5

The Perception of Color

- Basic Principles of Color Perception
- Step 1: Color Detection
- Step 2: Color Discrimination
- Step 3: Color Appearance
- Individual Differences in Color Perception
- From the Color of Lights to a World of Color
- What Is Color Vision Good For?

Basic Principles of Color Perception

Color is not a physical property but a psychophysical property.

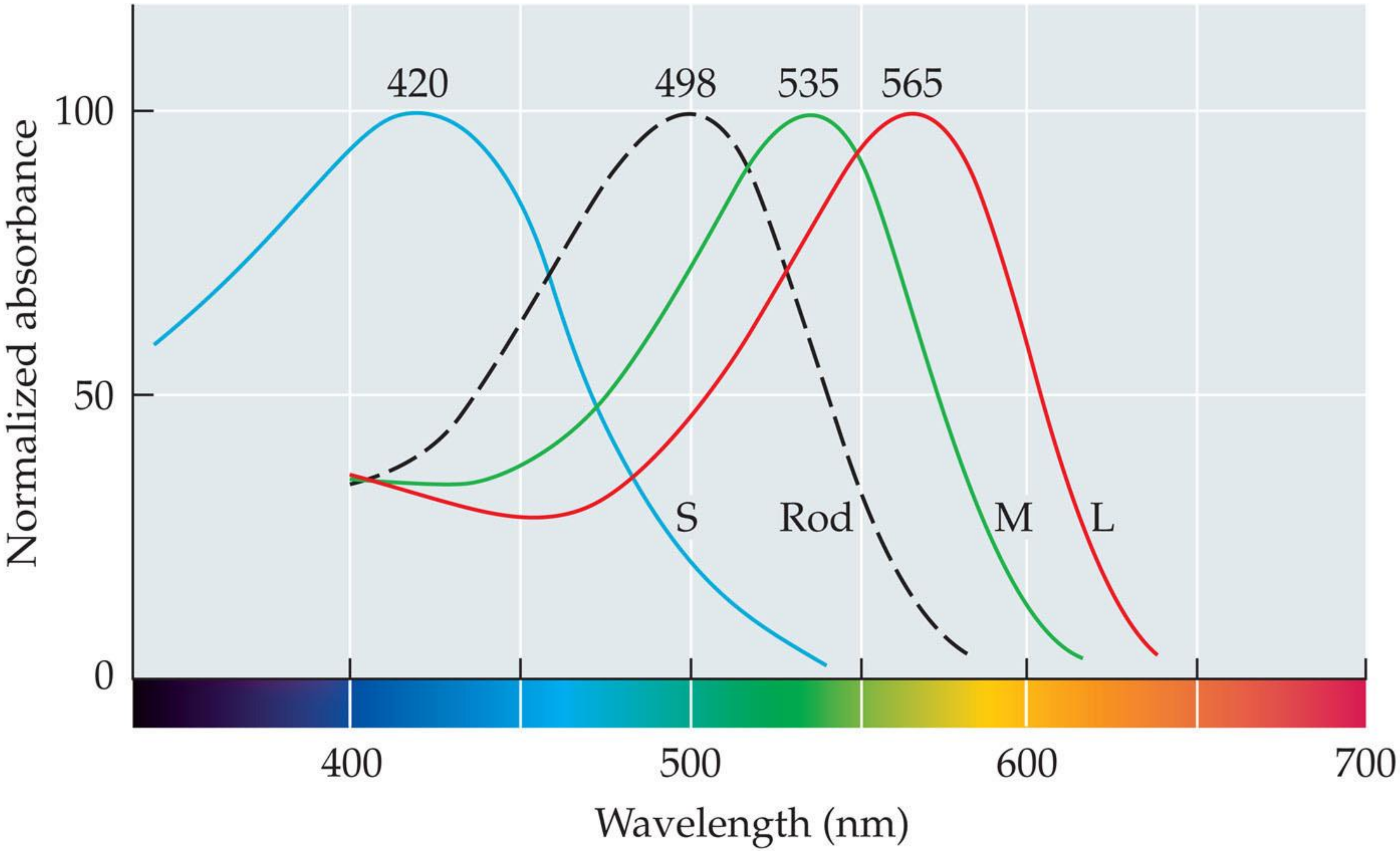
- “There is no red in a 700 nm light, just as there is no pain in the hooves of a kicking horse.” –Steven Shevell (2003)

Basic Principles of Color Perception

Most of the light we see is reflected.

- Typical light sources: Sun, light bulb, fire
- We see only part of the electromagnetic spectrum, between 400 and 700 nm.

Figure 5.1 The retina contains four types of photoreceptors



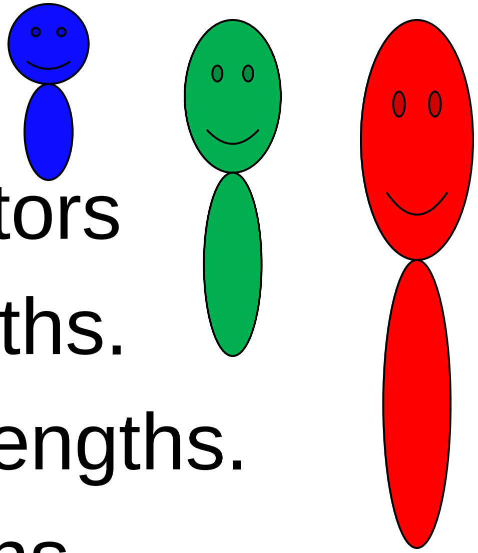
SENSATION & PERCEPTION 4e, Figure 5.1

Basic Principles of Color Perception

Three steps to color perception

1. Detection: Wavelengths of light must be detected in the first place.
2. Discrimination: We must be able to tell the difference between one wavelength (or mixture of wavelengths) and another.
3. Appearance: We want to assign perceived colors to lights and surfaces in the world and have those perceived colors be stable over time, regardless of different lighting conditions.

Step 1: Color Detection



- Three types of cone photoreceptors
  - S-cones detect short wavelengths.
  - M-cones detect medium wavelengths.
  - L-cones detect long wavelengths.
- More accurate to refer to them as “short,” “medium,” and “long” rather than “blue,” “green,” and “red,” since they each respond to a variety of wavelengths
  - The L-cone’s peak sensitivity is 565 nm, which corresponds to yellow, not red!

Basic Principles of Color Perception

- Photopic: Light intensities that are bright enough to stimulate the cone receptors and bright enough to "saturate" the rod receptors to their maximum responses.
  - Sunlight and bright indoor lighting are both photopic lighting conditions.

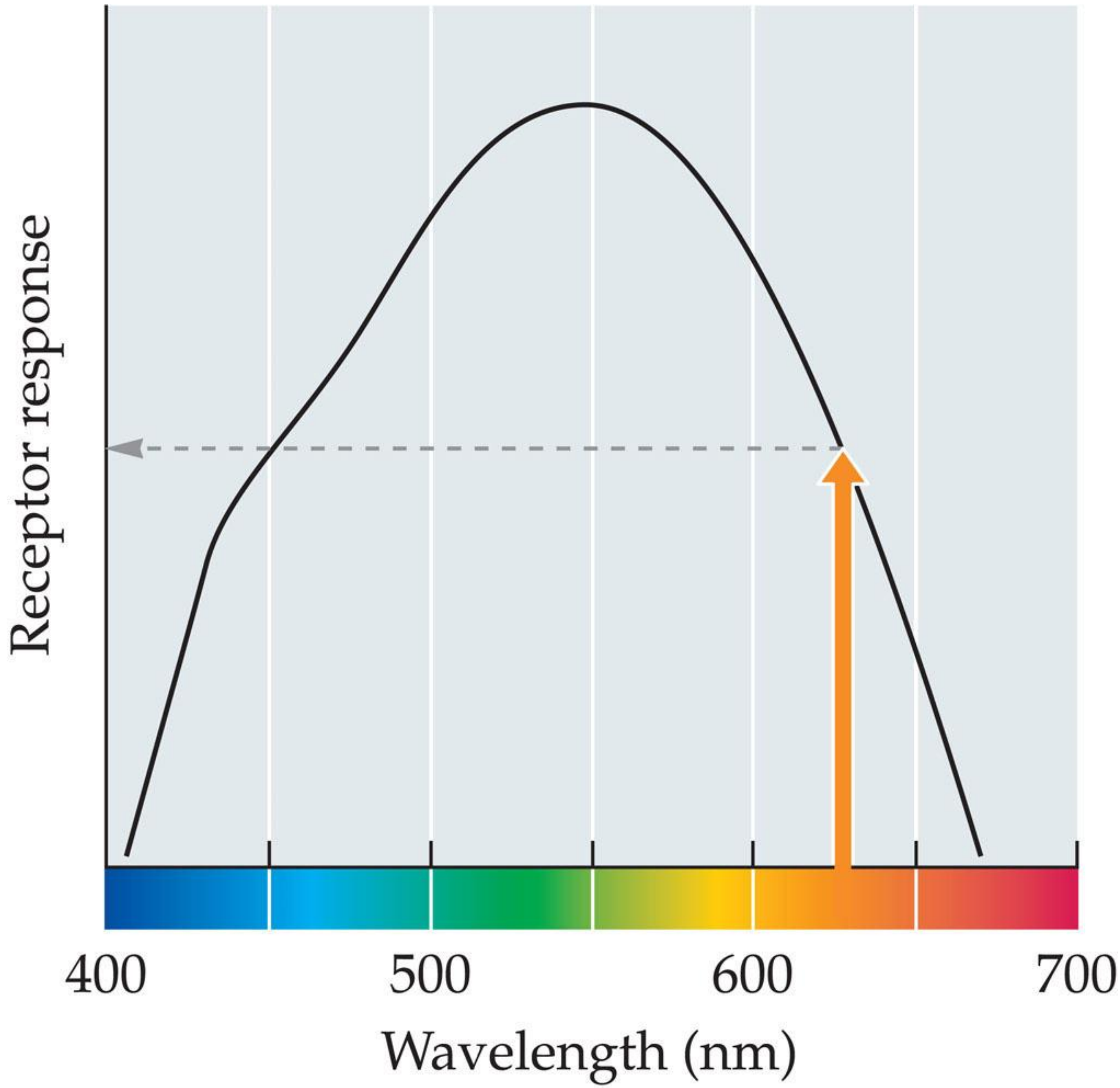
Basic Principles of Color Perception

- Scotopic: Light intensities that are bright enough to stimulate the rod receptors but too dim to stimulate the cone receptors.
  - Moonlight and extremely dim indoor lighting are both scotopic lighting conditions.

Step 2: Color Discrimination

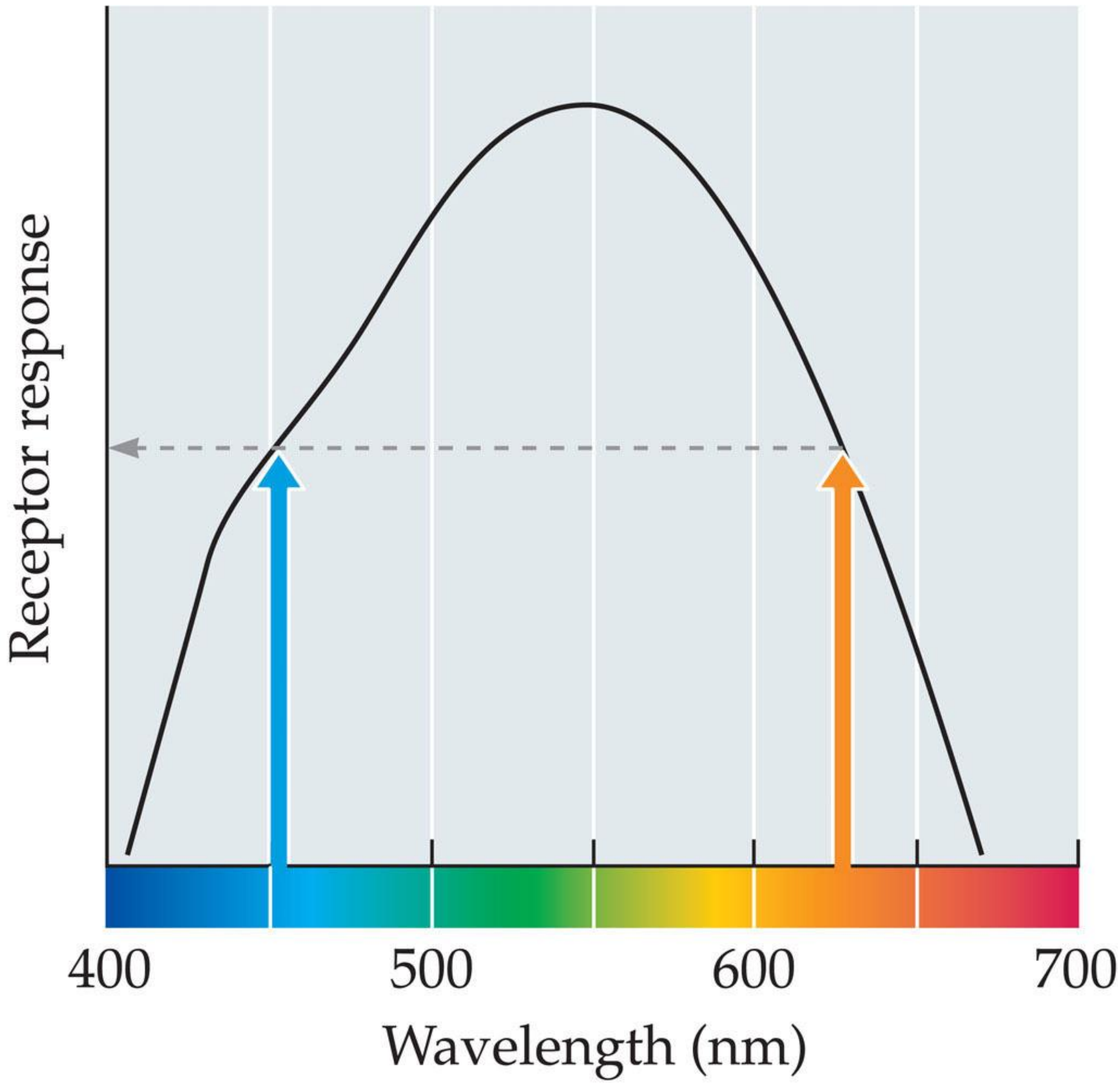
- The principle of univariance: An infinite set of different wavelength-intensity combinations can elicit exactly the same response from a single type of photoreceptor.
  - Therefore, one type of photoreceptor cannot make color discriminations based on wavelength.

Figure 5.2 A single photoreceptor shows different responses to lights of different wavelengths but the same intensity



SENSATION & PERCEPTION 4e, Figure 5.2

Figure 5.3 Lights of 450 and 625 nm each elicit the same response from the photoreceptor whose responses are shown here and in Figure 5.2



SENSATION & PERCEPTION 4e, Figure 5.3

Rods are sensitive to scotopic light levels.

- All rods contain the same photopigment molecule: rhodopsin.
- All rods have the same sensitivity to various wavelengths of light.
- Therefore, rods obey the principle of univariance and cannot sense differences in color.
- Under scotopic conditions, only rods are active, so that is why the world seems drained of color.

Figure 5.4 The moonlit world appears devoid of color because we have only one type of rod photoreceptor transducing light under these scotopic conditions

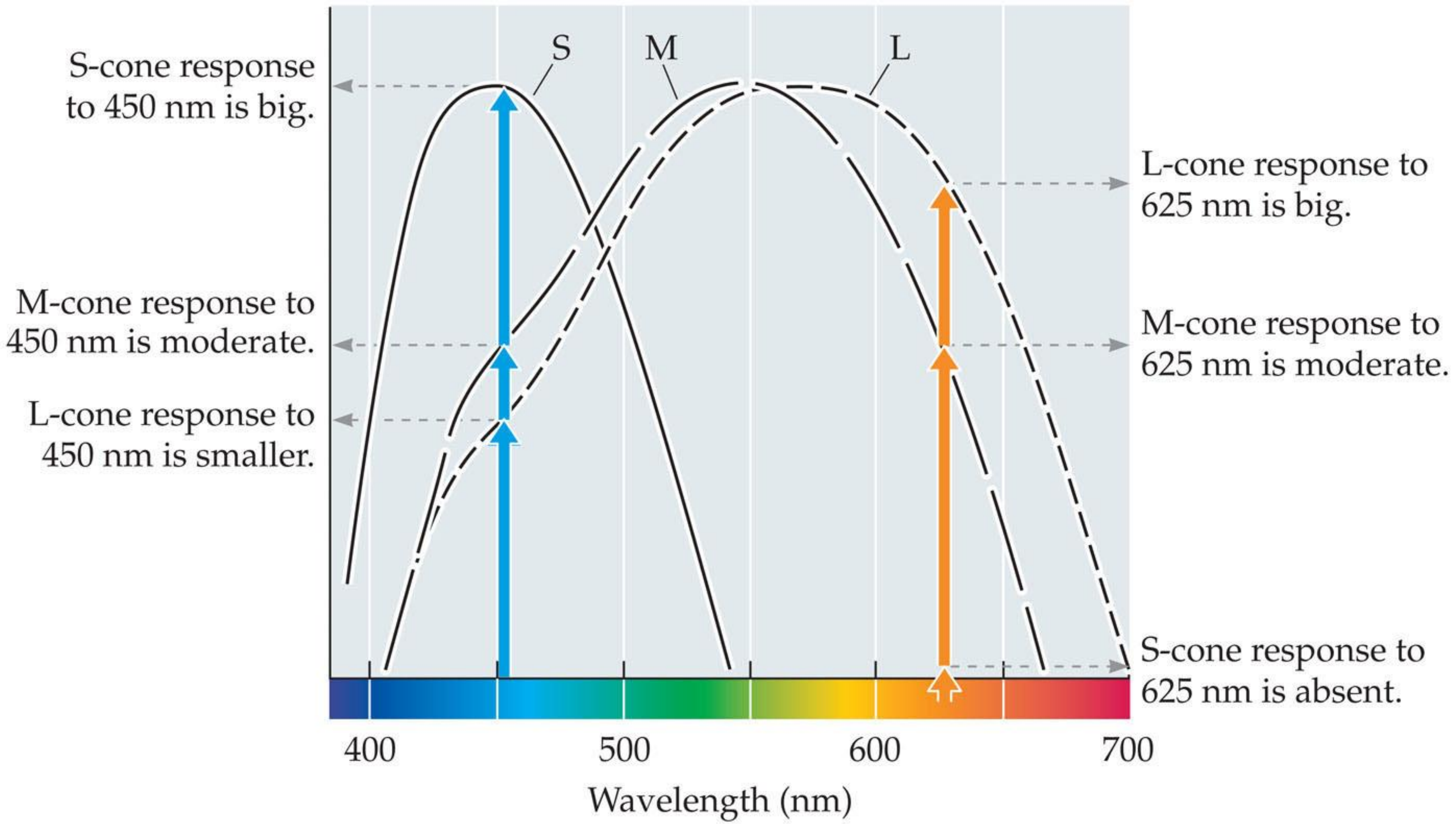
SENSATION & PERCEPTION 4e, **Figure 5.4**

Basic Principles of Color Perception

With three cone types, we can tell the difference between lights of different wavelengths.

