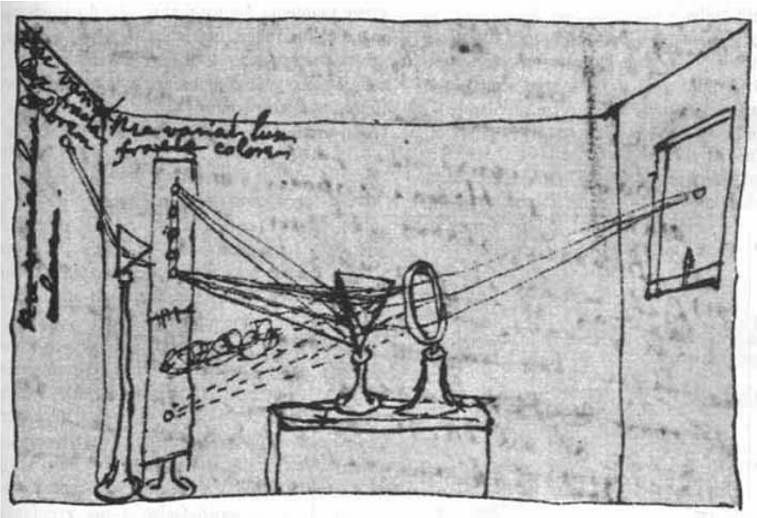
Newton's Color Experiments
1671



Newton's Conclusions

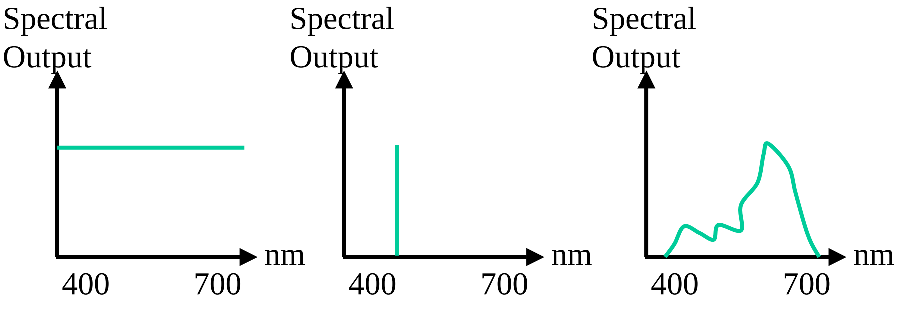
- White light has seven constituent components: red, orange, yellow, green, blue, indigo and violet.
- Dispersed light can be recombined to form white light.
- Magenta and purple can be obtained by combining only portions of the spectrum.

Color and Color Vision

The perceived color of an object depends on four factors:

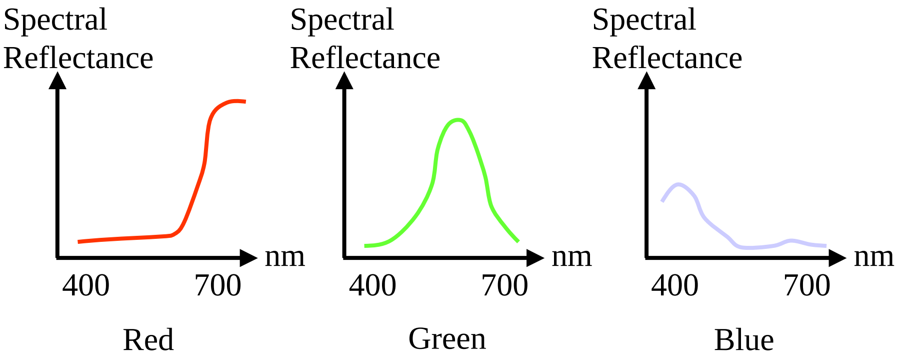
1. Spectrum of the illumination source
2. Spectral Reflectance of the object
3. Spectral response of the photoreceptors (including bleaching)
4. Interactions between photoreceptors

Light Sources



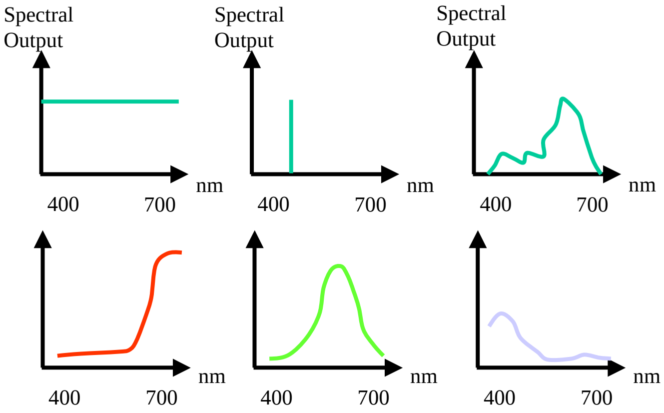
White Monochromatic Colored

Pigments

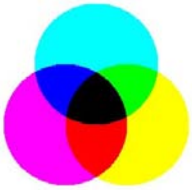


Subtractive Colors

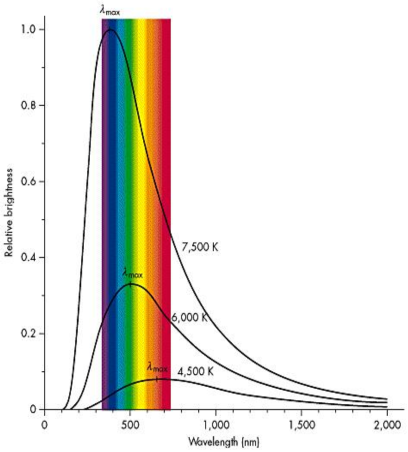
Pigments (e.g. paints and inks) absorb different portions of the spectrum



Multiply the spectrum
of the light source by
the spectral
reflectivity
of the object to find
the distribution
entering the eye.



Blackbody Radiation

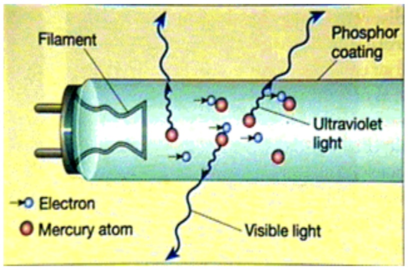


For lower temperatures, blackbodies appear red. As they heat up, the shift through the spectrum towards blue.

Our sun looks like a 6500K blackbody.

Incandescent lights are poor efficiency blackbodies radiators.

Gas-Discharge & Fluorescent Lamps



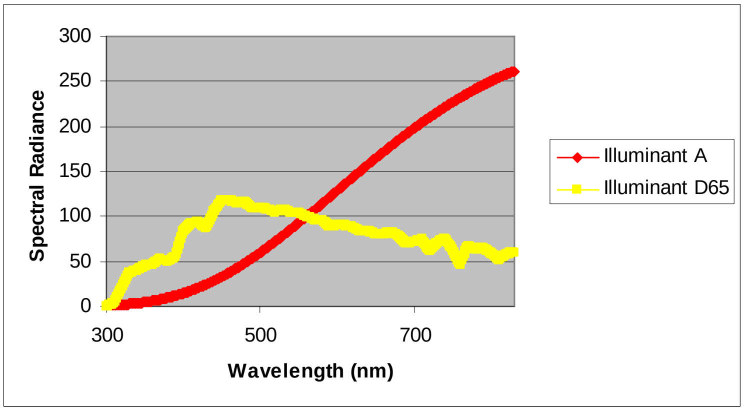
A low pressure gas or vapor is encased in a glass tube. Electrical connections are made at the ends of the tube. Electrical discharge excites the atoms and they emit in a series of spectral lines. We can use individual lines for illumination (e.g. sodium vapor) or ultraviolet lines to stimulate phosphors.

