Color Vision

Intro to Data Visualization

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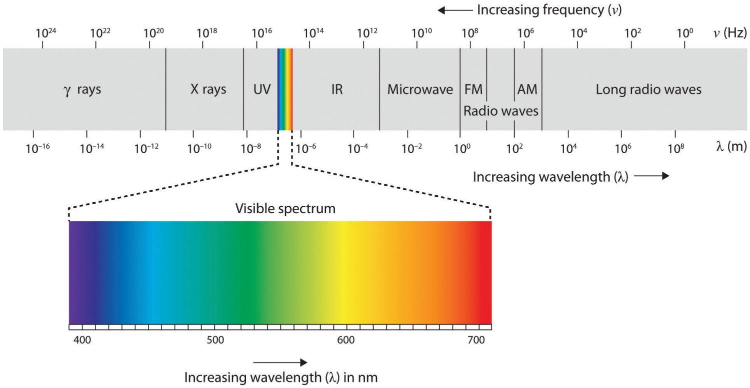
Light and Color

Light Recap

- Light is a form of electromagnetic radiation.
- Electromagnetic radiations are characterized by their wavelength.
- Visible light has wavelengths in a narrow band centered on 600 nanometers.

Electromagnetic Spectrum



http://open.lib.umn.edu/intropsyc/chapter/4-2-seeing/

Visible Light

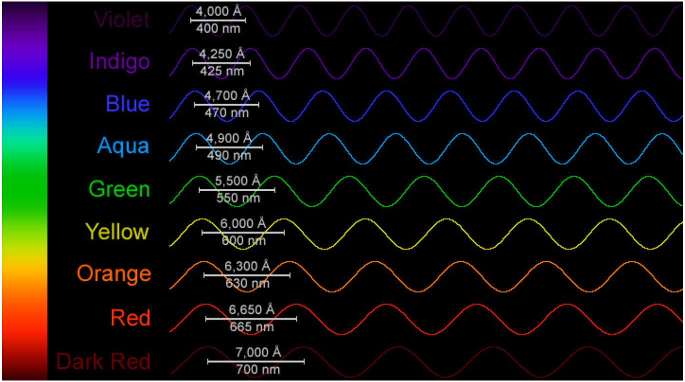
Visible Spectrum

If the electromagnetic spectrum spanned the distance from Los Angeles to New York City, the part visible to the human eye would span the width of a dime.

Visible Light

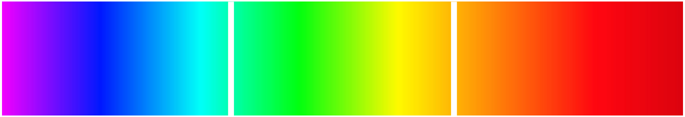
- Our eyes detect wavelengths in a tiny portion of the *EM* spectrum.
- We call this the *visible light spectrum*.
- We perceive short wavelengths as blue.
- We perceive longer wavelengths as red.
- We cannot perceive wavelength beyond the limits of the visible spectrum.
- Shorter wavelengths of ultraviolet light.
- Longer wavelengths of infrared radiation.

Electromagnetic Spectrum



www.astronomersgroup.org/EMspectrum.html

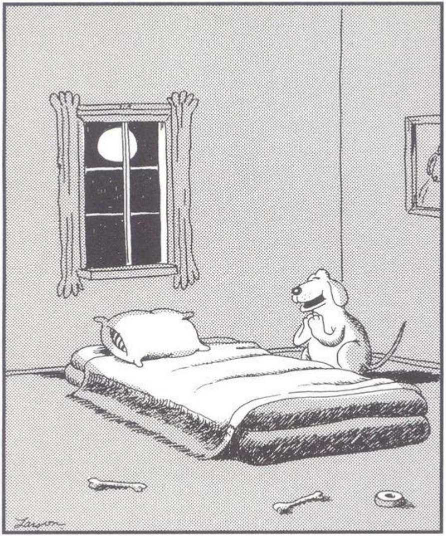
Visible Spectrum



If the visible spectrum is divided into thirds, the predominant colors are blue, green, and red.

