Chapter Six

Light, Color, and Vision

Vision is one of the five physical senses (i.e., touching, tasting, hearing, smelling, and seeing) that connect us human beings to our environment. It allows us to detect approaching danger, enjoy the beauty of our surroundings, and communicate in a very personal manner with fellow human beings. While light is only one component of a building design, it is a very important consideration. Particularly the maximum utilization of daylight leading to energy conservation efficiencies, can be a dominant factor in the layout of spaces and the planning of the building as a whole. The constraints that may be imposed on a floor plan, if the optimization of daylight is a primary design criterion, can be quite severe. For example, most architects would agree that for classrooms to be adequately served by daylight alone they should receive this light from two opposite sides. This will require each classroom to have at least two partial external walls (i.e., partial, because both daylight sources could be highlights above party walls).

6.1 Some Historical Background

We understand today that vision is made possible by the interaction of a physical entity called light and a biological organ called the eye that is sensitive to light and in combination with the brain, allows us to see. This understanding was achieved only gradually. The ancient Greeks thought that vision was produced by something traveling between an object and the beholder. Pythagoras explained vision as images traveling from objects to the eye. Euclid, some 200 years later, reversed the travel direction by suggesting that *visual rays* travel from the eye to the object. A few years later Aristotle advocated a more sophisticated theory. He suggested that apparently transparent substances such as air and water become transparent only in the presence of some light source. This was a very clever concept that provided a plausible explanation of our inability to see in the dark. According to this theory air is made transparent by the light from the sun (or some other source such as a fire or candle) and this allows us to see because the colors of the objects in the environment are able to travel to our eyes.

It took another 1,300 years for the understanding to emerge that the eye is a detector of light. This decisive distinction between a physical entity and a biological detector, first proposed by the Arab scholar Alhazen, set the stage in the Middle Ages for the investigation of the characteristics of light within a new field of science called to this day *geometrical optics*. Knowledge of the rules of geometrical optics was acquired relatively rapidly and allowed the design and fabrication of optical devices such as lenses, microscopes and telescopes. However, the question of what is light itself lingered into the 20th Century.

6.2 Light Speed and Color

If light is a mobile physical entity, then it should be possible to measure its speed. Early in the 17th Century the Italian philosopher and astronomer, Galileo[1], devised an experiment to measure the speed of

1 Galileo Galilei (1564-1642) was not the inventor of the telescope but improved the magnification of a telescope from four to about nine. However, his major contributions relate to his interpretation of

light. He positioned himself and an assistant separately on two hilltops at night. The hilltops were several kilometers apart with a clear line of sight between them. By flashing light signals back and forth between himself and his assistant, Galileo sought to measure the round-trip travel time of the light signals. Taking into account the human reaction time, he found that there was no time interval left to attribute to the movement of the light. He realized that the speed of light must be very fast and could therefore not be measured with this kind of earthly line of sight experiment.

The solution of this problem came indirectly through astronomical observations in the later part of the 17th Century. While observing the movement of the moons of Jupiter through a telescope, the Danish astronomer Roemer[2] discovered that the prediction of the eclipses of the moons by Jupiter (i.e., whenever Jupiter is located directly between one of its moons and the earth) was consistently incorrect. The prediction was based on the measurement of the orbital periods of the moons, which could be calculated with reliable precision. Roemer reasoned that the error might be due to the changing distance between the moons and the earth, as they travel in their orbits around Jupiter. Since these astronomical distances are very large, they could affect the time it takes for light to transmit the image of the moon's location at any particular time to the eyes of the observer on earth. As further explanation it should be noted that we can see an event occurring only when light from that event reaches our eyes. Roemer was absolutely correct in his supposition. Today, using very precise instruments, we know the speed of light to be close to 300,000 km/sec or 186,000 miles/sec. No wonder that Galileo failed with his experiment. Even if the two hilltops had been 20 miles apart the time taken for a return trip light signal would have been less than a thousandth of a second.

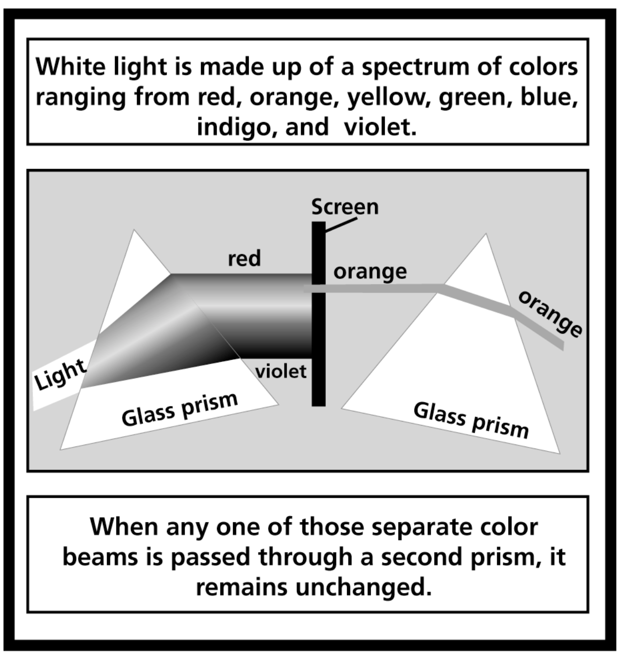

Figure 6.1: A second prism has no effect on the color of any one of the spectrum components

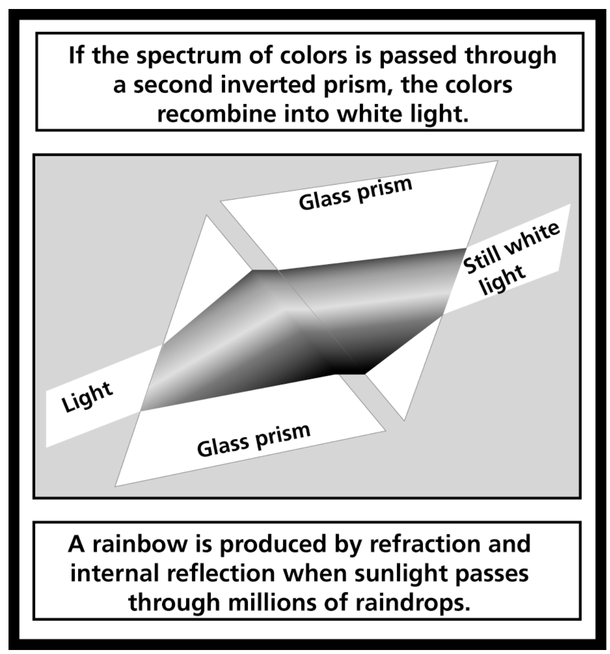

Figure 6.2: A second inverted prism will recombine the spectrum into white light

what he was able to observe through the telescope and his application of mathematics to the laws of motion.

2 Ole Roemer (1644-1710) was also an ingenious builder of precision instruments such as the *transit*, which is a telescope devised to observe stars as they cross the meridian and used for determining time.

Around about the same time in the 17th Century the renowned English scientist Isaac Newton shed light on the nature of color. The origin of color had been another perplexing issue. While it was already known that when light is passed through a glass prism it clearly separates into the colors of a rainbow, Newton took this experiment a step further (Figure 6.1). He showed that when he passed one of these separate color beams through a second prism this had no effect on the color of that beam. He inferred from this experiment that color was not due to any change in the nature of the light as it passes through the prism, but that the prism simply separates the light beam into a spectrum of colors. In other words, all of the colors are contained in light. He further proved this point by reuniting the separated colors into the original white light by passing them through a second inverted prism (Figure 6.2). Newton proceeded to place objects of various colors in the path of a colored light beam. He found that a colored object would effectively reflect light of the same color but absorb light of another color. For example, a blue object will appear blue under blue light, but nearly black under a red light. Newton correctly concluded that objects have color because of the way in which they reflect certain colors of the spectrum while absorbing the light of other colors[3].

6.3 What is Light?

The question of *what exactly is light* turned out to be a more difficult issue that was not fully resolved until the 20th Century. During the 17th Century there were two prevailing theories about the nature of light. The first theory advocated by Newton held light to be a flow of particles, while the second theory postulated light to be a form of wave motion. There was the obvious need for advocates of either theory to be able to explain the optical phenomena that were known at that time. These included:

Reflection, which occurs when light strikes a polished surface and is reflected away from the surface in such a way that the angle of incidence is equal to the angle of reflection.

Refraction, which occurs when light passes from one transparent or translucent medium to another. In other words, the light appears to bend slightly as it enters the second medium.

Diffraction, according to which light bends slightly around corners. For example, if we place an opaque object between a light source and a screen then the light will bend slightly around the object resulting in the projection of a shadow that is smaller than might be expected (Figure 6.3).

Polarization, which occurs when light passes through some transparent medium and only a portion of light appears to be transmitted. For example, looking through polarized sunglasses eliminates the glare normally seen when light is reflected from a shiny surface such as the water surface of the ocean (Figure 6.4).

[3] Isaac Newton (1643-1727) laid the foundations for differential and integral calculus several years before its independent discovery by Leibnitz. Utilizing differentiation, he was able to unify the solutions of many problems that hitherto had been approached through several largely unrelated techniques under one mathematical umbrella.

Both theories provided quite plausible explanations of the reflection, refraction and diffraction phenomena. However, the polarization of light constituted a challenging problem. Newton as the principal proponent of the particle theory argued that light consists of slightly elongated particles that are oriented in random directions in normal light, but in the same direction in polarized light. The advocates of the wave theory simply could not explain the polarization phenomenon because they incorrectly regarded light to be a *longitudinal*[4] wave form. Therefore, for almost 100 years the particle theory was accepted as providing the best explanation of the nature of light.

It was not until the 19th Century that a decisive experiment by the English scientist, Thomas Young (1773-1829), gave new life to the wave theory. He showed that when light is passed through two narrow slots, not two as might be expected, but a series of alternating lines of light and dark are projected onto a screen (Figure 6.5). He argued correctly that this phenomenon was caused by the interference of two sets of light waves passing through the two narrow slits (Figure 6.6). Based on Young's experiments the French physicist Augustin Fresnel (1788-1827) developed a detailed mathematical explanation of transverse light waves that very quickly replaced the particle theory.

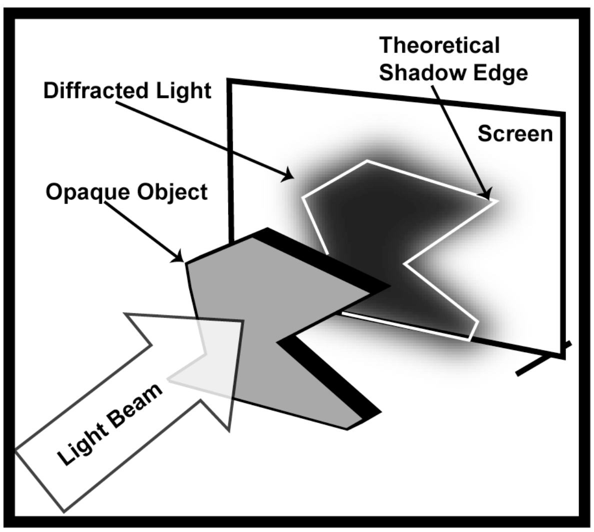

Figure 6.3: Diffraction of light around an object

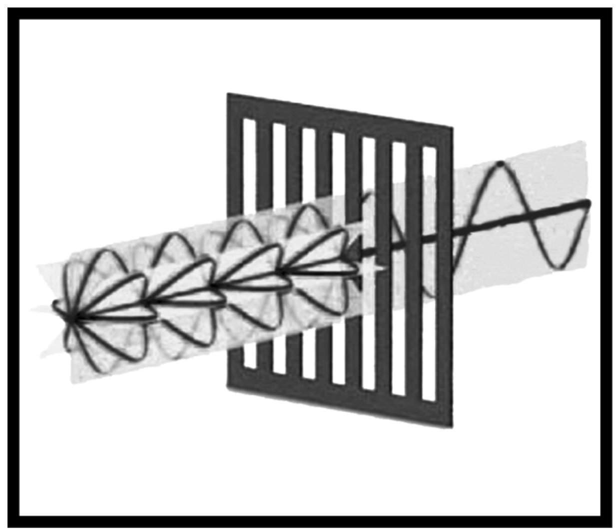

Figure 6.4: Polarization of light

Even though the wave theory of light had now triumphed, there was still a great deal of speculation about the nature of the medium that could support the propagation of transverse light waves. The separate contributions of two British physicists, Michael Faraday[5] and James Maxwell, and the German physicist

4 There are two types of wave forms, namely *longitudinal* and *transverse*. In longitudinal wave motion the particles of the medium through which the wave travels are physically displaced in the direction of the wave motion. However, the particles do not travel with the wave but rather oscillate back and forth about their mean positions as the wave progresses through the medium. In transverse waves, for example when we create a wave in a horizontally stretched rope, the up and down movement of the rope is transverse to the direction of the wave along the rope. Again, the material that makes up the rope does not travel with the wave but moves up and down (vertically) as the wave moves (horizontally) along the rope.

