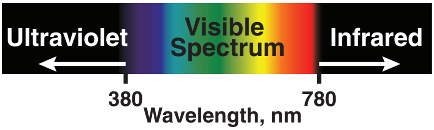
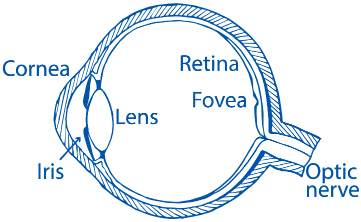
## Colorimetry and Color Modeling

**Colorimetry** is the science of measuring color. **Color modeling**, for the purposes of this *Field Guide*, is defined as the mathematical constructs necessary to produce specific colors using either additive or subtractive mixing. **Color** results from **colored stimuli** detected through receptors in our eyes and processed in our brain. The stimuli could be emitted electromagnetic radiation from the **visible wavelength spectrum** or the combination of said radiation and an object. A **wavelength** is the spatial period of a wave of electromagnetic radiation. Wavelengths in the visible spectrum range from approximately 380 to 780 nm.





> The **rods** and **cones** are the receptors, where the rods detect very low levels of light and only quantify levels of gray. The cones are our color receptors, and the majority of these are found in the **fovea**.

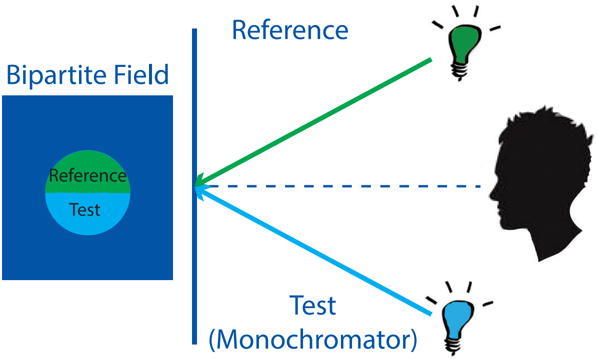
Colorimetry and color modeling give us the tools necessary to replicate specific colors under equivalent viewing conditions, and define what colors can be physically produced. Experimental observations involving color matching were recorded at the turn of the last century, and the data are still used to calculate different color metrics. The experiments started by defining how an observer compared the brightness of different colored light sources, and then advanced to how an observer performed color matching using multiple colors of light.

## Brightness versus Color

In the early 1900s, it was observed that light sources of equal power were not equal in brightness if they differed in color. In 1923, several university studies were performed comparing **brightness** versus **color** for two light sources of the same size and power. There were many issues with these experiments:

- The studies did not represent a diverse enough observer group (i.e., white, male graduate students), which may not generalize to other populations.
- Incandescent lamps do not emit well in the blue/violet wavelength regions.
- The standard deviation of data from all of the studies was significantly large in the violet region of the visible.
- Narrow bandpass filters were difficult to procure for monochromators used in the studies.
- It was difficult to create a uniform field across a large area that was bright enough to only activate the cones and prevent **rod intrusion**. Thus, the field had to be limited to a small, 2-deg **bipartite** field.

Regardless of the experimental limitations, the averaged data were published in 1924.



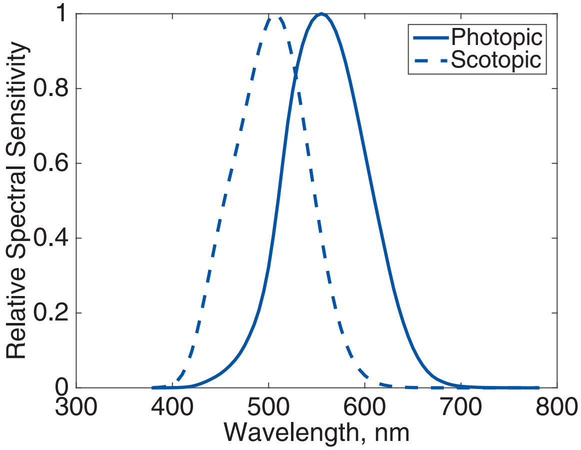
## Luminous Efficiency, $V(\lambda)$ and $V'(\lambda)$

**Spectral luminous efficiency** is the ratio of the radiant flux at wavelength $\lambda_m$ to that at wavelength $\lambda$, such that both produce equally intense luminous sensations under specified photometric conditions. $\lambda_m$ is chosen so that the maximum value of this ratio equals one.