Some considerations

- Color is part of how we sense the world around us.
- Light enters the eyes.
- It is processed by light receptors (cones and rods).
- And sent via the optic nerves to the brain for further processing and interpretation.
- Light varies in wavelengths, which our eyes and brain interpret as varying colors.



"...And please let Mom, Dad, Rex, Ginger, Tucker, me, and all the rest of the family see color."

Color Vision Theories

Color Vision Theories

There are two complementary color vision theories that explain how we perceive colors, and how our brain “sees” colors

- **Trichromatic** theory.
- **Opponent** theory.

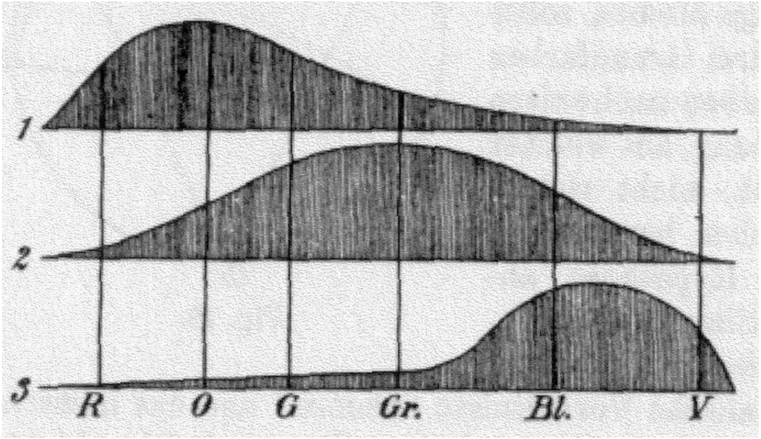
Trichromatic Theory

Trichromatic Theory

Young-Helmholtz Theory

- Originally proposed by Thomas Young in 1802.
- Further expanded by Hermann von Helmholtz.
- Human color vision could be explained by the existence of 3 receptors: Red, Green, and Blue.
- https://en.wikipedia.org/wiki/Young%E2%80%93Helmholtz_theory

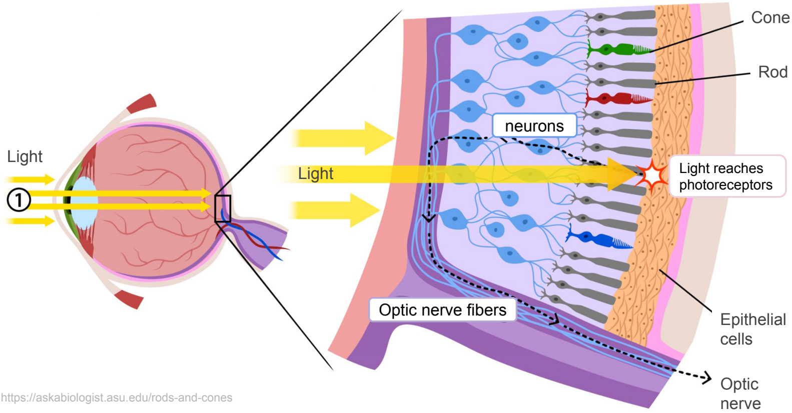
3 kinds of light receptors



Trichromatic Theory

- Young suggested that the eye contained different photoreceptor cells.
- Each cell was sensitive to different wavelengths of light in the visible spectrum.
- Young's original theory was based on Red, Green, and Blue receptors.
- We now know that there are really three kinds of color receptors in the eye.
- As a result the 3 kinds of cones in the eye are called **R**, **G**, and **B**.

Retina Cell Receptors



https://askabiologist.asu.edu/rods-and-cones

Trichromatic Theory

Young-Helmholtz Theory

Helmholtz used color-matching experiments where participants would alter the amounts of three different wavelengths of light to match a test color.

Participants could not match the colors if they used only two wavelengths, but could match any color in the spectrum if they used three (Red, Green, Blue).

Opponent Theory

Opponent Theory

Opponent-Process Theory

- Predates Young-Helmholtz theory. Dates as far back as Leonardo Da Vinci.
- The color pairs red-green and yellow-blue are in opposition.
- No color can simultaneously exhibit both redness and grenness, or blueness and yellowness.

