations of Ogle's four types.

This is the standard way to display the response of the disparity vergence system to the vergence stimulus. BI and BO prism - which creates retinal disparity and stimulates vergence - is plotted on the x-axis. The disparity vergence response, that is, how closely the visual axes keep up with the stimulus, is plotted on the y-axis. Specifically, this test process helps evaluate the fine disparity vergence system.

The five most important features of the disparity vergence response function (fixation disparity curve) are:

- \* the y-intercept, which shows the fixation disparity

- \* the x-intercept, which shows the associated phoria
- \* slope of the curve at the y-intercept
- \* curve type (I, II, III, or IV)
- \* inflection point, or center of symmetry of the curve

A theoretical ideal response would be a symmetric Type I curve, which crosses near the origin. This would indicate a low fixation disparity, low associated phoria, and a system which is able to follow BI and BO prism equally well. This is not necessarily a requirement for normal, comfortable binocular vision, but departures from the ideal can be used to evaluate a possible binocular problem.

#### Fixation disparity

A large fixation disparity can indicate that the binocular system is under stress, either due to excessive demands (intense near work), or inherent weakness in the system. Normal fixation disparities should be between **6 arc minutes exo or 4 arc minutes eso**.

#### Associated phoria

The prism needed to correct any fixation disparity is called the **associated phoria**, since it is measured while the patient is binocularly fusing. The **dissociated phoria** is the normal heterophoria and is measured when the eyes are dissociated, that is, when binocular fusion is broken. In the Von Graefe phoria test, dissociating prisms are used to interrupt binocularity.

#### Slope of the curve

Steepness of the slope was discussed above. Some doctors think that a slope greater than **1 arc min/ prism diopter**, may be associated with visual discomfort.

#### Curve type

If the Type I curve is considered an ideal response, the other curves may be an indication of some degree of binocular dysfunction. Type II curves are usually found in patients with esophoria, while Type III curves are associated with exophores. With vision therapy Type III curves sometimes change into Type I curves, but Type II responses are more resistant to change. Type IV response patterns are not well understood, but they are associated with binocular dysfunction. With vision therapy, these can also be converted to a Type I response.

#### *C. Form Perception*

*1. Static visual acuity (including test configurations, various acuity tasks, and factors influencing acuity including blur, intensity and contrast); specification of visual acuity*

Adler's Ch.. 17, VSII Lecture 10.

Visual acuity is a psychophysical threshold task in which the spatial dimension is the variable (Adler's). It is limited by the quality of the retinal image, the spacing of the retinal receptors and neural processing of the image.

Several **optical factors** affect image quality:

1. Diffraction. When the pupil is smaller than about 2-3 mm diffraction is the primary factor which causes image blur.
2. Aberrations. Beyond a pupil diameter of ~ 3 mm, optical aberrations become greater than diffraction and blur the image. For large pupils this can be very significant. Best image quality is usually for a 3 mm pupil.
3. Scatter of light in the ocular media.
4. Absorption.
5. Defocus due to refractive error, incorrect accommodation, etc.

**Retinal anatomy** limits spatial resolution. In the fovea, the cone diameter is about 0.5 arc min, so even if the eye had perfect optics, the minimum separation between two points which can be resolved is 0.5 arc min. In the periphery, larger numbers of rods feed into a single ganglion cell, so spatial resolution is much worse.

20/20 Snellen acuity letter configuration: Letter height 5', limb/gap width 1'. **Landholt C**: ring outer diameter 5', limb/gap width 1'. On grating patterns, the line width and gap is 1'. On checkerboard patterns the square is 1' on a side. The line/gap width corresponds with the **minimum angle of resolution (MAR)**. The MAR is easy to compute from the Snellen fraction by the formula,

$$(\text{Snellen fraction})^{-1} = \text{MAR in arc minutes}$$

The several categories of visual acuity tasks are summarized in the table below:

Category	minimum visible	minimum resolvable	minimum discriminable
Threshold type	<b>Detection</b> a line	<b>resolution</b> (clinical VA)	Vernier ( <b>hyper</b> ) <b>acuity</b>
Description	thinnest line which can be seen	minimum distance for 2 lines to be seen as 2	minimum offset of two lines which can be seen
Variable	Line width	gap size	displacement of 2 lines
Detect what?	DI from background	DI between 2 adjoining areas	difference in local positions
Optimal threshold	~ 1 arc second	~ 30 arc seconds	~ 3 arc seconds

Some letters are easier to read than others so in designing Snellen acuity tests certain sets of letters or certain font may be selected. One well know letter set is the **Sloan letters set** which uses the 10 letters, C, D, H, K, N, O, R, S, V, Z.

The steps between lines in the common Snellen acuity chart do not represent equal steps in terms of difficulty. A more logical progression would be to have letter size increase as a logarithm of the MAR. Some charts use a logMAR progression such a the **Bailey-Lovie chart** or **ETDRS (Early Treatment of Diabetic Retinopathy) chart**. The following chart (next page) shows how Snellen acuities would progress if the chart started at 20/10 and letter size increased at 0.1 logMar steps.