5 Michael Faraday (1791-1867) discovered that a suspended magnet will revolve around a current bearing wire and inferred from these experiments that magnetism is a circular force. He also invented the dynamo and discovered electromagnetic induction.

Heinrich Hertz (1857-1894) finally led to the understanding that light waves are electromagnetic waves. Essentially, light waves are produced by electric charges that can travel through any transparent or translucent medium. Unlike sound waves, which are transmitted by the progressive oscillation of the particles in the medium, the transmission of light waves does not require the physical particles of the medium to be set into vibration. Therefore, while sound cannot exist without a medium made up of particles (i.e., atoms and molecules), light can travel through a vacuum.

As shown in Figure 6.4, a light wave can be characterized as a beam that consists of a bundle of waves at all angles like the spokes of a bicycle wheel, so that the plane of each wave is perpendicular to the direction of the light beam. When this bundle of light waves passes through a Polaroid filter then all of the light waves in one plane (i.e., either the vertical or the horizontal plane) are blocked and only the waves in the other plane are transmitted.[6]

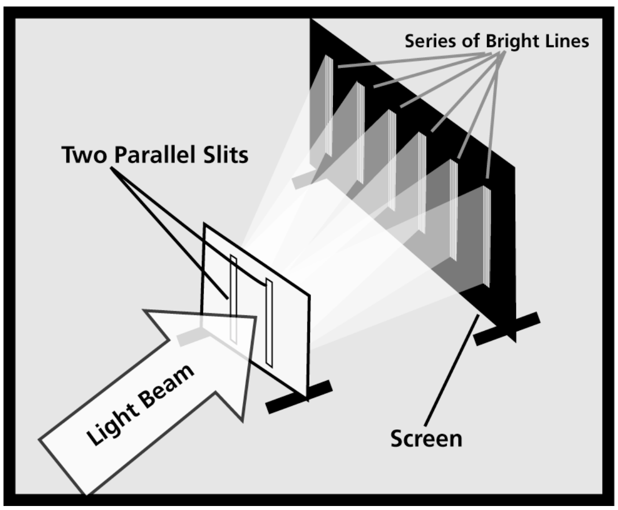

Figure 6.5: Young's double slit experiment

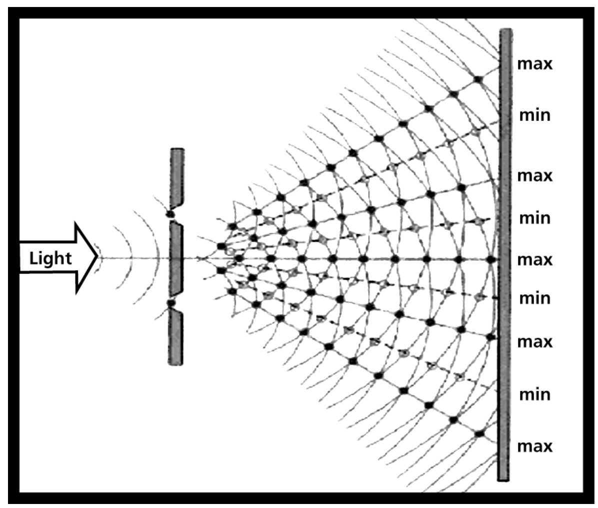

Figure 6.6: Explanation of Young's experiment

The realization that light is a form of electromagnetic radiation constituted a major break with the 19th Century view in physics that any phenomenon could and should be explained in mechanical terms. Contrary to this prevailing view Maxwell had shown that physical objects could influence each other through lines of force (i.e., electrical or magnetic field lines) without being in direct contact with each other. However, even the understanding of light as electromagnetic radiation was insufficient. Not all of the characteristics of light could be described in terms of wave motion. Particularly troubling was the large discrepancy between the theoretically predicted and measured emission of light from an object raised to a high temperature. This puzzle was solved at the turn of the 20th Century by Albert Einstein (1879-1955) building on the earlier work of the German physicist Max Planck (1858-1947). Planck had proposed that electromagnetic radiation is produced in discrete units called photons, rather than as a continuous flow. Einstein used this concept to explain the *photoelectric effect*[7],

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[6] A Polaroid filter is made of special material with long-chain molecules aligned in the same direction. If these molecules are aligned vertically then the filter will block the vertical waves and allow the horizontal waves to pass through. In other words, the vertical waves are absorbed by the vertically aligned long-chain molecules.

[7] When light of a particular color (i.e., frequency) illuminates a metal surface then electrons are emitted at a particular velocity. Increasing the intensity of light increases the number of ejected electrons, but

postulating that light behaves like a wave and also like a flow of particles, and thereby adding credence to the quantum theory[8] of physics that began to emerge at that time.

The photons that light consists of can be looked upon as discrete bundles of energy. Therefore, light is a form of energy just as heat, electricity and sound are other forms of energy. One of the properties that the various forms of energy share is the ability to change from one form of energy to another. For example, when we take a photograph with a non-digital camera light energy is converted into chemical energy in the film of the camera.

6.4 Light Viewed as Mechanical Waves

Although it is now accepted that light consists of discrete units of energy, it does obey to a limited extent the laws of wave motion. Photons can interfere with each other like the waves shown in Figure 6.6, in the explanation of Young's experiment. They can also diffract around corners as seen in Figure 6.3 or be polarized (Figure 6.4) like transverse waves. In fact, so many of the properties of light can be quite accurately described in terms of wave motion that it has become common practice to refer to light as electromagnetic waves. While this oversimplification of the nature of light is quite acceptable for the lighting design of buildings, there are properties of light in the realm of physics that can only be explained by treating light as a stream of individual energy bundles (i.e., photons).

The ability of electromagnetic waves to travel through a vacuum is due to the fact that they are produced by a vibrating electric charge. However, electric charges also generate magnetism and therefore the term electromagnetic. In other words, electromagnetic waves have both an electric and a magnetic component. Like mechanical waves they can be characterized in terms of just three attributes (Figure 6.7). Amplitude is a measure of the intensity of the wave, wavelength is equal to the distance between two successive crests (i.e., maxima) or troughs (i.e., minima), and the number of complete wavelengths passing a particular point in one second is referred to as the frequency.

While the electromagnetic spectrum ranges over an enormously large number of wavelengths, the part of that spectrum that stimulates the retina of our eyes and is therefore visible to us is a very narrow band of microscopically small wavelengths. The wavelengths that constitute light are measured in millimicrons (also referred to as nanometers) ranging from approximately 350mμ to 750mμ, where one millimicron (mμ) or nanometer (nm) is equal to one billionth of a meter. As shown in Figure 6.8, each individual wavelength within the spectrum of light is representative of a particular color, ranging from red to violet in descending wavelengths. The reason why Isaac Newton was able to demonstrate that light contains the colors of the rainbow (Figures 6.1 and 6.2) when it passes through a translucent prism is because each wavelength will bend to a slightly different degree as it passes through the prism. When all of the

not the velocity. At the same time, different colored lights of the same intensity cause electrons to be ejected with different velocities. This is referred to as the *photoelectric effect*.

[8] The laws of Newtonian physics break down at the microscopic subatomic level of electrons, protons, neutrons, and quarks. For example, electrons do not rotate around a nucleus like planets rotate around a sun. Instead, they follow the very different laws of quantum physics, such as Heisenberg's uncertainty principle. This law states that the more we know about one attribute of the current state of a subatomic particle, the less we know about another attribute. Therefore, if we are 70% sure of the velocity of an electron, we can be only 30% sure of its position at any given point in time. Quantum physics is derived from the term *quanta*, which is the smallest package of energy that an electron can absorb or give off as it changes its energy level.

wavelengths of the visible spectrum are perceived by our eyes at the same time, then we refer to this as white light. However, strictly speaking *white* is not a color at all but simply the presence of the complete spectrum of light. Similarly, neither is *black* a color but rather the absence of all of the wavelengths of the visible spectrum.

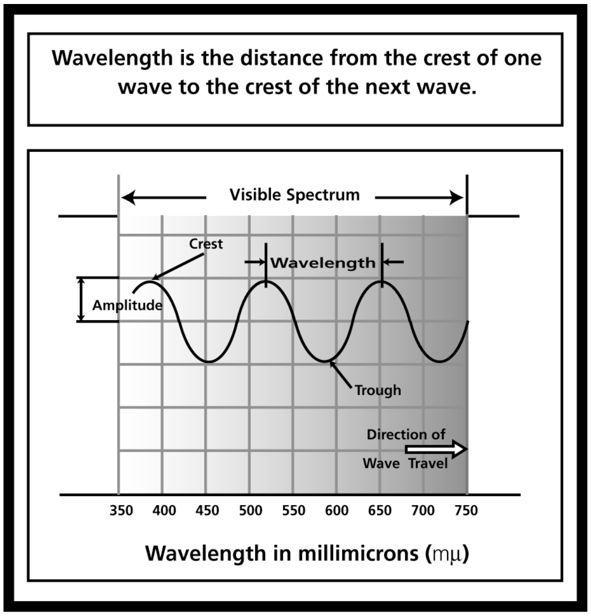


Figure 6.7: Properties of light waves

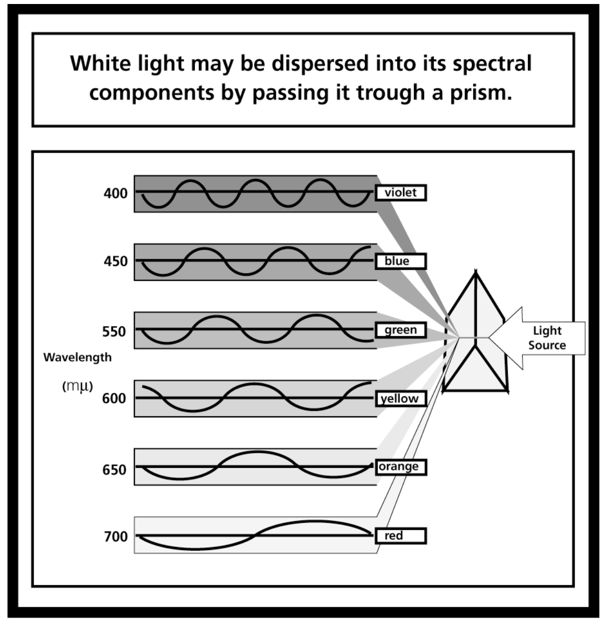


Figure 6.8: Spectral colors of light

There are many forms of electromagnetic energy the effect of each depending on its energy content, so that high frequency radiation will have high energy content and low frequency radiation will have correspondingly lower energy content. As shown in Figure 6.9, the visible spectrum or light as we perceive it occupies a very narrow band (i.e., 350 to 750 mμ), although it is possible by means of fluorescence to create perceptible light from ultra-violet radiation. We will discuss the latter in some detail in a later chapter dealing with the creation of light by artificial means. However, in the study of natural lighting we are concerned only with the visible spectrum of electromagnetic radiation as perceived by the human eye.

