Principles

Psychophysics is part psycho and part physics.

Theory: linear systems.

Methodology: matching.

Computation: linear summation, static nonlinearity, adaptation.

Principle of univariance.

Parallel pathways.

Perceptual constancy (lightness, color, size, etc.), adaptation, and visual illusions (e.g., aftereffects).

Color Outline

Wavelength encoding (trichromacy)

Three cone types with different spectral sensitivities. Each cone outputs only a single number that depends on how many photons were absorbed. If two physically different lights evoke the same responses in the 3 cones then the two lights will look the same (metamers). Explains when two lights will look the same, not what they will look like.

Color appearance

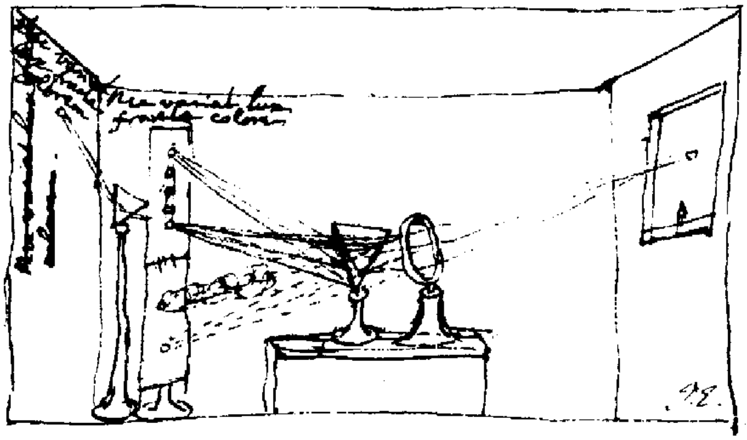
Color opponency: appearance depends on the differences between cone responses (R-G and B-Y).

Chromatic adaptation: color appearance also depends on context because the each cone adapts (like light and dark adaptation) to the ambient illumination.

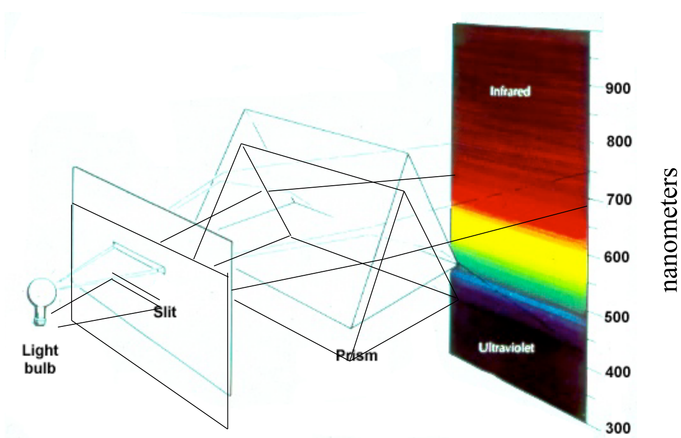
Color constancy: visual system infers surface color, despite changes in illumination.