In 1924, the **Commission Internationale de l'Eclairage (CIE)** agreed on the values of luminous efficiency for **photopic vision** $V(\lambda)$. In 1951, the CIE agreed on values for **scotopic vision** $V'(\lambda)$.

- Photopic vision represents the average visual sensations for the cones of a **color-normal** human eye under well-lit conditions (i.e., luminance levels of $>3$ cd/m$^2$). The photopic curve peaks at 555 nm in the visible wavelength spectrum.
- Scotopic vision represents the average visual sensations for the rods of a color-normal human eye under low-light conditions (i.e., luminance levels of $<0.03$ cd/m$^2$). The scotopic curve peaks at a shorter wavelength of 505 nm.

The values for $V(\lambda)$ and $V'(\lambda)$ can be found in the Appendix.

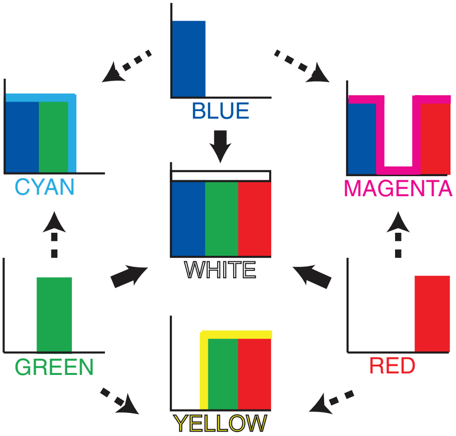


## Additive Color Mixing

The combination of different colors of light adds their spectral power distributions to create a new colored light. This process is called **additive color mixing**.

The colors **red, green, and blue (RGB)** are referred to as **additive primaries** because the combination of two equal primaries will result in the colors yellow, cyan, or magenta. If all three are equally combined, the result is white light. Examples of additive light mixtures can be found in televisions and other display screens where the background light sources consist only of red, green, and blue.

| COMBINED PRIMARIES | RESULT |
|---|---|
| **RED + BLUE** | **MAGENTA** |
| **GREEN + BLUE** | **CYAN** |
| **RED + GREEN** | **YELLOW** |
| **RED + GREEN + BLUE** | **WHITE** |

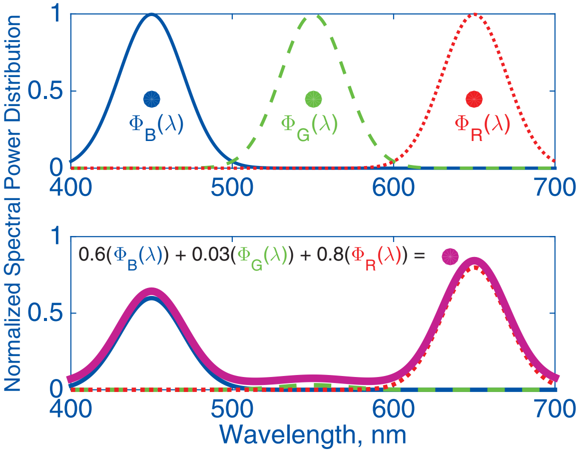


## Grassmann's Law

In 1853, Hermann Grassmann showed that the colors of light produced by combining different amounts of red, green, and blue light followed an algebraic model. For example,

$$\Phi_R(\lambda) = \text{Red light primary}$$
$$\Phi_G(\lambda) = \text{Green light primary}$$
$$\Phi_B(\lambda) = \text{Blue light primary}$$
$$\Phi_{total}(\lambda) = \mathrm{R}\cdot\Phi_R(\lambda) + \mathrm{G}\cdot\Phi_G(\lambda) + \mathrm{B}\cdot\Phi_B(\lambda)$$

where R, G, and B are the scalars.



