

Graphical Perception

Michael Friendly

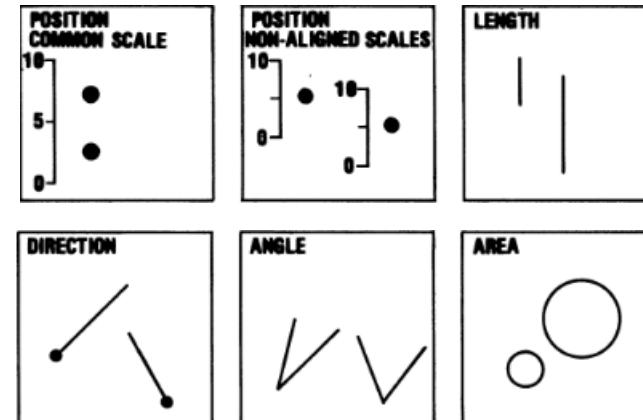
Psych 6135

<https://friendly.github.io/6135>

Graphical Perception

- In constructing a graph, **quantitative** and **categorical** information is encoded by visual attributes:

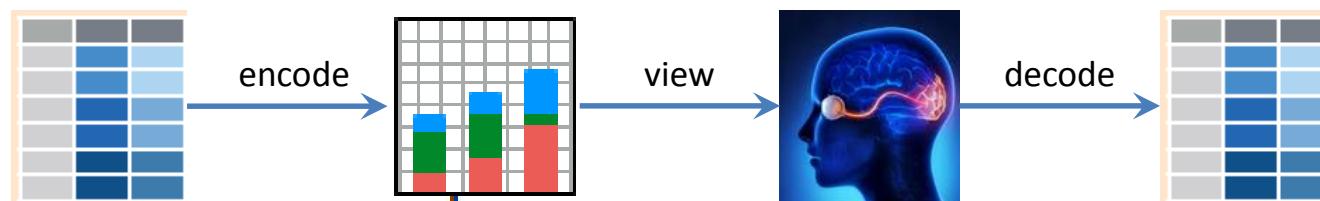
- Length
- Position along axis
- Angle
- Area
- Color, shape, line style



- What determines the ability of graph viewers to:
 - Make **comparisons** (which is larger?)
 - Estimate a magnitude?
 - See **patterns**, trends, unusual features?

Encoding & decoding

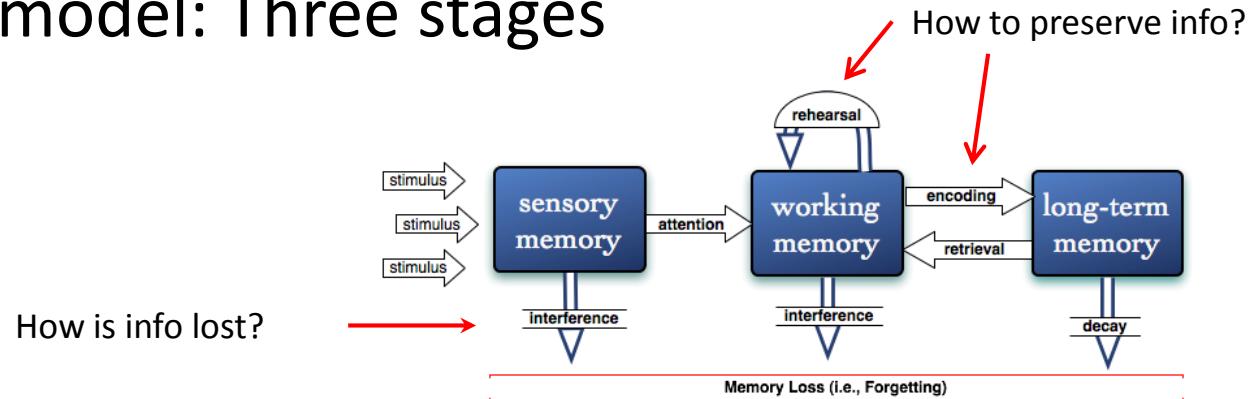
- When we construct a graph, we **encode** a numerical or categorical variable as a graphical attribute
- When we view a graph, the goal is to **decode** the graphical attributes and extract information about the data that was encoded



- 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

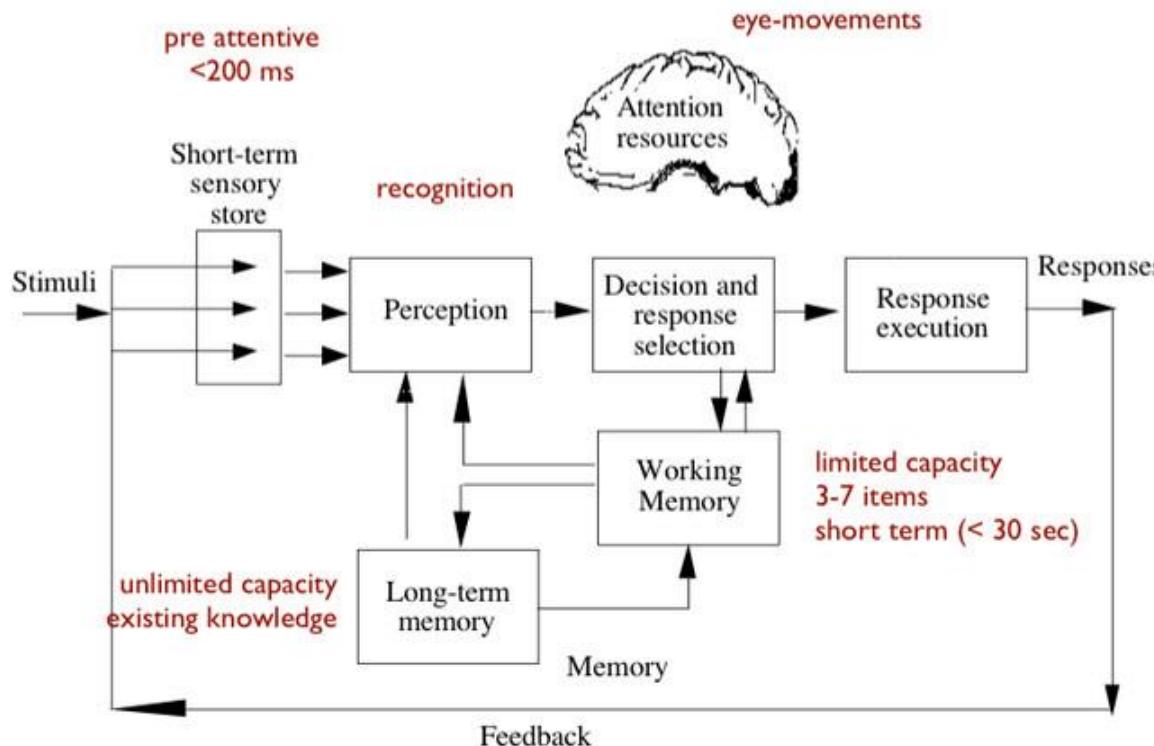


- Sensory (iconic) memory
 - pre-attentive, automatic, feature detection
 - massively parallel, short duration, easily fooled (“thinking fast”)
- Working memory
 - requires attention, limited capacity (~ 4-6 “chunks”)
- Long-term memory
 - real-world knowledge, ~ unlimited capacity, inference (“thinking slow”)

Perception vs. cognition

Another coarse distinction:

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



A nice scientific or textbook diagram

But where is cognition?



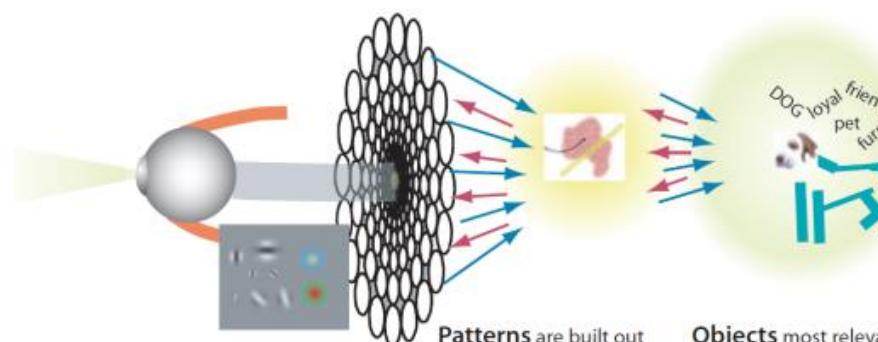
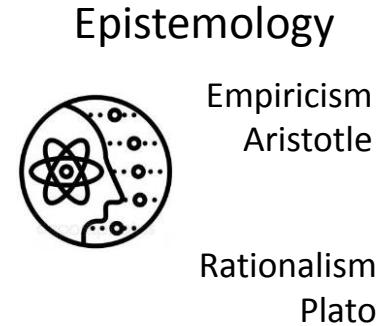
Perception: Bottom-up & Top-down

- Bottom-up processing

- Low level: features → pattern → object
- Detect edges, contours, color, motion

- Top-down processing

- Driven by goals, expectations
- Uses prior knowledge, experience, filters what we “see”



Features are processed in parallel from every part of the visual field. Millions of features are processed simultaneously.

Patterns are built out of features depending on attentional demands. Attentional tuning reinforces those most relevant.

Objects most relevant to the task at hand are held in Visual Working Memory. Only between one and three are held at any instant. Objects have both non-visual and visual attributes.

Bottom-up information drives pattern building

Top-down attentional processes reinforce relevant information

Perception: Bottom-up

How many 5s in this display?

1561321203658413076510374627
4173127527327592732990709742
1703707774179527931749270973
4019743217909370945179279417

How many 5s in this display?

1561321203658413076510374627
4173127527|327592732990709742
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

Perception: Top-down

What is in this scene?



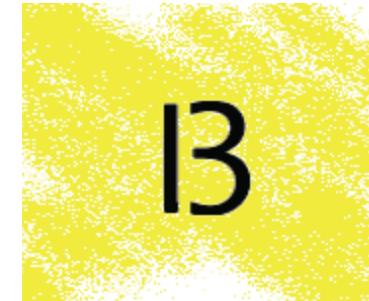
What is the middle letter in each word?

TAE CAT

What is the middle character?



What here?



An ambiguous figure!

All of these are demonstrations of the role of **expectations** (top-down) in determining what we “see”



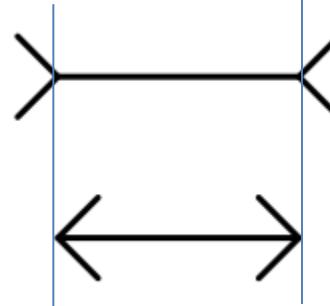
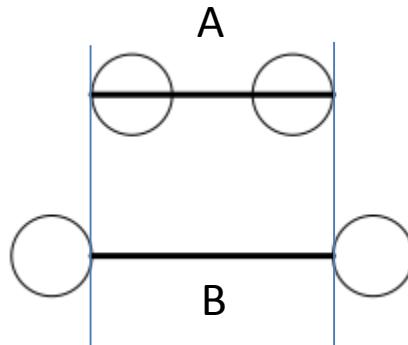
Illusions: The Eye-Brain Barrier

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?

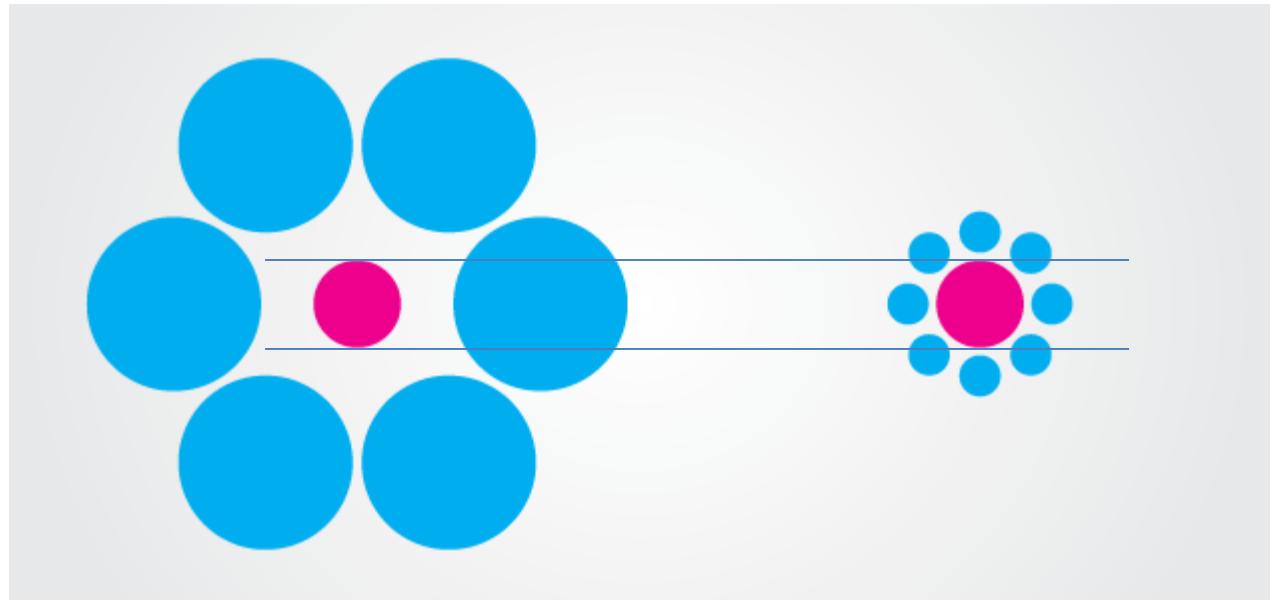


Surrounding context pulls perception of length in its direction
This is the famous **Müller-Lyre** illusion

Illusions: Area

Surrounding context matters in judging the **area** of objects.

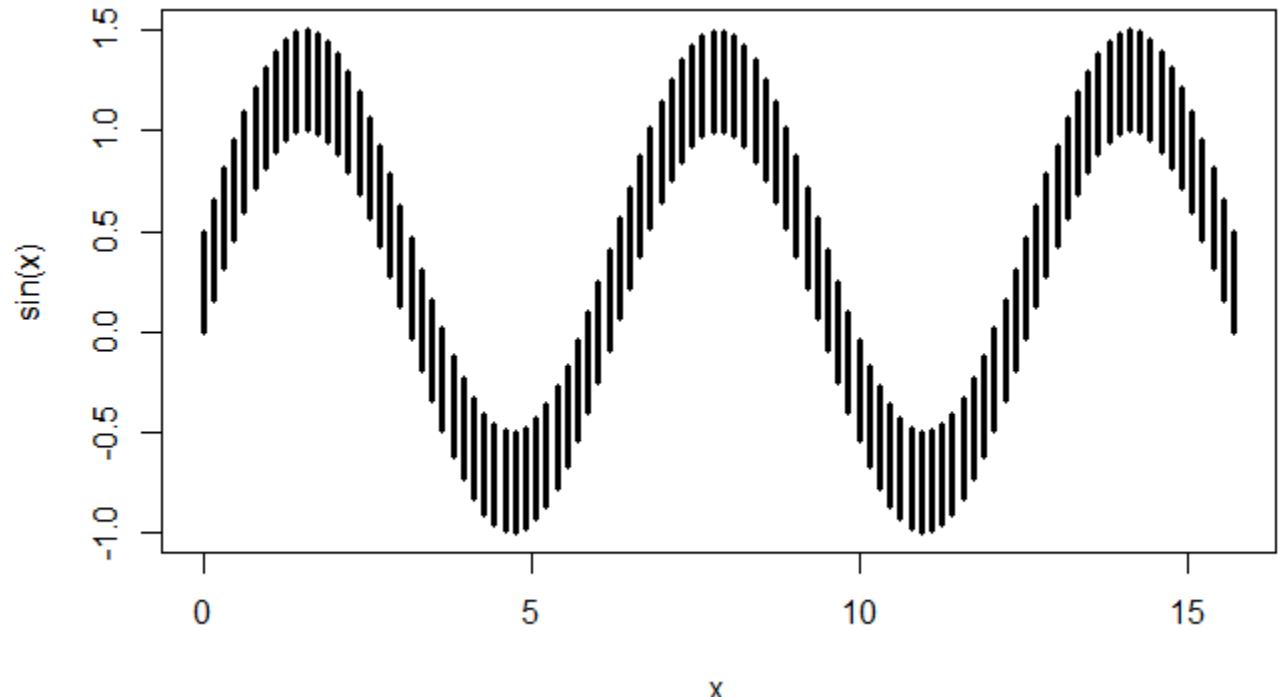
Which **red** circle is larger? Or are they the same?



Surrounding context pulls perception of area against the background
This is often called the **Ebbinghaus** illusion or the **Tichener** illusion

Illusions: Length

Which of the bars are longer? Or, are they all the same length?

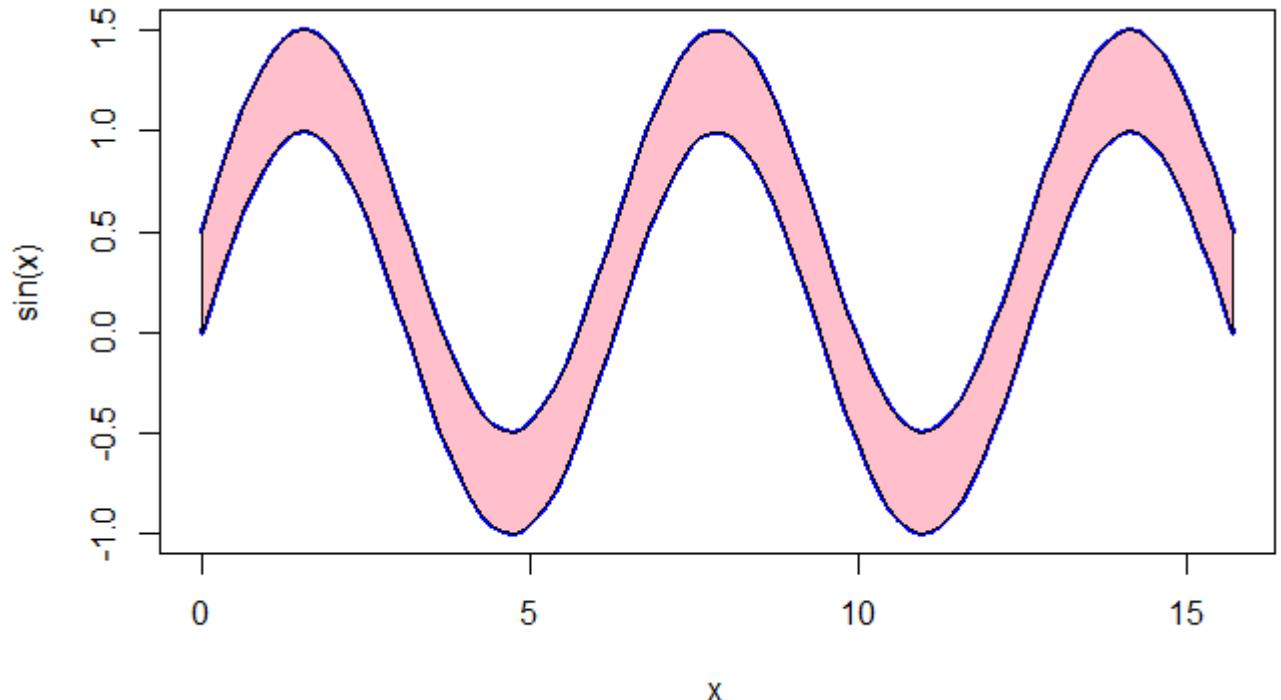


R code:

```
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)
```

Illusions: Difference

Where are **differences** between curves are larger? Or, are they all the same?



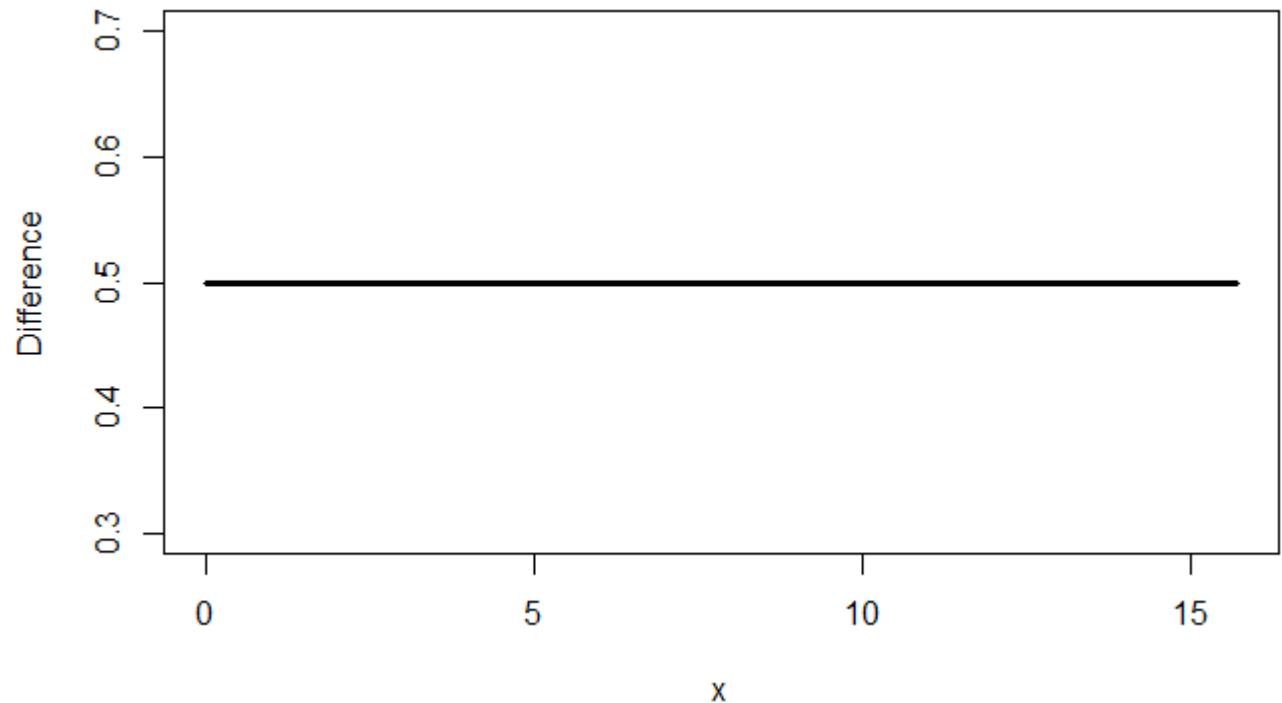
This is sometimes called the “sine illusion”

Illusions: Difference

Plotting the difference directly gives the answer.



OMG!

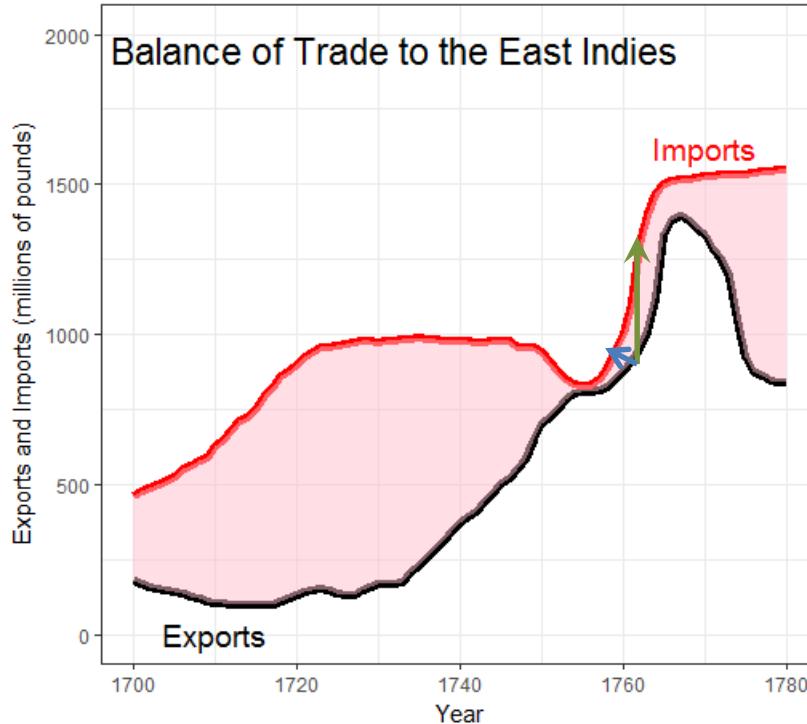


Why does this matter?

