Information Visualization
PERCEPTION and COLOR

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Let’s do an experiment ...
What is Color?

= the set of *perceptions* elicited by the spectral distribution of light
Color Vision

• What we call color is generated by the visual brain.
• There is no one to one relationship between the colors seen and wavelengths.
Functions of Color Perception

Color helps us to:

- Identify things
- Classify things

Through

- Grouping
- Background segregation
How do we describe color?

Physical World
- Lights, surfaces, objects

Visual System
- Eye, optic nerve, visual cortex

Mental Models
- Red, green, brown
- Bright, light, dark, vivid, colorful, dull

Color Models
- RGB, CMYK, CIE XYZ, CIE Lab
- HSV/HSB, ...

“Yellow”
Retina is stimulated by three factors:

- illumination (light source)
- reflectance (from object)
- transmittance (atmosphere)

Simple Anatomy of the Retina, Helga Kolb
You do not see individual photons or light waves
- Eyes make limited measurements
- Eyes physically adapt to circumstance
- You brain adapts in various ways
- Weird stuff happens
Example: Lightness vs. Luminance

- **LUMINANCE**: an objective measurement of light intensity per unit area (e.g. cd/m²; physical)

- **LIGHTNESS**: a subjective impression of the intensity of light reflected from on object surface (no units; psychophysical)
Lightness experiment

The two circles are physically the same
Lightness experiment

The two circles are still physically the same, but the lightness you perceive is not
White’s illusion: the opposite effect

A is surrounded by more black but seems darker than B, which is surrounded by more white.
The Cornsweet Edge

As a result of two gradients, but why does this happen?

Mach bands

Even harder to explain:
WHAT IS GOING ON?
The Inverse Problem

• What the retina receives as input (stimulus) is a combination of photons/light waves
  – From illumination sources
  – From reflectance of objects
  – From transmittance through objects

• How do we know who contributed what?

→ We have learned what the relationships are between the physical world and our perceived information are, to solve this problem
WHAT IS COLOR?
Some definitions

**Physical measurement:**
the relative intensities of wavelengths in light measured with a spectrophotometer

**Psychophysical measurement:**
report of the color seen by a normal subject, typically made by comparison
Physical World – The Nature of Light

We have evolved to see a range of wavelengths: ~400 - 700nm

Light of a single wavelength is *monochromatic*
What do you notice?
Monochromatic colors

Can be obtained with one or more rays of light with a single wavelength

http://www.science4all.org/article/colors/
BUT...

Light rays are typically composed of multiple wavelengths
How do we describe a beam of light?

Could be any radiometric or photometric quantity (luminance, radiance, ...)

spectral power distribution (SPD)

http://www.science4all.org/article/colors/
Non-mono-chromatic color spectra
How do we know which color this would be?

http://www.science4all.org/article/colors/
Physically speaking

If you want to see different wavelengths at different energies across the spectrum

→ you need to have multiple photo receptors that can be compared
Trichromatic Theory

• Also called: Young-Helmholtz theory of color vision
• One of the earliest theories on how we perceive color
• Early 1800s, Young suggested that the eye contained different photoreceptor cells that were sensitive to different wavelengths of light in the visible spectrum.
• Mid-1800s: Hermann von Helmholtz suggested that the cone receptors were:
  – short-wavelength (blue),
  – medium-wavelength (green),
  – or long-wavelength (red).
  ...and the strength of the signals detected determined how the brain interpreted color in the environment.
It took about another 100 years before CONFIRMATION IN THE BODY
Physical World ➔ Visual System

Rods
No color (sort of)
All over the retina
More sensitive

Cones
Three different kinds of “color receptors”
Mostly in the center
Less Sensitive

Simple Anatomy of the Retina, Helga Kolb
Cone response

- LMS (Long, Middle, Short) cones
- Capture different wavelengths (some better than others)
- Transmit a signal to the brain
Cone response

Input Stimulus

Cone Response Curves

Product \rightarrow \text{Integrate} \rightarrow \text{Response}

A Field Guide to Digital Color, Maureen Stone
Cumulated intensities detected

\[ S \]

\[ M \]

\[ L \]

SML decomposition

http://www.science4all.org/article/colors/
This is the color the eye sees
This is not necessarily the color the brain sees!
HOW IS THE CAPTURED COLOR INFORMATION PROCESSED?
Color Opponency Theory

Ewald Hering 1878

Proposal:
Color experience is built from 4 primary chromatic colors
Arranged in opponent pairs
Color Opponency

The experiment was taken as evidence for color opponency

- Now we know do with cells whose center of the receptive field is sensitive to green and the surround to red = color opponent cells (also exists for blue and yellow)

- (too much detail for our purposes)
HOW TO DESCRIBE COLOR PERCEPTION
Color Terms

- **Hue**: Color we see (red, green, blue, ...)
- **Saturation**: degree to which hue differs from neutral gray
- **Lightness/Brightness**: the intensity of a colored surface or source

https://designingfortheweb.co.uk/images/compare.png
Color Spaces
XYZ Color Model

• created by the International Commission on Illumination (CIE) in 1931

• Derived from color perception experiments
  – Relates physical wavelengths to physiologically perceived colors in human color vision.

