Chapter

5

Light, Vision, and Photometry

5.1 Introduction

Vision results from stimulation of the eye by light and consequent interaction through connecting nerves with the brain.[1] In physical terms, light constitutes a small section in the range of electromagnetic radiation, extending in wavelength from about 400 to 700 nanometers (nm) or billionths (10^{-9}) of a meter. (See Figure 5.1.)

Under ideal conditions, the human visual system can detect:

- Wavelength differences of 1 millimicron (10 Ä, 1 Angstrom unit = 10^{-8} cm)
- Intensity differences as little as 1 percent
- Forms subtending an angle at the eye of 1 arc-minute, and often smaller objects

Although the range of human vision is small compared with the total energy spectrum, human discrimination—the ability to detect differences in intensity or quality—is excellent.

5.2 Sources of Illumination

Light reaching an observer usually has been reflected from some object. The original source of such energy typically is radiation from molecules or atoms resulting from internal (atomic) changes. The exact type of emission is determined by:

- The ways in which the atoms or molecules are supplied with energy to replace what they radiate

1 Portions of this chapter were adapted from: Jerry C. Whitaker and K. B. Benson (eds.), *Standard Handbook of Video and Television Engineering*, 3rd ed., McGraw-Hill, New York, NY, 1999. Used with permission.

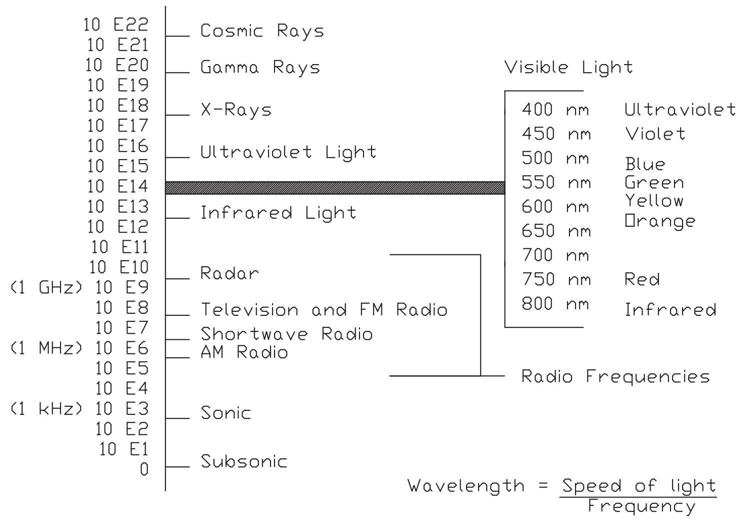

Figure 5.1 The electromagnetic spectrum.

- The physical state of the substance, whether solid, liquid, or gaseous

The most common source of radiant energy is the thermal excitation of atoms in the solid or gaseous state.

5.2.1 The Spectrum

When a beam of light traveling in air falls upon a glass surface at an angle, it is *refracted* or bent. The amount of refraction depends upon the wavelength, its variation with wavelength being known as *dispersion*. Similarly, when the beam, traveling in glass, emerges into air, it is refracted (with dispersion). A glass prism provides a refracting system of this type. Because different wavelengths are refracted by different amounts, an incident white beam is split up into several beams corresponding to the many wavelengths contained in the composite white beam. This is how the spectrum is obtained.

If a spectrum is allowed to fall upon a narrow slit arranged parallel to the edge of the prism, a narrow band of wavelengths passes through the slit. Obviously, the narrower the slit, the narrower the band of wavelengths or the "sharper" the spectral line. Also, more dispersion in the prism will cause a wider spectrum to be produced, and a narrower spectral line will be obtained for a given slit width.

It should be noted that purples are not included in the list of spectral colors. The purples belong to a special class of colors; they can be produced by mixing the light from two spectral lines, one in the red end of the spectrum, the other in the blue end.

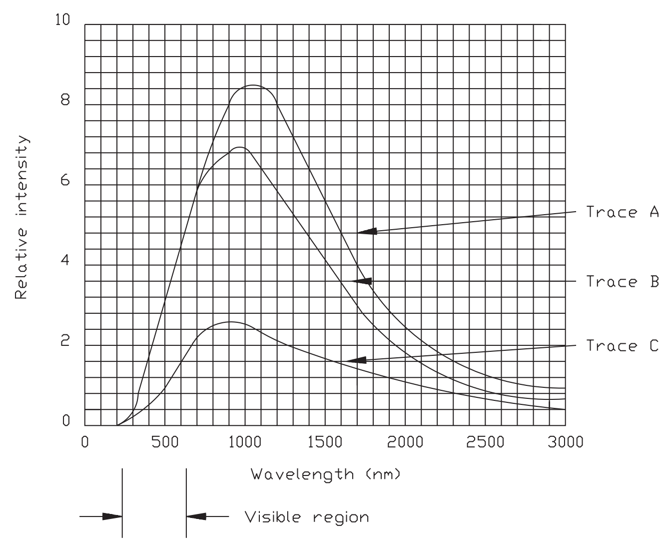

Figure 5.2 The typical radiating characteristics of tungsten: (trace *A*) the radiant flux from 1 cm^2 of a blackbody at 3000 K, (trace *B*) radiant flux from 1 cm^2 of tungsten at 3000 K, (trace *C*) radiant flux from 2.27 cm^2 of tungsten at 3000 K (equal to curve *A* in the visible region). (*After* [1].)

Purple (magenta is a more scientific name) is therefore referred to as a *nonspectral color.*

A plot of the power distribution of a source of light is indicative of the watts radiated at each wavelength per nanometer of wavelength. It is usual to refer to such a graph as an *energy distribution curve*.