- Under photopic conditions, the S-, M-, and L-cones are all active.

Figure 5.5 The two wavelengths that produce the same response from one type of cone (M) produce different patterns of responses across the three types of cones



SENSATION & PERCEPTION 4e, Figure 5.5

Basic Principles of Color Perception

Trichromacy: The theory that the color of any light is defined in our visual system by the relationships of three numbers, the outputs of three receptor types now known to be the three cones.

- Also known as the *Young-Helmholtz theory*

Results of Additive Color Mixing

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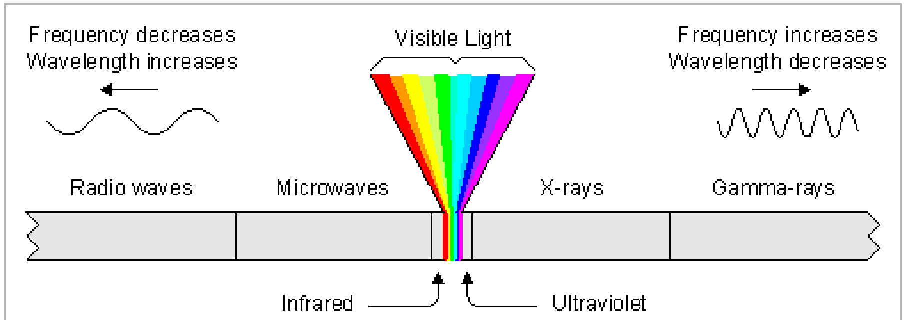
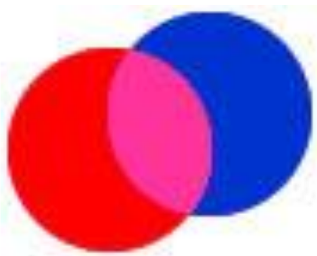
G+R LIGHT = YELLOW

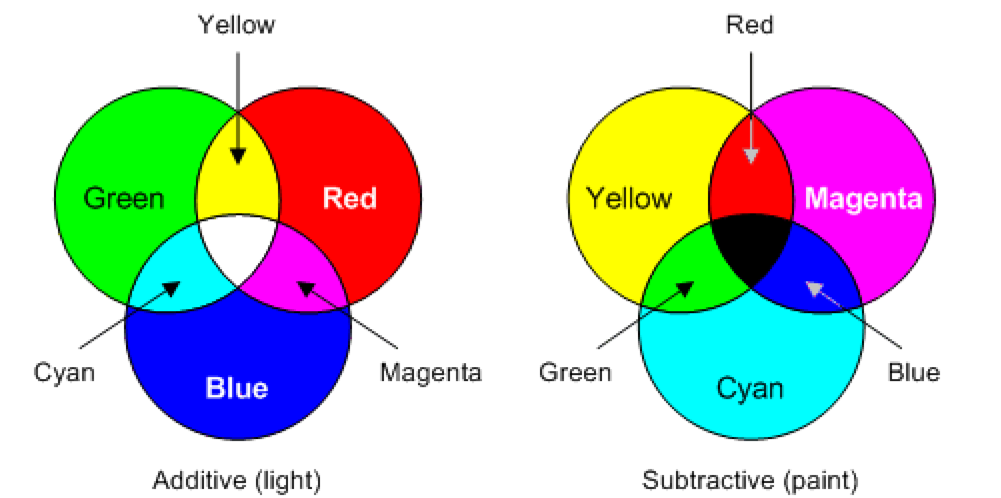


The visible portion of the electromagnetic spectrum

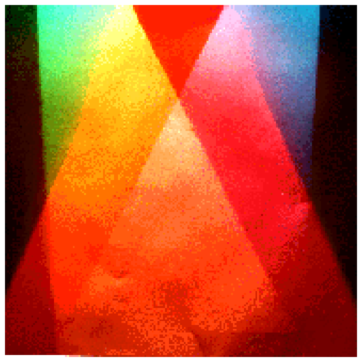
G+B LIGHT = CYAN



R+B LIGHT = MAGENTA



Additive and subtractive color combinations



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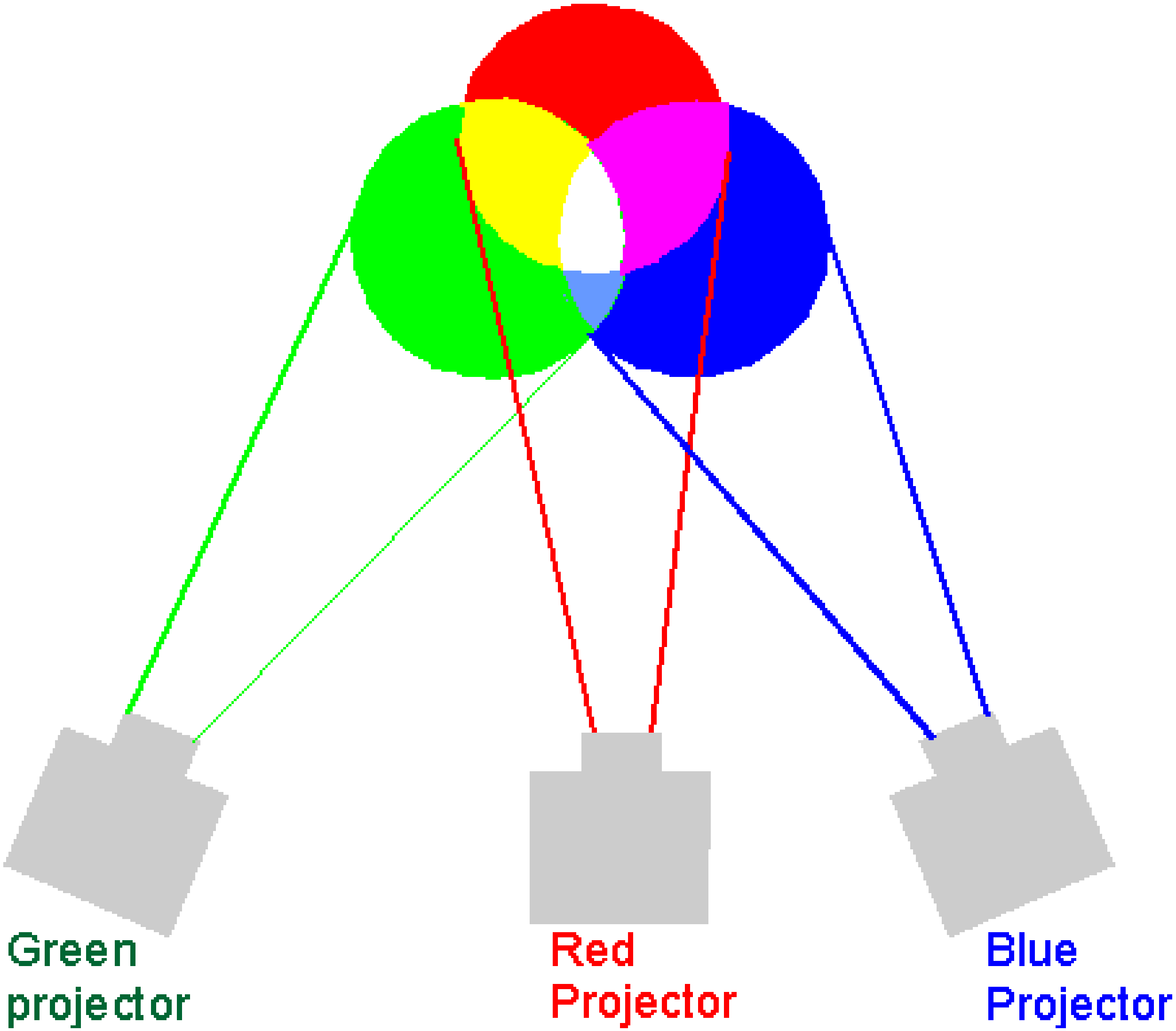
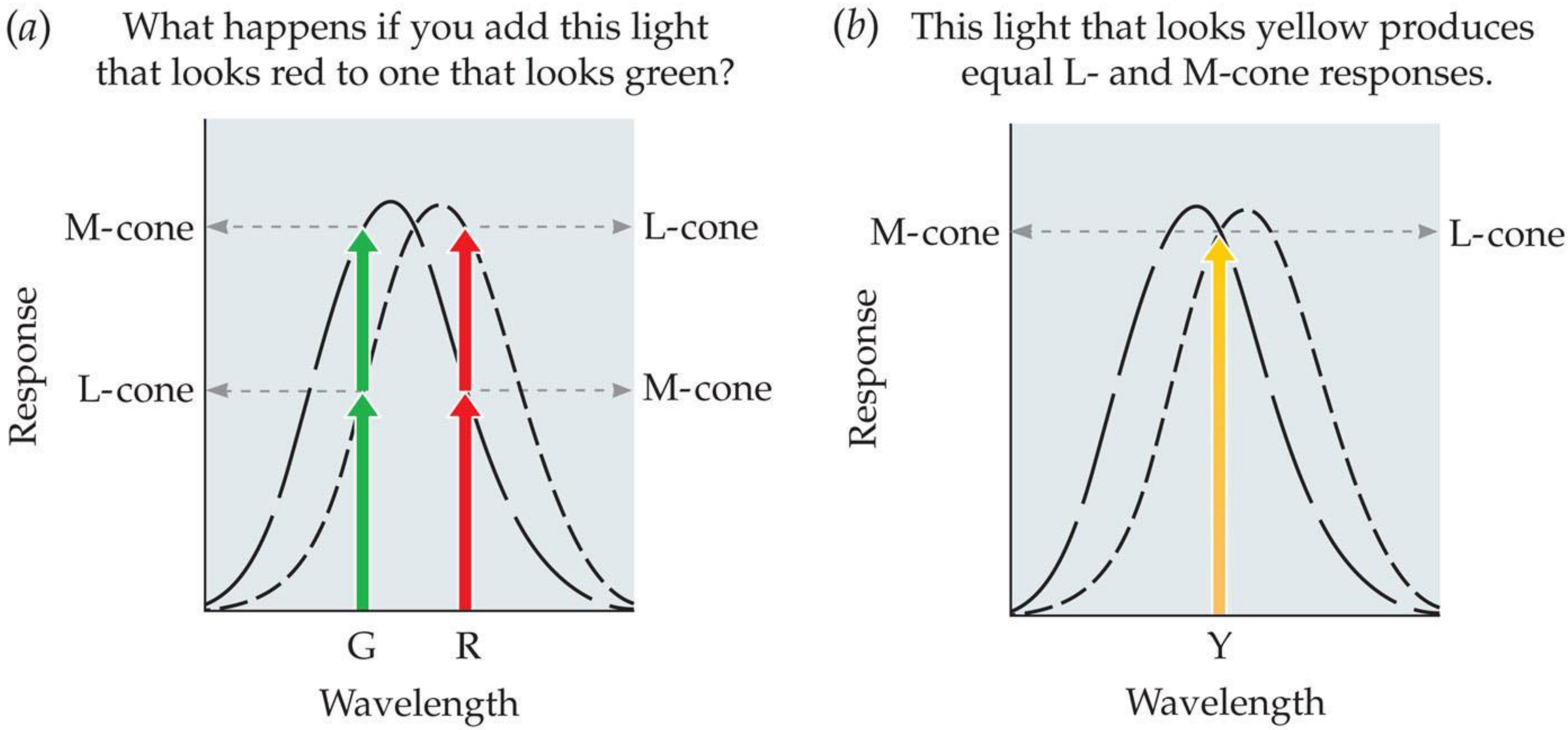
Additive Color mixing with lights



Metamers: Different mixtures of wavelengths that look identical; more generally, any pair of stimuli that are perceived as identical in spite of physical differences.

Figure 5.7 (*a*) The long-wavelength light that looks red and the shorter-wavelength light that looks green mix to produce the same response as does the medium-wavelength light that looks yellow (*b*)

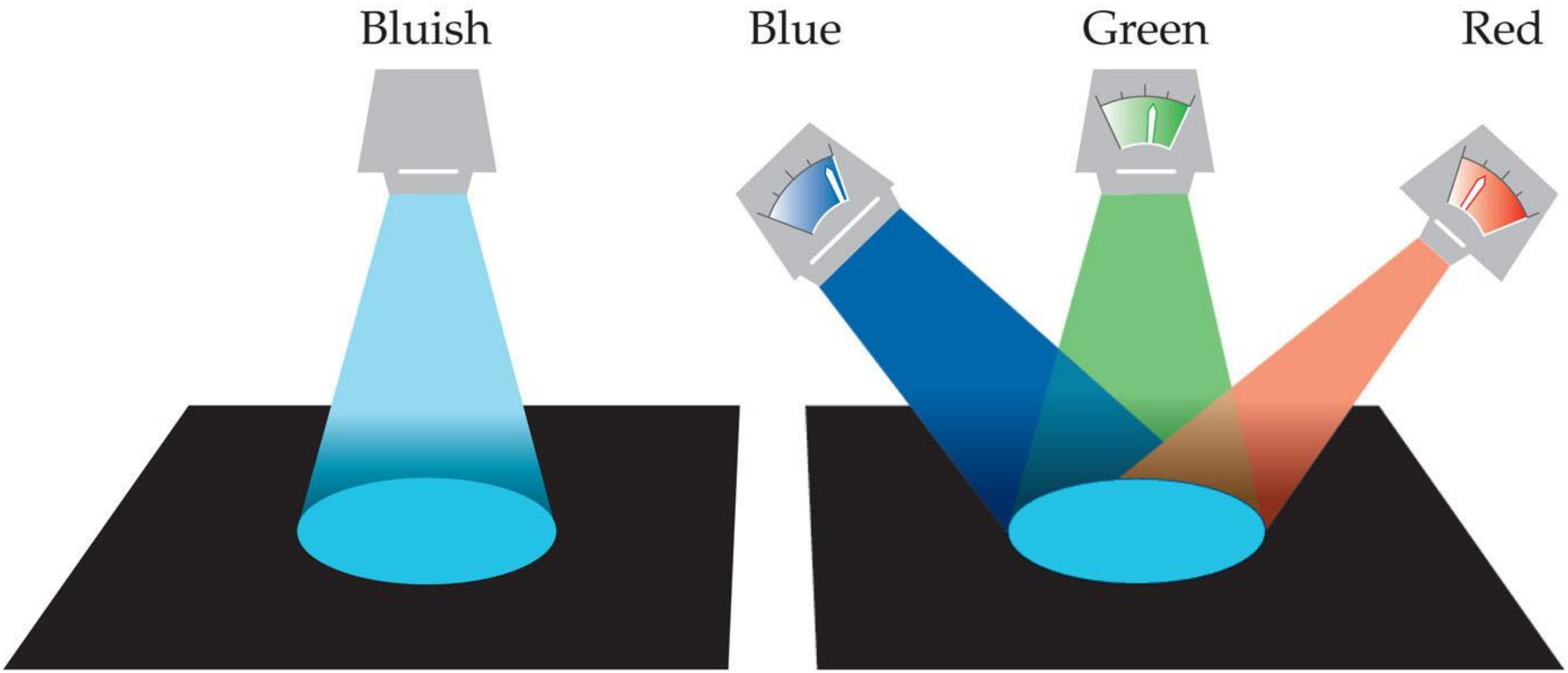


SENSATION & PERCEPTION 4e, Figure 5.7

History of color vision

- Thomas Young (1773–1829) and Hermann von Helmholtz (1821–1894) independently discovered the trichromatic nature of color perception.
  - This is why trichromatic theory is sometimes called the “Young-Helmholtz theory”
- James Maxwell (1831–1879) developed a color-matching technique that is still being used today.

