Color Perception

- Color vision is a key aspect of “perceptual organization”. It can be useful for detecting objects against a background.
- Color is related to wavelength. The perceptual dimensions of color are hue, saturation, and brightness.
- The perception of color has been described in terms of a trichromatic theory and an opponent process theory. Human perception seems to involve both.
- Color is one of the properties coded by the parvocellular system (the ventral pathway).

Terms and Basic Colors

Achromatic refers to black, white, and the grey scale in between. The achromatic colors result from a mixture of all wavelengths.

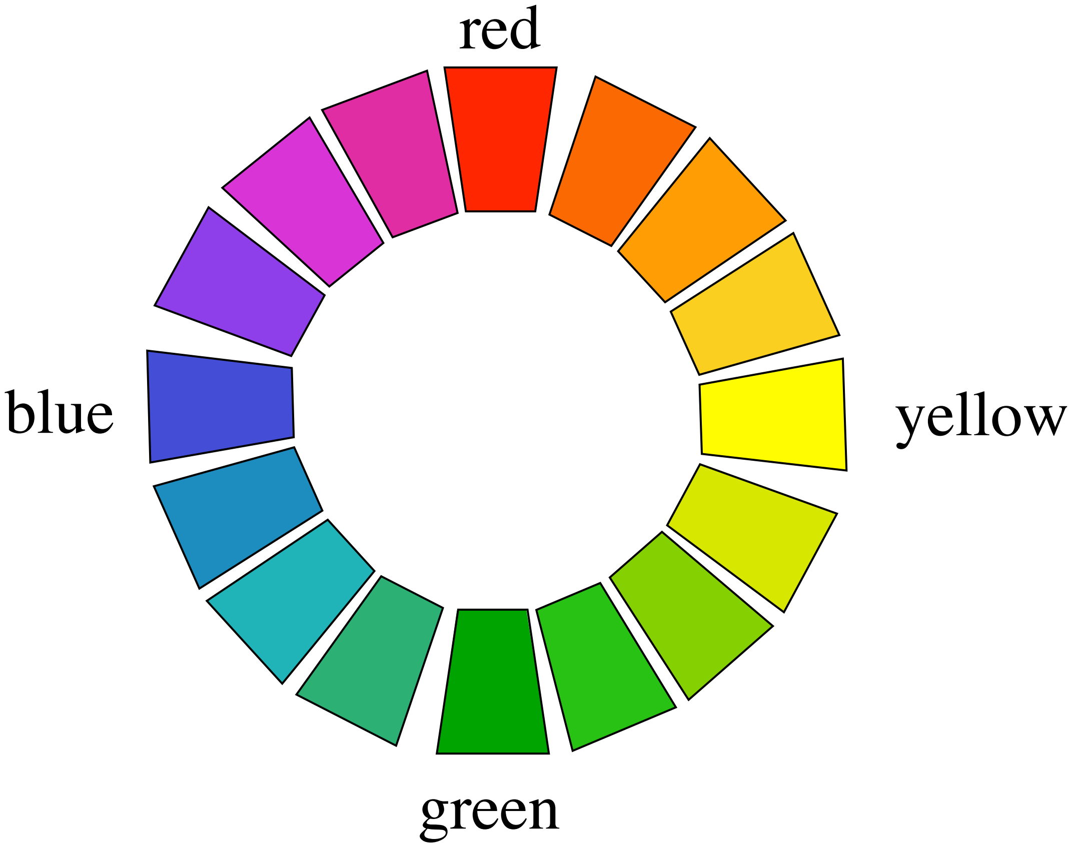
Chromatic color refers to blue, red, yellow, green, etc. We also refer to chromatic color as hue.

As white is mixed in with a hue, it appears washed-out. The hue is still the same, but the experience of color changes. This is the dimension of saturation. Pink and red are color terms that reflect a change in saturation.

As the intensity of any wavelength or set of wavelengths is changed, we experience a change in brightness.