CIE Standard Illuminants

Illuminant A - Tungsten lamp looking like a blackbody of 2856 K
Illuminant B - (discontinued) Noon sunlight.
Illuminant C - (discontinued) Noon sunlight.

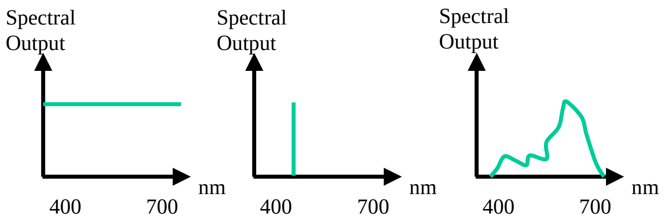
Illuminant D55 - (Occasionally used) 5500 K blackbody
Illuminant D65 - 6500 K blackbody, looks like average sunlight and replaces Illuminants B and C.
Illuminant D75 - (Occasionally used) 7500 K blackbody

Illuminants A and D_{65}



Additive Colors

Self-luminous Sources (e.g. lamps and CRT phosphors) emit different spectrums which combine to give a single apparent source.



Add the spectrums of the different light sources to get the spectrum of the apparent source entering the eye.

Color Models

- Attempt to put all visible colors in a ordered system.
- Mathematics based, art based and perceptually based systems.

RGB Color Model

A red, green and blue primary are mixed in different proportions to give a color

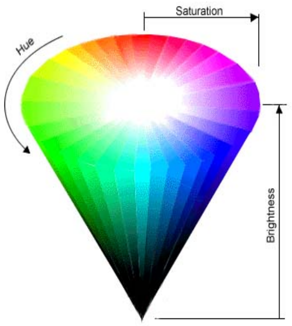
(1,0,0) is red
(0,1,0) is green
(0,0,1) is blue

24 bit color on computer monitors devote 8 bits (256 values) to each primary color (i.e. red can take on values (0…255) / 255)

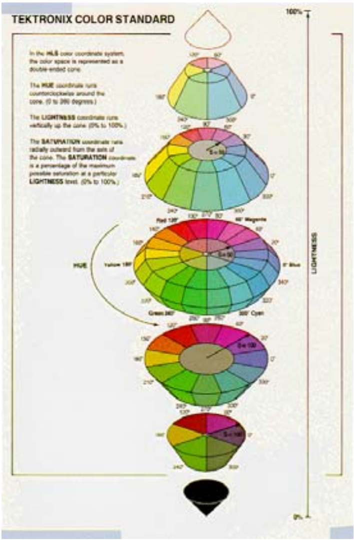
(1,1,1) is white
(0,0,0) is black

HSB (HSV) Color Model

Hue – color is represented by angle
Saturation – amount of white represented by radial position
Brightness (Value) – intensity is represented by the vertical dimension



HLS Color Model



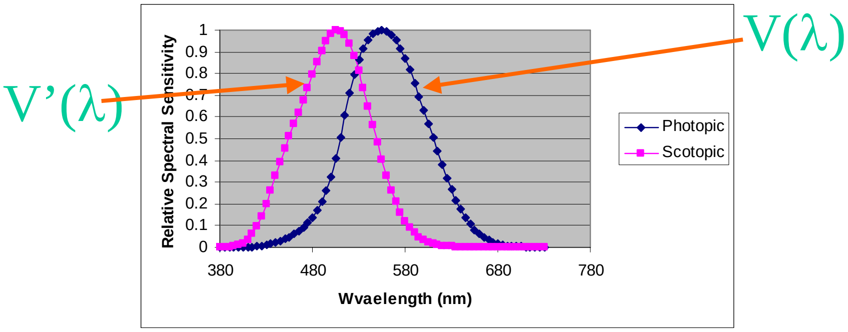
Hue – color is represented by angle
Lightness – intensity is represented by the vertical dimension
Saturation – amount of white represented by radial position

CIE

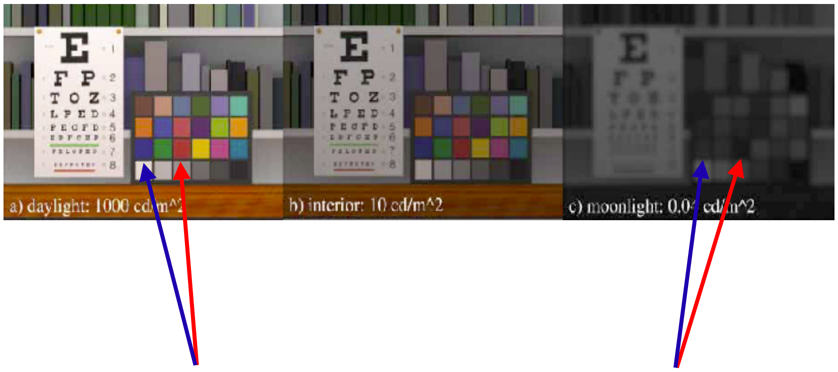
- 90 year old commission on color
- Recognized as the standards body for illumination & color.
- Has defined standard illuminants and human response curves.

Luminosity Functions

The spectral responses of the eye are called the luminosity functions. The The $V(\lambda)$ curve (photpic response) is for cone vision and the $V'(\lambda)$ curve (scoptopic response) is for rod vision. $V(\lambda)$ was adopted as a standard by the CIE in 1924. There are some errors for λ<500 nm, that remain. The $V'(\lambda)$ curve was adopted in 1951 and assumes an observer younger than 30 years old.



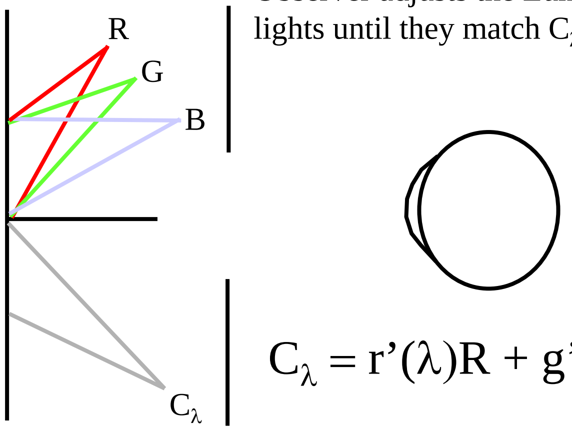
Purkinje Shift



Note how the brightness of reds and blues change with decreasing illumination. This is due to the sensitivity of the eye shifting from photopic to scoptic

Human Color Models

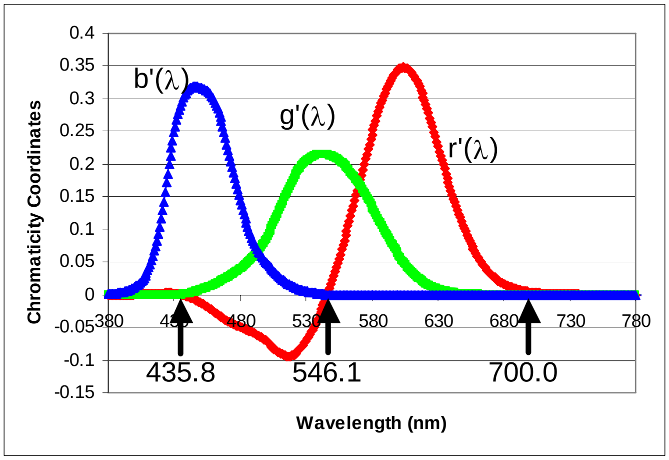
Observer adjusts the Luminances of R, G and B lights until they match C_λ