Trichromacy and the color matching experiment

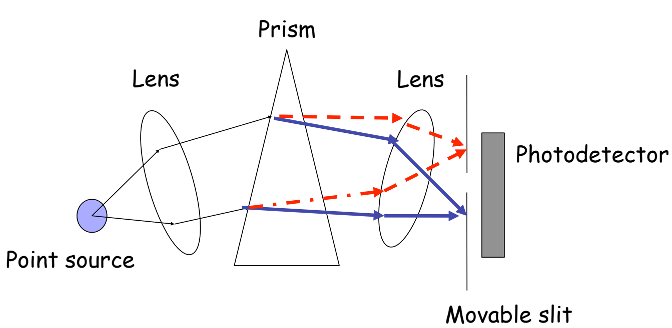
Wavelength and light



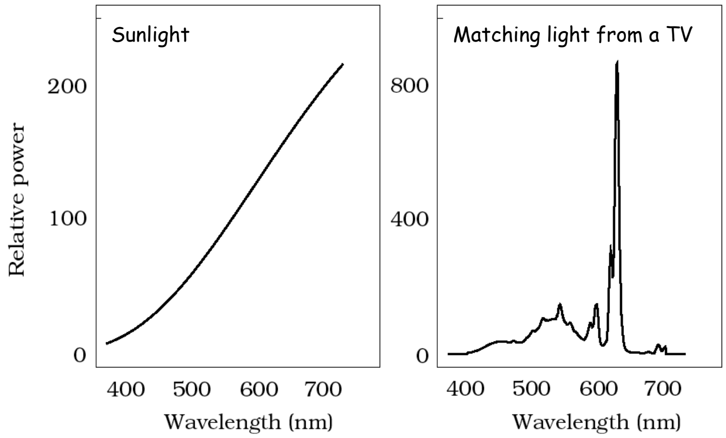
Electromagnetic spectrum



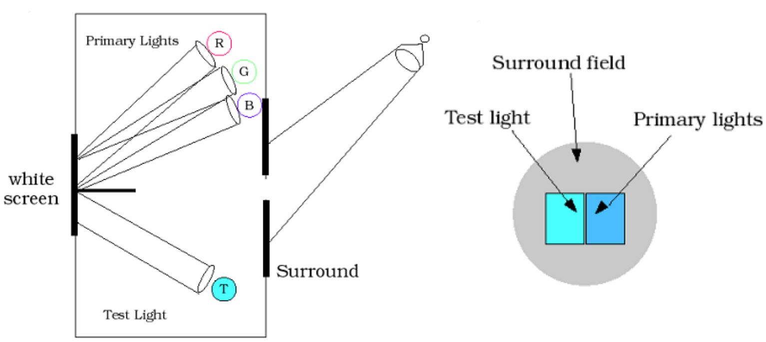
Spectro-radiometer



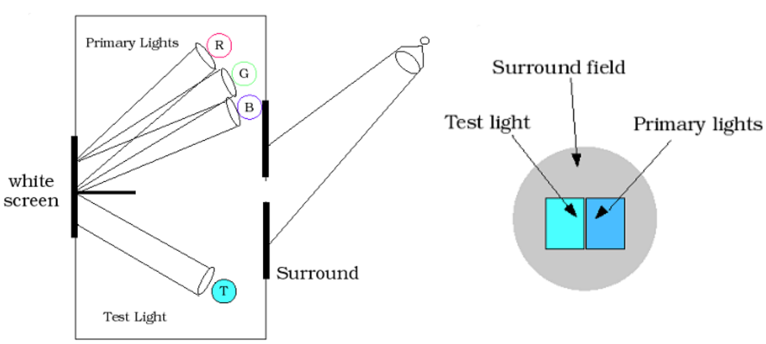
Spectral power distributions



Color matching experiment



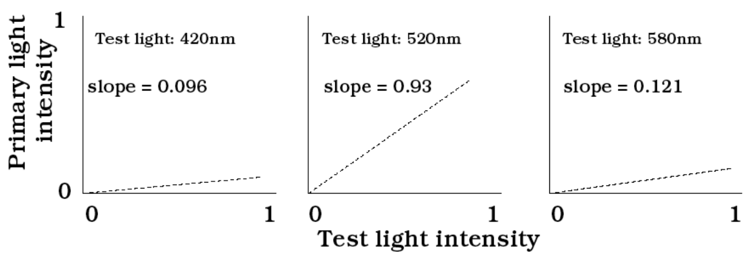
Color matching experiment



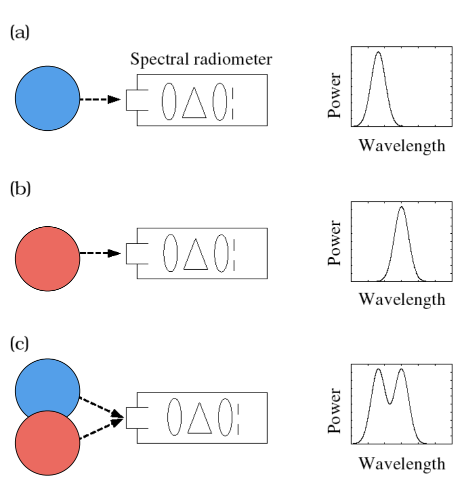
1. Lights that are physically different can look the same (metamers).
2. Three primaries are enough to match any test light.
3. People behave like linear systems in the color matching experiment.

