Color Vision II

Lecture 11
(Chapter 5, Part 2)

Jonathan Pillow
Sensation & Perception (PSY 345 / NEU 325)
Princeton University, Fall 2023
Exam #1: Thursday 3/09

Format: multiple-choice, fill-in-the-blank, & short answer

What to study:
- all material from lectures & slides
- precept readings (basic gist & findings of each article)

(If something appeared only in the book, and not at all in class or precept or slides, you can probably safely ignore it)

Review session: Tuesday (3/7), 2:00-3pm @ PNI A32.
Color space: A three-dimensional space that describes all possible color percepts.

Several ways to describe this space:

1. **RGB color space**: Defined by the outputs of Long, Medium, Short wavelength (or R, G, B) lights.
Cone responses entirely determine our color percepts:

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>M</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>100</td>
<td>100</td>
<td>→</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>50</td>
<td>→</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>→</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>0</td>
<td>→</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>0</td>
<td>→</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>100</td>
<td>→</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
<td>0</td>
<td>→</td>
</tr>
<tr>
<td>0</td>
<td>100</td>
<td>100</td>
<td>→</td>
</tr>
</tbody>
</table>

“non-spectral hues”

- percept couldn’t be produced by any single-wavelength light
**Color space**: A three-dimensional space that describes all possible color percepts.

Several ways to describe this space:

1. **RGB color space**: Defined by the outputs of Long, Medium, Short wavelength (or R, G, B) lights.

2. **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
RGB space

HSB space

SENSATION & PERCEPTION 5e, Figure 5.13
© 2018 Oxford University Press
• hue around the edge
• saturation increasing from center to edge
• brightness not shown
Trichromatic color vision:
(Young & Helmholtz theory)

- three lights needed to make a specific color percept, due to use of 3 distinct cones with different sensitivities

- colors uniquely defined by combinations of cone activations
However, trichromatic theory doesn’t explain everything about color vision

**Trichromatic color vision:**
(Young & Helmholtz theory)

- three lights needed to make a specific color percept, due to use of 3 distinct cones with different sensitivities

- colors uniquely defined by combinations of cone activations
Opponent color theory:

- perception of color is based on the output of three channels, each based on an opponency between two colors

Opponent Channels:

• L-M (red - green)
• S - (L+M) (blue - yellow)
• L+M - (L+M) (black - white)
Some Retinal Ganglion Cells have center-surround receptive fields with “color-opponency”

- Red-Green (L - M) Color-Opponent cell
- Carries info about red vs. green
Some Retinal Ganglion Cells have center-surround receptive fields with “color-opponency”

- Red-Green (M-L) Color-Opponent cell
- Carries info about red vs. green
Some Retinal Ganglion Cells have center-surround receptive fields with “color-opponency”

- Blue-Yellow ($S-(M+L)$) Opponent cell
- Carries info about blue vs. yellow
(Negative) Afterimage: visual image seen after a stimulus has been removed

polarity is the opposite of the original stimulus:

- Colors are complementary:
  - Red produces Green afterimages
  - Blue produces Yellow afterimages
  - Light stimuli produce dark negative afterimages
examine color after-effects

lilac chaser:

https://michaelbach.de/ot/col-lilacChaser/index.html
So far we’ve addressed:

1) Illuminant - power spectrum
2) Cones - absorption spectrum

Q: what’s missing?

3) Objects in the world!

What properties of an object determine the properties of the reflected light that hits our eyes?
Surface reflectance function:

Describes how much light an object reflects, as a function of wavelength.

Think of this as the *fraction* of the incoming light that is reflected back.
By now we have a complete picture of how color vision works:

- **Illuminant**: defined by power (or “intensity”) spectrum
  - amount of light energy at each wavelength

- **Object**: defined by its reflectance function
  - certain percentage of light at each wavelength is reflected

- **Cones**: defined by absorption spectrum
  - each cone class adds up light energy according to its absorption spectrum

- **Cone responses**: three spectral measurements
  - convey all color information to brain via opponent channels
source (lightbulb) power spectrum

incandescent bulb

object reflectance

light from object

wavelength (nm)

400 500 600 700

400 500 600 700

“red”

“gray”

= 

×

= 

×

from object
But in general, this doesn’t happen:

We don’t perceive a white sheet of paper as looking reddish under a tungsten light and blueish/grayish under a halogen light.
Color Constancy

The visual system uses a variety of tricks to make sure things look the same color, regardless of the illuminant (light source)

- **Color constancy** - tendency of a surface to appear the same color under a wide range of illuminants
- To achieve color constancy, we must discount the illuminant and determine the surface color, regardless of how it appears
Illusion illustrating Color Constancy

Same yellow in both patches
Same gray around yellow in both patches

(the effects of lighting/shadow can make colors look different that are actually the same!)
Exact same light coming to your eye from these two patches

But the brain infers that less light is hitting this patch, due to shadow

CONCLUSION: the lower patch must be reflecting a higher fraction of the incoming light (i.e., it’s brighter)
Color Computations
Rationale for color constancy:

• Visual system tries to discount the effects of the illuminant: it cares about the properties of the surface, not the illuminant.