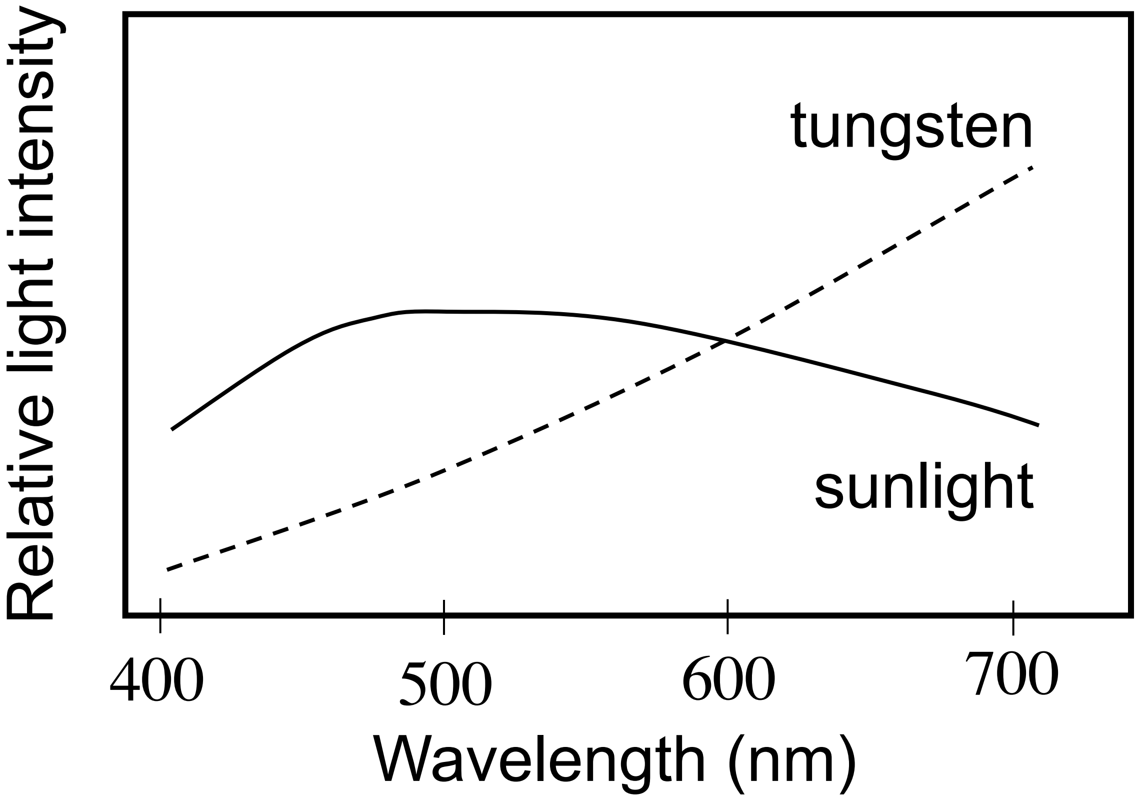
The Color Wheel

If we arrange hues so that similar colors are next to one another, we get a circular figure - the color wheel.



Color is Reflected Light

Different light sources are composed of different relative intensities of the wavelengths in the spectrum.



Hue versus Wavelength

The table below shows how the basic colors correspond to wavelengths.

Reflected Wavelengths	Perceived color
short	blue
medium	green
long	red
medium and long	yellow
a little medium and long	orange
short and long	purple
short, medium and long	white

Mixing Pigment

Mixing paint is subtractive color mixing. The wavelengths reflected from the mixture are only those also reflected by each component pigment.

wavelengths

	blue	green	yellow	orange	red
Blue Paint	Reflects all	Reflects some	Absorbs all	Absorbs all	Absorbs (most)all
Yellow Paint	Absorbs all	Reflects some	Reflects all	Absorbs all	Absorbs all

Trichromatic Theory

From color matching experiments, we know that a human can match any color by mixing (varying the intensities) of three suitable “primary” colors.

For example, given control over the intensities of lights of 420, 560, and 640 nm, the observer can match the color of any arbitrary mixture of wavelengths. Because humans require three primaries, our color vision is known as trichromatic.

If given only two primaries, there are colors that can not be matched.

Trichromatic Theory - 2

Young and Helmholtz proposed that color vision was mediated by three different receptors that absorbed light of different wavelengths to different degrees.

Color perception was proposed to be based on the pattern of responses from the three receptors. Thus, humans could match any color by mixing three suitable primaries.

This theory, based on psychophysical data, preceded the discovery of three different types of cones by over a century.

Trichromatic Theory - 3

Based on trichromatic theory, we expect to find three types of dichromatic color-blindness. One would correspond to the loss of each of the three different receptors.

There are three forms of dichromatism: protanopia, deuteranopia, and tritanopia.

However, there are also data that trichromatic theory has a hard time explaining.

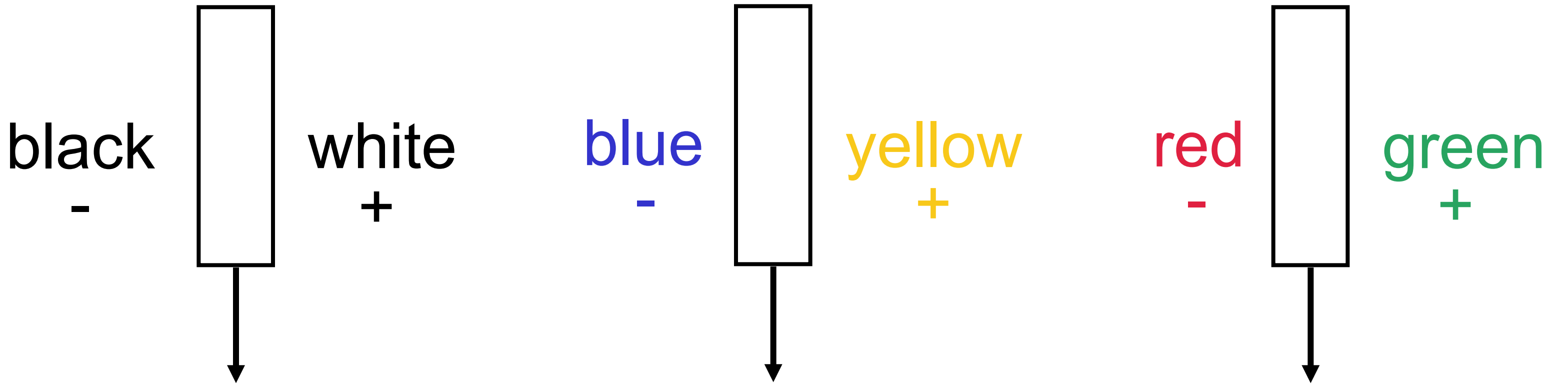
Opponent Process Theory

What are the basic colors? Is yellow any less basic than red, green, and blue?

When you stare at a color, then look at a white area, you see an afterimage. Blue and yellow are paired (stare at blue, see a yellow afterimage) and vice versa. Similarly, red and green are paired. Why?

To account for observations like these, Hering proposed the opponent process theory of color vision.

Opponent Process - 2



black - | white +

blue - | yellow +

red - | green +

Hering proposed that colors are signaled by three mechanisms that respond in opposite ways to the two colors in their pair. While Hering's proposal does not describe the receptors in the retina, it does have a relation to the physiology of color vision.