Linear systems

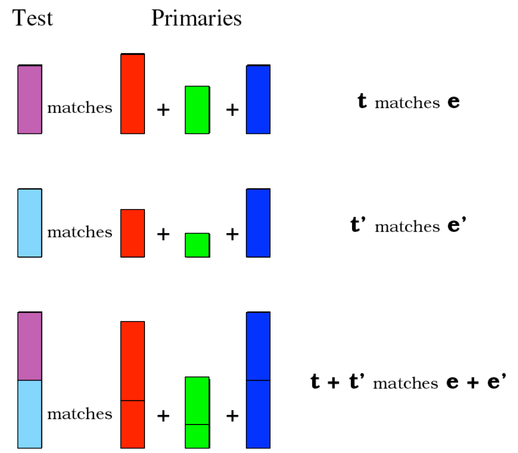
Color matching: scaling



Superposition of light: SPDs add



Color matching: additivity



Color matching as matrix multiplication

$$\underbrace{\begin{pmatrix} R \\ G \\ B \end{pmatrix}}_{\text{Color match settings}} = \underbrace{\begin{pmatrix} r(\lambda_1) & r(\lambda_2) & \dots & r(\lambda_N) \\ g(\lambda_1) & g(\lambda_2) & \cdots & g(\lambda_N) \\ b(\lambda_1) & b(\lambda_2) & \cdots & b(\lambda_N) \end{pmatrix}}_{\text{Color matching functions}} \underbrace{\begin{pmatrix} t(\lambda_1) \\ t(\lambda_2) \\ . \\ . \\ . \\ t(\lambda_N) \end{pmatrix}}_{\text{SPD of test light}}$$

Intensities of the three primary lights

wavelengths: $\lambda_1 = 400, \lambda_2 = 401, \dots$

Color matching: scaling

Scaling the input by α scales the output by α:

$$\underbrace{\begin{pmatrix} \alpha R \\ \alpha G \\ \alpha B \end{pmatrix}}_{\text{Color match settings}} = \underbrace{\begin{pmatrix} r(\lambda_1) & r(\lambda_2) & \dots & r(\lambda_N) \\ g(\lambda_1) & g(\lambda_2) & \cdots & g(\lambda_N) \\ b(\lambda_1) & b(\lambda_2) & \cdots & b(\lambda_N) \end{pmatrix}}_{\text{Color matching functions}} \underbrace{\begin{pmatrix} \alpha t(\lambda_1) \\ \alpha t(\lambda_2) \\ . \\ . \\ . \\ \alpha t(\lambda_N) \end{pmatrix}}_{\text{SPD of test light}}$$

Color matching: additivity

Adding two inputs gives the sum of the two outputs:

$$\begin{pmatrix} R_1 \\ G_1 \\ B_1 \end{pmatrix} = \begin{pmatrix} r(\lambda) \\ g(\lambda) \\ b(\lambda) \end{pmatrix} \begin{pmatrix} t_1(\lambda) \end{pmatrix} \qquad \begin{pmatrix} R_2 \\ G_2 \\ B_2 \end{pmatrix} = \begin{pmatrix} r(\lambda) \\ g(\lambda) \\ b(\lambda) \end{pmatrix} \begin{pmatrix} t_2(\lambda) \end{pmatrix}$$

$$\begin{pmatrix} R_1 + R_2 \\ G_1 + G_2 \\ B_1 + B_2 \end{pmatrix} = \begin{pmatrix} r(\lambda) \\ g(\lambda) \\ b(\lambda) \end{pmatrix} \begin{pmatrix} t_1(\lambda) + t_2(\lambda) \end{pmatrix}$$

Measuring the color matching functions

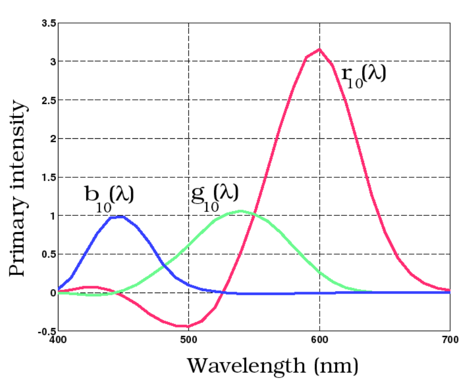
Color match settings = Color matching functions × SPD of test light

$$\begin{pmatrix} r(\lambda_1) \\ g(\lambda_1) \\ b(\lambda_1) \end{pmatrix} = \begin{pmatrix} r(\lambda_1) & r(\lambda_2) & \cdots & r(\lambda_N) \\ g(\lambda_1) & g(\lambda_2) & \cdots & g(\lambda_N) \\ b(\lambda_1) & b(\lambda_2) & \cdots & b(\lambda_N) \end{pmatrix} \begin{pmatrix} 1 \\ 0 \\ \cdot \\ \cdot \\ \cdot \\ 0 \end{pmatrix}$$

monochromatic test light

Repeat with monochromatic test lights of each wavelength, always using the same 3 primary lights.