Figure 5.8 Modern version of Maxwell's color-matching experiment

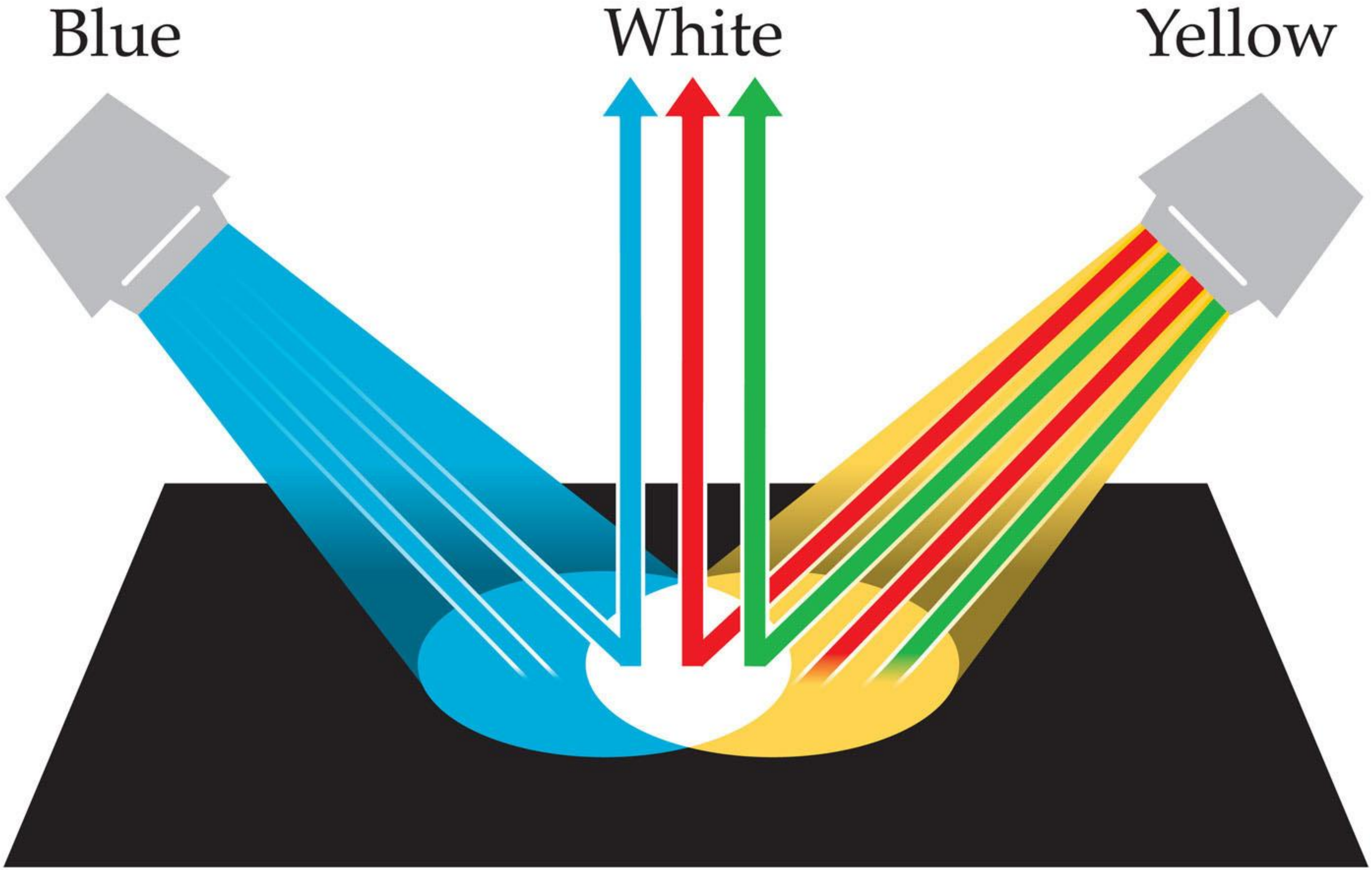


SENSATION & PERCEPTION 4e, **Figure 5.8**

Additive color mixing: A mixture of lights

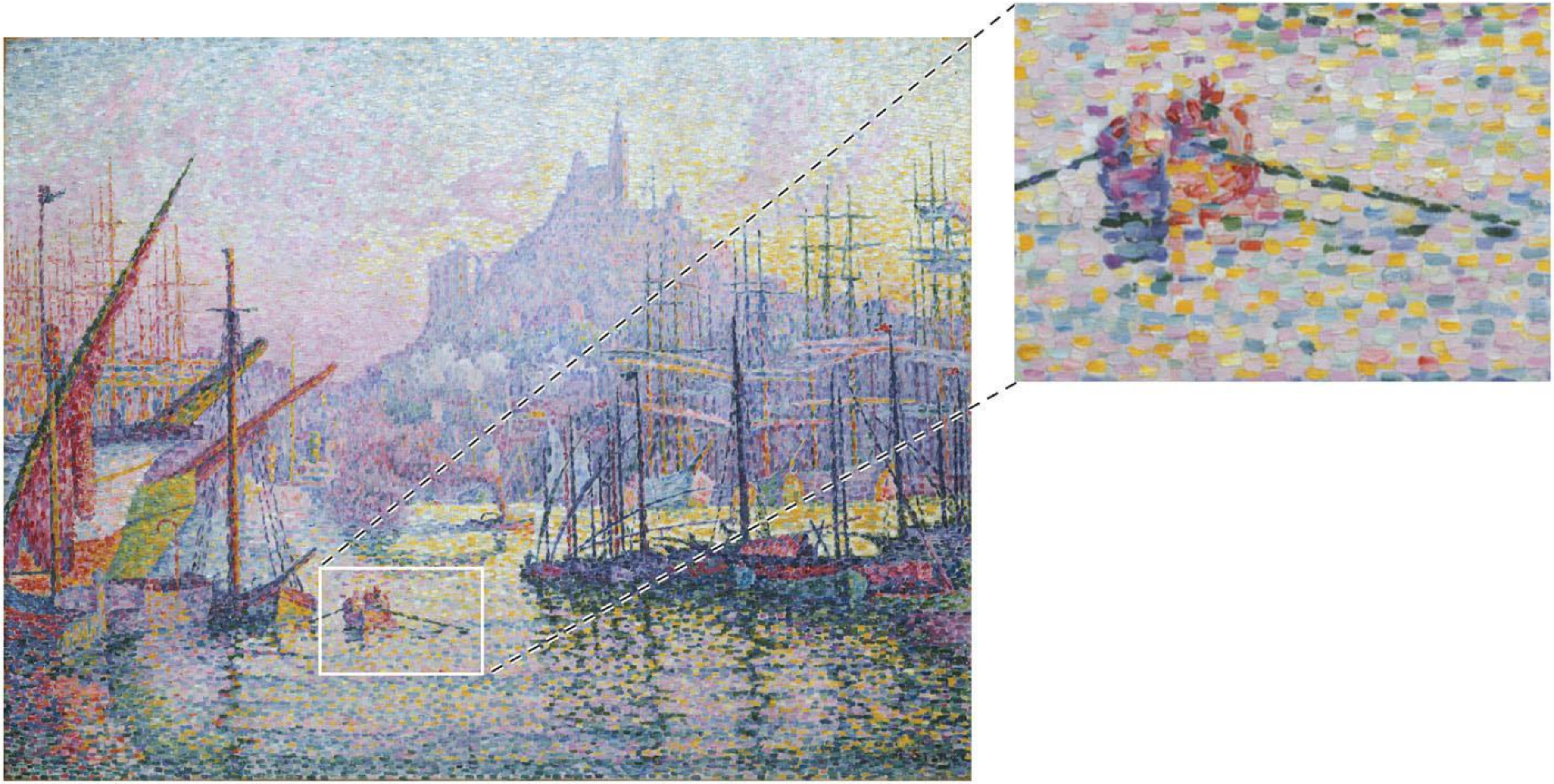
- If light A and light B are both reflected from a surface to the eye, in the perception of color, the effects of those two lights add together.

Figure 5.10 Shining a light that looks blue and a light that looks yellow on an area of paper, the wavelengths add, producing an additive color mixture



SENSATION & PERCEPTION 4e, Figure 5.10

Figure 5.11 Pointillism



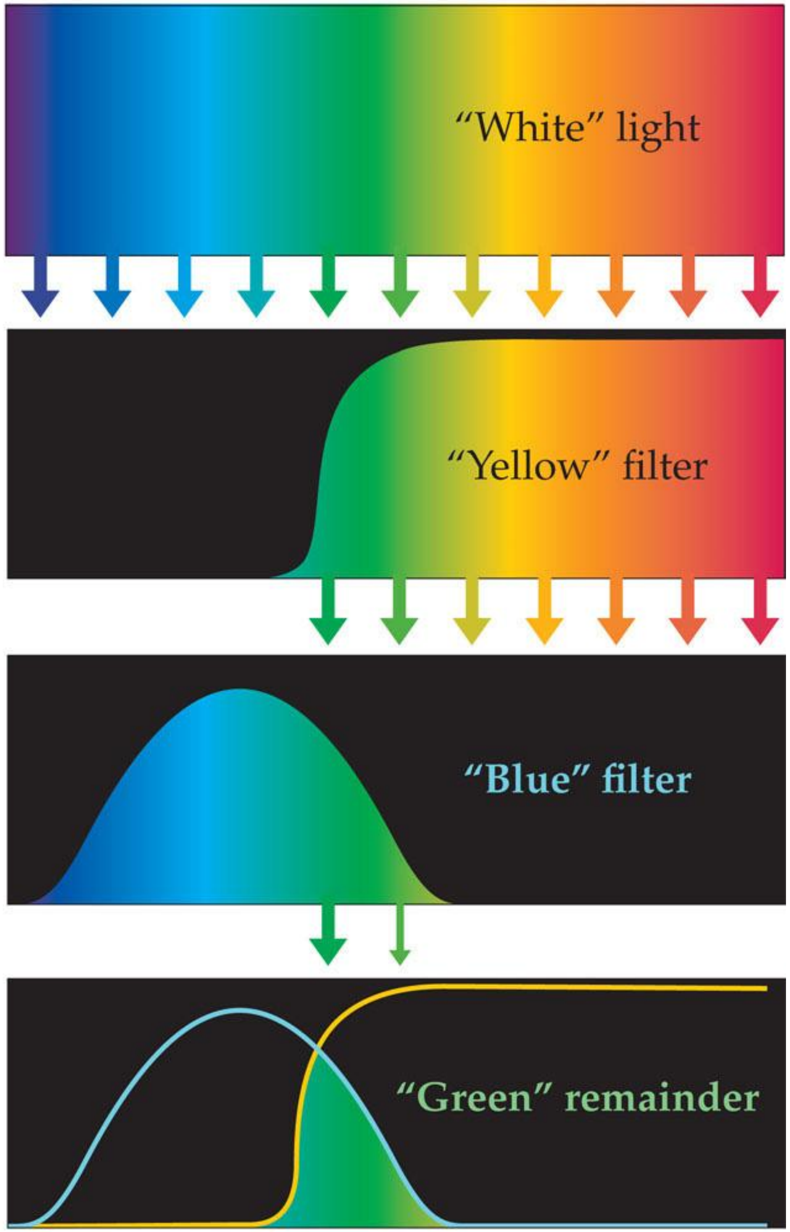
***SENSATION & PERCEPTION 4e,* Figure 5.11**

Subtractive color mixing: A mixture of pigments

- If pigment A and B mix, some of the light shining on the surface will be subtracted by A and some by B. Only the remainder contributes to the perception of color.

Figure 5.9 In this example of subtractive color mixture, "white"—broadband—light is passed through two filters

1. Take "white" light that contains a broad mixture of wavelengths.
2. Pass it through a filter that absorbs shorter wavelengths. The result will look yellowish.
3. Pass that through a bluish filter that absorbs all but a middle range of wavelengths.
4. The wavelengths that make it through both filters will be a mix that looks greenish.



SENSATION & PERCEPTION 4e, **Figure 5.9**

Basic Principles of Color Perception

Lateral geniculate nucleus (LGN) has cells that are maximally stimulated by spots of light.

- Visual pathway stops in LGN on the way from retina to visual cortex.
- LGN cells have receptive fields with center-surround organization.

Cone-opponent cell: A neuron whose output is based on a difference between sets of cones

- In LGN there are cone-opponent cells with center-surround organization.

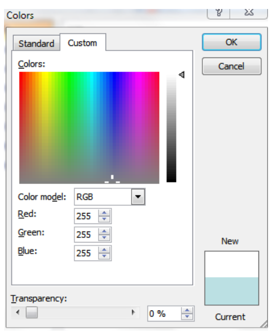
Step 3: Color Appearance

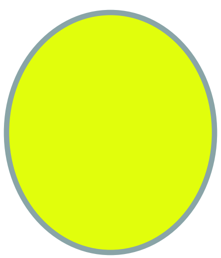
- Color space: A three-dimensional space that describes all colors. There are several possible color spaces.
  - RGB color space: Defined by the outputs of long, medium, and short wavelength lights (i.e., red, green, and blue).

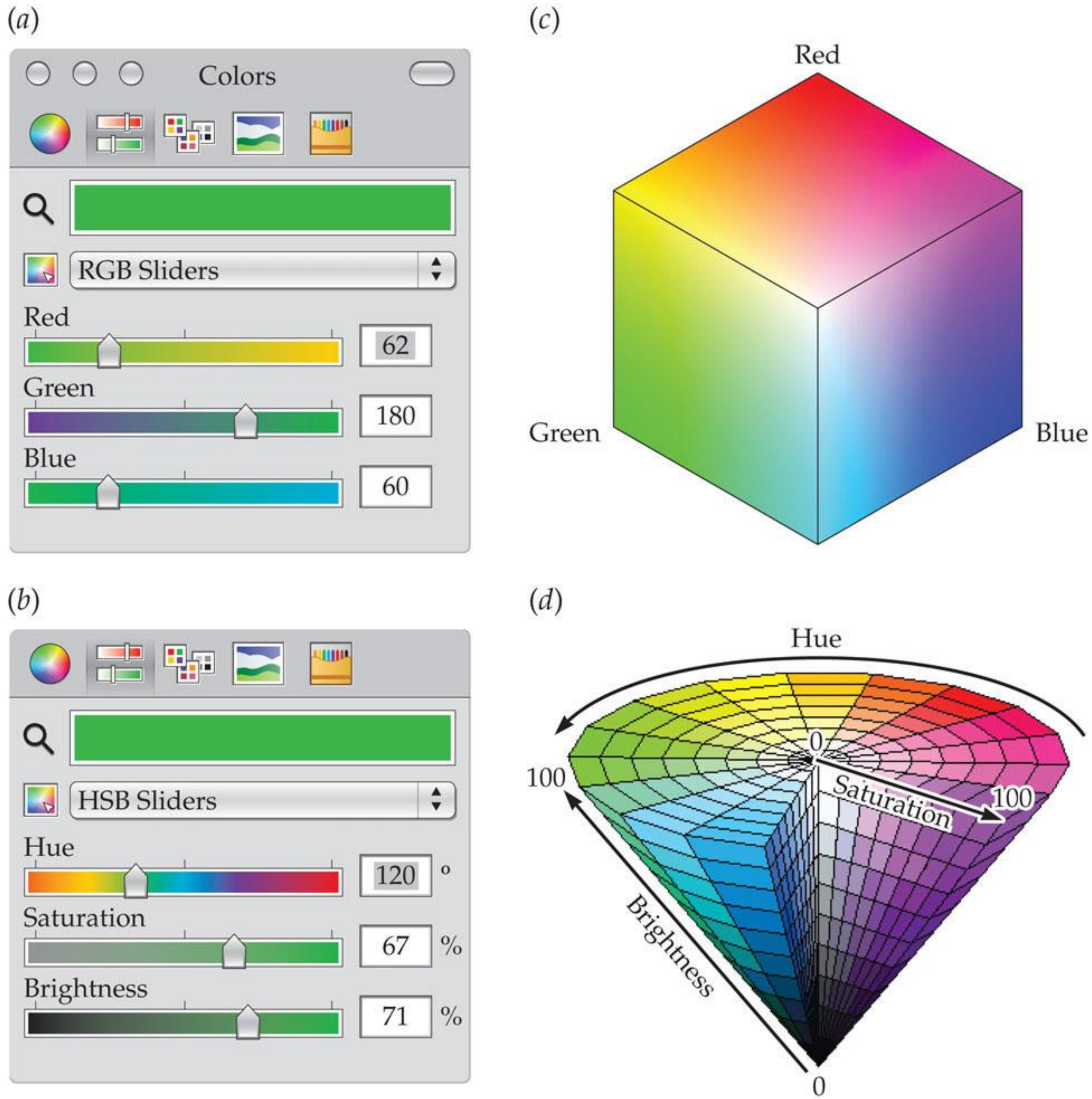
Step 3: Color Appearance (*continued*)

- HSB color space: Defined by hue, saturation, and brightness.
  - Hue: The chromatic (color) aspect of light.
  - Saturation: The chromatic strength of a hue.
  - Brightness: The distance from black in color space.

