Color Perception 2

Acknowledgments

Descriptive
Normative

Color matching as matrix multiplication

Descriptive

Color matching: scaling

Scaling the input by $a$ scales the output by $a$.

<table>
<thead>
<tr>
<th>Color match settings</th>
<th>Color matching functions</th>
<th>SPD of test light</th>
</tr>
</thead>
<tbody>
<tr>
<td>$aR$</td>
<td>$ar(\lambda_1) \cdots ar(\lambda_n)$</td>
<td>$aR(\lambda)$</td>
</tr>
<tr>
<td>$aG$</td>
<td>$ag(\lambda_1) \cdots ag(\lambda_n)$</td>
<td>$aG(\lambda)$</td>
</tr>
<tr>
<td>$aB$</td>
<td>$ab(\lambda_1) \cdots ab(\lambda_n)$</td>
<td>$aB(\lambda)$</td>
</tr>
</tbody>
</table>

Color matching: additivity

Adding two inputs gives the sum of the two outputs.

<table>
<thead>
<tr>
<th>$R_1$</th>
<th>$r(\lambda_1)$ \cdots $r(\lambda_n)$</th>
<th>$R(\lambda_1)$ \cdots $R(\lambda_n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_1$</td>
<td>$g(\lambda_1)$ \cdots $g(\lambda_n)$</td>
<td>$G(\lambda_1)$ \cdots $G(\lambda_n)$</td>
</tr>
<tr>
<td>$B_1$</td>
<td>$b(\lambda_1)$ \cdots $b(\lambda_n)$</td>
<td>$B(\lambda_1)$ \cdots $B(\lambda_n)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$R_1 + R_2$</th>
<th>$r(\lambda_1) + r(\lambda_n)$</th>
<th>$R(\lambda_1) + R(\lambda_n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G_1 + G_2$</td>
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<td>$B_1 + B_2$</td>
<td>$b(\lambda_1) + b(\lambda_n)$</td>
<td>$B(\lambda_1) + B(\lambda_n)$</td>
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</tbody>
</table>
Measuring the color matching functions

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

Rod spectral sensitivity

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

Measuring cone photocurrents

Baylor et al. 500 nm 659 nm

Cone photocurrent

Baylor et al.
**Cone responses are nonlinear**
(but can be equated by scaling intensity)

Flash photon density (photons per square micron)

- 500 nm
- 659 nm

![Graph showing peak response (pA) with flash photon density](image)

**Cone spectral sensitivities**

![Graph showing cone spectral sensitivities](image)

**Cone responsivities**
(and optical filters)
predict color matching functions

![Graph showing cone responsivities](image)

**Wavelength encoding equation**

\[
\begin{pmatrix}
L \\
M \\
S
\end{pmatrix} =
\begin{pmatrix}
\cdots & l(\lambda) & \cdots \\
\cdots & m(\lambda) & \cdots \\
\cdots & s(\lambda) & \cdots \\
\end{pmatrix}
\begin{pmatrix}
t_1 \\
t_2 \\
\vdots \\
t_n
\end{pmatrix}
\]

**Metamers revisited**

SPDs of two lights

\[
\begin{pmatrix}
L \\
M \\
S
\end{pmatrix} =
\begin{pmatrix}
\cdots & l(\lambda) & \cdots \\
\cdots & m(\lambda) & \cdots \\
\cdots & s(\lambda) & \cdots \\
\end{pmatrix}
\begin{pmatrix}
t_1 \\
t_2 \\
\vdots \\
t_n
\end{pmatrix}
\]

**Displays and color matching**

![Diagram showing displays and color matching](image)
Color matching and trichromacy caveats

1. The 3 primary lights must be linearly independent:

   \[ \begin{bmatrix} R_1 & G_1 & B_1 \\ R_2 & G_2 & B_2 \\ R_3 & G_3 & B_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} \]

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.

RGB
red, green, blue—used in TVs
Additive mixing of light sources

CMYK
cyan, magenta, yellow, black—used in printing
Subtractive mixing of absorbing pigments

Color blindness

• Dichromats: missing one of the three photopigment/cone types.
• Can match with 2 primaries in the color matching experiment
• Will accept trichromat’s match but trichromat will not always accept dichromats match.
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.

Type of Color Deficiency

Common (X-chromosome linked)
- Protanope - missing L cones
- Deuteranope - missing M cones
- Protanomalous - has two variants of M cones, no L cones
- Deuteranomalous - has two variants of L cones, no M cones

Less common
- Tritanope - missing S cones
- Tritanomalous - missing S, has three types of L/M cones
- S-cone monochromat - missing L & M cones
- Rod monochromat - missing all cones
L and M Genes on X chromosome

highly homologous segments
single-copy DNA

L  M

Dichromacy Occurs When One Gene is Missing

highly homologous segments
single-copy DNA

L  M

X-Linked Genetics of Dichromacy

Gene Therapy for Color Blindness ?

Color opponency
**Color appearance**

**Hue cancellation experiment**

**Hue cancellation experiment**

**Hue cancellation**

Blue curve, wavelengths that appear blue were cancelled by adding yellow light. Likewise for red and green.

Why is the curve red below 475nm as well as above 580nm?

Hurvich & Jameson (1957)

**Color opponent neural computation**

**Light and dark adaptation**
Surface luminance levels

- Sunlight: $10^5 \text{ candelas/meter}^2$ (cd/m$^2$)
  - Approx. $10^2 \text{ photons/m}^2\text{sec}$
  - $3\%-90\%$ of photons are reflected as luminance
  - $3\%$ for black surfaces, $90\%$ for white surfaces
  - Only some of the reflected photons enter the pupil of eye
- Indoor lighting, CRTs: $10^2 \text{ cd/m}^2$
- Moonlight: $10^{-1} \text{ cd/m}^2$
- Starlight: $10^{-3} \text{ cd/m}^2$
- The eye can adjust to changes in light level by a factor of 100,000,000!
- Yet firing rates typically range from only 0-400Hz.

Mechanisms of light/dark adaptation

1. Pupil size
2. Switchover between rods and cones
3. Bleaching/regeneration of photopigment
4. Feedback from horizontal cells to control the responsiveness of photoreceptors

Dark adaptation

Contrast

Responses increase with contrast
Color constancy

Color signaling

Surface-illuminant equations

Cameras do not have color constancy

Principles

Psychophysics is part psycho and part physics.
Theory: linear systems.
Methodology: matching.
Computation: linear summation, static nonlinearity, adaptation.
Principle of univariance.
Parallel pathways.
Perceptual constancy (lightness, color, size, etc.), adaptation, and visual illusions (e.g., aftereffects).
S-cones have low resolution

Color and pattern

Monochrome MTF
Chromatic MTF

Asymmetric color matching

Receptor
L M S

Color

Pattern

Perceptual Match

Asymmetric color matching results

Dichoptic color-matching: adaptation


Courtesy E.J. Chichilnisky