#### Factors which can affect visual acuity

1. Refractive error
2. Retinal eccentricity - drops to about 20/100 at 10 degrees, 20/200 at 20 degrees (Adler's Fig. 17-9).
3. Retinal illuminance - Increases with illumination but the curve has two lobes, one for rods, one for cones (Adler's Fig 17-10).
4. Contrast - resolution decreases with lower contrast
5. Pupil size - Below 2.5 mm acuity decreases. 2-6 mm not much change. Above 6 mm acuity declines.
6. Exposure duration - gets worse below 500 msec

7. Target movement - eye can keep up with small movements, otherwise acuity degrades.
8. Meridian - some tests shows slightly better acuity in horizontal and vertical meridians than in oblique meridians.
9. Crowding effect - if letters are too close, acuity decreases.
10. Age (See Adler's Fig. 17-12)

Snellen 20/x	Decimal acuity	MAR	log MAR
10	2.00	0.50	-0.3
13	1.58	0.63	-0.2
16	1.26	0.79	-0.1
20	1.00	1.00	0.0
32	0.63	1.58	0.2
40	0.50	2.00	0.3
50	0.40	2.51	0.4
63	0.32	3.16	0.5
80	0.25	3.98	0.6
100	0.20	5.01	0.7
126	0.16	6.31	0.8
159	0.13	7.94	0.9
200	0.10	10.00	1.0
252	0.08	12.59	1.1

2. *Spatial contrast sensitivity function (including factors influencing the function).*

Schwartz Ch.. 7; VSII Lectures 7, 8, 9

The spatial sine wave grating is an elementary target which can be used to test spatial vision by varying the targets spatial frequency and contrast. Figure 3 shows a sine wave grating with it's corresponding luminance profile.

**Michelson contrast** is defined as:

$$\text{contrast} = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{I}{I_{\text{mean}}}$$

1.0 means high contrast (I(max) is pure black, I(min) is pure white), close to 0 means low contrast (faint gray stripes on a gray background).

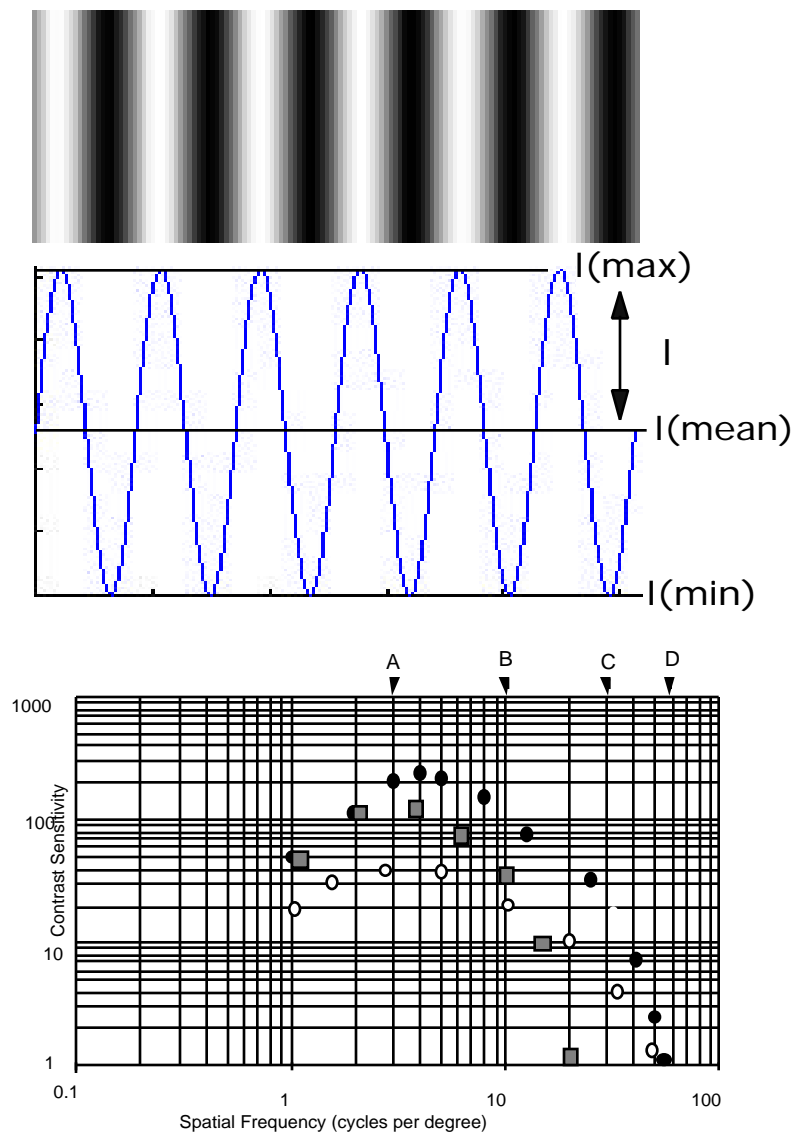
Spatial frequency describes how fine the grating pattern is and is expressed in cycles/degree of visual angle. One cycle includes one light and one dark band, so in a visual acuity test, 1/2 cycle correspond to the MAR. Therefore, the spatial frequency which equates to 20/20 is,

- 1) 20/20 = 1 minute of arc for one dark bar.
- 2) Therefore, one dark + one light (one cycle) takes up 2 minutes of arc.
- 3) One degree is 60 arc minutes, so 30 cycles of these cycles would fit in one minute.