The eye is not a photometer and does not measure absolute physical brightness levels. Objects are perceived through the eyes by virtue of their brightness and color, or more precisely, by the differences in brightness and color. In other words, our eyes measure brightness differences. When we drive a car at night on a two-way road the headlights of an on-coming car tend to temporarily blind us. This will be particularly the case if the driver of the on-coming car forgot to dip his or her headlights and they remain on full beam. If we were to encounter the same car on the same road during the day in bright sunshine, we would be hard pressed to even recognize whether the car has its headlights on full beam or not. Obviously, the amount of light emitted by the headlights is exactly the same during nighttime and daytime. What is different is the background illumination level. During a dark night the headlights of a car, particularly if on full beam, will be several orders of magnitude brighter than the ambient illumination level. However, during a bright day under a clear sky even the full beam headlights of a car are unlikely to be much brighter than the sunlight reflected from the asphalt paving of the road. Consequently, the headlights of an on-coming car will appear to be much dimmer during the day than at night.

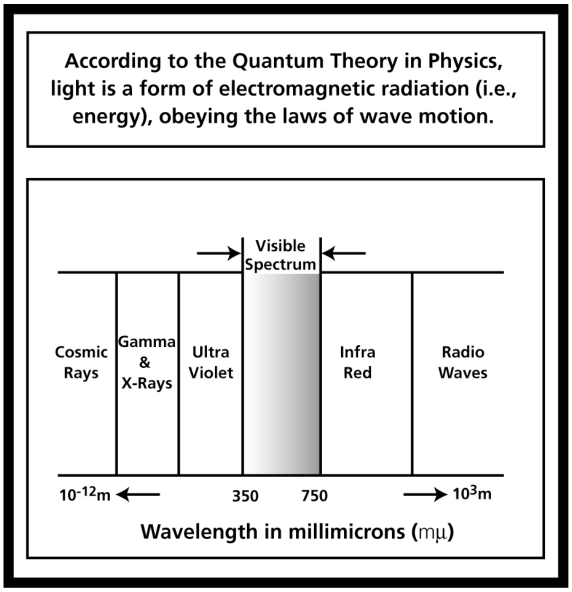
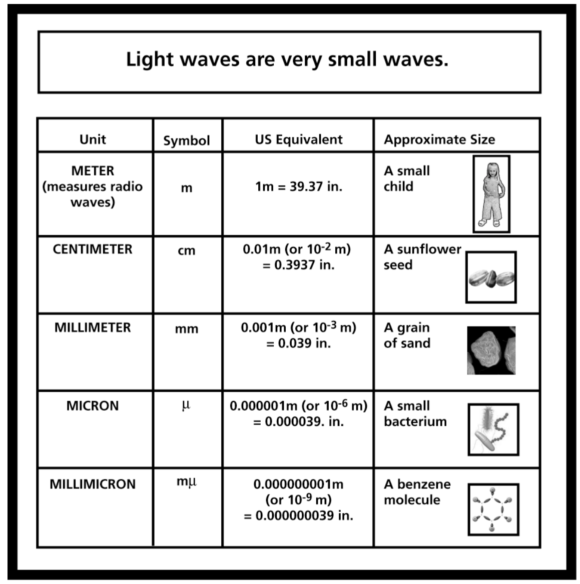


Figure 6.9: The full spectrum of electromagnetic radiation



Unit	Symbol	US Equivalent	Approximate Size
METER (measures radio waves)	m	1m = 39.37 in.	A small child
CENTIMETER	cm	0.01m (or 10^{-2} m) = 0.3937 in.	A sunflower seed
MILLIMETER	mm	0.001m (or 10^{-3} m) = 0.039 in.	A grain of sand
MICRON	μ	0.000001m (or 10^{-6} m) = 0.000039. in.	A small bacterium
MILLIMICRON	mμ	0.000000001m (or 10^{-9} m) = 0.000000039 in.	A benzene molecule

Figure 6.10: Comparative measures of wavelength size

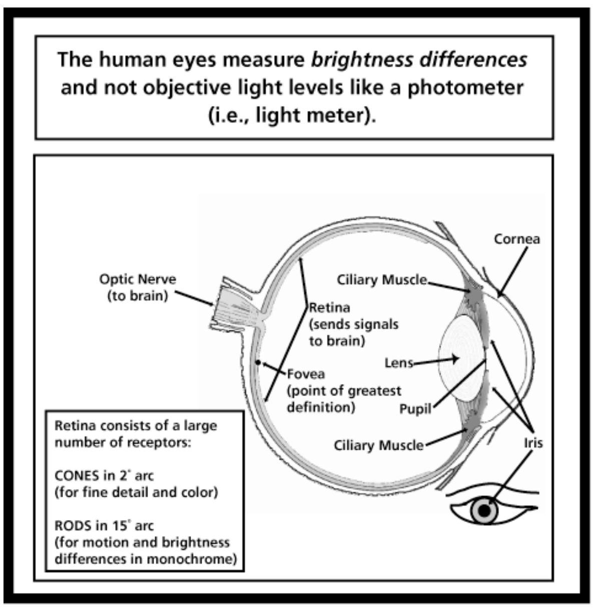


Figure 6.11: Section through the human eye

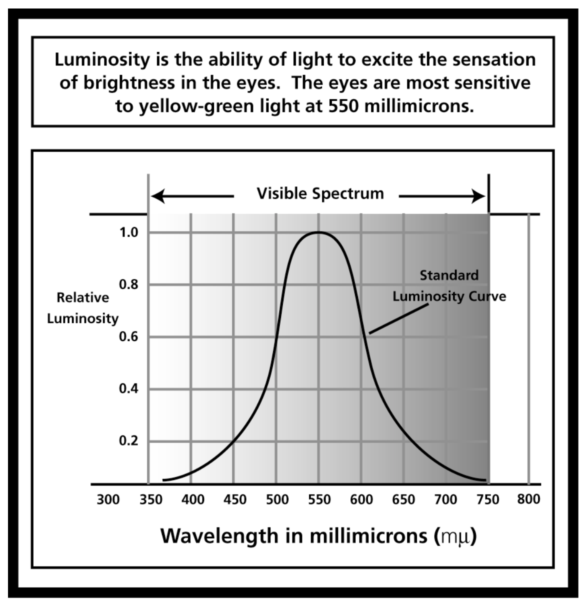


Figure 6.12: The standard luminosity curve

The central area of the retina (Figure 6.11), called the fovea is covered by cones in an approximately 2˚ arc. Cones are required for fine detail and color vision[9]. Therefore, the very small fovea region is also the area of greatest definition. Outside this area we

[9] Experimental results only fairly recently (1965) confirmed that there are three types of cones with different color sensitivities. These correspond approximately to red, green and blue sensitive receptors. The green and red sensitive cones are grouped closely within the fovea area, while the blue sensitive cones are found mostly in the para-fovea area. About 64% of the cones are red sensitive, about 32% are green sensitive and only about 2% are blue sensitive.

enter into the para-fovea region, in which the number of rods increases. Rods are used in the perception of brightness differences and motion, but in monochrome. Accordingly, color vision is limited to some 15° arc around the fovea. Both cones and rods are light receptors that pass the light stimulus through the optic nerve to the brain for interpretation.

Although the eye is sensitive to a very wide range of luminosity (i.e., brightness) it takes time to see. However, the time it takes for the eyes to adjust is reduced by higher luminance. We experience this in our daily activities. For example, if we decide to see a movie during the daytime and have to enter the theater after the start of the show, we find that it takes a minute or two until our eyes adjust to the semi-darkness and we are able to vaguely make out the shapes of people, empty seats and steps. Conversely, when we leave the cinema at the end of the show we are able to adjust to the bright sunshine of the exterior much more quickly. While vision speed increases with higher levels of illumination, visibility increases with greater object brightness.

Increased illumination also increases visual acuity (i.e., the ability to see fine details). However, this does not mean that we can simply increase the illumination of the task area at will, to improve our ability to resolve small visual details. At some point the difference between the brightness of the task area and the immediate surround will become a source of glare. This is due to the fact that our eyes measure brightness differences, and if these brightness differences are excessive then the rods in the para-fovea area of the eye will be over-stimulated.

As shown in Figure 6.12, the sensitivity of the human eye varies considerably within the visible range. Our eyes are most sensitive to yellow-green light with a wavelength of around 550 mμ. Below wavelengths of 480 mμ and above 620 mμ our sensitivity is reduced by more than 50%. For this reason, in most countries, highway signs are given a green background color. However, it must be noted that the Standard Luminosity Curve shown in Figure 6.12 represents a statistical average. Individual persons vary slightly in their response to luminosity and this may contribute to individual differences in taste, particularly as far as color preferences are concerned.

The fact that the human eye perceives subjective brightness differences forms the basis of the Apparent Brightness Theory of lighting design, which will be discussed in some detail later in this chapter. It suffices here to define *apparent brightness* as the subjective perception (i.e., through the human eye) of physical brightness. Accordingly, the apparent brightness of any area in the visual field is determined by the luminance (i.e., physical brightness) of the field and the average luminance of all objects in the field. The average luminance of all objects in the visual field is further known as the *adaptation level*.

In summary, the following characteristics of the human eye are of particular interest:

- Individuals vary in their response to luminosity and this fact may largely contribute to differences in taste among persons.
- Although the eye is sensitive to a very wide range of luminosity it takes time to see and this time is reduced by higher luminance.
- Visual acuity is the ability to resolve small visual details. An increase in luminance increases visual acuity.
- Vision speed increases with higher levels of illumination, and visibility improves with increased object brightness.
- Pictures or images received by the eye are inverted.

- The retina consists of a very large number of receptors known as rods and cones. Cones are concentrated in the actual fovea area and are responsible for our ability to see fine details and color. Rods increase in numbers in the para-fovea area and are responsible for the detection of brightness differences and movement.
- The retina sends signals to the brain, where the images received by the receptors in the retina are interpreted.
- The fovea is the point of the greatest definition.

The subjective aspects of vision are related to the more general concept of sensation and stimulus. By sensation we understand a sensing or feeling by a human being, purely on a subjective basis. For example, when the level of illumination in a room is measured with a light meter, the reading will not be a measure of the sensation produced by the light, but the physical stimulus. Accordingly, the physical stimulus measured in units of physical energy gives rise to subjective sensations, which are related in magnitude to the amount of stimulation.

6.5 Measurement Units of Light

Since the perception of light is related to the sensitivity of the eye, it is only appropriate that the units of light should be quite separate from the normal units of power and energy found in the thermal, electrical, and mechanical fields. There are essentially only four characteristics of light that are directly relevant to the lighting design of building spaces, namely: light flux; luminous intensity; illumination level (also referred to as illuminance); and, luminance.

