

Light and Optics

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The quest to understand the nature of light has led curious human beings down into the innermost secrets of the atom and out to the farthest reaches of the starry universe.

—Ben Bova

FUNDAMENTALS

For illuminating engineering purposes, the Illuminating Engineering Society of North America (IESNA) defines light as radiant energy that is capable of exciting the human retina and creating a visual sensation.

As a physical quantity, light is defined in terms of its relative efficiency throughout the electromagnetic spectrum lying between approximately 380 and 780 nm. Visually, there is some individual variation in efficiency within these limits.

Theories

One of the earliest theories to describe light involved the notion that light was emitted from the eyes, and that they were rendered visible when they were struck by the emissions. Aristotle rejected this theory when questioning why we could not see in the dark. Since then, many alternative theories have been advanced. From a physical point of view, these theories generally regarded light as an energy transfer from one location to another. Some theories¹⁻⁴ are briefly discussed below.

Corpuscular Theory. This theory follows from the observation that moving particles, or corpuscles, possess kinetic energy. This position was advocated by Sir Isaac Newton (1642–1727). It is based on three premises:

1. Luminous bodies emit radiant energy in particles.
2. The particles are intermittently ejected in straight lines.
3. The particles act on the retina, stimulating a response that produces a visual sensation.

Wave Theory. This theory follows from the observation that waves can transfer energy even though the medium itself does not travel. This position was advocated by Christian Huygens (1629–1695). It too is based on three premises:

1. Light results from the molecular vibration in the luminous material.

2. The vibrations are transmitted through an “ether” as wavelike movements (comparable to ripples in water), and the vibrations slow down upon entering denser media.
3. The transmitted vibrations act on the retina, stimulating a response that produces a visual sensation.

Electromagnetic Theory.⁵ The theory was advanced by James Clerk Maxwell (1831–1879), and is based on three premises:

1. Luminous bodies emit light in the form of radiant energy.
2. Radiant energy is propagated in the form of electromagnetic waves.
3. The electromagnetic waves act upon the retina, stimulating a response that produces a visual sensation.

Quantum Theory. A modern form of the corpuscular theory was advanced by Max Planck, and is based on two premises:

1. Energy is emitted and absorbed in discrete quanta (photons).
2. The magnitude of each quantum, Q , is determined by the product of h and ν , where h is 6.626×10^{-34} J-s (Planck’s constant), ν is the frequency of the photon vibration in Hz, and Q is energy in Joules.

This theory provides a means of determining the amount of energy in each quantum. It follows from this theory that energy increases with frequency.

Unified Theory. The theory proposed by Louis de Broglie and Werner Heisenberg is based on two premises:

1. Every moving element of mass has associated with it a wave whose length is given by the equation

$$\lambda = \frac{h}{mv} \quad (1-1)$$

where

λ = wavelength of the wave motion,
 h = Planck’s constant,
 m = mass of the particle,
 ν = velocity of the particle.

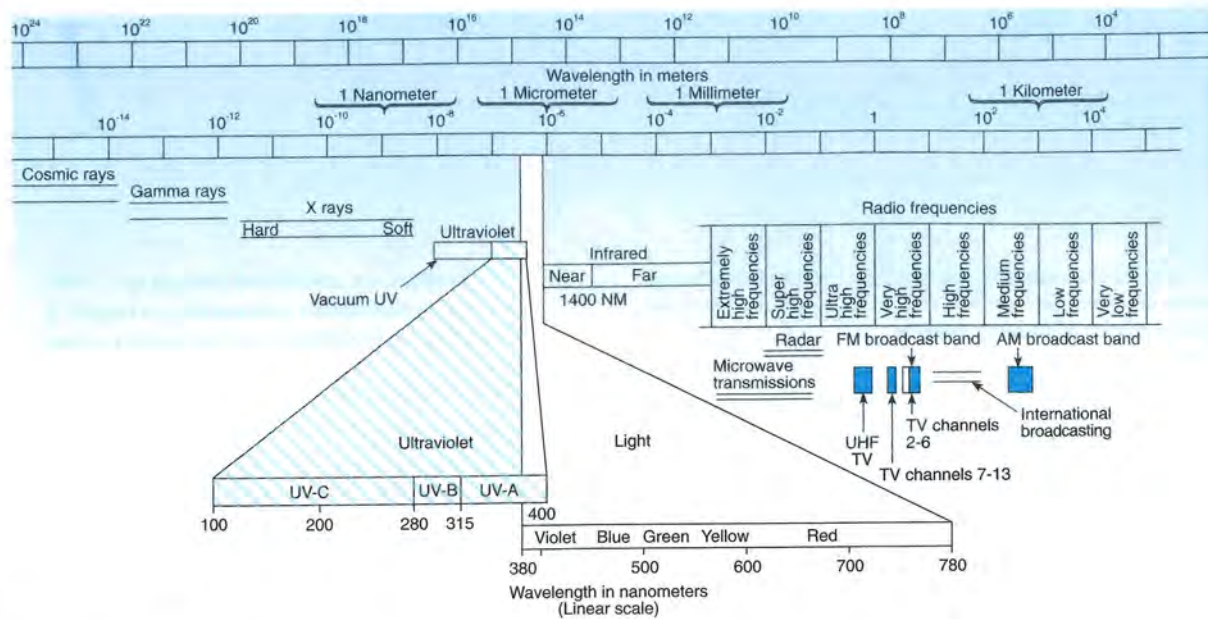


Figure 1-1. The radiant energy (electromagnetic) spectrum.

2. It is impossible to simultaneously determine all of the properties that are distinctive of a wave or a corpuscle.

The quantum and electromagnetic wave theories provide an explanation of those characteristics of radiant energy of concern to the illuminating engineer. Whether light is considered as a wave or a photon, it is radiation that is produced by electronic processes in the most exact sense of the term. It is produced in an incandescent body, a gas discharge, or a solid-state device by excited electrons just having reverted to more stable positions in their atoms, releasing energy.

Light and the Energy Spectrum^a

The wave theory permits a convenient graphical representation of radiant energy in an orderly arrangement according to its wavelength or frequency. This arrangement is called a spectrum (Figure 1-1). It is useful in indicating the relationship between various radiant energy wavelength regions. Such a graphical representation should not be construed to indicate that each region of the spectrum is divided from the others in any physical way; there is a gradual transition from one region to another. The radiant energy spectrum extends over a range of wavelengths from 10^{-16} to 10^5 m. The Angstrom unit ($\text{\AA}$), the nanometer (nm), and the micrometer (μm), which are respectively 10^{-10} , 10^{-9} , and 10^{-6} m, are commonly used units of length in the visible spectrum region. The nanometer is the preferred unit of wavelength in the ultraviolet (UV) and visible regions of the spectrum. The micrometer is normally used in the infrared (IR) region.

Of particular importance to illuminating engineering are three regions of the electromagnetic spectrum: UV, visible, and IR. On the basis of practical applications and the effect obtained, the UV region is divided into the following bands (for engineering purposes, the "black light" region extends slightly into the visible portion of the spectrum):

Ozone-producing	180 to 220 nm
Bactericidal (germicidal)	220 to 300 nm
Erythema	280 to 320 nm
Black light	300 to 400 nm

Another division of the UV spectrum, often used by photobiologists, is given by the Commission Internationale de l'Éclairage (CIE):

UVA	315 to 400 nm
UVB	280 to 315 nm
UVC	100 to 280 nm

Radiant energy in the visible spectrum lies between 380 and 780 nm. For practical purposes, infrared radiant energy is within the wavelength range of 0.78 to $10^3 \mu\text{m}$. This band is arbitrarily divided as follows:

Near (short wavelength) infrared	0.78 to $1.4 \mu\text{m}$
Mid (medium wavelength) infrared	1.4 to $3.0 \mu\text{m}$
Far (long wavelength) infrared	3.0 to $10^3 \mu\text{m}$

In general, unlike UV energy, IR energy is not evaluated on a wavelength basis but rather in terms of all such energy

Figure 1-2. Speed of Light for a Wavelength of 589 nm (Na D-lines)

Medium	Speed (meters per second)
Vacuum	2.99793×10^8
Air (760 mm at 0°C)	2.99724×10^8
Crown Glass	1.98223×10^8
Water	2.24915×10^8

incident upon a surface. Examples of these applications are industrial heating, drying, baking, and photoreproduction. However, some applications, such as IR viewing devices, involve detectors sensitive to a restricted range of wavelengths; in such cases the spectral characteristics of the source and receiver are of importance.

All forms of radiant energy are transmitted at the same speed in vacuum (299,793 km/s, or 186,282 mi/s). However, each form differs in wavelength and thus in frequency. The wavelength and velocity may be altered by the medium through which it passes, but the frequency remains constant, independent of the medium. Thus, through the equation

$$\text{velocity} = \frac{\lambda \nu}{n} \quad (1-2)$$

where

n = index of refraction of the medium,
 λ = wavelength in a vacuum,
 ν = frequency in Hz,

it is possible to determine the velocity of radiant energy and also to indicate the relationship between frequency and wavelength. Figure 1-2 gives the speed of light in different media for a frequency corresponding to a wavelength of 589 nm in air.

Light is . . . a certain motion or an action, conceived in a very subtle manner, which fills the pores of all other bodies. . .

—René Descartes, in *La Dioptrique*, 1637

Blackbody Radiation

The intensity and spectral properties of a blackbody radiator are dependent solely upon its temperature. A blackbody radiator may be closely approximated by the radiant power emitted from a small aperture in an enclosure, the walls of which are maintained at a uniform temperature (Figure 1-3).

Emitted light from a practical light source, particularly from an incandescent lamp, is often described by comparison with that from a blackbody radiator. In theory, all of the energy emitted by the walls of the blackbody radiator is eventually reabsorbed by the walls; that is, none escapes from the enclosure. Thus, a blackbody will, for the same area, radiate more total power and more power at a given wavelength than any other light source operating at the same temperature.

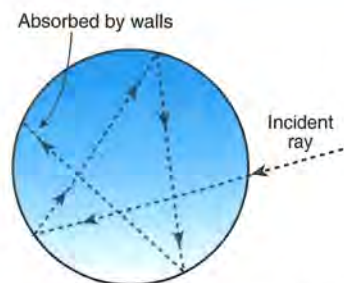


Figure 1-3. Small aperture in an enclosure exhibits blackbody characteristics.

From 1948 to 1979, the luminance of a blackbody, operated at the temperature of freezing platinum (2042 K), was used as an international reference standard to define the unit of luminous intensity. Specifically, it has a luminance of 60 cd/m². Since operating and maintaining a blackbody radiator at the freezing point of platinum is a major undertaking, a new definition of the candela was adopted in 1979. The candela is now, essentially, the luminous intensity of a 555.016 nm source whose radiant intensity is 1/683 W/sr. The new photometric unit is based on an electrical unit, the watt, which can be accurately and conveniently measured with an electrically calibrated radiometer. A further advantage of this definition is that the magnitude of the unit is independent of the international temperature scale, which occasionally changes.

Planck Radiation Law. Data describing blackbody radiation curves were obtained by Lummer and Pringsheim using a specially constructed and uniformly heated tube as the source. Planck, introducing the concept of discrete quanta of energy, developed an equation depicting these curves. It gives the spectral radiance of a blackbody as a function of wavelength and temperature. See the definition of Planck's radiation law in the Glossary.

Figure 1-4 shows the spectral radiance of a blackbody, on a logarithmic scale, as a function of wavelength for several absolute temperatures.

Wien Radiation Law. In the temperature range of incandescent filament lamps (2000 to 3400 K) and in the visible wavelength region (380 to 780 nm), a simplification of the Planck equation, known as the Wien radiation law, gives a good representation of the blackbody distribution of spectral radiance (see the Glossary).

Wien Displacement Law. This gives the relationship between the peak wavelength of blackbody radiation at different temperatures (see line AB in Figure 1-4, and the Glossary).

Stefan-Boltzmann Law. This law, obtained by integrating Planck's expression for L_λ from zero to infinity, states that the total radiant power per unit area of a blackbody varies as the fourth power of the absolute temperature (see the Glossary). It should be noted that this law applies to the total

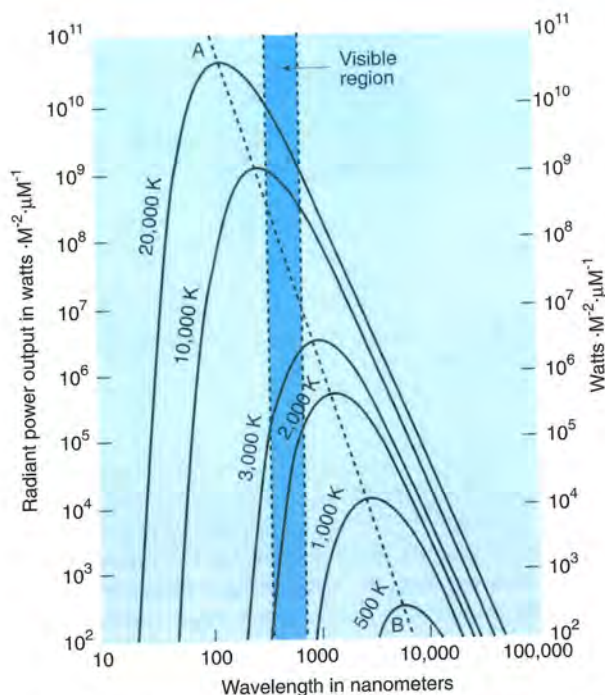


Figure 1-4. Blackbody radiation curves for operating temperatures between 500 and 20,000 K, showing Wein displacement of peaks. The shaded area in the region of visible wavelengths.

power, that is, the whole spectrum. It cannot be used to estimate the power in the visible portion of the spectrum alone.

Spectral Emissivity

No known radiator has the same emissive power as a blackbody. The ratio of the output of a radiator at any wavelength to that of a blackbody at the same temperature and the same wavelength is known as the spectral emissivity, $\epsilon(\lambda)$, of the radiator.

Graybody Radiation

When the spectral emissivity is constant for all wavelengths, the radiator is known as a graybody. No known radiator has a constant spectral emissivity for all visible, IR, and UV wavelengths, but in the visible region a carbon filament exhibits nearly uniform emissivity; that is, a carbon filament is nearly a graybody for this region of the electromagnetic spectrum.

Selective Radiators

When the emissivity of all known material varies with wavelength, the radiator is called a selective radiator. In Figure 1-5, the radiation curves for a blackbody, a graybody, and a selective radiator (tungsten), all operating at 3000 K, are

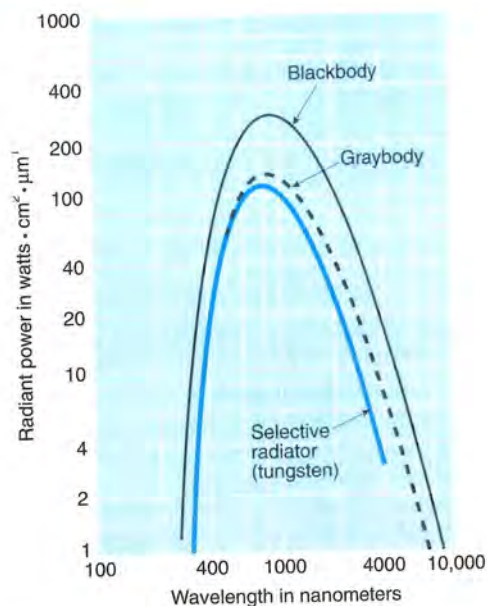


Figure 1-5. Radiation curves for blackbody, graybody, and selective radiators operating at 3000 K.

plotted on the same logarithmic scale to show the characteristic differences in radiant power.

Color Temperature and Distribution Temperature

The radiation characteristics of a blackbody of unknown area may be specified with the aid of the Planck's equation by fixing only two quantities: the magnitude of the radiation at any given wavelength, and the absolute temperature. The same type of specification may be used with reasonable accuracy in the visible region of the spectrum for tungsten filaments and other incandescent sources. However, the temperature used in the case of selective radiators is not that of the filament but a value called the color temperature.

The color temperature of a selective radiator is that temperature at which a blackbody would have to be operated to produce the same color as that of the selective radiator. Color temperature is calculated from the chromaticity coordinates (u, v) of the source; small differences between chromaticities of a blackbody and an incandescent filament lamp are not of practical importance. This is true because the interreflections that occur at the inner surfaces of the helix formed by the coils used in many tungsten lamps act somewhat like a blackbody radiator. Thus, the spectral power distributions from coiled filaments exhibit combined characteristics of a straight filament and of a blackbody operating at the same temperature.

Distribution temperature is the temperature of a blackbody whose relative spectral power distribution is the closest

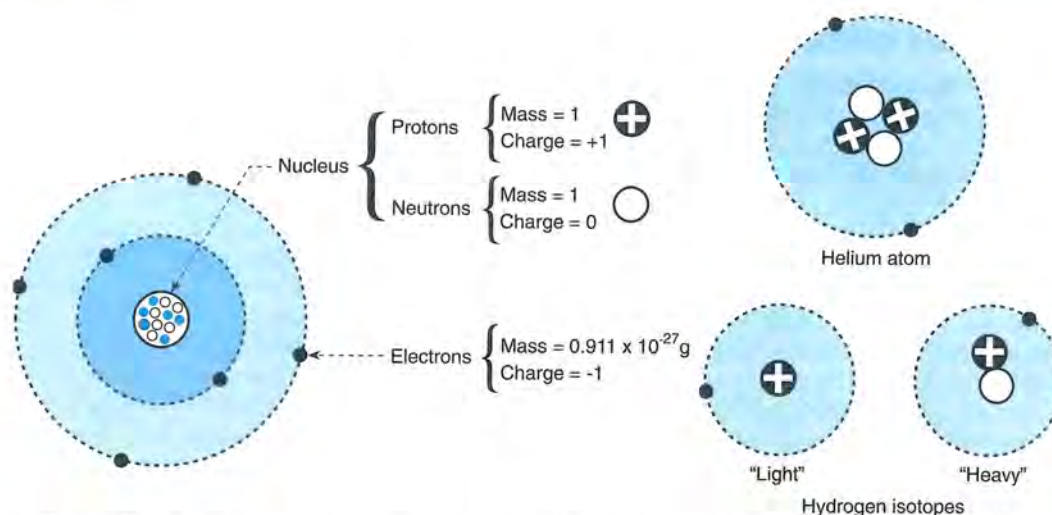


Figure 1-6. Schematic structure of the atom, showing electron orbits around a central nucleus. Hydrogen and helium atoms are the simplest of all atomic structures.

to that of the given selective radiator. Distribution temperature is defined from the spectral power distribution of the source.⁷

Color temperature and distribution temperature apply only to incandescent sources. Correlated color temperatures are used to describe the light emitted from other types of sources. Color is discussed in greater detail in Chapter 4, Color.

Atomic Structure and Radiation

The atomic theories first proposed by Rutherford and Bohr in 1913 have since been expanded upon and confirmed by an overwhelming amount of experimental evidence. They hypothesize that each atom resembles a minute solar system, such as that shown in Figure 1-6.

The atom consists of a central nucleus possessing a positive charge $+n$, about which revolve n negatively charged electrons. In the normal state these electrons remain in particular orbits, or energy levels, and radiation is not emitted by the atom.

The orbit described by a particular electron rotating about the nucleus is determined by the energy of that electron. In other words, there is a particular energy associated with each orbit. The system of orbits or energy levels is characteristic of each element and remains stable unless disturbed by external forces.

The electrons of an atom can be divided into two classes. The first class includes the inner shell electrons, which are not readily removed or excited except by high-energy radiation. The second class includes the outer shell (valence) electrons, which cause chemical bonding into molecules. Valence electrons are readily excited by UV or visible radiation

or by electron impact and can be removed with relative ease. The valence electrons of an atom in a solid, when removed from their associated nuclei, enter the so-called conduction band and confer on the solid the property of electrical conductivity.

Upon the absorption of sufficient energy by an atom in the gaseous state, the valence electron is pushed to a higher energy level further from the nucleus. Eventually, the electron returns to the normal orbit, or an intermediate one, and in so doing the energy that the atom loses is emitted as a quantum of radiation. The wavelength of the radiation is determined by Planck's formula:

$$E_2 - E_1 = h\nu_{21} \quad (1-3)$$

where

E_2 = energy associated with the excited orbit,

E_1 = energy associated with the normal orbit,

h = Planck's constant,

ν_{21} = frequency of the emitted radiation as the electron moves from level 2 to level 1.

This formula can be converted to a more usable form:

$$\text{wavelength} = \frac{1239.76}{V_d} \text{ nm} \quad (1-4)$$

where

V_d = potential difference in volts between two energy levels through which the displaced electron has fallen in one transition.

Luminous Flux and the Lumen^{8,9}

Of particular importance to illuminating engineering is the lumen. The goal of this section is to show how electric power of radiant flux (in watts) is converted into luminous flux (in lumens), and to describe the underlying rationale for this process. The lumen is, in fact, a unit relating radiant flux (in watts) to visually effective radiation (i.e., light) for a standard human observer.

There are two classes of photoreceptors in the human eye, rods and cones. The photopic function V_λ describes the spectral luminous efficiency function for photopic (cone) vision, and the scotopic function V'_λ describes the spectral luminous efficiency for scotopic (rod) vision (Figure 1-7).¹⁰

The photopic luminous efficiency function V_λ was established in 1924 by Commission Internationale de l'Éclairage (CIE) and is based on data from several experimenters using different techniques. The two primary techniques used were flicker photometry and step-by-step heterochromatic brightness matching.

Flicker photometry is the least variable technique for determining the photopic efficiency function. With this technique, two lights are seen alternately in rapid succession. The radiance of one light, called the reference light, is held constant while the radiance of the other light, called the test light, which is monochromatic, is varied to the point where minimum flicker is perceived. At this point the luminances of both lights are defined to be the equal. Each test light wavelength is compared with the reference light in this way. The wavelength associated with the reciprocal of the minimum radiance needed to match the reference light is defined as the unit value of the photopic spectral luminous function ($V_\lambda = 1$).

In heterochromatic brightness matching, the reference light of constant radiance is juxtaposed with the test wavelength of variable radiance. The subject simply adjusts the radiance of each test wavelength until it appears to be equal in brightness to the reference. This technique is highly variable and produces results very different from flicker photometry unless the spectral difference between the test wavelength and the reference light is small. To obtain useful results, then, the reference light must be different for different regions of the spectrum. Since the reference light changes across the spectrum, this method is known as the step-by-step heterochromatic brightness matching technique. Again, the wavelength associated with the minimum value needed to match the reference light(s) is defined as the unit value of the photopic function.

Several consistent experimental conditions were used in these early experiments. The test fields were small, usually less than 2° across; the luminance was fairly low due to light source limitations, and a natural pupil was used by the subjects during testing. Gibson and Tyndall¹¹ pieced together results from several experiments and recommended a particular spectral luminous efficiency function for the photopic

(cone) system, which was approved by a committee of the CIE in 1924.

Modification to the CIE 1924 curve followed, based on work by Judd in 1951. The 1924 curve was shown to be inadequate in describing visual sensitivity in the short-wavelength region of the visible spectrum. This modified curve was later published by the CIE.¹² Since not all test fields of interest to experimentalists were 2° or less, a standard function for a 10° field was devised in 1964, which shows a still greater sensitivity to short wavelengths on the photopic curve. This is likely due to the macula lutea screening pigment (see Chapter 3, Vision and Perception).

In 1951 the CIE also established a scotopic luminous efficiency function (Figure 1-7) based on the heterochromatic brightness matching technique (not step-by-step). Test wavelengths were compared with a large, approximately 20° , "white" test field with a luminance of approximately 0.00003 cd/m^2 . The field was viewed by subjects using natural pupils after an extended period in darkness (see also Figure 3-8).

It is important to point out that everyone in the previous studies was color normal. A small percentage of the population (approximately 8%, mostly males) do not have all three cone photopigments or do not have the same ones as color-normal people. The photopic luminous efficiency curves will be different for these people because the cone photopigments determine the shapes of these curves.

The photopic luminous efficiency function applies to visual stimuli to the fovea and at luminance levels higher than approximately 3 cd/m^2 . The scotopic luminous efficiency function applies to visual stimuli in regions outside the fovea and to luminances below approximately 0.001 cd/m^2 . A family of mesopic luminous efficiency functions is required for application to luminous stimuli between approximately 0.001 and 3 cd/m^2 . Research in this area is on-going.^{13,14} Presently, mesopic luminous efficiency functions remain to be defined officially.¹⁵ With the exception of special measurements for research purposes, almost all photometric quantities are measured photopically, even at luminances below 3 cd/m^2 and for peripheral vision. See Chapter 3, Vision and Perception, for additional discussion on photopic, scotopic, and mesopic vision.

Luminous Efficacy of Light Sources

The luminous efficacy of a light source is defined as the ratio of the total luminous flux (in lumens) to the total power input (in watts).

There are 683 lumens/watt at 555 nm. Since the scotopic luminous efficiency function peaks at a different wavelength (507 nm), it is necessary to establish different scaling factors for the photopic and for the scotopic luminous efficiency functions. Therefore, the photopic lumens, F , and the scotopic lumens, F' , must be determined from the spectral power distribution of the light source:

Figure 1-7. Photopic Luminous Efficiency, $V(\lambda)$, and Scotopic Luminous Efficiency, $V'(\lambda)$ Functions

Wavelength (nm)	$V(\lambda)$	$V'(\lambda)$	Wavelength (nm)	$V(\lambda)$	$V'(\lambda)$
360	3.917E-06		585	8.163E-01	8.990E-02
365	6.965E-06		590	7.570E-01	6.550E-02
370	1.239E-05		595	6.949E-01	4.690E-02
375	2.202E-05		600	6.310E-01	3.315E-02
380	3.900E-05	5.890E-04	605	5.668E-01	2.312E-02
385	6.400E-05	1.108E-03	610	5.030E-01	1.593E-02
390	1.200E-04	2.209E-03	615	4.412E-01	1.088E-02
395	2.170E-04	4.530E-03	620	3.810E-01	7.370E-03
400	3.960E-04	9.290E-03	625	3.210E-01	4.970E-03
405	6.400E-04	1.852E-03	630	2.650E-01	3.335E-03
410	1.210E-03	3.484E-02	635	2.170E-01	2.235E-03
415	2.180E-03	6.040E-02	640	1.750E-01	1.497E-03
420	4.000E-03	9.660E-02	645	1.382E-01	1.005E-03
425	7.300E-03	1.436E-01	650	1.070E-01	6.770E-04
430	1.160E-02	1.998E-01	655	8.160E-02	4.590E-04
435	1.684E-02	2.625E-01	660	6.100E-02	3.129E-04
440	2.300E-02	3.281E-01	665	4.458E-02	2.146E-04
445	2.980E-02	3.931E-01	670	3.200E-02	1.480E-04
450	3.800E-02	4.550E-01	675	2.320E-02	1.026E-04
455	4.800E-02	5.130E-01	680	1.700E-02	7.150E-05
460	6.000E-02	5.670E-01	685	1.192E-02	5.010E-05
465	7.390E-02	6.200E-01	690	8.210E-03	3.533E-05
470	9.098E-02	6.760E-01	695	5.723E-03	2.501E-05
475	1.126E-01	7.340E-01	700	4.102E-03	1.780E-05
480	1.390E-01	7.930E-01	705	2.929E-03	1.273E-05
485	1.693E-01	8.510E-01	710	2.091E-03	9.140E-06
490	2.080E-01	9.040E-01	715	1.484E-03	6.600E-06
495	2.586E-01	9.490E-01	720	1.047E-03	4.780E-06
500	3.230E-01	9.820E-01	725	7.400E-04	3.482E-06
505	4.073E-01	9.980E-01	730	5.200E-04	2.546E-06
510	5.030E-01	9.970E-01	735	3.611E-04	1.870E-06
515	6.082E-01	9.750E-01	740	2.492E-04	1.379E-06
520	7.100E-01	9.350E-01	745	1.719E-04	1.022E-06
525	7.932E-01	8.800E-01	750	1.200E-04	7.600E-07
530	8.620E-01	8.110E-01	755	8.480E-05	5.670E-07
535	9.149E-01	7.330E-01	760	6.000E-05	4.250E-07
540	9.540E-01	6.500E-01	765	4.240E-05	3.196E-07
545	9.803E-01	5.640E-01	770	3.000E-05	2.413E-07
550	9.950E-01	4.810E-01	775	2.120E-05	1.829E-07
555	1.000E+00	4.020E-01	780	1.499E-05	1.390E-07
560	9.950E-01	3.288E-01	785	1.060E-05	
565	9.786E-01	2.639E-01	790	7.466E-06	
570	9.520E-01	2.076E-01	795	5.258E-06	
575	9.154E-01	1.602E-01	800	3.703E-06	
580	8.700E-01	1.212E-01			

$$F = 683 \sum_{360}^{800} P_{\lambda} V_{\lambda} \Delta\lambda \quad (1-5)$$

and

$$F' = 1700 \sum_{380}^{780} P_{\lambda} V'_{\lambda} \Delta\lambda \quad (1-6)$$

where

P_{λ} = spectral power, in watts, of the source at the wavelength λ ,

V_{λ} = photopic luminous efficiency function value at λ ,

$\Delta\lambda$ = interval over which values of the spectral power were measured,

where

V'_{λ} = scotopic luminous efficiency function value at λ .

The maximum luminous efficacy of an ideal white source, defined as a radiator with constant output over the

visible part of the spectrum and no radiation in other parts, is approximately 220 lm/W.

LIGHT GENERATION

Natural Phenomena

Sunlight. Energy with a color temperature of approximately 6500 K is received from the sun just outside the earth's atmosphere at an average rate of about 1350 W/m². About 75% of this energy reaches the earth's surface at sea level (on the equator) on a clear day.

The average luminance of the sun is approximately 1600 Mcd/m² viewed from sea level. The illuminance on the earth's surface by the sun may exceed 100 klx (10,000 fc); on cloudy days the illuminance drops to less than 10 klx (1000 fc). Formulas to calculate these values are in Chapter 8, Daylighting.

Sky Light. A considerable amount of light is scattered by the earth's atmosphere. The investigations of Rayleigh first showed that this was a true scattering effect. On theoretical grounds the scattering should vary inversely as the fourth power of the wavelength when the size of the scattering particles is small compared to the wavelength of light, as in the case of the air molecules themselves. The blue color of a clear sky and the reddish appearance of the rising or setting sun are common examples of this scattering effect. If the scattering particles are relatively large (the water droplets in a cloud, for example), scattering is essentially the same for all wavelengths (clouds appear white). The scattered light from parts of the sky is partially polarized, up to 50%.

Moonlight. The moon shines solely by reflection of sunlight. Since the reflectance of its surface is rather low, its luminance is only on the order of 2500 cd/m². The correlated color temperature of moonlight is around 4100 K but will vary widely depending on material suspended in the atmosphere. Illumination of the earth's surface by the moon can be as high as 0.1 lx (0.01 fc).

Lightning. Lightning is a meteorological phenomenon arising from the accumulation, in the formation of clouds, of tremendous electrical charges, usually positive, which are suddenly released in a spark discharge. The lightning spectrum corresponds closely to that of an ordinary spark in air, consisting principally of nitrogen bands, although hydrogen lines sometimes appear owing to dissociation of water vapor.

Aurora Borealis (Northern Lights) and Aurora Australis (Southern Lights). These hazy patches or bands of greenish light, on which white, pink, or red streamers sometimes are superposed, appear 100 to 200 km (60 to 120 mi) above the earth. They are caused by electron streams spiraling into the atmosphere, primarily at polar latitudes. Some of the lines in their spectra have been identified with transitions of valence electrons from metastable states of oxygen and nitrogen atoms.

Bioluminescence. "Living light" is a form of chemiluminescence in which special compounds manufactured by plants and animals are oxidized, producing light. The light-producing compounds are not always required to be in a living organism. Many bioluminescent compounds can be dried and stored many years and then, in response to exposure to oxygen or some other catalyst, emit light.

Fabricated Sources

Historically, light sources have been divided into two types, incandescent and luminescent. Fundamentally, the cause of light emission is the same: electronic transitions from higher to lower energy states. The mode of electron excitation and the resultant spectral distribution of the radiation are different, however. Incandescent solid substances emit a continuous spectrum, while gaseous discharges radiate mainly in discrete spectral lines. There is some overlap, however. Incandescent rare-earth elements can emit discrete spectra, whereas high-pressure discharges produce a continuous spectrum.

The two classic types, with subdivisions showing associated devices or processes, are listed as follows (see also Chapter 6, Light Sources, for discussion on some of the following):

- I. Incandescence
 - A. Filament lamps
 - B. Pyroluminescence (flames)
 - C. Candoluminescence (gas mantle)
 - D. Carbon arc radiation
- II. Luminescence
 - A. Photoluminescence
 1. Gaseous discharges
 2. Fluorescence
 3. Phosphorescence
 4. Lasers
 - B. Electroluminescence
 1. Electroluminescent lamps (ac capacitive)
 2. Light-emitting diodes
 3. Cathodoluminescence (electron excitation)
 - C. Miscellaneous luminescence phenomena
 1. Galvanoluminescence (chemical)
 2. Crystalloluminescence (crystallization)
 3. Chemiluminescence (oxidation)
 4. Thermoluminescence (heat)
 5. Triboluminescence (friction or fracture)
 6. Sonoluminescence (ultrasonics)
 7. Radioluminescence (α , β , γ , and X rays)

INCANDESCENCE

Incandescent Filament Lamps

All familiar physical objects are combinations of chemically identifiable molecules, which in turn are made up of atoms.

In solid materials the molecules are packed together, and the substances hold their shape over a wide range of physical conditions. In contrast, the molecules of a gas are highly mobile and occupy only a small part of the space filled by the gas.

Molecules of both gases and solids are constantly in motion at temperatures above absolute zero (0 K or 273°C), and their movement is a function of temperature. If the solid or gas is hot, the molecules move rapidly; if it is cold, they move more slowly.

At temperatures below approximately 873 K (600°C), only IR energy (heat) is emitted by a body, for example, a coal stove or an electric iron. Electronic transitions in atoms and molecules at temperatures above approximately 600°C result in the release of visible radiation along with the heat.

The incandescence of a lamp filament is caused by the heating action of an electric current. This heating action raises the filament temperature substantially above 600°C, producing light.

Pyroluminescence (Flame Luminescence)

A flame is the most often noted visible evidence of combustion. Flame light may be due to recombination of ions to form molecules, reflection from solid particles in the flame, incandescence of carbon or other solid particles, or any combination of these.

The combustion process is a high-temperature energy exchange between highly excited molecules and atoms. The process releases and radiates energy, some of which is in that portion of the electromagnetic spectrum called light. The quality and the amount of light generated depend on the material undergoing combustion. For example, a flashbulb containing zirconium yields the equivalent of 56 lm/W, whereas an acetylene flame yields 0.2 lm/W.

Candoluminescence (Gas Mantle)

Incandescence is exhibited by heated bodies which give off shorter wavelength radiation than would be expected according to the radiation laws, because of fluorescence excited by incandescent radiation. Materials producing such emission include zinc oxide, as well as rare-earth elements (cerium, thorium) used in the Welsbach gas mantle.

Carbon Arc Radiation

A carbon arc source radiates because of incandescence of the electrodes and because of luminescence of vaporized electrode material and other constituents of the surrounding gaseous atmosphere. Considerable spread in the luminance, total radiation, and spectral power distribution may be achieved by varying the electrode materials.

LUMINESCENCE¹⁶⁻²⁰

Radiation from luminescent sources results from the excitation of single valence electrons of an atom, either in a gaseous state, where each atom is free from interference from its neighbors, or in a crystalline solid or organic molecule, where the action of its neighbors exerts a marked effect. In the first case, line spectra result, such as those of mercury or sodium arcs. In the second case, narrow emission bands result, which cover a portion of the spectrum (usually in the visible region). Both cases contrast with the radiation from incandescent sources, where the irregular excitation at high temperature of the free electrons of innumerable atoms gives rise to all wavelengths of radiation to form a continuous spectrum of radiation, as discussed in "Black-body Radiation" above.

Photoluminescence

Gaseous Discharge. Radiation, including light, can be produced by gaseous discharges as discussed previously under "Atomic Structure and Radiation." A typical mechanism for generating light (photons) from a gaseous discharge (such as in a fluorescent lamp) is described below (Figure 1-8).

1. A free electron emitted from the cathode collides with one of the two valence electrons of a mercury atom and excites it by imparting to it part of the ki-

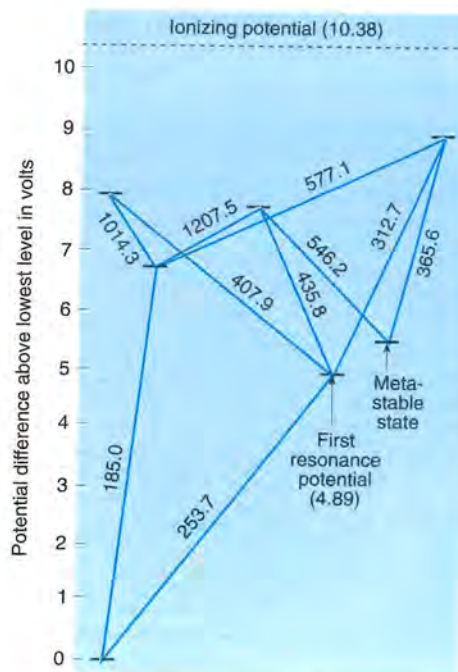


Figure 1-8. Simplified energy diagram for mercury, showing a few of the characteristic spectral lines.

netic energy of the moving electron, thus raising the valence electron from its normal energy level to a higher one.

2. The conduction electron loses speed in the impact and changes direction, but continues along the tube to excite or ionize one or more additional atoms before losing its energy stepwise and completing its path. It generally ends at the wall of the tube, where it recombines with an ionized atom. A part of the electron current is collected at the anode.
3. Conduction electrons, either from the cathode or formed by collision processes, gain energy from the electric field, thus maintaining the discharge along the length of the tube.
4. After a short delay the valence electron returns to its normal energy level, either in a single transition or by a series of steps from one excited level to a lower level. At each of these steps a photon (quantum of radiant energy) is emitted. If the electron returns to its normal energy level in a single transition, the emitted radiation is called resonance radiation (Figure 1-9).
5. In some cases (as in the high-pressure sodium lamp) a portion of the resonance radiation is self-absorbed by the gas of the discharge before it leaves the discharge envelope. The absorbed energy is then re-radiated as a continuum on either side of the resonant wavelength, leaving a depressed or dark region at that point in the spectrum.

Fluorescence. In the fluorescent lamp, UV radiation resulting from luminescence of the mercury vapor due to a gas

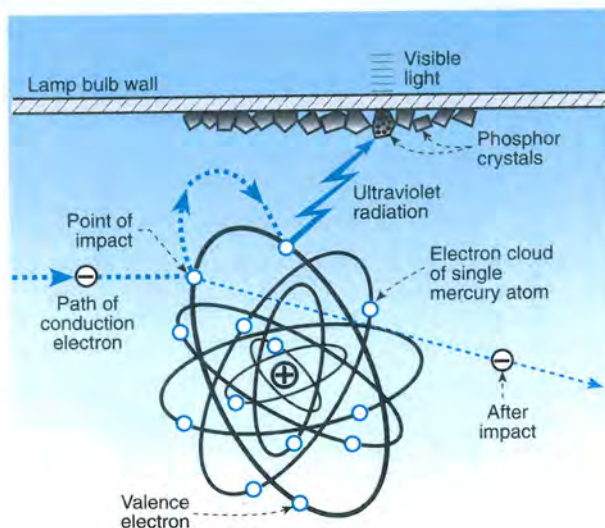


Figure 1-9. Magnified cross section of a fluorescent lamp, schematically showing progressive steps in the luminescent process, which finally result in the release of visible radiation.

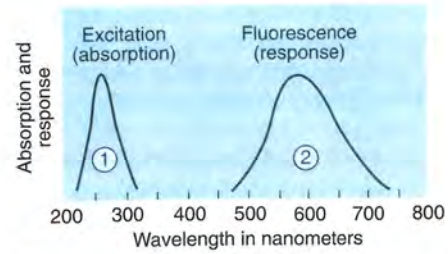


Figure 1-10. Fluorescence curve of a typical phosphor, showing initial excitation by ultraviolet rays and subsequent release of visible radiation.

discharge is converted into light by a phosphor coating on the inside of the tube or outer jacket. If this emission continues only during the excitation, it is called fluorescence. Figure 1-9 shows schematically a greatly magnified section of a part of a fluorescent lamp.

The phosphors used in fluorescent lamps are crystalline inorganic compounds of exceptionally high chemical purity and of controlled composition to which small quantities of other substances (the activators) have been added to convert them into efficient fluorescent materials. With the right combination of activators and inorganic compounds, the color of the emission can be controlled. A typical schematic model for a phosphor is given in Figure 1-10, and an energy diagram for a typical phosphor is shown in Figure 1-11. In the

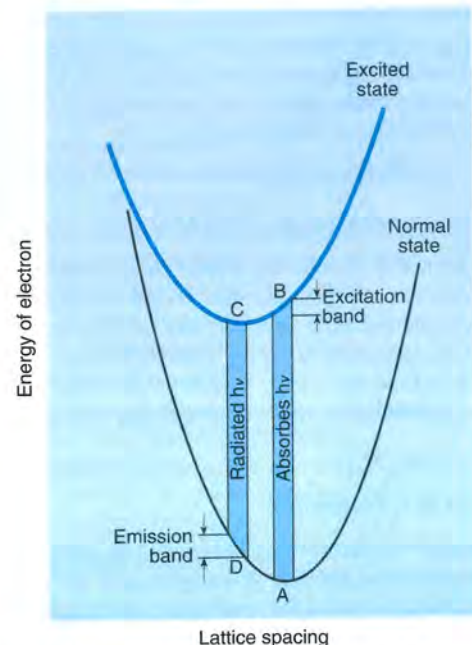


Figure 1-11. Simplified energy diagram for a typical phosphor.

Figure 1-12. Color Characteristics of Important Fluorescent Lamp Phosphors

Material	Activator	Peak of Fluorescent Band*	Color of Fluorescence
Calcium phosphate	Thallium	310	Ultraviolet
Barium disilicate	Lead	355	Pale blue
Barium strontium magnesium silicate	Lead	370	Pale blue
Calcium tungstate	Lead	440	Blue
Strontium chloroapatite	Europium	445	Blue
Barium magnesium aluminate	Europium	450	Blue
Strontium pyrophosphate	Tin	470	Blue
Magnesium tungstate	None	480	Blue white
Calcium halophosphate	Antimony	480	Blue white
Barium titanium phosphate	Titanium	490	Blue green
Zinc silicate	Manganese	520	Green
Cerium terbium magnesium aluminate	Terbium	545	Green
Calcium halophosphate	Antimony and manganese	590	White to yellow
Calcium silicate	Lead and manganese	610	Pink
Yttrium oxide	Europium	612	Orange red
Calcium borate	Manganese	615	Pink
Strontium magnesium phosphate	Tin	620	Pink
Calcium strontium phosphate	Tin	640	Pink
Magnesium fluorogermanate	Manganese	660	Red
Lithium pentaaluminate	Iron	743	Infrared

* Wavelength in nanometers

normal state the electron oscillates about position A on the energy curve in Figure 1-11, as the lattice expands and contracts due to thermal vibration. For the phosphor to emit light it must first absorb radiation. In the fluorescent lamp this is chiefly at 253.7 nm. The absorbed energy transfers the electron to an excited state at position B. After loss of excess energy to the lattice as vibrational energy (heat), the electron again oscillates around a stable position C for a very short time, after which it returns to position D on the normal energy curve, with simultaneous emission of a photon of radiation. Stokes' law, stating that the radiation emitted must be of longer wavelength than that absorbed, is readily explained by this model. It then returns to A with a further loss of energy as heat and is ready for another cycle of excitation and emission.

Because of the oscillation around both stable positions A and C, the excitation and emission processes cover ranges of wavelength, commonly referred to as bands.

In some phosphors two activators are present. One of these, the primary activator, determines the absorption characteristics and can be used alone, as it also gives emission. The other, the secondary activator, does not enter into the absorption mechanism but receives its energy by transfer within the crystal from a neighboring primary activator. The emitted light from the secondary activator is longer in wavelength than that from the primary activator. The relative amount of emission from the two activators is determined by the concentration of the secondary activator. The phosphors now used in most "white" fluorescent lamps are doubly activated calcium halophosphate phosphors in combination with rare-earth-activated phosphors.

Figure 1-12 shows the characteristic colors and uses of phosphors currently employed in the manufacture of fluorescent lamps. Figure 1-13 gives the characteristics of some phosphors useful with mercury and metal halide lamps. Impurities other than activators and excessive amounts of activators have a serious deleterious effect on the efficiency of a phosphor.²⁰

Phosphorescence. In some fluorescent materials, electrons can be trapped in metastable excited states for a time varying from milliseconds to days. After release from these states they emit light. This phenomenon is called phosphorescence. The metastable states lie slightly below the usual excited states responsible for fluorescence, and energy usually derived from heat is required to transfer the electron from the metastable state to the emitting state. Since the same emitting state is usually involved, the color of fluorescence and phosphorescence is generally the same for a given phosphor. In doubly activated phosphors the secondary activator phosphoresces longer than the primary activator, so the color changes with time. Short-duration phosphorescence is important in fluorescent lamps in reducing flicker in alternating current (ac) operation.

Phosphors activated by IR radiation have an unusual type of phosphorescence. After excitation they show phosphorescence, which becomes invisible in a few seconds. However, they retain a considerable amount of energy trapped in metastable states, which can be released as light by IR radiation of the proper wavelength.

Solid Laser.²¹⁻²³ Lasers (light amplification by stimulated emission of radiation) are of major interest to illuminating

Figure 1-13. Color Characteristics of Some Phosphors for Mercury and Metal Halide Lamps

Material	Activator	Peak of Fluorescent Band*	Color of Fluorescence
Strontium chlorapatite	Europium	445	Blue
Strontium-magnesium phosphate	Tin	610	Orange red
Strontium-zinc phosphate	Tin	610	Orange red
Yttrium-vanadate	Europium	612	Orange red
Yttrium-vanadate phosphate	Europium	612	Orange red
Magnesium fluorogermanate	Manganese	660	Deep red
Magnesium arsenate	Manganese	660	Deep red

* Wavelength in nanometers

engineers (see Chapter 6, Light Sources). In addition to amplifying light, lasers produce intense, highly monochromatic, well-collimated, coherent light.

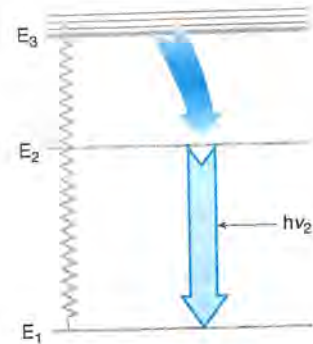
Coherent light consists of radiation whose waves are in phase with regard to time and space. Ordinary light, although it may contain a finite proportion of coherent light, is incoherent because the atomic processes that cause its emission occur in a random fashion. In a laser, however, electronic transitions are triggered (stimulated) by a wave of the same frequency as the emitted light. As a consequence, a beam of light is emitted, all of whose waves are in phase and of the same frequency.

A prerequisite to laser action is a pumping process whereby an upper and a lower electron level in the active material undergo a population inversion. The pumping source may be a light, as in a ruby laser, or electronic excitation, as in a gas laser.

The choice of laser materials is quite limited. First, it must be possible to highly populate an upper electronic level; second, there must be a light-emitting transition from this upper level with a long lifetime; third, a lower level must exist that can be depopulated either spontaneously or through pumping.

