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White Paper

TAOS TEXAS ADVANCED OPTOELECTRONIC SOLUTIONS®

TAOS Colorimetry Tutorial

"The Science of Color"

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February 28, 2006

ABSTRACT

The purpose of this paper is to give a brief overview of colorimetry. Colorimetry is the science of measuring color and color appearance. The main focus of colorimetry has been the development of methods for predicting perceptual matches on the basis of physical measurements. This topic is much too broad to be covered by one document, so a general coverage of the subject will be introduced.

COLOR AND LIGHT

The question of what is color would seem to be an easy one at face value. If a child was asked what color an apple was, they would say red. But what does red really mean? Most people have been asked the riddle, "if a tree falls in the forest and no one is there to hear it, does it make a sound?" The answer is it makes a sound wave, but it is not a sound until a brain interprets the sound wave. The same can be said if the riddle asks, "what color is a tree if no one is there to see it?" A 'color' is an interaction between a very small range of electromagnetic waves and the eyes and brain of a person. What people call red, green, or blue are just ways of categorizing what their brain experiences.

The spectrum of light the eye can see is called the visible region as can be seen in Figure 1. Light is a type of energy, which makes up a small portion of the electromagnetic spectrum, as does radio and TV signals. Electromagnetic waves that are used for radio and TV are generally discussed in terms of frequency. Visible light could be expressed as a frequency, but the magnitude is so large people generally express the wavelength of light in units of nanometers (10^{-9} meters) to describe light. The speed, frequency, and wavelength of light are related by equation (1).

$$c = f*\lambda \quad (1)$$

Where c is the speed of light that is approximately 3×10^{8} m/s in a vacuum, f is frequency given in Hz, and λ is the wavelength in units of meter.

The region of visible light consists of light with a wavelength between approximately 380 nm to 780 nm. The visible colors and their corresponding range of wavelengths can be found in Table 1.

Table 1. Color vs. Wavelength Range

Color	Wavelength Range (nm)
Violet	380~410
Indigo	410~450
Blue	450~510
Green	510~560
Yellow	560~600
Orange	600~630
Red	630~780

There are many wavelengths in the electromagnetic spectrum the eye cannot see. Wavelengths that are just shorter than blue region are called ultraviolet. This is the light that causes sun burns. Wavelengths that are just longer than red are called infrared. These are the wavelengths that produce heat. White light is a mixture of all the colors of the entire visible spectrum. Black is a total absence of light.

Figure 1. Electromagnetic radiation

THE WORKINGS OF THE HUMAN EYE

Light enters the front of the eye through a lens and is focused on the retina in the back of the eye. The human retina has rods and cones located on it. The rods and cones contain pigments. Pigments absorb light with absorption sensitivities that are wavelength dependent. The pigments allow the rods and cones to react to light in the visible region and pass that information to the optic nerve. Each eye has around 120 million rods, which are concentrated around the edges of the retina. See Figure 2 for a drawing of the inner eye.

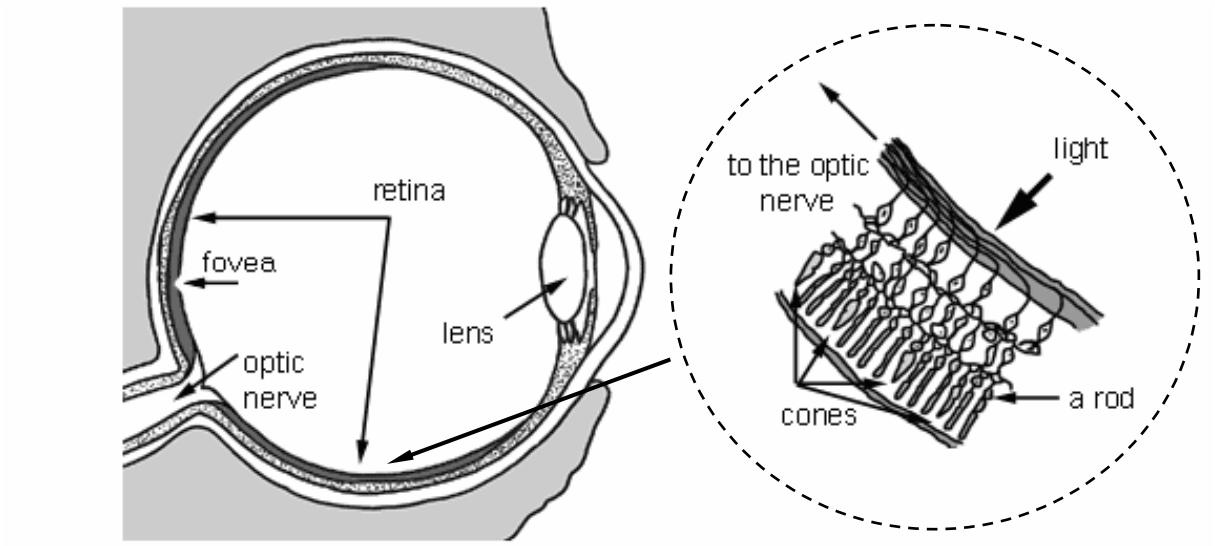

Figure 2. Human Eye and Retina

Rods are optimal at low light levels (**scotopic** vision), such as night vision, and provide the brain with information about light and dark which is good for seeing motion at night. At luminance levels below approximately 0.034 cd/m^2, vision is classified as scotopic and is completely lacking in color. The rods have a peak reponsivity to light around 510 nm in the blue-green region, and have little to no effect on color vision. See Figures 4 and 5.

