Color perception

SINA – 08/09

- Color adds another dimension to visual perception
- Enhances our visual experience
- Increase contrast between objects of similar lightness
- Helps recognizing objects

- However, it is clear that color is not essential for visual perception (b/w TV, photography)
- It is a pure psychological phenomenon

Light rays are NOT colored: they are radiations of electromagnetic energy of different wavelengths, what we call color is a product of our visual system

What is color?

- Color is a property of an object
- The wavelength composition of the light reflected from the object is determined not only by its reflectance, but also by the wavelength composition of the light illuminating it
- Color vision compensates for the variation of the composition of the light so that objects appear the same under different conditions (*color constancy*)
- The brain somehow is able to analyze the object in relation to its background
- Color vision is not a simple measure of wavelength, but a sophisticated abstracting process

- Light is absorbed by the photopigment of the cones
- It is convenient to speak in terms of # of photons absorbed, and their energy

$$E = h\upsilon = ch/\lambda$$

h is the Planck's constant

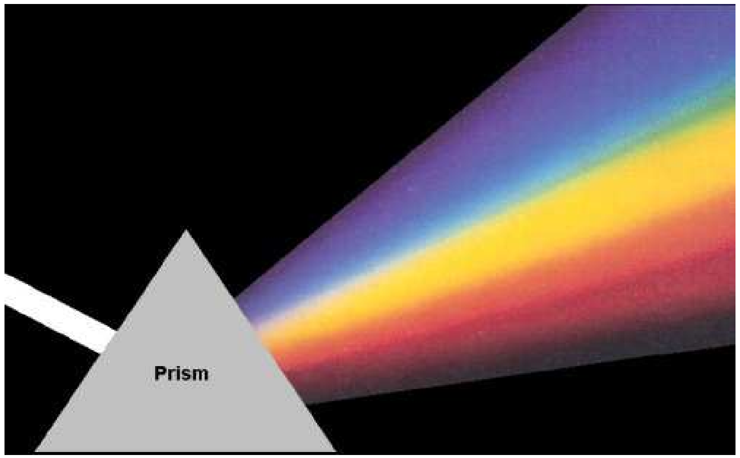
c speed of the wave

v frequency

λ wavelength

- Irradiance: incident power (amount of energy per unit time) of electromagnetic radiation per unit area, when the radiation is perpendicular to the surface [W/m^{-2}]

- Monochromatic light: all photons have the same energy
- Natural lights are *broad band*: they contain significant amount of a large portion of the electromagnetic spectrum
- The light of the sun contains almost an equal amount of all wavelengths (*white light)*
- Newton’s prism decomposition



How do we characterize light?

- Spectrum: how much energy there is at each wavelength in a given light (or spectral irradiance, $Wm^{-2}m^{-1}$)

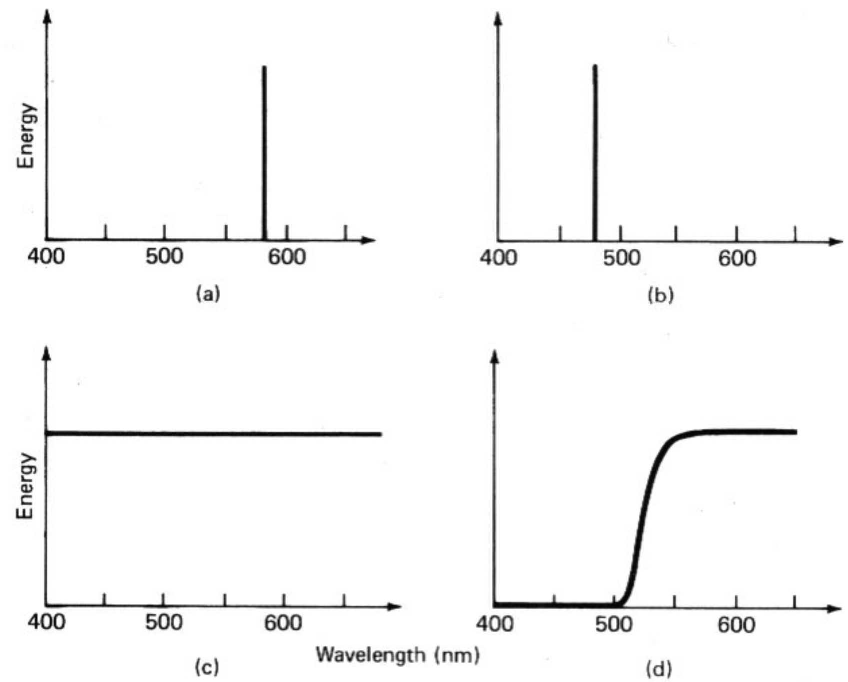


Fig. 14.1 Spectra of various lights. (a) Monochromatic yellow light, wavelength = 580 nm. (b) Monochromatic blue light, wavelength = 480 nm. (c) Equal energy white light. (d) Yellow light such as you might obtain by passing sunlight through yellow cellophane.

Color can be described as:

Hue: the color itself, wavelength, we can discriminate about 200 different hues

Saturation: richness of hue, how much the color is “pure” (absence of white), we can discriminate about 20 steps of saturation at the borders of the spectrum, only 5 in the middle

Brightness: amount of energy (orange-brown, gray-white), about 500 levels of brightness

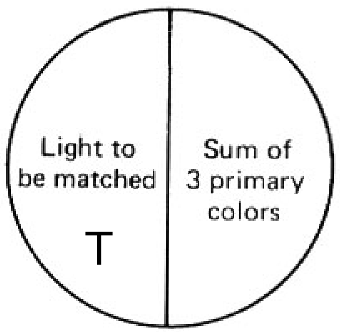
Psychophysics of color

- Human perception of color is complex function of context: illumination, memory, object identity…
- The simplest question is to understand which spectral radiances produce the same response
- For example consider the following task

- Two colors are in view on a black background
- Display with two halves: on the left there is the color to be matched (*test color*), on the right the sum of the three primary colors (*primaries*) to be used to make the match:

$$T = w_1 P_1 + w_2 P_2 + \ldots$$

- The match is purely subjective, as the two halves just looks alike, but are physically different (metameric match)



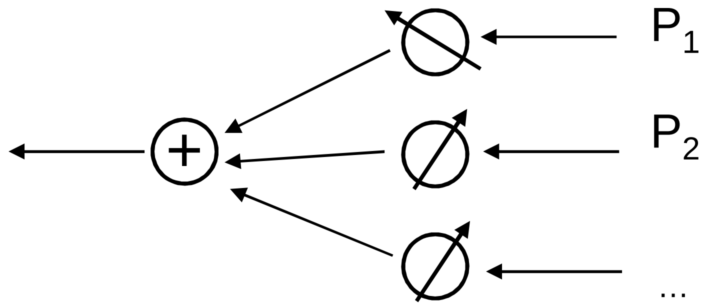
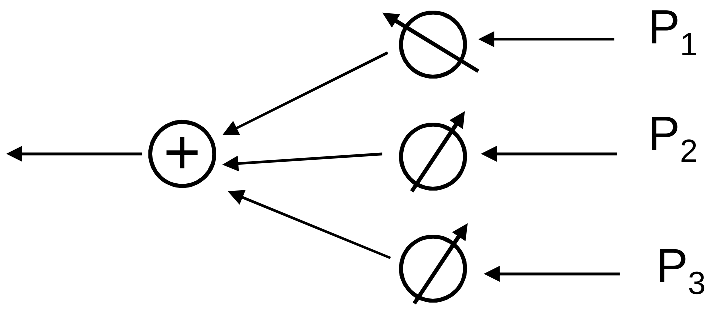


Fig. 14.5 Stimulus display for metameric matching.

Trichromacy

- Experimentally it can be shown that for most subjects **any colored light can be matched by a combination of three primary lights**
- This happens if the following conditions are met:
  - subtractive matching must be allowed
  - primaries must be independent (no mixture of two primaries may match a third)
- With good accuracy, under these conditions matching is linear (Grassman's law)



$$T = w_1 P_1 + w_2 P_2 + w_3 P_3$$

Grassman's laws

- If we mix two test lights, then mixing the matches will match the result:

$$T_a = w_{a1}P_1 + w_{a2}P_2 + w_{a3}P_3, T_b = w_{b1}P_1 + w_{b2}P_2 + w_{b3}P_3$$

$$T_a + T_b = \left(w_{b1} + w_{a1}\right)P_1 + \ldots$$

= here means "match"

- If two test lights can be matched with the same set of weights they will match each other:

$$T_a = w_1P_1 + w_2P_2 + w_3P_3, T_b = w_1P_1 + w_2P_2 + w_3P_3 \Rightarrow T_a = T_b$$