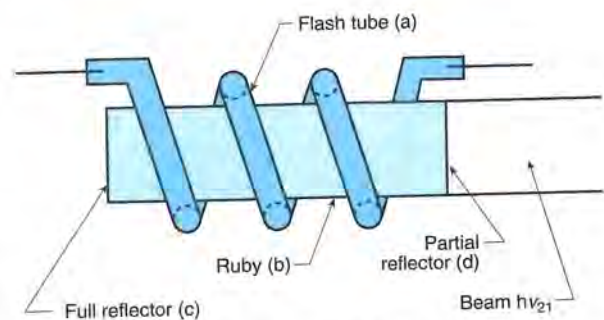
Laser construction is as important to laser action, as is the source material. Since light wavelengths are too short to allow building a resonant cavity, long multi-nodal chambers are made with parallel reflectors at each end to feed back radiation until lasing takes place. The effect is to produce well-collimated light that is highly directional.

Consider as an example the pink ruby laser, whose electronic transitions are shown in Figure 1-14, and whose mechanical construction is indicated in Figure 1-15. This laser is pumped by a flash tube (a), and electrons in the ruby (b) are raised from level E_1 to E_3 . The electrons decay rapidly and spontaneously from E_3 to E_2 . They can then spontaneously move from E_2 to E_1 and slowly emit fluorescent light, $h\nu_{21}$ (see Equation 1-3), or they can be stimulated to emit coherent light, $h\nu_{21}$. The full reflector (c) and the partial reflector (d) channel the coherent radiation, $h\nu_{21}$, until it has built up enough to emit coherent light $h\nu_{21}$ through (d). The fact that this light has been reflected many times by par-

**Figure 1-14.** Simplified diagrammatic representation of electronic transitions in a ruby laser.

allel mirrors ensures that it is well collimated. The electrons are then available for further pumping (Figure 1-16).

Gas Laser. In a solid laser there are three requirements: a material that reacts energetically to light, a population inversion generated by pumping in energy at the correct level and a growth of the internal energy caused by the reflection of photons within the solid. While the same requirements are met in a gas laser, two other characteristics are available, namely strong, narrow spectral lines and unequal emission at different energy levels. An example of such a gas laser is

**Figure 1-15.** Simplified diagram of a ruby laser.

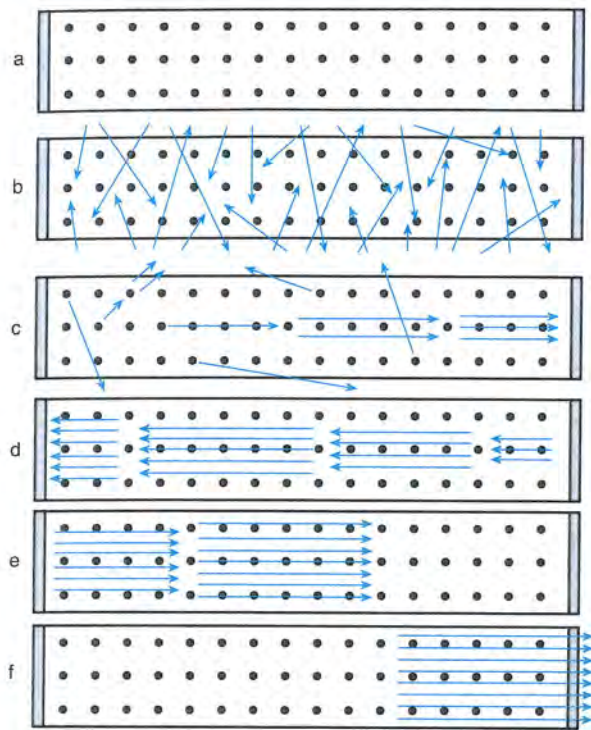


Figure 1-16. Photon cascade in a solid laser. Before the buildup begins, atoms in the laser crystal are in the ground state (a). Pumping light [arrows in (b)] raises most of the atoms to the excited state. The cascade (c) begins when an excited atom spontaneously emits a photon parallel to the axis of the crystal (photons emitted in other directions pass out of the crystal). The buildup continues in (d) and (e) through thousands of reflections back and forth from the silvered surfaces at the ends of the crystal). When amplification is great enough, light passes out at (f).

that containing a mixture of helium and neon (Figure 1-17). Helium is used as the energizing gas because it has a level from which it can lose energy only by collision. This level corresponds to the one at which neon radiates energy in the form of red light. On energizing helium in a gas discharge inside a cavity whose ends are reflecting and that contains both helium and neon, the helium transfers energy by collision with neon. The excited neon emits photons, which begin to amplify by cascading between the two reflecting surfaces until the internal energy is so large that the losses through the partially transmitting mirror become equal to the internal gains and the laser becomes saturated.

Semiconductor Laser. A third type of laser uses a semiconducting solid material where the electron current flowing across a junction between p-type (electron-deficient) and n-type (electron-rich) material produces extra electrons in the conduction band (Figure 1-18). These radiate upon their transition back to the valence band or lower-energy states. If the junction current is large enough, there will be more elec-

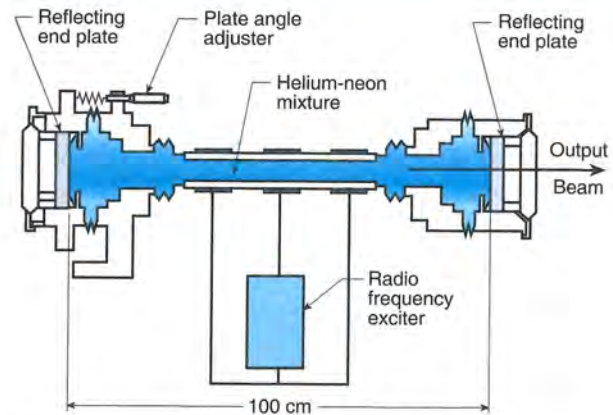


Figure 1-17. Structure of helium-neon gas laser, showing essential parts. Operation of the laser depends on the right mixture of helium and neon to provide an active medium. A radio-frequency exciter puts energy into the medium. The output beam is built up by repeated passes back and forth between reflecting end plates.

trons near the edge of the conduction band than there are at the edge of the valence band, and a population inversion may occur. To use this effect, the semiconductor crystal is polished with two parallel faces perpendicular to the junction plane. The amplified waves can then propagate along the plane of the junction and are reflected back and forth at the surfaces.

Electroluminescence²⁴

Certain phosphors convert ac energy directly into light, without using an intermediate step as in a gas discharge, by utilizing the phenomenon of electroluminescence.

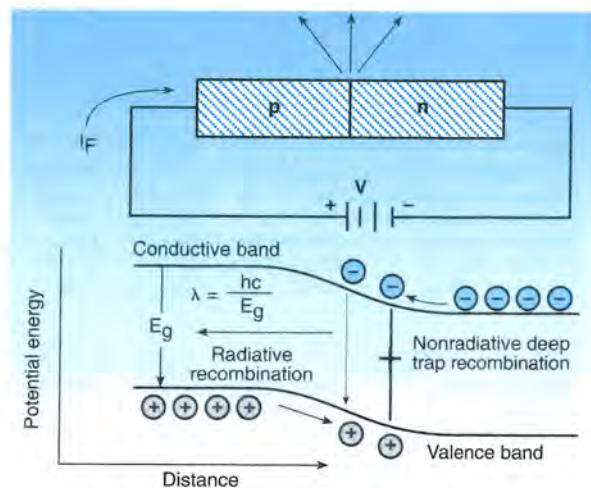


Figure 1-18. Diagram of an LED p-n junction.



Figure 1-19. Diagrammatic cross section of an electroluminescent lamp.

Electroluminescent Lamps (ac capacitive). An electroluminescent lamp is composed of a two-dimensional area conductor (transparent or opaque) on which a dielectric-phosphor layer is deposited. A second two-dimensional area conductor of transparent material is deposited over the dielectric-phosphor mixture.

An alternating electric field is established between the two conductors with the application of a voltage across the two-dimensional (area) conductors. Under the influence of this field, some electrons in the electroluminescent phosphor are excited. During the return of these electrons to their ground or normal state the excess energy is radiated as light.

Figure 1-19 shows a cross-sectional view of an electroluminescent lamp. Figure 1-20 gives the properties of some electroluminescent phosphors.

The color of the light emitted by an electroluminescent lamp is dependent on frequency, while the luminance is dependent on frequency and voltage. These effects vary from phosphor to phosphor.

The efficacy of electroluminescent devices is low compared to incandescent lamps. It is of the order of a few lumens per watt.

Light-Emitting Diodes. Light-emitting diodes (LEDs) produce light by electroluminescence when low-voltage direct current is applied to a suitably doped crystal containing a p-n junction (Figure 1-18). The doping is typically carried out with elements from column III and V of the periodic table of elements. When activated by a forward biased cur-

rent, I_f , the p-n junction emits light at a wavelength defined by the active region energy gap, E_g .

The phenomenon was observed as early as 1923 in naturally occurring junctions, but was not considered practical due to its low luminous efficacy in converting electric energy to light. Efficacy has increased considerably since then such that LEDs are used for signals, indicators, signs, and displays.

When the forward biased current I_f is applied, minority carrier electrons are injected into the p-region and corresponding minority carrier electrons are injected into the n-region. Photon emission occurs as a result of electron-hole recombination in the p-region. Electron energy transitions across the energy gap, called radiative recombinations, produce photons (i.e., light), while shunt energy transitions, called nonradiative recombinations, produce phonons (i.e., heat).

The energy band gap E_g , shown in Figure 1-18, is the separation between the conduction energy band and the valence energy band in the semiconductor crystal. The characteristics of the energy band gap determine the quantum efficiency and the radiative wavelengths of the LED device. For example, the radiative energy wavelength, λ , is given by

$$\lambda = \frac{hc}{E_g}$$

where h is Planck's constant and c is the speed of light.

The luminous efficacies of typical AlInGaP LEDs and InGaP LEDs for different peak wavelengths are shown in Figure 1-21.

The efficacy is dependent on the visible energy generated at the junction and losses due to reabsorption when light tries to escape through the crystal. Due to the high index of refraction of most semiconductors, light is reflected back from the surface into the crystal and highly attenuated before finally exiting. The efficacy expressed in terms of this ultimate measurable visible energy is called the external efficacy. The external efficacies are moderate, though the internal efficacies are calculated to be very high. For more information see Chapter 6, Light Sources.

Cathodoluminescence. Cathodoluminescence is light emitted when a substance is bombarded by an electron beam from a cathode, as in cathode-ray and television picture tubes.

Figure 1-20. Properties of Some Electroluminescent Phosphors

Material	Activators	Color of Light
Cubic zinc sulfide	Copper (low), lead	Blue
Cubic zinc sulfide	Copper (high), lead	Green
Cubic zinc sulfide	Copper (high), lead, manganese	Yellow
Hexagonal zinc sulfide	Copper (very high)	Green
Hexagonal zinc sulfide	Copper (very high), manganese	Yellow
Zinc sulfo selenide	Copper	Green to yellow
Zinc cadmium sulfo selenide	Copper	Yellow to pink

Figure 1-21. Properties of AlInGaP and InGaP LEDs

	AlInGaP	InGaP
Energy gap (E_g)	1.8–2.31 eV	3.4 eV (blue)
Peak wavelength (λ)	585 nm (amber)	460 nm (blue) 520 nm (green)
Luminous efficacy (external)	20–25 lm/W (amber)	6 lm/W (blue) 30 lm/W (green)

Miscellaneous Luminescence Phenomena

Galvanoluminescence. Galvanoluminescence is light that appears at either the anode or the cathode when solutions are electrolyzed.

Crystalloluminescence. Crystalloluminescence (lyoluminescence) is observed when solutions crystallize; it is believed to be due to rapid reformation of molecules from ions. The intensity increases upon stirring, perhaps on account of triboluminescence (see below).

Chemiluminescence. Chemiluminescence (oxyluminescence) is the production of light during a chemical reaction at room temperatures. True chemiluminescences are oxidation reactions involving valence changes.

Thermoluminescence. Thermoluminescence is luminescence exhibited by some materials when slightly heated. In all cases of thermoluminescence, the effect is dependent on some previous illumination or radiation of the crystal. Diamonds, marble apatite, quartz, and fluor spar are thermoluminescent.

Triboluminescence. Triboluminescence (piezoluminescence) is light produced by shaking, rubbing, or crushing crystals. Triboluminescent light may result from unstable light centers previously exposed to some source or radiation, such as light, X rays, radium emissions, and cathode rays; centers not exposed to previous radiation but characteristic of the crystal itself; or electrical discharges from fracturing crystals.

Sonoluminescence. Sonoluminescence is light that is observed when sound waves are passed through fluids. It occurs when the fluids are completely shielded from an electrical field and is always connected with cavitation (the formation of gas or vapor cavities in a liquid). It is believed the minute gas bubbles of cavitated gas develop a considerable charge as their surface increases. When they collapse, their capacitance decreases and their voltage rises until a discharge takes place in the gas, causing a faint luminescence.

Radioluminescence. Radioluminescence is light emitted from a material under bombardment from α rays, β rays, δ rays, or X rays.

LIGHT DETECTION

Historically, the eye was used for most photometric assessments. Today, physical detectors have all but eliminated visual assessment for photometric purposes. Two common physical detector types in use today are photodiodes and photomultiplier tubes. Thermal detectors and photoconductive detectors are used for IR measurements.

Photodiodes

Photodiodes are the most commonly used photodetectors for photometry and radiometry. Because of their excellent linearity and stability (freedom from fatigue), they replaced sele-

mium cells, which had been widely used. Photodiodes are based on solid-state p-n junctions that react to external stimuli such as light. Rather than emitting light for the LED p-n junction, photons are absorbed in the p-n junction (Figure 1-18). Detectors are made of specific solid-state materials such as silicon, germanium, and indium-gallium-arsenide (InGaAs). Silicon photodiodes have sensitivity from the UV to near-IR region of the spectrum, and their spectral responsivity generally increases approximately linearly with wavelength throughout the visible region of the spectrum. Combined with a filter for photopic spectral response, silicon photodiodes are commonly employed in photometers. Recent high-quality silicon photodiodes have a dynamic range of eight orders of magnitude or larger and can also be used with special electronics for very low levels where photomultipliers had been required.

Based on the quantum physics of photodiodes, some types of high-quality silicon photodiodes can be used as high-accuracy radiometric standards. This method, called the silicon photodiode self-calibration technique, was introduced during the late 1970s.^{25,26} Today, the highest-accuracy radiometric standards employ cryogenic radiometers, but silicon photodiodes are widely used as the most stable transfer standards in radiometry in the visible and near-IR region of the electromagnetic spectrum.

Photomultiplier Tubes

Photomultiplier tubes (PMTs) are widely used as detectors for photometric and radiometric applications requiring high sensitivity (Figure 1-22). A PMT is a vacuum tube with a photocathode, a number of dynodes (i.e., a series of electrodes), and an anode. High voltages are applied between

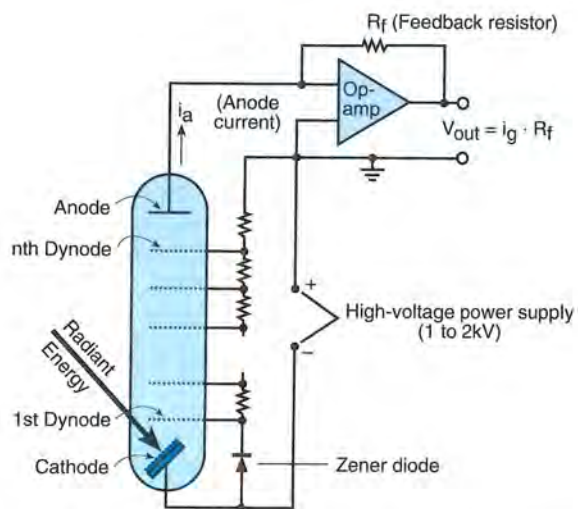


Figure 1-22. Schematic diagram of a photomultiplier and its electric circuit. From: G. Wyszecki, and W. Stiles, *Color science*. Copyright © 1982. Reprinted with permission of John Wiley & Sons, Inc.

photocathode and dynodes and anode. The first element, the photocathode, is negatively biased and will eject photons (called photoelectrons) in response to radiant energy, due to the photoelectric effect. The photoelectrons hit the next dynodes with higher energy, creating more electrons (secondary electrons), which flow to the next dynode where even more electrons are emitted, eventually causing a cascade effect that multiplies the original number of photoelectrons by several orders of magnitude. Thus, photomultipliers have very high sensitivity. Spectral response ranges depend on the photocathode and the type of glass in the outer envelope, but they generally cover the visible region. Some others extend to the UV and near-IR regions of the spectrum. The stability of the voltage supply to PMT is especially critical to accurate measurements. Silicon photodiodes generally are more stable than PMTs. Photometers employing a PMT generally require an internal calibration source.

Thermal Detectors

Thermopiles and bolometers are known as thermal detectors. Thermal detectors have a light-receiving surface coated with black material such as carbon black and gold black. When light is incident on the black surface, it causes the surface temperature to rise due to absorbed radiation. The increase in temperature is proportional to the power of the absorbed radiation. Thermopiles employ a series of thermocouples to measure temperature. Bolometers employ metal or semiconductor materials having temperature-dependent resistance.

Thermal detectors are seldom used in photometry due to their low sensitivity (several orders of magnitude lower than silicon photodiodes) and slow response time. An advantage of thermal detectors, however, is that they have generally nonselective spectral response, and are consequently well suited for radiant power measurements. Thermal detectors are often used in the IR region of the spectrum where other quantum detectors are not available.

Photoconductive Detectors

Photoconductive detectors are semiconductors whose resistance changes directly as a result of photon absorption. These detectors use materials such as lead sulfide (PbS), lead selenide (PbSe), mercury cadmium telluride (HgCdTe), cadmium sulfide (CdS), and cadmium selenide (CdSe). Photoconductive detectors are widely used for IR measurements.

OPTICAL CONTROL²⁷⁻²⁹

Optical control may be provided in a number of ways. All are applications of one or more of the following phenomena: reflection, refraction, polarization, interference, diffraction, diffusion, and absorption.

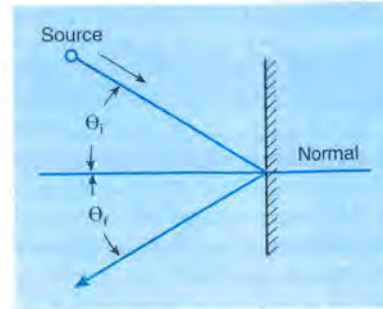


Figure 1-23. The law of reflection states that the angle of incidence, θ_i , equals the angle of reflection, θ_r .

Reflection and Reflectors

Reflection is the process by which a part of the light falling on a medium leaves that medium from the incident side. Reflection may be specular, spread, diffuse or compound, and selective or nonselective. Reflection from the front of a transparent plate is called first-surface reflection, and that from the back is called second-surface reflection. Refraction and absorption by supporting media are avoided in first-surface reflection.

Specular Reflection. If a surface is polished, it reflects specularly; that is, the angle between the reflected ray and the normal to the surface will equal the angle between the incident ray and the normal, as shown in Figure 1-23. If two or more rays are reflected, they may produce a virtual, erect, or inverted image of the source.

Specular Reflectors. Examples of specular reflectors are:

1. Smooth polished metal and aluminized or silvered smooth glass or plastic surfaces. Reflector lamps use first-surface reflection when the bulb interior is coated with a thin metal reflecting mirror surface, as shown in Figure 1-24b. Light reflected from the upper surface of a transparent medium, such as glass plate, as in Figure 1-24a and c, also is an example of first-surface reflection. As shown in Figure 1-25, less than 5% of the incident light is reflected at the first surface unless it strikes the surface at wide angles from the normal. The sheen of silk and the shine from smooth or coated paper are images of light sources reflected in the first surface.
2. Rear-surface mirrors. Some light, the quantity depending on the incident angle, is reflected by the first surface. The rest goes through the transparent medium to a rear-surface mirror coating, where it is reflected as shown in Figure 1-24c.

Reflection from Curved Surfaces. Figure 1-26 shows the reflection of a beam of light by a concave surface and by a convex surface. A ray of light striking the surface at point T

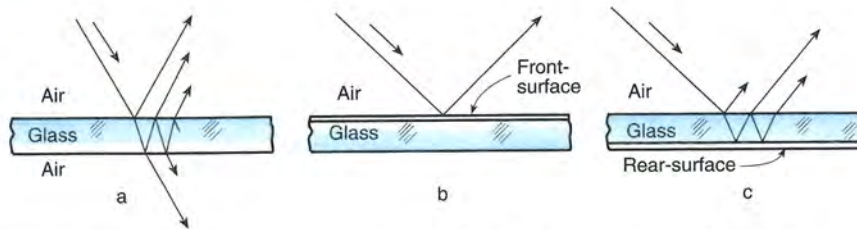


Figure 1-24. Reflections from (a) a transparent medium, such as clear plate glass, and from (b) front-surface and (c) rear-surface mirrors.

obeys the law of reflection (Figure 1-25), and by taking each ray separately, the paths of various reflected rays may be constructed.

In the case of parallel rays reflected from a concave surface, all the rays can be directed through a common point F by properly designing the curvature of the surface. This is called the focal point. The focal length FA is denoted by f .

Spread Reflection. If a reflecting surface is not smooth (that is, corrugated, etched, or hammered), it spreads parallel rays into a cone of reflected rays, as shown in Figure 1-27b.

Spread Reflectors. Slightly textured or hammered surfaces reflect individual rays at slightly different angles, but

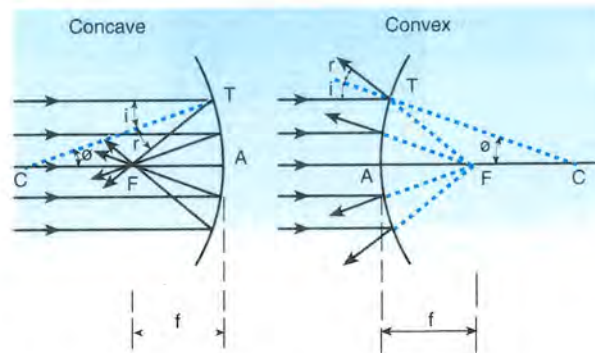


Figure 1-26. Focal point and focal length of curved surfaces.

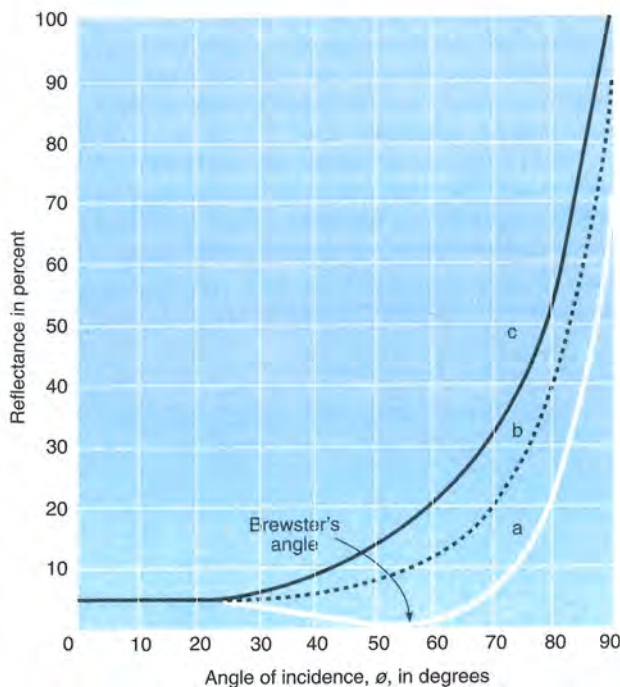


Figure 1-25. Effect of angle of incidence and state of polarization on the percentage of light reflected at an air-glass surface: (a) Light that is polarized in the plane of incidence; (b) unpolarized light; (c) light that is polarized in a plane perpendicular to the plane of incidence.

all in the same general direction. These are used to smooth beam irregularities and where moderate control or minimum beam spread is desired.

Corrugated, brushed, dimpled, etched, or pebbled surfaces consist of small specular surfaces in irregular planes. Brushing the surface spreads the image at right angles to the brushing. Pebbled, peened, or etched surfaces produce a random patch of highlights. These are used where wide beams free from striations and filament images are required.

The angle through which reflections are spread can be controlled by proper peening, for which equations describing peen radius and depth are available. Shot- or sandblasting and etching may cause serious losses in efficiency as a result of multiple reflections in random directions.

Diffuse Reflection. If a material has a rough surface or is composed of minute crystals or pigment particles, the reflection is diffuse. Each ray falling on an infinitesimal particle obeys the law of reflection, but as the surfaces of the particle are in different planes, they reflect the light at many angles, as shown in Figure 1-27c.

Diffuse Reflectors. Flat paints and other matte finishes and materials reflect at all angles and exhibit little directional control. These are used where wide distribution of light is desired.

Compound Reflection. Most common materials are compound reflectors and exhibit all three reflection components

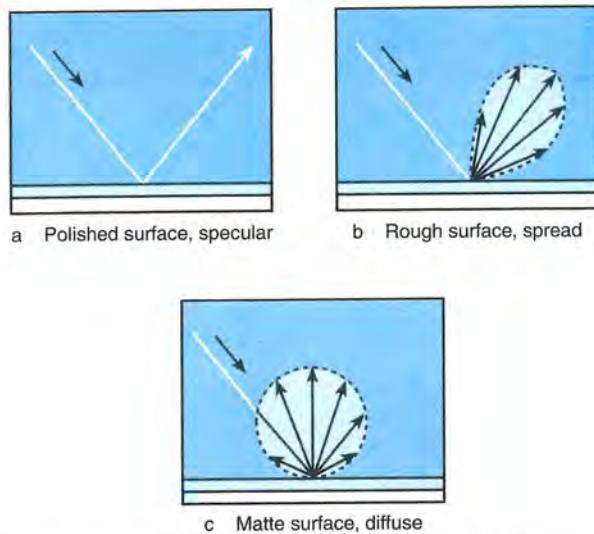


Figure 1-27. The type of reflection depends on the surface: (a) polished surface (specular); (b) rough surface (spread); (c) matte surface (diffuse).

(specular, spread, and diffuse) to varying degrees. In some, one or two components predominate, as shown in Figure 1-28. Specular and narrowly spread reflections (usually surface reflections) cause the sheen on etched aluminum and semigloss paint.

Diffuse-Specular Reflectors. Porcelain enamel, glossy synthetic finishes, and other surfaces with a shiny transparent finish over a matte base exhibit no directional control except for a specularly reflected ray as shown in Figure 1-28a, with an intensity of approximately 5 to 15% of the incident light.

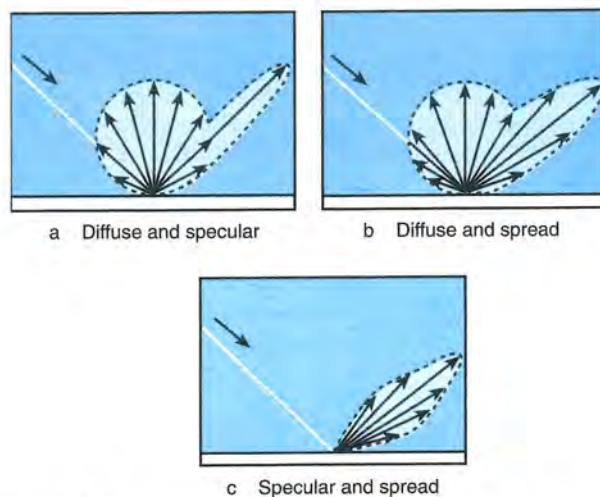


Figure 1-28. Examples of compound reflection: (a) diffuse and specular; (b) diffuse and spread; (c) specular and spread.

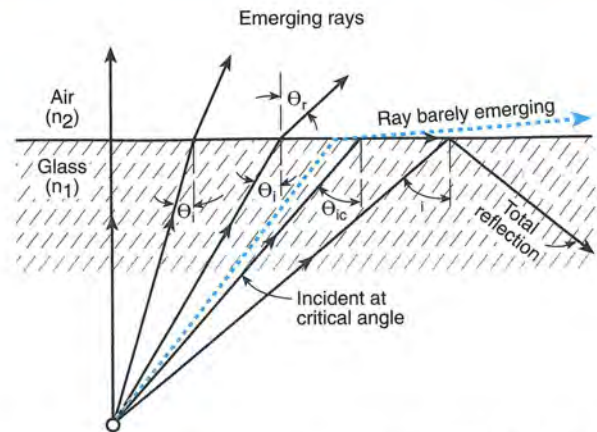


Figure 1-29. Total reflection occurs when $\sin r = 1$. The critical angle i_c varies with the medium.

Total Reflection. Total reflection of a light ray at a surface of a transmitting medium (Figure 1-29) occurs when the angle of incidence (θ_i) exceeds a certain value whose sine equals n_2/n_1 , the ratio of indices of refraction. If the index of refraction of the first medium (n_1) is greater than that of the second medium (n_2), $\sin \theta_i$ will become unity when $\sin \theta_i$ is equal to n_2/n_1 . At angles of incidence greater than this critical angle, the incident rays are reflected totally (Figure 1-30). In most glass total reflection occurs whenever $\sin \theta_i$ is greater than 0.66, that is, for all angles of incidence greater than 41.8° (glass to air). Light piping by edge lighting and light transmission through rods and tubes are examples of total (internal) reflection.

When light, passing through air, strikes a piece of ordinary glass ($n_2/n_1 \approx 1.5$) normal to its surface, approximately 4% is reflected from the upper surface and 4% from the lower surface. Approximately 92% of the light is transmitted. The proportion of reflected light increases as the angle of incidence is increased (Figure 1-25).

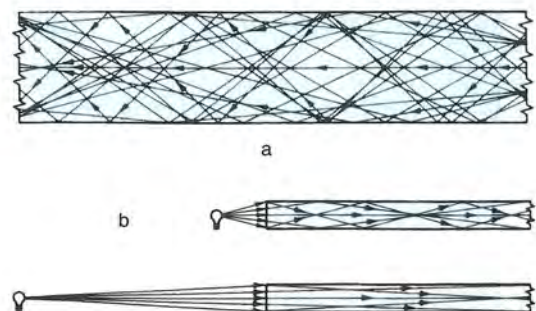


Figure 1-30. Representation of light transmission through a single fiber of a fiber-optics system, showing (a) internal reflections and (b) the effect of light source location on collimation of light.

Fiber Optics. Fiber optics is the branch of optical science concerned with thin, cylindrical glass or plastic fibers of optical quality. Light entering one end of the fiber is transmitted to the other end through the process of total internal reflection (Figure 1-30). In order to prevent light leaking from a fiber, it is coated with a lower-refractive-index material. Large numbers of fibers (from 100 to 1,000,000) can be clustered together to form a bundle. Fiber bundles are of two major types: coherent and noncoherent. The first are used for transmitting images, and each individual fiber is carefully oriented with respect to its neighbors in the entire bundle. Noncoherent bundles have random fiber locations in the bundle, but are suitable for transmitting light between points.

Refraction and Refractors

A change in the velocity of light (speed of propagation, not frequency) occurs when a ray leaves one material and enters another of greater or lower optical density. The speed will be reduced if the medium entered is denser, and increased if it is less dense.

Except when light enters at an angle normal to the surface of the new medium, the change in speed always is accompanied by a bending of the light from its original path at the point of entrance, as shown in Figure 1-31. This is known as refraction. The degree of bending depends on the relative densities of the two substances, on the wavelength of the light, and on the angle of incidence, being greater for large differences in density than for small. The light is bent toward the normal to the surface when it enters a denser medium, and away from the normal when it enters a less dense material.

When light is transmitted from one medium to another, each ray follows the law of refraction. When rays strike or enter a new medium, they may also be scattered in many di-

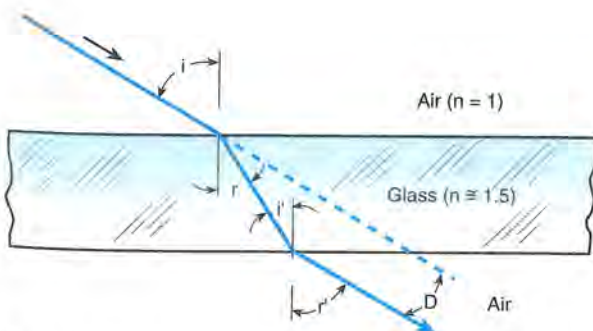


Figure 1-31. Refraction of light rays at a plane surface causes bending of the incident rays and displacement of the emergent rays. A ray passing from a rare to a denser medium is bent toward the normal to the interface, while a ray passing from a dense to a rarer medium is bent away from the normal.

rections because of irregularities of the surface, such as fine cracks, mold marks, scratches or changes in contour, or because of foreign deposits of dirt, grease, or moisture.

Snell's Law. The law of refraction (Snell's law) is expressed as follows:

$$n_1 \sin \theta_i = n_2 \sin \theta_r \quad (1-7)$$

where

- n_1 = index of refraction of the first medium,
- θ_i = angle the incident light ray forms with the normal to the surface,
- n_2 = index of refraction of the second medium,
- θ_r = angle the refracted light ray forms with the normal to the surface.

When the first medium is air, of which the index of refraction usually is taken as 1 (the vacuum value; this approximation is correct to three decimal places), the formula becomes

$$\sin \theta_i = n_2 \sin \theta_r \quad (1-8)$$

The two interfaces of the glass plate shown in Figure 1-31 are parallel, and therefore the entering and emerging rays also are parallel. The rays are displaced from each other (a distance D) because of refraction.

Examples of Refraction. A common example of refraction is the apparent bending of a straw at the point where it enters the water in a drinking glass. Although the straw is straight, light rays coming from that part of the straw under water are refracted when they pass from the water into the air and appear to come from higher points.

Prismatic light directors, such as shown in Figure 1-32a and b, may be designed to provide a variety of light distributions using the principles of refraction. Lens systems controlling light by refraction are used in automobile headlights and in beacon, floodlight, and spotlight Fresnel lenses.

Prisms. Consider Snell's law:

$$n_2 = \frac{\sin \theta_i}{\sin \theta_r} = \frac{\text{velocity of light in air}}{\text{velocity of light in a prism}} \quad (1-9)$$

This equation suggests, since the velocity of light is a function of the indices of refraction of the media involved and also of wavelength, that the exit path from a prism will be different for each wavelength of incident light and for each angle of incidence (Figure 1-33). This orderly separation of incident light into its spectrum of component wavelengths is called dispersion.

Refracting Prisms. The degree of bending of light at each prism surface is a function of the refractive indices of the media and the prism angle (A in Figure 1-33). Light can be directed accurately within certain angles by having the proper angle between the prism faces.

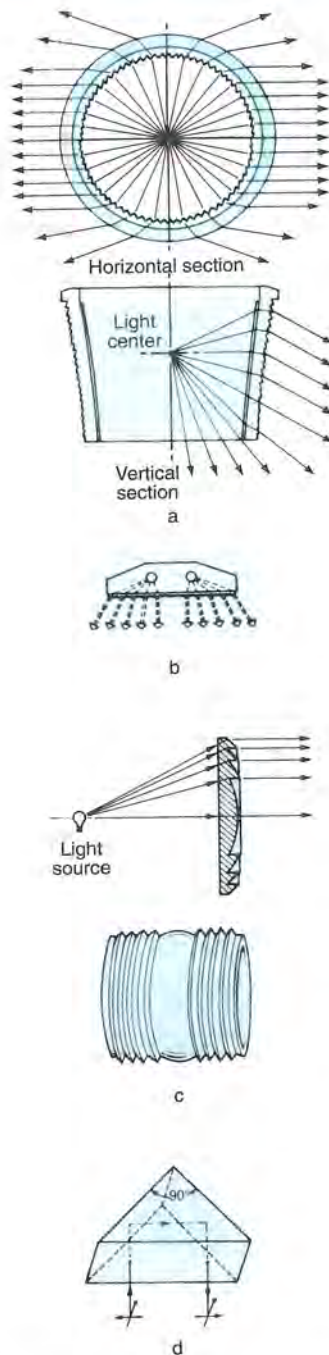


Figure 1-32. Optical systems utilizing the refractive properties of prisms and lenses: (a) Street lighting unit in which the outer piece controls the light in vertical directions (concentrating the rays into a narrow beam at about 75° from the vertical) and the inner piece redirects the light in the horizontal plane. The result is a “two-way” type of intensity distribution. (b) Prismatic lens for a fluorescent lamp luminaire intercepts as much light as possible, redirecting part from the glare zone to more useful directions (c) Cylindrical and flat Fresnel lenses. (d) Reflecting prism.

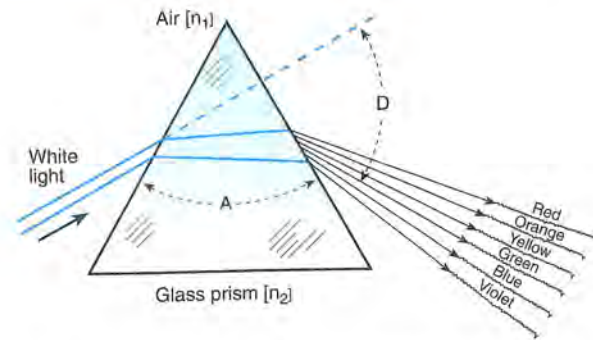


Figure 1-33. White light is dispersed into its component colors by refraction when passed through a prism. The angle of deviation D (illustrated for green light) varies with wavelength.

Refracting prisms are used in such devices as headlight lenses and refracting luminaires. In the design of refracting equipment, the same general considerations of proper flux distribution hold true as for the design of reflectors. Following Snell's law of refraction, the prism angles can be computed to provide the proper deviation of the light rays from the source. For most commercially available transparent materials like glasses and plastics, the index of refraction lies between 1.4 and 1.6.

Often, by proper placement of the prisms, it is possible to limit the prismatic structure to one surface of the refractor, leaving the other surfaces smooth for easy maintenance. The number and the sizes of prisms used are governed by several considerations. Among them are ease of manufacture and convenient maintenance of lighting equipment in service. Use of a large number of small prisms may magnify the effect of rounding of prisms that occurs in manufacture; on the other hand, small prisms produce greater accuracy of light control.

Ribbed and Prisms Surfaces. These can be designed to spread rays in one plane or scatter them in all directions. Such surfaces are used in lenses, luminous elements, glass blocks, windows, and skylights.

Reflecting Prisms. These reflect light internally, as shown in Figure 1-32d, and are used in luminaires and retro-directive markers. Their performance quality depends on the flatness of reflecting surfaces, accuracy of prism angles, elimination of dirt in optical contact with the surface, and elimination (in manufacturing) of prismatic error.

Lenses. Positive lenses form convergent beams and real inverted images as in Figure 1-34a. Negative lenses form divergent beams and virtual, inverted images as in Figure 1-34b.

Stepped and Fresnel Lenses. The weight and cost of glass in large lenses used in illumination equipment can be reduced by making cylindrical steps in the flat surface. The hollow, stepped back surface reduces the total quantity of glass used in the lens. In a method developed by Fresnel, as

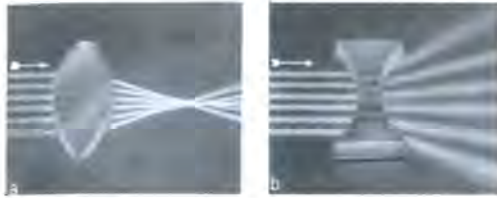


Figure 1-34. Ray path races through lenses: (a) positive; (b) negative.

shown in Figure 1-33c, the curved face of the stepped lens becomes curved rings and the back is flat. Both the stepped and Fresnel lenses reduce the lens thickness, and the optical action is approximately the same. Although outside prisms are slightly more efficient, they are likely to collect more dust. Therefore, prismatic faces are often formed on the inside.

Lens Aberrations. There are, in all, seven principal lens aberrations: spherical aberration, coma, axial and lateral chromatism, astigmatism, curvature, and distortion (Figure 1-35). Usually they are of little importance in lenses used in common types of lighting equipment. The simpler the lens system, the more difficult it is to correct the aberrations.

Transmission and Transmitting Materials

Transmission is a characteristic of many materials: glass, plastics, textiles, crystals, and so forth. The luminous transmittance τ of a material is the ratio of the total emitted light to the total incident light; it is affected by reflections at each surface of the material, as explained in Figure 1-24, and by absorption within the material. Figure 1-36 lists characteristics of several materials.

Bouguer's or Lambert's Law. Absorption in a clear transmitting medium is an exponential function of the thickness of the medium traversed:

$$I = I_0 e^{-\alpha d} \quad (1-10a)$$

$$I = I_0 \tau^d \quad (1-10b)$$

where

- I = intensity of transmitted light,
- I_0 = intensity of light entering the medium after surface reflection,
- α = absorption coefficient that characterizes the absorbing properties of a unit thickness of the medium,
- τ = transmittance of a unit thickness,
- d = thickness of the medium traversed. The optical density D is the common logarithm of the reciprocal of the transmittance:

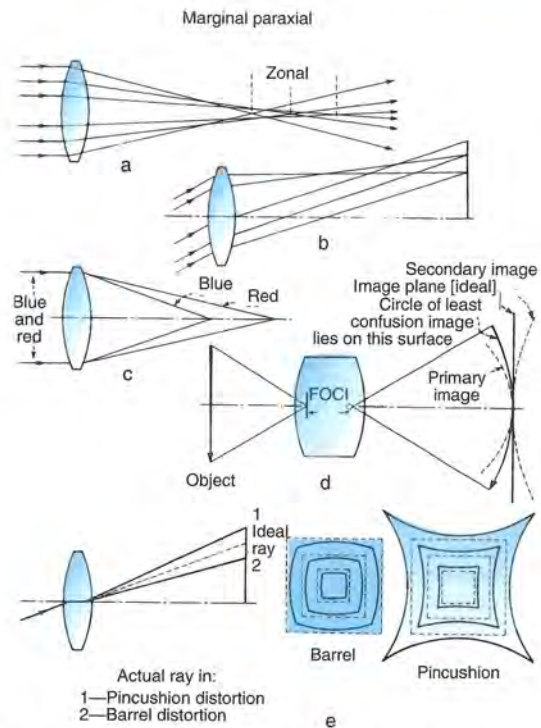


Figure 1-35. Lens aberrations. (a) Spherical aberration: convergence of parallel rays at different focal points at different distances from the axis of a lens. (b) Coma: difference in the lateral magnification of rays passing through different zones of a lens. (c) Chromatism: a difference in focal length for rays of different wavelengths. (d) Astigmatism and curvature: existence in two parallel planes of two mutually perpendicular line foci and a curved image plane. (e) Distortion: a difference in the magnification of rays passing through a lens at different angles.

$$D = \log_{10}(1/\tau) \quad (1-11)$$

Spread Transmission. Spread transmission materials offer a wide range of textures. They are used for brightness control, as in frosted lamp bulbs, in luminous elements where accents of brilliance and sparkle are desired, and in moderately uniform brightness luminaire-enclosing globes. Care should be used in placing lamps to avoid glare and spotty appearance.

Figure 1-37a shows a beam of light striking the smooth side of a piece of etched glass. In Figure 1-37b, the frosted side is toward the source, a condition that with many ground or otherwise roughened glasses results in appreciably higher transmittance. For outdoor use, the rough surface usually must be enclosed to avoid excessive dirt collection.

Diffuse Transmission. Diffusing materials scatter light in all directions, as shown in Figure 1-37c. White, opal, and prismatic plastics and glass are widely used where uniform brightness is desired.

Figure 1-36. Reflecting and Transmitting Materials

Material	Reflectance* or trans- mittance† (percent)	Characteristics
Reflecting		
Specular		
Mirrored and optical coated glass	80 to 99	Provide directional control of light and brightness at specific viewing angles. Effective as efficient reflectors and for special decorative lighting effects.
Metallized and optical coated plastic	75 to 97	
Processed anodized and optical coated aluminum	75 to 95	
Polished aluminum	60 to 70	
Chromium	60 to 65	
Stainless steel	55 to 65	
Black structural glass	5	
Spread		
Processed aluminum (diffuse)	70 to 80	General diffuse reflection with a high specular surface reflection of from 5 to 10 per cent of the light.
Etched aluminum	70 to 85	
Satin chromium	50 to 55	
Brushed aluminum	55 to 58	
Aluminum paint	60 to 70	
Diffuse		
White plaster	90 to 92	Diffuse reflection results in uniform surface brightness at all viewing angles. Materials of this type are good reflecting backgrounds for coves and luminous forms.
White paint‡	75 to 90	
Porcelain enamel‡	65 to 90	
White terra-cotta‡	65 to 80	
White structural glass	75 to 80	
Limestone	35 to 65	
Transmitting		
Glass		
Clear and optical coated	80 to 99	Low absorption; no diffusion; high concentrated transmission. Used as protective cover plates for concealed light sources.
Configured, obscure, etched, ground, sandblasted, and frosted	70 to 85	Low absorption; high transmission; poor diffusion. Used only when backed by good diffusing glass or when light sources are placed at edges of panel to light the background.
Opalescent and alabaster	55 to 80	Lower transmission than above glasses; fair diffusion. Used for favorable appearance when indirectly lighted.
Flashed (cased) opal	30 to 65	Low absorption; excellent diffusion. Used for panels of uniform brightness with good efficiency.
Solid opal glass	15 to 40	Higher absorption than flashed opal glass; excellent diffusion. Used in place of flashed opal where a white appearance is required.
Plastics		
Clear prismatic lens	70 to 92	Low absorption; no diffusion; high concentrated transmission. Used as shielding for fluorescent luminaires, outdoor signs and luminaires.
White	30 to 70	High absorption; excellent diffusion. Used to diffuse lamp images and provide even appearance in fluorescent luminaires.
Colors	0 to 90	Available in any color for special color rendering lighting requirements or aesthetic reasons.
Marble (impregnated)	5 to 30	High absorption; excellent diffusion; used for panels of low brightness. Seldom used in producing general illumination because of the low efficiency.
Alabaster	20 to 50	High absorption; good diffusion. Used for favorable appearance when directly lighted.

* Specular and diffuse reflectance.

† Inasmuch as the amount of light transmitted depends upon the thickness of the material and angle of incidence of light, the figures given are based on thicknesses generally used in lighting applications and on near normal angles of incidence.

‡ These provide compound diffuse-specular reflection unless matte finished.

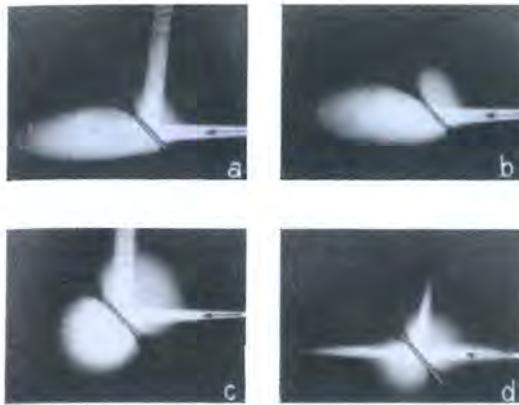


Figure 1-37. (a) Spread transmission of light incident on the smooth surface of figured, etched, ground, and hammered glass samples. (b) Spread transmission of light incident on the rough surface of the same samples. (c) Diffuse transmission of light incident on solid opal and on flashed opal glass, white plastic or marble sheet. (d) Mixed transmission through opalescent glass.

Mixed Transmission. Mixed transmission is a result of a spectrally selective diffusion characteristic exhibited by certain materials such as fine opal glass, which permits the regular transmission of certain colors (wavelengths) while diffusing other wavelengths. This characteristic in glass varies greatly, depending on such factors as its heat treatment, composition, thickness, and the wavelengths of the incident light.