Individual narrow bands of wavelengths of light are seen as strongly colored elements. Increasingly broader bandwidths retain the appearance of color, but with decreasing purity, as if white light had been added to them. A very broad band extending throughout the visible spectrum is perceived as white light. Many white light sources are of this type, such as the familiar tungsten-filament electric light bulb (see Figure 5.2). Daylight also has a broad band of radiation, as illustrated in Figure 5.3. The energy distributions shown in Figures 5.2 and 5.3 are quite different and, if the corresponding sets of radiation were seen side by side, would be different in appearance. Either one, particularly if seen alone, would represent a very acceptable white. A sensation of white light can also be induced by light sources that do not have a uniform energy distribution. Among these is fluorescent lighting, which exhibits sharp peaks of energy through the visible spectrum. Similarly, the light from a monochrome (black-and-white) video cathode ray tube is not uniform within the visible spectrum, generally exhibiting peaks in the yellow and blue regions of the spectrum; yet it appears as an acceptable white (see Figure 5.4).

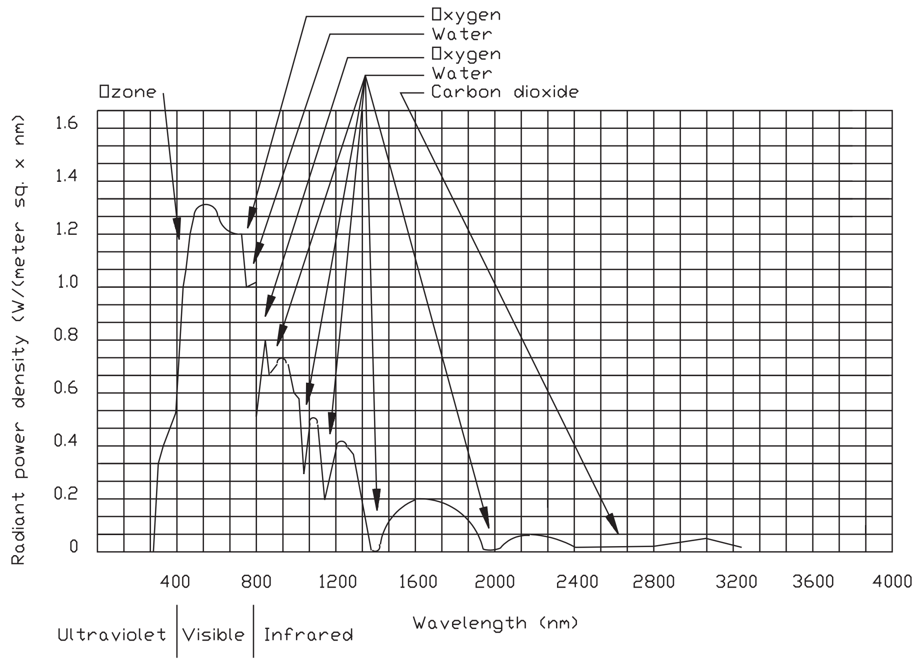

Figure 5.3 Spectral distribution of solar radiant power density at sea level, showing the ozone, oxygen, and carbon dioxide absorption bands. (*After* [1].)

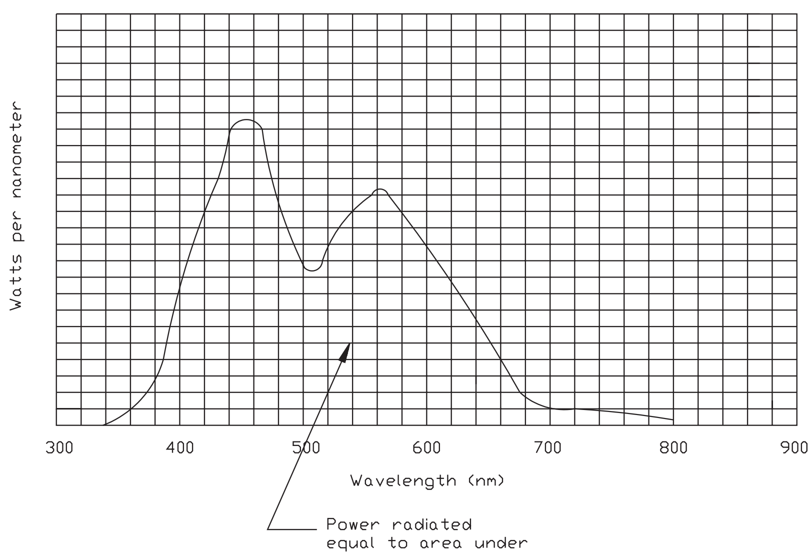

Figure 5.4 Power distribution of a monochrome video picture tube light source. (*After* [2].)

Table 5.1 Psychophysical and Psychological Characteristics of Color

Psychophysical Properties	Psychological Properties
Dominant wavelength	Hue
Excitation purity	Saturation
Luminance	Brightness
Luminous transmittance	Lightness
Luminous reflectance	Lightness

5.2.2 Monochrome and Color Vision

The color sensation associated with a light stimulus can be described in terms of three characteristics:

- Hue
- Saturation
- Brightness

The spectrum contains most of the principal hues: red, orange, yellow, green, blue, and violet. Additional hues are obtained from mixtures of red and blue light. These constitute the purple colors. Saturation pertains to the strength of the hue. Spectrum colors are highly saturated. White and grays have no hue and, therefore, have zero saturation. Pastel colors have low or intermediate saturation. Brightness pertains to the intensity of the stimulation. If a stimulus has high intensity, regardless of its hue, it is said to be "bright."

