16

Human eye sensitivity and photometric quantities

The recipient of the light emitted by most visible-spectrum LEDs is the human eye. In this chapter, the characteristics of human vision and of the human eye and are summarized, in particular as these characteristics relate to human eye sensitivity and photometric quantities.

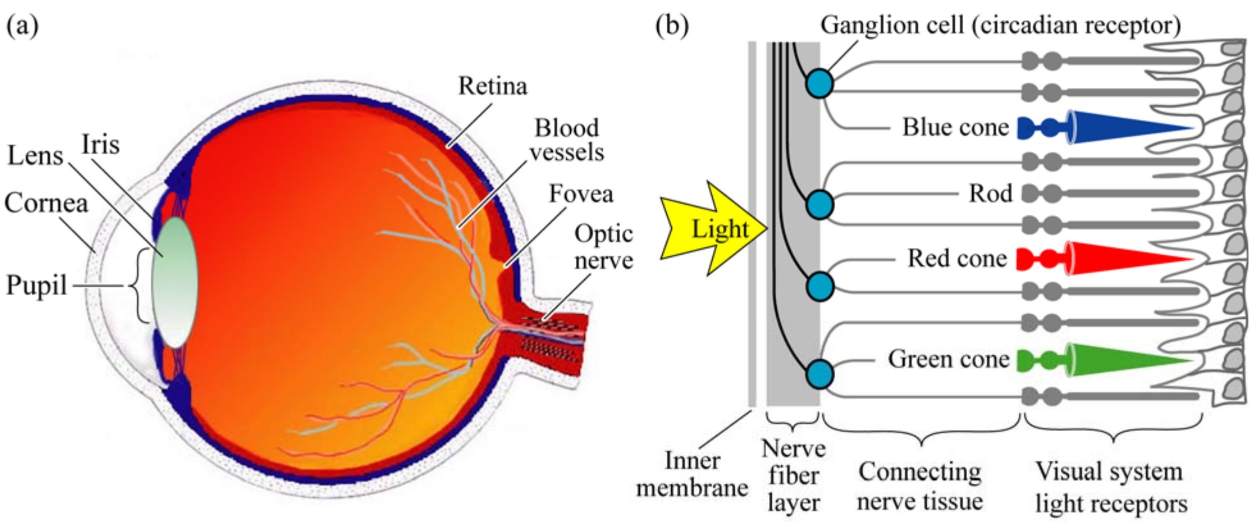

Fig. 16.1. (a) Cross section through a human eye. (b) Schematic view of the retina including rod and cone light receptors (adapted from Encyclopedia Britannica, 1994).

16.1 Light receptors of the human eye

Figure 16.1 (a) shows a schematic illustration of the human eye (Encyclopedia Britannica, 1994). The inside of the eyeball is clad by the retina, which is the light-sensitive part of the eye. The illustration also shows the fovea, a cone-rich central region of the retina which affords the high acuteness of central vision. Figure 16.1 (b) shows the cell structure of the retina including the light-sensitive ***rod cells*** and ***cone cells***. Also shown are the ganglion cells and nerve fibers that transmit the visual information to the brain. Rod cells are more abundant and more light sensitive than cone cells. Rods are sensitive over the entire visible spectrum. There are three types of cone cells, namely cone cells sensitive in the red, green, and blue spectral range. The cone cells are therefore denoted as the red-sensitive, green-sensitive, and blue-sensitive cones, or simply as the red, green, and blue cones.

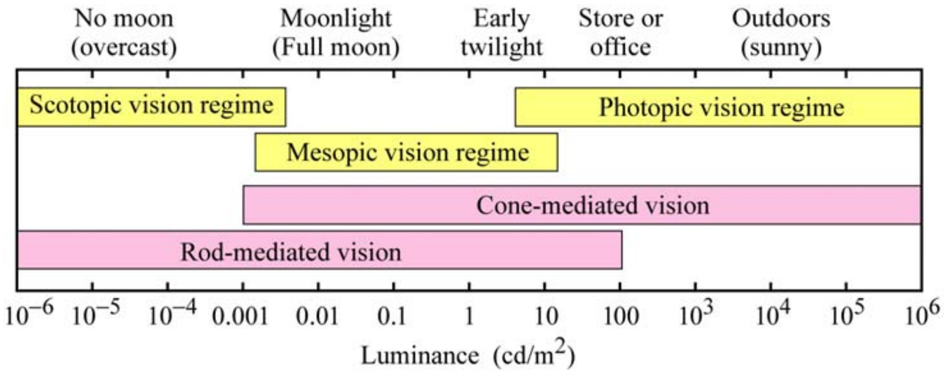

Fig. 16.2. Approximate ranges of vision regimes and receptor regimes (after Osram Sylvania, 2000).

Three different vision regimes are shown in Fig. 16.2 along with the receptors relevant to each of the regimes (Osram Sylvania, 2000). ***Photopic vision*** relates to human vision at high ambient light levels (e.g. during daylight conditions) when vision is mediated by the cones. The photopic vision regime applies to luminance levels > 3 cd/m^2. ***Scotopic vision*** relates to human vision at low ambient light levels (e.g. at night) when vision is mediated by rods. Rods have a much higher sensitivity than the cones. However, the sense of color is essentially lost in the scotopic vision regime. At low light levels such as in a moonless night, objects lose their colors and only appear to have different gray levels. The scotopic vision regime applies to luminance levels < 0.003 cd/m^2. ***Mesopic vision*** relates to light levels between the photopic and scotopic vision regime (0.003 cd/m^2 < mesopic luminance < 3 cd/m^2).