Polarization

Unpolarized light consists of visible electromagnetic waves having transverse vibrations of equal magnitude in an infinite number of planes, all of which oscillate about the line representing the direction of propagation (Figure 1-38). In explaining the properties of polarized light, it is common to resolve the amplitude of the vibrations of any light ray into components vibrating in two orthogonal planes each containing the light ray. These two principal directions are usually referred to as the horizontal and vertical vibrations. The horizontal component of light is the summation of the horizontal components of the infinite number of vibrations making up the light ray. When the horizontal and vertical components are equal, the light is unpolarized. When these two components are not equal, the light is partially or totally polarized as shown in Figure 1-38.

The percentage polarization of light from a source or luminaire at a given angle is defined by the following relation:²⁹

$$\text{percent vertical polarization} = \frac{(I_v - I_h)}{(I_v + I_h)} \times 100 \quad (1-12)$$

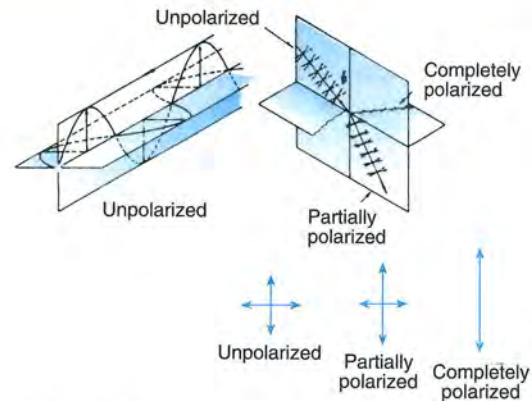


Figure 1-38. Graphical representations of polarized and unpolarized light.

where I_v and I_h are the intensities of the vertical and horizontal components of light, respectively, at the given angle.

Reference to vertically polarized light or horizontally polarized light can be misleading in that it suggests that all light waves vibrate either horizontally or vertically. A better terminology would be to refer to light at a given instant as consisting of one component vibrating in a horizontal plane and another component vibrating in a vertical plane. A general terminology would identify the light components in terms of two reference planes as shown in Figure 1-39. One plane is the plane of the task at the point of the incident light ray, and the second plane is the plane of incidence: the plane perpendicular to the plane of the task and containing the incident light ray. Then the two components of light would be referred to as the parallel component, or the component in the plane of incidence, and the perpendicular component. This terminology would apply to any task position and would be free of ambiguity with respect to spatial orientation. Polarized light can be produced in four ways: (1) scattering, (2) birefringence, (3) absorption, and (4) reflection and refraction.

Scattering is the mechanism of polarization in daylighting; that is, light from a clear blue sky is partially polarized due to the scattering of light by particles in the air.

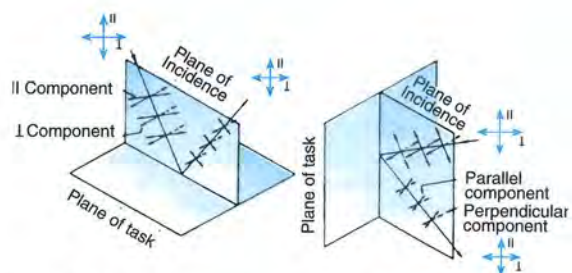


Figure 1-39. Reference planes of a task.

The birefringence, or double refraction property, of certain crystals can be used to achieve polarization. However, the size of these crystals limits this technique to scientific applications; it is not suitable for general lighting.

Polarization by absorption can be achieved by using dichroic polarizers. These polarizers absorb all of the light that is in one particular plane and transmit a high percentage of the light polarized in a perpendicular plane. A high percentage of polarization can be obtained by this method, but with a loss of total luminous transmittance. This type of polarizer is commonly used in sunglasses, where it is oriented to transmit the vertical component of light while suppressing the horizontal (typically reflected) component.

Light may be polarized by utilizing the reflection characteristics of dielectric materials. When light is reflected from a glass surface, it is partially polarized; a larger percentage of the horizontal component is reflected than of the vertical component. At approximately 57° (Brewster's angle), the reflected light contains only the horizontal component (Figure 1-25). For this one surface, however, only 15% of the incident horizontal component is reflected. The light transmitted through a plate at this angle is made up of the remaining portion of the horizontal component and all the vertical component of the original beam. The resulting light is partially polarized (Figure 1-40). As additional glass plates are added to the system, more and more of the horizontal component is reflected and the transmitted light is more completely vertically polarized. A stack of glass plates, as shown in Figure 1-41, thus becomes a method of producing polarization, and the polarizing effect is greatest at Brewster's angle. The percentage polarization is less at all other angles and is zero for a light ray at normal incidence. Polarization by this method can be obtained by arranging glass or plastic flakes in a suitable material.

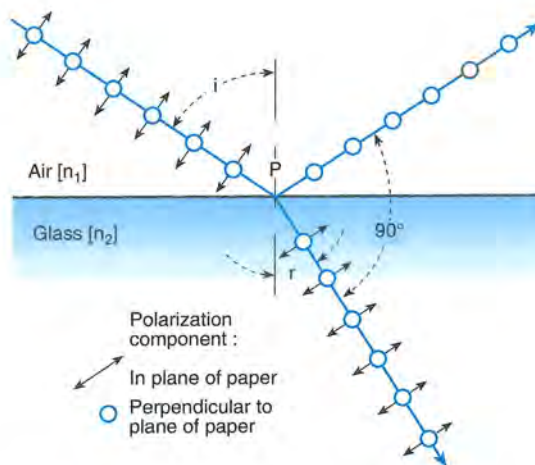


Figure 1-40. Polarization by reflection at a glass-air surface is at a maximum when the angle of incidence i plus the angle of refraction r equals 90° .

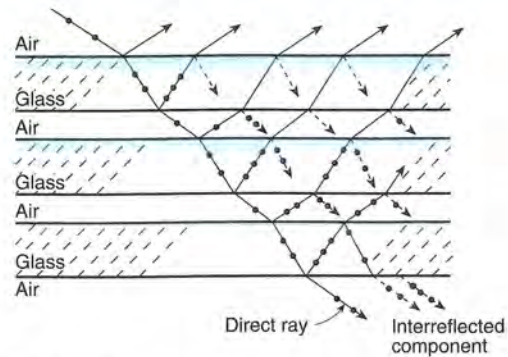


Figure 1-41. Principle of multilayer polarizers.

Interference

When two light waves of the same wavelength come together at different phases of their vibration, they combine to make up a single wave whose amplitude is between the difference and the sum of the amplitudes of the two, depending on their relative phase. Figure 1-42 illustrates this concept for waves of water in a pool. The waves tend to cancel each other at the node lines. Figure 1-43 shows the resulting interference when light refracts and reflects from thin films. Part of the incident light ab is first reflected as bc . Part is refracted as bd , which again reflects as de , and finally emerges as ef . If waves bc and ef have wavefronts of appreciable width, they will overlap and interfere. Optical interference coatings have been used for many years in cameras, projectors, and other optical instruments and can reduce reflection from transmitting surfaces, separate heat from light, transmit or reflect light according to color, increase reflections from reflectors, or perform other light control functions. Naturally occurring examples of interference are soap bubbles and oil slicks. Also, many birds, insects, and fish get



Figure 1-42. Interference.

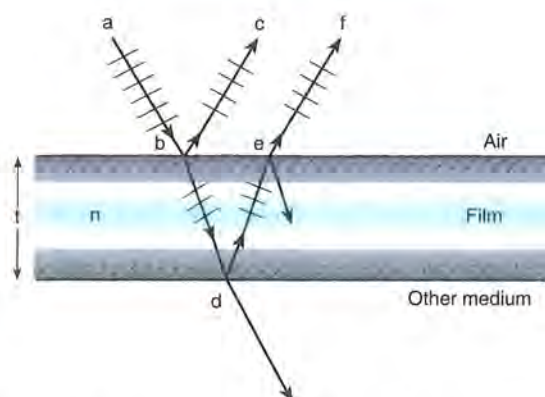


Figure 1-43. Constructive and destructive interference.

their iridescent colors from interference films. The application of interference coatings can significantly increase the reflectance of reflectors and the transmittance of luminaire glass or plastic enclosures.

Low-Reflectance Films. Dielectric optical interference films are applied to surfaces to reduce reflectance, increase transmittance, and consequently improve contrast relationships. Films that are one-quarter wavelength thick with an index of refraction between that of the medium surrounding the glass and that of the glass are used. The hardest and most permanent films are those of magnesium fluoride condensed on the transmitting surface after thermal evaporation in vacuum.

The usual 4% reflection at uncoated air-to-glass surfaces may be reduced to less than 0.5% at each filmed surface at normal incidence, as a result of the canceling interference between the waves reflected at the air-to-film and film-to-glass surfaces. Dielectric coatings can be made very specific to one reflected wavelength or, by varying the layer's thickness or index of refraction, spread over a wide wavelength interval.

Dichroic (Dielectric) Coating. A multilayer coating that selectively transmits or reflects portions of the spectrum can be added to optical materials. Often called hot or cold mirrors, such coatings are efficient in their selective reflection and transmission, respectively, of IR energy. The coatings are typically designed for incident radiation at 45° or 90° to the coated surface. Deviations from the design angle will change the reflected and the transmitted energy. Undesirable results occur when dichroic filters are used in wide beams of light, since the color varies across the resulting beam.

Hot-mirror lamp envelopes, which reflect IR back to a filament, are used with special tungsten-halogen lamps to increase their efficacy without increasing their wattage and reducing their life.

Diffraction

Due to its wave nature, light will be redirected as it passes by an opaque edge or through a small slit. The wavefront broadens as it passes by an obstruction, producing an indistinct, rather than sharp, shadow of the edge. The intensity and spatial extent of the shadow depends on the geometric characteristics of the edge, the physical extent (size and shape) of the source, and the spectral properties of the light. Light passing through a small slit will produce alternating light and dark bars as the wavefronts created by the two edges of the slit interfere with one another.

Diffusion

Diffusion is the breaking up of a beam of light and the spreading of its rays in many directions by irregular reflection and refraction from microscopic crystalline particles, droplets or bubbles within a transmitting medium, or from microscopic irregularities of a reflecting surface. Perfect diffusion seldom is attained in practice but sometimes is assumed in calculations in order to simplify the mathematics (Figures 1-27c).

Absorption

Absorption occurs when a light beam passes through a transparent or translucent medium or meets a dense body such as an opaque reflector surface. If the intensity of all wavelengths of the light passing through a transparent body is reduced by nearly the same amount, the substance is said to show general absorption. The absorption of certain wavelengths of light in preference to others is called selective absorption. Most colored objects owe their color to selective absorption in some part of the visible spectrum, with resulting reflection and transmission in other selected parts of the spectrum.

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Measurement of Light and Other Radiant Energy

2

PRINCIPLES OF PHOTOMETRY AND RADIOMETRY

Introduction

Progress in a branch of science or engineering is very much dependent on the ability to measure the associated quantities. Lord Kelvin (1824–1907) expressed this most bluntly:

When you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.

The earliest instruments for measuring luminous quantities depended on visual appraisal. Such methods lacked both precision and accuracy, largely because the results were dependent on the individual observers making the measurement. Even for a particular observer, measurement reproducibility was poor because a number of variables influencing the measurements could not be controlled or explained. These visual methods are now rarely used. Today measurements usually are made using calibrated physical instruments that respond to radiant energy.

The human visual system responds only to radiation in a very narrow band of the electromagnetic spectrum. This range of wavelengths is approximately from 380 to 780 nm, depending on the individual observer. It should be kept in mind that for any source of illumination, the radiant energy produced is rarely limited to wavelengths within these boundaries. Although the primary concern in this chapter is the measurement of radiation that results in visual sensation, measurements of radiant quantities outside the visible spectrum are also important because of the nonvisual effects that this radiation produces (see Chapter 5, Nonvisual Effects of Optical Radiation).

Optical radiation generally refers to all radiation that can be measured using certain techniques and equipment (mirrors, lenses, filters, diffraction gratings, prisms). Thus visible, ultraviolet (UV), and infrared (IR) radiation are collectively considered as optical radiation. The measurement of optical radiation is called radiometry. Radiometry is the sci-

ence of measuring radiant quantities without regard for the visual effects of the radiation. Light almost always refers to wavelengths visible to humans, although sometimes invisible radiation is also called light when describing radiation on plants or on skin.

Photometry, a special branch of radiometry, is the measurement of radiation in terms of human visual response. The Commission Internationale de l'Éclairage (CIE) has established a standard observer response curve (also known as the photopic luminous efficiency function), denoted by $V(\lambda)$ (see Chapter 1, Light and Optics). This standard observer response curve, with its peak at approximately 555 nm, is used as a standard weighting function that, when applied to a spectral power distribution (SPD) of the light being measured, is an approximation of the perceived brightness of that light.

The standardization of the eye spectral sensitivity function is the key to photometry, removing the influence of the observer from the measurements. However, despite the industry-wide acceptance of this function, one should recognize that it represents a compromise in assuming a predictable correlation of physical measurements with visual response, and that there are some circumstances where the system works poorly (see Chapter 3, Vision and Perception).¹

Photopic, Mesopic, and Scotopic Vision. Vision can be categorized with reference to the adaptive state of the rod and cone photoreceptors of the retina. At very low luminance levels, below approximately 0.01 cd/m^2 —the scotopic region—the light energy is insufficient to energize the cone photoreceptor system, but is adequate to stimulate the rod photoreceptor system. The standard luminous efficiency function for scotopic vision is represented by the function $V'(\lambda)$, with its peak near 507 nm (see Chapter 1, Light and Optics).

At luminance levels greater than approximately 3 cd/m^2 —the photopic region—colors can be distinguished, and objects having fine detail can be readily seen in the central visual field, where the density of the cone population of the retina is highest, that is, in the fovea. Strictly speaking, the photopic luminous efficiency function applies to visual fields of size 2° or less.

At intermediate luminance levels, between approxi-

mately 0.01 and 3 cd/m²—the mesopic region—both rod and cone photoreceptors contribute to vision. Because of methodological difficulties, there is presently no standard luminous efficiency function for this range of adaptation luminance, although it is of practical importance for roadway, security, and other exterior nighttime conditions (see “mesopic vision” in Chapter 3, Vision and Perception).

Basic Concepts

Units of Measurement. The International System of Units, abbreviated SI, is accepted worldwide as a standard system of units of measurement. In that system, the fundamental photometric quantity, luminous intensity, is expressed in candelas (cd). The magnitude of the candela has a historical basis. At one time called the candlepower, it was defined in terms of flame or filament standards. For practical purposes the terms candela and candlepower are equivalent and, although no longer standard, the latter term is still occasionally used. The current definition of the candela is²

... the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and that has a radiant intensity in that direction of 1/683 W/sr.

The candela is now formally defined on this radiometric basis because of advances that have been made in this area of metrology. The definition expresses the candela in terms of the watt and the steradian. The steradian is defined as the solid angle subtending an area on the surface of a sphere equal to the square of the sphere's radius. The steradian is an SI supplementary unit. The unit of power, the watt, is likewise not a base SI unit but can be defined as 1 J/s (energy per unit time) or, in base units, $1 \text{ m}^2 \times \text{kg} \times \text{s}^{-3}$. Since the formal definition of the candela is at a single wavelength (at the peak of the photopic luminous efficiency function), $V(\lambda)$ must be applied to measurements of radiant power produced by real sources in order to reduce them to candelas.

In casual discussions, the terms “energy” and “power” often are used interchangeably; in general discussions on measurements of optical radiation, the term “radiant energy” is most commonly used (as in the title of this chapter). However, it should be kept in mind that it is radiant power (that is, the transfer of energy per unit of time) weighted in terms of an eye sensitivity curve, and not radiant energy, that acts as the visual stimulus. The terms “radiant power” and “radiant flux” are used synonymously. There is no photopic weighting inherent in the concept of radiant flux; it is strictly a radiometric quantity. The unit of radiant flux is the watt.

Two important derived units based on the candela are those of luminous flux and illuminance. To understand how these two quantities are related to the luminous intensity, consider a hypothetical model, illustrated in Figure 2-1. An isotropic point source of radiation (that is, one that radiates

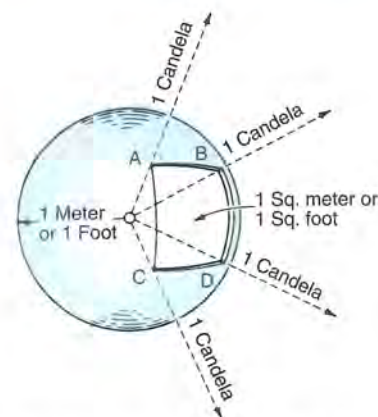


Figure 2-1. Relationship between candelas, lumens, lux, and footcandles. A point source (luminous intensity = 1 cd) is shown at the center of a sphere of unit radius whose surface has a reflectance of zero. The illuminance at any point on the sphere is 1 lx if the radius is 1 m, or 1 fc if the radius is 1 ft. The solid angle subtended by the area ABCD is 1 sr. The flux density is therefore 1 lm/sr, which corresponds to a luminous intensity of 1 cd as originally assumed. The sphere has a total area of $4\pi \text{ m}^2$ or ft^2 , and there is a luminous flux of 1 lm falling on each unit area. Thus, the source provides a total of $4\pi \text{ lm}$.

energy uniformly in all directions) is located at the geometric center of an ideal sphere of zero reflectance (all incident radiation is absorbed). Any portion of the inner sphere's surface receives only direct radiation from the point source itself and no reflected radiation from other parts of the sphere's surface. For a sphere having a radius of one unit, a one-square-unit area on the sphere's surface represents a solid angle of one steradian. (The two-dimensional shape of this area is irrelevant; it might be a circle, in which case the steradian would be represented by a cone. This becomes clearer when the strict definition of luminous intensity is given in terms of a limit.) The luminous intensity of the source in this model is the same in all directions and assumed to be 1 cd. The radiant flux falling on a unit area of the sphere's surface can now be defined to be the luminous flux.

The unit of luminous flux is the lumen (lm); the quantity of luminous flux falling on one square unit of the sphere's surface is defined as 1 lm. Note that the unit itself is arbitrary, since the total quantity of flux that will be incident on this area is independent of the size of the sphere. For a sphere of unit radius, it can be shown by simple geometry that the area of the sphere's surface is equal to 4π square units; thus the isotropic source having a luminous intensity of 1 cd produces a total luminous flux of $4\pi \text{ lm}$.

The concentration of luminous flux falling on a surface, that is, the incident flux per unit area, is called illuminance. To define a unit of illuminance, the sphere must now be given real dimensions because the flux density diminishes

with increasing distance from the source. If the sphere's radius is 1 m, the illuminance on the sphere's wall is 1 lm/m², or 1 lux (lx). If the radius is 1 ft, the illuminance is 1 lm/ft², or 1 footcandle (fc).

Another important luminous quantity is luminance. This quantity is more difficult to grasp, and the sphere model is not useful for that purpose. Luminance relates directly to perceived brightness, that is, the visual effect that illumination produces. Luminance depends not only on the illuminance on an object and its reflective properties, but also on its projected area on a plane perpendicular to the direction of view. There is a direct relationship between the luminance of a viewed object and the illuminance of the resulting image on the retina of the eye. This is analogous to the exposure requirements in photography. The unit of luminance is the candela per square meter (cd/m²).

Photometric quantities, along with their radiometric counterparts, are discussed and defined in the Glossary.

Radiometric and photometric measurements frequently involve a consideration of the inverse square law (which is strictly applicable only for point sources) and the cosine law.

Inverse Square Law. The inverse square law (Figure 2-2a) states that the illumination E at a point on a surface varies directly with the luminous intensity I of the source, and inversely as the square of the distance d between the source and the point. If the surface at the point is normal to the direction of the incident light, the law may be expressed as follows:

$$E = \frac{I}{d^2} \quad (2-1)$$

This equation holds true within 1% when d is at least five times the maximum dimension of the source (or luminaire) as viewed from the point on the surface. For a further discussion of this "five-times rule," see Chapter 9, Lighting Calculations.

Cosine Law. The cosine law (Figure 2-2b), also known as Lambert's law, states that the luminance on any surface varies as the cosine of the angle of incidence. The angle of

incidence, θ , is the angle between the normal to the surface and the direction of the incident light. The inverse square law and the cosine law can be combined as follows:

$$E = \frac{I}{d^2} \cos \theta \quad (2-2)$$

Cosine-Cubed Law. A useful extension of the cosine law is the cosine-cubed equation (Figure 2-2c). By substituting $h/\cos \theta$ for d , the above equation may be written

$$E = \frac{I \cos^3 \theta}{h^2} \quad (2-3)$$

Other Measurable Quantities. The principal photometric quantities have been discussed. These and other quantities of interest are summarized in Figure 2-3 and in the Glossary.

PHOTOMETRY IN PRACTICE: GENERAL REQUIREMENTS

Traceability and Accreditation

Contractual agreements often require that measurements made by laboratories be traceable to national and international measurement standards and that the laboratories be able to support claims of traceability with appropriate documentation and records of equipment used in the measurement process. Such agreements are becoming more common with increasing awareness and adoption of documented quality management systems based on the ISO 9000 series of standards, which states that:

4.11.2b [The supplier shall:] identify all inspection, measuring, and test equipment that can affect product quality, and calibrate and adjust them at prescribed intervals, or prior to use, against certified equipment having a known valid relationship to internationally or nationally recognized standards. Where no such standards exist, the basis for calibration shall be documented.

The requirement for traceability³ involves the ability to relate individual measurement results, with a stated uncer-

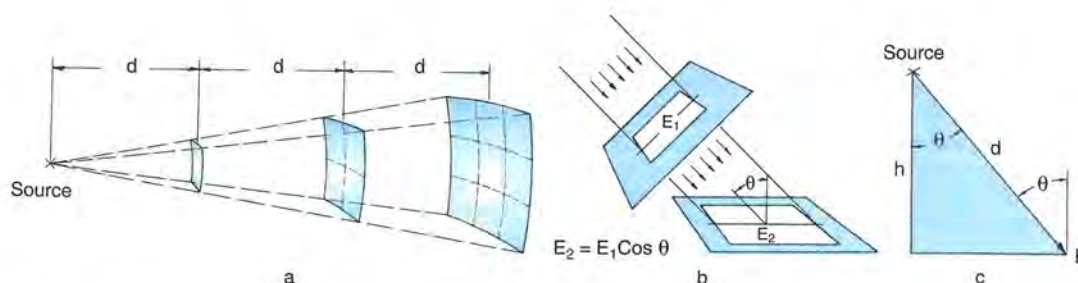


Figure 2-2. (a) The inverse-square law illustrating how the same quantity of light flux is distributed over a greater area, as the distance from source to surface is increased. (b) The Lambert cosine law showing that light flux striking a surface at angles other than normal is distributed over a greater area. (c) The cosine-cubed law explaining the transformation of the formula.

Figure 2-3. Some Measurable Characteristics of Light, Light Sources, and Lighting Materials

Characteristic	Dimensional Unit	Equipment	Technique
Light			
Wavelength	Nanometer	Spectrometer	Laboratory
Color	None	Spectrophotometer and colorimeter	Laboratory
Flux density (illuminance)	Lumen per unit area (lux and footcandle)	Photometer	Laboratory or field
Orientation of polarization	Degree (angle)	Analyzing Nicol prism	Laboratory
Degree of polarization*	Percent (dimensionless ratio)	Polarization photometer	Laboratory
Light Sources			
Energy radiated	Joule per square meter	Calibrated radiometer	Laboratory
Color temperature	Kelvin (K)	Colorimeter or filtered photometer	Laboratory or field
Luminous intensity	Candela	Photometer	Laboratory or field
Luminance	Candela per unit area	Photometer or luminance meter	Laboratory or field
Spectral power distribution	Watts per nanometer	Spectroradiometer	Laboratory
Power consumption	Watt	Wattmeter or voltmeter and ammeter for dc, and unity power factor ac circuits	Laboratory or field
Light output (total flux)	Lumen	Integrating sphere photometer	Laboratory
Zonal distribution	Lumen or candelas	Distribution or goniophotometer	Laboratory
Lighting Materials			
Reflectance	Percent (dimensionless ratio)	Reflectometer	Laboratory or field
Transmittance	Percent (dimensionless ratio)	Photometer	Laboratory or field
Spectral reflectance and transmittance	Percent (at specific wavelengths)	Spectrophotometer	Laboratory
Optical density	Dimensionless number	Densitometer	Laboratory

* Committee on Testing Procedures for Illumination Characteristics of the IES: "Resolution on Reporting Polarization," *Illum. Eng.*, Vol. LVIII, 386, May 1963.

tainty, through an unbroken chain of comparisons to a stated reference source. In this way, the reference source is transferred from the national standards through to the end user of the national measurement system.

To assure the end user of traceability and competence throughout the chain, laboratories may seek recognition through assessment and accreditation by a recognized accreditation body. The assessments are discussed in Reference 49, which sets out the general management and technical requirements for calibration or testing laboratories. Laboratories that comply with this guide also comply, by definition, with the requirements of ISO 9002 for the scope of the testing and calibration services covered by their quality management system. The reverse is not true since ISO 9002 registration gives no recognition of the quality of the laboratory's specific measurements. In the United States, a number of federal and private agencies offer calibration laboratory assessment and accreditation services. Contact the National Institute of Standards and Technology (NIST) for additional information. In Canada, contact the National Research Council of Canada (NRC).

Standards^{4,5}

Primary Standards. A primary standard is a standard that is designated or widely acknowledged as having the highest

metrological quantities and whose value is accepted without reference to other standards of the same quantity. The candela, maintained by the Bureau International des Poids et Mesures (BIPM), is a primary standard.

National (Measurement) Standards. National standards that define radiometric and photometric quantities are maintained by national standard laboratories.² These standards typically are developed from international standards through a specified, usually complex, experimental procedure. In North America, measurement standards for lighting, including the candela, are maintained by NIST and NRC. National measurement standards are not directly accessible by other laboratories.

Transfer Standards. Transfer standards are necessary to link the measurement systems of one laboratory (e.g., a national measurement laboratory) to another. They are defined simply as intermediaries used to compare standards. They can be called travelling standards when intended for transport between different locations.

Reference Standards. Reference standards are standards having the highest metrological quantity available at a given location or in a given organization, from which the measurements made there are derived. Reference standards can be derived directly from a national measurement standard or

from the reference standards of other laboratories in the calibration chain. They usually are prepared with precise electrical and radiometric measurement equipment.

Working Standards. Working standards are used for routine measurements in a laboratory and usually are prepared and calibrated by that same laboratory from its own reference standard.

The preceding classification of standards is based on the 1993 International Vocabulary of Basic and General Terms in Metrology published by the BIPM. Other nomenclatures have evolved from historical usage. They do not represent the internationally accepted BIPM definitions, and they are not all consistent. For example, the term “primary standard” often is used to designate a standard source that was obtained from a national standards laboratory and that is used only to make other working standards for everyday use in that laboratory. Sometimes, a primary standard is called a “master standard.” The term “secondary standard” is also commonly used in private laboratories to distinguish a standard from the one called primary, and sometimes the terms “secondary standard” and “working standard” are used interchangeably. The term “tertiary standard” is used if there are three levels of standards deployed. To avoid confusion, the BIPM definitions should be used.

Documentation of Standards. It is most important to document the lineage of all standards back to the national measurement standards. The documentation should define the calibration procedure and also the state of any influencing environmental conditions. Measurement uncertainty should be documented in accordance with the ISO Guide to the Expression of Uncertainty in Measurement (1995). It should include the uncertainty due to random and systematic error. Without such documentation, measurements cannot be properly compared.

Types of Standards. Incandescent lamps of various wattages are commonly used to establish a traceability chain for photometric quantities outside NIST and NRC. Alternative standards are calibrated detectors from which sources themselves can be calibrated. Such detectors can also be used to calibrate other photometric detectors. Ideal standard lamps and detectors have two principal characteristics: they both are accessible and invariant. In the United States, lamp and detector standards can be purchased from NIST. In Canada, consult NRC. Photometric standards can also be purchased from private laboratories. This adds one or more steps in the calibration chain and increases the uncertainties in the measured quantities. If the supplier of photometric standards is not accredited to ISO/IEC Guide 25 for calibration of the specific type of standard, it is the responsibility of the user of those standards to verify that the supplier has the management and technical procedures in place to carry out the calibrations competently.

Handling, Operation, and Storage of Calibrated Lamps. Calibrated lamps, as with all measurement standards, should be handled, operated, and stored with special care. Figure 2-4 summarizes key considerations in this re-

Figure 2-4. How Does One Treat a Standard Lamp?

Physical considerations

- Handle with care—no bumps or jars!—filaments are fragile.
- Don't touch with bare hands
- Use and store in a clean, dust-free environment.
- Clean with care.
- Align properly—in the same direction as it was calibrated.

Electrical Considerations

- Use correct electrical polarity.
- Apply and remove electrical power gradually.
- Never exceed stated current and voltage.
- Operate at the stipulated current or voltage, as given in the calibration report.
- Use a sufficiently stable power supply.
- Use a proper 4-terminal electrical measuring circuit with an accurate (and calibrated) voltmeter and ammeter.

Operating Considerations

- Allow lamp to stabilize at its operating point.
- Operate in a stable, draft-free environment.
- Use working standards for routine use.

Recalibration Considerations

- Maintain records so that changes in operation can be noticed. The records should include: date, start time and end time, burn time, (cumulative burn time), current, voltage, and such comments as who used the lamp, why it was used, and if any problems were noticed.
- Compare with other standards—a group of 3 is recommended.
- Recalibrate or remove from service when the maximum cumulative burn time is reached, when the lamp has been stressed, or when a change in performance is suspected.
- Use the type of standard lamp appropriate to the measurement.

gard.⁶ Additional information for specific measurement applications is available in the IESNA Lighting Measurements Testing and Calculation Guides (LM-5 through to LM-61).

Other Radiometric Standards. Spectral standards are calibrated in terms of radiometric units. These are usually tungsten-halogen lamps, most often calibrated for spectral irradiance. The calibration typically includes portions of the UV and IR regions of the spectrum. Deuterium standards provide greater flux than tungsten-halogen lamps in the UV and extend the calibration range to below 250 nm.

General Methods

Photometric measurements, in general, make use of the basic laws of photometry previously described. Three types of photometric measurement procedures are:

Direct Photometry. Direct photometry consists of the simultaneous comparison of a standard lamp and an unknown light source.

Substitution Photometry. Substitution photometry consists in the sequential evaluation of the desired photometric characteristics of a standard lamp and an unknown light source in terms of an arbitrary reference.

Relative Photometry. To avoid the use of standard lamps, the relative method is widely applied. It consists of the evaluation of the photometric characteristic of a lamp by comparison with the assumed lumen or spectral output of a test lamp.

MEASURING EQUIPMENT

Radiometric measurement instrumentation consists of a detector, a means of conditioning or amplifying the output of the detector, a method of displaying or storing the measurement, and possibly an optical element or system of elements to collect the radiant quantity to be measured. Depending on the geometric relationship between the source and detector, the quantity measured is radiance, irradiance, or radiant intensity (or the corresponding photometric quantities: luminance, illuminance, or luminous intensity).

A radiometer measures radiant power over a wide range of wavelengths that can include the UV, visible, and IR regions of the spectrum. It can employ a detector that is nonselective in wavelength response or one that gives adequate response in a specific wavelength band. Optical filtering can be used to level (flatten) the radiometer's response over a particular range of wavelengths or to approximate a desired function. For example, a number of useful action functions have been defined in the UV range, to which detector responses can be matched. Examples are industrial polymerization functions used for photoresist exposures and for UV curing. Another example is the erythral effectiveness function (action spectrum) (see Chapter 5, Nonvisual Effects of Optical Radiation). The filtering must compensate not only for the spectral selectivity of the detector but also for the transmission characteristics of any optical components incorporated into the radiometer. Filtering also can be used to suppress the detector's response to radiant power outside the desired range.

A radiometer that has been optically or electronically filtered to approximate a spectral sensitivity function of the fovea is called a photometer. The spectral response characteristic of a photometer is typically designed to match the CIE photopic standard observer. Photometers can also be filtered to provide a response similar to the CIE scotopic standard observer.

A more elaborate radiometer is the colorimeter, which incorporates multiple detectors corrected to respond according to the CIE tristimulus functions. See Chapter 4, Color, for information on the CIE tristimulus functions. Filter colorimeters are used extensively to measure the color characteristics of visible radiation.

Detectors

There is a broad range of detector options available. Choosing the correct detector will depend on the application in terms of spectral response, geometry, and quality. The char-

acteristics of the signal, such as signal-to-noise ratio, amplitude, time response, and frequency bandwidth, all influence the choice of detector. The detector system's linearity range, field of view, noise equivalent power, and window transmission, as well as other factors, affect the measurement.

Thermal Detectors. Thermal detectors include thermopiles, bolometers, and pyroelectric detectors. They produce a voltage proportional to the absorbed radiant power. The absorbing surface of the detector is usually blackened, making it nonselective over a wide range of wavelengths. The signal levels of these detectors are very low, and the detectors are very sensitive to ambient temperature changes. Once used extensively, they are now largely confined to laser light measurements.

Phototubes. A phototube is a vacuum- or gas-filled glass tube containing a photoemissive surface as the source of electrical current. Photons striking the photoemissive surface release electrons by the photoelectric effect, and those electrons are collected by an anode having a higher voltage. The smallness of the resulting current limits the usefulness of vacuum phototubes to applications with high levels of radiant power.

Adding a gas to a phototube and impressing a high voltage on the anode produces an avalanche amplification of the current. Gas-filled phototubes can measure lower levels of radiant power; however, their nonlinear response to power makes them a poor choice for measurement purposes.

The most useful form of phototube is the photomultiplier tube (PMT). PMTs employ a photocathode, which emits electrons when irradiated. The spectral sensitivity of a photomultiplier tube depends on the entrance window and photocathode material, for which many choices are available. Generally the photocathode has either a side-on or a head-on (or end-on) configuration. The side-on type is commonly used in spectroscopy applications and general photometric systems. The head-on type is commonly used for high-energy physics and scintillation counting. When photons strike the photocathode, electrons are emitted and then accelerated through a series of electron multipliers (dynodes), where the signal is greatly multiplied. The electrons are collected by an anode, where the output current is measured. A voltage divider chain connects the elements in the PMT in such a way that electrons are accelerated from one stage to the next. Typical PMT designs employ several to 15 stages of dynodes and produce signal gains from several thousand to hundreds of millions. The voltage required to operate the PMT can vary from 500 to 2000 V, depending on the tube construction and number of dynodes. The overall gain of the PMT is controlled by the voltage applied between elements. A high degree of voltage regulation is required for accurate operation.

PMT detectors differ from solid-state devices in that they produce an output signal (dark current) in the absence of light, due to thermionic emission. The dark current can be reduced by lowering the temperature of the PMT. Most

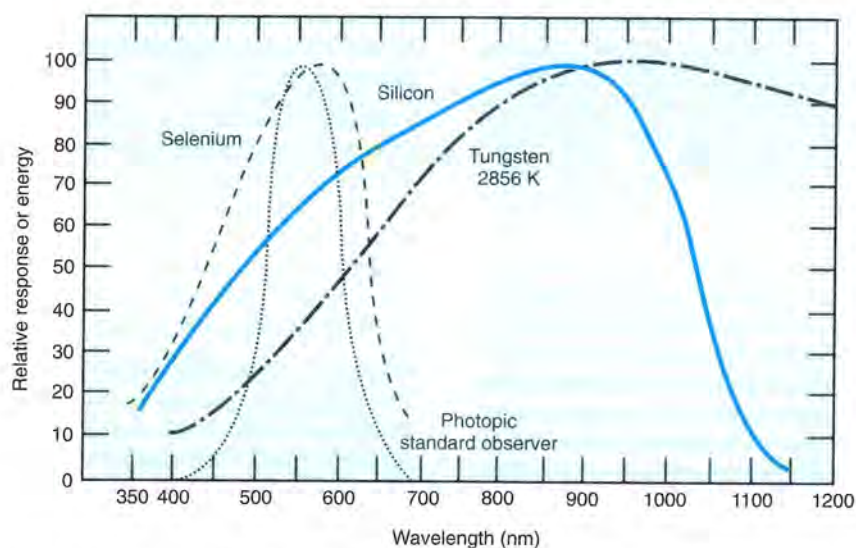


Figure 2-5. The relative spectral sensitivity of selenium and silicon photovoltaic cells, the spectral distribution of tungsten radiation at 2856 K, and the spectral sensitivities assigned to the photopic standard observer. From A. Stimson, *Photometry and radiometry for engineers*. Copyright © 1974. Reprinted by permission of John Wiley & Sons, Inc.

PMTs exhibit gain differences when exposed to magnetic fields or when their orientation in the earth's magnetic field is changed. Magnetic shielding is required in most applications. Most PMTs are shock sensitive, and rough handling can cause failure or loss of previous calibration. All phototubes have highly selective spectral response characteristics. Depending on the photoemissive cathode material used, a phototube can be used for UV, visible, or near-IR measurement; however, a single phototube cannot cover this entire spectral range.

Solid-State Detectors. Solid-state detectors comprise a very large category of detectors incorporating semiconducting materials. All exhibit similar spectral response characteristics; their sensitivity to longer wavelengths increases up to a photon energy limit, where the detector response drops to zero. The useful spectral ranges of solid-state detectors extend from the UV to the far IR region. Some detectors are used in the photovoltaic mode, where the short-circuit current is measured; others are used as photoconductors, that is, a reverse bias voltage is applied and the device is treated as a radiation-sensitive variable resistor. Examples of photoconductive detectors include cadmium sulfide and cadmium selenide cells.

The photovoltaic mode is most frequently used for radiant power measurements because of its inherent linearity of current as a function of incident radiant power level. The quantum nature of photovoltaic detectors makes them ideal for instruments that must perform over a wide range of radiation levels. The selenium barrier-layer cell, an early type of photovoltaic solid-state detector, was widely used in laboratory photometers but is now not recommended in photometers due to nonlinearity, fatigue, and instability. Today sili-

con photodiodes are commonly used in laboratory and commercial photometers. They offer a broader spectral range than the older selenium-based detectors (Figure 2-5) and the ability to measure lower levels of radiant power. The silicon photodiode can be combined with a glass filter to match its spectral responsivity to the CIE photopic luminous efficiency curve. Silicon detectors are also used in self-scanning linear arrays, facsimile (fax) machines, spectral measuring instruments, and two-dimensional charge-coupled devices (CCDs). For more information see "Imaging Photometers" below.

Photodiodes perform best when operated as current sources into "zero-impedance" amplifier circuitry. The linearity of silicon photodiodes has been shown to extend over 10 decades with appropriate amplification. Because very small currents are involved (typically 10^{-13} to 10^{-3} A), proper amplifier design is essential for the performance of these photometric instruments. Test methods, classes, and performance characteristics are discussed in more depth in Reference 18.

General Considerations

Spectral Response. The detector is the primary component affecting the spectral response of a radiant-power-measuring instrument. Photomultiplier tubes (PMTs) and silicon photodiodes are the most commonly used detectors in radiometers and photometers. As previously noted, these detectors respond differently to different regions of the spectrum. The spectral range of the detector should be matched to the spectral region to be measured. This can significantly improve sensitivity or relieve the burden of filtering. Pho-

tometers require good suppression of both UV and IR and good correction to the CIE luminous efficiency function. The CIE f_1' parameter is the only internationally agreed, illuminant-independent designation for the spectral error of photometers. Contrary to other designations in use, this one does not allow positive departures from $V(\lambda)$ to cancel negative ones and is dependent of the spectral distribution of illuminant A.

Transient Effects. Selenium photovoltaic cells, when suddenly exposed to constant illumination, require a short rise time to reach a stable output and thereafter can decrease slightly over a longer time due to fatigue. By contrast, silicon photodiodes typically exhibit microsecond rise times and no fatigue. The rise and fall times for most photometers employing silicon photodiodes are usually limited by the amplification circuitry. PMTs have nanosecond rise times but exhibit hysteresis, requiring from seconds to minutes to adapt to light-level changes. Precision radiometers and photometers usually employ PMTs with minimum hysteresis.

Temperature Effects. Temperature variations affect the performance of all photodetectors. Selenium photovoltaic cells exhibit significant changes in shunt resistance with temperature, which can interact with external circuit impedance and produce gain changes. In addition, selenium cells can be permanently damaged by temperatures above 50°C (120°F). Silicon photodiodes are considerably less affected by temperature; however, problems can arise from the effects of temperature on detector response. The transmission of the spectral correction filters can also be affected by temperature. Correction factors can be employed when using photovoltaic detectors at temperatures other than their calibrated temperature (typically 25°C), or means can be provided to maintain the instrument temperature near the calibration temperature. Hermetically sealed detectors provide protection against the effects of humidity and some insulation against temperature cycling. Care should be taken that the effects of high temperature or temperature cycling do not damage cemented layers of the detector filter.

PMTs are quite temperature sensitive. Both dark current and noise increase at higher temperatures. Also, the spectral response can vary significantly with temperature changes. Thermoelectric temperature control is frequently used to control the dark current, noise, and spectral characteristics of PMTs.

Effect of Pulsed or Cyclical Variation of Light.⁷⁻¹³ Electric discharge sources flicker when operated on alternating-current (ac) power supplies (see "Flicker and Stroboscopic Effect" below). Precautions should be taken with regard to the effects of frequency, pulse rate, and pulse width when measuring the luminous properties of lamps.^{4,14-17} It cannot be assumed that an instrument will treat modulation of a light source in the same way as the human eye. The internal capacitance of the detector, the response time of the amplifier, and the response of the readout device (whether analog or digital) to pulsating signals must be considered. Special me-

tering circuitry for the integration of pulsed light is available for the measurement of flashing incandescent and pulsed xenon sources.

Instrument Zeroing. It is important to check the photometer or radiometer zeroing prior to taking measurements. For any type of equipment using an amplifier, it might be necessary to zero both the amplifier and the dark current. Where possible, it should be verified that the instrument remains correctly zeroed when the range is changed. Alternatively, any deviation from zero under dark current conditions should be measured and subtracted from the measurements.

Electrical Interference. With electronic instrumentation, electrical interference can be induced in the leads between the detector and the instrumentation. This effect can be minimized by using filter networks, shielding, grounding, or combinations of the above.

Magnetic Fields. As previously noted, radiometers and photometers containing PMTs can be affected by strong magnetic fields. Commercial instruments containing PMTs use magnetic shielding adequate to protect them from most ambient magnetic fields; however, it is advisable to keep them away from heavy-duty electrical machinery.

Signal Conditioning. The current produced by photovoltaic detectors usually requires amplification and other kinds of signal conditioning. The most common signal conditioning method uses an operational amplifier in a current follower configuration. This configuration provides low input impedance, and the output voltage is the product of the detector current and the feedback resistance. Although PMTs provide much higher signal currents, they are frequently used with a similar circuit to assure linearity. The output of the operational amplifier can drive most displays, whether analog or digital. Frequently, commercial instrumentation provides other kinds of signal conditioning. If signal currents are very low, integration can be used to increase the signal level and to improve the signal-to-noise ratio. Analog-to-digital conversion can be introduced in order to provide an interface to digital computing or a means of signal averaging. Memory may also be provided for data logging. Computing can be done inside the instrument by a microprocessor or by an external computer by means of a data link.

Measuring Instruments

Instruments for photometric measurement are defined by their application. A photometric instrument can be used as a stand-alone system such as an illuminance or luminance meter, or combined with auxiliary equipment such as an integrating sphere to form a lamp measurement photometer system. CIE Publication 69¹⁸ serves as a guide for characterizing the performance parameters of photometers for luminance and illuminance (Figure 2-6a and 2-6b). Digital instrumentation for display and computer data acquisition further enhance the utility of modern photometric systems.

a. Illuminance Meters	
Characteristics	Representative error value
V(λ) match (f_1')	2%
UV response	0.2%
IR response	0.2%
Cosine response	1.5%
Linearity error	0.2%
Fatigue	0.2%
Polarization	2%
b. Luminance Meters	
Characteristics	Representative error value
V(λ) match(f_1')	3%
UV response	0.2%
IR response	0.2%
Directional response	2%
Effect from the surrounding field	1%
Linearity error	0.2%
Fatigue	0.1%
Polarization	0.1%
Errors of focus	0.4%

Figure 2-6, a and b, is excerpted from CIE Publication No. 69 (1987) and contains a summary of the expected errors of an illuminance meter and a luminance meter, respectively. Representative error values for best available commercial instruments have been estimated for several parameters. For all photometers the V(λ) match is of special importance, and should be as small as possible.

Illuminance Meters

Typical Configurations. The simplest illuminance meters consist of a photodiode with a photopic correction filter. The photodiode is connected to an operational amplifier with a display. These can be bench top, rack mountable, or portable. They can be enclosed in one case, or, as is more common with laboratory photometers, the detector and filter can be in one module that is connected by a cable to a console, at a convenient distance, containing the amplifier and display. The electrical scheme can be anything from a simple amplifier with manual controls to a programmed micro-processor with routines for calibration, measurement, and conversion of display units. Some meters include communication ports for remote operation and data manipulation. Various commercial instruments are shown in Figure 2-7.

Effect of Angle of Incidence (Cosine Effect). Illuminance meters are frequently used to measure the luminous flux density incident on a surface such as a table top, a wall, or a road surface. Part of the light reaching the detector at high angles of incidence is reflected by the cell surface or the filter or cover glass in front of it, and some may be obstructed by the rim of the case surrounding the detector. The resultant error increases with angle of incidence; where an appreciable portion of the flux comes at large angles, values as much as 25% below the true illuminance value can be obtained.

The component of illuminance contributed by single sources at large angles of incidence can be determined by orienting the plane of the detector perpendicular to the direction of the light, and multiplying the reading thus obtained by the cosine of the angle of incidence. Detectors used in most illuminance photometers now have diffusing covers or some means of correcting the readings to a true cosine response. Solutions to the cosine problem include placing over the detector a flashed opal glass, diffusing acrylic disk, or an integrating sphere with a knife edge entrance port. With flashed opal glass and the diffusing



Figure 2-7. Various commercial illuminance meters. (a) Portable illuminance meter with small integrating sphere; (b) laboratory grade system that includes a photometer, a radiometer, and a fiber-optic power meter; (c) multifunction portable illuminance meter with detachable receptor head.

acrylic disk at high angles of incidence, however, light will reflect specularly, so that the readings remain too low. This can be compensated by allowing light to enter through the edges of the diffuser. The readings at very high angles will then be too high but can be corrected by using a screening ring. The addition of auxiliary optics to improve cosine response can affect the photometric and directional response. CIE Publication 69 suggests correction methods for these errors.¹⁸

Leveling. Particularly during photometry of lighting systems where light is received from one or a small number of discrete sources, such as in roadway lighting, accurate leveling of the illuminance meter head is important. Instruments are available in which the detector is gimbal mounted and self-leveling. This removes problems when trying to measure horizontal illuminance on uneven or sloping surfaces.

Luminance Meters (Telephotometers)

Luminance meters are essentially illuminance meters with the addition of suitable optics to image an object onto the detector (Figure 2-8). A means of viewing the object is usually provided so that the user can see the area that is being measured as well as the surrounding field. Because of the similarity of this optical system to a telescope, these instruments are also called telephotometers.

Changing the focal length of the objective lens changes the field of view and thus the size of the measurement field. Some systems have apertures of various sizes to further define the measured area. Angular measurement fields from seconds of arc to several degrees can be selected.