The psychophysical analogs of hue, saturation, and brightness are

- Dominant wavelength
- Excitation purity
- Luminance

This principle is illustrated in Table 5.1.

By using definitions and standard response functions, which have received international acceptance through the International Commission on Illumination, the dominant wavelength, purity, and luminance of any stimulus of known spectral energy distribution can be determined by simple computations. Although roughly analogous to their psychophysical counterparts, the psychological attributes of hue, saturation, and brightness pertain to observer responses to light stimuli and are not subject to calculation. These sensation characteristics—as applied to any given stimulus—depend in part on other visual stimuli in the field of view and upon the immediately preceding stimulations.

Color sensations arise directly from the action of light on the eye. They are normally associated, however, with objects in the field of view from which the light comes. The objects themselves are therefore said to have color. *Object colors* may be described in terms of their hues and saturations, such as with light stimuli. The intensity aspect is usually referred to in terms of lightness, rather than brightness. The psychophysical analogs of lightness are *luminous reflectance* for reflecting objects and *luminous transmittance* for transmitting objects.

At low levels of illumination, objects may differ from one another in their lightness appearances, but give rise to no sensation of hue or saturation. All objects appear as different shades of gray. Vision at low levels of illumination is called *scotopic vision*. This differs from *photopic vision*, which takes place at higher levels of illumination. Table 5.2 compares the luminosity values for photopic and scotopic vision.

Only the rods of the retina are involved in scotopic vision; cones play no part. Because the fovea centralis is free of rods, scotopic vision takes place outside the fovea. Visual acuity of scotopic vision is low compared with photopic vision.

At high levels of illumination, where cone vision predominates, all vision is color vision. Reproducing systems such as black-and-white photography and monochrome video cannot reproduce all three types of characteristics of colored objects. All images belong to the series of grays, differing only in relative brightness.

The relative brightness of the reproduced image of any object depends primarily upon the luminance of the object as seen by the photographic or video camera. Depending upon the camera pickup element or the film, the dominant wavelength and purity of the light may also be of consequence. Most films and video pickup elements currently in use exhibit sensitivity throughout the visible spectrum. Consequently, marked distortions in luminance as a function of dominant wavelength and purity are not encountered. However, their spectral sensitivities seldom conform exactly to that of the human observer. Some brightness distortions, therefore, do exist.

5.2.3 Luminosity Curve

A *luminosity curve* is a plot indicative of the relative brightnesses of spectrum colors of different wavelength or frequency. To a normal observer, the brightest part of a spectrum consisting of equal amounts of radiant flux per unit wavelength interval is at about 555 nm. Luminosity curves are, therefore, commonly normalized to have a value of *unity* at 555 nm. If, at some other wavelength, twice as much radiant flux as at 555 nm is required to obtain brightness equality with radiant flux at 555 nm, the luminosity at this wavelength is 0.5. The luminosity at any wavelength λ is, therefore, defined as the ratio P_{555}/P_{λ}, where P_{λ} denotes the amount of radiant flux at the wavelength λ, which is equal in brightness to a radiant flux of P_{555}.

The luminosity function that has been accepted as standard for photopic vision is given in Figure 5.5. Tabulated values at 10 nm intervals are given in Table 5.2. This function was agreed upon by the International Commission on Illumination (CIE) in 1924. It is based upon considerable experimental work that was conducted over a number of years. Chief reliance in arriving at this function was based on the step-by-step equality-of-brightness method. Flicker photometry provided additional data.

Table 5.2 Relative Luminosity Values for Photopic and Scotopic Vision

Wavelength, nm	Photopic Vision	Scotopic Vision
390	0.00012	0.0022
400	0.0004	0.0093
410	0.0012	0.0348
420	0.0040	0.0966
430	0.0116	0.1998
440	0.023	0.3281
450	0.038	0.4550
460	0.060	0.5670
470	0.091	0.6760
480	0.139	0.7930
490	0.208	0.9040
500	0.323	0.9820
510	0.503	0.9970
520	0.710	0.9350
530	0.862	0.8110
540	0.954	0.6500
550	0.995	0.4810
560	0.995	0.3288
570	0.952	0.2076
580	0.870	0.1212
590	0.757	0.0655
600	0.631	0.0332
610	0.503	0.0159
620	0.381	0.0074
630	0.265	0.0033
640	0.175	0.0015
650	0.107	0.0007
660	0.061	0.0003
670	0.032	0.0001
680	0.017	0.0001
690	0.0082	
700	0.0041	
710	0.0021	
720	0.00105	
730	0.00052	

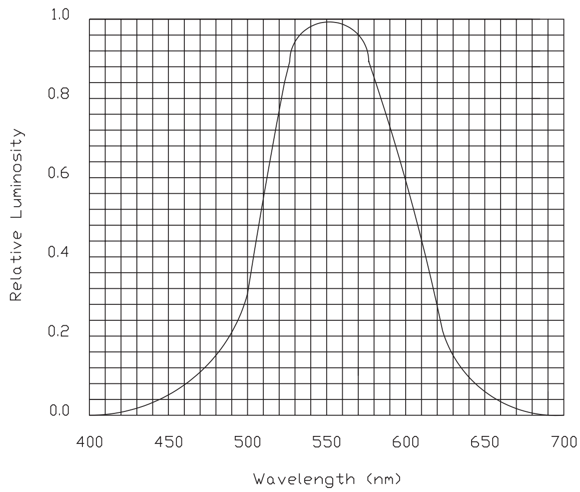

Figure 5.5 The photopic luminosity function. (*After* [2].)