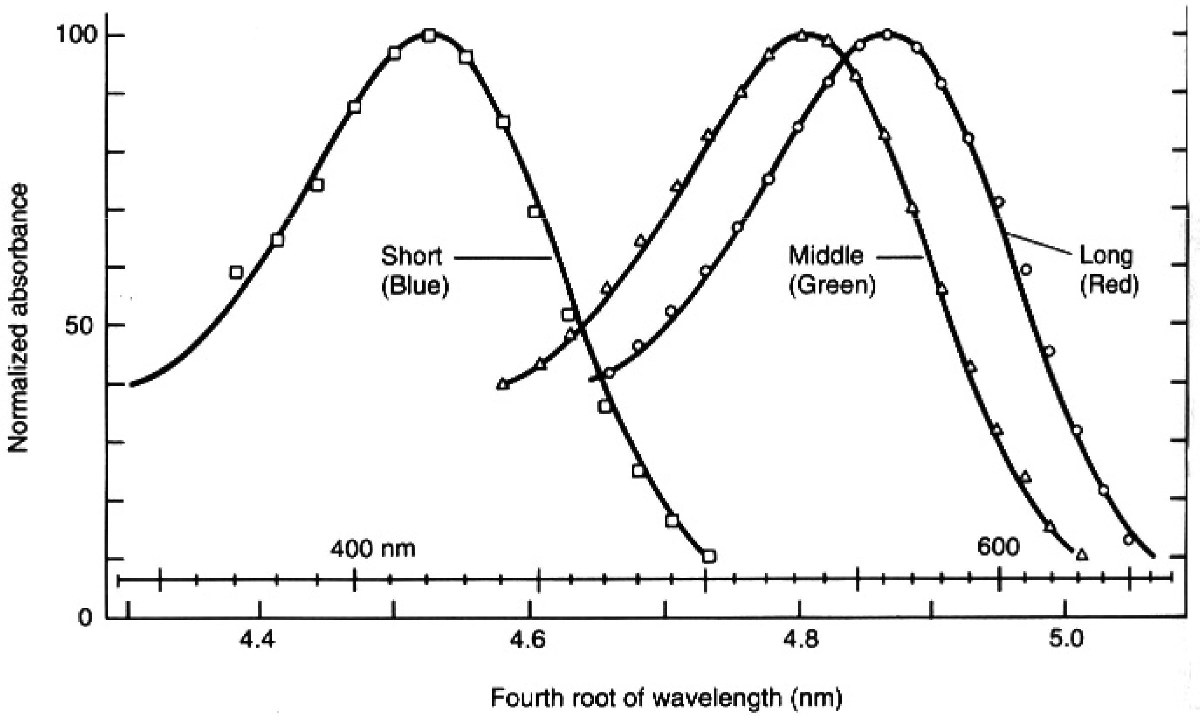
- Matching is linear:

$$T_a = w_1P_1 + w_2P_2 + w_3P_3$$

$$kT_a = \left(kw_1\right)P_1 + \left(kw_2\right)P_2 + \left(kw_3\right)P_3, k \geq 0$$

Why three colors?

- Three different cone types in the retina
- Each type contains only one of three pigments



- S cones tuned to *short* wavelengths stronger contribution to the perception of **blue**
- M cones tuned to *middle* wavelengths, stronger contribution to the perception of **green**
- L cones tuned to *long* wavelengths, stronger contribution to the perception of **red**

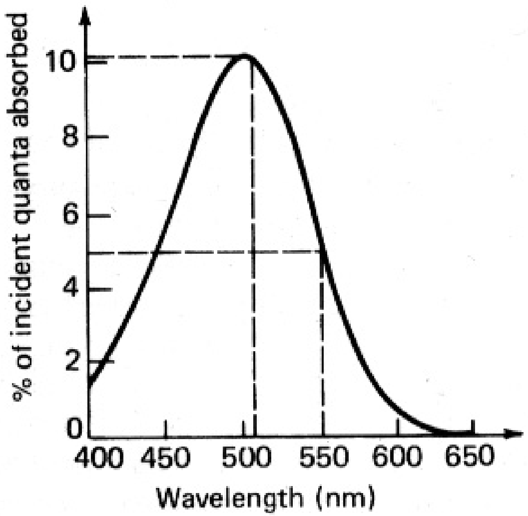
Principle of Univariance

- Photoreceptors respond weakly or strongly, but do not signal the wavelength of the light falling on them
- We can model the response of the k-th type receptor:

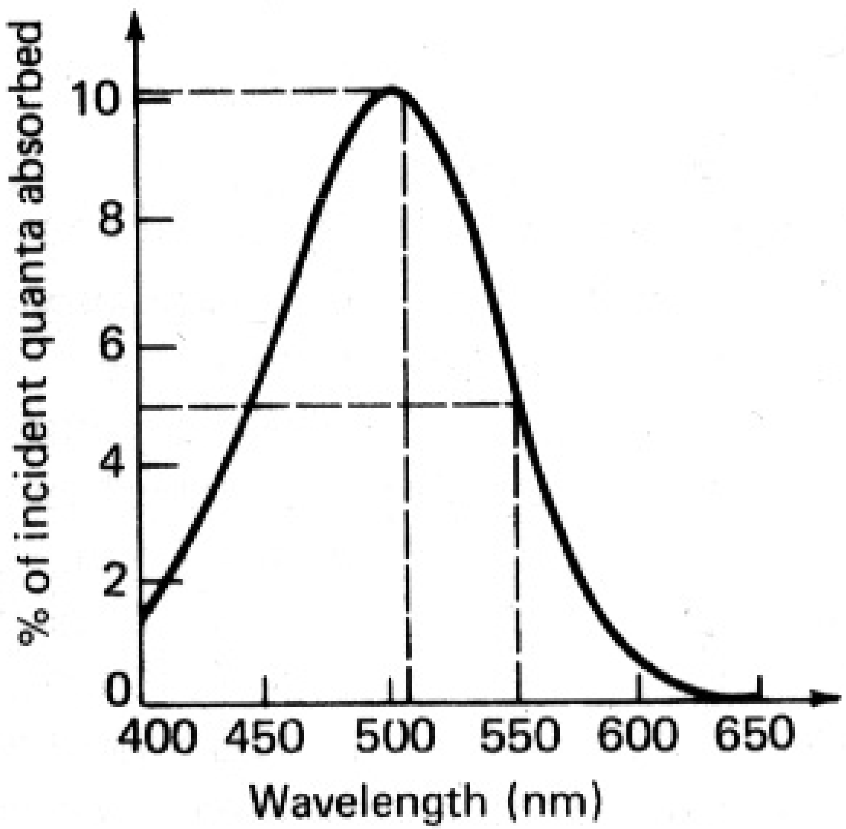
$$p_k = \int \sigma_k(\lambda) E(\lambda) d\lambda$$

$\sigma_k(\lambda)$ spectral sensitivity

$E(\lambda)$ light arriving at the receptor

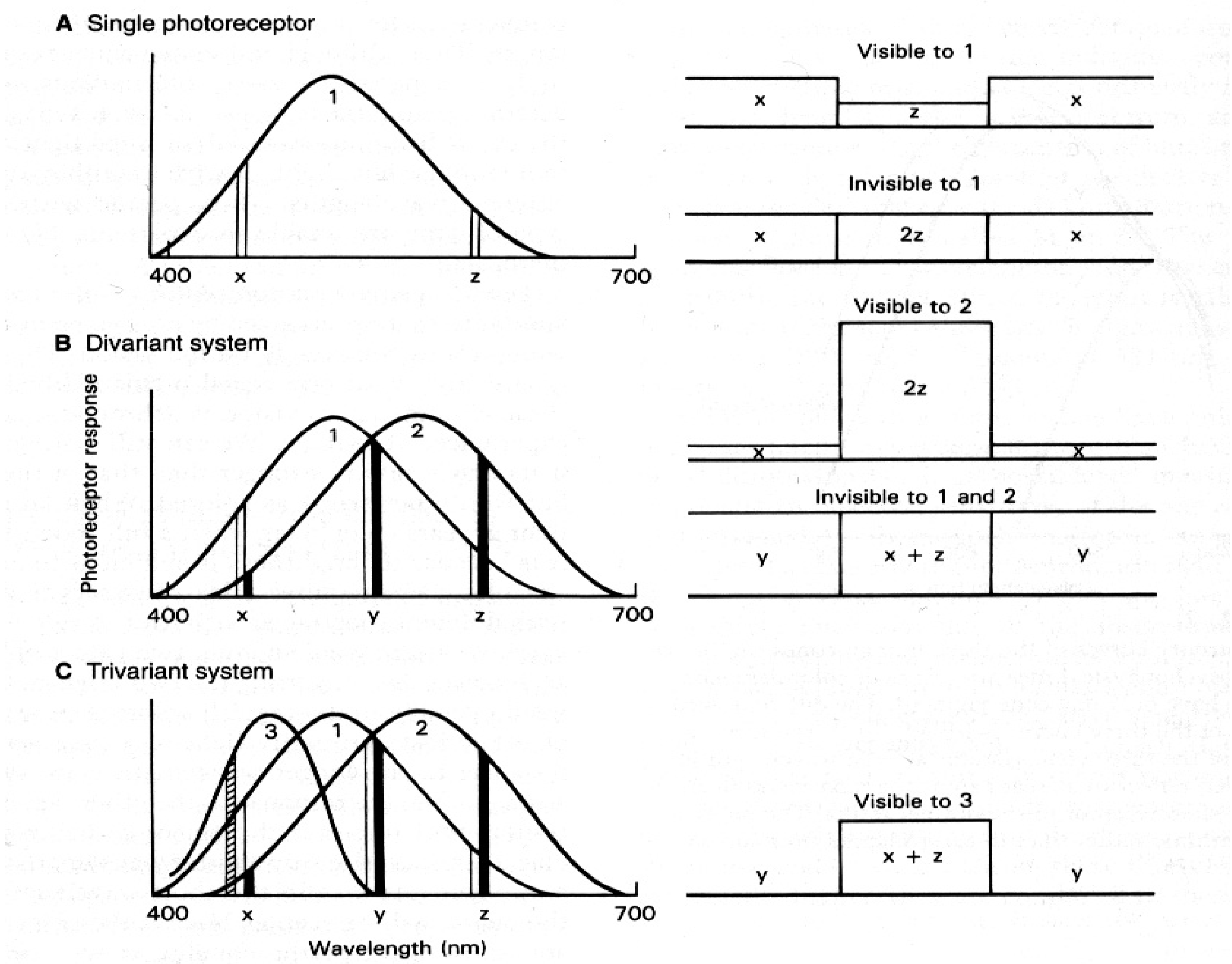


- the number of photons absorbed depends on the wavelength of the light
- .. but also on its intensity
- In a system with a single photoreceptor type, it is possible to vary the intensity of any primary color to match any colored light



a single photoreceptor system results in vision similar to that experienced in dim light, which relies on rod vision only

