Color Vision

Wu Xihong

Peking University

What is color?

- "Objects look colored because they are colored."
- "The sky looks blue because it is blue."

Facebook's logo

- Color is a psychological property of our visual experiences when we look at objects and lights, not a physical property of them.
- Color is the result of complex interactions between physical light in the environment and our visual nervous systems.

The effect of color in object detection

The effect of color in object recognition

The computational problem of color perception

Marr proposed that the best place to start in understanding any complex information processing system is at the computational level, describing the input, the output, and the principles underlying the mapping from input to output.

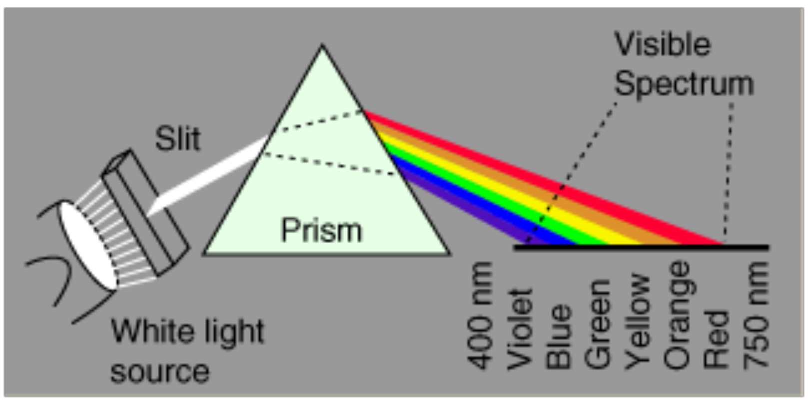
Input information: physics

How to map?

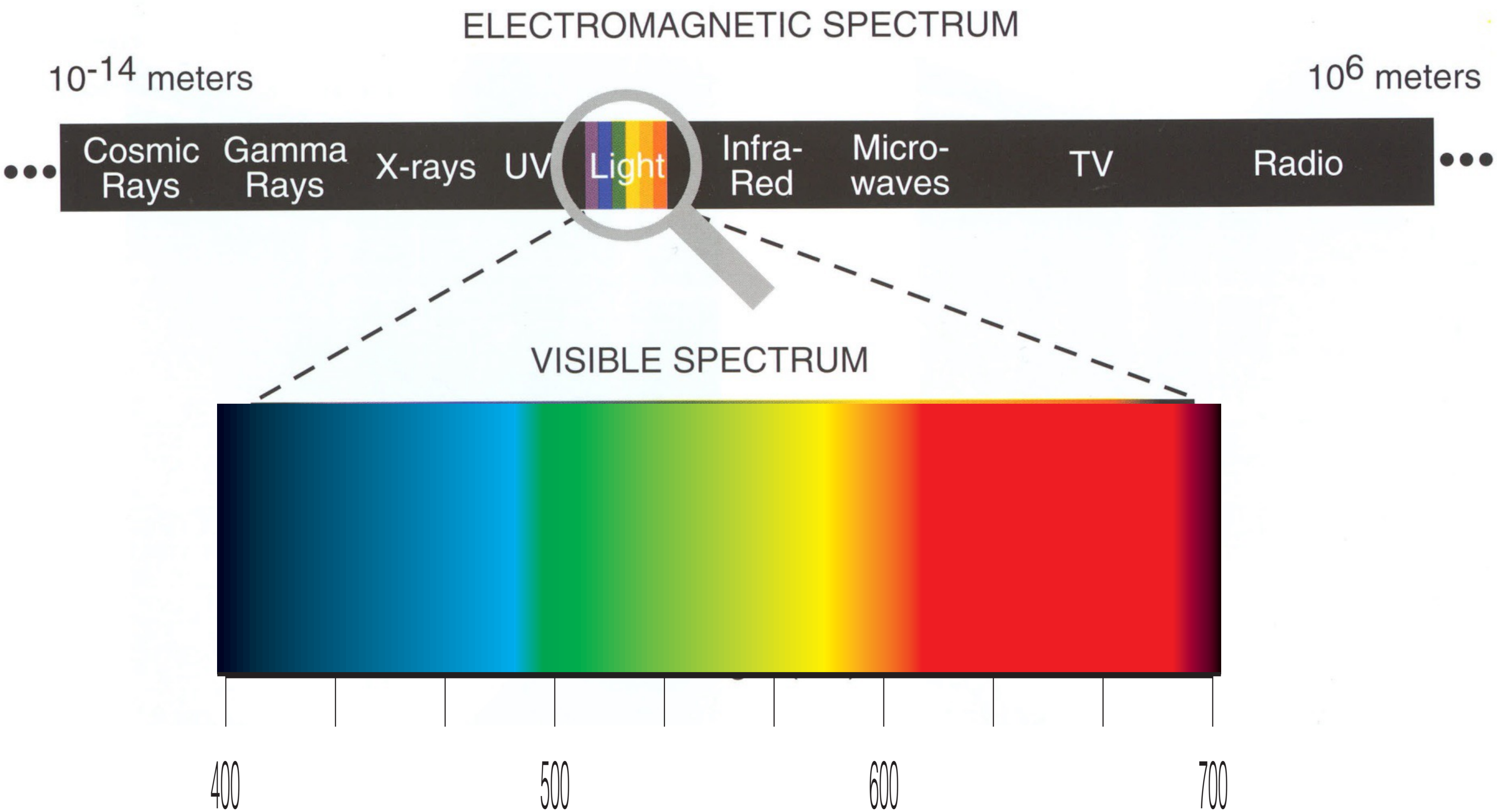
Output information: psychology

1. The Computational Description of Color Perception

The physical description of light



- Great English physicist Isaac Newton
- Realize that the “colors” were not in the light itself, but in the effect of the light on the visual system.

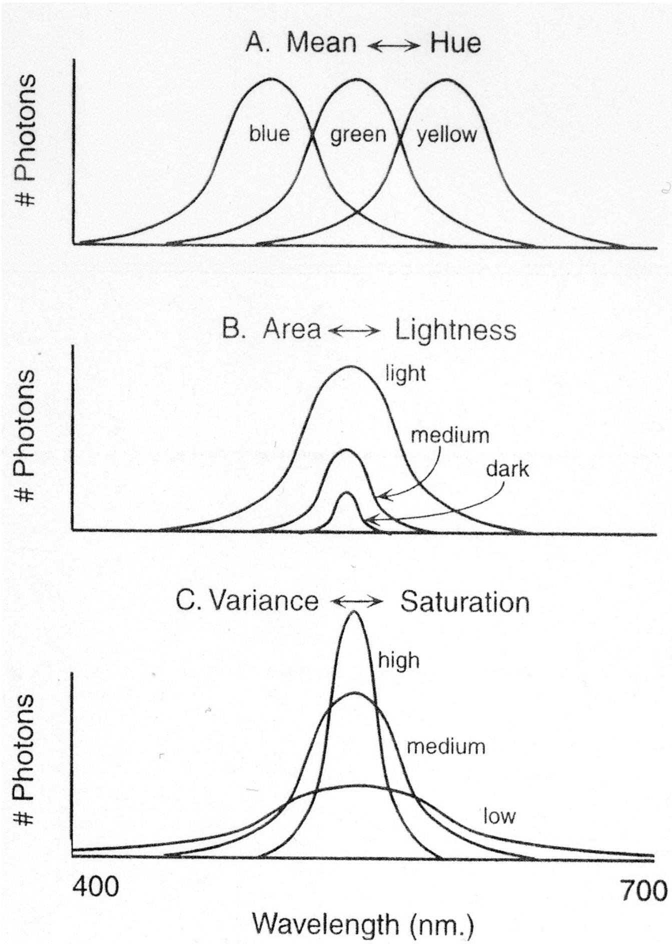


The Human visual system is sensitive only to photons with wavelengths between about 380 and 740 nanometers.

The psychological description of color

- Color becomes relevant only when light enters the eyes of an observer who is equipped with the proper sort of visual nervous system to experience it.
  - "The rays to speak properly are not colored."
  - "Whether a tree that falls in the forest makes a sound if nobody is there to hear it."

The psychophysical correspondence

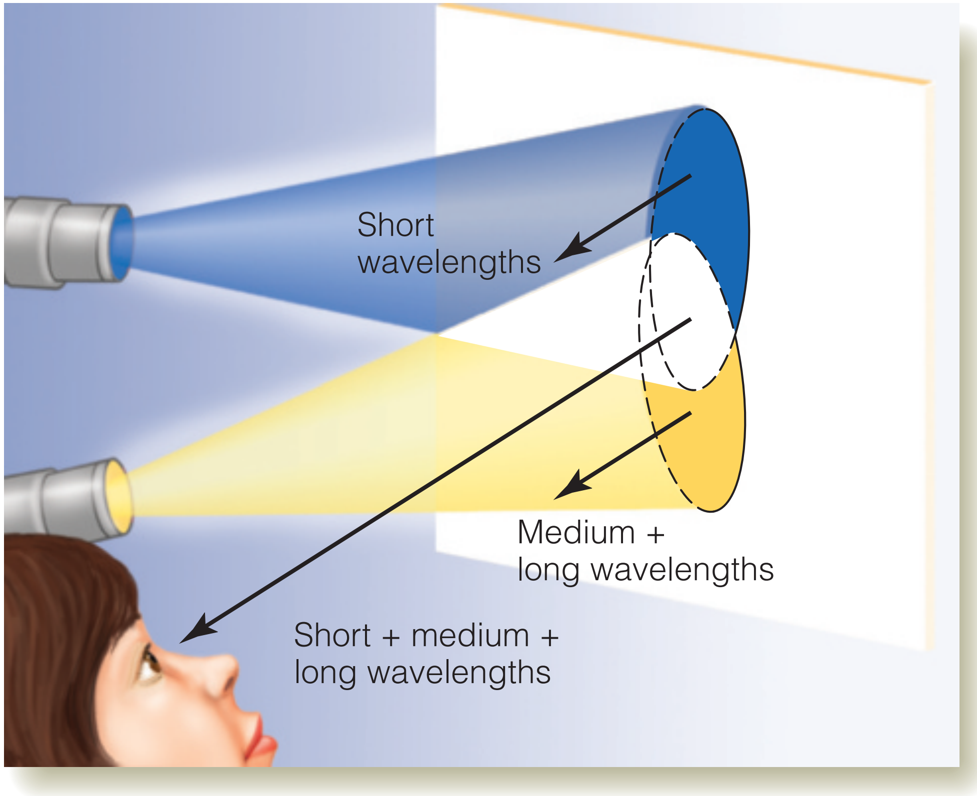


- Mean wavelength determines hue.
- Spectral area determines lightness
- Variance (width) determines saturation.

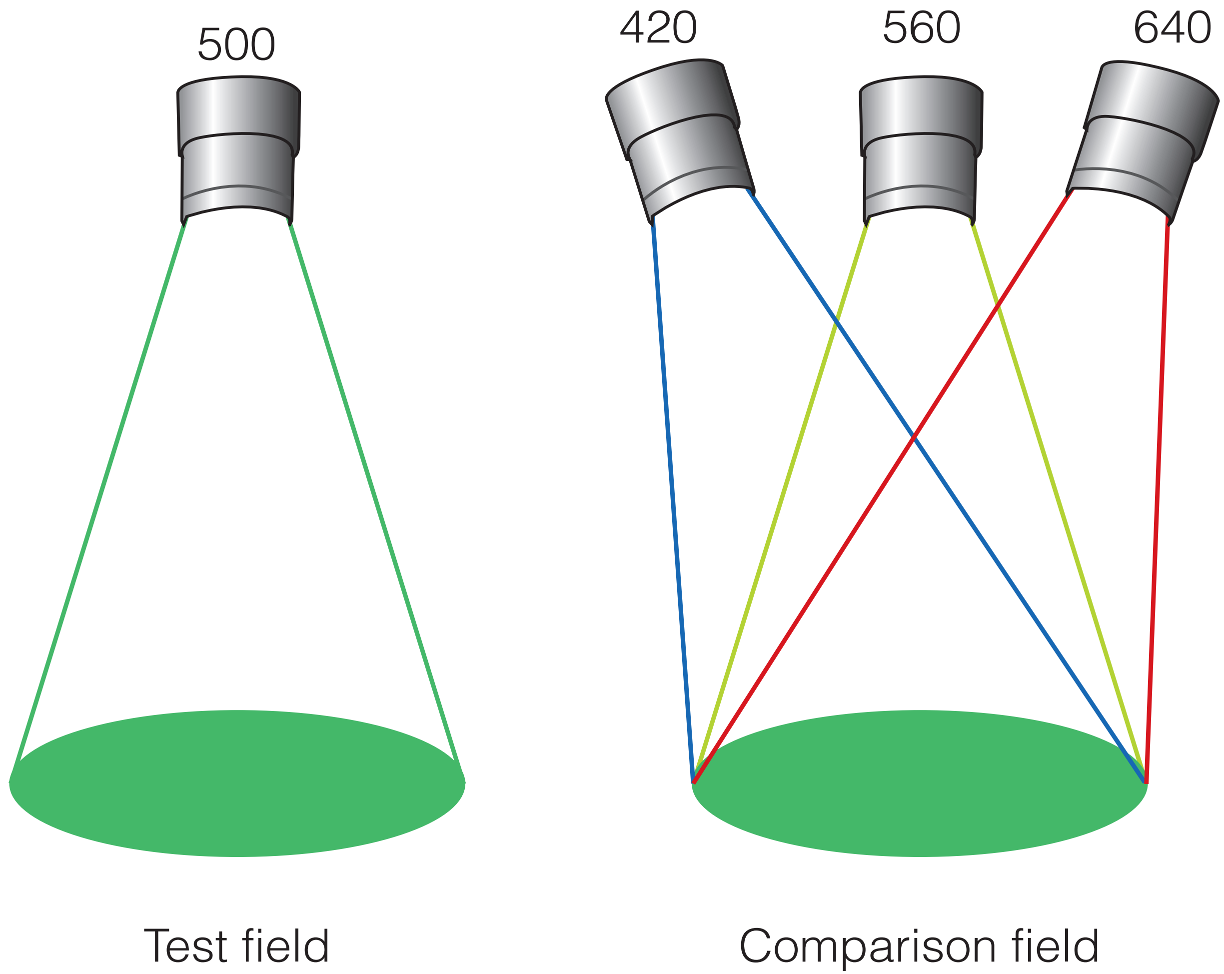
Physics	Psychology
亮度 luminosity	明度 brightness/lightness
主波长 dominant wavelength	色调 hue
纯度 purity	饱和度 saturation

2. Basic Phenomena

2.1 Additive Color Mixture

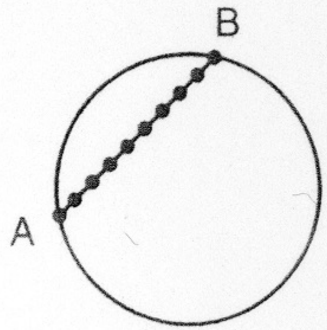


Color Mixing Projector

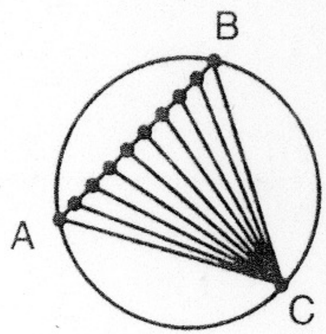


In a color-matching experiment, the observer adjusts the amount of three wavelengths in one field (right) so that it matches the color of the single wavelength in the other field (left).

Light Mixture



A. Mixing Two Lights

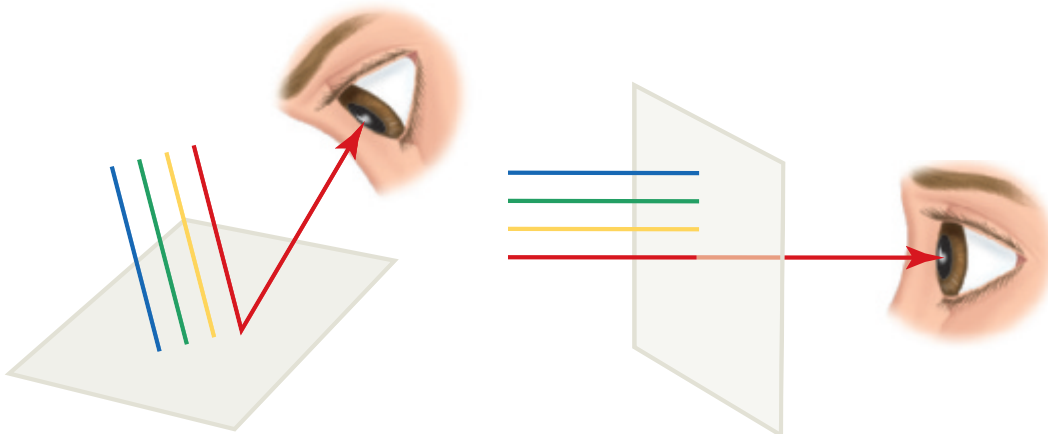


B. Mixing Three Lights

Any color within the triangle formed by A, B, C can be matched exactly by some combination of these three lights.