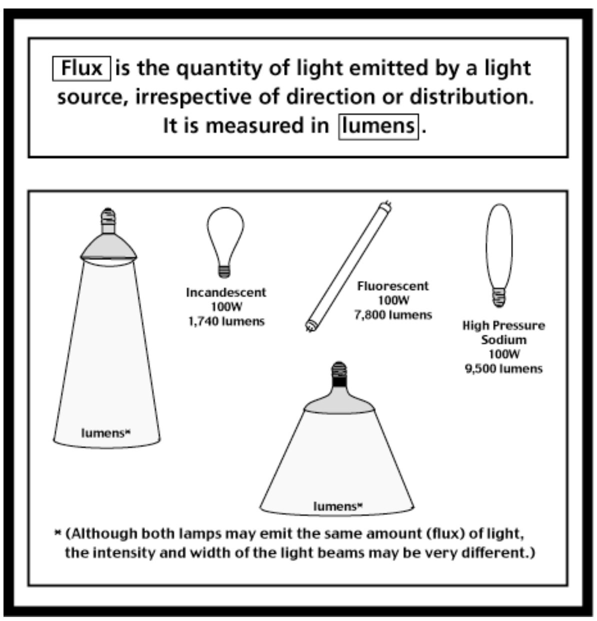


Figure 6.13: Light flux

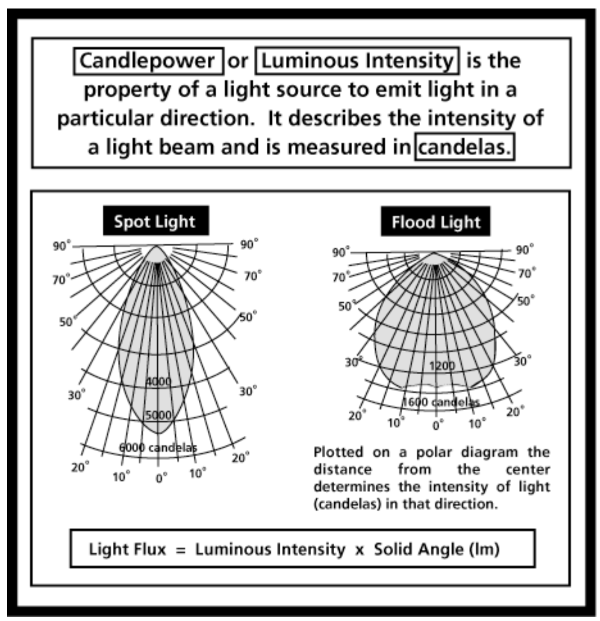


Figure 6.14: Luminous intensity

Flux is the quantity of light emitted by a light source, irrespective of direction or distribution (Figure 6.13). Strictly speaking the units of flux should be *lumen* per second, but it is common practice to neglect the time element. The performance of a lamp is stated in terms of the number of lumens it emits, and its efficiency in terms of the number of lumens emitted per watt of input energy.

Luminous intensity is the property of a source to emit light in a given direction, and is measured in *candela*, where one candela is approximately equal to the light emitted by a single candle[10] (Figure 6.14). Light flux (F lumen) from a point source is related to the luminous intensity (I candela) of the source by the expression:

Light flux (F) = luminous intensity (I) x solid angle (W) lm …………….. (6.1)

A solid angle is a spherical angle that is subtended by a surface to the center of a sphere[11]. In the case of the luminous intensity of light the 'surface' is the area illuminated by the light source and the 'center of the sphere' is the light source itself.

Luminous intensity is particularly useful for describing the characteristics of artificial light sources. As shown in Figure 6.14, the distribution of light provided by a luminaire can be plotted on a polar diagram as concentric rings of luminous intensity, measured in candela. However, it should be noted that the area depicted on the polar diagram is not a measure of the amount of light emitted by the lamp, but simply represents the distribution of light. In other words, a larger area does not indicate that a given luminaire provides more light than a luminaire with a smaller area. What it does indicate is that the available light is spread over a larger or smaller area, respectively.

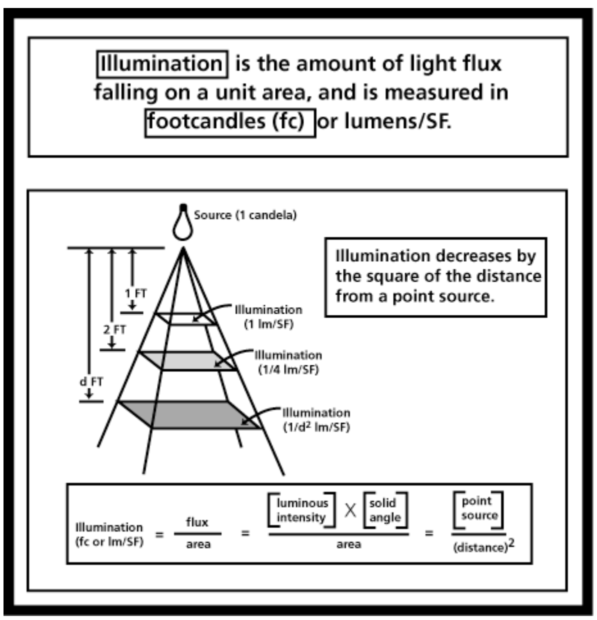


Figure 6.15: Illumination or illuminance

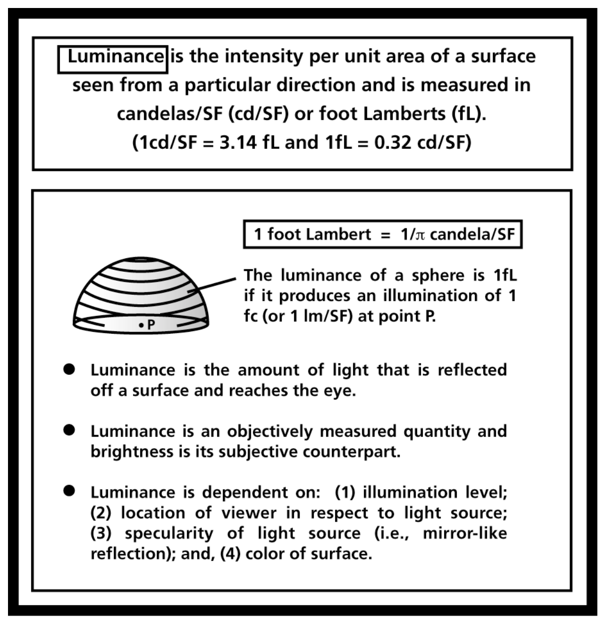


Figure 6.16: Luminance

[10] The light emitted by a single candle is about 12 lumens. In comparison, the light emitted by a 100-watt incandescent (i.e., filament) lamp is about 1,000 lumens.

[11] A solid angle is measured in *steridians* and is somewhat like an inverted circular pyramid or cone. The solid angle of the entire surface of a sphere is equal to 4π steridians.

Illumination level or illuminance is the amount of light flux falling on a surface area (A SF) and is measured in lumen/SF (lm/SF) or footcandle (fc)[12]. Accordingly, illumination (E) is given by the formula:

illumination (E) = flux (F) / area (A) lm/SF or fc………………………….. (6.2)

As shown in Figure 6.15, illumination decreases by the square of the distance for a point source[13]. Therefore, the illumination (E) at a distance (D) from a point source of luminous intensity (I) acting through a solid angle (W), is expressed by:

illumination (E) = flux (F) / area (A) = I x W / A = I / D^2 lm/SF or fc……(6.3)

If the surface is inclined at some angle θ to the direction of the emitted light, then:

illumination (E) = I cos θ / D^2 lm/SF or fc…………………………………. (6.4)

The concept of *unit sphere* defines the relationship between luminous intensity and illumination level. Imagine a candle flame at the center of a sphere that has a radius of one foot. The amount of light flux falling on any one square foot of the surface of that sphere is one lumen/SF or one footcandle. Since the total surface area of the sphere is equal to 4π, then the amount of light flux generated by the candle is 4π lm or 12.57 lm.

Luminance is the intensity per unit area of a surface seen from a particular direction and is measured in candela/SF or foot lamberts (ft-L). The performance of a large light source may be determined by dividing it up into a number of elements, each of which could have a different intensity distribution. Accordingly, the concentration of flux emitted in a given direction from the projected area of each of these elements is referred to as the luminance of that element (Figure 6.16). It can be shown that if the surface of a sphere has a uniform luminance, then a numerically equal illumination is produced by that luminance at the center of the sphere. This means that a uniform sky with a luminance of 1,000 ft-L will produce an outdoor illumination on a horizontal surface of 1,000 lm/SF (or 1,000 fc).

Luminance, illumination and reflectance are closely related in the following manner. The illumination on a surface may be defined as the incident luminous flux per unit area expressed in lumen per square foot (or footcandle). However, some of the light flux falling on this surface is reflected so that the amount of light reaching the eyes of the observer is proportional to the amount of flux falling on the surface and the ability of the surface to reflect light. The luminance of this surface is also a function of the incident flux per unit area and the reflectance of the surface.

As shown in Figure 6.17, the human eye can detect luminance over an enormously wide range that extends from the over 450 million ft-L generated by the sun to under 1 ft-L under moonlight. Of course, looking directly into a light source with a very high luminance, such as direct sunlight, must be avoided because it can cause permanent damage to the retina of the eye. In fact, our eyes already start to squint involuntarily when subjected to a luminance of around 2,000 ft-L.

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12 The units of illumination, lumen/square foot and footcandle, are numerically equal (i.e., 20 lm/SF = 20 fc).

13 The Inverse Square law applies only to a point source. For a line source the illumination decreases simply by the linear distance (i.e., luminous intensity divided by distance from the line source), and for an area source the illumination is approximately equal to the luminous intensity.

While luminance is an entirely objective quantity that can be measured with a luminance meter, the perception of luminance by our eyes is relative and subjective. This subjective equivalent of luminance is referred to as *brightness*, and is relative to the adaptation level of the surroundings.

A comparison of Metric and American[14] lighting units of measurement is shown in Figure 6.18, with the respective conversion factors. For both light flux (lumen or lm) and luminous intensity (candela or cd) the units of measurement are the same in both the Metric and American systems. However, in the case of illumination and luminance conversion factors are necessary as follows:

For illumination or illuminance: 1 lm/SF or 1 fc is approximately equal to 10 lux.

For luminance: 100 ft-L is approximately equal to 3 cd/m^2

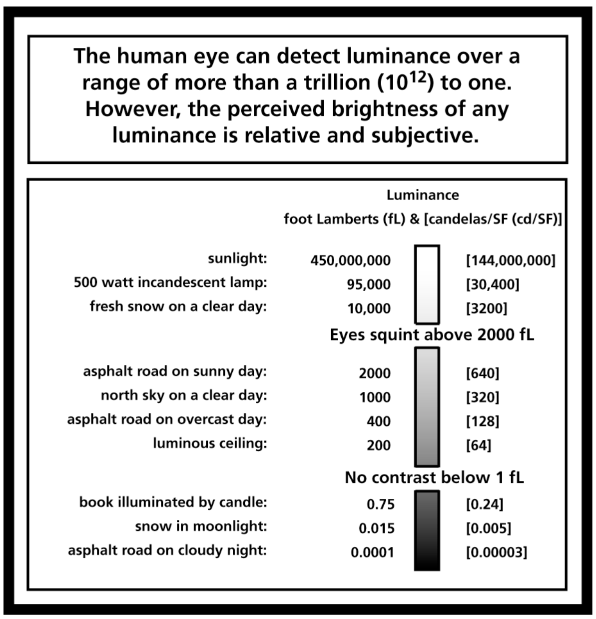
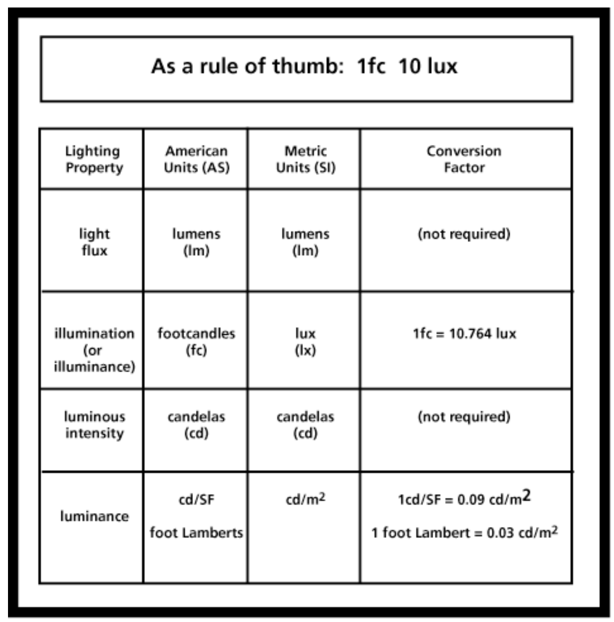


Figure 6.17: Perception of luminance as brightness by the human eye



As a rule of thumb: 1fc 10 lux

Lighting Property	American Units (AS)	Metric Units (SI)	Conversion Factor
light flux	lumens (lm)	lumens (lm)	(not required)
illumination (or illuminance)	footcandles (fc)	lux (lx)	1fc = 10.764 lux
luminous intensity	candelas (cd)	candelas (cd)	(not required)
luminance	cd/SF foot Lamberts	cd/m^2	1cd/SF = 0.09 cd/m^2 1 foot Lambert = 0.03 cd/m^2

Figure 6.18: Comparison of Metric and American units of measurement

6.6 Light Reflection, Absorption, and Transmission

When light is incident on any opaque material then some of the light will be reflected and the remaining light will be absorbed. If the material is translucent then some of the light will also be transmitted. The proportions of light that are reflected, transmitted and absorbed depend on the characteristics of the material and the nature (i.e., the spectral distribution) of the incident light. To determine exactly how much light is reflected we must know not only the reflectance curve of the material[15], but also the intensity of the incident light at each wavelength of its spectrum.