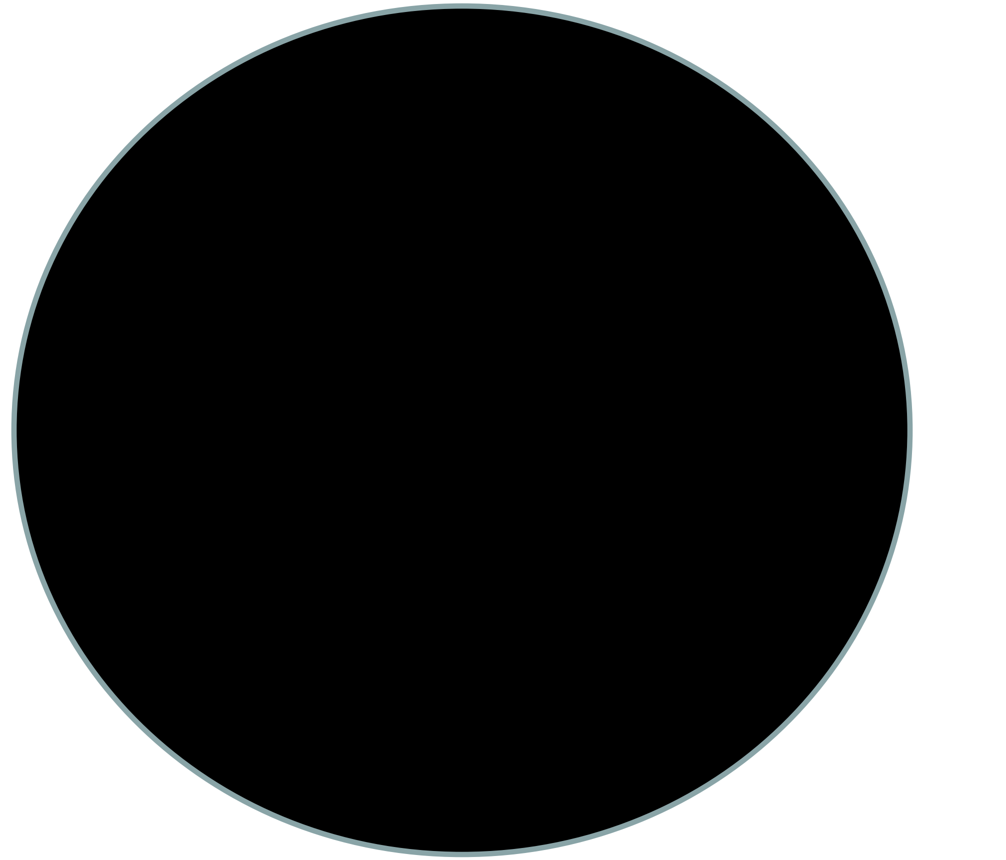
Figure 5.12 A color picker may offer several ways to specify a color in a three-dimensional color space







SENSATION & PERCEPTION 4e, Figure 5.12



Opponent color theory: The theory that perception of color depends on the output of three mechanisms, each of them based on an opponency between two colors: red–green, blue–yellow, and black–white.

- Some LGN cells are excited by L-cone activation in center, inhibited by M-cone activation in their surround (and vice versa).
    - Red versus green

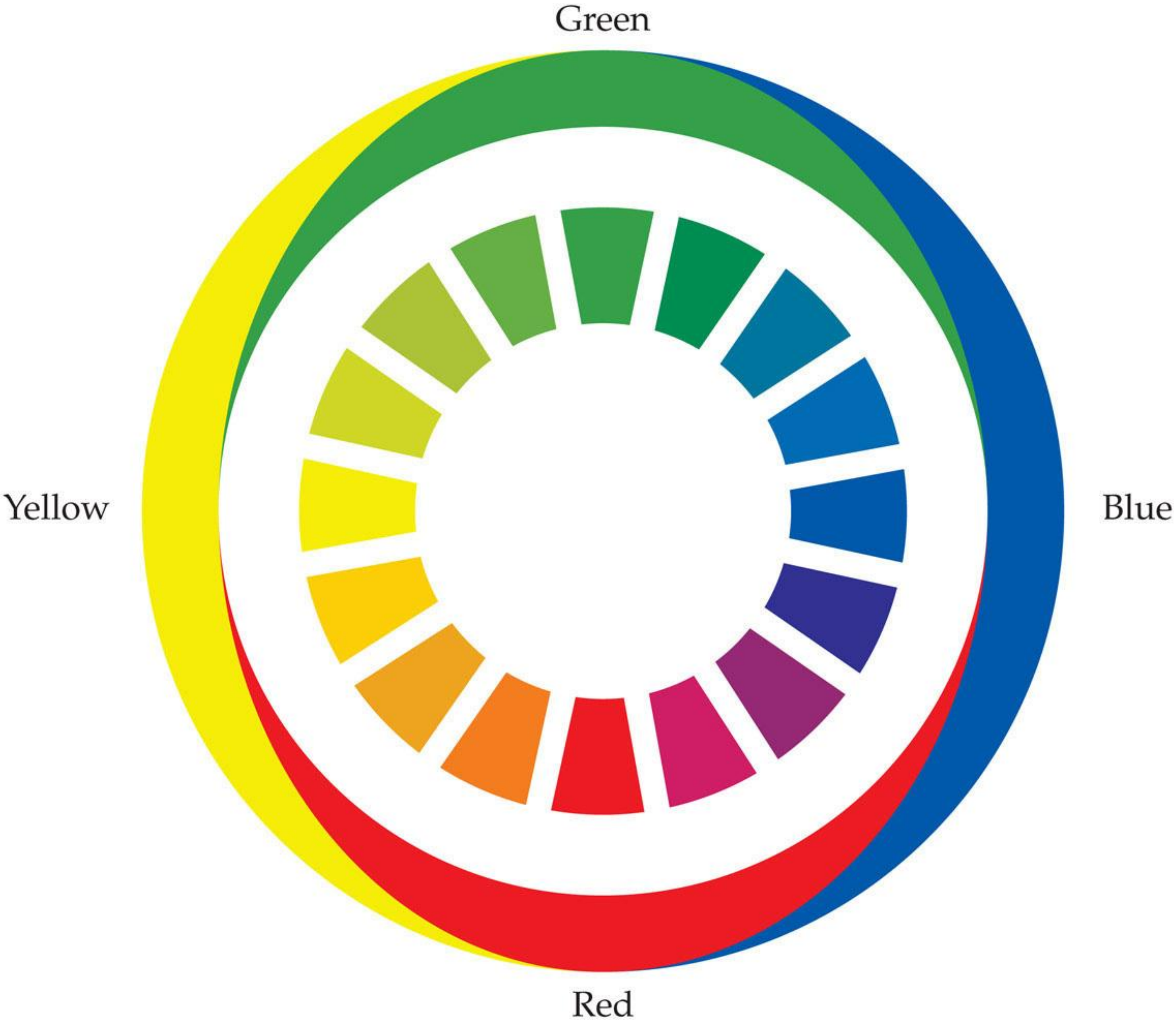
- Other cells are excited by S-cone activation in center, inhibited by (L + M)-cone activation in their surround (and vice versa).
  - Blue versus yellow

Basic Principles of Color Perception

Ewald Hering (1834–1918) noticed that some color combinations are “legal” while others are “illegal.”

- We can have bluish green (cyan), reddish yellow (orange), or bluish red (purple).
- We cannot have reddish green or bluish yellow.

Figure 5.14 Hering's idea of opponent colors

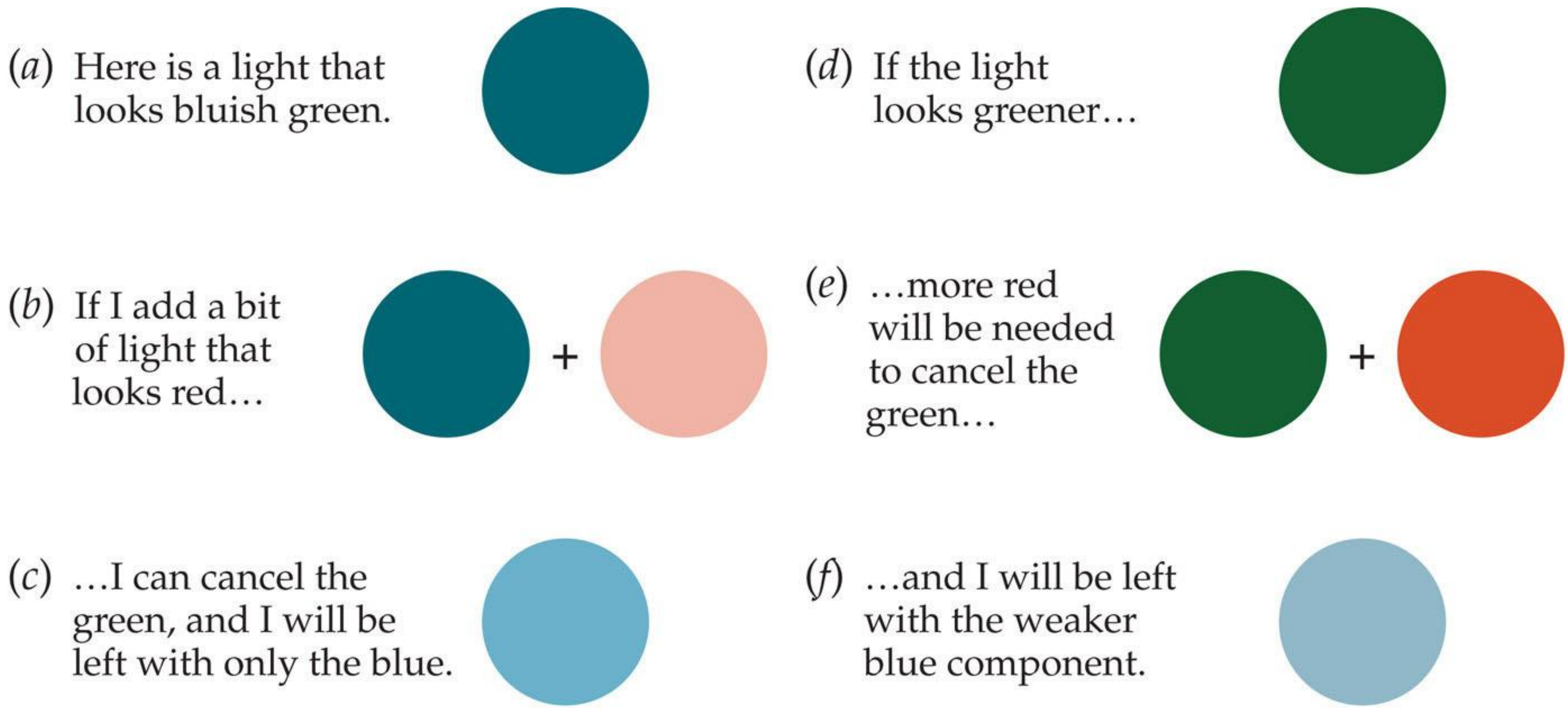


SENSATION & PERCEPTION 4e, Figure 5.14

Hue cancellation experiments

- Start with a color, such as bluish green.
- The goal is to end up with pure blue.
- Shine some red light to cancel out the green light.
    - Adjust the intensity of the red light until there is no sign of either green or red in the blue patch.

Figure 5.15 A hue cancellation experiment

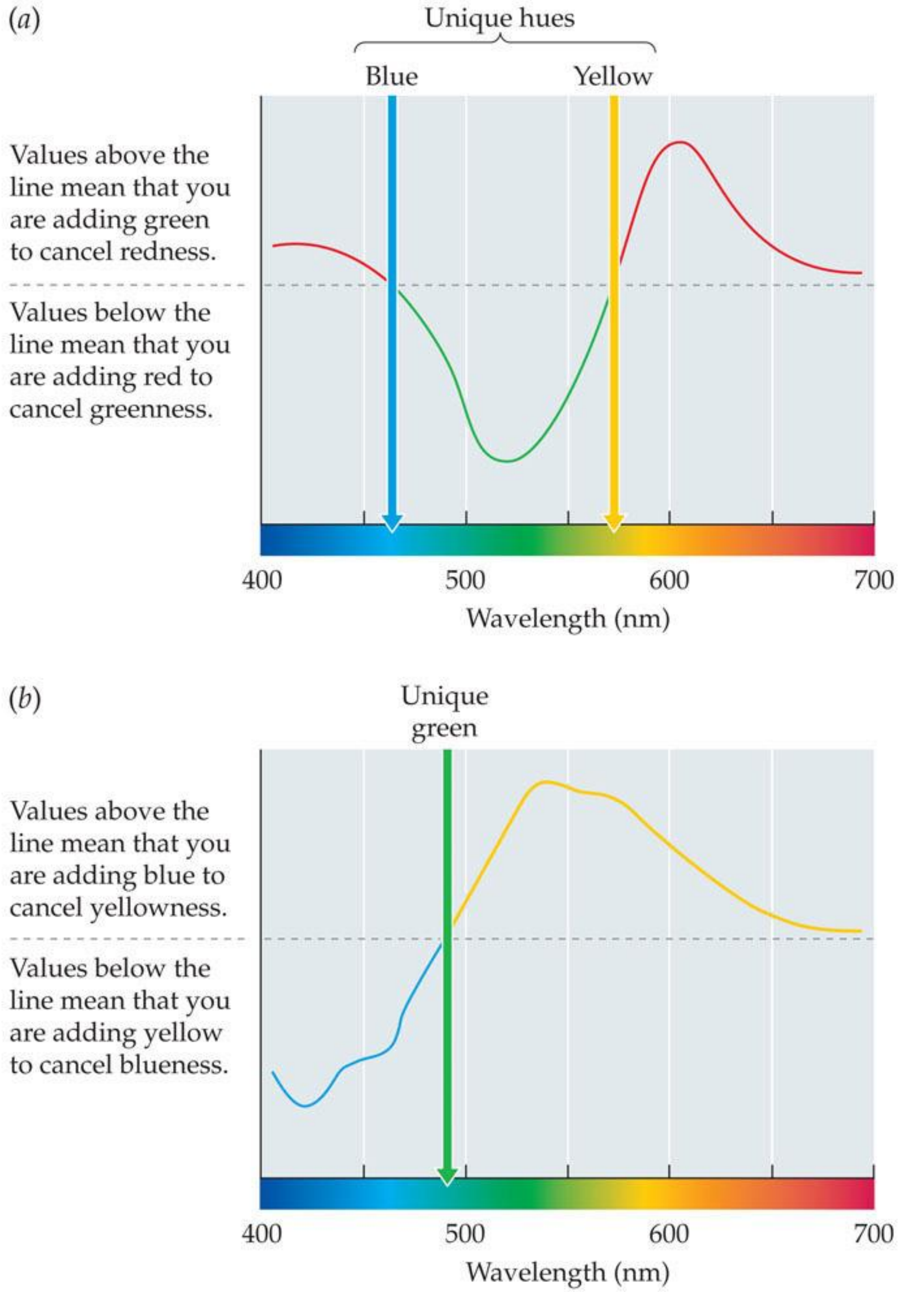


***SENSATION & PERCEPTION 4e*, Figure 5.15**

We can use the hue cancellation paradigm to determine the wavelengths of unique hues.

- Unique hue: Any of four colors that can be described with only a single color term: red, yellow, green, blue.
- For instance, unique blue is a blue that has no red or green tint.

Figure 5.16 Here are results from a hue cancellation experiment



SENSATION & PERCEPTION 4e, Figure 5.16

The three steps of color perception, revisited

- Step 1: Detection—S, M, and L cones detect light.
- Step 2: Discrimination—cone-opponent mechanisms discriminate wavelengths.
  - [L – M] and [M – L] compute red vs. green.
  - [L + M] – S and S – [L + M] compute blue vs. yellow.
- Step 3: Appearance—further recombination of the signals creates final color-opponent appearance.

Figure 5.17 Three steps to color perception (Part 1)