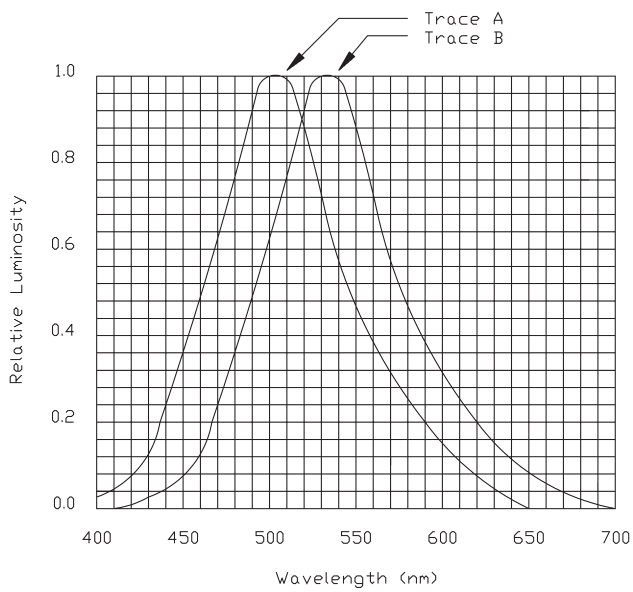

Figure 5.6 Scotopic luminosity function (trace *A*) as compared with photopic luminosity function (trace *B*). (*After* [2].)

In the scotopic range of intensities, the luminosity function is somewhat different from that of the photopic range. The two curves are compared in Figure 5.6. Values are listed in Table 5.2. While the two curves are similar in shape, there is a shift for the scotopic curve of about 40 nm to the shorter wavelengths.

5.2.4 Luminance

Brightness is a term used to describe one of the characteristics of appearance of a source of radiant flux or of an object from which radiant flux is being reflected or transmitted. Brightness specifications of two or more sources of radiant flux should be indicative of their actual relative appearances. These appearances will greatly depend upon the viewing conditions, including the state of adaptation of the observer's eye.

Luminance, as previously indicated, is a psychophysical analog of brightness. It is subject to physical determination, independent of particular viewing and adaptation conditions. Because it is an analog of brightness, however, it is defined to relate as closely as possible to brightness.

The best established measure of the relative brightnesses of different spectral stimuli is the luminosity function. In evaluating the luminance of a source of radiant flux consisting of many wavelengths of light, the amounts of radiant flux at the different wavelengths are weighted by the luminosity function. This converts radiant flux to luminous flux. As used in photometry, the term *luminance* applies only to extended sources of light, not to point sources. For a given amount (and quality) of radiant flux reaching the eye, brightness will vary inversely with the effective area of the source.

Luminance is described in terms of luminous flux per unit projected area of the source. The greater the concentration of flux in the angle of view of a source, the brighter it appears. Therefore, luminance is expressed in terms of amounts of flux per unit solid angle or *steradian*.

In considering the relative luminances of various objects of a scene to be captured and reproduced by a video system, it is convenient to normalize the luminance values so that the "white" in the region of principal illumination has a relative luminance value of 1.00. The relative luminance of any other object then becomes the ratio of its luminance to that of the white. This white is an object of highly diffusing surface with high and uniform reflectance throughout the visible spectrum. For purposes of computation it may be idealized to have 100 percent reflectance and perfect diffusion.

5.2.5 Luminance Discrimination

If an area of luminance B is viewed side by side with an equal area of luminance $B + \Delta B$, a value of ΔB may be established for which the brightnesses of the two areas are just noticeably different. The ratio of $\Delta B/B$ is known as *Weber's fraction*. The statement that this ratio is a constant, independent of B, is known as *Weber's law*.

Strictly speaking, the value of Weber's fraction is not independent of B. Furthermore, its value depends considerably on the viewer's state of adaptation. Values as determined for a dark-field surround are shown in Figure 5.7. It is seen that, at very low intensities, the value of $\Delta B/B$ is relatively large; that is, relatively large values of ΔB, as compared with B, are necessary for discrimination. A relatively constant value of

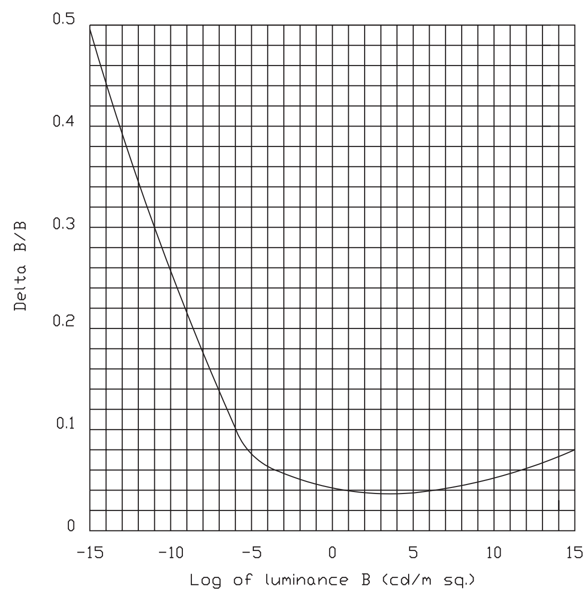

Figure 5.7 Weber's fraction $\Delta B/B$ as a function of luminance B for a dark-field surround. (*After* [3].)

roughly 0.02 is maintained through a brightness range of about 1 to 300 cd/m^2. The slight rise in the value of $\Delta B/B$ at high intensities as given in the graph may indicate lack of complete adaptation to the stimuli being compared.

