Graphical Perception

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Psych 6135

http://euclid.psych.yorku.ca/www/psy6135/
In constructing a graph, **quantitative** and **categorical** information is encoded by visual attributes:

- Length
- Position along axis
- Angle
- Area
- Color, shape, line style

What determines the ability of graph viewers to:

- Make *comparisons* (which is larger?)
- Estimate a magnitude?
- See *patterns*, trends, unusual features?
When we construct a graph, we **encode** a numerical or categorical variable as a graphical attribute.

When we view a graph, the goal is to **decode** the graphical attributes and extract information about the data that was encoded.

- Encoding should rely on features that can easily be decoded.
- Often, easier said than done! The devil is in the details.
Visual & cognitive systems

- **A simplified model: Three stages**

  - **Sensory (iconic) memory**
    - pre-attentive, automatic, feature detection
    - massively parallel, short duration, easily fooled (“thinking fast”)

  - **Working memory**
    - requires attention, limited capacity (~ 4-6 “chunks”)

  - **Long-term memory**
    - real-world knowledge, ~ unlimited capacity, inference (“thinking slow”)

- **How is info lost?**

- **How to preserve info?**
Another coarse distinction:

- **Perception**: Processing of the signals coming in: what you “see”
- **Cognition**: How you understand and interpret what you see

Based on slide from G. Grinstein

A nice scientific or textbook diagram
But where is cognition?
Perception: Bottom-up & Top-down

• **Bottom-up processing**
  ▪ Low level: features $\rightarrow$ pattern $\rightarrow$ object
  ▪ Detect edges, contours, color, motion

• **Top-down processing**
  ▪ Driven by goals, expectations
  ▪ Uses prior knowledge, experience, filters what we “see”
Perception: Bottom-up

How many 5s in this display?

1561321203658413076510374627
4173127527327592732990709742
1703707774179527931749270973
4019743217909370945179279417

Numerals differ only in shape, and are high-level symbols
You have to literally scan them all & count the 5s.
The distinction of color is immediate & pre-attentive
You only have to scan & count the 5s.

This is why color is an important visual attribute for a categorical variable in graphs.
What is in this scene?

What is the middle character?

What is the middle letter in each word?

All of these are demonstrations of the role of expectations (top-down) in determining what we “see”
Illusions: The Eye-Brain Barrier

Perceptual illusions give some guidance on what not to do in data graphics.
Illusions: Length

Surrounding context matters in judging the length of objects.

Which line is longer? Or are they the same?

Surrounding context pulls perception of length in its direction

This is the famous Müller-Lyre illusion
Illusions: Area

Surrounding context matters in judging the area of objects.

Which red circle is larger? Or are they the same?

Surrounding context pulls perception of area against the background. This is often called the Ebbinghaus illusion or the Tichener illusion.
Which of the bars are longer? Or, are they all the same length?

R code:

```r
x <- seq(0, 5 * pi, length.out = 100)
w <- 0.5
plot(x, sin(x), ylim = c(-1, 1 + w), type = "n")
segments(x0 = x, y0 = sin(x), y1 = sin(x) + w, lwd = 3)
```
Where are differences between curves are larger? Or, are they all the same?

This is sometimes called the “sine illusion”
Plotting the difference directly gives the answer.

Why does this matter?
Distances between curves

Playfair didn’t know that judgments of distance between curves are biased. We tend to see the perpendicular distance rather than the vertical distance.

Original graph

Plot of difference

Balance of Trade to the East Indies

Exports and Imports (millions of pounds)

Year

Exports

Imports

Balance = Imports - Exports (millions of pounds)

Year

Our Deficit

where did this spike come from?
Which thick line is longer? Or, both the same?

Which figure is tallest?
Or, all the same?

This is often called the Ponzo illusion: We judge the size of real-world objects relative to their background and perspective.
Context illusions

Perception of elements of a scene is affected by context, background, etc.

Are the squares straight or tilted?

Are the pink lines straight or curved?

Does the rectangle change in darkness?
Illusions: Semantic/cognitive

Perception of object figures often shows a preference for orientation in nature

Is this image a duck, or a rabbit? Duck or rabbit?
Selective attention

https://www.youtube.com/watch?v=vJG698U2Mvo
How large are transport accidents?
How much bigger than non-transport accidents?

Estimation of length or ratios of length are more accurate than the same judgments of area.
Area vs. length judgments

How much larger is South Africa than Egypt?