So, **30 cycles/degree** corresponds to **20/20**. Accordingly, 20/40 corresponds to 15 cycles/degree and 20/10 corresponds to 60 cycles/deg. An easy way to convert between the Snellen denominator (VA) and spatial frequency in cycles per degree (sf) is to divide either number into 600 to get the other.

$$\frac{600}{(\text{sf})} = (\text{VA}) \quad \text{and} \quad \frac{600}{(\text{VA})} = (\text{sf})$$

To test a patient's contrast sensitivity, present them with a sine wave grating with a particular spatial frequency, for example, 40 cycles/degree (20/15). Find the lowest contrast they can see in that spatial frequency, for example, 1.0. This is the **contrast threshold**. The inverse of contrast threshold is **contrast sensitivity**, which in this case is 1.0. Repeat the test for other spatial frequencies and plot spatial frequency along the x axis and contrast sensitivity along the y axis. The figure below shows an example of some contrast sensitivity functions.



The function indicated by the black dots shows a typical normal contrast sensitivity function which drops to 1.0 at about 55 c/d and shows a **peak sensitivity at about 4 c/d**. Compared to the peak in the mid-spatial frequency range, the function shows a reduction in contrast sensitivity at higher and lower spatial frequencies. The **high frequency cut-off** is the high contrast visual acuity limit. The gratings are so fine that they cannot be seen unless the contrast is at the max of 1.0. Note that clinical visual acuity (high contrast resolution limit) is only one point on the contrast sensitivity curve. See Schwartz **Fig. 7-11**.

**Defocus** makes it harder to see small letters and small gratings. On the contrast sensitivity curve this means the curve will be shifted to the left and downward, mainly in the higher spatial frequencies. This is indicated by the squares in the figure (also see Fig 7-13).

**Optical quality limits the highest spatial frequency** which can be resolved, but if you had perfect optics, the highest spatial frequency which could be resolved would be limited by the retinal cone mosaic. The limit would be one cycle per two receptors (Fig 7-12). The resolution limit which is set by the receptor array is called the **Nyquist limit**. If, for example, there are 150 receptors per degree on the fovea, the highest spatial frequency that retina could resolve would be one 75 c/d (20/8).

The low spatial frequency drop off is caused by **spatial antagonism** in the retina (Fig 7-14). Certain optical defects such as light scatter or glare caused by **cataracts** can cause a **general reduction in the contrast sensitivity** curve as shown by the white circles in the figure above. The person might still manage 20/20 in clinic, but they would have great difficulty with large, low contrast images.

### 3. Illusions, constancies, and figure-ground relations

Schwartz Ch.. 10; p. 235-, VSIV Lectures 39; [http://www.illusionworks.com/html/hall\\_of\\_illusions.html](http://www.illusionworks.com/html/hall_of_illusions.html)

**Size constancy** - The perceived size of an object doesn't change with distance, in spite of the fact that the image size on the retina changes. The visual system takes into account other information than just retina image size in developing your perception of size. Sometimes, however you can fool the visual system and create interesting illusions. **Distance constancy** = size constancy.

**Shape constancy** - The perceived shape of an object remains the same, even when viewed from different angles.

**Brightness constancy** - The perceived brightness of an object remains the same even if its luminance changes due to different lighting conditions changes. For example, a black cloth still looks black in moonlight or sunlight, even though its luminance is much higher in sunlight.

**Figure-ground** - We tend to organize what we see into figure and ground. The figure is the object you see, while the ground has no specific shape. The figure is usually closer, but the ground seems to be less localized (like background). The figure is usually the shape within your view which is more meaningful. Camouflage tries to make it difficult for you to pick the figure out of the ground. The face/vase illusion is an example of how you can switch your perception of figure and ground. F (see <http://www.wiley.com/college/huffman/faces.html#a1>)

Some illusions to know:

Corridor illusion (Fig. 10-6)

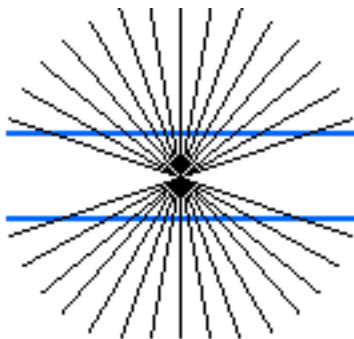
Moon illusion - size constancy fooled.

<http://abcnews.go.com/sections/science/DyeHard/dyehard000105.html>

Müller-Lyer (Fig. 10-8)



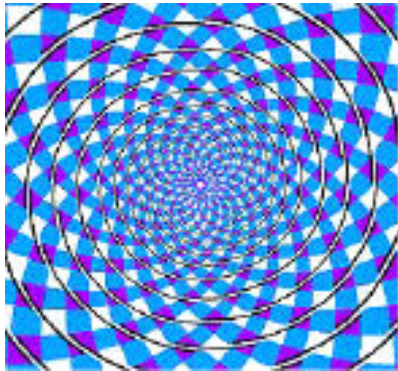
Zollner illusion



**Hering**

Hering illusions

Autokinetic illusion/effect/phenomenon/ or visual autokinesis - small stationary object appears to move when continuously viewed against a dark background.



Fraser's spiral

4. Simultaneous contrast and spatial interactions (Mach bands)

Schwartz Ch.. 7, p 190; **Fig. 7-14, p. 194, Fig. 7-17, p 263-266, Figs 11-10, 11-11;**  
Do you assume that the perceived brightness of an object is a direct function of its actual brightness? That is, parts of a scene with greater luminance always appear brighter than parts with

lower luminance? That seems reasonable, but it is wrong.

In some cases, two parts of a scene which have the exact same luminance may appear to have different brightness, usually due to interaction from a neighboring region. This is called, **simultaneous contrast**.