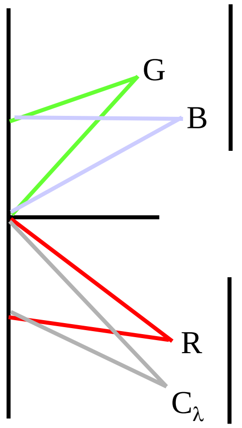
R = 700.0 nm
G = 546.1 nm
B = 435.8 nm

$$C_\lambda = r'(\lambda)R + g'(\lambda)G + b'(\lambda)B$$

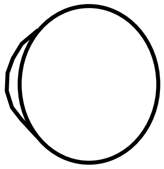
1931 CIE Color Matching Functions



Color Matching Functions



What does a negative value of the Color Matching Function mean? Bring one light to the other side of the field. Observer now adjusts, for example, the Luminances of G and B lights until they match C_λ + R

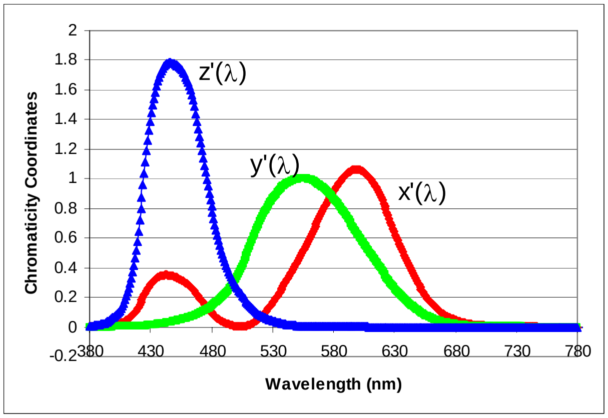


R = 700.0 nm
G = 546.1 nm
B = 435.8 nm

$$C_\lambda + r'(\lambda)R = g'(\lambda)G + b'(\lambda)B$$

1931 CIE Color Matching Functions

The CIE defined three theoretical primaries x’, y’ and z’ such that the color matching functions are everywhere positive and the “green” matching function is the same as the photopic response of the eye.



Conversion x’y’z’ to r’g’b’

$$\begin{bmatrix} r' \\ g' \\ b' \end{bmatrix} = \begin{bmatrix} 0.41846 & -0.15860 & -0.08283 \\ -0.09117 & 0.25243 & 0.01571 \\ 0.00092 & -0.00255 & 0.17860 \end{bmatrix} \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$$

The x’, y’, z’ are more convenient from a book-keeping standpoint and the relative luminance is easy to determine since it is related to y’.

The consequence of this conversion is that the spectral distribution of the corresponding primaries now have negative values. This means they are a purely theoretical source and can not be made.

Tristimulus Values X, Y, Z

$$X = \int_0^\infty P(\lambda)x'(\lambda)d\lambda$$

$$Y = \int_0^\infty P(\lambda)y'(\lambda)d\lambda$$

$$Z = \int_0^\infty P(\lambda)z'(\lambda)d\lambda$$

The tristimulus values are coordinates in a three dimensional color space. They are obtained by projecting the spectral distribution of the object of interest P(λ) onto the color matching functions.

Chromaticity Coordinates x, y, z

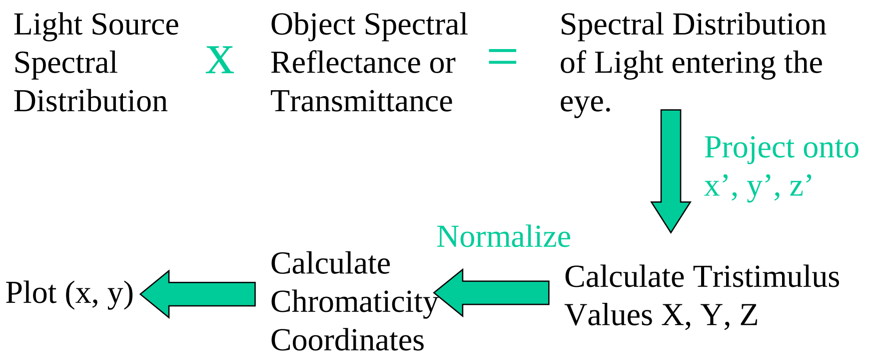
$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

The chromaticity coordinates are used to normalize out the brightness of the object. This way, the color and the brightness can be spearated. The coordinate z is not independent of x and y, so this is a two dimensional space.

Chromaticity Coordinates



Light Source Spectral Distribution X Object Spectral Reflectance or Transmittance = Spectral Distribution of Light entering the eye.

Project onto x’, y’, z’

Calculate Tristimulus Values X, Y, Z

Normalize

Calculate Chromaticity Coordinates

Plot (x, y)

Example - Spectrally Pure Colors

Suppose $P(\lambda) = \delta(\lambda-\lambda_o)$

$$X = \int_0^\infty \delta(\lambda-\lambda_o)x'(\lambda)d\lambda = x'(\lambda_o)$$

$$x = \frac{x'(\lambda_o)}{x'(\lambda_o)+y'(\lambda_o)+z'(\lambda_o)}$$

$$Y = \int_0^\infty \delta(\lambda-\lambda_o)y'(\lambda)d\lambda = y'(\lambda_o)$$

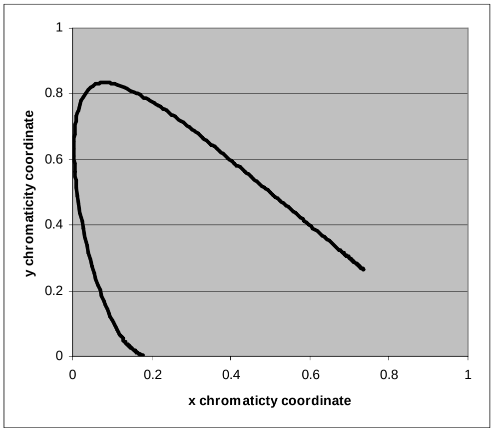
$$y = \frac{y'(\lambda_o)}{x'(\lambda_o)+y'(\lambda_o)+z'(\lambda_o)}$$

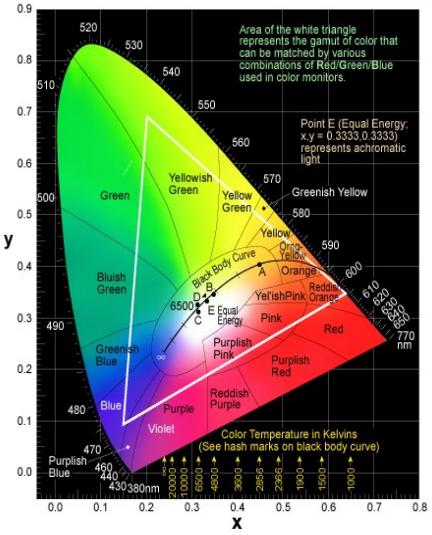
$$Z = \int_0^\infty \delta(\lambda-\lambda_o)z'(\lambda)d\lambda = z'(\lambda_o)$$