14 Known previously as Imperial units of measurement, which were used throughout the British Commonwealth until these countries adopted the Metric system of units in the 1960s and 1970s. Today (2005), the US is the only remaining major country that has not adopted the Metric system.

15 The reflectance curve of a material provides the percent reflectance at each wavelength.

Therefore, if light with an intensity of 20 candela in the red wavelength (i.e., around 700 mμ) is incident on a predominantly blue material that has only 10% reflectance at the red wavelength then only 2 (i.e., 0.1 x 20 = 2) candela will be reflected at that wavelength.

The *reflectance* of a surface is defined as the percentage of light incident on the surface that is reflected from the surface, and the *Reflectance Factor (RF)* is simply the decimal equivalent of the reflectance percentage. As shown in Figure 6.19 there are two basic types of reflection, which depend on the size of the surface irregularities in relationship to the wavelength of the incident light. A smooth or polished surface produces *specular reflection* in which light is reflected in a single direction and the angle of incidence is equal to the angle of reflection. If the surface is rough in relationship to the wavelength of the incident light, then the light will be scattered and this is referred to as *diffuse reflection*. A perfectly diffuse reflector is known as a Lambertian surface[16] with the property that its reflected brightness is the same when viewed from any direction. Of course, most surfaces exhibit both specular and diffuse reflection characteristics.

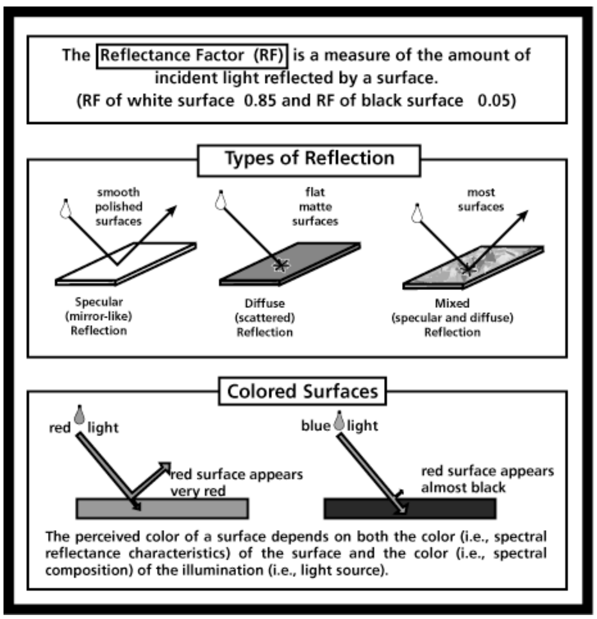
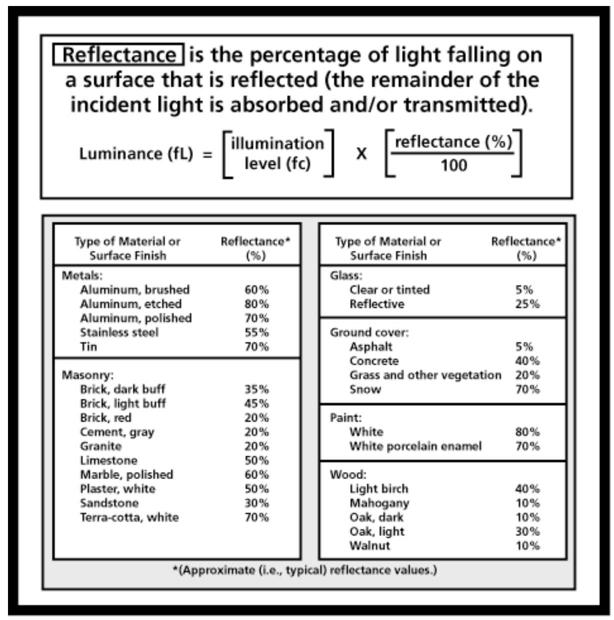


Figure 6.19: Reflectance Factor (RF)



Reflectance is the percentage of light falling on a surface that is reflected (the remainder of the incident light is absorbed and/or transmitted).

$$\text{Luminance (fL)} = \left[\text{illumination level (fc)}\right] \times \left[\frac{\text{reflectance (\%)}}{100}\right]$$

Type of Material or Surface Finish	Reflectance* (%)
Metals:	
Aluminum, brushed	60%
Aluminum, etched	80%
Aluminum, polished	70%
Stainless steel	55%
Tin	70%
Masonry:	
Brick, dark buff	35%
Brick, light buff	45%
Brick, red	20%
Cement, gray	20%
Granite	20%
Limestone	50%
Marble, polished	60%
Plaster, white	50%
Sandstone	30%
Terra-cotta, white	70%

Type of Material or Surface Finish	Reflectance* (%)
Glass:	
Clear or tinted	5%
Reflective	25%
Ground cover:	
Asphalt	5%
Concrete	40%
Grass and other vegetation	20%
Snow	70%
Paint:	
White	80%
White porcelain enamel	70%
Wood:	
Light birch	40%
Mahogany	10%
Oak, dark	10%
Oak, light	30%
Walnut	10%

*(Approximate (i.e., typical) reflectance values.)

Figure 6.20: Reflectance of common materials

When light is transmitted through a translucent material some of the light may be absorbed and some of it may collide with particles inside the material and deflected (i.e., scattered) into another direction (Figure 6.21). Successive scattering inside the material may actually return some of the light back to the incident surface as reflected light. It is interesting to note that the absorption of light, while it is being transmitted through a translucent material, is also due to a form of collision. In this case the obstruction is a molecule that contains *chromophores*. For example, inks and dyes contain chromophores. According to Lambert's Law of Absorption, for

16 Named after the 18th Century scientist Johann Lambert (1728-1777) who discovered several laws relating to the transmission of light. For example: Lambert's Law of Absorption that defines the exponential decrease of light passing through an absorbing medium of uniform transparency; and, Lambert's Cosine Law, which states that the brightness of a diffusely radiating plane surface is proportional to the cosine of the angle formed by the line of sight and the normal to the surface.

materials in which no internal scattering of light occurs, the amount of light transmitted decreases exponentially with the concentration of dye molecules, the thickness of the material, and a constant that describes the characteristics of the chromophore of the dye molecule[17].

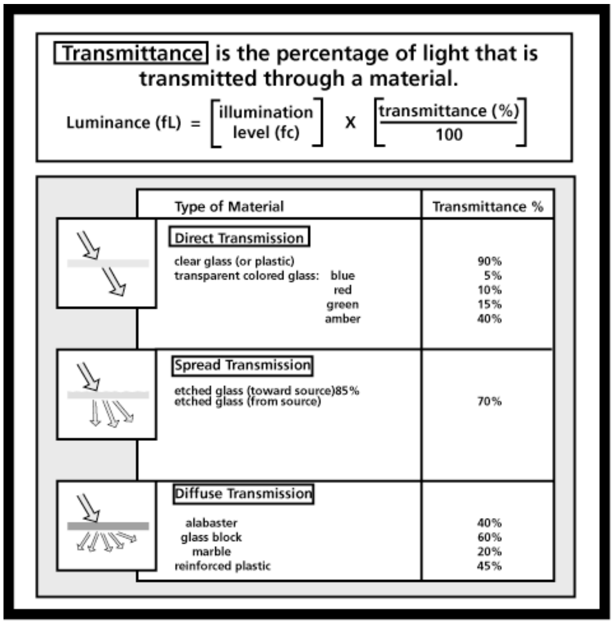


Figure 6.21: Transmittance of light

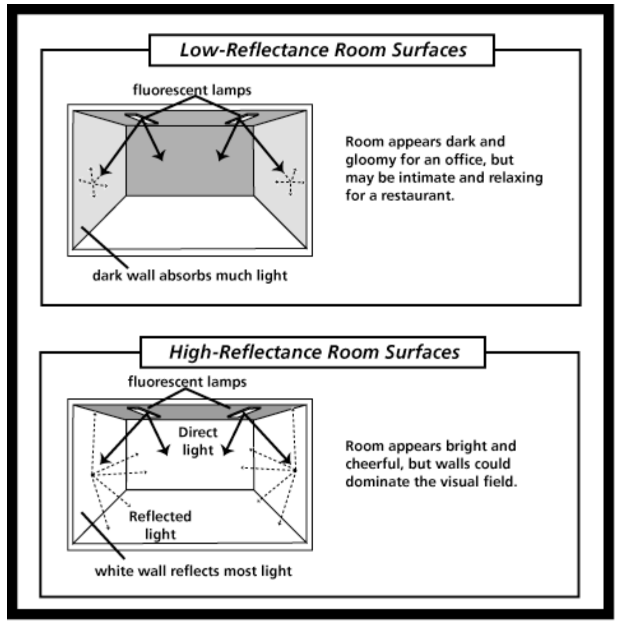


Figure 6.22: Impact of light reflectance

As shown in Figure 6.22, the reflectances of the surfaces in a room can greatly influence the ambient atmosphere conveyed by the appearance of the room. Ceiling and wall surfaces with a low Reflectance Factor tend to give a room a darker appearance, which might provide a desirably intimate environment for a restaurant but an undesirably gloomy environment for a classroom or office space.

6.7 The Visual Field and Adaptation Level

As discussed earlier, our eyes measure brightness differences and not absolute light levels. Therefore, lighting design in buildings involves largely the control of brightness contrasts. As can be seen in Figure 6.23, contrast allows us to recognize the shape of physical objects and can be a determining factor in visual performance. For example, lack of contrast can seriously inhibit our ability to read signs, while excessive contrast in the field of view can cause visual discomfort and in extreme cases actually prevent us from seeing details. Methods that the lighting designer can use to control brightness contrasts, include:

- Choice of the types of light sources and their locations in a building space. For example, if most of the light is directed to the ceiling then this will result in a diffuse illumination within the space because much of the available light will have been reflected from the ceiling.

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[17] The fundamental characteristic of the chromaphore is called the *extinction factor* and is a property of the molecular structure of the dye.

- Choice of surface finishes (i.e., materials) in respect to reflection and transmission properties (e.g., translucent, opaque, matt, glossy, etc.), color, and texture.
- Variation of intensity of light from area to area, as well as the spectral distribution of the light source itself.