African Countries by GDP

Judgments here based on area

Judgment here based on position along a scale
Stevens’ Power Law

- How does perceived magnitude of a sensation relate to stimulus intensity?
- S. S. Stevens (1957) showed that, for many domains

\[ \text{Sensation} \propto \text{Intensity}^p \]

- These provide ways to assess the accuracy of magnitude estimation for visual encodings
  - length judgments most accurate
- But: graph perception is not always a matter of estimating magnitudes.

Fig. 5.7 from: Munzner, Visualization Analysis & Design
Cleveland & McGill (1984) and later Heer & Bostock (2010) carried out experiments to assess the relative accuracy of magnitude judgments for different visual encodings.

The task here is to estimate the %age of the smaller highlighted portion.

The details of these studies are interesting & important – more next week.

The graph of these results is a great model for data display.

Fig. 5.8 from: Munzner, *Visualization Analysis & Design*
Based on this, Munzner (2015) proposes a ranking of visual attributes for ordered & categorical variables in data displays

These hold when the task is to estimate a magnitude.

A different ranking may occur for other graph-based tasks.

angle (pie charts) – good for % of total judgments

color (mosaic plots) – good for pattern perception

**Channels: Expressiveness Types and Effectiveness Ranks**

**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

Fig. 5.6 from Munzner, *Visualization Analysis & Design*
Integral & separable encodings

- Some encodings can be viewed *independently*
  - two different variables *can* be decoded separately
- Some *combine* with each other to some degree.
  - different variables *cannot* be easily decoded separately

From: Ware, *Information visualization: Perception for Design*
Integral dimensions

A bivariate U.S. county-level map showing % diabetic (saturation) and % obese (hue)

It is difficult to see variations in diabetes separately from obesity

The eye is attracted to the positive correlation between these dark (blue, red) vs. light color.
Separable dimensions

Bivariate map of N. C.: disability (size) and unemployment rate (saturation)

• These can be seen separately
• (However, using TOTAL disability is confounded with population density)
Anomaly detection

Find the red dot in each of the following displays

• This task is easiest when all the rest are blue dots
• Next easiest when only shape distinguishes the red dot
• Hardest when both color and shape vary

Sometimes called “popout” effect. Not a good term.

This is important in designing graphs to highlight some points.
Anomaly detection

For each display, find the anomaly shown at the left
Color and shape: What is easy or hard depends on the background
**Encodings: Lessons**

- **Ordered variables**
  - Prefer encodings at the top of the hierarchy (position along a scale) to those at the bottom (color saturation, curvature)

- **Favor separable encodings**
  - Use color and another attribute---shape, size, orientation
  - Don’t overload symbols---probably two at most
  - Avoid mixing two aspects of color or two aspects of shape

- **Small multiples**
  - Reduces the need for multiple encodings within a panel
  - But, makes direct comparison more difficult

- **Highlighting**: to draw attention to one group, use a pre-attentive attribute
Encodings: Lessons

• Best to show quantitative variables with position or length
  • Bar charts:
    ▪ Best encoding via length → start at 0
    ▪ Avoid stacked bars (not aligned), where possible
  • Dot charts:
    ▪ Best encoding via position along a scale → start at 0
  • Frequency data:
    ▪ area/color encoding to show patterns
    ▪ sqrt or log scale often useful to show magnitude
• Color: choose sensibly ordered hues or saturation
• Arrangement
  ▪ make comparisons easier by placing things to be compared nearby
Gestalt principles

- Perception as top-down process governed by holistic principles. “Gestalt” = “form”
  - **proximity**: elements close together likely to belong to the same unit
  - **similarity**: more common visual elements increases belonging together
  - **good continuation**: elements that blend together are likely in the same unit
  - **common region**: elements in the same region likely belong together
Gestalt principles

- (a) **proximity** creates impression of 2 groups
- (b) **similarity**: 3 groups via color & shape
- (c) **good continuation** gives impression of 2 groups
Gestalt principles

More gestalt ideas

Why lines are good in time series graphs

From: http://blog.yhwu.me/notes/visualizations/cs171.html
Figure - Ground

What is the figure? What is the background?

Face or vase?  Black or white soldiers?  Face or park?

These examples all use different techniques to create ambiguous figures
This graph inverts the y-axis, and shades the area above the curve. A more conventional version of the same graph.

We tend to see 1999 & 2005 as high points.

Gun deaths increased after the ‘Stand your ground’ law.

From: Andy Kirk, *Data Visualization: A Handbook for Data Driven Design*
What perceptual features or principles are involved in your reading or understanding of these figures?

Top-down?  
Bottom-up?  
Gestalt?

What about this?

or this?

or this?
Color serves to: **highlight**, **identify**, and **group** elements in a visual display.

Find the cherries in this display: Color acts as a preattentive attribute here.