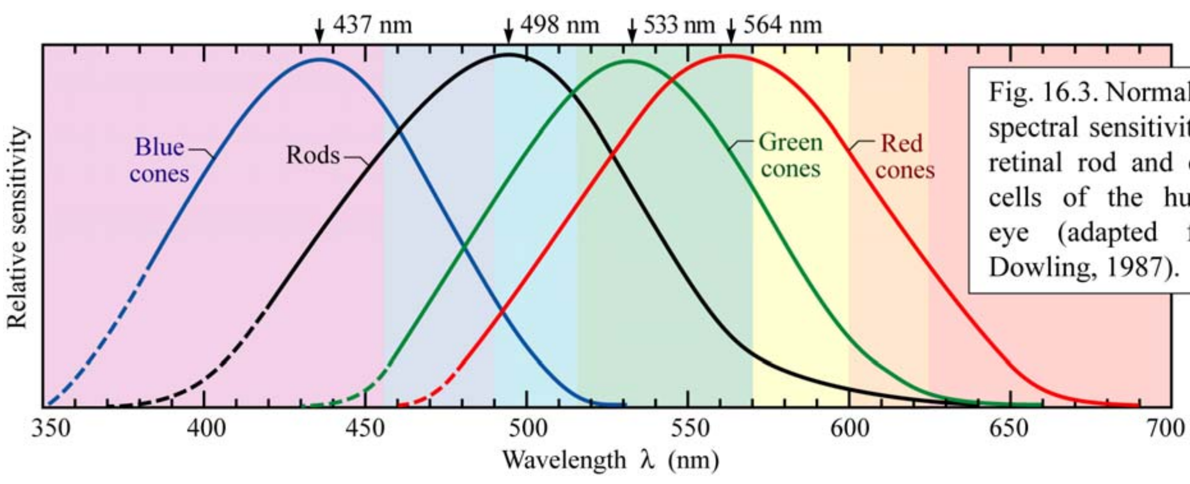

Fig. 16.3. Normalized spectral sensitivity of retinal rod and cone cells of the human eye (adapted from Dowling, 1987).

The approximate spectral sensitivity functions of the rods and three types or cones are shown in Fig. 16.3 (Dowling, 1987). Inspection of the figure reveals that night-time vision (scotopic vision) is weaker in the red spectral range and thus stronger in the blue spectral range as compared to day-time vision (photopic vision). The following discussion mostly relates to the photopic vision regime.

16.2 Basic radiometric and photometric units

The physical properties of electromagnetic radiation are characterized by ***radiometric units***. Using radiometric units, we can characterize light in terms of physical quantities; for example, the number of photons, photon energy, and ***optical power*** (in the lighting community frequently called the ***radiant flux***). However, the radiometric units are irrelevant when it comes to light perception by a human being. For example, infrared radiation causes no luminous sensation in the eye. To characterize the light and color sensation by the human eye, different types of units are needed. These units are called ***photometric units***.

The ***luminous intensity***, which is a photometric quantity, represents the light intensity of an optical source, as perceived by the human eye. The luminous intensity is measured in units of ***candela*** (cd), which is a base unit of the International System of Units (SI unit). The present definition of luminous intensity is as follows: *a monochromatic light source emitting an optical power of (1/683) watt at 555 nm into the solid angle of 1 steradian (sr) has a luminous intensity of 1 candela (cd).*

The unit *candela* has great historical significance. All light intensity measurements can be traced back to the candela. It evolved from an older unit, the ***candlepower***, or simply, the ***candle***. The original, now obsolete, definition of one candela was the light intensity emitted by a plumber's candle, as shown in Fig. 16.4, which had a specified construction and dimensions:

one standardized candle emits a luminous intensity of 1.0 cd .

Fig. 16.4. Plumber's candle, as used by plumbers in the nineteenth century to melt lead solder when joining water pipes.

The luminous intensity of a light source can thus be characterized by giving the number of standardized candles that, when combined, would emit the same luminous intensity. Note that *candlepower* and *candle* are non-SI units that are no longer current and rarely used at the present time.

The ***luminous flux***, which is also a photometric quantity, represents the light power of a source as perceived by the human eye. The unit of luminous flux is the ***lumen*** (lm). It is defined as follows: *a monochromatic light source emitting an optical power of (1/683) watt at 555 nm has a luminous flux of 1 lumen (lm)*. The lumen is an SI unit.

A comparison of the definitions for the candela and lumen reveals that 1 candela equals 1 lumen per steradian or cd = lm/sr. Thus, an isotropically emitting light source with luminous intensity of 1 cd has a luminous flux of 4π lm = 12.57 lm.

The ***illuminance*** is the luminous flux incident per unit area. The illuminance measured in ***lux*** (lux = lm/m^2). It is an SI unit used when characterizing illumination conditions. Table 16.1 gives typical values of the illuminance in different environments.

Table 16.1. Typical illuminance in different environments.

Illumination condition	**Illuminance**
Full moon	1 lux
Street lighting	10 lux
Home lighting	30 to 300 lux
Office desk lighting	100 to 1 000 lux
Surgery lighting	10 000 lux
Direct sunlight	100 000 lux

The ***luminance*** of a ***surface source*** (i.e. a source with a non-zero light-emitting surface area such as a display or an LED) is the ratio of the luminous intensity emitted in a certain direction (measured in cd) divided by the *projected surface area* in that direction (measured in m^2). The luminance is measured in units of cd/m^2. In most cases, the direction of interest is normal to the chip surface. In this case, the luminance is the luminous intensity emitted along the chip-normal direction divided by the chip area.

The *projected surface area* mentioned above follows a cosine law, i.e. the projected area is given by $A_{\text{projected}} = A_{\text{surface}} \cos\Theta$, where Θ is the angle between the direction considered and the surface normal. The light-emitting surface area and the projected area are shown in Fig. 16.5. The luminous intensity of LEDs with lambertian emission pattern also depends on the angle Θ according to a cosine law. Thus the luminance of lambertian LEDs is a constant, independent of angle.