Monochromacy, dichromacy and thrichromacy



Representing Color

- Is it possible to describe colors in a objective way?
- Linear Color Spaces: a possibility is to agree on a set of primaries and then describe any colored light by the three values of weights people would use to match the light using those primaries

- Because color matching is linear, the combination of primaries is obtained by matching the primaries to each of the single wavelength sources and then adding up these weights:

$$S = a + b + c$$
$$a = w_{a1}P_1 + w_{a2}P_2 + w_{a3}P_3$$
$$b = w_{b1}P_1 + w_{b2}P_2 + w_{b3}P_3$$
$$c = w_{c1}P_1 + w_{c2}P_2 + w_{c3}P_3$$

$$S = a + b + c =$$
$$= \left(w_{a1} + w_{b1} + w_{c1}\right)P_1 +$$
$$+ \left(w_{a2} + w_{b2} + w_{c2}\right)P_2 +$$
$$+ \left(w_{a3} + w_{b3} + w_{c3}\right)P_3$$

- If we suppose that every source S can be obtained as a weighted sum of single wavelength sources:

$$S = \int S(\lambda)U(\lambda)d\lambda$$

- For each λ, we can store the weight of each primary required to match a single wavelength source (color matching functions):

$$U\left(\lambda\right) = f_1(\lambda)P_1 + f_2(\lambda)P_2 + f_3(\lambda)P_3$$

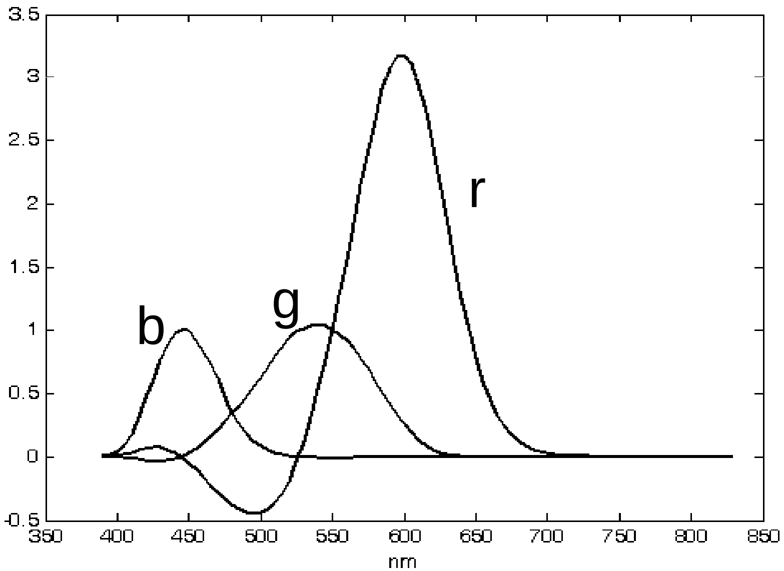
at each λ, f_1, f_2 and f_3 give the weights required to match U(λ)

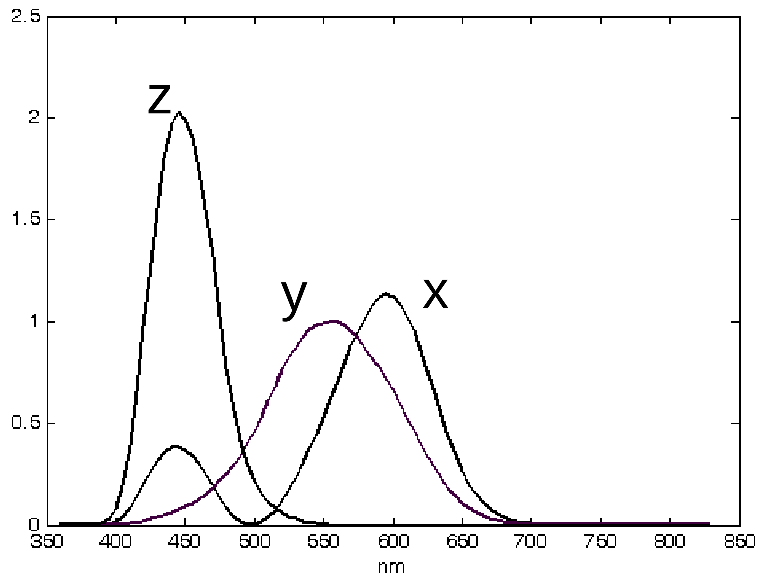
- We get:

$$S = \int S(\lambda)U(\lambda)d\lambda =$$

$$= \left\{\int f_1(\lambda)S(\lambda)d\lambda\right\}P_1 + \left\{\int f_2(\lambda)S(\lambda)d\lambda\right\}P_2 + \left\{\int f_3(\lambda)S(\lambda)d\lambda\right\}P_3$$

- If we use real lights as primaries, at least of the color matching functions will be negative for some wavelengths
- However, we can start by specifying positive color matching functions; in this case we obtain imaginary primaries
- Imaginary primaries cannot be used to create colors, but we are more interested in the resulting *weights* as a means to define/compare colors
- An example is the standard CIE XYZ color space





data from: www-cvrl.ucsd.edu/index.htm

The CIE XYZ color space

- Created in 1931 by the International Commission on Illumination
- Color matching functions were chosen to be positive everywhere
- Not possible to obtain X,Y,Z primaries, they are negative for some wavelengths, but useful to describe colors
- It is difficult to plot in 3-d, usually we suppress the brightness of a color, intersect the XYZ space with the plane X+Y+Z=1

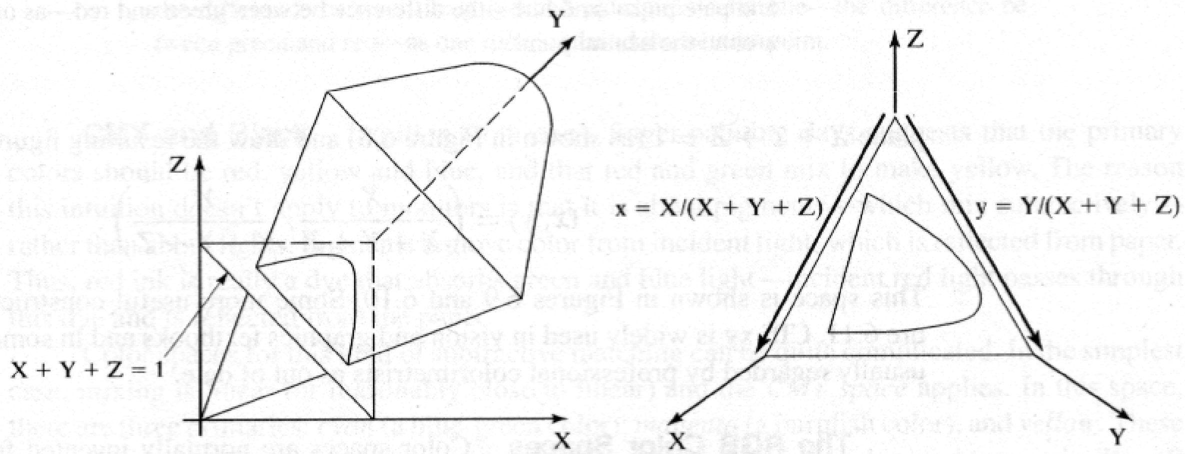


Figure 6.8 The volume of all visible colors in CIE XYZ coordinate space is a cone whose vertex is at the origin. Usually it is easier to suppress the brightness of a color, which we can do because to a good approximation perception of color is linear, and we do this by intersecting the cone with the plane $X + Y + Z = 1$ to get the CIE xy space shown in Figures 6.9 and 6.10