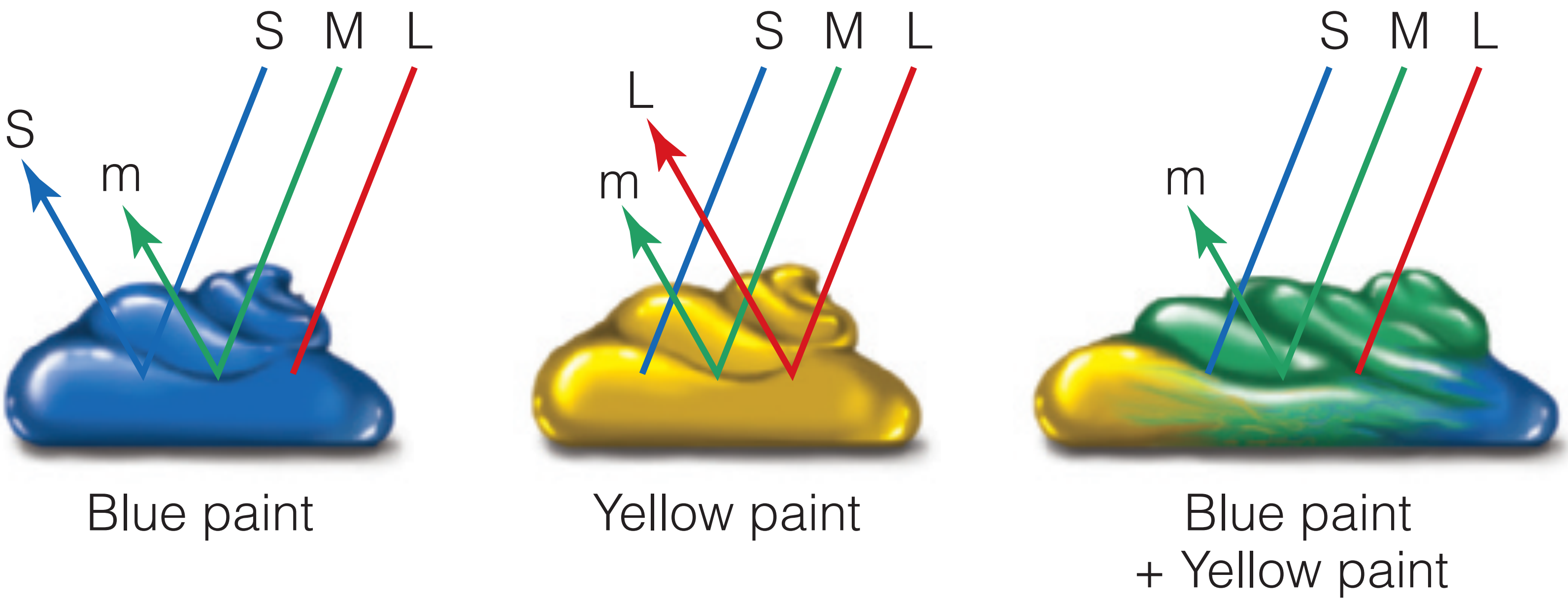
--James Clerk Maxwell

2.2 Subtractive color mixture

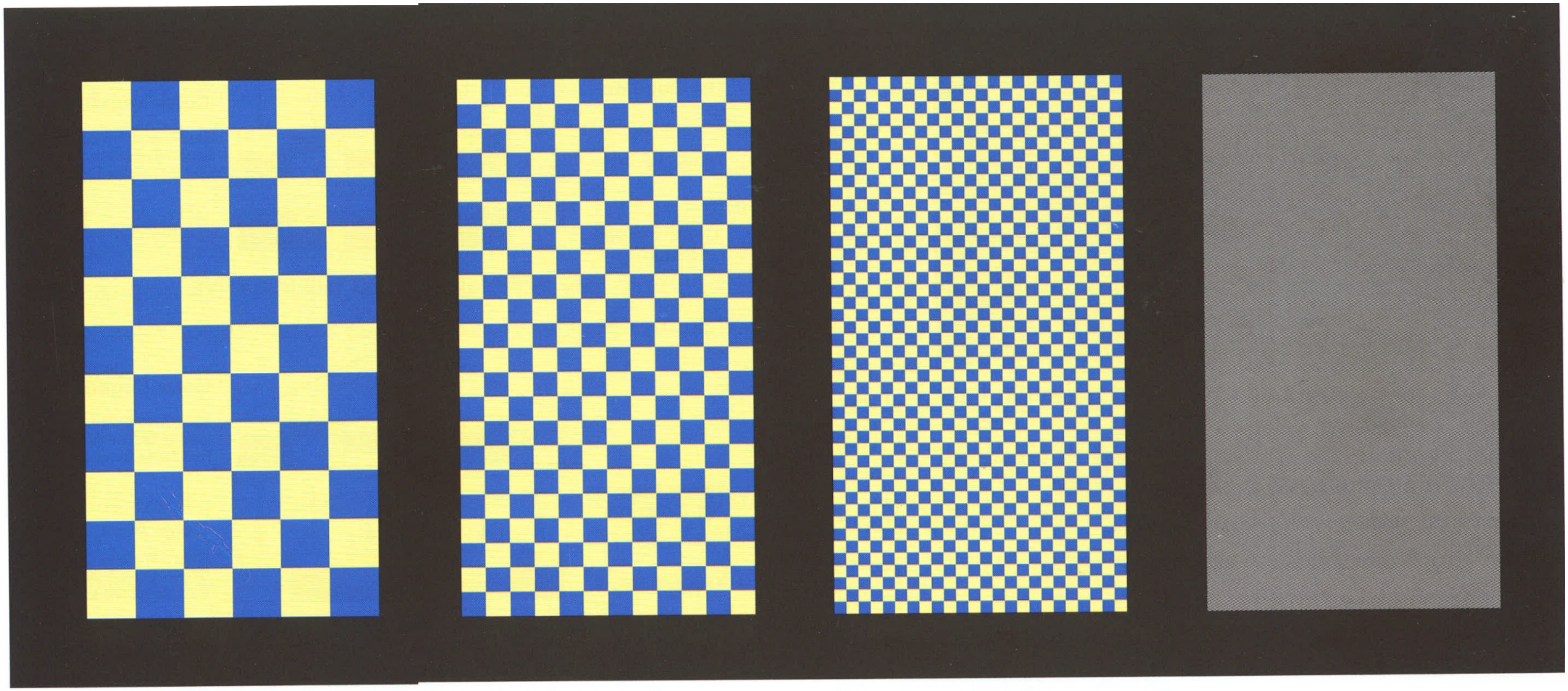


(a) Selective reflection (b) Selective transmission

- Additive color mixture
  - Yellow + Blue => white
- Subtractive color mixture
  - Yellow + Blue => Green



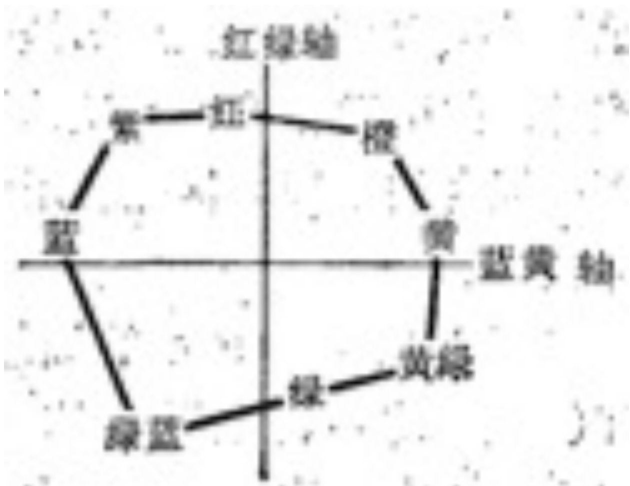
Color mixing with paint, This is subtractive color mixture.



Additive mixture of paints and inks by spatial adjacency. When small blue and yellow regions are juxtaposed and viewed from far enough away that they cannot be resolved, their combined effect is the same as the additive mixture of these two colors.

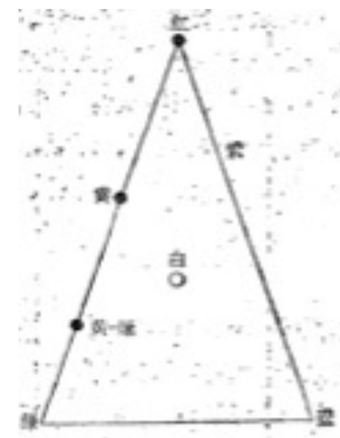
2.3 Color System

- Based on color similarity
  - One dimension: purple-blue-green-yellow-red



Two dimensions

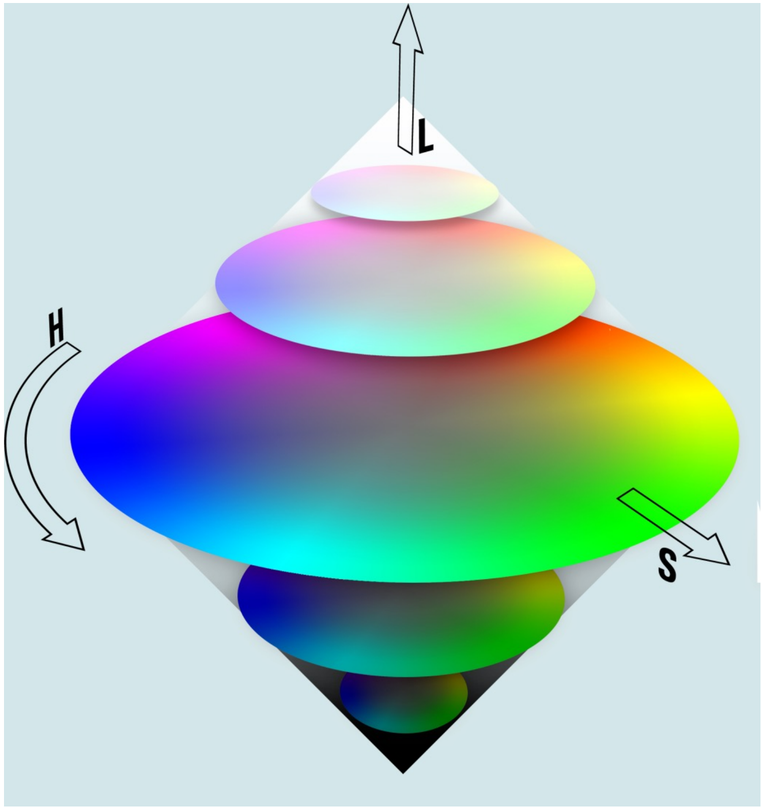
Newton’s color circle



Young’s color triangle

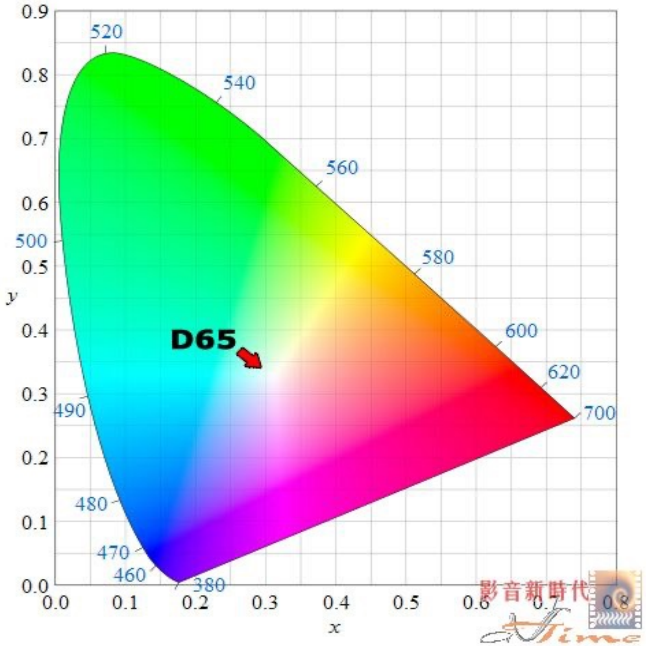
Natural Color System(NCS):

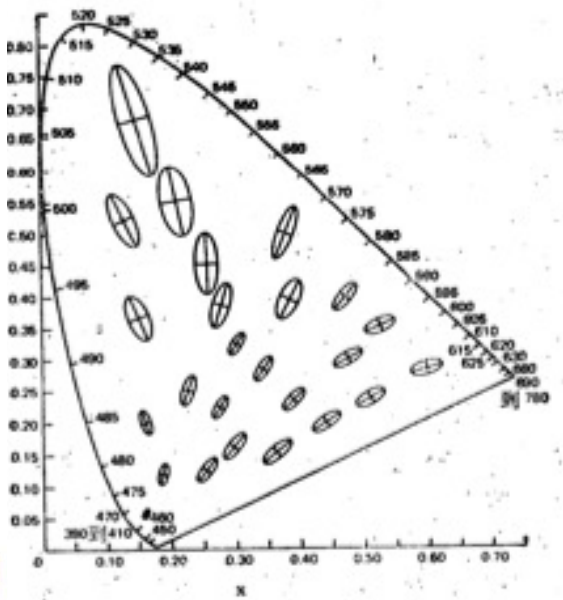
- Three dimensions: Hue, Saturation, Lightness

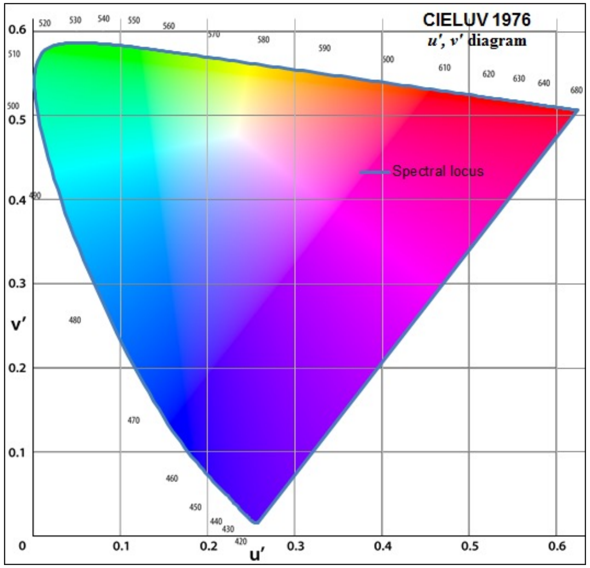


NCS Color Space

CIE system







CIE 1931

CIE 1967 (LUV)

$$u' = \frac{4x}{(x + 15y + 3z)} \text{ 或 } u' = \frac{4x}{(-2x + 12y + 3)}$$

$$v' = \frac{9y}{(x + 15y + 3z)} \text{ 或 } v' = \frac{9y}{(-2x + 12y + 3)}$$

Printing Industry: YMCK　　Video Industry：YUV

RGB<—>YUV

$$Y = 0.299R + 0.587G + 0.114B$$

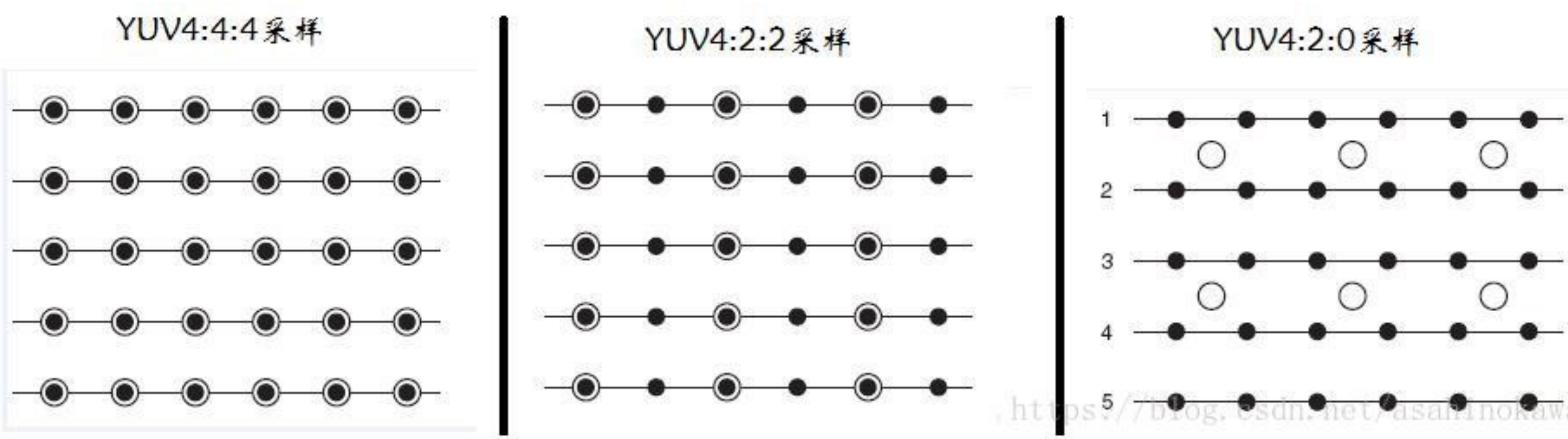
$$U = -0.147R - 0.289G + 0.436B = 0.564(B-Y)$$

$$V = 0.615R - 0.515G - 0.100B = 0.713(R-Y)$$

$$R = Y + 1.140V$$

$$G = Y - 0.394U - 0.581V$$

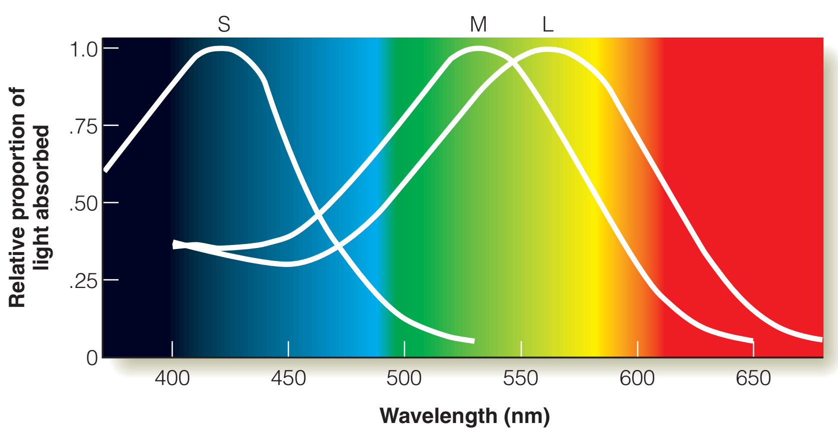
$$B = Y + 2.032U$$



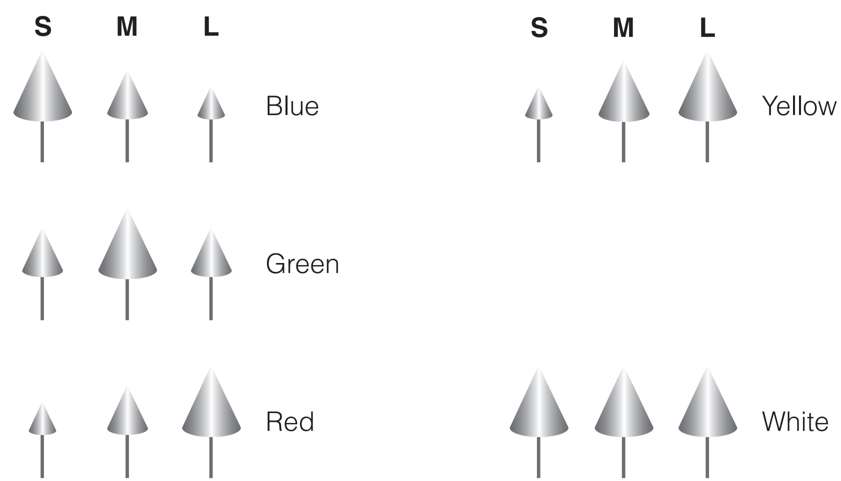
3. Color Theories

Trichromatic Theory (Young-Helmholtz)

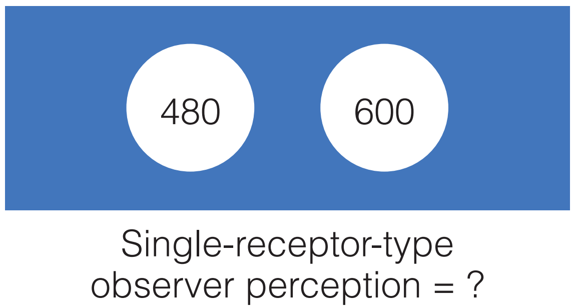
- There are three types of color receptors in the human eye.
- The three kinds of color receptors respond differently as a function of the wave length of photons falling on them.
- The three receptor functions overlap, any given wavelength would stimulate the three receptor systems to different degrees.



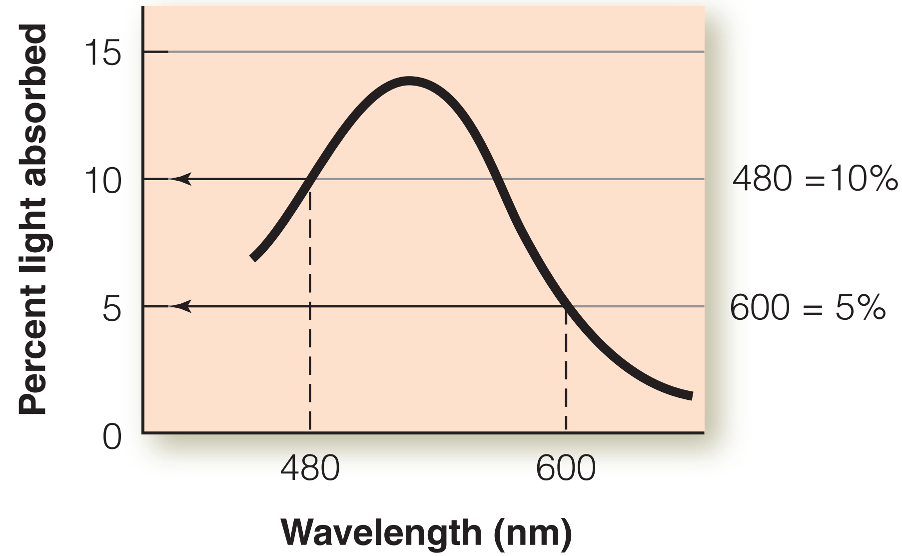
Absorption spectra of the three cone.



