Chapter 5: Perceiving Color

Stare at the fixation spot
Newton’s Prism Experiment (1704)
The of light entering the eye is the product of the illuminant and the surface reflectance of objects.

Spectral composition of two common illuminants
Surface reflectance of some common objects

Which is raw hamburger, which cooked?
Spectral composition of light entering the eye after being reflected from a surface =

Spectral composition of the illuminant \( \times \) Reflectance of the surface

Consider a ripe orange illuminated with a bright monochromatic blue (420 nm) light. What color will the orange appear to be?

a. bright orange
b. dark/dim orange
c. black
d. dark/dim blue
Spectral composition of light entering the eye after being reflected from a surface =

Spectral composition of the illuminant \times \text{Reflectance of the surface}

Subtractive mixtures

Occur with paints (pigments) and filters. The only wavelengths reflected by the mixture are those that are reflected by all components in the mixture.

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.
Additive mixtures – computer monitors, projectors, and impressionism

You can create additive mixtures by putting pixels very close together
Georges Seurat’s painting *La Parade* (1887–1888)
Psychology and Color

• Physical dimensions of color
  Spectral composition = light source X reflectance

• Psychological dimensions of color
  1. Hue (e.g., red, blue, green)
  2. Saturation (e.g., pastel, ‘deep & rich’)
  3. Brightness (e.g., dim, bright)
Hue, saturation & brightness
How do we get from the physical properties of light:

To the psychological dimensions of color?

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
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'.

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

(a)

(b)

blue  green

red  yellow
Why are red and green opposites? Why are yellow and blue 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 **YELLOW/BLUE** opponent mechanism
The Red-Green opponent system subtracts $M$ from $L$ cone responses.

The Yellow-Blue opponent system subtracts $2S$ from $L+M$ cone responses.
Now with $RG = L - M$ and $YB = (L+M) - 2S$, we can predict the appearance of any arbitrary spectrum of light.
Now with RG = L-M and YB = (L+M) – 2S, we can predict the appearance of any light spectrum.

Blue: 450 nm  Green: 520 nm

How much blue must I add to eliminate any hint of yellow? – We want “pure” green

How much red must I add to eliminate any hint of green? – We want “pure” yellow.
Our experience of color is shaped by physiological mechanisms, both in the receptors and in opponent neurons.

Adaptation aftereffects
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
  - 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

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 almost always missing the short wavelength pigment
   - Individuals see short wavelengths as green
   - Neutral point (gray) occurs at 570nm
   - Above neutral point, they see red
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.
We differentiate colors (at least partly) based on learned categories.

‘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
1. Take a collection of color patches under a 'white' light.
2. The “gray” patch excites S, M, and L-cones equally.
3. The gray patch looks gray, and the green patch looks green.
4. Change the illuminant to a reddish light.
5. Now, what was the “green” patch excites S, M, and L-cones equally.
Chromatic adaptation supports color constancy
Chromatic adaptation supports color constancy
Chromatic adaptation supports color constancy
But color constancy also involves higher level processes

- Can deal with local illumination differences
- And shadows

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

(b) Luminance change with hue change looks less like a shadow.
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.
Adelson's lightness illusion