• still unknown how the brain does this: believed to be in cortex (V1 and beyond).
• *but*: color-constancy is not perfect

• possible to fool the visual system:

  – using a light source with unusual spectrum
    (most light sources are broad-band; narrow-band lights
    will make things look very unusual)

  – showing an image with little spectral variation
    (e.g., a blank red wall).
"guys please help me - is this dress white and gold, or blue and black? Me and my friends can't agree and we are freaking the fuck out."
So what’s going on?

object of interest → [diagram]

illuminant power spectrum

surface reflectance function

light hitting eye

\[ \text{energy} \times \text{reflectance} = \text{energy} \]

400 wavelength 700
Possibility #1: dress in blueish light (or shadow)

blueish light source

white stripe!

\[ \text{energy} \times \text{reflectance} = \text{energy} \]

\[
\text{energy} \quad 400 \quad \text{wavelength} \quad 700
\]
Possibility #2: dress in yellow light

yellowish light source

blue stripe!

\[
\text{energy} \times \text{reflectance} = \text{energy}
\]

400 \quad \text{wavelength} \quad 700
So: percept depends on inferences about the light source!

https://nathanfairbairn.tumblr.com/post/112246531934/about-that-dress
So: percept depends on inferences about the light source!

Of course: we have no idea (so far) why people are making such radically different inferences about light
Color mixing

- Mixing of lights (additive) vs Mixing of paints (subtractive)
Mixing of lights:

- **Additive color mixing**
- If light A and light B both arrive at the eye, the effects of those two lights add together
- (that is, the power spectra add)
Georges Seurat’s painting *La Parade* (1888)
• illustrates the effect of *additive* color mixture
• reflected light from nearby dots adds together when blurred by the eye

This is the same effect we get from a TV monitor with 3 kinds phosphors.
• **Subtractive color mixing**

• 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.
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.

This is the same result we’d get from mixing together yellow & blue paints.
color blindness

- About 8% of male population, 0.5% of female population has some form of color vision deficiency: Color blindness

- Mostly due to missing M or L cones (sex-linked; both cones coded on the X chromosome)
Types of color-blindness:

**dichromat** - only 2 channels of color available (contrast with “trichromat” = 3 color channels).

Three types, depending on missing cone:

- **Protanopia**: absence of L-cones
- **Deuteranopia**: absence of M-cones
- **Tritanopia**: absence of S-cones

Frequency:

<table>
<thead>
<tr>
<th>Cone Type</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>M / F</td>
<td>2% / 0.02%</td>
</tr>
<tr>
<td>M / F</td>
<td>6% / 0.4%</td>
</tr>
<tr>
<td>M / F</td>
<td>0.01% / 0.01%</td>
</tr>
</tbody>
</table>

includes true dichromats and color-anomalous trichromats
Scene Viewed by Protanope

Same Scene Viewed by Normal Trichromat
Scene Viewed by Deuteranope

Same Scene Viewed by Normal Trichromat
Other types of color-blindness:

- **Monochromat**: true “color-blindness”; world is black-and-white
- **cone monochromat** - only have one cone type (vision is truly b/w)
- **rod monochromat** - visual in b/w AND severely visually impaired in bright light
Rod monochromacy
standard trichromat

protanope

deuteranope

tritanope

monochromat

scotopic light levels
Color Vision in Animals

• most mammals (dogs, cats, horses): dichromats
• old world primates (including us): trichromats
• marine mammals: monochromats
• bees: trichromats (but lack “L” cone; ultraviolet instead)
• some birds, reptiles & amphibians: tetrachromats!
Color vision doesn’t work at low light levels!
Two Regimes of Light Sensitivity

- **Photopic**: Light intensities that are bright enough to stimulate the cone receptors and bright enough to “saturate” the rod receptors
  - Sunlight and bright indoor lighting

- **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
another interesting tidbit

• “S” cone: has some sensitivity to UV
• but lens filters out (most) UV

• Remove lens (“Aphakia”) ⇒ you can see UV (a little)
• Monet had one lens removed at age 82
• **claim**: the ability to see UV affected his painting
Summary

• trichromacy: 3-dimensional color vision (vs. hyper-spectral cameras!)
• metamers
• color-matching experiment
• color space (RGB, HSB)
• non-spectral hues
• opponent channels, negatives & after-images
• color-opponent channels
• surface reflectance functions
• color constancy
• photopic / scotopic light levels
• additive / subtractive color mixing
• color blindness