Patterns of firing of the three types of cones to different colors.

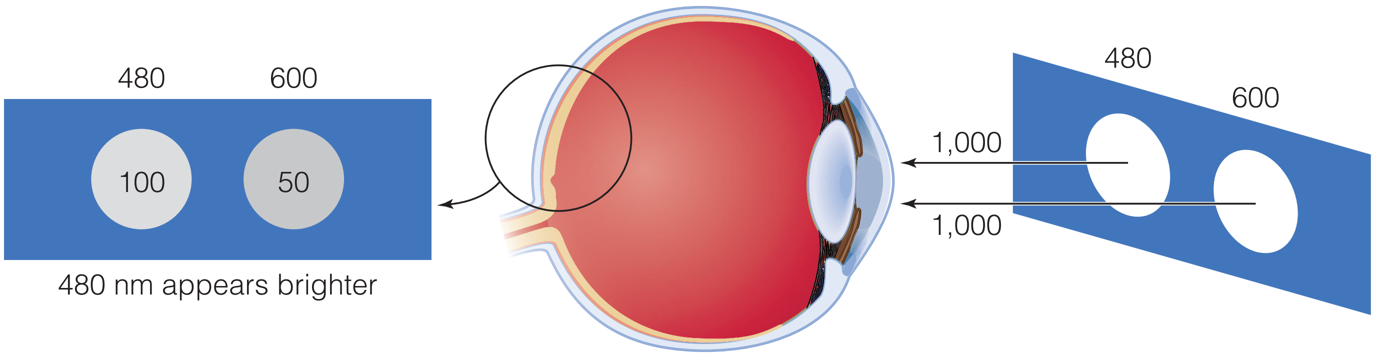


(a)

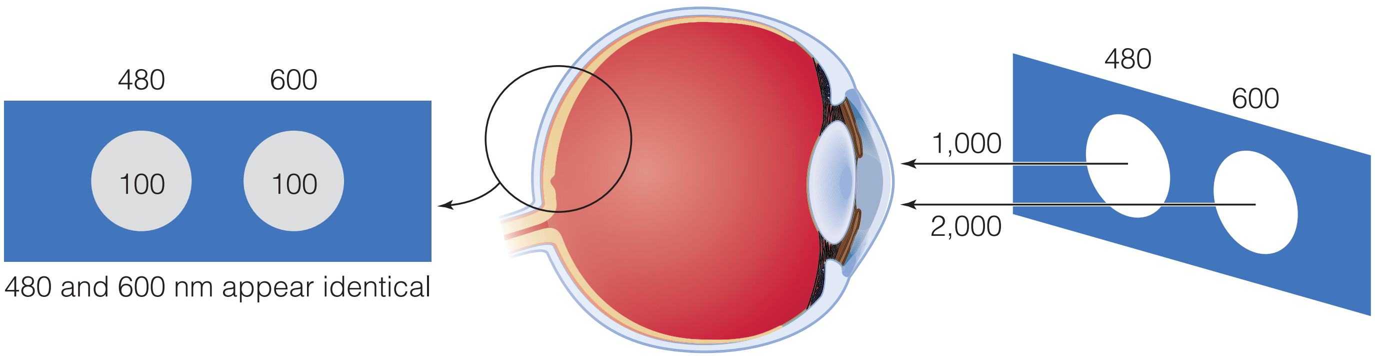


(b)

a) Two lights, 480 nm on the left and 600 nm on the right.
b) Absorption spectrum of a visual pigment that absorbs 10 percent of 480-nm light and 5 percent of 600-nm light.

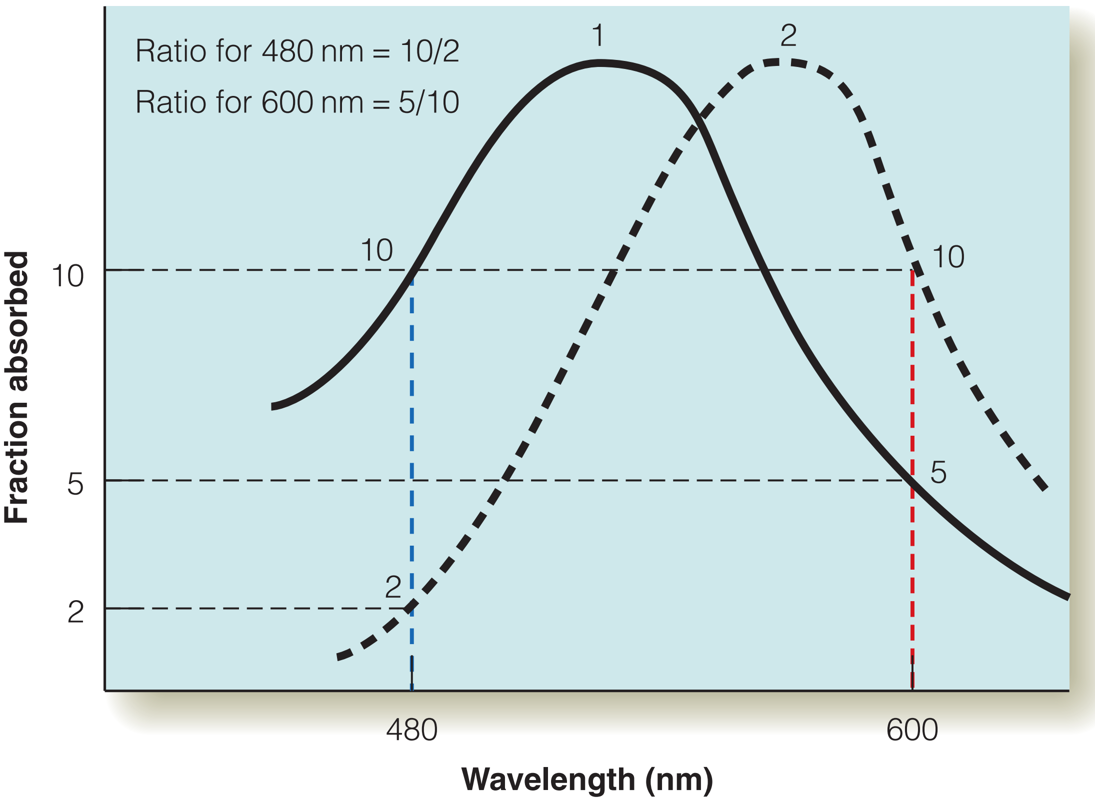


(a) Intensities of both lights equal 1,000 photons



(b) 600-nm light increased to 2,000 photons

Calculation of how many molecules of the visual pigment are isomerized.
a) When the intensity of both is 1,000 photons, the 480-nm light looks brighter.
b) When the intensity of the 600-nm light is increased to 2,000, the two wavelengths are perceived as identical.

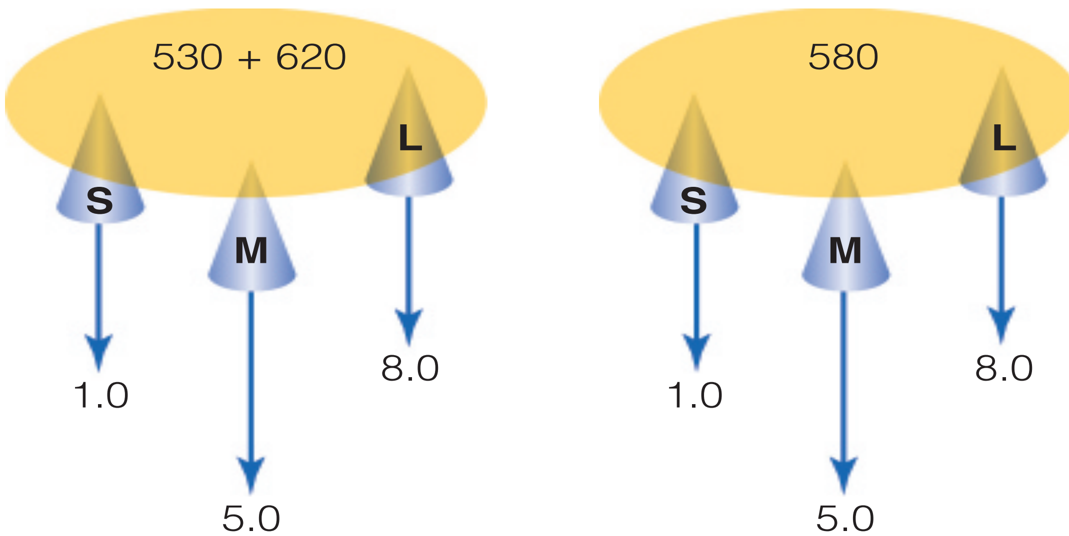


Adding a second pigment (dashed curve) to the one. Now the 480-nm and 600-nm lights can be identified by the ratio of response in the two pigments.

- The ratio for the 480-nm light is 10/2.
- The ratio for the 600-nm light is 5/10.

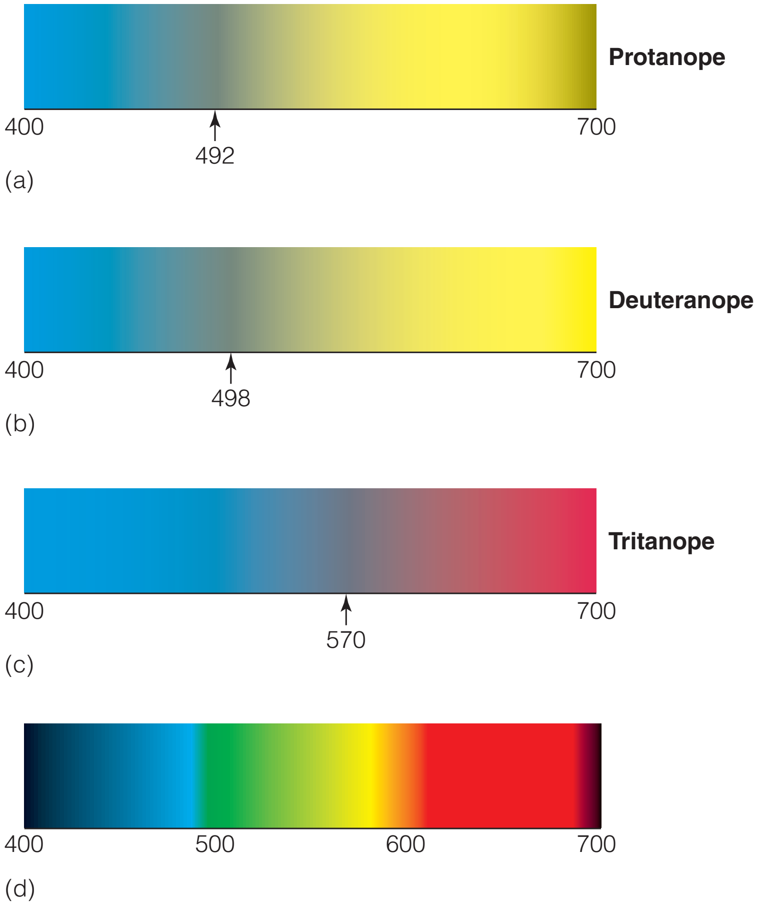
These ratios occur no matter what the intensity of the light.

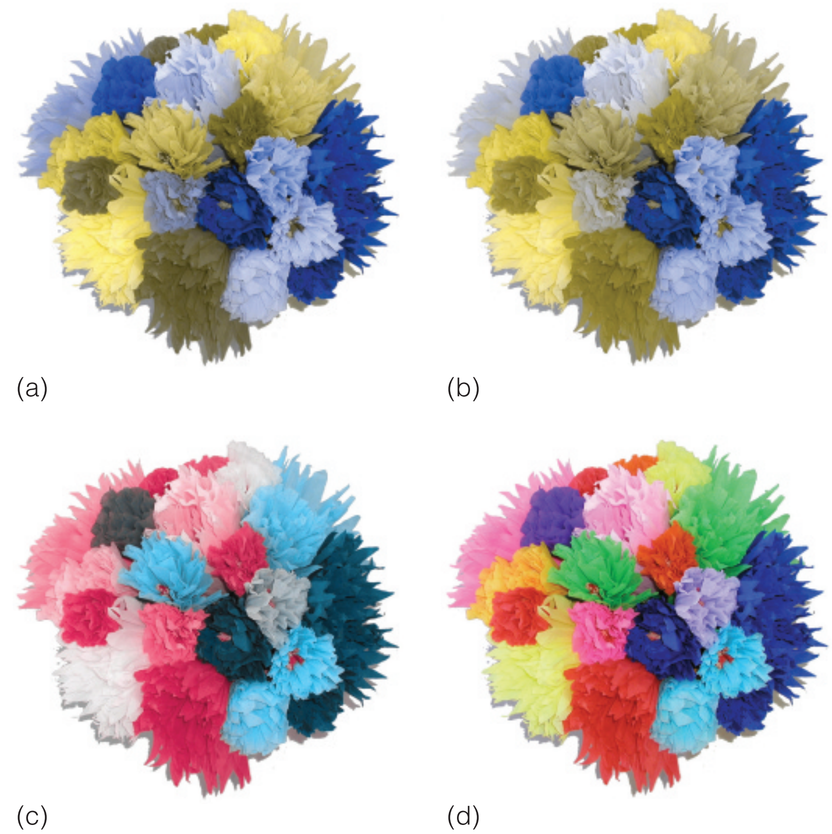
Principle behind metamerism



- The proportions of 530- and 620-nm lights in the field on the left have been adjusted so that the mixture appears identical to the 580-nm light in the field on the right.
  - The numbers indicate the responses of the short-, medium-, and long-wavelength receptors.
  - There is no difference in the responses of the two sets of receptors, so the two fields are perceptually indistinguishable.

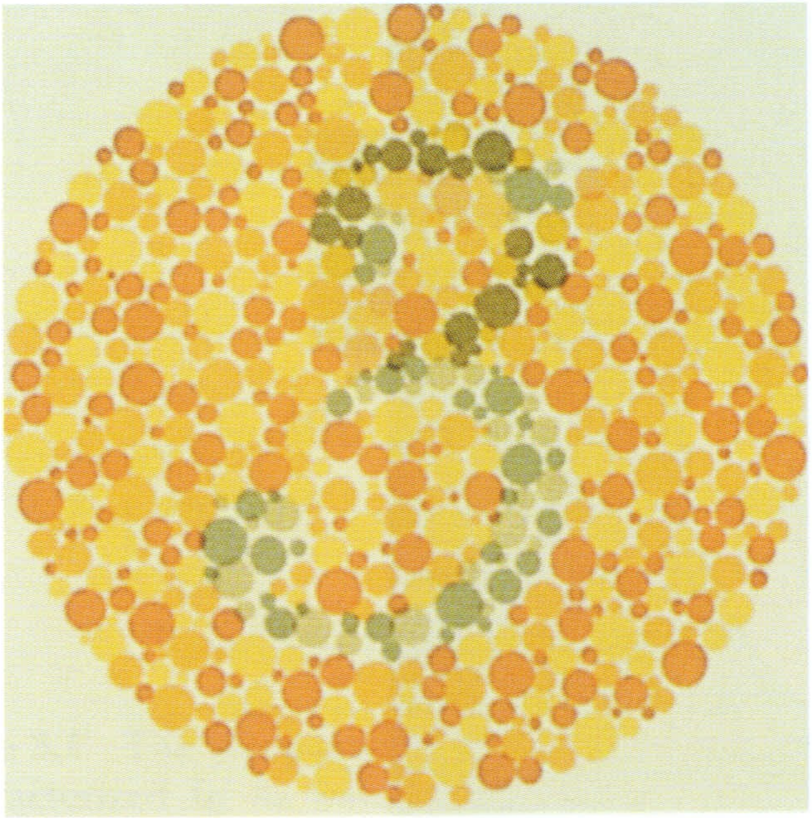
Color Blindness



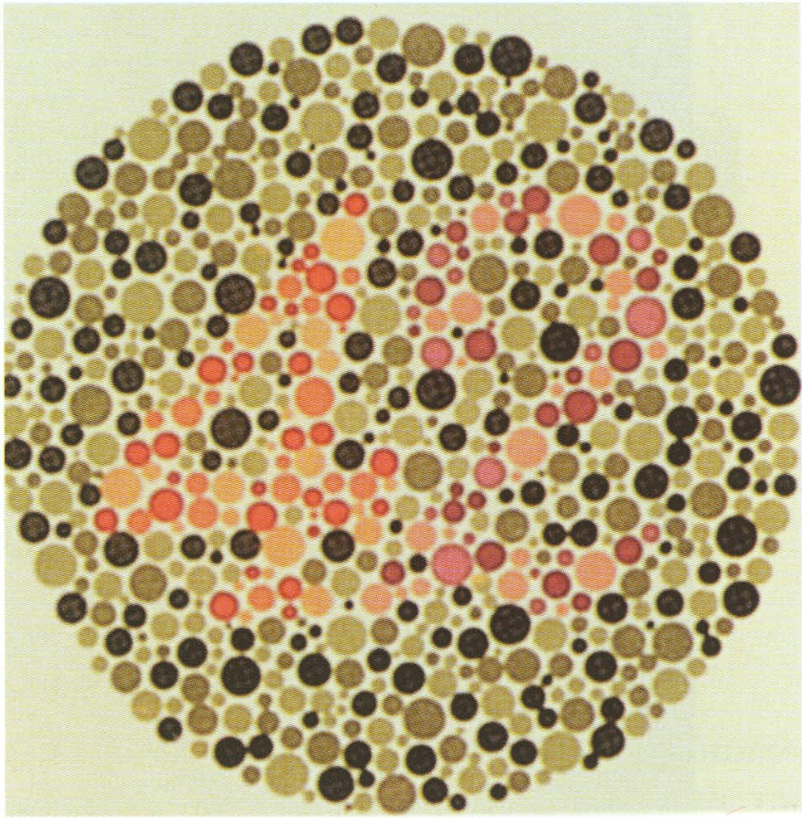


The visible spectrum and colored paper flowers appear to (a) protanopes; (b) deuteranopes; (c) tritanopes; and (d) trichromats.

A



B



A test for color blindness.