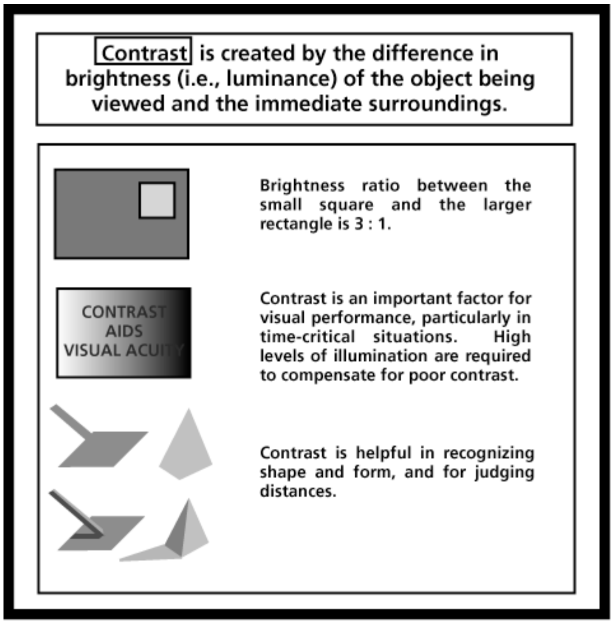

Figure 6.23: Brightness differences

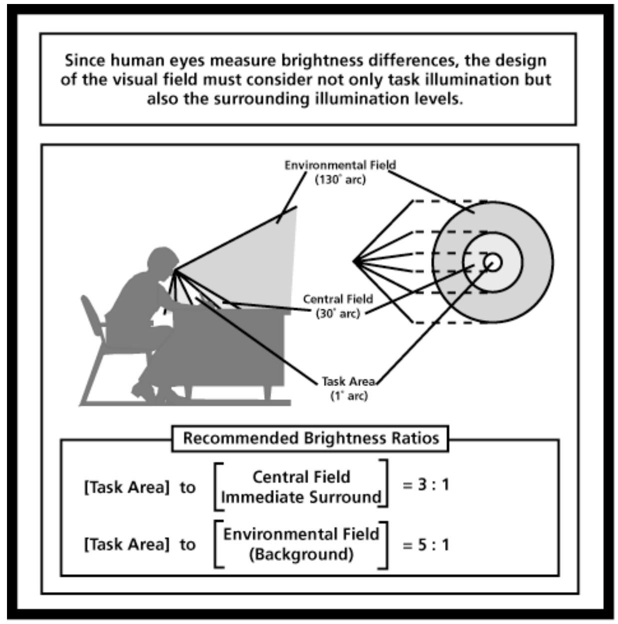

Figure 6.24: Components of the visual field

Broadly speaking the visual field can be divided into three components (Figure 6.24). The *task area*, which is the visual focus for detailed activities such as reading and writing, requires the highest level of illumination. However, it is typically restricted to a very narrow cone that may be no larger than a 1º arc. The *immediate surround* to the task area (i.e., 30º arc), which is also referred to as the *central field*, should be less bright than the task area so that the latter will appear to be highlighted. However, the contrast between these two component fields should not be too great and therefore a 3:1 brightness ratio is normally recommended. Finally, the *environmental field* or background illumination should be the least bright area. Its boundaries are normally circumscribed within a 130º arc, with a recommended brightness ratio of 5:1 to the task area. While these recommended ratios may relate the three component fields to each other to produce a comfortable visual environment, they do not account for the ability of our visual facilities to scale up and down from bright sunlight to minimal nighttime illumination and still maintain the same comfort level.

So what is the mechanism that allows our cognitive system to automatically judge that some part of the visual field is brighter or less bright than another part of the field, and how can we achieve this feat within the enormous range of brightness that our visual facilities are capable of processing? The answer to this question is that our visual facilities will automatically establish an *adaptation level* in any current lighting environment. This adaptation level is dynamically modified as the average light intensity of the visual environment changes.

The adaptation level serves as a benchmark for comparing the apparent brightness levels of objects or surfaces within the visual field. The word *apparent* is used purposely in this context because the brightness perceived by the eyes is not a measure of the actual (i.e., objective) light intensity, but simply a relative and subjective comparison with the current adaptation level. For example, with bright sunshine coming directly through a window the shadows within a room will appear very dark. However, if we shield our eyes from the sunlight (i.e., screen the window with our hand) the same shadows will appear much lighter. The graph shown in Figure 6.25 represents an apparent brightness scale. It allows us to determine the apparent brightness of any surface based on the prevailing adaptation level. For example, a surface with a measured luminance of 10 ft-L will have an apparent brightness of about 60 if the adaptation level is 100 ft-L and over 120 if the adaptation level should fall to 1 ft-L.

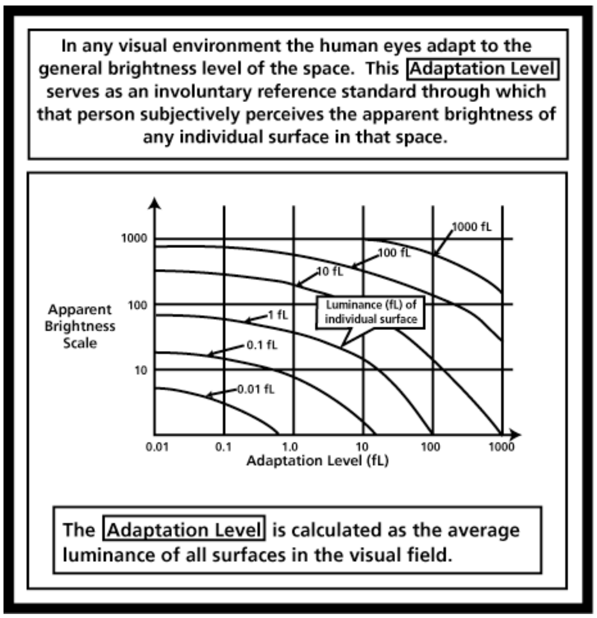

Figure 6.25: The Apparent Brightness Scale

The required task illumination level depends on the visual intensity of the task and the background illumination (i.e., the Adaptation Level).

Class of Visual Task or Type of Work	Local Illumination (fc)	Background Illumination (fc)
Casual Seeing: corridors, storage areas, etc.	10-15 fc	10-15 fc
Intermittent Tasks: casual reading and writing, cursory inspection, etc.	20-30 fc	10-15 fc
Prolonged Tasks: machine work, office work, prolonged reading and writing.	40-50 fc	15-25 fc
Severe Prolonged Tasks: with small detail and poor contrast.	60-70 fc	20-25 fc
Very Intense Visual Tasks: watch repairs, gauge inspection, etc. medical surgery, etc.	150-300 fc	25-90 fc

Figure 6.26: Typical illumination levels

The notion that what we perceive visually depends not only upon the actual intensity of light (i.e., objective measurement of the amount of light) but also on the state of our visual sensors, conditioned by the current adaptation level, is a fundamental consideration in lighting design. It immediately suggests that the prescription of minimum illumination levels for different tasks is inappropriate unless these are also related to the total amount of light in the entire visual field. A rule of thumb measure of the adaptation level is the illumination level of the environmental field or background illumination (Figure 6.24). For this reason, the local illumination levels recommended for tasks requiring different degrees of visual acuity, in Figure 6.26, are related in each case to suggested background illumination levels. The reason why the ratios between the recommended local and background levels are less than the 5:1 discussed earlier (Figure 6.24) for the lower local illumination levels is that at least a minimum amount of background illumination is necessary for practical reasons and safety.

The physiological process of light adaptation is very complex and not fully understood at this time. It is certainly much more than the contraction and expansion of the pupils as we transition from one level of brightness to another that is much brighter or much less bright. This involuntary reaction is simply a first level protective mechanism that attempts to shield our eyes from harm. While the eye can adapt to a brightness range in excess of 100,000 it does so at the expense of visual comfort and performance. For example, if we look out of a window to the bright sky on a sunny day and then look back into the room, the interior space will appear gloomy and devoid of details until our eyes have re-adjusted to the much lower brightness of the room. It is important that the lighting designer ensures that the occupants of the building are not subjected to lighting conditions where they have to adapt too quickly over too wide a range of brightness. In this respect, of special concern is the interface between the exterior and the interior that occurs at any external window. Direct view of the sky through a window will expose the eye to a brightness level that could easily be 100 times the adaptation level inside the room. In fact, glare conditions inside buildings occur most commonly at external windows (see Section 6.8).

6.8 Perceptional Constancy

Closely related to the phenomena of apparent brightness and adaptation level is our ability to perceive a visual scene the way we know it should be, rather than as it really is. This ability, which is known as *perceptional constancy*, allows us to perceive an object with little change even though the actual image on our retina may have changed considerably due to a different viewing angle, a different orientation of the object, or a change in the ambient lighting conditions. Research suggests that there are several factors involved in this complex visual capability. Certainly, experience and context are two of these factors. Research studies involving the very small number of persons who have had their sight restored after being blind from birth or early infancy due to cataracts, showed that these persons were unable to see their environment accurately. For example, they had difficulties with complex images such as faces. This was probably due to the fact that the neurons and synapses in the visual areas of the brain had received little (if any) stimulation during their life. In respect to the role of context, our visual experience creates in our memory an expectation of what a certain object or scene should look like. Conversely, this same preconditioned expectation can be misleading as, for example, in some cases of eyewitness police reports.

Perceptional constancy will manifest itself in several ways. Three of these manifestations are of particular interest to the lighting designer.

- ***Lightness Constancy*** is our ability to judge the lightness of a surface to be the same even though the illumination level has changed. If we take a sheet of white paper into a windowless room fitted with artificial lights and a dimming device, then the paper will appear to be white whether we have the lights on full (e.g., providing an illumination level of 100 footcandles) or dimmed down to just a few footcandles. The reason appears to be that the eye is more concerned about the relative amount of light reflected by the paper in relationship to other objects in the room, then the actual amount of light reflected. The fact that the ratio of reflected light between two surfaces remains the same under different illumination levels can be proven by the following example. Assume a sheet of white paper with a large gray square on it.

reflectance of white paper area = 90% (or 0.90)
reflectance of gray square area = 30% (or 0.30)

If the illumination level is 200 fc, then:

ratio of light reflected from the two surfaces = (200 x 0.90) / (200 x 0.30) = ⅓

If the illumination level is only 10 fc then:

ratio of light reflected from the two surfaces = (10 x 0.90) / (10 x 0.30) = ⅓

- ***Color Constancy*** is our ability to perceive the color of an object to be the same even though the lighting conditions may have changed. In a room with a very brightly colored red wall, the light reflected from the wall onto a white ceiling will give it a distinct pink hue. If we look at the ceiling facing the red wall (i.e., with the red wall in our visual field) then the ceiling will appear to be white. However, if we look at the ceiling facing away from the red wall then we will easily detect the slight pinkiness of the ceiling.
- ***Shape Constancy*** is our ability to continue to perceive the actual shape of an object although by virtue of the view angle the shape of the object on the retina is distorted. For example, if we hold a book vertically in front of our eyes, we see its shape to be rectangular. Now if we tilt the top edge of the book away from us then we will still perceive the shape of the book to be rectangular although the image of the book on the retina will be a trapezoid. It appears that shape constancy occurs because our visual facilities take depth into consideration.

Perceptional constancy is of course by no means fool proof. Many experiments can be performed to demonstrate the failings of, for example, our lightness constancy capabilities under particular conditions. Four such conditions are shown in Figures 6.27, 6.28, 6.29, and 6.30[18].

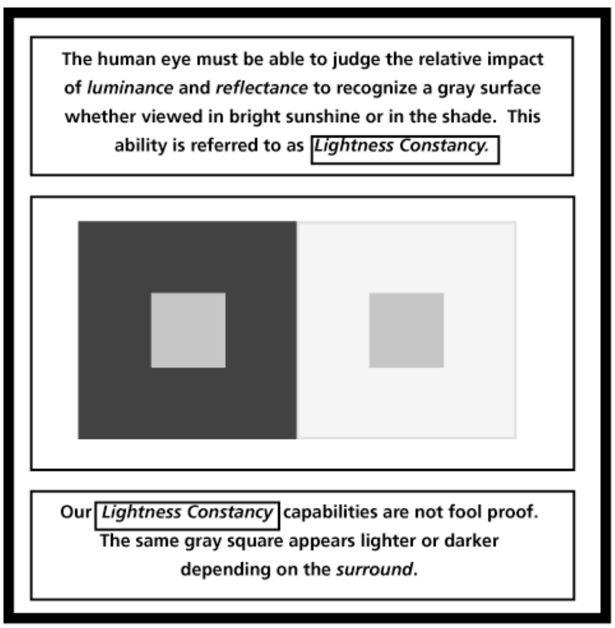

Figure 6.27: Simultaneous contrast effect

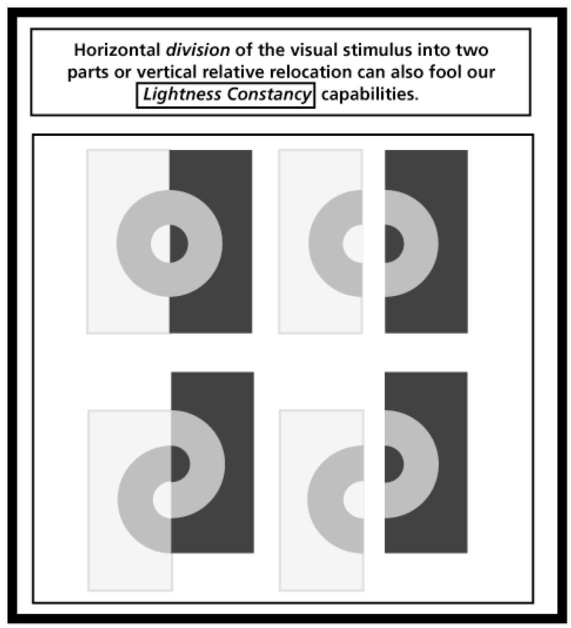

Figure 6.28: Spatial configuration effect

Figure 6.27 shows the well-known simultaneous contrast effect. The two smaller squares are precisely the same shade of gray, yet the one surrounded by the large black square appears to be a lighter shade of gray than the one surrounded by the large white square. Variations of the Koffka ring illusion (Figure 6.28) show how changes in spatial configuration can elude our lightness constancy capabilities. The gray ring at the top left of Figure 6.28 appears to be of a uniform shade of gray. When the ring is split into two parts vertically, either moving the two

[18] From: Adelson, E. H. (2000); 'Lightness Perception and Lightness Illusions'; in Gazzaniga M. (ed.) The New Cognitive Neurosciences, 2nd Edition, MIT Press, Cambridge, MA (pp.339-351).

parts of the ring apart horizontally or sliding them vertically causes one half of the ring to appear darker than the other half.