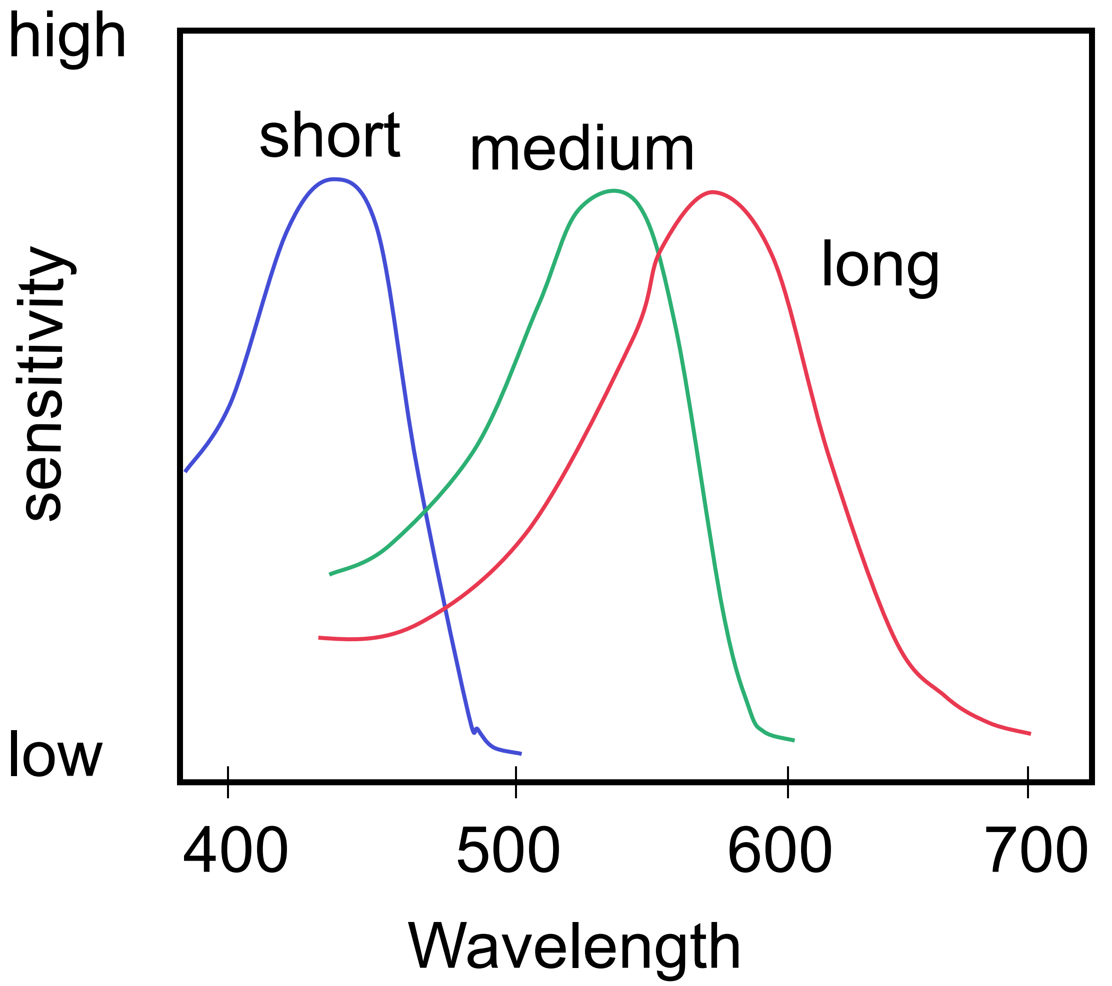
Physiology of Color Vision

Trichromatic theory describes the operation of the receptors (cones) in the retina. There are three different cones that have different spectral absorption curves.

This is the reason why it takes three primaries for a human to mix and match any other color.

This leads to metamers - Different combinations of wavelengths that appear the same because they stimulate the receptors in the same ratios. For example, it is possible to adjust the intensities of 530 nm and 620 nm lights so that when mixed the result appears identical to a single, 580 nm light.