$$x = X/(X+Y+Z)$$
$$y = Y/(X+Y+Z)$$
$$z = Z/(X+Y+Z) = 1 - x - y$$

image from: Forsyth and Ponce

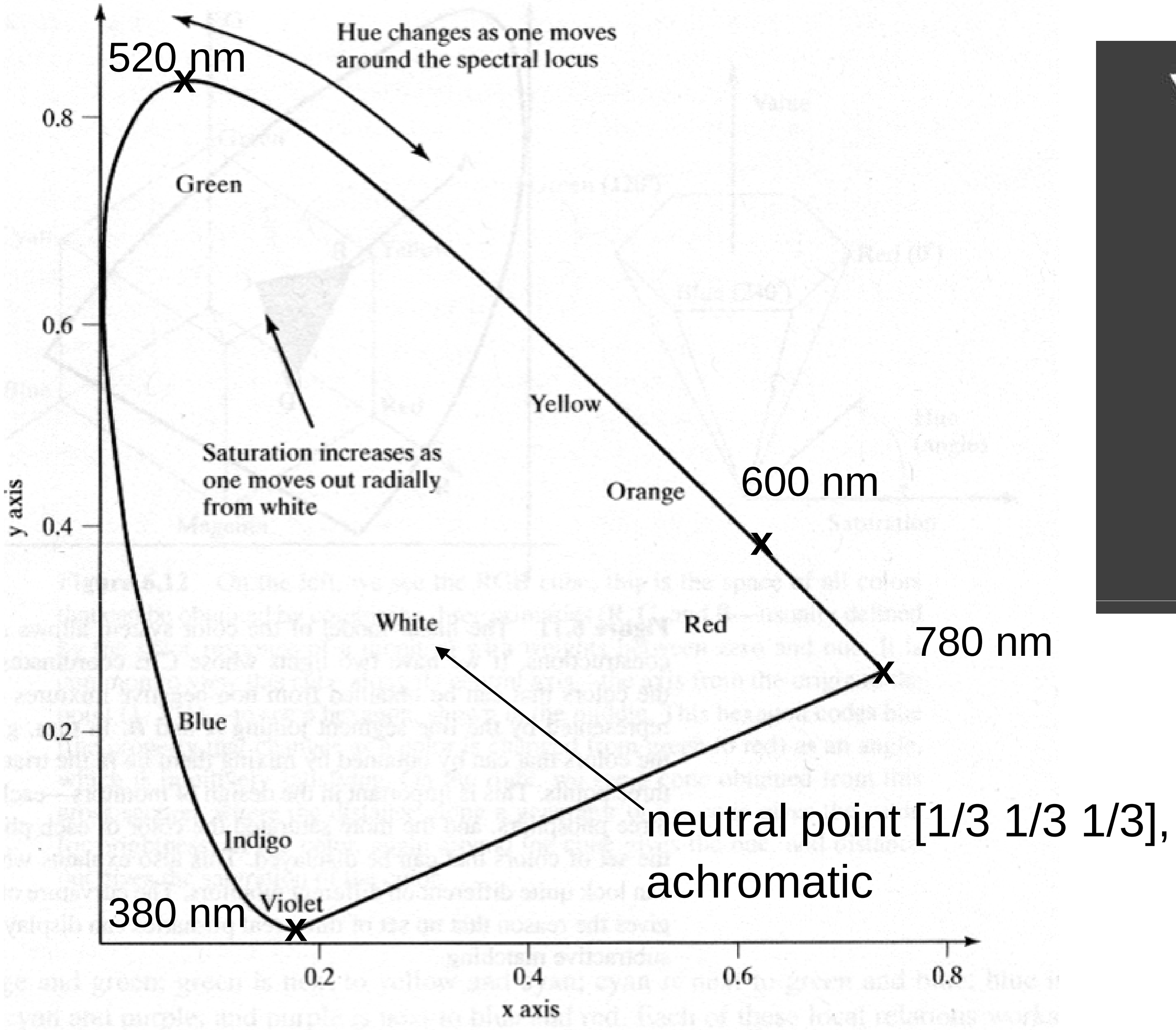


Figure 6.10 The figure shows a constant brightness section of the standard 1931 standard CIE xy color space, with color names marked on the diagram. Generally, colors that lie farther away from the neutral point are more saturated—the difference between deep red and pale pink—and hue—the difference between green and red—as one moves around the neutral point.

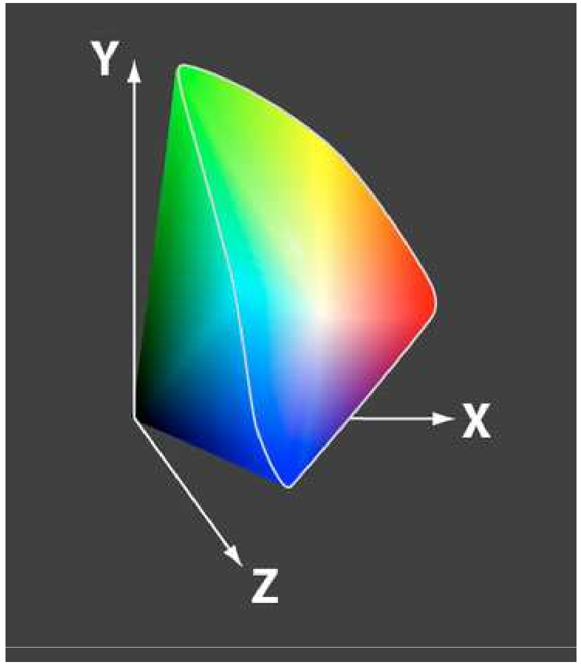
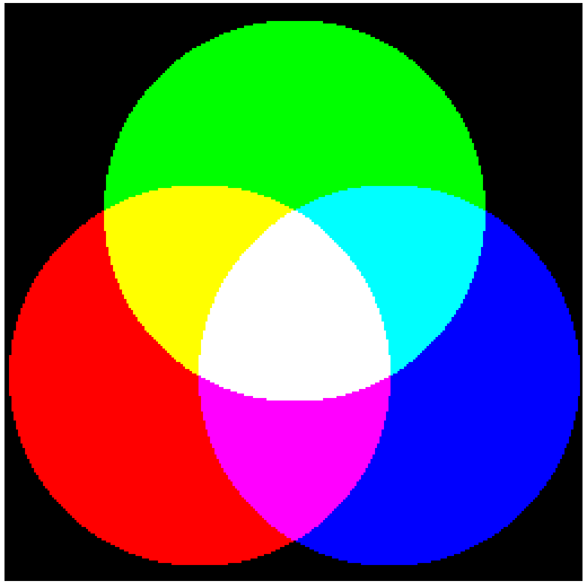


image from: Forsyth and Ponce

Other spaces: additive mixture

- Two or more lights are added to each other to make a new light
  - superimposition (e.g. TV projector)
  - proximity: if patches of different light are close together they fall into the same receptive field, and they are summed together (color TV/computer screen)
- Usually Red, Green and Blue are taken as primary colors of additive mixture (645.16nm, 526.32nm and 444.44 nm)



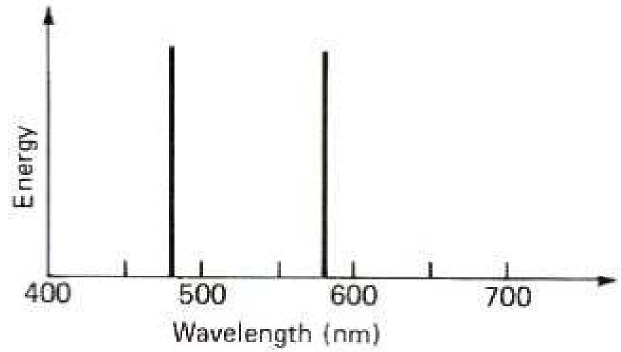
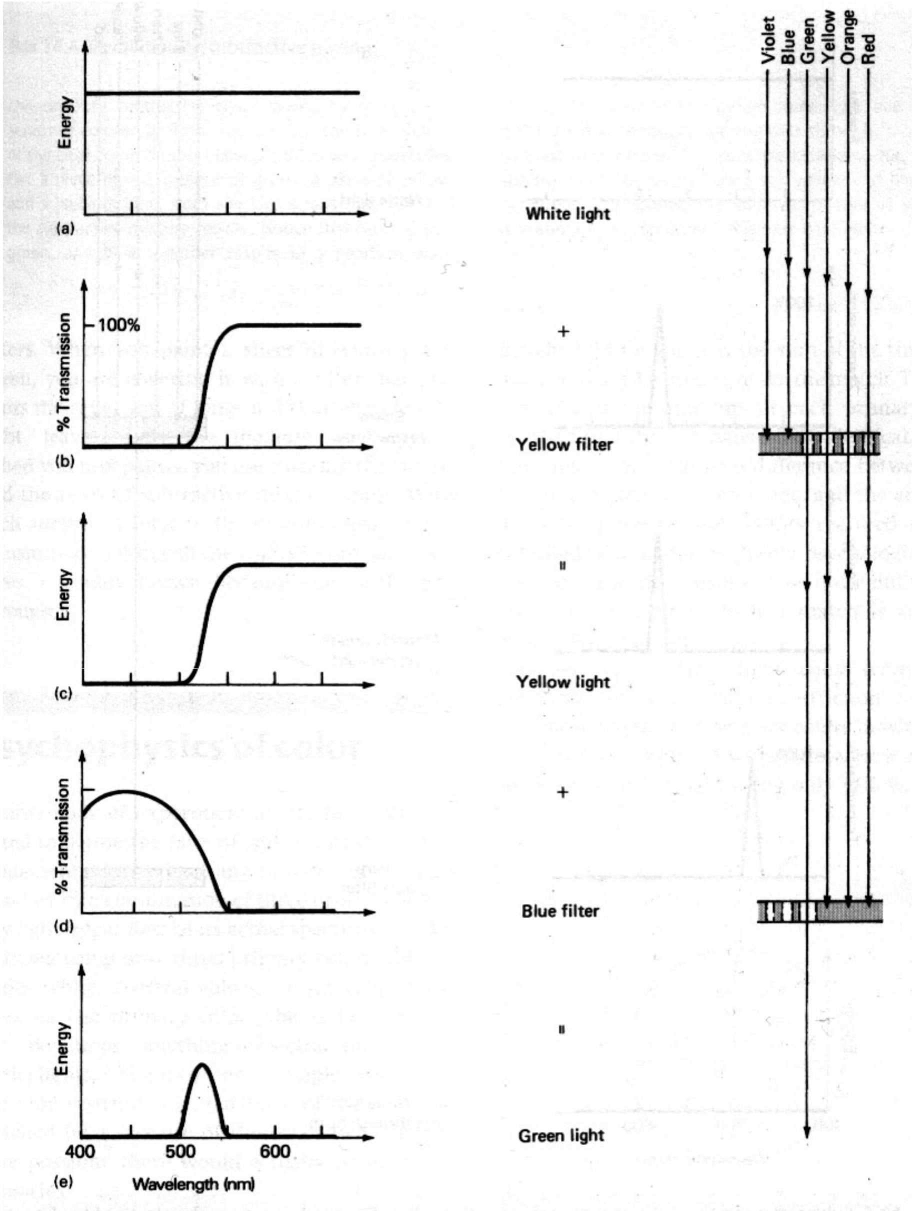
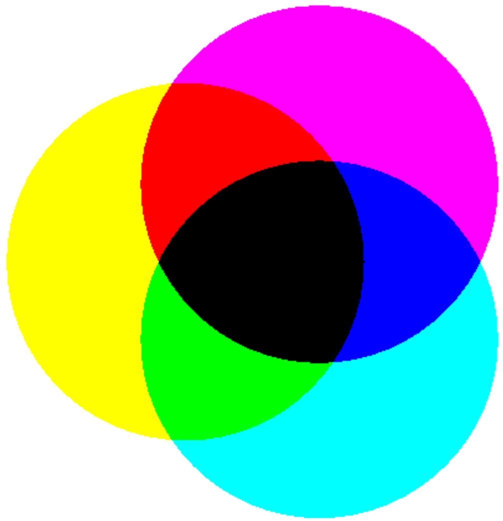


Fig. 14.2 Spectrum of the white light made by an additive mixture of monochromatic blue light (480 nm) with monochromatic yellow light (580 nm).