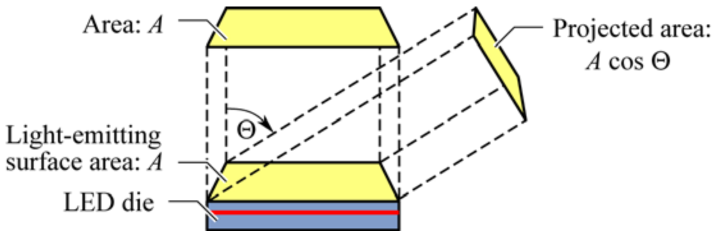

Fig. 16.5. Area of LED, A, and projected area, $A \cos \Theta$, used for the definition of the luminance of an LED.

For LEDs, it is desirable to maximize luminous intensity and luminous flux while keeping the LED chip area minimal. Thus the luminance is a measure of how efficiently the valuable semiconductor wafer area is used to attain, at a given injection current, a certain luminous intensity.

There are several units that are used to characterize the luminance of a source. The names of these common units are given in Table 16.2.

Typical luminances of displays, organic LEDs, and inorganic LEDs are given in Table 16.3. The table reveals that displays require a comparatively low luminance because the observer directly views the display from a close distance. This is not the case for high-power inorganic LEDs used for example in traffic light and illumination applications.

Photometric and the corresponding radiometric units are summarized in Table 16.4.

Table 16.2. Conversion between common SI and non-SI units for luminance.

Unit	Common name
1 cd/cm^2	1 stilb
$(1/\pi)$ cd/cm^2	1 lambert
1 cd/m^2	1 nit
$(1/\pi)$ cd/m^2	1 apostilb
$(1/\pi)$ cd/ft^2	1 foot-lambert

Table 16.3. Typical values for the luminance of displays, LEDs fabricated from organic materials, and inorganic LEDs.

Device	Luminance (cd/m^2)
Display	100 (operation)
Display	250–750 (max. value)
Organic LED	100–10 000
III–V LED	1 000 000–10 000 000

Table 16.4. Photometric and corresponding radiometric units.

Photometric unit	Dimension	Radiometric unit	Dimension
Luminous flux	lm	Radiant flux (optical power)	W
Luminous intensity	lm / sr = cd	Radiant intensity	W / sr
Illuminance	lm / m^2 = lux	Irradiance (power density)	W / m^2
Luminance	lm / (sr m^2) = cd / m^2	Radiance	W / (sr m^2)

Exercise: ***Photometric units***. A 60 W incandescent light bulb has a luminous flux of 1000 lm. Assume that light is emitted isotropically from the bulb.

(a) What is the luminous efficiency (i.e. the number of lumens emitted per watt of electrical input power) of the light bulb?
(b) What number of standardized candles emit the same luminous intensity?
(c) What is the illuminance, E_{lum}, in units of lux, on a desk located 1.5 m below the bulb?
(d) Is the illuminance level obtained under (c) sufficiently high for reading?
(e) What is the luminous intensity, I_{lum}, in units of candela, of the light bulb?
(f) Derive the relationship between the illuminance at a distance r from the light bulb, measured in *lux*, and the luminous intensity, measured in *candela*.
(g) Derive the relationship between the illuminance at a distance r from the light bulb, measured in *lux*, and the luminous flux, measured in *lumen*.
(h) The definition of the cd involves the optical power of (1/683) W. What, do you suppose, is the origin of this particular power level?

Solution: (a) 16.7 lm/W. (b) 80 candles. (c) E_{lum} = 35.4 lm/m^2 = 35.4 lux. (d) Yes. (e) 79.6 lm/sr = 79.6 cd. (f) $E_{lum}\, r^2 = I_{lum}$. (g) $E_{lum}\, 4\pi r^2 = \Phi_{lum}$.
(h) Originally, the unit of luminous intensity had been defined as the intensity emitted by a real candle. Subsequently the unit was defined as the intensity of a light source with specified wavelength and optical power. When the power of that light source is (1/683) W, it has the same intensity as the candle. Thus this particular power level has a historical origin and results from the effort to maintain continuity.

16.3 Eye sensitivity function

The conversion between radiometric and photometric units is provided by the ***luminous efficiency function*** or ***eye sensitivity function***, $V(\lambda)$. In 1924, the CIE introduced the photopic eye sensitivity function $V(\lambda)$ for point-like light sources where the viewer angle is 2° (CIE, 1931). This function is referred to as the ***CIE 1931 V(λ) function***. It is the current photometric standard in the United States.

A *modified* $V(\lambda)$ function was introduced by Judd and Vos in 1978 (Vos, 1978; Wyszecki and Stiles, 1982, 2000) and this modified function is here referred to as the ***CIE 1978 V(λ) function***. The modification was motivated by the underestimation of the human eye sensitivity in the blue and violet spectral region by the CIE 1931 $V(\lambda)$ function. The modified function $V(\lambda)$ has higher values in the spectral region below 460 nm. The CIE has endorsed the CIE 1978 $V(\lambda)$

function by stating "the spectral luminous efficiency function for a point source may be adequately represented by the Judd modified *V*(λ) function" (CIE, 1988) and "the Judd modified *V*(λ) function would be the preferred function in those conditions where luminance measurements of short wavelengths consistent with color normal observers is desired" (CIE, 1990).