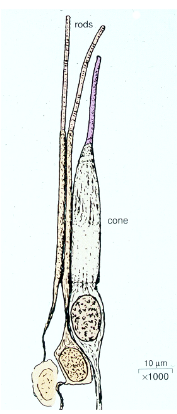
Standardized color matching functions

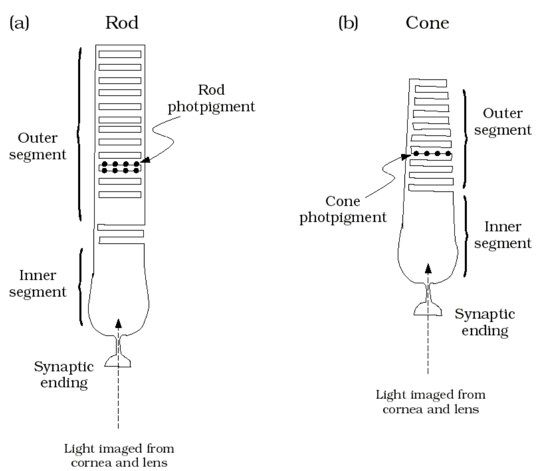


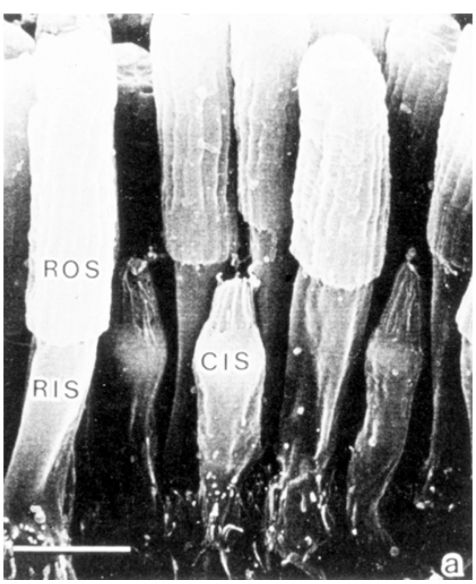
Commission Internationale d'Eclairage (CIE) standard set in 1931 using 3 monochromatic primaries at wavelengths of 435nm, 546nm, and 700nm.