The cones are what give humans the ability to distinguish colors at higher light levels (**photopic** vision). At luminance levels above approximately 3.4 cd/m^2, vision is classified as photopic. There are around 6 million cones in each eye. The cones are mainly located in the center of the retina, called the Fovea Centralis. The Fovea Centralis is a tiny dimple on the retina where light is focused. Photopic vision has a peak response around 555 nm in the green region of the visible spectrum. The cones contain photo pigments that react to light in certain areas of the visible region. There are three types of cones which are classified as long (L), medium (M), and short (S) relative to their peak wavelength sensitivity in the visible spectrum. The three pigments have maximum absorptions at about 430, 530, and 560 nm. The cones are often associated with red, green or blue response because these are the primary colors within each band. However, the spectral bands they detect are wider than any one perceived color and overlap each other. See Figure 5 for the cones spectral response. The L and M cones add together, with a scaling factor, to create the photopic curve which represents luminance detection in Figure 4. The S cones do not contribute to luminance detection, but are very important for hue and saturation perception, especially for yellow to blue discrimination. See Figures 4 and 5.

There is a region of vision between low light levels (scotopic) and high light levels (photopic) called **mesopic** where both rods and cones contribute to vision. An example of mesopic vision is when the sun starts to set. During this time, reddish colors fade to grey shades, followed by greens, and finally blues. Mesopic vision is not fully understood and is still a subject of much research. See Figure 3 for the three levels of vision and corresponding luminance levels of common sources.