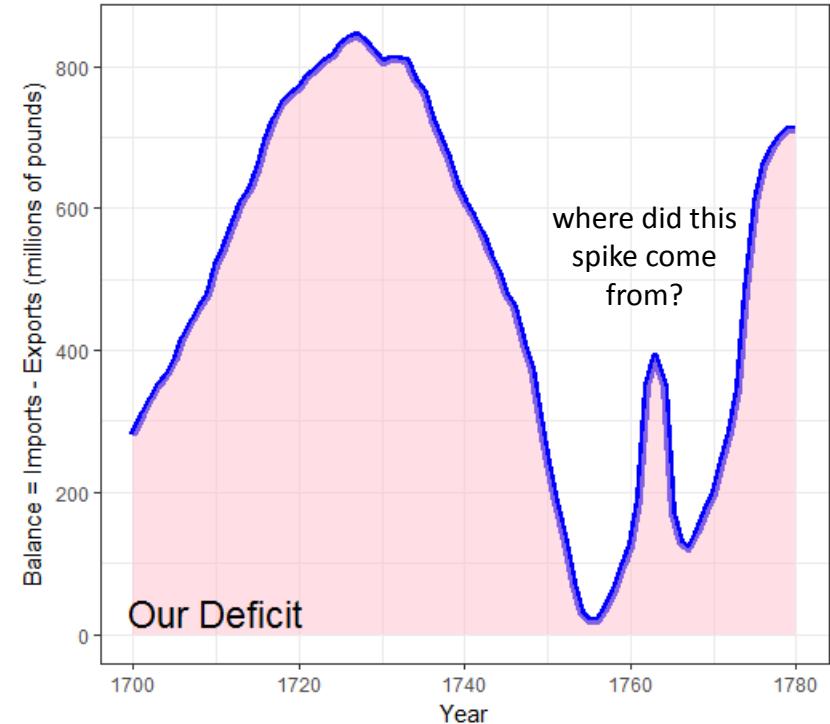
Distances between curves

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

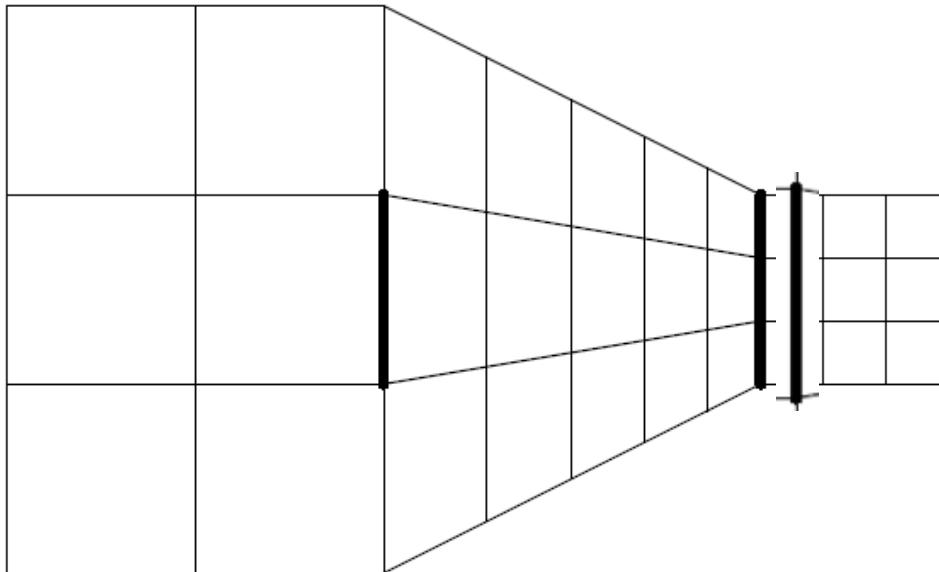


Plot of difference

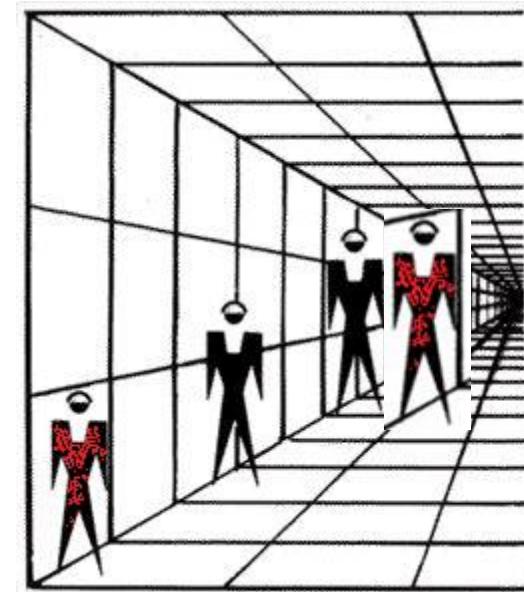


Illusions: Perspective

Which **thick** line is longer? Or, both the same?



Which figure is tallest?
Or, all the same?

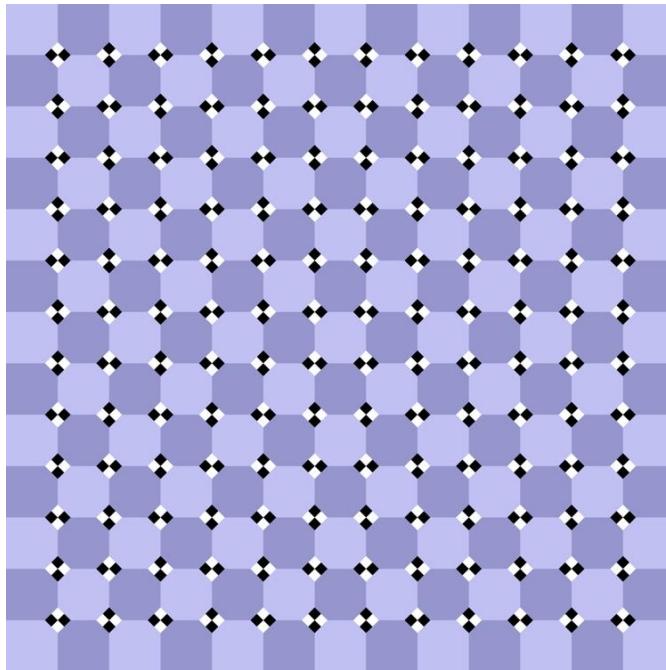


This is often called the **Ponzo** illusion: We judge the **size** of real-world objects relative to their background and perspective.

Context illusions

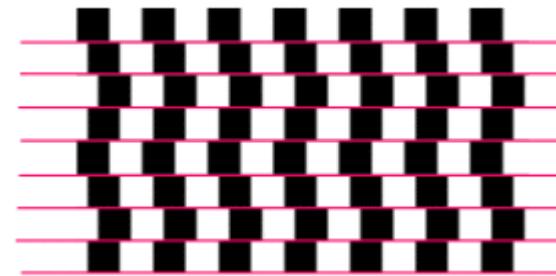
Perception of elements of a scene is affected by context, background, etc.

Are the squares straight or tilted?

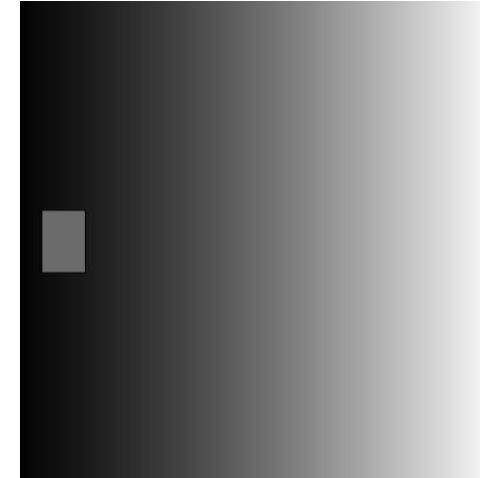


It is hard not to be fooled by these!

Are the pink lines straight or curved?

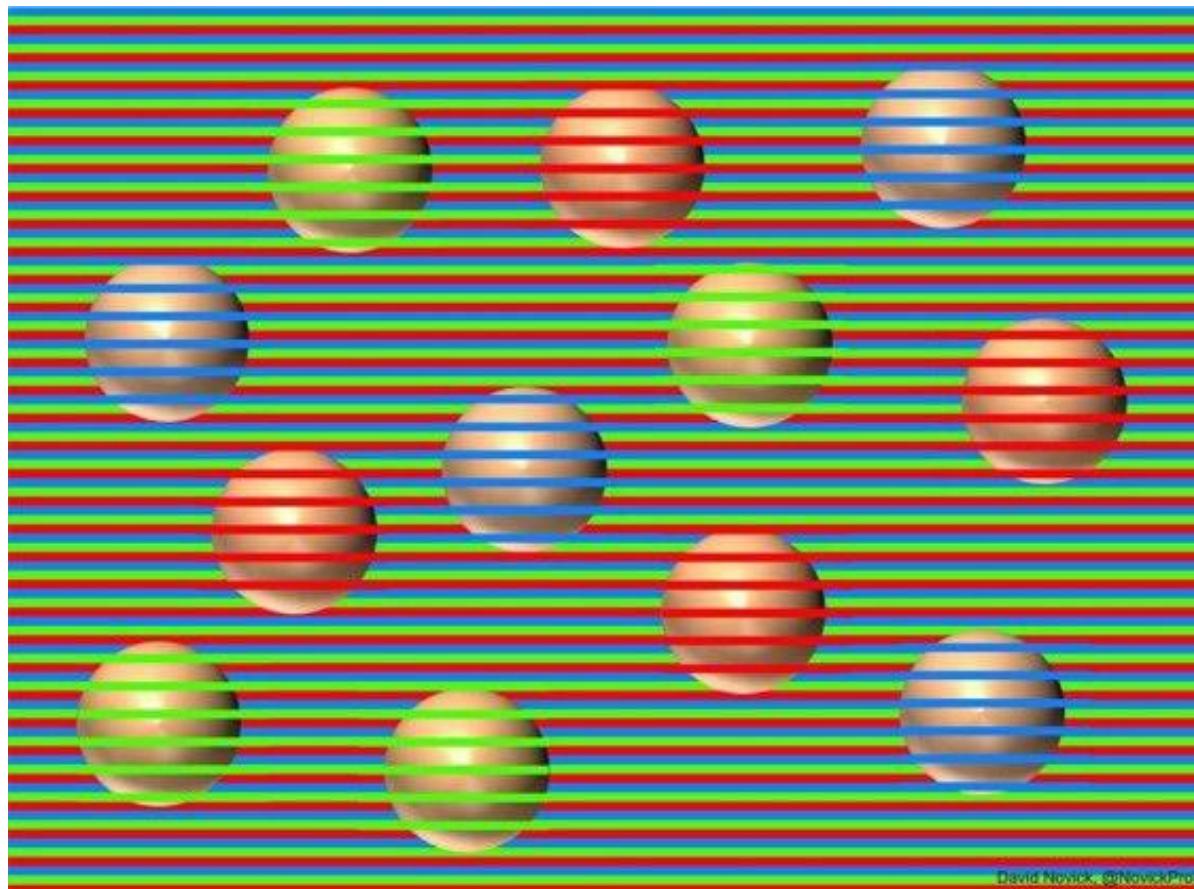


Does the rectangle change in darkness?



Context illusions: Color

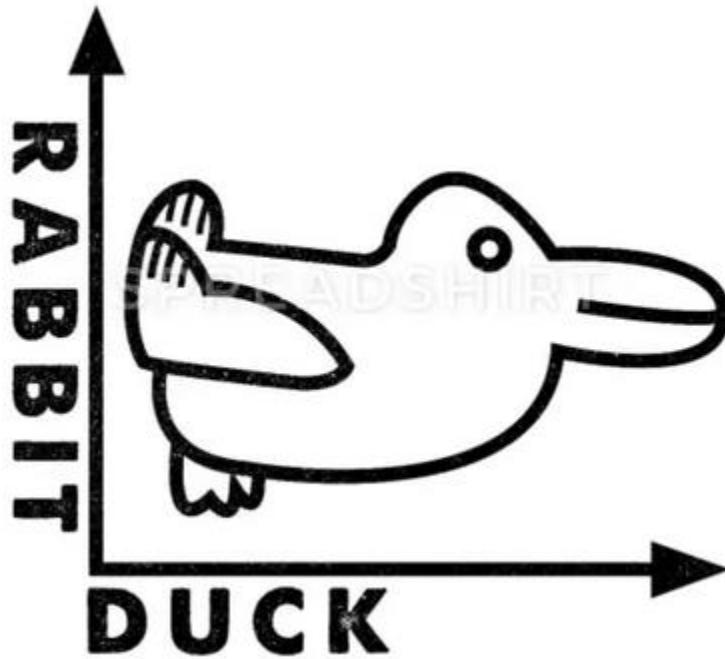
Are the balls different colors or are they all the same color?



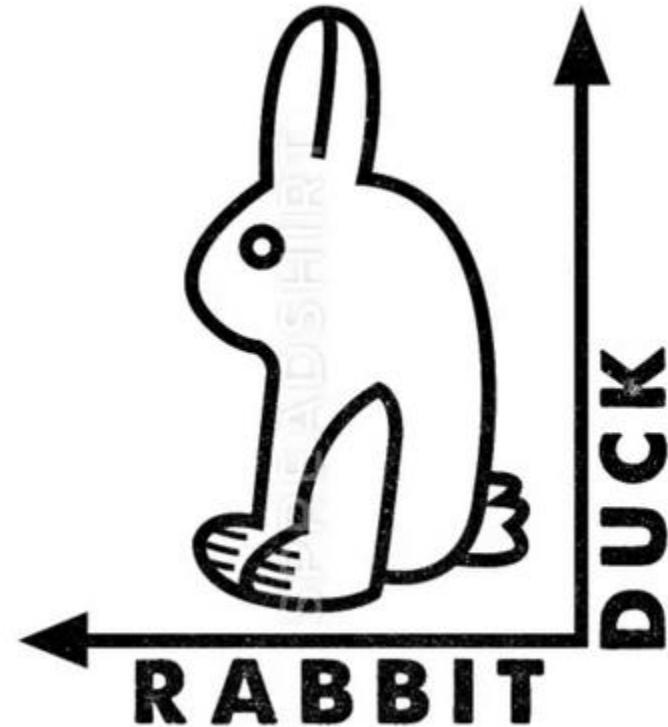
Illusions: Semantic/cognitive

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

Is this image a duck, or a rabbit?



Duck or rabbit?



Catalog of visual/auditory illusions

<https://www.illusionsindex.org/illusions>

A large collection of illusions with references to research studies.

The Illusions Index

HOME ABOUT EXPLORE SUGGEST DONATE FEEDBACK QUIZ

Home / Explore

Filter by Tags

Sort By Most Visited

Found 63 matching results

YOUNG WOMAN OR OLD WOMAN

WATERFALL ILLUSION

EXPLORE ILLUSIONS

The Illusions Index is a fully searchable curated collection of illusions. Browse the illusions below to find out more.

You can also search by keyword or by one or more pre-defined tags, which allow you to compare and contrast different types of illusions.

ADELSON'S CHECKER-SHADOW ILLUSION

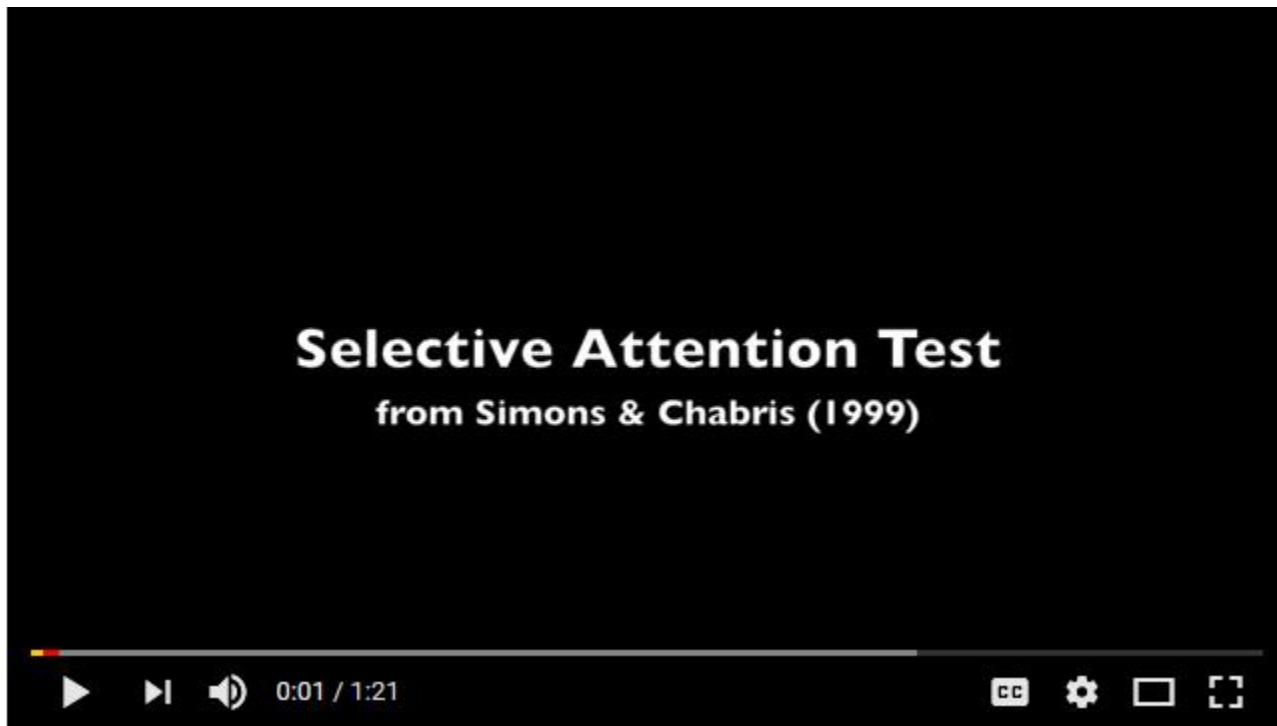
TROXLER EFFECT

NEGATIVE AFTERIMAGES

20

The screenshot shows the homepage of The Illusions Index. At the top, there's a navigation bar with links for HOME, ABOUT, EXPLORE (which is underlined), SUGGEST, DONATE, FEEDBACK, QUIZ, and a magnifying glass icon for search. Below the navigation is the site's logo, "The Illusions Index". Underneath the logo is a breadcrumb trail: Home / Explore. There are two dropdown menus: "Filter by Tags" and "Sort By" set to "Most Visited". A message says "Found 63 matching results". The main content area displays a grid of nine cards, each representing a different illusion. The visible cards are: "YOUNG WOMAN OR OLD WOMAN" (a classic bistable image), "WATERFALL ILLUSION" (a circular motion illusion), "EXPLORE ILLUSIONS" (an introductory card with text about the site), "ADELSON'S CHECKER-SHADOW ILLUSION" (a checkerboard illusion with a green cylinder), and "TROXLER EFFECT" (an owl illusion). Each card has a small caption at the bottom.

Selective attention



<https://www.youtube.com/watch?v=vJG698U2Mvo>

Attention strongly focused on some feature(s) steals attention from others

Magnitude estimation

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

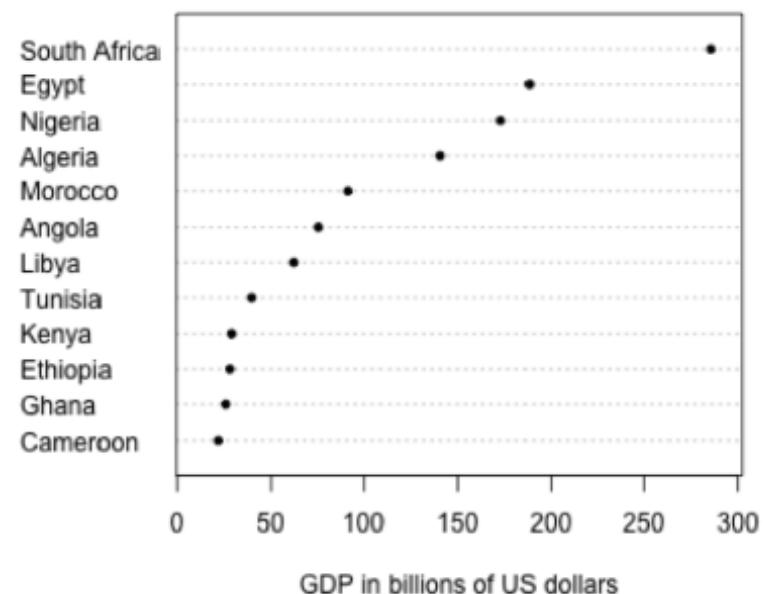
Easy: Which is larger— South Africa or Egypt?

Harder: How much larger is South Africa than Egypt? (% or ratio)

African Countries by GDP



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.

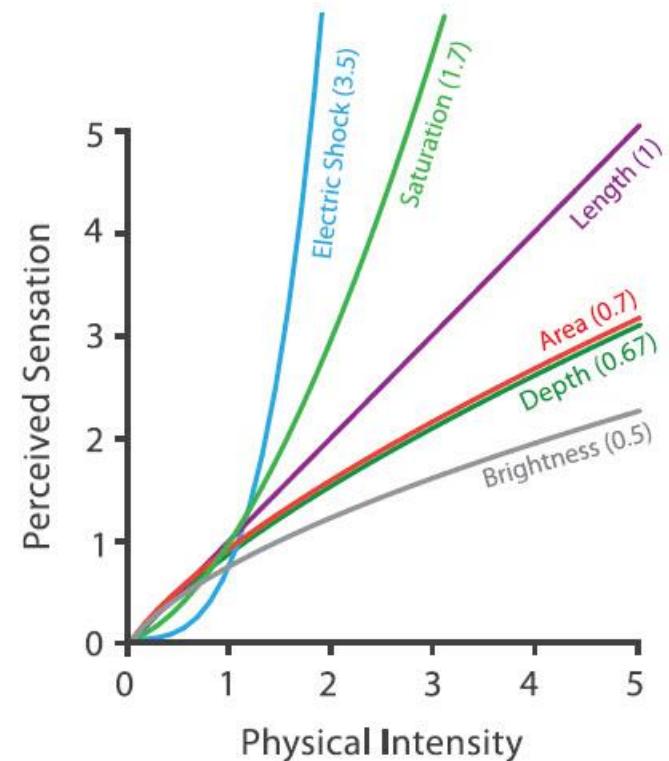


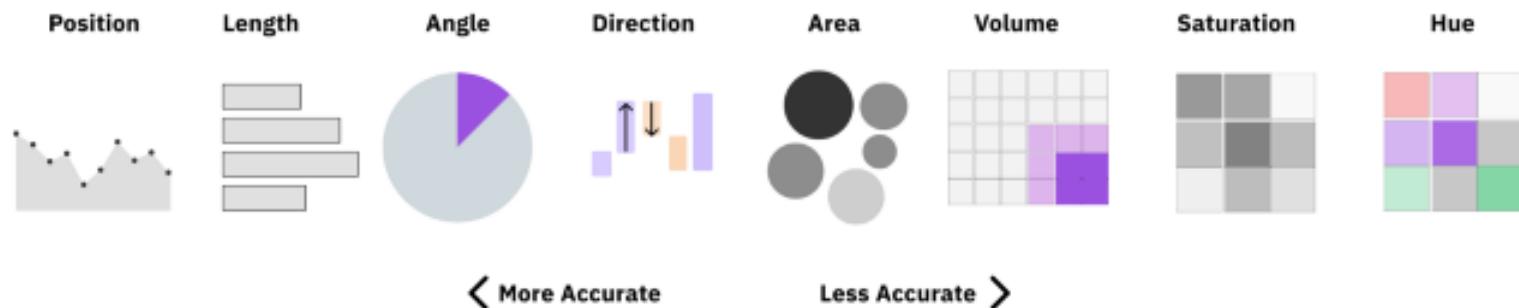
Fig. 5.7 from: Munzner, *Visualization Analysis & Design*

Scale of accuracy

The commonly used “scale” of accuracy of magnitude judgments of relative size

- How much smaller/larger is A compared to B?