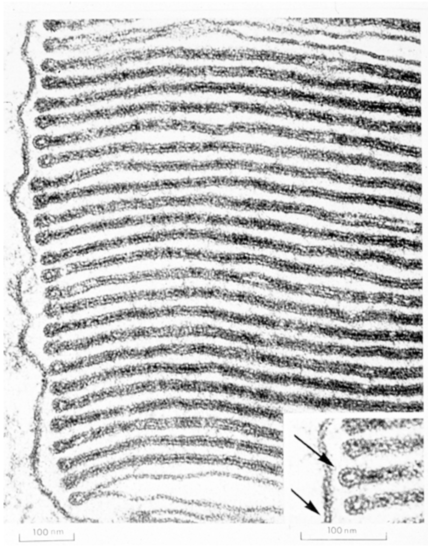
Physiology of color matching

Photoreceptors: rods and cones

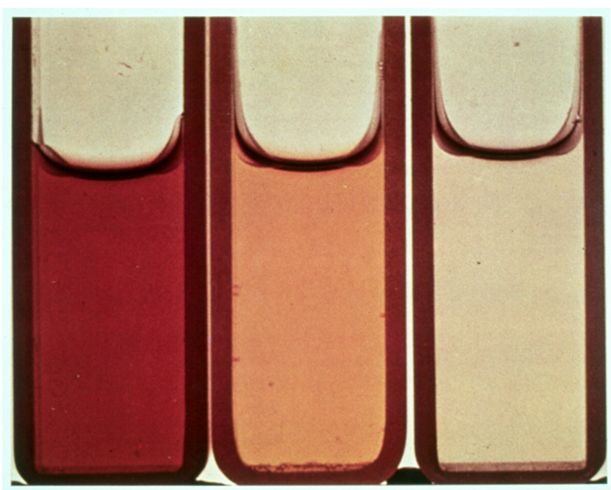








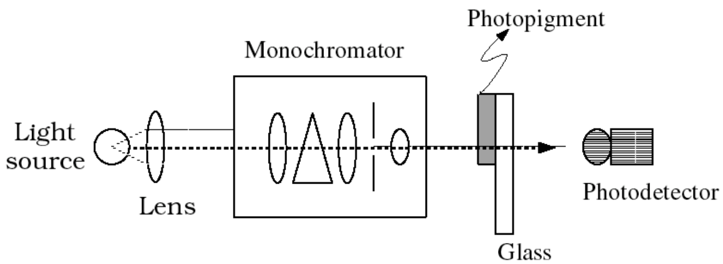
Rhodopsin



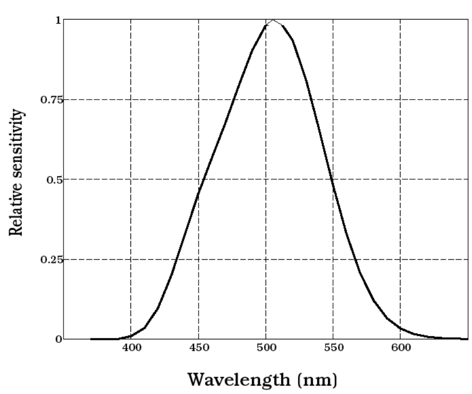
In the dark

Bleached by light

Measuring rod spectral sensitivity
(wavelength-dependence of rhodopsin absorption)



Rod spectral sensitivity



Let's say you have a 500nm light with intensity 10. Can you match it's appearance with a 550nm light? If so, what will be the intensity of the matching light?

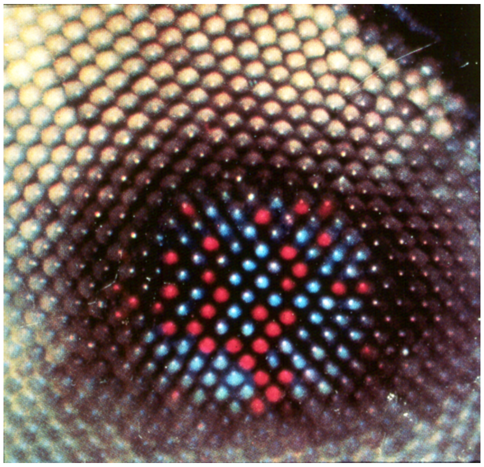
The principle of univariance

The response of a photoreceptor is a function of just one variable (namely, the number of photons absorbed).

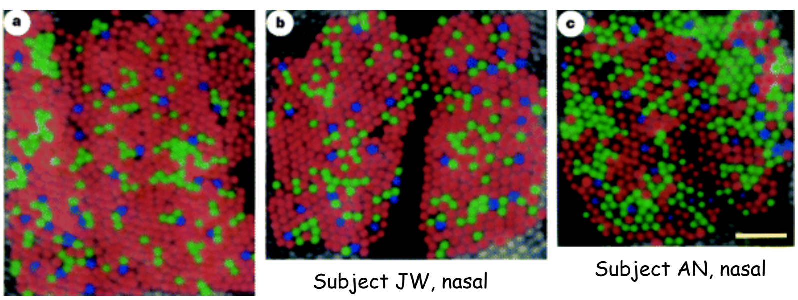
Thus, the response can be identical for:

- a weak light at the wavelength of peak sensitivity
  (few incident photons, a large fraction of them absorbed)
- a strong light at a wavelength of lower sensitivity
  (many incident photons, a small fraction of them absorbed)