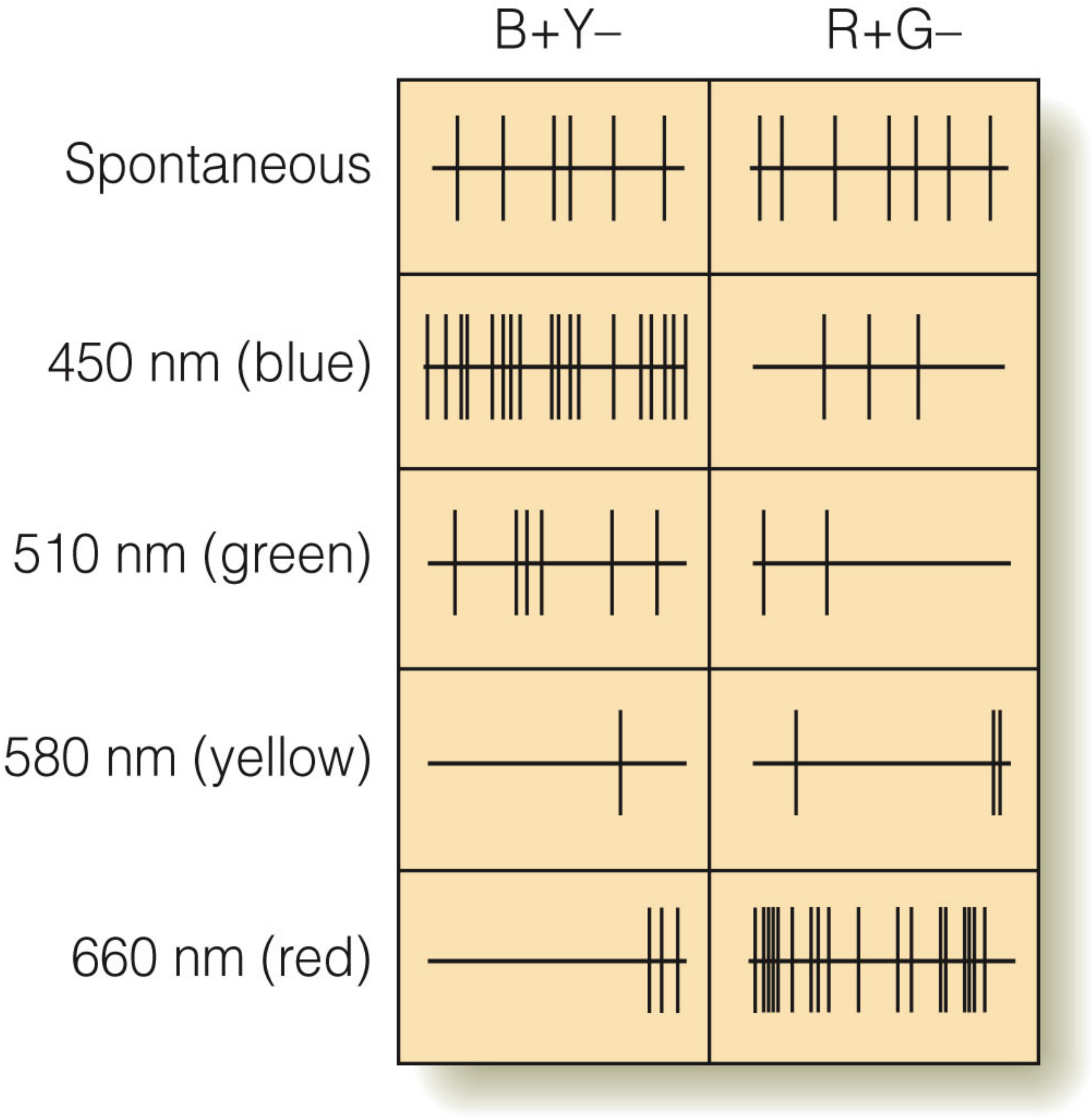
Three Cones - Spectral Absorption



Opponent Processes Physiology

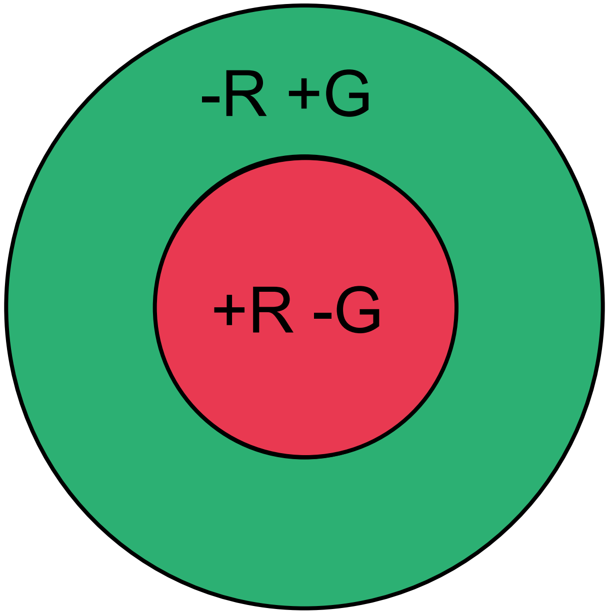
In the ganglion cells of goldfish, the cells are color sensitive. They behave in an opponent fashion where a cell may respond positively to blue but be inhibited (fire less than its spontaneous rate) by yellow. The colors blue and yellow and red and green are always paired.

In the LGN of the monkey, the color sensitive cells in the parvocellular system show the same property (see next slide).


B+Y–
R+G–
Spontaneous
450 nm (blue)
510 nm (green)
580 nm (yellow)
660 nm (red)

Opponent Process Physiology - 2

In the cortex of the monkey we find double opponent cells. In the center, this cell might be excited by red and inhibited by green. In the surround, the opposite pattern is found with excitation by green and inhibition by red.



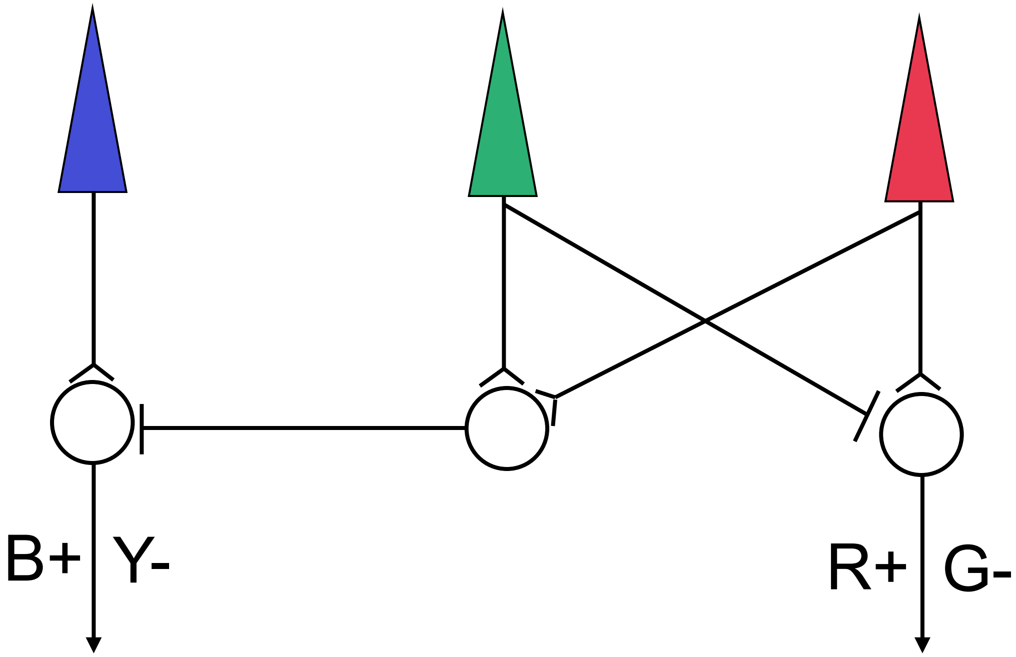
Opponent Process Physiology - 3

In the striate cortex, if we look within a hypercolumn, we discover that all of the color sensitive cells in a hypercolumn respond to the same color pair and an adjacent hypercolumn would code the other color pair.

