Light Measurements and the Human Eye Explained

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The "Big Deal" about Light.

Our lives are intimately connected to light; without light we could not see. There are many sources of light: the sun, a campfire, an LED (Light Emitting Diode), a CFL, Halogen, and others. These sources can be beneficial, harmful, make reading comfortable, hurt our eyes, or even help those with vision problems. We are fortunate that with the choice of many sources, we can fashion a source that can be optimum for some specific purpose. This paper is designed to give the reader some understanding about the relationship between light sources and the human eye and the techniques that can identify or fashion a particular light source with suitable characteristics that will provide a successful and pleasant experience for the user.

Basic Measurements

The primary goal of measuring light is to measure light in a way that the results of the measurement correlates with the visual sensation observed by a normal human. The human eye is sensitive to a small part of the light spectrum. This small part consists of the colors that we see when observing a rainbow; red through violet. Light has several properties and so there are ways to measure each of these properties. Luminous flux (**lumen**, or abbreviated **lm**) is perhaps the most fundamental measurement unit. This measurement is taken at the light source and measures the rate of energy flow for that part of the light that is visible only to the human eye. Thus energy flow outside of the visible range is not included in the measurement.

Lumens is a significant and practical measurement in dealing with the human eye since the light usable by the eye is less than the light emitted from the source. As the watt is the unit for total power from the source, lumens is the unit for that part of the total power that the eye can use. The ratio of lumens to watts is called Efficacy.

$$efficacy = \frac{lumens}{watts}$$

Furthermore, the eye responds more to some parts of the visible light than to other parts of the visible light (see Figure 2).

The lumen and watt concepts used here are not to be confused with the power of an emitter such as a 100 watt incandescent light bulb. The 100 watt rating is the electric power **input** to the bulb, not the output.

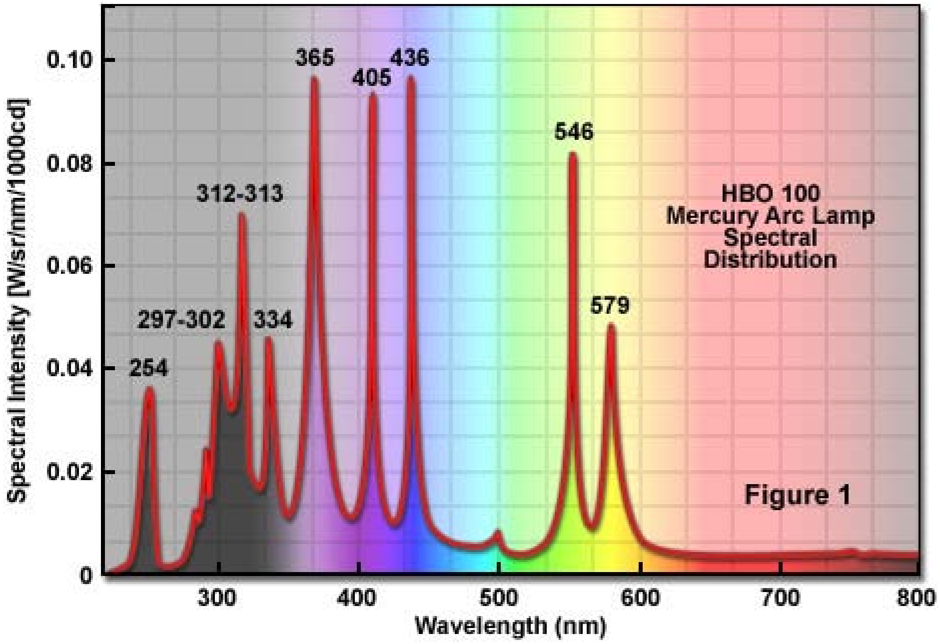
The term **illuminance** (similar to the word *illumination*) refers to the measurement of light impinging on a surface. It has the units of *lumens per square meter* and is called **LUX**, abbreviated **lx**. If an artificial light source is used such as an incandescent bulb or LED, then further parameters are specified such as the distance from the source to a surface placed at a right angle to the source. The amount of LUX will decrease as the source and the illuminated surface separate. This decrease goes as the square of the distance. There is an equivalent to LUX: the **Footcandle** (**fc**) and is measured in *lumens per square foot*. In the case of reading, lux is a very important parameter because it measures the brightness of the light at the location of use – a book for example, not at the light source.

Therefore lux and lumens are distinctly different. For a fixed light source with a certain amount of lumens, the amount of lux can be and in most cases is variable. Moving the illuminated object away from the light source will decrease the brightness – the amount of lux. Adding a lens or reflector to the light source can focus the light to a particular area and yield higher brightness in that area (even though the lumens and distances are the same); a good example is the flashlight.

Color Measurements

Light can be broken up into different colors as we see by looking at a rainbow or passing light through a prism. Different light sources are made up of different colors. These different colors that the source emits is called the source's *spectrum*. A plot of this spectrum is obtained by laboratory measurements. An example is shown in Figure 1. The intensity is the vertical scale and the *wavelength* in nanometers is the horizontal scale.

Light is an electric wave much like the electric waves that carry our radio signals to the antennas in our cars. Different stations are selected by changing the frequency on the radio dial. For light it is more convenient to measure wavelength rather than frequency: wavelength = c divided by frequency – c is a constant. A nanometer, abbreviated nm, is 10^{-9} meters or one billionth of a meter.