Accuracy Of Visual Cues



Not necessarily the same for other tasks (Part-whole: What % is A of total?)

Accuracy: Experimental evidence

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

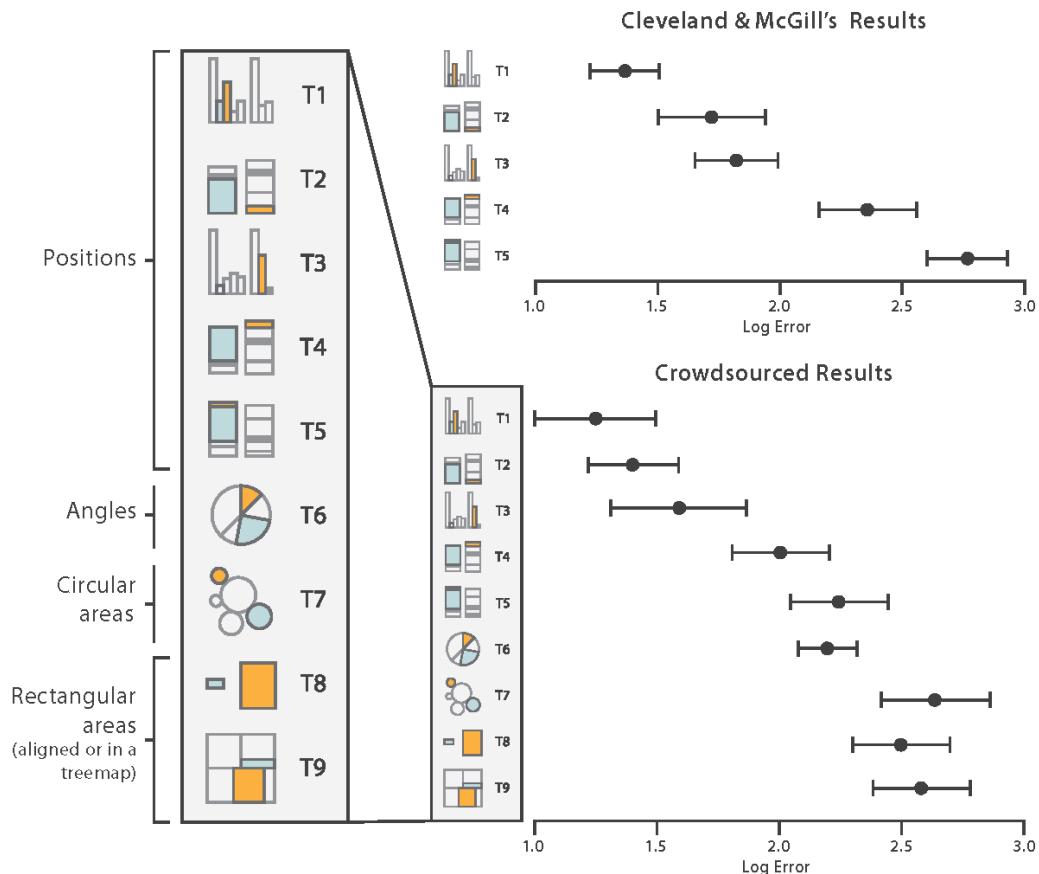


Fig. 5.8 from: Munzner, *Visualization Analysis & Design*

Encodings: Types & ranks

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

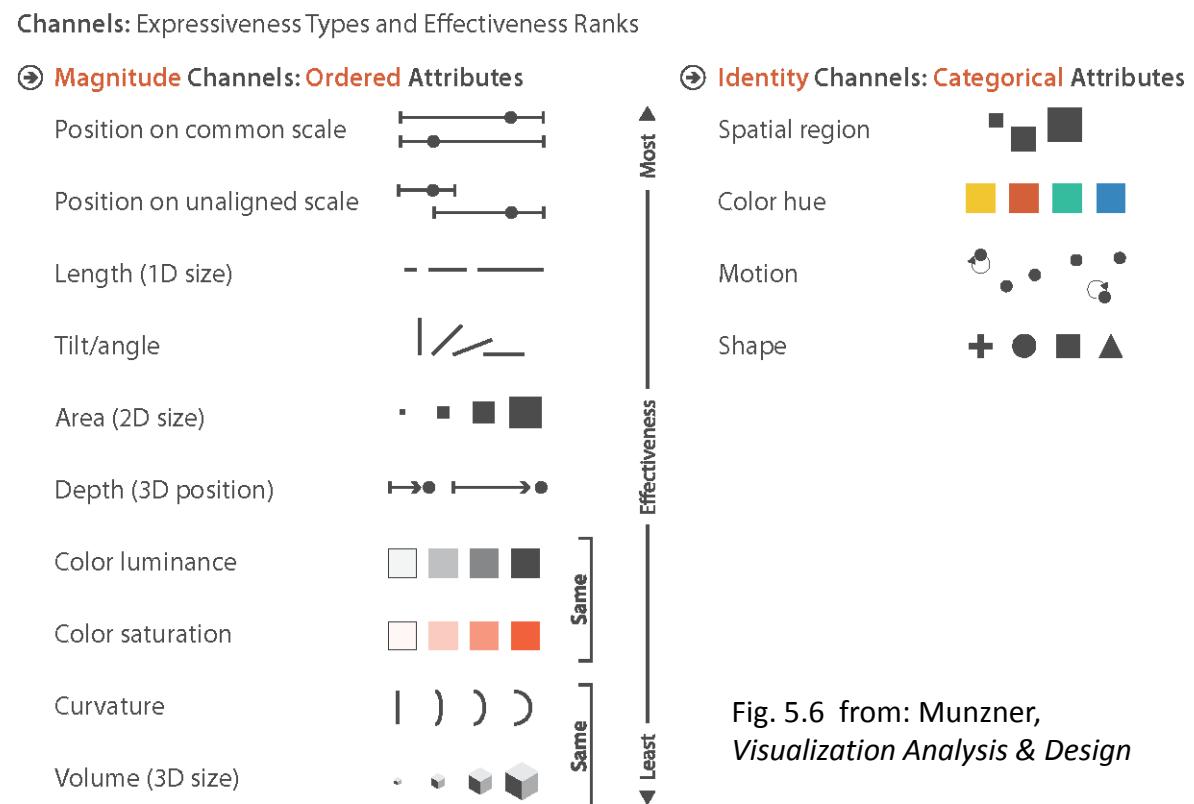


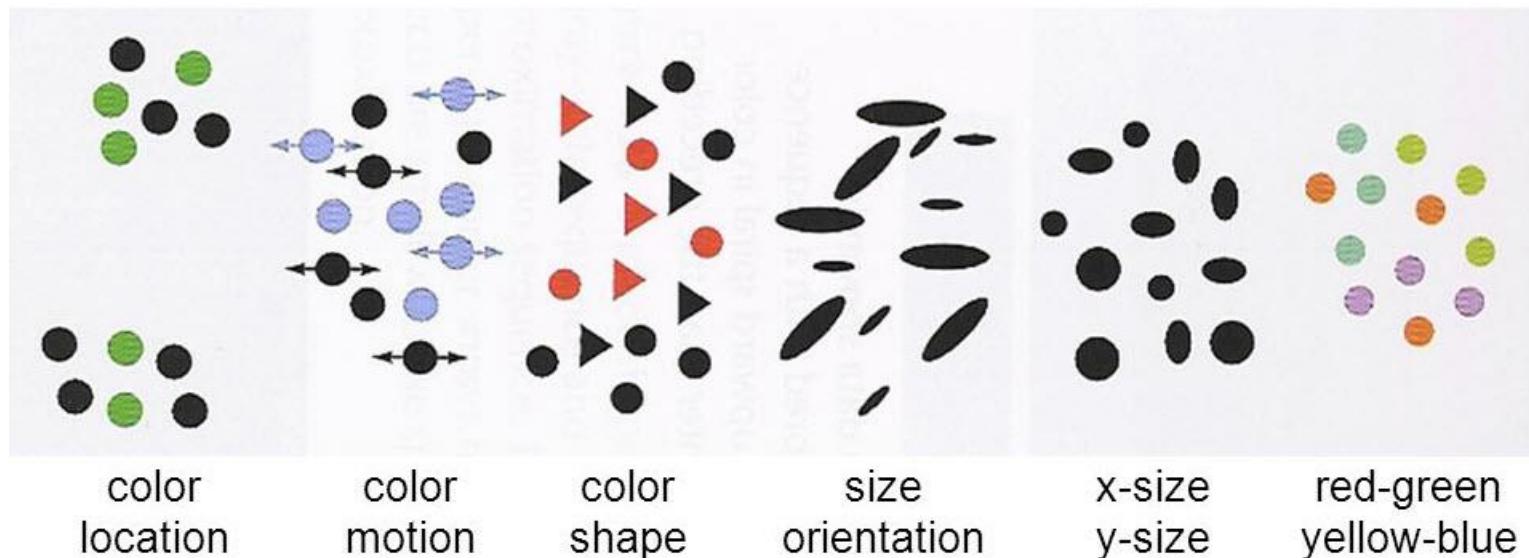
Fig. 5.6 from: Munzner,
Visualization Analysis & Design

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

← Separable

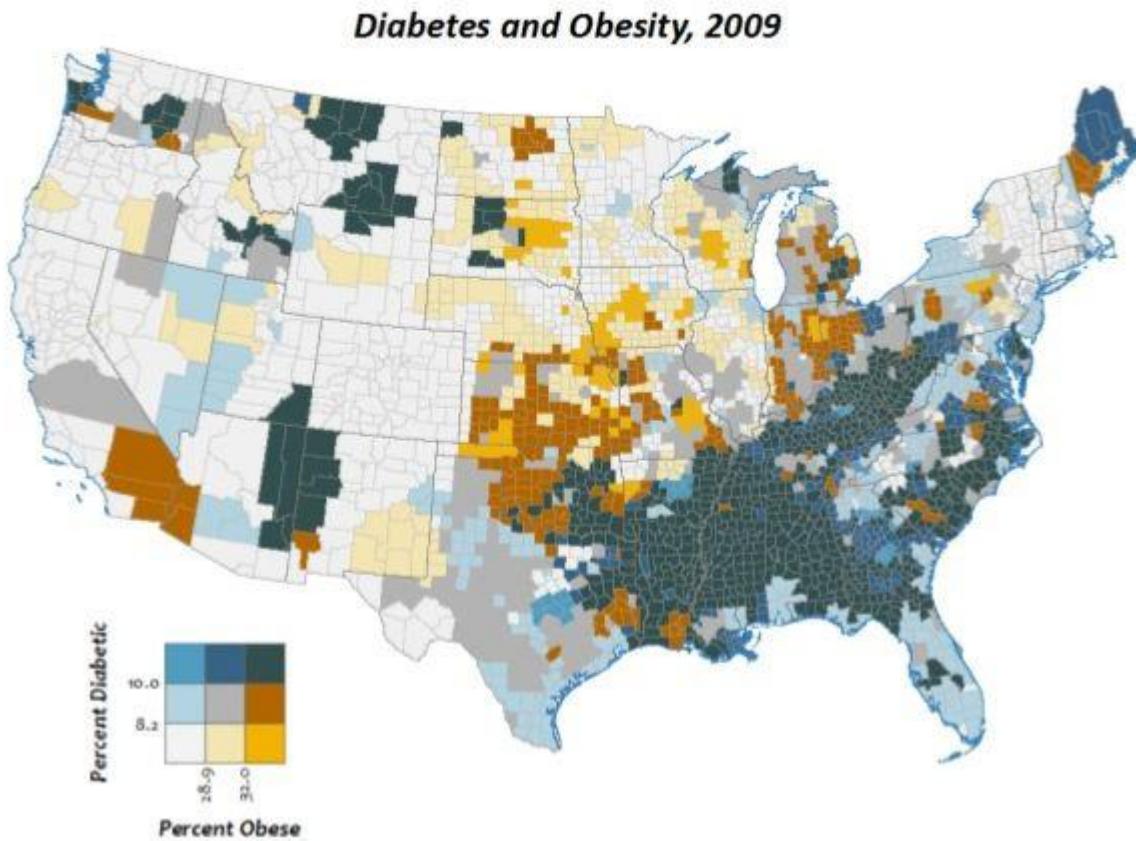
Integral →



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

Integral dimensions

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



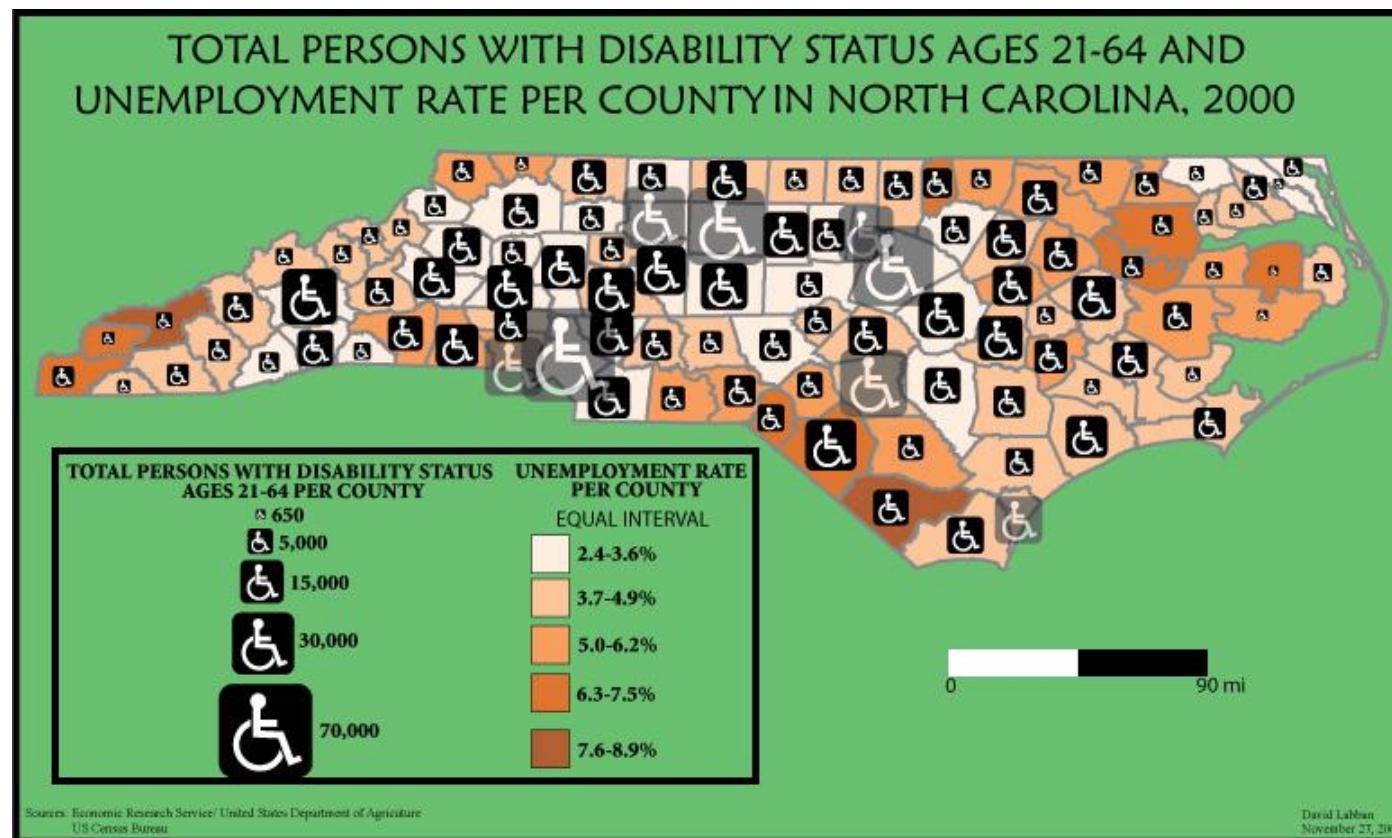
It is difficult to see variations in diabetes separately from obesity

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, TOTAL disability is confounded with population density)



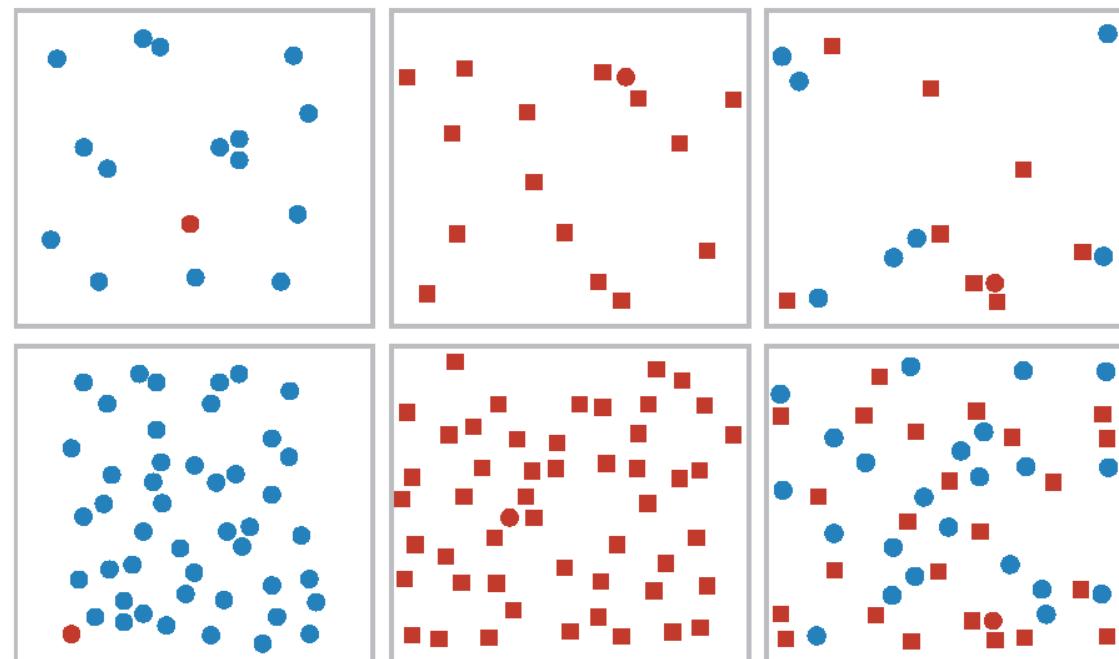
Anomaly detection

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

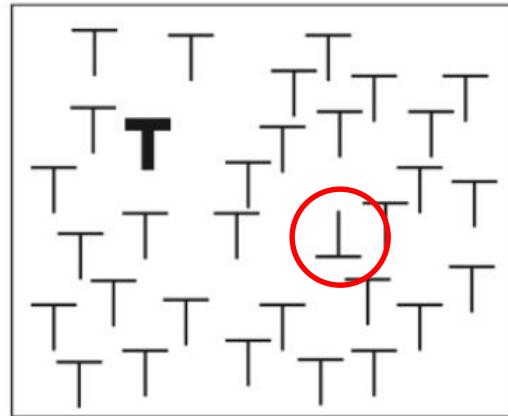
Color and shape: What is easy or hard depends on the background



difficult



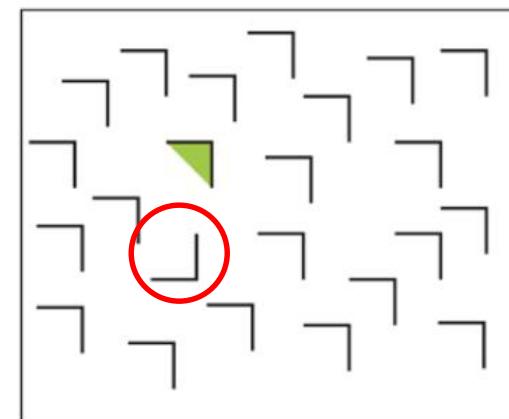
easy



difficult



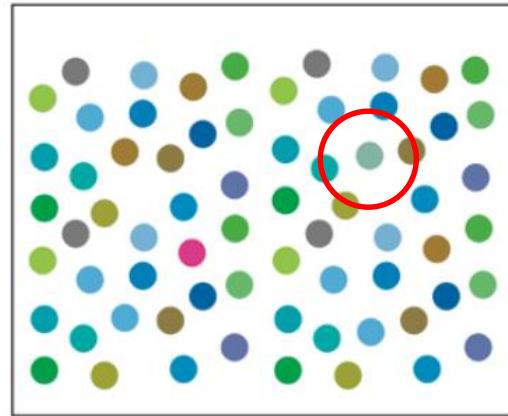
easy



difficult



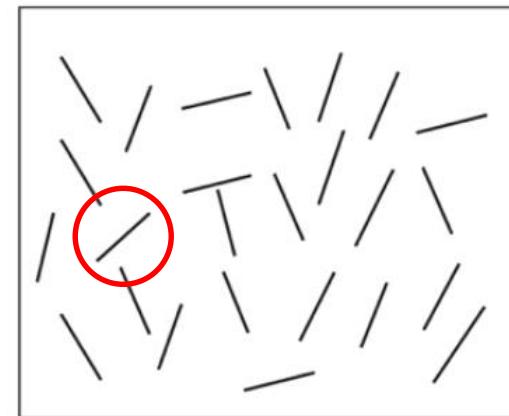
easy



difficult



easy



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

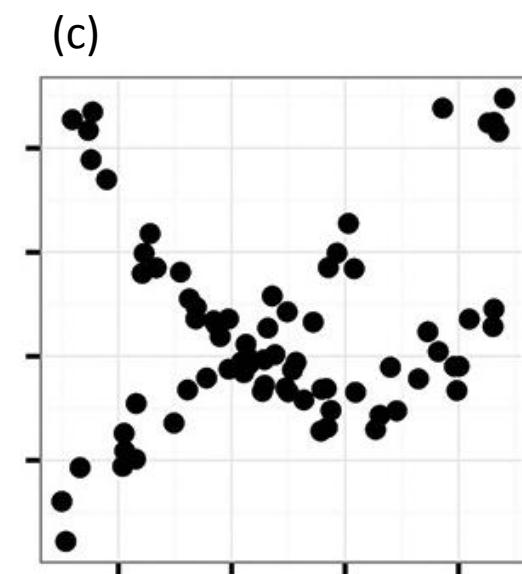
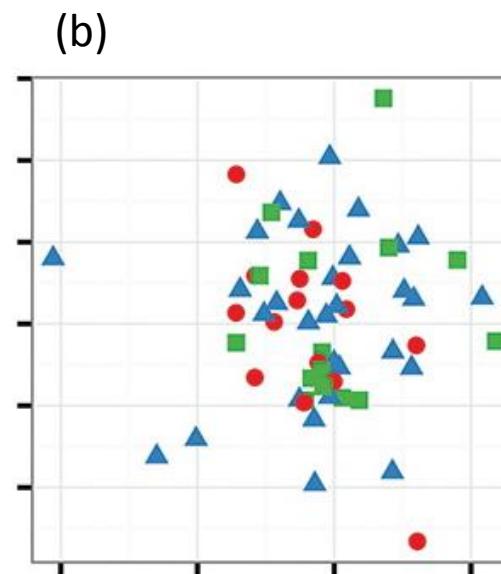
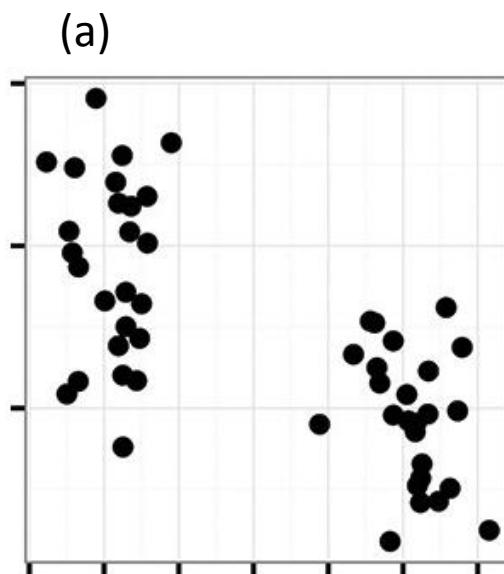
- Best to show quantitative variables with **position or length**
- Bar charts:
 - Best encoding via length → start at 0
 - Avoid stacked bars (not aligned), where possible
- Dot charts:
 - Best encoding via position along a scale → start at 0
- Frequency data:
 - area/color encoding to show patterns
 - 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