How does the trichromatic coding of color at the receptor get converted to an opponent color scheme?

Why have an opponent scheme?

Wiring in Color Vision



Properties of the Hybrid Model

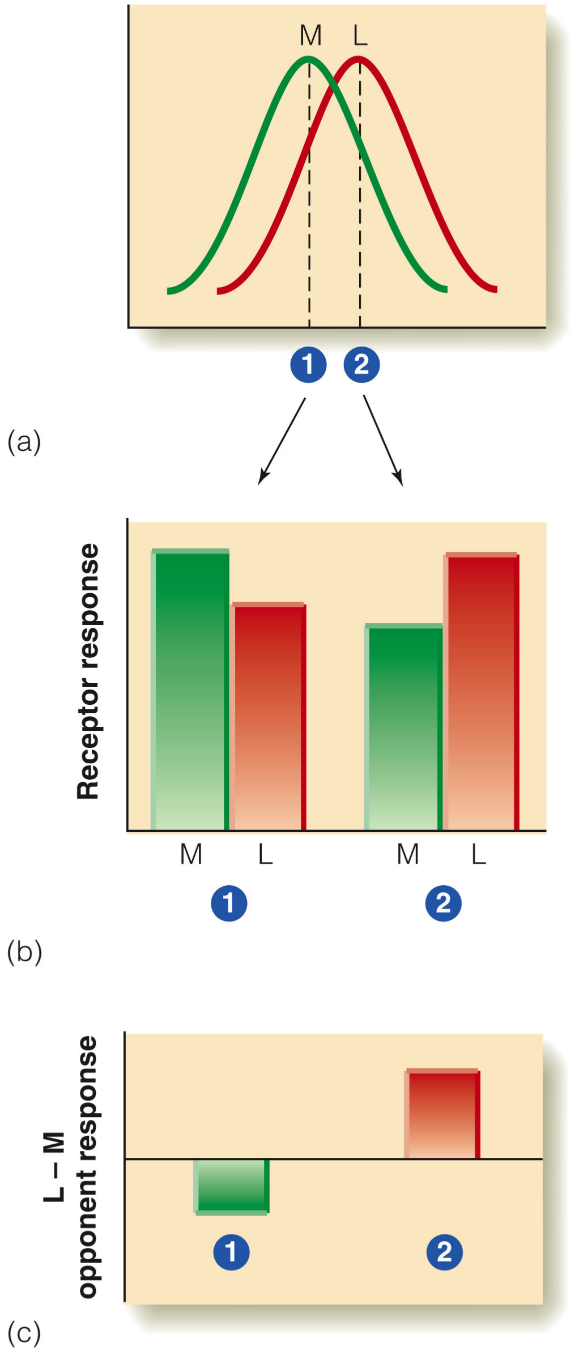
1. Color mixing would depend upon three primaries.

2. Yellow/Blue and Red/Green exist in opponent pairs.

3. Three types of dichromatic color blindness are predicted - Two are red/green and one is blue/yellow.

4. Long wavelength reds should look a bit yellow. An "optimal" red is the result of mixing a small amount of short wavelength with the predominantly long wavelength.

5. The neural coding reduces the overlap in color by sharpening the differences between adjacent cone spectral absorption (see next slide).


M
L
1
2
(a)
Receptor response
M
L
M
L
1
2
(b)
L – M
opponent response
1
2
(c)

Color Blindness

1. Monochromatism. Rod only vision. Hereditary and occurs in about 10 in 1,000,000 people.

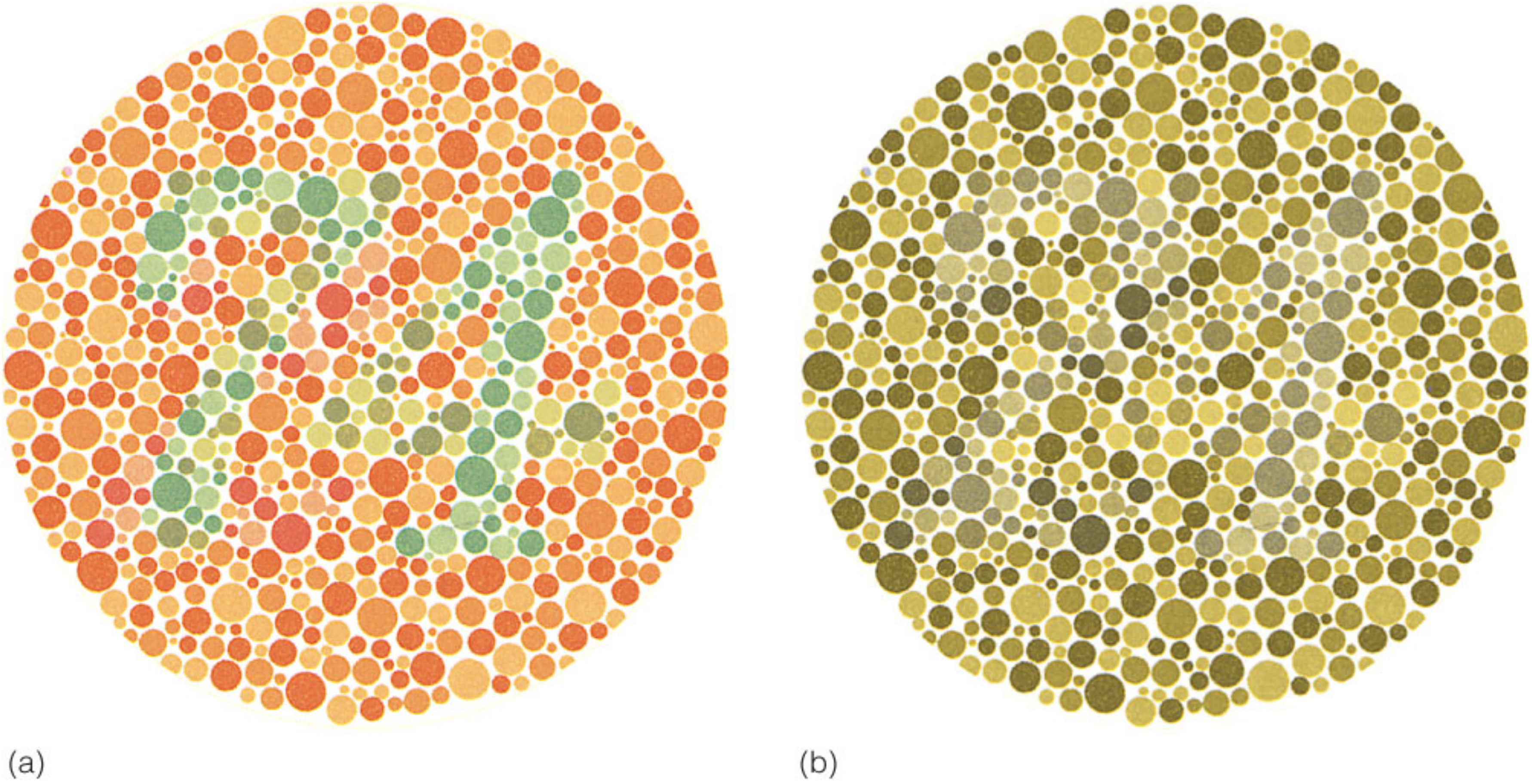
2. Dichromatism - Three types corresponding to loss of long wavelength cone (protanopia), medium wavelength cone (deuteranopia) and [we think] the short wavelength cone (tritanopia). Sex-linked, inherited disorder (based on X chromosome).