Typically, modern luminance meters use silicon photodiodes or PMTs. The amplifier sensitivity may be either manually selected or automatic. Color filters can be incorporated for color measurements, and neutral density filters to extend the dynamic range.

Photodetectors are typically silicon for portable and low-sensitivity instruments and PMT for high-sensitivity instru-

ments. Most instruments have at least a sensitivity dynamic range of four, and many incorporate attenuation screens or neutral-density filters for additional range. Most instruments in current manufacture incorporate digital displays. The electrical scheme can be anything from a simple amplifier with manual controls to a programmed microprocessor with routines for calibration, measurement, and conversion of display units. Some meters include communication ports for remote operation and data manipulation.

Beamsplitter Spot Meters. This type of photometer employs, behind the objective lens, a beamsplitter, which divides the incoming radiation into two paths. Approximately half of the radiation passes through the beamsplitter and is focused on an aperture defining the measurement field. The radiation passing through the aperture can be measured with either a PMT or a solid-state detector. The radiation reflected from the beamsplitter is focused on a reticle having an etched pattern with the same dimensions as the measurement aperture. A viewing system with an eyepiece allows the user to see the field of view and an outline of the area being measured. The reticle must be carefully aligned with the measuring field. Readings are usually in cd/m^2 or cd/ft^2 . Some instruments may include colorimetric filter options. Field-of-view capabilities may range from 0.25° to 10° , with sensitivity ranging from 10^{-2} to 10^6 cd/m^2 .

Although good measurements can be made with this type of instrument, it does have some noteworthy disadvantages. Among these are loss of illumination to both the detector and the viewer; introduction of polarization, which affects the measurement of polarized sources (see Chapter 1, Light and Optics); and the difficulty of changing apertures and reticles for different measurement fields. In general, a low-cost instrument using a beamsplitter will provide adequate but not exact location of the measured spot.

Aperture Mirror Photometers. Most of the problems of the beamsplitter spot meter are addressed by the aperture mirror photometer. There is no beamsplitter to introduce polarization error or reduce the brightness at either the measuring aperture or the viewed image. The image formed by the objective lens falls on an angled first surface mirror with a through hole for the measuring aperture. The viewing optics are focused on the aperture, which appears as a black circle. The field around the measurement aperture is clearly seen in the eyepiece. This arrangement allows apertures to be changed without the need to change precisely aligned reticles as well. A disadvantage of the aperture mirror photometer is that if a small source is imaged within the measuring aperture, it cannot be seen in the viewing optics. Instruments of this class usually employ high-quality detectors, one or more neutral-density range-multiplying filters, lens options, and some degree of colorimetric capability. They are available with internal microprocessor control and direct reading capability for luminance in several units, for color chromaticity coordinates, and for color temperature. The full-scale sensitivity for the best laboratory instruments ranges from 10^{-4} to 10^8 cd/m^2 .



Figure 2-8. Luminance meter with data processor.

Imaging Photometers. Recent developments in imaging devices have provided a powerful tool for luminance measurements of complete scenes. Cameras equipped with a charge-coupled device (CCD) array are able to capture and digitize electronic images of visual scenes.^{19,20} Providing the proper controls are applied, the digital image can be used to determine the luminance at every point in the scene, corresponding to the pixels of the camera's CCD array. See Figure 2-9.

A complete photometric capture can be carried out and saved in seconds. As the information is provided in digital form, complicated functions of luminance images can be analyzed and reported quickly for uniformity, contrast, spatial characteristics, and other photometric values. Some systems also provide chromaticity values.

This form of photometry requires many factors to be controlled in the instrument and software if accurate results are to be obtained. The CCD and optical attachments must be of high quality. "Field flattening" adjustments are required for all lenses that spatially distort the image to at least some degree. To measure the complete dynamic range of luminances in most interior scenes, earlier 8-bit systems required capture of multiple images at different exposure settings. Today, 16-bit systems are available that cover a dynamic range of over 65,000 : 1. For low luminance capability, cooling of the CCD array is required to reduce noise, to increase the detection limit, and to minimize susceptibility to changes in ambient temperature.

Applications for imaging photometers include the energy distribution of lamps (e.g., floodlamps and automobile headlights), production line quality control, luminance uniformity

of a projected scene, and complicated analyses of scene illumination.

Reflectometers

Reflectometers are reflectance measurement photometers. Reflectance measurements typically fall under three categories: diffuse, specular, and a mix of specular and diffuse reflectances. The design of the reflectometer and the method of measurement depend on the reflectance properties of the sample material and what part of the reflectance one desires to measure. ASTM²¹ provides over seventy standards on color and appearance measurements, some of which employ reflectometers.

Reflectance, the ratio of reflected light to incident light, is not simply a property of a material. Rather, it also depends on the measurement geometry, that is, the spatial relationship between the source and the detector.

The fraction of the incident light reflected is very difficult to determine directly, particularly for diffuse reflection. To bring some order into what could be a chaotic measurement situation, reflectance is usually expressed as a reflectance factor, the ratio of the reflectance of a sample to that of a reflectance standard under the same measurement geometry. Three commonly used reflectance standards are a polished front surface mirror, a polished black glass having a specified index of refraction, and a total diffuse reflector (e.g., BaSO_4).

In one method commonly used for measuring total reflectance, the sample is illuminated by a narrow cone of light from a given angle, typically 10° or less from the normal to the sample surface, and the reflected light is collected over the entire hemisphere surrounding the sample. Instruments of this type are said to employ a conical-hemispherical geometry. The hemispherical flux collection is often accomplished by means of an integrating sphere with a detector, arranged so that it does not receive light reflected directly from the sample, but rather views the sphere wall. In this way the signal is proportional to the total flux reflected from the sample.

The same type of instrument also can be used to measure only that part of the light that is diffusely reflected. One example of a sample that one might measure in this way is one with a very smooth dielectric surface that reflects strongly by scattering from pigments or other inclusions beneath the surface. In this case, light specularly reflected from the sample is allowed to escape through an specular subtraction port in the sphere wall, where a light trap can be positioned to absorb the specular reflected beam.

For measuring color, a 45/0 reflectometer is often used to evaluate the spectral character of diffusely reflected light. Figure 2-10a illustrates a typical mechanical layout. The source and the detector are mounted in a fixed relationship in the same housing. Light is incident on the surface from an angle of 45° , and the detector is positioned above and normal to the sample surface.



Figure 2-9. The battery-powered 496×288 pixel camera of a commercially available imaging photometric system with zoom lens and dynamic range of 0.05 to 500,000 cd/m². The camera connects to a laptop computer by a parallel printer cable. The system can measure the luminances in an entire scene and automatically analyze, archive, and report the results.

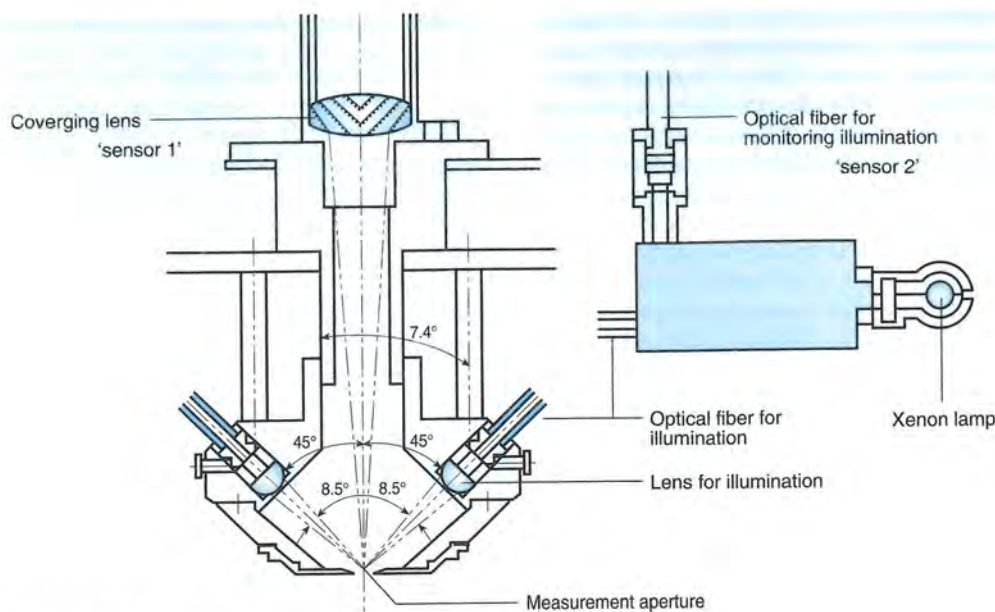


Figure 2-10a. A 45/0 reflectometry geometry.

Reflectances from plane samples can be measured in many ways. One method employs a reflectometer that compares, with the aid of an auxiliary mirror, the incident flux with the flux after two reflections from the sample. Such a reflectometer is often available as an accessory to commercial spectrophotometers. Another method employs a goniophotometer that allows the user to position the light source and detector at any known angle. In some models, the sample holder can also be repositioned. Applications of the goniophotometer include measurements of gloss, luster, and haze.

Another type^{22,23} of instrument, a Taylor Baumgartner sphere reflectometer, shown in Figure 2-10b, measures total reflectance. It consists of an integrating sphere, light source, and a photodiode. The sample is placed at the sample port of the integrating sphere. A collimated beam of light is directed onto the sample from approximately 30° to the normal, and the total reflected light, integrated by the sphere, is measured by the photodiode mounted in the sphere wall. The collimated light source is then rotated so that the light is incident on the sphere wall, and a second reading is taken. The sample is in place during both measurements, so that the effect on both readings of the small area of the sphere surface it occupies is the same.²⁴ The ratio of the first reading to the second is the reflectance of the sample for the conditions of the test. Samples of translucent materials should be backed by a light trap.

Various other instruments are available for measuring reflectance characteristics of materials.²⁵⁻²⁹ For any reflectance measurements, the reflectometer geometry employed should be specified, and for reflectance factor measurements the ideal reflector should also be specified.

Spectral Measuring Systems³⁰

General Principles. The spectral response of a particular detector can be modified using optical or electronic filters to approximate some desired spectral response function (such as photopic correction). The detector itself, of course, must have adequate sensitivity over the spectral range being measured. Measurements with instruments that use corrected detectors are often called broadband or heterochromatic radiometric measurements.

Good-quality detectors are stable over time, and once they are calibrated, accurate measurements can be made without frequent corrections. Broadband instruments are very practical because they are inexpensive and simple to use.

A disadvantage to broadband measurement is that it is difficult to design a filter correction to fit a desired function exactly, and although corrections can be applied, these corrections are usually themselves approximations. This can be a problem for the most critical measurements that demand the highest accuracy. In some circumstances, measurement errors can be very large if the corrections are not appropriately applied or if there is a wide departure in filter correction from the ideal response function at wavelengths where a test source produces significant energy.³ Sometimes, as in the case of a photopically corrected detector, a very accurate fit can be achieved only at substantial cost, and even if the fit is initially satisfactory, the response of the detector or the filter can, at least theoretically, change over time. Commercial instruments usually provide an approximate correction, stating in their specification how closely

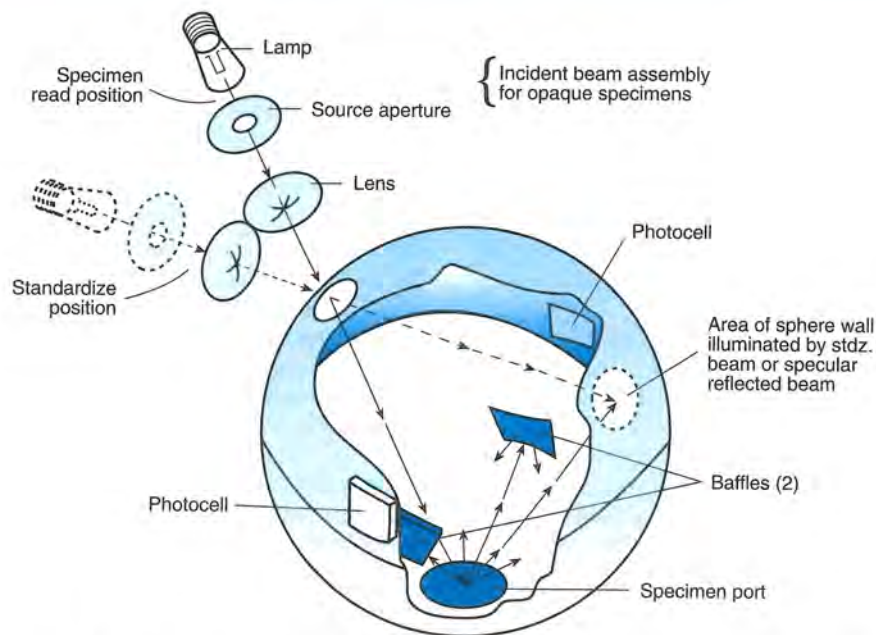


Figure 2-10b. A Taylor Baumgartner sphere reflectometer. From R.S. Hunter, and R.W. Harold, *The measurement of appearance*, 2nd ed. Copyright © 1987. Reprinted by permission of John Wiley & Sons, Inc.

their detector conforms to an ideal function. The only meaningful specification, however, is f_1' (Figures 2-6a and b and CIE¹⁸), the only internationally accepted specification that does not allow negative departures from $V(\lambda)$ to cancel positive departures.

Methods have been developed for correcting measurement errors due to imperfect filter design. For measurements on light sources, errors can be minimized by calibrating a detector with sources that have a known output and a spectral power distribution similar to that of the test source. There are also methods for characterizing a given detector and providing an analytical correction to the measurements.¹⁸

Perhaps the most important disadvantage of broadband measurement is the loss of specific wavelength information, resulting from the integration of radiation by the detector. Although detailed spectral information is not always needed, for some purposes the complete spectral power distribution (SPD) of a source, that is, the radiant power per unit wavelength as a function of wavelength, must be known.

Spectral measurement systems are capable of determining the SPD in a very small band of wavelengths. The measurement of an SPD is considered fundamental; from these data, absolute radiometric, photometric, and colorimetric properties of a source can be determined.

In comparison with broadband measuring systems, spectral measuring systems are complex and costly. The measurements also are generally more difficult and time consuming to make, often requiring a trained operator.

There are different types of spectral measuring systems

to suit specific applications, but they all generally incorporate the following elements: collection optics to receive and limit the radiation to be measured, a monochromator, a detector or detector array, electronics to process the detector or array signal, and some kind of readout or display. The monochromator houses a dispersing element such as a prism or diffraction grating that separates the various wavelengths of the spectrum. The monochromator has an entrance aperture, usually in the form of a rectangular slit, through which the collected radiation enters; maybe some optical elements that image the entrance slit onto the dispersing element(s); and an exit slit through which selected wavelengths of the dispersed radiation pass. A suitable detector or array is positioned at the exit slit to measure the SPD at the source. To make the many measurements necessary for a complete SPD, an automated system is recommended. There are many variations, on the automation scheme, but typical scanning spectrometers incorporate a drive system to scan through a range of wavelengths (such as a means of rotating the monochromator grating) and a means of reading and storing the detector output for each sample, performing the necessary calculations and reporting the results (in printouts or graphs). This entire process is usually carried out using a computer. Detector array spectrometers acquire spectral data simultaneously without mechanical moving parts. Only a computer is needed for data processing.

Types of Systems. A spectroradiometer is used to measure the SPD of light sources and relative spectral responsivities of detectors. Two methods are usually employed. For the

first method, the collection fore-optics of a spectroradiometer system directs the radiation into a small integrating sphere or diffuser plate positioned in front of the entrance slit of the monochromator. This geometry is typically used to measure the spectral irradiance of a light source. For the second method, fore-optics of a spectroradiometer system directs radiance from a uniform source integrating sphere, an irradiated highly reflecting diffuse target, or a diffusely emitting lamp into the entrance slit of the monochromator. For the case of calibrating a detector, an appropriate lamp is chosen for its known spectral distribution.

A spectrophotometer is used to determine spectral reflectance and transmittance properties of materials. Measurement results provide a means of examining the color of a material for analysis, standardization, and specification. In addition, it is the only means of color standardization that is independent of material color standards (always of questionable permanence) and independent of the differences in color vision existing among even so-called normal observers. Although called a spectrophotometer because of its principal application to measurements in the visible spectrum, this type of instrument is often designed for measuring UV and near-IR radiation. Some spectrophotometers are, in fact, designed specifically for UV or IR measurements.

Spectroradiometers and spectrophotometers are closely related instruments in that they involve similar dispersion methods, detectors, and automation requirements. The principal difference is that a spectroradiometer performs measurements with the source(s) external to the system itself, whereas a spectrophotometer incorporates internal sources and an integrating sphere or chamber in which test samples are placed. It should be kept in mind that in using spectrophotometers for color standardization, it is really the reflectance properties of the test sample that are being measured and that the actual color appearance is dependent on the SPD of the source being used to evaluate the sample.

Both of these instruments can be used in a spectrograph configuration. In this type of instrument, the exit slit is replaced by photographic film. Because there is no restrictive aperture, the dispersed radiation falls on the film plane and consequently the various wavelengths are spread out simultaneously. The exposed film provides a qualitative "picture" of the spectral components present. This is particularly useful in studying line emission sources, where the lines provide a "signature" of the source or material present. A means of measuring the optical density of the photographic emulsion where the various lines appear can provide quantitative information as to the intensity of the lines. This type of system obviates for mechanical scanning through the spectrum. In the form of a spectroradiometer, the instrument is used as an astronomical tool to evaluate the chemical composition of stellar objects.

In modern instruments, the spectrograph employs diode arrays in the place of a photographic emulsion. Each diode detects incident radiation in a narrow wavelength band. Many modern spectroradiometers and spectrophotometers

use this approach. Electronically scanned silicon photodiode arrays provide nearly instantaneous determination of a spectral power distribution. For many applications, array radiometry has replaced scanning systems, with the advantage of much greater measurement speed and the elimination of complex moving parts. For routine work, this reduced measurement time allows many more measurements to be taken, and changes in the SPD of a nonstable test source over time can be monitored. The disadvantages of array systems are that they inherently have more stray light, which is usually the limiting factor, and they do not have the absolute accuracy and sensitivity of the best scanning systems.

Another very simple spectral measuring instrument, used to examine a spectrum visually rather than with a photodetector, is a spectroscope.

Special Considerations. The ranges of spectral response in spectral measurement systems generally depend on the nature of the detector. Scanning spectroradiometers usually employ PMTs because of their high sensitivity. The response of PMTs extends from 125 to 1100 nm.³¹ Various types of silicon photodiodes cover the range from 200 to 1200 nm.³¹ For IR measurements several compounds can be used: intrinsic germanium (900 to 1500 nm), lead sulfide (1000 to 4000 nm), indium arsenide (1000 to 3600 nm), indium antimonide (2000 to 5400 nm), various types of doped germanium (zinc-doped, 2000 to 40,000 nm), and mercury cadmium telluride (1000 to 13,000 nm).³²⁻³³ The response of nonselective detectors spans a range from the near UV to beyond 30,000 nm.^{32,33} Where monochromators utilize diffraction gratings, the grating itself also influences the system response, so gratings must be carefully selected for the range of wavelengths being measured.

For accurate quantitative measurements, the electrical output of the detector must be known as a function of the input radiation to a spectral measuring system. Thus, for processing the electrical output of detectors (voltage, current, or charge), the instrumentation and the measurement method must be carefully selected with regard to a number of parameters, such as signal level (saturation), signal-to-noise ratios, fatigue, linearity, and response times (for rapidly varying signals). Photon counting and charge integration techniques are sometimes used for extremely low radiation levels.^{34,35}

The influence of stray radiation on the measurement results must be minimized. This can be accomplished by designing an optical system to prevent unwanted wavelengths from reaching the detector. In all radiometric work there are two types of unwanted radiation: out-of-band radiation (radiation that is not completely dispersed) and higher-order radiation coming from diffraction gratings. Out-of-band radiation can usually be minimized by using a double monochromator (dispersing the radiation twice) or a single monochromator with appropriate filters. This type of unwanted radiation limits the use of diode-array spectroradiometers. It arises primarily from the properties of diffraction, so it can-

not be eliminated entirely. Higher-order radiation can also be effectively limited by appropriate filters or by using a double monochromator employing a prism as one of the dispersing elements.

Radiated flux of some wavelengths (mainly UV below 200 nm) is dispersed or absorbed by a layer of air between the radiator and the detector. In this case consideration must be given to the placement of the source and the detector, and to the surrounding medium.

All observed spectroradiometric data (sometimes called raw data) are a function not only of the SPD of the light source but also of the spectral throughput of the optical system, the spectral bandwidth of the monochromator, and the spectral responsivity of the detector. Collectively, these define the system responsivity, which is determined by measuring at each wavelength the output of a calibration or standard source having a known output. Once this function is known, the test-source observed data can be corrected by multiplying each value by the known output of the standard source divided by its observed value at that wavelength.

Photometric Measuring Systems: Basic Equipment Types

Optical Bench Photometers. Optical bench photometers are used for the calibration of instruments for illuminance measurement. They provide a means for mounting sources and detectors in proper alignment and a means for easily determining these relative distances between them. If the source is of known luminous intensity in a specified direction and is distant enough from the detector so that its radiation can be treated spatially as if it were emanating from a point, the inverse square law (Equation 2-1) can be used to compute illuminance.

Distribution Photometers. For characterizing the spatial distribution of illumination from a source, a series of luminous intensity measurements are made on a distribution photometer, which can be one of the following types:

- Goniometer and single detector
- Fixed multiple detector
- Moving detector
- Moving mirror

All types of distribution photometers have advantages and disadvantages. The significance attached to each advantage or disadvantage is dependent on other factors, such as available space and facilities, polarization requirements, and economic considerations.

Goniometer and Single Detector. The light source is mounted on a goniometer, which allows it to be rotated about both horizontal and vertical axes. The luminous intensity is measured by a single fixed detector.

There are several different versions of goniometers. Each is related to the type of source or luminaire being measured

and the facilities in which it is located. With the use of computers, the coordinate system of a goniometer system can be easily transformed to another coordinate system;³⁶ thus consistent data-reporting formats become practical. Figures 2-11a, 2-11b, and 2-11c show three types of goniometer systems, known as Type A, B, and C. Details are provided in

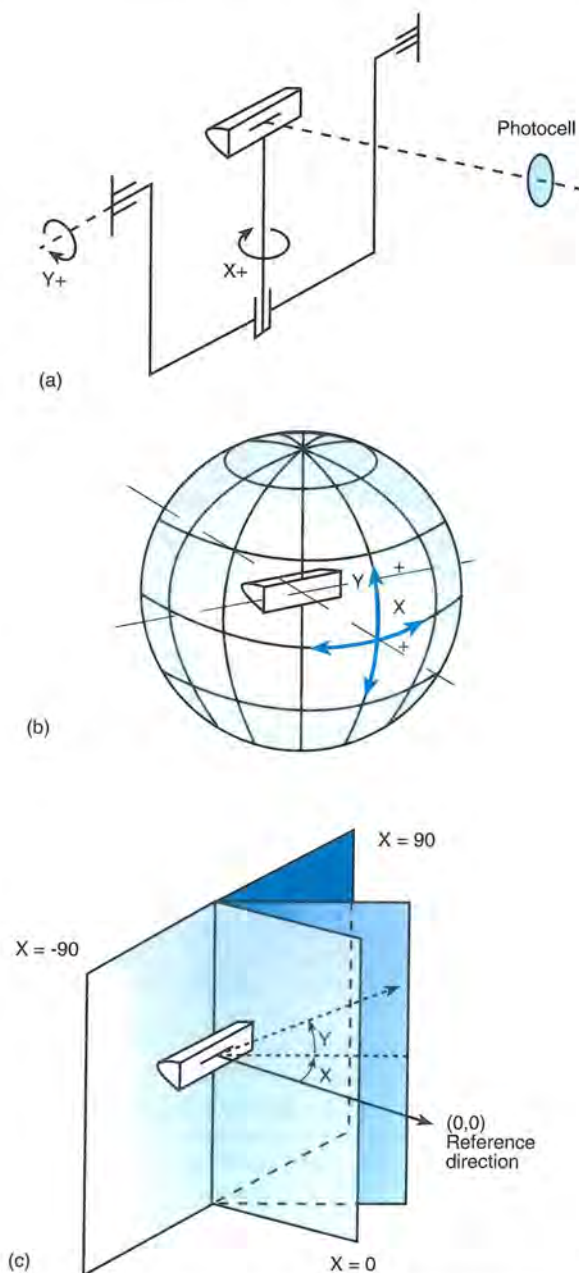


Figure 2-11a. Type A goniometer with fixed horizontal axis: (a) related coordinate systems; (b) representation on a sphere of the X-Y coordinate system; and (c) X-Y coordinate system.

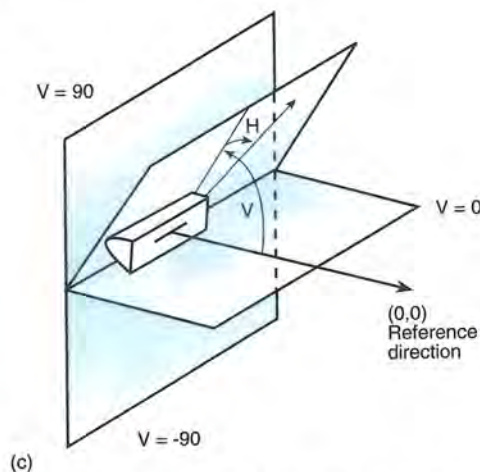
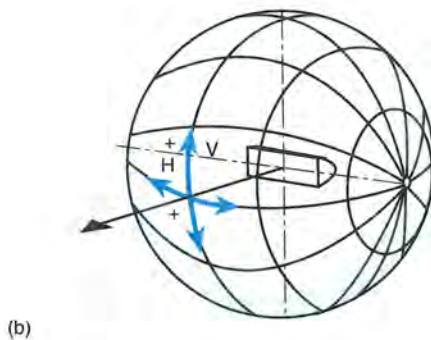
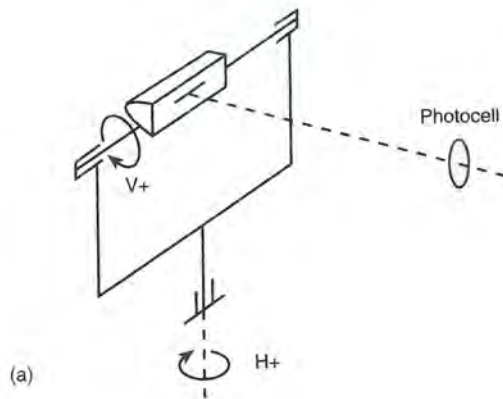


Figure 2-11b. Type B goniometer with fixed vertical axis: (a) related coordinate system; (b) representation on a sphere of the V-H coordinate system; and (c) V-H coordinate system.

LM-35-1989.³⁷ Types B and C are most commonly used for outdoor and indoor sources, respectively. Note that these designations differ from the Types A, B, and C photometry defined by the CIE.

Fixed-Multiple-Detector Photometer. Numerous individual detectors are positioned at various angles around the

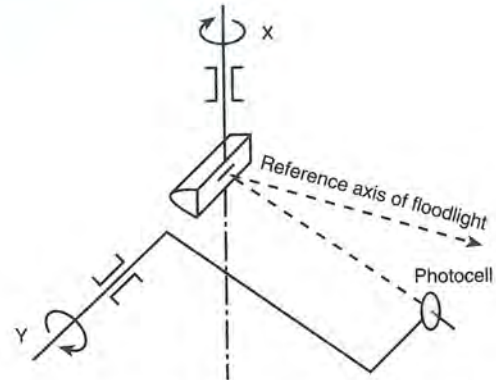


Figure 2-11c. Type C goniometer with a photocell or mirror movable around a horizontal axis.

light source under test. Readings are taken on each detector to determine the intensity distribution. See Figure 2-12.

Moving-Detector Photometer. This device consists of a detector that rides on a rotating boom or arc-shaped track; the light source is centered in the arc traced by the detector. Readings are collected with the detector positioned at the desired angular settings. Sometimes a mirror is placed on a boom to extend the test distance. See Figure 2-13.

Moving-Mirror Photometer. This is a Type C photometer in which the mirror rotates around the light source, reflecting the light to a single detector. Readings are taken at each desired angle as the mirror moves to that location. See Figure 2-14.

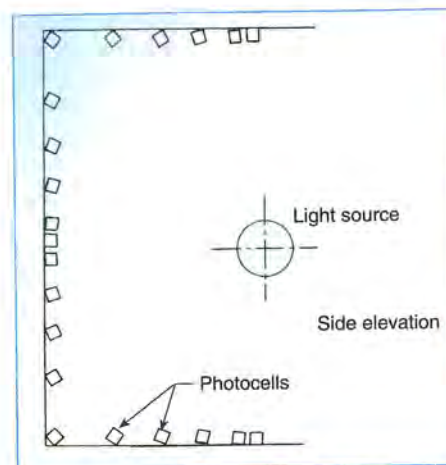


Figure 2-12. Schematic side elevation of a fixed multiple cell photometer.

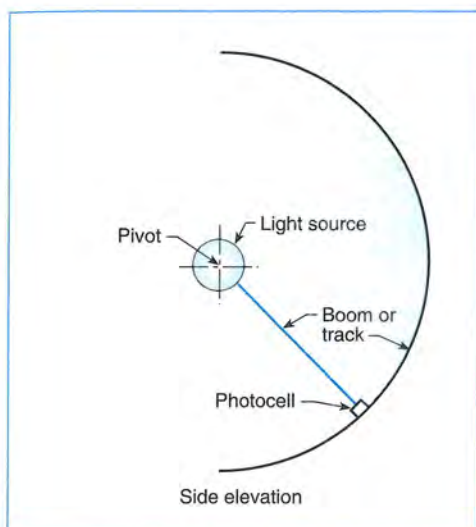


Figure 2-13. Schematic diagram of a moving cell photometer.

Integrating-Sphere Photometer. The integrating-sphere photometer is used to measure the total luminous flux from a source (lamp or luminaire). The most common type is the Ulbricht³⁸ sphere. The theory of the integrating sphere assumes an empty sphere whose inner surface is perfectly diffusing and of uniform nonselective reflectance. Every point on the inner surface then reflects to every other point, and the illuminance at any point is therefore made up of two components: the flux coming directly from the source and that reflected from other parts of the sphere wall. With these assumptions, it follows that the illuminance, and hence the luminance, of any part of the wall due to reflected light only is proportional to the total flux from the source, regardless of its distribution. The luminance of a small area of the wall, or the luminance of the outer surface of a uniformly diffuse transmitting window in the wall, when carefully screened from direct light from the source but receiving light from other portions of the sphere, is therefore a relative measurement of the total luminous flux from the source. Figure 2-15 shows the Ulbricht-type integrating sphere with a high-re-

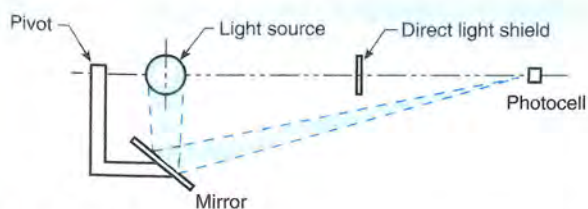


Figure 2-14. Schematic diagram of a moving mirror photometer.



Figure 2-15. Ulbricht-type integrating sphere with diffuse high-reflectance coating, shown here at the National Institute of Standards and Technology (NIST).

flectance, diffuse white interior. Diffuse coatings of lower reflectance are also used. There are advantages as well as disadvantages to the level of reflectance of the sphere coating or material used. An integrating sphere coated with an 80% diffuse reflectance coating is less susceptible to spectral errors due to surface contamination than that from a sphere coated with a diffuse high-reflectance coating. The compromise is reduced efficiency. If a reference source of known output (in terms of luminous flux) is measured in the integrating sphere, a calibration constant can be determined, and thus the luminous flux of a source of unknown output can be determined.

The presence of a source having finite dimensions, its supports and electrical connections, the necessary baffles or shields, auxiliary accessories, and the exit window or ports are all departures from the basic assumptions of the integrating-sphere theory. While durable high-reflectance diffuse material (Figure 2-15) and coatings are now available for sphere interiors, none exhibits the ideal properties of perfect diffusivity and spectral nonselectivity. Despite these limitations, if the reference source and the test source are similar in shape, size, surface reflectance characteristics, and light distribution patterns, the errors introduced by a imperfect integration can be small. For accurate measurements of sources dissimilar from the reference source, corrections

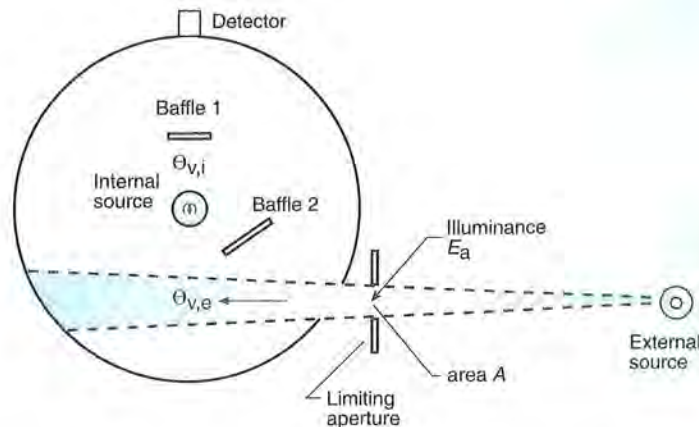


Figure 2-16. Alternative geometry for luminous flux measurements.

must be applied for self absorption, spectral mismatch, and spatial nonuniformity, which are inherent with integrating sphere lamp measurement photometry.^{4,39-43}

Alternatives to the Ulbricht-type integrating sphere exist.⁴⁴ Recently, an alternative integrating-sphere method using an external source has been developed at the National Institute of Standards and Technology (NIST) (Figure 2.16).⁵ In this geometry the total luminous flux $\phi_{v,i}$ of a source in the integrating sphere is calibrated against an external reference source calibrated for illuminance, at an aperture outside the integrating sphere. The total luminous flux $\phi_{v,e}$ of the external source can be determined from Ea and aperture area A .

Despite its shortcomings, the integrating sphere is an important tool for photometric measurements. It can produce results quickly with a single measurement, and suitable accuracy can be achieved if good instrumentation and proper procedures are employed.

LABORATORY MEASUREMENTS^{4,45-48}

Precision and accuracy of laboratory measurements can be consistently attained by correctly following a set of standard procedures and using good equipment. Such procedures are prepared and published by standardizing committees or consensus organizations to serve as a common basis for measurements. IESNA guides provide detailed procedures for the many required electrical and photometric tests for different lamp types. These should be consulted when testing or calibration is being performed. The following information is a general overview of good laboratory practices.

Important elements that standard procedures embody are:

- Controlling the electrical supply characteristics
- Ensuring electrical stability of reference and working standards
- Securely mounting the source

- Minimizing the influence of stray light
- Frequently checking instrument readings
- Stabilizing sources and auxiliaries by operating and maintaining them for a sufficient period of time before measurements are taken
- Compensating for the inherent nonsymmetry of sources and luminaires⁴⁸
- Using instruments that have adequate precision and accuracy to meet the requirements of the test
- Understanding the limitations of instruments used with respect to sensitivity, linearity, and dynamic range
- Ensuring that the instruments are suitably calibrated and maintained

The laboratory must provide an adequate test distance for sealed beam, floodlight, and projector lamp measurements. Space can be conserved by using mirrors to fold the effective test distance. Large integrating spheres can require extending the ceiling height. There must be adequate space surrounding the sphere to gain access to the sphere interior. Temperature and air circulation control are critical requirements for discharge lamp photometry. Cleanliness, provision of suitable electric power, and storage space for lamps, luminaires, and instruments are also important requirements in any photometric laboratory, as are the provision of suitable training and the maintenance of records of the response or output of instruments and reference standards. These and other general guidelines are described in ISO/IEC Guide 25, General Requirements for the Competence of Calibration and Testing Laboratories.⁴⁹ See "Traceability and Accreditation," earlier in this chapter.

Electrical Measurements

Photometric results depend on the electrical operating characteristics of the source being tested. For this reason, electri-

cal and photometric measurements are almost always made concurrently, and both sets of data are included in the report.

Electrical measuring instruments should be selected to have current and voltage ratings corresponding to the circuit conditions to be encountered and should give indications of the desired precision and accuracy. Digital instrumentation has replaced analog instruments in most cases, and their use is highly recommended. A comprehensive discussion on instrumentation requirements is given in the IES guide "Selection, Care, and Use of Electrical Instruments in the Photometric Laboratory."⁵⁰ If analog instruments are used, it is especially important to consult this reference so that appropriate instrument corrections can be applied for the type of measurement being performed.

Test lamps must be stable before attempting any accurate electrical measurement. It is necessary to season the test lamps in accordance with established procedures.⁵¹

Instrumentation

Direct-Current Circuits

CURRENT. Current-measuring instruments, or ammeters, are inserted in series with the source and have low impedance, thus adding little to the load on the power supply. They can be self-contained, but this type of instrument might not have sufficient range to directly measure the current through high-wattage sources. When current exceeds several amperes, it is usually determined using an accurate digital voltmeter (DVM) in combination with a calibrated current shunt. The shunt resistance should be sufficient to produce a voltage drop that can be measured accurately, although too high a resistance will lower the current appreciably. For most lamp types, an appropriate shunt resistance is between 0.1 and 1 Ω .

VOLTAGE. The voltage applied to the light source is measured by means of a voltmeter connected in parallel with the source. It should have the highest impedance possible so as not to disturb the circuit. To avoid corrections to compensate for a voltage drop in the ammeter or across the current shunt, the voltmeter is usually connected directly across the load. Often, separate voltage leads are connected to the base of the lamp through special lampholders (kelvin sockets) to avoid voltage drop errors resulting from socket-to-lamp connections.

POWER. Power can be computed as the product of current and voltage.

Alternating-Current Circuits. Instruments that measure alternating current must be compatible with the waveform and frequency of the voltage or current being measured. They should have a frequency response comparable to the supply frequency. For measurements of sinusoidal waveforms, instruments that indicate rms values are satisfactory. For accurate measurements of distorted waveforms that contain harmonics, true rms instruments with frequency response capabilities well above the fundamental frequency are required.

In some ac circuits, a dc component can also be present. In this case a true rms instrument that measures ac and dc must be used; otherwise a separate dc measurement is necessary to determine the true rms value of the voltage or current. Many measuring instruments do not include the dc component in the measurement, and this feature needs to be verified.

As described for dc instruments, ac instruments are connected to the test circuit, and the same impedance considerations apply.

In electrical measurements with high-intensity discharge lamps, some instruments require protection from transient voltages (on the order of 1500 to 4500 V) that occur when lamps are turned on and off. This is usually accomplished by providing switches to connect the instruments into the circuit only after the lamp is operating.

CURRENT. Ammeters for use in ac circuits can be self-contained; however, as with dc circuits, the rating of many meters is too low. A transformer or ac current shunt can be used in combination with a digital meter to achieve a more extensive measuring range. The shunt should be noninductive to avoid current waveform distortion and phase shifting. For this reason, dc current shunts are generally unsuitable.

VOLTAGE. As with dc circuits, voltage can be measured directly across the load using an ac voltmeter. The measuring range can be extended using a potential transformer or voltage divider.

POWER. In a resistive circuit (e.g., an incandescent filament lamp) the ac power load can be either computed as the volt-ampere product or measured directly with a wattmeter. In reactive circuits (e.g., a circuit with a magnetic ballast or where distorted waveforms are present), power is measured with a wattmeter, which measures or computes the real power by averaging all the instantaneous volt-ampere products over one cycle of lamp operation. Such an instrument should be capable of responding to harmonics well above that of the fundamental. Older analog wattmeters require corrections to achieve high accuracy. Modern digital power-measuring instruments are often capable of performing all the necessary electrical measurements and seldom require corrections. The specification of the instrument should be checked to ensure the instrument is capable of accurately measuring the specific waveforms.

Electrical Measurements of Incandescent Lamp Circuits

Incandescent filament lamps usually are measured on a dc circuit where accurate measurement results can be obtained using inexpensive dc power sources and measuring instruments. High-accuracy electrical measurements of incandescent lamps are especially desirable because lamp output is very sensitive to small changes in electrical settings. For example, a 1% change in current through a typical filament lamp results in a 5 to 7% change in light output.

Some incandescent sources have integral electronic com-

ponents such as diodes and are designed to operate only on ac circuits. True rms instruments that also measure the dc component of a waveform should be used for measurements on this type of source.

Electrical Measurements on Discharge Lamp Circuits.

All electric discharge lamps have negative volt-ampere characteristics and must therefore be operated in conjunction with internal or external current-limiting devices, such as resistors or reactors. These are described in Chapter 6, Light Sources. Because of the presence of distorted waveforms, true rms measuring instruments must be used for any measurements on discharge lamp circuits.

Such measurements may involve lamps or ballasts. In some cases the two are inseparable and measurements are made on the combination as a single device. Because of normal manufacturing tolerances, commercial ballasts supply lamps with some variation in voltage and current characteristics, which affect the electrical input and the light output of lamps. To promote uniformity of testing, the International Electrotechnical Commission (IEC), working through the American National Standards Institute (ANSI), the Canadian Standards Association (CSA), and similar national standardizing bodies throughout the world, has established or is establishing standardized testing procedures for determining the electrical characteristics for most of the common types of discharge lamps. These standard tests are performed using reference circuits and reference ballasts that comply with specified electrical requirements.

Where international standards have not been established, national standards are used.

Lamp Testing. Lamp parameters are influenced by many factors. Detailed, accepted testing procedures where these factors are controlled or specified are described in the appropriate IESNA guides.⁵²⁻⁵⁴ Some of the more important conditions affecting lamp test results are listed below:

- Ambient temperature
- Drafts
- Lamp position
- Lamp connections
- Lamp stabilization
- Power-supply characteristics
- Ballast characteristics
- Lamp circuit characteristics

Ballast Testing. Ballast parameters are influenced by many factors. Detailed accepted testing procedures are described in the appropriate ANSI standards.⁵⁵⁻⁶⁰ Ballast testing requires consideration of some or all of the following.

VOLTAGE RANGE. For most tests, ballasts should be operated at their rated primary voltage.

REFERENCE LAMPS. Some tests on ballasts specify that the ballast shall be operating a reference lamp. Reference lamps are seasoned lamps that, when operated under stated conditions with the specified reference ballast, operate within

specified tolerances of electrical values established by the appropriate existing or proposed specifications.

OPEN-CIRCUIT VOLTAGE. This measurement is necessary only for ballasts containing a transformer.

ELECTRODE HEATING VOLTAGE. On ballasts for use with lamps having continuously heated electrodes, the electrode heating voltages are measured with the electrode windings loaded with a specified dummy load.

SHORT-CIRCUIT CURRENT (ballasts for high-intensity discharge lamps). An ammeter is inserted in the circuit in place of the lamp, and the short-circuit current of the ballast is measured.

STARTING CURRENT. Ballasts for instant-start fluorescent lamps, a resistor and ammeter, in series, with a total resistance equivalent to the value specified in the appropriate standard,⁵⁵⁻⁶¹ is used instead of the lamp. For ballasts used with high-intensity discharge lamps, the secondary circuit is short-circuited.

ELECTRODE PREHEATING CURRENT (preheat ballasts for fluorescent lamps). This measurement is made with an ammeter connected in series with the lamp electrodes while the lamp is maintained in the preheat condition.

BALLAST OUTPUT FOR FLUORESCENT LAMPS. For preheat and instant start ballasts, specifications are in terms of the power delivered to a reference lamp operated by the ballast under test, as compared with the power delivered to the same lamp by the appropriate reference ballast.

With continuously heated electrodes, specifications are in terms of the light output of a reference lamp operated with the ballast under test, as compared with the light output of the same reference lamp when operated with the appropriate reference ballast.

BALLAST REGULATION FOR FLUORESCENT LAMPS. Relative lamp power input and light output are measured at 90% and 110% of rated ballast input voltage.

FLUORESCENT LAMP CURRENT. The current of a reference lamp should be measured on both the ballast under test and the reference ballast.

For lamps with continuously heated electrodes,⁶¹ unless the internal connections of the ballasts are accessible, measurement of lamp current requires special instrumentation to supply the vector summation of currents in the two leads to an electrode.

Photometric Measurements

Incandescent Filament Lamps.⁶² In determining the photometric characteristics of bare incandescent filament lamps, the requirements for electrical measurements previously described should be observed. Test lamps (except series types) are usually measured at rated voltage.

Reference lamps⁶³⁻⁶⁵ can be purchased from or recalibrated by NIST, NRC, or other established national or commercial laboratories. Reference lamps are usually rated for lumens at a current or voltage a little below their nominal rating in order to extend the burning time. The correct color

temperature and lamp filament temperature should be maintained. Nickel-plated bases are used on these standards to reduce corrosion and high-resistance problems over their life.

Working standards usually are calibrated against reference standards. They should have the loops of filament supports closed firmly around the filament to avoid the possibility of random short-circuiting of a portion of the filament by the support. They should be adequately seasoned and selected by successive comparisons with reference standards for stability. All standards should be handled carefully to avoid exposure to electrical and mechanical shocks. Exposure to current or voltage above the standard value may alter lamp ratings. For a more in-depth discussion on photometric standards see Reference 42. It is recommended that the voltage applied to the test lamp be ramped up slowly to its final setting (Figure 2-4).

Intensity Measurements. Sources can be measured on an optical bench photometer if either the luminous intensity in a particular direction or a mean horizontal luminous intensity is desired. Lamps standardized for unidirectional measurements are usually marked to indicate the orientation. A common practice is to inscribe a circle and a vertical line on opposite sides of the bulb. The standardized direction is from the circle toward the line, when they are centered on each other, looking toward the receiver.

Total Flux Measurements. Most routine photometric measurements on incandescent filament lamps are for total light output or total luminous flux and are made in a sphere (Figure 2-15). Best results are obtained when the standard lamp has approximately the same physical size, lumen output, color temperature, and location in the sphere as the test lamp.

Lamp depreciation measurements usually are taken at 70% of rated lamp life. By this time, some blackening of the bulb is likely. This blackening can lead to errors in photometric measurements taken with an integrating sphere because the blackened area of the lamp absorbs some of the interreflected light. To overcome these errors, a third lamp, commonly called the "absorption," "comparison," or "auxiliary" lamp, should be installed in the sphere so that it is shielded from both the integrating sphere detector and the test lamps. Successive readings should be taken with the absorption lamp operating; first with the reference (known) lamp installed but not operating, then with the blackened (aged) lamp installed but not operating. The difference between these readings represents the light absorbed by the blackened lamp and can be used to correct the values given by the integrating sphere. The same general procedure can be followed in most cases where the characteristics of the integrator are altered during the test by the introduction of light-absorbing elements (see the above discussion on "Integrating-Sphere Photometer").

Photometry of Discharge Lamps.⁶⁶⁻⁶⁸ As with incandescent lamp measurements, the photometric characteristics of

discharge lamps usually are determined in conjunction with electrical measurements, whose general requirements have been given. The substitution method is normally employed for photometric measurements. Complete, detailed photometry procedures can be found in IESNA test guides.⁵²⁻⁵⁴

Equipment

BALLASTS. When a lamp is measured for rating purposes, it should be operated on the appropriate reference ballast. If no standard exists, the ballast should comply with the general lamp requirements. In general practice, photometric measurements of fluorescent lamps burning on commercial ballasts should be made with the ballast operating at rated input voltage, and measurements on high-intensity discharge lamps should be made with the lamp operating at rated wattage. The ballast should be operated long enough to reach thermal equilibrium. The use of commercial ballasts should conform to the procedures given in the appropriate standards.⁴⁷

DETECTORS. Detectors should be selected according to the criteria given in "Illuminance Meters" above. Additional corrections may have to be applied to the measured data.

