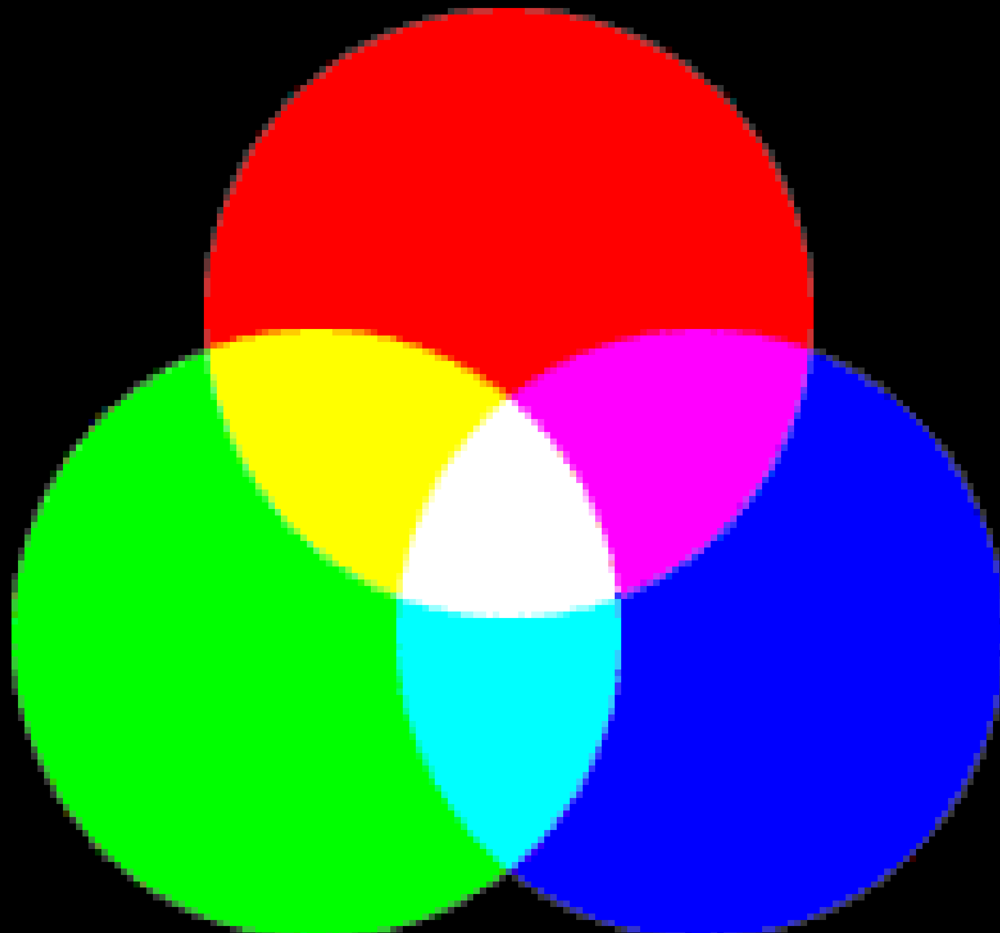
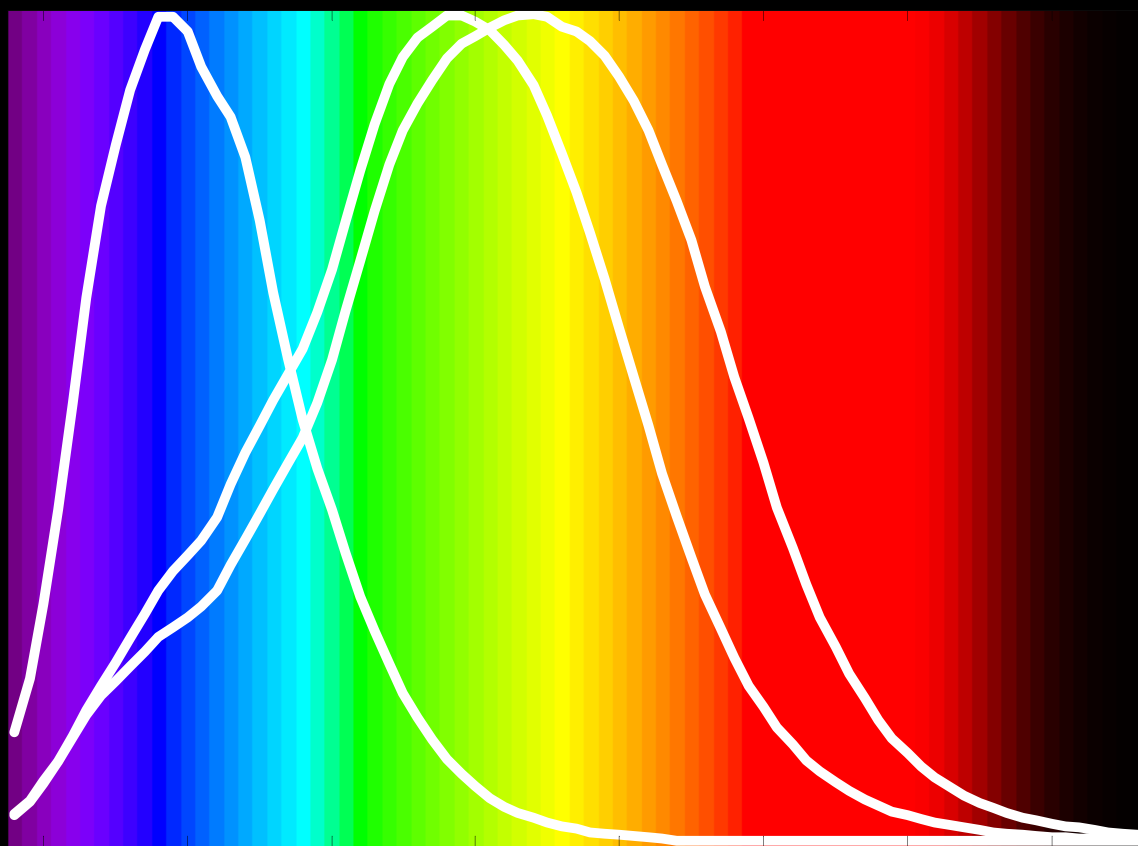
TV's with three phosphors work because almost any color can be generated by adding different amounts of the three primary colors.



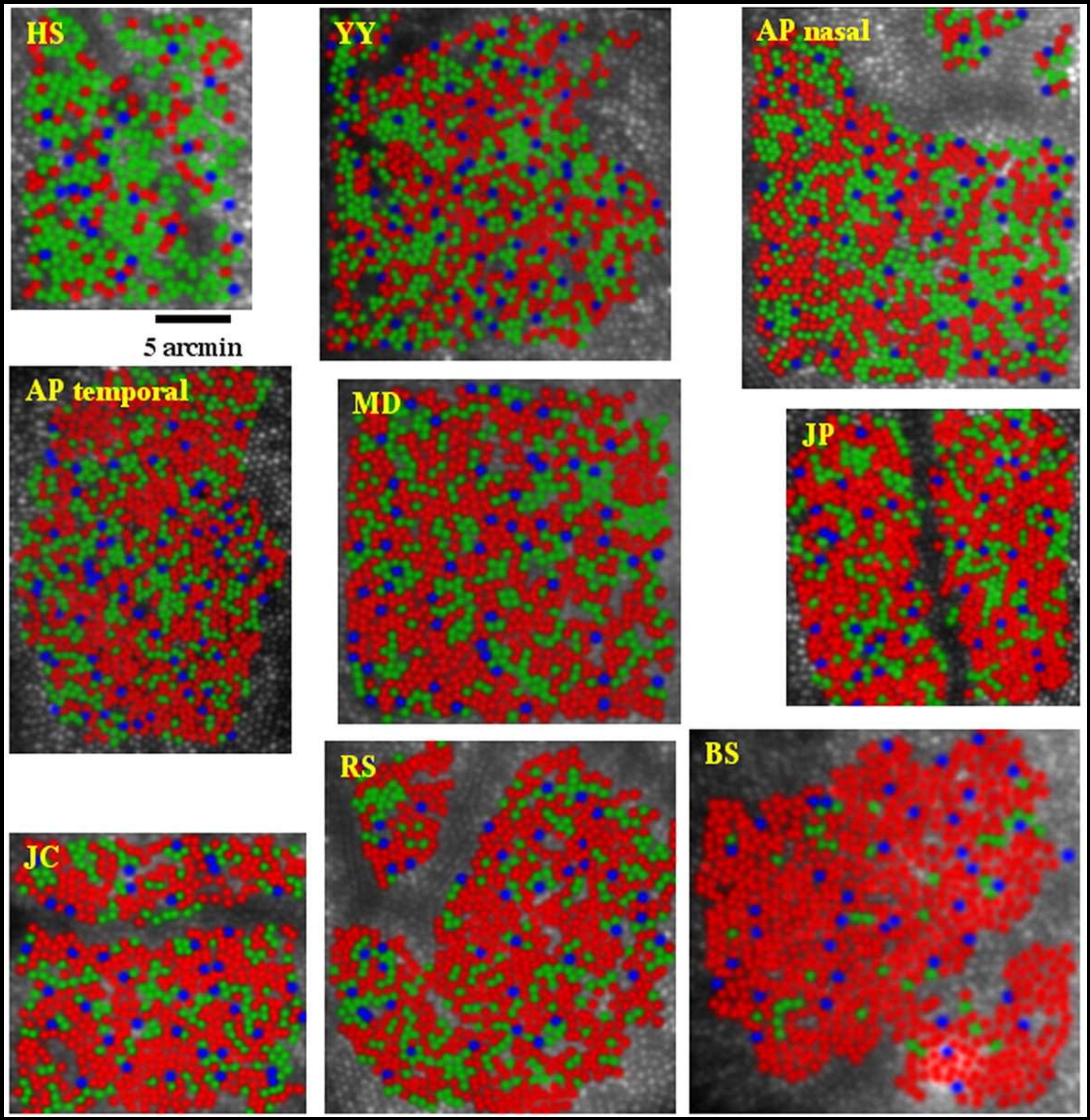
TV's with three colors (phosphors) work because almost any color can be generated by adding different amounts of the three primary colors.

Why? Because we have three types of photoreceptors.



Physiology of color vision

The normal retina contains three kinds of cones (S, M and L), each maximally sensitive to a different part of the spectrum.



Hofer, H. et al. J. Neurosci. 2005;25:9669-9679

Trichromatic theory of color vision

Young-Helmholtz Theory (1802,1852).

Our ability to distinguish between different wavelengths depends on the operation of **three different kinds of cone receptors**, each with a unique spectral sensitivity.

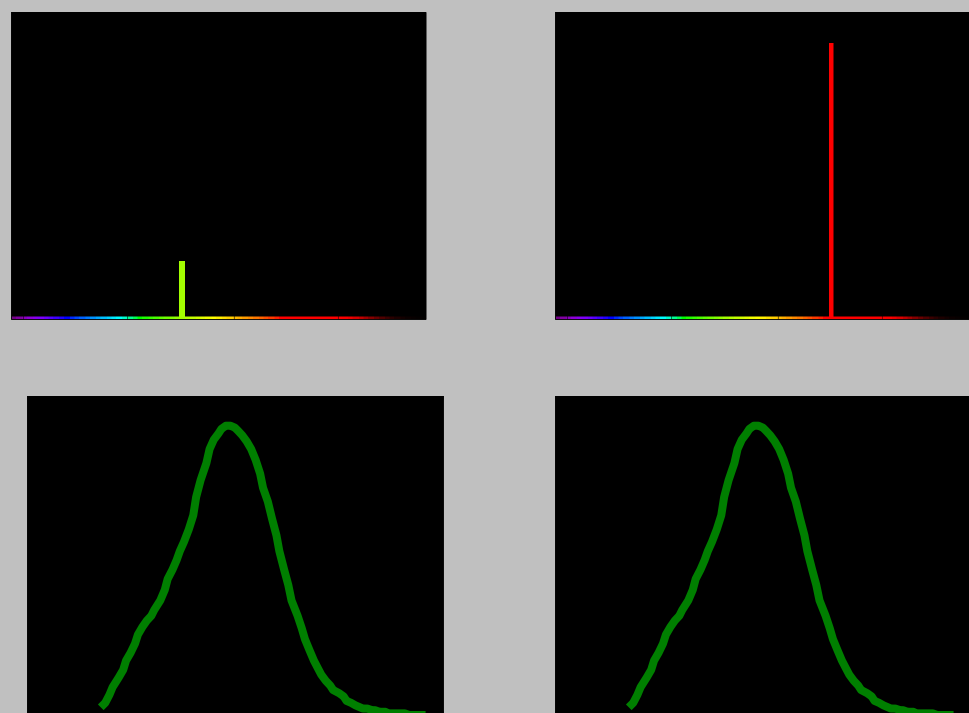
Each wavelength of light produces a **unique pattern of activation** in the three cone mechanisms.

Perceived color is based on the **relative amount of activity—the pattern of activity—**in the three cone mechanisms.

