Color

Jeffrey Heer  University of Washington
Purpose of Color

To label
To measure
To represent and imitate
To enliven and decorate

“Above all, do no harm.”

- Edward Tufte
Topics

Perception of Color
Light, Visual system, Mental models

Color in Information Visualization
Categorical & Quantitative encoding
Guidelines for color palette design
Perception of Color
What color is this?
What color is this?

“Yellow”
What color is this?
What color is this?

“Blue”
What color is this?
What color is this?

“Teal” ?
Perception of Color

Light → Cone Response → Opponent Signals

“Yellow” → Color Cognition → Color Appearance → Color Perception
Physicist’s View

Light as electromagnetic waves

**Wavelength**

Visible spectrum is 370-730 nm

**Power** or "Relative luminance"

A Field Guide to Digital Color, M. Stone
Emissive vs. Reflective Light

Additive (digital displays)

Subtractive (print, e-paper)
Perception of Color

Light → Cone Response → Opponent Signals

“Yellow” → Color Cognition

Color Cognition → Color Appearance → Color Perception

Mark D. Fairchild
COLOR APPEARANCE MODELS
Retina

Simple Anatomy of the Retina, Helga Kolb
As light enters our retina...

LMS (Long, Middle, Short) Cones
Sensitive to different wavelengths

A Field Guide to Digital Color, M. Stone
As light enters our retina...

LMS (Long, Middle, Short) Cones
Sensitive to different wavelengths
Integration with input stimulus

A Field Guide to Digital Color, M. Stone
Effects of Retina Encoding

Spectra that stimulate the same LMS response are indistinguishable (a.k.a. "metamers").

"Tri-stimulus"

Computer displays
Digital scanners
Digital cameras
CIE XYZ Color Space

Standardized in 1931 to mathematically represent tri-stimulus response from cones on the retina. "Standard observer" response curves
CIE Chromaticity Diagram

Colorfulness vs. Brightness

\[ x = \frac{X}{X+Y+Z} \]
\[ y = \frac{Y}{X+Y+Z} \]
CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.
CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.
CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.
CIE Chromaticity Diagram

Spectrum locus

Purple line

Mixture of two lights appears as a straight line.
Display Gamuts

Typically defined by:
3 Colorants
Convex region
Display Gamuts

Deviations from sRGB specification

Example:
(R, G, B) coordinates ranging from 0-255.
Displays may produce different colors for a coord!
Color Vision Deficiency (CVD)

Missing one or more cones or rods in retina.

Protanope  Deuteranope  Luminance
Normal Retina

Protanopia
Color Vision Simulators

Simulate color vision deficiencies
Browser plug-ins
Photoshop plug-ins, etc.
Perception of Color

Light

Cone Response

Opponent Signals

“Yellow”

Color Cognition

Color Appearance

Color Perception
Primary Colors

To paint “all colors”: Leonardo da Vinci, circa 1500 described in his notebooks a list of simple colors…

Yellow
Blue
Green
Red
Opponent Processing

LMS are combined to create:

Lightness
Red-green contrast
Yellow-blue contrast

[Fairchild]
Opponent Processing

LMS are combined to create:
Lightness
Red-green contrast
Yellow-blue contrast
Opponent Processing

LMS are combined to create:

- Lightness
- Red-green contrast
- Yellow-blue contrast

Experiments:
- No reddish-green, no blueish-yellow
- Color after images
CIE LAB and LUV Color Spaces

Standardized in 1976 to mathematically represent opponent processing theory.

Non-linear transformation of CIE XYZ
CIE LAB Color Space

Axes correspond to opponent signals

- **L*** = Luminance
- **a*** = Red-green contrast
- **b*** = Yellow-blue contrast

Much more perceptually uniform than sRGB!

Scaling of axes to represent “color distance”

- **JND** = Just noticeable difference (~2.3 units)

D3 + Vega include LAB color space support!
Perception of Color

- **Light**
- **Cone Response**
- **Opponent Signals**
- **“Yellow”**
- **Color Cognition**
- **Color Appearance**
- **Color Perception**
Albert Munsell

Developed the first perceptual color system based on his experience as an artist (1905).
Hue, Value, and Chroma
Hue, Value and Chroma
Hue, Value and Chroma
Hue, Value and Chroma
Munsell Color System

Perceptually-based
Precisely reference a color
Intuitive dimensions
Look-up table (LUT)
Munsell Color System

[Image of Munsell Color System chart]

- Value: 9, 8, 7, 6, 5, 4, 3, 2, 1, 0
- Hue: 6.00YR, N, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24, 26, 28
- Chroma: > > > >