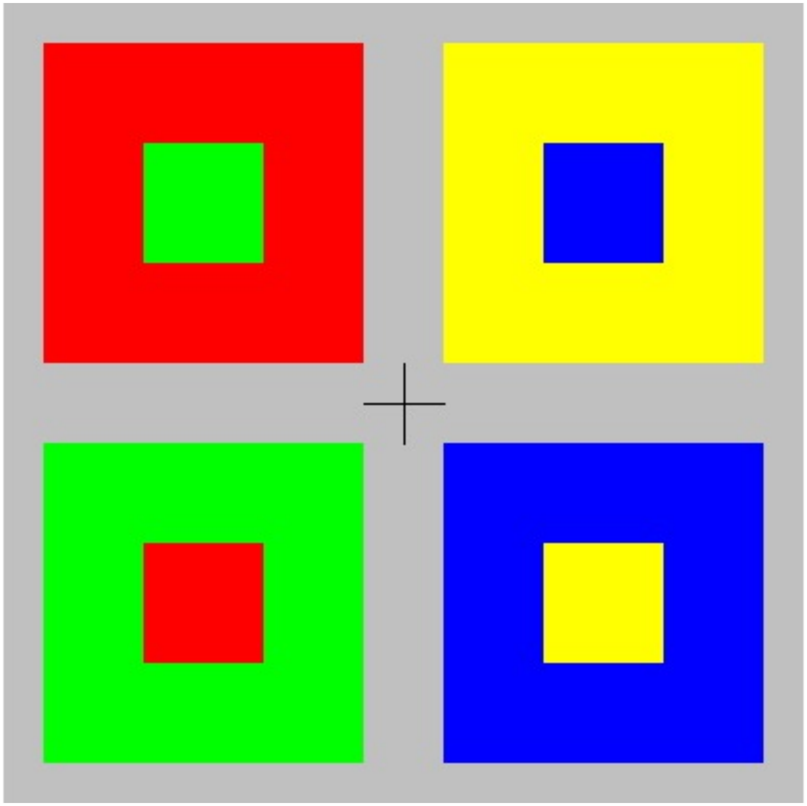
(Protanopes, Deuteranopes)

The shortcomings of trichromatic theory

- Can’t explain why color blindness are always lost in certain pairs: R/G, B/Y
- Colors are never lost singlely, nor are they lost in other pairings.
- The subjective experience of yellow does not appear to be a mixture of red and green in anything like the sense that the subjective experience of purple looks like the mixture of red and blue.

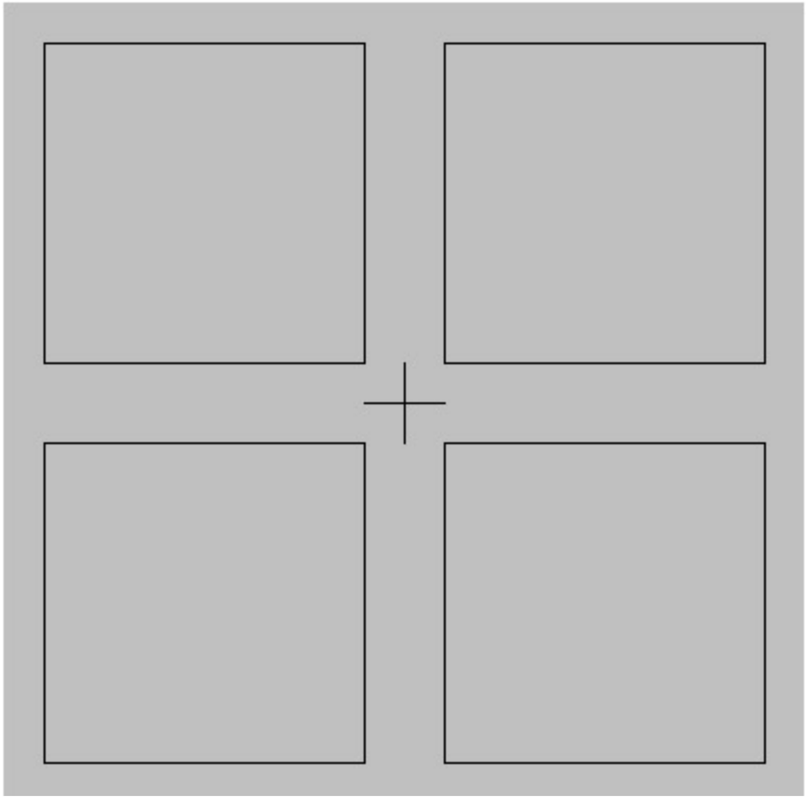
Color Afterimages

The aftereffects of viewing highly saturated colors for prolonged period of time.



Color Afterimages

The aftereffects of viewing highly saturated colors for prolonged period of time.

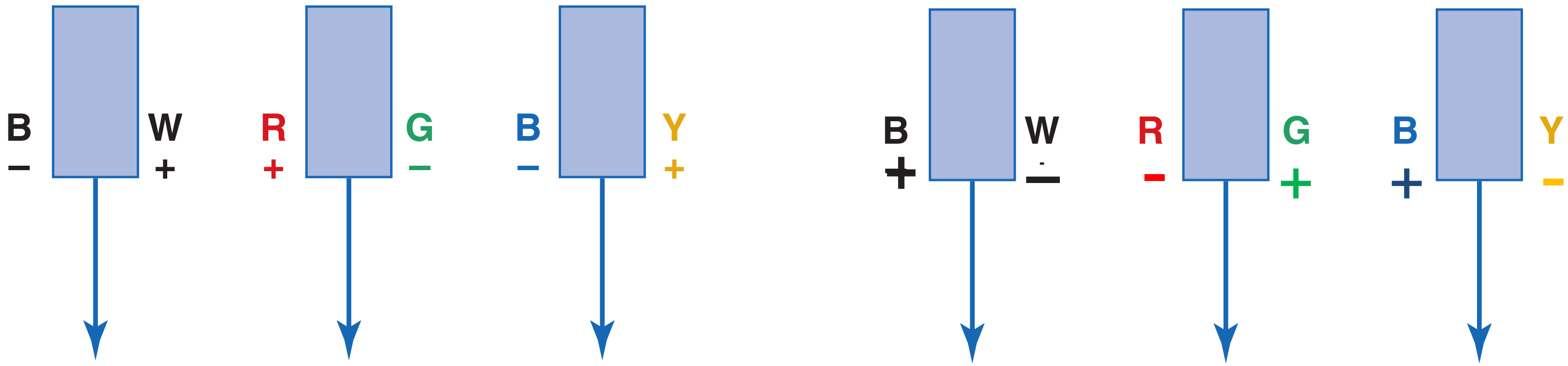


Results of afterimage and simultaneous contrast demonstration.

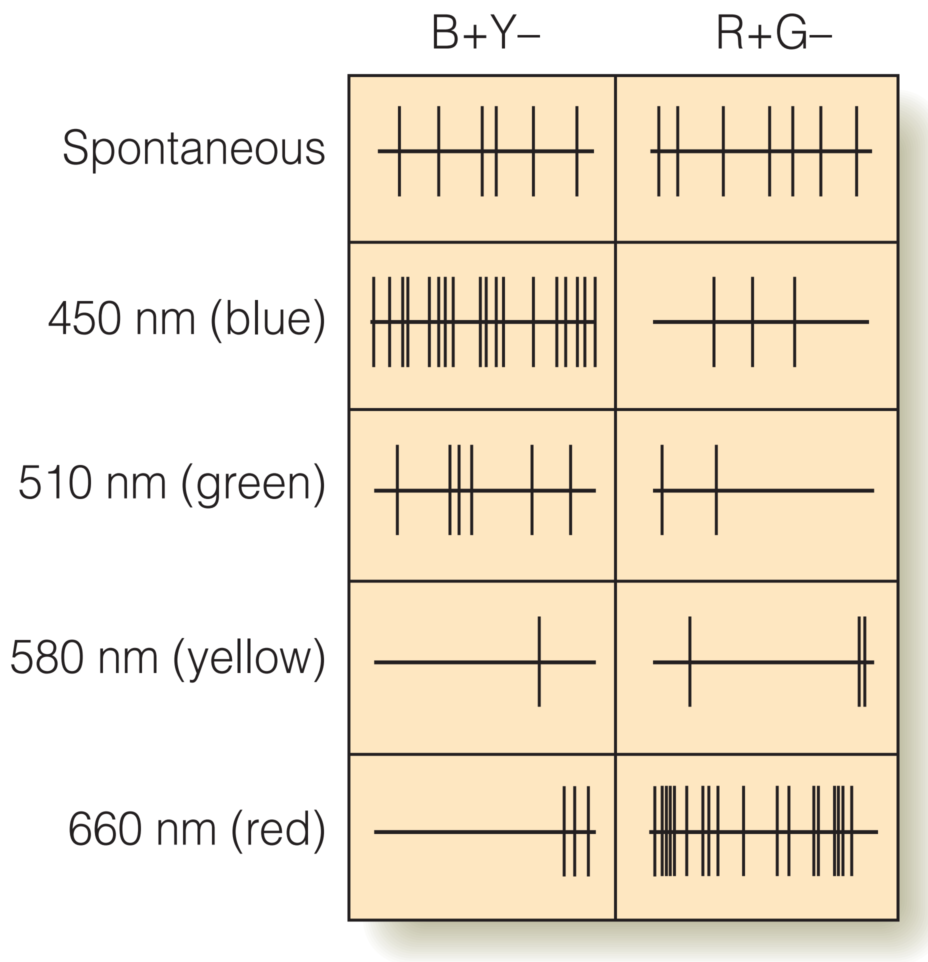
ORIGINAL SQUARE	COLOR OF OUTSIDE AFTERIMAGE	COLOR OF INSIDE AFTERIMAGE
Green	Red	Green
Red	Green	Red
Blue	Yellow	Blue
Yellow	Blue	Yellow

Opponent Process Theory

– There are four chromatic primaries rather than three, and they are structured into pairs of polar opposites: R/G, B/Y

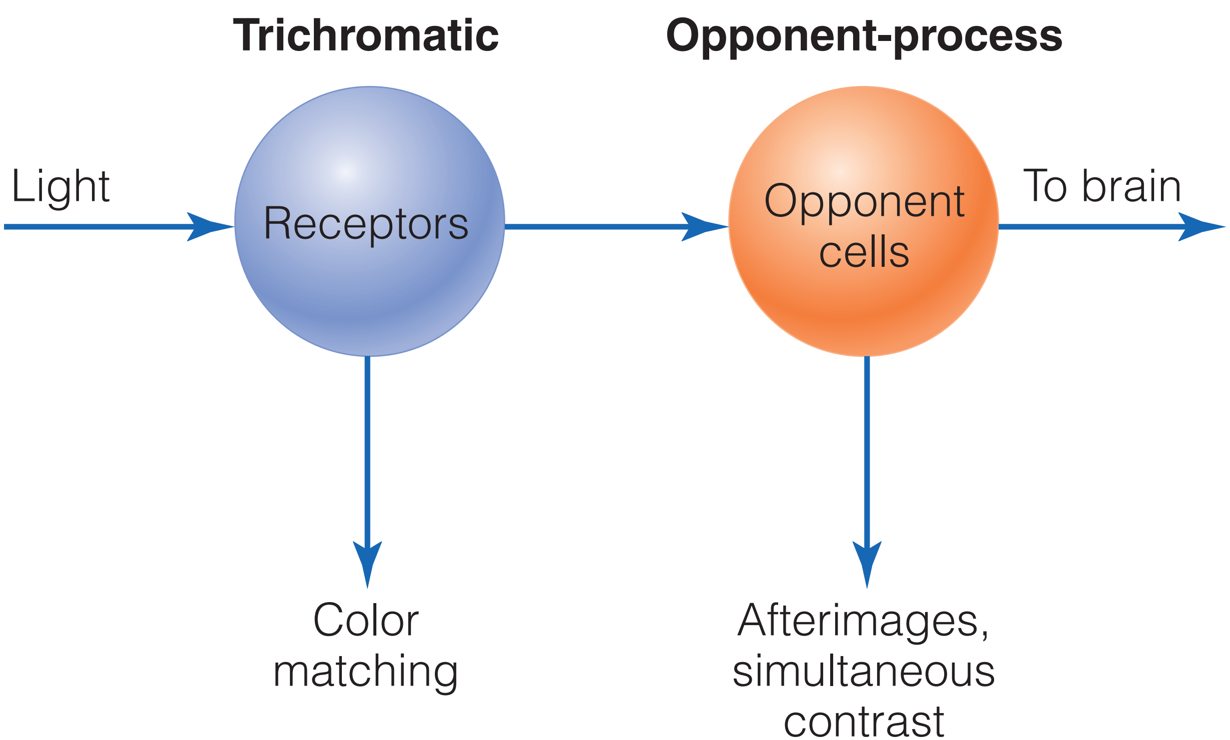


The three opponent mechanisms proposed by Hering.



Responses of B+ Y– and R+ G– opponent cells in the monkey‘s lateral geniculate nucleus.

Dual Process Theory

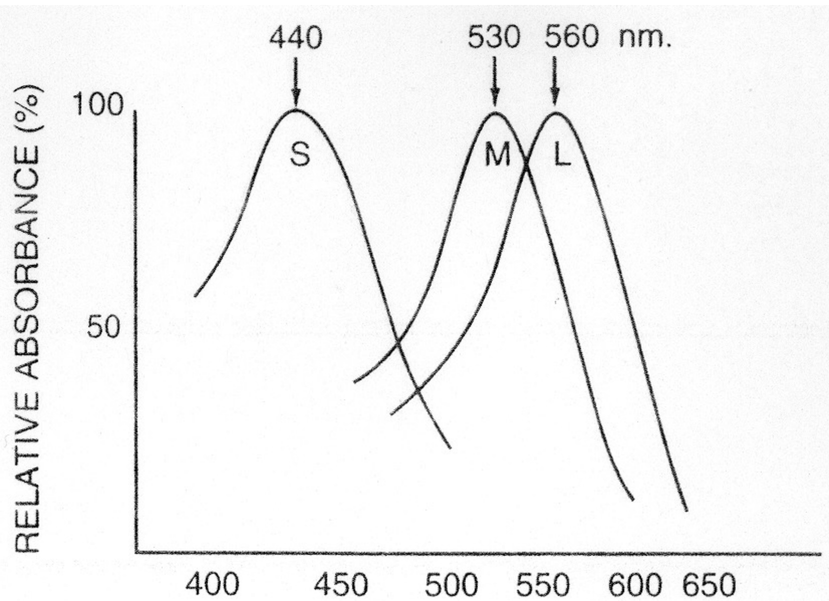


Our experience of color is shaped by physiological mechanisms, both in the receptors and in opponent neurons.

- Both stages of this dual process theory are now known to be performed in the retina itself.
- Theories that are based on strictly behavioral analyses have frequently preceded knowledge of the underlying physiological mechanisms.
- It is generally easier to work from the more abstract functional level downward toward the physical implementation than to work in the reverse direction.