Other spaces: subtractive mixture

- Exact opposite of additive mixture: light is successively removed, there is less light in the mixture, than in the components
- Starting from white light: stack of filters, each blocking certain wavelengths
- Example: mixture of inks in color printing (or paints…), pigments remove color from incident light, which is reflected from paper





CYM(K) color model

cyan~blue+green
magenta~blue+red
yellow~red+green

The RGB cube

- Simplest way to represent color: place colors on a cube with components r,g,b

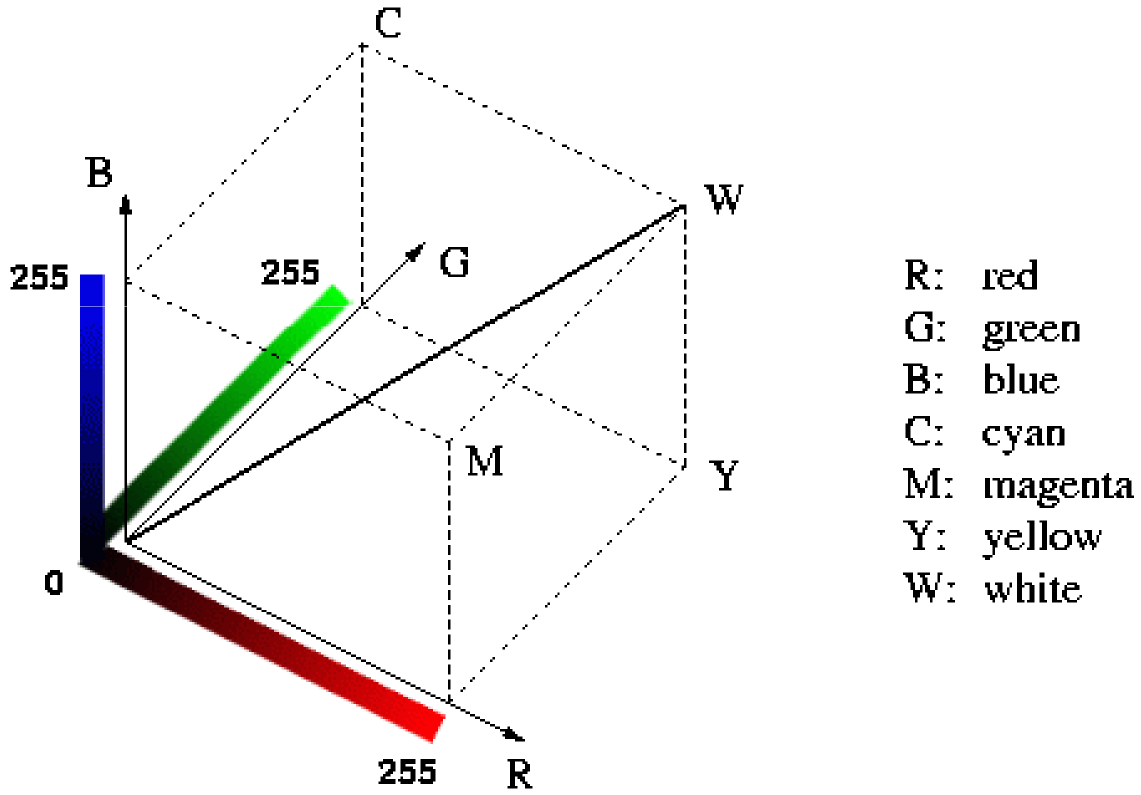
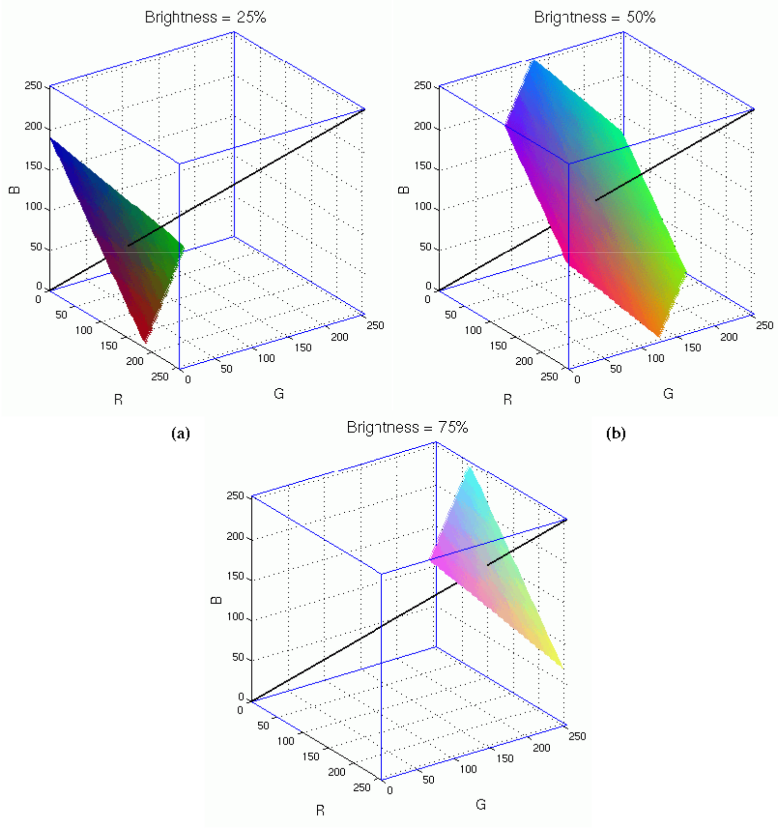


image from: http://gimp-savvy.com

Hue-based representations

- More intuitive to speak in terms of: *brightness, hue and saturation*

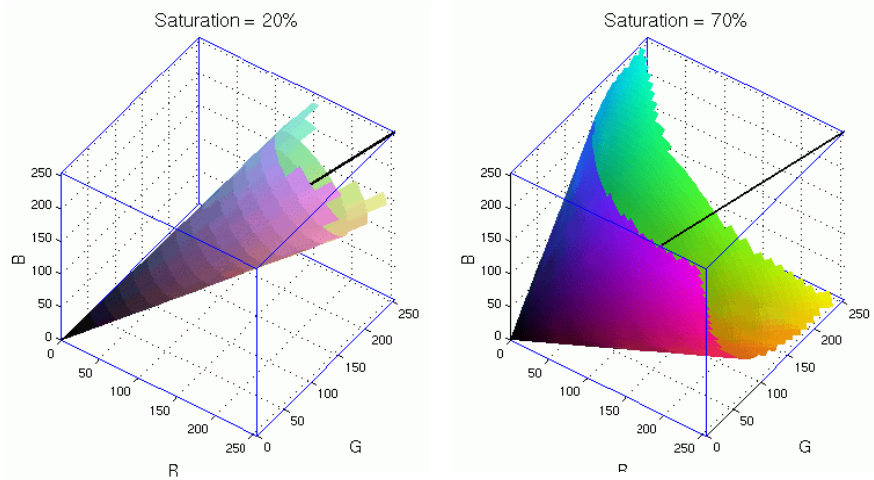


(a) (b) (c)

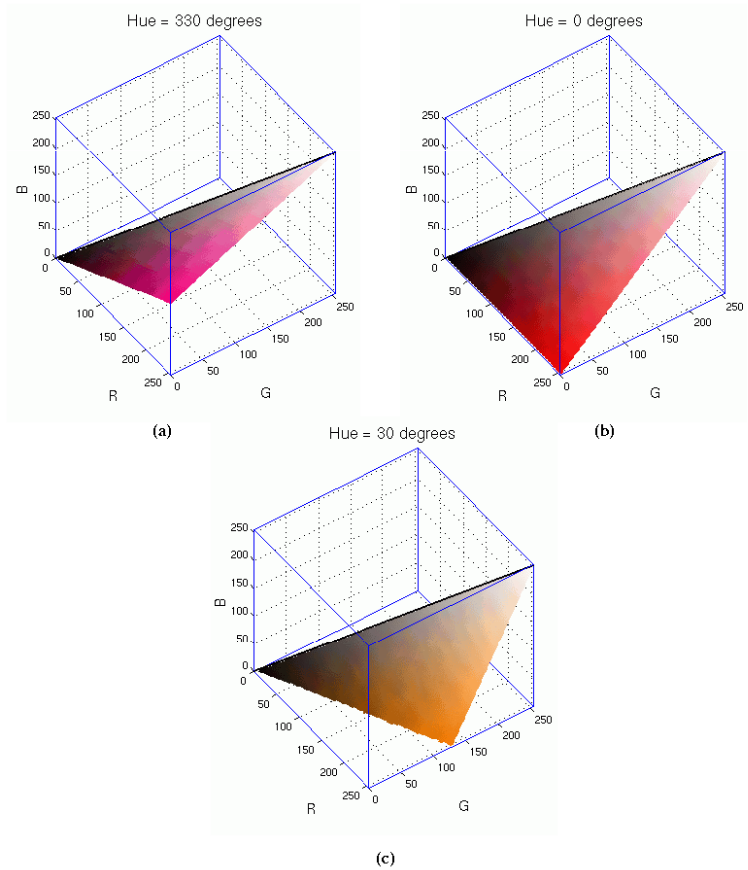
Let's draw planes of *constant brightness:* R+G+B=const (from black to white)

Neutral axis: the cube diagonal from (0,0,0) to (255,255,255)

- The amount of color is the distance of the point from the neutral axis
- **Saturation** is the amount of color with respect to brightness



- **Hue** is related to how we perceived the color: the angular position of the point around the neutral axis