The plot of $\Delta B/B$ as a function of B will change significantly if the comparisons between the two fields are made with something other than a dark surround. The greatest changes are for luminances below the adapting field. The loss of power of discrimination proceeds rapidly for luminances less by a factor of 10 than that of the adapting field. On the high-luminance side, adaptation is largely controlled by the comparison fields and is relatively independent of the adapting field.

Because of the luminance discrimination relationship expressed by Weber's law, it is convenient to express relative luminances of areas from either photographic or video images in logarithmic units. Because $\Delta(\log B)$ is approximately equal to $\Delta B/B$, equal small changes in $(\log B)$ correspond reasonably well with equal numbers of brightness discrimination steps.

5.2.6 Perception of Fine Detail

Detail is seen in an image because of brightness differences between small adjacent areas in a monochrome display or because of brightness, hue, or saturation differences in a color display. Visibility of detail in a picture is important because it determines the extent to which small or distant objects of a scene are visible, and because of its relationship to the "sharpness" appearance of the edges of objects.

"Picture definition" is probably the most acceptable term for describing the general characteristic of "crispness," "sharpness," or image-detail visibility in a picture. Picture definition depends upon characteristics of the eye, such as visual acuity, and upon a variety of characteristics of the picture-image medium, including its resolving power, luminance range, contrast, and image-edge gradients.

The extent to which a picture medium, such as a photographic or a video system, can reproduce fine detail is expressed in terms of *resolving power* or *resolution*. Resolution is a measure of the distance between two fine lines in the reproduced image that are visually distinct. The image is examined under the best possible conditions of viewing, including magnification.

Resolution in photography is usually expressed as the maximum number of lines (counting only the black ones or only the white ones) per millimeter that can be distinguished from one another. In addition to the photographic material itself, measured values of resolving power depend upon a number of factors. The most important ones typically are:

- Density differences between the black and the white lines of the test chart photographed
- Sharpness of focus of the test-chart image during exposure
- Contrast to which the photographic image is developed
- Composition of the developer

Resolution in a video system is expressed in terms of the maximum number of lines (counting both black and white) that are discernible when viewing a test chart. The value of horizontal (vertical lines) or vertical (horizontal lines) resolution is the number of lines equal to the dimension of the raster. Vertical resolution in a well-adjusted system equals the number of scanning lines, roughly 500 in conventional television. In normal broadcasting and reception practice, however, typical values of vertical resolution range from 350 to 400 lines.

5.2.7 Sharpness

The appearance evaluation of a picture image in terms of the edge characteristics of objects is called *sharpness.* The more clearly defined the line that separates dark areas from lighter ones, the greater the sharpness of the picture. Sharpness is, naturally, related to the transient curve in the image across an edge. The average gradient and the total density difference appear to be the most important characteristics. No physical measure has been devised, however, that predicts the sharpness (appearance) of an image in all cases.

Picture resolution and sharpness are to some extent interrelated, but they are by no means perfectly correlated. Pictures ranked according to resolution measures may be rated somewhat differently on the basis of sharpness. Both resolution and sharpness are related to the more general characteristic of picture definition. For pictures in which, under particular viewing conditions, effective resolution is limited by the visual acuity of the eye rather than by picture resolution, sharpness is probably a good indication of picture definition. If visual acuity is not the limiting factor, however, picture definition depends to an appreciable extent on both resolution and sharpness.

5.2.8 Response to Intermittent Excitation

The brightness sensation resulting from a single, short flash of light is a function of the duration of the flash and its intensity. For low-intensity flashes near the threshold of vision, stimuli of shorter duration than about 1/5 s are not seen at their full intensity. Their apparent intensities are nearly proportional to the action times of the stimuli.

With increasing intensity of the stimulus, the time necessary for the resulting sensation to reach its maximum becomes shorter. A stimulus of 5 mL reaches its maximum apparent intensity in about 1/10 s; a stimulus of 1000 mL reaches its maximum in less than 1/20 s. Also, for higher intensities, there is a brightness overshooting effect. For stimulus times longer than what is necessary for the maximum effect, the apparent brightness of the flash is decreased. A 1000 mL flash of 1/20 s will appear to be almost twice as bright as a flash of the same intensity that continues for 1/5 s. These effects are essentially the same for colors of equal luminances, independent of their chromatic characteristics.

Intermittent excitations at low frequencies are seen as successive individual light flashes. With increased frequency, the flashes appear to merge into one another, giving a coarse, pulsating *flicker effect*. Further increases in frequency result in finer and finer pulsations until, at a sufficiently high frequency, the flicker effect disappears.

The lowest frequency at which flicker is not seen is called the *critical fusion frequency* or simply the *critical frequency*. Over a wide range of stimuli luminances, the critical fusion frequency is linearly related to the logarithm of luminance. This relationship is called the *Ferry-Porter law*. Critical frequencies for several different wavelengths of light are plotted as functions of retinal illumination (*trolands*) in Figure 5.8. The second abscissa scale is plotted in terms of luminance, assuming a pupillary diameter of about 3 mm. At low luminances, critical frequencies differ for different wavelengths, being lowest for stimuli near the red end of the spectrum and highest for stimuli near the blue end. Above a retinal illumination of about 10 trolands (0.4 ft·L) the critical frequency is independent of wavelength. This is in the critical frequency range above approximately 18 Hz.

The critical fusion frequency increases approximately logarithmically with the increase in retinal area illuminated. It is higher for retinal areas outside the fovea than for those inside, although fatigue to flicker effects is rapid outside the fovea.