Opponent Theory

Opponent-Process Theory

- Formally developed by Ewald Hering.
- Hering noted color combinations that we never see
  reddish-green or yellowish-blue
- This theory suggests that color perception is controlled by the activity of three opponent systems:
  white and black, blue and yellow, and red and green.
- https://en.wikipedia.org/wiki/Opponent-process_theory

Opponent Theory

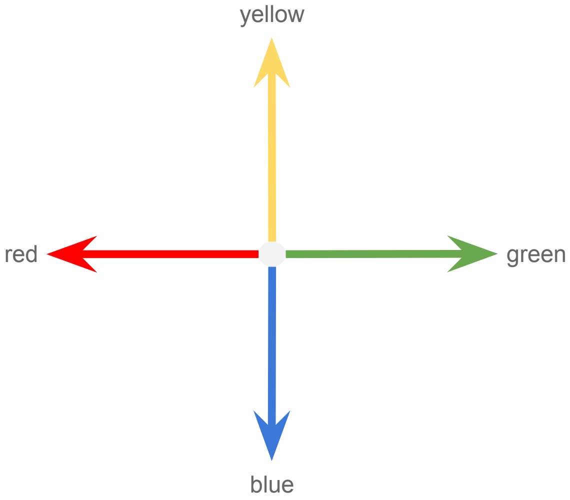
Opponent-Process Theory

Colors are created by the eye and brain as combinations of red-green, and yellow-blue color signals.

R-G and B-Y pairs

Our eyes and brain create four basic colors: yellow, blue, red, and green, arranged in two pairs.

Color Pairs of Opponent Theory



Opponent Theory

A color can be described by three parameters

- Where it lies on a light/dark scale
- Where it lies on a red/green scale
- Where it lies on a blue/yellow scale

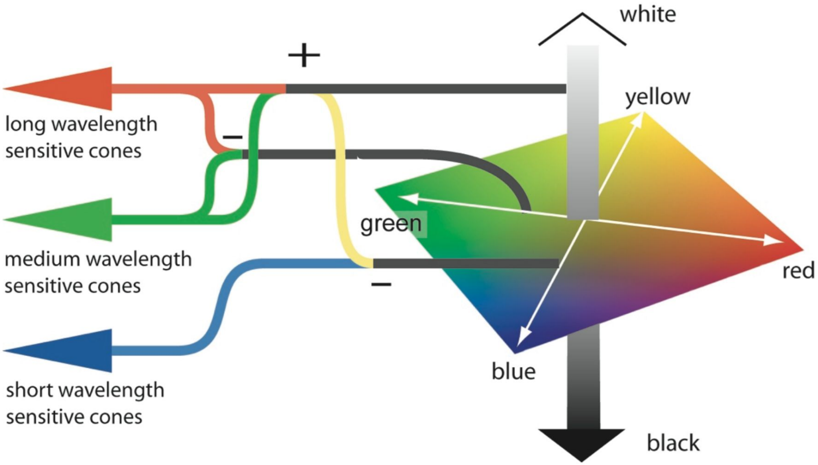
These three dimensions, “green or red,”, “blue or yellow,” and brightness, form the foundation for the way our brain perceives color.

Opponent Theory

Our sensation of color comes from nerve cells that send messages to the brain about:

- The brightness of color.
- Greenness vs. redness.
- Blueness vs. yellowness.
- Color nerves sense green or red, but never both.
- Likewise color nerves sense blue or yellow, but never both.
- We never see bluish-yellows or reddish-greens.

Color Opponency



C. Ware, “Visual Thinking for Design”

Opponent Colors and Television

- Initially, television was only available in black and white.
- Later on, technology became available to make color television.
- Engineers faced the problem of how to transmit the color information but still remain compatible with all the existing black and white sets.
- They chose to add the color information by adding two additional color signals.
- The two signals were the color positions on the opponent red/green and yellow/blue scales.

Evolution of Color Vision

Evolution of Color Vision

- The human color vision system appears to have evolved in steps.
- Initially our (very remote) ancestors had a single class of light sensitive cells.
- At a point predating the evolution of the mammals this single class of cells differentiated into separate yellow and blue classes.
- Much later, in primates, the class of yellow sensitive cells differentiated into separate red and green sensitive classes.