Dichromatism

Protanopia and Deuteranopia are two forms of red/green colorblindness. Each occurs in about 100 in 10,000 males (1%) and 2 in 10,000 females (.02%).

What colors does a dichromat see? Rarely, a human is trichromatic in one eye and dichromatic in the other. Based on their description, reds and greens that look normal in the trichromatic eye look “beige” (yellowish) in the dichromatic eye.

For both protanopes and deuteranopes, there is a neutral point between blue and yellow.


(a)
(b)

Dichromatism - 2

Tritanopia is blue/yellow color blindness. It is very rare (about 2 in 100,000 males and less than 1 in 100,000 females). It is thought to represent the loss of the short wavelength cone.

Color Vision Summary

- Color vision is both trichromatic at the receptors and opponent process at the LGN and later.
- Color is coded in a separate set of neurons and is part of the parvocellular system and the ventral pathway.
- Dichromatism is the result of the loss of one type of cone, but results in the loss of a pair of colors.
- Color is a “synthetic” percept. It is a creation of the brain. Color perception is a private, mental experience.

Perceptual Constancy

- As you move, or objects move, or lighting changes, the image on the retina (proximal stimulus) changes. However, perception is of a constant distal stimulus. This is perceptual constancy.
- In vision, this occurs for color, lightness, shape and size.
- Knowledge has only a limited effect on perceptual constancy.

Color Constancy

When the spectrum of light that falls on an object changes, color perception is only slightly altered. Incandescent light has more of the red end of the spectrum and less of the blue than sunlight. However, colors look basically the same under the two. This is color constancy.

In comparison, if the same photographic film is used with both sunlight and incandescent light, colors that look normal under sunlight will all look orangish/reddish under incandescent.

The objects being photographed have not changed. Our perception seems to follow this distal stimulus. How?

Color Constancy - 2

Factors affecting color constancy include:

1) Chromatic adaptation

2) Effects of surrounding areas

3) Memory for color

Chromatic adaptation

In chromatic adaptation, the cones adjust to the ambient amount of reflected light at each wavelength. Under incandescent light, the overall amount of long wavelengths (the red end of the spectrum) reaching the eye is higher.

The long wavelength cones bleach out more (more of their photo pigment is used up). This makes the eye less sensitive to the long wavelengths. So, the balance among the wavelengths in their influence on perception is (partly) restored and your perception of color is unchanged.

Chromatic adaptation experiment

An observer views a patch of paper normally seen as green under the conditions below. When the light illuminating the patch does not match the observer's chromatic adaptation, color constancy disappears.

Condition	Light on Paper	Observer Adaptation	Perception
Baseline	white	white	green
No chromatic adaptation	red	white	yellow (shifted toward red)
Chromatic adaptation	red	red	Green (slightly shifted to red)

Surroundings

When color constancy is tested on a plain white background, it “works” less well. Here, observers report more of an apparent change in color.

When color constancy is tested on a background of other, varied colors, then the object being tested appears the same color.

Memory

Color constancy can be demonstrated for meaningless stimuli that can have any color, such as a square.

If objects that have a consistent color are used in color matching task (e.g. heart and apple are characteristically red), then the color that an observer matches them to will tend toward their characteristic color.

When an observer matches the background color to the object color of a red apple, heart, mushroom or bell, the background color chosen is redder for the heart or apple.

Color constancy physiology

Simultaneously record from neurons in V1 and V4 that respond to +G-R in same receptive field.

For “green” square illuminated with white light, both V1 and V4 neurons fire.

For the same “green” square illuminated with reddish light, V1 neuron does not fire, but V4 neuron does.

Thus, V1 neuron responds to wavelength (proximal stimulus) but V4 neuron responds to color (distal stimulus). V4 neuron probably gets input from adjacent areas (influence of surroundings).

