Chapter 2

Measurement Matters

2.1 What Is Light?

Light is associated with a very narrow region of the electromagnetic spectrum between about 380 and 780 nanometers (nm), and is formally defined as optical radiation that can evoke a visual response in humans. Two classes of photoreceptors—rods and cones—found in the human retina transduce electromagnetic radiation into neural signals that ultimately evoke visual responses. Interestingly, light is the only physical quantity defined in terms of the human condition. All other physical quantities, such as length, mass, and time would continue to exist if the human species were to become extinct (Bureau International des Poids et Mesures, 1983; 2005; 2006). Only the definition of light would have to undergo a major revision by the species that succeeds us.

Photometry is the measurement of light. Several orthodox photometric quantities are used to characterize light sources and light fixtures and to specify or regulate the application of light. The base unit in orthodox photometry is the candela (cd), which is a measure of the luminous intensity of a light source in a particular direction. The luminous intensity of a source varies with angle, so light sources will produce different luminous intensities in different directions. The luminous intensity distribution of a frosted incandescent lamp is nearly the same in any direction, whereas an automobile headlight will have a maximum intensity in the direction of travel with much lower luminous intensities orthogonal to the maximum.

Formally, one candela is defined as having a radiant intensity of 1/683 watts (W) per unit solid angle at 555 nm. For polychromatic light sources (i.e., all practical sources of illumination) the photopic luminous efficiency function [$V(\lambda)$] is almost always used to weight energy in the electromagnetic spectrum for the determination of luminous intensity (Fig. 2.1). The spectral power distribution (SPD) of the radiation emitted by a source is integrated with $V(\lambda)$ to determine the photopic luminous intensity (in candelas) of the source in the direction of measurement. This quantity is equal to the number of lumens (lm) per steradian (sr) in the direction

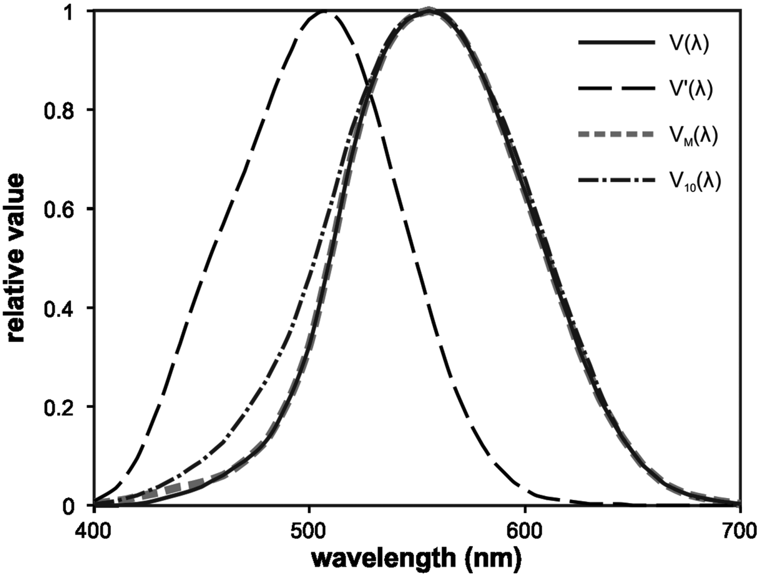

Figure 2.1 Formally sanctioned spectral luminous efficiency functions by the Commission Internationale de l'Éclairage (CIE) (CIE, 1978; 1990; 2005). $V(\lambda)$ is the original photopic luminous efficiency function adopted by the CIE in 1924. It is based on the spectral sensitivity of central (2-deg) vision and therefore largely reflects the spectral sensitivity of the cone photoreceptors in the fovea. $V'(\lambda)$ is the scotopic luminous efficiency function based on the spectral sensitivity of the peripheral retina under very dim lighting conditions where only rod photoreceptors provide input to visual sensation. $V_M(\lambda)$, the so-called Judd–Vos correction, is a second photopic luminous efficiency function adopted by CIE to reflect slightly enhanced sensitivity to short wavelengths in central (2-deg) vision. $V_{10}(\lambda)$ is a third photopic luminous efficiency function adopted by CIE to reflect the spectral sensitivity of central (10-deg) vision. $V(\lambda)$ is the only luminous efficiency function incorporated into commercially available photometric instruments and the only one used internationally for lighting application standards.

of measurement. The significance of $V(\lambda)$ for determining the benefit of light will be discussed in much more detail, but this particular spectral weighting function underlies all units in orthodox photometry. (A complete list of acronyms, abbreviations, and notation is provided in Appendix 1.)

