# RADIOMETRY, PHOTOMETRY, THE V(Λ) FUNCTION

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## THIS CHAPTER WILL INCLUDE A REVIEW OF:

- Radiometry
- Photometry
- CIE luminosity function
- Basic quantities measured in photometry

## RADIOMETRY

**Q. What is radiometry? What is the difference between radiometry and photometry?**

**A. Radiometry describes the physical properties of light, but photometry describes light from a perceptual frame of reference. Radiometry measures energy, whether or not that energy is detected by the visual system; photometry quantifies light as it would be perceived by a standard human observer.**

### ENERGY AND POWER

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

1 watt = 1 joule / 1 second

A light bulb rated at 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. This describes the total energy output of the light source in all directions.

# RADIOMETRY (CONT.)

## RADIANT INTENSITY

A *point source* emits radiant energy in all directions. If located at the center of a sphere, its energy or power would be distributed across the inside surface of the sphere. In some cases you need to know how concentrated the power is in a particular direction. That is, how much power is contained within a defined volume. 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 solid angle (cone size) is the steradian (Schwartz Fig. 4-5).

Steradian = Area at cone opening/(cone length)$^2$

To get a feel for the size of one steradian, imagine a fat ice cream cone with an opening that is 17.15 cm in diameter and has a length of 15,24 cm. Such a cone has an angular volume of about 1 steradian. Radiant intensity quantifies the concentration of light coming from a point source only and is expressed in watts/steradian.

## RADIANCE

An extended source such as a long fluorescent light tube can be thought of as a collection of points. The amount of radiant power emitted from an extended source is called its **radiance**. Radiance is expressed in units of watts/steradian/m$^2$.

## IRRADIANCE

The amount of radiant power falling on a surface is the **irradiance**. Irradiance is expressed in watts/m$^2$ . Be careful not to confuse radiance and irradiance. Radiance refers to the energy emitted from a surface (energy coming off). Irradiance refers to energy falling onto a surface (energy falling on).

# PHOTOMETRY

With this general background on radiometry, we will next study the topic of photometry. Radiometry describes the physical properties of light, but photometry describes light from a perceptual frame of reference. Radiometry measures energy, whether or not that energy is detected by the visual system; photometry quantifies light as it would be perceived by a **standard human observer.**

In optometry, we are usually more interested in photometry than radiometry, but there are certain cases in which radiometry is more relevant. For example, when studying the effect of lasers on ocular tissues, we are not so concerned about how bright it looks, but rather how much energy is transferred to the tissues to treat ocular diseases or to do damage to those tissues. In that case, you would be more interested in radiometric than photometric data.

Photometry is closely related to radiometry, but be careful not to confuse them. Obviously for visible light, more energy or more power will make it appear brighter. That is why a 100-watt light bulb appears brighter than a 60-watt bulb. For ultraviolet or infrared light, even with more energy, we will not see the light.

When comparing the apparent brightness of lights of different wavelength, you must take into account the sensitivity of the eye for different wavelengths. For example a 5-mW laser green laser will look brighter than a 5-mW red laser, because the eye is more sensitive to green than to red light.

## CIE LUMINOSITY FUNCTIONS

For simplicity, let's first consider a monochromatic (single wavelength) light source that is visible to the human eye. In order to compute its brightness for a standard observer, that is, the **photometric intensity** of the light, you must know its:

- Radiometric power (in watts)
- Wavelength
- Eye's sensitivity at that wavelength

The eye's sensitivity to different wavelengths, for a standard observer, was established by the CIE (Commission Internationale de l'Eclairage or International Commission on Illumination) in 1924. This standardized data set is fundamental to the field of photometry and is known as the:

- Luminous efficiency function of the human eye
- Spectral luminosity function
- **Photopic** luminosity function
- 1924 CIE V(λ) function or V lambda curve for cone (photopic) vision

This function describes the normal relative sensitivity of the eye for different wavelengths under light-adapted conditions. That is, during daylight rather than night viewing conditions. In this case, the cone photoreceptors are working.

When dark adapted, the eye's maximum sensitivity shifts toward shorter wavelengths, when the rods are working. The corresponding sensitivity function under dark adapted conditions is the **scotopic** luminosity function or the 1951 CIE V'(λ) function (V-prime lambda function). We will usually work with the photopic V(λ) function, but you should be aware that there is a different spectral luminosity function for scotopic (dark adapted) vision.

Figure 5-1 shows the V(λ) and V'(λ) functions on the same graph. Note that both curves are bell-shaped. The V(λ) curve peaks at about 555 nm (peak cone sensitivity), therefore the relative luminous efficiency of the human eye at this wavelength is given a value of 1.0 V(λ555) = 1.0.

The V'(λ) (scotopic) curve is shifted toward shorter wavelengths and peaks at about 507 nm (peak rod sensitivity). The relative luminous efficiency under scotopic conditions, at this wavelength, is given a value of 1.0. V'(λ507) = 1.0. (Schwartz Fig. 4-8)