The HSV model

$$Hue \in [0,360]$$

$$Value, Saturation \in [0,1]$$

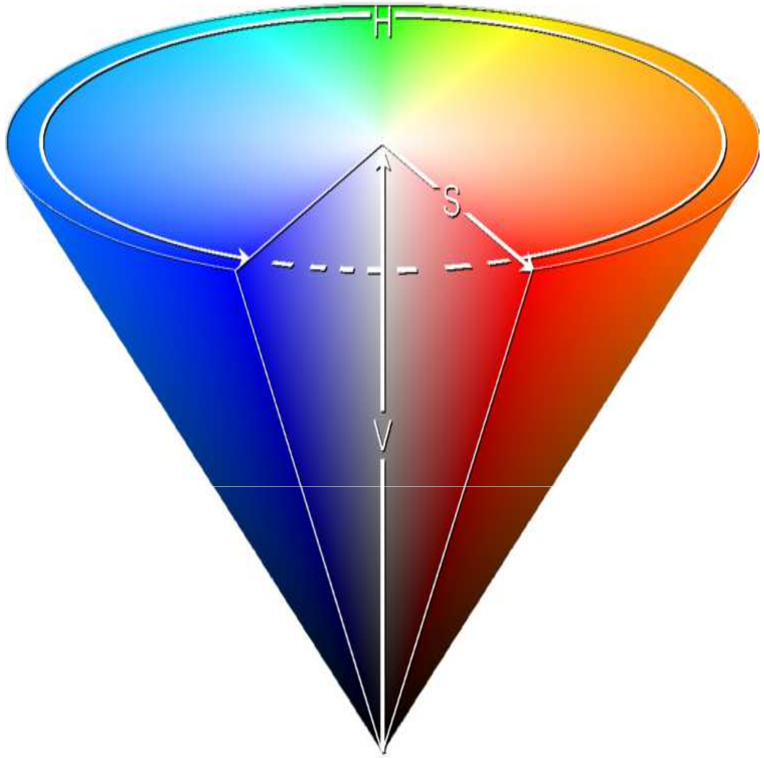
$R, G, B \in [0,1]$

$MAX = \max(R, G, B), MIN = \min(R, G, B)$

$V = MAX$

$$S = \begin{cases} 0 & \text{if } MAX = 0 \\ 1 - \dfrac{MIN}{V} & \text{otherwise} \end{cases}$$

$$H = \begin{cases} 60 \cdot \dfrac{G-B}{MAX-MIN} & if \;\; MAX = R \;\; and \;\; G \geq B \\ 60 \cdot \dfrac{G-B}{MAX-MIN} + 360 & if \;\; MAX = R \;\; and \;\; B > G \\ 60 \cdot \dfrac{B-R}{MAX-MIN} + 120 & if \;\; MAX = G \\ 60 \cdot \dfrac{R-G}{MAX-MIN} + 240 & if \;\; MAX = B \\ undefined & if \;\; MAX = MIN, S = 0 \end{cases}$$



http://en.wikipedia.org/wiki/HSV_color_space

The HSI/HSL model

$$Hue \in [0,360]$$

$$Value, Saturation \in [0,1]$$

$$R, G, B \in [0,1]$$

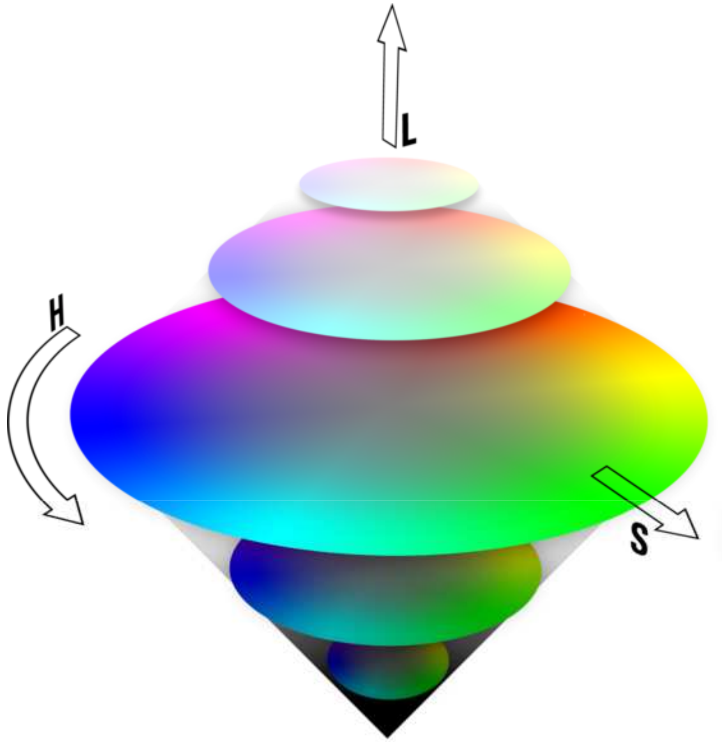
$$I = \frac{R+G+B}{3}$$

$$S = 1 - \min(R,G,B)/I$$

$$H = \cos^{-1} \frac{(R-G)+(R-B)}{2\sqrt{(R-G)^2 + (R-B)(G-B)}}$$

$if\;\; S = 0$, H is meaningless

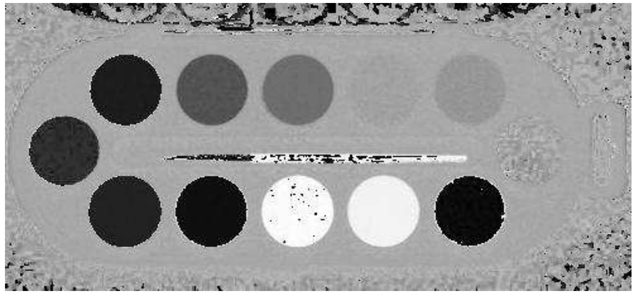
$if\;\; B > \mathrm{G}\;\; \mathrm{H} = 360\text{-H}$



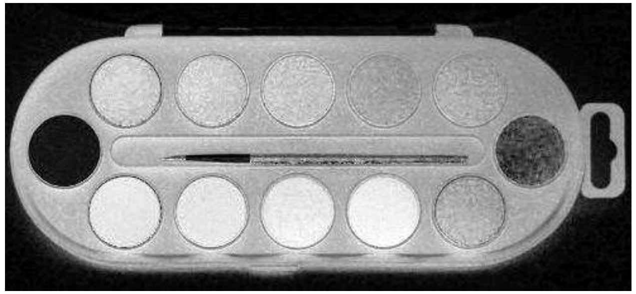
http://fourier.eng.hmc.edu/e161/lectures/color_processing/index.html

Example: HSV decomposition

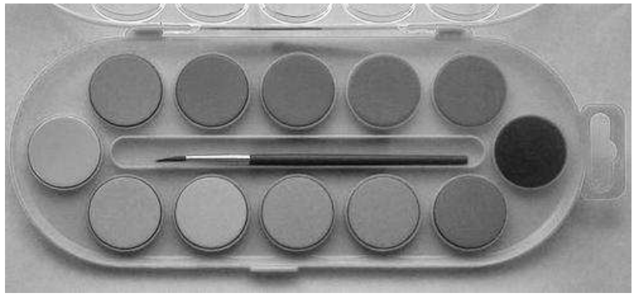
hue



saturation



value



```
function separateHSV(name)

A=imRead(name);

H=rgb2hsv(A);

hue=H(:,:,1);
sat=H(:,:,2);
val=H(:,:,3);

figure(1), imShow(A);
figure(2), imShow(hue);
figure(3), imShow(sat);
figure(4), imShow(val);
```

Normalized RGB

$$r = R/(R+G+B)$$

$$g = G/(R+G+B)$$

$$b = B/(R+G+B)$$

- Sometimes called *pure colors*
- Reduce sensitivity to illumination changes (a color vector multiplied by a scalar does not change)
- Preserve chrominance
- Because *r+g+b=1*, only *r* ang *g* are required to describe the color of the pixel (we discard intensity) → *rg-Chromaticity plane*

Uniform Color Spaces

- Usually colors cannot be reproduced exactly, so it is important to know if a color difference would be noticeable to a human viewer
- This is in general useful for small color difference (large color differences are difficult to compare)
- We could estimate *just noticeable differences* by modifying a color shown to an observer until he detects that the color has changed
- We can plot these differences as regions in color space whose color are indistinguishable from the original one (at the center of the region itself); usually ellipses are fitted to these regions (*MacAdam ellipses*)