**Mach bands** are a classic example of simultaneous contrast. Brightness constancy is closely related to simultaneous contrast. They are caused by lateral inhibitory processes in the visual system which cause dark regions to influence the perception of neighboring light regions and vice versa. These mechanisms tend to enhance the contrast of edges and borders. Mach bands also support the theory that the visual system works like a **Fourier analyzer** and processes high and low spatial frequencies through different channels.

#### *D. Light perception*

##### *1. Detection characteristics at the absolute light threshold (including spectral, spatial and temporal aspects).*

VSII Lectures 3,4

From the experiment of Hecht, Schlaer and Pirenne (Lecture 5) we learned that conditions must be carefully controlled to find the absolute threshold of the eye for detecting light.

Dark adaptation - 40+ minutes in the dark

Test spot location - 20° nasal to fixation (max rod density)

Test spot size should be about 10' diameter for maximum spatial summation.

Flash duration - less than 100 msec for maximum temporal summation

Flash color - Monochromatic 510 nm near the scotopic sensitivity peak.

Conclusion from their experiment: **A rod can capture and be activated by a single photon of light.**

##### *2. Brightness-difference thresholds at various adaptation levels (Weber's and DeVries-Rose laws); specification of contrast*

Schwartz Ch. 3, p. 45-47, Fig. 3-15, Ch. 11, p 263-266, Fig. 11-9; VSII Lecture 5

A subject views a background of a certain luminance ( $I$ ) and tries to detect a central light stimulus whose luminance ( $I + \Delta I$ ) is slowly increased starting from the background level until it is detected. This is the **brightness-difference threshold** or the **JND (just noticeable difference)**. The threshold is tested for various levels of background illumination starting from total darkness to very bright. Plot  $\Delta I$  as a function of  $I$  (Fig. 3-15).

The **DeVries-Rose law** says that at over a certain range of very low light levels, the  $\Delta I$  is equal to the square-root of  $I$ .

Over a broad range of more moderate light levels, the  $\Delta I$  is a fixed fraction of  $I$ . This is an application of **Weber's law**, which states that the JND needed to detect the stimulus is a constant fraction (**Weber's fraction or Weber's constant**) of the background. The Weber's fraction for rods is  $\sim 0.14$ . For cones it is 0.015 indicating that the cones are much more sensitive to small changes in contrast. These indicate that the visual system is primarily a **contrast** detector.

Rod saturation occurs when about 10% of the rhodopsin has been bleached. See the definition above for the Michelson definition of contrast.

### 3. Dark and light adaptation and theories

Schwartz Ch. 3, p 30-36, p 29-33 **Fig. 3-8.** VSII Lectures 4, 5

Rapid drop in threshold for detecting a flashing light against a dark background within the first **5 minutes**. This indicates the rapid recovery (dark adaptation) of the cones. Rods recover more slowly and are still relatively insensitive. Cone sensitivity levels off, then from about **10-40 minutes** the threshold again decreases (sensitivity increases) to a minimum. The second drop in the curve represents the rod recovery. The abrupt change in the curve is the **rod-cone break** and represents the time and threshold level when the rods pass the cones in sensitivity.

Photoreceptor sensitivity varies according to wavelength and can be plotted on the two  **$V_{\lambda}$  curves** (Fig. 3-6). The rods are more sensitive than cones for most wavelengths, and the **scotopic spectral sensitivity** peaks at about 507 nm, then begins to decline. The **photopic spectral sensitivity** curve peaks at about 555 nm then declines. For longer wavelength (above about 650 nm) the rods become very insensitive and are almost as insensitive as cones. The difference in sensitivity between the rods and cones for any wavelength is called the **photochromic interval**. The photochromic interval is large for shorter wavelength, but it gets smaller and becomes zero for longer wavelengths.

If two color objects, one with a dominant wavelength of about 507 nm (blue) and another with 555 nm (yellow-green), are view in scotopic conditions (dark adaptation), the blue object will appear brighter. This because, under photopic conditions, rods are more sensitive to 507 nm than 555. Under photopic conditions, however, the 555 nm object will appear brighter. The shift in relative brightness to longer wavelengths in photopic compared to scotopic conditions is called the **Purkinje shift**. Therefore in the late afternoon, a yellow flower may appear brighter than a blue flower, but at dusk the blue flower may appear relatively brighter.

The rod-cone break in the dark adaptation curve is most pronounced if the stimulus is of shorter wavelength, since the photochromic interval is greatest there. If the dark adaptation test stimulus is of a long wavelength, where the photochromic interval is zero, there will be no rod-cone break. The rods never become more sensitive than the rods at that wavelength.

Dark adaptation is only partially due to the regeneration of the photopigments which were bleached in the light. Neural processing also plays a role in dark adaptation.

### 4. Spatial and temporal summation characteristics (Ricco's, Piper's and Bloch's laws)

Schwartz Ch. 3, p. 47-55; Lecture 5

Within a **critical diameter** of retinal area, all the light falling on those photoreceptors are summed. If a dark adapted subject is presented with a very small spot of light, the total number of quanta necessary to reach threshold remains constant as spot size is increased up to a point (about 10 arc min). Beyond this size, more light is needed for detection. (Fig. 3-18) This is due to spatial summation or **Ricco's law** and is represented by the equation:

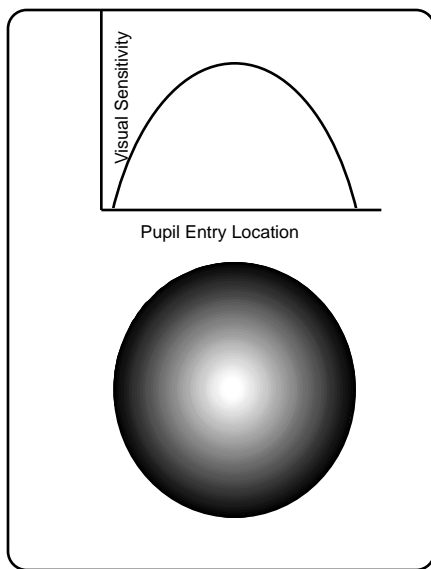
**Ricco's law** - For foveal vision and small images, the product of image area and light intensity is constant to reach threshold. Spatial summation.  $IA = K$

**Piper's law** - For small images viewed by peripheral vision, the product of intensity and the square root of image area is constant to reach threshold.  $I \sqrt{A} = K$

Within a **critical duration** all the light is summed. This temporal summation is called **Bloch's law** or **time-intensity reciprocity**. The formula is:  $It = K$

Bloch's law is the temporal equivalent of Ricco's law. Intensity / duration reciprocity.

The **Stiles-Crawford Effect** (of the first kind; SCE) is not on the boards outline, but you should know it. The SCE is a cone (photopic) only phenomenon. It says that light entering the periphery of the pupil is not as effective at stimulating the cones as light coming in through the center - as if you had a circular gradient sun tint over your pupil. This is due to the **waveguide properties** of the cones. Like a small fiber optic tube, the cone aperture accepts light most readily if it comes straight into the tube. Light which is incident at an angle is not captured as well and less photopigment is bleached. (Fig 3-22). Cones are somewhat mobile and they orient themselves toward the center of the pupil to maximize light capture. Rods show no SCE and can collect light over a broader angle of incidence. This is consistent with the rod's greater sensitivity and the cone's greater spatial resolution. The SCE is an important consideration in visual optics whenever the pupil size is large and you see it mentioned in refractive surgery and corneal optics studies.



Stiles-Crawford Effect

*E. Motion perception*

- 1. Factors involved in the detection of real and apparent motion, detection of displacements*
- 2. Motion after-effects*
- 3. Dynamic visual acuity, visual performance with a moving object, and visual performance with a moving observer*

VSII Lecture 12, VSIV Lecture 39; Schwartz Ch. 9

When we observe real objects in motion, the image of the object actually moves across the retina. Often we perceive **illusory motion** by the sequential flash of two images. This is the principle behind television, video display and motion pictures. This is also referred to as **stroboscopic motion** or the **phi-phenomenon**.

Stroboscopic motion may be thought of as simple a change in luminance in a certain part of the retina. Some scientist use drifting sine wave gratings to study this rather basic kind of motion, which is known as **first order motion**. A complex motion perception occurs when we integrate information from many moving objects in the visual field. Random-dot kinetograms, consisting of

a field of dots moving in random directions, are used to study this more complex, **second order** or **global motion**. In some experiments, a portion of the random dots move in a correlated manner. By increasing the percentage of dots moving in the same direction, you can measure the person's ability to detect the common movements among those dots, from the other randomly moving dots. This is called the **coherence threshold**.

Motion perception is predominantly (but not exclusively) processed by the magno cellular pathway. Neurons carrying motion information from the primary visual cortex eventually synapse in **visual area 5 (V5)**, which is also known as the **middle temporal area (MT)**. This appears to be a special motion center in the brain. The prefrontal cortex may also be involved in motion processing. The pathways that carries motion information is known as the **parietal pathway**, the **dorsal processing stream** or the **where system**.

**Motion detection threshold**, best at fovea = 1-3 arc minute / sec

To produce a perception of motion, an object must show a

- 1) Spatial displacement
- 2) Temporal shift

That is, a delayed input from a spatially adjacent retinal location. Some models associate an excitatory response to this input, in others, inhibitory. Barlow and Levick's theory, based on rabbits, proposed an inhibitory response.

**Motion after-effects** occur when you observe a moving object for a period of time and your visual system becomes adapted to that motion. If you then look at a stationary object it appears to drift in the opposite direction of the previously observed motion. This is a form of **masking**, when the visual system becomes insensitive to stimulus which it observed for a time. Examples: the **waterfall illusion**, **plateau spiral illusion**.

When viewing a moving object, **dynamic visual acuity** remains about the same until the velocity of the stimulus reaches 60-60 degrees/second. Beyond this velocity, dynamic visual acuity deteriorates quickly, probably because the eyes have difficulty keeping up with the moving object.

During very rapid, saccadic eye movements, a special process known as **saccadic suppression** prevents the blurring of the images as it moves across the retina. It appears that, immediately before, during and after a saccade, the magnocellular system is suppressed during saccadic suppression.

#### *F. Temporal perception*

1. *Critical flicker fusion frequency, including factors influencing test objects (size, location and adaptation level).*

2. *Subfusional flicker phenomenon (Bartley brightness enhancement)*

4. *Temporal contrast sensitivity function*

Schwartz Ch.. 8, VSII Lectures 10, 11

The basic stimulus used to study temporal vision is a **flickering light**. The two main variables which can be adjusted are its modulation depth and temporal frequency.