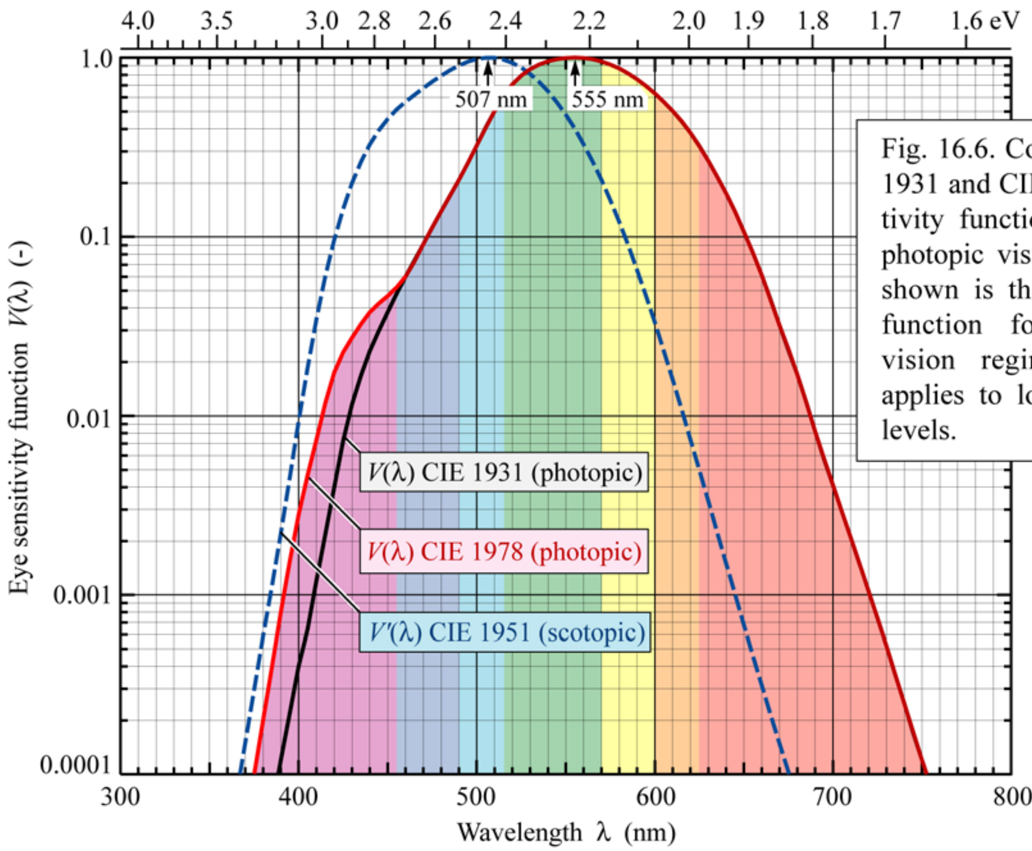

Fig. 16.6. Comparison of CIE 1931 and CIE 1978 eye sensitivity functions *V*(λ) for the photopic vision regime. Also shown is the eye sensitivity function for the scotopic vision regime, *V*′(λ), that applies to low ambient light levels.

The CIE 1931 *V*(λ) function and the CIE 1978 *V*(λ) function are shown in Fig. 16.6. The photopic eye sensitivity function has maximum sensitivity in the green spectral range at 555 nm, where *V*(λ) has a value of unity, i.e. *V*(555 nm) = 1. Inspection of the figure also reveals that the CIE 1931 *V*(λ) function underestimated the eye sensitivity in the blue spectral range (λ < 460 nm). Numerical values of the CIE 1931 and CIE 1978 *V*(λ) function are tabulated in Appendix 16.1.

Also shown in Fig. 16.6 is the scotopic eye sensitivity function *V*′(λ). The peak sensitivity in the scotopic vision regime occurs at 507 nm. This value is markedly shorter than the peak sensitivity in the photopic vision regime. Numerical values of the CIE 1951 *V*′(λ) function are tabulated in Appendix 16.2.

Note that even though the CIE 1978 $V(\lambda)$ function is preferable, it is not the standard, mostly for practical reasons such as possible ambiguities created by changing standards. Wyszecki and Stiles (2000) note that even though the CIE 1978 $V(\lambda)$ function is not a standard, it has been used in several visual studies. The CIE 1978 $V(\lambda)$ function, which can be considered the most accurate description of the eye sensitivity in the photopic vision regime, is shown in Fig. 16.7.