Butterfly eye



Human cone mosaic



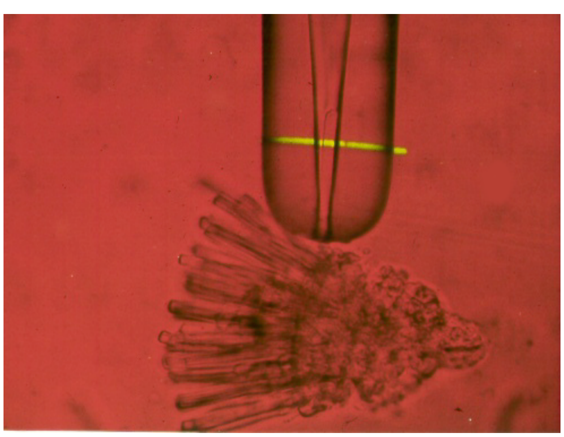
Subject JW, temporal

Subject JW, nasal

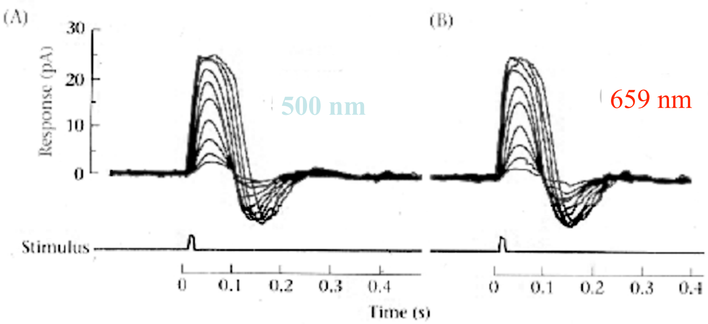
Subject AN, nasal

one degree eccentricity

Measuring cone photocurrents

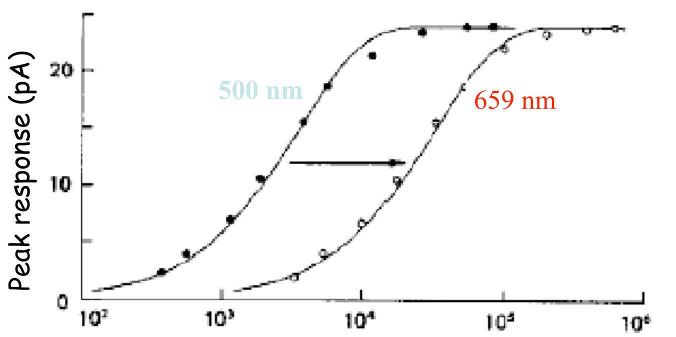


Cone photocurrent

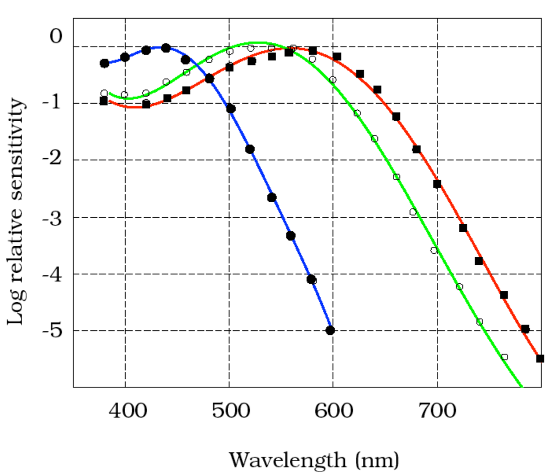


Cone responses are nonlinear

(but can be equated by scaling intensity)



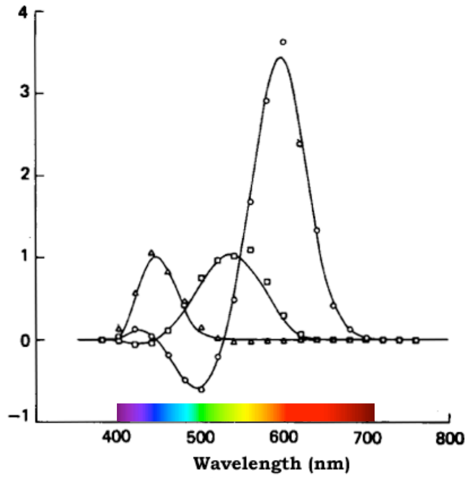
Cone spectral sensitivities



Cone responsivities

(and optical filters)

predict color matching functions



Trichromacy equations

Wavelength encoding equation

Input SPD

Response

Cone responsivity

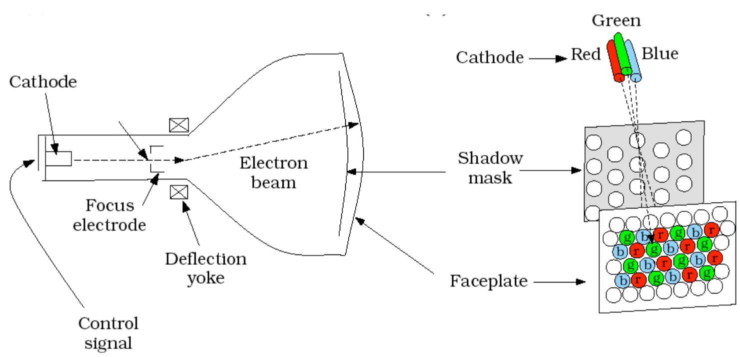
$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} \cdots & l(\lambda) & \cdots \\ \cdots & m(\lambda) & \cdots \\ \cdots & s(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} t_1 \\ \vdots \\ t_n \end{pmatrix}$$

Metamers revisited

$$\begin{pmatrix} L \\ M \\ S \end{pmatrix} = \begin{pmatrix} \cdots & l(\lambda) & \cdots \\ \cdots & m(\lambda) & \cdots \\ \cdots & s(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} t_1 \\ \vdots \\ t_n \end{pmatrix} = \begin{pmatrix} \cdots & l(\lambda) & \cdots \\ \cdots & m(\lambda) & \cdots \\ \cdots & s(\lambda) & \cdots \end{pmatrix} \begin{pmatrix} s_1 \\ \vdots \\ s_n \end{pmatrix}$$