The *Principal of Univariance*

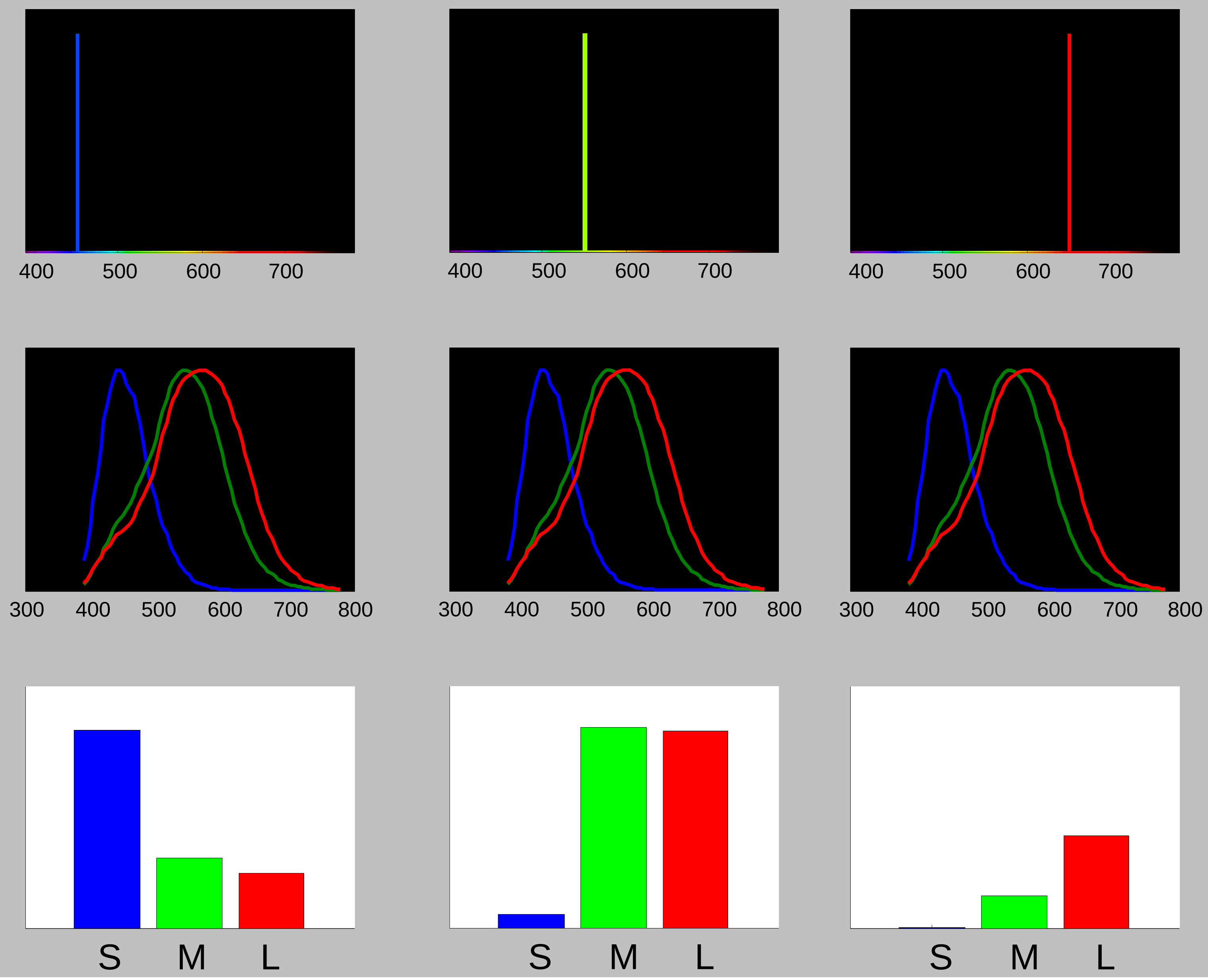
the absorption of a photon of light by a cone produces the same effect no matter what the wavelength.

A given cone system will respond the same to a dim light near peak wavelength as a bright light away from the peak.

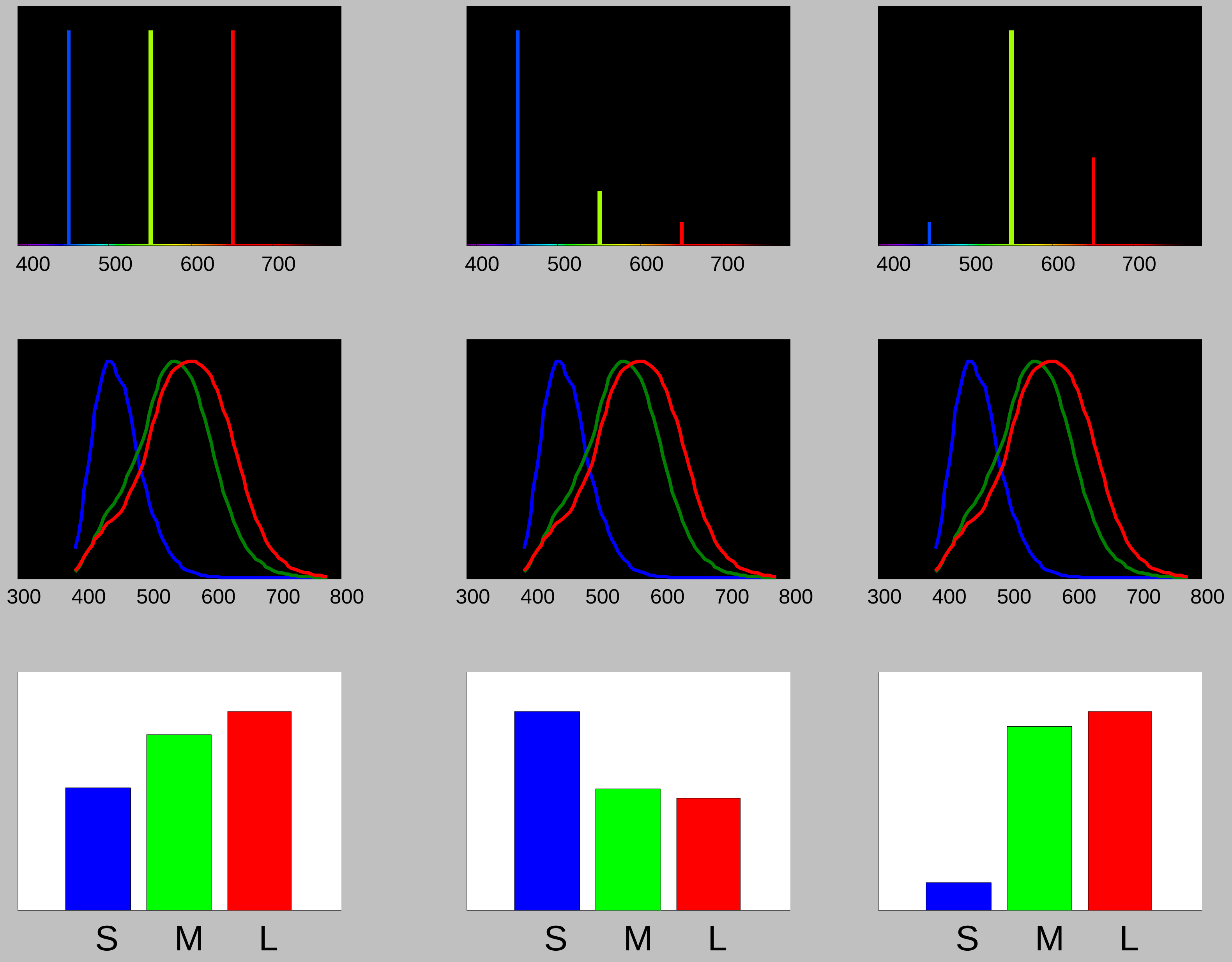


For example, the M cones will respond equally to a dim green light as a bright red light. As far as the M cones are concerned, these lights look the same.

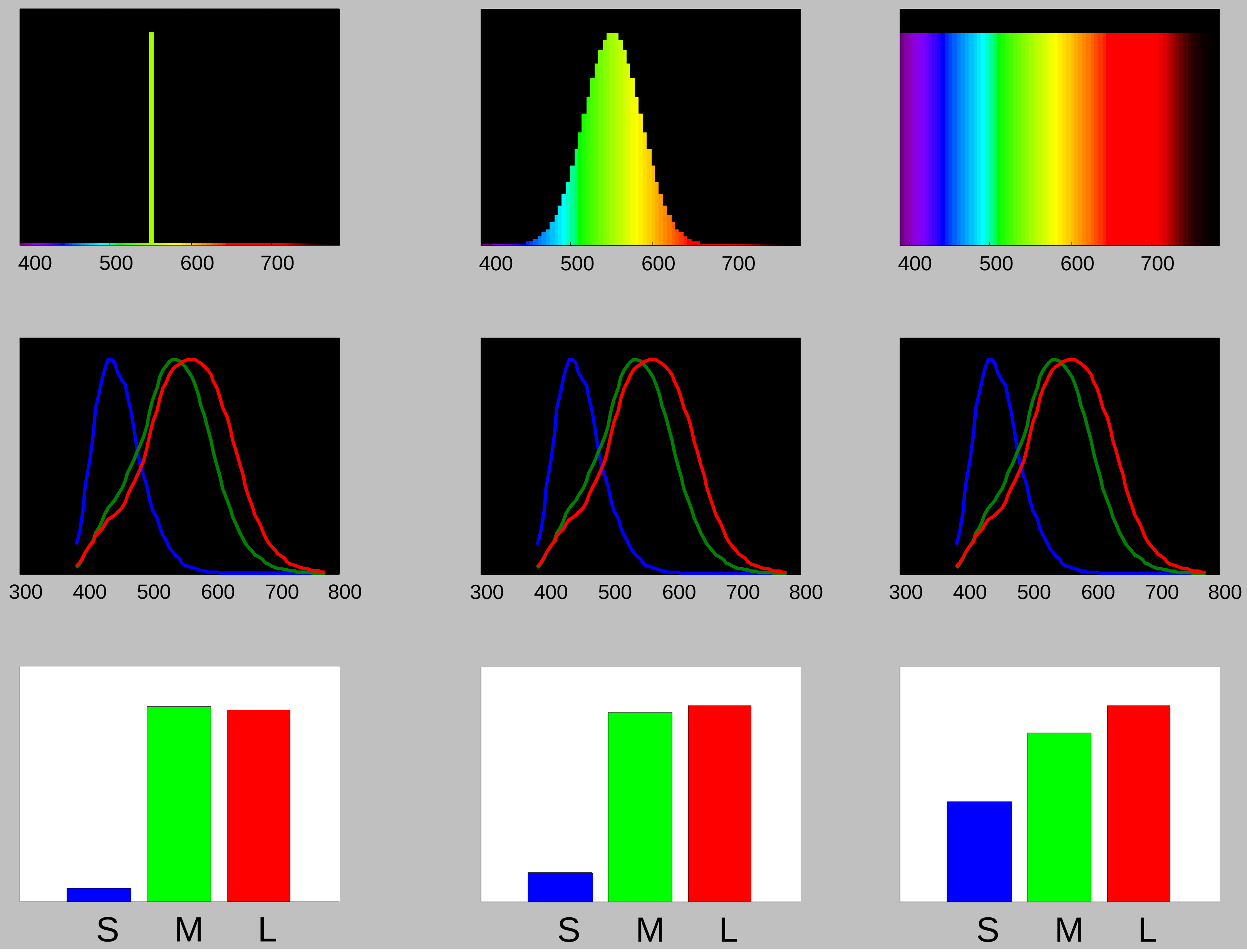
A given light will excite the L, M, and S cones differently



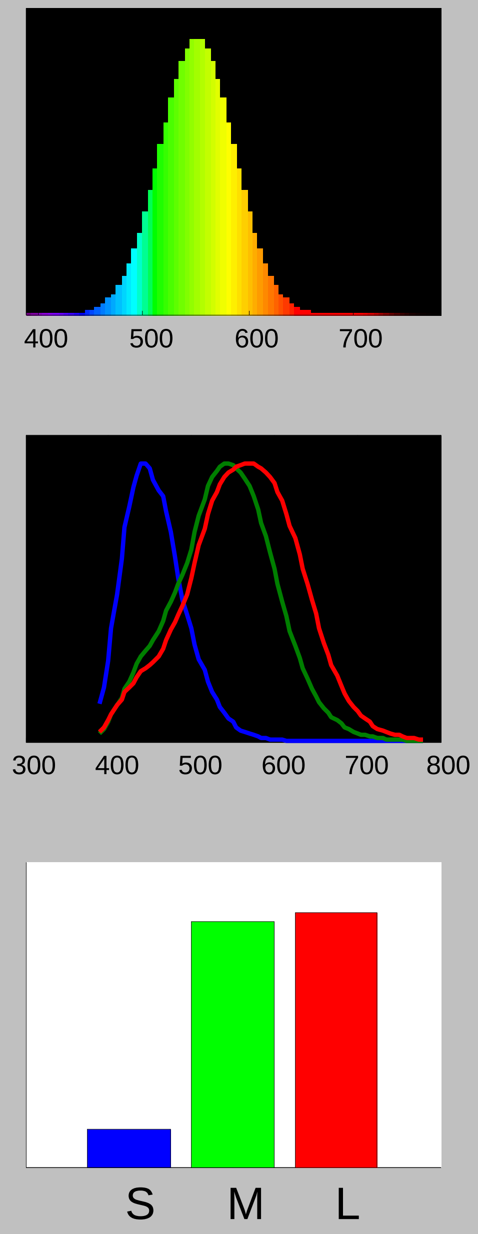
We can add lights to predict L, M and S responses to different amounts of 3 primaries



We can also predict L, M and S responses to different levels of saturation

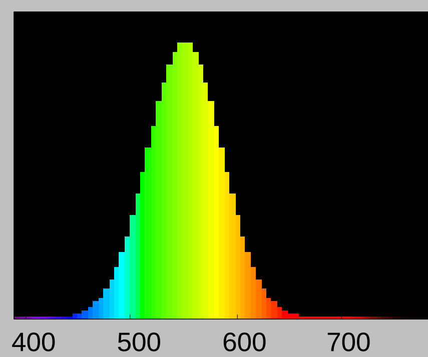


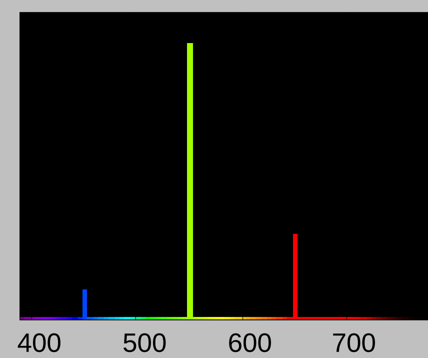
Given almost any light, it's possible to find intensities of the 3 primaries that produce the same L, M and S responses

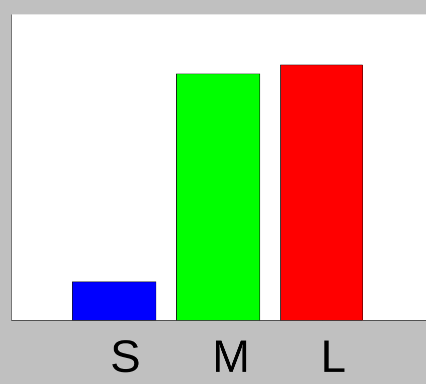


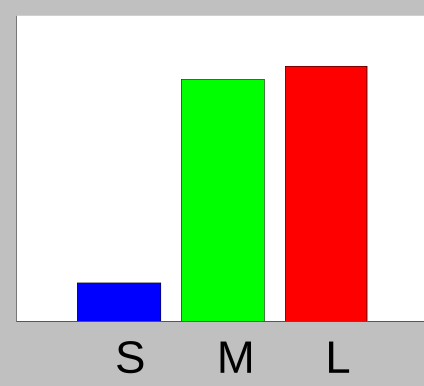
Because of the principle of univariance, two different spectra that produce the same L, M and S cone responses will look exactly the same.