From: Colin Ware, *Information Visualization: Perception for Design*
W.E.B. Du Bois presented this as part of an exhibition on The American Negro at the 1900 Paris Exposition.

It is a landmark graphic, but shows no understanding of the use of color for a quantitative variable.

Q: Are there more Negroes per sq. mile in Texas or Louisiana?
Object color

What makes an orange look orange, a green apple look green, or a strawberry red?

Objects absorb colors from the rainbow, but reflect their own.

From: Miriah Meyer, lecture notes, cs6330
Color: Aspects in data graphics

• Perception: trichromatic theory
  ▪ How the eye sees color

• Color spaces:
  ▪ RGB (additive), CMYK (subtractive)
  ▪ HSV, HCL: perceptually based

• Color palettes for computer graphics
  ▪ ColorBrewer: sequential, diverging, qualitative
  ▪ Color-blind safe?
  ▪ Photocopy safe?

• Transparency
Perception: The human eye

- Retina:
  - rods (monochromatic),
  - cones (R, G, B)

It is of interest to see the wide variety of ways this is conveyed in scientific diagrams:
Perception: color sensitivity

- Cells in the retina are differentially sensitive to colors of different wavelength
  - Each have a distribution of sensitivity for short, medium & long
  - Their peaks are used to name them as Blue, Green, Red

This figure also stimulates questions of scientific visualization
- Rods & cones are “normalized”
- Are they all equal in what we see?
Perception: color sensitivity

This slide, found at http://slideplayer.com/slide/6329532/ shows color sensitivity on three different scales:

- Cone receptors least sensitive to (least output for) to blue

Relative sensitivity curves for the three types of cones, log vertical scale, cone spectral curves from Vos & Walraven, 1974

Relative sensitivity curves for the three types of cones, the Vos & Walraven curves on a normal vertical scale
Color perception, even of gray, is influenced by contrast against a background.

Q: Which gray square at right is most similar to that at the left?

A: it is the same gray square against a changing background

Most people say A, because it is shown on a white background.
Luminance contrast

Showing blue text on a black background doesn’t work very well. There is insufficient luminance contrast.

Showing blue text on a white background works better. There is sufficient luminance contrast.

Showing yellow text on a white background doesn’t work very well. There is insufficient luminance contrast.

Showing yellow text on a black background works better. There is sufficient luminance contrast.

TIP: For presentations, light text on a dark background is often preferred. I don’t do this, because I’m also concerned with printing slides. (With LaTeX Beamer, it is easy to have separate setups for presentation & print)
Early color theory

Tobias Mayer (1755) – color theory composed of (blue, red, yellow) as basic colors

Johannes Lambert (1772) – A color pyramid, composed of 7 layers

Introduces the idea of color “primaries”

Introduces the idea of color saturation
Color space: Munsell colors

• Color space is 3D
  ▪ How to specify a given color in perceptual terms?
  ▪ Albert Munsell (~1930): hue, chroma, lightness (HCL)
  ▪ These form perceptually uniform & independent dimensions

By SharkD - CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=8401562
Munsell’s color scheme was highly influential in Psychology research
Nearly every lab investigating color used standard sets of Munsell color chips
CIE color space

• How do we know about the perceptual properties of colors, taking spectral sensitivity into account?

Experiments used a color-matching task:
• Adjust the intensity of pure R, G, B lights to match a given color
• This defines a new color theory connecting physical properties and human perception (spectral sensitivity).
• The CIE (International Commission on Illumination) becomes the standard to calibrate color in scientific instruments and human experiments
The International Commission on Illumination (CIE) in 1931 defines a color space of \((x,y,z)\) coordinates based on color-matching experiments combining R, G, B light sources in additive mixtures, and a “standard colorimetric observer.”

This defines a new color theory connecting physical properties and human perception (spectral sensitivity). There are eventually a variety of CIE color spaces (CIELab, CIELuv, …) and lots of formulas for converting among them.
Enter technology: how to produce color?

- **RGB:**
  - Combine light: R + G + B = white
  - Used in computer monitors, TV, film
- **CMYK:**
  - Combine ink: Cyan + Magenta + Yellow = Black
  - Used in color laser printers, the print industry

**TIP:** for publishing, you may need to prepare or convert graphics from RGB to CMYK.

Some software offer useful tools for this:
- Adobe Acrobat Pro
- ImageMagik
The standard gamut of colors available for different display media are a restricted subset of what the human eye can see.