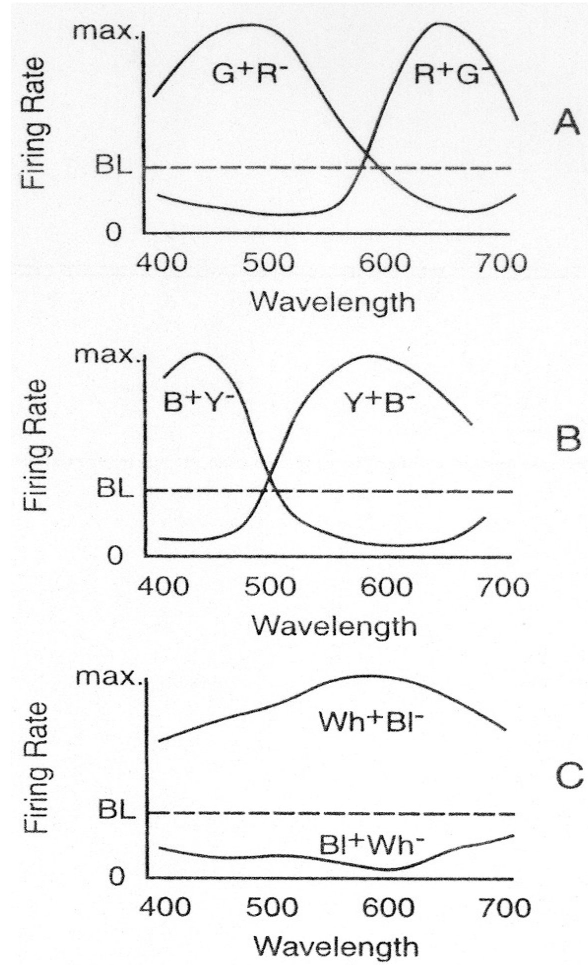
2.3 Physiological mechanisms

Three cone systems

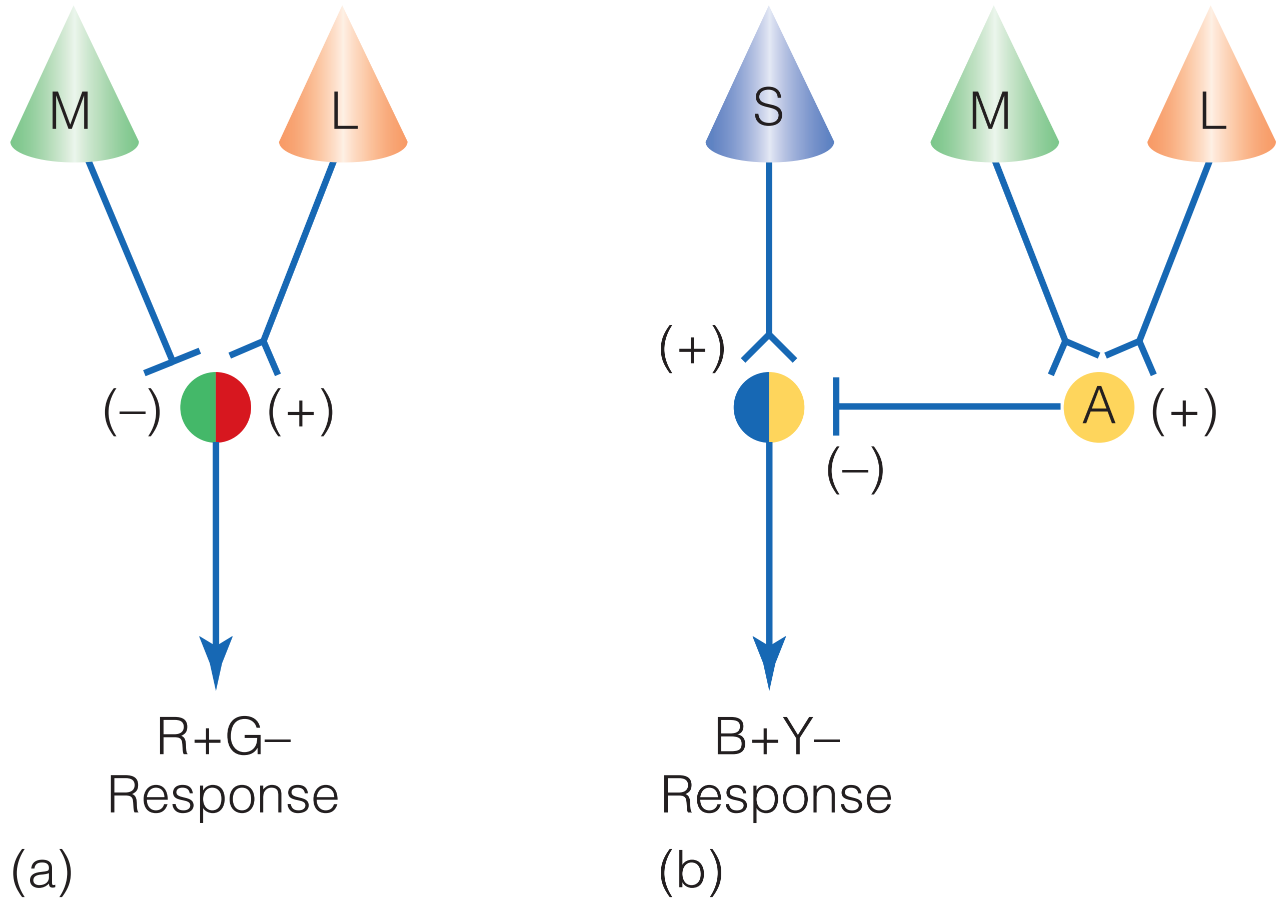


Neural response curves for the three types of cones

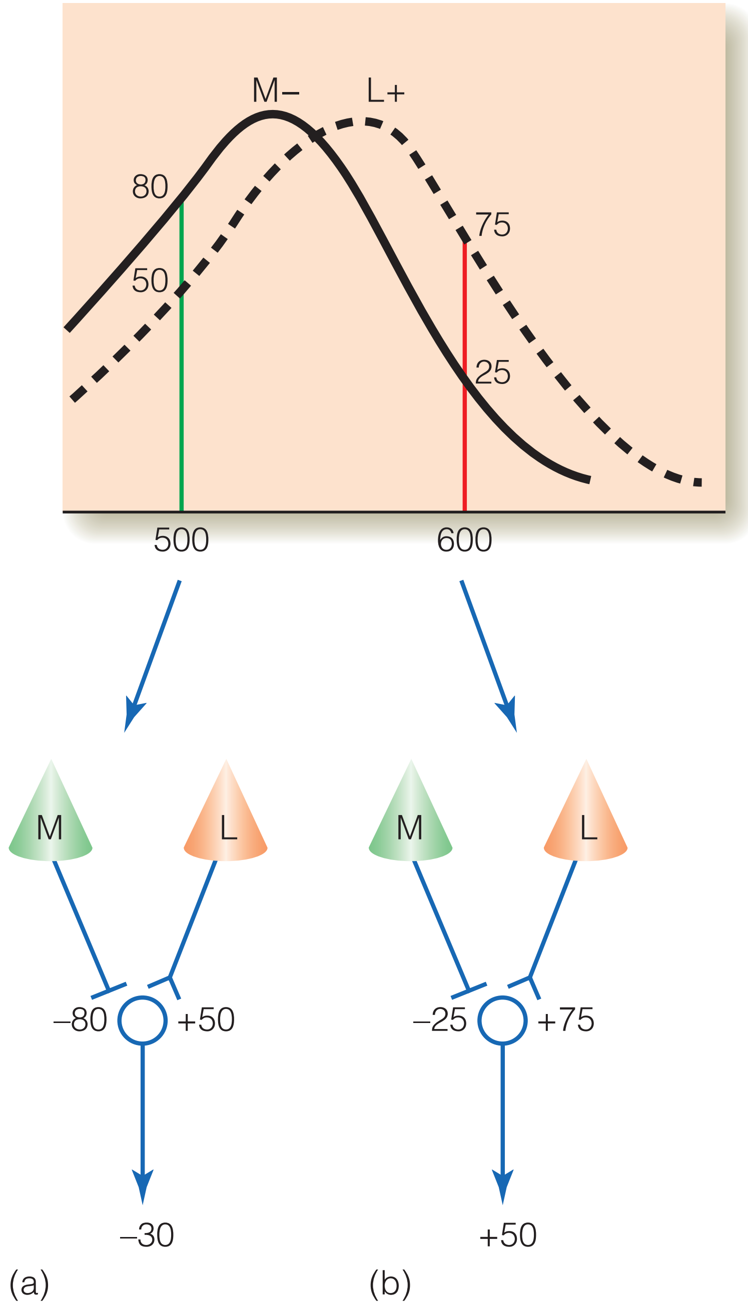
Color opponent cells



Neural response curves of opponent process cells



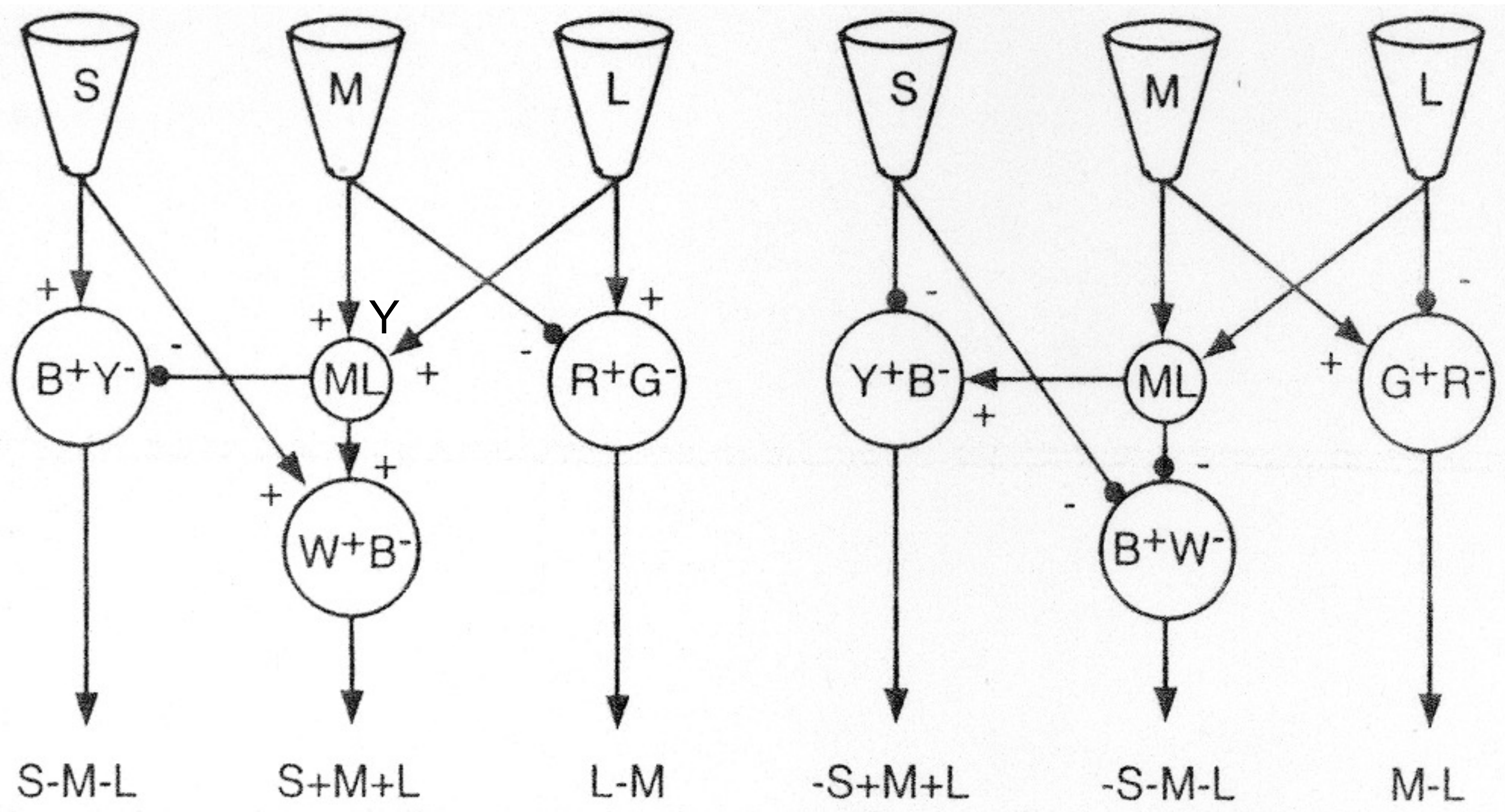
Neural circuits showing how (a) the red–green and (b) the blue–yellow mechanisms can be created by excitatory and inhibitory inputs from the cone receptors



How opponent neurons determine the difference between the receptor responses to different wavelengths.

(a) The response of the L+ M– neuron to a 500-nm light is negative, The action of the 500-nm light on this neuron will cause a decrease in any ongoing activity.

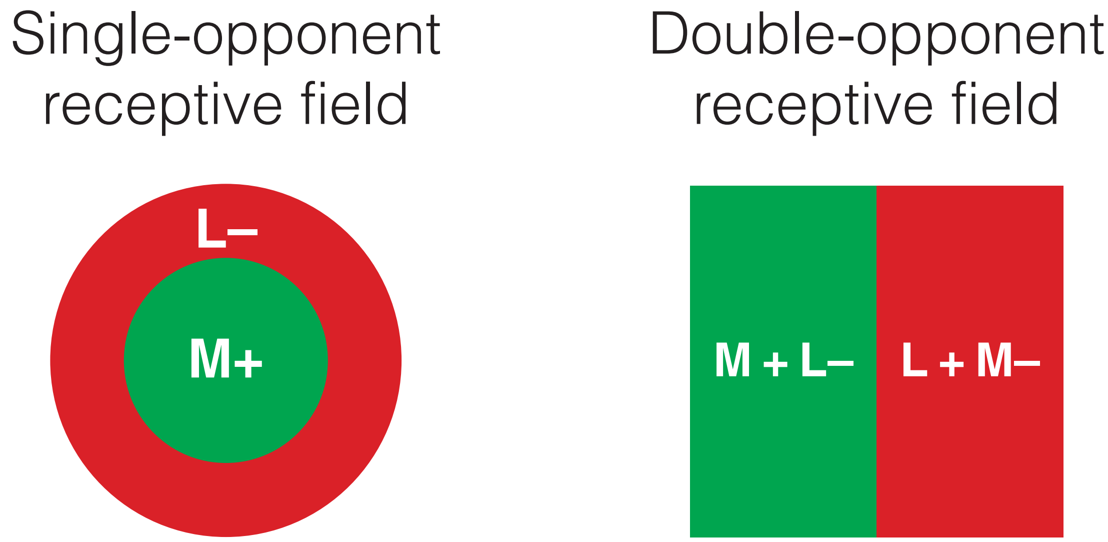
(b) The response to a 600-nm light is positive, so this wavelength causes an increase in the response of this neuron.



Possible neural circuits for dual process theory

Color in the Cortex

- Is there a single color center in the cortex?

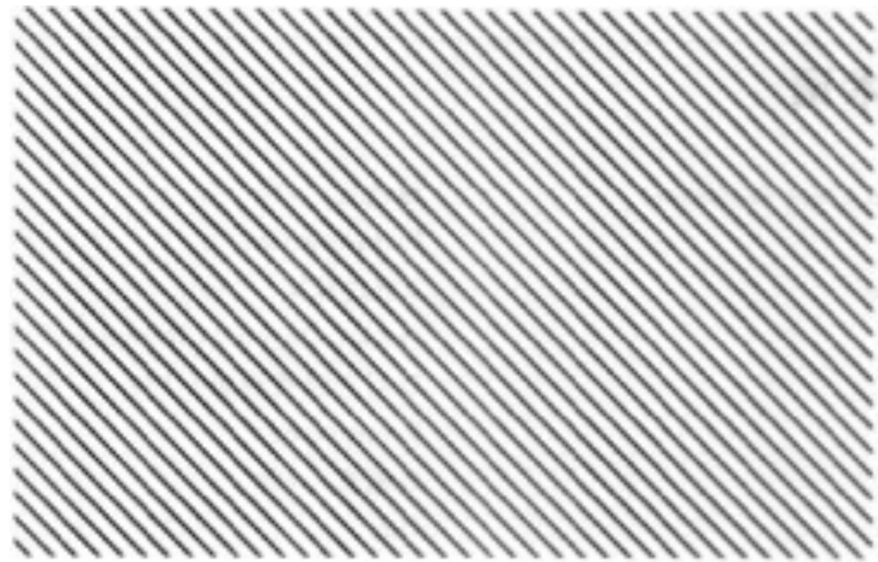


(a) Receptive field of a single-opponent cortical neuron. This M+L– neuron has a center-surround receptive field.

(b) Receptive field of a double-opponent cortical neuron. When the M+L– area is stimulated, firing increases to medium wavelength light and decreases to long-wavelength light. When the L+M– area is stimulated, firing increases to a long-wavelength light and decreases to a medium-wavelength light.

Subjective Colors

Benham’s top: rotation.

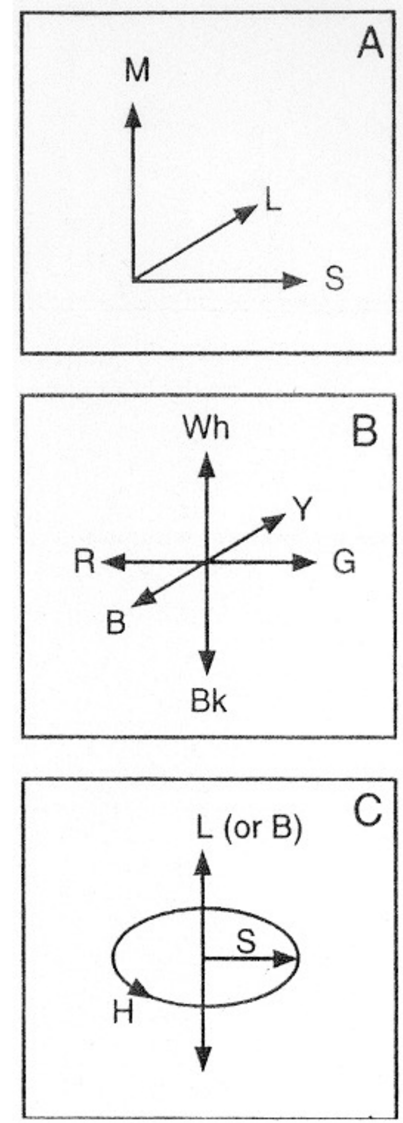


Piggins，Kingham & Holmes, 1972

Land's Color Effect

Why might the visual system contain the different color representations?

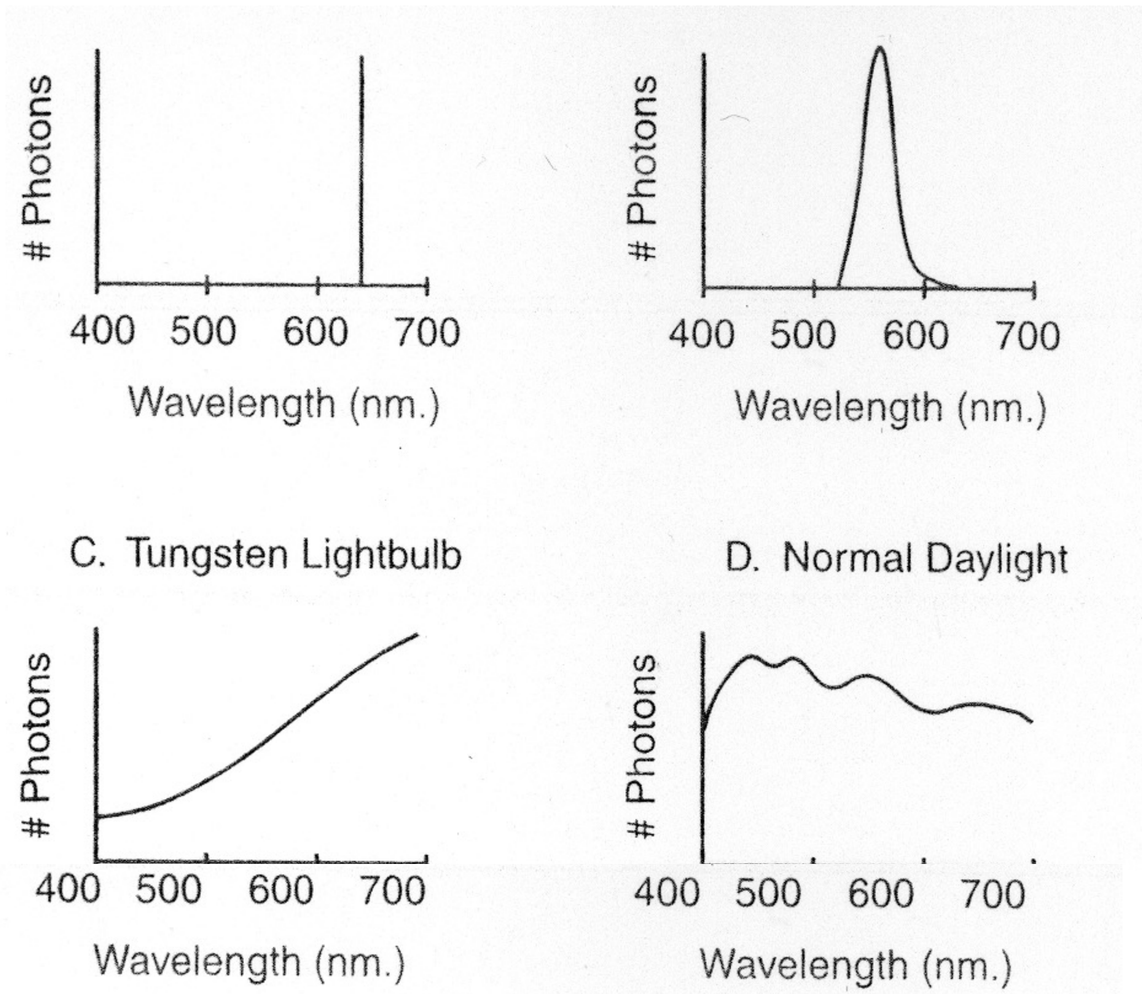
- The trichromatic representation is useful because it is an efficient and effective way to extract information about the spectral composition of light in physical receptor systems.
- The opponent representation is more useful because it helps determine which differences between adjacent retinal regions result from changes in the level of illumination.
- The phenomenology of color perception



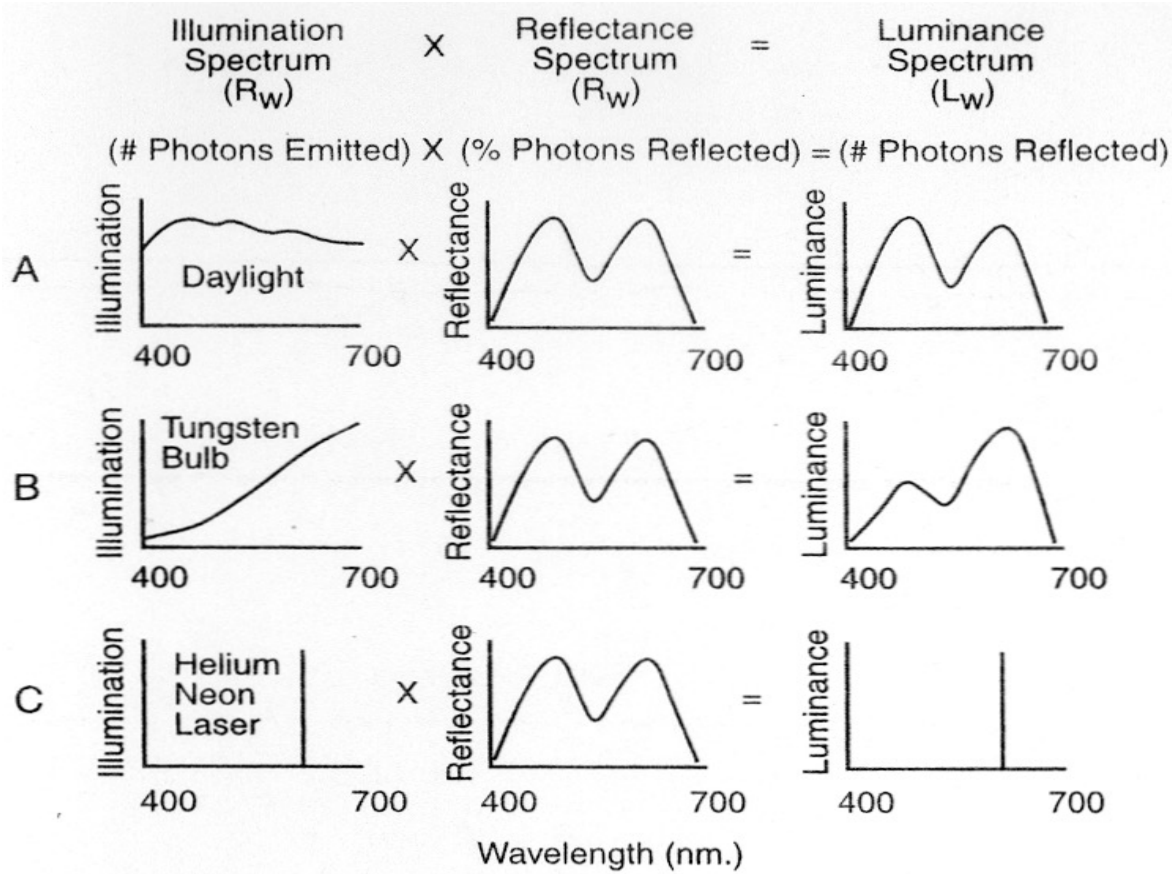
3. Real-world Color Perception

Physical spectra of various lights

A. Helium Neon Laser B. Gallium Phosphide Crystal



3.1 Computational Task



The problem of color constancy

The task is to disentangle the effects of reflectance and illumination so that the invariant property of surface reflectance can be perceived.----- inverse problem.

