Color Perception

Acknowledgments
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David Heeger

Color – What’s it good for?

Color, What is It Good For?

perceptual organization

Color, What is It Good For?

perceptual organization
Color, What is It Good For?

Color, What is It Good For?

signaling ripeness

sexual signaling

Color – what is it good for?

• improved discrimination, grouping
• signaling
• remote sensing of surface properties

Color Outline

Wavelength encoding (trichromacy)

Three cone types with different spectral sensitivities. Each cone outputs only a single number that depends on how many photons were absorbed. If two physically different lights evoke the same responses in the 3 cones then the two lights will look the same (metamers). Explains when two lights will look the same, not what they will look like.

Color appearance

Color opponency: appearance depends on the differences between cone responses (R-G and B-Y).

Chromatic adaptation: color appearance also depends on context because the each cone adapts (like light and dark adaptation) to the ambient illumination.

Color constancy: visual system infers surface color, despite changes in illumination.

Image Formation

1. Lights that are physically different can look the same (metamers).
2. Three primaries are enough to match any test light.
3. People behave like linear systems in the color matching experiment.
Linear systems

Superposition of light: SPDs add

Color matching: scaling

Color matching as matrix multiplication

Color matching: additivity

Color matching: scaling

\[
\begin{bmatrix}
R \\
G \\
B
\end{bmatrix} =
\begin{bmatrix}
r(\lambda_1) & r(\lambda_2) & \cdots & r(\lambda_n) \\
g(\lambda_1) & g(\lambda_2) & \cdots & g(\lambda_n) \\
b(\lambda_1) & b(\lambda_2) & \cdots & b(\lambda_n)
\end{bmatrix}
\begin{bmatrix}
t(\lambda_1) \\
t(\lambda_2) \\
t(\lambda_n)
\end{bmatrix}
\]

wavelengths: \(\lambda_1 = 400\), \(\lambda_2 = 465\), etc.

Scaling the input by \(\alpha\) scales the output by \(\alpha\).
Color matching: additivity
Adding two the inputs gives the sum of the two outputs.

\[
\begin{pmatrix}
R_1 \\
G_1 \\
B_1
\end{pmatrix} = \begin{pmatrix}
r(\lambda) \\
g(\lambda) \\
b(\lambda)
\end{pmatrix} \begin{pmatrix}
\lambda \\
\lambda \\
\lambda
\end{pmatrix}
\]

\[
\begin{pmatrix}
R_2 \\
G_2 \\
B_2
\end{pmatrix} = \begin{pmatrix}
r(\lambda) \\
g(\lambda) \\
b(\lambda)
\end{pmatrix} \begin{pmatrix}
\lambda \\
\lambda \\
\lambda
\end{pmatrix}
\]

\[
\begin{pmatrix}
R_1 + R_2 \\
G_1 + G_2 \\
B_1 + B_2
\end{pmatrix} = \begin{pmatrix}
r(\lambda) \\
g(\lambda) \\
b(\lambda)
\end{pmatrix} \begin{pmatrix}
\lambda \\
\lambda \\
\lambda
\end{pmatrix}
\]

Measuring the color matching functions

<table>
<thead>
<tr>
<th>Color match settings</th>
<th>Color matching functions</th>
<th>SPD of test light</th>
</tr>
</thead>
</table>
| \begin{pmatrix}
r(\lambda_1) \\
g(\lambda_1) \\
b(\lambda_1)
\end{pmatrix} | \begin{pmatrix}
r(\lambda_2) & r(\lambda_3) & \ldots & r(\lambda_n)
\end{pmatrix} | \begin{pmatrix}
1 \\
0 \\
0
\end{pmatrix} |
| \begin{pmatrix}
g(\lambda_1) \\
b(\lambda_1) \\
b(\lambda_1)
\end{pmatrix} | \begin{pmatrix}
g(\lambda_2) & g(\lambda_3) & \ldots & g(\lambda_n)
\end{pmatrix} | \begin{pmatrix}
0 \\
1 \\
0
\end{pmatrix} |
| \begin{pmatrix}
b(\lambda_1) \\
b(\lambda_1) \\
b(\lambda_1)
\end{pmatrix} | \begin{pmatrix}
b(\lambda_2) & b(\lambda_3) & \ldots & b(\lambda_n)
\end{pmatrix} | \begin{pmatrix}
0 \\
0 \\
1
\end{pmatrix} |

Repeat with monochromatic test lights of each wavelength, always using the same 3 primary lights.