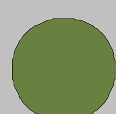
These pairs are called ‘***metamers***’. They make a ***‘metameric match***’

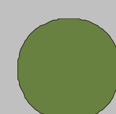




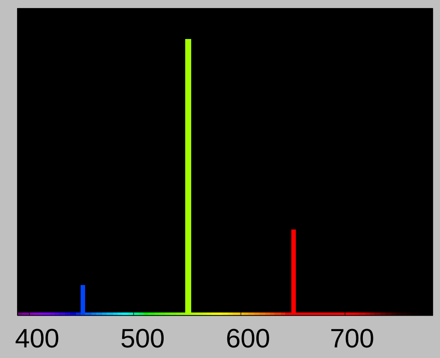








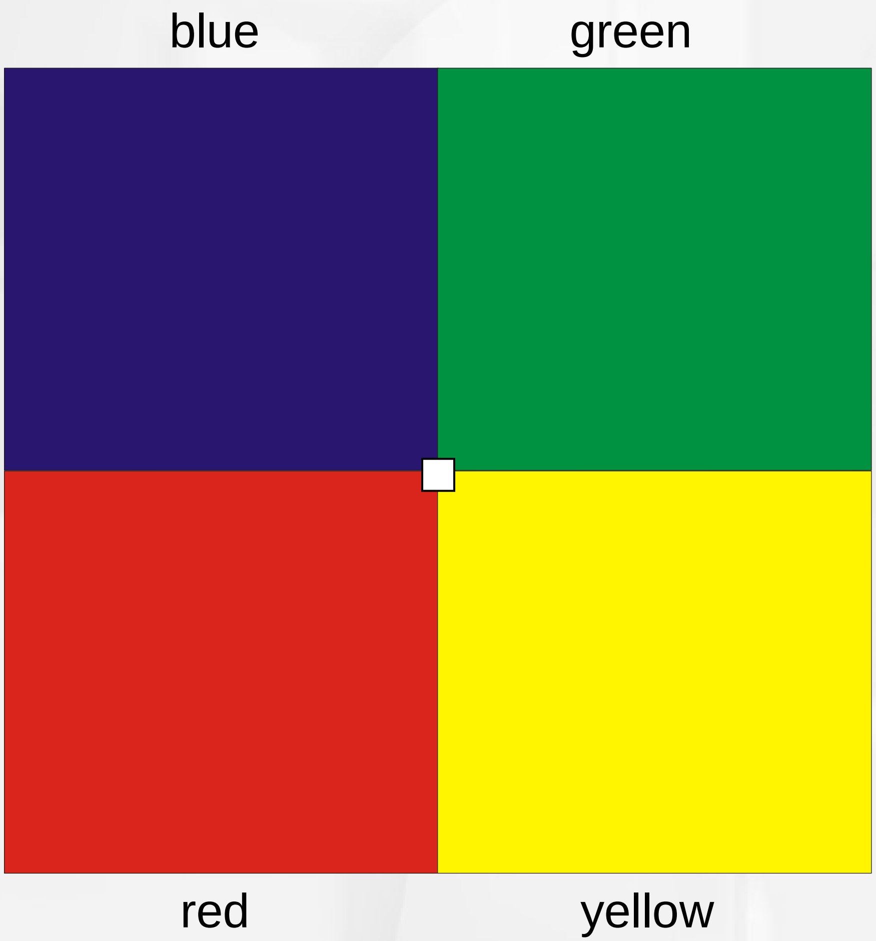
So the theory of trichromacy explains why we only need three primaries to produce a variety of colors. But what does an arbitrary sum of primaries *look* like?



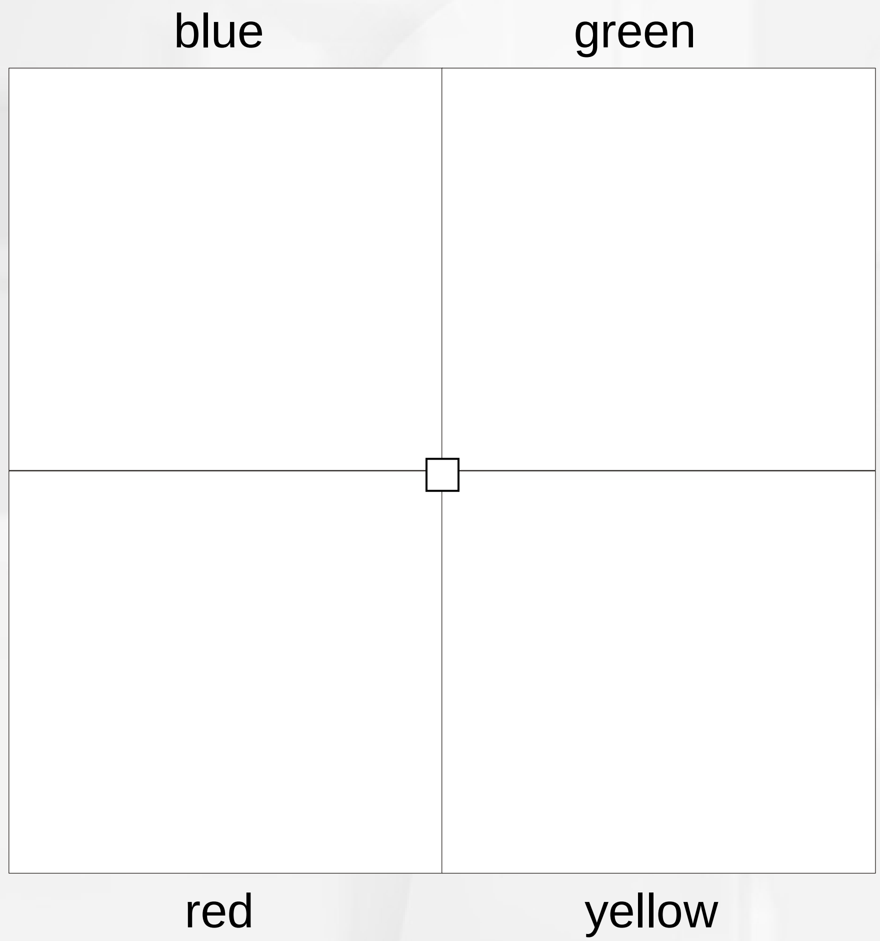
In 1878, Hering argued that trichromacy wasn't enough. He asked:

Why don't we ever see yellowish blues? Or reddish greens?

Color aftereffects



Color aftereffects

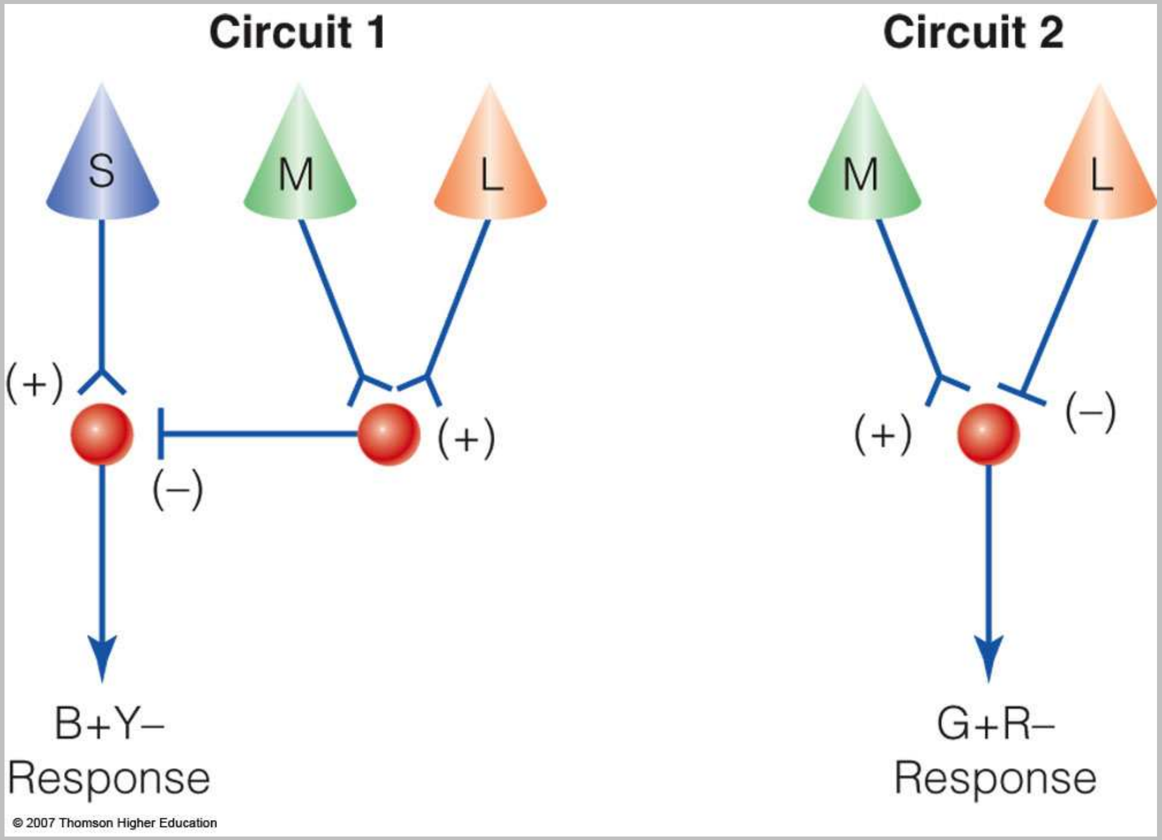


Why are red and blue opposites? Why are yellow and green opposites?

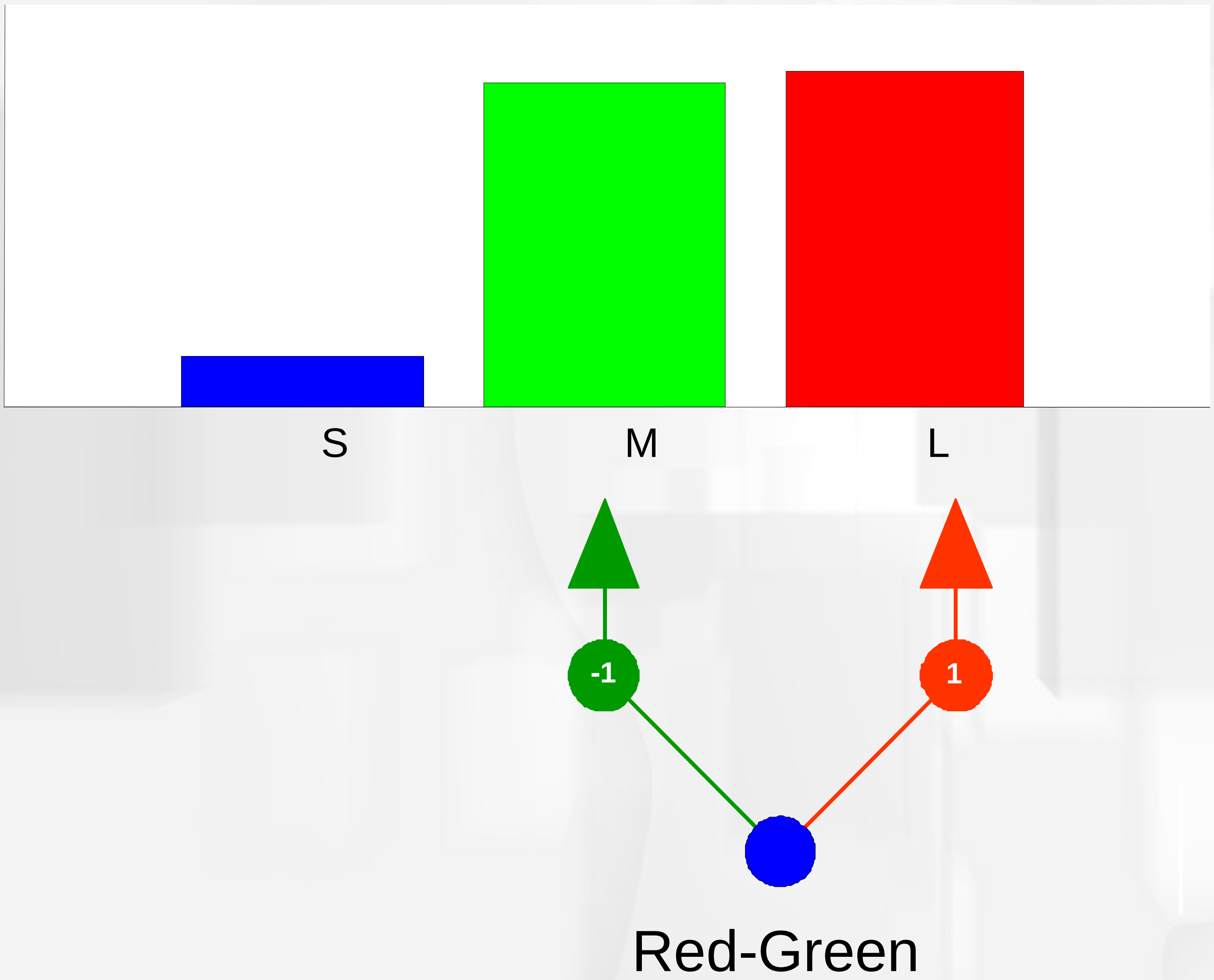
Hering proposed the *Opponent Process Theory*

Color vision is based on the activity of two opponent-process mechanisms:

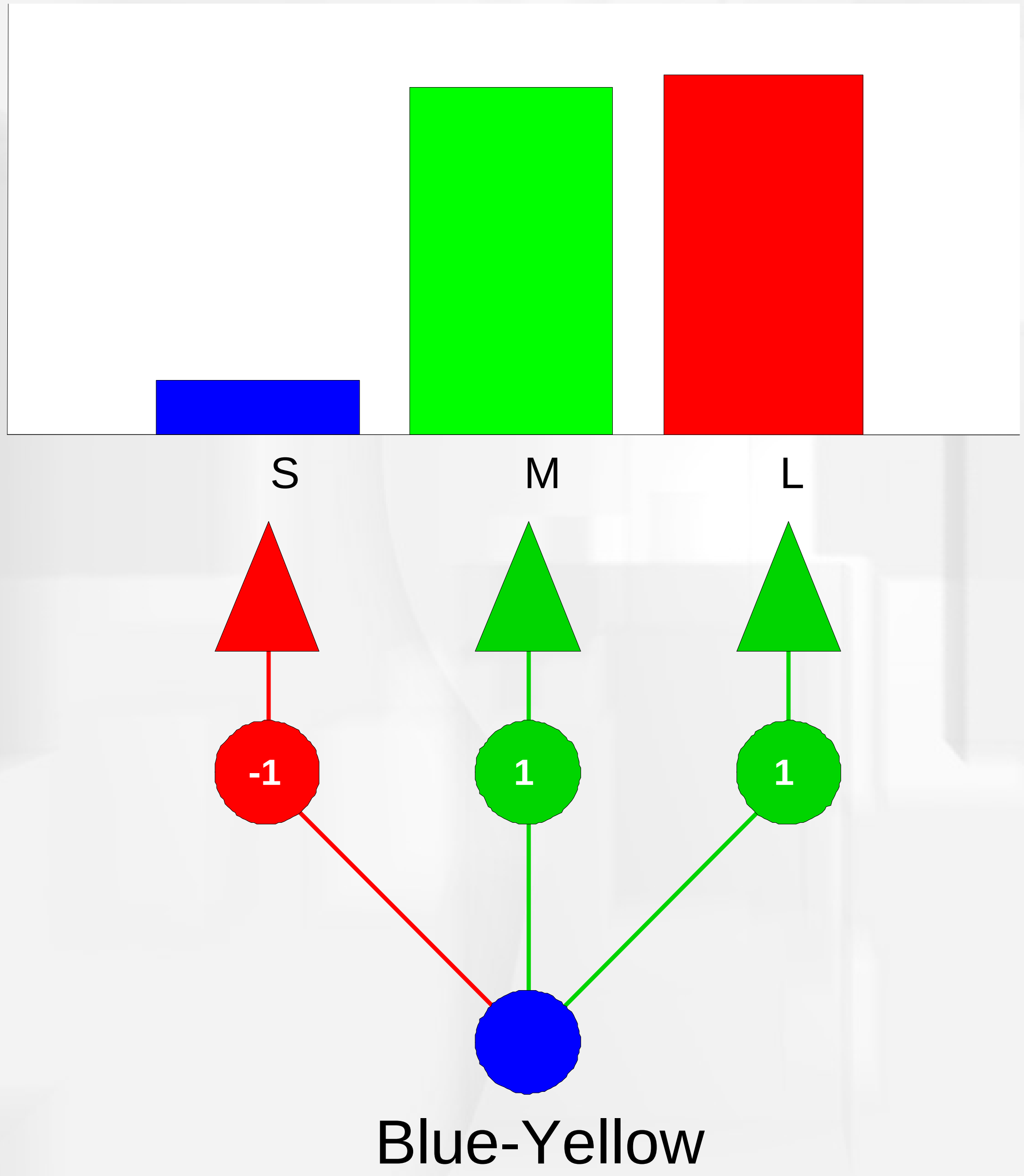
1. A RED/GREEN opponent mechanism.
2. A BLUE/YELLOW opponent mechanism



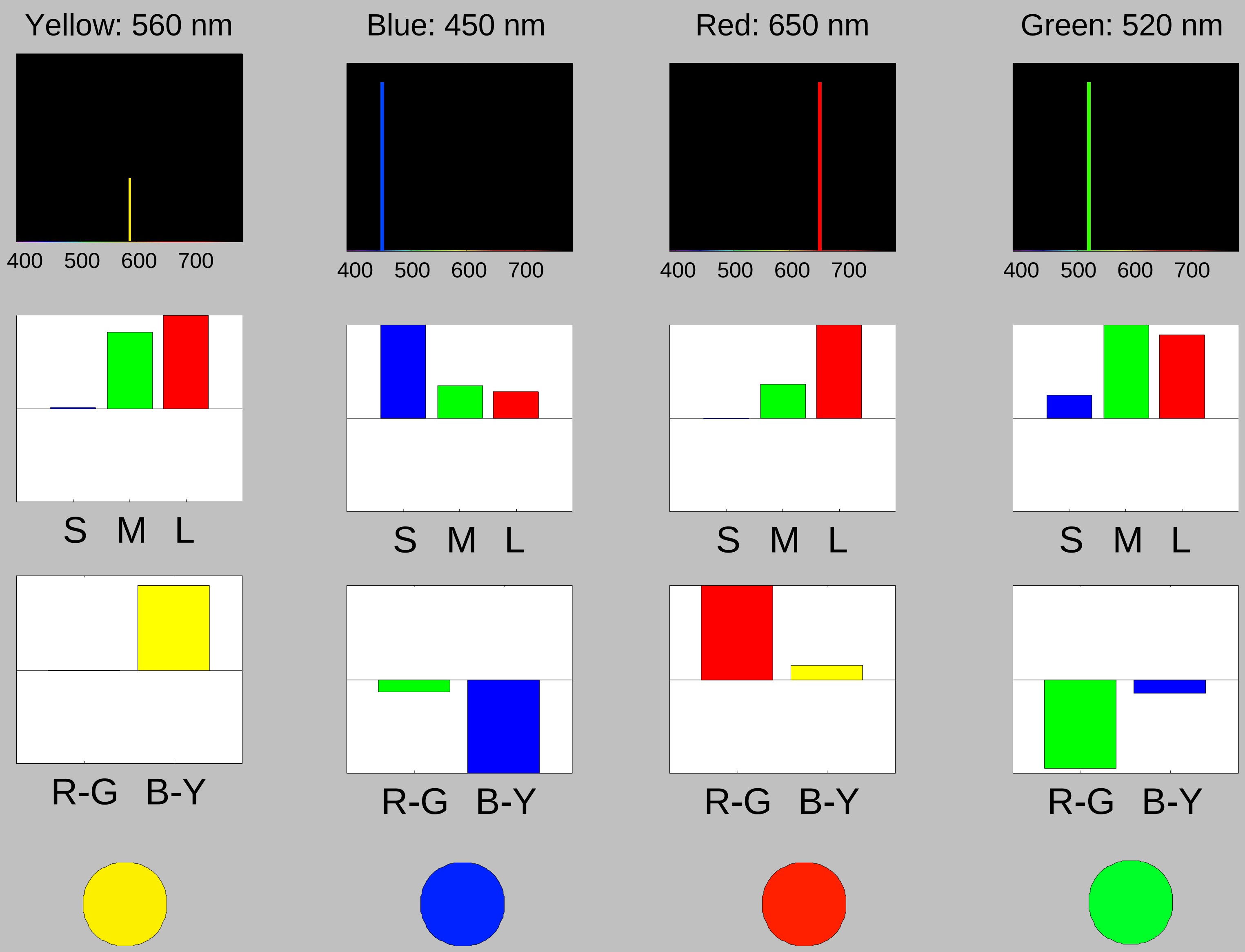
The Red-Green opponent system subtracts M from L cone responses



The Blue-Yellow opponent system subtracts S from L+M cone responses



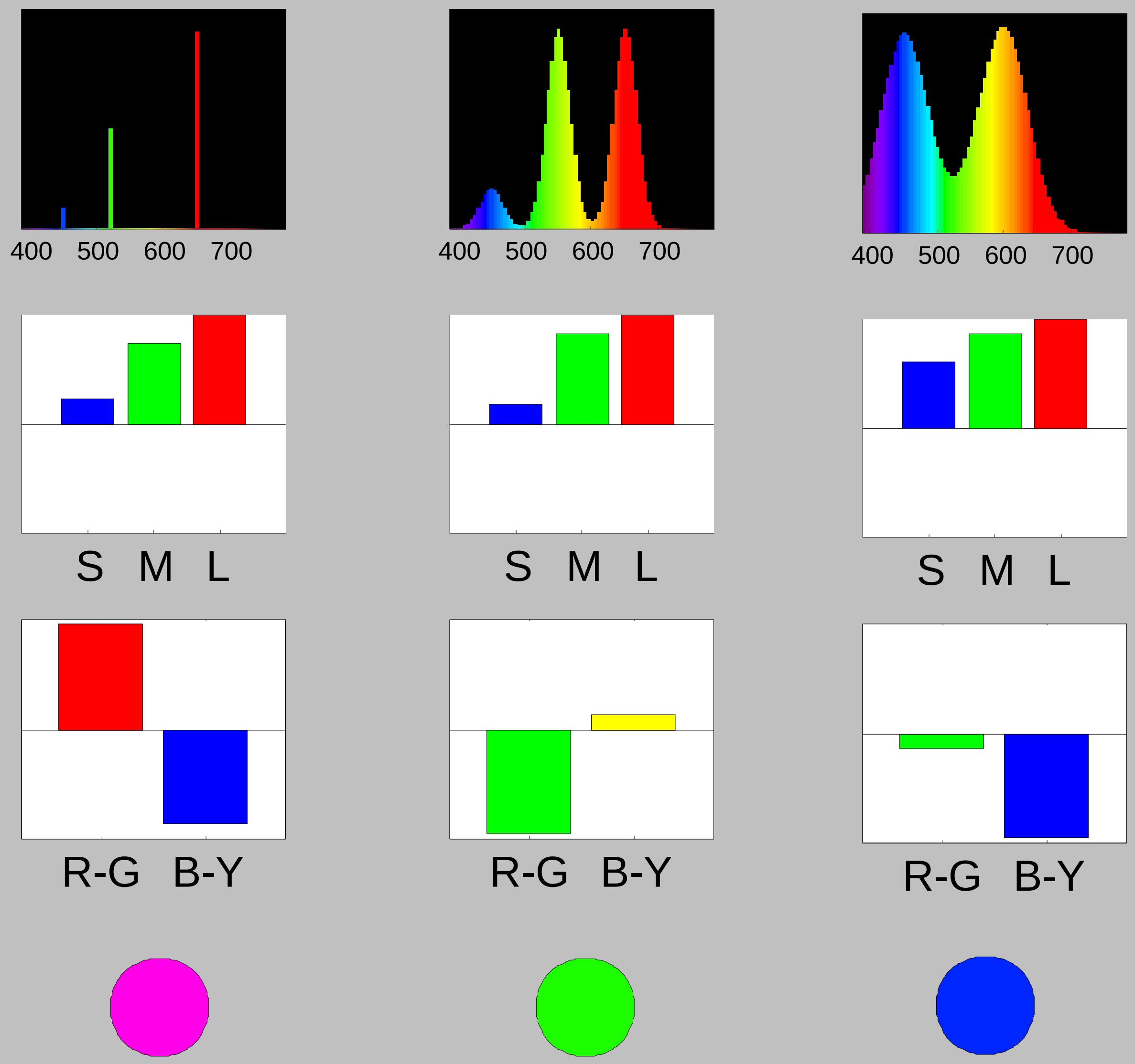
Now with RG = L-M and BY = (L+M) – S,
we can predict the appearance of any arbitrary spectrum of light.



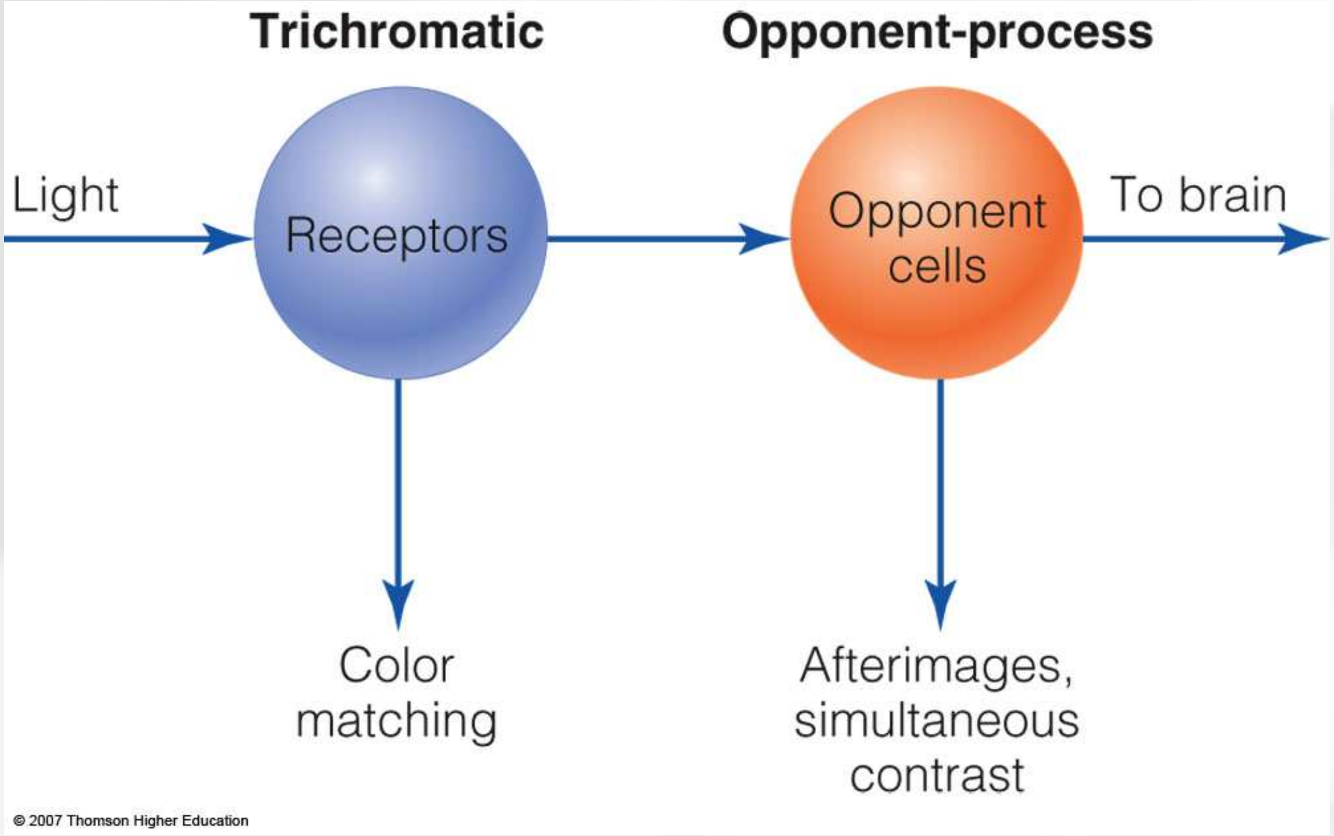
Now with RG = L-M and BY = (L+M) – S,
we can predict the appearance of any arbitrary spectrum of light.

Sum of primaries:

Or more complex spectra:



Our experience of color is shaped by physiological mechanisms, both in the receptors and in opponent neurons.