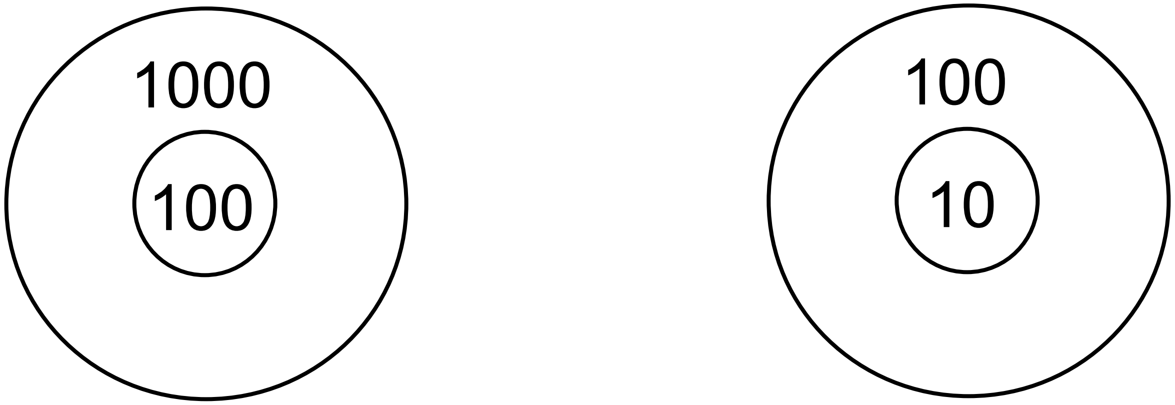
Lightness Constancy

On a sunny day with snow cover in winter, a black surface outdoors will reflect more total light than a light grey or white surface does indoors. However, the outdoors black looks black and the indoors white looks white. How?

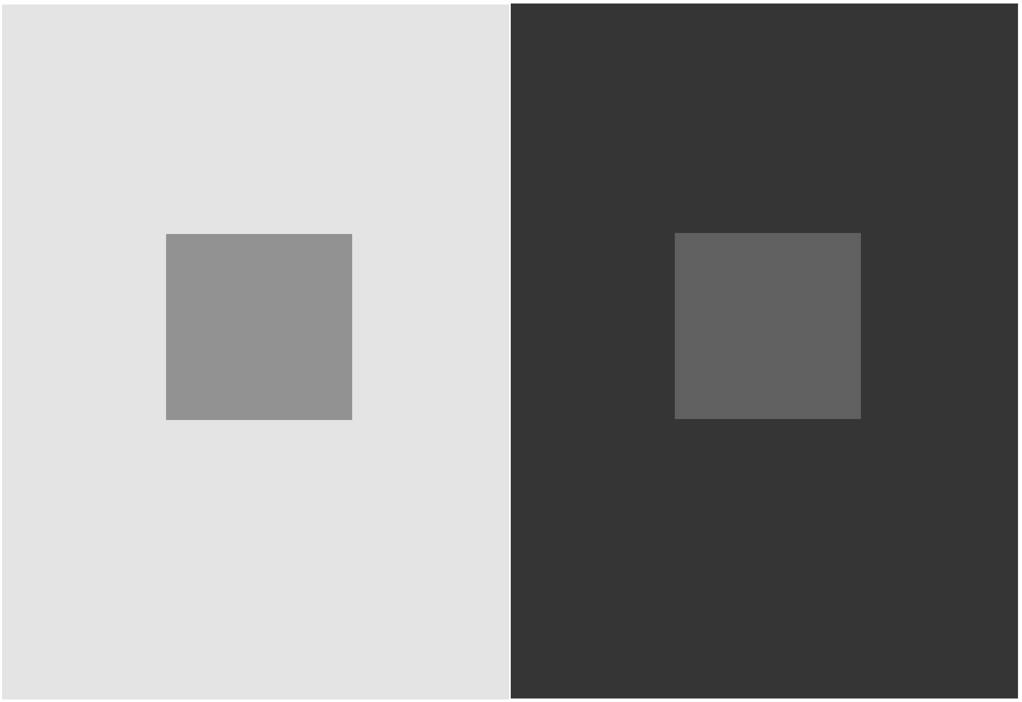
The starting point for our answer is the same as with color. Pigment bleaching in the retina reduces sensitivity and objects are compared to their surroundings.

Lightness constancy - Ratios

The effect of the surroundings is to provide an invariant (something that does not change with changes in illumination) for lightness - the ratio of reflectance across different, adjacent areas. In the disks below, the ratio between center and surround is the same and the relative lightness of the two sets will look the same.



Lightness Ratios - 2



In this display, the two small squares look to be about the same lightness. This is because their ratios to their backgrounds are the same. The two small squares are quite different.

Lightness Ratios - 3

Here are the two small squares on the same background. They no longer appear the same.