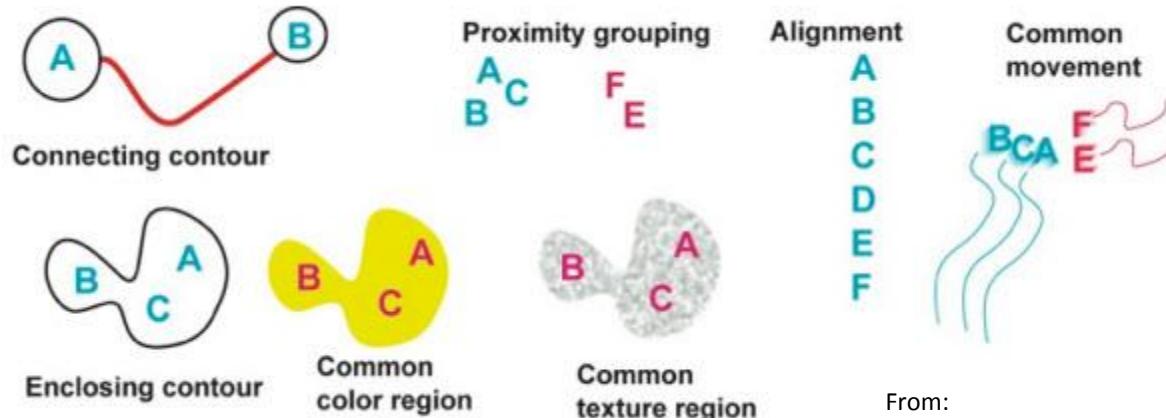
Gestalt principles

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



Gestalt principles

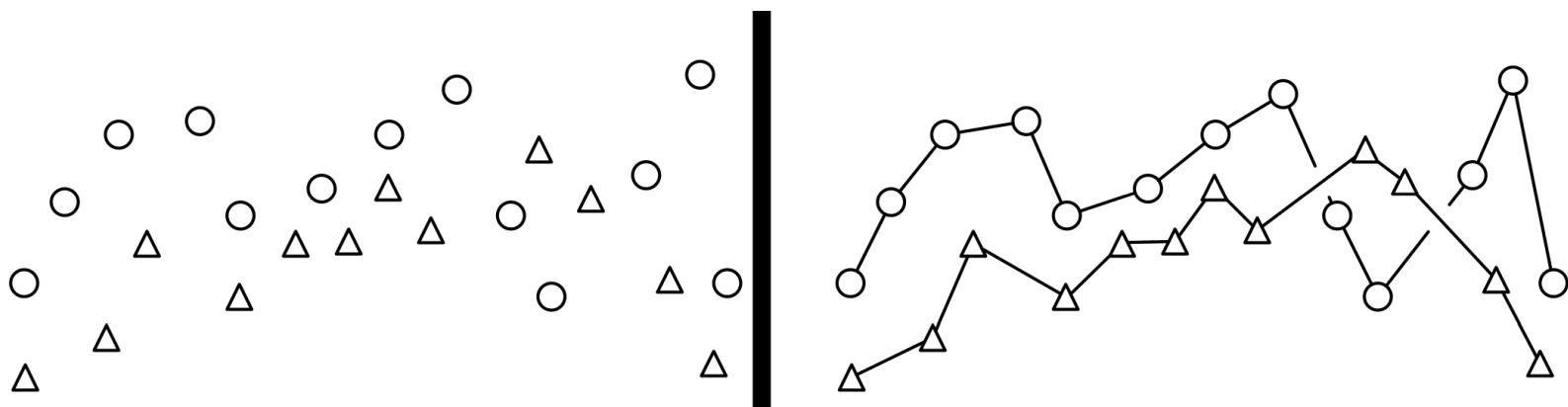
More gestalt ideas



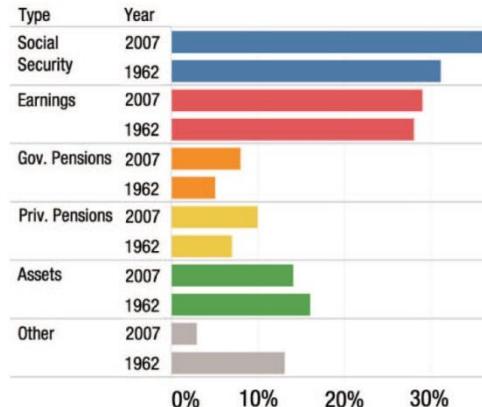
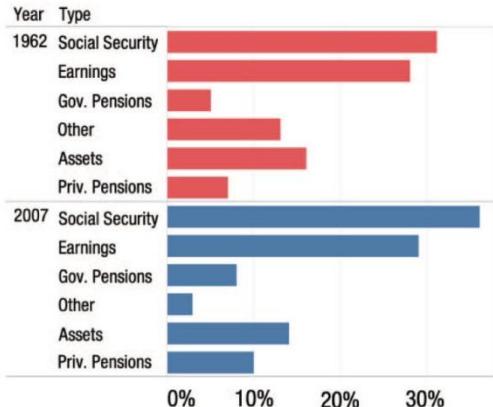
From:

<http://blog.yhwu.me/notes/visualizations/cs171.html>

Why lines are good in time series graphs



Visual grouping & comparisons



combination of color & proximity grouping leads to different visual comparisons across the two bar graphs

shoot ceremony glove speakers
menu diploma tablecloth double play
touch bounce dribble procession
pitcher clap fingers dishes
first base dunk tassel waiter
palm home run batter net
bill

menu	home run
waiter	first base
dishes	double play
tablecloth	pitcher
bill	batter
fingers	bounce
palm	diploma
touch	tassel
clap	net
glove	shoot
	speakers
	dribble
	dunk
	ceremony
	procession

comparisons in a word cloud are weakly controlled by color grouping; more strongly controlled with proximity grouping

From: Franconeri et al (2021) Source DOI: [10.1177/15291006211051956](https://doi.org/10.1177/15291006211051956).

Visual grouping & comparisons

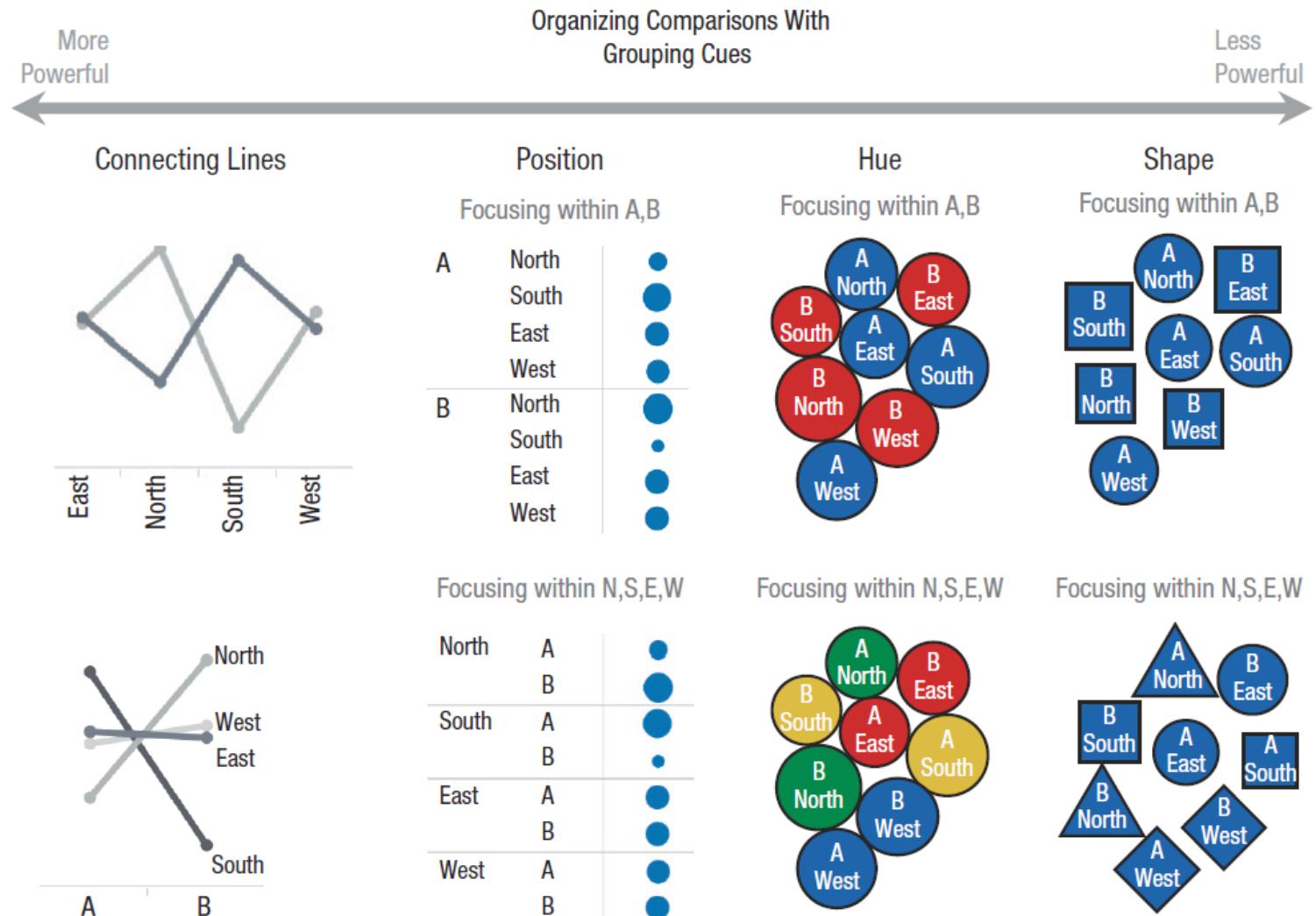
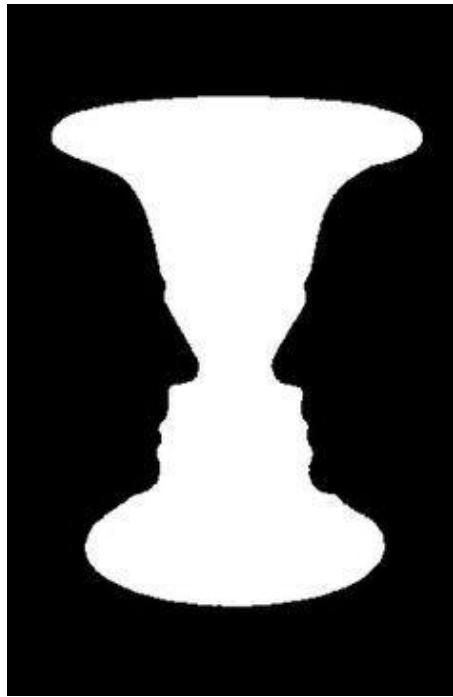


Fig. 8. Several grouping cues that can control how data values are compared. Connecting lines are particularly powerful cues, followed by proximity, color, and shape (Brooks, 2015).

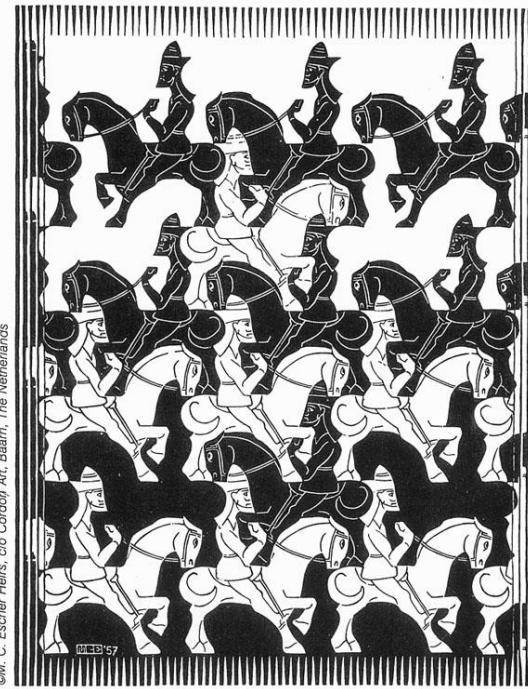
Figure - Ground

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

Ambiguous figures: Priming

Can you see the poodle in this scene?

What about the man?

Semantic priming: Suggestion increases likelihood of perception

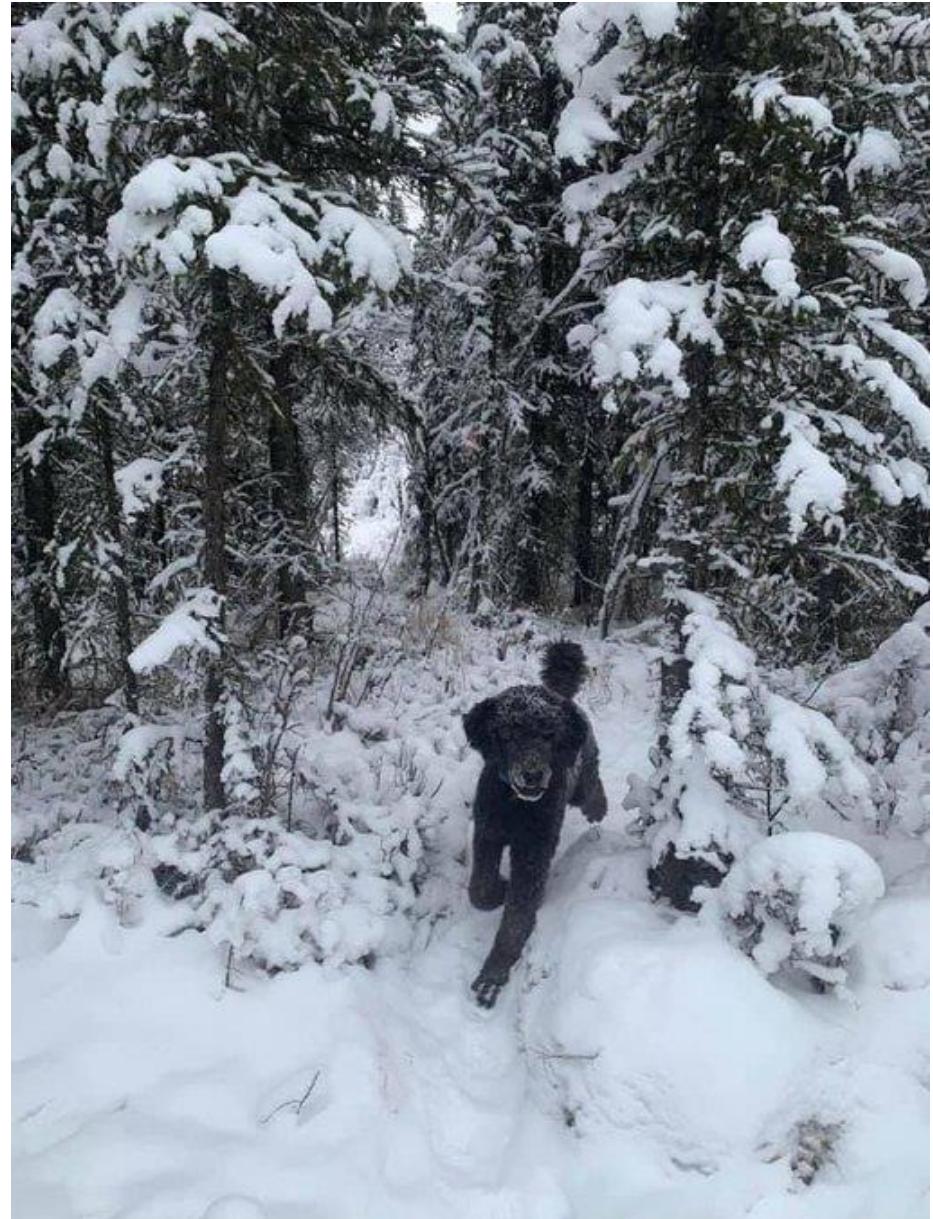
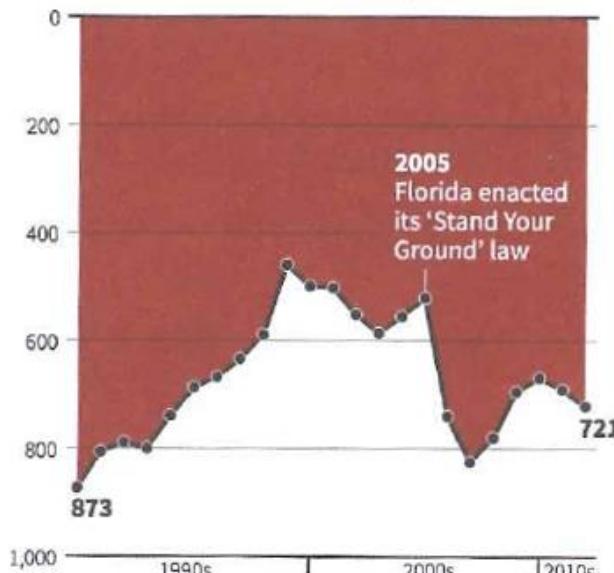


Figure - Ground

This graph inverts the y-axis, and shades the area above the curve

Gun deaths in Florida

Number of murders committed using firearms



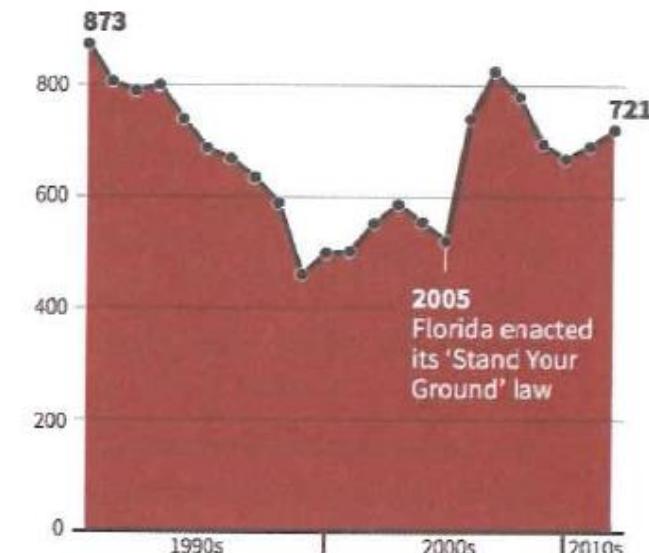
Source: Florida Department of Law Enforcement

REUTERS

A more conventional version of the same graph

Gun deaths in Florida

Number of murders committed using firearms



Source: Florida Department of Law Enforcement

We tend to see 1999 & 2005 as high points

Gun deaths increased after the
'Stand your ground' law

Discussion

What perceptual features or principles are involved in your reading or understanding of these figures?

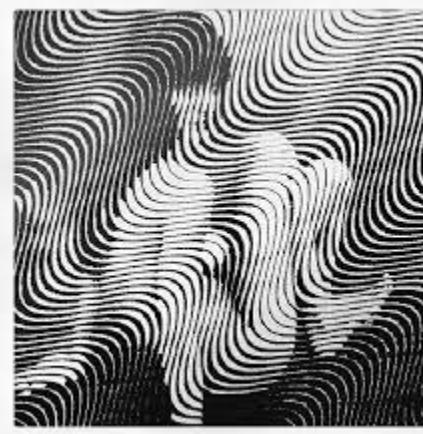
or this?



What about this?



Top-down ?
Bottom-up?
Gestalt?



or this?