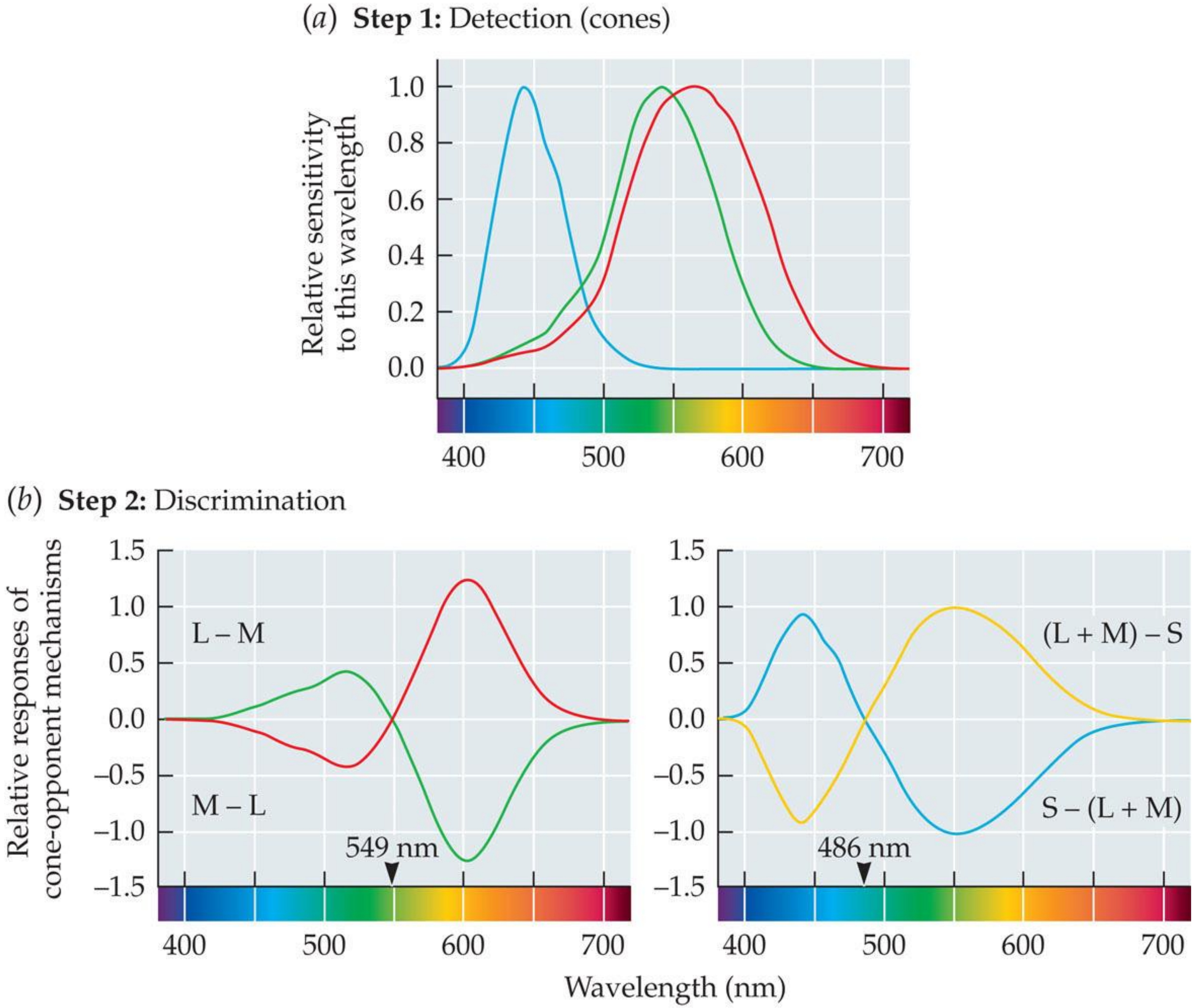
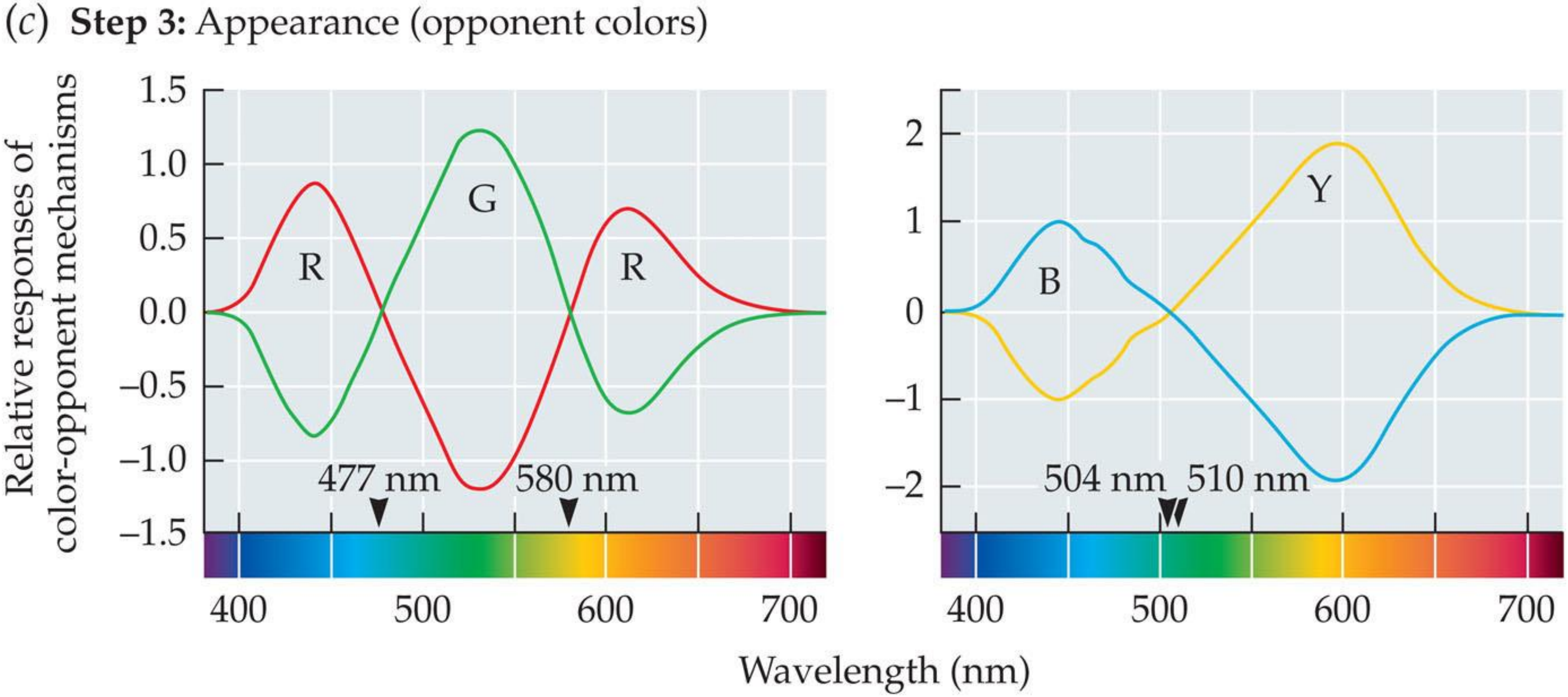


Figure 5.17 Three steps to color perception (Part 2)



SENSATION & PERCEPTION 4e, Figure 5.17 (Part 2)

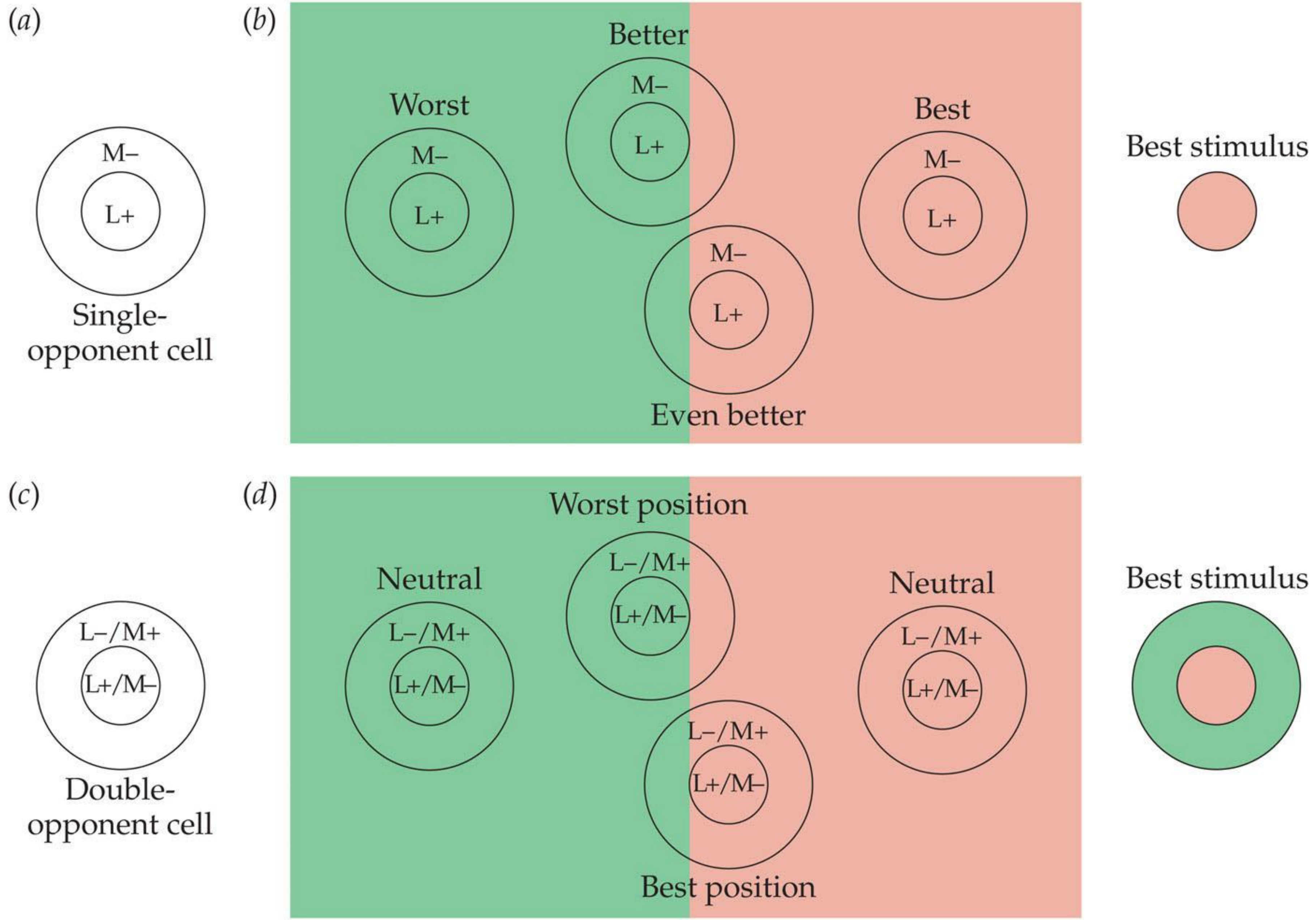
Color in the visual cortex

- Some cells in LGN are cone-opponent cells.
  - Similar to ON-center/OFF-surround retinal ganglion cells
  - These respond to RED-center/GREEN-surround and vice-versa.

- In primary visual cortex, double-opponent color cells are found for the first time.
  - These are more complicated, combining the properties of two color opponent cells from LGN.

Achromatopsia: An inability to perceive colors that is caused by damage to the central nervous system.

Figure 5.18 Color-opponent receptive fields



SENSATION & PERCEPTION 4e, Figure 5.18

Photosnesitive Melanopsin receptors

There are recently discovered photosensitive receptor, a ganglion cell, receiving input from rods and cones but also has its own photopigment, called melanopsin, which can detect light.

Output from these cells go directly to the pineal gland which controls circadian rhythm.

That is why jetlag and blue screens can affect even people who do not have (other) photoreceptors and no conccious perception of light.

Individual Differences in Color Perception

Qualia: Private conscious experiences of sensation and perception.

- The question, "Is my perception of blue the same as your perception of blue?" is a question about qualia.

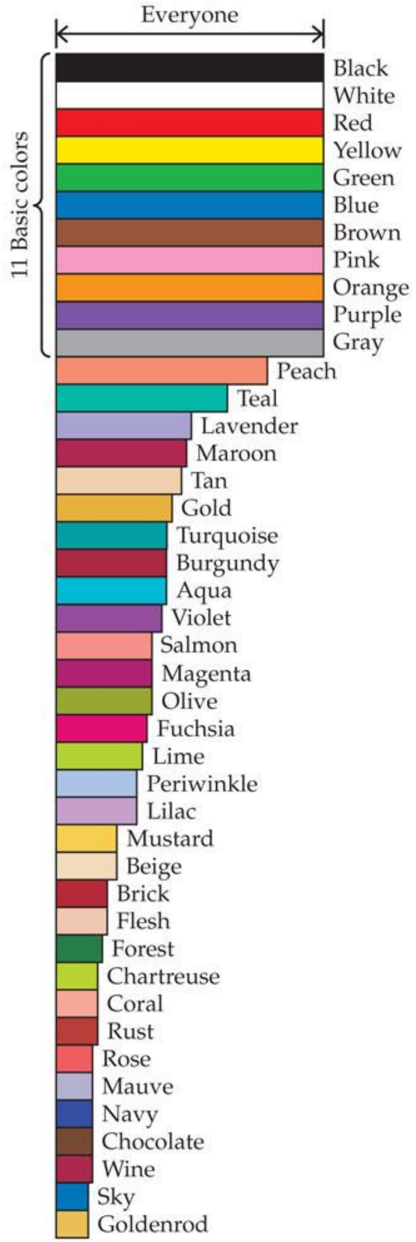
An interesting question, then, is "Does everyone see colors the same way?"

Individual Differences in Color Perception

Does everyone see colors the same way?—*Yes.*

- General agreement on colors
  - Basic color terms: Single words that describe colors and have meanings that are agreed upon by speakers of a language.

Figure 5.19 When Lindsey and Brown asked Americans to name color patches, everyone used the 11 “basic” colors



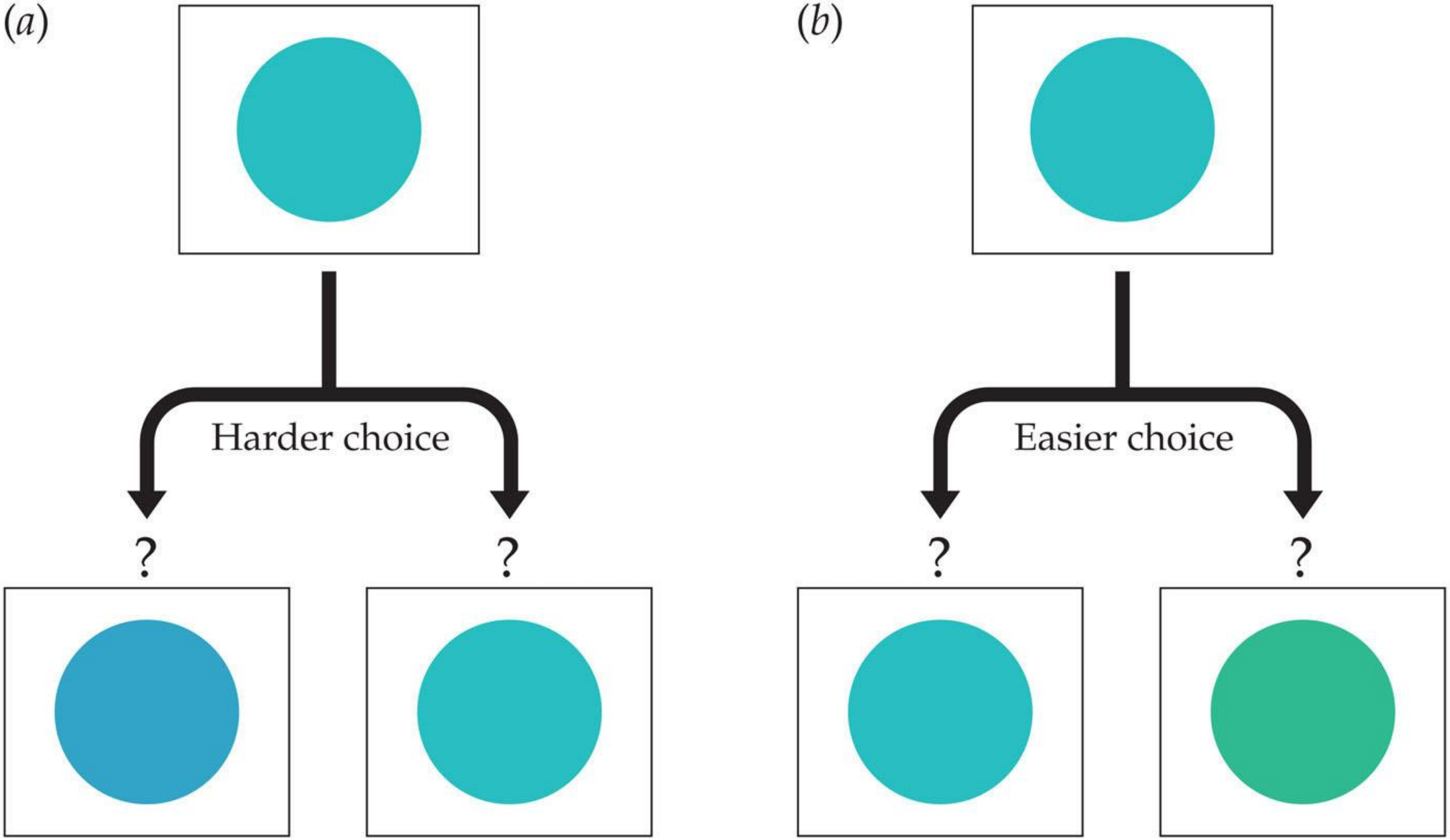
SENSATION & PERCEPTION 4e, **Figure 5.19**

Individual Differences in Color Perception

Does everyone see colors the same way?—*Maybe.*

- Various cultures describe color differently.
- Cultural relativism: In sensation and perception, the idea that basic perceptual experiences (e.g., color perception) may be determined in part by the cultural environment.

Figure 5.20 It is easier to remember which of two colors you have seen if the choices are categorically different



SENSATION & PERCEPTION 4e, Figure 5.20

Individual Differences in Color Perception

Does everyone see colors the same way?—*No.*

- About 8% of male population and 0.5% of female population has some form of color vision deficiency: “color blindness.”
  - Color-anomalous: A term for what is usually called “color blindness.” Most “color-blind” individuals can still make discriminations based on wavelength. Those discriminations are just different from the norm.