3.2 Chromatic Adaptation

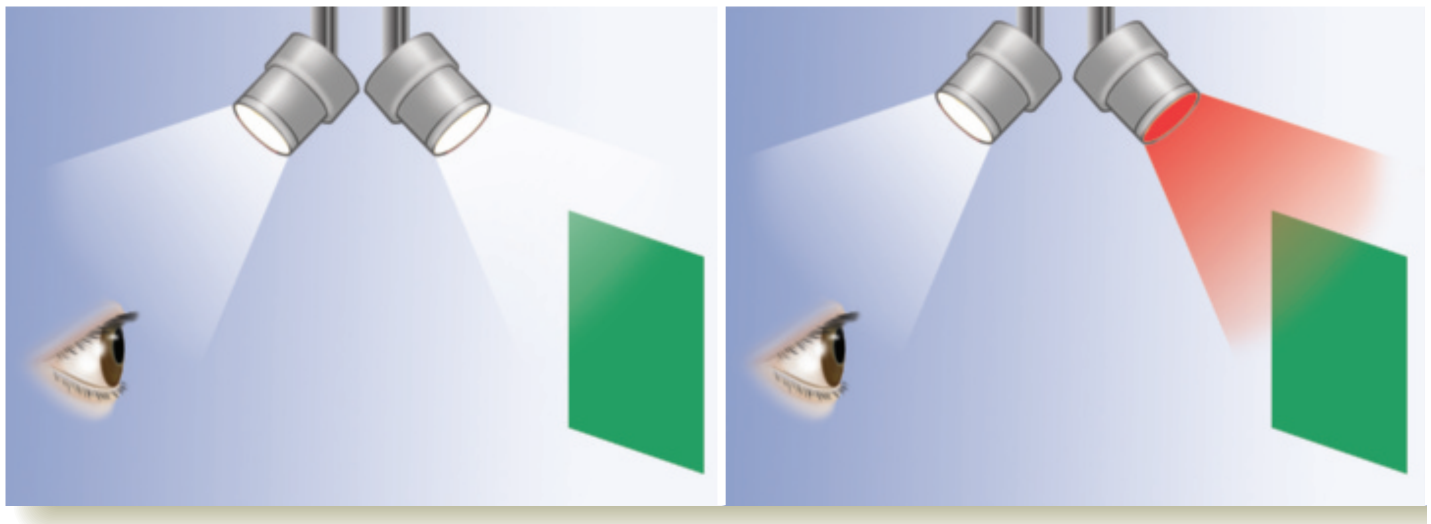
Ganzfeld (whole field):

- A completely uniform stimulus over the entire visual field.
- Regardless of its initial color, any Ganzfeld is eventually experienced as neutral gray.
- Example: Yellow Ping-Pong ball.

The effect of the Surroundings

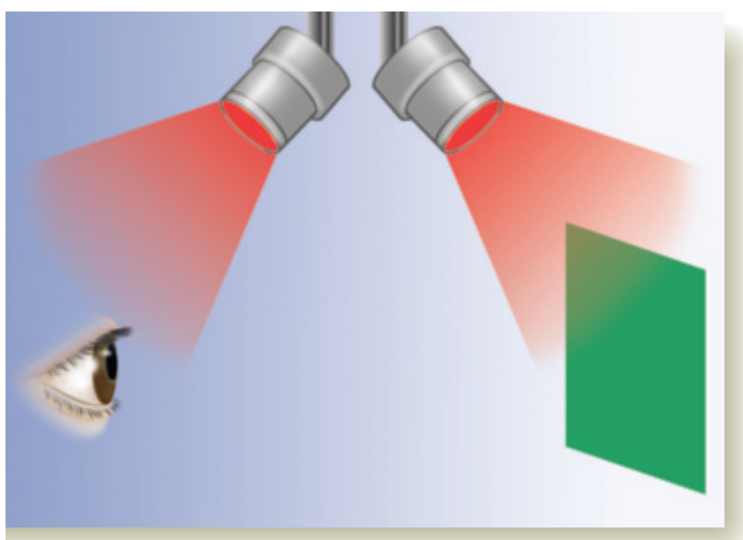
Perception: Paper is green

Perception: Paper shifted toward red



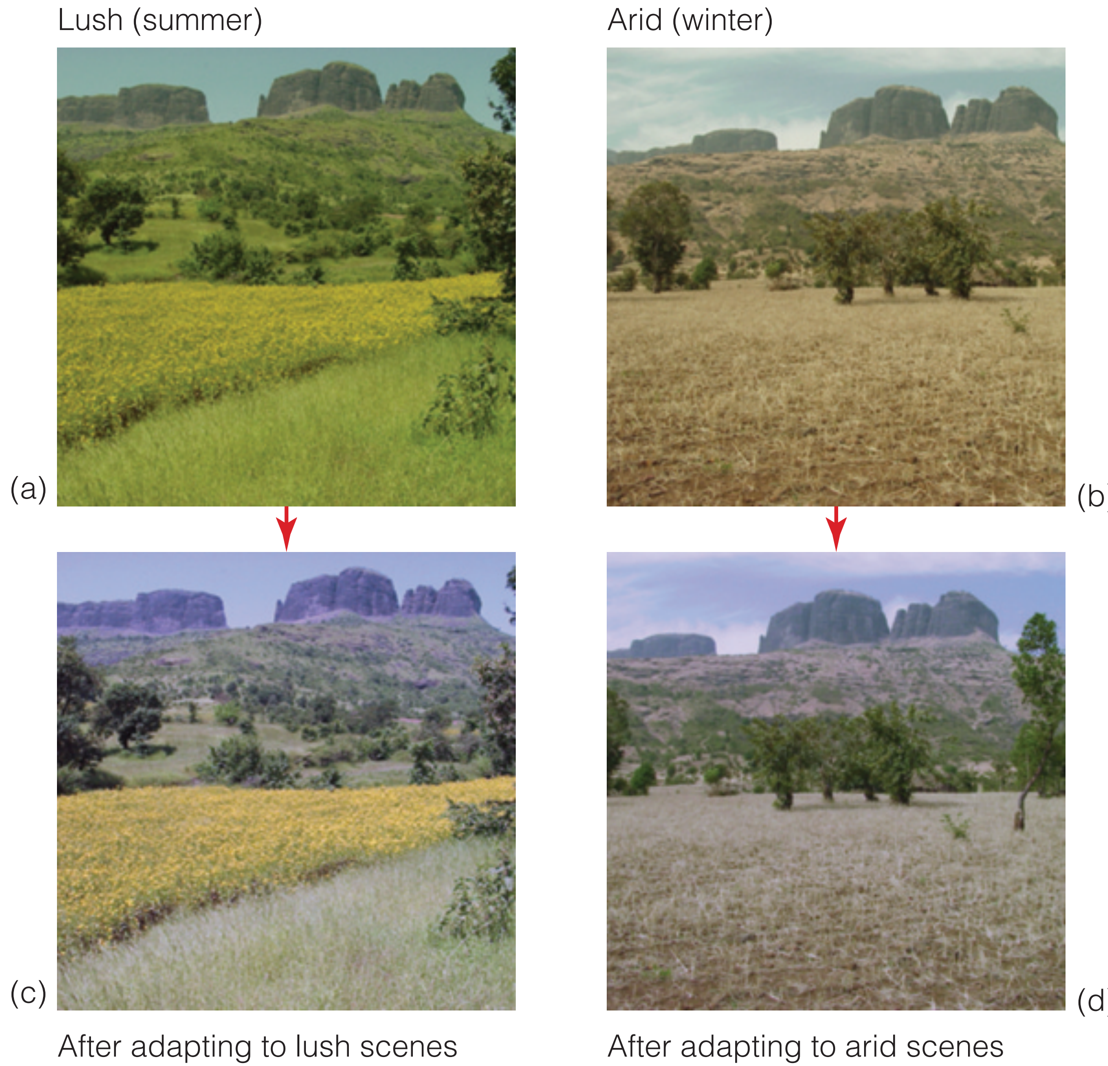
(a) Baseline

(b) Observer not adapted



(c) Observer adapted to red

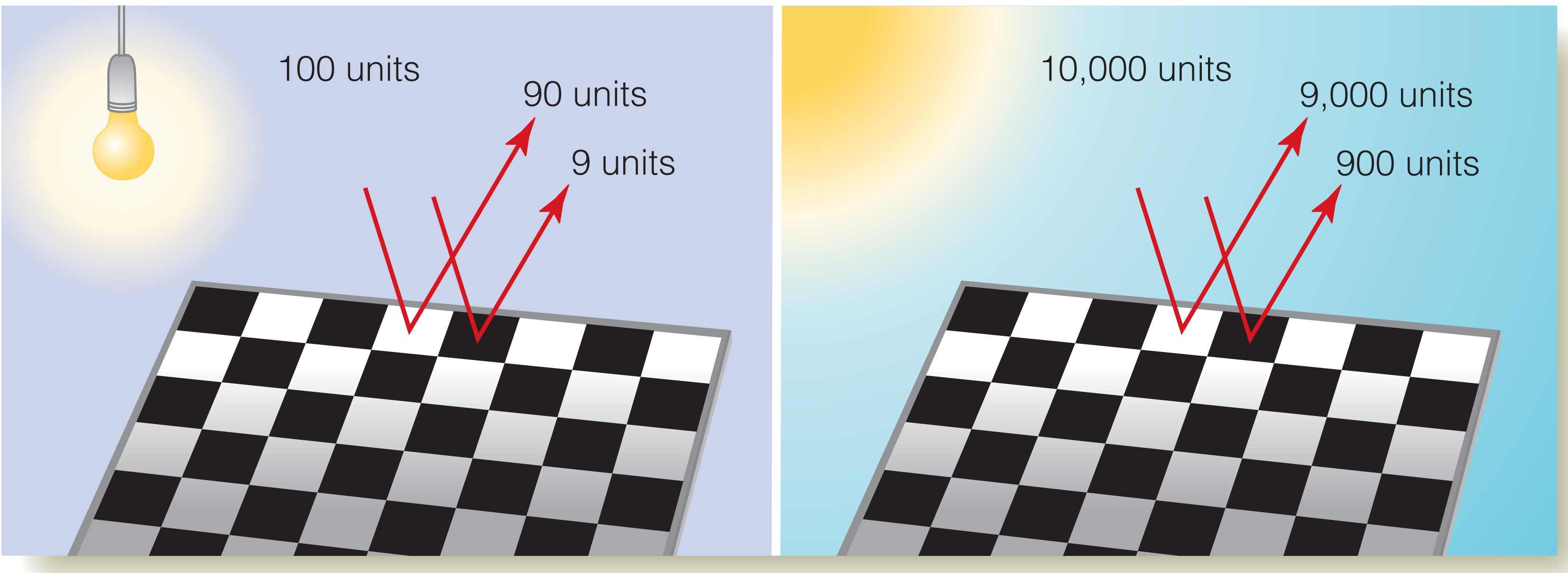
Perception: Paper shifted only slightly toward red so it appears more yellowish.



How chromatic adaptation to the dominant colors of the environment can influence perception of the colors of a scene.

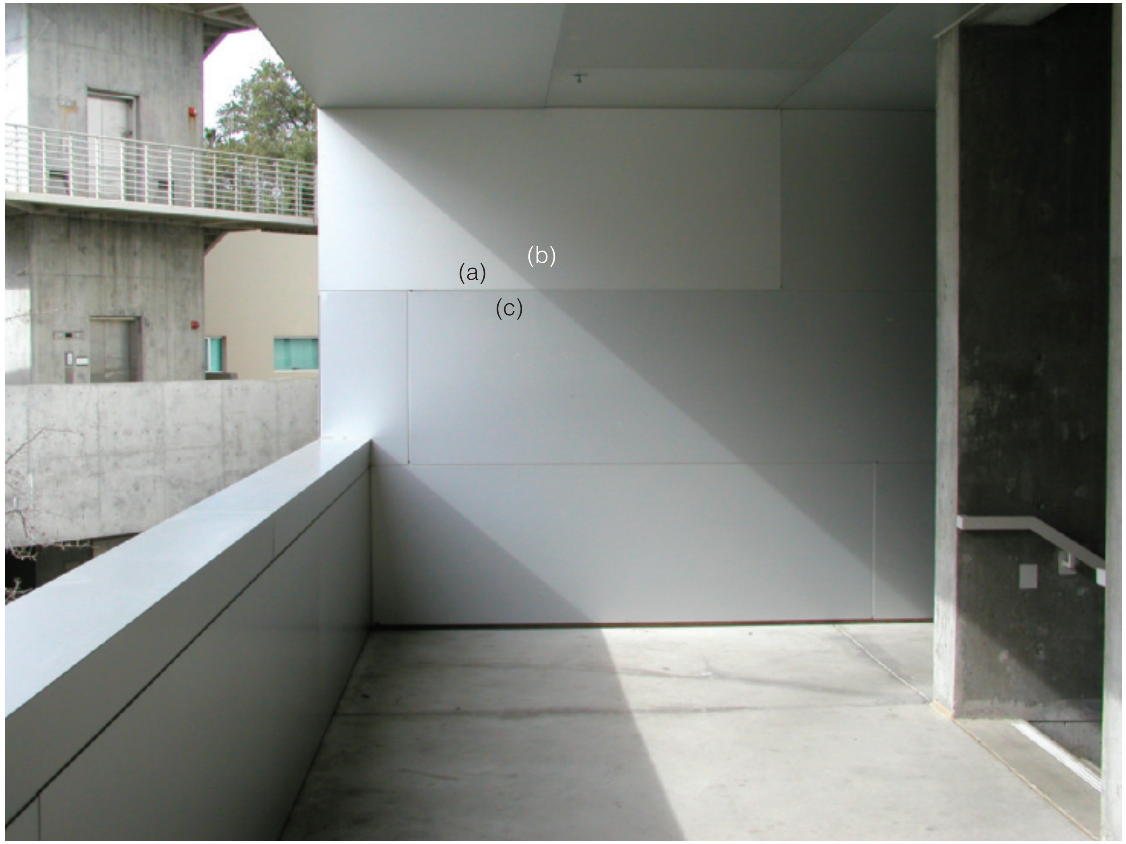
- The dominant color of the scene in (a) is green.
- The dominant color of the arid scene in (b) is yellow.

3.3 Lightness constancy



(a) (b)

Relational theory: the relative amounts of light reflected from one region with respect to another stay very much the same.



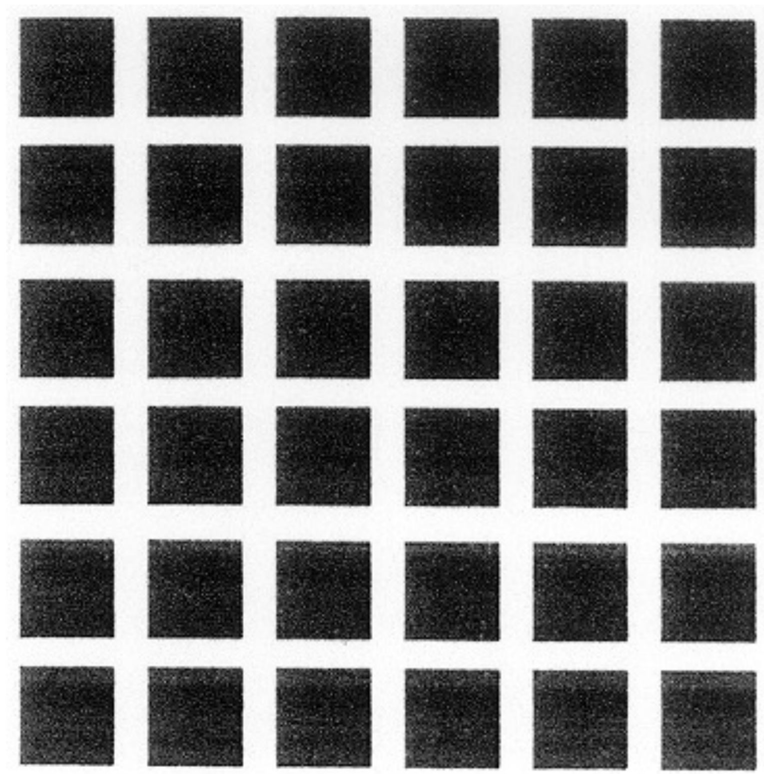
This unevenly illuminated wall contains both reflectance edges (between *a* and *c*) and illumination edges (between *a* and *b*).

The perceptual system must distinguish between these two types of edges to accurately perceive the actual properties of the wall, as well as other parts of the scene.

The information in Shadows

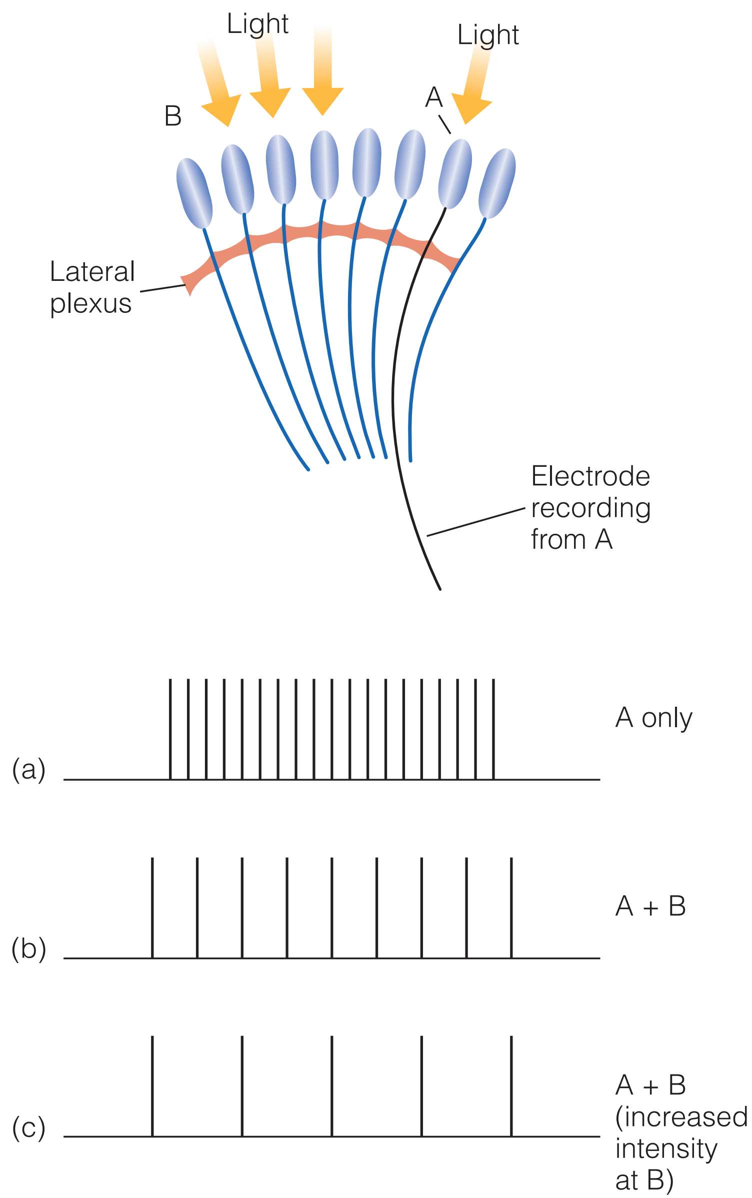
You assume that the shadowed and unshadowed areas are bricks with the same lightness, but that less light falls on some areas than on others because of the shadow cast by the tree.