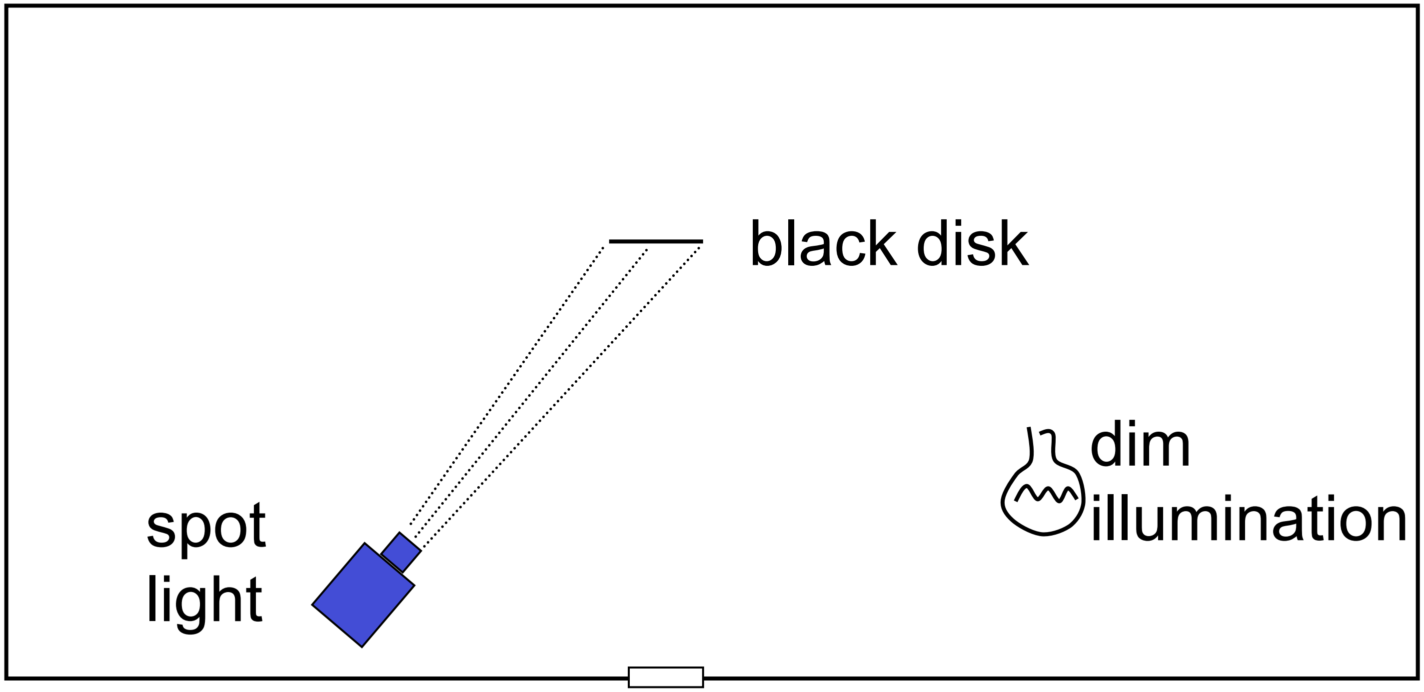
Lightness constancy experiment

Gelb had an observer view a disk that was black. The observer looked through a viewport. The interior was dimly illuminated. Under these conditions, the disk looked black.

Next, a narrow spotlight, unseen by the observer, illuminates only the disk. Now, the disk looks white.

Finally, a small white rod is positioned in front of the illuminated disk, now the disk looks black. As the rod is removed from view, the disk flips back to white. Re-introduce the white rod, the disk looks black. The knowledge of the observer has virtually no influence on lightness perception here.

Lightness constancy experiment - 2

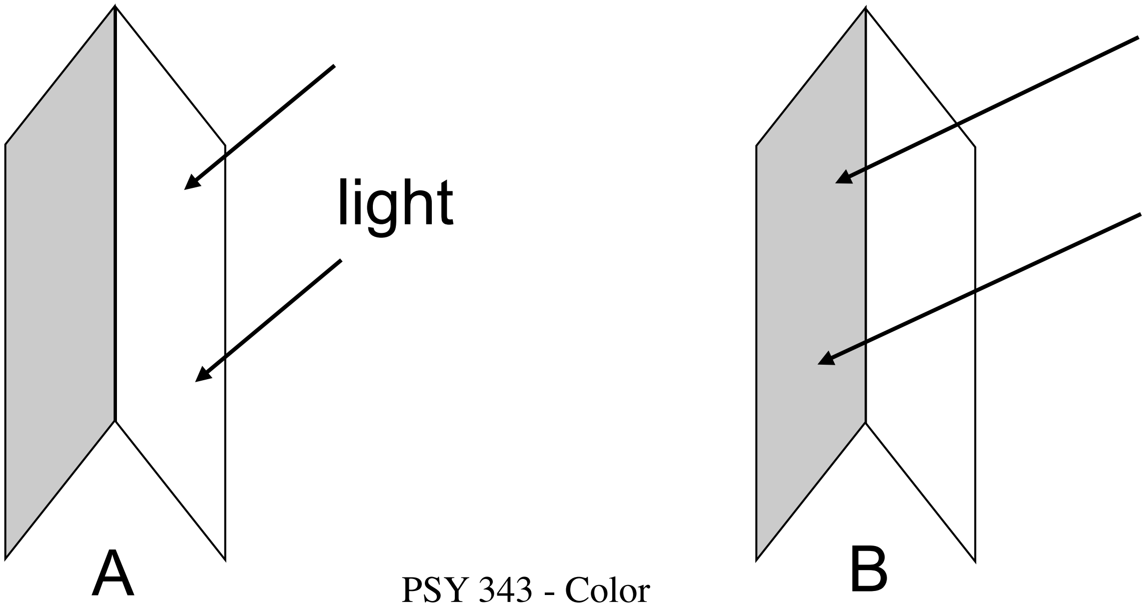


observer

Lightness - Interpretation

The perception of lightness is altered by the interpretation of the surface. This includes effects of depth and shadows.

Depth - a surface in depth can be illuminated or in shadow. If the apparent depth changes, then the apparent lightness of the surfaces changes.



Lightness - Interpretation 2

In display A, the center edge appears to project toward the viewer. The card appears uniform even though the left side is in shadow and reflecting less light.

In display B, the same card appears to have the center edge further away (like an open book). The left side then must be in the light and the right in shadow. However, the left side is reflecting less light and the right side is reflecting more. The perceptual interpretation is that the left side is darker and the right side is lighter.

Lightness - Shadows

Areas of a surface in shadow are seen as the same color and lightness as the areas not in shadow. If the edge (penumbra) of the shadow is covered, then the shadowed area appears to be a different lightness.

Lightness constancy - Physiology

Part of the explanation is lateral inhibition. We used this to account for simultaneous contrast, and it works well here for the same situations.

For influences of depth and shadows, other factors are needed. The higher cortical mechanisms that produce lightness constancy have not (yet) been discovered.