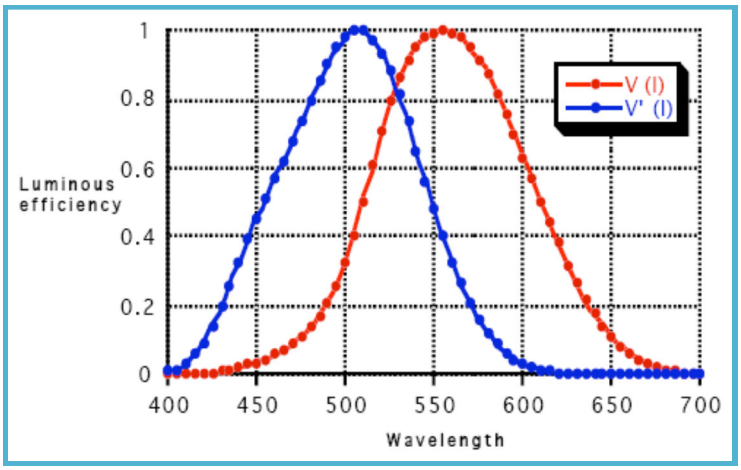


***Figure 5.1:*** *The CIE V(λ) (right, red) and V'(λ) (left, blue) curves*

# CIE LUMINOSITY FUNCTIONS (CONT.)

## DERIVATION OF THE PHOTOPIC LUMINOSITY FUNCTION

How can you experimentally determine the photopic luminosity function? That is, how bright do different wavelengths appear to the human eye? One way (Schwartz Fig. 4-9) would be to compare a reference light with fixed wavelength and radiance, with another light of different wavelength. The subject would adjust the radiance of the test light until it appears to have the same brightness as the reference light (Fig. 5-2). Unfortunately this procedure gives variable results because it is very difficult to match the brightness of stimuli that have different wavelengths.

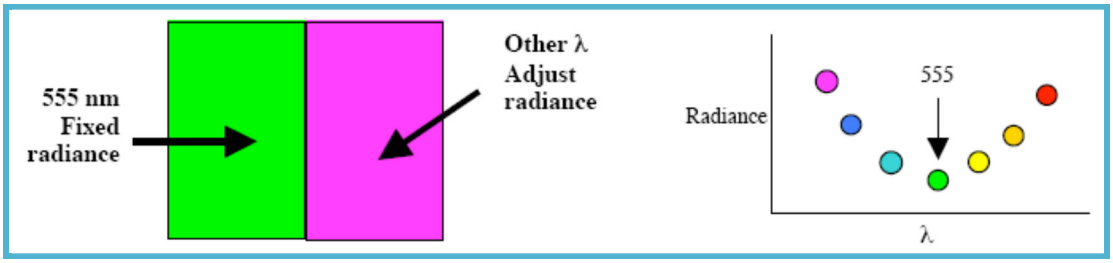


***Figure 5.2:*** *Experiment to compare relative luminous efficiency for different wavelengths*

Another clever method, known **as heterochromatic flicker photometry (HFP)**, was developed to overcome this problem. A single illuminated stimulus is designed so that it alternately flickers between two wavelengths (Fig. 5-3 A, and Schwartz Fig. 4-10) at a rate of about 15 cycles/sec (or 15 Hz). For example, one wavelength may be 555 nm with a fixed radiance (Fig. 5-3, B), while the other wavelength is variable, and its radiance can be adjusted (Fig. 5-3, C). The alternating colors will appear to fuse into another in-between color, but if their perceived brightness's are not equal, the light will appear to flicker. The radiance of the test wavelength is adjusted until the flicker disappears or is minimized. At that point, the luminance (perceived brightness for a standard human observer) is equal. The procedure is repeated for many test wavelengths. The CIE 1924 data is based on experiments using this method.

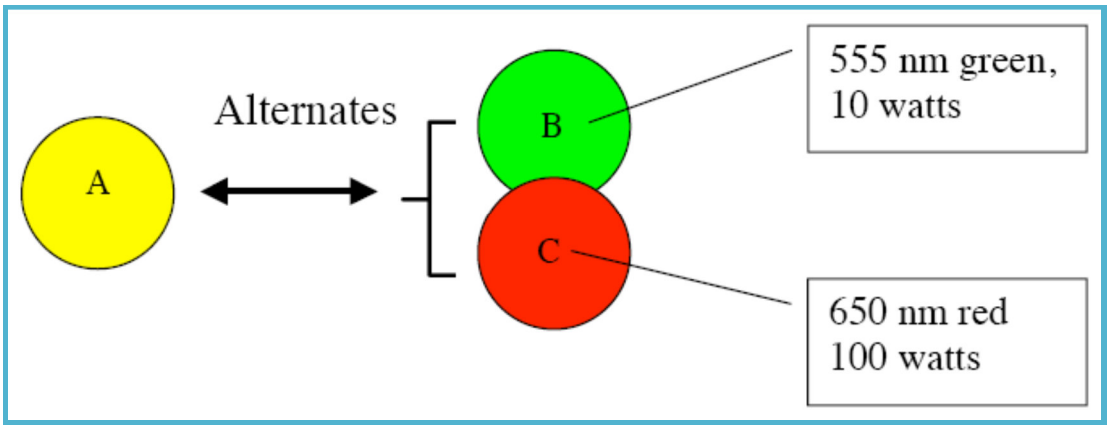


***Figure 5.3:*** *Heterochromic flicker photometry. The yellow spot, whose color is seen as a fusion of the two alternating colors, appears to flicker until the luminance of the two colors become equal (equal perceived brightness's). In this example, red must be set to ten times the radiant power of the reference green light, therefore the eye must be 1/10th as sensitive at 650 nm; hence the V(λ) value at 650 nm is 0.1*

In the **Minimally Distinct Border method** shown in Schwartz Fig. 4-11, the standard wavelength and test wavelength stimuli occupy two halves of a square patch (similar to the stimulus shown in Fig. 5-2) and share a common border. The radiances are adjusted until the border becomes minimally distinct (i.e., it appears to be "fuzzy" instead of sharp). At that radiance the brightness's appear to be equal, so luminance is equal. The results agree well with HFP results.

# BASIC QUANTITIES MEASURED IN PHOTOMETRY

## LUMINOUS POWER

Whereas radiant power is simply a function of how much energy is present, *luminous power* indicates perceived brightness (for a standard human observer). 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 at one particular wavelength is expressed in lumens, where one lumen is defined as:

lumen = (radiant power in watts)Vλ(680)

This equation appears in Schwartz and uses a constant that has been rounded to 680. Other references may use 683 or 685. Note that this formula is for photopic lumens. See the examples in Schwartz Fig. 4-2.