$$z = 1 - x - y$$

Plotting x vs. y for spectrally pure colors gives the boundary of color vision

CIE Chromaticity Chart





Example - White Light

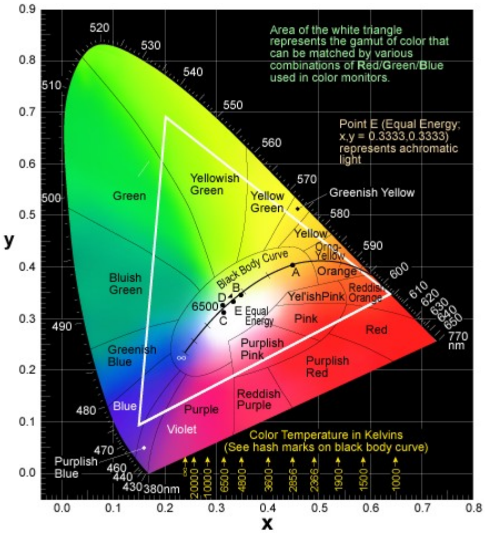
Suppose P(λ) = 1

$$X = \int_0^\infty x'(\lambda)d\lambda = 1 \qquad x = \frac{1}{1+1+1} = 0.33$$

$$Y = \int_0^\infty y'(\lambda)d\lambda = 1 \qquad y = \frac{1}{1+1+1} = 0.33$$

$$Z = \int_0^\infty z'(\lambda)d\lambda = 1 \qquad z = 1 - x - y = 0.33$$

CIE Chromaticity Chart

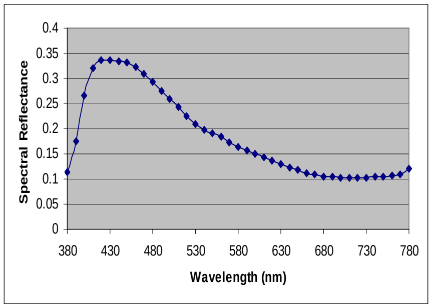


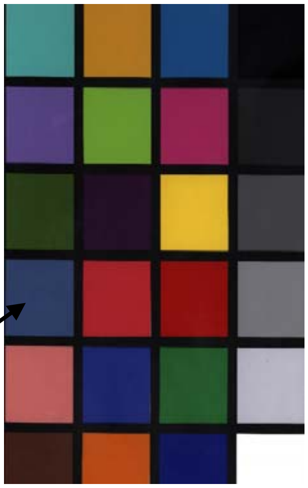
Area of the white triangle represents the gamut of color that can be matched by various combinations of Red/Green/Blue used in color monitors.

Point E (Equal Energy; x,y = 0.3333,0.3333) represents achromatic light

Color Temperature in Kelvins (See hash marks on black body curve)

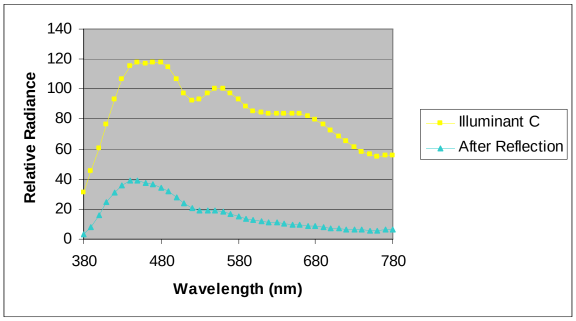
Example - MacBeth Color Checker





Blue Sky

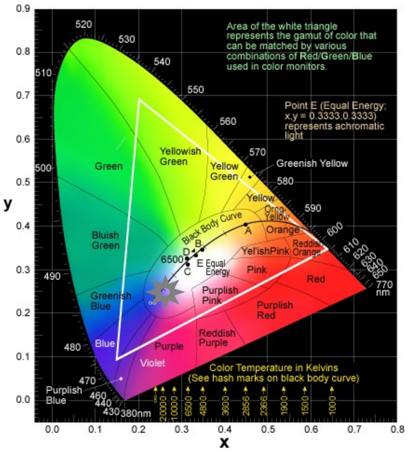
Example - Blue Sky Patch



The Macbeth color checker assumes that Illuminant C is used for illumination.

Multiply the spectral distribution of Illuminant C by the spectral reflectance of the color patch to get the light entering the eye.

Example Blue Sky Patch



$$X = \sum P(\lambda)x'(\lambda)\Delta\lambda = 188.1\Delta\lambda$$

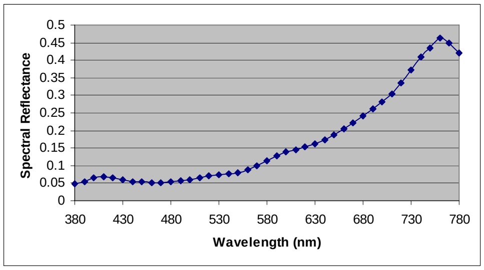
$$Y = \sum P(\lambda)y'(\lambda)\Delta\lambda = 192.6\Delta\lambda$$

$$Z = \sum P(\lambda)z'(\lambda)\Delta\lambda = 379.9\Delta\lambda$$

$$x = 188.1/(188.1+192.6+379.9) = .247$$

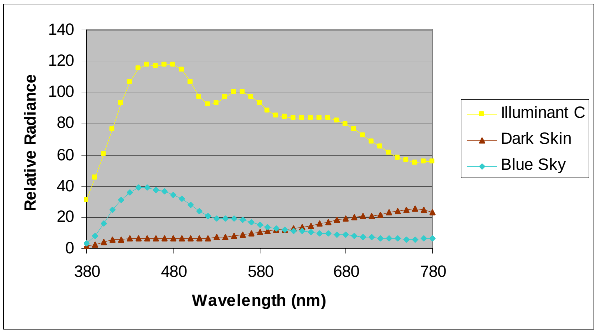
$$y = 192.6/(188.1+192.6+379.9) = .253$$

Example - MacBeth Color Checker



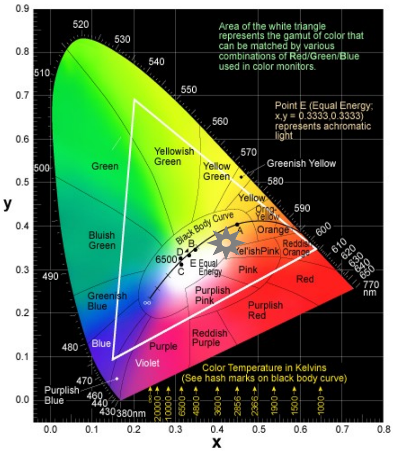
Dark Skin

Example - Dark Skin Patch



Dark skin is much darker than the blue sky. The chromaticity coordinates, however, remove the luminance factor and only look at color.

Example Dark Skin



$$X = \sum P(\lambda)x'(\lambda)\Delta\lambda = 113.6\Delta\lambda$$

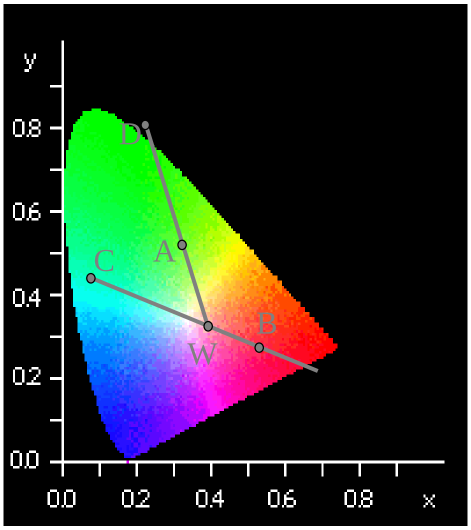
$$Y = \sum P(\lambda)y'(\lambda)\Delta\lambda = 98.8\Delta\lambda$$

$$Z = \sum P(\lambda)z'(\lambda)\Delta\lambda = 66.2\Delta\lambda$$

$$x = 188.1/(188.1+192.6+379.9) = 0.41$$

$$y = 192.6/(188.1+192.6+379.9) = 0.35$$

CIE Chromaticity Diagram



Think of this as a distorted version of the HSB color model.