Intermittent stimulations sometimes result from rapid alternations between two color stimuli, rather than between one color stimulus and complete darkness. The critical frequency for such stimulations depends upon the relative luminance and chromatic characteristics of the alternating stimuli. The critical frequency is lower for chromatic differences than for luminance differences.

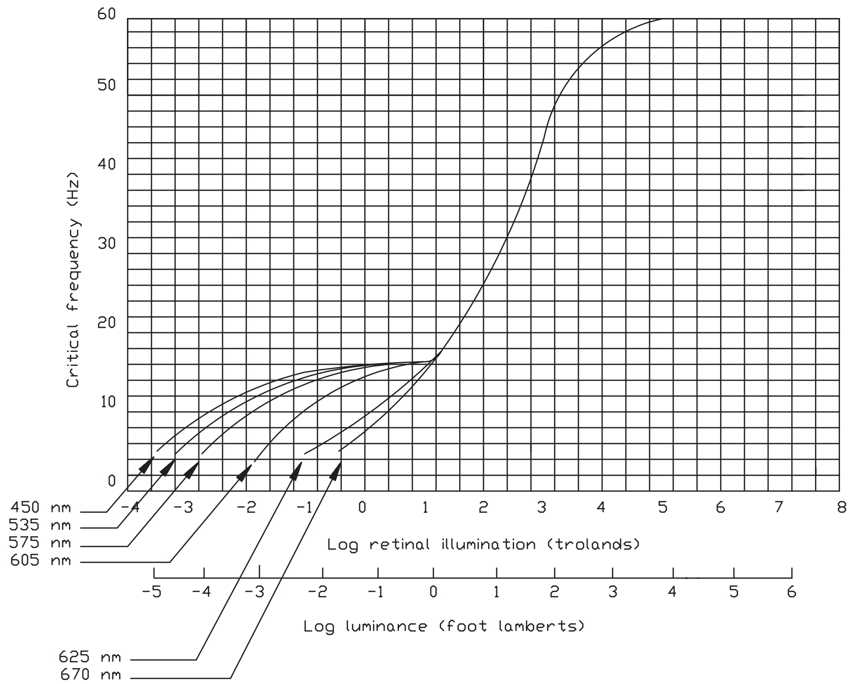

Figure 5.8 Critical frequencies as they relate to retinal illumination and luminance (1 ft·L ≅ cd/m^2; 1 troland = retinal illuminance per square millimeter pupil area from the surface with luminance of 1 cd/m^2). (*After* [4].)

5.3 References

1. *IES Lighting Handbook*, Illuminating Engineering Society of North America, New York, NY, 1981.
2. Fink, D. G., *Television Engineering*, 2nd ed., McGraw-Hill, New York, NY, 1952.
3. Hecht, S., "The Visual Discrimination of Intensity and the Weber-Fechner Law," *J. Gen Physiol*., vol. 7, pg. 241, 1924.
4. Hecht, S., S. Shiaer, and E. L. Smith, "Intermittent Light Stimulation and the Duplicity Theory of Vision," Cold Spring Harbor Symposia on Quantitative Biology, vol. 3, pg. 241, 1935.

5.4 Bibliography

Benson, K. B., and J. C. Whitaker, *Television Engineering Handbook*, revised ed., McGraw-Hill, New York, NY, 1991.

Boynton, R. M., *Human Color Vision*, Holt, New York, NY, 1979.

Committee on Colorimetry, Optical Society of America, *The Science of Color*, New York, NY, 1953.

Davson, H., *Physiology of the Eye*, 4th ed., Academic, New York, NY, 1980.

Evans, R. M., W. T. Hanson, Jr., and W. L. Brewer, *Principles of Color Photography*, Wiley, New York, NY, 1953.
Kingslake, R. (ed.), *Applied Optics and Optical Engineering*, vol. 1, Academic, New York, NY, 1965.
Polysak, S. L., *The Retina*, University of Chicago Press, Chicago, IL, 1941.
Schade, O. H., "Electro-optical Characteristics of Television Systems," *RCA Review*, vol. 9, pp. 5–37, 245–286, 490–530, 653–686, 1948.
Wright, W. D., *Researches on Normal and Defective Colour Vision*, Mosby, St. Louis, MO, 1947.
Wright, W. D., *The Measurement of Colour*, 4th ed., Adam Hilger, London, England, 1969.

5.5 Tabular Data

Table 5.3 Typical Luminance Values (*After* [2].)

Illumination	Illuminance, ft-L
Sun at zenith	4.82×10^8
Perfectly reflecting, diffusing surface in sunlight	9.29×10^3
Moon, clear sky	2.23×10^3
Overcast sky	$9\text{-}20 \times 10^2$
Clear sky	$6\text{-}17.5 \times 10^2$
Motion-picture screen	10

Table 5.4 Conversion Factors for Illuminance Units (*After* [2].)

Parameter	Lux	Phot	Footcandle
Lux (meter-candle); lumens per square meter	1.00	1×10^{-4}	9.290×10^{-2}
Phot; lumens per square centimeter	1×10^4	1.00	9.290×10^2
Footcandle; lumens per square foot	1.06×10	1.076×10^{-3}	1.00
Multiply the quantity expressed in units of *X* by the conversion factor to obtain the quantity in units of *Y*.			

Table 5.5 Conversion Factors for Luminance and Retinal Illuminance Units (*After* [2].)