Figure 6.29 demonstrates that the simultaneous contrast effect shown in Figure 6.27 can be enhanced if the surround is broken up into many different areas. This is referred to as the anchoring phenomenon that is produced by an articulated surround. In Figure 6.30, the horizontal gray strips are all the same shade of gray. We would expect the left strips to appear darker than the right ones. However, the right strips appear distinctly darker than the left ones. This reversal of the normal visual illusion has been explained in terms of the T-junction effect. According to this explanation patches straddling the stem of a T are grouped together and the cross-bar of the T serves as a boundary.

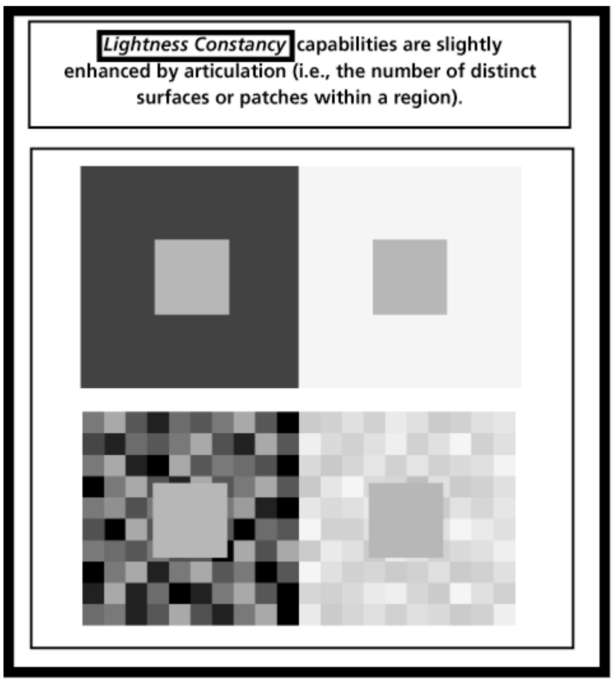

Figure 6.29: Anchoring within a framework

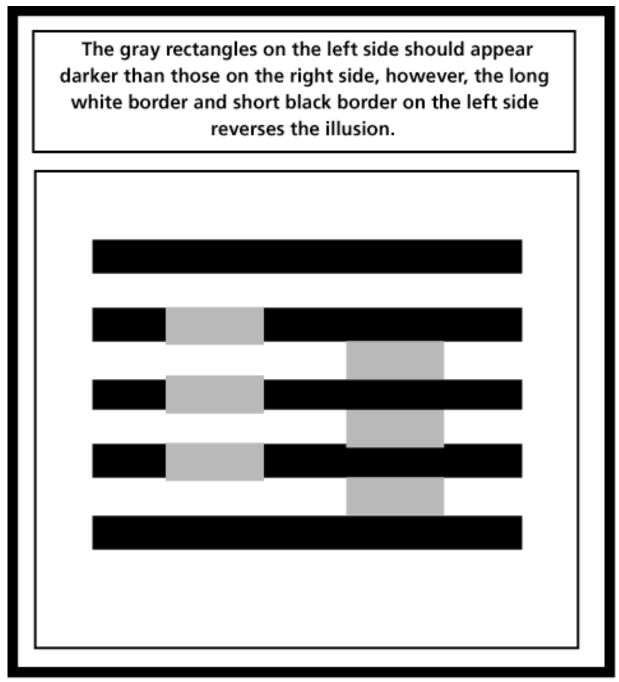

Figure 6.30: The T-junction illusion

It appears that our visual facilities process information on at least three levels. Low-level vision occurs in the retina and appears to include light adaptation. High-level vision occurs within the brain and is said to involve cognitive processes that are based on knowledge about objects, materials and scenes. In between these two levels there is mid-level vision, which is a fuzzy area that may deal with the effects of surfaces, contours and groupings.

6.9 The Nature of Glare

Whenever the variations of brightness in the visual field are too great the brightest area will become a source of glare. Glare appears to be the result of an over-excitation of the visual receptors in the retina. If the brightness ratio is very large than the glare conditions will actually impair our ability to see any details immediately surrounding the glare area. This form of glare is appropriately referred to as *Disability Glare*. Less severe brightness ratios will cause discomfort and may lead to undesirable physiological responses such as a headache, but will not affect our visual performance directly. These kinds of glare conditions are commonly characterized as *Discomfort Glare*.

As shown in Figure 6.31 there are fundamentally two kinds of Disability Glare. Our visual functions will be impaired under *direct glare* conditions when there is a direct line of sight between our eyes and an area of excessive brightness, such as a bright artificial light source without a shade or a window through which we can see the bright sky. The brightness ratios of 3:1 (between the task area and the immediate surround) and 5:1 (between the task area and the background) suggested earlier in Figure 6.24 are well below the glare threshold. Brightness ratios in excess of 20:1 should generally be avoided in buildings and ratios of 40:1 and above are guaranteed to produce glare conditions.

Disability Glare may also occur when a bright source of light is indirectly reflected from a shiny surface into our eyes. For example, the light from a well-shaded lamp may be reflected from the glossy pages of a book into the eyes of the reader. This situation produces a veiling condition in the task area and may occur even if the light source is not excessively bright. Fortunately, changing the position of the reflecting task area and/or the eyes relative to the light source easily rectifies such reflected glare situations. Normally, we would simply tilt the book slightly to overcome a reflected glare condition while reading. However, reflected glare is sufficiently prevalent for it to influence the choice of paper for newspapers, magazines and most books.

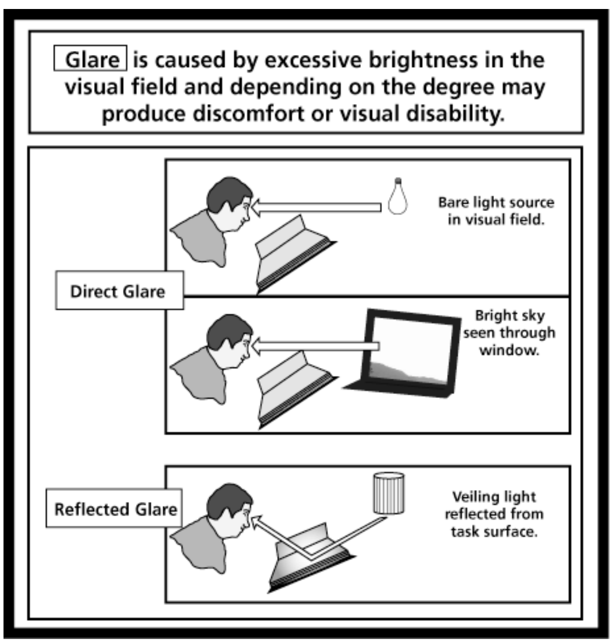

Figure 6.31: Direct Glare and Reflected Glare

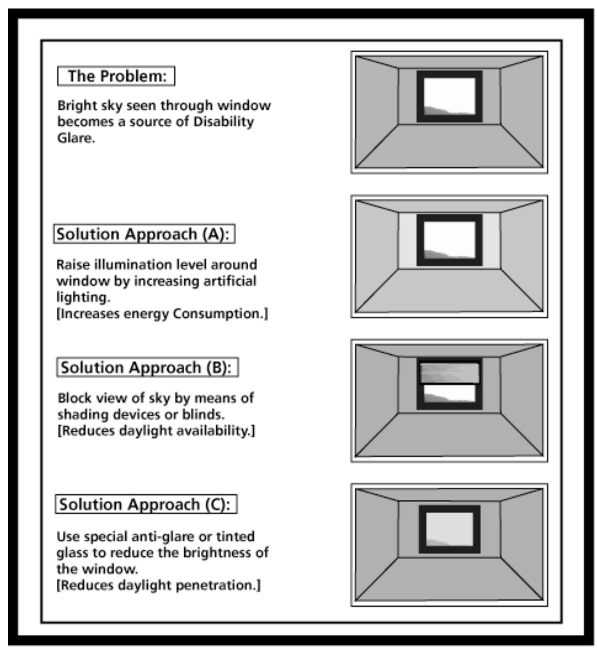

Figure 6.32: Glare mitigation approaches

With the exception of reflected glare, Disability Glare is typically not caused by artificial light sources since electric lamps rarely generate sufficient light flux to produce brightness ratios in excess of 20:1. However, a common source of Disability Glare is the view of a portion of a bright sky seen through a window. In the absence of adequate foresight by the designer this situation can occur when a window is placed in the end-wall of a long corridor. Particular care must be taken to avoid this problem in multi-story hotels, apartments, and dormitories. Walking toward such a misplaced window the surround of the window will appear almost black, since the eyes are unable to adjust to the excessive brightness difference between the bright sky and the relatively dim interior lighting of the corridor.

While the corridor situation described above is an extreme example, this type of direct glare can occur in any room with an external window that provides a view of the sky and therefore warrants further discussion. As shown in Figure 6.32, there are essentially three viable approaches for mitigating such Disability Glare conditions caused by the interface between the interior and exterior lighting conditions. Since glare is caused by excessive brightness differences any efforts to mitigate direct glare conditions should be focused on reducing the brightness ratio. This can of course be achieved in two ways, by either decreasing the higher level or increasing the lower level of the brightness levels in the visual field. Raising the interior illumination level near the window will increase the consumption of energy and may therefore not be a viable solution in climatic regions that are blessed with plenty of sunshine and mostly clear skies. However, in parts of the world where skies are typically overcast this solution approach is not uncommon. It leads to the apparently paradoxical situation where the artificial lighting requirements during daytime may be greater than at night.

The more common approach to mitigating direct glare conditions at windows is to reduce the brightness of the window. Unfortunately, this approach inevitably also reduces the amount of daylight available in the room. Design strategies include exterior shading devices, interior blinds, and special tinted or anti-glare glass. The advantage of internal blinds, such as Venetian blinds, is that they are adjustable both in respect to the angle of the blades and the degree to which they cover the window.