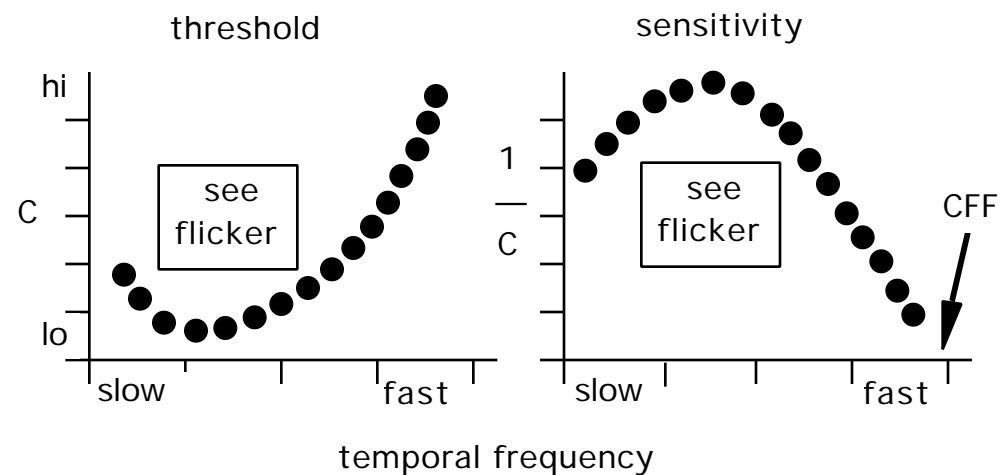
1) **Modulation depth** (temporal contrast). For low modulation depth the luminance difference between the on and off light level is not much different - low contrast flicker.

For high modulation depth the difference in luminance between the on and off settings would be great - high contrast flicker.

2) **Temporal frequency** in Hz (cycles/sec) - how quickly it's flickering.

The spatial **modulation transfer function (MTF)** tests image quality of an optical system with sinusoidal gratings with different spatial frequencies (vary stripe width) with different contrasts. The human eye's **contrast sensitivity function** also tests vision over a range of spatial frequencies and contrasts.

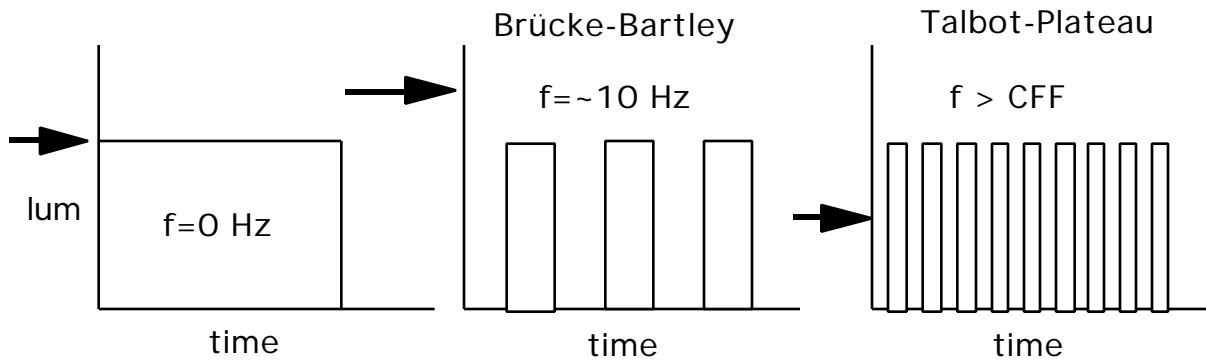
The **temporal modulation transfer function** tests the eye's ability to see flickering lights which can be varied by their temporal frequency and temporal contrast (modulation depth).



To determine the temporal MTF, first measure the temporal contrast threshold at each temporal frequency. The inverse of threshold is sensitivity. Plot sensitivity as a function of temporal frequency. Note that sensitivity is best for 5-10 Hz but drops off at lower and higher frequencies. The highest frequency flicker which the eye can see is the **CFF (critical flicker fusion frequency)**. It is the **temporal resolution limit** of the eye and is analogous to the visual resolution limit for spatial vision.

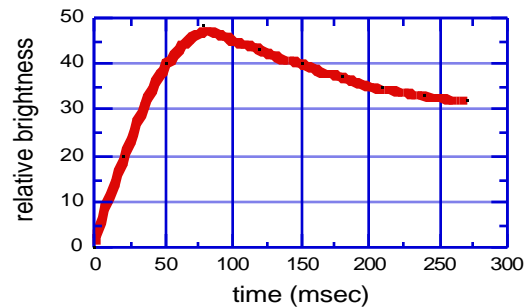
The CFF varies with test conditions:

- \* **Ferry-Porter law** - CFF increases linearly with the log of retinal illumination. The **photopic (cone) CFF is higher than the scotopic (rod) CFF** (Fig 8-8). In other words, with higher levels of light adaptation the CFF is higher.
- \* For a small stimulus, the **CFF is lower in the peripheral retina** since rods will determine the CFF and the rod CFF is lower than for cones.
- \* **Granit-Harper law** - CFF increases with the log of stimulus area. Large stimuli have a higher CFF.



**Brücke-Bartley effect (brightness enhancement)** - a light flashing about 10 Hz starts to look brighter than if it were left on all the time. In the middle figure above, the arrow indicates the perceived brightness.

**Talbot-Plateau law** - say that the perceived brightness of a very rapidly flickering light (above the CFF) is the same as its time-averaged luminance. In the example above, a light which is on half of the time looks half as bright.



**Broca-Sulzer effect** - related to the Brücke-Bartley effect. If a light is left on for various durations, it appears slightly brighter if it's left on for 50-100 msec, than if it's left on for short or longer durations (Fig 8-9).