• Seldom used directly but acts as a basis for color descriptions and transformations
XYZ Color Model

Definition of three primary colors: X, Y, Z

- Color-matching functions (the numerical description of the chromatic response of the observer)
  - Here non-negative
- Y follows the standard human response to luminance, i.e., the Y value represents perceived brightness
- Can represent all perceivable colors

Stone 2005
XYZ CIE Color Space

- plotting XYZ space in 3D
- all colors that are perceivable by humans form a deformed cone
- $X$, $Y$, and $Z$-axes are outside this cone

Foley et al. 1990
CIE Chromaticity Diagram

- projection of XYZ space onto X+Y+Z = 1 (to factor out a color’s brightness):
  \[ x = X/(X+Y+Z) \quad y = Y/(X+Y+Z) \]
- monochromatic colors on curved boundary

Foley et al. 1990
RGB and XYZ

- RGB to XYZ conversion
  - RGB space: distorted cube
  - black: origin of XYZ and projection center
  - RGB projected to triangle

Stone 2005
http://www.techmind.org/

Foley et al. 1990
Can RGB Represent All Visible Colors?

• no, because all colors form horseshoe shape in CIE chromaticity diagram and RGB gamut is triangular

• But my shiny new 30” UHD OLED is state-of-the-art, it can surely show all colors!”

• → Let’s see a color that it cannot show …

http://www.techmind.org/
Let’s see REAL cyan ...
THE STRANGE WAYS WE EXPERIENCE COLOR...
Color Perception → Color Naming

What color is this? "Yellow"
Color Perception → Color Naming

What color is this?

“Blue”
Color Perception → Color Naming

What color is this?

“Teal?” “Turquoise?” “Blue-Green?” “Sarcelle?”
Color according to gender?

**Color names if you're a girl...**
- Maraschino
- Cayenne
- Maroon
- Plum
- Eggplant
- Grape
- Orchid
- Lavender
- Carnation
- Strawberry
- Bubblegum
- Magenta
- Salmon
- Tangerine
- Cantaloupe
- Banana
- Lemon
- Honeydew
- Lime
- Spring
- Clover
- Fern
- Moss
- Flora
- Sea Foam
- Spindrift
- Teal
- Sky
- Turquoise

**Color names if you're a guy...**
- Red
- Purple
- Pink
- Orange
- Yellow
- Green
- Blue

*Doghouse Diaries*
"We take no as an answer."
Color according to XKCD

A crowdsourced color-labeling game
~5 million colors
~222,500 user sessions

http://blog.xkcd.com/2010/05/03/color-survey-results/
Color according to XKCD

Actual color names if you’re a girl ...

Actual color names if you’re a guy ...

- red
- magenta
- purple
- blue
- pink
- hot pink
- hot pink
- orange
- yellow
- light green
- lime green
- neon green
- green
- aqua
- teal
- blue
We associate and group colors together, often using the name we assign to the colors.
Are there natural boundaries?

This chart shows the dominant color names over the three fully-saturated faces of the RGB cube (colors where one of the RGB values is zero).
Basic Color Terms

• Brent Berlin & Paul Kay 1969
• let’s look at two specific places
World Color Survey

Surveyed 2616 speakers of 110 languages using 330 different color chips

see also: http://wals.info/feature/132A?tg_format=map#2/32.5/153.5
Results from WCS (Mexico)
Results from WCS (South Pacific)
But language-color interaction

- Himba tribe in Namibia – only few color words:
  - **zoozu**: most dark colors (red, blue, green, violet)
  - **vapa**: white, also some yellow
  - **borou**: some green and blue colors
  - **dumbu**: many green but also red colors
But language-color interaction

- experiment: how long to find a differing color?

difficult to impossible for Himba people
But language-color interaction

- experiment: how long to find a differing color?

easy for Himba people: different words for both types of green
Universal (?) Basic Color Terms

Basic color terms recur across languages

- White
- Red
- Pink
- Grey
- Yellow
- Brown
- Black
- Green
- Orange
- Blue
- Purple

Interesting factoid: Cartographers found out that they need 4 unique hues to unambiguously distinguish all areas on an arbitrarily complex map.
Evolution of Basic Color Terms

Proposed universal evolution of color names across languages.
Some other color usage problems

This one is called COLOR CONTRAST: the same spectral input can appear as a different color
Color Constancy

• Background color and lighting have a big effect on how we see color
• Two different color spectra can look identical
CONCLUSION

• Color vision (just like brightness) does not correspond to physical measurements

• Be mindful in how you apply color in your computer-generated scenes!
COLOR FOR VISUALIZATION
Why are color choices important?