The V(λ) curve refers to the photopic luminosity function. Since rods are more sensitive to light, that is, they can see dim lights better than cones, the perceived brightness of a light in the scotopic system is different, and there is a different formula for *scotopic lumens.*

scotopic lumen = (radiant power in watts)V'λ(1700)

It turns out that at 555 nm, the scotopic luminous efficiency is 0.4, so for a 1-watt light source at that wavelength, there are 680 scotopic lumens. We won't use scotopic lumens much in this course. In the photopic system, luminous efficiency at 555 nm is 1.0, so for a 1-watt source at that wavelength, there are 680 photopic lumens.

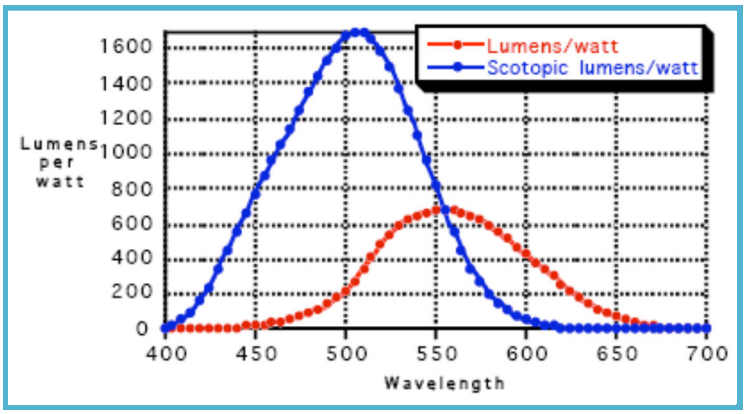


***Figure 5-4:****Photopic & scotopic lumens compared*

Figure 5-4: shows the number of photopic and scotopic lumens at each wavelength, assuming a radiant power of 1 watt. Schwartz mentions that at 555 nm, both the number of photopic and scotopic lumens is equal to 680. At 507 nm there are 1699 scotopic lumens per watt. Schwartz rounds it to 1700.

If the light source is polychromatic (multiple wavelengths), the total luminous power is equal to the sum of the luminous power computed separately for each wavelength. The additive nature of luminous power at each wavelength is called **Abney's law of additivity**. (Schwartz Fig. 4-3)

## LUMINOUS INTENSITY

This photometric term is similar to radiant intensity (watts/steradian). It is used for a point source only and the unit for luminous intensity is the candela.

1 candela = 1 lumen / 1 steradian

# BASIC QUANTITIES MEASURED IN PHOTOMETRY (CONT.)

## LUMINANCE

The perceived brightness of an extended source (for the standard observer) is referred to as the **luminance** and is similar to radiance in that it quantifies light given off by an extended surface area. The basic metric unit for luminance is the **nit**.

1 nit = 1 candela / 1 $m^2$

Another metric unit for luminance is the **apostilb** and the similar English unit is the **footlambert**. These are specifically used with *Lambertian* surfaces, which we will discuss in the next section. They are defined as follows:

1 apostilb = ((candela / $m^2$) / π) = (1/π) nits
1 footlambert = (candela / ft2) / π

## ILLUMINANCE

This term is similar to irradiance in that it quantifies light falling onto a surface. The metric unit for illuminance is the **lux**. The English unit for illuminance is the **foot-candle**.

1 lux = 1 lumen / $m^2$
1 foot-candle = 1 lumen / $ft^2$

Schwartz Table 4-1 lists recommended illuminance values for various sites or activities, and may be a useful reference for you. Other units for luminance and illuminance are in Schwartz Table 4-2.

Be careful not to confuse *luminance* and *illuminance*. Luminance refers to the brightness of light coming off a surface. Illuminance refers to the brightness of the light falling on a surface.

Table 5-1 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 V(λ) value for each particular wavelength considered.

***Table 5-1:*** *Comparison of radiometric and photometric units*

| DESCRIPTION | RADIOMETRY | UNIT | PHOTOMETRY | UNIT |
|---|---|---|---|---|
| Energy | Energy | Joule | | |
| Energy/time (power) | Radiant power | Joules/sec (watt) | Luminous power | Lumen |
| Intensity from a point source | Radiant intensity | Watts/steradian | Luminous intensity | Lumens/steradian (candela) |
| Energy emitted from an extended source | Radiance | Watts/str/$m^2$ | Luminance | Lum/str/$m^2$ (candela/$m^2$) (nit) |
| Energy falling on a surface | Irradiance | Watts/$m^2$ | Illuminance | Lumens/$m^2$ (lux) |

## SELECTED READING/REFERENCES


- Schwartz SH. **Visual Perception - A Clinical Orientation, 3rd Edition**. Appleton & Lange, Stamford, Connecticut, 2004

# LIGHT ADAPTATION, WEBER'S LAW, SPATIAL SUMMATION

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## THIS CHAPTER WILL INCLUDE A REVIEW OF:

- Light adaptation
- Clinical application
- Spatial summation

## LIGHT ADAPTATION

Just as your eyes adjust their sensitivity when going from light to dark, your eyes also have the capacity to adjust when moving from dark to light. This is called **light adaptation**. Light adaptation is studied by measuring the person's ability to detect a faint light against a uniform background (increment threshold) as you gradually increase the background luminance. This is illustrated in Schwartz, 2004 Fig. 3-15.

Schwartz Figure 3-15A shows the stimulus is a test light in the center of an annulus (ring) that serves as a background light. At first the subject adapts to a completely dark background (the annulus). The luminance of the center is then increased slightly above the background until he/she can just detect it. Next, the annulus luminance is increased. The subject adapts to the new background brightness and again determines the minimum luminance increment above the background that he/she can detect. The process continues with increasingly brighter background.

## LIGHT ADAPTATION (CONT.)

Typical results of such an experiment are shown in Figure 9-1. Sections of the curve marked 1-4 show light adaptation for rods. After that the cones take over.