STANDARD LAMPS. These lamps should have characteristics similar to the lamp under test with respect to light output, physical size, shape, and spectral distribution.

INTEGRATING SPHERES.^{38,44} The integrating sphere to be used should comply with the requirements described in the previous discussion of integrating-sphere photometers. To provide acceptable performance, integrating spheres should be of adequate size for the lamp being tested. Direct substitution is not always possible, and generally the larger the integrator with respect to the test lamp dimensions, the smaller any necessary corrections will be. Also, the ambient temperature in a larger sphere is less affected by heat generated by the test lamp. The sphere diameter should be at least 1.5 m for high-intensity discharge lamps and at least 1.2 times the length of the lamp for straight lamps; the area of the light source should not exceed 2% of the interior surface of the sphere. If direct substitution is used, these requirements are less stringent.

DISTRIBUTION PHOTOMETER.⁶⁹⁻⁷¹ The lamp is mounted in open air with the distance between receiver and lamp at least five times the lamp length or 3 m, whichever is greater. Except as stipulated below, the lamp should be operated in the same burning position as associated with the luminaire for which it is intended, and it should be held stationary during measurement. Movement can disturb its stabilization.⁵²⁻⁵⁴ The total light output can be computed if the lumen-candlepower ratio is known, or if strict substitution is practiced. The measured luminous intensity values for a lamp are established by multiplying the test readings by the photometric calibration constant. The total light output is the sum of products of these values with the appropriate zonal lumen constants. Measures should be taken to exclude stray light, to control ambient temperature and drafts, and to reduce the

effects of light-absorbing or -reflecting materials. For fluorescent lamp measurements the lamp is mounted in a horizontal position and measurements taken normal to the axis of the lamp. To provide the greatest accuracy, these measurements must be taken at several angular positions by rotating the lamp around its axis between sets of measurements. For measurements of high-intensity discharge lamps, especially metal halide lamps, the lamp should be placed in its designed operating position. If this is vertical, measurements can be made while the lamp is rotating slowly on its longitudinal axis. Holding the lamp stationary is desirable for stabilization and accuracy. If the lamp is to be operated in any other position, it must be held stationary during measurement, since the light distribution from a high-intensity discharge lamp is a function of arc position, which is influenced by gravity.

Reflector-Type Lamps.⁷² For purposes of identification, a reflector-type lamp is defined as a lamp having a reflective coating applied to part of the bulb, this reflector being specifically contoured for control of the luminous distribution. Included are pressed or blown lamps such as PAR and ER lamps, as well as other lamps with optically contoured reflectors. Excluded are lamps of standard bulb shape to which an integral reflector is added, such as silvered-bowl and silvered-neck lamps; lamps designated for special applications, such as automotive headlamps and picture projection lamps, for which special test procedures are already established; lamps having translucent coatings, such as partially phosphor-coated mercury lamps; and reflector fluorescent lamps.

Intensity Distribution. Several methods for measuring intensity distribution are available, depending on the type of lamp and the purpose of the test. The photometric center of the lamp is usually taken as the center of the bulb face, disregarding any protuberances or recesses in the face. The test distance should be great enough so that the inverse square law applies (Equation 2-1).

The intensity distribution of a circular beam is commonly represented by an average curve in a plane along the beam axis. (The beam axis is that axis around which the average distribution is substantially symmetrical; the beam axis and photometric axis are adjusted to coincide.) The curve is obtained either by taking measurements with the lamp rotating about the beam axis, or by averaging a number of curves (at least eight) taken in planes at equally spaced azimuthal intervals about the axis.

The intensity distribution of a lamp whose beam is oval or rectangular in cross section is not adequately represented by one average curve. For some lamps, two curves through the beam axis, one in the plane of each axis of symmetry, can supply sufficient information. The necessary number of traverses, their distribution within the beam, and the intervals between individual readings vary considerably with the type of lamp; sufficient measurements should be made to describe the average distribution pattern adequately.

When reflector-type lamps are considered for a specific application, test results will be most readily comparable when in the same form as that for equipment used for the same application. For example, when a direct performance comparison of a reflector lamp with floodlighting luminaires is desired, the lamp should be tested according to approved floodlight testing procedures.³⁷ The same is true for indoor luminaire applications.

Total Luminous Flux Measurements.⁴ The total luminous flux can be obtained by direct measurement in an integrating sphere or by calculation from intensity distribution data. Because of the high-intensity spot produced by most reflector-type lamps, special precautions should be taken when using an integrating sphere. One possible position for the test lamp in the sphere is with its base close to the sphere wall and the beam aimed through the sphere center, thus distributing the flux over as large an area of the sphere as possible. An appropriate baffle should be placed between the light source and the detector.

When reflector-type standards are available, the calibration of the sphere follows the usual substitution procedure, and for maximum accuracy the standard lamp should be of the same type as the test lamps.

Beam and Field Flux. The beam and field flux can be calculated from an average intensity distribution curve or from an isocandela diagram. Of particular interest is the flux contained within the limits of 50% and 10%, respectively, of the maximum intensity. The beam angle is defined as the total angular spread of the cone intercepting the 50%-of-maximum intensity. The field angle is defined as the total angular spread of the cone intercepting the 10%-of-maximum intensity.

Flicker and Stroboscopic Effect.⁷³ All light sources operated on alternating current will flicker. The degree to which flicker is perceived, if at all, depends on the frequency of the alternating current, the persistence of light generated by the source, and the viewing conditions.

Flicker has special significance for objects moving within the field of view. Objects may appear to move discretely rather than continuously under flickering illumination; this is known as the stroboscopic effect. The magnitude of the effect depends on the rate and amplitude of the flicker, the rate of object motion, and the viewing conditions.

The flicker index⁷³ has been established as a reliable relative measure of the cyclic variation in output of various sources at a given power frequency. It takes into account the waveform of the light output as well as its amplitude. It is calculated by dividing the area above the line of average light output by the total area under the light output curve for a single cycle (Figure 2-17). Area 2 in Figure 2-17 may be close to zero if light output varies as periodic spikes.

The flicker index assumes values from 0 to 1.0, with 0 for steady light output. Higher values indicate increased possibility of noticeable stroboscopic effect, as well as lamp flicker.

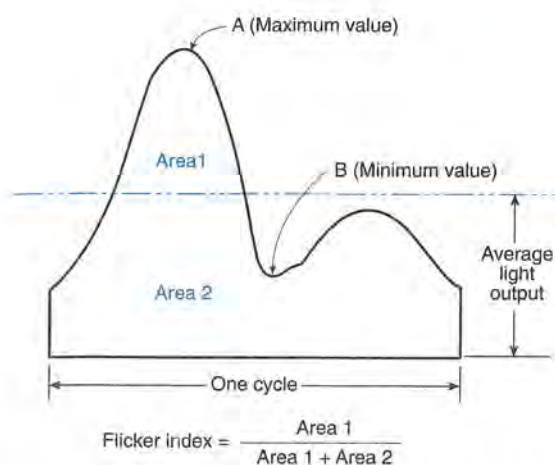


Figure 2-17. Curve of the light output variation from a lamp during each cycle, showing the method of calculating the flicker index.

Spectroradiometric Measurements of Light Sources^{30,74}

Spectroradiometric measurements of light sources can be reported in relative terms or as absolute values. The units of the latter are generally watts per unit area as a function of specified wavelength bands for spectral irradiance, and watts within the wavelength bands for spectral flux. Extended light sources typically are measured for their spectral radiance in units of watts per unit area per solid angle per unit wavelength. Spectroradiometric measurements provide the fundamental data for the determination of radiant quantities; all other quantities can be computed from these measurements.

Measurement Methods. Spectroradiometric measurement involves the comparison of two light sources: a reference source of known SPD and a test source whose SPD is to be determined. The two sources can be compared wavelength by wavelength with a scanning monochromator, or they can be measured sequentially by completely scanning each source throughout the spectrum.

When the sources are compared wavelength by wavelength, the two sources are operated simultaneously. This approach necessitates discontinuous wavelength scanning, pausing at each measurement point. It also requires that the reference and test source not drift over the lengthy measurement period. The advantage of this method is the minimizing of errors due to short-term drift in the instrument's response.

When the sources are measured sequentially, either continuous or discontinuous wavelength scanning can be adopted. When this method is used, the spectral response of the measuring system must remain constant throughout the measurement period. Instrument drift can be checked by re-measuring the standard source.

With discontinuous measurements, several readings at each wavelength can be taken and averaged, or other filtering methods can be employed to minimize the effect of electrical noise on the measurement.

With continuous measurements, the spectrum is scanned from one end to the other at a uniform rate, and the signal from the detector is integrated over discrete intervals within the scanning period. This approach effectively converts the spectral power distribution into a histogram, the height of a segment being proportional to the power emitted by the source over that interval. In principle, this method does not require that the scanning intervals and the monochromator bandwidths be perfectly correlated, but the best resolution is obtained when they are. An advantage of this method is excellent rejection of electrical noise, which is integrated out of the measurement in the signal averaging that takes place over each interval. It is also efficient, as there is no stopping and starting of the wavelength drive. When this method is adopted, the timing requirements are critical and the system response time must be adequate to capture the rapidly changing signal levels encountered during the scanning process. This is especially important when strong spectral lines are present.

Modern spectroradiometers incorporate a means of automating both the operation of the system and the data collection process.^{75,76} Some form of immediate presentation of the data, such as a graph on a chart recorder, is desirable to aid in the recognition of malfunctions in the measurement system or instability in the test source.

The final presentation of the data is usually in the form of a series of values that describe the SPD of the light source over a particular spectral range. Typically, an SPD curve accompanies the report of numerical data on output versus wavelength.

A suitable wavelength interval for a particular test is chosen by considering the type of spectra being measured. Excessively small intervals are wasteful, requiring the collection of unnecessary data. Excessively large intervals can result in missed information. For optimum results, the sample interval and the bandwidth of the instrument are the same. The SPD from an incandescent lamp can be adequately represented by a series of measurements at 10-nm intervals across the spectrum, since the intensity changes gradually with wavelength. For measurements on discharge lamps, whose spectra include a number of emission lines, a smaller interval is required. For the calculation of chromaticity, which is one of the most important applications of spectroradiometric data, a 2-nm sample interval and bandwidth gives values of the chromaticity coordinates x and y accurate to ± 0.001 for almost any type of source, and this is adequate for most purposes.

Color Appearance of Light Sources

For measurement of the color appearance of a light source, see Chapter 4, Color.

Life Performance Testing of Lamps

Life tests are performed on a very small portion of the products under consideration. Under such conditions, test program planning, sampling techniques, and data evaluation become especially important.⁷⁷⁻⁷⁹

It is not practical to test lamps under all of the many variables that occur in service; hence specific reproducible procedures must be included in the test experiment plan.

Incandescent Lamp Life Testing.⁸⁰⁻⁸³ Life tests of incandescent filament lamps can be divided into two classes: rated-voltage and overvoltage tests.

Rated Voltage. Lamps are operated in the specified burning position at a voltage or current held within $\pm 0.25\%$ of rated value. Sockets should be designed to assure good contact with lamp bases, and the racks should not be subjected to excessive shocks or vibration. If lamps are removed for interim photometric readings, care should be taken to avoid accidental filament breakage. Sockets should be lubricated, because vibration can break a filament that has been rendered brittle by burning.

Overvoltage (Accelerated) Tests. Lamp life is shortened by voltages in excess of rated. Extreme overvoltage life testing, sometimes called "high forced testing," exponentially shortens lamp life so that lamps can be tested in less time. The exponents are empirical and require many comparison tests at rated voltages to determine them.

Electric Discharge Lamp Life Testing.⁸⁴⁻⁸⁶ Tests generally are made using ac supply. The power supply should have a voltage waveform in which the harmonic content does not exceed 3% of the fundamental. The line voltage should be regulated. There is no widely accepted method of accelerated life testing of discharge lamps.

Auxiliaries. Since an electric discharge lamp must be operated with auxiliaries, which often affect lamp life, they must be selected to conform to the requirements of the appropriate guides, test methods, and specifications.

Test Cycles. An on-off cycle is normally employed to simulate field conditions. The commonly accepted cycles are 3 h on and 20 min off for fluorescent lamps, and 11 h on and 1 h off for high-intensity discharge lamps, although others are in use. It is known that more rapid cycling (that is, shorter off-times) shortens lamp life, but the correlation with the standard cycle is not sufficiently accurate to predict the life on the standard cycle.

Environment. Vibration, shock, room temperature, and drafts should be controlled to minimize their effect on measurement results.

Orientation. Lamps should be tested in an orientation recommended by the lamp manufacturer. See the IESNA guides for testing specific lamp types.^{37,52-54,62}

Luminaire Photometry

The purpose of making photometric measurements of a luminaire is to determine its light distribution and characteris-

tics in a way that will most adequately describe its performance. Characteristics such as intensity distribution, zonal lumens, efficiency, luminances, beam widths, and typing are necessary in designing, specifying, and selecting lighting equipment. Photometric data are essential in deriving and developing additional application information.

The information that follows is only a rudimentary guide to the photometry of luminaires. Specific photometric guides and practices are referenced below and should be consulted to obtain the detailed testing procedure for each type of luminaire. The IES Practical Guide to Photometry⁴⁷ provides information covering general photometric practices, equipment, and related matters. Each specific type of luminaire (indoor lighting, task lighting, floodlighting, or streetlighting) requires different testing procedures. However, there are several general requirements that should be met in all tests. The luminaire to be tested should be (1) typical of the unit it is to represent, (2) clean and free of defects (unless it is the purpose of the test to determine the effects of such conditions), (3) equipped with lamps of the size and type recommended for use in service, and (4) installed with the light source in the recommended operating position for service. If the location of the source in a beam-producing luminaire is adjustable, it should be positioned as recommended to obtain such a beam as is desired in service.

To provide an accurate description of the characteristics of the materials used in the manufacture of a luminaire, measurements should be made of the reflectances of reflecting surfaces where applicable.

Luminaires should be tested in a controlled environment under controlled conditions. The photometric laboratory temperature should be held steady. Typically, for fluorescent photometry, where lamps are sensitive to temperature variations, the room temperature should be held to $25 \pm 1^\circ\text{C}$. Power supplies should be regulated and free of distortion to minimize any effects of line voltage variations. Test rooms should be painted black or provided with sufficient baffling to minimize or eliminate extraneous and reflected light during testing.

For accurate measurements, the distance between the luminaire and the light sensor should be great enough that the inverse square law applies (Equation 2-1). The minimum test distance is governed by the dimensions of the luminaire. This distance should not be less than 3 m (10 ft) and at least five times the maximum dimension of the luminous area of the luminaire. For best accuracy the test distance should be measured from the center of the apparent source to the surface of the detector. However, from a practical standpoint, the following rules should suffice: (1) for recessed, coffered, and totally direct luminaires, the test distance should be measured to the plane of the light opening (plane of the ceiling); (2) for luminous-sided luminaires the test distance should be measured to the geometric center of the lamps; (3) for suspended luminaires, (a) if the light center of the lamp(s) is within the bounds of the reflector and there is no refractor, the test distance should be measured to the plane

of the light opening, (b) if the light center of the lamp(s) does not fall within the bounds of the reflector and there is no refractor, the test distance should be measured to the light center of the lamp(s), and (c) if a refractor is attached, then the test distance should be measured to the geometric center of the refractor.

General-Lighting Luminaires

Intensity Distribution. See the following IESNA guides for specific information on testing general-lighting luminaires: Photometric Testing of Indoor Fluorescent Luminaires,⁸⁷ Photometric Testing of Indoor Luminaires Using High Intensity Discharge or Incandescent Filament Lamps,⁸⁸ and Reporting General Lighting Equipment Engineering Data.^{89,90}

The basic measurement made in a photometric test of a luminaire is the luminous intensity in specified planes and angles. The resulting intensity distribution is used to determine zonal lumens, efficiency, and average luminances. It is therefore essential that sufficient data be taken to adequately describe the intensity distribution and the luminaire's total luminous flux.

Luminaires having a symmetric distribution can be measured in five to twelve equally spaced planes and the results averaged. Most fluorescent luminaires are measured in five planes per quadrant in opposite quadrants, and the results for the two quadrants averaged to give the five-plane data. To adequately describe a highly asymmetric luminaire it might be necessary to measure in planes at 10° (or smaller) intervals.

The distribution in each vertical plane is determined by taking readings at 10° (or smaller) intervals. If the luminaire is of the beam-forming type, the intensity measurements should be made at smaller intervals within the beam-forming area. If visual comfort probability calculations are to be made, it is recommended that intensity measurements be made at least at every 5° in the vertical plane, and preferably every 2 1/2°.

Most luminaires are measured using the relative method, similar to that for lamps. From these readings, total luminous flux can be estimated using the zonal lumen method. The lumen rating of the lamp is divided by this value to give the constant factor for that lamp on that photometer. By multiplying by that constant, the readings taken on the luminaire can be converted to luminous intensity for the lamps operating as rated.

The intensity distribution data generally are presented in tabular form on the test report sheet. Data for a lens or indoor luminaire are given in five planes. Three distributions (parallel to the lamps, 45° to parallel, perpendicular to the lamps) usually are presented in the form of polar distribution curves.

Luminance. Either before or after the photometric test, while the lamps are still installed and stabilized, the maximum luminance of the luminaire should be measured at the angles specified in the appropriate guide and at the shielding

angles. The readings should be taken both crosswise and lengthwise in the case of fluorescent luminaires or luminaires giving asymmetric distributions. The projection of the measurement field should be circular and of 6.45 cm² (1 in.²) area. The luminance photometer must be calibrated for the SPD of the test lamps.

If average luminance values are desired, they can be calculated by using the intensity measurements obtained from the test data. By definition, luminance is the luminous intensity (candlepower) of any surface in a given direction per unit of projected area of the surface viewed from that direction.⁹¹

Total Luminous Flux. The total luminous flux from of the luminaire, needed to establish its efficiency in terms of the total luminous flux of the installed lamps(s), can be determined in an integrating-sphere photometer or by computations from the intensity distribution data.

If it is to be measured in a sphere, the efficiency can be determined by the relative method (Figure 2-18). First, lamps are mounted at the center of the sphere and a reading taken. A reading is then taken on an auxiliary lamp mounted at another point in the sphere. The luminaire is then mounted at the center of the sphere, and a reading is taken. Another reading is then taken with the auxiliary lamp mounted in the sphere. The efficiency is then calculated as follows:

$$\text{efficiency} = \frac{R_3 R_2}{R_1 R_4} \times 100\% \quad (2-4)$$

where

R_1 = reading of lamp(s) at the center of the sphere,

R_2 = auxiliary lamp reading,

R_3 = luminaire reading,

R_4 = auxiliary lamp reading with luminaire in the sphere.

Only one lamp (or one luminaire) should be operated whenever a reading is being taken. The sphere method is not considered to be as accurate as the method using luminous intensity distribution data.

Intensity distribution data are used to compute the luminous flux in any angular zone from nadir to 180°. The product of the midzone intensity and the zonal constant gives the zonal lumens. The summation of the zonal lumens multiplied by 100 and divided by the nominal lamp lumens gives the efficiency in percent.

Constants useful in calculating luminous flux from intensity data are given in Figures 2-19 and 2-20. For computing the luminous flux, the average luminous intensity at the center of each zone should be multiplied by the zonal constant (Figure 2-19) equal to $2\pi(\cos \theta_1 - \cos \theta_2)$. In Figure 2-18, the zone limits represent θ_1 and θ_2 . The measurements should be made at the midpoint of this interval.

The constants in Figure 2-20 are computed for intensity measurements on projector-type luminaires made on a goniometer of the type shown in Figure 2-11b. In this figure,

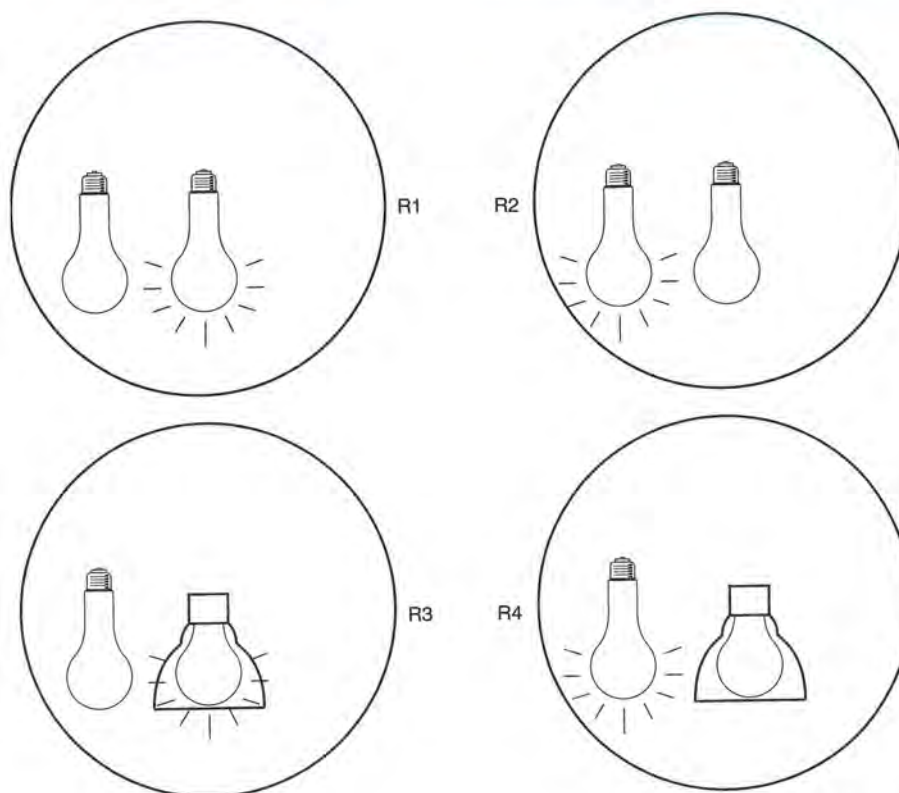


Figure 2-18. Luminaire and lamp positions within an integrating sphere for the relative method of determining luminaire efficiency. The diameter of the sphere should be at least twice the maximum dimension of the luminaire to be measured.

Figure 2-19. Constants for Use in the Zonal Method of Computing Luminous Flux from Intensity Data

1° Zones		2° Zones		5° Zones		10° Zones	
Zone Limits (degrees)	Zonal Constant	Zone Limits (degrees)	Zonal Constant	Zone Limits (degrees)	Zonal Constant	Zone Limits (degrees)	Zonal Constant
0-1	0.0009	0-2	0.0038	0-5	0.0239	0-10	0.095
1-2	.0029	2-4	.0115	5-10	.0715	10-20	.283
2-3	.0048	4-6	.0191	10-15	.1186	20-30	.463
3-4	.0067	6-8	.0267	15-20	.1649	30-40	.628
4-5	.0086	8-10	.0343	20-25	.2097	40-50	.774
5-6	.0105	10-12	.0418	25-30	.2531	50-60	.897
6-7	.0124	12-14	.0493	30-35	.2946	60-70	.993
7-8	.0143	14-16	.0568	35-40	.3337	70-80	1.058
8-9	.0162	16-18	.0641	40-45	.3703	80-90	1.091
9-10	.0181	18-20	.0714	45-50	.4041		
				50-55	.4349		
				55-60	.4623		
				60-65	.4862		
				65-70	.5064		
				70-75	.5228		
				75-80	.5351		
				80-85	.5434		
				85-90	.5476		

Figure 2-20. Constants* (K) for Converting Beam Intensity of Projector-Type Luminaires (Searchlights, Floodlights, and Spotlights) into Luminous Flux

Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 0.1° Vertical						Spacing 0.1° Vertical <i>Continued</i>					
0.1° Horizontal						0.4° Horizontal <i>Continued</i>					
0.05	0. ⁵ 3046	2.75	0. ⁵ 3043	5.45	0. ⁵ 3032	1.4	1218	4.2	1215	7.0	1210
0.15	3046	2.85	3042	5.55	3032	1.8	1218	4.6	1215	7.4	1208
0.25	3046	2.95	3042	5.65	3031	2.2	1217	5.0	1214	7.8	1207
0.35	3046	3.05	3042	5.75	3031	2.6	1217	5.4	1213		
0.45	3046	3.15	3042	5.85	3030						
0.55	3046	3.25	3041	5.95	3030	0.6° Horizontal					
0.65	3046	3.35	3041	6.05	3029	0.3	0. ⁴ 1827	3.3	0. ⁴ 1825	5.7	0. ⁴ 1819
0.75	3046	3.45	3041	6.15	3029	0.9	1827	3.9	1824	6.3	1816
0.85	3046	3.55	3040	6.25	3028	1.5	1827	4.5	1822	6.9	1814
0.95	3046	3.65	3040	6.35	3028	2.1	1827	5.1	1821	7.5	1810
1.05	3046	3.75	3040	6.45	3027	2.7	1826				
1.15	3046	3.85	3039	6.55	3026	0.8° Horizontal					
1.25	3045	3.95	3039	6.65	3026	0.4	0. ⁴ 2437	3.6	0. ⁴ 2432	6.0	0. ⁴ 2424
1.35	3045	4.05	3039	6.75	3025	1.2	2436	4.4	2429	6.8	2420
1.45	3045	4.15	3038	6.85	3024	2.0	2435	5.2	2427	7.6	2416
1.55	3045	4.25	3038	6.95	3024	2.8	2434				
1.65	3045	4.35	3037	7.05	3023	1.0° Horizontal					
1.75	3045	4.45	3037	7.15	3023	0.5	0. ⁴ 3046	3.5	0. ⁴ 3041	6.5	0. ⁴ 3027
1.85	3045	4.55	3037	7.25	3022	1.5	3045	4.5	3037	7.5	3020
1.95	3044	4.65	3036	7.35	3021	2.5	3043	5.5	3032		
2.05	3044	4.75	3036	7.45	3021	Spacing 0.2° Vertical					
2.15	3044	4.85	3035	7.55	3020	0.2° Horizontal					
2.25	3044	4.95	3035	7.65	3019	0.1	0. ⁴ 1219	2.9	0. ⁴ 1217	5.5	0. ⁴ 1213
2.35	3044	5.05	3034	7.75	3018	0.3	1219	3.1	1217	5.7	1212
2.45	3043	5.15	3034	7.85	3018	0.5	1218	3.3	1217	5.9	1212
2.55	3043	5.25	3033	7.95	3017	0.7	1218	3.5	1216	6.1	1212
2.65	3043	5.35	3033			0.9	1218	3.7	1216	6.3	1211
0.2° Horizontal						1.1	1218	3.9	1216	6.5	1211
0.1	0. ⁵ 6092	2.9	0. ⁵ 6085	5.5	0. ⁵ 6065	1.3	1218	4.1	1215	6.7	1210
0.3	6092	3.1	6084	5.7	6063	1.5	1218	4.3	1215	6.9	1210
0.5	6092	3.3	6083	5.9	6061	1.7	1218	4.5	1215	7.1	1209
0.7	6092	3.5	6081	6.1	6058	1.9	1218	4.7	1214	7.3	1209
0.9	6091	3.7	6080	6.3	6056	2.1	1218	4.9	1214	7.5	1208
1.1	6091	3.9	6079	6.5	6054	2.3	1218	5.1	1214	7.7	1208
1.3	6091	4.1	6077	6.7	6051	2.5	1217	5.3	1213	7.9	1207
1.5	6090	4.3	6076	6.9	6049	2.7	1217				
1.7	6089	4.5	6074	7.1	6046	0.4° Horizontal					
1.9	6089	4.7	6073	7.3	6044	0.2	0. ⁴ 2437	3.0	0. ⁴ 2434	5.8	0. ⁴ 2425
2.1	6088	4.9	6071	7.5	6041	0.6	2437	3.4	2433	6.2	2423
2.3	6087	5.1	6069	7.7	6038	1.0	2437	3.8	2432	6.6	2421
2.5	6087	5.3	6067	7.9	6035	1.4	2436	4.2	2430	7.0	2419
2.7	6086					1.8	2436	4.6	2429	7.4	2417
0.4° Horizontal						2.2	2435	5.0	2428	7.8	2414
0.2	0. ⁴ 1219	3.0	0. ⁴ 1217	5.8	0. ⁴ 1212	2.6	2434	5.4	2426		
0.6	1218	3.4	1216	6.2	1211						
1.0	1218	3.8	1216	6.6	1210						

Figure 2-20. *Continued*

Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 0.2° Vertical <i>Continued</i>						Spacing 0.4° Vertical <i>Continued</i>					
0.6° Horizontal						0.6° Horizontal <i>Continued</i>					
0.3	0. ⁴ 3655	3.3	0. ⁴ 3649	5.7	0. ⁴ 3637	2.1	7306	5.1	7282	7.5	7248
0.9	3655	3.9	3647	6.3	3633	2.7	7302				
1.5	3654	4.5	3644	6.9	3629						
2.1	3653	5.1	3641	7.5	3624						
2.7	3651										
0.8° Horizontal						0.8° Horizontal					
0.4	0. ⁴ 4874	3.6	0. ⁴ 4864	6.0	0. ⁴ 4848	0.4	0. ⁴ 9747	3.6	0. ⁴ 9728	6.0	0. ⁴ 9694
1.2	4872	4.4	4858	6.8	4840	1.2	9746	4.4	9719	6.8	9679
2.0	4870	5.2	4854	7.6	4832	2.0	9742	5.2	9707	7.6	9662
2.8	4868					2.8	9736				
1.0° Horizontal						1.0° Horizontal					
0.5	0. ⁴ 6092	3.5	0. ⁴ 6082	6.5	0. ⁴ 6054	0.5	0. ³ 1218	3.5	0. ³ 1216	6.5	0. ³ 1211
1.5	6090	4.5	6074	7.5	6040	1.5	1218	4.5	1215	7.5	1208
2.5	6086	5.5	6064			2.5	1217	5.5	1212		
Spacing 0.4° Vertical						Spacing 0.6° Vertical					
0.2° Horizontal						0.2° Horizontal					
0.1	0. ⁴ 2437	2.9	0. ⁴ 2434	5.5	0. ⁴ 2426	0.1	0. ⁴ 3655	2.9	0. ⁴ 3650	5.5	0. ⁴ 3638
0.3	2437	3.1	2434	5.7	2425	0.3	3655	3.1	3650	5.7	3637
0.5	2437	3.3	2433	5.9	2424	0.5	3655	3.3	3649	5.9	3636
0.7	2437	3.5	2432	6.1	2423	0.7	3655	3.5	3649	6.1	3635
0.9	2437	3.7	2432	6.3	2422	0.9	3655	3.7	3648	6.3	3634
1.1	2437	3.9	2431	6.5	2421	1.1	3655	3.9	3647	6.5	3632
1.3	2436	4.1	2431	6.7	2420	1.3	3654	4.1	3646	6.7	3631
1.5	2436	4.3	2430	6.9	2419	1.5	3654	4.3	3645	6.9	3629
1.7	2436	4.5	2430	7.1	2418	1.7	3654	4.5	3644	7.1	3628
1.9	2436	4.7	2429	7.3	2417	1.9	3653	4.7	3643	7.3	3626
2.1	2435	4.9	2428	7.5	2416	2.1	3653	4.9	3642	7.5	3625
2.3	2435	5.1	2427	7.7	2415	2.3	3653	5.1	3641	7.7	3622
2.5	2434	5.3	2426	7.9	2414	2.5	3652	5.3	3640	7.9	3621
2.7	2434					2.7	3652				
0.4° Horizontal						0.4° Horizontal					
0.2	0. ⁴ 4874	3.0	0. ⁴ 4867	5.8	0. ⁴ 4849	0.2	0. ⁴ 7310	3.0	0. ⁴ 7301	5.8	0. ⁴ 7273
0.6	4874	3.4	4865	6.2	4846	0.6	7310	3.4	7299	6.2	7268
1.0	4874	3.8	4863	6.6	4842	1.0	7310	3.8	7295	6.6	7262
1.4	4872	4.2	4861	7.0	4838	1.4	7308	4.2	7292	7.0	7256
1.8	4872	4.6	4858	7.4	4834	1.8	7307	4.6	7288	7.4	7250
2.2	4870	5.0	4855	7.8	4829	2.2	7306	5.0	7283	7.8	7243
2.6	4869	5.4	4852			2.6	7303	5.4	7278		
0.6° Horizontal						0.6° Horizontal					
0.3	0. ⁴ 7310	3.3	0. ⁴ 7299	5.7	0. ⁴ 7274	0.3	0. ³ 1097	3.3	0. ³ 1095	5.7	0. ³ 1091
0.9	7310	3.9	7294	6.3	7267	0.9	1097	3.9	1094	6.3	1090
1.5	7308	4.5	7288	6.9	7258	1.5	1096	4.5	1093	6.9	1089
						2.1	1096	5.1	1092	7.5	1087
						2.7	1095				

Figure 2-20. *Continued*

Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 0.6° Vertical <i>Continued</i>						Spacing 0.8° Vertical <i>Continued</i>					
0.8° Horizontal						1.0° Horizontal					
0.4	0. ³ 1462	3.6	0. ³ 1459	6.0	0. ³ 1454	0.5	0. ³ 2437	3.5	0. ³ 2432	6.5	0. ³ 2421
1.2	1462	4.4	1458	6.8	1452	1.5	2436	4.5	2429	7.5	2416
2.0	1461	5.2	1456	7.6	1449	2.5	2435	5.5	2426		
2.8	1460										
1.0° Horizontal						Spacing 1.0° Vertical					
0.5	0. ³ 1828	3.5	0. ³ 1824	6.5	0. ³ 1816	0.1° Horizontal					
1.5	1827	4.5	1822	7.5	1812	0.05	0. ⁴ 3046	2.75	0. ⁴ 3043	5.45	0. ⁴ 3032
2.5	1826	5.5	1819			0.15	3046	2.85	3042	5.55	3032
Spacing 0.8° Vertical						0.25	3046	2.95	3042	5.65	3031
0.2° Horizontal						0.35	3046	3.05	3042	5.75	3031
0.1	0. ⁴ 4874	2.9	0. ⁴ 4867	5.5	0. ⁴ 4851	0.45	3046	3.15	3042	5.85	3030
0.3	4874	3.1	4867	4.7	4850	0.55	3046	3.25	3041	5.95	3030
0.5	4874	3.3	4866	5.9	4848	0.65	3046	3.35	3041	6.05	3029
0.7	4874	3.5	4865	6.1	4846	0.75	3046	3.45	3041	6.15	3029
0.9	4874	3.7	4864	6.3	4845	0.85	3046	3.55	3040	6.25	3028
1.1	4874	3.9	4862	6.5	4842	0.95	3046	3.65	3040	6.35	3028
1.3	4872	4.1	4862	6.7	4841	1.05	3046	3.75	3040	6.45	3027
1.5	4872	4.3	4860	6.9	4838	1.15	3046	3.85	3039	6.55	3026
1.7	4872	4.5	4859	7.1	4837	1.25	3045	3.95	3039	6.65	3026
1.9	4871	4.7	4858	7.3	4834	1.35	3045	4.05	3039	6.75	3025
2.1	4870	4.9	4856	7.5	4833	1.45	3045	4.15	3038	6.85	3024
2.3	4870	5.1	4854	7.7	4830	1.55	3045	4.25	3038	6.95	3024
2.5	4869	5.3	4853	7.9	4828	1.65	3045	4.35	3037	7.05	3023
2.7	4869					1.75	3045	4.45	3037	7.15	3023
0.4° Horizontal						1.85	3045	4.55	3037	7.25	3022
0.2	0. ⁴ 9747	3.0	0. ⁴ 9734	5.8	0. ⁴ 9698	1.95	3044	4.65	3036	7.35	3021
0.6	9747	3.4	9730	6.2	9691	2.05	3044	4.75	3036	7.45	3021
1.0	9747	3.8	9726	6.6	9683	2.15	3044	4.85	3035	7.55	3020
1.4	9744	4.2	9722	7.0	9675	2.25	3044	4.95	3035	7.65	3019
1.8	9743	4.6	9717	7.4	9667	2.35	3044	5.05	3034	7.75	3018
2.2	9741	5.0	9710	7.8	9658	2.45	3043	5.15	3034	7.85	3018
2.6	9738	5.4	9704			2.55	3043	5.25	3033	7.95	3017
0.6° Horizontal						2.65	3043	5.35	3033		
0.3	0. ³ 1462	3.3	0. ³ 1460	5.7	0. ³ 1455	0.2° Horizontal					
0.9	1462	3.9	1459	6.3	1453	0.1	0. ⁴ 6092	2.9	0. ⁴ 6085	5.5	0. ⁴ 6065
1.5	1462	4.5	1458	6.9	1452	0.3	6092	3.1	6084	5.7	6063
2.1	1461	5.1	1456	7.5	1450	0.5	6092	3.3	6083	5.9	6061
2.7	1460					0.7	6092	3.5	6081	6.1	6058
0.8° Horizontal						0.9	6092	3.7	6080	6.3	6056
0.4	0. ³ 1949	3.6	0. ³ 1946	6.0	0. ³ 1939	1.1	6092	3.9	6079	6.5	6054
1.2	1949	4.4	1944	6.8	1936	1.3	6090	4.1	6077	6.7	6051
2.0	1948	5.2	1941	7.6	1932	1.5	6090	4.3	6076	6.9	6049
2.8	1947					1.7	6089	4.5	6074	7.1	6046
						1.9	6089	4.7	6073	7.3	6044
						2.1	6088	4.9	6071	7.5	6041
						2.3	6087	5.1	6069	7.7	6038
						2.5	6087	5.3	6067	7.9	6035
						2.7	6086				

Figure 2-20. Continued

Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K	Horizontal Angle and Setting	K
Spacing 1.0° Vertical Continued						Spacing 2° Vertical Continued					
0.4° Horizontal						2° Horizontal Continued					
0.2	0. ³ 1219	3.0	0. ³ 1217	5.8	0. ³ 1212	19	115	49	080	79	23
0.6	1218	3.4	1216	6.2	1211	21	114	51	077	81	19
1.0	1218	3.8	1216	6.6	1210	23	112	53	073	83	15
1.4	1218	4.2	1215	7.0	1210	25	110	55	070	85	11
1.8	1218	4.6	1215	7.4	1208	27	108	57	066	87	06
2.2	1217	5.0	1214	7.8	1207	29	107	59	063	89	02
2.6	1217	5.4	1213								
0.6° Horizontal						5° Horizontal					
0.3	0. ³ 1828	3.3	0. ³ 1825	5.7	0. ³ 1819	2.5	0. ² 3046	32.5	0. ² 2570	62.5	0. ² 1406
0.9	1828	3.9	1824	6.3	1816	7.5	3020	37.5	2416	67.5	1166
1.5	1827	4.5	1822	6.9	1814	12.5	2970	42.5	2246	72.5	0918
2.1	1827	5.1	1821	7.5	1810	17.5	2906	47.5	2060	77.5	658
2.7	1826					22.5	2814	52.5	1856	82.5	396
						27.5	2702	57.5	1638	87.5	134
0.8° Horizontal						10° Horizontal					
0.4	0. ³ 2437	3.6	0. ³ 2432	6.0	0. ³ 2424	5	0. ² 6066	35	0. ² 4986	65	0. ² 2572
1.2	2436	4.4	2430	6.8	2420	15	5876	45	4306	75	1576
2.0	2436	5.2	2427	7.6	2416	25	5576	55	3494	85	0530
2.8	2434										
1.0° Horizontal						Spacing 5° Vertical					
0.5	0. ³ 3046	3.5	0. ³ 3041	6.5	0. ³ 3027	5° Horizontal					
1.5	3045	4.5	3037	7.5	3020	2.5	0. ² 760	32.5	0. ² 642	62.5	0. ² 352
2.5	3043	5.5	3032			7.5	755	37.5	604	67.5	291
						12.5	744	42.5	562	72.5	229
						17.5	726	47.5	514	77.5	165
						22.5	704	52.5	463	82.5	099
						27.5	676	57.5	409	87.5	033
Spacing 2° Vertical						10° Horizontal					
2° Horizontal						5	0.015165	35	0.012465	65	0. ² 6430
1	0. ² 122	31	0. ² 104	61	0. ³ 59	15	14690	45	10765	75	3940
3	122	33	102	63	55	25	13790	55	08735	85	1325
5	121	35	100	65	51						
7	121	37	097	67	48						
9	120	39	095	69	44						
11	120	41	092	71	40						
13	119	43	089	73	36	5	0.0304	35	0.0249	65	0.0129
15	118	45	086	75	32	15	294	45	214	75	076
17	116	47	083	77	27	25	276	55	174	85	026

* Note: Small numbers following the decimal point indicate number of zeros following the decimal point but before the numbers shown.

the vertical spacing is ϕ and the horizontal angle and setting represents the midpoint between θ_1 and θ_2 . If the measurements have been made with the type shown in Figure 2-11a, the same constants can be used by interchanging the vertical and horizontal angular arguments, that is, by substituting the word "vertical" wherever "horizontal" appears, and vice versa. The zonal constants for Figure 2-20 were computed as $\phi\pi(\sin \theta_2 - \sin \theta_1)/180$, where ϕ is the vertical interval

and θ_1 and θ_2 are the limits of the horizontal interval. If a goniometer of the type in Figure 2-11a is used, the constant is equal to $\theta\pi(\sin \phi_2 - \sin \phi_1)/180$, where θ is the horizontal interval and ϕ_1 and ϕ_2 are the limits of the vertical interval. See Reference 91 for additional zonal constants.

If a number of constants are to be calculated for the same interval, the following shortcut method is useful and accurate. For the first formula above, let θ_m be the midzone angle

and let P equal one-half the zone interval. The formula becomes

$$4\pi \sin P \sin \theta_m \quad (2-5)$$

The zone width is often the same for a series of constants. In these cases, the first factor is simply multiplied successively by the sines of the midzone angles.

For the second formula above, let θ_m be the median angle on the horizontal interval. The formula then becomes

$$2\pi \frac{\theta}{180} \sin P \cos \theta_m \quad (2-6)$$

It is commonly assumed that a ballast operated at its rated input voltage delivers rated wattage to a lamp, and that a lamp operated at its rated wattage delivers rated total luminous flux. In many instances, the assumption is invalid. Therefore, a procedure has been developed⁹² to provide a factor called the equipment operating factor to be applied to photometric data on luminaires to adjust them to the specific combination of luminaire, lamp type, and ballast used in a system. By repetitive tests, this procedure can be used to determine variations of system performance exclusive of lamp variations. Such a factor can be applied specifically to total luminous flux, intensity, and illuminance as given on photometric data sheets.

Two possibilities are recognized: the first (LLB1) in which the lamp is used in the operating position for which it is rated, and the second (LLB2) in which the lamp is operated in a position other than the one for which it is rated. The factors determined are equipment-specific (luminaire-lamp-ballast combination) under initial conditions unless specified otherwise.

The procedures essentially involve a relative measurement of total luminous flux. The test luminaire is operated at the rated supply voltage, after operating conditions have stabilized. Relative flux measurements are obtained with the test ballast and, without extinguishing the lamp, with the reference ballast operated at its rated input voltage. The equipment operating factor is the ratio of the first to the second measurement of total luminous flux.

Floodlight-Type Luminaires. The following applies to floodlighting equipment having total beam spread (divergence) of more than 10° . For specific information on testing this type of equipment, consult the IES Approved Method for Photometric Testing of Floodlights Using Incandescent Filament or Discharge Lamps.³⁷ For equipment having a beam spread less than 10° , see the IES Guide for Photometric Testing of Searchlights.⁹³

The classification of floodlights is based on horizontal and vertical beam width. The classification is designated by National Electrical Manufacturers Association (NEMA) type numbers.⁹⁴ For symmetrical beams the floodlight type is defined by the average of the horizontal and vertical beam spreads. For asymmetrical beams it is defined by the hori-

zontal and vertical beam spreads in that order; for example, a floodlight with a horizontal beam spread of 75° (Type 5) and a vertical beam spread of 35° (Type 3) would be designated as a Type 5 $\times$ 3 floodlight.

Stray light is defined as light emitted by the floodlight that is outside the classified beam. In some instances, stray light is useful in illumination. It can also be detrimental, depending on its magnitude and direction. To determine the amount and direction of stray light, it is necessary to make measurements as far horizontally and vertically as the readings have significant values in relation to the measuring system.

If the geometric center of the emitted light is not enclosed by the reflector, the floodlight should be mounted on the goniometer so that the light center of the lamp is at the goniometric center. If the lamp light center is within the reflector, the floodlight should be positioned so that the center of the reflector opening coincides with the goniometric center.

Either the direct or the relative method of photometry can be used for floodlights. The relative method has an advantage in that cumulative errors can be reduced and maintenance of standards of luminous intensity and flux is not necessary. In the latter method, relative intensity readings for the test lamp alone made with a distribution photometer, and for the lamp-floodlight combination made with a floodlight photometer, are taken with the lamp operating under identical electrical conditions in both tests.

The method of taking intensity readings is to traverse the beam with such angular spacings as to give approximately 100 uniformly spaced readings throughout the beam. For the definition of the beam limit, see Reference 95. By interpolating between these readings, an isocandela diagram can be plotted on rectangular coordinates (see Chapter 9, Lighting Calculations). The total luminous flux in the beam can be computed using the constants in Figure 2-20.

The information usually reported for floodlights includes the following: NEMA type, horizontal and vertical beam distribution curves, maximum beam luminous intensity, average maximum beam luminous intensity, beam spread in both horizontal and vertical directions, beam flux, beam efficiency, total floodlight flux, and total efficiency. The report should also indicate whether the data were obtained with a Type A, Type B, or Type C goniometer (Figure 2-11 a, b, and c).^{96,97}

Roadway Luminaires. A guide has been prepared to provide test procedures and methods of reporting data to promote consistent evaluation of roadway luminaires performance that use incandescent filament or high-intensity discharge lamps.⁹⁸

Luminaires selected for test should be representative of the manufacturer's product. A test distance of 8 to 10 m (25 to 30 ft) should be sufficient for most beam-forming luminaires. The photometric test distance is generally defined as the distance from the light center to the surface of the detector, taking into account the distances to and from any mirrors that might be used.

The number of planes explored during photometric measurements should be determined by the symmetry or irregularity of the distribution and by the purpose of the test. The number of vertical angles at which readings are taken depends on how the readings are to be used. If an isocandela diagram is to be plotted, readings might have to be taken at close intervals, especially if the values change rapidly. Computer acquisition systems provide comprehensive evaluation of luminaires and lighting application designs; readings taken at vertical angle intervals through the beam section do not exceed $2\frac{1}{2}^\circ$.

For luminaires having a distribution that is symmetrical about a vertical axis (IES Type V), readings should be taken in ten or more vertical planes and averaged.

For luminaires having a distribution that is symmetrical about a single vertical plane (IES Types II, III, IV, and II four-way), readings should be taken in vertical planes that are no more than 10° apart. To simplify data processing, it can be advantageous to divide the beam section laterally into 10° zones and measure at the midzone angle. Averages may be taken of the readings at corresponding angles on the opposite sides of the plane of symmetry. Any computations that are to be performed can then be done on one side of the plane of symmetry, using the averaged data.

For luminaires having a distribution that is symmetric about two vertical planes (IES Type I), readings should be taken as above, but the computations may be performed in one quadrant of the sphere.

For luminaires having a distribution that is symmetric about four vertical planes (IES Type I four-way), readings may be taken as above, but the computations may be performed in one octant of the sphere.

For luminaires having an asymmetric distribution, readings should be taken in vertical planes that no more than are 10° apart. Since there is no symmetry, any computations performed should be done without averaging the data obtained from different planes.