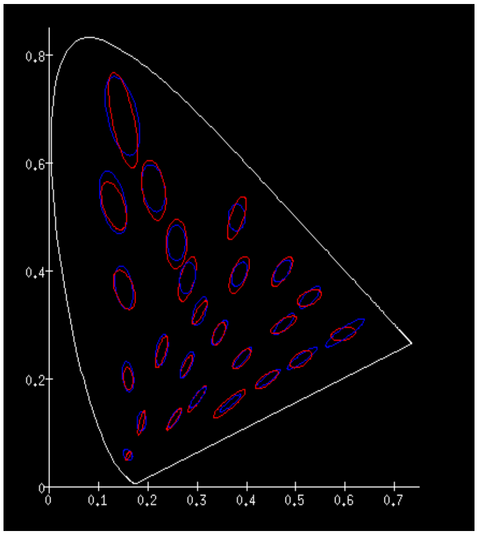
W = White Point (0.33,0.33)
D = Dominant Wavelength (hue)

$$p = \text{excitation purity} = \frac{WA}{WD}$$

C = Complimentary Color

$$p = \text{excitation purity} = \frac{WB}{WC}$$

MacAdam Ellipses



Just noticeable differences for two similar colors is nonlinear on the CIE diagram. Would like a color space that these ellipses become circles. (ellipses are 3x larger than actuality)

1976 CIELUV

Television and Video

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{1/3} - 16 \quad \text{for } \frac{Y}{Y_n} > 0.008856$$

$$L^* = 903.292\left(\frac{Y}{Y_n}\right) \quad \text{for } \frac{Y}{Y_n} \leq 0.008856$$

$$u^* = 13L^*\left[u' - u_n\right]$$

$$v^* = 13L^*\left[v' - v_n\right]$$

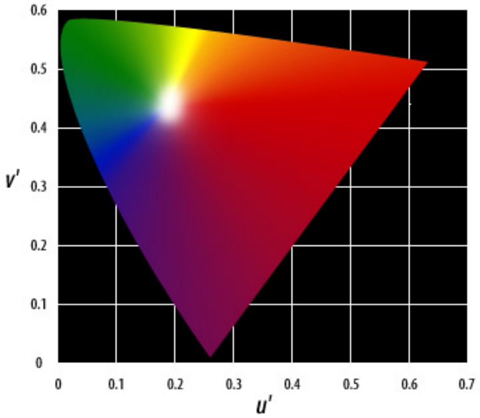
$$u' = \frac{4X}{X + 15Y + 3Z} = \frac{4x}{-2x + 12y + 3}$$

$$v' = \frac{9Y}{X + 15Y + 3Z} = \frac{9y}{-2x + 12y + 3}$$

L* is related to the lightness and is nonlinear to account for the nonlinear response of the visual system to luminance. The u's and v's distort the CIE diagram to make the MacAdam ellipses more round.

Y_n, u_n and v_n are for white

1976 CIELUV



CIELUV Color Difference

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2}$$

1976 CIELAB

Plastic, Textile & Paint

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500\left[f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right]$$

$$b^* = 200\left[f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right]$$

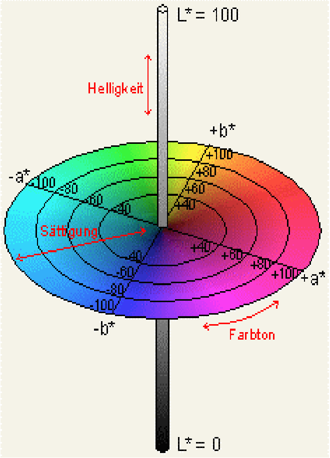
$$\text{where } f(s) = s^{1/3} \quad \text{for } s > 0.008856$$

$$f(s) = 7.787s + 16/116 \quad \text{for } s \leq 0.008856$$

L* is related to the lightness and is nonlinear to account for the nonlinear response of the visual system to luminance. The a's and b's distort the CIE diagram to make the MacAdam ellipses more round.

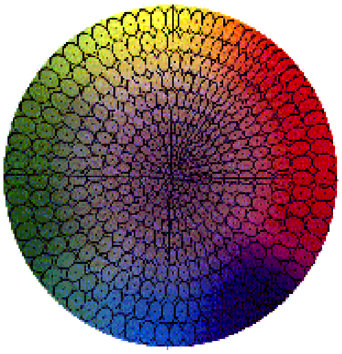
X_n, Y_n and Z_n are for white

1976 CIELAB

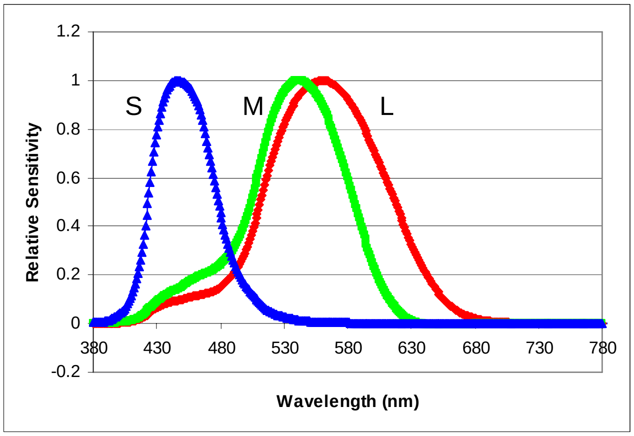


CIELAB Color Difference

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

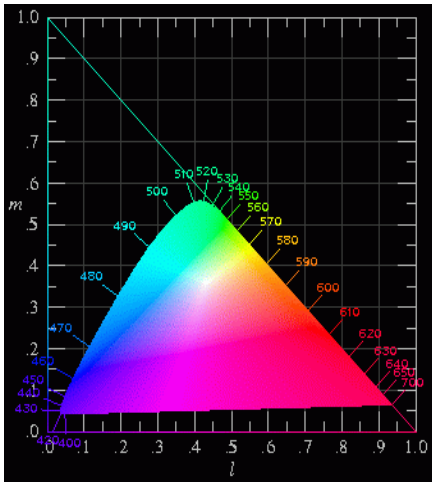


Human Cone Sensitivities



Only during the 1990s were researcher able to distinguish the cone sensitivities

LMS Color Space

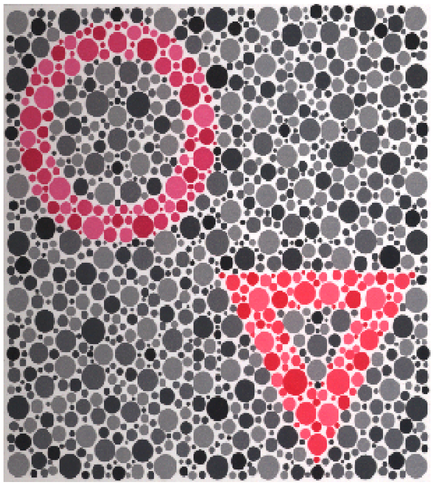


Project P onto LMS color matching functions. The (l,m) is analogous to (x,y) chromaticity coordinates.