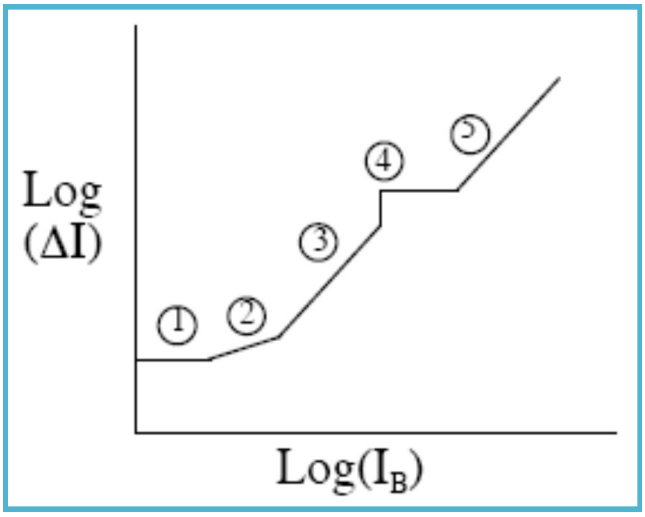


***Figure 9-1:*** *Log of increment luminance (ΔI) plotted as a function of log background luminance (IB). Sections 3 and 5 have slopes equal to 1.0, which indicates that Weber's law holds over most of the scoptopic and photopic ranges, respectively. [Thanks to Andrew Carkeet, PhD (Singapore) for his suggestions on this figure. Compare this to Schwartz Fig. 3- 15]*

**Note the following:**

- **Section 1** - Very dark background, neural noise (or "dark light") determines the increment (ΔI) required for detection
- **Section 2** - Still very low background luminance; fluctuations in background (annulus) luminance largely determine the increment threshold. The DeVries-Rose law predicts that over this portion, the increment (ΔI) increases with the square root of background luminance (Ib)
- **Section 3** - Long section covering a 4-log unit range has a slope of about 1 (when plotted on log/log coordinates). This indicates that the increment (ΔI) increases as a constant proportion of the background because Weber's law applies. That is, over this range the increment threshold is a constant fraction of the background

The constant fraction is called **Weber's fraction or Weber's constant**, and we will be studying this in more detail later (Schwartz Ch. 11). Weber's fraction for rods is ~0.14. Therefore if the background luminance is 100, an increment of 14 above background is needed to detect the stimulus. If the luminance is 1000, the increment must be 140. This illustrates an important principle of visual perception. The eye is designed more to respond to relative differences in luminance (or ratios of light levels) rather than absolute levels of luminance. This is closely related to the concept of contrast, which we will also study in greater detail later.

It also means that sensitivity, in terms of the ability to detect an absolute increment, decreases with increasing illumination. This is necessary to allow the eye to operate over a wide range of illumination and is called **sensitivity regulation or gain control**.

- **Section 4** shows an infinite slope, and this indicates that the rods are saturated and at their limit. This actually occurs when only about ~10% of the rhodopsin is bleached
- **Section 5** shows the cone portion. It also shows a constant slope of 1.0 therefore, Weber's law holds for cones. Weber's fraction for cones is ~ 0.015. Cones therefore show a smaller relative reduction in sensitivity with increasing light than do the rods

## LIGHT ADAPTATION (CONT.)

The most important point to observe in Figure 9-1 is that the slopes for Sections 3 (scotopic range) and 5 (photopic range) are equal to 1.0. On log-log axes, this occurs when the increment (ΔI) values are a constant fraction of the background (IB). This is consistent with Weber's law, which says that the increment threshold in a psychophysical task will be a fixed fraction (Weber's fraction) (Fig. 9-2) of the background.

The following table and figures show that, when Weber's law holds, and log increment threshold is plotted as a function of log background intensity, the slope is equal to 1.0.

***Table 9-1:*** *Demonstration that when Weber's law holds, the slope of the log increment threshold, plotted as a function of the log of the background is equal to 1.0. This is true for any value for Weber's fraction.*

| BACKGROUND | LOG BACKGROUND | INCREMENT (W = 0.14) | LOG INCREMENT | INCREMENT (W = 0.015) | LOG INCREMENT |
|---|---|---|---|---|---|
| 0.1 | −1.00 | 0.014 | −1.85 | 0.0015 | −2.82 |
| 1 | 0.00 | 0.14 | −0.85 | 0.015 | −1.82 |
| 10 | 1.00 | 1.4 | 0.15 | 0.15 | −0.82 |
| 100 | 2.00 | 14 | 1.15 | 1.5 | 0.18 |
| 1000 | 3.00 | 140 | 2.15 | 15 | 1.18 |
| 10000 | 4.00 | 1400 | 3.15 | 150 | 2.18 |
| 100000 | 5.00 | 14000 | 4.15 | 1500 | 3.18 |

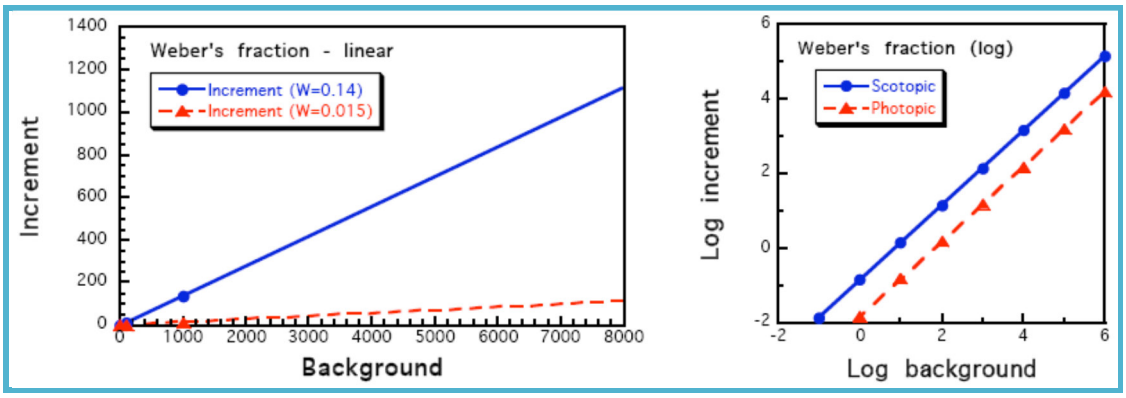


***Figure 9-2:*** *When the relationship summarized by Weber's law is plotted on linear axes,the slope is equal to Weber's fraction. When plotted on log axes, the slope is equal to 1.0 for both lines*