Primitive Color

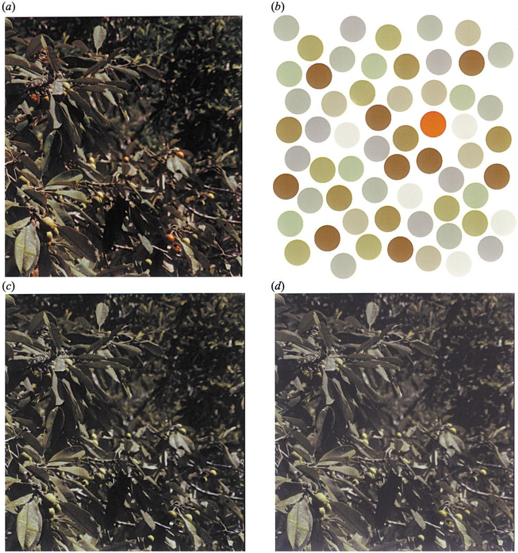
image as it would appear to an animal with just a yellow/blue based vision system

Primate Color

image as it would appear to a primate with a red/green/blue based vision system

Primate Color Vision: Searching for Fruits

Trichromatic vision



Orange circle

Dichromatic (protanope)

Dichromatic (deuteranope)

Fruits and Primate Color Vision

- Natural task facing monkeys foraging for fruit (*a*).
- Typical stimulus array from laboratory: searching for orange circle (*b*).
- Photograph as it would appear to a protanope (*c*).
- Photograph as it would appear to a deuteranope (*d*).

Regan et al. (2001) Fruits, foliage and the evolution of primate colour vision. The Philos Trans R Soc Lond B Biol Sci. 356, 229-283.

Trichromatic and Opponent Theories

Trichromatic and Opponent Theories

- Both theories are complementary
- The Thrichromatic theory applies in the eyes (physical-sensory)
- The Opponent theory applies in the brain (cognition)

Trichromatic and Opponent Theories

Color vision in three major processes

- **Trichromatic input**: information is recorded by the responses of the L, M and S cone cells in the retina.
- **Opponent output**: responses from the L, M and S cones are converted into signals for yellowness vs blueness and redness vs greenness, plus total brightness.
- **Processing for color constancy**: color information from the visual field is analyzed, interpreting object properties (i.e. hue, value and chroma) and lighting properties (i.e. hue, brightness and saturation of the illumination).

Colorimetry

Colorimetry

Definition

Colorimetry is the science and technology used to quantify and describe physically the human color perception.

https://en.wikipedia.org/wiki/Colorimetry

Color Matching

Definition

Most of the research behind modern color theory was performed in the 1920s and 1930s (primarily in the UK) with two main goals:

- Understand color vision
- Develop commercial technology for color matching

Some Notes

- The experiments that provided the eye-cones sensitivity curves were performed in the second half of the 20th century.
- Any trichromatic theory cannot generate all the colors perceived by the human brain.
- Three chromatic signals go from the eye to the brain.
- Some processing occurs near the light receptors: two color difference signals plus a lightness level are transmitted to the brain.

Color Matching Experiments

- In the 1920s William Wright and John Guild independently conducted a series of **color matching experiments**
- These experiments mapped out all the colors that the “average human” can see
- In 1931, color scientists used Wright’s and Guild’s results to create the 1931 CIEXYZ color space, a.k.a. *CIE*.

Commission Internationale de L'eclairage

- CIE: The International Commission on Illumination.
- Created in 1913.
- Based in Vienna, Austria.
- International authority on light, illumination, colour, and colour spaces.
- Develops standards to measure light and lighting.
- http://www.cie.co.at/

CIE Standard Observer

CIE standardization

In 1931, the *Commission Internationale de l'Eclairage* (CIE) established standard for color representation based on physiological perception of light.

Standard Observer

The CIE standards are built on a set of three *color-matching functions* collectively called the **standard observer**, related to the red, green, and blue cones in the eye.