Color and the Human Eye

The human eye does not respond to a light spectrum like a laboratory instrument would. A plot of human eye color sensitivity is shown in Figure 2. This means that the color observed by a person may not be the same as the color emitted by the light source. This creates a problem in choosing or designing artificial light sources since certain spectra may not be pleasing to the eye. Some spectra may be harmful. This is addressed by special means that convert the laboratory determined spectrum of the light source into what the human eye would see.

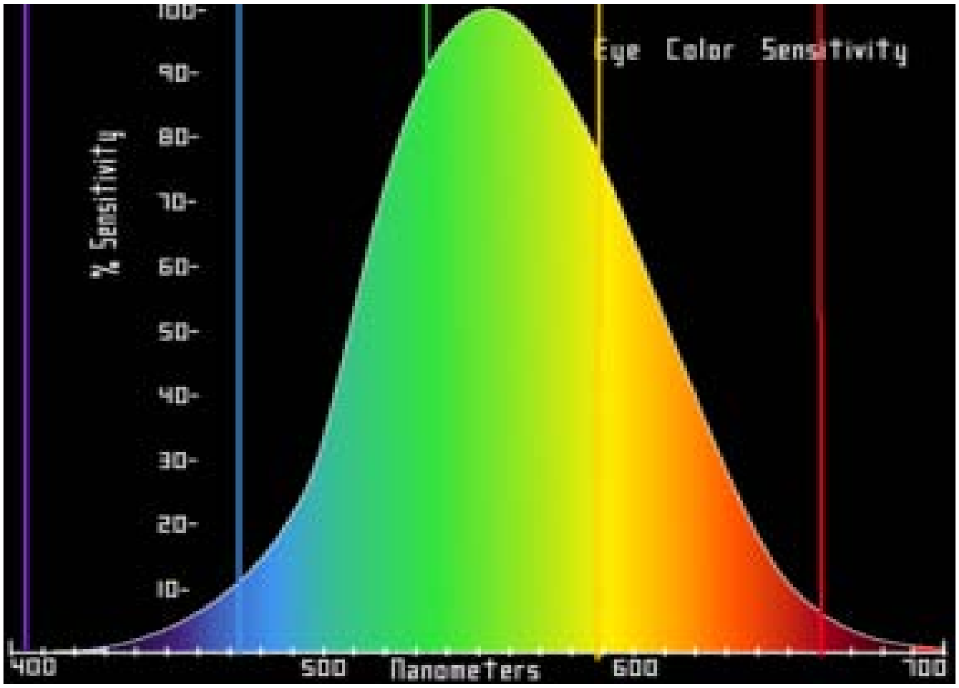


Figure 2

Black Body Radiation and Temperature Measurement

Black body radiation is a convenient method for measuring properties of a light source. First some introduction to black body radiation. There is no ideal physical black body, but there are some that come close in the laboratory. The ideal black body has a known spectrum that changes with the temperature of the body. The temperature is measured with respect to absolute zero, -273 Celsius and the temperature unit is the **Kelvin (K)**. The effect can be observed when heating charcoal in your cooking grill. When cold, the charcoal is black (sort of) then turns red when heated. When heated further (don't try this at home), the charcoal turns orange, then yellow, then eventually white. The Kelvin temperature is based on the color emitting the most power and does not indicate anything about the light source spectrum or its total radiating power.

Correlated Color Temperature (CCT)

Correlated Color Temperature is a measure of the actual color appearance of light when viewed by the human eye. It is expressed in Kelvin units of a heated black body that most closely matches what the human eye sees when viewing some light source. When there is a match, the black body Kelvin temperature is the Correlated Color Temperature.

As the Correlated Color Temperature rises, the observed color moves from the red to yellow and continues to white. Yellow and red hues will have CCTs of about 1500 K and white appearing light is at about 7500 K. Note that the light source that is being measured for its CCT is no where near the high temperatures of the black body. It is common practice to call yellow and red hues "warm" and white or blue lights "cool". Note that this labeling of warm and cool is opposite to the CCT values. Human perception is no indication of the energy of the light.

Color Rendering Index (CRI)

The Color Rendering Index of a source is a number, usually on a 20 to 100 scale that describes how well the source's light emission affects the appearance and vibrancy of an illuminated object's color. More accurately, it is a quantitative measure of the ability of a light source to reproduce the colors of various objects faithfully in comparison with an ideal or natural light source. It does not indicate the color of the light source. The Color Rendering Index is determined by comparing the source with a reference source of the same Kelvin temperature. Actual measurement is quite involved and is beyond the scope of this paper.

Typically the source of light for reading purposes emits white light. However, light sources are not necessarily "pure white" but exist in what is termed shades of white (rough partition): Warm White 2600K to 3500K, Neutral White 3600K to 4400K, and Cool White 4500K to 6000K. A typical CRI is greater than 80 when CCT is less than 3700K; the warmer the white, higher the CRI.

LED Light Sources

LED light sources are made from diodes – devices that pass electric current in only one direction and have the capability to emit light when electric current flows through them. These diodes are tiny and normally come encapsulated in a package that is about the size of your little finger nail. The light emitted from these diodes can vary greatly, but for illumination the usual CCT range is 2600K to 6000K. Packaged LEDs can be manufactured for a specific CCT within a specified tolerance. Therefore all LEDs are not the same. This feature of the LED to come in different CCT values opens the door to designing lamps that can be tailored to the needs of people with Macular Degeneration. Each person is different and has a pleasing reading experience with a lamp with a certain CCT and brightness – a feature not possible in other light sources.