Print (CMYK) is most restricted, and requires a more careful choice of color in graphics.
Color is often hard to use effectively in software, because the ways to specify it are so varied:

- Color names: “black”, “red”, “green3”, “skyblue”, “cyan”
- RGB: black=(0,0,0); green3=(0, 205, 0), cyan=(0, 255, 255)
- Hex: black=“#000000”; cyan=“#00FFFF”

See: [http://research.stowers.org/mcm/efg/R/Color/Chart/] for R color charts
WTF! Give me a break, please:

- Make it easier to **compute** with colors: define blends of colors or a color ramp
- Make it easier to specify color **schemes** with decent **perceptual** properties
- Make it easier to map colors to **data features** I want to show

*Every time you are forced to say “#008B8B” or “cyan4” a puppy dies somewhere*

-- MF, 2018
Software: palettes

- R (and other software) provide palettes of colors used for **defaults** in graphs
  - Not all are nice—depends on your purpose
  - But, there are lot of choices
  - You can change them once for all graphs in a session or paper

```r
> (pal <- palette())
[1] "black"  "red"    "green3" "blue"    "cyan"   "magenta" "yellow" "gray"
> pie(rep(1, length(pal)), labels = sprintf("%d (%s)", seq_along(pal), pal), col = pal)
```

```r
colours = rainbow(8)
pie(rep(1, length(colours)), labels = sprintf("%s", seq_along(colours)), col = colours)
```
n <- 12
pie(rep(1, n), col=rainbow(n))

pie(rep(1, n), col=heat.colors(n))

pie(rep(1, n), col=terrain.colors(n))

pie(rep(1, n), col=topo.colors(n))
Discussion Q:
- Which of these are better for quantitative variables?
- Which for categorical?

These are shown for area fill. How effective would they be for:
- point colors
- line colors

E.g., yellow is bright as an area, but nearly invisible as points or lines or text on a white background
ColorBrewer, by Cynthia Brewer provides an interactive application for choosing color pallets, [http://colorbrewer2.org](http://colorbrewer2.org)

This is one example of a multi-hue scheme for a *quantitative, sequential* variable, shown from low to high with 4 color classes.

- **variable type**
- **choose different versions of the scheme**
- **export color specs to HEX, RGB, CMYK**

This example: [http://colorbrewer2.org/#type=sequential&scheme=BuGn&n=4](http://colorbrewer2.org/#type=sequential&scheme=BuGn&n=4)
Diverging schemes are designed to show a quantitative variable, where we want to see what is low vs. what is high, leaving the middle of less visual impact – difference from average, residuals, ...

[Image: A map with a color scheme for diverging data classes.

This example: http://colorbrewer2.org/#type=diverging&scheme=RdBu&n=5]
Qualitative schemes are designed to show a categorical variable, where we want to see differences among unordered categories.

These are all available in the RColorBrewer package.

This example: [http://colorbrewer2.org/#type=qualitative&scheme=Accent&n=5](http://colorbrewer2.org/#type=qualitative&scheme=Accent&n=5)
palettes: ColorBrewer

RColorBrewer::display.brewer.all()

sequential

qualitative

diverging
The colorspace package in R has an interactive palette widget.

It also provides functions for many kinds of color manipulations.

The R Color cheatsheet, by Malcolm Fraser is a goto source for all aspects of color in R:

Viridis palettes

Designed by Stéfan van der Walt and Nathaniel Smith for Python; ported to R in the viridis package.

Goals:

• **Colorful**, spanning as wide a palette as possible so as to make differences easy to see

• **Perceptually uniform**: values close to each other have similar-appearing colors and values far away from each other have more different-appearing colors

• **Robust to colorblindness**: these properties hold true for people with common forms of colorblindness, as well as in grey scale printing

• **Pretty**: much nicer as a defaults in software

These assertions are largely untested. Perhaps a good research topic!
Comparing palettes

For a quantitative variable and a continuous color scale, there are many choices. How well do they work?

R base palettes

- rainbow
- heat

ggplot default palette

- ggplot default

ColorBrewer palettes

- brewer blues
- brewer yellow-green-blue

viridis palettes

- viridis
- magma

This is a bit tricky: ideally, we want a wide range of color
Comparing palettes

What is shown in this map?

The rainbow color scale obscures the main features

Now we can see it—elevation in the Florida coast: above or below 0

This color scheme was designed to reveal the essential topography of the map & to have perceptually equal elevation steps

Comparing palettes

```r
df <- data.frame(x = rnorm(10000), y = rnorm(10000))
g <- ggplot(df, aes(x = x, y = y)) + geom_hex(bins=40) + coord_fixed() + theme_bw()
g
```

```r
library(viridis)
g + scale_fill_viridis()
```
Graphics designed in color often have to consider what happens when graphs are reproduced in B/W: grayscale

- This is particularly hard for a **diverging** color scale
- My original design for mosaic plots used solid vs. dashed lines to distinguish $+$ vs. $-$.
The design of this graphic table was crafted to preserve readability if printed in B/W. NB: text for numbers changes from black to white depending on background color.