Multiply Quantity Expressed in Units of X by Conversion Factor to Obtain Quantity in Units of Y

X \ Y	Candelas per square centimeter	Candelas per square meter	Candelas per square inch	Candelas per square foot	Lamberts	Millilamberts	Footlamberts	Trolands†‡
Candelas per square centimeter	1	1×10^{4}	6.452	9.290×10^{2}	3.142	3.142×10^{3}	2.919×10^{3}	7.854×10^{3}
Candelas per square meter (nit)§	1×10^{-4}	1	6.452×10^{-4}	9.290×10^{-2}	3.142×10^{-4}	3.142×10^{-1}	2.919×10^{-1}	7.854×10^{-1}
Candelas per square inch	1.550×10^{-1}	1.550×10^{3}	1	1.440×10^{2}	4.869×10^{-1}	4.869×10^{2}	4.524×10^{2}	1.217×10^{3}
Candelas per square foot	1.076×10^{-3}	1.076×10	6.944×10^{-3}	1	3.382×10^{-3}	3.382	3.142	8.454
Lamberts	3.183×10^{-1}	3.183×10^{3}	2.054	2.957×10^{2}	1	1×10^{3}	9.290×10^{2}	2.5×10^{3}
Millilamberts	3.183×10^{-4}	3.183	2.054×10^{-3}	2.957×10^{-1}	1×10^{-3}	1	9.290×10^{-1}	2.500
Footlamberts	3.426×10^{-4}	3.426	2.210×10^{-3}	3.183×10^{-1}	1.076×10^{-3}	1.076	1	2.691
Trolands‡	1.273×10^{-4}	1.273	8.213×10^{-4}	1.183×10^{-1}	4.000×10^{-4}	4.000×10^{-1}	3.716×10^{-1}	1

†In converting luminance to trolands it is necessary to multiply the conversion factor by the square of the pupil diameter in millimeters.
‡In converting trolands to luminance it is necessary to divide the conversion factor by the square of the pupil diameter in millimeters.

§As recommended at Session XII in 1951 of the International Commission on Illumination, one nit equals one candela per square meter.

Table 5.6 CIE Colorimetric Data (1931 Standard Observer)

Wave-length (nm)	Trichromatic Coefficients r	g	Distribution Coefficients, Equal-Energy Stimulus $\bar{r}$	$\bar{g}$	$\bar{b}$	Energy Distributions for Standard Illuminants E_A	E_B	E_C	E_{D65}
380	0.0272	-0.0115	0.0000	0.0000	0.0012	9.80	22.40	33.00	49.98
390	0.0263	-0.0114	0.0001	0.0000	0.0036	12.09	31.30	47.40	54.65
400	0.0247	-0.0112	0.0003	0.0001	0.0121	14.71	41.30	63.30	82.75
410	0.0225	-0.0109	0.0008	-0.0004	0.0371	17.68	52.10	80.60	91.49
420	0.0181	-0.0094	0.0021	-0.0011	0.1154	20.99	63.20	98.10	93.43
430	0.0088	-0.0048	0.0022	-0.0012	0.2477	24.67	73.10	112.40	86.68
440	-0.0084	0.0048	-0.0026	0.0015	0.3123	28.70	80.80	121.50	104.86
450	-0.0390	0.0218	0.0121	0.0068	0.3167	33.09	85.40	124.00	117.01
460	0.0909	0.0517	-0.0261	0.0149	0.2982	37.81	88.30	123.10	117.81
470	-0.1821	0.1175	-0.0393	0.0254	0.2299	42.87	92.00	123.80	114.86
480	-0.3667	0.2906	-0.0494	0.0391	0.1449	48.24	95.20	123.90	115.92
490	-0.7150	0.6996	-0.0581	0.0569	0.0826	53.91	96.50	120.70	108.81
500	1.1685	1.3905	0.0717	0.0854	0.0478	59.86	94.20	112.10	109.35
510	-1.3371	1.9318	-0.0890	0.1286	0.0270	66.06	90.70	102.30	107.80
520	-0.9830	1.8534	-0.0926	0.1747	0.0122	72.50	89.50	96.90	104.79
530	-0.5159	1.4761	0.0710	0.2032	0.0055	79.13	92.20	98.00	107.69
540	0.1707	1.1628	0.0315	0.2147	0.0015	85.95	96.90	102.10	104.41
550	0.0974	0.9051	0.0228	0.2118	-0.0006	92.91	101.00	105.20	104.05
560	0.3164	0.6881	0.0906	0.1970	-0.0013	100.00	102.80	105.30	100.00
570	0.4973	0.5067	0.1677	0.1709	-0.0014	107.18	102.60	102.30	96.33
580	0.6449	0.3579	0.2543	0.1361	0.0011	114.44	101.00	97.80	95.79
590	0.7617	0.2402	0.3093	0.0975	-0.0008	121.73	99.20	93.20	88.69
600	0.8475	0.1537	0.3443	0.0625	-0.0005	129.04	98.00	89.70	90.01
610	0.9059	0.0494	0.3397	0.0356	0.0003	136.35	98.50	88.40	89.60
620	0.9425	0.0580	0.2971	0.0183	-0.0002	143.62	99.70	88.10	87.70
630	0.9649	0.0354	0.2268	0.0083	-0.0001	150.84	101.00	88.00	83.29
640	0.9797	0.0205	0.1597	0.0033	0.000	157.98	102.20	87.80	83.70
650	0.9888	0.0113	0.1017	0.0012	0.0000	165.03	103.90	88.20	80.03
660	0.9940	0.0061	0.0593	0.0004	0.0000	171.96	105.00	87.90	80.21
670	0.9966	0.0035	0.0315	0.0001	0.0000	178.77	104.90	86.30	82.28
680	0.9984	0.0016	0.0169	0.0000	0.0000	185.43	103.90	84.00	78.28
690	0.9996	0.0004	0.0082	0.0000	0.0000	191.93	101.60	80.20	69.72
700	1.0000	0.0000	0.0041	0.0000	0.0000	198.26	99.10	76.30	71.61
710	1.0000	0.0000	0.0021	0.0000	0.0000	204.41	96.20	72.40	74.15
720	1.0000	0.0000	0.0011	0.0000	0.0000	210.36	92.90	68.30	61.60
730	1.0000	0.0000	0.0005	0.0000	0.0000	216.12	89.40	64.40	69.89
740	1.0000	0.0000	0.0003	0.0000	0.0000	221.67	86.90	61.50	75.09
750	1.0000	0.0000	0.0001	0.0000	0.0000	227.00	85.20	59.20	63.59
760	1.0000	0.0000	0.0001	0.0000	0.0000	232.12	84.70	58.10	46.42
770	1.0000	0.0000	0.0000	0.0000	0.0000	237.01	85.40	58.20	66.81
780	1.0000	0.0000	0.0000	0.0000	0.0000	241.68	87.00	59.10	63.38