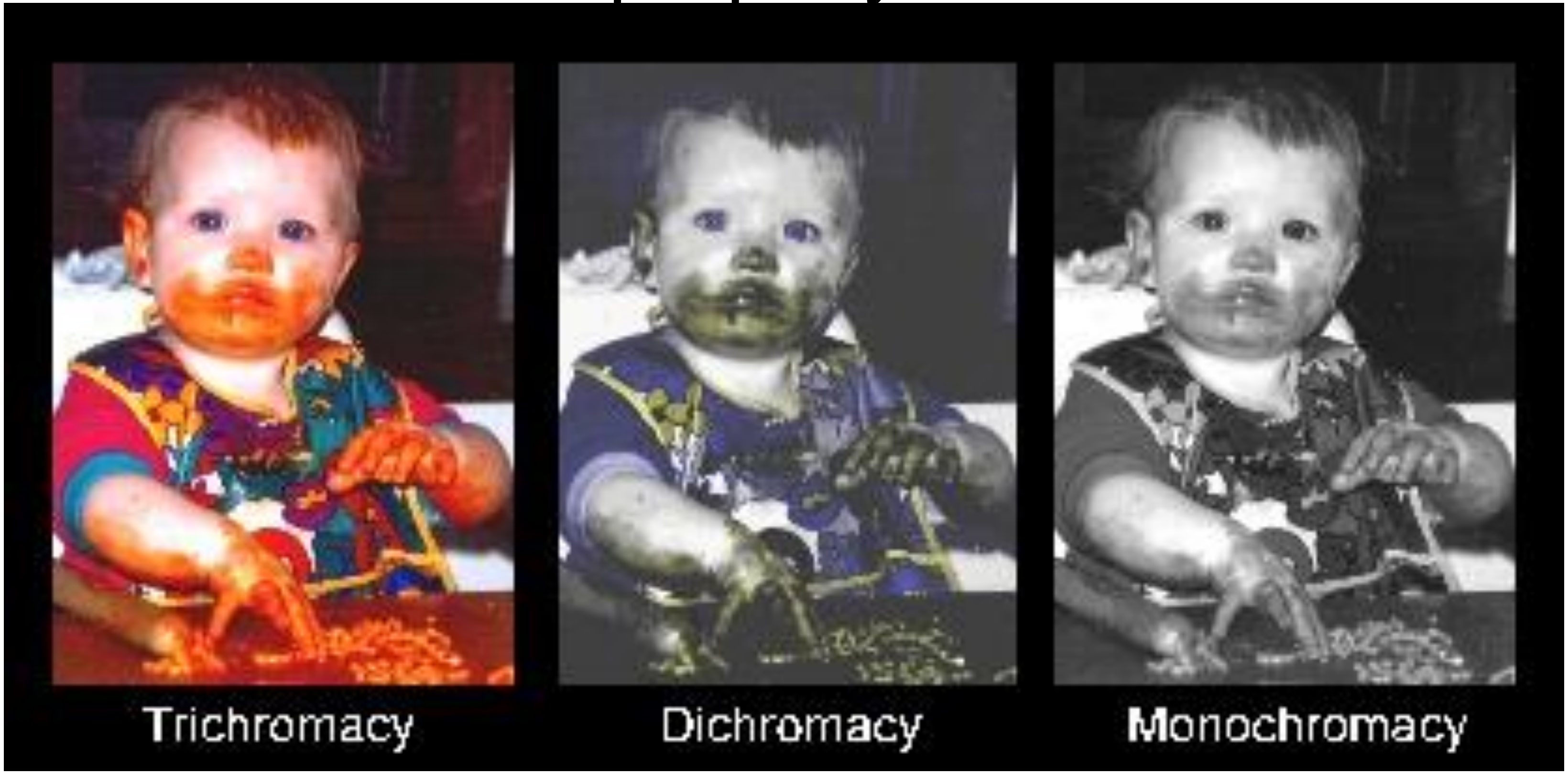
Individual Differences in Color Perception

Several types of color-blind/color-anamolous people

- Deuteranope: Due to absence of M-cones.
- Protanope: Due to absence of L-cones.
- Tritanope: Due to absence of S-cones.
- Cone monochromat: Has only one cone type; truly color-blind.

Color-blindness

Results whenever we are either missing one of our cones or one of our cones doesn't work properly.



Individual Differences in Color Perception

Several types of color-blind/color-anamolous people (*continued)*

- Rod monochromat: Has no cones of any type; truly color-blind and very visually impaired in bright light.
- Achromatopsia: Inability to see color due to cortical damage.
- Anomia: Inability to name objects or colors in spite of the ability to see and recognize them. Typically due to brain damage.

From the Color of Lights to a World of Color

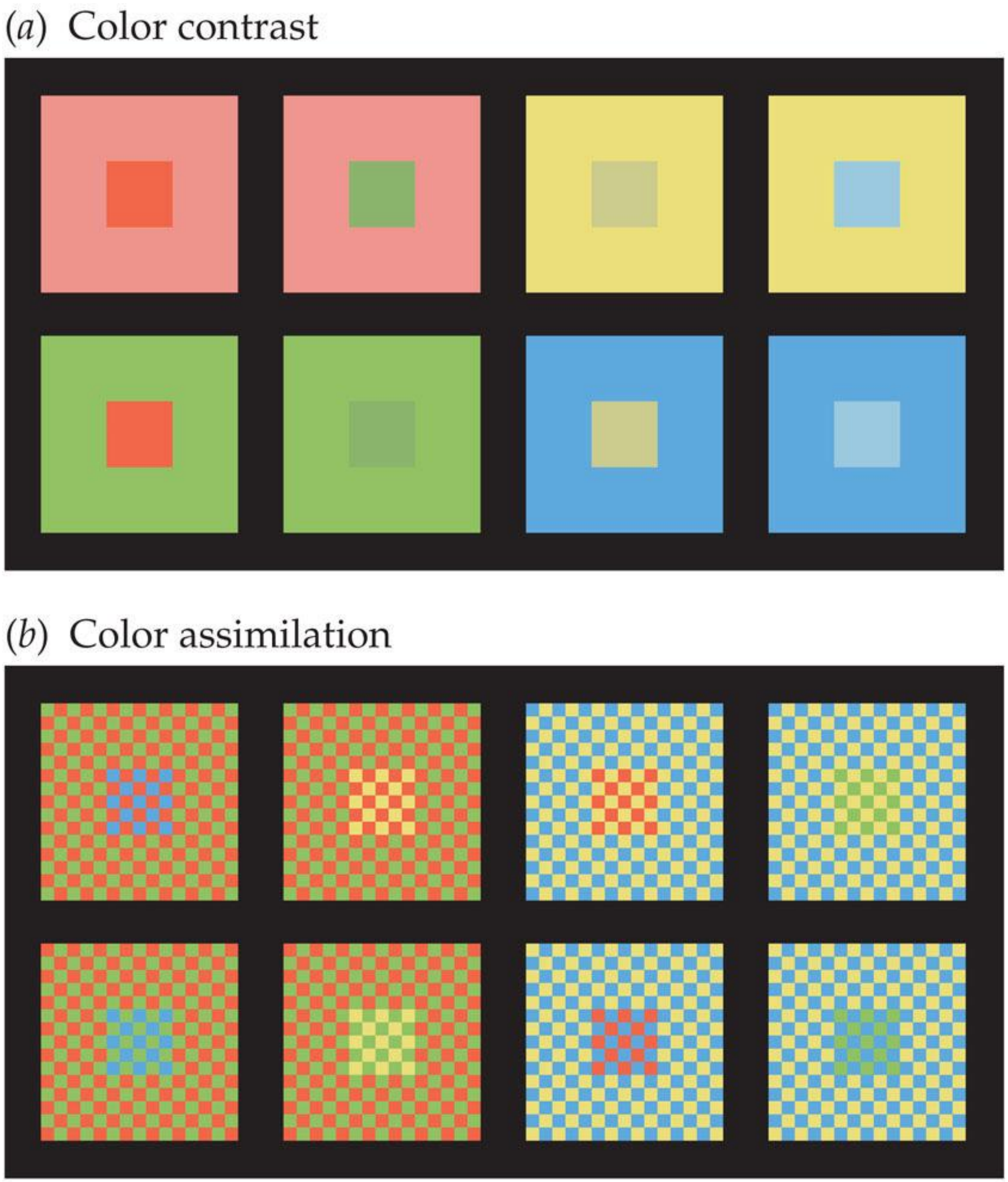
Colors very rarely appear in isolation. Usually, many colors are present in a scene.

- When many colors are present, they can influence each other.

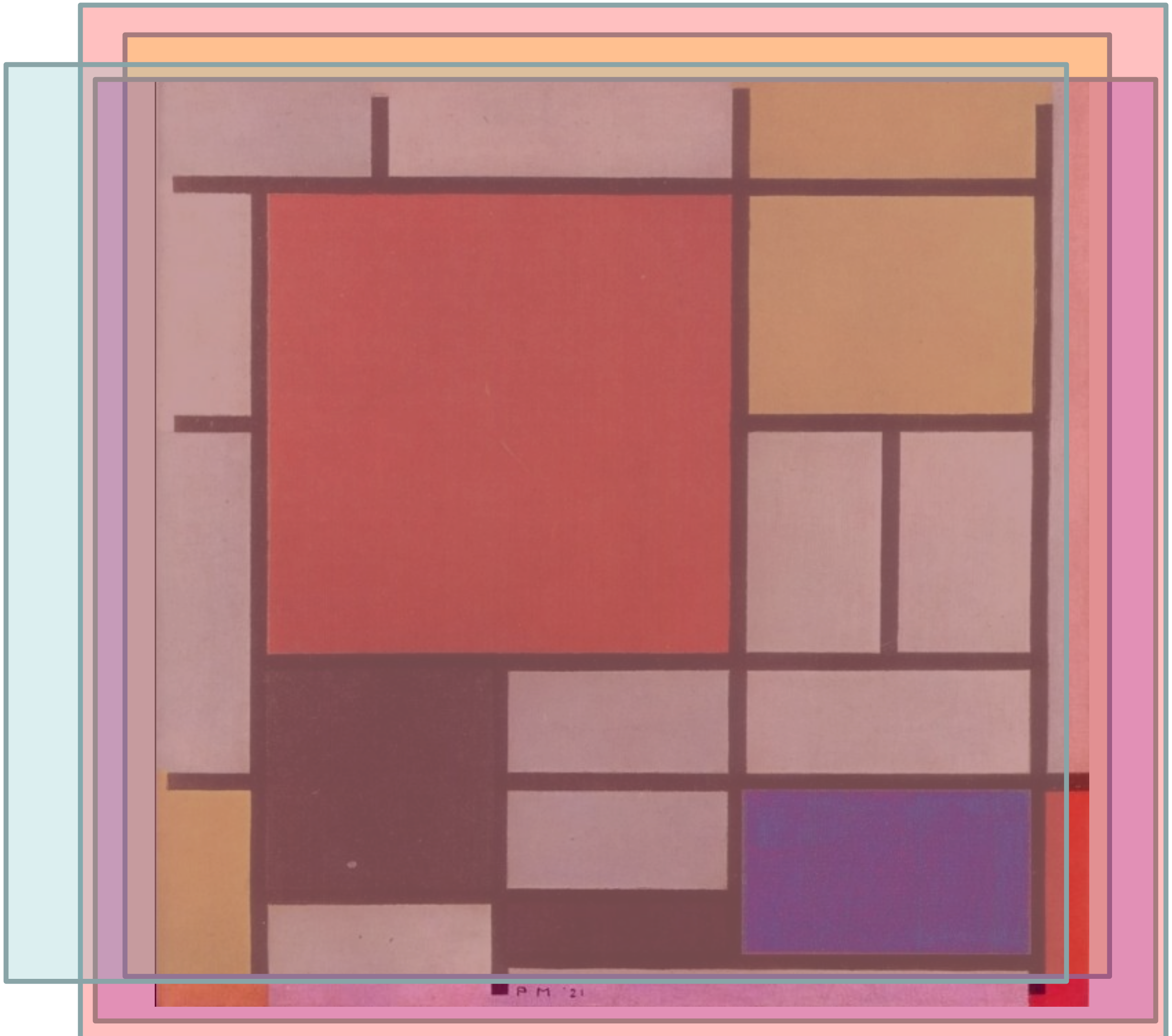
Color contrast: A color perception effect in which the color of one region induces the opponent color in a neighboring region.

Color assimilation: A color perception effect in which two colors bleed into each other, each taking on some of the chromatic quality of the other.

Figure 5.21 Color contrast and color assimilation



SENSATION & PERCEPTION 4e, Figure 5.21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From the Color of Lights to a World of Color

Unrelated color: A color that can be experienced in isolation.

Related color: A color, such as brown or gray, which is seen only in relation to other colors.

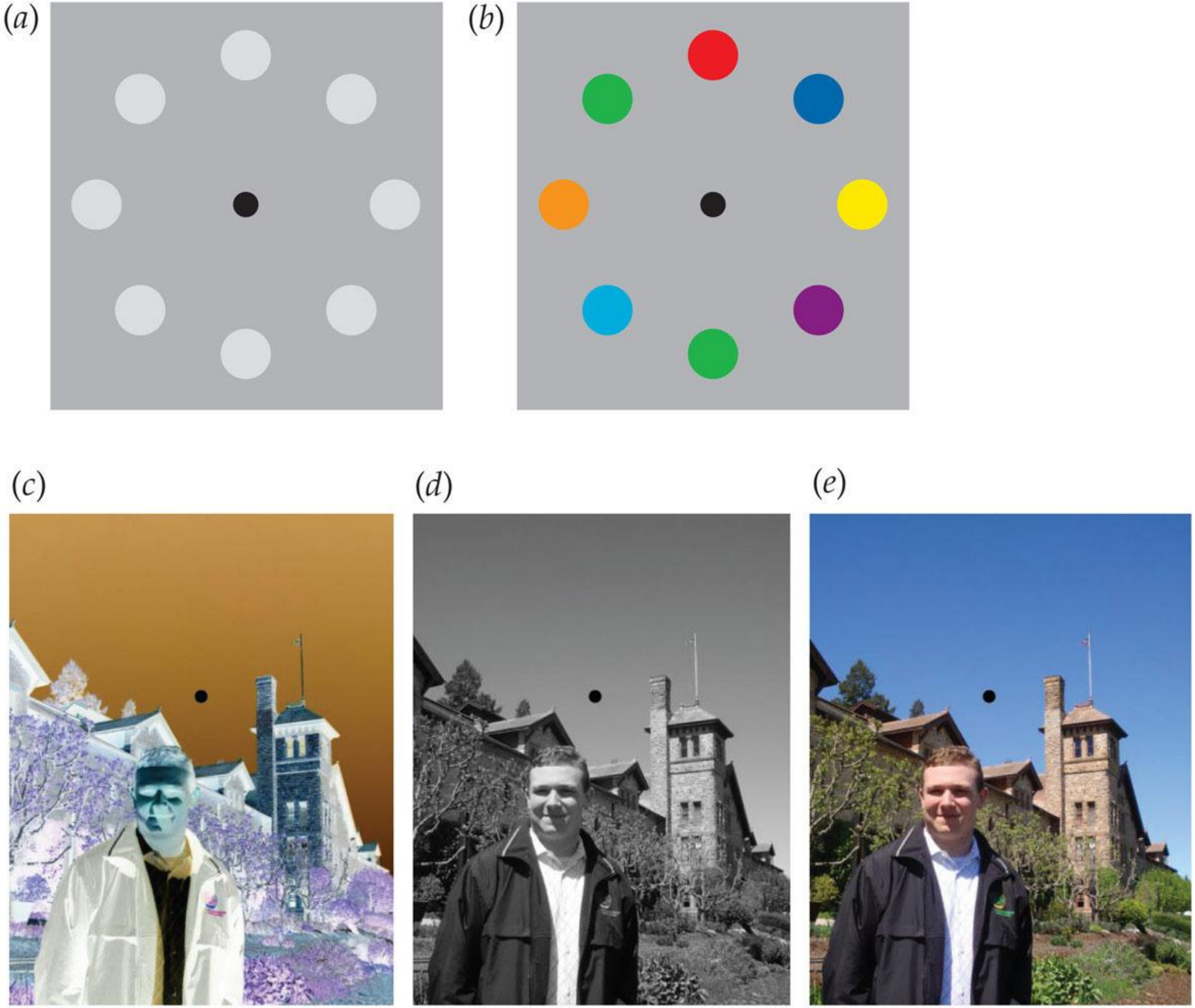
- A “gray” patch in complete darkness appears white.

Afterimages: A visual image seen after a stimulus has been removed.

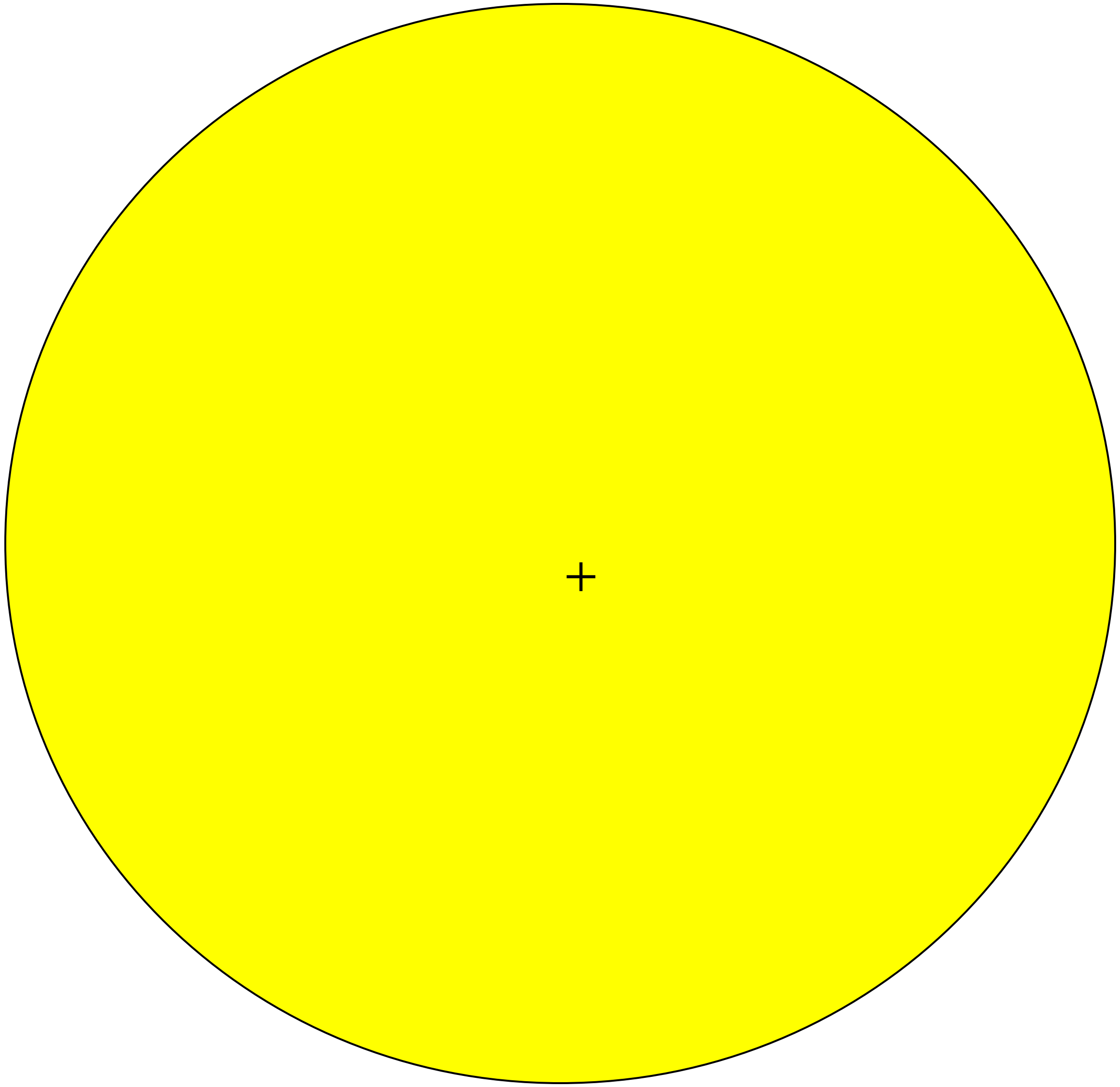
Negative afterimage: An afterimage whose polarity is the opposite of the original stimulus.