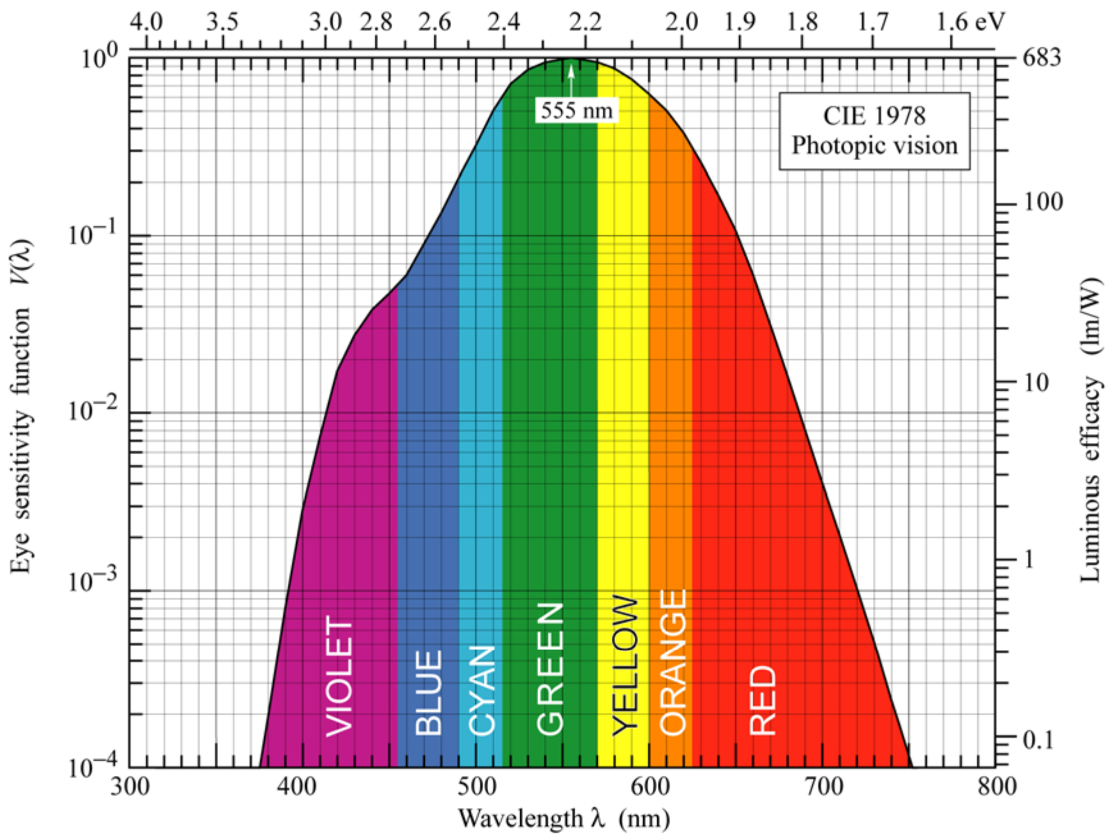

Fig. 16.7. Eye sensitivity function, $V(\lambda)$, (left-hand ordinate) and luminous efficacy, measured in lumens per watt of optical power (right-hand ordinate). $V(\lambda)$ is maximum at 555 nm (after 1978 CIE data).

The eye sensitivity function has been determined by the ***minimum flicker method***, which is the classic method for luminance comparison and for the determination of $V(\lambda)$. The stimulus is a light-emitting small circular area, alternatingly illuminated (with a frequency of 15 Hz) with the standard color and the comparison color. Since the hue-fusion frequency is lower than 15 Hz, the hues fuse. However, the brightness-fusion frequency is higher than 15 Hz and thus if the two colors differ in brightness, then there will be visible flicker. The human subject's task is to adjust the target color until the flicker is minimal.

Any desired chromaticity can be obtained with an infinite variety of spectral power distributions $P(\lambda)$. One of these distributions has the greatest possible luminous efficacy. This limit can be obtained in only one way, namely by the mixture of suitable intensities emitted by two monochromatic sources (MacAdam, 1950). The maximum attainable luminous efficacy obtained with a single monochromatic pair of emitters is shown in Fig. 16.8. The maximum luminous efficacy of *white* light depends on the color temperature; it is about 420 lm/W for a color temperature of 6500 K and can exceed 500 lm/W for lower color temperatures. The exact value depends on the exact location within the white area of the chromaticity diagram.

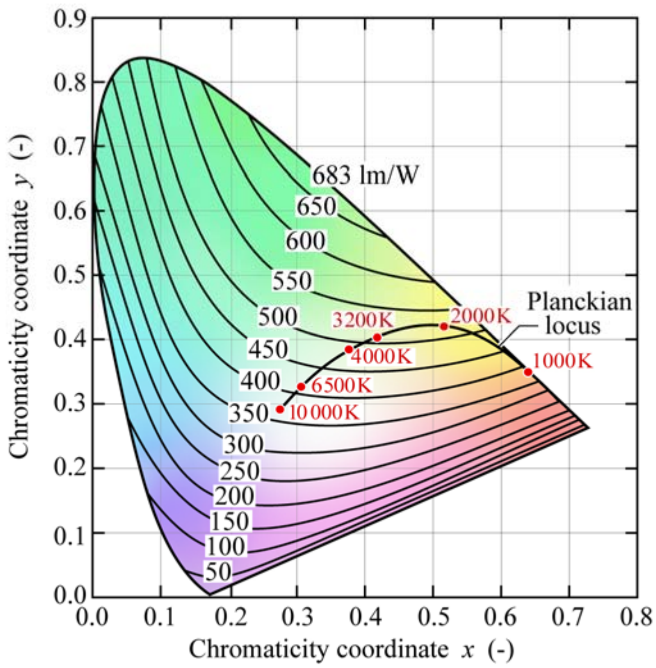

Fig. 16.8. Relation of maximum possible luminous efficacy (lumens per optical watt) and chromaticity in the CIE 1931 *x*, *y* chromaticity diagram (adapted from MacAdam, 1950).

16.4 Colors of near-monochromatic emitters

For wavelengths ranging from 390 to 720 nm, the eye sensitivity function $V(\lambda)$ is greater than 10^{-3}. Although the human eye is sensitive to light with wavelengths < 390 nm and > 720 nm, the sensitivity at these wavelengths is extremely low. Therefore, the wavelength range 390 nm ≤ λ ≤ 720 nm can be considered the *visible wavelength range*. The relationship between color and wavelength within the visible wavelength range is given in Table 16.5. This relationship is valid for monochromatic or near-monochromatic light sources such as LEDs. Note that color is, to some extent, a subjective quantity. Also note that the transition between different colors is continuous.

Table 16.5. Colors and associated typical LED peak wavelength ranges

Color	Wavelength
Ultraviolet	< 390 nm
Violet	390–455 nm
Blue	455–490 nm
Cyan	490–515 nm
Green	515–570 nm

Color	Wavelength
Yellow	570–600 nm
Amber	590–600 nm
Orange	600–625 nm
Red	625–720 nm
Infrared	> 720 nm

.