Example: The Rainbow Color Scale

- Represent data by varying hue across (approximately) the full range of visible wavelengths
- One of the most common color scales in use today

And it’s (usually) a huge mistake!
General Bathymetric Chart of the Ocean

Every color mark signals:
longitude, latitude, sea/land, depth/altitude

Where is the land?
Where is the sea the deepest?
Now describe what kind of color scale was possibly used here.
Perceptual Ordering

Rainbow Color Scale
- Is ordered by wavelength
- Is not perceptually ordered

Gray Scale
- Increases luminance (value) from dark to light
- Is perceptually ordered

From: Rainbow Color Map (Still) Considered Harmful, CG&A 07
Color Scale Luminance

Rainbow Color Scale

- The visual system perceives high spatial frequencies through changes in luminance
- Is isoluminant (for large portions), changes only appear at color boundaries
- Obscures small details in the data

From: Rainbow Color Map (Still) Considered Harmful, CG&A 07
Color Scale Transitions

Rainbow color scale

- appears separated into bands of almost constant hue
- sharp transitions between hues are perceived as sharp transitions in the data

![Color Scale Transitions Diagram](image)

- rainbow color scale
- gray scale
- heated color scale
- isoluminant green-red scale

From: Rainbow Color Map (Still) Considered Harmful, CG&A 07
HOW TO PICK COLORS
A Few General Rules

• Always have **high luminance contrast** between foreground and background

• **Use only a few distinct colors**

> 12 colors will likely not work
~5 colors recommended
Using Color to Label
(For groups, categories, highlights, etc.)

Colors should be distinctive and named

- "Blue"
- "Blue-er?"
- "Other Blue???

Use cultural conventions & appreciate symbolism

- Fruits: Apple, Banana, Blueberry, Cherry, Grape
- Brands: Apple, AT&T, Home Depot, Kodak, Starbucks

Lin et al. (2013) Selecting Semantically-Resonant Colors for Data Visualization

Beware of bad interactions
Using Color for Scales

(For ordinal or quantitative data)

Use a scale that varies **lightness** in addition to color.

Shades of **gray** or shades of **a single color** are easiest.

For **diverging scales**, use a lighter, desaturated value for the critical mid-point and darker hues for the ends.
ColorBrewer

Highly recommended!

Designed originally for maps but will also work well for other types of visualizations

http://colorbrewer2.org/
http://colorbrewer2.org/
Every ColorBrewer Scale

For CSS and JavaScript (by Mike Bostock)

http://bl.ocks.org/mbostock/5577023
ONE WARNING ABOUT RED-GREEN

7% of the viewers may not see anything if you use red-green,

The following slides on the topic are adapted from Tobias Isenberg’s
Color Vision Deficiency

approx. 7% of male population color-deficient

mostly red-green color deficiency (deuteranopia or protanopia) – but other forms exist as well
Color Deficiency Test (Ishihara Test)
Color Deficiency Test
Color Deficiency
Examples from VIS/InfoVis 2004
Better: Red-Blue Contrast
Check Your Visualizations!

When possible, avoid red-green color contrasts for visualization purposes.

To test your visualizations, use proofing modes in PhotoShop and GIMP, or try VisCheck
http://www.vischeck.com/
Color Resources

Maureen Stone’s Resources
A Field Guide to Digital Color
http://www.stonesc.com

Cindy Brewer’s ColorBrewer
http://colorbrewer2.org
For CSS and JavaScript
http://bl.ocks.org/mbostock/5577023

Community Palette Sharing
http://www.colourlovers.com
http://kuler.adobe.com
(Fun) Color Resources!

**Wired** “The Crayola-fication of the World”  
by Aatish Bhatia  

**RadioLab** “Colors”  
WNYC Podcast  
PERCEPTION OF OTHER VISUAL ENCODINGS
There are **lots** of possible visual encodings.

Their **effectiveness** is related to how they are handled by our perceptual system.
Elementary Graphical Perception Tasks

William S. Cleveland (1980s)

Performed **controlled experiments** to determine how effectively people could judge changes in visual features.