Table 5.6 CIE Colorimetric Data (continued)

Wave-length (nm)	Trichromatic Coefficients x	y	Distribution Coefficients, Equal-Energy Stimulus $\bar{x}$	$\bar{y}$	$\bar{z}$	Distribution Coefficients Weighted by Illuminant C $E_c\bar{x}$	$E_c\bar{y}$	$E_c\bar{z}$
380	0.1741	0.0050	0.0014	0.0000	0.0065	0.0036	0.0000	0.0164
390	0.1738	0.0049	0.0042	0.0001	0.0201	0.0183	0.0004	0.0870
400	0.1733	0.0048	0.0143	0.0004	0.0679	0.0841	0.0021	0.3992
410	0.1726	0.0048	0.0435	0.0012	0.2074	0.3180	0.0087	1.5159
420	0.1714	0.0051	0.1344	0.0040	0.6456	1.2623	0.0378	6.0646
430	0.1689	0.0069	0.2839	0.0116	1.3856	2.9913	0.1225	14.6019
440	0.1644	0.0109	0.3483	0.0230	1.7471	3.9741	0.2613	19.9357
450	0.1566	0.0177	0.3362	0.0380	1.7721	3.9191	0.4432	20.6551
460	0.1440	0.0297	0.2908	0.0600	1.6692	3.3668	0.6920	19.3235
470	0.1241	0.0578	0.1954	0.0910	1.2876	2.2878	1.0605	15.0550
480	0.0913	0.1327	0.0956	0.1390	0.8130	1.1038	1.6129	9.4220
490	0.0454	0.2950	0.0320	0.2080	0.4652	0.3639	2.3591	5.2789
500	0.0082	0.5384	0.0049	0.3230	0.2720	0.0511	3.4077	2.8717
510	0.0139	0.7502	0.0093	0.5030	0.1582	0.0898	4.8412	1.5181
520	0.0743	0.8338	0.0633	0.7100	0.0782	0.5752	6.4491	0.7140
530	0.1547	0.8059	0.1655	0.8620	0.0422	1.5206	7.9357	0.3871
540	0.2296	0.7543	0.2904	0.9540	0.0203	2.7858	9.1470	0.1956
550	0.3016	0.6923	0.4334	0.9950	0.0087	4.2833	9.8343	0.0860
560	0.3731	0.6245	0.5945	0.9950	0.0039	5.8782	9.8387	0.0381
570	0.4441	0.5547	0.7621	0.9520	0.0021	7.3230	9.1476	0.0202
580	0.5125	0.4866	0.9163	0.8700	0.0017	8.4141	7.9897	0.0147
590	0.5752	0.4242	1.0263	0.7570	0.0011	8.9878	6.6283	0.0101
600	0.6270	0.3725	1.0622	0.6310	0.0008	8.9536	5.3157	0.0067
610	0.6658	0.3340	1.0026	0.5030	0.0003	8.3294	4.1788	0.0029
620	0.6915	0.3083	0.8544	0.3810	0.0002	7.0604	3.1485	0.0012
630	0.7079	0.2920	0.6424	0.2650	0.0000	5.3212	2.1948	0.0000
640	0,7190	0.2809	0.4479	0.1750	0.0000	3.6882	1.4411	0.0000
650	0.7260	0.2740	0.2835	0.1070	0.0000	2.3531	0.8876	0.0000
660	0.7300	0.2700	0.1649	0,0610	0.0000	1.3589	0.5028	0.0000
670	0.7320	0.2680	0.0874	0.0320	0.0000	0.7113	0.2606	0.0000
680	0.7334	0.2666	0.0468	0.0170	0.0000	0.3657	0.1329	0.0000
690	0.7344	0.2656	0.0227	0.0082	0.0000	0.1721	0.0621	0.0000
700	0.7347	0.2653	0.0114	0.0041	0.0000	0.0806	0.0290	0.0000
710	0.7347	0.2653	0.0058	0.0021	0.0000	0.0398	0.0143	0.0000
720	0.7347	0.2653	0.0029	0.0010	0.0000	0.0183	0.0064	0.0000
730	0.7347	0.2653	0.0014	0.0005	0.0000	0.0085	0.0030	0.0000
740	0.7347	0.2653	0.0007	0.0003	0.0000	0.0040	0.0017	0.0000
750	0.7347	0.2653	0.0003	0.0001	0.0000	0.0017	0.0006	0.0000
760	0.7347	0.2653	0.0002	0.0001	0.0000	0.0008	0.0003	0.0000
770	0.7347	0.2653	0.0001	0.0000	0.0000	0.0003	0.0000	0.0000