3. Successive contrast and masking

5. Stabilized retinal images and monocular suppression (Troxler effect)

6. Saccadic suppression

Schwartz Ch. 8 p. 219-220, 210-211

Masking refers to the use of one stimulus (the mask) to reduce the visibility of another (the target). The mask may be presented at the same time (**simultaneous masking**) or before (**forward masking, paracontrast**) or after (**backward masking, metacontrast**) the target.

**Successive contrast** is the contrast manifested when two stimuli are presented in succession, and is

related to masking.

The reduction in the temporal MTF for low temporal frequencies shows the eye's relative insensitivity to very slowly changing luminance levels on the retina. An example is a **stabilized retinal image** such as the shadows of the retinal vasculature. Since the luminance pattern falling on the retinal location does not change over time, this is a visual stimulus whose contrast changes with a temporal frequency of 0. The eye is insensitive to this kind of stimulus, therefore the image of the retinal vessels fade from view. By shifting the light, the shadows move and, in effect, the temporal frequency increases to the part of the MTF curve where the eye can now see the vessel. The now visible vasculature is the **Purkinje tree**.

Microscopic involuntary eye movements ensure that under most conditions, when viewing an object, its retinal image is never perfectly stabilized and it doesn't disappear. Sometimes, however, when staring at a small stationary object, the object may fade and disappear - the **Troxler phenomenon**.

During saccades, vision is suppressed and pupil responsiveness to light is also suppressed. The **saccadic suppression** of vision actually begins before the eye movement starts.

## D. Psychology

### 1. Psychophysical Methodology

#### A. Basic Psychophysical methods and theory

1. Measurement of absolute and difference thresholds
2. Methods of limits, adjustment, and constant stimuli

Schwartz Ch. 11; VSII Lectures 13, 14

**Psychophysics** is the branch of science which studies the interrelationship of physical stimuli and perception and is used extensively in studying vision. In fact most of our clinical vision tests are psychophysical tasks.

**Threshold** - minimum amount of the stimulus which can be detected. Marks the theoretical limit of perception. The dividing line between seeing and not seeing. This is an **absolute threshold**. In some experiments you may require the subject to detect the difference between two stimuli, the **just noticeable difference (JND)**. These are **increment or difference thresholds**. Theoretically there is a fixed threshold. Anytime the stimulus exceed the threshold the person should see the stimulus (Fig. 10-1). But it is not usually so clear cut. Slightly below threshold they may see it sometimes. Slightly above threshold they may miss it sometimes. Usually the percentage of seeing gradually increases over a range of stimulus intensity values. The response of the subject to the stimulus intensity can be plotted as a **psychometric function**, which typically is an S-shaped or **ogive curve** near the threshold intensity. An ogive is a **cumulative normal distribution**.

The famous German scientist, Fechner developed the basic principles of psychophysics. He developed three main methods for measuring thresholds:

**Method of constant stimuli**

**Method of limits**

**Method of adjustment**

#### 1) Constant stimuli

Start with an estimate of the threshold range and preselect about 5-9 levels of stimulus intensity covering this range with some values far enough below threshold that they can never be detected and some values high enough above that they will always be detected. Select equal stimulus

intensity steps between these. Present the stimulus many times at the different intensity levels, but in random order. Record the percentage of seeing at each level. Plot stimulus intensity (x axis) and % seeing (y axis) for a psychometric function. It will probably yield an ogive shaped curve. The 50% seeing is usually used to determine the threshold intensity (**Fig 11-1**).

Note that, because stimuli are presented randomly, the subject cannot anticipate when it will be seen. It is called “constant stimuli”, not because the stimuli intensities are kept constant, but because the level of expectation for the subject is kept constant. This can be used to measure absolute or difference thresholds. This is a very useful laboratory method, but very time consuming.

## 2) Method of limits

Less accurate than constant stimuli method, but faster, therefore popular. Three basic forms: Ascending limits, Descending limits, Staircase method

### **Ascending limits method**

Start below threshold & increase intensity until stimulus seen. Stop, record value.

Numerous trial run and mean of the results is taken as the threshold.

Error on bottom line of Schwarz p. 250: Not plotted as psychometric function.

### **Descending limits method**

Start well above threshold and decrease stimulus intensity until stimulus not seen.

Problem with these techniques: **Errors of habituation**: subject may fall into the habit of saying, “yes” after the same number of presentations within a trial. For example, in an ascending series, he may say, “yes” on about the 5<sup>th</sup> or 6<sup>th</sup> presentation. **Errors of expectation**: Subject may start to anticipate “seeing” the stimulus and respond prematurely.

### **Staircase method**

Begin with either an ascending or descending series. When the is endpoint reached, reverse direction until the opposite endpoint is found. Continue up and down for several reversals. The mean of several reversals is taken as the threshold. This is a fast way to locate the threshold. See Fig. 11-2.

3) Method of adjustment - Give the subject the control knob and let him find his threshold. Convenient but it is very subject to the person’s threshold criterion which can be variable.

Variability on threshold criteria is always a problem but can be minimized by using **forced choice methods** which are called, “**criteria free methods**”. In a **2AFC**, the person must always say, in which of two presentation the stimulus is located. Even if they can’t see it in either, they must choose one. You can also design 4AFC or 10AFC, etc. Threshold is taken as 50% above guessing. For example, the guessing rate for a 2AFC experiment is 50%. Half way between guessing and 100% seeing is 75%, so it is taken as the threshold (**Fig 11-3**).