## CLINICAL APPLICATION

Weber's law has some important applications to clinical optometry:

### LOOKING FOR CELLS IN THE ANTERIOR CHAMBER DURING A SLIT-LAMP EXAM

Injuries to the cornea or anterior segment often cause iritis, which releases scattered leucocytes into the anterior chamber. Doctors use this sign (cells in the anterior chamber), to diagnose and monitor iritis. For low grades of iritis, the cells are extremely difficult to see, especially for new clinicians. This is because the contrast of the tiny white cells against the dark background of the pupil is so low. You can increase contrast by increasing brightness of the slit-lamp. This increases the ΔI value, while the background (the black pupil) remains the same. If you increase ΔI to the point that it exceeds Weber's Fraction, the clinician will then be able to see the cells.

# CLINICAL APPLICATION (CONT.)

## VISUAL FIELDS TESTING

This was also an important consideration in the design of the Humphrey Visual Field Analyzer. Quoting from p. 21 and 22 of *Automated Static Perimetry*, by DR Anderson and VM Patella (2nd Ed., Mobsy, St. Louis, 1999):

> *The intensity of a perimeter's background illumination affects visual threshold. Most significantly, it determines the state of the light- versus dark-adapted retina. The visibility of a stimulus is not simply a matter of its luminous intensity; it also is affected by its contrast with the background illumination*.

The contrast of an object under view (a stimulus) with its background is in fact the governing factor for visibility under strongly photopic conditions. When threshold visibility strictly is a matter of contrast, the mathematical representation of threshold stimulus intensity is a constant if expressed as the contrast ratio (known as the Weber fraction) of the stimulus intensity to the background intensity (Weber's law).

There are theoretical advantages if perimetry is performed with a background sufficiently intense to have Weber's law operating. First, increasing or decreasing the pupil area has little effect on stimulus contrast because both background and stimulus are affected equally. Second, small changes in background intensity do not change the visibility of a stimulus if its intensity changes by an equal percentage. Goldmann took advantage of this principle to improve the reliability of his perimeter. It has only one light bulb, which supplies both the stimulus and the background lighting, and if the bulb varies in intensity (e.g., from variations in electric voltage), both the stimulus and the background intensities are affected equally - contrast, and thus stimulus visibility, stays more or less constant.

# SPATIAL SUMMATION

In order to see under a broad range of light levels, we need the special features provided by both the scotopic and the photopic systems.

## PHOTOPIC SYSTEM

- Operates when retinal illumination is high
- Light is abundant
- Designed to provide highly detailed vision; VA, contrast sensitivity, color vision etc.
- Compromises absolute sensitivity

## SCOTOPIC SYSTEM

- Operates when retinal illumination is low
- Light is limited and photons are sparse
- Designed to provide maximum sensitivity: low detection thresholds
- Compromises quality of vision (poor VA [poor spatial resolution], no color perception, etc.)

**Quoting from Schwartz, 2004 p. 44-45:**

> *While visual resolution and contrast sensitivity are superior under photopic conditions, absolute sensitivity is greater under scotopic conditions. This trade-off between visual resolution and visual sensitivity is, to a large extent, due to the manner in which the rods and cones are connected to the post-receptoral elements of the retina. Rods are connected in such a manner as to sum up information over space and time. This produces great sensitivity, but poor resolution. Cones, on the other hand, manifest connections that maximize visual resolution at the expense of sensitivity*.

Schwartz Fig. 3-16 (top) illustrates the flow of information from a large array of rods that collect light over a large area and funnel their data into one ganglion cell. To interpret this figure, recall from the study by Hecht et al. that a minimum of 10 photons must be absorbed by a group of rods in close proximity in order to detect the light. Two relatively widely separated lights shine on a patch of retina containing many rods, all of which are connected to one ganglion cell. Since these rods all send information to the same ganglion cell, the effect of light stimulation of these rods is summed or pooled together and treated as one signal and one spot of light. In this case, the signal for 10

photon absorptions is combined. Note that the ganglion cell can only signal the presence of one light, even though two spots of light (5 photons each) are shining on this zone of the retina.

Schwartz Fig. 3-16 (bottom) shows the corresponding organization for cones. Fewer cones are connected to a single ganglion cell. They each cover a smaller area of the retina. Let's assume that the same stimulus as before (two faint spots, but more closely spaced) illuminates the retina. Assume that the threshold for detection of a light received by one ganglion cell is 10 photons worth of signal from the photoreceptors. We see that in this example, each group of cones pooling into each ganglion cell receives only 5 quanta of input from its respective set of cones. This is sub-threshold and no light will be seen. If, however, we double the brightness so that there are 10 photons in each spot, this will be sufficient to stimulate each ganglion cell. Since two separate ganglion cells are stimulated, the two lights will be resolved as two.

In the scotopic system, ganglion cells receive input from a large number of rods (300+). In effect, it integrates (adds up) all the input it receives within this area. This is known as spatial summation—the input collected across an area is summed and treated as one signal.

The benefit of spatial summation is that it allows us to see under very low light conditions. On the other hand, large spatial summation results in poor spatial resolution, that is, poor visual acuity. Scotopic visual acuity is only about 20/200 at best. Patients with cone dystrophies may have acuities of these levels.