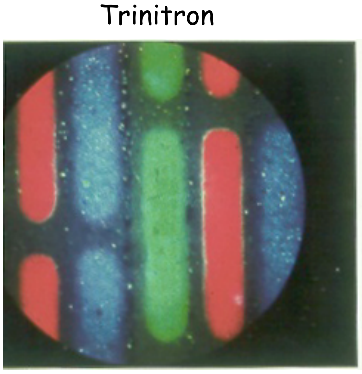
SPDs of two lights

Displays and color matching

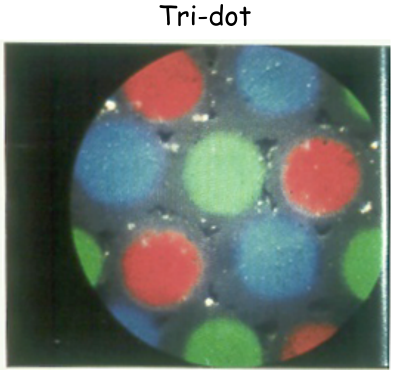


Application: Color TV

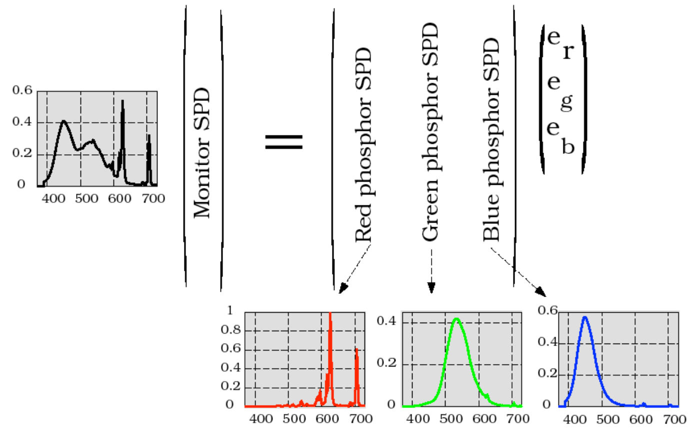
Trinitron



Tri-dot

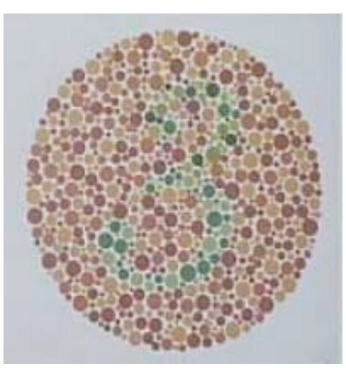


Color display equation

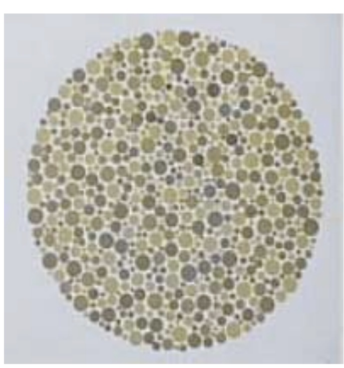


Color blindness

Color blindness

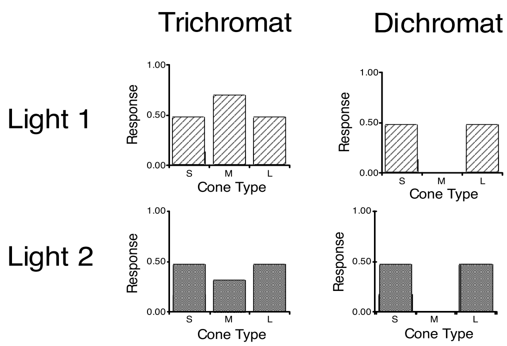


Ishihara plate



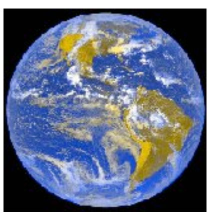
What a red/green color-blind person might see

Color blindness and color matching



Color blindness

normal



red/green color blind

blue-yellow color blind

- Dichromats: missing one of the three photopigment/cone types.
- Can match with 2 primaries in the color matching experiment
- Will accept trichromat's match but trichromat will not always accept dichromats match.