While Disability Glare actually impairs our immediate visual performance, the effects of Discomfort Glare are annoying with milder physiological consequences if exposure continues over many hours. Discomfort glare occurs quite frequently in artificially lit building spaces if light sources are inadequately shielded. The degree of glare is primarily related to the location and type of light source, the nature of the task, and the luminance of the surrounding visual field. Specifically, Discomfort Glare is governed by:

- ***The luminance of the glare source.*** The size of the glare source, normally an artificial light source in the form of a lamp, is also a factor. If the light flux is spread over a larger surface area then this will tend to increase the brightness of the immediate surround, thereby mitigating glare conditions.
- ***The general background illumination level.*** This may be quantified as the Adaptation Level discussed earlier, which is defined as the average luminance of all surfaces in the visual field. It may be calculated by measuring the luminance of each surface and multiplying this measurement by the area of the surface. The sum of the resulting values divided by the total surface area is the Adaptation Level expressed in foot Lambert (fL) units (see Figure 6.25).
- ***The location of the glare source relative to the observer.*** If the offending light source is located directly in the line of vision it will be much more annoying than if it is just visible through the corner of the eyes.
- ***The luminance of the immediate surround of the glare source.*** Raising the brightness of the surround will decrease the brightness ratio. A simple measure such

as a highly reflective finish (e.g., a white ceiling) may be quite effective in reducing the severity of the glare condition.

It is apparent from the foregoing discussion of glare conditions that the reduction of glare requires a reduction in the brightness ratio seen by the eyes. What the reader may have found to be surprising and even counterintuitive is that we can mitigate excessively bright conditions by adding more light. The fact is that our visual performance is impacted less by actual objectively measured illumination levels than by the perception of these illumination levels as brightness differences. If we further take into consideration that the eye can detect an enormous range of luminances (i.e., from 0.0001 ft-L to over 100,000 ft-L, see Figure 6.17) then it is perhaps less surprising that the addition of light can be as effective as the reduction of light in reducing glare conditions. This can be demonstrated experimentally as shown by the Constant Glare Curve in Figure 6.33, which traces the influence of raising the background luminance on glare conditions.

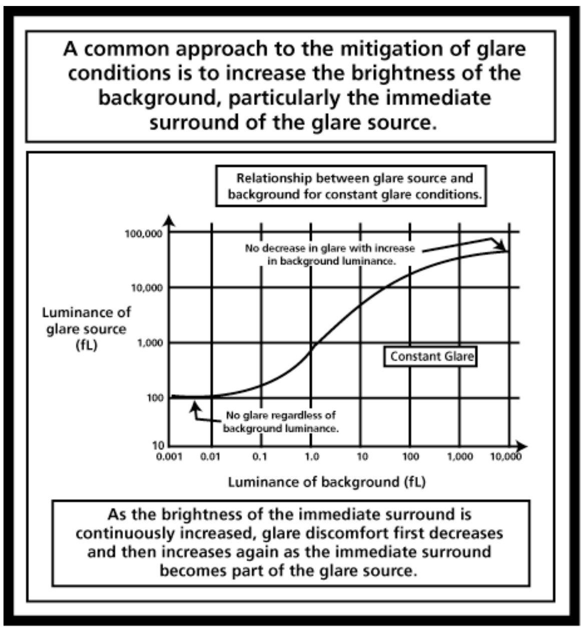

Figure 6.33: The Constant Glare Curve

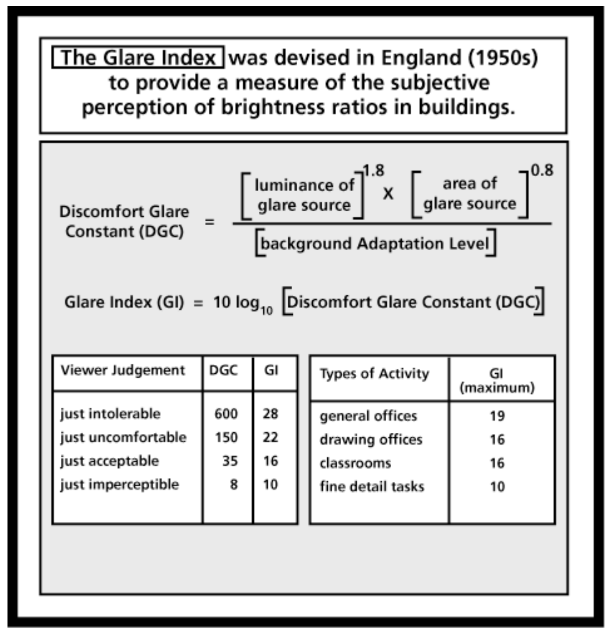

Figure 6.34: The Glare Index

The non-linear slope of the Constant Glare Curve in Figure 6.33 provides some insight into the nature of glare. We notice that for the same glare conditions raising the luminance of the background (i.e., raising the Adaptation Level) is much more effective at lower luminance levels of the glare source than at higher levels. In other words, as our eyes become exposed to more and more light our ability to prevent glare by proportionally increasing the surround and background luminances becomes less effective. Finally, at some point any further increase in the luminance of the surround simply increases the effective area of the glare source (i.e., the surround becomes part of the glare source).

The concept of a Glare Index was proposed in England during the 1950s (Figure 6.34) for the quantification of Discomfort Glare conditions. Based on subjective human assessments an empirical formula was derived for the calculation of a Discomfort Glare Constant (DGC) as a function of the luminance of the glare source, the area of the glare source, and the Adaptation Level. The Glare Index (GI) was then established as a logarithmic equivalent of the DGC:

$$\textbf{Glare Index (GI)} = 10 \log_{10} [\textbf{Discomfort Glare Constant (DGC)}] \quad \ldots\ldots\ldots \quad \textbf{(6.5)}$$

It is important to note that the Glare Index applies only to Discomfort Glare conditions and not to Disability Glare. An indication of this limited applicability are the viewer judgments, which range from only 'just intolerable' to 'just imperceptible' and do not take into account the ability to see details. Nevertheless, the Glare Index does provide sound design guidelines by recommending acceptable brightness ratios for different types of activities.

6.10 Questions Relating to Chapter 6

Answers to the following multiple-choice questions with references to the appropriate text (by page number) may be found at the back of the book.

1. **The visible spectrum of electromagnetic radiation or light as we perceive it, occupies a narrow band which extends from approximately:**
   - A. 350 to 750 microns
   - B. 4,000 to 7,000 millimicrons
   - C. 40 to 700 microns
   - D. 350 to 7,500 millimicrons
   - E. None of the above is correct.

2. **The human eye is not a photometer for it does not measure physical brightness. Objects are perceived through the eyes by the virtue of:**
   - A. Their movement
   - B. Their movement and color
   - C. Their brightness and color
   - D. Differences in brightness and color
   - E. Their color

3. **The retina (of the eye) consists of a very large number of receptors known as rods and cones. Which of the following statements is not correct:**
   - A. Rods are used in the perception of brightness differences and motion.
   - B. Color vision is limited to some 15˚ arc around the FOVEA.
   - C. The central area of the retina called the FOVEA is covered by cones in an approximately 2˚ arc.
   - D. Rods are responsible for color vision.
   - E. None of the above (i.e., A, B, C, and D) is correct.

4. **Vision is <u>related</u> to the perception of heat and sound because all of these:**
   - A. Are objective responses.
   - B. Are subjective responses.
   - C. Obey the laws of wave motion.
   - D. Are dealt with in the study of building science.

E. None of the above (i.e., A, B, C, and D) is correct.

5. **Which of the following statements (if any) is not correct:**

   A. Individuals vary in their response to luminosity and this fact may largely contribute to differences in 'taste' among persons.

   B. Although the eye is sensitive to a very wide range of luminosity, it takes time to see.

   C. Vision speed increases with higher levels of illumination, but visibility improves with decreased object brightness.

   D. Visual acuity is the ability to resolve small visual details.

   E. All of the above statements (i.e., A, B, C, and D) are correct.

6. **Which of the following definitions is <u>not</u> correct:**

   A. Flux is the quantity of light emitted by a light source, irrespective of direction or distribution.

   B. Luminous intensity is the property of a source to emit light in a given direction.

   C. Illumination is the amount of light flux falling on unit area.

   D. Luminance is the intensity per unit distance (from the observer) of a surface seen from any direction.

   E. All of the above definitions (i.e., A, B, C, and D) are correct.

7. **Which of the following units (if any) is not correctly stated:**

   A. Flux (lumen)

   B. Luminous intensity (candela)

   C. Luminance (Foot Lambert or candela per square foot)

   D. All of the above (i.e., A, B, and C) are correct.

   E. None of the above (i.e., A, B, C, and D) are correct.

8. **Which of the following statements is not correct? Shadows are an important aspect of the visual field because they enable the observer to:**

   A. Detect motion.

   B. Ascertain the relative position of objects.

   C. Discriminate between fine textures.

   D. Rest the observer's eyes.

   E. See fine details.

9. **Choose the missing words. The Apparent Brightness of any object in the visual field depends on its_____________and on the _____________.**

   A. luminance; luminous intensity of the source

B. luminance; luminance of the surrounding environment

C. level of illumination; reflectance of the surrounding surfaces

D. size; reflectance of its surfaces

E. None of the above (i.e., A, B, C, and D) is correct.

10. **Which of the following statements are <u>correct?</u>**

A. Luminance is the brightness of a surface seen from a particular direction and is measured in candela/SF or foot Lamberts.

B. Illumination from a point source decreases by the square of the distance.

C. Most surfaces provide both specular and diffuse reflection of light.

D. All of the above statements (i.e., A, B, and C) are correct.

E. None of the above statements (i.e., A, B, C, and D) is correct.

11. **According to the Quantum Theory in Physics light is a form of electromagnetic radiation. Which of the following statements are <u>correct</u>?**

A. Light waves are relatively long waves, although they are shorter than radio waves.

B. Ultra-violet radiation is on the right-hand side of the visible spectrum.

C. In the American system the units of illumination are footcandles or lumen/SF.

D. More than one of the above statements (i.e., A, B, and C) are correct.

E. All of the above statements (i.e., A, B, C, and D) are incorrect.

12. **Which of the following statements are <u>incorrect</u>?**

A. A yellow surface viewed under a yellow light will appear more tan/brown.

B. A good brightness ratio between the illumination of the task area and the background is about 2:1.

C. Specular reflection is produced by a matte surface.

D. All of the above statements (i.e., A, B, and C) are correct.

E. All of the above statements (i.e., A, B, C, and D) are incorrect.

13. **Which of the following statements are <u>incorrect</u>?**

A. Perceptional Constancy allows us to track moving objects by virtue of changes in Apparent Brightness.

B. Lightness Constancy allows us to judge a surface such as a ceiling to be of uniform color even though shadows may be cast upon it.

C. Color Constancy is responsible for our ability to judge the color of a surface to be the same before and after a change in lighting conditions.

D. All of the above statements (i.e., A, B, and C) are correct.

E. All of the above statements (i.e., A, B, C, and D) are incorrect.

14. **Which of the following statements are <u>incorrect</u>?**

A. Reflected Glare is a form of Discomfort Glare, rather than Disability Glare, because it cannot cause permanent damage to the retina of the eye.

B. Discomfort Glare occurs most commonly in dimly lit long corridors with a window in the end-wall that provides a clear view of the sky.

C. Disability Glare is fairly common in modern buildings due to the development of more energy efficient artificial light sources that also produce a great deal more light flux.

D. All of the above statements (i.e., A, B, and C) are correct.

E. All of the above statements (i.e., A, B, C, and D) are incorrect.

15. **Which of the following factors govern the degree of Discomfort Glare when such a glare condition exists in a building space:**

1. **The luminance of the glare source.**
2. **The luminance of the immediate surround of the glare source.**
3. **The size of the room.**
4. **The color of the immediate surround of the glare source.**

A. All of these factors (i.e., 1, 2, 3, and 4) govern the degree of Discomfort Glare.

B. Only factors 1 and 2 govern the degree of Discomfort Glare.

C. Only factors 1, 2, and 4 govern the degree of Discomfort Glare.

D. Only factor 1 governs the degree of Discomfort Glare.

E. None of the four factors govern the degree of Discomfort Glare.

16. **How many errors (if any) are there in the following statement? "Since glare is due to excessive brightness differences in the visual field, we can reduce the degree of glare by either increasing the Adaptation Level or decreasing the luminance of the glare source. However, in the case of Disability Glare the color spectrum of the light source is also an important factor."**

A. One error.

B. Two errors.

C. Three errors.

D. More than three errors.

E. No errors.