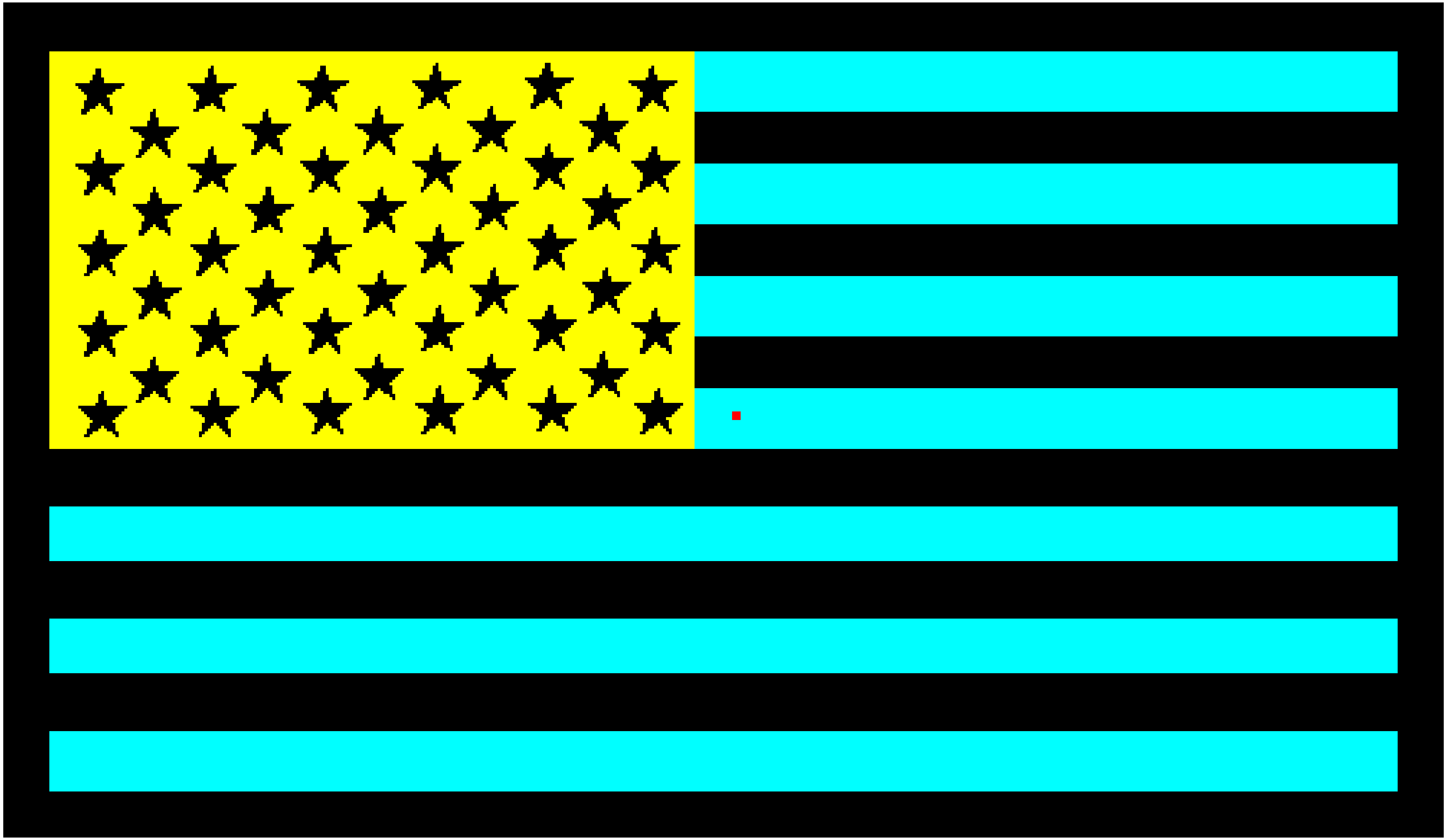
- Light stimuli produce dark negative afterimages.
- Colors are complementary. Red produces green afterimages and blue produces yellow afterimages (and vice versa).
- This is a way to see opponent colors in action.

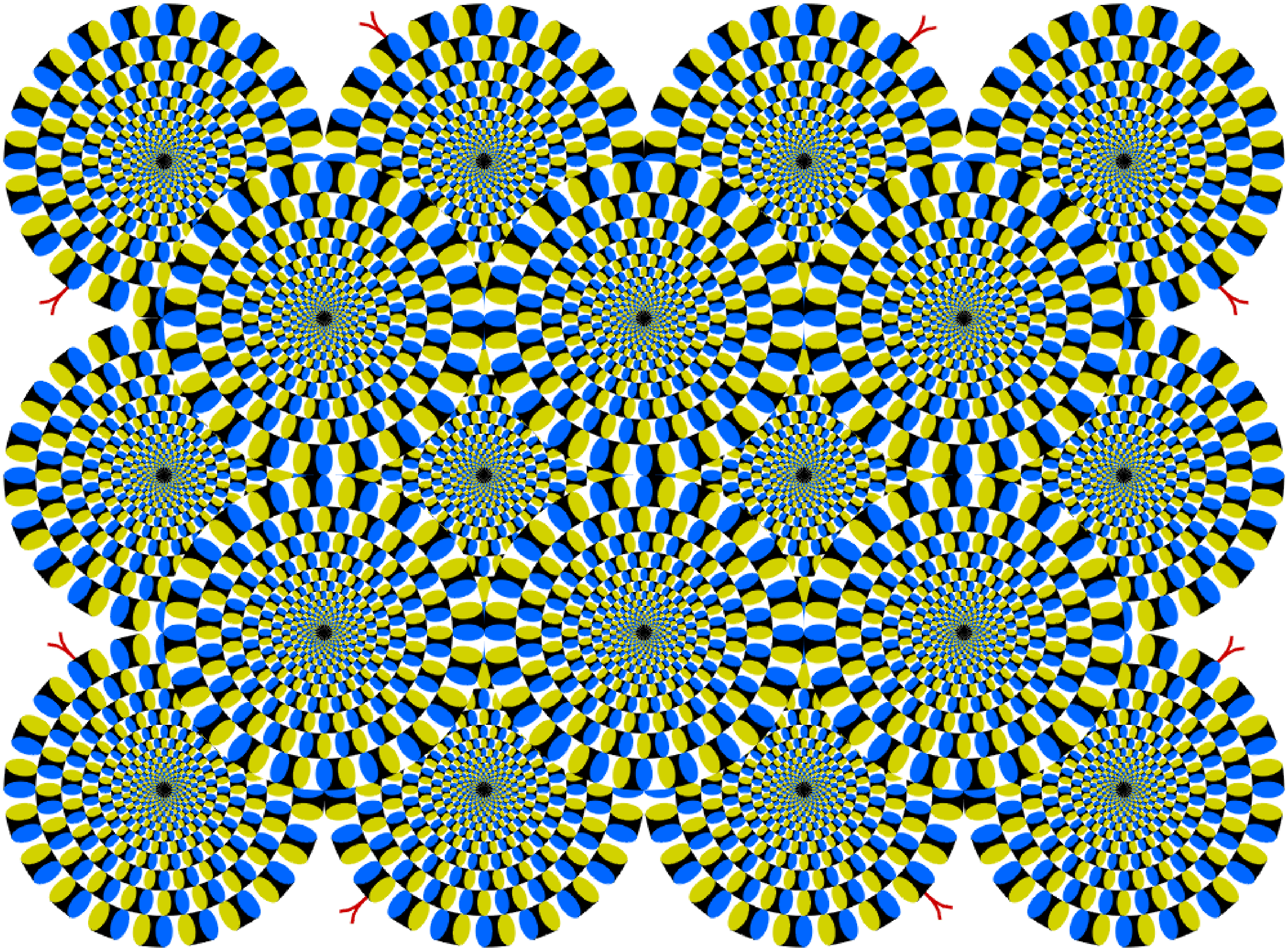
Figure 5.22 Negative afterimages



SENSATION & PERCEPTION 4e, Figure 5.22





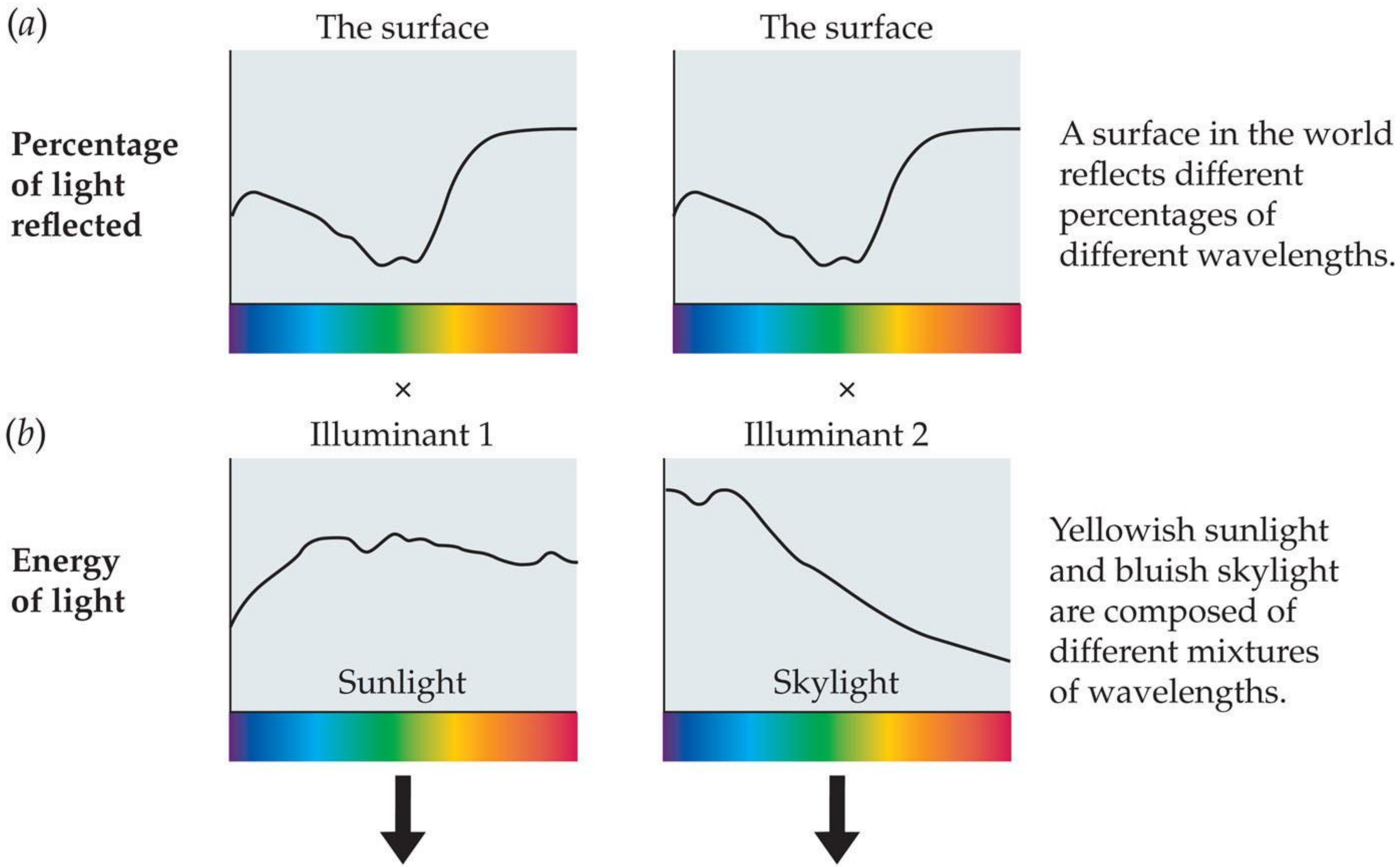


Color constancy: The tendency of a surface to appear the same color under a fairly wide range of illuminants.

- To achieve color constancy, we must discount the illuminant and determine what the true color of a surface is regardless of how it appears.

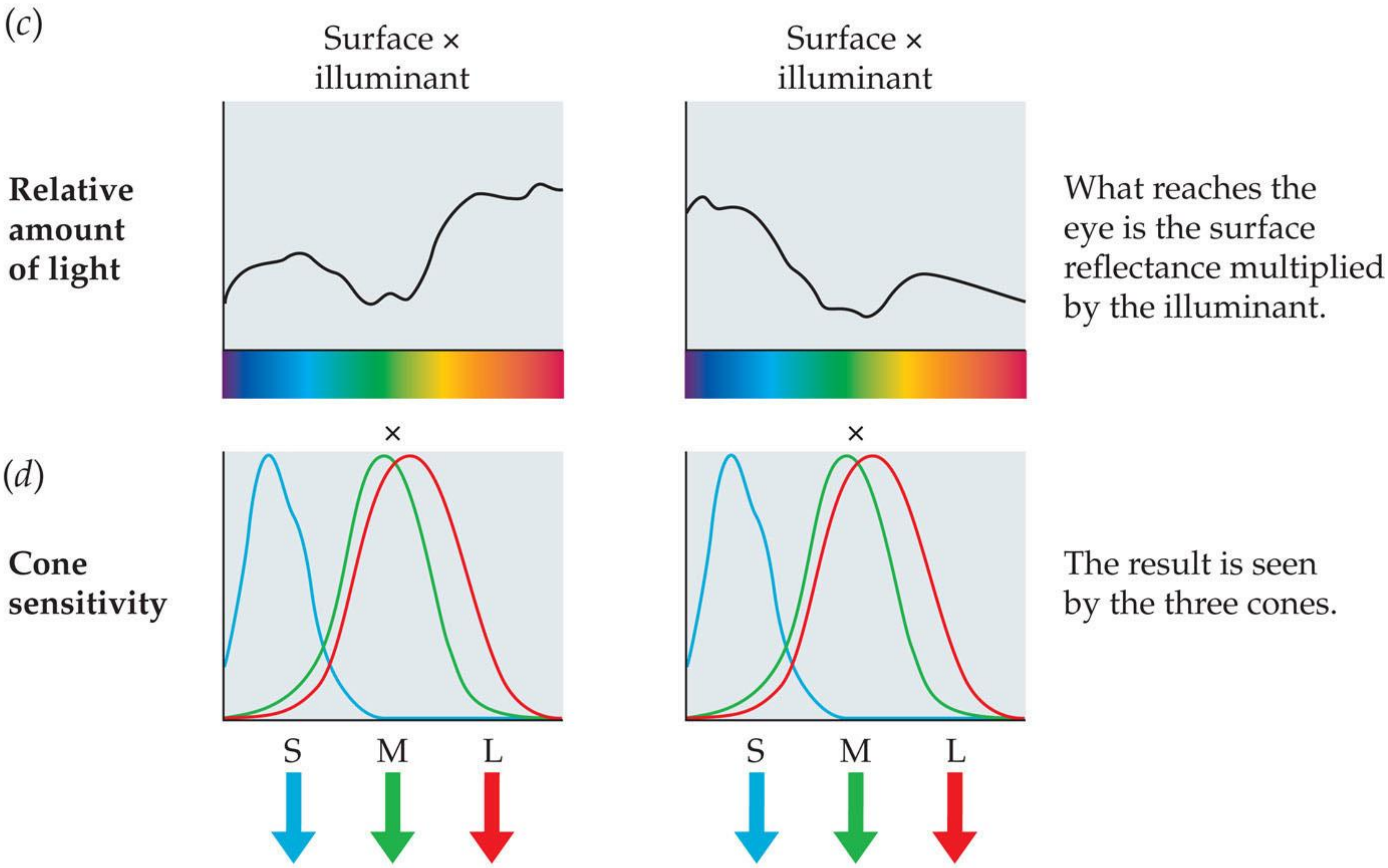
Illuminant: The light that illuminates a surface.