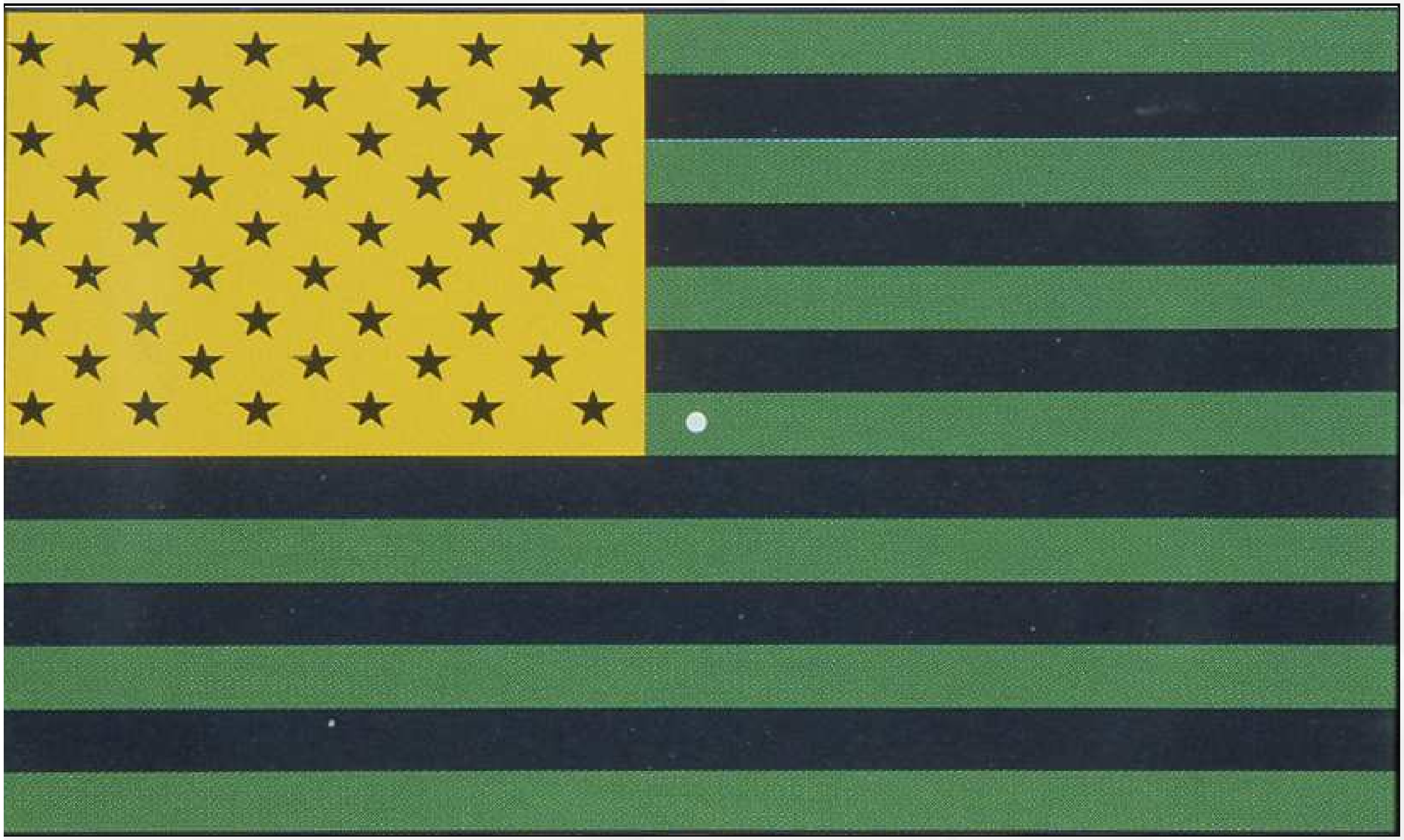


But, color perception depends on more than wavelength

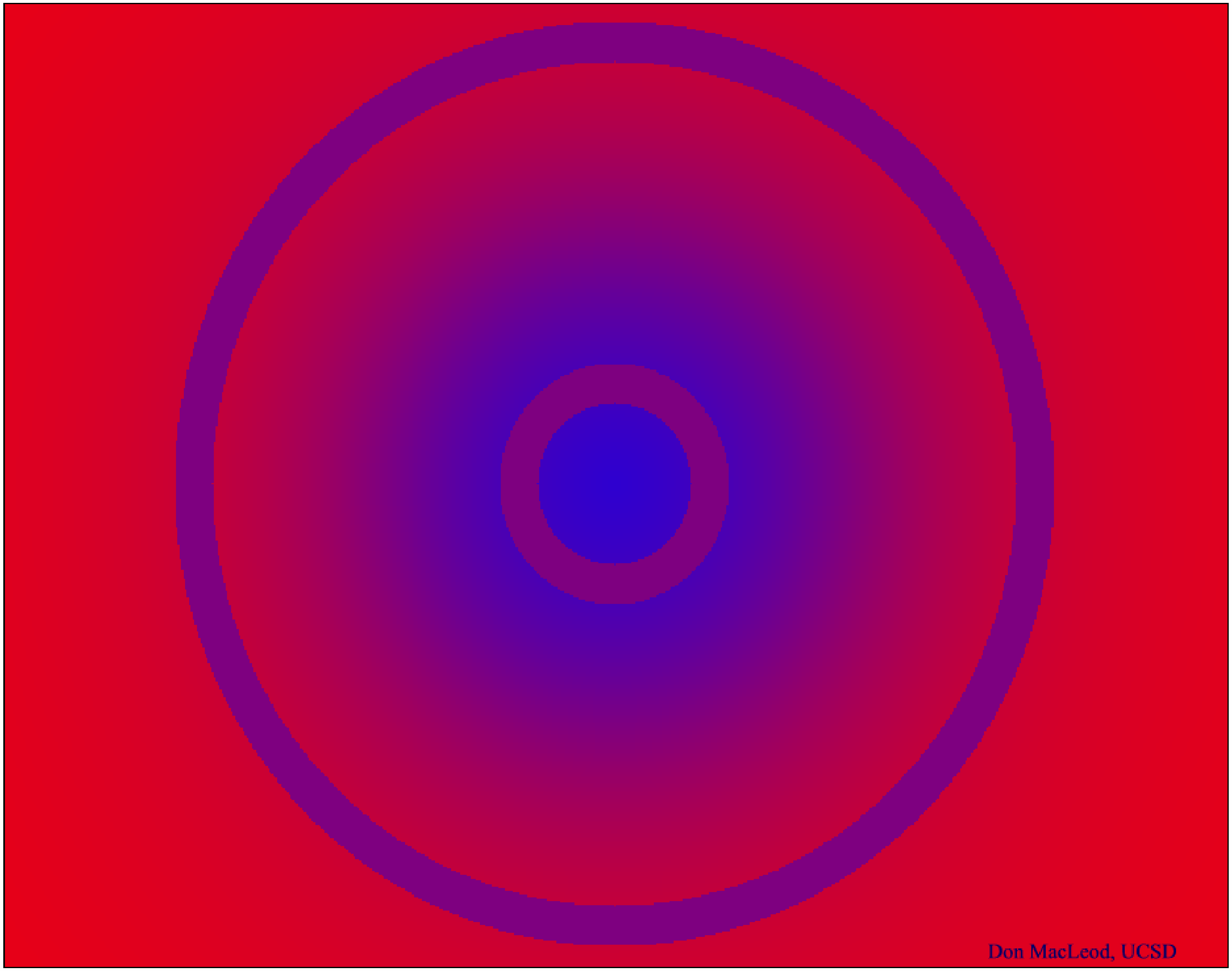
Examples:

- Light/dark adaptive state (Purkinje shift)
- Adaptation aftereffects
- Simultaneous contrast effects
- Color constancy

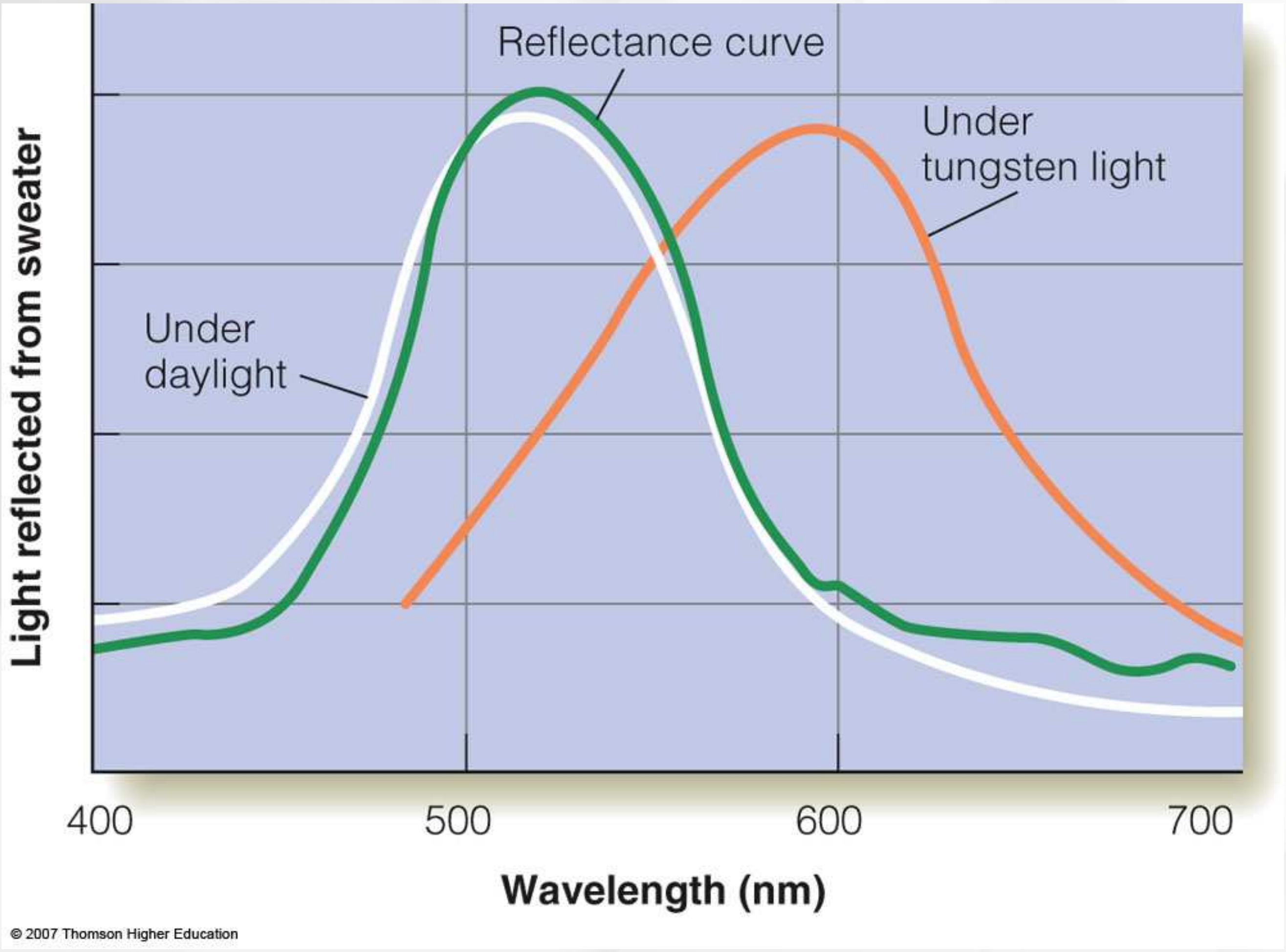
Adaptation aftereffects



Simultaneous contrast effects



‘**Color Constancy**’, is when the perceived color of objects does not vary much with changes in the illumination, even though these changes cause huge changes in the spectral light entering the eye.

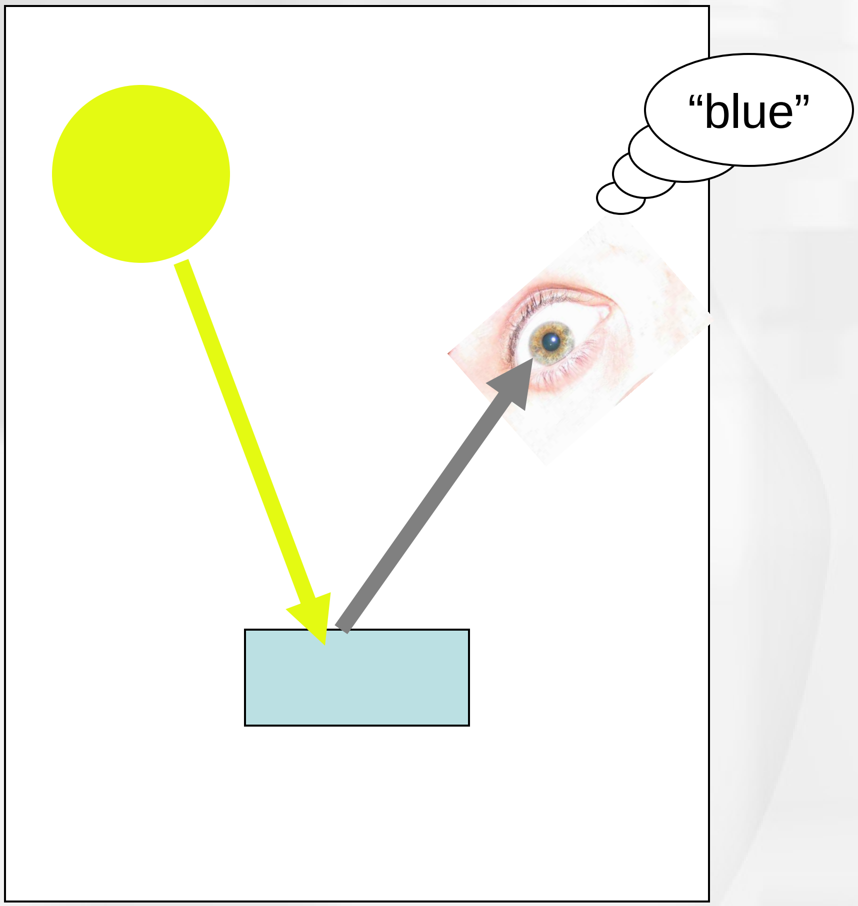


The reflectance curve of a sweater (green curve) and the wavelengths reflected from the sweater when it is illuminated by daylight (white) and by tungsten light (yellow).