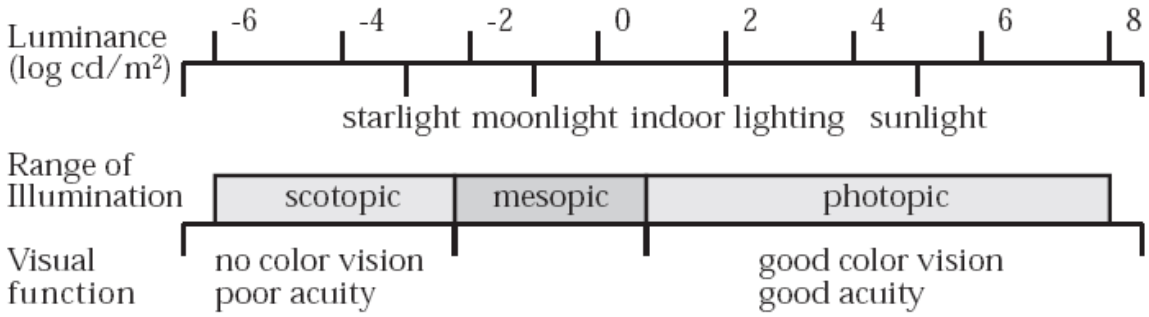

Figure 3. Types of Vision

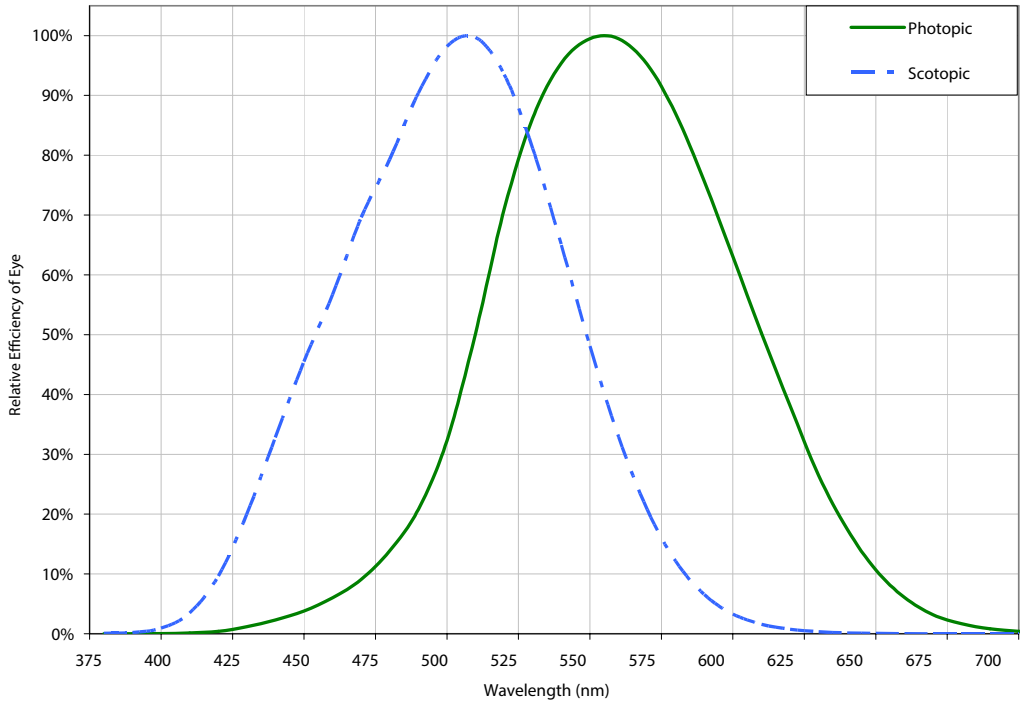

Figure 4. Scotopic and Photopic Vision

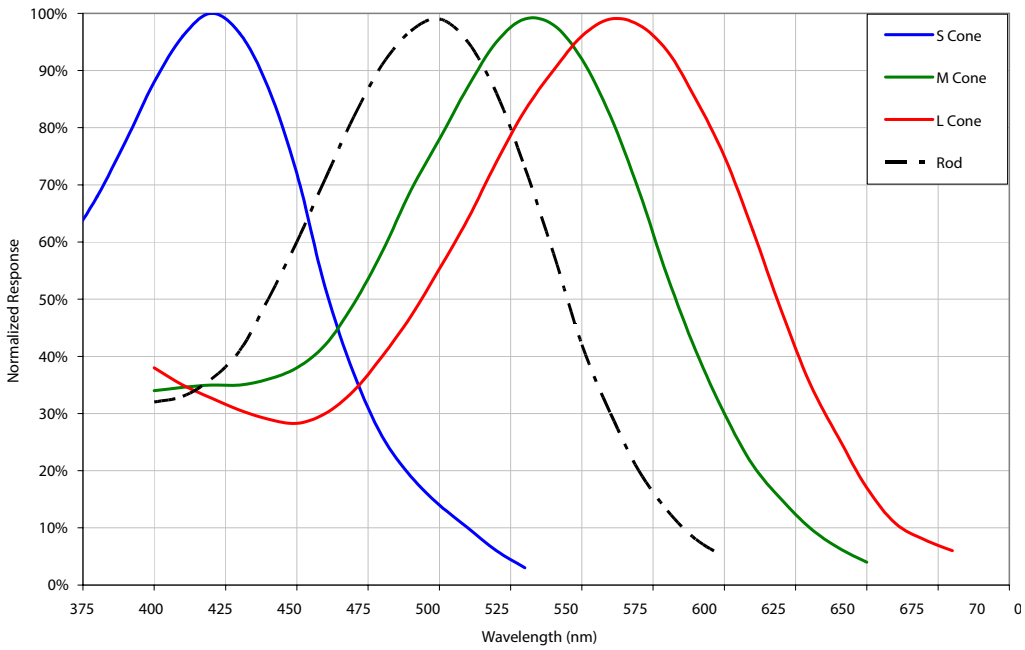

Figure 5. Eye Cones and Rod Response

The brain is ultimately the deciding factor in how people categorize a color, but the color information is processed based on the spectrum of light that reaches our retina. This spectrum of light is determined by the light source that produces the light and the adsorption and transmission characteristics of all the materials that interact with the light. A 'white' object reflects all or most of the light that falls upon it, while a 'black' object absorbs all or most of the light. Plants appear green because they have pigments which absorb wavelengths from the red and blue parts of the visible spectrum and only allow the 'green' wavelengths to be reflected back to the eye. This process of absorbing parts of the spectrum not only happens when light is reflected off of surfaces, but also when it is transmitted through substances. A bluish glass, for example, will absorb many of the longer green and red wavelengths entering the glass and pass through more of the shorter 'blue' wavelengths. An important concept to understand is that light sources and objects may appear to have the same color but have different spectral power densities, absorption, and transmission properties. Most of the colors people see are able to be replicated by mixing Red, Green and Blue (RGB) or Cyan, Magenta and Yellow (CMY).

Colors can be created in one of two ways. One method to produce color is called the **Subtractive** color process. This is accomplished by absorbing certain wavelengths which are subtracted from the full spectrum of visible light. The resulting wavelengths which reflect off a surface make up the color people see. The colors seen in everyday life are often a result of the Subtractive color process. The subtractive method is also used in the printing and film photography business.

The other method to produce color is the **Additive** color process. In this method, narrow bands of visible light are added together to produce a combination of light that is a different color. This is the method many light sources use to produce colored light. Monitors used for televisions and computers use the Additive color process by using the primary colors of Red, Green, and Blue to produce white and other colors.