Sufficient data should be obtained to allow classification of the light distribution in accordance with recommended practice (see Chapter 22, Roadway Lighting) as well as to provide an isolux (isofootcandle) diagram, the utilization efficiency, and the total and four-quadrant efficiencies.

Projector Luminaires.^{98,100} The equipment required for photometric measurements of projectors, searchlights, and beacons is similar in most respects to that required for other types of photometry.

When the projector luminaire is of unusual size and weight, it might be necessary to use its own mounting and goniometric facilities for the photometric work, or to hold the luminaire fixed and traverse the beam by moving the detector.

Since projector luminaires can have a total beam spread of less than 1° and furthermore can be massive, the mechanical requirements on the goniometer are severe (Figure 2-21). Rigidity, freedom from backlash, and accuracy of angular



Figure 2-21. Typical goniometer for indoor photometric range. Two rotary tables of the type used in large machine tools are incorporated into the goniometer to provide two of the three rotations available. For horizontal distributions either the rotary table on which the outer frame is mounted or the inner table on which the test equipment is mounted may be used. This makes for flexibility and is especially useful for obtaining polar angle distributions. The inner frame with the test unit mounted can then be balanced with the adjustable counterweights. After balancing, a small constant torque is applied to the inner frame through the use of the pulley and weight at the side, thus eliminating backlash.

measurements are prime requirements. There should be provision for accurate angular settings of the order of 0.1° or less.

Indoor photometric measurements are preferred but frequently impracticable because of the lengths required. For photometry on the relatively short indoor ranges, proper photometric procedures must be followed.^{31,43,92,101} Outdoor ranges require much more attention to methods of reducing stray light, minimizing atmospheric disturbances, and correcting for atmospheric transmission. Range sites should be selected where the terrain is flat and uniform. The range should be as high off the ground as practicable. Stray light should be minimized by a suitable system of diaphragms. Any remaining stray light should be measured and subtracted from all readings.

Ranges should not be located where atmospheric disturbances occur regularly or where dust or moisture are prevalent. The absorption and scattering of light by moisture, smoke, and dust particles, even in an apparently clear atmosphere, can introduce considerable errors in measurements.^{102,103} Therefore, it is desirable to measure the atmospheric transmittance before and after the test. A standard

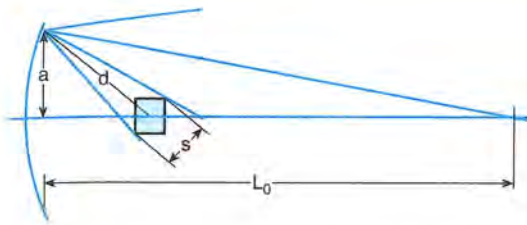


Figure 2-22. Diagram showing distances and dimensions used to determine minimum inverse-square distance.

reference projector is frequently employed, calibrated either by repeated observations in the clearest weather, when the atmospheric transmittance can be accurately estimated or independently measured, or by laboratory measurement methods.

The illuminance from searchlights, beacons, or other highly collimating luminaires, if measured at distances greater than a certain minimum, obeys the inverse square law (Equation 2-1). The minimum distance is a function of the focal length of the reflector, the diameter of the reflector aperture, and the diameter of the smallest element of the light source (arc stream or filament). This minimum distance is called the beam crossover point and is the distance where the optic is seen to be completely flashed, that is, the minimum distance where the refracting lens or the reflector is seen as completely luminous. Only at distances greater than this does the inverse square law apply. This minimum distance can be calculated by using the following general formula (Figure 2-22):

$$L_0 = \frac{ad}{Ks} \quad (2-7)$$

where

- L_0 = minimum distance for optic under consideration,
- a = distance from the optical axis to the outermost flashed point when viewed from a distance point on the optical axis,
- d = distance from the centroid of the light source to the same outermost flashed point as used to determine a ,
- s = diameter of the smallest element of the light source (for example, the arc stream width of an arc source, or one coil of a multicoil filament lamp),

K = constant equal to 500 when a , d , and s are in mm and L_0 is in m; and 6 when a , d , and s are in inches and L_0 is in ft.

The above calculation determines the minimum inverse square distance based on ideal light sources and axial measurements, and therefore should be considered approximate. In practice, the range used should be much larger than this calculated distance to ensure conformance. Methods for using shorter ranges and "zero-length photometry" have been devised; however, the full length range gives the highest accuracy. These methods and a fuller discussion of minimum inverse-square-distance calculations can be found in References 92, 100, and 104.

Luminance Measurements¹⁰⁵

Luminance measurements of lamps and luminaires should be made by either the absolute or the relative method. With the absolute method, reference standards must be available for equipment calibration. In practice the relative method is generally used.

The published luminances of symmetric fluorescent lamps are computed from the rated lumen output of the lamp according to the following formula:¹⁰⁶

$$L_{avg} = \frac{K \times (\text{total lamp lumens})}{(\text{lamp diameter}) \times (\text{lamp luminous length})} \quad (2-8)$$

where L_{avg} is the average luminance of the full width of the lamp at its center, in candelas per square meter. The diameter and length are expressed in meters or inches, and K for T-12 lamps is as follows:

Size		K
(m)	(in.)	
1.22	48	0.118
1.83	72	0.115
2.44	96	0.113

To compute the approximate luminance L_θ of a fluorescent lamp at any angle to the lamp axis, the following formula is used:

$$L_\theta = \frac{\text{total lamp lumens}}{K_\theta \times (\text{lamp diameter}) \times (\text{lamp luminous length}) \times \sin \theta}$$

where K_θ is as shown in Figure 2-23.

Figure 2-23. Values at Various Angles of the Lamp: Intensity Ratio K_θ for Preheat-Starting Types of Fluorescent Lamps (Average for 15, 20, 30, 40, and 100 W Lamps)

Angle (degrees)	0	10	20	30	40	50	60	70	80	90
K_θ	—	172.0	46.0	24.7	17.1	13.3	11.3	10.1	9.5	9.25

A luminance meter should be used to make direct measurements of the luminaire luminance. The characteristics of the luminance meter should be such that the field of measurement corresponds to a projected area of 645 mm² (1 in.²) normal to its axis at the distance of measurement.¹⁰⁷ This can be achieved with an appropriate lens system and a measurement distance determined from the manufacturer's specifications. This technique has the advantage of the observer being able to view the exact area being measured through the luminance photometer.

Calorimetry of Luminaires

A thermal testing method has been developed for compiling data on air-cooled heat transfer luminaires.¹⁰⁸ The method uses a calorimeter to measure the thermal energy distribution of the luminaires. The entire laboratory room in which the calorimeter is located becomes a part of the calorimetric system. The room must be controlled closely with respect to temperature, air motion, and relative humidity. Varying conditions can affect the results of the calorimetric measurements. The room conditions should be as follows: the temperature should be controlled at $25 \pm 0.3^\circ\text{C}$; the velocity of the air in the space containing the calorimeter should be held constant and not exceed 0.15 m/s (30 ft/min); the relative humidity should be held constant at any convenient value between 20 and 50%; and the room should not be affected by external conditions.

The selection of a calorimeter type is determined by the purpose of the device and the degree to which its conditions can be controlled. Three types of calorimeters are the zero-heat-loss calorimeter, a calorimeter constructed to compensate for the heat transfer through its walls; the calibrated-heat-loss calorimeter (the approved IESNA type), a box in which the heat loss can be determined by dissipating a measured quantity of energy in the plenum; and the continuous-fluid-flow calorimeter, a modification of the zero-heat-loss calorimeter consisting of a heavily insulated heat exchanger installed over the luminaire.

Precision instrumentation is needed to measure temperature (thermometers, thermocouples, thermistors, and resistance elements), pressure (manometers, micromanometers, draft gauges, and swinging-vane gauges), mass flow rate of air and water, electrical quantities, and luminous flux.

Each luminaire that is to be tested for energy distribution should first be measured photometrically in accordance with accepted procedures. During calorimetry, the photometer should be installed at luminaire nadir, not less than 300 mm (1 ft) from the bottom of the enclosure. The distance at which the detector should be mounted below the luminaire is limited by the distance required for the cell to integrate flux over the entire luminous area of the luminaire. It is necessary that precautions be taken to prevent the detector from responding to luminous flux other than that transmitted by the luminaire under test. Its position must not be changed during the test.

The data to be recorded and reported should include the description and size of the luminaire, mode of operation, test

conditions (space and plenum temperatures), relative light output from a 25°C base with the luminaire operated in free air outside the calorimeter, energy to space, energy removed by the exhaust air stream, and exhaust air temperature, all as functions of the exhaust flow rate. Energy and relative luminous flux should be reported as a function of the air volume flow rate.

FIELD MEASUREMENTS

In evaluating an actual lighting installation in the field it is necessary to measure or survey the quality and quantity of lighting in the particular environment.

Field measurements apply only to the conditions that exist during the survey. Recognizing this, it is very important to record a complete detailed description of the surveyed area and all factors that might affect results, such as interior surface reflectances, lamp type and age, voltage, and instruments used in the survey.

In measuring illuminance, detectors should be cosine and color corrected (Figure 2-6).¹⁰⁹ They should be used at a temperature above 15°C (60°F) and below 50°C (120°F), if possible. Care should be exercised while taking readings to avoid casting shadows on the detector of the measuring instrument, and also by standing far enough away from the detector, especially when wearing light-colored clothes, to prevent light from the source from being reflected onto it. A high-intensity discharge or fluorescent system must be lighted for at least 1 h before making measurements. In new lamp installations, at least 100 h of operation of a gaseous source should elapse before measurements are taken. With incandescent lamps, seasoning is accomplished in a shorter time (20 h or less for common sizes).

The IESNA has developed a uniform survey method for measuring and reporting the necessary data for interior applications.¹¹⁰ The results of the uniform surveys can be used alone or with those of other surveys for comparison purposes, to determine compliance with specifications, and to reveal the need for maintenance, modification, or replacement. The IESNA survey method was compared with other survey methods and with comprehensive illuminance measurements on horizontal working planes in 11 different rooms under actual conditions of use.¹¹⁰ The rooms varied in room cavity ratio and in luminaire configurations. They included five of the six room types shown in Figure 2-24. The study found that the IESNA method was generally reliable to within an accuracy of 10%. Larger errors can be expected for spaces with unusual room cavity ratios or poor uniformity. It was concluded that, of all the survey methods studied, the IESNA method has the advantage of requiring the smallest number of measurement points and has no problems of coincidence of luminaire and measurement grids because the measurement points are fixed to the luminaires. The rigidity of the method is a disadvantage, however, in spaces that are obstructed, lack orthogonal geometry, or

have highly nonuniform illumination. In these cases, a measurement grid can be used.

Interior Measurements

Illuminance Measurements—Average

Determination of Average Illuminance on a Horizontal Plane From General Lighting Only. The measuring instrument should be positioned so that when readings are taken, the surface of the detector is in a horizontal plane and 760 mm (30 in.) above the floor. This can be facilitated by means of a small portable stand to support the detector. Daylight can be excluded during illuminance measurements by taking the readings either at night or with shades, blinds, or other opaque covering on the fenestration. The area should be divided into approximately sized squares, taking a reading in each square and calculating the arithmetic mean. A measurement grid of 0.6 m (2 ft) is suitable for many spaces. For spaces with unusual room cavity ratios or highly nonuniform illumination, as in corridors under emergency lighting conditions, see Chapter 9, Lighting Calculations.

Ouellette et al.⁽¹⁾ have shown that nonuniform lighting, as, for example, in some emergency lighting applications, may require several hundred randomly selected measurement points to obtain a representative value for average illuminance. This study illustrates how difficult it is to obtain an accurate representative value for illuminance in highly nonuniform illuminated spaces.

Regular Area with Symmetrically Spaced Luminaires in Two or More Rows. See Figure 2-24a.

1. Take readings at stations r-1, r-2, r-3, and r-4 for a typical inner bay. Repeat at stations r-5, r-6, r-7, and r-8 for a typical centrally located bay. Average the eight readings. This is R in Equation 2-8.
2. Take readings at stations q-1, q-2, q-3, and q-4 in two typical half bays on each side of the room. Average the four readings. This is Q in Equation 2-8.
3. Take readings at stations t-1, t-2, t-3, and t-4 in two typical half bays at each end of the room. Average the four readings. This is T in Equation 2-8.
4. Take readings at stations p-1 and p-2 in two typical corner quarter bays. Average the two readings. This is P in Equation 2-8.
5. Determine the average illuminance in the area by using the equation

average illuminance

$$= \frac{R(N-1)(M-1) + Q(N-1) + T(M-1) + P}{NM} \quad (2-8)$$

where

N = number of luminaires per row,
 M = number of rows.

Regular Area with Symmetrically Located Single Luminaire. See Figure 2-24b. Take readings at stations p-1, p-2, p-3, and p-4 in all four quarter bays. Average the four readings. This is P , the average illuminance in the area.

Regular Area with Single Row of Individual Luminaires. See Figure 2-24c.

1. Take readings at stations q-1 through q-8 in four typical half bays located two on each side of the area. Average the eight readings. This is Q in Equation 2-9.
2. Take readings at stations p-1 and p-2 for two typical corner quarter bays. Average the two readings. This is P in Equation 2-9.
3. Determine the average illuminance in the area by using the equation

$$\text{average illuminance} = \frac{Q(N-1) + P}{N} \quad (2-9)$$

where

N = number of luminaires.

Regular Area with Two or More Continuous Rows of Luminaires. See Figure 2-24d.

1. Take readings at stations r-1 through r-4 located near the center of the area. Average the four readings. This is R in Equation 2-10.
2. Take readings at stations q-1 and q-2 located at each midside of the room and midway between the outside row of luminaires and the wall. Average the two readings. This is Q in Equation 2-10.
3. Take readings at stations t-1 through t-4 at each end of the room. Average the four readings. This is T in Equation 2-10.
4. Take readings at stations p-1 and p-2 in two typical corners. Average the two readings. This is P .
5. Determine the average illuminance in the area by using the equation

average illuminance

$$= \frac{RN(M-1) + QN + T(M-1) + P}{M(N+1)} \quad (2-10)$$

where

N = number of luminaires per row,
 M = number of rows.

Regular Area with Single Row of Continuous Luminaires. See Figure 2-24e.

1. Take readings at stations q-1 through q-6. Average the six readings. This is Q in Equation 2-11.
2. Take readings at stations p-1 and p-2 in typical corners. Average the two readings. This is P in Equation 2-11.

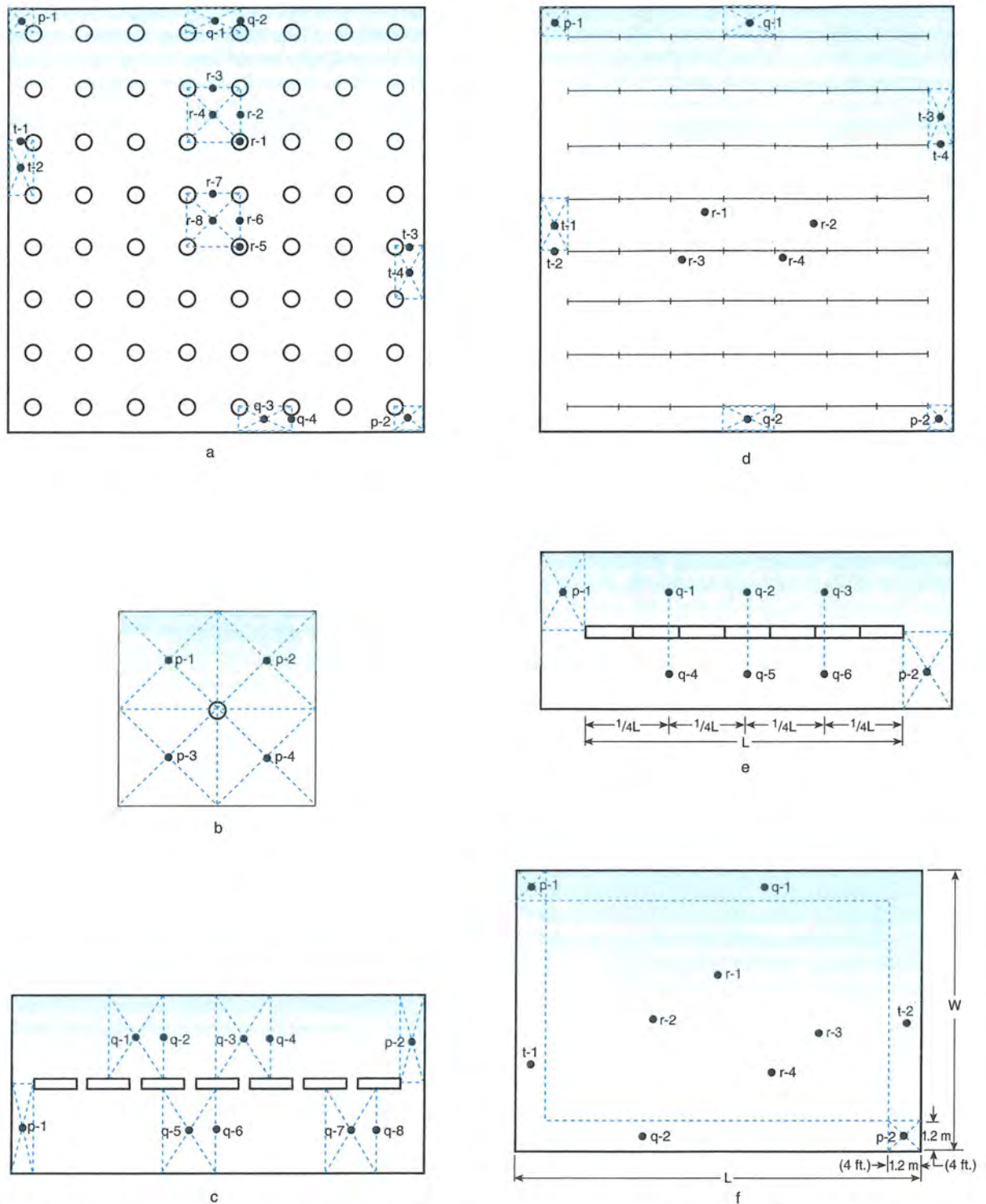


Figure 2-24. Location of illuminance measurement stations in (a) regular area with symmetrically located single luminaire; (b) regular area with symmetrically located single luminaire; (c) regular area with single row of continuous luminaires; (d) regular area with two or more continuous rows of luminaires; (e) regular area with single row of continuous luminaires; (f) regular area with luminous ceiling.

Figure 2-25. Form for Tabulation of Point Illuminance Measurements

Work Point	Description of Work Point	Height Above Floor	Plane (horizontal, vertical, or inclined)	Illuminance	
				Total (general + supplementary)	General Only
1—(max.)					
2—(min.)					
3—					
4—					
5—					

3. Determine the average illuminance in the area by using the equation

$$\text{average illuminance} = \frac{QN + P}{N + 1} \quad (2-11)$$

where

N = number of luminaires;

Regular Area with Luminous or Louvered Ceiling. See Figure 2-24f.

1. Take readings at stations r-1 through r-4 located at random in the central portion of the area. Average the four readings. This is R in Equation 2-12.
2. Take readings at stations q-1 and q-2 located 0.6 m (2 ft) from the long walls, at random lengthwise of the room. Average the two readings. This is Q in Equation 2-12.
3. Take readings at stations t-1 and t-2 located 0.6 m (2 ft) from the short walls, at random crosswise of the room. Average the two readings. This is T in Equation 2-12.
4. Take readings at stations p-1 and p-2 located at diagonally opposite corners 0.6 m (2 ft) from each wall. Average the two readings. This is P in Equation 2-12.
5. Determine the average illuminance in the area by using the equation

$$\text{average illuminance} = \frac{R(L - 8)(W - 8) + 8Q(L - 8) + 8T(W - 8) + 64P}{WL} \quad (2-12)$$

where

W = number of luminaires per row,
 L = number of rows.

Illuminance Measurements—Point

With task, general, and supplementary lighting in use, the illuminance at the point of work should be measured with the worker in his or her normal working position. The measuring instrument should be located so that when readings are taken, the surface of the light-sensitive cell is in the plane of the visual task or of that portion of the visual task on which the critical visual processing is required—horizontal, vertical, or inclined. Readings should be recorded as shown in Figure 2-25.

Luminance Measurements

Luminance surveys should be made under actual working conditions and from a specified work point location with the combinations of daylight and electric lighting facilities available. Consideration should be given to sun position and weather conditions, both of which can have a marked effect on the luminance distribution. All lighting in the area—task, general, and supplementary—should be in normal use. Work areas used only in the daytime should be surveyed in the daytime; work areas used both day and night should be surveyed under both conditions, as the luminance distribution and the possibilities of comfort and discomfort can differ markedly between them. Nighttime surveys should be made at night or with shades drawn. Daytime surveys should be made with shades adjusted to positions actually set by the occupants.

On a floor plan sketch of the area, an indication should be made of which exterior wall or walls, if any, were exposed to direct sunlight during the time of the survey by writing the word “Sun” in the appropriate location. Readings should be taken, successively, from the worker’s position at each work point location A , B , C , etc., and luminance readings from each location recorded as shown in Figure 2-26.

Outdoor Measurements

In roadway and many floodlight installations, light is projected to the surface to be lighted, and each luminaire must

Figure 2-26. Form for Tabulation of Luminance Measurements

Work Point Location*	Luminance					
	A	B	C	D	E	F
Luminaire at 45° above eye level						
Luminaire at 30° above eye level						
Luminaire at 15° above eye level						
Ceiling, above luminaire						
Ceiling, between luminaires						
Upper wall or ceiling adjacent to a luminaire						
Upper wall between two luminaires						
Wall at eye level						
Dado						
Floor						
Shades and blinds						
Windows						
Task						
Immediate surroundings of task						
Peripheral surroundings of task						
Highest luminance in field of view						

* Describe locations A thru F.

be adjusted carefully to produce the best utilization and quality of illumination. For an accurate evaluation of this type of installation, illuminance must be measured carefully.

Preparation for the Survey¹¹²⁻¹⁷⁴

1. Inspect and record the condition of the luminaires (globes, reflectors, refractors, lamp positioning, etc.). In the case of roadway lighting, make sure the luminaires are level and their vertical and lateral placement is as designed. Unless the purpose of the test is to check depreciation or actual in-service performance, all units should be cleaned and new lamps installed. New lamps should be seasoned properly.⁹⁵⁻⁹⁷ While inoperative lamps are readily noticed in roadway installations, they can easily be overlooked in large floodlighting systems. If these lamps are not replaced for the field survey, proper consideration must be given when evaluating the results.
2. Measure and record the mounting heights of the luminaires.
3. Measure and record the locations of the poles, the number of luminaires per pole, the wattage of the lamps, and other pertinent data. Check these data against the recommended layout; a small change in the location or adjustment of the luminaires can make a considerable difference in illuminance.
4. Determine and record the burning hours of the installed lamps.
5. Consider the impact of stray light on the measurements. The survey should be made only when the atmosphere is reasonably clear. Extraneous light

produced by a store, a service station, or other lights in the vicinity requires careful attention in street lighting tests.

6. Luminaire voltage should be measured because it can affect illuminance. At night, during the hours when the luminaires are normally used, record the voltage at the lamp socket with all of the lamps operating. The voltage at the main switch can be used instead, provided allowance is made for the voltage drop to the individual luminaires. If discharge lamps are used, record the input voltage to the ballast at the ballast terminals. Discharge lamps should be operated at least 60 min to reach normal operating conditions before measurements are made.

Survey Procedures. Measurements should be made with a recently calibrated, color-corrected, and cosine-corrected photometer (Figure 2-6) capable of being leveled for horizontal measurements or positioned accurately for other measurement planes as required. The photometer should be selected for its portability, repeatability, and measurement range.

1. For roadway lighting systems, at least one traffic lane must be closed for substantial periods of time. Because of this difficulty and expense of making field measurements of pavement luminance, it is common to use a computerized design procedure using point calculations of horizontal illuminance level at each of the pavement luminance measurement points recommended. As a check on the computer calculations, it is necessary only to measure the illuminance at a reduced number of points.¹¹²
2. For roadway signs, the minimum and maximum illuminance levels are determined by scanning the sign face. Additional illuminance measurements are taken at specific locations according to the sign size. Luminance measurements are also made for both externally and internally illuminated signs.¹¹⁴
3. For sports installations,¹¹³ the sports area (or the portion of the area under immediate consideration) should be divided into test areas of approximately 5% of the total area, and readings should be taken at the center of each area. Where lighting for color television is involved,¹¹⁵ horizontal illuminance readings need to be taken at each station. Another set of readings should be made with the detector tilted 15° from vertical in the direction of each camera location and 0.9 m (36 in) above ground level (unless otherwise specified for the particular activity). This will help ensure adequate illumination for the color television cameras.
4. Readings should be made at each test station, with repeat measurements at the first station frequently enough to assure stability of the system and re-

peatability of results. Readings should be reproducible within 5%. Enough readings should be taken so that additional readings in similar locations will not change the average results significantly.

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Vision and Perception

3

... [S]eeing, regarded as a supply for the primary wants of life is in its own right the superior sense
—Aristotle (384–322 BC)

INTRODUCTION

Vision depends on light. Lighting should provide visual conditions in which people can function effectively, efficiently, and comfortably. To predict human behavior as a function of the lighting conditions, it is important to understand the physical, physiological, and perceptual characteristics of the visual system. This chapter highlights some of the basic relationships between light and vision. It provides some fundamental data that the illuminating engineer may find useful, and calls attention to the factors that need to be considered when designing lighting for visual performance and comfort.

VISUAL SYSTEM STRUCTURE

The visual system is an image processing system. It involves the eye and brain working together to interpret the visual environment (Figures 3-1 and 3-2). The optical elements of the eye form an image of the world on the retina. At the retina, photons of light are absorbed by the photoreceptors and converted to electrical signals. These signals are transmitted by the optic nerve to the lateral geniculate nucleus (LGN) and then to the visual cortex for visual processing. In addition to the neural pathways from the eye to the visual cortex, there are a number of other pathways leaving the optic nerve shortly after it exits the eye that control pupil size, eye movements, and circadian rhythms.

The Eye

The structure of the eye can be divided into three distinct parts: the oculomotor components (the eye muscles), the optical components (the cornea, crystalline lens, pupil, and intraocular humors), and the neurological components (the retina and optic nerve).

Oculomotor Components. The oculomotor components of the eye consist of three pairs of muscles (Figure 3-3). These muscles position the lines of sight of the two eyes so that they are both pointed towards the same object of regard

(Figures 3-4 and 3-5). The line of sight of the eye passes through the part of the retina used for discriminating fine detail, the fovea. If the image of a target does not fall on the fovea, the resolution of target detail will be reduced. Additionally, if the foveas of both eyes are not aimed at the same target, the target may be seen as double (diplopia).

Eye movements can take several different forms.¹ Among the more important are:

1. **Saccades.** High-velocity movements, usually generated to move the line of sight from one target to another, are called saccades. Velocities may range up to 1000 degrees per second, depending upon the distance moved. Saccadic eye movements have a latency of 150 to 200 ms, which limits how frequently the line of sight can be moved in a given time period; approximately five movements per second is the maximum. Visual functions are substantially limited during saccadic movements. Eye movements during reading characterize a series of alternate fixations and saccades, along a row of print.
2. **Pursuit.** Smooth eye movements called pursuits are used to follow a smoothly moving target after a saccade has been used to bring the retinal image of the target onto the fovea. The pursuit system cannot follow smoothly moving targets at high velocities, nor can it follow slowly but erratically moving targets. If the eye cannot follow the target, resolution of target details decreases because the target's retinal image is no longer on the fovea. To catch up, binocular pursuit and jump movements are made, which are referred to as version movements when they involve objects in a frontal plane. For these movements, the two eyes make equal movements in the same direction, so there is no change in their angle of convergence (Figure 3-4).
3. **Vergence movements.** Movements of the two eyes that keep the primary lines of sight converged on a target or that may be used to switch fixation from a target at one distance to a new target at a different distance are called vergence movements (Figure 3-5). These can occur as a jump movement or can smoothly follow a target moving in a fore-and-aft direction. Both types of movement involve a change in the angle between the eyes. When the primary lines of sight drift apart so that they fail to

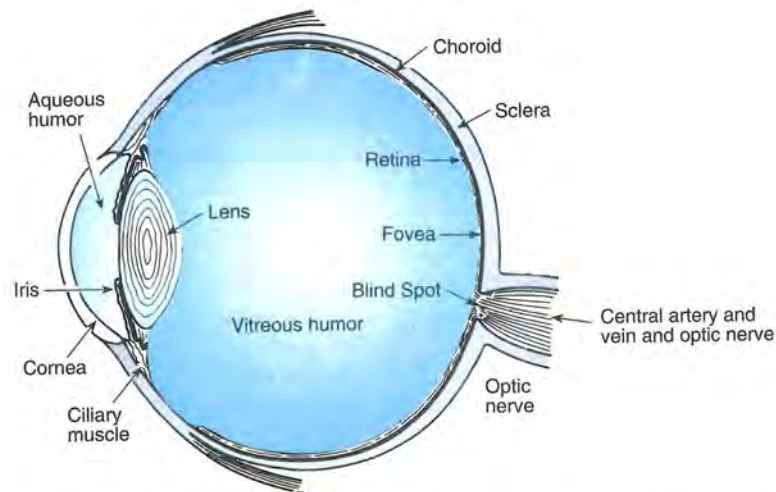


Figure 3-1. A horizontal section through the eye. The approximate length from the cornea to the retina is 24 mm. The thickness of the choroid is about 0.05 mm and the sclera 1.0 mm.

converge at the intended point of fixation, vergence movements play a major role in making the eyes see the target.

Optical Components. The function of the optical components of the eye is to form an image of the target on the retina. For this to occur, light has to be transmitted through the eye without excessive absorption and scattering, and the image of the target has to be focused on the retina (Figure 3-1).

The transmittance of the eye varies with wavelength and

with age.² In young and old eyes, the cornea absorbs most of the incident radiation shorter than 300 nm. In contrast, the human crystalline lens gradually develops a yellow pigmentation as it ages. This pigmentation attenuates the total transmission of radiant energy to the retina, especially in the shorter-wavelength portion of the visible and UV spectrum (Figure 3-6).³ As shown in more recent work (see Chapter 5, Nonvisual Effects of Optical Radiation, and Figure 5-4), newborn human lenses transmit UV energy.⁴ This transmission is greatly reduced but not entirely lost by early adult-

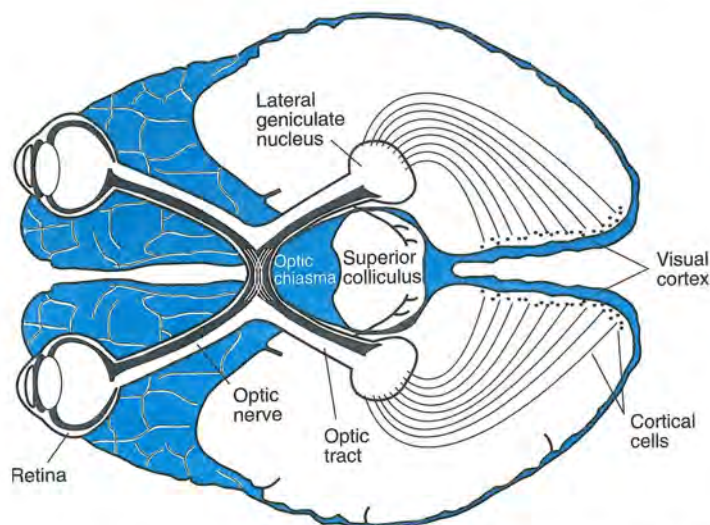


Figure 3-2. A schematic diagram of the structure of the visual system. Used, by permission, from R. Sekuler and R. Blake, *Perception*. © 1994. McGraw-Hill.

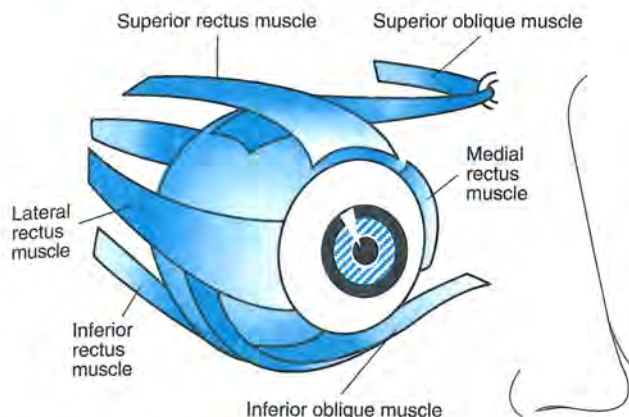


Figure 3-3. An eye and the extraocular muscles used to move it. Used, by permission, from R. Sekuler and R. Blake, *Perception*. © 1994. McGraw-Hill.

hood. Later in adulthood the UV transmission is entirely lost, and there are also significant reductions in transmission of short-wavelength portions of the visible spectrum. Accordingly, the retina receives radiation in the range from 380 to 950 nm with limited attenuation. Beyond 950 nm, transmittance is variable, with major absorption in the infrared (IR) water bands. Very little IR radiation beyond 1400 nm reaches the retina.

In the visible region of the spectrum, the optics of the eye transmit more light at long wavelengths (the red end) than at short wavelengths (the blue end), a tendency that is enhanced at the fovea by the additional short wavelength absorption of the macula lutea, a yellow filter that lies immediately above the fovea and parafovea. On average, some 70 to 85% of the visible spectrum reaches the retina in young eyes.⁴ As one ages, there is a general reduction in the

transmittance at all wavelengths combined with a marked reduction (greater than 4 times) in short-wavelength transmittance, due primarily to thickening and yellowing of the crystalline lens (Figure 3-7).⁵

While absorption of light reduces the magnitude of the stimulus to the visual system, it does not degrade the quality of the retinal image, that is, it does not blur the retinal image nor reduce its luminance contrast. Such degradation occurs when light is scattered in the eye or additional light is generated within the eye. Scattering within the eye is primarily large-particle scattering, which is not wavelength dependent. In young eyes, some 25% of the scattered light is produced by the cornea,⁶ another 25% by the fundus⁷⁻⁹ (see "Neurological and Supportive Components" below), and the rest by the lens and the vitreous humor. The aqueous humor causes little scattering, if any. The amount of scattered light in the eye increases with age. Consequently, older eyes are more susceptible to disability glare, as discussed later. Almost all of the increased scattering with age is due to changes in the lens.¹⁰ The quality of the retinal image can also be reduced by light generation within the eye, caused by fluorescence in the lens. This phenomenon occurs primarily in the elderly and is produced by absorption of short wavelength visible and ultraviolet radiation in the lens which is then re-emitted at longer wavelengths to which the visual system is more sensitive.¹¹

There are three optical components involved in the ability of the eye to refract or to focus an image on the retina. The first is the thin film of tears on the cornea. This film is important because it cleans the surface of the eye, starts the optical refraction (light bending) process necessary for focusing objects, and smoothes out small imperfections in the surface of the cornea. The second optical component is the cornea. This covers the transparent anterior one-fifth of the eyeball (Figure 3-1). With the tear layer, it forms the major refracting component of the eye and gives the eye about

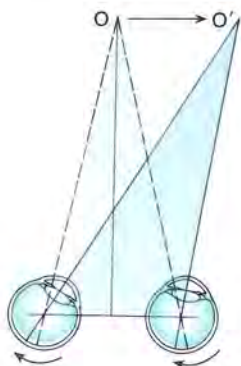


Figure 3-4. In a version movement, as the target moves from point O to point O', the angle between the eyes remains constant.

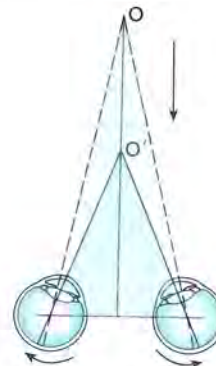


Figure 3-5. In a vergence movement, as the target moves from point O to point O', the angle between the eyes changes.

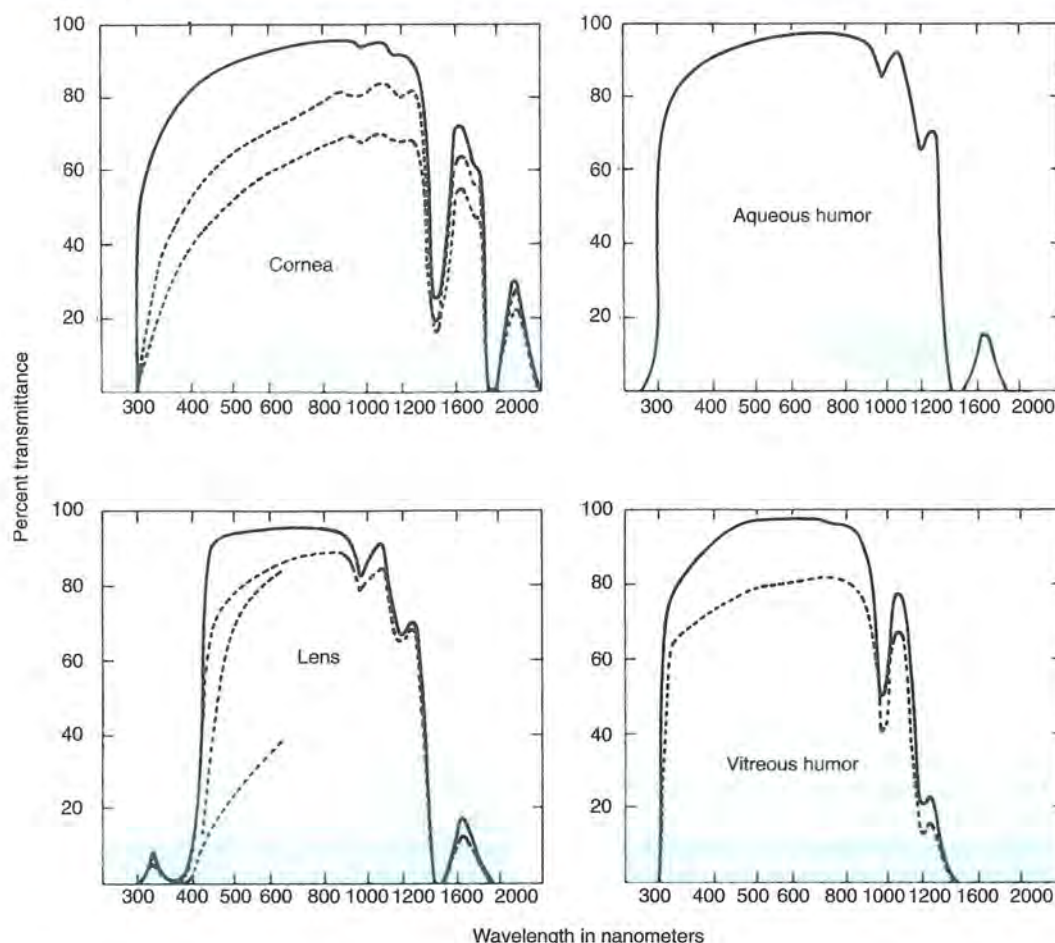


Figure 3-6. Spectral transmission properties of the human ocular media. The solid curves refer to the total light transmittance through the medium. The dashed curves refer to the direct, unscattered components only. The difference between the solid and dashed curve at each wavelength indicates the amount of light that is scattered by transmission through the medium. Where more than one dashed curve is shown the lower ones are for older eyes.

70% of its refractive power. The crystalline lens provides most of the remaining 30% of the refracting power. The ciliary muscles have the ability to change the curvature of the lens and thereby adjust the power of the eye's optical system, when needed, in response to changing target distances or certain types of refractive errors; this change in power is called accommodation.

Accommodation is always a response to an image of the target located on or near the fovea rather than in the periphery. It is used to bring a defocused image into focus or to change focus from one target to another at a different distance. It may be gradually changed to keep in focus a target that is moving in a fore-and-aft direction. Any condition, either physical or physiological, that handicaps the fovea, such as a low light level, will adversely affect accommodative ability. Blurred vision and eyestrain can be consequences of limited accommodative ability.¹²

When there is no stimulus for accommodation, as in complete darkness or in a uniform luminance visual field such as occurs in a dense fog, the accommodation system typically accommodates to approximately one meter away.¹³

Neurological and Supportive Components. The posterior 80% of the eye is enclosed by three layers of tissue (Figure 3-1). Collectively, they protect and nourish the eye and transduce light into electrical signals:

1. The sclera. The outermost covering of the globe, which is continuous with the cornea, protects the eye's contents and defines its shape.
2. The choroid. A highly vascular tissue that contains the blood supply to much of the eye.
3. The retina. The innermost layer, which converts radiant energy into electrical signals that are sent to the brain.

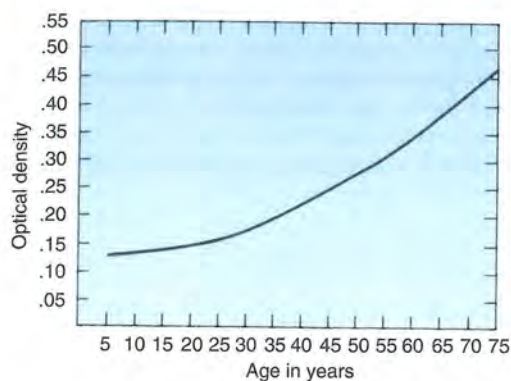


Figure 3-7. The optical density of the human lens at 490nm as a function of age (optical density $D = \log (1/t)$ where t = total transmittance).

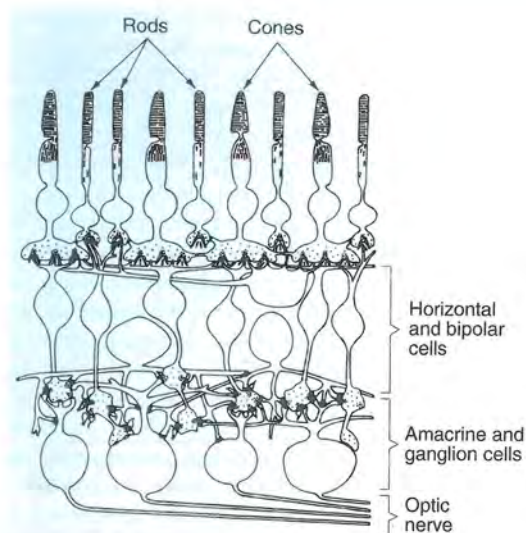


Figure 3-8. A simplified diagram of the connections among the neural elements in the retina. The regions where the cells are contiguous are synapses. The direction of incident light is from the bottom of this diagram.

Together, the choroid and the retina constitute the fundus.

Photoreceptors. The retina contains two main classes of light-sensitive receptors, rods and cones, which are differentiated by their morphology and by the spectral sensitivity of the photopigments which they contain (Figure 3-8).

Rods, which are absent in the fovea, increase in number to a maximum at about 20° of eccentricity and then gradually decrease towards the edges of the retina (Figure 3-9). All rods contain the same photopigment (rhodopsin), which has a peak spectral sensitivity at approximately 507 nm (Figure 3-10).

Cones are divided into three known classes, each characterized by the photopigment that it contains: erythrolabe,

chlorolabe, or cyanolabe (also known as L-type, M-type, and S-type or long-, middle-, and short-wavelength type) (Figure 3-11). Cones are concentrated in the fovea, although there are cones in all parts of the retina (Figure 3-9). All three cone types acting together have a peak spectral sensitivity at approximately 555 nm (Figure 3-10). The different photopigments in the cones make color discrimination possible.¹⁴

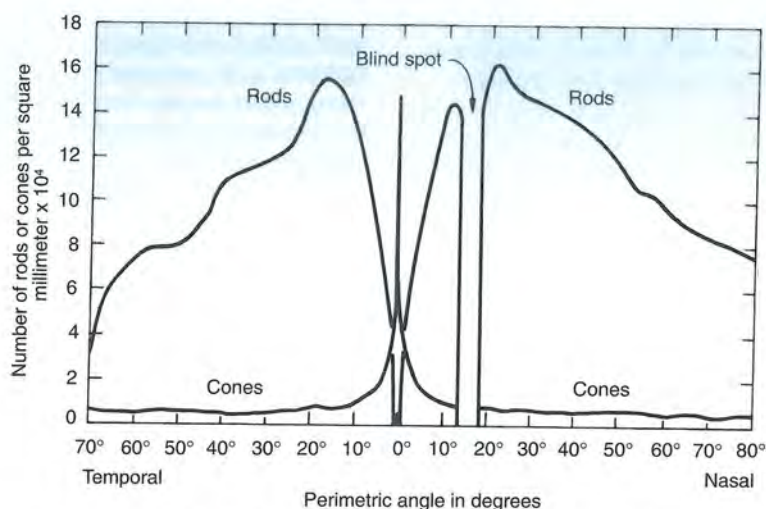


Figure 3-9. The distribution of rod and cone photoreceptors across the retina. The 0° point represents the fovea.

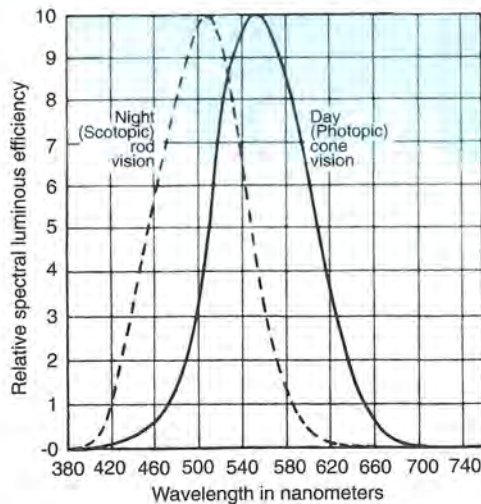


Figure 3-10. The CIE Standard Photopic and Scotopic Observers, representing the relative spectral sensitivity of the cone and rod photoreceptors, respectively.

Receptive Fields. Photoreceptors do not send their information directly to the brain, but rather to several other cells in the retina, which in turn send them to ganglion cells, whose terminal axons constitute the optic nerve (Figure 3-8). In this way, light received by a number of receptors is “pooled” to provide a signal strong enough to stimulate a

ganglion cell. The area of retina that stimulates a ganglion cell is called a receptive field. Although photoreceptors are the primary transducers of light into electrical signals, the receptive fields begin the image processing, which enables the visual system to interpret the visual environment.

Ganglion cell receptive fields are comprised of two distinct, juxtaposed areas: a circular center and an annular surround. These two areas receive signals from different, individual bipolar cells (Figure 3-8), which have received information from different photoreceptors.

In the fovea, the center area of the receptive field receives neural signals from a single bipolar cell, which itself receives signals from a single cone photoreceptor. At greater eccentricities from the fovea, receptive field centers are larger because they receive input from many photoreceptors, both rods and cones, through the bipolar layer. Receptive field surrounds commonly receive input from several bipolar cells, which are fed not only by direct links to photoreceptors but also from special cells in the retina which laterally connect other bipolar cells. Some of the lateral connections are illustrated in the bipolar layer of Figure 3-8.

These facts reflect the tradeoff in the retina between fine spatial resolution and high sensitivity to light. Large receptive fields, like those found in the periphery, can gather very few photons and sum them to produce a neural signal for “light.” Every photon captured within a receptive field produces the same neural response; hence, the location of each photon capture within a receptive field cannot be spatially segregated. Very small receptive fields, like those in the fovea, are needed to precisely locate objects on the retina. Thus, the fovea has excellent spatial resolution but low sensitivity to light, whereas the periphery has high sensitivity to light and poor spatial resolution.