Color blindness

normal

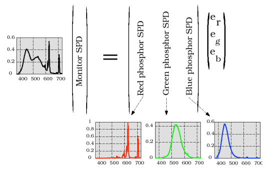
red/green color blind

blue/yellow color blind

People with color deficiencies may have difficulty distinguishing certain colors (e.g., a red/green color deficiency means that reds and greens are more difficult to distinguish). But as this photo demonstrates, many other colors are just as distinguishable to a person with a color deficiency as to someone with normal color vision.

Color matching and trichromacy cavaets

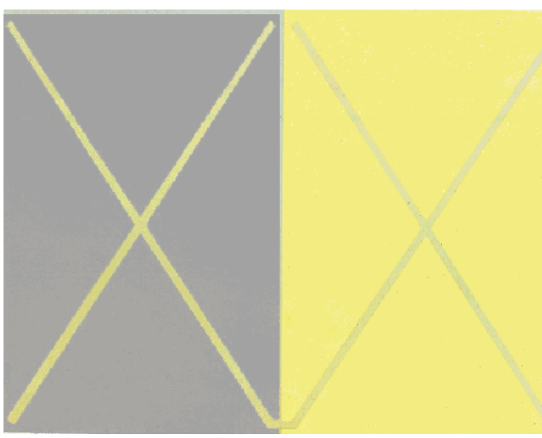
1. The 3 primary lights must be linearly independent:



2. For any set of primaries, there are test lights that are out of range such that the primary intensities must be higher than achievable or "negative" (which is physically impossible).
3. Trichromacy determines when two lights look the same, not what they look like.
4. Additive vs "subtractive" color mixtures.

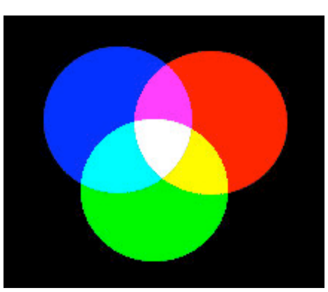
Simultaneous color contrast

(identical lights look different in a different context)



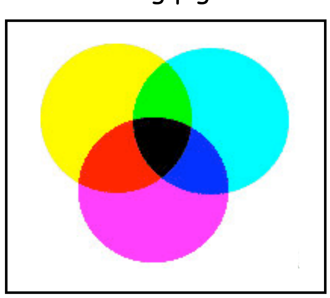
RGB

red, green, blue--
used in TVs
Additive mixing of light sources



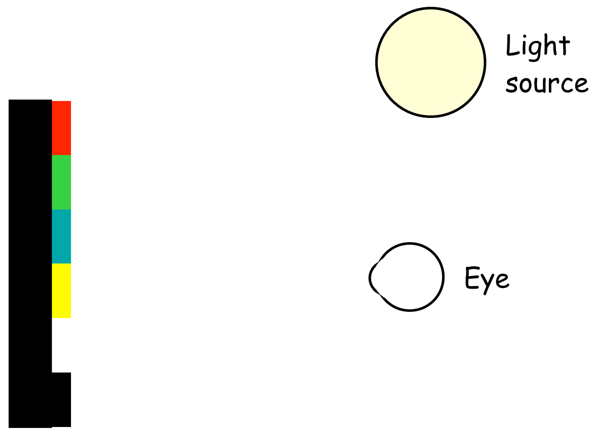
CMYK

cyan, magenta, yellow, black–
used in printing
Subtractive mixing of absorbing pigments

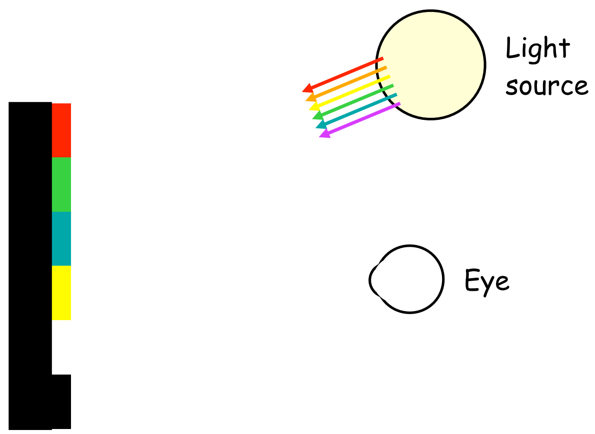


http://www.bbso.njit.edu/Documentations/gimpdoc-html/color.html

"Subtractive" color mixture:
surface reflectance



"Subtractive" color mixture:
surface reflectance



"Subtractive" color mixture:
surface reflectance