3.4 Lateral Inhibition



The Hermann grid.

Notice the gray “ghost images” at the intersections of the white areas, which decrease or vanish when you look directly at an intersection.



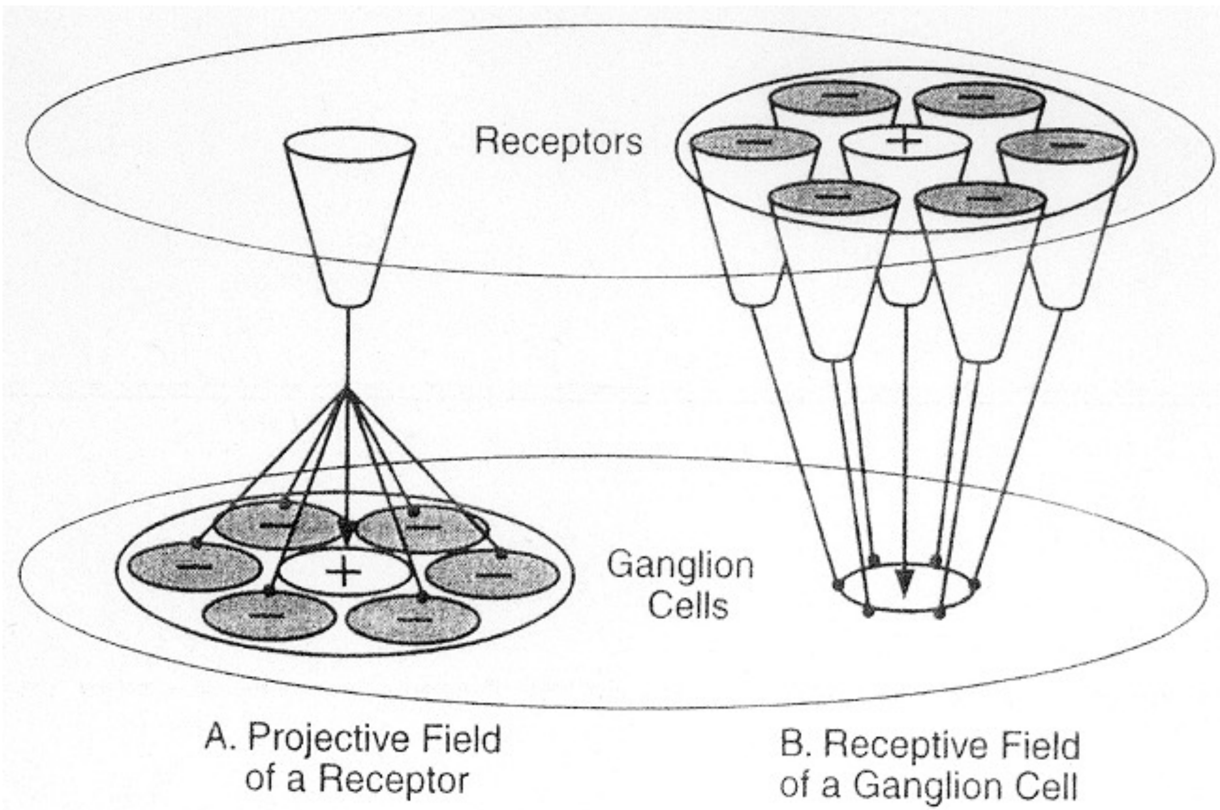
The records show the response recorded by the electrode in the nerve fiber of receptor A:

(a) when only receptor A is stimulated;

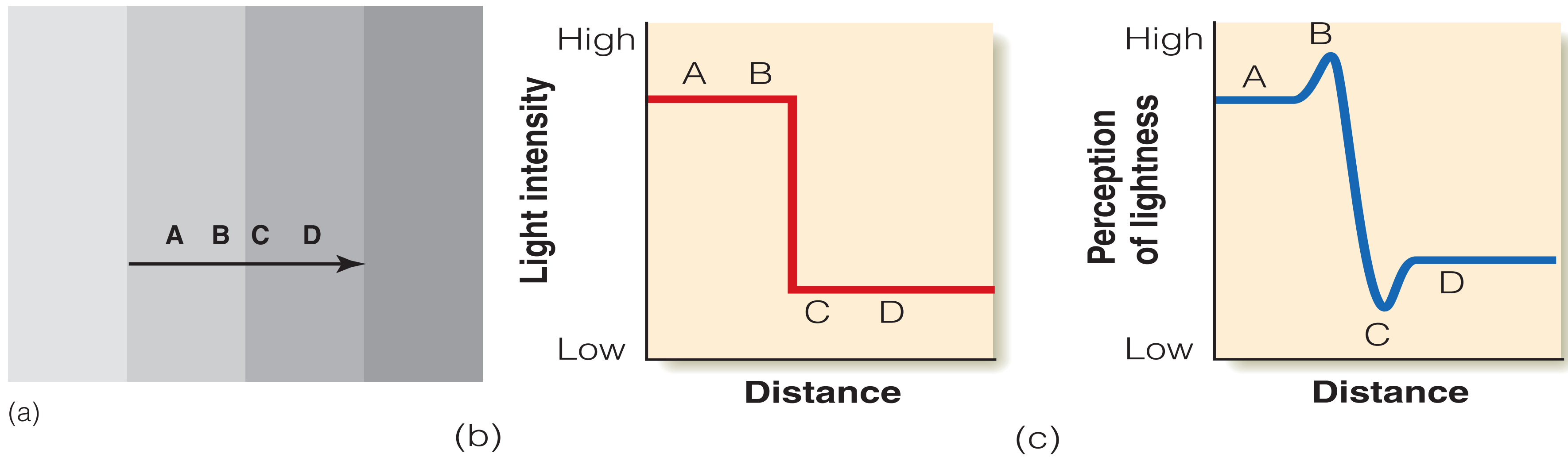
(b) when receptor A and the receptors at B are stimulated together;

(c) when A and B are stimulated, with B at an increased intensity.

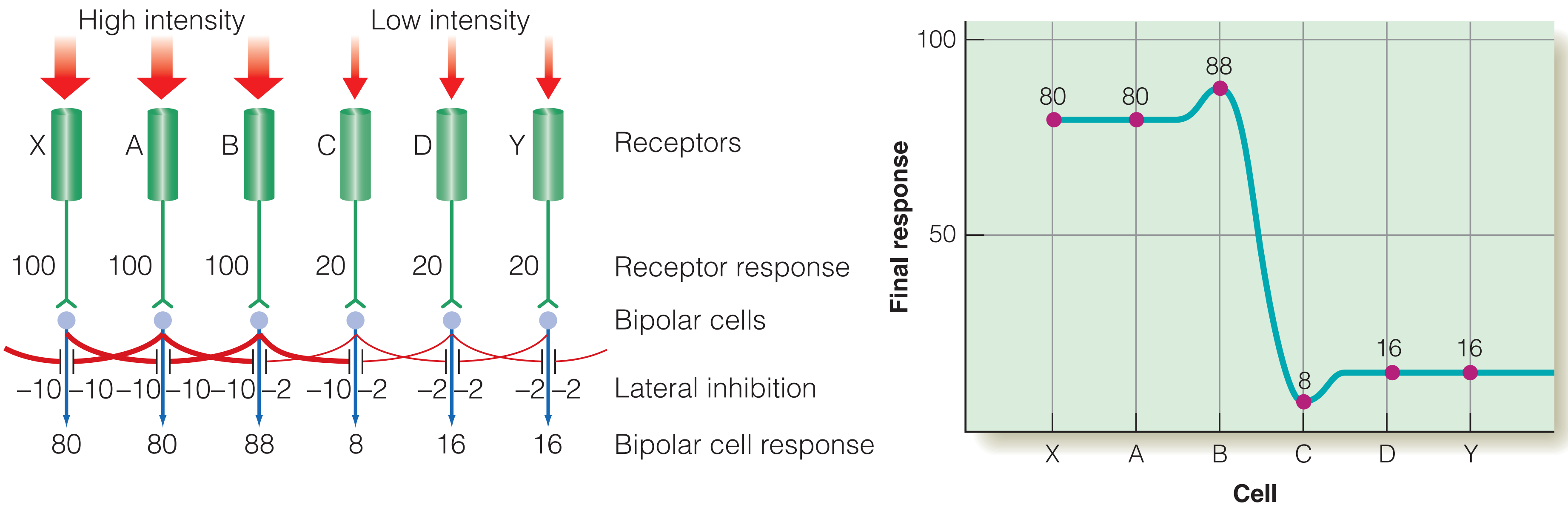
Lateral Inhibition—Physiological Structure



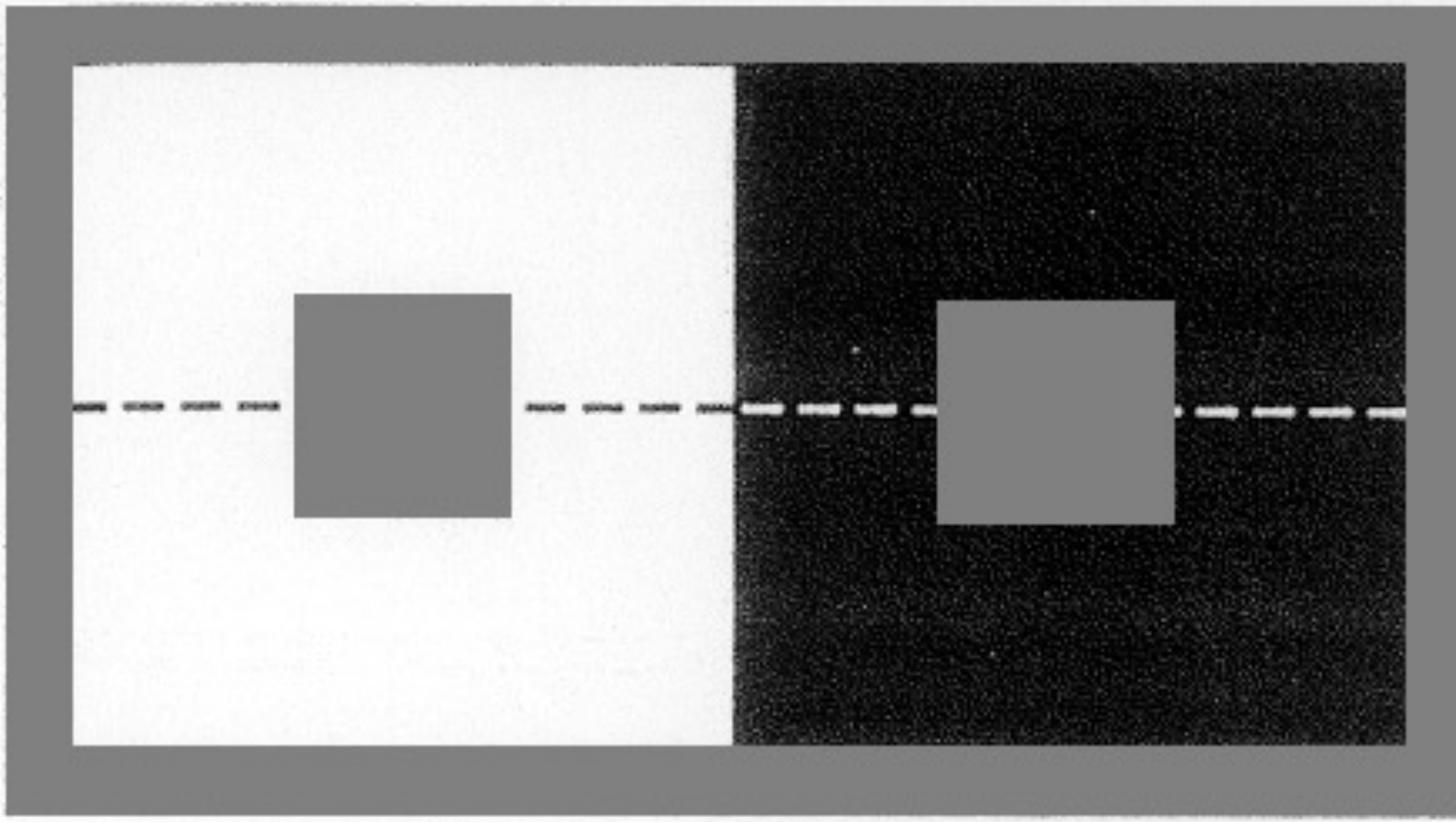
Mach bands

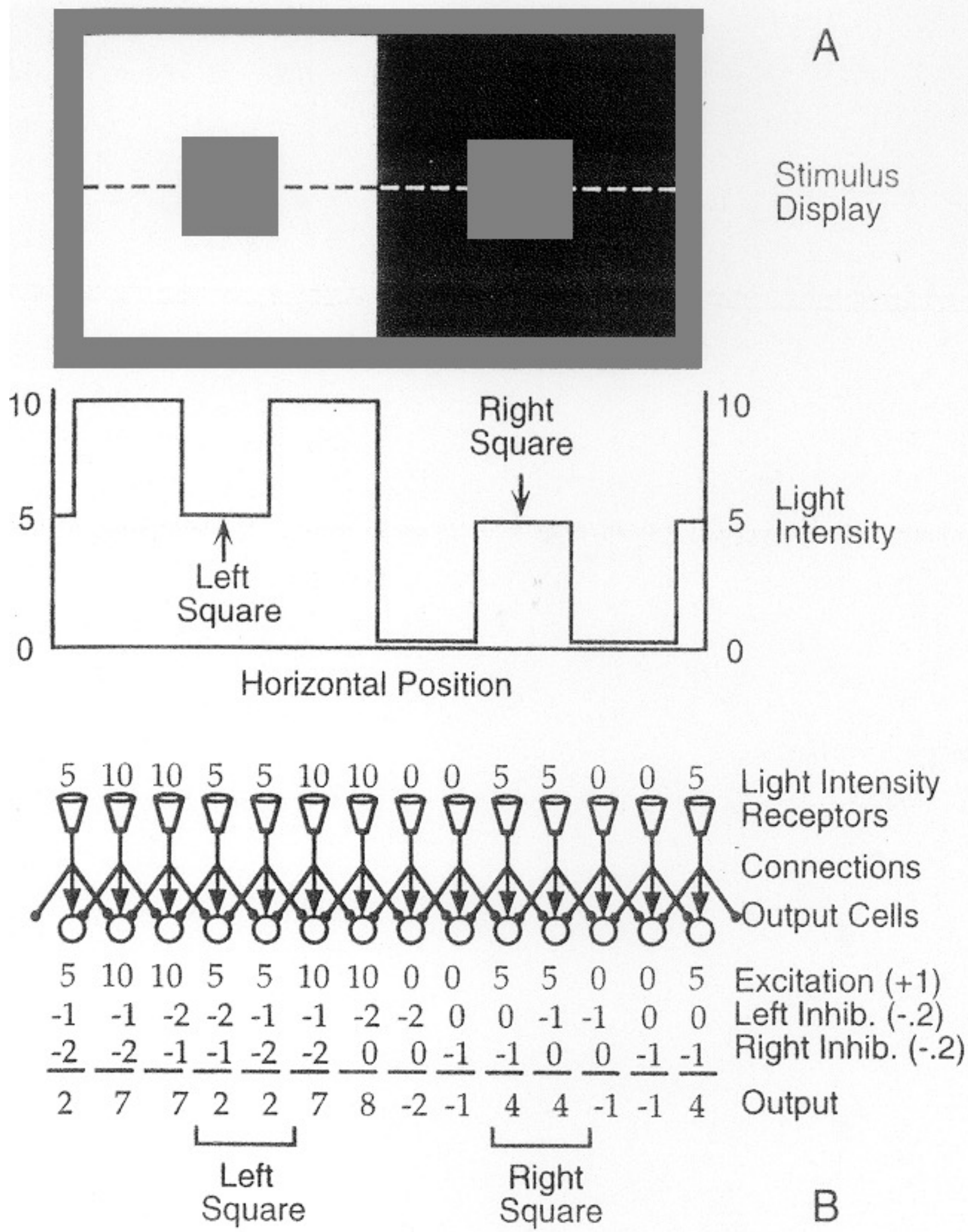


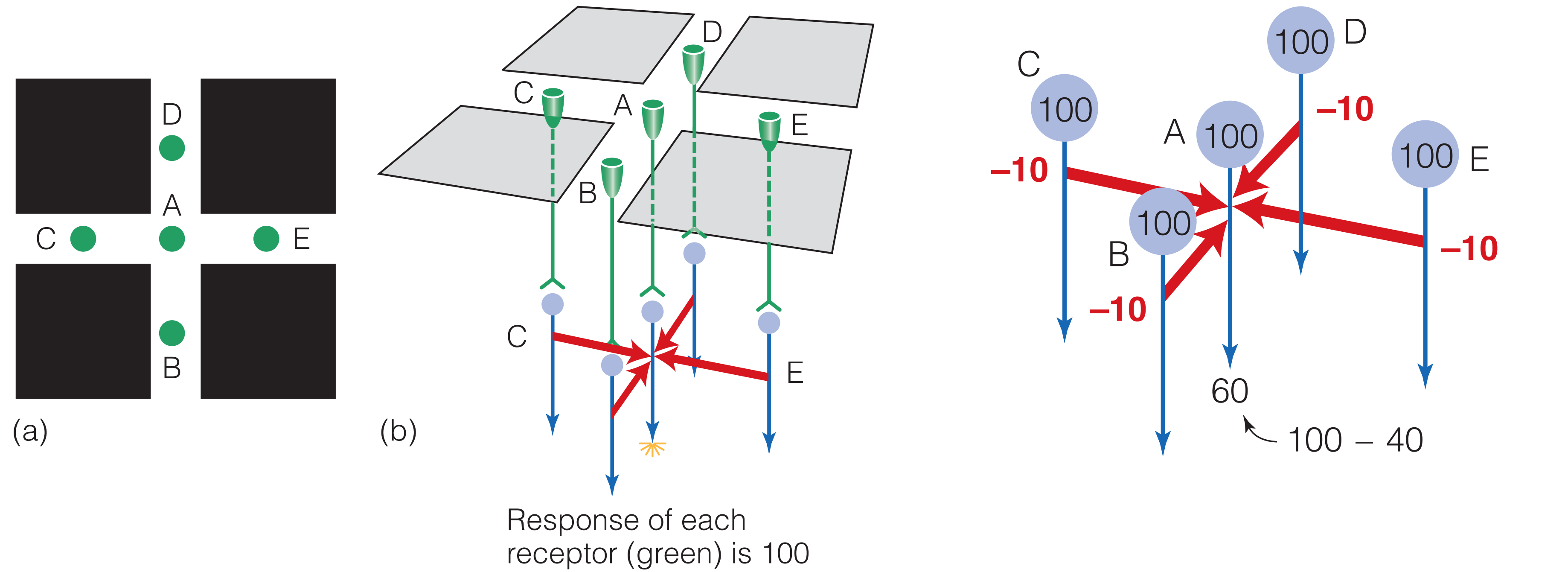
Mach bands at a contour between light and dark.
(a) Just to the left of the contour, near B, a faint light band can be perceived, and just to the right at C, a faint dark band can be perceived.
(b) The physical intensity distribution of the light, as measured with a light meter.
(c) A plot showing the perceptual effect described in (a).