A very important aspect of this center-surround organization is the ability to enhance the contrast of images at the boundary. The eye is a very poor optical system fraught with many types of aberrations and imperfections (see “Focusing Problems”). To overcome its severe optical limitation, the visual system has developed the center-surround receptive field organization to provide a simple, yet elegant, image enhancement system.

The center and surround areas produce opposite neural polarities in the ganglion cell when stimulated by light. Light striking the center of the receptive field will increase the neural firing rate of the ganglion cell, whereas the same light striking the surround will decrease the firing rate. Light striking both the center and surround will produce an intermediary response because the excitation produced by the light stimulating the center area will be counteracted by the inhibitory effect of light stimulating the surround.

Consider then an image of a white disc on a black background focused and precisely covering the center of a receptive field. This configuration will produce the maximum excitation to the ganglion cell because the center is maximally stimulated and the surround is minimally stimulated. The net effect is the strongest possible signal from the gan-

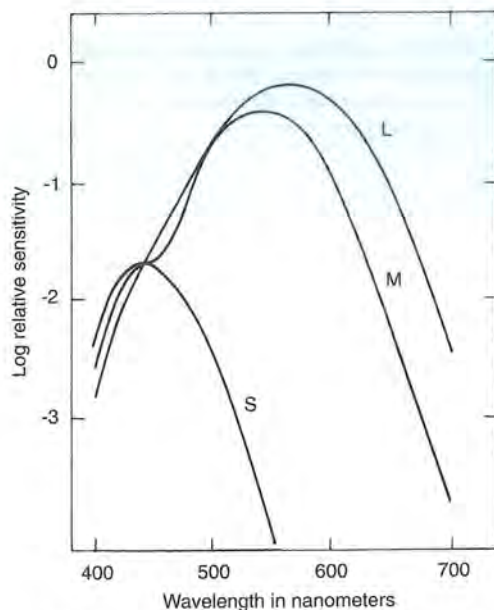


Figure 3-11. The relative spectral sensitivity curves of the three cone photoreceptors: long (L), middle (M), and short (S).

gion cell and, therefore, the highest possible contrast between the white center and black surround. Larger or smaller discs imaged at the same location will have smaller impact on the ganglion cell; a larger disc will increase the inhibitory response of the surround, and a smaller disc will not stimulate the center as strongly because it does not completely cover the center of the receptive field. With a little thought, the magnitude of contrast enhancement for other image shapes can be surmised on the basis of how their edges are positioned within the receptive field. The common result, however, is that the contrast of juxtaposed light and dark areas of an image will be enhanced if they are focused at the boundary between a receptive field center and its surround.

At any location in the retina there is an equal proportion of receptive fields with excitatory centers and inhibitory centers. Therefore, the contrast of both black discs and white discs will be enhanced. Also at any location in the retina, there is a distribution of receptive field sizes. This enables the retina to enhance the contrast of variously sized images. Nevertheless, there is an optimum target size for any retinal location; smaller images are seen best in the fovea, and larger ones are seen best in the periphery.

It is important to note that receptive field sizes are not constant, but rather they change size with light level. As light level increases, receptive field sizes increase as they collect signals through their lateral connections from more distant locations in the retina. In effect, this greater inhibition from the receptive field surround makes the center of the receptive field functionally smaller. Indeed, the center of a receptive field in the fovea can become smaller than the diameter of single cone at high light levels. This reduction in the size of the receptive field center enables us to improve acuity as light level is increased (Figure 3-27).

Color vision also depends on this organization. Consider a receptive field where L-cones exclusively populate an excitatory center and M-cones populate an inhibitory surround. Consider now two colored lights that cover the entire receptive field. If the L-cones are stimulated more than the M-cones for one of the colored lights this ganglion cell will signal "red" by increasing its neural firing rate. If the other light produces a greater response in the M-cones, the ganglion cell will signal "green" because its firing rate decreases. Because of this receptive field polarity, red and green hues are perceptual opposites; this is why one cannot see, for example, a "reddish green" light. Yellow and blue are also opposed through ganglion cell receptive field organization. Yellow is created by the sum of the input of the L and M cones in opposition to blue, which is produced by the input from the S cone. There are also some spatial implications of this receptive field organization. For example, very small images in the center of the fovea cannot produce perceptions of yellow or blue because there are no S-cones in the center of the fovea. Further information on color vision may be found throughout this chapter and in Chapter 4, Color.

Neural Pathways. Electrical signals from the receptive fields in the retina are transmitted over the optic nerve. Approximately 20% of optic nerve fibers project to the superior colliculus, and 80% to the lateral geniculate nucleus (LGN) and on to the visual cortex (Figure 3-2).

At the optic chiasm, the fibers from each eye divide into two sets; one set remains on the same side of the head as the eye, and the other set crosses over to the other side. The result is two optic tracts, both of which contain nerve fibers from both eyes; one tract transmits the signal from the left side of both eyes to the left side of the visual cortex, and the other transmits the signals from the right side of both eyes to the right side of the visual cortex (Figure 3-2).

The superior colliculus is a phylogenetically older part of the brain and in humans is involved in controlling eye movements. Because the superior colliculus also receives signals from the ears, it is believed that its role is directing eye and head movements towards targets located away from the point of fixation. It is not involved in the detailed image processing.

The LGN contains an orderly representation of the retina. Investigations of its functioning have revealed that it continues processing the retinal image by sorting the information it contains into distinct categories. This is accomplished with two channels of information flow, the magnocellular channel and the parvocellular channel. The magnocellular channel transmits primarily temporal information and is dominant in the periphery of the retina. The parvocellular channel transmits primarily spatial information and is dominant in the fovea. This pattern is consistent with how the periphery of the retina identifies changes in the visual environment and the fovea determines the nature of those changes.

The visual cortex takes the information sorted by the LGN and refines and interprets it in terms of past experience. Approximately 80% of the visual cortex is assigned to analyze and interpret the central 10° of the visual field. This pattern of assignment is called cortical magnification.

Although the components involved in transforming patterns of photons of light into visual perceptions have been discussed separately, it is important to appreciate that there is considerable interaction between them. An example of such interactions is the system of color vision (see Chapter 4, Color, and "Color Discrimination" in this chapter). The ability to discriminate among wavelengths of light is due to a combination of photochemical and neurological processes. Signals from the three cone types are coded in the retina and the lateral geniculate body into chromatic and achromatic information. As a first-order model of color and brightness perception, chromatic information is a result of a subtraction of photoreceptor signals, while achromatic information is a result of the addition of photoreceptor signals. However, many experiments using various testing procedures and stimuli demonstrate that this is an oversimplification of how the visual system processes light signals. Chromatic, achromatic, spatial, and temporal information are combined in complicated ways to give final perceptions of light and

color. For example, equal-luminance colored lamps may have different apparent brightnesses because of the interaction between achromatic and chromatic channels.¹⁵ Figure 3-12 is a proposed model of how the visual system combines the information from these various channels to produce human perceptions.¹⁶

Dark and Light Adaptation

For the visual system to be able to function well, it has to be adapted to the prevailing light condition. The human visual system can process information over an enormous range of luminances (approximately 12 log units), but not all at once. To cope with the wide range of retinal illuminations to which it might be exposed, from a dark night to a sunlit beach, the visual system changes its sensitivity through a

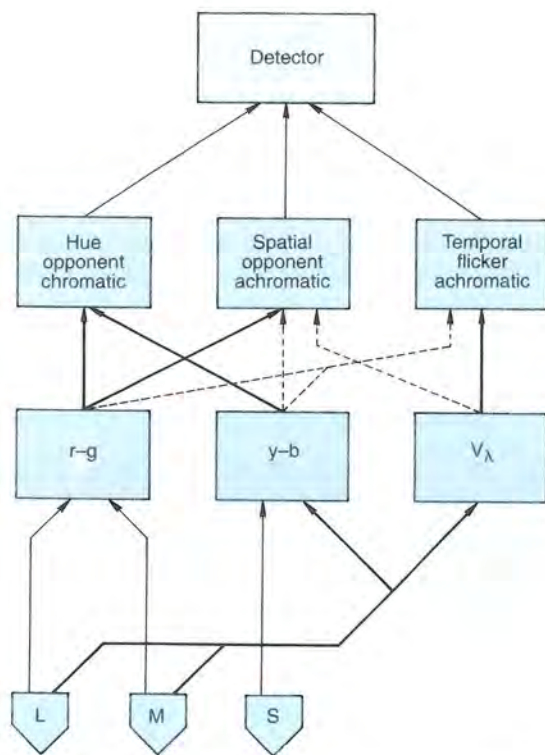


Figure 3-12. A proposed model for the neural connections in the visual system. Information from the first stage photoreceptors (R,G,B) goes to mechanisms that sum or subtract input to give achromatic and chromatic information, respectively. Subsequent "cortical analysis" mechanisms receive multiple inputs from the second stage. Such a model attempts to qualitatively describe some of the nonlinearities in the visual system that have been discovered using stimuli that vary in several dimensions (spatial, temporal, chromatic and achromatic). The solid lines indicate well-established inputs, while the dashed lines are more speculative.

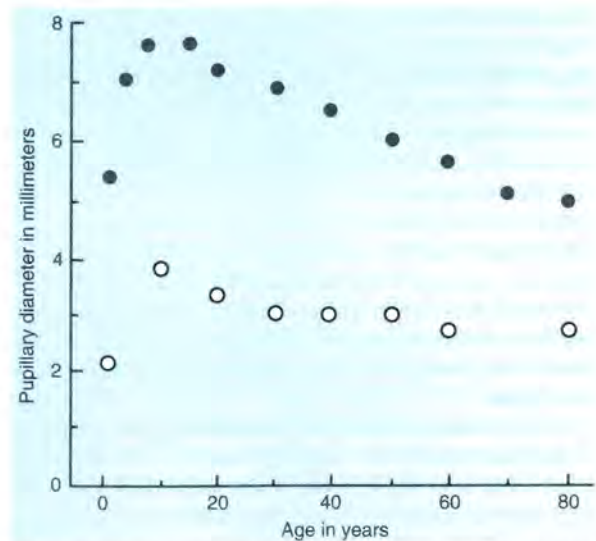


Figure 3-13. Pupil diameter for light-adapted (open circles) and dark-adapted (filled circles) conditions, plotted against the age of the observer. From R.A. Weale, *The senescence of human vision*, © 1992, used by permission of Oxford University Press.

process called adaptation. Adaptation involves three distinct processes:

1. **Change in Pupil Size.** The iris (Figure 3-1) constricts and dilates in response to increased and decreased levels of retinal illumination. Iris constriction has a shorter latency and is faster (approximately 0.3 s) than dilation (approximately 1.5 s).¹⁷ There are wide variations in pupil sizes among individuals and for any particular individual at different times for the same visual stimulus. Pupil size is influenced by emotions, such as fear or elation. Thus, for a given luminous stimulus, some uncertainty is associated with an individual's pupil size until it is measured. The typical range in pupil diameter for young people is from 3 mm for high retinal illuminances to 8 mm for low retinal illuminances.¹⁸ This change in pupil size in response to retinal illumination can only account for a 1.2 log unit change in sensitivity to light. Older people tend to have smaller pupils under comparable conditions (Figure 3-13).
2. **Neural Adaptation.** This is a fast (less than 200 ms) change in sensitivity produced by synaptic interactions in the visual system.¹⁹ Neural processes account for virtually all the transitory changes in sensitivity of the eye where cone photopigment bleaching has not yet taken place (discussed below), in other words, at luminance values commonly encountered in electrically lighted environments, below approximately 600 cd/m². The facts that neural adaptation is fast, is operative at moder-

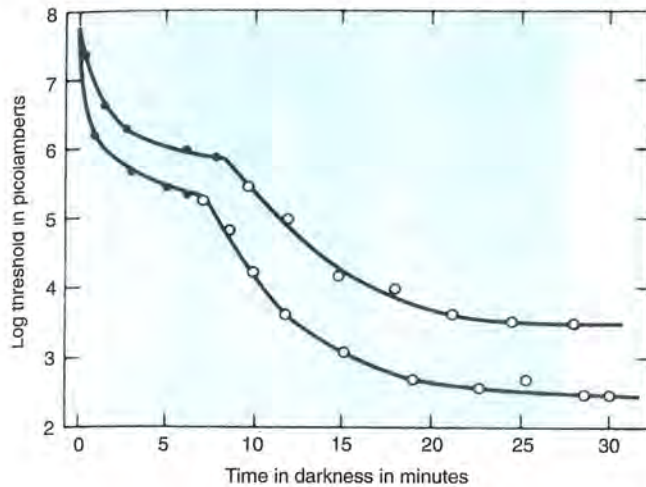


Figure 3-14. The increase in sensitivity to light (decrease in threshold) as a function of time in the dark, after exposure to a bright light. Sensitivity is measured at a point 7° from the fovea. The two curves represent the extremes of the normal range of observers. (1 picolambert = 3.2×10^{-9} cd/m²)

ate light levels, and is effective over a luminance range of 2 to 3 log units explain why it is possible to look around most lit interiors without being conscious of being misadapted.

3. **Photochemical Adaptation.** The retinal photoreceptors contain four photopigments. When light is absorbed, the pigment breaks down into an unstable aldehyde of vitamin A and a protein (opsin) and gives off energy that generates electrical signals that are relayed to the brain and interpreted as light. In the dark, the pigment is regenerated and is again available to absorb light. The sensitivity of the eye to light is largely a function of the percentage of unbleached pigment. Under conditions of steady retinal irradiance, the concentration of photopigment is in equilibrium; when the retinal irradiance is changed, pigment is either bleached or regenerated to reestablish equilibrium. Because the time required to accomplish the photochemical reactions is on the order of minutes, changes in the sensitivity often lag behind the stimulus changes. The cone system adapts much more rapidly than does the rod system; even after exposure to high irradiances, the cones achieve their maximum sensitivity in 10 to 12 min, while the rods require 60 min (or longer) to achieve their maximum sensitivity (Figure 3-14).²⁰

Exactly how long it takes to adapt to a change in retinal illumination depends on the magnitude of the change, the extent to which it involves different photoreceptors, and the direction of the change. For changes in retinal illumination of approximately 2 to 3 log units, neural adaptation is sufficient,

so adaptation is in less than a second. For larger changes, photochemical adaptation is necessary. If the change in retinal illumination lies completely within the range of operation of the cone photoreceptors, a few minutes is sufficient for adaptation to occur. If the change in retinal illumination covers from cone photoreceptor operation to rod photoreceptor operation, tens of minutes can be required. As for the direction of change, once the photochemical processes are involved, changes to a higher retinal illuminance can be achieved much more rapidly than changes to a lower retinal illuminance.

When the visual system is not completely adapted to the prevailing retinal illumination, its capabilities are limited.²¹ This state of changing adaptation is called transient adaptation. Transient adaptation is unlikely to be noticeable in interiors in normal conditions but can be significant where sudden changes from high to low retinal illumination occur, such as on entering a long road tunnel on a sunny day or in the event of a power failure in a windowless building.

Photopic, Scotopic, and Mesopic Vision

This process of adaptation takes the visual system through three distinct operating states.

1. **Photopic vision.** This operating state of the visual system occurs at luminances higher than approximately 3 cd/m². For these luminances, the retinal response is dominated by the cone photoreceptors. This means that color is perceived and fine detail can be resolved in the fovea.
2. **Scotopic vision.** This operating state of the visual system occurs at luminances less than approximately 0.001 cd/m². For these luminances only the rod photoreceptors respond to stimulation, so the fovea of the retina is inoperative. There is no perception of color, and what resolution of detail there is occurs in the periphery within a few degrees of the fovea.
3. **Mesopic vision.** This operating state of the visual system is intermediate between the photopic and scotopic states. In the mesopic state both cones and rod photoreceptors are active. As luminance declines through the mesopic region, the fovea, which contains only cone photoreceptors, slowly declines in absolute sensitivity without significant change in spectral sensitivity,²² until vision fails altogether as the scotopic state is reached. In the periphery, the rod photoreceptors gradually come to dominate the cone photoreceptors, resulting in gradual deterioration in color vision and resolution and a shift in spectral sensitivity to shorter wavelengths.

The relevance of these different operating states for lighting practice varies. Scotopic vision is largely irrelevant to lighting practice. Nearly every lighting installation provides

enough light to at least move the visual system into the mesopic state. Most interior lighting ensures the visual system is operating in the photopic state. Current practice in exterior lighting ensures the visual system operates near the boundary of the photopic and mesopic states.

The spectral sensitivities of the visual system in the photopic and scotopic states have been defined by the Commission Internationale de l'Éclairage (CIE). Figure 3-10 shows the CIE Standard Photopic and Standard Scotopic Observers. These two luminous efficiency functions are used in the fundamental definition of light, to convert from radiometric quantities to photometric quantities (see Chapter 1, Light and Optics). The mesopic state has been extensively studied but has not been defined officially by the CIE, partly because of problems with additivity.^{23–26} Problems with additivity are to be expected for any system based on brightness because brightness perception uses the parvocellular channel, which combines both achromatic and chromatic responses in a complex way. Recently, an alternative approach to mesopic photometry has been proposed, based on measurements of reaction time.²⁷

Because scotopic vision is irrelevant and the mesopic state has not officially been defined, virtually all photometric quantities used in lighting practice are measured using the CIE Standard Photopic Observer, even for exterior lighting where the visual system may be operating in the mesopic state. It should be realized that the use of the CIE Photopic Observer can give discrepancies between measured photometric quantities in a space and the perception of brightness in the space. The CIE Standard Photopic Observer is based on the relative amounts of power at each wavelength required to produce a criterion brightness response in a 2° foveal field of view. It is an average response derived from several different experimental techniques, including techniques using direct brightness judgments involving the parvocellular channel and techniques based on flicker perception involving the magnocellular channel.⁸ Studies have shown that, even with the visual system operating in the photopic state, the CIE Standard Photopic Observer slightly underestimates the influence of the short wavelength region of the visible spectrum on brightness, even for a 2° field of view;²⁸ and the underestimation is greater for a 10° field of view,⁸ because this larger field extends beyond the macula lutea. This discrepancy between photometric quantities and brightness perception is slight for light sources with a spectral content distributed over the whole visible spectrum. However, when light sources with a very discrete spectral content are compared, the limitations of the CIE Standard Photopic Observer can become important. This is particularly so for colored signal lights, where the brightness of the light is what matters.²⁹

Individual Differences

Although the visual systems of all people have the same basic structure, as in most living things, there are individual

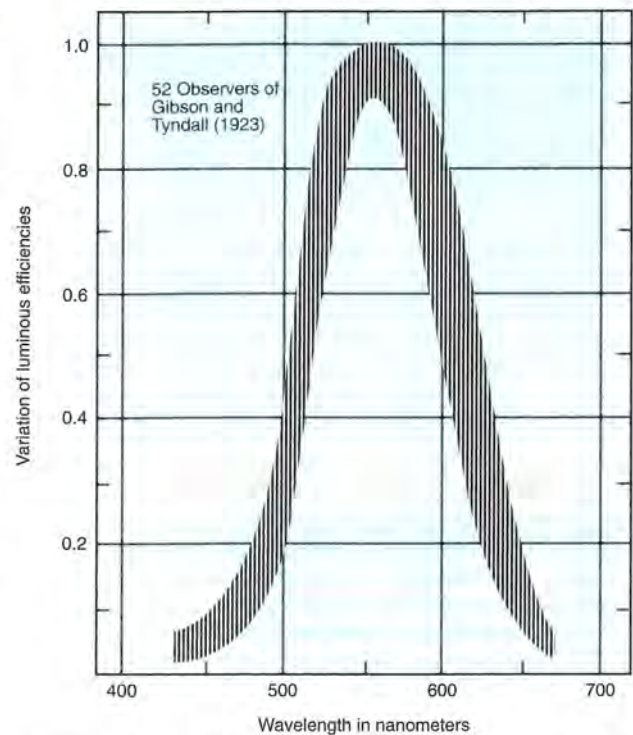


Figure 3-15. The range of luminous efficiency values for 52 observers.

differences. For example, Figure 3-15 shows a wide variation in luminous efficiency for 52 individuals.³⁰ Many of these differences are ignored when considering lighting for use by the general public, but some are sufficiently large and their effects so predictable that they need to be taken into account in some lighting applications. This is especially true when lighting for the aged and partially sighted, as discussed later (see “Aging and Partial Sight”).

Focusing Problems. As discussed above in “Ocular Components,” the eye adjusts its optical power to focus objects at different distances on the retina. This is possible for a wide range of distances when there is a match between the combined optical power of the cornea and lens and the dimensions of the eye. However, when there is a mismatch between the optical power and the distance from the lens to the retina, a sharp image cannot be formed on the retina. This blurred retinal image is called a refractive error. There are several different forms of refractive error. They are:

1. Myopia. The optical power is greater than necessary so objects at a distance are focused in front of the retina (Figure 3-16a).
2. Hyperopia. The optical power is less than necessary so objects at a distance are focused behind the retina (Figure 3-16b).

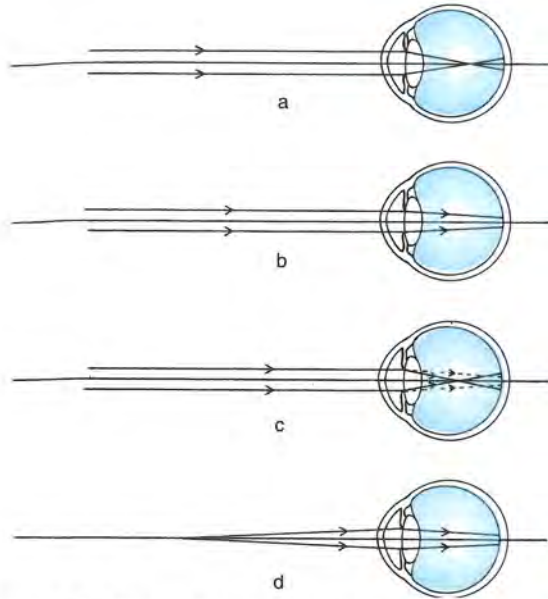


Figure 3-16. The relationship between the image of a point object and the retina in common refractive errors. (a) In myopia, the image forms in front of the retina. (b) In hyperopia, the image forms behind the retina. (c) In astigmatism, multiple foci are formed due to different optical powers occurring in the various meridians of the eye. (d) In presbyopia, accommodation is sufficiently limited that near objects focus behind the retina.

3. Astigmatism. The optical power is not equal in all planes so objects are focused in front of, behind and on the retina for different planes (Figure 3-16c).
4. Presbyopia. The adjustment of optical power is limited. Typically, near objects are focused behind the retina (Figure 3-16d).

Most of these refractive errors can be corrected by the use of spectacles or contact lenses, although even when the eye is perfectly corrected for refractive errors, a residual blur can remain due to spherical and chromatic aberrations.

1. Spherical aberration. Light rays that enter through the periphery of the cornea are refracted more than those that enter through the central zones (Figure 3-17). Thus, light in the retinal image is partially redistributed over a larger retinal area than would be the case in an aberration-free system. The amount and type of spherical aberration varies with the state of accommodation (Figure 3-18).
2. Chromatic aberration. Shorter wavelengths are refracted more than longer wavelengths (Figure 3-19). As in spherical aberration, the results of the different foci cause blur (Figure 3-20).

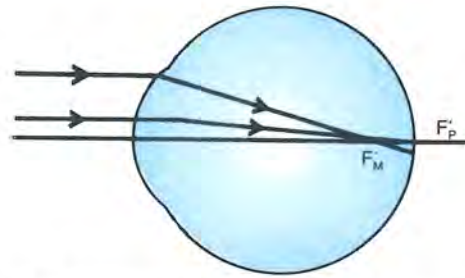


Figure 3-17. Spherical aberration: marginal rays (F'_m) are focused in front of rays entering the eye near the center of the pupil (F'_p).

These aberrations (and others) are mainly of theoretical interest. They are partially compensated by the image processing of the visual system and usually can be neglected in practical lighting design. They may, however, be important in certain specialized applications, such as work under reduced illuminances where pupil sizes can be large.

Abnormal Color Vision. Approximately 8% of males and 0.2% of females have some form of abnormal color vision. Abnormal color vision occurs because of abnormal photoreceptor photopigments. The reason for the preponderance of

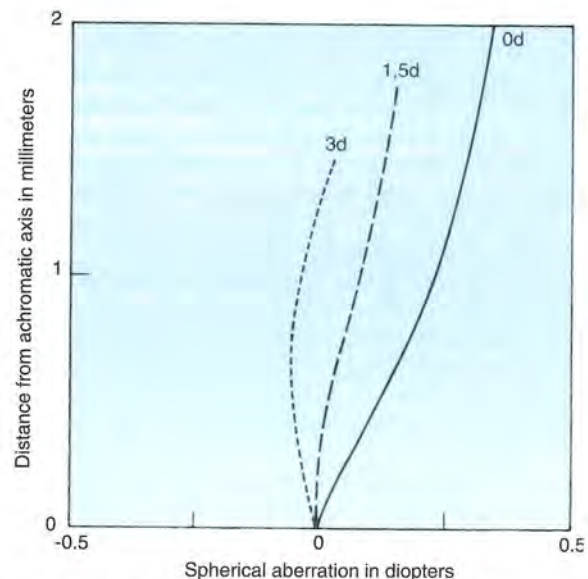


Figure 3-18. Spherical aberration: the amount of spherical aberration (in diopters, D) is on the horizontal axis (positive when undercorrected) and the distance from the achromatic axis is on the vertical axis. The solid line corresponds to the unaccommodated eye; the dashed line corresponds to 1.5 D accommodation; the dotted line corresponds to 3.0 D accommodation.

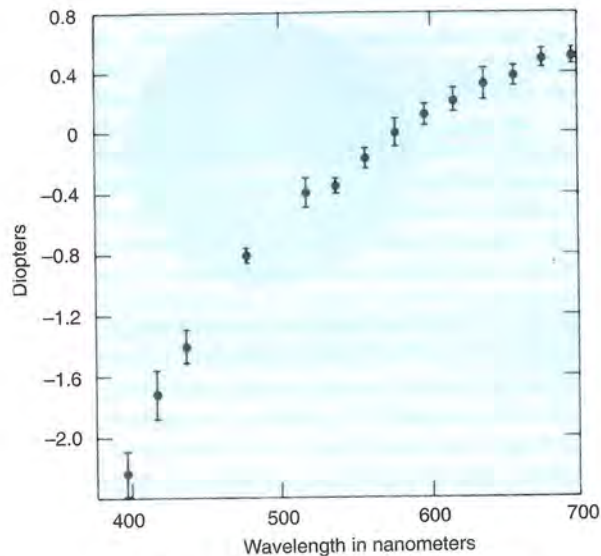


Figure 3-19. Chromatic aberration: the optical power necessary to correct the focus of an eye for differences in refraction at different wavelengths (zero correction is arbitrarily set at 589 nm).

males is that abnormal color vision is due to a genetic difference on the X-chromosome. Males have only one X-chromosome, but females have two, and for a female to have abnormal color vision, both X-chromosomes must have the same abnormal gene.

Figure 3-21 tabulates the different types of abnormal color vision, their causes, and their prevalence. For most activities, abnormal color vision causes few problems, either because the exact identification of color is unnecessary or because there are other cues by which the necessary information can be obtained (e.g., relative location in traffic sig-

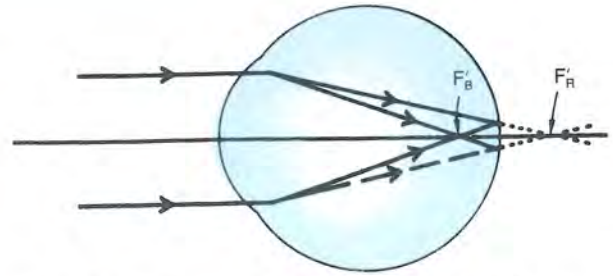


Figure 3-20. Chromatic aberration: because the eye's index of refraction is greater for short wavelengths than for long wavelengths, the eye focuses short wavelengths (F'_B) in front of long wavelengths (F'_R).

nals). Abnormal color vision does become a problem when color is the sole or dominant means used to identify objects, for example, in some forms of electrical wiring. People with abnormal color vision have difficulty with such activities.

Where self-luminous colors are used as signals, colored lights should be restricted to those that can be distinguished by people with the more common forms of color abnormality. The CIE has recently recommended areas on the CIE 1931 Chromaticity Diagram within which red, green, yellow, blue, and white signal lights should lie (see Figure 26.17 in Chapter 26). These areas are designed so that the red signal will be named as red and the green as green, even by dichromats, who are missing either a long or middle-wavelength photoreceptor pigment.³¹ It should be noted that for people with the most common form of abnormal color vision, the anomalous trichromats, the ability to discriminate colors shows wide individual differences. Some anomalous trichromats are barely distinguishable for people with normal color vision, whereas others resemble dichromats in their ability to discriminate colors.

Figure 3-21. The Classification, Characteristics, and Prevalence of Defective Color Vision

Name	Cause	Consequences	Prevalence
Dichromacies			
Protanopia	Missing L-type pigment	Confuses 520–700 Has neutral point	M: 1.0% F: 0.02%
Deutanopia	Missing M-type pigment	Confuses 530–700 Has neutral point	M: 1.1% F: 0.1%
Tritanopia	Missing S-type pigment	Confuses 445–480 Has neutral point	Very rare
Anomalous Trichromacies			
Protanomaly	Abnormal L-type pigment	Abnormal matches Poor discrimination*	M: 1.0% F: 0.02%
Deutanomaly	Abnormal M-type pigment	Abnormal matches Poor discrimination*	M: 4.9% F: 0.04%

Note: "M" indicates males; "F" females. Wavelengths that are confused are given in nanometers. An asterisk (*) means that only some members of this group exhibit this problem.

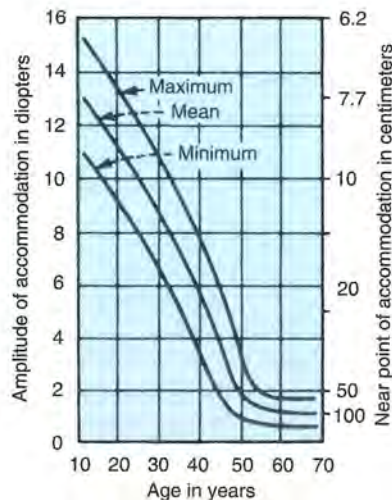


Figure 3.22. The decrease in the amplitude of accommodation with age.

Aging. As the visual system ages, a number of changes in its structure and capabilities occur.¹⁸ Usually, the first obvious change is loss of accommodation. Accommodative function decreases rapidly with age, so that by age 45 most people can no longer focus at near-working distances (approximately 40 cm) and might need optical assistance. This is known as presbyopia. By age 60, there is very little accommodative ability remaining in most of the population (Figure 3-22), resulting in a fixed-focus optical system. This lack of focusing ability is compensated somewhat by the physiologically smaller pupils in the elderly (senile myosis) because these increase the depth of field of the eye. However, the smaller pupils in turn increase the requirement for task luminance to maintain the same retinal illuminance as when the pupils were larger.

While the increasing rigidity of the lens, as well as many other forms of focusing difficulty, can be compensated by adjusting the optical power of the eye's optical system with spectacles and contact lenses, the other changes that occur in the eye cannot. As the visual system ages, the amount of light reaching the retina is reduced, more of the light entering the eye is scattered, and the spectrum of the light reaching the retina is altered by preferential absorption of the short visible wavelengths. The rate at which these changes occur accelerates after age 60. In addition to these changes in the optical characteristics of the eye, deterioration in the neurological components of the visual system also occurs in later life.¹⁸ The consequences of these changes with age are reduced visual acuity, reduced contrast sensitivity, reduced color discrimination, increased time taken to adapt to large and sudden changes in luminance, and increased sensitivity to glare.^{18,32,33}

Lighting can be used to partially compensate for these changes. Specifically, in an extensive long-term field study,

the quality of life of the elderly has been shown to be improved by increasing the quality of their lighting.³⁴ This raises the question of how to improve the quality of lighting for the elderly. Simply providing more light might not be enough. The light must be provided in a way that both disability and discomfort glare are controlled and veiling reflections are avoided. Where elderly people are likely to be moving from a well-lighted area to a dark area, such as a supermarket to a parking lot, a transition zone with a gradually reducing illuminance is desirable. Such a transition zone allows their visual system more time to make the necessary changes in adaptation.

Partial Sight. Partial sight is a state of vision that falls between normal vision and total blindness. While some people are born with partial sight, the majority of people with partial sight are elderly. Among the partially sighted, 20% became partially sighted between birth and 40 years, 21% between 41 and 60 years and 59% after 60 years of age.³² Surveys in the United States and the United Kingdom suggest that the proportion of the total population who are classified as partially sighted are in the range 0.5 to 1%.^{35,36}

The three most common causes of partial sight are cataract, macular degeneration, and glaucoma.³⁴ These causes involve different parts of the eye and have different implications for how lighting might be used to help people with partial sight.

1. **Cataract.** This is an opacity developing in the lens. The effect of cataract is to absorb and scatter more of the light passing through the lens. This increased absorption and scattering occurring in the lens results in reduced visual acuity and reduced contrast sensitivity over the entire visual field because the scattered light degrades the contrast of the retinal image. This is known as disability glare, which occurs when light is scattered in the eye. The extent to which more light can help a person with cataract depends on the balance between absorption and scattering. More light will help overcome the increased absorption but if scattering is high, the consequent deterioration in the luminance contrast of the retinal image will reduce visual capabilities. The use of dark backgrounds against which objects are to be seen will also help.^{37,38}
2. **Macular degeneration.** This occurs when the macular photoreceptors and neurons become inoperative due to bleeding or atrophy. The fovea is at the center of the macula lutea, and any loss of vision implies a serious reduction in visual acuity, color vision, and contrast sensitivity at high spatial frequencies. Typically, these changes make reading difficult, if not impossible. However, peripheral vision is largely unaffected so wayfinding is unchanged. Providing more light, usually by way of a task light, will help people in the early stage of

macular degeneration to read, although as the deterioration progresses, additional light is less effective. Increasing the visual size of the retinal image by magnification or by getting closer is helpful at all stages, because this can increase the size of the retinal image sufficiently to reach parts of the retina beyond the macula.

3. **Glaucoma.** Glaucoma is due to an increase in intraocular pressure that damages the retina and the anterior optic nerve. Glaucoma is shown by a progressive narrowing of the visual field, which continues until complete blindness occurs or the intraocular pressure is reduced. As glaucoma develops, in addition to a reduction in visual field size, poor night vision, slowed transient adaptation, and increased sensitivity to glare occur, all due to the destruction of peripheral photoreceptors and neurons. However, the resolution of detail seen on axis is unaffected until the final stage. Lighting has limited value in helping people in the early stages of glaucoma, because where damage has occurred, the retina has been destroyed. However, consideration should be given to providing enough light for exterior lighting at night to enable the fovea to operate. Such lighting will be helpful only if glare is controlled.

While the benefits of additional light depend on the specific cause of partial sight, there is one approach that is generally useful for all those with partial sight. This approach is to simplify the visual environment and to make its salient details more visible. Details can be made more visible by increasing their size, luminance contrast, and color difference. As an example, consider the problem of how to set a table so that a person with partial sight can eat with confidence. The plate holding the food and the associated cutlery can be made more visible by using a contrasting tablecloth, e.g., a dark tablecloth with a white plate and cutlery. The food on the plate can be made easier to identify by using an over-large plate so that individual food items can be separated from each other. The whole scene can be simplified by using solid colors rather than patterns. This same approach of simplification and enhanced visibility of salient information can be applied to whole rooms, for example, by painting a door frame in a contrasting color to the door so that the door is easily identified. Advice on designing lighting for the partially sighted is given in CIE Technical Report 123.³⁷

THRESHOLD VISUAL PERFORMANCE

Measurements of threshold visual performance are concerned with the limits of the visual system's capabilities. As an example of a threshold, consider the measurement of the minimum difference in luminance that can be detected between a region and an otherwise uniform surround. This

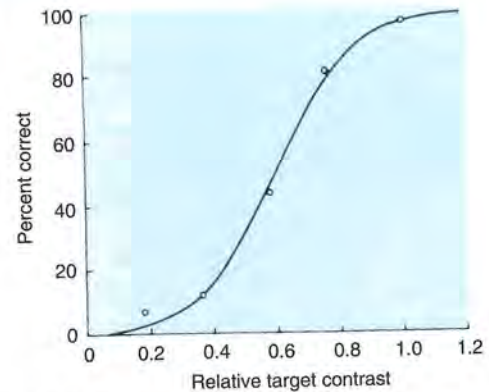


Figure 3-23. A frequency of seeing function. As luminance contrast (see Equation 3-6) is increased, the number of times it is correctly seen relative to the number of times it is presented increases to a maximum of 100%.

function has been studied in great detail³⁹ and has been used to relate the probability of detecting a small disc test object on a uniform background to the luminance contrast of the disc and the luminance of the background (Figure 3-23). As the luminance contrast of the disc is raised, the probability of seeing increases until, at a certain contrast, it can be detected 100% of the time. The luminance contrast at which the object can be detected 50% of the time is conventionally called the threshold luminance contrast.

Threshold visual performance measurements can be made for the ability to resolve detail, to detect luminance differences and color differences, and to see temporal changes in luminance. All such threshold measurements depend greatly on the characteristics of the lighting, the task, and the visual system of the observer. Among the variables that have been shown to be important are:

- Retinal illumination to which the visual system is adapted
- Spectral content of the illuminant
- Light distribution around the target
- Visual size of target (in units of angle or solid angle)
- Visual size of background (in units of angle or solid angle)
- Luminance of the target
- Luminance of the immediate background
- Luminance contrast of the target
- Color of the target
- Color of the background
- Color difference between the target and the background
- Duration of exposure
- Temporal frequency characteristics
- Location of the target relative to the line of sight
- Movement of the target in the field of view
- Retinal image quality, as determined by the state of

accommodation, pupil size, light scatter, and lens fluorescence

Additionally, such cognitive factors as attention, expectation, and habituation affect the measurement of threshold detectability and recognition of targets.

The practitioner can control such variables as the illuminance, the light spectrum, and the light distribution. These variables are sometimes important, per se, and can affect such other important factors as target luminance contrast and color contrast. Occasionally, the practitioner can influence such task variables as target size and duration of exposure. Extensive details of the threshold performance of the visual system are given in Reference 40.

Some Definitions

Retinal Illuminance. For a given individual looking at a given scene, the illuminance on the scene governs the luminances of the surfaces and hence the retinal illuminance. Luminances in object space can be related to retinal illuminance by the following function:

$$E_r = e_t \times \tau \times \left(\frac{\cos \theta}{k^2} \right) \quad (3-1)$$

where

E_r = retinal illuminance in lm/m^2 ,

τ = ocular transmittance,

θ = angular displacement of surface from the line of sight,

k = constant whose value is 15,

e_t = amount of light entering the eye in trolands, and is calculated by

$$e_t = L \times p \quad (3-2)$$

where

L = surface luminance in cd/m^2 ,

p = pupil area in mm^2 .

It should be noted that the amount of light entering the eye, e_t , measured in trolands, is often referred to as retinal illumination. This is misleading because it does not take into account the transmittance of the ocular media and therefore does not represent the luminous flux density on the retina.

Visual Size. For a target to be seen, it has to be larger than a minimum size. The relevant size of a target is an angular measure and depends on the physical dimensions, d , of the object itself; the angle of inclination, θ , of the target from normal to the line of sight; and the distance from the viewer, l . Size can be measured in a plane of two dimensions as a visual angle or in a volume in three dimensions as a solid angle, as shown in Figures 3-24a and 3-24b, respectively.

Visual angle of an object can be approximated by the following equation:

$$\text{Visual angle} = 2 \arctan \left(\frac{d \times \cos \theta}{2l} \right) \quad (3-3)$$

For small angles, this can be simplified to:

$$\text{Visual angle} = \arctan \left(\frac{d \times \cos \theta}{l} \right) \quad (3-4)$$

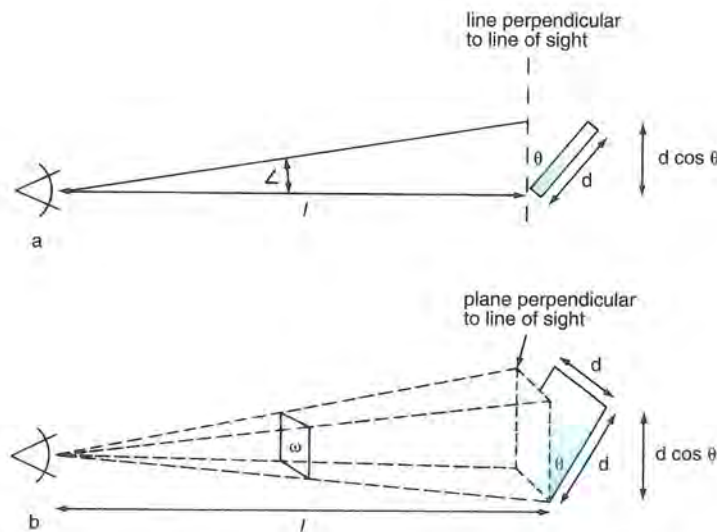


Figure 3-24. Dimensions required for calculating (a) visual angle and (b) solid angle.

Solid angle is given by the following equation:

$$\text{Solid angle} = \frac{d^2 \cos \theta}{l^2} \text{ in steradians} \quad (3-5)$$

The choice between visual angle and solid angle as a measure of visual size is largely determined by the symmetry of the object. Where the object is radially symmetrical such as a disc, or symmetrical in one dimension such as a grating, then visual angle is all that is required. Where there is no symmetry in the object, such as a letter F, solid angle is a better measure of visual size. Many times, visual angle or solid angle will be small. In this situation, visual size is measured in minutes of arc (60 minutes equals 1 degree) and solid angle is measured in microsteradians.

Luminance and Luminance Contrast. Given that a target is above the minimum size, it will be visible only if it differs from its immediate background in luminance or color. If it differs in luminance from the immediate background, the target has a luminance contrast.

Luminance contrast is defined in several ways:

$$C = \left| \frac{(L_t - L_b)}{L_b} \right| \quad (3-6)$$

where

L_t = luminance of the target,
 L_b = luminance of the background.

This equation results in luminance contrasts that range between 0 and 1 for targets that are darker than their backgrounds, and between 0 and infinity for targets that are brighter than their backgrounds. This equation is used most often in the former case, where the background is brighter than the target (e.g., printed text).

$$C = \frac{(L_g - L_l)}{L_g} \quad (3-7)$$

where

L_g = greater luminance,
 L_l = lesser luminance.

This equation results in contrasts between 0 and 1 for all objects, whether brighter or darker than their backgrounds. It is especially applicable in a situation like a bipartite pattern in which neither of the areas on the two sides of the border can be identified as target or background.

$$C = \frac{(L_{max} - L_{min})}{(L_{max} + L_{min})} \quad (3-8)$$

where

L_{max} = maximum luminance,
 L_{min} = minimum luminance.

The quantity defined by this equation is often called contrast, or Michelson contrast, but is usually and more prop-

erly called modulation. It gives a value between 0 and 1 for all objects. It applies to periodic patterns, such as gratings, which have one maximum and one minimum in each cycle.

Because there are several different definitions of luminance contrast and different definitions have different ranges of possible values, it is important to know which definition is being used when the contrast of a target is specified.

When a target and its background are both diffuse reflectors, the luminance contrast is not affected by changing the illuminance, so the luminance contrast can be calculated from the reflectances. However, if either the object or the background are directional reflectors, luminance must be used to calculate contrast.

It should be noted that for calculating luminance contrast, it does not matter how the luminance is achieved. It makes no difference whether the luminance is produced by reflection from a surface, such as print; from a self-luminous source, such as a VDT screen; or by some combination, such as a display on a VDT screen with a reflected image superimposed.

Color Difference. Visual targets that are larger than the minimum size but have the same luminance as the immediate background, that is, zero luminance contrast, can still be discerned by differences in color. Color difference can be calculated as a distance between the colors of the object and the immediate background using either the CIELAB or the CIELUV color spaces described in Chapter 4, Color, or other approximately uniform color space. It should be noted that one dimension of these color spaces is luminance, so a difference expressed across these color spaces includes both luminance and color difference. To measure only color differences, the separation of the color of the object and its immediate background on a plane of constant lightness in the CIELAB or CIELUV color spaces or the two-dimensional CIE 1976 u', v' diagram can be used.

Spatial Resolution

Spatial Summation. In complete darkness, the smallest amount of light that can be detected varies inversely with the area over which the light occurs. In other words, the total number of photons received in unit time, for detection, is constant. This relationship, which is known as Ricco's Law, takes the form:

$$I \times A = \text{constant} \quad (3-9)$$

where

I = threshold luminous flux, measured in photons
per unit area per unit time,
 A = target area.

Spatial summation is relevant only for very small targets. Above a certain size, spatial summation ceases so that further increases in size make no difference to the smallest amount of light that can be detected. This critical size varies

with location on the retina. For foveal vision, it is approximately 6 min of arc, increasing to approximately 0.5° for a target 5° off axis, and 2.0° for a target 35° off axis.

Visual Acuity. The word “acuity” is used to describe the ability to resolve fine details. Several different kinds of acuity are recognized.

1. Resolution acuity. The ability to detect that there are two stimuli, rather than one, in the visual field. It is measured in terms of the smallest angular separation between two stimuli that can still be seen as separate, such as two nighttime stars. Typically, resolution acuity is of the order of 1 min of arc.
2. Recognition acuity. The ability to correctly identify a visual target, as in differentiating between a G and a C. Visual acuity testing performed using letters, as is done clinically, is a form of recognition acuity testing. Typically, recognition acuity is of the order of minutes of arc.
3. Vernier acuity. The ability to identify a misalignment between two lines. Vernier acuity is typically of the order of seconds of arc.

Several examples of acuity test objects are shown in Figure 3-25. Gratings, letters, and Landolt rings have all been used as acuity test objects.

As with many other threshold tasks, visual acuity varies with retinal illuminance, size of background field, exposure duration and target motion. It also varies with luminance contrast, but by convention acuity is measured only at high luminance contrast. In general, acuity is finest when the target falls on the fovea (Figure 3-26) and improves as the retinal illuminance increases, because increasing the retinal illuminance decreases receptive field size. As for the size of the background field, Lythgoe⁴¹ has shown that acuity continues to improve with background luminance as long as the background is large; when the background field is small, there is an optimum luminance for visual acuity, above which acuity declines (Figure 3-27).

Visual acuity also increases as the exposure duration increases, up to approximately 500 ms, after which no further improvement occurs (Figure 3-28). Target movement can limit the exposure duration and the ability to keep the retinal



Figure 3-25. Commonly used test objects for determining resolution limits and visual acuity. The critical size is represented by the dimension d .

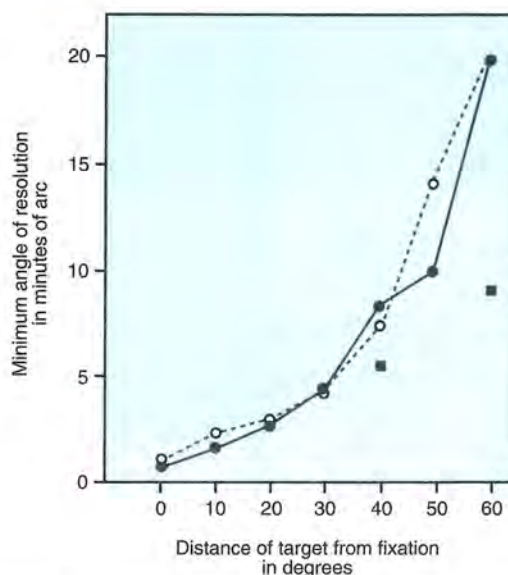


Figure 3-26. Minimum resolution in minutes of arc, as a function of angular separation from the fovea. Three different targets were used: Landolt rings at a background luminance of 2.45 cd/m^2 (open circles); Landolt rings at a background luminance of 245 cd/m^2 (filled circles); sinewave gratings at a background luminance of 1118 cd/m^2 (filled squares).

image on the fovea. As might be expected, increasing target speed tends to reduce visual acuity (Figure 3-29). The only condition under which the fovea fails to have the best visual acuity is scotopic vision. In this condition, the fovea is inactive and the best visual acuity is found a few degrees off the line of sight.