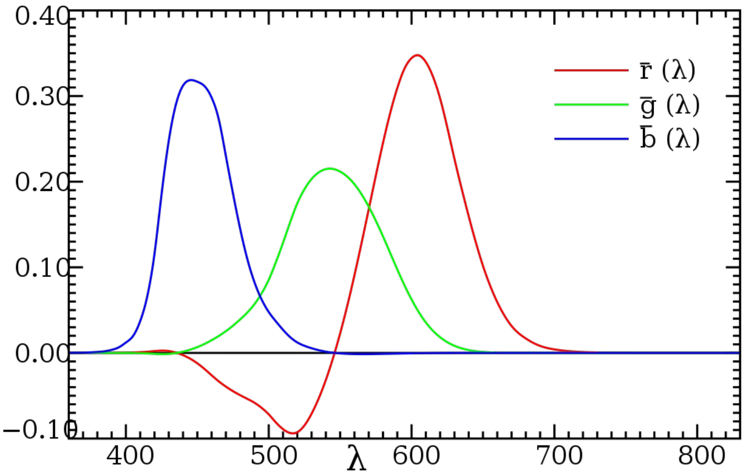
CIE Standard Observer

- The tristimulus values depend on the observer's field-of-view.
- CIE defined a color-mapping function called the standard (colorimetric) observer.
- Represents an average human's chromatic response within a 2 degree arc inside the fovea
- The CIE 1931 Standard Observer function is also known as the CIE 1931 2° Standard Observer.

CIE Theoretical Primaries

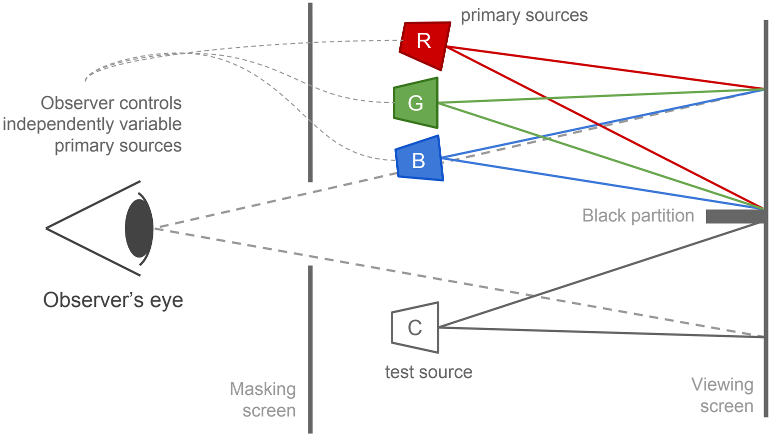
- The CIE has established a set of theoretical "red", "green", and "blue" primary colors.
- When combined, the standard primaries cover the full gamut of human color vision.
- A combination of the three can match any monochromatic light source.

CIE 1931 Primaries Color Matching Functions



https://en.wikipedia.org/wiki/CIE_1931_color_space

Color Matching Experiments



How much of the primaries R, G and B does it take to match to C?

Color Matching Functions

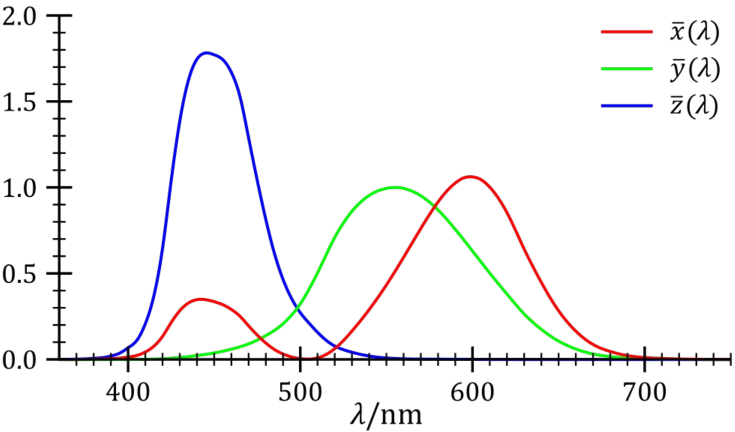
Color Matching Experiments

The color matching functions were derived by showing subjects color patches and asking them to match the color by adjusting the output of three pure colors.