Colors with a dotted border cannot be displayed correctly on a CRT.
Perceptual Brightness

Color palette
Perceptual Brightness

Color palette

HSL Lightness
(Photoshop)
Perceptual Brightness

Color palette

Luminance Y (CIE XYZ)
Perceptual Brightness

Color palette

Munsell Value
Perceptual Brightness

Color palette

Munsell Value
L* (CIE LAB)
Perceptually-Uniform Color Space

Munsell colors in CIE LAB coordinates
Perception of Color

Light

Cone Response

Opponent Signals

“Yellow”

Color Cognition

Color Appearance

Color Perception

Yellow Light Cone Response Opponent Signals

Perception of Color

“Yellow” Color Cognition Color Appearance Color Perception

Mark D. Fairchild
COLOR APPEARANCE MODELS
If we have a perceptually-uniform color space, can we predict how we perceive colors?
“In order to use color effectively it is necessary to recognize that it deceives continually.”

- Josef Albers, *Interaction of Color*
Simultaneous Contrast

Josef Albers
Simultaneous Contrast

Inner & outer rings are the same physical purple.
Bezold Effect

Color appearance depends on adjacent colors
Crispening

Perceived difference depends on background

Color Appearance Models, Fairchild
Perception of Color

Light

Cone Response

Opponent Signals

“Yellow”

Color Cognition

Color Appearance

Color Perception
Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.
Basic Color Terms

Chance discovery by Brent Berlin and Paul Kay.

Initial study in 1969
Surveyed speakers from 20 languages
Literature from 69 languages
World Color Survey
World Color Survey
World Color Survey

Naming information from 2,616 speakers from 110 languages on 330 Munsell color chips
Results from WCS

Language #19 (Camsa)
Mutual info = 0.939 / Contribution = 0.467

Language #24 (Chavacano)
Mutual info = 0.939 / Contribution = 0.513
Results from WCS

Language #72 (Mixteco)
Mutual info = 0.942 / Contribution = 0.476

Language #98 (Tlapaneco)
Mutual info = 0.942 / Contribution = 0.524
Universal (?) Basic Color Terms

Basic color terms recur across languages.
Evolution of Basic Color Terms

Proposed term evolution across languages.
Naming Effects Color Perception

Color name boundaries

Green  Blue
We associate and group colors together, often using the name we assign to the colors.
We associate and group colors together, often using the name we assign to the colors.
We associate and group colors together, often using the name we assign to the colors.
Icicle Tree with Rainbow Coloring

Color names conflict with tree structure!
Color Naming Models [Heer & Stone ’12]

Model 3 million responses from XKCD survey

Bins in LAB space sized by saliency:

How much do people agree on color name?

Modeled by entropy of $p(\text{name} \mid \text{color})$

$L^* = 55$
Perception of Color

Light

Cone Response

Opponent Signals

“Yellow”

Color Cognition

Color Appearance

Color Perception
Designing Colormaps
Colormap Design Considerations

Perceptually distinguishable colors
Value distance matches perceptual distance
Colors and concepts properly align
Aesthetically pleasing, intriguing
Respect color vision deficiencies
Should survive printing to black & white
Don’t overwhelm people’s capability!
Discrete (Binary, Categorical)

Symbol Legend

Continuous (Sequential, Diverging, Cyclic)

Gradient Legend

Discretized Continuous

Discrete Gradient
Categorical Color
Superficial dissection of the right side of the neck, showing the carotid and subclavian arteries. (http://www.bartleby.com/107/illus520.html)
Allocation of the Radio Spectrum

http://www.ntia.doc.gov/osmhome/allochrt.html
Issues:

Too many colors

Hard to remember mapping

Colors not distinctive, some are very similar

Poor grouping: similar colors, different values

Labels cause clutter

Color surround effects

Colors interactions may not look good together

http://www.ntia.doc.gov/osmhome/allochrt.html
Palette Design & Color Names

Minimize overlap and ambiguity of colors.