Contrast Threshold

The visual system gives virtually no useful information when the retina is uniformly illuminated, but is highly specialized to gather information about luminous edges and gradients in the visual field.

The ability to detect a target against a background can be quantified by its threshold contrast. By convention, threshold contrast is the luminance contrast of the target that can be detected on 50% of the occasions it is presented (Figure 3-23). Many factors affect threshold contrast. Among the more important are target size and retinal illuminance. Figure 3-30 shows the change in contrast threshold for a 4 min arc disc displayed for 200 ms plotted against adaptation luminance, for people of two different age groups. It shows that as adaptation luminance increases, the contrast threshold decreases, rapidly at first and then more slowly.^{33,42} Targets of different sizes exposed for different times give different absolute values of contrast threshold but all follow the same trend.

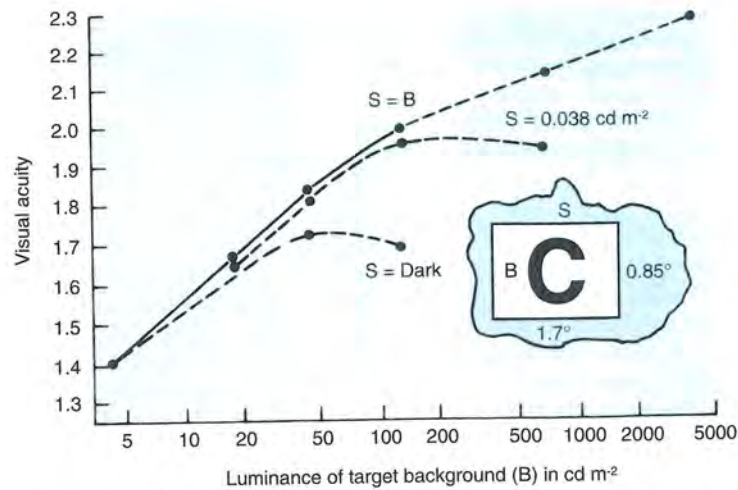


Figure 3-27. Effect of background luminance on visual acuity. The targets are Landolt rings on a background field measuring 0.85° by 1.7° . When the luminance of the surround field (S) equals the luminance of the target background (B) visual acuity continues to improve as background luminance increases.

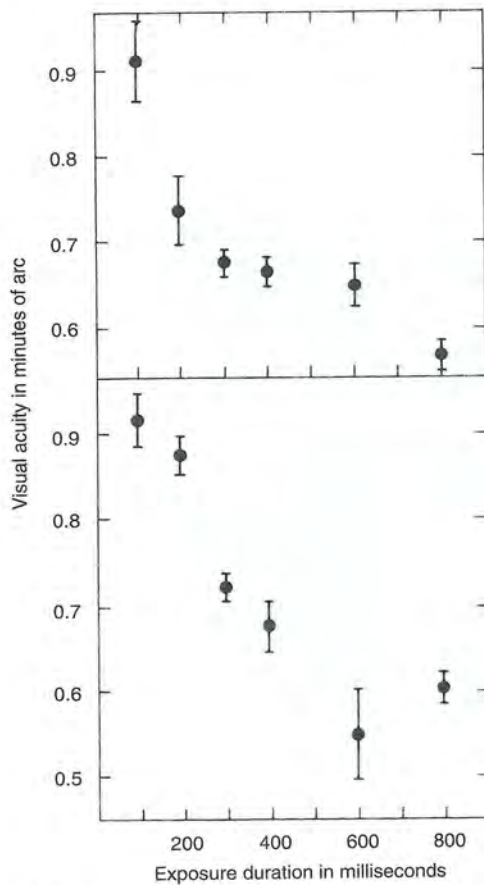


Figure 3-28. Minimum spatial resolution in minutes of arc plotted against target exposure duration. Resolution improves as exposure duration increases up to about 500 ms. Longer exposure durations do not affect minimum resolution.

Contrast Sensitivity Function

Visual acuity and threshold contrast separately define two aspects of a target that defines its visibility. Visual acuity sets the minimum size for a target to be seen and threshold contrast sets the minimum luminance contrast that is required for a target of a given size to be seen. The contrast sensitivity function combines these two measures by showing the minimum contrast required for targets of different sizes to be seen. Specifically, the contrast sensitivity function is a plot of contrast sensitivity against spatial frequency (Figure 3-31). It is usually based on data collected from grating targets of different spatial frequency. Spatial fre-

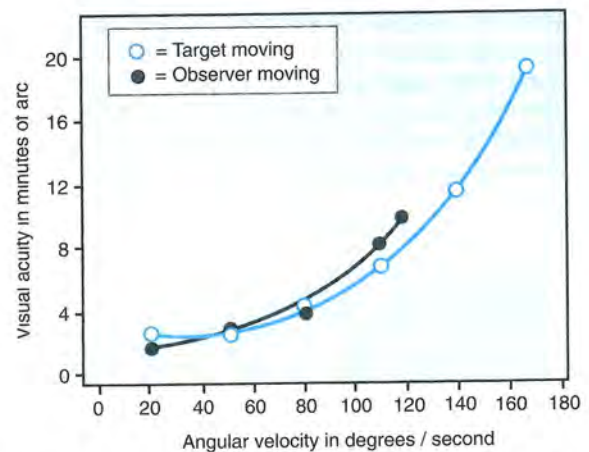


Figure 3-29. Minimum spatial resolution in minutes of arc plotted against angular velocity of target and observer movement.

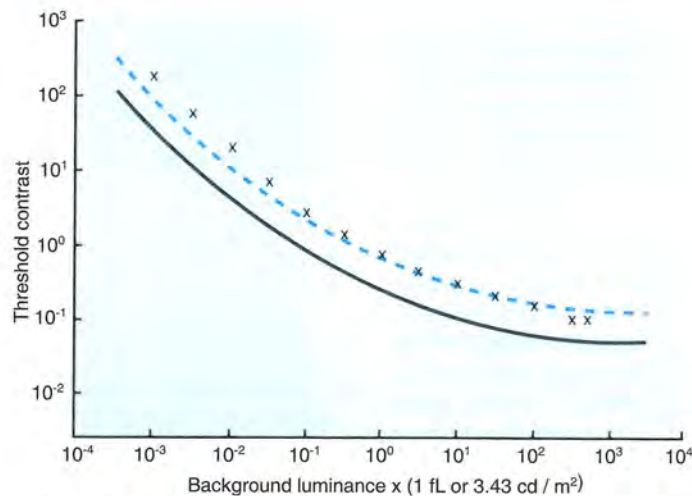


Figure 3-30. Threshold contrast data for a group of 60- to 70-year-olds (x) compared to the threshold contrast curve for a group of 20- to 30-year-olds (solid line), as a function of luminance. The dashed curve is the same as the solid curve but displaced upward by a factor of 2.51. Threshold contrast was calculated according to Equation 3-6.

quency is the reciprocal of the visual angle of one period of the grating and is measured in cycles / degree. Contrast sensitivity for a given spatial frequency is the reciprocal of the luminance contrast of the grating at threshold. Targets that have a spatial frequency and contrast sensitivity such that they lie above the contrast sensitivity function are invisible (i.e., can be detected on fewer than 50% of the occasions presented) and those that lie below the contrast sensitivity function are visible (i.e., can be detected on more than 50% of occasions presented). For complex targets that contain many different spatial frequencies, the contrast sensitivity

function can be used to determine if and how the target will appear by breaking it into its spatial frequency components.⁴³ The target will be visible only if at least one spatial frequency component has a contrast sensitivity less than the contrast sensitivity function. Exactly how the target will appear will depend on the weighting given to each of its spatial frequency components by the contrast sensitivity function.

Many factors affect the contrast sensitivity function. Among the most important are the adaptation luminance, the location in the visual field, and the number of cycles of the stimulus. Figure 3-31 shows the variation of contrast sensi-

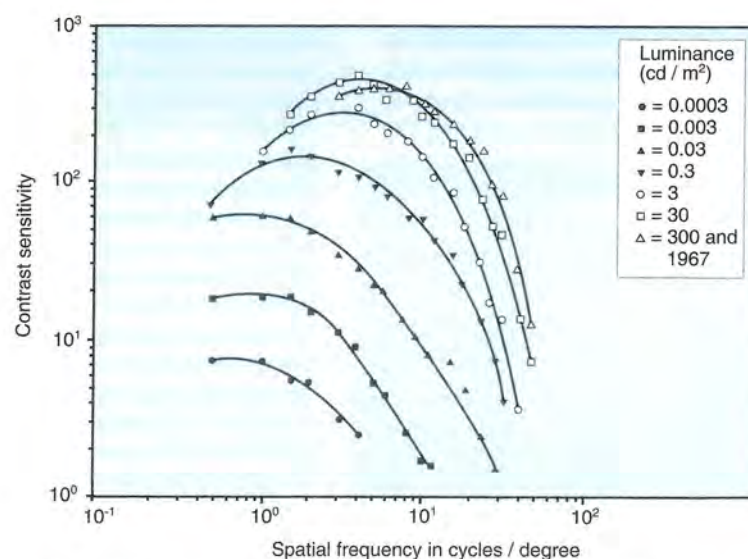


Figure 3-31. The spatial contrast sensitivity function for foveal vision, at different target luminances.

tivity function with adaptation luminance. As the adaptation luminance changes the operating state of the visual system from scotopic to photopic, the contrast sensitivity increases for all spatial frequencies; the spatial frequency at which the peak contrast sensitivity occurs increases, and the highest spatial frequency that can be detected increases.

As for the effect of the location in the visual field, contrast sensitivity is reduced at all spatial frequencies with increasing eccentricity, but the decrement is greater for high spatial frequencies. More details of the changes in contrast sensitivity functions with different lighting and visual conditions and examples of its diagnostic use can be found in Reference 40.

Temporal Resolution

Just as the visual system responds to variations of luminance in space, it also responds to variations of luminance in time.

Temporal Summation. For single brief flashes of light (less than 100 ms), any combination of luminance (L) and flash duration (t) with the same product produces the same perception. This characteristic is known as Bloch's law:

$$L \times t = \text{constant} \quad (3-10)$$

For single brief flashes of light longer than approximately 100 to 200 ms, the perception of the flash is solely a function of stimulus luminance (Figure 3-32).

Flicker. As a repetitive flashing stimulus is increased in frequency, it eventually reaches a point where it is perceived as steady rather than as intermittent; this is the critical flicker frequency (or critical fusion frequency, CFF). The frequency at which the fusion occurs varies with stimulus size, shape, retinal location, adaptation luminance, and modulation depth. Figure 3-33 shows the relationship of CFF to adaptation luminance for centrally fixated test objects of different sizes.

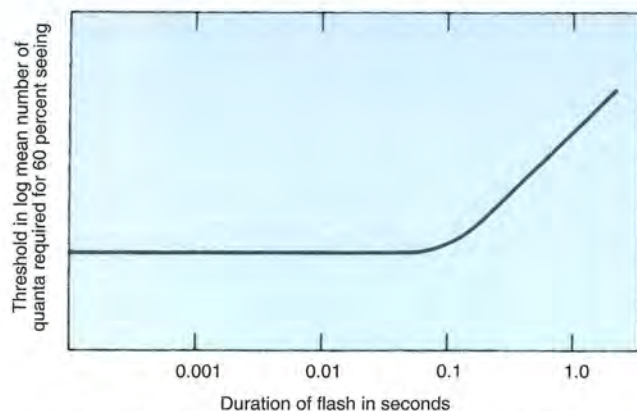


Figure 3-32. Total number of quanta for seeing a flash of light as a function of the duration of the flash.

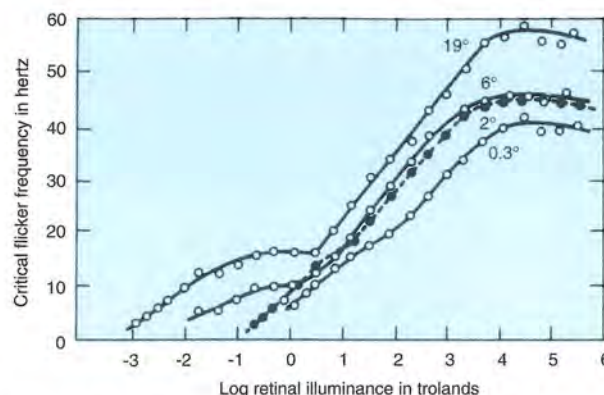


Figure 3-33. Critical flicker frequency (CFF) as a function of source area and retinal illuminance.

The CFF rarely exceeds 60 Hz even for a large visual area with 100% modulation, seen at a high adaptation luminance. This is just as well because all light sources that operate from an ac electrical supply show some fluctuation in light output. The electrical supply frequency in North America is 60 Hz, which means the fundamental frequency of oscillation in light output is 120 Hz although there might be some 60 Hz component present. The fundamental frequency of the light output oscillation (120 Hz) is twice the fundamental frequency of the electrical supply (60 Hz) because of the positive and negative halves of the ac cycle.

Another way of considering the combined effects of temporal modulation and temporal frequency is through the temporal modulation transfer function (MTF). This is the equivalent in time of the spatial contrast sensitivity function (Figure 3-31). Figure 3-34 shows the temporal MTF for different adaptation luminances. The vertical axis is the reciprocal of percent temporal modulation and the horizontal axis is the frequency of fluctuation measured in cycles per second. Figure 3-34 shows that in photopic conditions (i.e., above approximately 3 cd/m²), the visual system is most sensitive to frequencies in the range 10 to 30 Hz and that as the adaptation luminance decreases, the absolute sensitivity to flicker decreases, the frequency at which the peak sensitivity occurs decreases, and the highest frequency that can be detected decreases. These temporal modulation transfer functions, and others for different conditions, can be used to determine the likelihood that a given fluctuation in light will be perceived as flickering. For a fluctuation with a complex waveform to be seen as flicker, at least one of its frequency components must have a modulation sufficiently high that the modulation sensitivity is below the temporal MTF. Knowledge of the visual system's temporal response is most helpful when considering the detection of flashing signals and the perception of animated signs.

Sensitivity to flicker differs across the retina. The fovea can follow flicker rates up to approximately 60 Hz at moder-

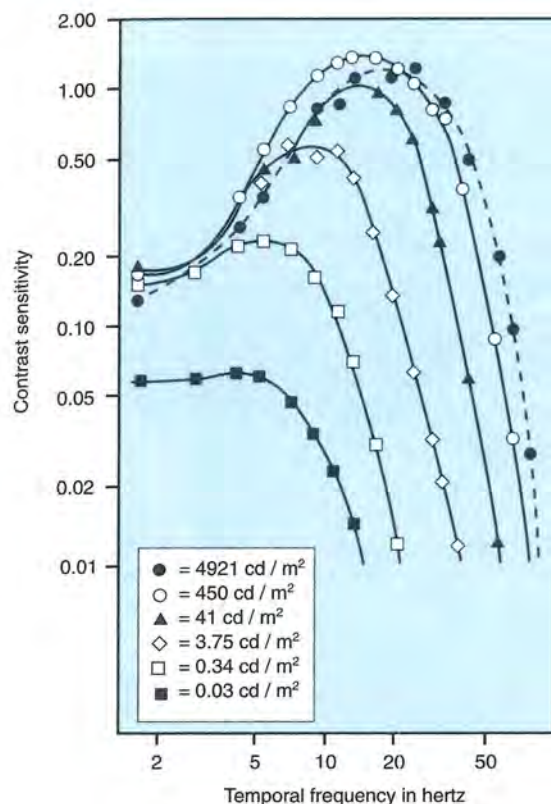


Figure 3-34. Temporal modulation transfer (contrast sensitivity) function for different adaptation luminances for a 68° field of view.

ate luminances, but is relatively insensitive to low frequency modulations. The peripheral retina, on the other hand, can detect flicker rates to approximately 15 Hz, but is very sensitive to small flicker amplitudes. This is why flicker is often detected in the peripheral field but disappears when the light is viewed directly.

It is widely recognized that visible fluctuations in light occurring over a large area can cause visual discomfort or annoyance. Recently, however, reductions in the prevalence of headaches have been reported when fluorescent lamps were operated on high-frequency electronic ballasts as compared to when they were operated on conventional (British) 50-Hz magnetic ballasts, even though flicker was not visible. This implies that flicker might have subliminal effects on the visual system. This hypothesis is supported by electrophysical recordings under such conditions.⁴⁴

Color Discrimination

The visual system varies in its ability to discriminate among wavelengths. There are regions of maximum wavelength discrimination in the middle of the visible spectrum but discrimination falls off rapidly at the spectral extremes.⁴⁵ Likewise,

the ability to discriminate hue from white is wavelength dependent. Monochromatic colors from the ends of the visual spectrum are more easily discriminated from white because they are more saturated than colors in the middle of the spectrum.⁴⁶ The ability to discriminate nonspectral colors is also related to their chromaticities.⁴⁷

Generally, color discrimination is best in the fovea and decreases toward the periphery. However, color discrimination for very small fields (20 min of arc or less) presented to the fovea is poor because there are very few short-wavelength S-cones in the center of the fovea. This effect is known as small-field tritanopia.⁴⁷

The ability to discriminate between colors can be estimated in terms of distances in a uniform 3-D chromaticity space (see Chapter 4, Color). MacAdam⁴⁸ produced a series of ellipses around the chromaticity coordinates of a number of different colors (Figure 3-35). Each ellipse sets the boundary at which a given percentage of people are able to determine that two colors, one with chromaticity coordinates at the center of the ellipse and one with chromaticity coordinates on the ellipse, are just noticeably different. Full details are given in Reference 8.

MacAdam's ellipses were determined in conditions that offer the maximum sensitivity to color differences: side-by-side comparison, unlimited observation time, foveal viewing, and photopic operation of the visual system. Changing any of these factors and adding distracting or confusing stimuli can be expected to increase the difference in color needed to reach discrimination threshold. Of particular importance is the amount and spectral power distribution of the light reaching the retina.

The retinal illuminance is important because it determines the operating state of the visual system. If the retinal illuminance is in the scotopic range, no colors can be seen and no discrimination is possible. In the mesopic range, colors can be seen but the discrimination of colors is poor, particularly for low reflectance colors. The color discrimination threshold is reduced as the retinal illuminance increases. This process continues until a retinal illuminance of approximately 30 trolands is reached, after which there is little change in the ability to discriminate colors. The light spectrum is important because it changes the stimulus to the visual system.

SUPRATHRESHOLD VISUAL PERFORMANCE

Threshold visual performance deals with what can just be seen. Suprathreshold visual performance is concerned with tasks that are visible because their important aspects are well above threshold levels. This raises the question as to why lighting conditions make a difference to task performance once what has to be seen is visible. The answer is that although the stimuli are visible, lighting influences the speed and accuracy with which the visual information extracted

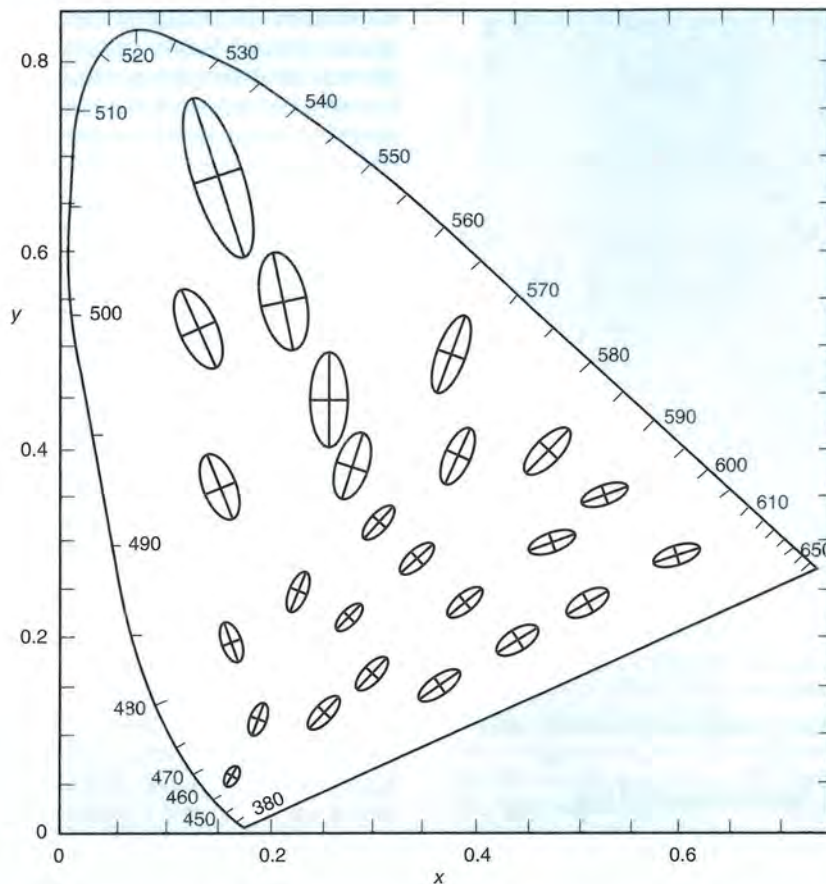


Figure 3-35. The 1931 CIE chromaticity diagram showing a selection of MacAdam ellipses, enlarged by a factor of ten. From G. Salvendy, *Handbook of human factors and ergonomics*, 2nd ed. Copyright © 1997. Reprinted by permission of John Wiley & Sons, Inc.

from the stimuli can be processed. Like threshold visual performance, suprathreshold visual performance is governed by such parameters as retinal illuminance, task contrast, visual size, and the characteristics of the visual system. Retinal illuminance is largely determined by the luminance of the visual field that is viewed and hence by the illuminance on the surfaces that form that field.

One approach to studying suprathreshold visual performance is to examine task performance for a variety of realistic tasks requiring vision. Several studies have been conducted mimicking realistic tasks to determine how illumination affects performance.⁴⁹⁻⁵³ This approach allows the experimenter to assess performance for a specific task in suprathreshold conditions, but it is difficult to generalize the results with high precision to other, even superficially similar tasks because it is impossible to separate visual from nonvisual components of performance. An example of nonvisual components would be the time taken to turn the page in a proofreading task (see “Visual Performance, Task Performance, and Productivity” below for a discussion of task structure).

Another approach was developed by Blackwell based on his extensive psychophysical measurements of threshold contrast.^{33,39,42} He developed several models for predicting suprathreshold performance from threshold performance.⁵⁴⁻⁵⁶ These systems all used the same concept as the basis of prediction, namely a simple multiplier derived from the ratio of the actual contrast presented by a target to the threshold contrast at the same adaptation luminance. This multiplier is known as Visibility Level. Unfortunately for simplicity, it was later shown that it is not possible to predict suprathreshold performance accurately from threshold performance, because if the stimuli at threshold are different, the same Visibility Level produces different suprathreshold performances.⁵⁷ Further, the complexities introduced by nonvisual components and off-axis working were not fully appreciated. As a result, the number of factors that had to be introduced to make the predictions fit a set of experimental data increased dramatically as the number of data sets increased, eventually leading to a loss of credibility. As a result, attempts to use the systems have been few.

As early as 1935, Weston^{58,59} recognized the importance

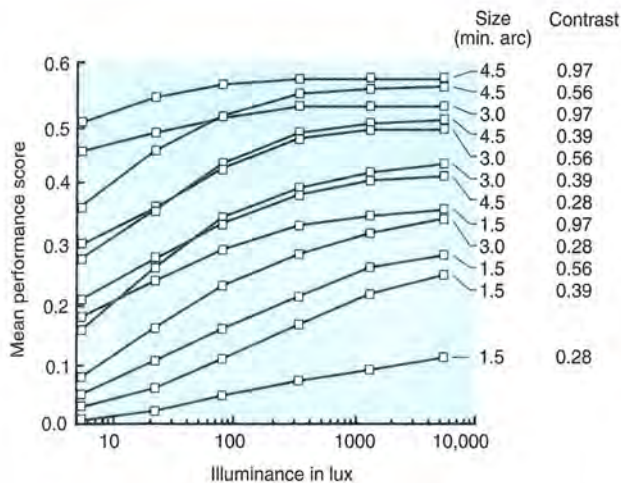


Figure 3-36. Mean performance scores for Weston's Landolt ring charts of different visual size and luminance contrast (see Equation 3-6), plotted against illuminance.

The performance score for each individual is given by the expression

$$\left[\left(\frac{\text{Total time taken}}{\text{Number of rings correctly cancelled}} \right) \times \left(\frac{\text{Total number of rings to be cancelled}}{\text{Number of rings correctly cancelled}} \right) - \text{manual time per ring} \right]^{-1}$$

of a systematic, direct study of suprathreshold performance utilizing variables that had been shown to be important to threshold vision, namely target size and target luminance contrast seen at different background luminances. The curves in Figure 3-36 demonstrate the effects of illuminance on detection of Landolt rings of different orientations and printed in different contrasts and sizes.^{38,39} Performance was defined, in these studies, as an aggregate score based on speed and accuracy.

An analysis of Weston's work⁶⁰ identified several design and analysis flaws, including a lack of documentation about specific visual characteristics and the use of a scoring system that failed to include correct rejections as part of the accuracy metric. Weston's performance data shown in Figure 3-36 can provide only general trends in suprathreshold response but, importantly, trends that cannot be gleaned from a knowledge of threshold vision.

In general, Weston showed that as background luminance increased, performance (measured in terms of speed and accuracy) increased rapidly at first but then less and less until a point was reached where very large changes in background luminance were required to make very small changes in performance. This trend of diminishing returns was more pronounced for high-contrast, large targets than for low-con-

trast, small targets. He also showed that performance for a small, low-contrast target could not be brought to the same level as a large, high-contrast target simply by increasing illuminance. Rather, changing the size and luminance contrast of the target often had a much larger effect on suprathreshold visual performance than increasing the illuminance over any practical range. Several studies of suprathreshold performance have extended Weston's approach.^{50-53,61} All of these studies have produced results consistent with the general trends shown by Weston.

Models of On-Axis Visual Performance

Weston's results illustrate the general form of the relationship between the visual size, luminance contrast of the target, and the retinal illuminance. Other researchers have provided quantitative models using more precise techniques. The general trends of suprathreshold performance, shown by Weston, have not been contradicted by these models.

The Relative Visual Performance (RVP) model of visual performance is a quantitative model based on an extensive dataset made up of the changes that occur in reaction time for the detection of visual stimuli seen by the fovea.⁶²⁻⁶⁵ The conditions covered in the dataset represent a wide range of adaptation luminances, luminance contrasts, and visual sizes. By using simple reaction time as a measure, this model attempts to minimize the nonvisual components in the task. By basing the model on the difference in reaction time that occurs for different combinations of adaptation luminance, luminance contrast, and visual size, the effect of any remaining nonvisual components is further minimized. Therefore, the RVP model shows the effect of adaptation luminance, luminance contrast and visual size on suprathreshold visual performance undiluted by nonvisual components.

Figure 3-37 shows the form of the relative visual performance (RVP) model for four different visual size tasks, each surface being for a range of luminance contrasts and retinal illuminances. The overall shape of the relative visual performance surface has been described as a plateau and an escarpment.⁶³ In essence, it shows that the visual system is capable of a high level of visual performance over a wide range of visual sizes, luminance contrasts, and retinal illuminations (the plateau) but at some point either visual size, luminance contrast, or retinal illumination become insufficient and visual performance collapses rapidly (the escarpment) towards a threshold state.

The RVP model provides a quantitative means of predicting the effects of changing either task size, luminance contrast, or adaptation luminance for on-axis, suprathreshold visual performance. It is applicable to luminances in the photopic range but does not take into consideration the effect of reduced retinal image quality caused by limited accommodation, nor the effect of color differences between the target and the background. It can be only applied once a decision is made as to what constitutes the true critical size of the target. The RVP model has been validated in that it

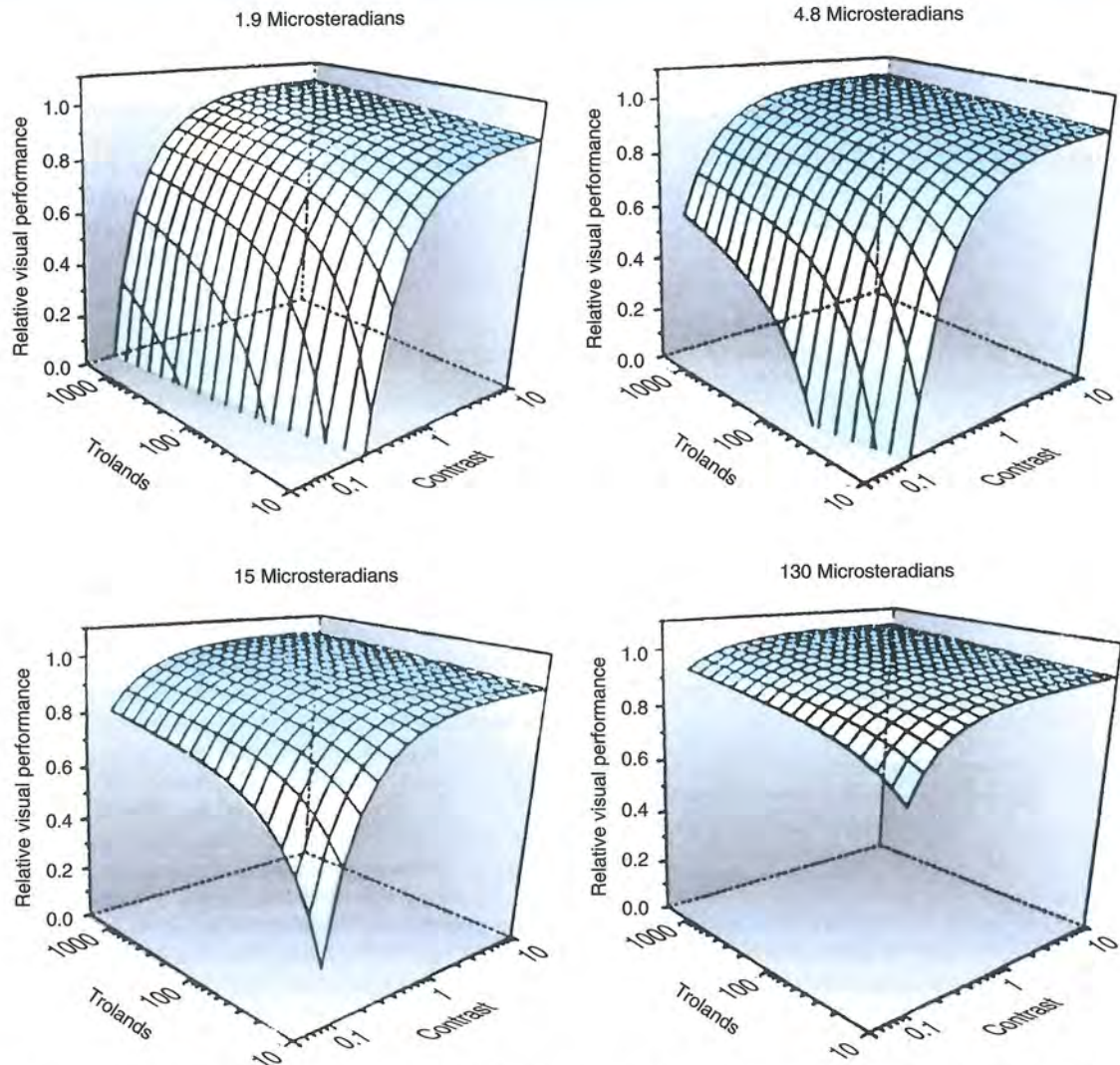


Figure 3-37. Relative visual performance (RVP) plotted as a function of task contrast (see Equation 3-7) and retinal illuminance (in trolands) for several different target sizes measured as solid angle (microsteradians).

has been shown to predict the form of the change in performance produced by different lighting conditions, measured in three independent experiments, using different visual tasks.^{60,66,67} It can be applied using input variables that can all be measured directly from the task.

The RVP model is based on reaction time data for detecting the presence of a square target. Such a target requires contrast discrimination but does not require resolution of detail. A task that does require resolution of detail is reading. Figure 3-38 shows task performance measured as reading speed plotted against the Visibility Level of the letters being read.⁶⁶ In this case, Visibility Level was defined as the ratio of the actual size to the threshold size of the letters of a given luminance contrast and at a set adaptation luminance. Figure 3-38 shows that reading speed changed little until the visi-

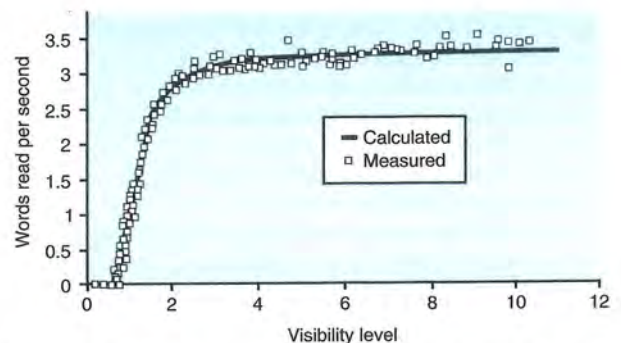


Figure 3-38. Reading speed in words/second plotted against visibility level (size).

bility level fell below a value of 3 but declined rapidly as the resolution threshold ($VL = 1$) was approached. Here too, there was a plateau and escarpment of task performance. For these reading speed data, a function based on Visibility Level was found to fit the data slightly better than the RVP model, most of the difference occurring for print sizes smaller than 6 point, where resolution might be expected to be important. Despite theoretical arguments,⁶⁸ in many ways the results of these studies of suprathreshold visual performance and task performance are more remarkable for their similarities than their differences. All show a plateau and escarpment form. This has important implications. The existence of a plateau of visual performance implies that for a wide range of visual conditions, visual performance changes little with changes in the lighting conditions. However, the RVP model does show that the plateau is not completely flat, there is a slight improvement in visual performance as adaptation luminance is increased, even when luminance contrast is high and visual size is large. What this means is that for many visual tasks, suprathreshold visual performance is insensitive to lighting conditions, but if it is required to maximize visual performance, increasing adaptation luminance can be effective.

It should also be noted that the RVP model is based on the luminance contrast presented to the observer, regardless of how that contrast is achieved. This means that both light polarization and distribution can affect visual performance for tasks that involve specularly reflecting materials, because both can change luminance contrast.^{60,69} Light distribution can produce veiling reflections (see "Lighting Conditions That Can Cause Discomfort" below) that can make luminance contrast larger or smaller, depending on the specific arrangement of the materials. The change in luminance contrast can be large but it is difficult to control because it depends critically on the geometry between the source of luminance being reflected, the task, and the observer. A small change in position of any of these entities can markedly change the luminance contrast.⁶¹ As for light polarization, in principle, polarized light is capable of eliminating specularly reflected light, but this too is very dependent on the geometry between the source of polarized light, the reflecting surface and the observer, as well as the magnitude and nature of the polarization.⁶⁹ A discussion on the physics of polarization is provided in Chapter 1, Light and Optics.

Visual Search

The RVP model discussed above is applicable to tasks that are imaged on the fovea. This is likely to be the situation when the observer knows where to look (e.g., reading). However, there is a class of tasks in which the object to be detected (i.e., target) can appear anywhere in the visual field (e.g., driving or industrial inspection). These tasks involve visual search. Visual search is typically undertaken through a series of eye fixations, the fixation pattern being guided either by expectations about where the target is most

likely to appear or by what part of the visual scene is most important. Typically, the target is first detected in the periphery of the retina. Detection is followed by eye movements that bring the detected target onto the fovea, where it is identified. The speed with which a visual search task is completed depends on the size, luminance contrast, and color difference of the target; the presence of other targets in the search area; and the extent to which the target is different from the other targets. The simplest visual search task is one in which the target appears somewhere in an otherwise empty field, such as paint scratches on a car body. The most difficult visual search task is one in which the target is situated in a cluttered field, where the clutter is very similar to the target to be found, such as searching for a particular face in a crowd.

The speed of visual search is determined by both the task characteristics and the lighting conditions. The task characteristics that hasten visual search are those that make the target stand out from its background (i.e., make it visible) and make it different from surrounding clutter (i.e., make it conspicuous).

To make a target visible, its visual size and luminance contrast must be well above the threshold values. To make a target conspicuous, it should differ from the surrounding clutter on as many perceptual dimensions as possible. Among such dimensions are size, shape, color, movement, and flicker.

The extent to which a lighting installation is effective in revealing a target can be estimated from the object's visibility lobe.⁷⁰ The visibility lobe is the distribution of the probability of detecting the object within one fixation pause (Figure 3-39). This probability is at maximum when the target is viewed with the fovea and decreases with increasing eccen-

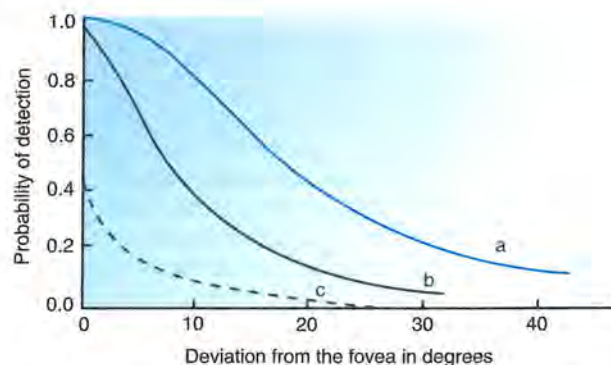


Figure 3-39. The probability of detection for targets of (a) contrast = 0.058, size = 19 min. arc; (b) contrast = 0.08, size = 10 min. arc; (c) contrast = 0.044, size = 10 min. arc; within a single fixation pause, plotted against deviation from the visual axis. Each curve can be used to form a "visibility lobe" for each target by assuming symmetry about the visual axis.

tricity from the fovea. The probability distribution is assumed to be radially symmetrical about the visual axis, resulting in circular contours of equal probability of detection within one fixation pause around the fixation point. Given that the interfixation distance is related to the visibility lobe and the search area is fixed, the time taken to find a target is inversely related to the size of the visibility lobe. For objects that appear on a uniform field, the visibility lobe is based on the detection of the object. For objects that appear among other similar objects, the visibility lobe is based on the discriminability of the object from the others surrounding it. Visual search is fastest for targets that have the largest visibility lobe.

Effect of Spectral Content on Suprathreshold Performance

The models of on-axis suprathreshold visual performance and visual search respectively discussed in "Models of On-Axis Visual Performance" and "Visual Search" ignore the possibility of the spectral content of the illuminant affecting the visual performance. This is reasonable given that previous research has shown little effect of spectral content on the performance of achromatic tasks.⁷¹ However, there is little doubt that the spectral content of the illuminant can affect the performance of tasks requiring color discrimination, nor that spectral content is important for visual search where color is one of the dimensions on which the target differs from other objects around it.⁷² In these situations, the spectral content of the illuminant changes the stimuli presented to the visual system. As a general rule, the higher the CIE General Color Rendering Index of the illuminant, the greater the color differences in the task and the easier it is to make the required discriminations.

While the spectral content of an illuminant might be expected to be important for any task where the spectral content changes an important aspect of the stimuli the task presents to the visual system, there is little evidence that it is important for all tasks. This has not stopped claims being made for what are called full-spectrum lamps. These lamps, which have no widely accepted definition, are typically fluorescent lamps with spectral emission in all parts of the visible spectrum and in the near UV, with a correlated color temperature of 5000 K or more and a CIE General Color Rendering Index of 90 or more. Claims have been made that the use of such lamps benefit task performance, human health, and happiness. These claims have little merit in most cases.⁷³

However, in recent years a number of studies by Berman and his colleagues have shown that spectral content can influence performance for achromatic resolution tasks such as reading or rapidly identifying gaps in a Landolt C acuity target (Figure 3-40).⁷⁴⁻⁷⁶ The proposed explanation of these findings rests on the role of pupil size. Specifically, pupil size in a large visual field is determined by the response of the rod photoreceptors, even in photopic conditions; the

larger the response from the rods, the smaller the pupil area.⁷⁷ The response from the rod photoreceptors can be increased by increasing the amount of short wavelength energy received at the eye. A smaller pupil area has three effects on the retinal image: it reduces the retinal illumination, it increases the depth of field, and it reduces aberrations. The first of these effects, the reduction in retinal illuminance, can be expected to degrade visual performance. The other two, increasing the depth of field and reducing aberrations, can be expected to improve the quality of the retinal image and hence to improve visual performance. All these effects are small, and how they trade off will depend on the inherent quality of the individual's optical system. An individual who is perfectly refracted will gain little from increasing the depth of field, so this person might be expected to experience deterioration of visual performance under a light source that produces smaller pupil sizes. However, most people do not have perfect refraction. For these people, the evidence suggests that light sources that do promote smaller pupil sizes can increase visual performance where the task conditions place it close to threshold, e.g., low luminance contrast, limited exposure time, and when the surfaces being viewed reflect most of the incident short wavelength light. Figure 5-18 gives spectral reflectances of a number of common building surfaces.

Visual Performance, Task Performance, and Productivity

Although our understanding of the effects of lighting conditions on visual performance has grown in recent years, it is important to realize that there is an inherent limitation on the generalizability of this understanding to the performance of all visual tasks. Figure 3-41 shows a conceptual relationship between visual stimuli, visual performance, task performance, and productivity. The stimuli to the visual system are determined by the task characteristics and the way the task is lighted. These stimuli and the operating state of the visual system determine visual performance. Most visual tasks have three components: visual, cognitive, and motor. The visual component refers to the process of extracting information relevant to the performance of the task using the sense of sight. The cognitive component is the process by which these sensory stimuli are interpreted and the appropriate action determined. The motor component is the process by which the stimuli are manipulated to extract information and the consequential actions carried out. As an example, consider the task of rectifying a software bug using an instruction manual. The visual component is to see the marks on the page of the instruction manual. The cognitive task is understanding what it means. The motor component is striking the right keys on the keyboard. Every task is unique in its balance between visual, cognitive, and motor components and hence in the effect lighting conditions have on task performance. It is this uniqueness that makes it impossible to generalize from the effect of lighting on the performance of

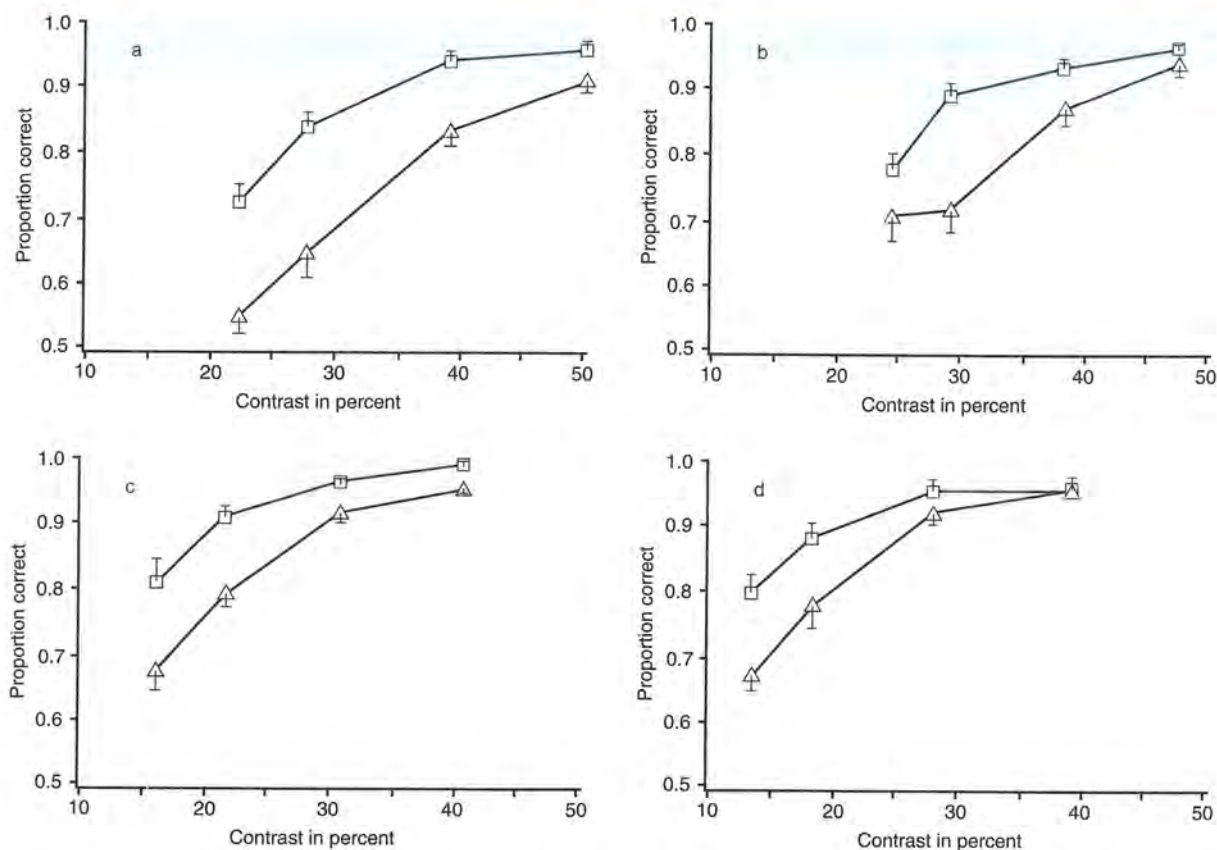


Figure 3-40. Means and associated standard errors of the proportion of Landolt ring orientations, presented for 200 ms on a spectrally neutral background, which were correctly identified; plotted against luminance contrast (see Equation 3-7), for four different target background luminances: (a) 11.9, (b) 27.7, (c) 47.0, (d) 73.4 cd/m^2 . In all four diagrams, the upper curve is for a scotopically enriched illuminant (surround field scotopic luminance = 228 cd/m^2), and the lower curve is for a scotopically deficient illuminant (surround field scotopic luminance = 13 cd/m^2). Both illuminants produce a surround field photopic luminance of 53 cd/m^2 .

one task to the effect of lighting on the performance of another. The RVP model of visual performance for on-axis tasks and the visual search model discussed above can be used to quantify the effects of lighting conditions on visual performance, but there is no general model to translate those results to task performance. Unfortunately, task performance is what is needed in order to measure productivity and to establish cost-benefit ratios comparing the costs of providing a lighting installation with the resulting benefits in terms of better task performance. When reading the literature, it is important to note that measures of task performance are sometimes erroneously called measures of visual performance.

Improving Visual Performance

The main purpose of many lighting installations is to enable people to perform their work quickly, easily, comfortably,

and safely. To achieve this aim, it is necessary to provide lighting that ensures people are operating on the plateau of visual performance and not on or close to the escarpment. Although the discussion above has been focused on lighting conditions, it is important to recognize that visual performance can be improved by changing the characteristics of the task as well as the lighting. The following list is divided into two parts: task changes and lighting changes. Not all the following suggestions apply in every situation, and not all are appropriate for every problem.

Changing the Task

- Increase the size of detail in the task, such as by magnification.
- Increase the luminance contrast of the detail in the task, for example, by adding toner to the printer.
- For off-axis tasks in a cluttered field, make the object to be detected clearly different from the sur-