Fewer cones are connected to a single ganglion cell; therefore cone spatial summation areas are smaller than those of the rods. The sizes of the spatial summation areas vary in different parts of the retina and they are smallest at the fovea where each cone photoreceptor has its own ganglion cell. This allows us to have very good visual acuity (i.e., 20/15 or better) in the fovea, but poor sensitivity for detecting dim lights. In general, diseases that affect the peripheral retina first, such as glaucoma, preserve visual acuity.

## RICCO'S LAW

When you are trying to determine the minimum number of quanta that the eye can see, as Hecht et al did, how will target size affect the results? This depends on how big the spatial summation area is. In Hecht's case, he found that, as long as the light all fell within a 10-arc-minute diameter area, the total number of quanta needed to reach threshold was constant.

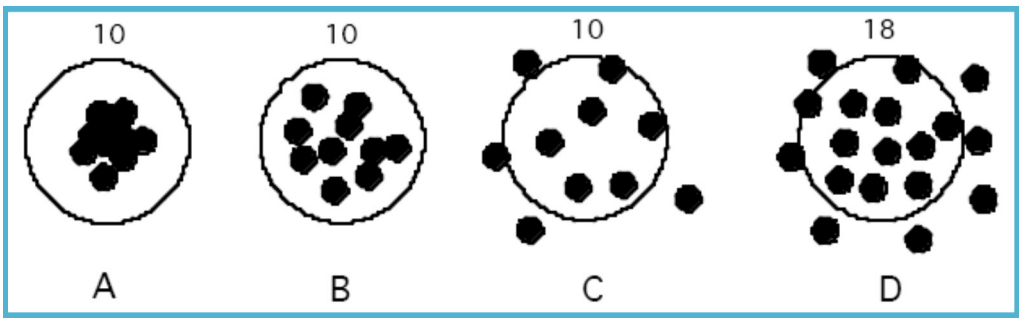


***Figure 9-3:*** *Various distributions of ten photons across a spatial summation field on the retina.*

Figure 9-3 shows the spot pattern for lights of various sizes shining on one summation area. Each dot represents a photon. In A, the spot size is small and all photons fall within the summation area. In B, the spot is larger, but still smaller than the summation zone, so all photon are collected, and their signal is sent to one ganglion cell. In C, the spot diameter exceeds the summation zone and some photons fall outside the summation area. The summation zone therefore will collect fewer than 10 photons and a sub-threshold signal will be sent to the ganglion cell. The light will not be seen; that is, the now larger light is no longer sufficiently intense for the person to detect. In D, the spot size is the same as in C, but the photon density is higher, and a threshold number of photons now fall within the summation area.

If a total of ten quantal absorptions within the summation area are needed for detection, it doesn't matter how large the light is, as long as all the photons fall within the summation zone. If the light is larger than the summation zone, some of the photon will fall outside the summation area and the actual number of quantal absorptions within the zone will be less than ten. A larger light must contain more photons to ensure that at least ten will fall inside the summation zone.

Figure 9-4 illustrates **Ricco's law** based on the principle illustrated in Figure 9-3. Ricco's law is also described by the mathematical equation (I*A = K) that states that, within a **critical diameter**, the product of image area and light intensity (quanta/area) is constant. In other words, for any size area that is smaller than the critical diameter, the total number of quanta (I*A) needed to detect the light is constant. If the illuminated area exceeds the critical diameter, more quanta will be needed as indicated by the ascending portion of the curve in Figure 9-4.

## SPATIAL SUMMATION (CONT.)

I*A = K

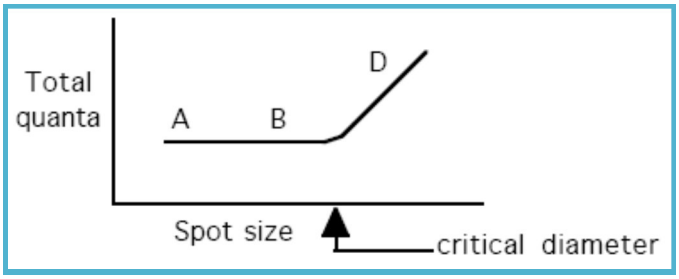


***Figure 9-4:*** *Ricco's law*

***Table 9-2:*** *Summary of the trade-off between sensitivity and visual acuity for the photopic and scotopic systems.*

| SYSTEM | SUMMATION AREAS | SENSITIVITY | SPATIAL RESOLUTION |
|---|---|---|---|
| Scotopic | large (up to 300+ rods) | excellent | poor (20/200) |
| Photopic | small (fovea: 1 cone) | poor | excellent (20/15) |

## SELECTED READING/REFERENCES

- Schwartz SH. **Visual Perception - A Clinical Orientation, 3rd Edition**. Appleton & Lange, Stamford, Connecticut, 2004

# LAMBERTIAN SURFACES, TROLANDS

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## THIS CHAPTER WILL INCLUDE A REVIEW OF:

- Luminance and illuminance
- Lambertian surfaces
- Retinal illumination
- Blackbody radiators and color temperature

## LUMINANCE AND ILLUMINANCE

The photometric units that we will use most frequently are those for luminance and illuminance. Both applyto extended sources or surfaces. The basic metric unit for luminance is the nit.

1 nit = 1 candela/$m^2$

Luminance describes how much luminous intensity is given off by an extended source or surface (in terms of projected surface area), which correlates with how bright it looks. An interesting property of luminance is that it does not change with viewing distance.

**Q. Can you explain why the luminance of an object doesn't change with distance?**
**A.** _____

**Illuminance** describes the amount of light falling onto a surface. The basic metric unit is the lux. The illuminance decreases with the inverse of the square of the distance *(inverse square law).* For example, if you increase the distance from a light source by a factor of two, the illuminance decreases by a factor of 1/4. Furthermore, a surface will receive maximum illumination if the surface is perpendicular to the light source. If the surface is tilted, the illuminance will decrease in proportion to the cosine of the surface tilt, relative to the perpendicular.