- In CIE XYZ, the size of these ellipses varies strongly with their position
- In other words, in the x,y space the difference:

$$\sqrt{(\Delta x)^2 + (\Delta y)^2}$$

is a poor indicator of the “perceived” difference of the corresponding colors

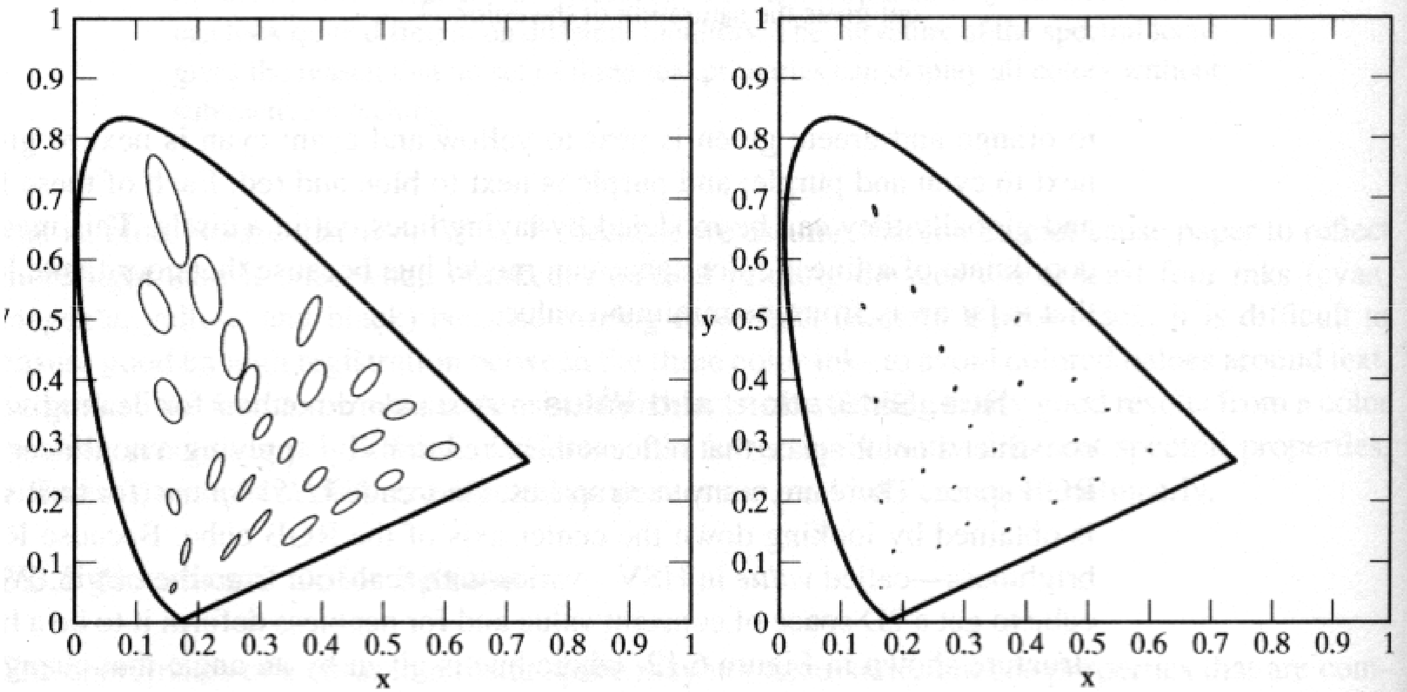


Figure 6.13 This figure shows variations in color matches on a CIE x, y space. At the center of the ellipse is the color of a test light; the size of the ellipse represents the scatter of lights that the human observers tested would match to the test color; the boundary shows where the just noticeable difference is. The ellipses in the figure on the **left** have been magnified 10x for clarity; on the **right** they are plotted to scale. The ellipses are known as MacAdam ellipses after their

image from: Forsyth and Ponce

CIE LAB

- CIE LAB is universally the most popular uniform color space
- Coordinates are obtained as a non linear mapping of the XYZ coordinates:

$$L = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16$$

$$a = 500\left[\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right]$$

$$b = 200\left[\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right]$$

X_n, Y_n, Z_n are X,Y,Z of a reference white patch

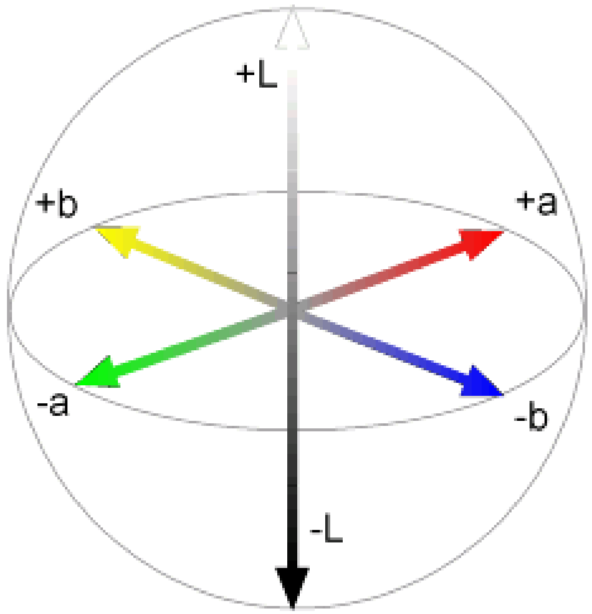
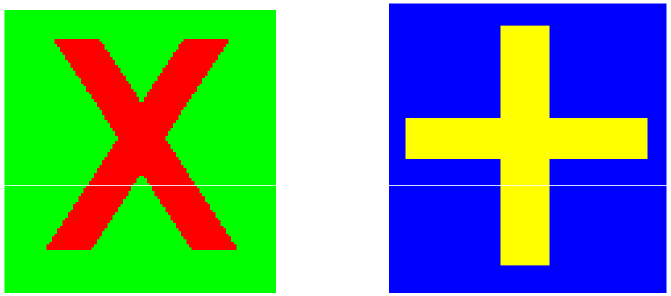


image from: http://www.tasi.ac.uk/advice/creating/colour.html

Opponency

- Some visual phenomena are difficult to explain on the basis of trichromatic theory alone
  - Afterimages:



  - naming experiment of monochromatic colors, unique colors: red, green, blue, yellow
  - a color is never described as “reddish-green” or “bluish-yellow”, these channels seem to cancel each other

Opponent-process theory

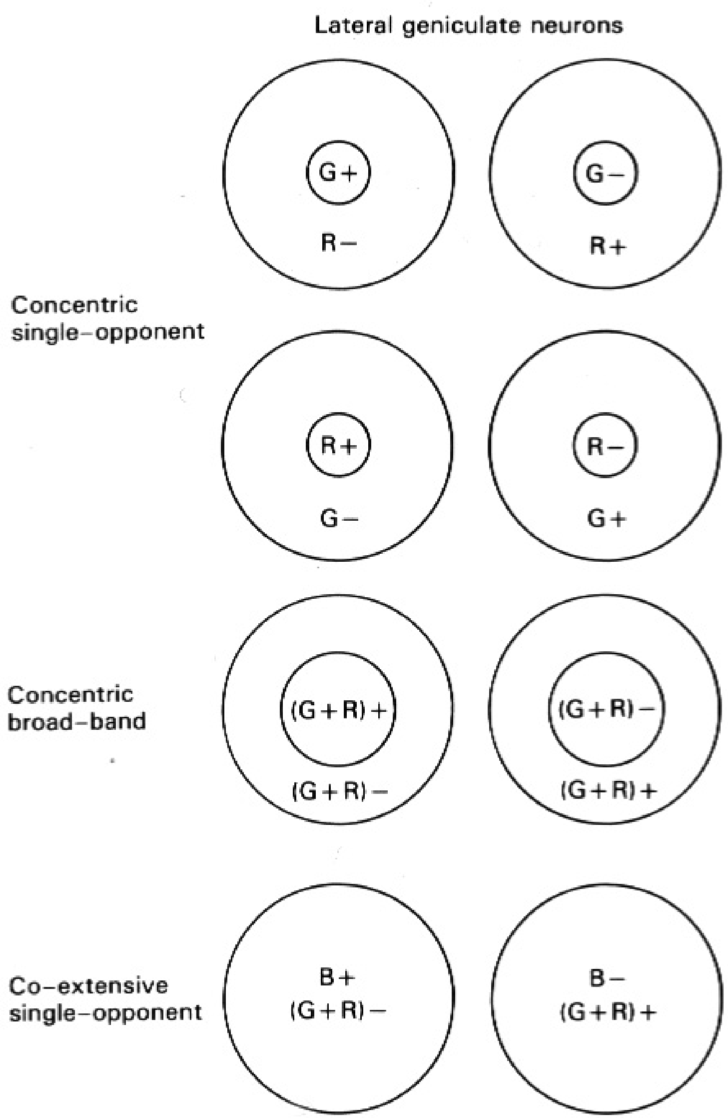
- Information is organized in three color-opponent channels:
  - Red-Green
  - Yellow-Blue
  - White-Black

- Concentric *broad-band* cells:

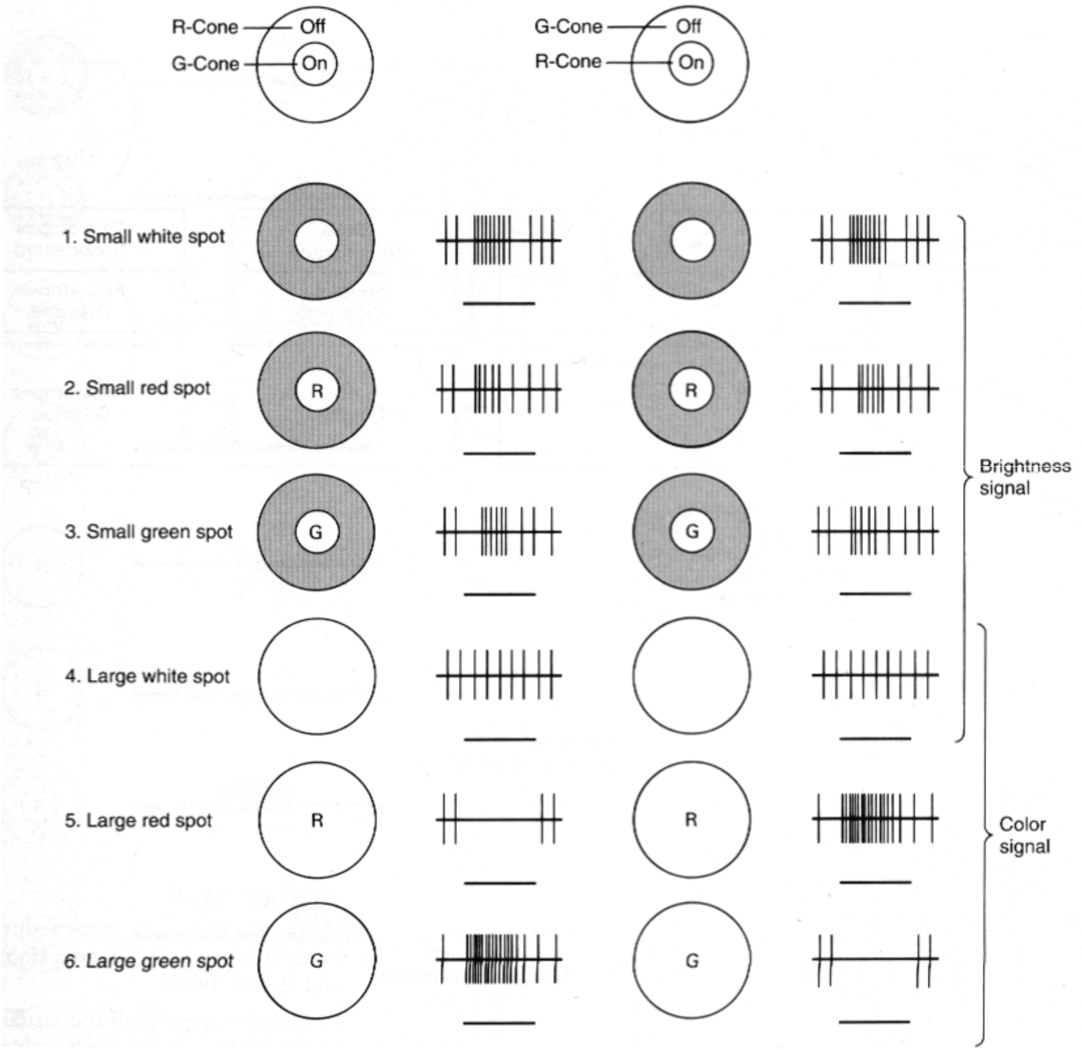
Center and surround combine input from both R and G cones, mostly respond to *brightness*