16.5 Luminous efficacy and luminous efficiency

The ***luminous flux***, Φ_{lum}, is obtained from the radiometric light power using the equation

$$\Phi_{\text{lum}} = 683 \frac{\text{lm}}{\text{W}} \int_\lambda V(\lambda)\, P(\lambda)\, d\lambda \tag{16.1}$$

where $P(\lambda)$ is the power spectral density, i.e. the light power emitted per unit wavelength, and the prefactor 683 lm/W is a normalization factor. The optical power emitted by a light source is then given by

$$P = \int_\lambda P(\lambda)\, d\lambda \ . \tag{16.2}$$

High-performance single-chip visible-spectrum LEDs can have a luminous flux of about 10–100 lm at an injection current of 100–1 000 mA.

The ***luminous efficacy of optical radiation*** (also called the ***luminosity function***), measured in units of lumens per watt of optical power, is the conversion efficiency from optical power to luminous flux. The luminous efficacy is defined as

$$\text{Luminous efficacy} = \frac{\Phi_{\text{lum}}}{P} = \left[683 \frac{\text{lm}}{\text{W}} \int_\lambda V(\lambda)\, P(\lambda)\, d\lambda \right] \Big/ \left[\int_\lambda P(\lambda)\, d\lambda \right] . \tag{16.3}$$

For strictly monochromatic light sources ($\Delta\lambda \rightarrow 0$), the luminous efficacy is equal to the eye sensitivity function $V(\lambda)$ multiplied by 683 lm/W. However, for multicolor light sources and especially for white light sources, the luminous efficacy needs to be calculated by integration over all wavelengths. The luminous efficacy is shown on the right-hand ordinate of Fig. 16.4.

The ***luminous efficiency of a light source***, also measured in units of lm/W, is the luminous flux of the light source divided by the electrical input power.

$$\boxed{\text{Luminous efficiency} \;=\; \Phi_{\text{lum}} \,/\, (I\,V)} \tag{16.4}$$

where the product ($I\,V$) is the electrical input power of the device. Note that in the lighting community, luminous efficiency is often referred to as *luminous efficacy of the source*.

Inspection of Eqs. (16.3) and (16.4) reveals that the luminous efficiency is the product of the luminous efficacy and the electrical-to-optical power conversion efficiency. The luminous efficiency of common light sources is given in Table 16.6.

Table 16.6. Luminous efficiencies of different light sources. (a) Incandescent sources. (b) Fluorescent sources. (c) High-intensity discharge (HID) sources.

Light source		**Luminous efficiency**
Edison’s first light bulb (with C filament)	(a)	1.4 lm/W
Tungsten filament light bulbs	(a)	15–20 lm/W
Quartz halogen light bulbs	(a)	20–25 lm/W
Fluorescent light tubes and compact bulbs	(b)	50–80 lm/W
Mercury vapor light bulbs	(c)	50–60 lm/W
Metal halide light bulbs	(c)	80–125 lm/W
High-pressure sodium vapor light bulbs	(c)	100–140 lm/W

The luminous efficiency is a highly relevant figure of merit for visible-spectrum LEDs. It is a measure of the perceived light power normalized to the electrical power expended to operate the LED. For light sources with a perfect electrical-power-to-optical-power conversion, the luminous source efficiency is equal to the luminous efficacy of radiation.

Exercise: ***Luminous efficacy and luminous efficiency of LEDs***. Consider a red and an amber LED emitting at 625 and 590 nm, respectively. For simplicity, assume that the emission spectra are monochromatic ($\Delta\lambda \rightarrow 0$). What is the luminous efficacy of the two light sources? Calculate the luminous efficiency of the LEDs, assuming that the red and amber LEDs have an external quantum efficiency of 50%. Assume that the LED voltage is given by $V = E_g / e = h\nu / e$.

Assume next that the LED spectra are thermally broadened and have a gaussian lineshape with a linewidth of $1.8\,kT$. Again calculate the luminous efficacy and luminous efficiency of the two light sources. How accurate are the results obtained with the approximation of monochromaticity?

Some LED structures attain excellent power efficiency by using small light-emitting areas (current injection in a small area of chip) and advanced light-output-coupling structures (see, for example, Schmid *et al*., 2002). However, such devices have low luminance because only a small fraction of the chip area is injected with current. Table 16.7 summarizes frequently used figures of merit for light-emitting diodes.

Table 16.7. Summary of photometric, radiometric, and quantum performance measures for LEDs.

Figure of merit	**Explanation**	**Unit**
Luminous efficacy	Luminous flux per optical unit power	lm/W
Luminous efficiency	Luminous flux per input electrical unit power	lm/W
Luminous intensity efficiency	Luminous flux per sr per input electrical unit power	cd/W
Luminance	Luminous flux per sr per chip unit area	cd/m^2
Power efficiency	Optical output power per input electrical unit power	%
Internal quantum efficiency	Photons emitted in active region per electron injected	%
External quantum efficiency	Photons emitted from LED per electron injected	%
Extraction efficiency	Escape probability of photons emitted in active region	%

16.6 Brightness and linearity of human vision

Although the term ***brightness*** is frequently used, it lacks a standardized scientific definition. The frequent usage is due to the fact that the general public can more easily relate to the term *brightness* than to photometric terms such as *luminance* or *luminous intensity*. Brightness is an attribute of visual perception and is frequently used as synonym for *luminance* and (incorrectly) for the radiometric term *radiance*.

To quantify the brightness of a source, it is useful to differentiate between point and surface area sources. For *point sources*, brightness (in the photopic vision regime) can be approximated by the luminous intensity (measured in cd). For *surface sources*, brightness (in the photopic vision regime) can be approximated by the luminance (measured in cd/m^2). However, due to the lack of a formal standardized definition of the term brightness, it is frequently avoided in technical publications.