Color Blindness

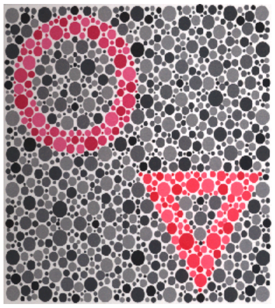
- Protanopia - No L Cones
  - – 1% men, rare in women
- Deutranopia - No M Cones
  - – 1% men, 0.01% women
- Tritanopia - No S Cones
  - – rare

Color Blindness

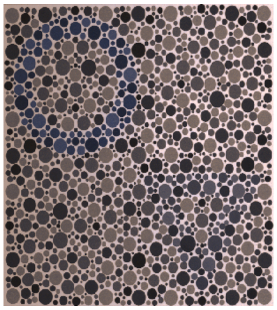


Color Blindness

Normal

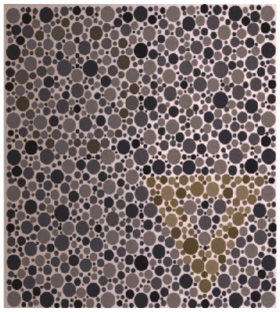


Protonopia



No L Cones

Deuteranopia



No M Cones

Color Blindness Examples

Normal

Deuteranopia

Protanopia

Color Space Conversions

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \begin{bmatrix} R_{709} \\ G_{709} \\ B_{709} \end{bmatrix}$$

This is a conversion from an RGB color model to XYZ trichromatic coordinates. The 709 refers to a standard set of phosphors used in most displays. RGB colors are assumed to range from 0..1. However, in the computer they usually range from 0..255. Simply divide the computer value by 255 to normalize.

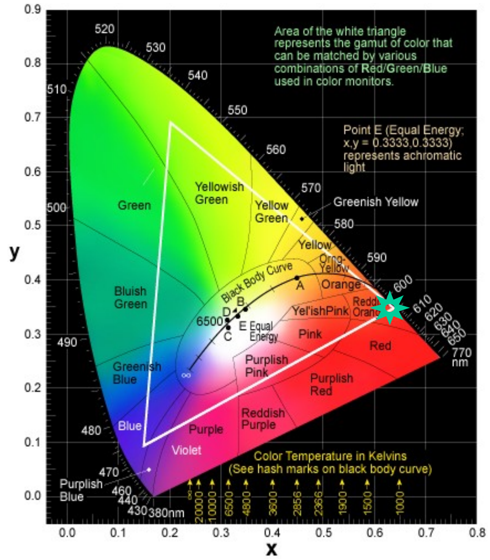
Color Space Conversions - Example

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$X = 0.412453$
$Y = 0.212671$
$Z = 0.019334$

$x = 0.412453/(0.412453+0.212671+0.019334)$
$x = 0.64$
$y = 0.212671/(0.412453+0.212671+0.019334)$
$y = 0.33$

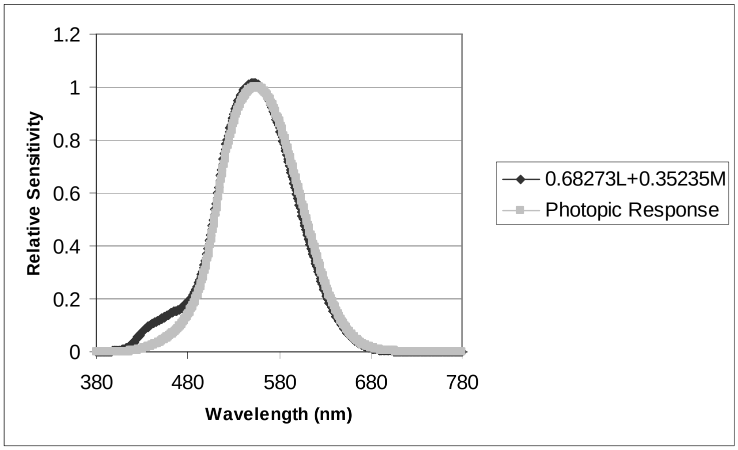
Example (1, 0, 0)



Color Space Conversions

$$\begin{bmatrix} L \\ M \\ S \end{bmatrix} = \begin{bmatrix} 0.3897 & 0.6890 & -0.0787 \\ -0.2298 & 1.1834 & 0.0464 \\ 0.0000 & 0.0000 & 1.0000 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

L+M Channels



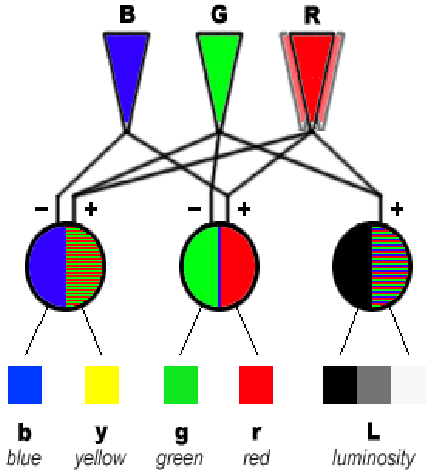
Opponent Processes

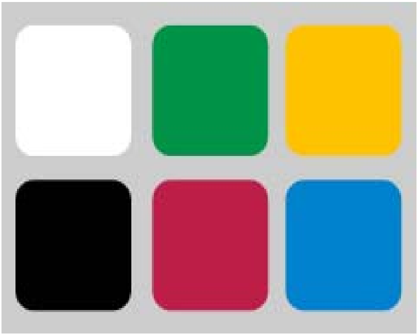
Opponent Colors

Questions on Trichromatic Theory

- What does bluish-yellow look like?
- What does greenish-red look like?
- Why do colorblind people either lose red-green or yellow-blue colors in pairs?
- Red, green and blue appear to be pure colors (i.e. not a mixture of other colors). Why does yellow also appear as a pure color?

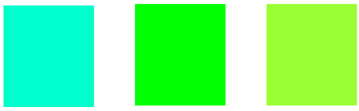
Opponent Process





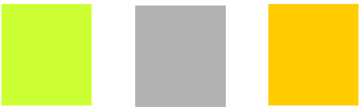
Opponent Process Test

How much yellow
is needed to cancel
blue tint?

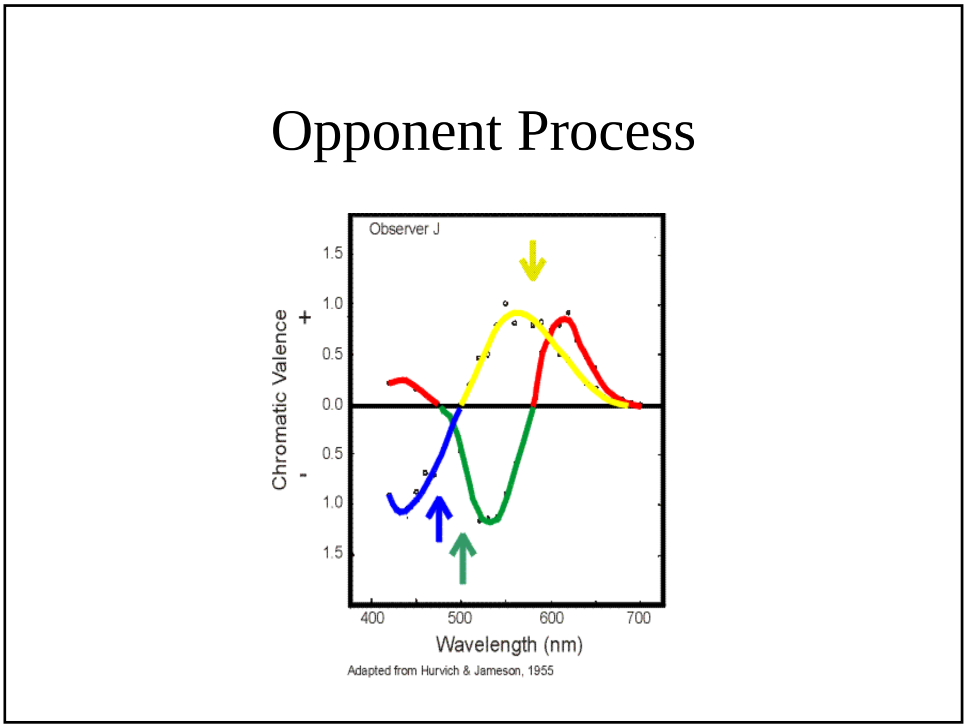


How much blue
is needed to cancel
yellow tint?