Circuit to explain the Mach band effect based on lateral inhibition. The circuit works like the one for the Hermann grid with each bipolar cell sending inhibition to its neighbors.

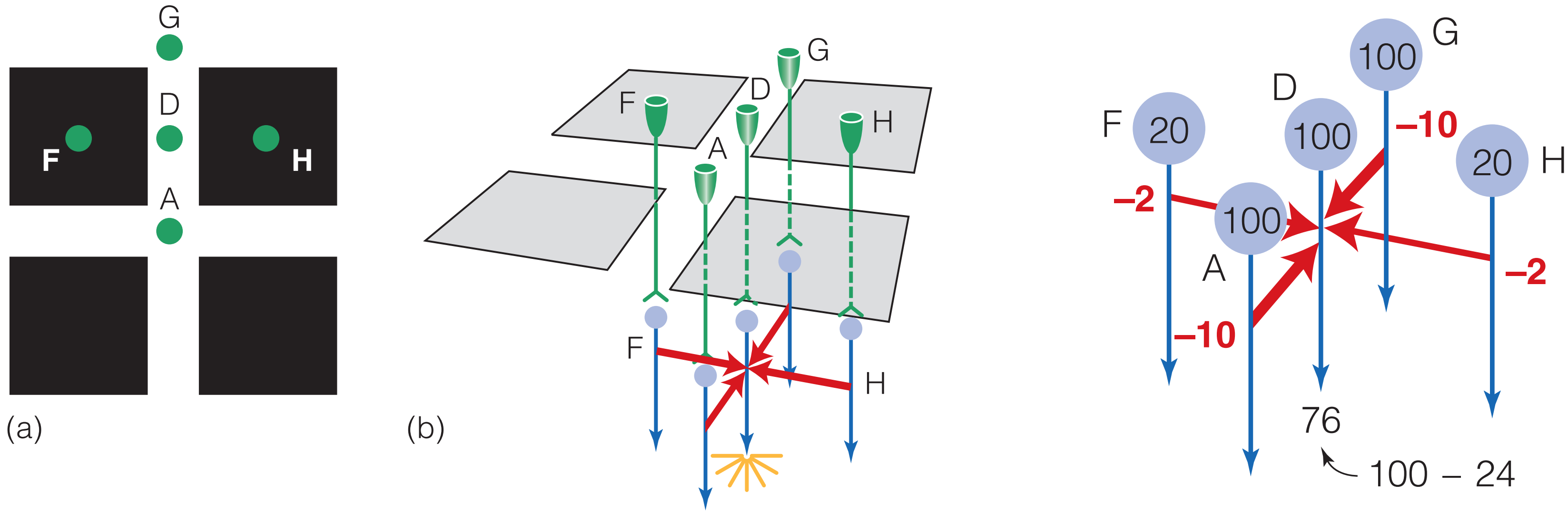



A
Stimulus
Display
10
5
0
Right
Square
Left
Square
Light
Intensity
Horizontal Position
5 10 10 5 5 10 10 0 0 5 5 0 0 5
Light Intensity
Receptors
Connections
Output Cells
5 10 10 5 5 10 10 0 0 5 5 0 0 5 Excitation (+1)
-1 -1 -2 -2 -1 -1 -2 -2 0 0 -1 -1 0 0 Left Inhib. (-.2)
-2 -2 -1 -1 -2 -2 0 0 -1 -1 0 0 -1 -1 Right Inhib. (-.2)
2 7 7 2 2 7 8 -2 -1 4 4 -1 -1 4 Output
Left
Square
Right
Square
B



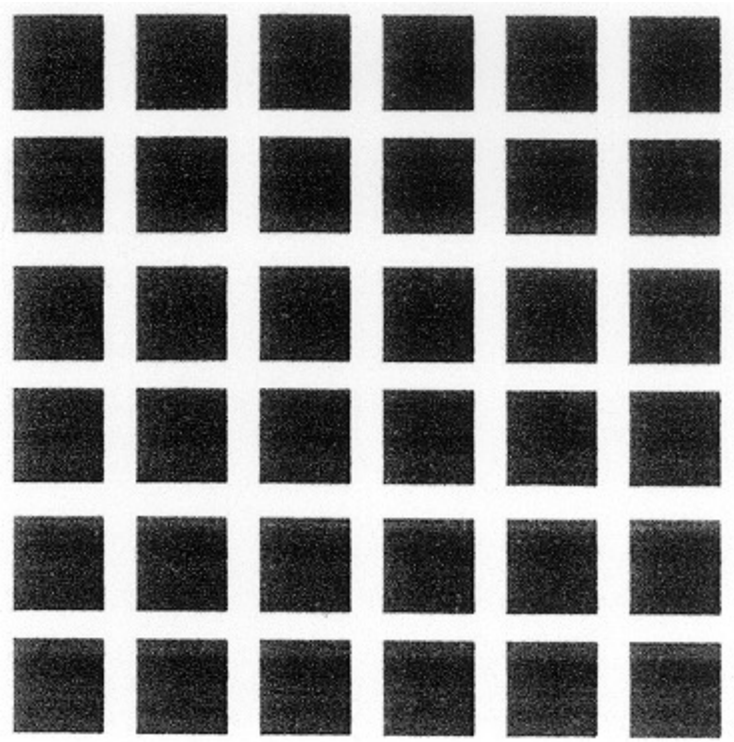
(a) Four squares of the Hermann grid, showing five of the receptors under the pattern.
(b) Showing how the receptors (green) connect to bipolar cells (blue). The response of all five receptors is 100. Lateral inhibition travels to bipolar cell A along the red pathways.

Each bipolar cell has an initial response of 100.
Bipolar cells B, C, D, and E each send 10 units of inhibition to bipolar cell A, as indicated by the red arrows.
Because the total inhibition is 40, the final response of bipolar A is 60.



(a) Now focusing on receptor D, which is flanked by two black squares.
(b) Perspective view of the grid and five receptors, showing how the receptors (green) connect to bipolar cells (blue). The response of receptors A and G is 100, and the response of F and H is 20.

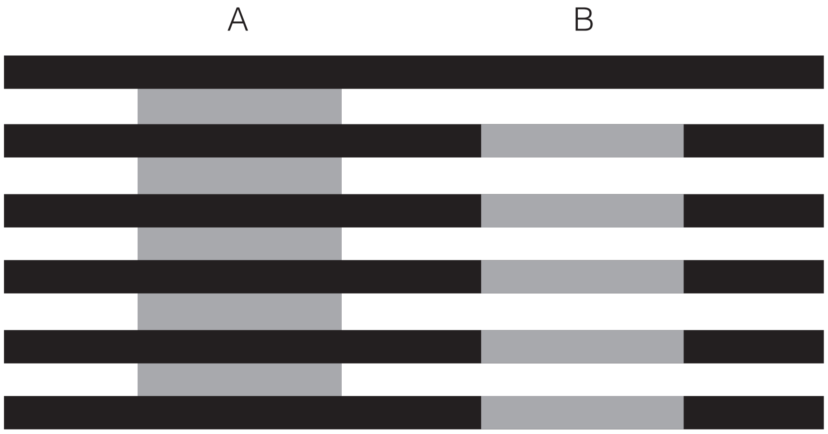
Bipolars A and G have an initial response of 100, and F and H have an initial response of 20.
Bipolars A and G each send 10 units of inhibition to bipolar cell D;
Bipolars F and H each send 2 units of inhibition to D.
The total inhibition is 24, so the final response of bipolar D is 76.

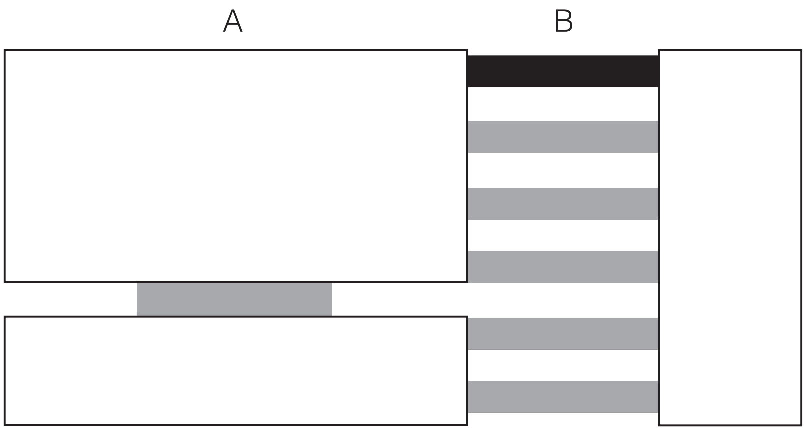


The Hermann grid illusion

• There is less lateral inhibition in the fovea than in the periphery.

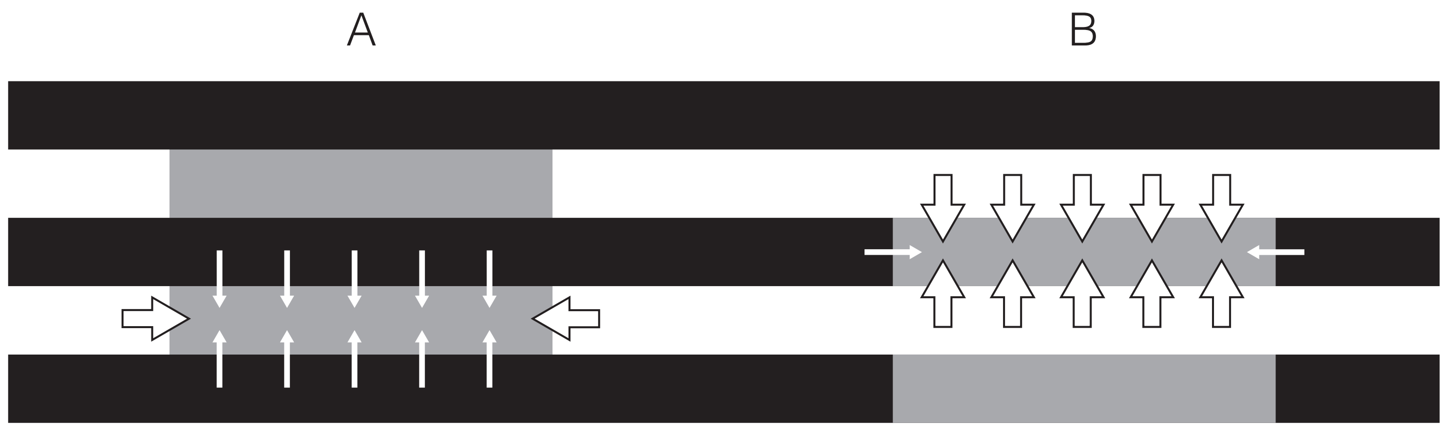
White's illusion



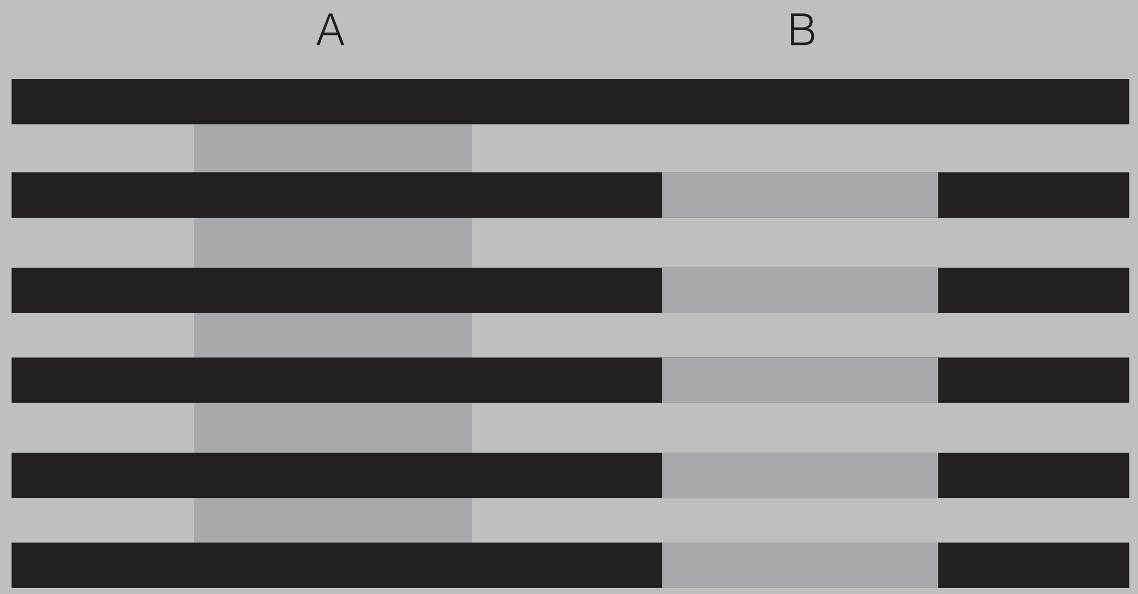


The rectangles at A and B appear different, even though they are printed from the same ink and reflect the same amount of light.

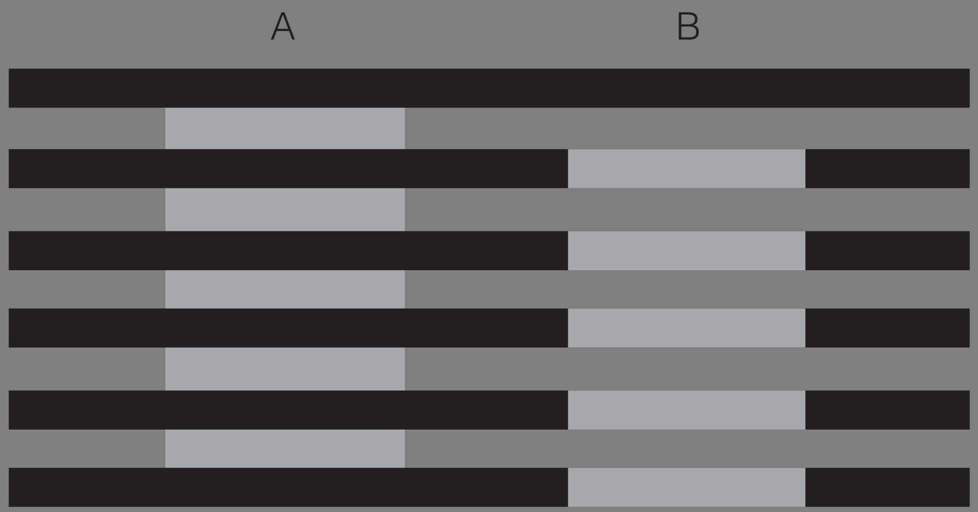
When mask off part of the White's illusion display, you can see that rectangles A and B are actually the same.



- This would predict that B should appear darker than A, but the opposite happens.
- A principle called belongingness, which states that an area’s appearance is influenced by the part of the surroundings to which the area appears to belong.
- We can’t explain some perceptions based only on what is happening in the retina, because there is still much more processing to be done before perception occurs.

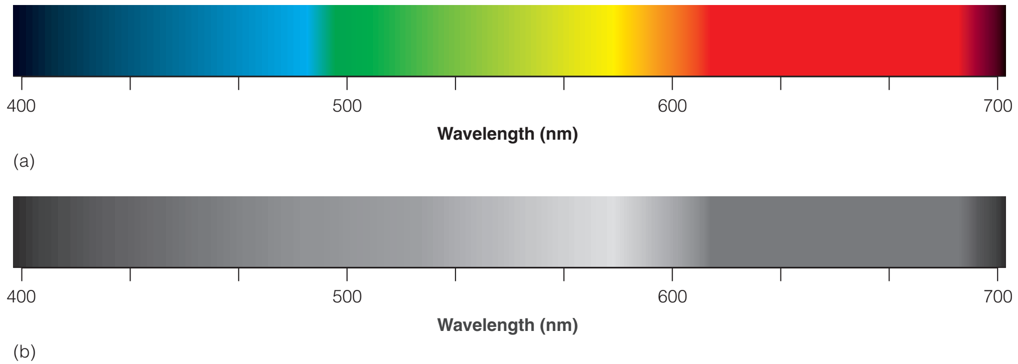


A
B


A
B

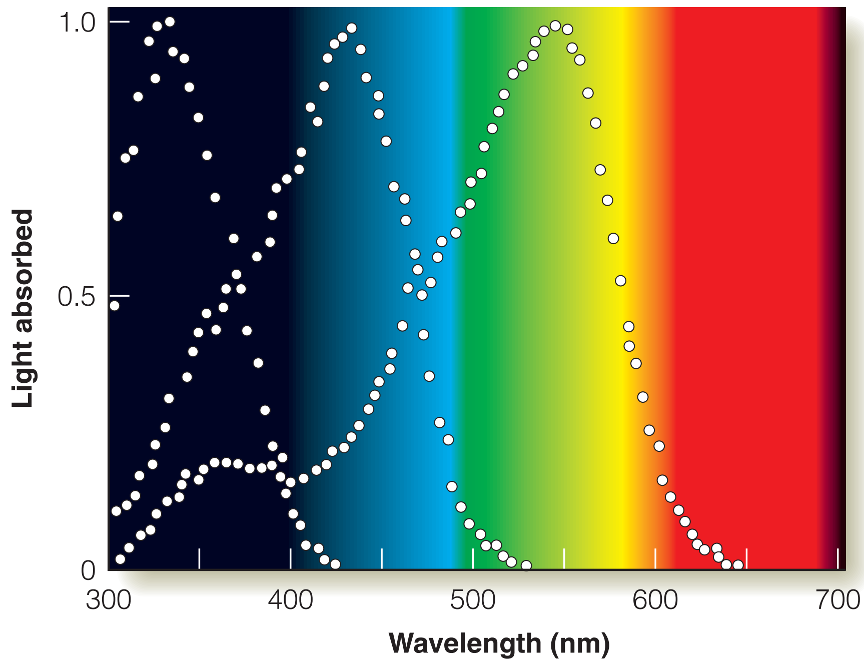

A
B

4. Color is a Construction of the Nervous System



(a) Visible spectrum.
(b) At low intensities, maximum sensitivity is shifted to shorter wavelengths, and color is lost.

- There is a connection between wavelength and color.
  - As it turns out, however, wavelengths are completely colorless.
  - As illumination decreases, hues such as blue, green, and red become less distinct and eventually disappear altogether.
- What has caused this transformation from chromatic to achromatic color?
  - Under high illumination, the three cones of trichromatic vision control perception, but under dim illumination, only the rods control perception.
  - We know from our earlier discussion that just one visual pigment can’t distinguish between different wavelengths, so when only the rods are active, there is no color perception.



Absorption spectra of honeybee visual pigments.

- The idea is that our perceptual experience is not only *shaped* by the nervous system, as in the example of rod and cone vision, the very essence of our experience is *created* by the nervous system.

Conclusion

- The psychophysical correspondence of color
- Image-based color perception
  - Some phenomena
  - Three theories
- Real world color perception
  - Lightness constancy
  - Relational theory
  - Lateral inhibition
- Color is a Construction of the Nervous System

Question?