Standardized color matching functions

Commission Internationale d’Eclairage (CIE) standard set in 1931 using 3 monochromatic primaries at wavelengths of 435nm, 546nm, and 700nm.

Physiology of color matching

The eye

Neural circuitry in the retina
Retina cross-section

- Photoreceptors
- Bipolar cells
- Ganglion cells
- Axons from ganglion cells

Photoreceptors: rods and cones

Rhodopsin: rod photopigment

Bleaching of rhodopsin

In the dark

Bleached by light
Measuring rod spectral sensitivity
(wavelength-dependence of rhodopsin absorption)

Let's say you have a 500nm light with intensity 10. Can you match its appearance with a 550nm light? If so, what will be the intensity of the matching light?

The principle of univariance

The response of a photoreceptor is a function of just one variable (namely, the number of photons absorbed). Thus, the response can be identical for:
- a weak light at the wavelength of peak sensitivity
  - few incident photons, a large fraction of them absorbed
- a strong light at a wavelength of lower sensitivity
  - many incident photons, a small fraction of them absorbed
**Cone responses are nonlinear**

but can be equated by scaling intensity

**Cone spectral sensitivities**

and optical filters predict color matching functions

**Trichromacy equations**

**Wavelength encoding equation**

$$
\begin{pmatrix}
L \\
M \\
S
\end{pmatrix}
= 
\begin{pmatrix}
\cdots \\
\cdots \\
\cdots
\end{pmatrix}
\begin{pmatrix}
l(\lambda) \\
m(\lambda) \\
s(\lambda)
\end{pmatrix}
\begin{pmatrix}
t_1 \\
\vdots \\
t_n
\end{pmatrix}
$$
Metamers revisited

\[
\begin{pmatrix}
L \\
M \\
S
\end{pmatrix}
= \begin{pmatrix}
\cdots & l(\lambda) & \cdots \\
\cdots & m(\lambda) & \cdots \\
\cdots & s(\lambda) & \cdots \\
\end{pmatrix}
= \begin{pmatrix}
l_{i} \\
m_{i} \\
s_{i}
\end{pmatrix}
\]

SPDs of two lights

Displays and color matching

Application: Color TV

Trinitron

Conventional tri-dot

Color display equation

Color blindness

Ishihara plate

What a red/green color-blind person might see
Trichromat

Dichromat

Color blindness

People with color deficiencies may have difficulty distinguishing certain colors (e.g., a red/green color deficiency means that reds and greens are more difficult to distinguish). But as this photo demonstrates, many other colors are just as distinguishable to a person with a color deficiency as to someone with normal color vision.

Color matching and trichromacy caveats

1. The 3 primary lights must be linearly independent:

2. For any set of primaries, there are test lights that are out of range such that the primary intensities must be higher than achievable or "negative" (which is physically impossible).

3. Trichromacy determines when two lights look the same, not what they look like.

4. Additive vs "subtractive" color mixtures.

Simultaneous color contrast

(identical lights look different in a different context)

RGB
cyan, magenta, yellow, black—used in printing
Additive mixing of light sources

CMYK
red, green, blue—used in TVs
Subtractive mixing of absorbing pigments

“Subtractive” color mixture: surface reflectance

Light source

Eye

“Subtractive” color mixture: surface reflectance

Light source

Eye

“Subtractive” color mixture: surface reflectance

Light source

Eye

Color calculations in matlab