<table>
<thead>
<tr>
<th>Color Name Distance</th>
<th>Salience</th>
<th>Name</th>
<th>Average</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>.47</td>
<td>blue</td>
<td>0.97</td>
<td>62.9%</td>
</tr>
<tr>
<td>0.00</td>
<td>.90</td>
<td>orange</td>
<td>1.00</td>
<td>93.9%</td>
</tr>
<tr>
<td>0.00</td>
<td>.47</td>
<td>green</td>
<td>0.97</td>
<td>79.8%</td>
</tr>
<tr>
<td>0.00</td>
<td>.67</td>
<td>red</td>
<td>1.00</td>
<td>80.4%</td>
</tr>
<tr>
<td>0.00</td>
<td>.47</td>
<td>purple</td>
<td>0.97</td>
<td>51.4%</td>
</tr>
<tr>
<td>0.00</td>
<td>.37</td>
<td>brown</td>
<td>0.97</td>
<td>54.0%</td>
</tr>
<tr>
<td>0.00</td>
<td>.58</td>
<td>pink</td>
<td>0.97</td>
<td>71.7%</td>
</tr>
<tr>
<td>0.00</td>
<td>.67</td>
<td>grey</td>
<td>0.97</td>
<td>79.4%</td>
</tr>
<tr>
<td>0.00</td>
<td>.18</td>
<td>yellow</td>
<td>0.97</td>
<td>31.2%</td>
</tr>
<tr>
<td>0.00</td>
<td>.25</td>
<td>blue</td>
<td>0.97</td>
<td>25.4%</td>
</tr>
</tbody>
</table>

Tableau-10

http://vis.stanford.edu/color-names
Palette Design & Color Names

Minimize overlap and ambiguity of colors.

<table>
<thead>
<tr>
<th>Color Name Distance</th>
<th>Salience</th>
<th>Name</th>
<th>Salience</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td></td>
<td>blue 50.5%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td></td>
<td>red 27.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td></td>
<td>green 36.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td></td>
<td>purple 67.3%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td></td>
<td>blue 36.6%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td></td>
<td>orange 51.9%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td></td>
<td>pink 29.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td></td>
<td>green 21.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00</td>
<td></td>
<td>purple 23.9%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Excel-10

| Average | 0.87 | .27 |
Quantitative Color
Rainbow Color Maps
Be wary of naïve rainbows?

1. Naive rainbows are unfriendly to color blind viewers
2. Hues are not naturally ordered
3. Some colors are less effective at high spatial frequencies
4. People segment colors into classes -> perceptual banding
But rainbow helpful for inference?

Rainbow found ineffective for value comparison [Liu '18]...

...but color name salience found to improve performance on inference task of distinguishing distributions [Reda '21]

Task matters!
Steps, rather than Gradients?
Classing Quantitative Data

Age-adjusted mortality rates for the United States. Common option: break into 5 or 7 quantiles.
Classing Quantitative Data

1. Equal interval (arithmetic progression)
2. Quantiles \textit{(recommended)}
3. Standard deviations
4. Clustering (Jenks’ natural breaks / 1D K-Means)
   - Minimize within group variance
   - Maximize between group variance
Quantitative Color Encoding

Sequential color scale
Ramp in luminance, possibly also hue
Higher value -> darker color (or vice versa)
Quantitative Color Encoding

**Sequential color scale**
Ramp in luminance, possibly also hue
Higher value -> darker color (or vice versa)

**Diverging color scale**
Useful when data has meaningful “midpoint”
Use neutral color (e.g., grey) for midpoint
Use saturated colors for endpoints
Quantitative Color Encoding

Sequential color scale
Ramp in luminance, possibly also hue
Higher value -> darker color (or vice versa)

Diverging color scale
Useful when data has meaningful “midpoint”
Use neutral color (e.g., grey) for midpoint
Use saturated colors for endpoints

Limit number of steps in color to 3-9
Why?
Quantitative Color Encoding

Sequential color scale
Ramp in luminance, possibly also hue
Higher value -> darker color (or vice versa)

Diverging color scale
Useful when data has meaningful “midpoint”
Use neutral color (e.g., grey) for midpoint
Use saturated colors for endpoints

Limit number of steps in color to 3-9
Avoid simultaneous contrast, hold mappings in memory
Sequential Scales: Single-Hue

Ramp primarily in luminance, subtle hue difference

http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html
Sequential Scales: Multi-Hue

Ramp luminance & hue in perceptual color space
Avoid contrasts subject to color blindness!
Sequential Scales: Multi-Hue

Viridis, https://bids.github.io/colormap/
Designing Diverging Scales

http://www.personal.psu.edu/faculty/c/a/cab38/ColorSch/Schemes.html
Designing Diverging Scales

Hue Transition

Carefully Handle Midpoint
Choose classes of values
Low, Average, High - Average should be gray

Critical Breakpoint
Defining value e.g., 0
Positive & negative should use different hues

Extremes saturated, middle desaturated
Hints for the Colorist

Use **only a few** colors (~6 ideal)

Colors should be **distinctive** and **named**

Strive for color **harmony** (natural colors?)

Use **cultural conventions**; appreciate symbolism

Get it right in **black and white**

Respect the **color blind**

Take advantage of **perceptual color spaces**

Color is cultural and a matter of taste!