1 lux = 1 lumen/$m^2$

# LAMBERTIAN SURFACES

Most objects we see are not self luminous, but are illuminated by some other light source – we see the light reflected off the object. Highly polished surfaces cause **specular** reflections. In the case of specular reflections, most of the light will reflect off the surface in only one direction. Examples include mirrors or metallic objects that look shiny.

Other objects do not appear shiny; they have a matte appearance because they reflect light in all directions. These surfaces are known as **diffuse** reflectors, **Lambertian surfaces** or **cosine diffusers**. **Lambert's cosine law** states that the luminous intensity in any direction is directly proportional to the cosine between that direction and the direction of incidence (angle θ in Figure 6-1).

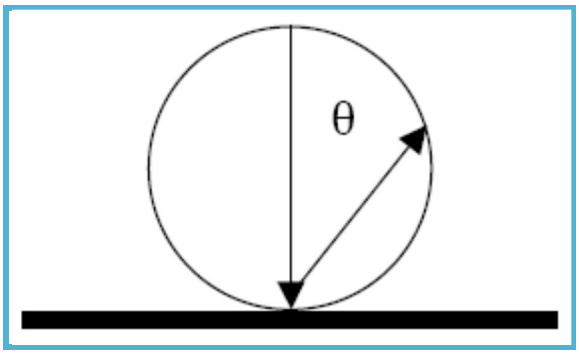


***Figure 6-1:*** *Lambert's cosine law for diffuse reflectors*

When looking at a diffusely reflecting surface such as a piece of paper, its luminous intensity decreases with the cosine of the viewing angle, but the projected area (size) of the paper also decreases with the cosine of the viewing angle. This leads to an interesting property of Lambertian surfaces: *When viewed from any angle, the luminance (brightness) of a Lambertian surface remains constant.*

## RELATIONSHIP BETWEEN ILLUMINANCE AND LUMINANCE

For a Lambertian surface that reflects 100% of the incident light (i.e., a piece of pure white paper), the relationship between illuminance in lux and luminance in nits is illustrated in Figure 6-2.

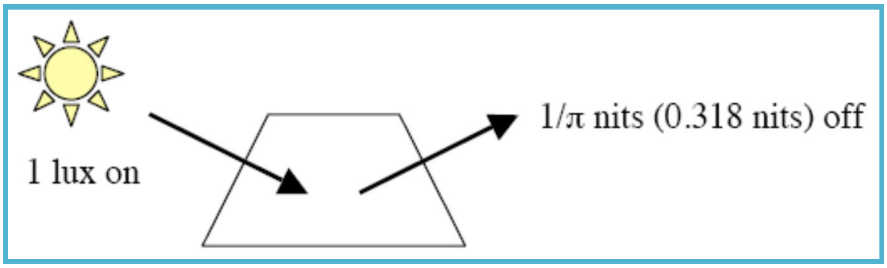


***Figure 6-2:*** *For a 100% reflecting Lambertian surface, 1 lux of illuminance produces 1/π nits of luminance.*

To simplify luminance computations with Lambertian surfaces, another unit of luminance, the apostilb was created. One apostilb is equal to 1/π nits, so when luminance is measured in apostilbs, the relationship between illuminance and luminance is as shown in Figure 6-3.

1 apostilb = 1/π candelas/m$^2$ = 1/π nits

## LAMBERTIAN SURFACES (CONT.)

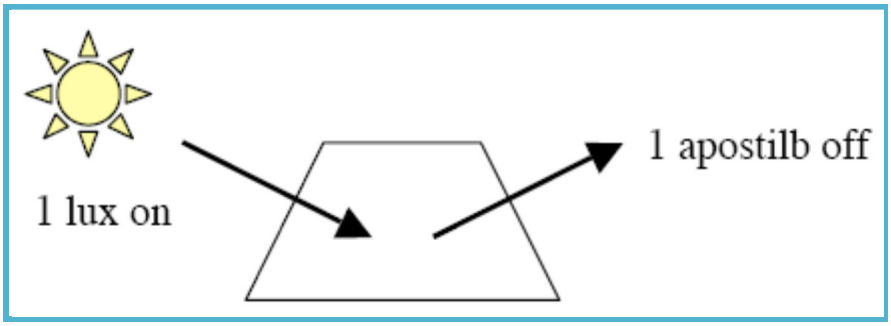


***Figure 6-3:*** *The relationship between illuminance and luminance when apostilbs are used for luminance. The 1:1 relationship between lux and apostilbs applies only for a 100% reflecting Lambertian surface. For a 50% reflecting surface, the relationship is direct, but the lux : apostilb ratio would become 2:1, as illustrated in Figure 6-4*

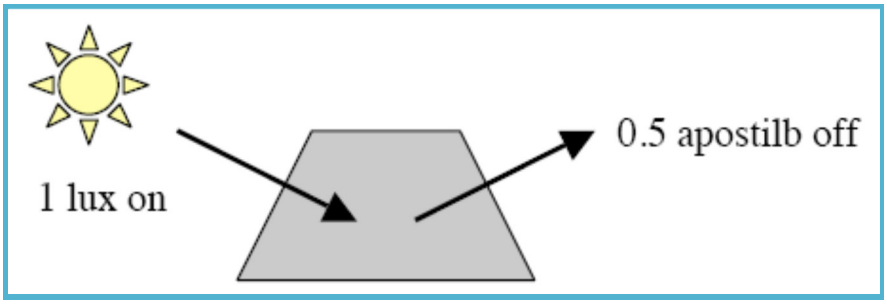


***Figure 6-4:*** *Illustration of a Lambertian surface that reflect 50% of the incident light*

The English units for illuminance and luminance (for Lambertian surfaces) are summarized in Table 6.1, below. Notice how they parallel the metric units. When English units are used, the relationship between footcandles of illuminance and footlamberts of luminance is the same as that shown in Figure 6.3, except that the units are footcandles (illuminance) and footlamberts (luminance); that is, 1 footcandle on produces 1 footlambert off.