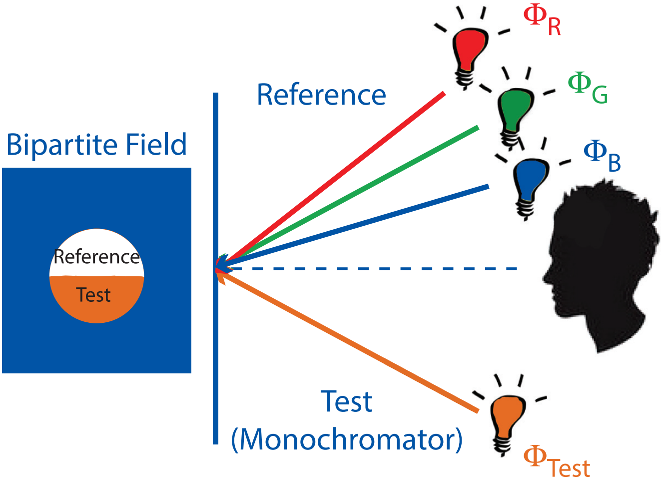
To verify this law experimentally, the following requirements are necessary:

- No single primary can be the result of the combination of either of the other two, and each cannot change their specific spectral shape.
- The level of illumination must be high enough or subtend a 2-deg viewing angle to only activate the cones in the fovea.
- The observer must have color-normal vision.

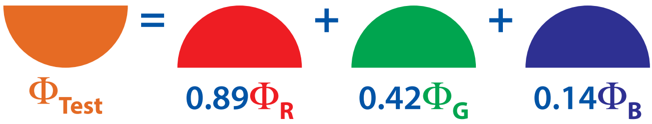
## First Experiment with RGB

The first color matching experiments compared three reference red, green, and blue light sources and a test monochromator illuminating a 2-deg bipartite field.

The three reference colors could be adjusted in light level by the observer to match the color being emitted by the test monochromator.

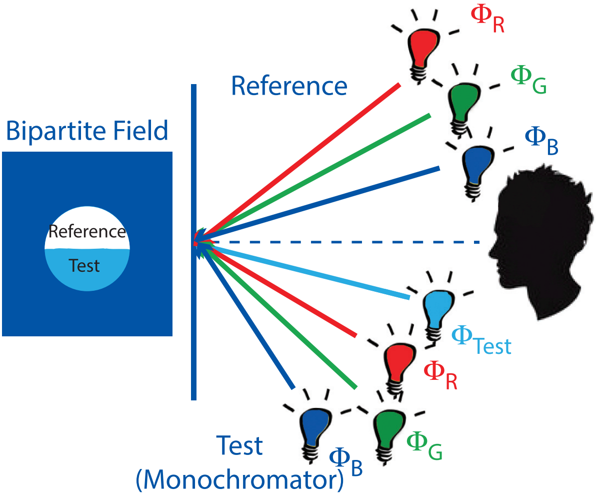


For example, the amount of red, green, and blue light necessary to match the orange color below is 89%, 42%, and 14%, respectively.



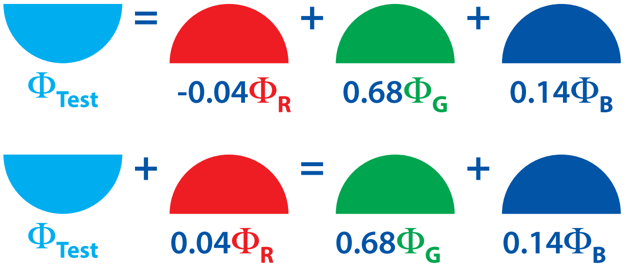
In this experiment, however, observers were not able to match every color on the monochromator successfully. The experiment needed to be refined, while still maintaining **Grassmann's law**, in order to create the exact test color emitted when combining the reference sources.

## Second Experiment with RGB



A new experiment was developed that included all three reference colors on the test side as well as on the reference side. When a red, green, or blue source emitted light on the test side, it would be equivalent to subtracting that source from the reference side.

For example, the amount of green and blue together cannot equal the cyan color below without subtracting some of the red source. The only way to create a subtracting source is to represent the red reference source on the test side.



## Color Matching Functions

A **color matching function (CMF)** is a formula that calculates the color stimulus of a single wavelength from a **monochromator** by combining a set of red, green, and blue light primaries.

A **tristimulus value** defines the amount of a set of primaries that, when combined, will equal a color match for a given color stimulus. $\bar{r}$ is the tristimulus value for the red primary, $\bar{g}$ is for green, and $\bar{b}$ is for blue. The bar over the letter denotes an average over multiple observations. The plots below are two separate CMFs for two sets of primaries $\Phi_R$, $\Phi_G$, and $\Phi_B$.