Standard CIE photometry assumes human vision to be ***linear*** within the photopic regime. It is clear that an isotropically emitting blue point source and an isotropically emitting red point source each having a luminous flux of, e.g., 5 lm, have the same luminous intensity. Assuming *linearity* of photopic vision, both sources still have the same luminous intensity as the luminous fluxes of the sources are increased from 5 to, e.g., 5000 lm.

However, if the luminous fluxes of the two sources are reduced so that the mesopic or scotopic vision regime is entered, the blue source will appear brighter than the red source due to the shift of the eye sensitivity function to shorter wavelengths in the scotopic regime.

It is important to keep in mind that the linearity of human vision within the photopic regime is an *approximation*. Linearity clearly simplifies photometry. However, human subjects may feel discrepancies between the experience of brightness and measured luminance of a light source, especially for colored light sources if the luminous flux is changed over orders of magnitude.

16.7 Circadian rhythm and circadian sensitivity

The human wake-sleep rhythm has a period of approximately 24 hours and the rhythm therefore is referred to as the ***circadian rhythm*** or ***circadian cycle***, with the name being derived from the Latin words *circa* and *dies* (and its declination *diem*), meaning *approximately* and *day*, respectively. Light has been known for a long time to be the synchronizing clock (*zeitgeber*) of the human circadian rhythm. For reviews on the development of the understanding of the circadian rhythm including the identification of light as the dominant trigger for the endogenous *zeitgeber*, see Pittendrigh (1993) and Sehgal (2004).

The wake-sleep rhythm of humans is synchronized by the intensity and spectral composition of light. Sunlight is the natural *zeitgeber*. During mid-day hours sunlight has high intensity, a high color temperature, and a high content of blue light. During evening hours, intensity, color temperature, and blue content of sunlight strongly decrease. Humans have adapted to this variation and the circadian rhythm is most likely synchronized by the following three factors: intensity, color temperature, and blue content.

Exposure to inappropriately high intensities of light in the late afternoon or evening can upset the regular wake-seep rhythm and lead to sleeplessness and even serious illnesses such as cancer (Brainard *et al*., 2001; Blask *et al*, 2003). It is therefore highly advisable to limit exposure to high intensity light in the late afternoon and evening hours, to not be counterproductive to the natural circadian rhythm (Schubert, 1997).

It was believed for a long time that rod cells and the three types of cone cells are the only optically sensitive cells in the human eye. However, Brainard *et al*. (2001) postulated that an unknown photoreceptor in the human eye would control the circadian rhythm. Evidence presented by Berson *et al*. (2002) and Hattar *et al*., (2002) indicates that retinal ganglion cells have an optical sensitivity as well. For a schematic illustration of ganglion cells, see Fig. 16.1. The spectral sensitivity of mammalian ganglion cells was measured and the responsivity curve is shown in Fig. 16.9. Inspection of the figure reveals a ganglion-cell peak-sensitivity at 484 nm, i.e. in the blue spectral range.

Berson *et al*. (2002) presented evidence that the photosensitive ganglion cells are instrumental in the control of the circadian rhythm. Due to their sensitivity in the blue spectral range, it can be hypothesized that the blue sky occurring near mid-day is a strong factor in synchronizing the endogenous circadian rhythm. The photosensitive ganglion cells have therefore been referred to as *blue-sky receptors*.

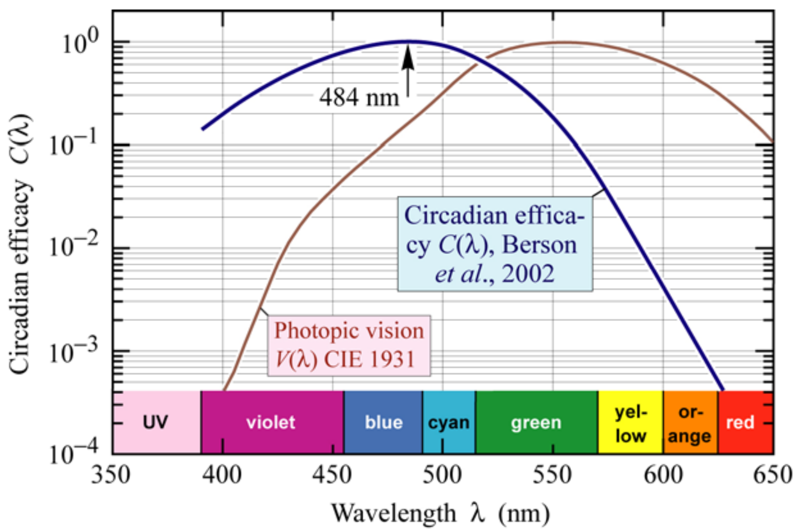

Fig. 16.9. Circadian efficacy curve derived from retinal ganglion cell photoresponse measurements. The ganglion cells on which the measurements were performed originated from mammals. The figure reveals the significant difference between circadian and visual sensitivity (adapted from Berson *et al*., 2002).

Inspection of the spectral sensitivity of the ganglion cells shown in Fig. 16.9 reveals the huge difference of red light and blue light for circadian efficacy: The efficacy of blue light in synchronizing the circadian rhythm can be three orders of magnitude greater than the efficacy of red light. This particular role of blue light should be taken into account in lighting design and the use of artificial lighting by consumers.

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Appendix 16.1

Tabulated values of the 2º degree CIE 1931 photopic eye sensitivity function and the CIE 1978 Judd–Vos-modified photopic eye sensitivity function for point sources (after CIE, 1931 and CIE, 1978).