How much red
is needed to cancel
green tint?



How much green
is needed to cancel
red tint?



Opponent Process

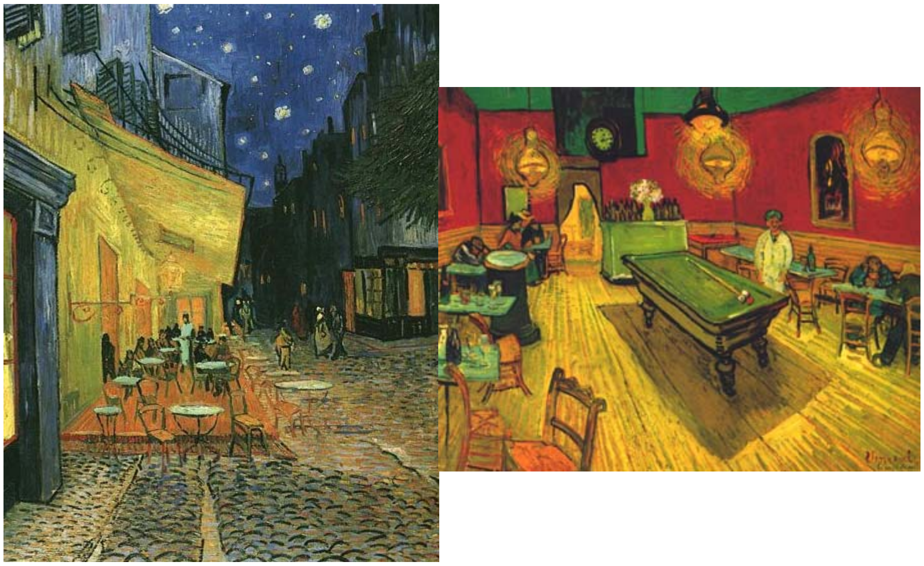
Adapted from Hurvich & Jameson, 1955

Opponent Process

Complements reside across the wheel from one another.

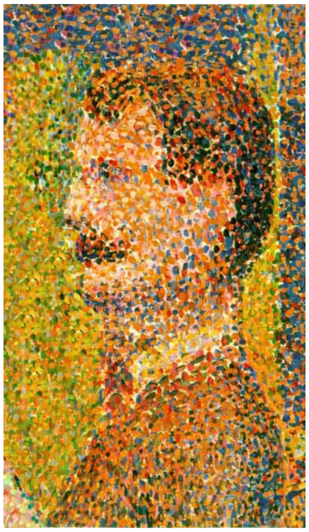
example

Opponent Process

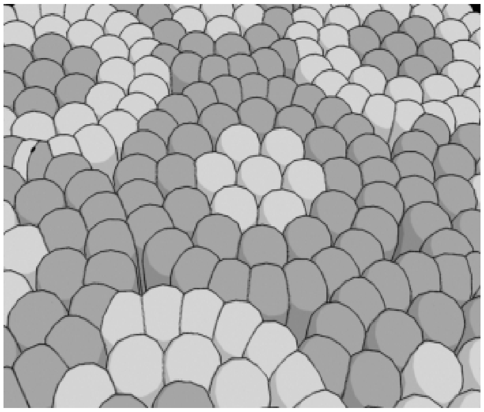


Opponent Colors

Georges Seurat

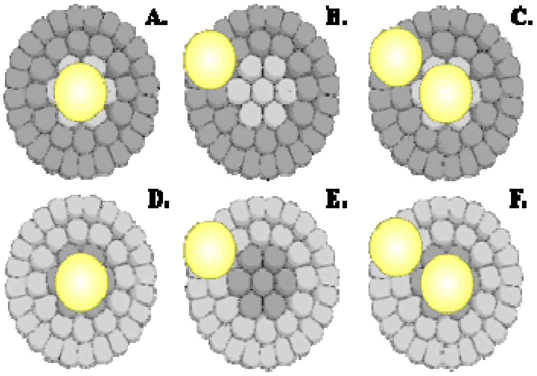


Receptive Fields



The lighter photoreceptors are the ones that activate in response to light while the others are the photoreceptors that activate in the absence of light. As you can see, some of the dark photoreceptors encircle the lighter ones and vice versa. In reality, however, these two types of photoreceptors look the same.