Focus on **quantitative information**

**Variables used**: angle, area (size), color hue, color saturation, density (value), length, position, slope, volume.
Elementary Graphical Perception Tasks
William S. Cleveland (1980s)
Color Value

What percentage in value is the right from the left?

100%  66%
Color Value

• What percentage in value is the right from the left?

100%  60%
Area

What percentage in size is the right from the left?

100%  52%
Area

What percentage in size is the right from the left?

100%  36%

More accurate ☐
Less accurate ☐
Volume

What percentage in size is the right from the left?

100%  40%
Why are people so bad at this?

Relationship between stimulus and perception isn’t always linear!

Stevens’ power law describes a relationship between a physical stimulus (S) and its perceived intensity or strength (P).

[Graph from Wilkinson 99, based on Stevens 61]
Perception

People tend to **correctly estimate lengths**

They tend to **underestimate areas and volumes**.

When asked to pick a circle *2 times* the size, people tend to pick a circle ~1.8 *times* larger.

This tendency **gets worse** as area grows.

**Volume is even worse!**

Circles drawn by absolute scaling

Circles drawn by apparent scaling (Flannery)

\[ S = 0.98A^{0.87} \] [from Flannery 71]
Area

- What percentage in size is the red from the blue (=100%)?

no idea – this is very difficult
Length

What percentage in length is the right from the left?

100%

75%
Length / Position

What percentage in length is the right from the left?

100%

25%
## Effectiveness of Data Encodings

Mackinlay 1986

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<thead>
<tr>
<th>Quantitative</th>
<th>Ordinal</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>Position</td>
<td>Position</td>
</tr>
<tr>
<td>Length</td>
<td>Density</td>
<td>Color Hue</td>
</tr>
<tr>
<td>Angle</td>
<td>Color Saturation</td>
<td>Texture</td>
</tr>
<tr>
<td>Slope</td>
<td>Color Hue</td>
<td>Connection</td>
</tr>
<tr>
<td>Area</td>
<td>Texture</td>
<td>Containment</td>
</tr>
<tr>
<td>Volume</td>
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<td>Density</td>
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<td>Density</td>
<td>Containment</td>
<td>Color Saturation</td>
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<td>Length</td>
<td>Shape</td>
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<td>Angle</td>
<td>Length</td>
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<td>Slope</td>
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<tr>
<td>Connection</td>
<td>Area</td>
<td>Slope</td>
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<tr>
<td>Containment</td>
<td>Volume</td>
<td>Area</td>
</tr>
<tr>
<td>Shape</td>
<td>Shape</td>
<td>Volume</td>
</tr>
</tbody>
</table>
**Magnitude Channels: Ordered Attributes**

- Position on common scale
- Position on unaligned scale
- Length (1D size)
- Tilt/angle
- Area (2D size)
- Depth (3D position)
- Color luminance
- Color saturation
- Curvature
- Volume (3D size)

**Identity Channels: Categorical Attributes**

- Spatial region
- Color hue
- Motion
- Shape
Elementary Graphical Perception Tasks

William S. Cleveland (1980s)

also beware of the physical presentation:
PREATTENTIVE PROCESSING
How many 3’s do you see?

1281768756138976546984506985604982826762
9809858458224509856458945098450980943585
9091030209905959595772564675050678904567
8845789809821677654876364908560912949686

From: Ware, Information Visualization using Vision to Think
How about now?
Preattentive Processing

• Some stimuli can be perceived without the need for focused attention
• Generally within 200-250 ms
• Seems to be done in parallel by the low-level vision system

Visual encoding has a big impact on this!
Visual encodings influence preattentive processing.

DETERMINE IF A RED CIRCLE IS PRESENT.
Hue

Yes, can be done preattentively

From: Healey, Perception in Visualization
Shape

Yes, can be done preattentively

From: Healey, Perception in Visualization
Hue and Shape

Cannot be done preattentively due to the conjunction of shape and hue → need to search

From: Healey, Perception in Visualization
Preattentive visual features (some)

- orientation
- length, width
- closure
- size
- curvature
- density, contrast
- number, estimation
- hue
- intensity
- depth cues
- flicker
- direction of motion
- velocity of motion
- 3D orientation
- artistic properties

From: Healey, Perception in Visualization
Preattentive visual features (some)

When designing visualizations, try to **use pre-attentive** features to support the **most important tasks**.

From: Healey, Perception in Visualization
Preattentive visual features (some)

Avoid conjunctions that inhibit preattentive recognition.

(Most conjunctions are require search.)