-Concentric *single-opponent* cells, receives input from R or G cones in the center and have larger antagonist surround receiving input from the other cones, responds to brightness (white or yellow for example) but also to large spots of monochromatic light (red or green)

- *Co-extensive single opponent* cells have a uniform receptive field, where inputs from B cones antagonize combined inputs from R and G cones



Receptive fields of concentric single-opponent cells in the retina of the cat



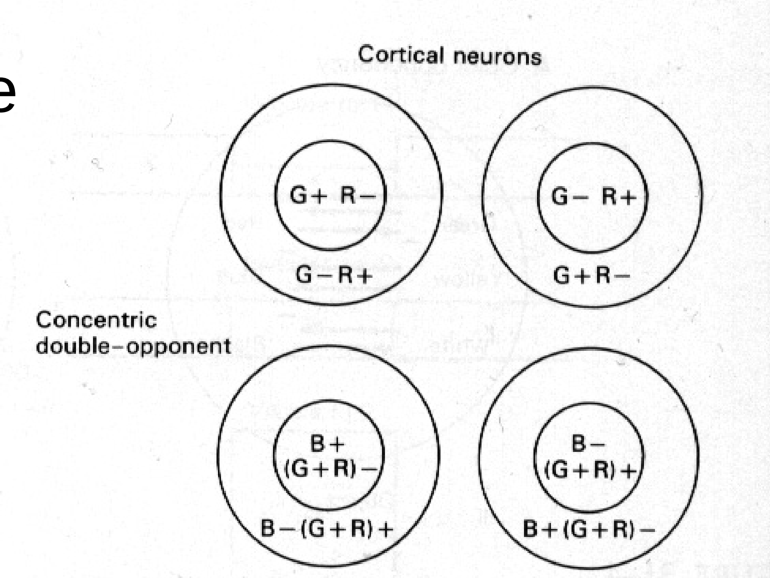
- Both cells are excited by small centered white spots
- Unresponsive to large white spots
- Respond best to large red/green spots

Color processing in the cortex

- Together with cells that are selective for orientation and achromatic, there are cells that have chromatic response

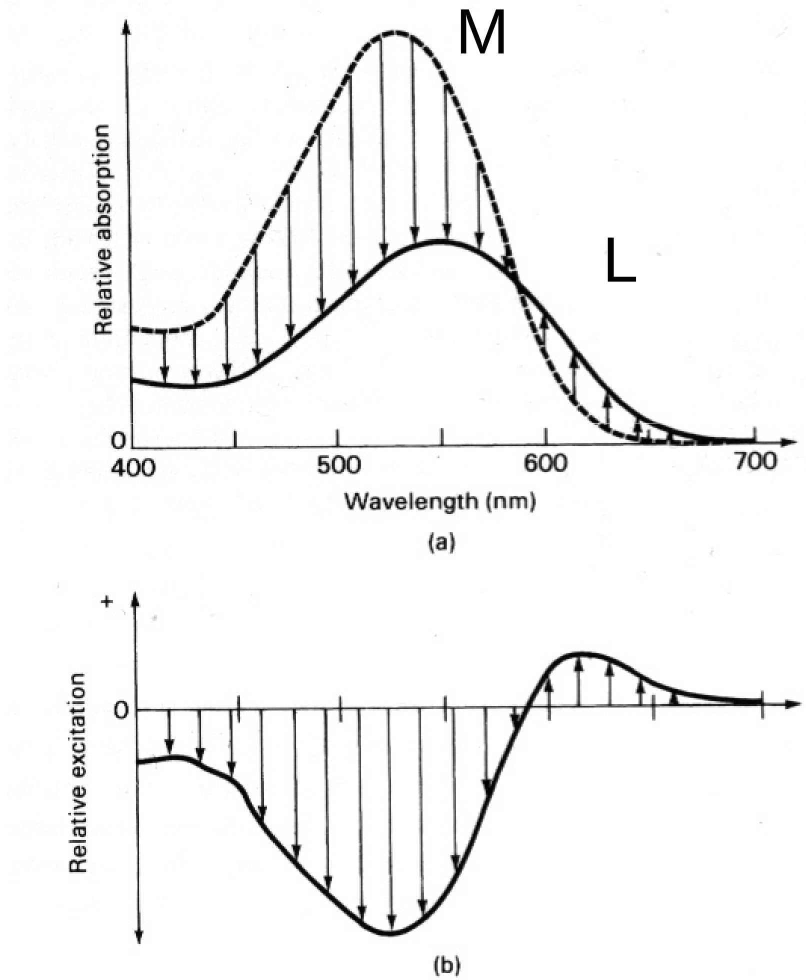
- Double opponent cells integrate input from the single-opponent cells

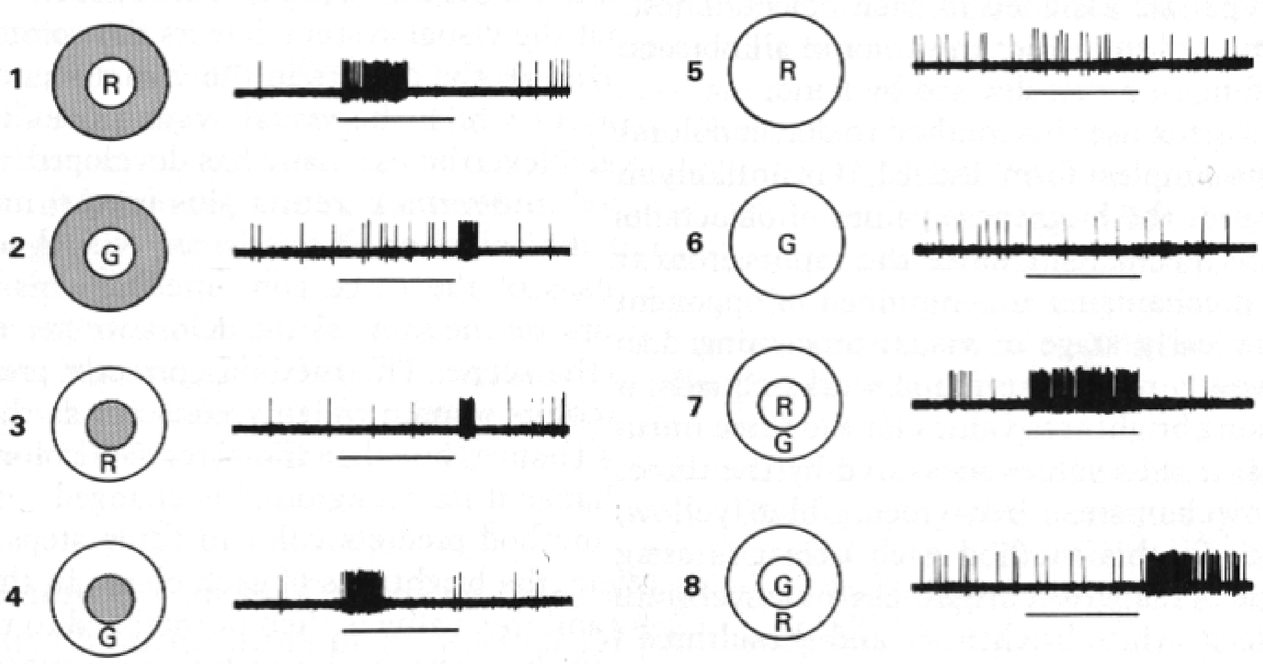
- In these cells, both R and G type cones operate in the center and the surround of the receptive field



Opponent process theory extends trichromacy

- It is generally accepted that S, M and L cones interact to produce the opponent channels
- On the right: how chromatic response processes may be generated for a +R-G cell
- Similar considerations could be done for a +Y-B/+B-Y cell, S cones in this case oppose the sum of M and L cones





- Double-opponent cells respond best to a red spot in the center against a green background or to a green spot against a red background
- They do not respond well to white light, because both R and G type cones cancel out each other’s effect

Color Constancy

- Double opponent cells help explain the phenomenon of color constancy
- The visual system seems to be more concerned with “color differences” than absolute values
- For example, an increase of long-wavelength of ambient light has little effect on a double opponent cell, because the increase of light is the same in both the center and the surround of the cell
- We will see how these considerations have influenced the design of artificial perceptual systems