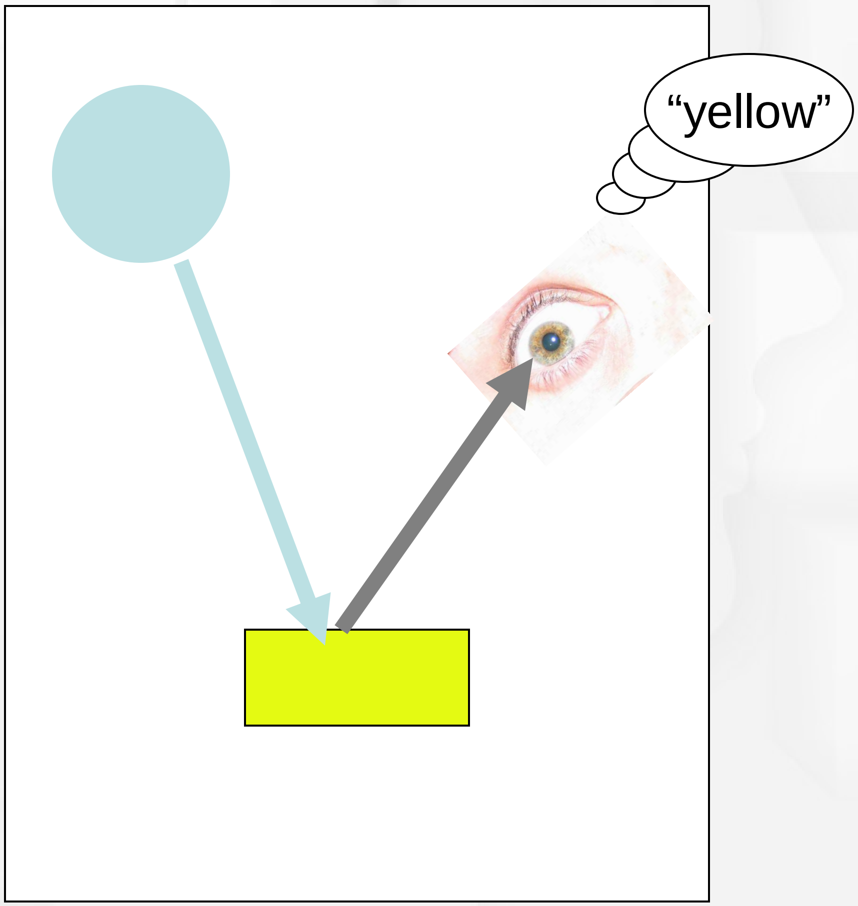
‘**Color Constancy**’, is when the perceived color of objects does not vary much with changes in the illumination, even though these changes cause huge changes in the spectral light entering the eye.

Example 1: same wavelengths entering the eye, different perceived color

Yellow light X blue surface =
gray light entering eye



Blue light X yellow surface =
gray light entering eye

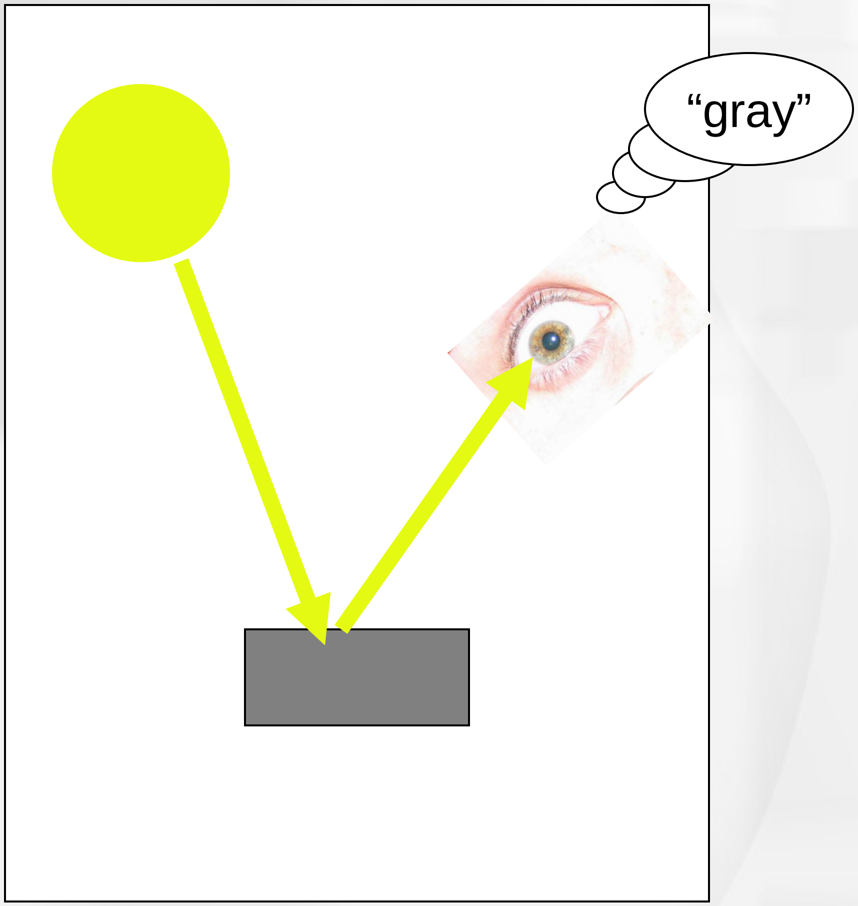


Color Constancy

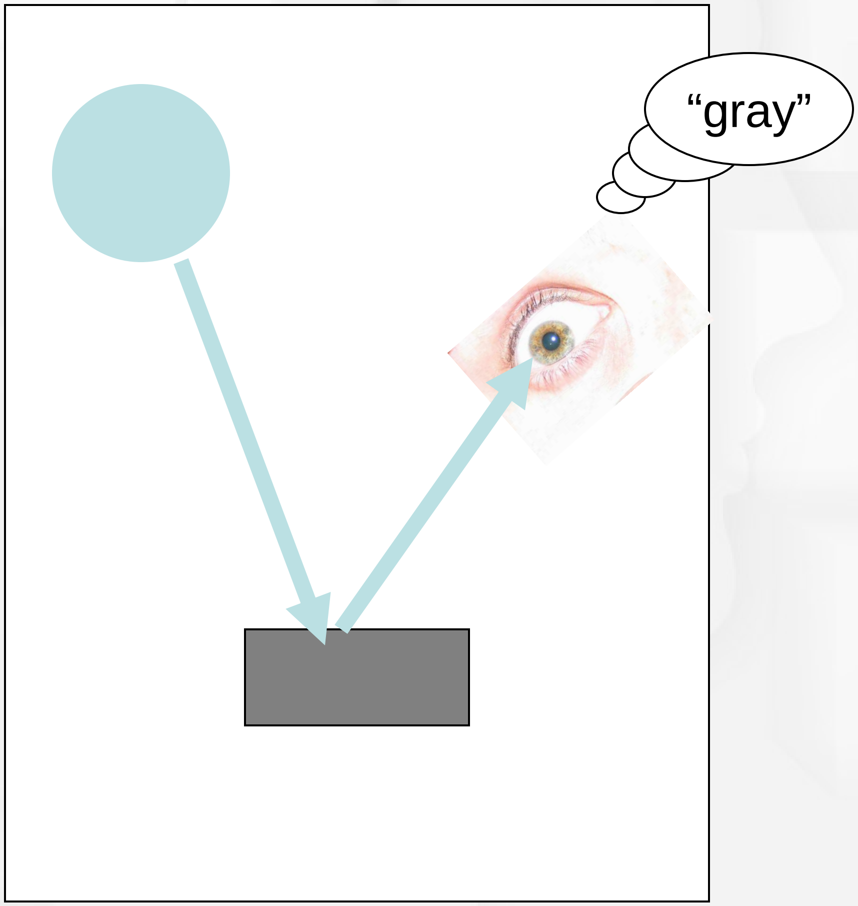
Somehow, the visual system knows the spectrum of the light source, and takes that into account when determining the reflectance properties of a surface.

Example 2: different wavelengths entering the eye, same perceived color

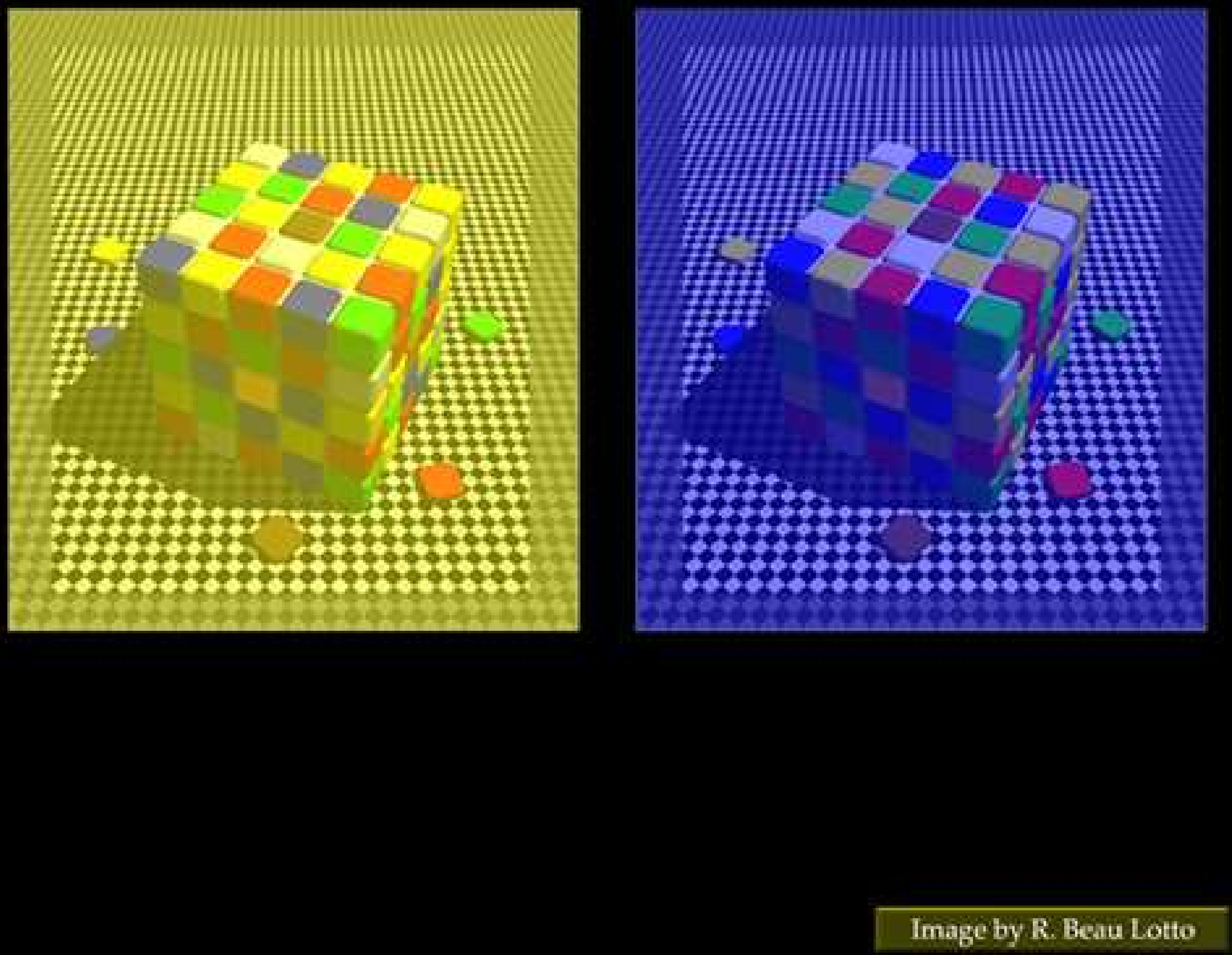
Yellow light X gray surface =
yellow light entering eye



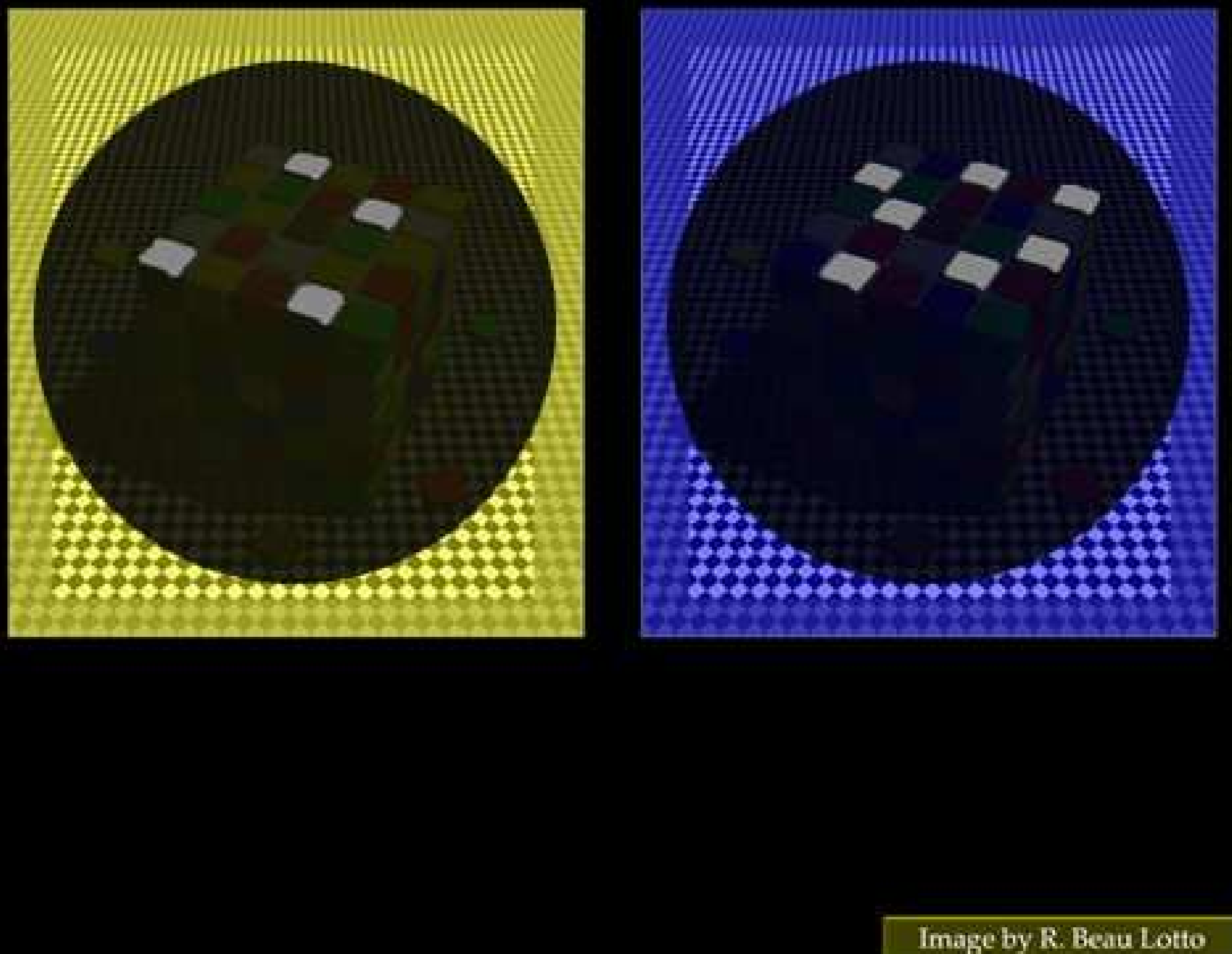
Blue light X gray surface =
blue light entering eye