**Background shading works equally well in color or B/W**

A+ for visual design!

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Most common forms are genetic, and involve a deficiency in one of the cone type sensitivities

- Protanopia (red deficient: L cone absent)
- Deuteranopia (green deficient: M cone absent)
- Tritanopia (blue deficient: S cone absent)

Some form of red-green insensitivity is most common
- about 6-8% of population
- more common in males

TIP: Avoid color scales with main variation between red & green
Colorblindness

What an image looks like with various forms of color deficiency

[Images showing normal color vision and various forms of color blindness]
Goal: Show employment growth, 2013—2015

Original design, using
• green: above average
• red: below average

How this looks to someone with red-green colorblindness

red & green become indistinguishable

From: http://www.mena-forum.com/category/u-s-a/
What would my graph look like to someone with color deficiency?

colorblindr simulates a graph under various conditions
A Toolbox for Manipulating and Assessing Colors and Palettes

<table>
<thead>
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<th>Color spaces</th>
<th>HCL-based palettes</th>
<th>ggplot2 scales</th>
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<tr>
<td>Luminance = 70</td>
<td>Qualitative</td>
<td>Species</td>
</tr>
<tr>
<td>Pastel 1</td>
<td>Pastel 1</td>
<td>Species</td>
</tr>
<tr>
<td>Dark 3</td>
<td>Pastel 1</td>
<td>setosa</td>
</tr>
<tr>
<td>Harmonic</td>
<td>Pastel 1</td>
<td>versicolor</td>
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<tr>
<td>Sequential (single-hue)</td>
<td>Sequential (multi-hue)</td>
<td>virginica</td>
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<tr>
<td>Blues 3</td>
<td>Purple-Blue</td>
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<td>Green-Brown</td>
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<td></td>
</tr>
<tr>
<td>Tropic</td>
<td>Tropic</td>
<td></td>
</tr>
</tbody>
</table>

See: [http://colorspace.r-forge.r-project.org/](http://colorspace.r-forge.r-project.org/)
swatchplot(): display collections of palettes in flexible ways

Effect of varying hue, chroma and luminance individually

```
swatchplot(
  "Hue" = sequential_hcl(5, h = c(0, 300), c = c(60, 60), l = 65),
  "Chroma" = sequential_hcl(5, h = 0, c = c(100, 0), l = 65, rev = TRUE, power = 1),
  "Luminance" = sequential_hcl(5, h = 260, c = c(25, 25), l = c(25, 90), rev = TRUE, power = 1),
  off = 0
)
```

Emulate different types of color vision deficiency for one or more palettes

```
swatchplot(palette.colors(), cvd = TRUE)
```
See how color palettes work in different kinds of statistical displays.
Color: Lessons

• Use colors to represent differences in meaning
  ▪ Avoid gratuitous use of multiple colors
  ▪ Use consistent color scheme across multiple graphs of the same data

• Consider presentation goal:
  ▪ Highlight one subset against the rest
  ▪ Group a categorical variable
  ▪ Encode a quantitative variable

• Consider differences in color perception, B/W printing
Consider encoding scheme:

- **Categorical**: Use a wide range of hues, of ~ same saturation

  ![Categorical Colors](image)

- **Sequential**: Use a small range of hues of varying intensity

  ![Sequential Colors](image)

- **Diverging**: Use two sequential schemes, decreasing toward the middle

  ![Diverging Colors](image)

Images from: Stephen Few,
Transparency

Colors can be made partially transparent, by adding an “alpha” channel, 
\[0 \leq \alpha \leq 1\] (opaque)

Filled areas combine to look more saturated
What do you see here?

This also works well with filled point symbols, which would otherwise be obscured when they overlap

Different colors “blend”
What do you see here?
Transparency: Adding another layer

Transparency also works well to combine different graphical features in a plot. Here, a filled boxplot and dots representing individual observations.

What number would you assign to the following phrases?

From: [https://github.com/zonination/perceptions](https://github.com/zonination/perceptions)
Summary

• In designing data graphics, consider the viewer
  - Info → encoding → image → decoding → understanding

• Perception: much is known, with ~ links to graphics
  - Bottom up: perceptual features, what grabs attention
  - Top down: expectations provide a context
  - Encoding attributes must consider what is to be seen

• Color: What is the presentation goal?
  - Color palettes for different purposes
  - Transparency increases the effective use of color