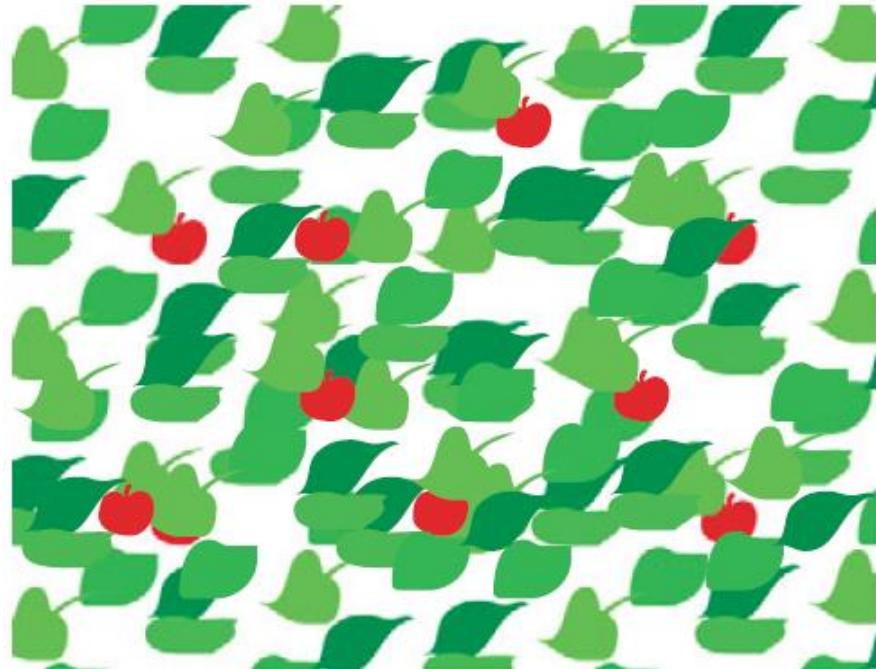
Color: Functions in data graphics

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



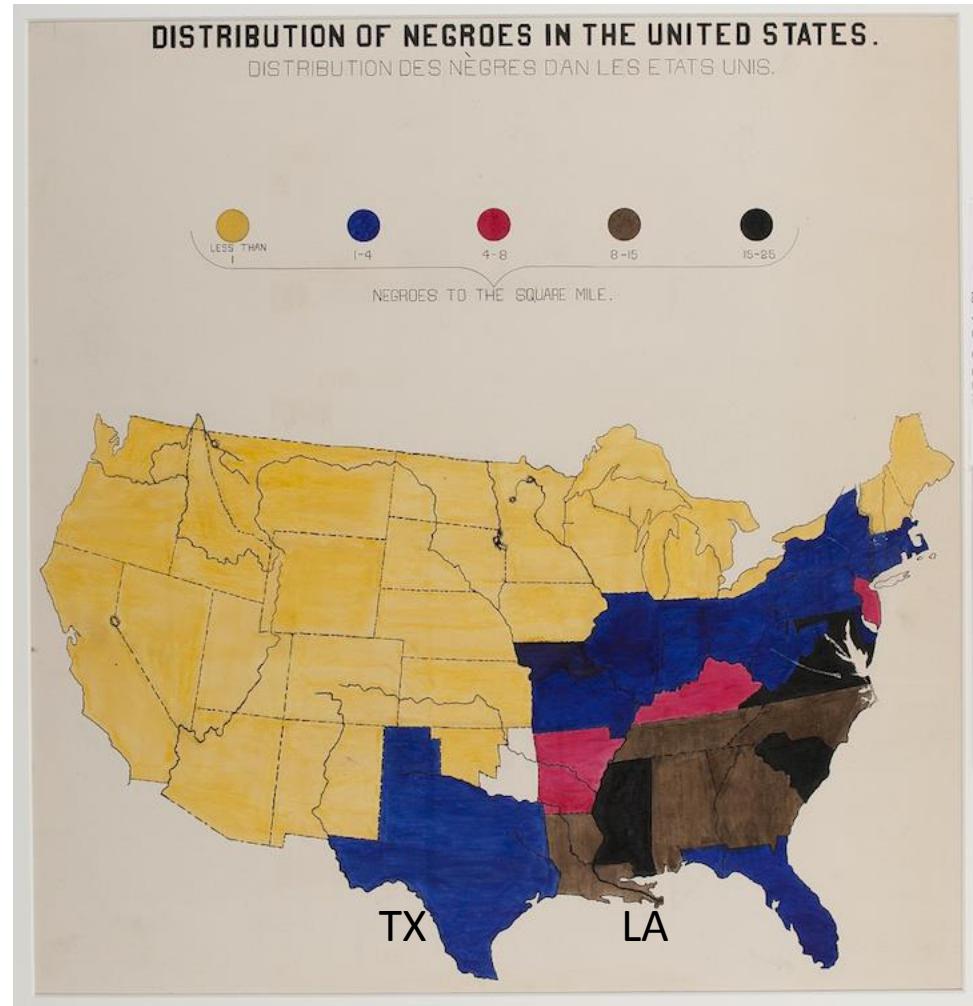
From: Colin Ware, *Information Visualization: Perception for Design*

Nice graphic, naïve about color

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.

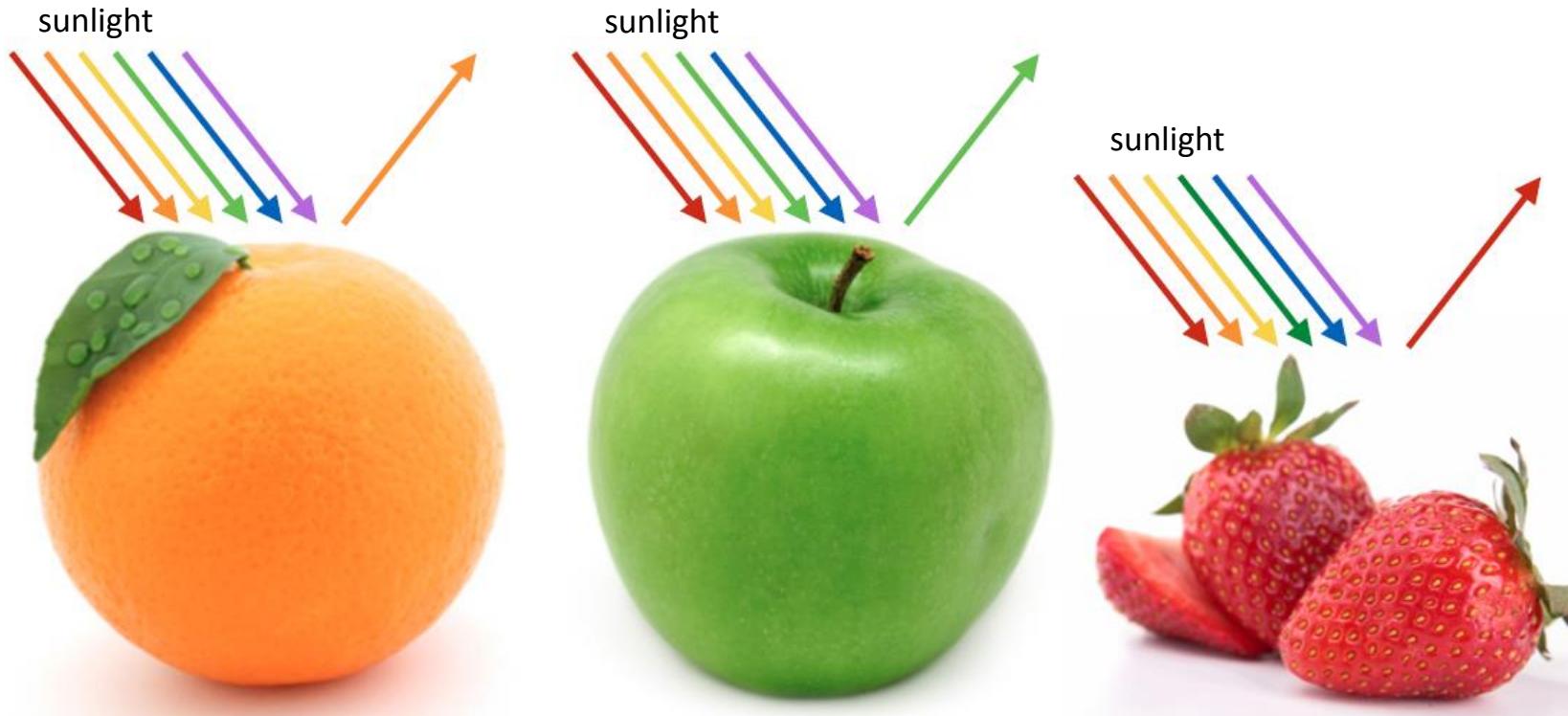
Q: Are there more Negroes per sq. mile in Texas (TX) or Louisiana (LA)?



Object color

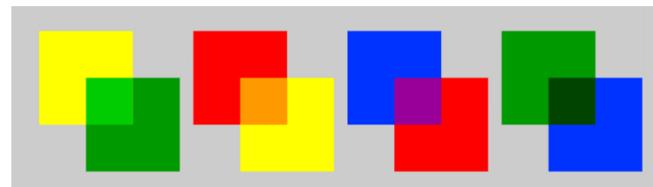
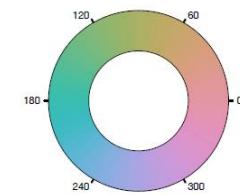
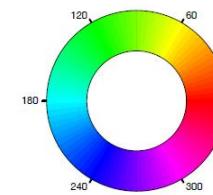
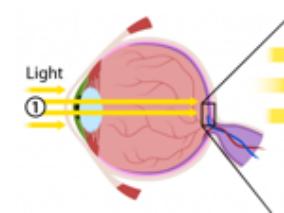
What makes an orange look **orange**, a green apple look **green**, or a strawberry **red**?

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



Color: Aspects in data graphics

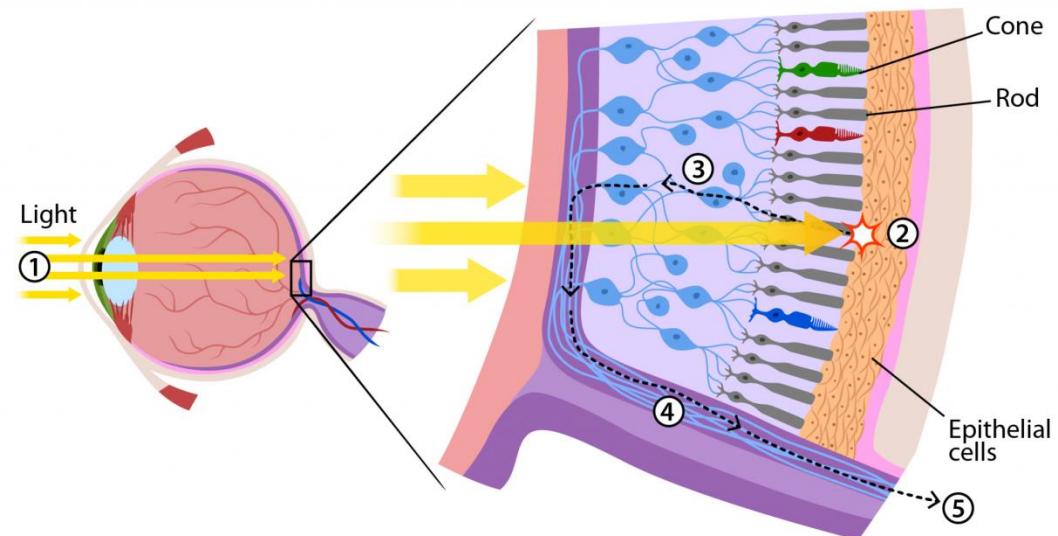
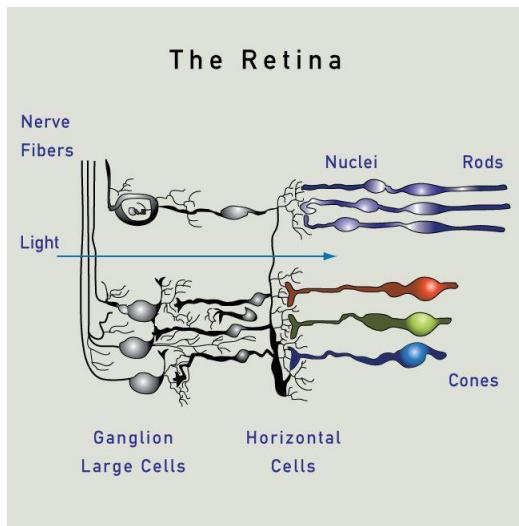
- Perception: trichromatic theory
 - How the eye sees color
- Color spaces:
 - RGB (additive), CMYK (subtractive)
 - HSV, HCL: perceptually based
- Color palettes for computer graphics
 - ColorBrewer: sequential, diverging, qualitative
 - Color-blind safe ?
 - Photocopy safe ?
- Transparency



Perception: The human eye

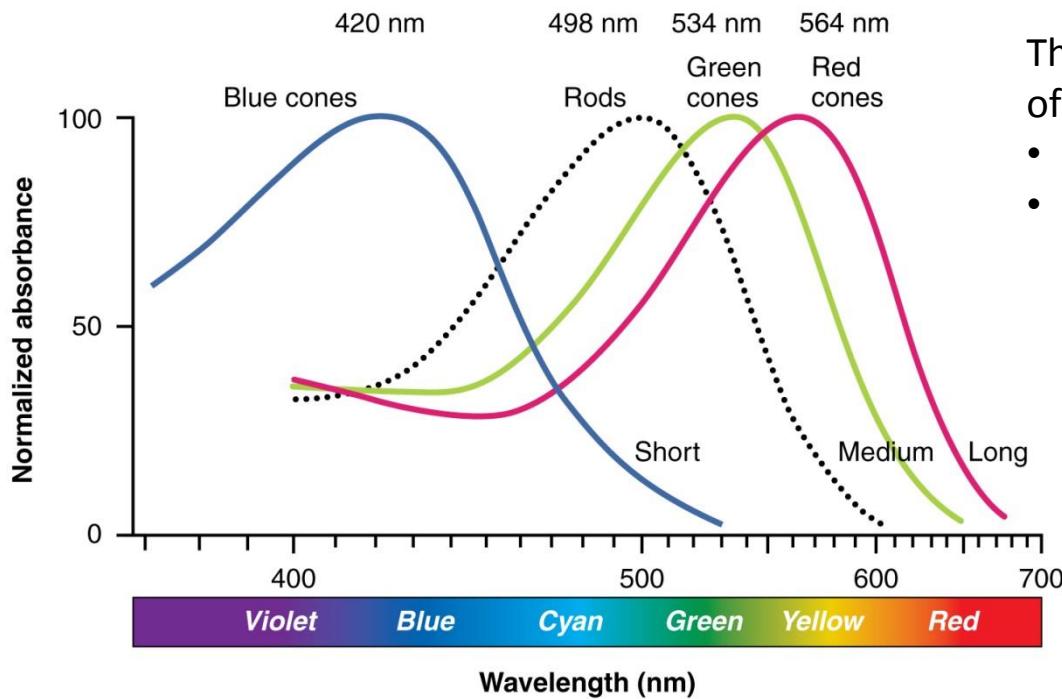
- Retina:
 - rods (monochromatic),
 - cones (R, G, B)

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** or Rods



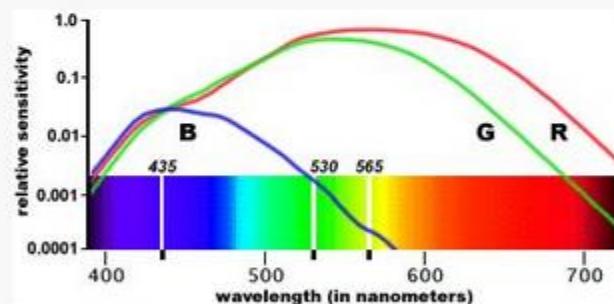
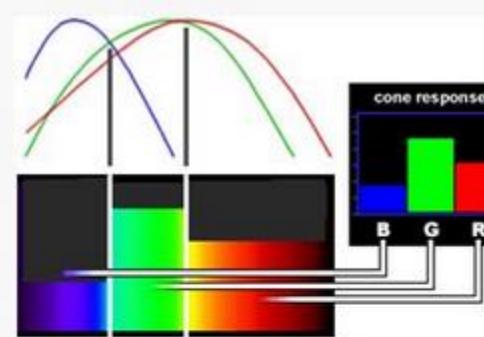
This figure also stimulates questions of scientific visualization

- Rods & cones are “normalized”
- Are they all equal in what we see?

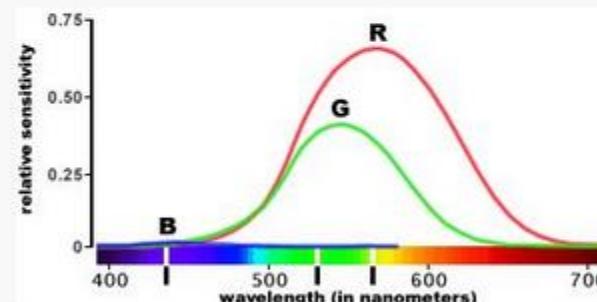
Perception: color sensitivity

This slide, from <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

Perception: Contrast

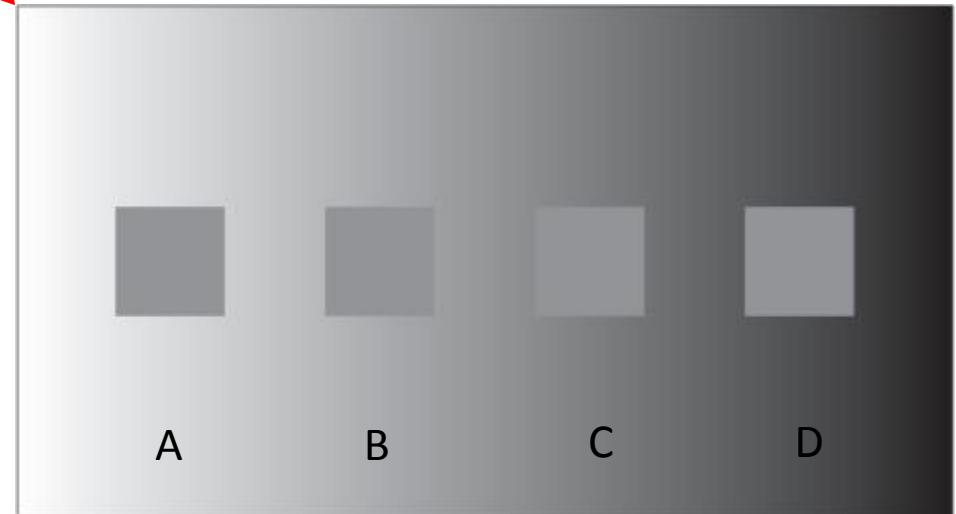
Color perception, even of gray, is influenced by **contrast** against a background

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

gray
square



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



Most people say **A**, because it is shown on a light 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)

Brightness illusion

Is the white at the center the **same** brightness as the white at the edges?
Or, is it **brighter**?

They are the **same**. We interpret the center as a source of light relative to the surrounding bright yellow.



The illusion also affects pupil size! <https://www.pnas.org/content/109/6/2162>

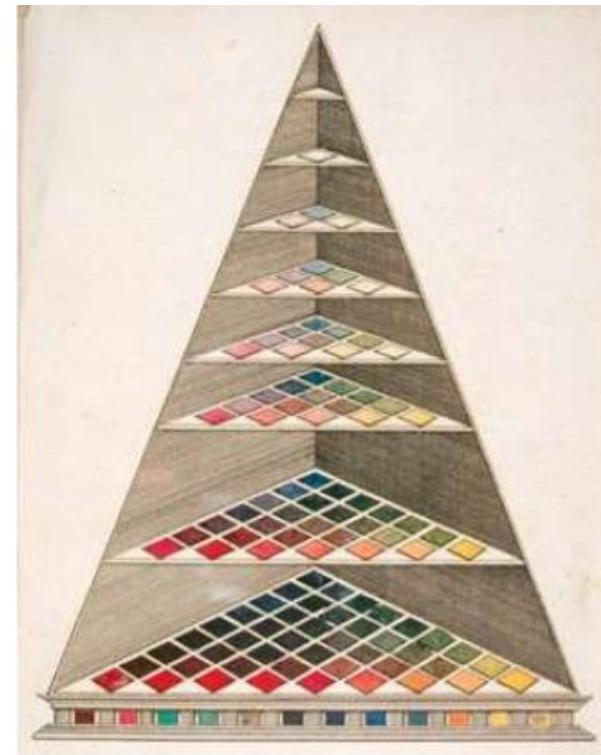
Early color theory

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



Introduces the idea of color “primaries”

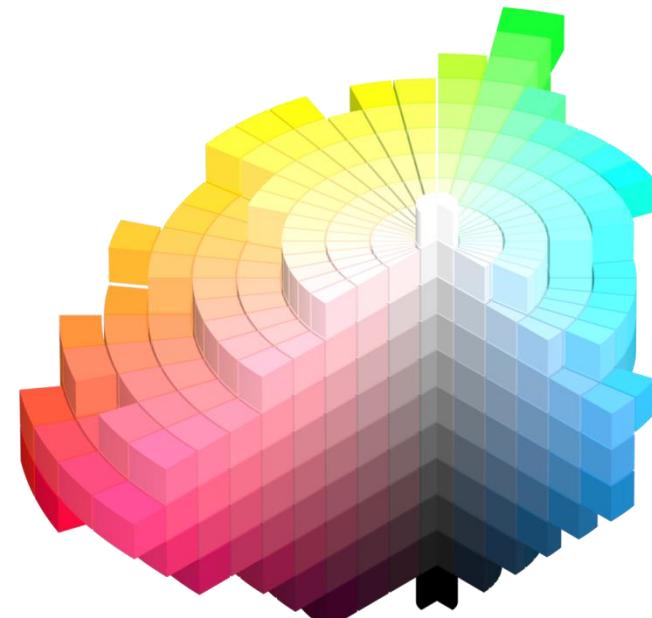
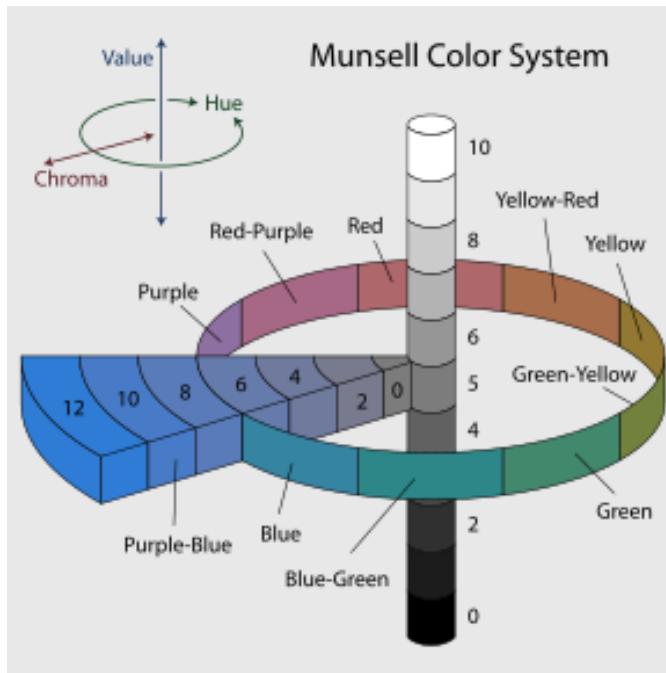
Johannes Lambert (1772) – A color pyramid, composed of 7 layers