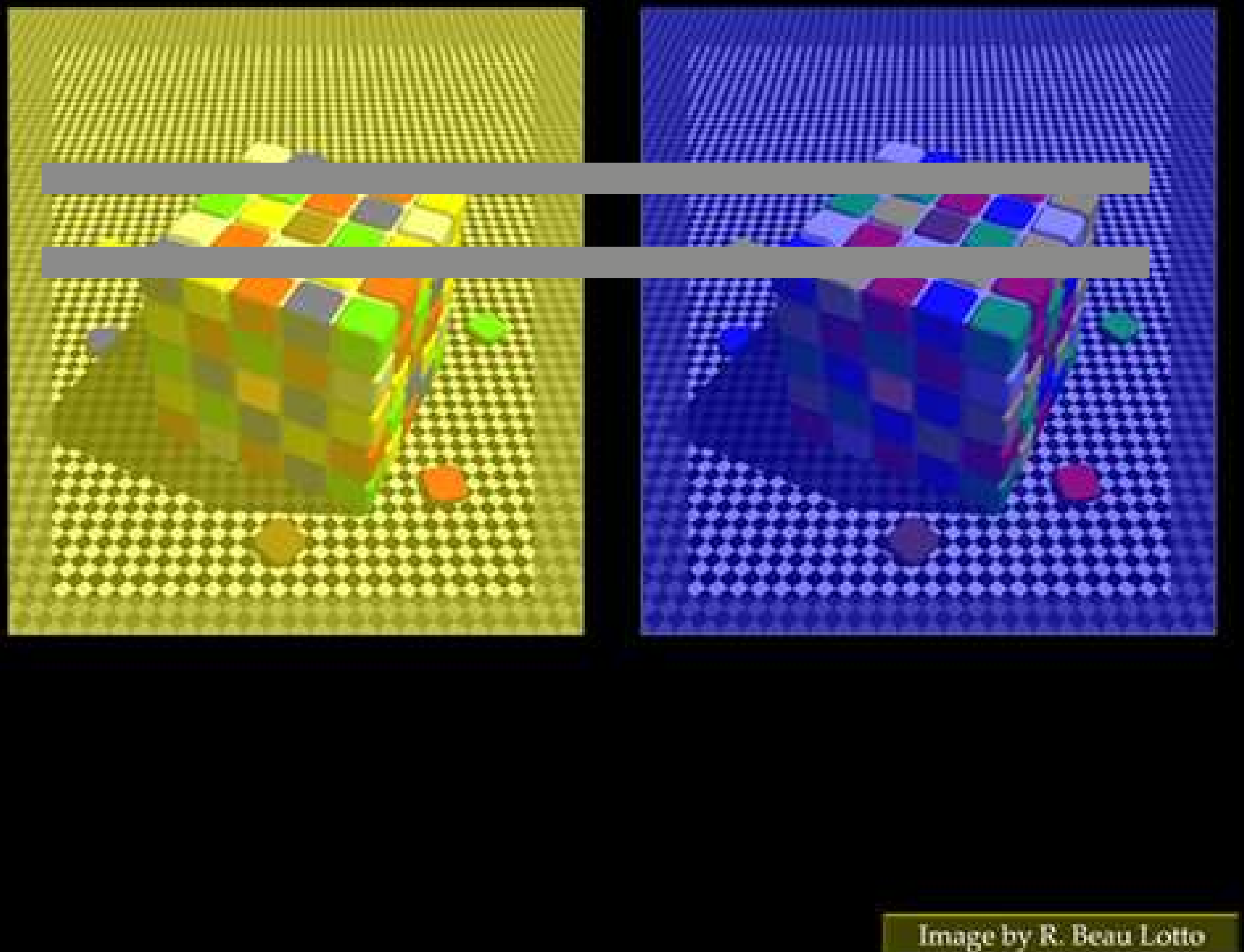
Blue squares on the left are physically the same as the yellow squares on the right!



Blue squares on the left are physically the same
as the yellow squares on the right!



Blue squares on the left are physically the same as the yellow squares on the right!

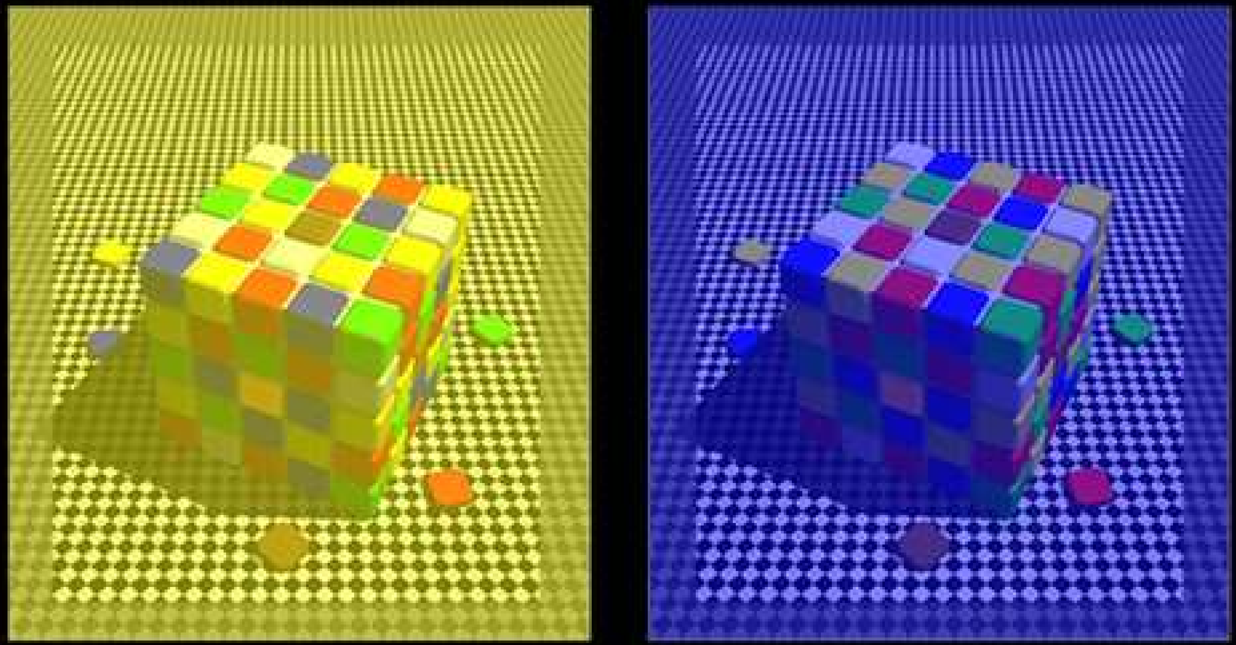


What’s going on with this illusion?

Remember, the light entering your eye is a combination of the light source and the reflectance properties of the object.

What’s important to you is the reflectance properties, not the light source.

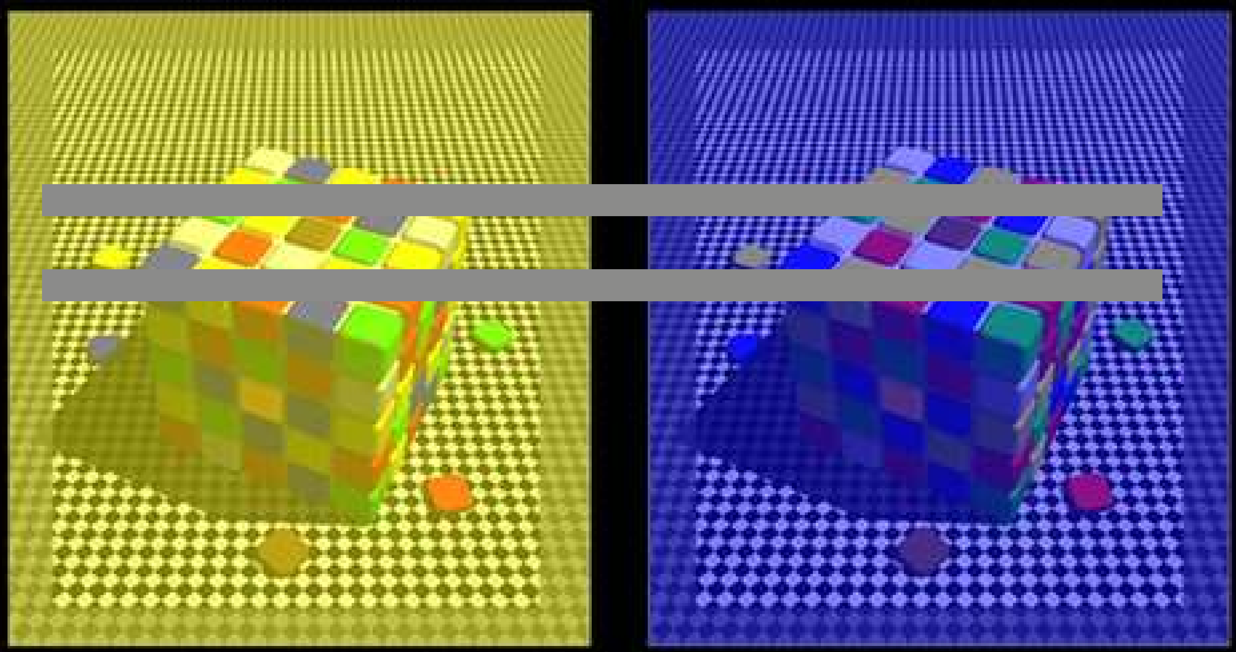
The images on the left and right are drawn to look like the same object, just illuminated by two different lights (yellow on left, blue on right).



The blue checks on the left and the yellow checks on the right are both physically gray.

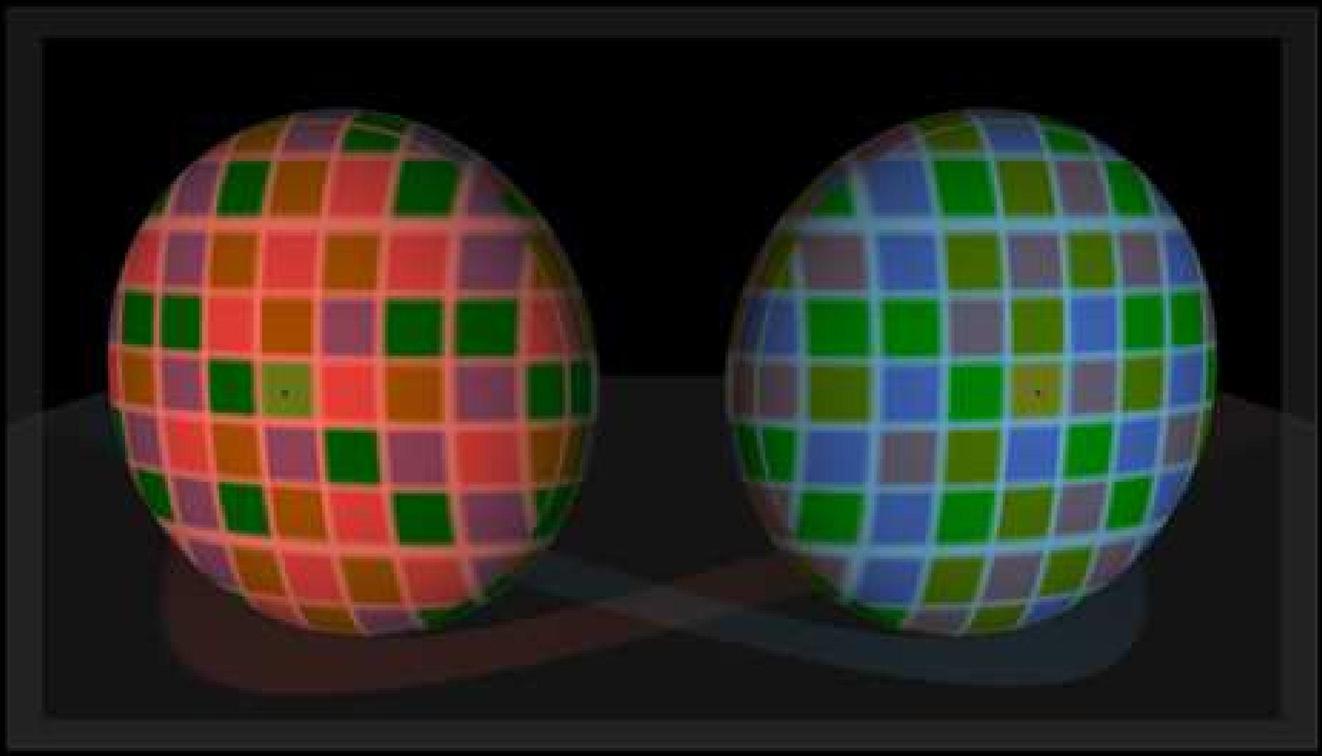
But with color constancy, the visual system knows that gray light under yellow illumination must be caused by a blue surface (left),

and the gray light under blue illumination must be caused by a yellow surface (right).