***Table 6-1:*** *English and metric units for illuminance and luminance.*

| PHOTOMETRIC QUANTITY | ENGLISH UNIT | METRIC UNIT |
|---|---|---|
| Illuminance | Footcandle<br>1 lumen/ft$^2$ | Lux<br>1 lumen/m$^2$ |
| Luminance<br>(Lambertian surfaces) | Footlambert<br>1/π candelas/ft$^2$ | Apostilb<br>1/π candelas/m$^2$ |

***Note:*** *That these examples assume that the Lambertian surface reflects 100% of the light. Not all Lambertian surfaces reflect 100% of the light. For example, a gray Lambertian surface might reflect 50% of the light, and the resulting luminance would be reduced by 50%*

# LAMBERTIAN SURFACES (CONT.)

## RETINAL ILLUMINANCE

Retinal illuminance refers to the amount of light falling on the retina, such as for the retinal image of some object. It remains constant for any object distance - if you look at an object, it does not become dimmer as it gets further away. However, according to the inverse square law, the illuminace reaching an eye decrease with the square of the distance. The area of the retinal image also decreases with the square of the distance, thus retinal illuminance remains constant.

Retinal illuminance is directly proportional to object luminance and pupil area, and is measured by a simple formula:

Troland = (luminance of the object in nits) x (pupil area in $mm^2$)

A common mistake in retinal illuminance calculations is to use pupil diameter rather than pupil radius when computing the area. The following examples show how to compute retinal illuminance.

**Example 1**

Suppose you are looking at a piece of paper in bright sunlight. What would the retinal illuminance be for the image of that paper on your retina, assuming the luminance of a piece of paper in sunlight is about 10,000 nits (refer to Schwartz, 2004 Table 3-1) and your pupil diameter is equal to 2.0 mm?

Pupil area = $\pi r^2 = (\pi 1^2) = 3.14\ mm^2$

Retinal illuminance = (10,000 nits) $\times$ (3.14 $mm^2$) = 31,400 trolands

**Example 2**

What would the retinal illuminance be if you are looking at a piece of white paper in starlight (luminance = 0.0001 nits; refer to Schwartz, 2004 Table 3-1) and the pupil diameter is equal to 8 mm?

Pupil area = $\pi r^2 = (\pi 4^2) = 50\ mm^2$

Retinal illuminance = (0.0001 nits) $\times$ (50 $mm^2$) = 0.005 trolands

# BLACKBODY RADIATORS AND COLOR TEMPERATURE

Incandescent light bulbs produce light when electricity passes through the filament and heats it, causing it to glow. You might assume that a white light contains an equal amount of radiant power at all wavelengths, but this is not necessarily true. Some 'white' lights produce relatively more power in the long wavelengths, while other lights produce relatively more short-wavelength content. The relative energy produced by a light source across the visible spectrum can be plotted, which shows three standard white light sources. Illustrated are standard illuminants A, B and C. Illuminant A represents the typical household incandescent light bulb. It produces more energy at the long wavelengths and therefore has a subtle reddish tint. **Standard illuminant C** is recommended for many color vision tests since it is relatively flat across the middle of the visible light range.

The energy spectrum produced by a light source can be specified by the plots mentioned above, or by its **color temperature**. Each standard illuminant has its own color temperature. Associated with each color temperature is a specific energy spectrum, and this is based on the concept of a **blackbody radiator**.

A blackbody radiator is a hypothetical object that glows when heated and emits electromagnetic radiation. The exact spectrum of the energy produced depends on the temperature of the blackbody radiator. For lower temperatures, it will glow with predominantly longer wavelengths; as you increase the temperature, the peak wavelength (wavelength with highest energy) gradually shifts to shorter wavelengths. Imagine heating a piece of steel. At first it glows red, but with increasing temperature it turns orange, then yellow, and then blue.

## BLACKBODY RADIATORS AND COLOR TEMPERATURE

This is expressed in **Wein's displacement law**, which states that the peak wavelength is inversely proportional to the temperature. The **Stefan-Boltzman law** says that the total power contained in the source is proportional to the temperature raised to the fourth power. The peak of the energy spectrum for a blackbody radiator with different temperatures shifts with increasing temperature, and the area under the curves (total power) also increases with temperature. Some incandescent light sources produce an energy spectrum similar to a blackbody radiator with a certain temperature, and this is referred to as the color temperature of the light source. This is a convenient way to specify the spectral output of a light source.

Our visual system does a good job of compensating for differences in color from different white light sources, but cameras sometimes have a harder time. In order to get the correct color balance for "white" light sources you may have to adjust the 'white balance' setting. Figure 6.5 shows 4 pictures of the same scene taken with different white balance settings. The room was illuminated by fluorescent lights, but also received much light from the windows. It was a cloudy, overcast day at about 11:00 AM in Eastern Oklahoma. Try to explain why they various settings cause the particular colored tint for the photo.

**FIGURE 6-5**

***Figure 6-5 (a):*** *Incandescent*

***Figure 6-5 (b):*** *Fluorescent*

***Figure 6-5 (c):*** *Cloudy*

***Figure 6-5 (d):*** *Daylight*

### FILTERS (COLORED AND NEUTRAL DENSITY)

Schwartz, 2004 Chapter 4, pages 79-85 reviews colored and neutral density filters.
Study those sections on your own.

## SELECTED READING/REFERENCES


- Schwartz SH. **Visual Perception - A Clinical Orientation, 3rd Edition**. Appleton & Lange, Stamford, Connecticut, 2004