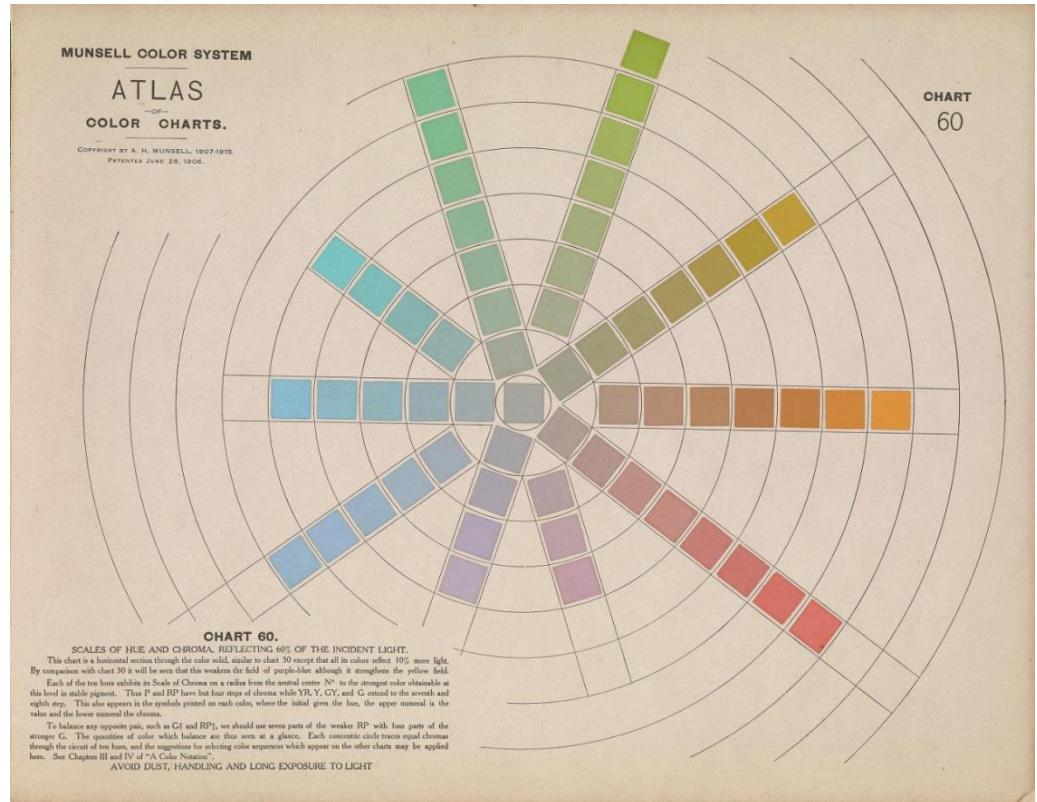
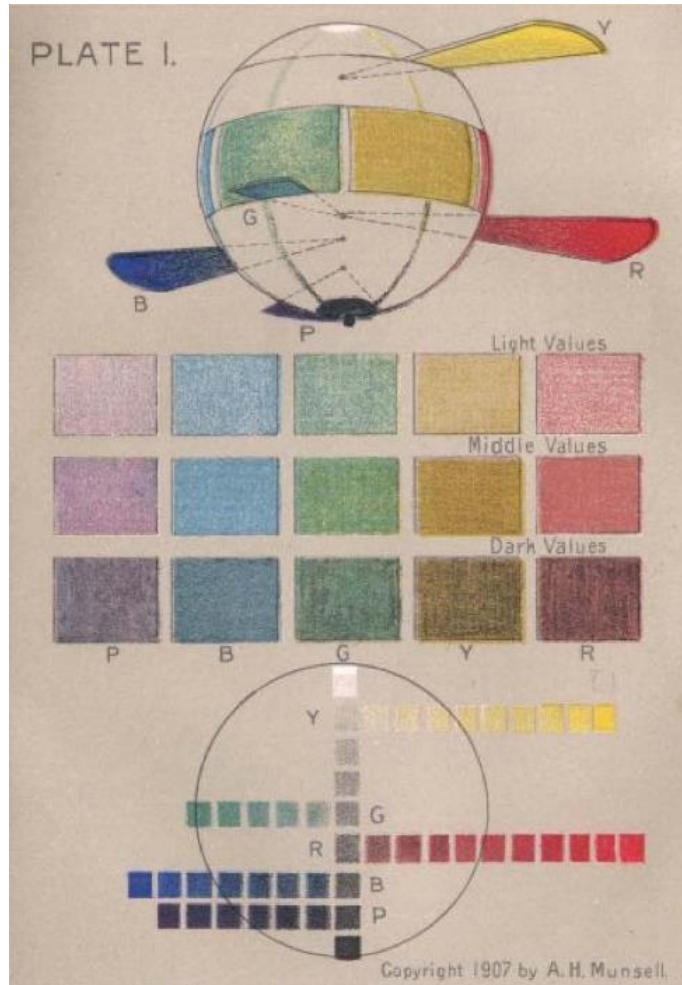
Introduces the idea of color saturation

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



Munsell's color scheme was highly influential in Psychology research
 Nearly every lab investigating color used standard sets of Munsell color chips

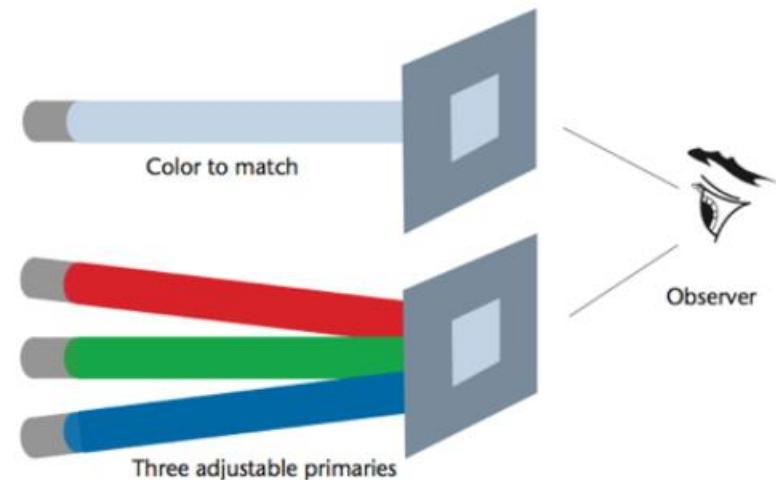


CIE color space

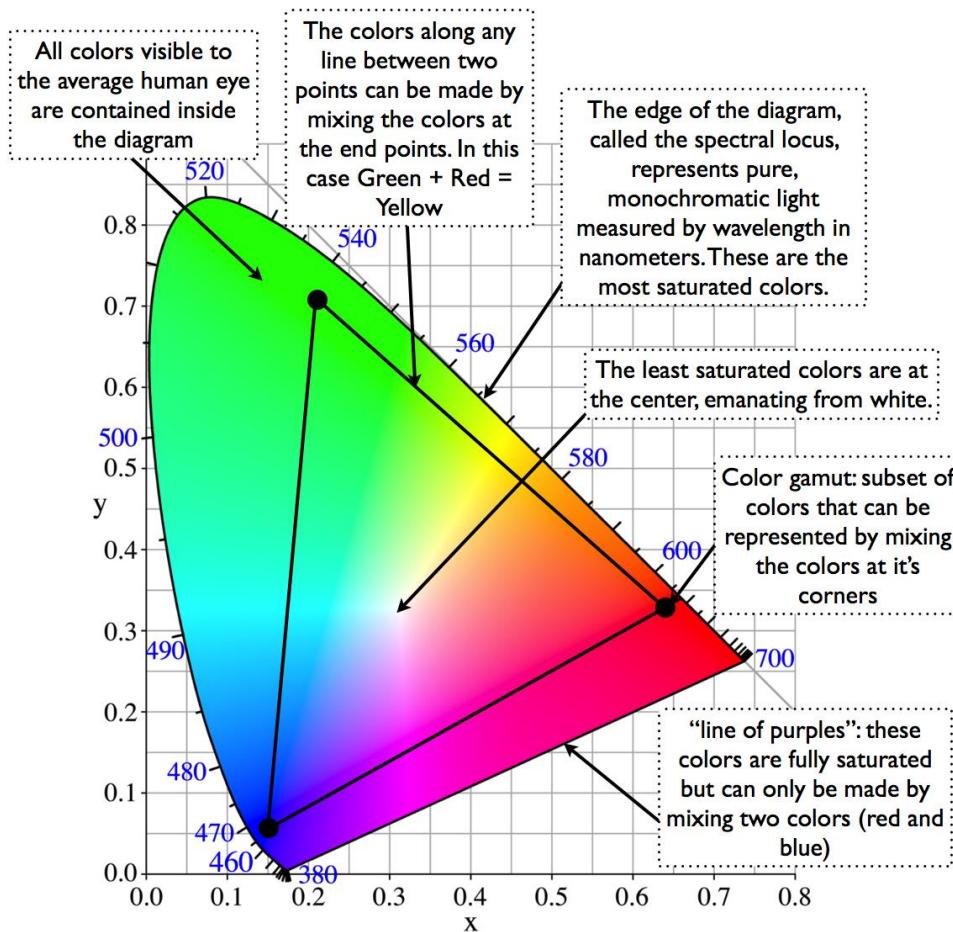
- How do we know about the **perceptual** properties of colors, taking spectral sensitivity into account?

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



CIE color space



Anatomy of a CIE Chromaticity Diagram

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.

Color space: RGB & CMYK

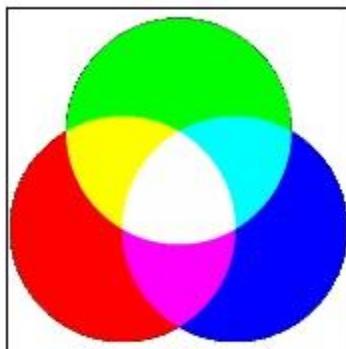
Enter technology: how to produce color?

- 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



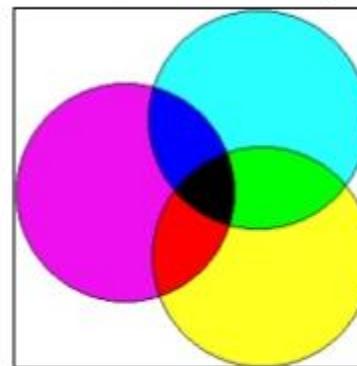
Caution: R, SAS, SPSS use RGB by default

Additive colour system



Mixture of primary light colours-
White

Subtractive Colour System



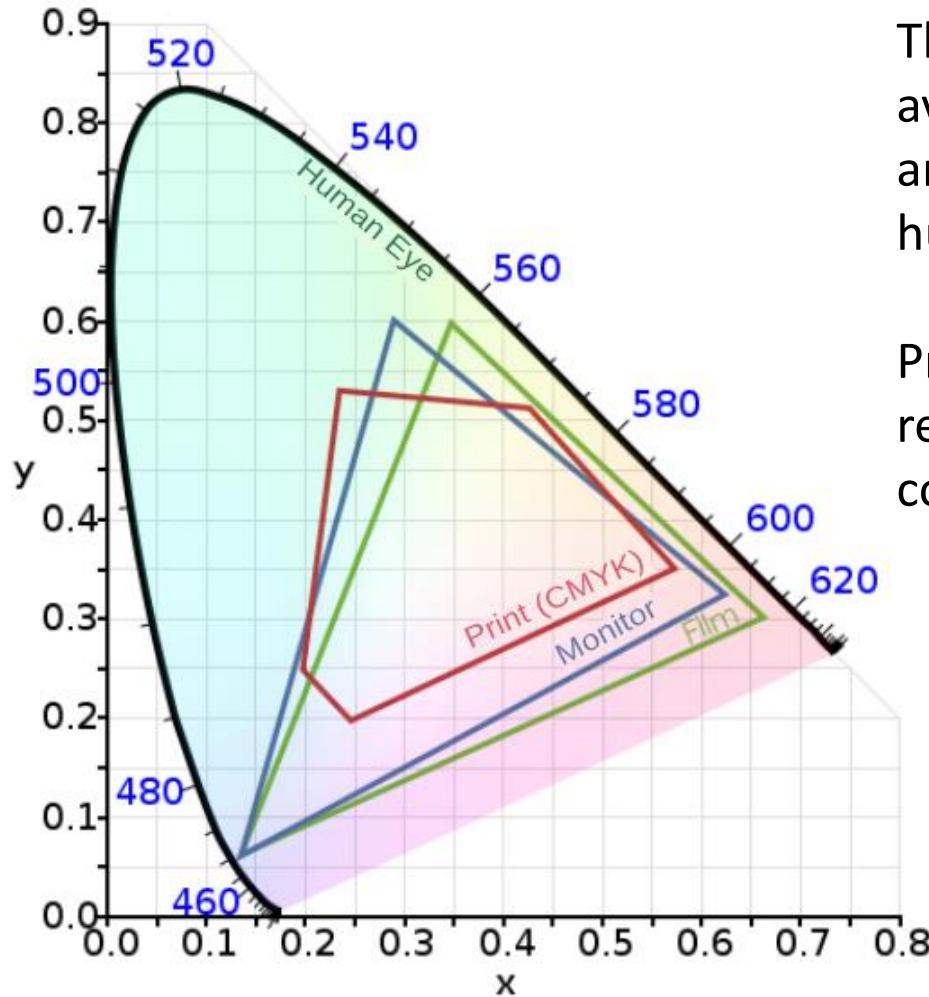
Mixture of primary pigment colours
Black

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

Color space: RGB & CMYK



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



Always check the display on different media.

Software: Color specification

- 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"

18	beige	#F5F5DC	245	245	220
19	bisque	#FFE4C4	255	228	196
20	bisque1	#FFE4C4	255	228	196
21	bisque2	#EED5B7	238	213	183
22	bisque3	#CDB79E	205	193	159
23	bisque4	#8B7D6B	139	125	107
24	black	#000000	0	0	0
25	blanchedalmond	#FFEBCD	255	235	205

68	cyan	#00FFFF	0	255	255
69	cyan1	#00FFFF	0	255	255
70	cyan2	#00EEEE	0	238	238
71	cyan3	#00CDCD	0	205	205
72	cyan4	#008B8B	0	139	139
73	darkblue	#00008B	0	0	139
74	darkcyan	#008B8B	0	139	139
75	darkgoldenrod	#B8860B	184	134	11

26	blue	#0000FF	0	0	255
27	blue1	#0000FF	0	0	255
28	blue2	#0000EE	0	0	238
29	blue3	#0000CD	0	0	205
30	blue4	#00008B	0	0	139
31	blueviolet	#8A2BE2	138	43	226
32	brown	#A52A2A	165	42	42

76	darkgoldenrod1	#FFB90F	255	195	15
77	darkgoldenrod2	#E9A0E	238	173	14
78	darkgoldenrod3	#CD950C	205	149	12
79	darkgoldenrod4	#8B650B	139	101	8
80	darkgray	#A9A9A9	169	169	169
81	darkgreen	#006400	0	100	0
82	darkgrey	#A9A9A9	169	169	169

Software: Color specification

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



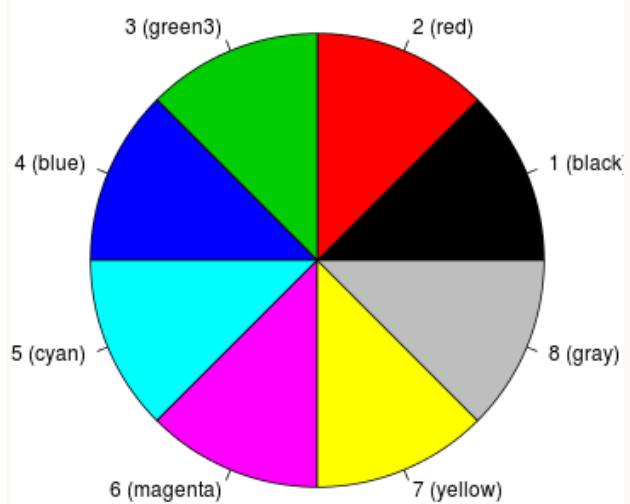
*Every time you are
forced to say
"#008B8B" or "cyan4"
a puppy dies
somewhere*

-- MF, 2018

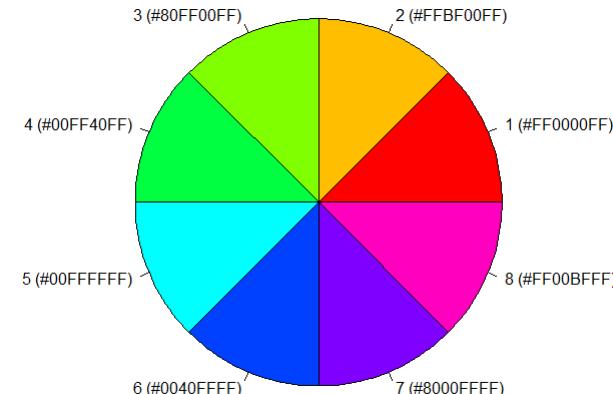
Software: palettes

- 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

```
> (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)
```



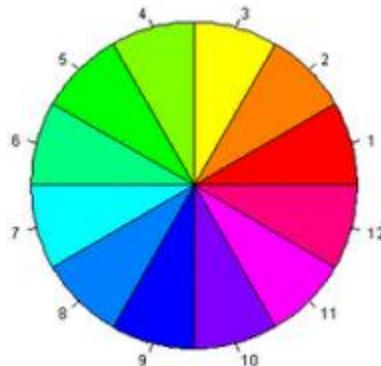
palette(rainbow(8)); pie(...)



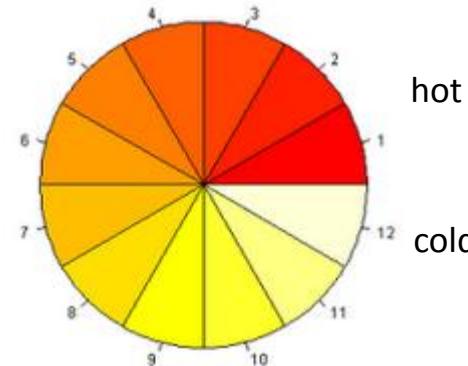
R: basic palettes

`n <- 12`

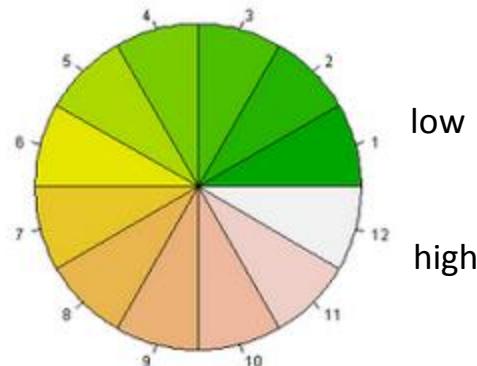
`pie(rep(1, n), col=rainbow(n))`



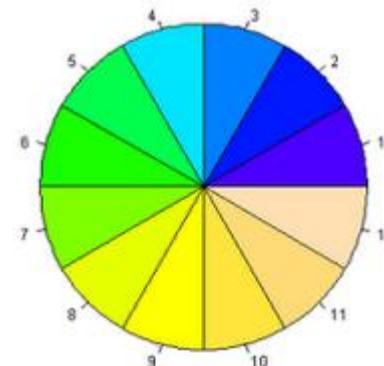
`pie(rep(1, n), col=heat.colors(n))`



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

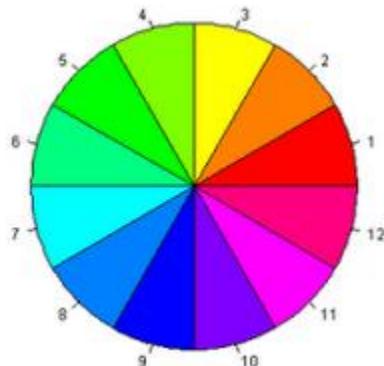


`pie(rep(1, n), col=topo.colors(n))`

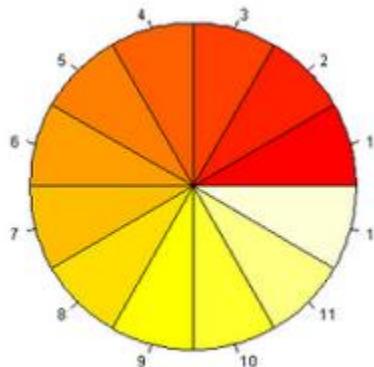


R: basic palettes

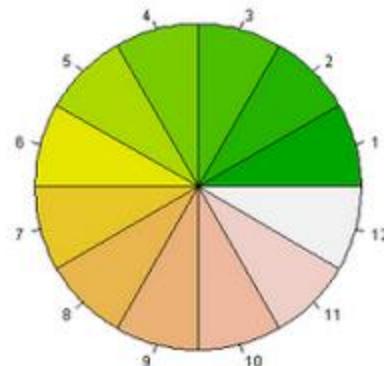
rainbow



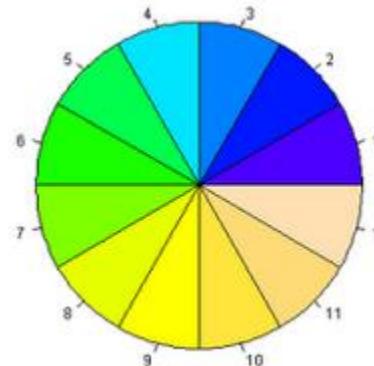
heat



terrain



topo



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**

palettes: ColorBrewer

ColorBrewer, by Cynthia Brewer provides an interactive application for choosing color palettes, <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

The screenshot shows the ColorBrewer 2.0 interface. On the left, there is a sidebar with various settings:

- variable type:** A red arrow points to the "sequential" radio button.
- choose different versions of the scheme:** A red arrow points to the color palette preview area, which shows two rows of four color schemes each.
- export color specs to HEX, RGB, CMYK:** A red arrow points to the "EXPORT" section, which includes dropdown menus for "HEX", "RGB", and "CMYK". Below these are color swatches and their corresponding hex codes: #edf8fb, #b2e2e2, #66c2a4, and #238b45.

The main right side of the interface displays a map of the United States where states are colored according to a sequential color scheme. The colors transition from light blue/turquoise in the West and Northeast to dark green in the South and Midwest. The map is overlaid with state boundaries and some internal county boundaries.