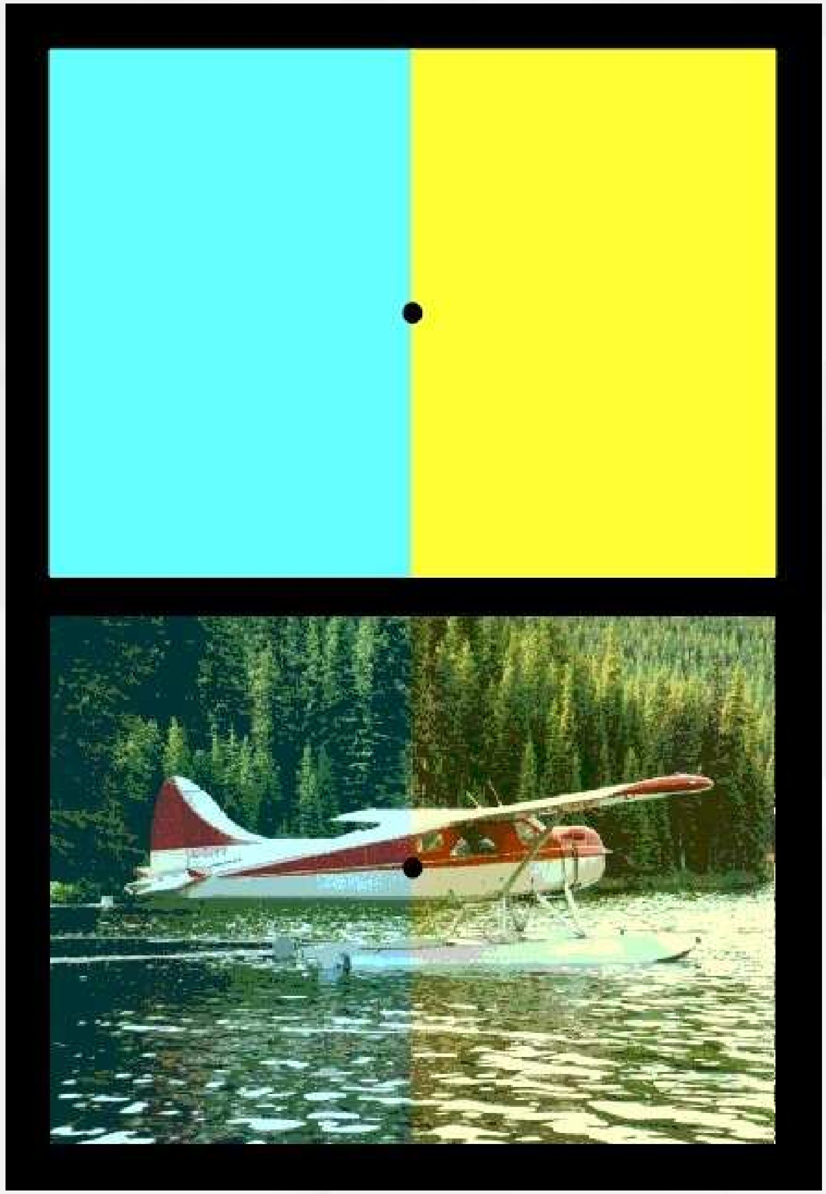


Another similar example. Center squares are physically the same, but look different.

The image is rendered to look like the two objects are illuminated by different colored lights.

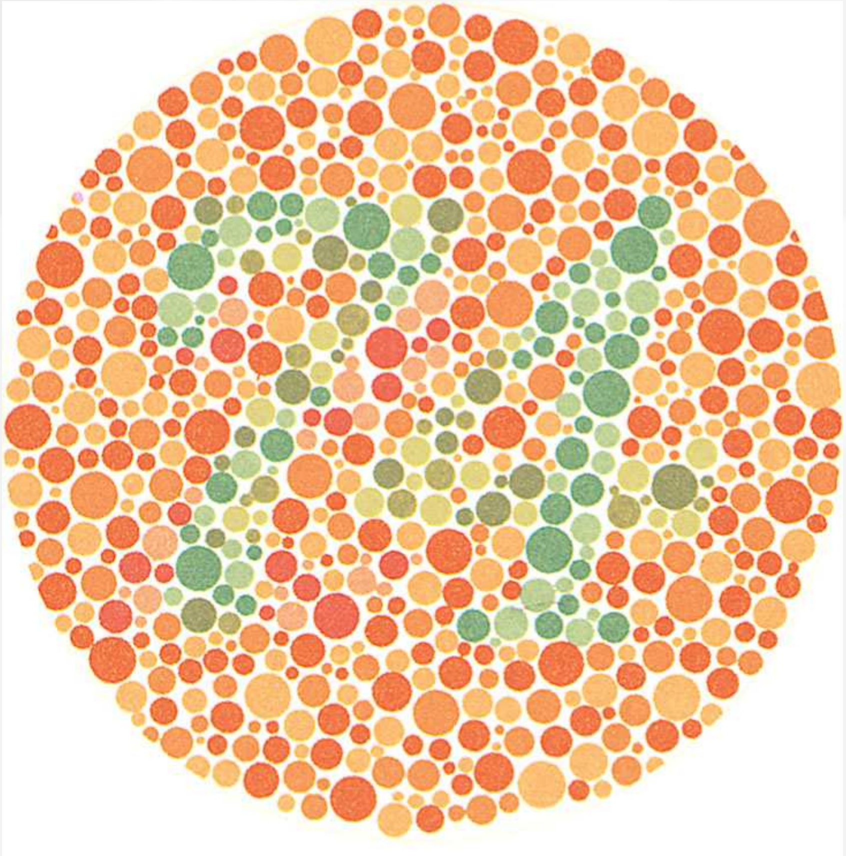


Chromatic adaptation supports color constancy



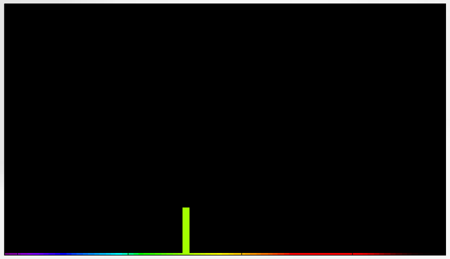
Color Deficiency ("Color Blindness")

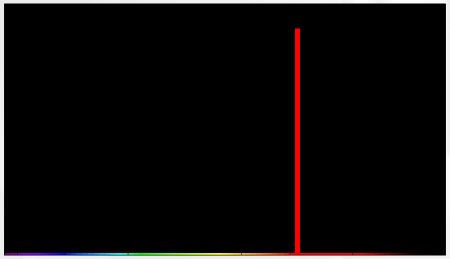
- Monochromat - person who needs only one wavelength to match any color
- Dichromat - person who needs only two wavelengths to match any color
- Anomalous trichromat - needs three wavelengths in different proportions than normal trichromat
- Unilateral dichromat - trichromatic vision in one eye and dichromatic in other

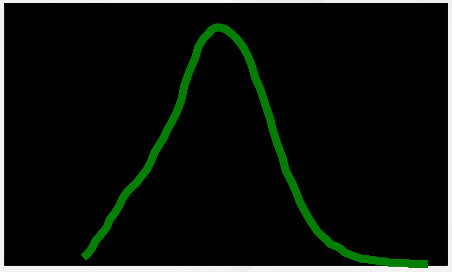


Color Experience for Monochromats

- Monochromats have:
  - A very rare hereditary condition
  - Only rods and no functioning cones
  - Ability to perceive only in white, gray, and black tones
    - Univariance
  - True color-blindness
  - Poor visual acuity
  - Very sensitive eyes to bright light







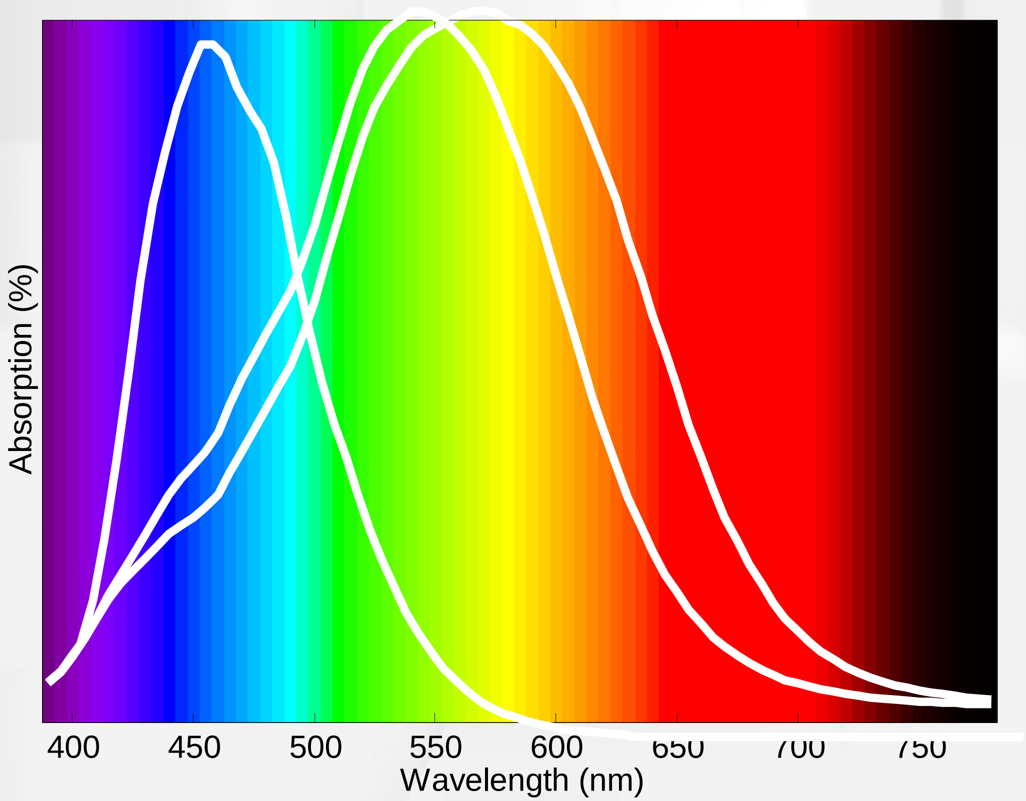
Dichromats – only two cone types

Dichromats are missing one of the three cone systems, so there are three types of dichromats.

Protanopes – missing L cones

Deuteranopes – missing M cones

Tritanopes – missing S cones



Dichromats – only two cone types

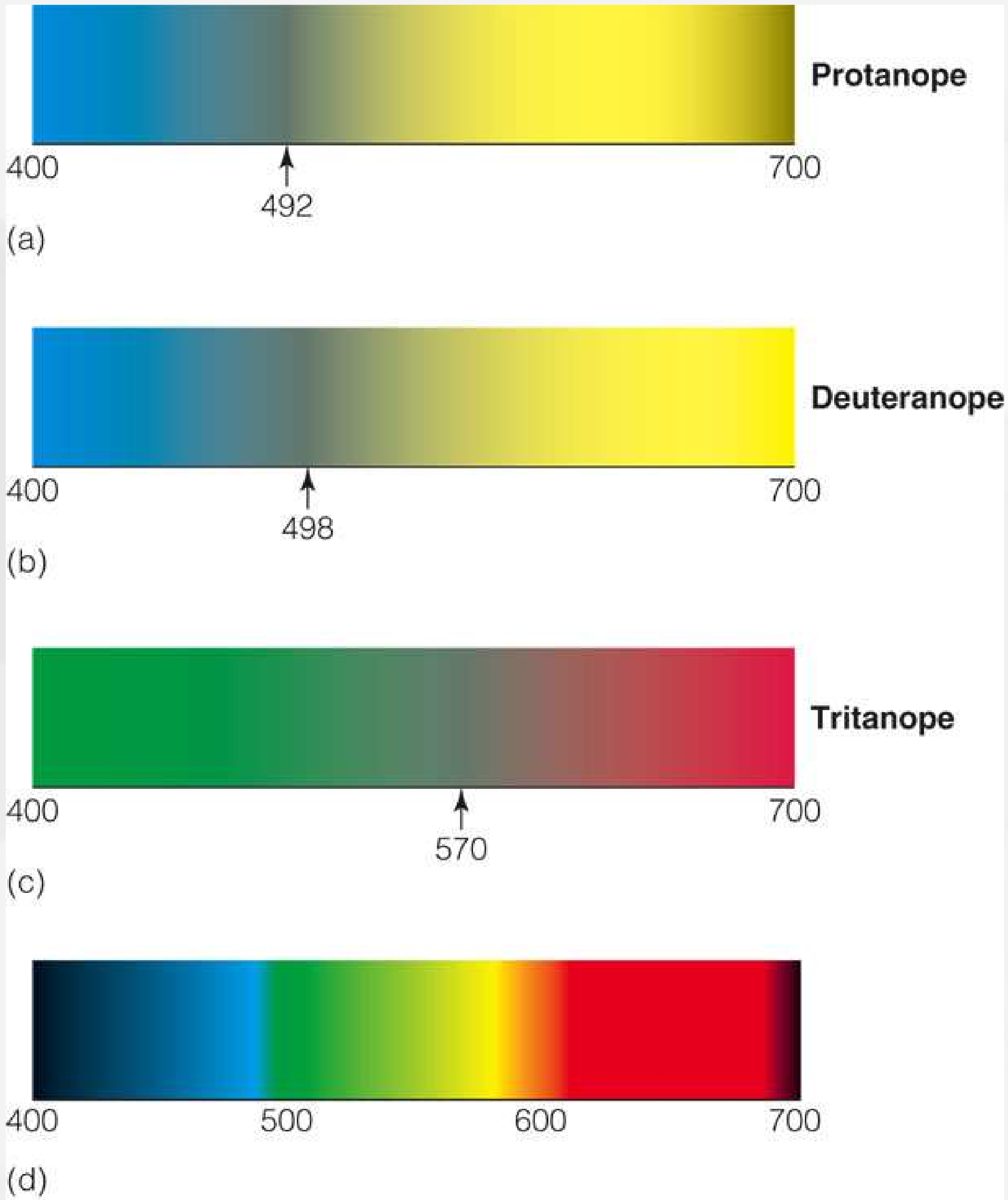
1. **Protanopia** affects 1% of males and .02% of females
   - They are missing the long-wavelength pigment
   - Individuals see short-wavelengths as blue
   - Neutral point (gray) occurs at 492nm
   - Above neutral point, they see yellow

Dichromats – only two cone types

2. **Deuteranopia** affects 1% of males and .01% of females
   - They are missing the medium wavelength pigment
   - Individuals see short-wavelengths as blue
   - Neutral point (gray) occurs at 498nm
   - Above neutral point, they see yellow

Dichromats – only two cone types

3. **Tritanopia** affects .002% of males and .001% of females
   - They are most probably missing the short wavelength pigment
   - Individuals see short wavelengths as blue
   - Neutral point (gray) occurs at 570nm
   - Above neutral point, they see red


Protanope
400
700
492
(a)
Deuteranope
400
700
498
(b)
Tritanope
400
700
570
(c)
400
500
600
700
(d)

Color Processing in the Cortex

- There is no single module for color perception
  - Cortical cells in V1, V2, and V4 respond to some wavelengths or have opponent responses

fMRI experiments on color vision show responses to color all over the visual cortex, but particularly strong responses in area V4.

V4 seems to be necessary for color vision. Damage to V4 leads to **cerebral achromatopsia** – complete color blindness, even though the cones are normal.