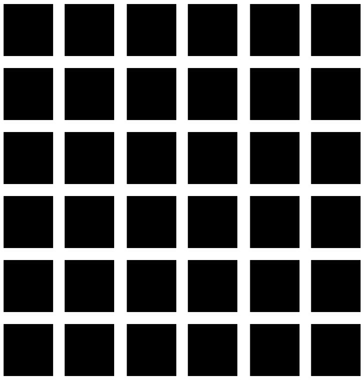
Receptive Fields



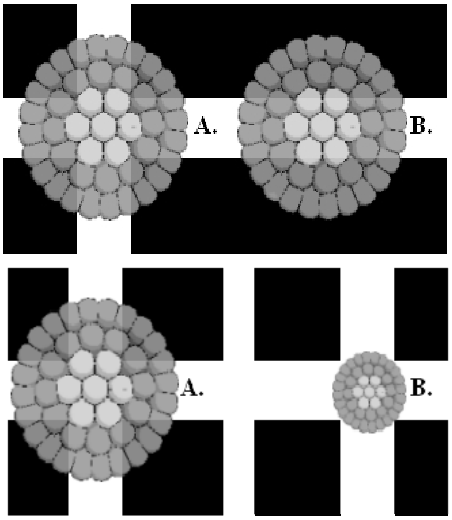
Center-ON

Center-OFF

Hermann’s Grid

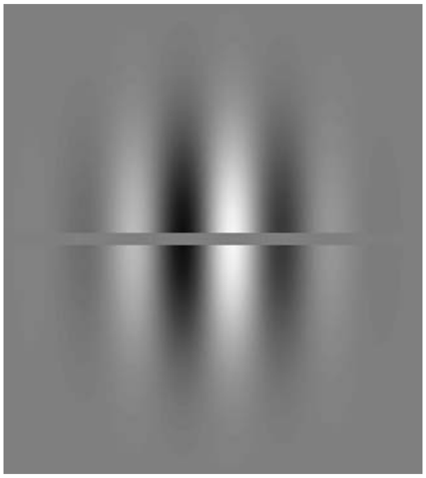


Hermann's Grid

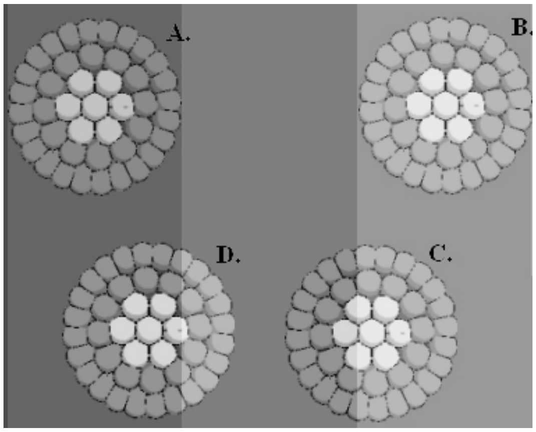


Mach Bands

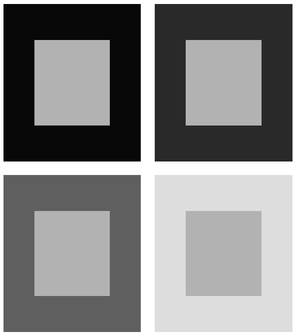
Mach Bands



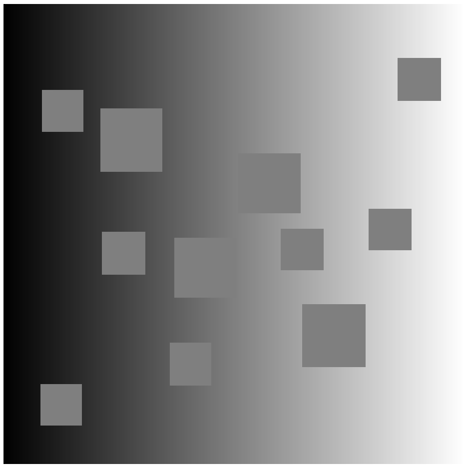
Mach Bands



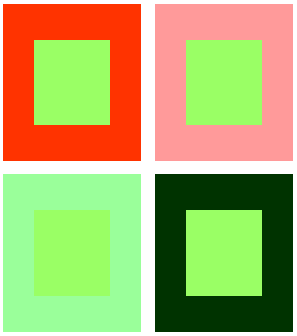
Lightness Contrast



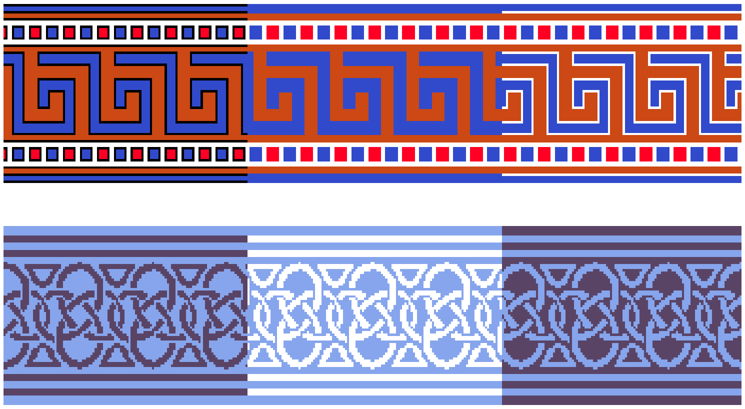
Lightness Contrast



Color Contrast



Complex Color Shifts



Rubik’s Cube??

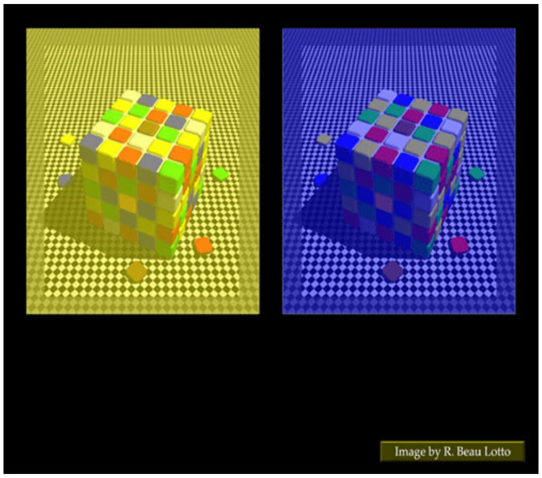


Image by R. Beau Lotto

Rubic’s Cube

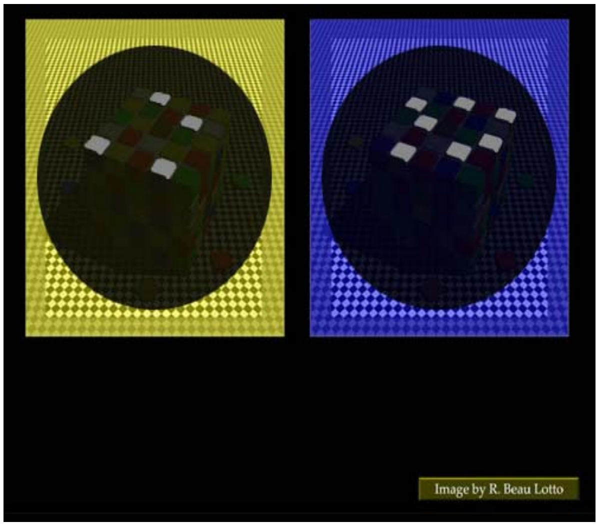


Image by R. Beau Lotto

Blue Dot

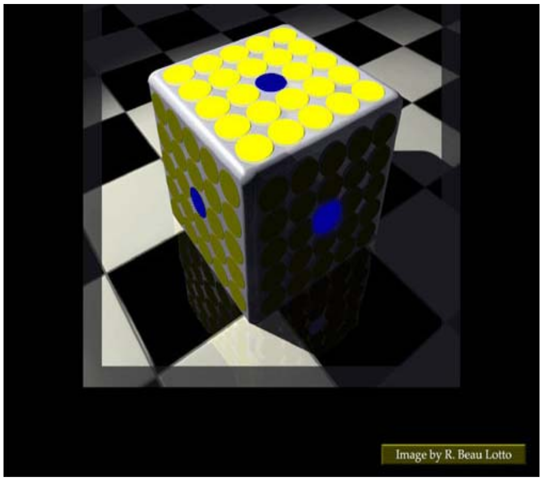


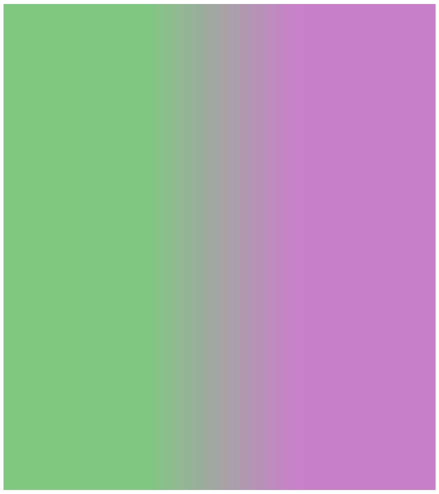
Image by R. Beau Lotto

Blue Dot

brightness contrast illusion

Image by R. Beau Lotto

Color Mach Bands



Form Perception

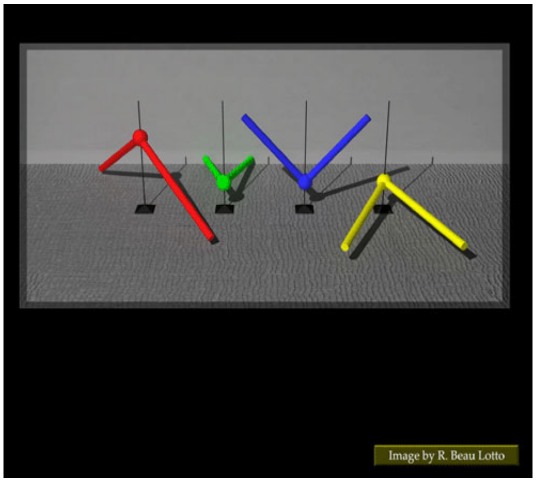


Image by R. Beau Lotto

Form Perception