Negative Color Amounts

- Some colors C cannot be matched by any combination of primary colors.
- A match can be made by adding a small amount of one of the primaries to C.
- When this is the case, the amount of that primary in the match is taken to be negative.

CIE 1931 XYZ Color Matching Functions



https://en.wikipedia.org/wiki/CIE_1931_color_space

Color matching functions

- The CIE's color matching functions are expressed as: $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$
- They are the numerical description of the chromatic response of the "standard observer."
- They can be thought of as the spectral sensitivity curves of three linear light detectors yielding the values X, Y, Z.

Some Remarks

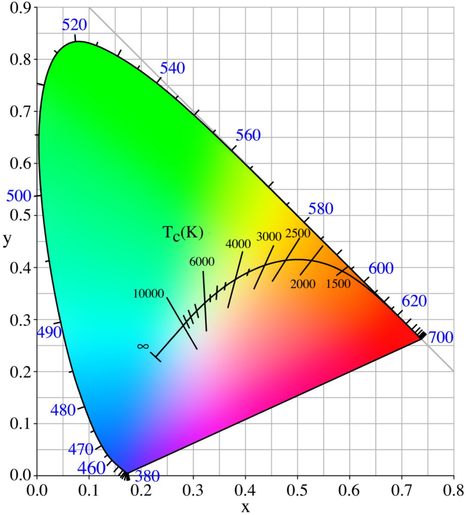
- Color matching functions were found to vary very little between individuals.
- This meant that an average of the color matching functions could be used as a description of a **standard observer**.
- The international color standards organization (the *Commission Internationale de l'Eclairage* or CIE) adopted the standard observer as the basis for color description.

The CIE XYZ Primaries

- The CIE felt that the negative color amounts which resulted from using RGB primaries were too difficult for practitioners to handle.
- Instead they adopted an alternative set of "imaginary" colour primaries X, Y and Z and used a mathematical conversion from RGB to XYZ to obtain the matching functions for XYZ.
- The XYZ matching functions $\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$ provide an absolute description of every possible color.

Chromaticity Diagram

Chromaticity Diagram



https://upload.wikimedia.org/wikipedia/commons/b/ba/PlanckianLocus.png

About CIE diagram

- Based on the trichromatic theory, a full plot of all visible colors is a three-dimensional figure.
- However, the concept of color can be divided into two parts:
  - Brightness
  - Chromaticity
- The CIE XYZ color space was deliberately designed so that the Y parameter is a measure of the luminance of a color.
- The chromaticity of a color is then specified by the two derived parameters x and y.

Color Mixing

- The fundamental property of chromaticities is that the chromaticity for a mixture of two colors lies on the line joining the individual chromaticities.
- This property makes the chromaticity diagram ideal for describing color mixing

1960 CIE UCS

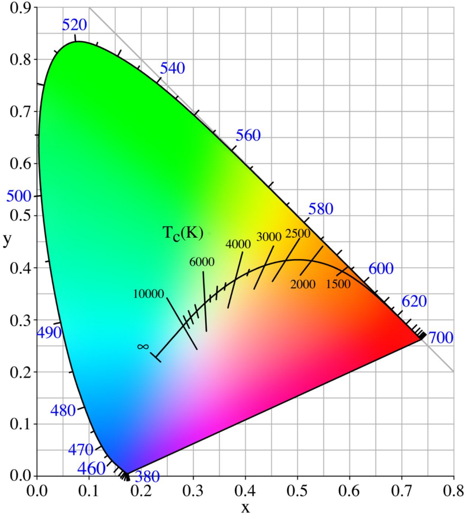
Limitations of the CIE 1931 chromaticity diagram

The chromaticity diagram is not without faults. Soon after it was issued it was found that it does not represent color gradations in a uniform matter.

1960 CIE Uniform Chromaticity Space

Attempts to transform the original diagram into a more uniform representation resulted in the 1960 CIE UCS, where projective transformations of the x and y space distort it to obtain somewhat more uniform u and v coordinates. Two standards derive from UCS: CIE 1976 L*a*b or CIELAB, and CIE 1976 L*u*v or CIELUV.

Chromaticity Diagram



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