λ (nm)	CIE 1931 $V(\lambda)$	CIE 1978 $V(\lambda)$
360	3.9170 E–6	0.0000E–4
365	6.9650 E–6	0.0000E–4
370	1.2390 E–5	0.0000E–4
375	2.2020 E–5	0.0000E–4
380	3.9000 E–5	2.0000E–4
385	6.4000 E–5	3.9556E–4
390	1.2000 E–4	8.0000E–4
395	2.1700 E–4	1.5457E–3
400	3.9600 E–4	2.8000E–3
405	6.4000 E–4	4.6562E–3
410	1.2100 E–3	7.4000E–3
415	2.1800 E–3	1.1779E–2
420	4.0000 E–3	1.7500E–2
425	7.3000 E–3	2.2678E–2
430	1.1600 E–2	2.7300E–2
435	1.6840 E–2	3.2584E–2
440	2.3000 E–2	3.7900E–2
445	2.9800 E–2	4.2391E–2
450	3.8000 E–2	4.6800E–2
455	4.8000 E–2	5.2122E–2
460	6.0000 E–2	6.0000E–2
465	7.3900 E–2	7.2942E–2
470	9.0980 E–2	9.0980E–2
475	0.11260	0.11284
480	0.13902	0.13902
485	0.16930	0.16987
490	0.20802	0.20802
495	0.25860	0.25808
500	0.32300	0.32300
505	0.40730	0.40540
510	0.50300	0.50300
515	0.60820	0.60811
520	0.71000	0.71000
525	0.79320	0.79510
530	0.86200	0.86200
535	0.91485	0.91505
540	0.95400	0.95400
545	0.98030	0.98004
550	0.99495	0.99495
555	1.00000	1.00000
560	0.99500	0.99500
565	0.97860	0.97875
570	0.95200	0.95200
575	0.91540	0.91558
580	0.87000	0.87000
585	0.81630	0.81623
590	0.75700	0.75700
595	0.69490	0.69483
600	0.63100	0.63100
605	0.56680	0.56654
610	0.50300	0.50300
615	0.44120	0.44172
620	0.38100	0.38100
625	0.32100	0.32052
630	0.26500	0.26500
635	0.21700	0.21702
640	0.17500	0.17500
645	0.13820	0.13812
650	0.10700	0.1.0700
655	8.1600 E–2	8.1652E–2
660	6.1000 E–2	6.1000E–2
665	4.4580 E–2	4.4327E–2
670	3.2000 E–2	3.2000E–2
675	2.3200 E–2	2.3454E–2
680	1.7000 E–2	1.7000E–2
685	1.1920 E–2	1.1872E–2
690	8.2100 E–3	8.2100E–3
695	5.7230 E–3	5.7723E–3
700	4.1020 E–3	4.1020E–3
705	2.9290 E–3	2.9291E–3
710	2.0910 E–3	2.0910E–3
715	1.4840 E–3	1.4822E–3
720	1.0470 E–3	1.0470E–3
725	7.4000 E–4	7.4015E–4
730	5.2000 E–4	5.2000E–4
735	3.6110 E–4	3.6093E–4
740	2.4920 E–4	2.4920E–4
745	1.7190 E–4	1.7231E–4
750	1.2000 E–4	1.2000E–4
755	8.4800 E–5	8.4620E–5
760	6.0000 E–5	6.0000E–5
765	4.2400 E–5	4.2446E–5
770	3.0000 E–5	3.0000E–5
775	2.1200 E–5	2.1210E–5
780	1.4990 E–5	1.4989E–5
785	1.0600 E–5	1.0584E–5
790	7.4657 E–6	7.4656E–6
795	5.2578 E–6	5.2592E–6
800	3.7029 E–6	3.7028E–6
805	2.6078 E–6	2.6076E–6
810	1.8366 E–6	1.8365E–6
815	1.2934 E–6	1.2950E–6
820	9.1093 E–7	9.1092E–7
825	6.4153 E–7	6.3564E–7

Appendix 16.2

Tabulated values of the CIE 1951 eye sensitivity function of the scotopic vision regime, $V'(\lambda)$ (after CIE, 1951).

λ (nm)	CIE 1951 $V'(\lambda)$	λ (nm)	CIE 1951 $V'(\lambda)$
380	5.890e-004	585	8.990e-002
385	1.108e-003	590	6.550e-002
390	2.209e-003	595	4.690e-002
395	4.530e-003	600	3.315e-002
400	9.290e-003	605	2.312e-002
405	1.852e-002	610	1.593e-002
410	3.484e-002	615	1.088e-002
415	6.040e-002	620	7.370e-003
420	9.660e-002	625	4.970e-003
425	1.436e-001	630	3.335e-003
430	1.998e-001	635	2.235e-003
435	2.625e-001	640	1.497e-003
440	3.281e-001	645	1.005e-003
445	3.931e-001	650	6.770e-004
450	4.550e-001	655	4.590e-004
455	5.130e-001	660	3.129e-004
460	5.670e-001	665	2.146e-004
465	6.200e-001	670	1.480e-004
470	6.760e-001	675	1.026e-004
475	7.340e-001	680	7.150e-005
480	7.930e-001	685	5.010e-005
485	8.510e-001	690	3.533e-005
490	9.040e-001	695	2.501e-005
495	9.490e-001	700	1.780e-005
500	9.820e-001	705	1.273e-005
505	9.980e-001	710	9.140e-006
510	9.970e-001	715	6.600e-006
515	9.750e-001	720	4.780e-006
520	9.350e-001	725	3.482e-006
525	8.800e-001	730	2.546e-006
530	8.110e-001	735	1.870e-006
535	7.330e-001	740	1.379e-006
540	6.500e-001	745	1.022e-006
545	5.640e-001	750	7.600e-007
550	4.810e-001	755	5.670e-007
555	4.020e-001	760	4.250e-007
560	3.288e-001	765	3.196e-007
565	2.639e-001	770	2.413e-007
570	2.076e-001	775	1.829e-007
575	1.602e-001	780	1.390e-007
580	1.212e-001		