## *C. Signal detection methods and theory*

Schwartz Ch. 11; VSII Lectures 14, 15

The theory of signal detection (TSD) tries to take into account the affect the subject’s criteria may have on test results. It assumes that a fixed detection criteria is associated with a certain level of sensory input or a neural signal. Whenever the neural signal exceed this criteria level, the person will always respond, “I see it”, etc. If the neural signal were caused only by the stimulus it would be simple. But the neural signal is produced by a combination of:

Background neural **noise** which is inherent in the nervous system and the **stimulus** signal. The

person will be presented with two possible detection situations. Either the stimulus will be turned on or not. When it is not turned on, they receive neural stimulation from the **noise** only. When it is turned on they receive neural input from the combined effects of the **signal + noise**. (See Fig 11-4)

The strength of the noise signal varies from time to time in a bell-shaped distribution. The signal is always added to the noise, so it will also acquire a bell-shaped frequency distribution, though the curve will be shifted to the right. When the stimulus is strong the two curves will be widely separated and the distance between their peak is the **detectability (d')**. With higher detectability, it is easier to detect when the stimulus (S+N) is present. The subject will set some criteria level of neural signal.

Whenever the signal exceeds that level, they will think they see the target, but, depending on where the curves (N and S+N) are located with respect to the criteria, sometimes the signal from the noise will exceed the criteria. This will cause a **“false alarm”** because they will think they see it when it’s just neural noise.

When the stimulus is turned, the S+N signal may exceed the criteria. This is a **“hit”** because they correctly detect the stimulus when it is present. **If your criteria is set low, you will increase the number of both false alarms and hits.**

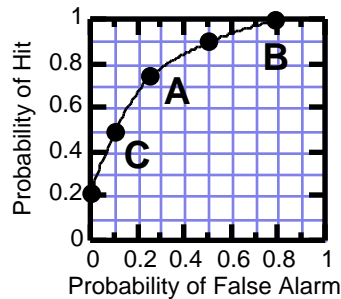
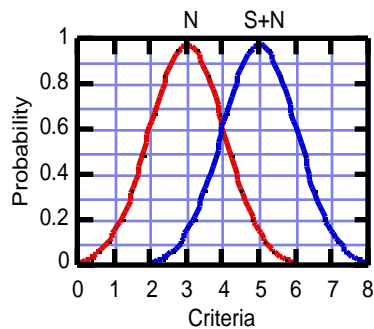
When the noise is below the criteria, the person will correctly say they don’t see the target. This is a **correct rejection**. Depending on the criteria, when the noise is very weak at the same time the stimulus is presented, the combined S+N might fall below the criteria. The person will say they don’t see it, when in fact the stimulus is present. This is a **“miss”**. **When the criteria is set high, you get more misses and more correct rejections.** See Fig 11-6.

Four possible results are summarize below:

	Stimulus is ON	Stimulus is OFF
Says, “See it.”	HIT	FALSE ALARM
Say, “Don’t see it.”	MISS	CORRECT REJECTION

You can estimate the probability of getting any of these four results from the relationship of the two curves (N and S+N) and a knowledge of the criteria. Probability is indicated by the area under the curve to the right or left of the criteria.

- On the N curve (no stimulus) there are two possibilities: Correct rejection or false positive  
 Area to left of criteria is probability of a correct rejection.  
 Area to right is probability of a false positive.
- On the S+N curve (stimulus + noise present), 2 possibilities: Hit or miss.  
 Area to the left of the criteria is probability of a miss.  
 Area to the right of the criteria is probability of a hit.



If you vary the criteria you will shift the line to the right or left and the probability of getting a hit or false alarm (both to the right of the line) will change. If you plot probability of false alarms (x axis) versus probability of a hit (y axis) for various criteria, you get an ROC curve (**Fig. 10-8**). For different detectability values, you'll get different ROC curves.

For one detectability level, a lax criteria results in a higher probability of false alarms, so the point will be further to the right on the ROC curve. As the criteria becomes stricter, the number of false alarms will decrease and the point on the ROC curve will move to the left.

For a detectability which approaches 0 (N and S+N curves nearly overlap; very small stimulus intensity), the ROC curve is close to a straight line with slope of 1.0. Since the two curve overlap the probability of false alarms and hits are equal and on the curve  $x = y$ . As detectability increases, the ROC curve moves away from this line and approaches the upper left corner. This is because the stimulus is easier to see and you get a higher probability of hits with a low probability of false alarms.

### B. Psychophysical scaling methods

Schwartz Ch. 11, p. 266-268

The concept of detecting a stimulus against a background is part of the theory of **Weber's law**, which describes how much an stimulus intensity above the background noise is necessary for the stimulus to be detected (reach threshold). Weber's law says that the increment threshold is a constant fraction of the background.

Above threshold, the magnitude of the sensation (for example, how bright it looks) maybe plotted as a function of the stimulus intensity.

**Fechner's log law** predicts that for suprathreshold stimuli, the magnitude of the sensation increases in proportion to the log of the stimulus intensity. He used the technique of **indirect scaling** by assuming that sensations increase in the same step size as the threshold detection increment.

Steven studied the problem by having subject directly assign a numerical value to their sensations (for example brightness) as the stimulus intensity was increased. This is **direct scaling**.

**Steven's power law** states that the magnitude of the sensation increase as a power (exponent) function rather than a log function:

$$S = I^C$$

## **2. Human Development**

*A. Normal vision development in the infant and child*

*1. Visual acuity*

Schwartz Ch.. 17, p. 366-376, Fig. 17-3

*D. Effects of early environmental restrictions*

Schwartz Ch.. 17, p. 355-366