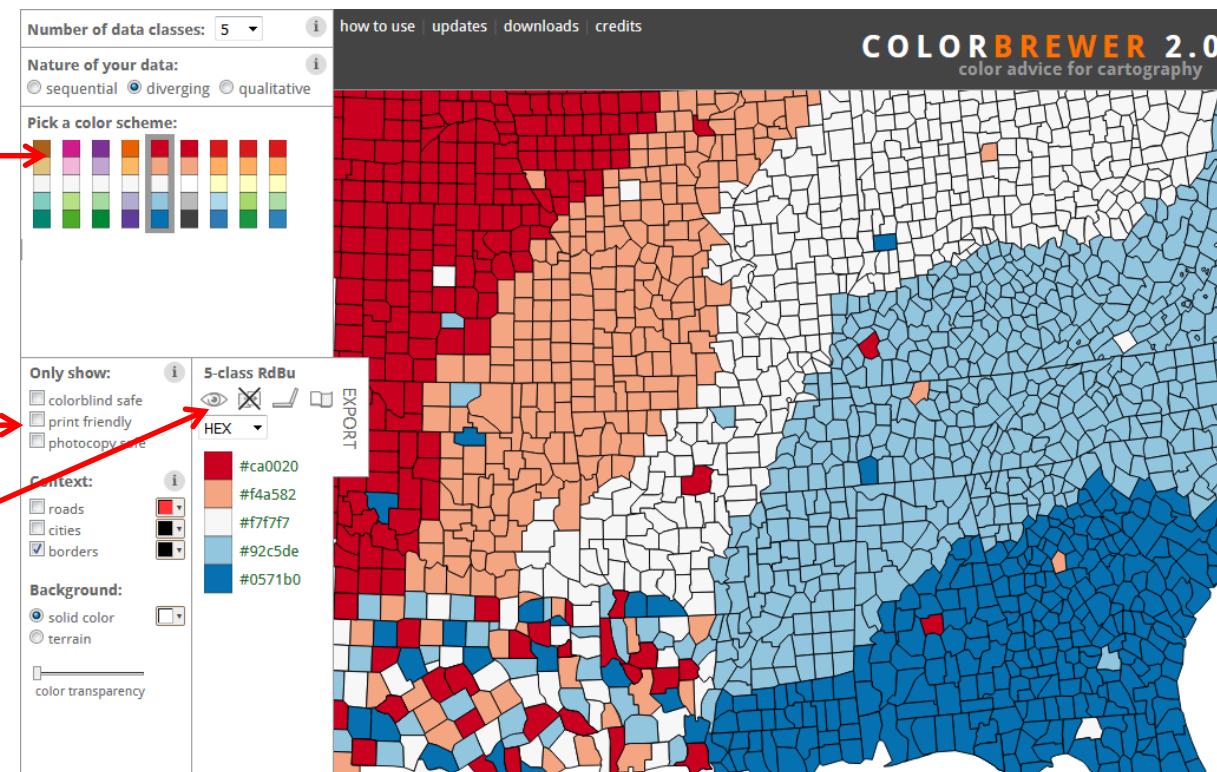
This example: <http://colorbrewer2.org/#type=sequential&scheme=BuGn&n=4>

palettes: ColorBrewer

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, ...

there are different schemes within this rubric

there are tools to filter for colorblind, print & B/W
Warnings when not friendly

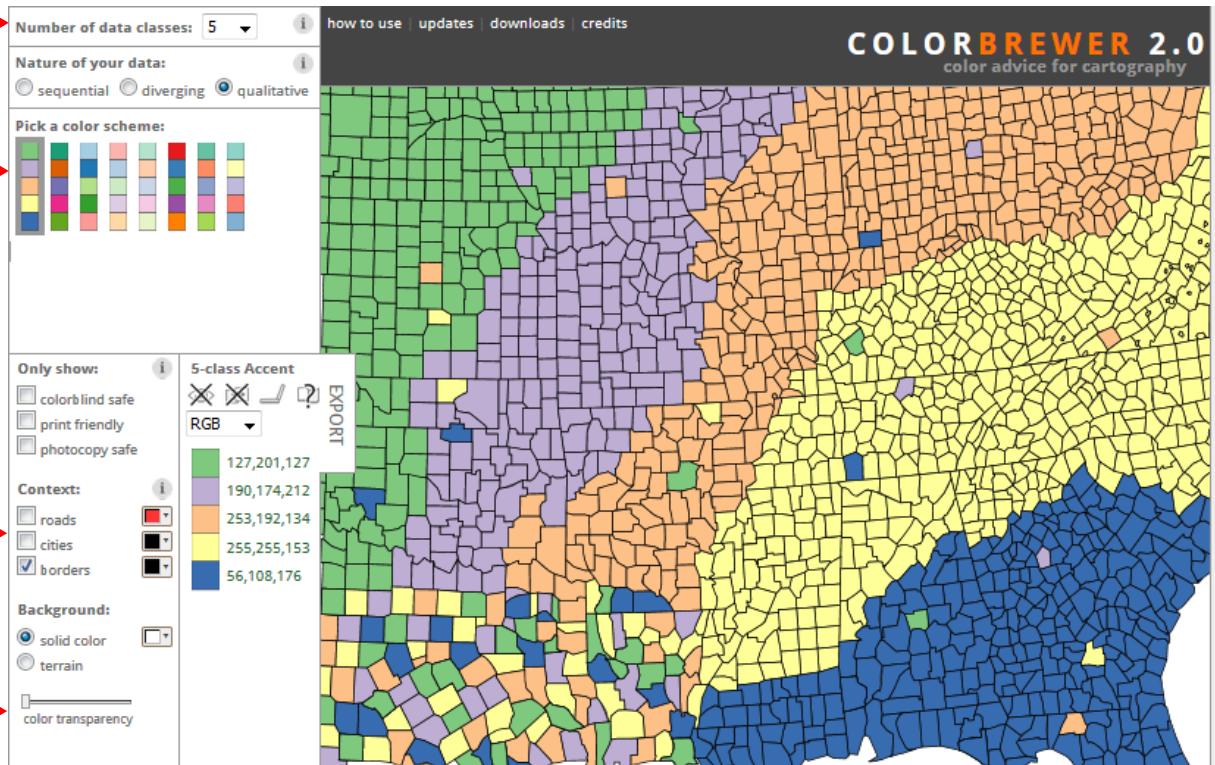


This example: <http://colorbrewer2.org/#type=diverging&scheme=RdBu&n=5>

palettes: ColorBrewer

Qualitative schemes are designed to show a categorical variable, where we want to see differences among unordered categories

choose # classes



Number of data classes: 5
Nature of your data:
 sequential diverging qualitative
Pick a color scheme:
Only show:
 colorblind safe
 print friendly
 photocopy safe
Context:
 roads
 cities
 borders
Background:
 solid color
 terrain
color transparency

5-class Accent
RGB
127,201,127
190,174,212
253,192,134
255,255,153
56,108,176

see other context



add transparency



These are all available in the RColorBrewer package

This example: <http://colorbrewer2.org/#type=qualitative&scheme=Accent&n=5>

palettes: RColorBrewer

```
RColorBrewer::display.brewer.all()
```

sequential



qualitative



diverging



R: choose_palette()

The colorspace package in R has an interactive palette widget.

It also provides functions for many kinds of color manipulations.

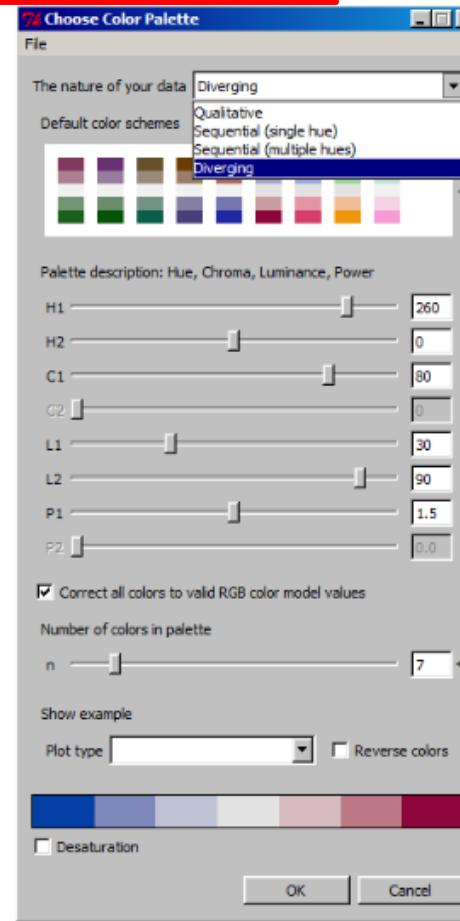
The R Color cheatsheet, by Malcolm Fraser is a goto source for all aspects of color in R:

<https://www.nceas.ucsb.edu/~frazier/RSpatialGuides/colorPaletteCheatsheet.pdf>

R color cheatsheet

Overview of colorspace palette selector

```
library("colorspace")
pal <- choose_palette()
```

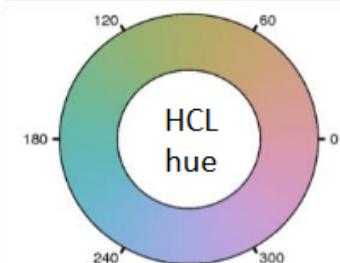


Select the type of color scheme based on the type of data

Default color schemes – can be used “as is” or as a starting point for modification

Interactively select:

- hue: color
- chroma: low chroma = gray
- luminance: high luminance = pastel
- power: how the color changes along a gradient



Select # of colors in palette

Save palette for future R sessions:
• txt file with hex codes
• .R file with a function describing how to generate the palette.
`source` can be used to import the

Viridis palettes

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

Goals:

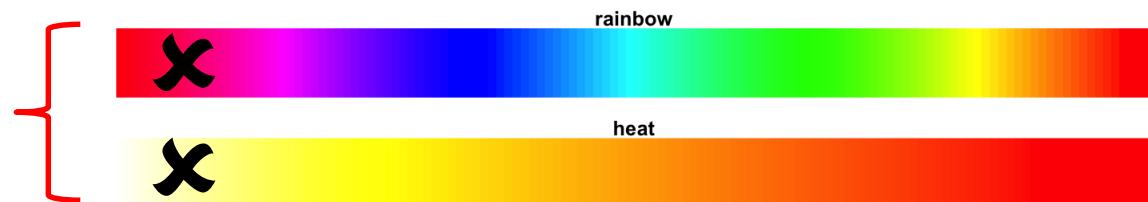
- **Colorful**, spanning as wide a palette as possible so as to make differences easy to see
- **Perceptually uniform**: values close to each other have similar-appearing colors and values far away from each other have more different-appearing colors
- **Robust to colorblindness**: these properties hold 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



ggplot default palette



ColorBrewer palettes



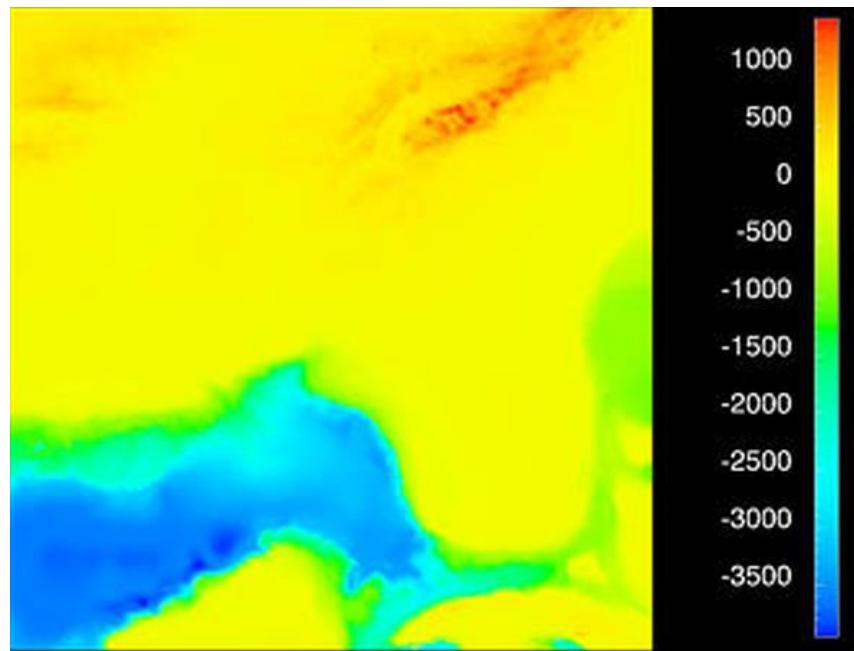
viridis palettes



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

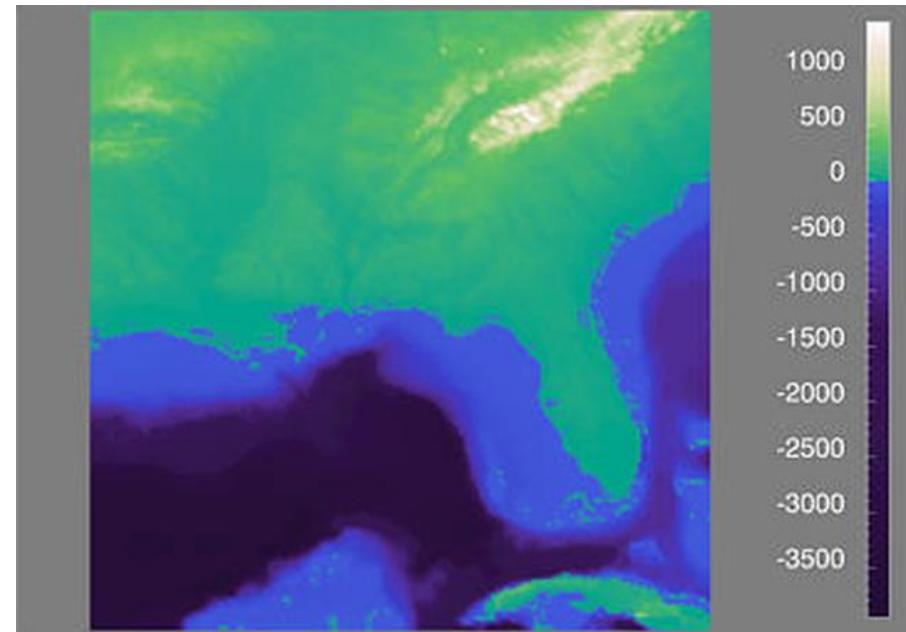
Comparing palettes

What is shown in this map?



The rainbow color scale obscures the main features

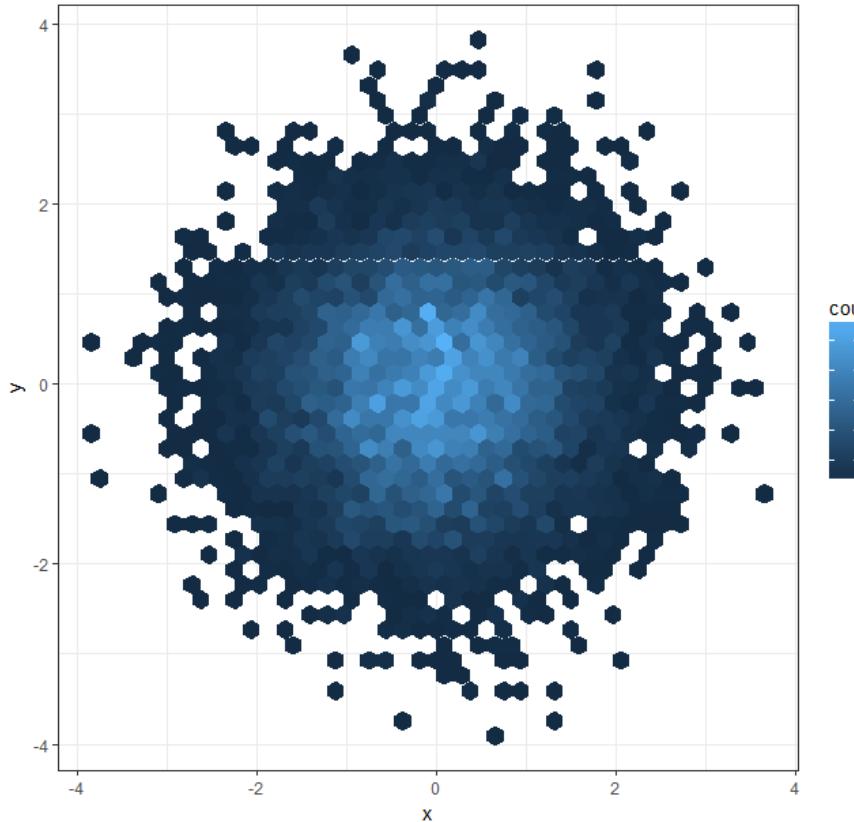
Now we can see it—elevation in the Florida coast: above or below 0



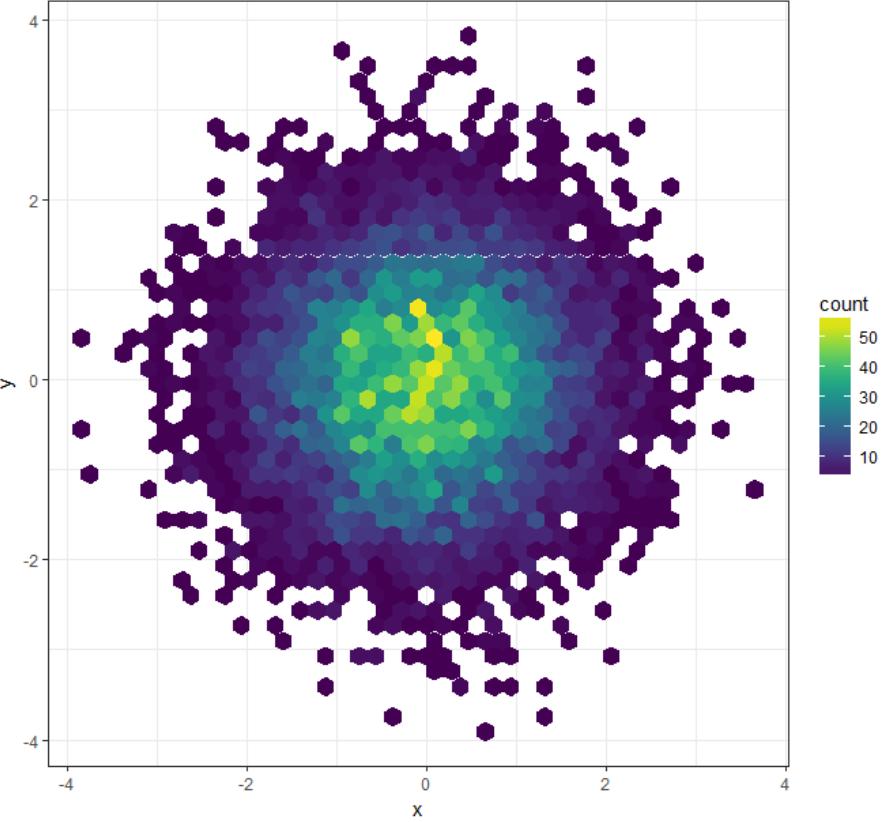
This color scheme was designed to reveal the essential topography of the map & to have perceptually equal elevation steps

Comparing palettes

ggplot default palette



viridis default palette



```
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
```

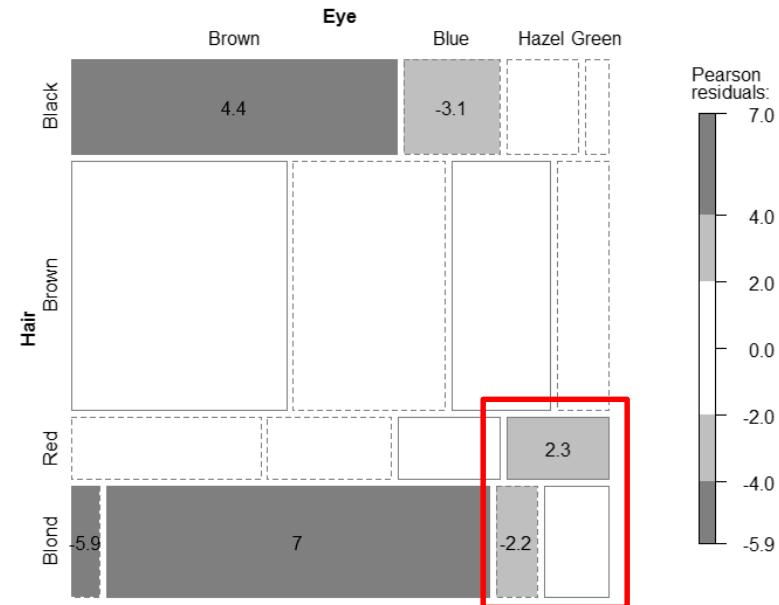
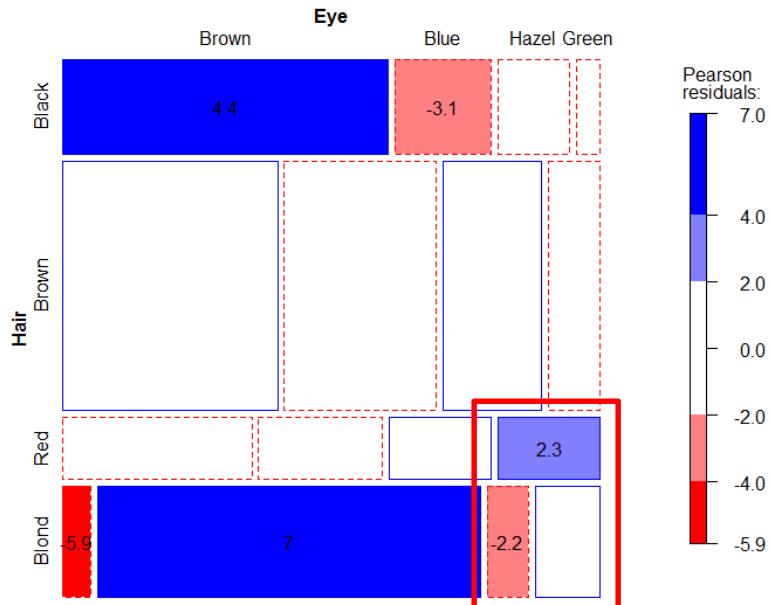
```
library(viridis)
g + scale_fill_viridis()
```

Color → B/W ?

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. **-**

```
mosaic(haireye, labeling=labeling_residuals, gp=shading_Friendly)
```



Color → B/W ?

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.

Figure 9: Section 37 benefits by type (1998–2015)

	1998– 2002	2003– 2005	2006– 2009	2010– 2013	2014– 2016	Scale
Roads, streetscapes	30	35	54	83	15	0 - 10
Culture, community, recreation	26	50	59	47	16	11 - 20
Parks	27	41	41	52	20	21 - 30
Affordable housing	17	26	38	56	11	31 - 40
Public art	26	25	41	32	4	41 - 50
Heritage	16	13	26	18	3	51 - 60
Transit	11	7	10	20	3	61 - 70
Libraries	6	2	5	11	1	71 - 80
Other	3	6	7	8	3	81 - 90

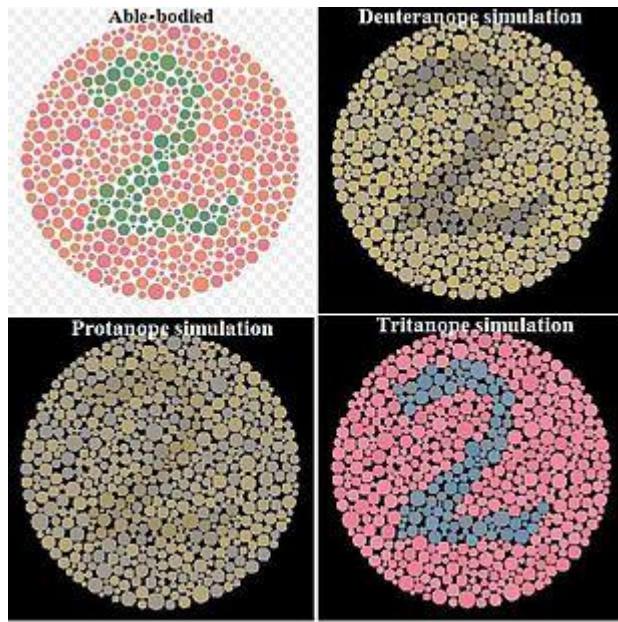
Figure 9: Section 37 benefits by type (1998–2015)

	1998– 2002	2003– 2005	2006– 2009	2010– 2013	2014– 2016	Scale
Roads, streetscapes	30	35	54	83	15	0 - 10
Culture, community, recreation	26	50	59	47	16	11 - 20
Parks	27	41	41	52	20	21 - 30
Affordable housing	17	26	38	56	11	31 - 40
Public art	26	25	41	32	4	41 - 50
Heritage	16	13	26	18	3	51 - 60
Transit	11	7	10	20	3	61 - 70
Libraries	6	2	5	11	1	71 - 80
Other	3	6	7	8	3	81 - 90

Background shading works equally well in color or B/W
 A+ for visual design!