Figure 5.23 Color constancy (Part 1)



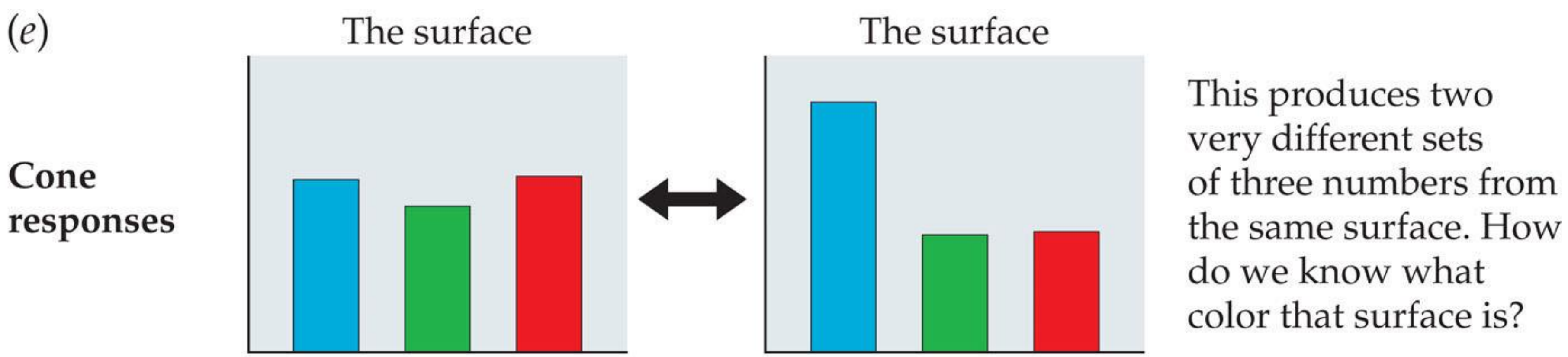
SENSATION & PERCEPTION 4e, **Figure 5.23 (Part 1)**

Figure 5.23 Color constancy (Part 2)



SENSATION & PERCEPTION 4e, **Figure 5.23 (Part 2)**

Figure 5.23 Color constancy (Part 3)



SENSATION & PERCEPTION 4e, **Figure 5.23 (Part 3)**

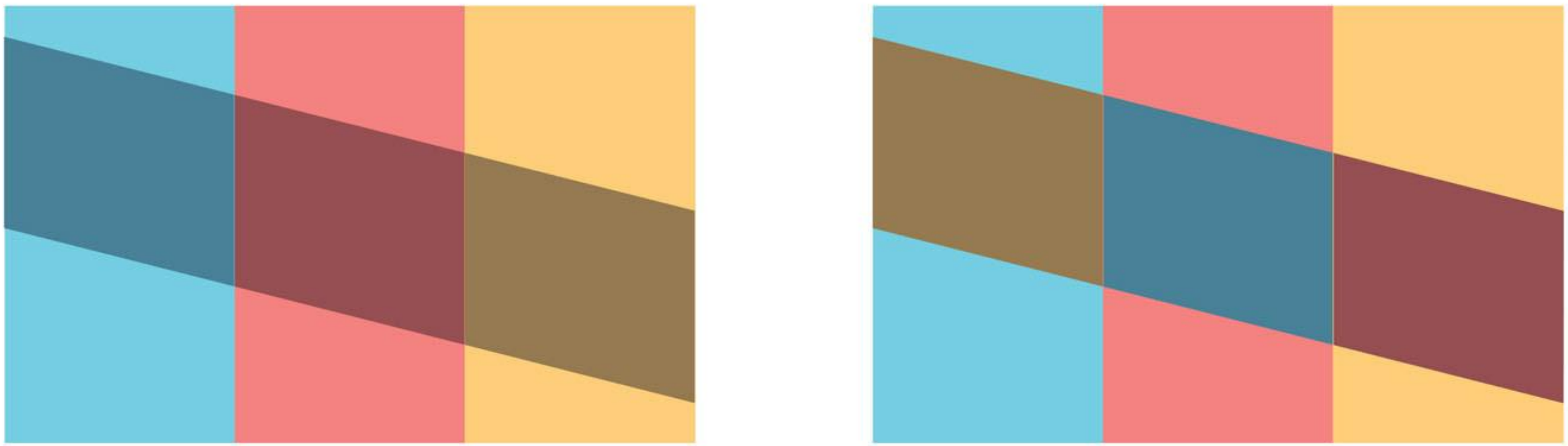
Physical constraints make constancy possible.

- Intelligent guesses about the illuminant
- Assumptions about light sources
- Assumptions about surfaces

Figure 5.24 The visual system “knows” that brightness changes across a shadow boundary, but hue does not

(*a*) Luminance change without hue change looks like a shadow.

(*b*) Luminance change *with* hue change looks less like a shadow.

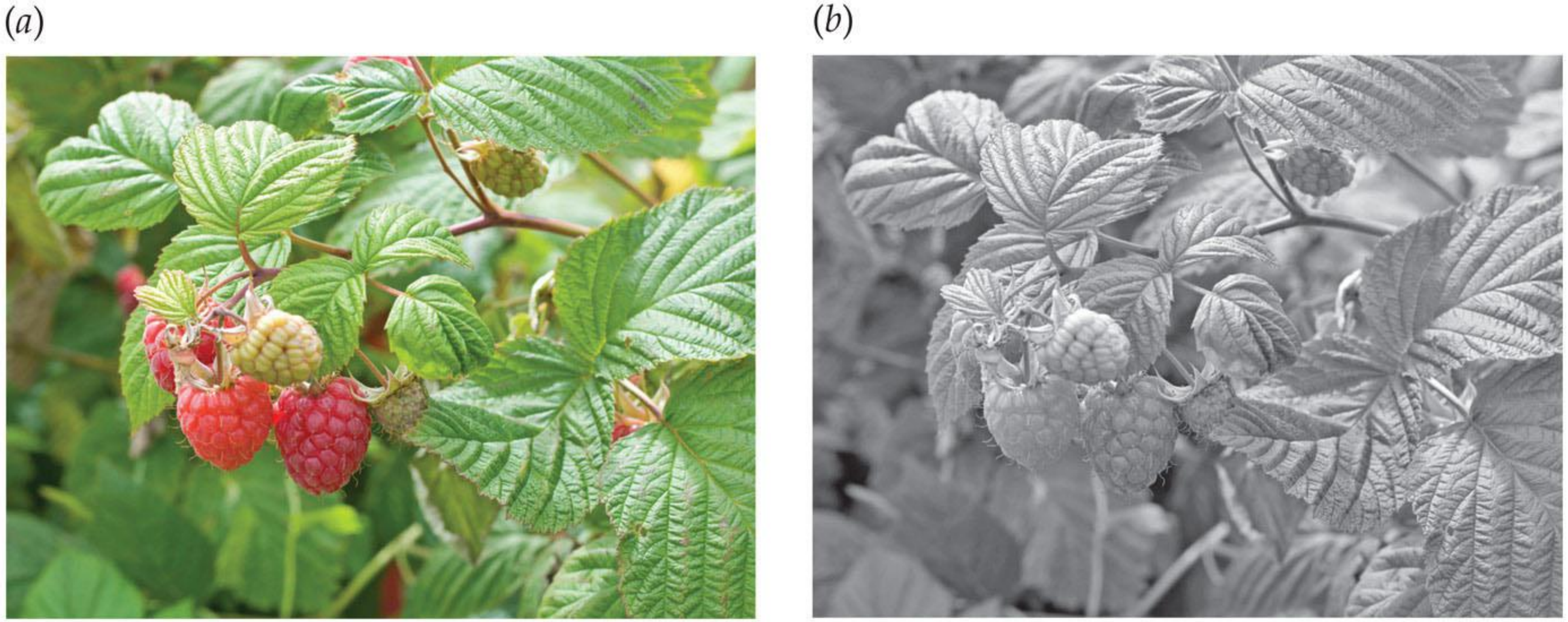


What is Color Vision Good For?

Animals provide insight into color perception in humans

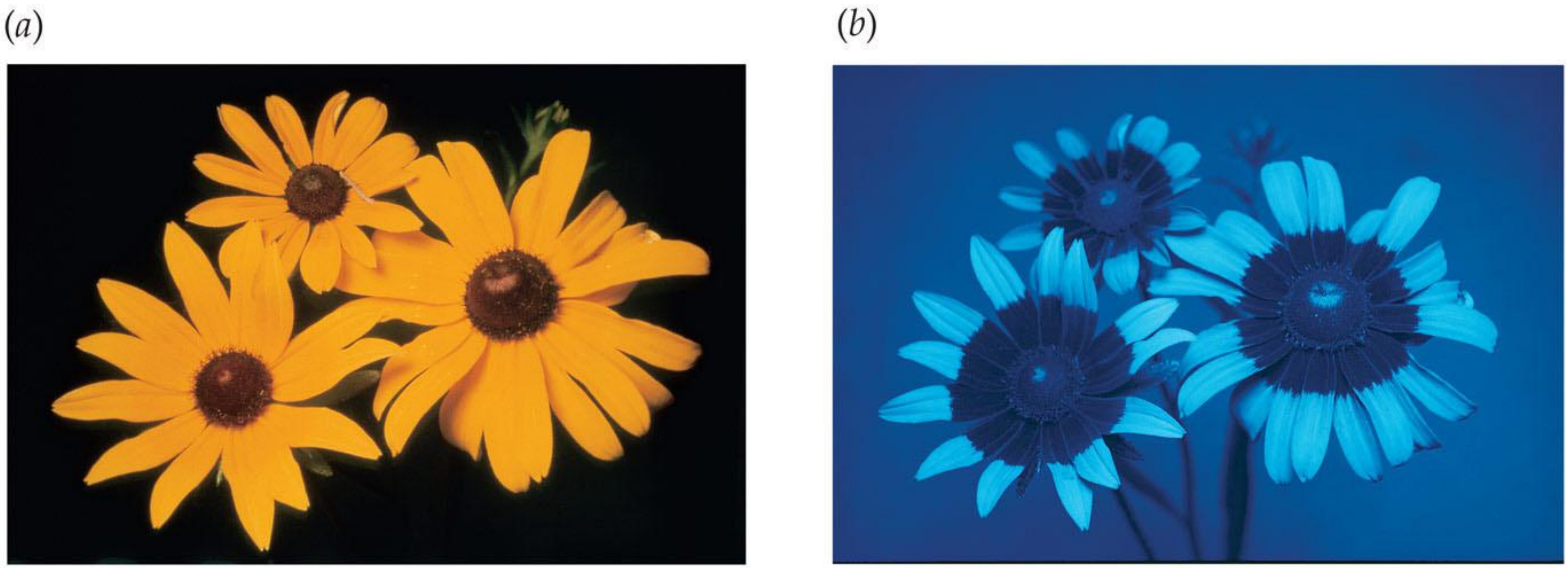
- Food
  - It is easier to find berries and determine when they are ripe with color vision.
  - Some flowers have ultraviolet markings that only bees can see.

Figure 5.27 Finding a raspberry is easier if you have color vision, as is deciding if that berry is ripe



***SENSATION & PERCEPTION 4e,* Figure 5.27**

Figure 5.28 Color vision in different species



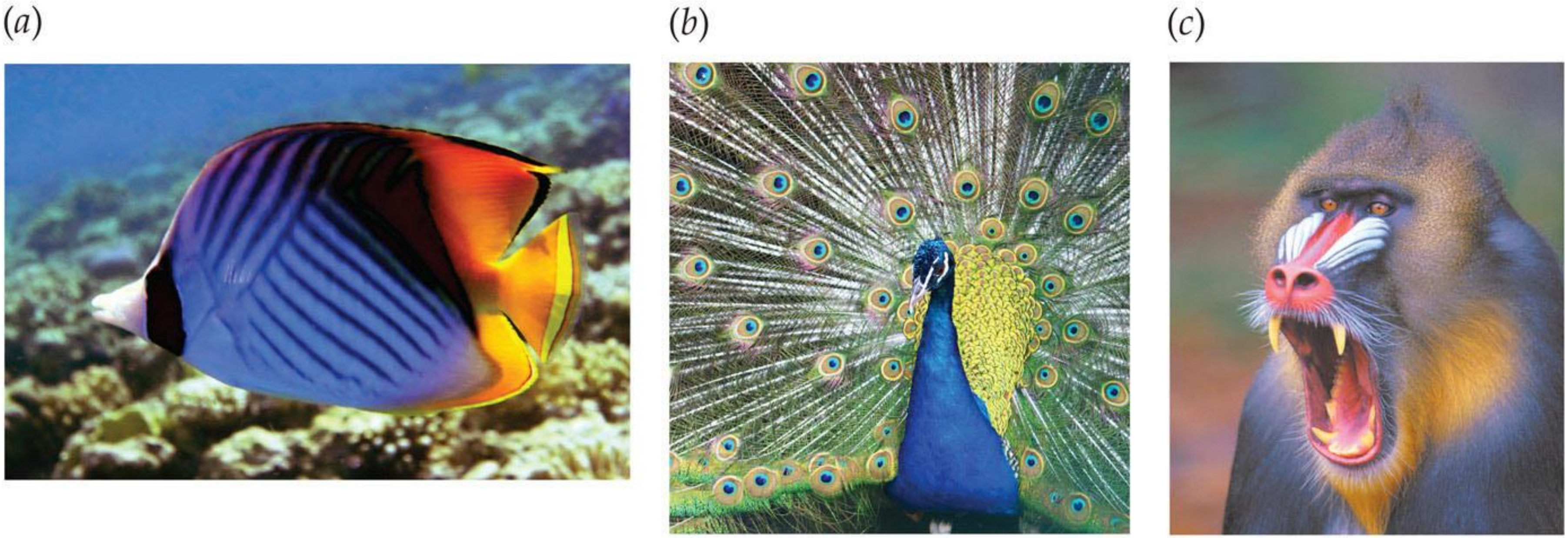
SENSATION & PERCEPTION 4e, Figure 5.28

What is Color Vision Good For?

Animals provide insight into color perception in humans (*continued)*

- Sex
  - Flower colors are advertisements for bees to trade food for sex (for pollination).
  - Colorful patterns on tropical fish and toucans provide sexual signals.

Figure 5.29 The colors of animals—from (a) tropical fish to (b) peacocks to (c) mandrills—are often advertisements to potential mates



SENSATION & PERCEPTION 4e, Figure 5.29

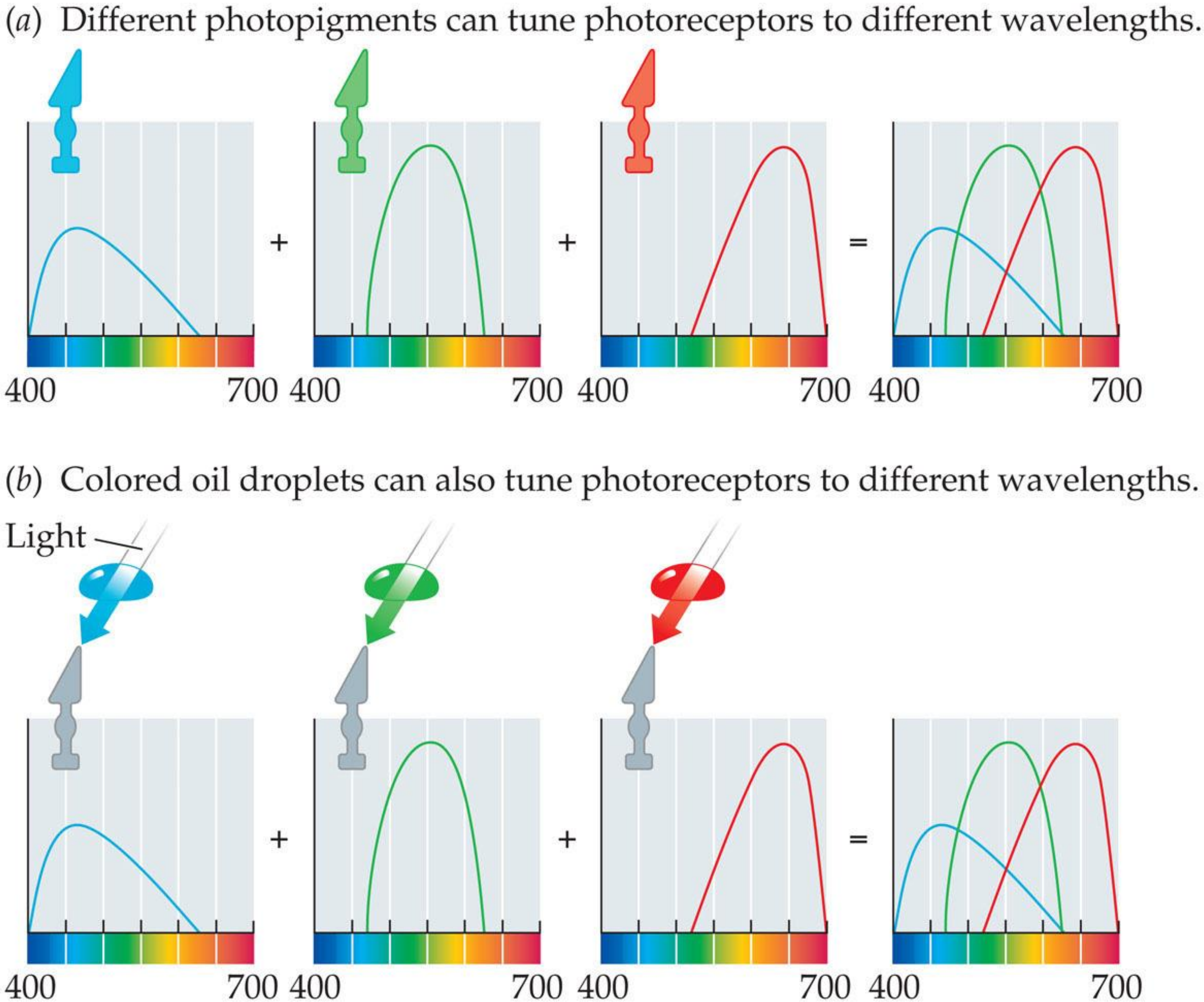
What is Color Vision Good For?

Humans and other mammals have color vision due to the different photopigments in our cones.

Other animals have evolved a different system for color vision.

- Birds and some reptiles have colored oils over each photoreceptor, which tunes them to different wavelengths.

Figure 5.30 Two ways to make photoreceptors with different spectral sensitivities



SENSATION & PERCEPTION 4e, Figure 5.30