From: Healey, Perception in Visualization
Applying what we know to

ASSESS VISUAL REPRESENTATIONS
Let’s evaluate...

<table>
<thead>
<tr>
<th>Car / Nation</th>
<th>USA</th>
<th>Japan</th>
<th>Germany</th>
<th>France</th>
<th>Sweden</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accord</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AMC Pacer</td>
<td>x</td>
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<td>Audi 5000</td>
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<td></td>
<td>x</td>
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</tr>
<tr>
<td>BMW 320i</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
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</tr>
<tr>
<td>Champ</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevy Nova</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Saab 9000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

What kind of data are we looking at?

- Nations: **Nominal**
- Cars: **Nominal**
- (Nation,Car): **Nominal**
Let’s evaluate...

Problem:
Length of bar suggests an order or quantity (e.g. Swedish cars are better)
Let’s evaluate...

Better!
Let’s evaluate...

**Banks: Market Cap**

- Market Value as of January 20\textsuperscript{th} 2009, $Bn
- Market Value as of Q2 2007, $Bn

**Market Capitalization =**
What would it cost to buy all of a company’s stock at the current price.

Compares 15 major banks on two dates:
- **January 20\textsuperscript{th}, 2009**
- **Q2 2007** (before banking crisis hit)

Source: Bloomberg, Jan 20\textsuperscript{th} 2009
Problems here?

Banks: Market Cap

- Market Value as of January 20th 2009, $Bn
- Market Value as of Q2 2007, $Bn

We are not good at comparing areas.
(And the areas here are actually misleading!)
Problems here?

We are not good at comparing areas. (And the areas here are actually misleading!)

\[
\frac{85}{165} = \sim 50\%
\]

But this is actually the ratio of the radii, not the areas!

A bar chart would be better.
There is likely a **bug or error** in the data

Pie slices are difficult to compare by **area** or by **angle**

**Similar colors** are difficult to distinguish

**Perspective distortion** adds to the problem
Similarly...3D bar charts are not recommended

These are much easier to read & compare!

Problem here?
Length Comparison

At first glance:
- A huge overall decline
- In 2003, Newsweek is 50% of Time

If we add a proper baseline at 0:
- The downward trend is less severe
- 2003: Newsweek is ~80% of Time
Moreover...

News Magazine Staff Size Over Time
Time and Newsweek select years 1983 - 2005

10 years each

1 year each
Redesign by Stephen Few

**Time Magazine’s vs. Newsweek Magazine’s Size Over Time**

- **Staff Count**
  - Time Magazine
  - Newsweek

- **Correspondent Count**
  - Time Magazine
  - Newsweek

- **Bureau Count**
  - Time Magazine
  - Newsweek

**NEWS MAGAZINE STAFF SIZE OVER TIME**

- Time and Newsweek, selected years 1983 - 2005

**NUMBER OF CORRESPONDENTS IN BUREAUS OVER TIME**

- Time and Newsweek, select years 1983 - 2005

**NEWS MAGAZINE BUREAUS OVER TIME**

- Time and Newsweek, selected years 1983 - 2005

Note: A dashed line connecting two points indicates that there are years between the points for which values were not available. If the values were available, the shape of the lines might vary significantly.
A few more (classic) guidelines!

Chart Rules

• Provide a proper baseline

A 10% increase. Good!

Already looks more impressive

Wow!
Chart Rules

- Provide a proper baseline & label your axes
Chart Rules

• Provide a **proper baseline & label your axes**
• Avoid **eye-candy**

The same data with eye-candy & no numbers ... but at least it tells the same general story.

Actual data

Impressive, but a lie!
Chart Rules

• Provide a **proper baseline & label your axes**
• Avoid **eye-candy**
• Avoid **area comparisons** whenever possible
Chart Rules

- Provide a **proper baseline & label your axes**
- Avoid **eye-candy**
- Avoid **area comparisons** whenever possible
- Provide **legends**
Chart Rules

- Provide a **proper baseline & label your axes**
- Avoid **eye-candy**
- Avoid **area comparisons** whenever possible
- Provide **legends**
- **Grids help** – but make them subtle
  (about 20% opacity – **no black lines**)

![Chart with Process and Visualization data]
Many more useful guidelines!
Summary

Today you learned

Details about the perception of color and a few other visual variables

Saw that the vision system is quicker and better at detecting certain visual variables

Learned how to critique visualizations
Müller-Lyer Sinusoidal Waves
New variant by Gianni A. Sarcone

Though the blue and red segments seem to oscillate, they are always the same length! Nothing moves except the arrows at the endpoints of each color segment...