Source: Friendly, A. R. (2017). *Land Value Capture and Social Benefits: Toronto and São Paulo Compared*. IMFG Papers on Municipal Finance and Governance, No 33, University of Toronto, <https://munkschool.utoronto.ca/imfg/>

Colorblindness



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

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

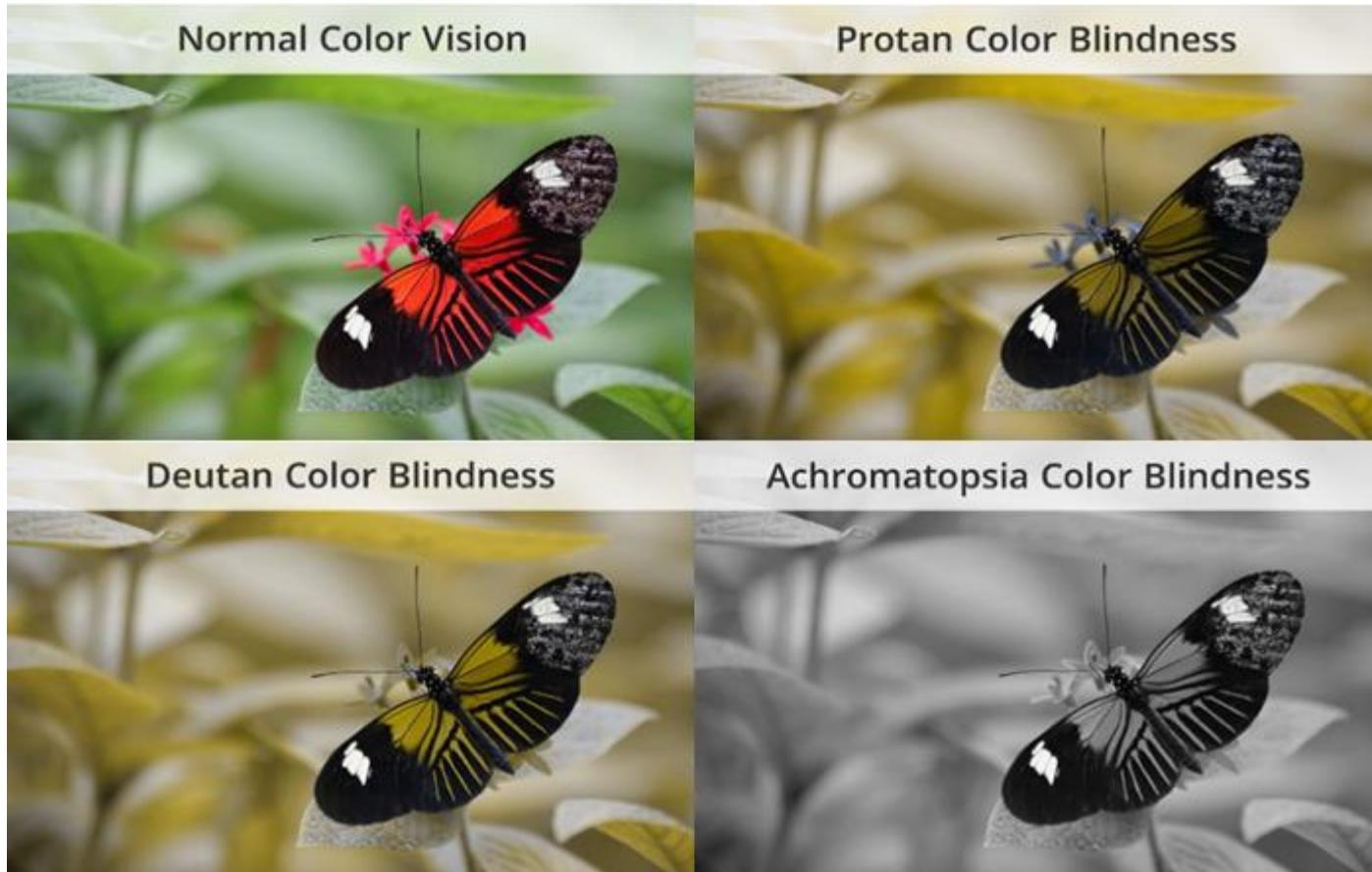
Some form of red-green insensitivity is most common

- about 6-8% of population
- more common in males

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

Colorblindness

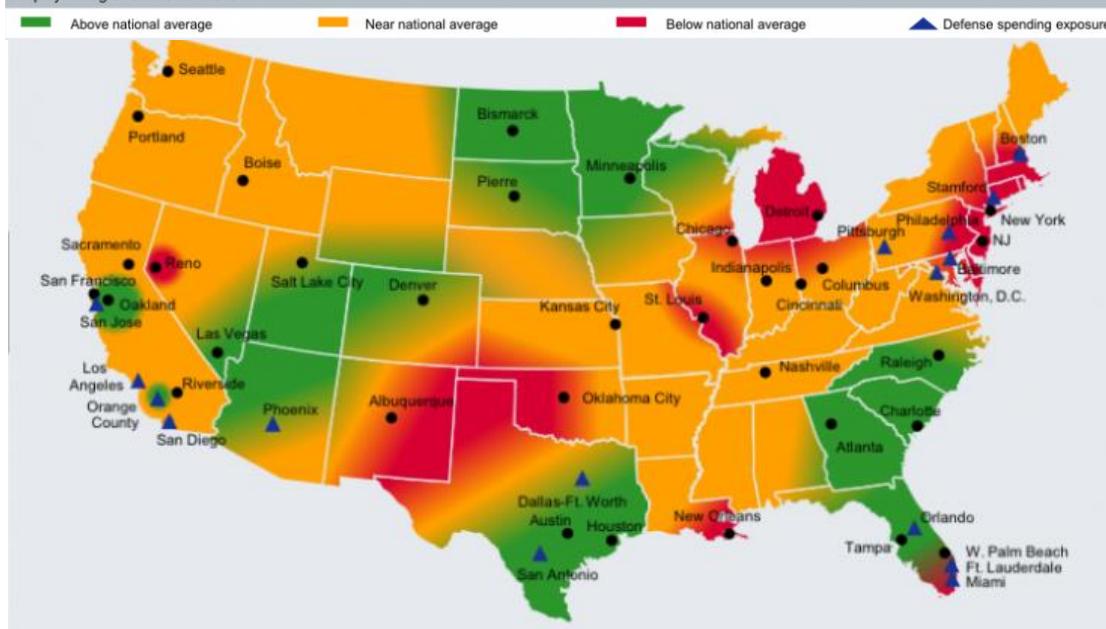
What an image looks like with various forms of color deficiency



Red-green colorblindness:

-R (protan) \approx -G (deutan)

Employment growth: 2013 - 2015

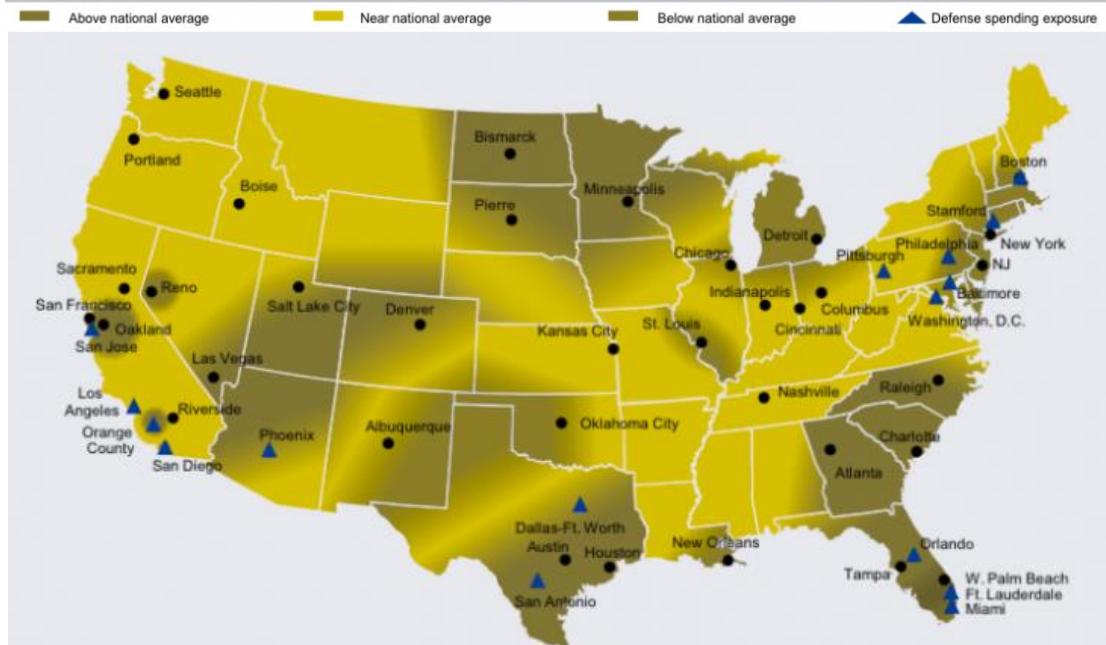


Goal: Show employment growth, 2013–2015

Original design, using

- green: above average
- red: below average

Employment growth: 2013 - 2015



How this looks to
someone with red-green
colorblindness

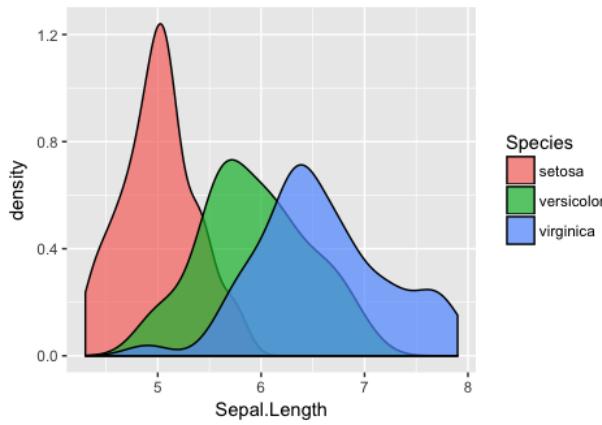
red & green become
indistinguishable

From: <http://www.mena-forum.com/category/u-s-a/>



colorblindr package

myfig

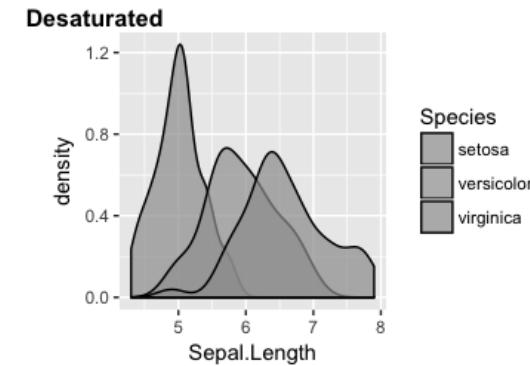
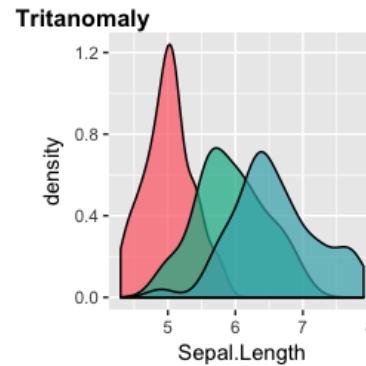
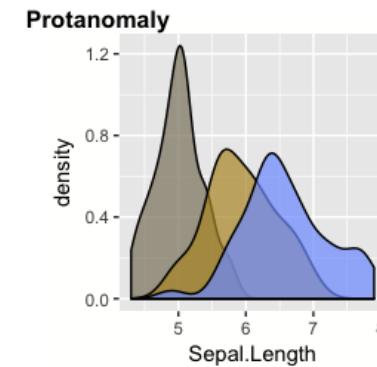
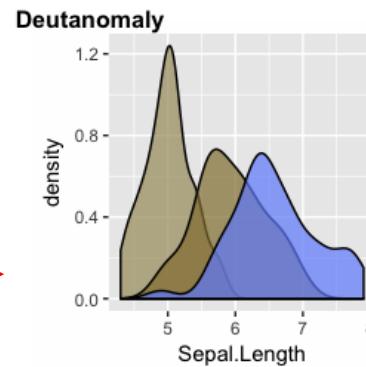


```
library(colorblindr)  
cvd_grid(myfig)
```



What would my graph look like to someone with color deficiency?

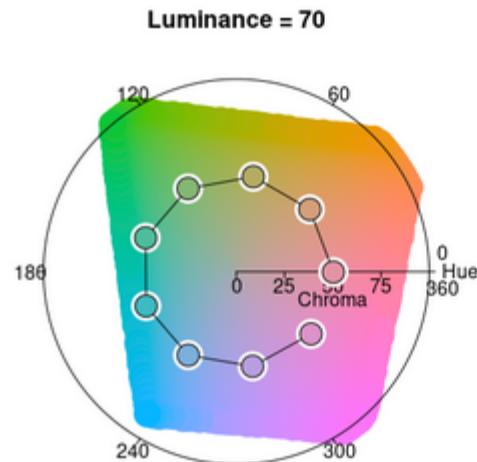
colorblindr simulates a graph under various conditions





A Toolbox for Manipulating and Assessing Colors and Palettes

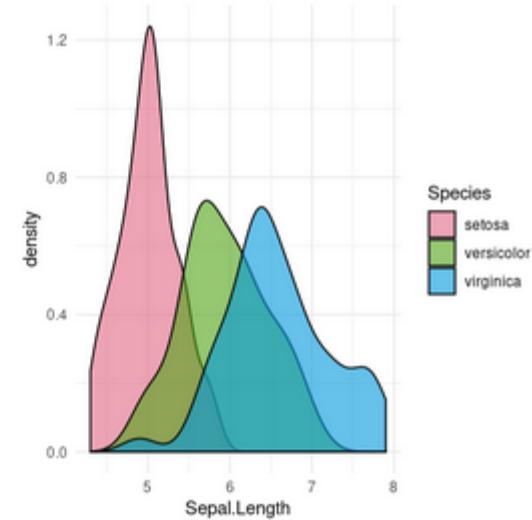
Color spaces



HCL-based palettes



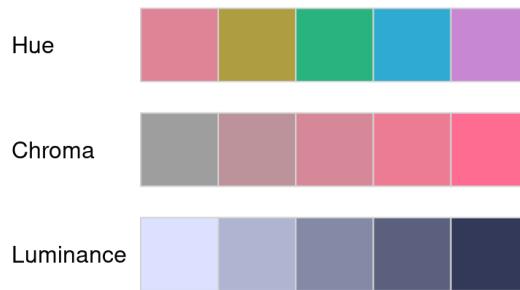
ggplot2 scales



See: <http://colorspace.r-forge.r-project.org/>

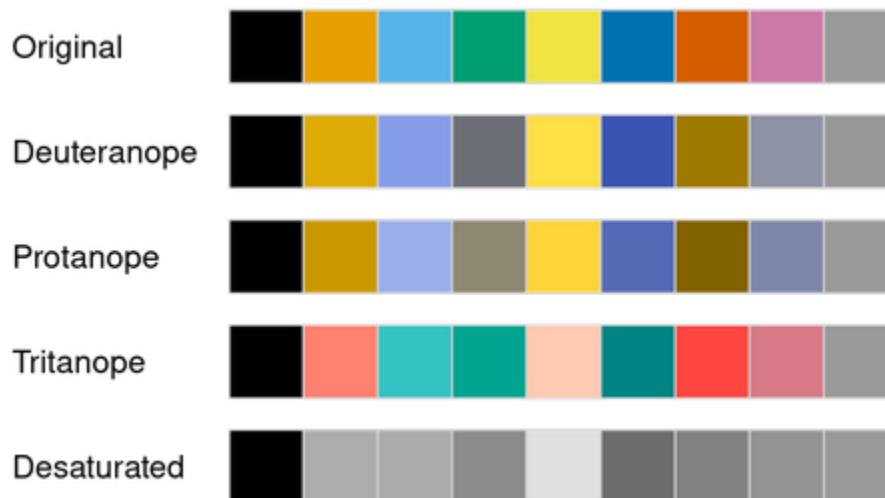
colorspace: palette visualization

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

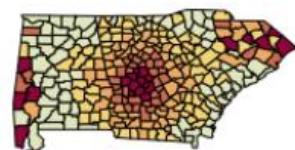
```
swatchplot(palette.colors(), cvd = TRUE)
```

colorspace: demoplot()

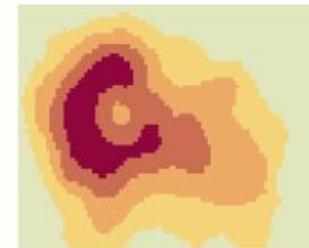
See how color palettes
work in different kinds
of statistical displays

demoplot(sequential_hcl(5, "Heat"))

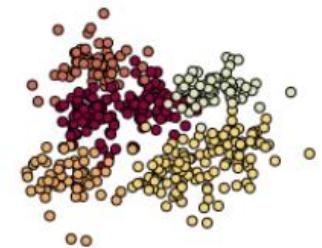
map



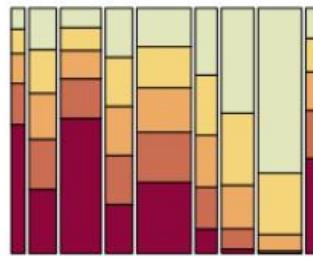
heatmap



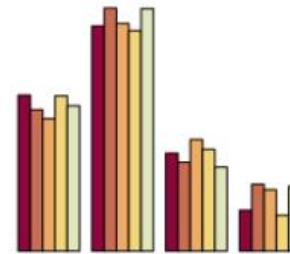
scatter



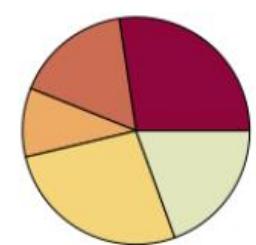
spine



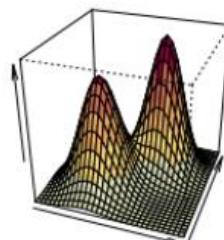
bar



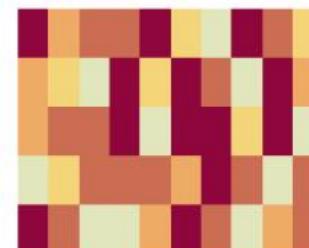
pie



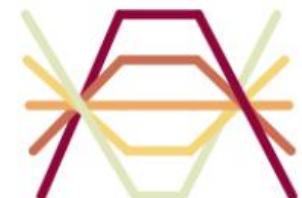
perspective



mosaic



lines



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

Color: Lessons

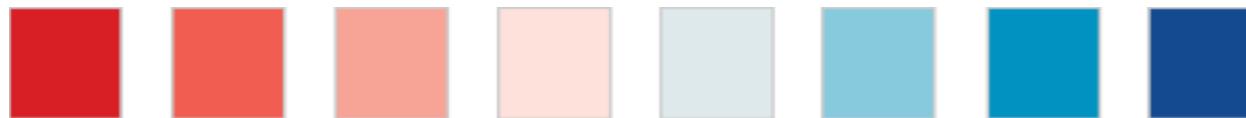
- Consider encoding scheme:
 - Categorical: Use a wide range of hues, of ~ same saturation



- Sequential: use a small range of hues of varying intensity



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



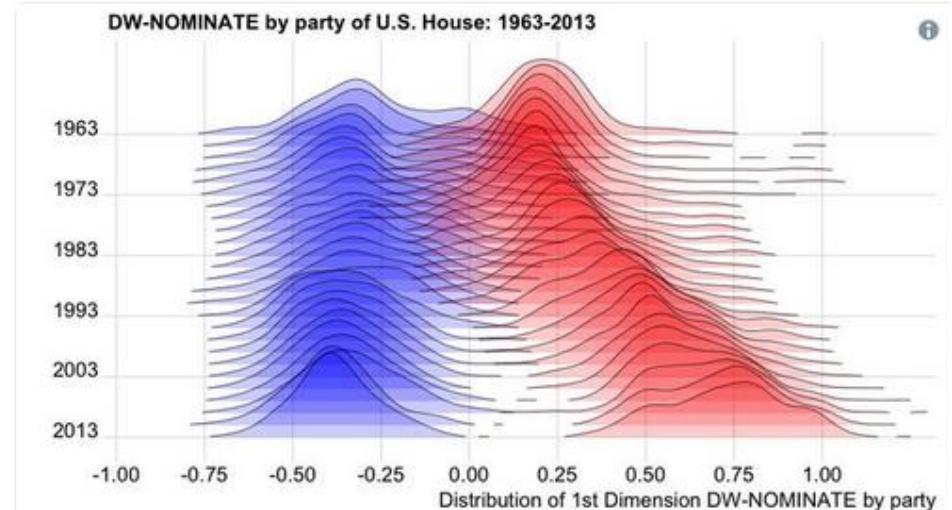
Transparency

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

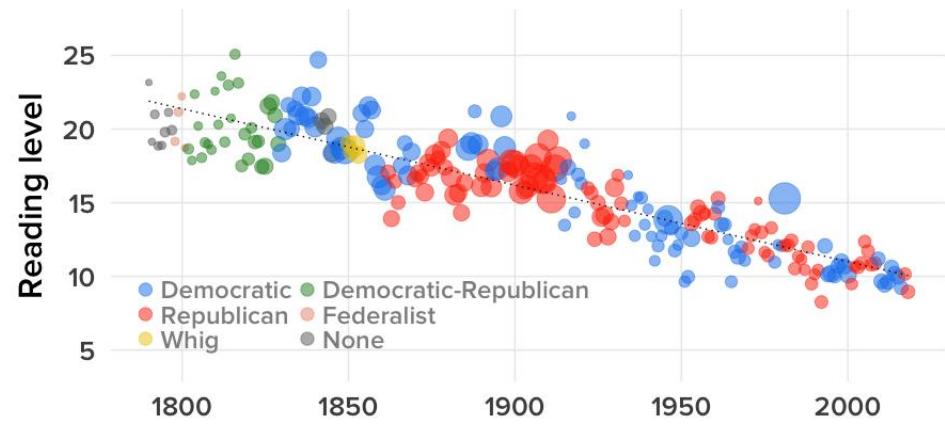
Filled areas combine to look more saturated
What do you see here?

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

Different colors “blend”
What do you see here?



Increasing polarization of votes in the US House

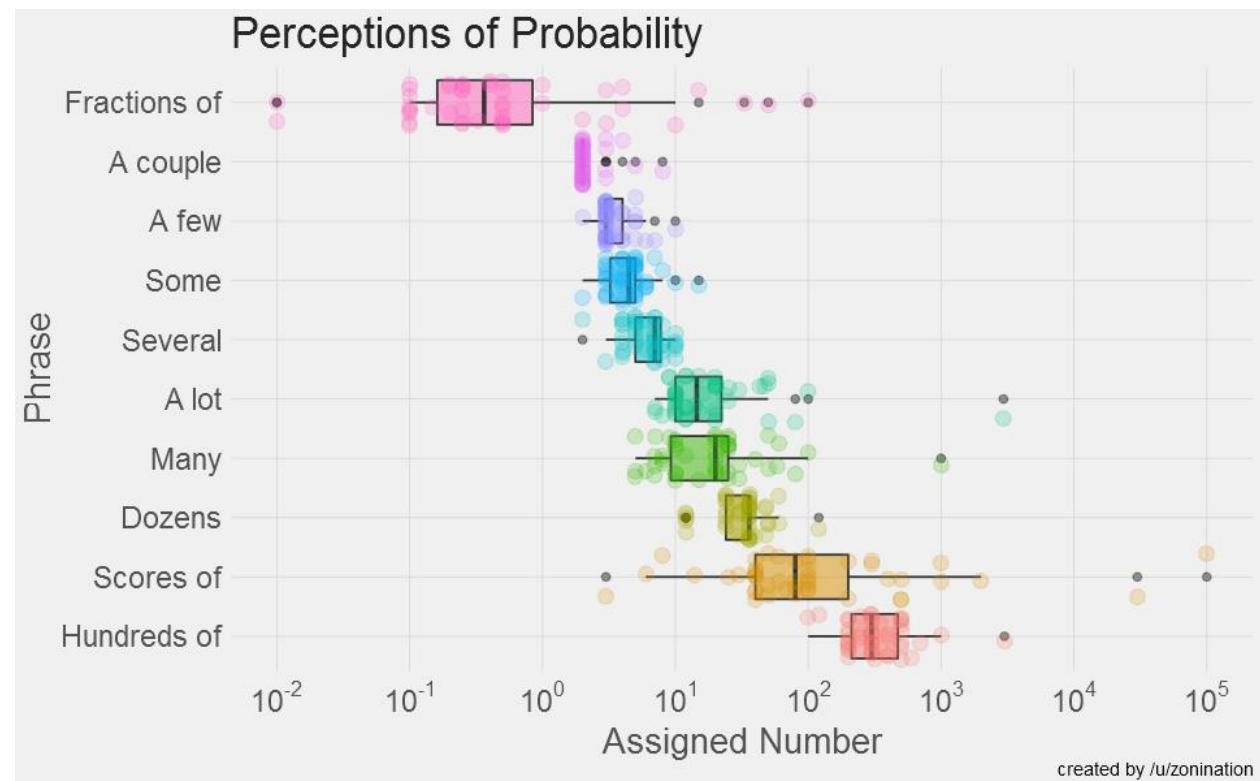


Reading level of US State of the Union Addresses

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/zonation/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