Often the total amount of light (or total luminous flux) emitted by the source is of interest rather than the luminous intensity distribution. The total luminous flux emitted by a source is actually a special case of luminous intensity and is equal to the number of lumens emitted into a sphere of 4πsr surrounding the source. Thus, the total luminous flux emitted by a source is the sum of the luminous intensities of the source in every direction.

Luminance is often referred to as photometric brightness because it is the measure of light that is most closely associated with how bright sources or objects appear. Qualitatively, luminance is the product of the light falling on a surface multiplied by the reflectance from (or transmission through) the surface. More formally, luminance is a measure of the intensity of the light per unit area in the direction of view and is most commonly measured in units of nits (or cd/m^2). Although luminance meters are commercially available, they are rarely used because they are relatively expensive and most lighting standards consider the light falling on a surface rather than the light reflected from or transmitted through a surface.

We rely most commonly on two measures of light, luminous efficacy and illuminance. Luminous efficacy is defined as the ratio of the total lumens emitted by a source or a fixture divided by the wattage needed to emit those lumens (lm/W). Those sources or fixtures that emit more lumens per watt of electric power are often considered more "energy efficient," but as will be discussed later, this measure of "energy efficiency" can easily obscure the efficacious application of light. Illuminance is perhaps the most common measure of light in architectural applications, both for specifying and regulating the amount of light to be used in a space. Illuminance is defined as the number of lumens incident on a surface area, such as a desk or a roadway. Lux (lm/m^2) is presently the most common unit of measurement for illuminance. Recommended and regulated levels of illuminance vary depending on the type of task being conducted in an architectural application. Tasks associated with higher levels of illuminance are those deemed by sanctioning bodies and regulators as more difficult to see or tasks in which errors are more important to avoid.

Table 2.1 is a summary of the most common photometric units used to measure light. As already noted, all photometric units integrate the electromagnetic spectrum emitted by a source or surface with the photopic luminous efficiency function [$V(\lambda)$].

2.1.1 The photopic luminous efficiency function

All practical measurements of light are based on $V(\lambda)$ shown in Fig. 2.1. In photometry, $V(\lambda)$ weights the effectiveness of the electromagnetic

Table 2.1 The most common photometric units used to measure light.

	Unit	Abbreviation	Equivalence
Luminous intensity	candela	cd	lm/sr
Luminous flux	lumen	lm	$lm/4\pi sr$
Illuminance	lux	lx	lm/m^2
Luminance	nit	—	cd/m^2
Luminous efficacy	—	—	lm/W

spectrum generated by every light source irrespective of its intended application. $V(\lambda)$ was developed from a particular set of human visual psychophysical studies performed in the 1920s. In those early studies human subjects used their foveae to view a small, 2-deg field (about the size of a beer bottle cap at arm's length) of light in an otherwise dark visual field. The fovea is a small region of the retina corresponding to what is called *central vision* and has the highest density of photoreceptors, thus providing the highest spatial resolution (i.e., acuity). In fact, only cone photoreceptors are found in the fovea, and among those, most are long-wavelength sensitive (L) cones and middle-wavelength sensitive (M) cones. The third cone photoreceptor type, the short-wavelength sensitive (S) cones, are largely absent from the central fovea (Fig. 2.2). Two techniques were used to assess the spectral sensitivity of human subjects to different narrowband, nearly monochromatic sources of light. Both of these techniques employed methods aimed at measuring "equality of sensation" while viewing the different sources of light. The first technique, known as side-by-side heterochromatic brightness matching, was very straightforward. The halves of the 2-deg field were each filled with different monochromatic lights, and the radiant power (in watts) of one half-field was adjusted by the human subjects to appear equally bright as the other half-field. The experimenter recorded the radiant power needed to make the brightness match so that the relative sensitivity to the two wavelengths could be computed. So, for example, it was found that it takes slightly more radiant power from a 550-nm light to match the brightness of a 555-nm light. The relative sensitivity at any wavelength can be determined by the reciprocal of the watts needed to match the reference wavelength, which is the wavelength that takes the fewest watts for equal brightness.

It became apparent to researchers at the time that this technique worked well only when the wavelength differences between the lights in the half-fields were small. Matching a 630-nm light with a 430-nm light was, for example, difficult for subjects, and the matches were highly variable, both between and within subjects. Thus, a second technique was developed, known as flicker photometry. Again, subjects viewed a 2-deg field, but instead of making a side-by-side brightness match, the two lights were matched temporally; that is, the two lights were matched in brightness while they were very quickly oscillated. At very slow oscillations, the 2-deg field would alternately appear as two distinct colors (e.g., red and yellow), but as the oscillation rate increased, the 2-deg field would appear as one color (e.g., orange), but it would appear to flicker in brightness. The subject would carefully adjust the radiant power of one color (e.g., red) until the (orange) light appeared to just stop flickering. As with the heterochromatic brightness matching technique, the relative