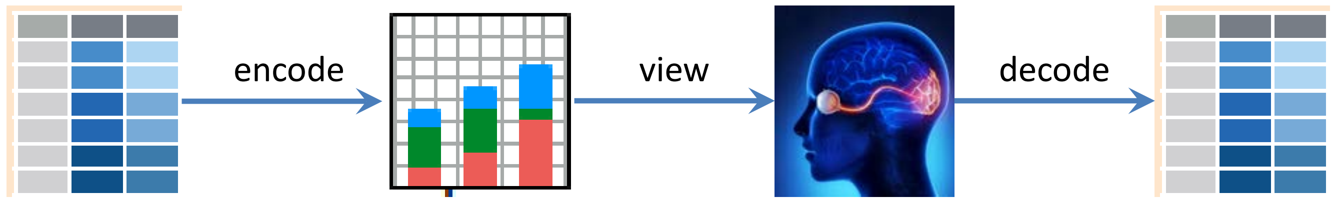


Graphical Perception

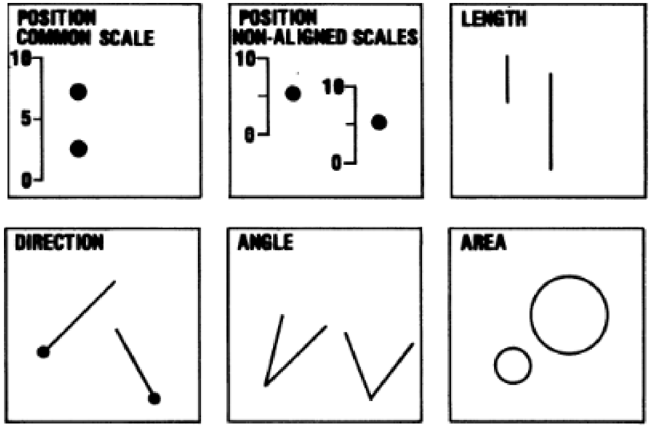
Michael Friendly

Psych 6135

http://euclid.psych.yorku.ca/www/psy6135/

Graphical Perception

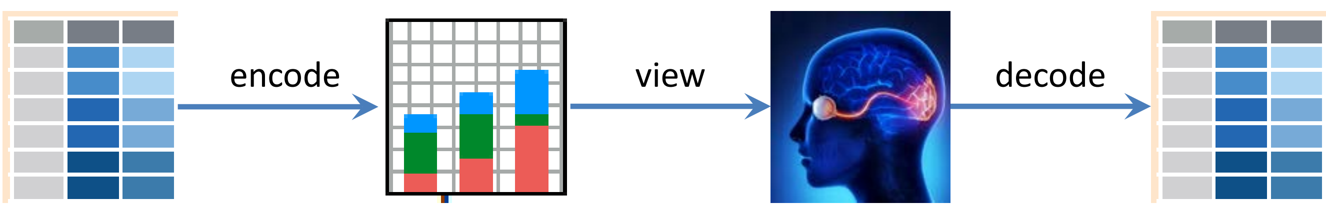
- In constructing a graph, quantitative and categorical information is encoded by visual attributes:
  - Length
  - Position along axis
  - Angle
  - Area
  - Color, shape, line style



- 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



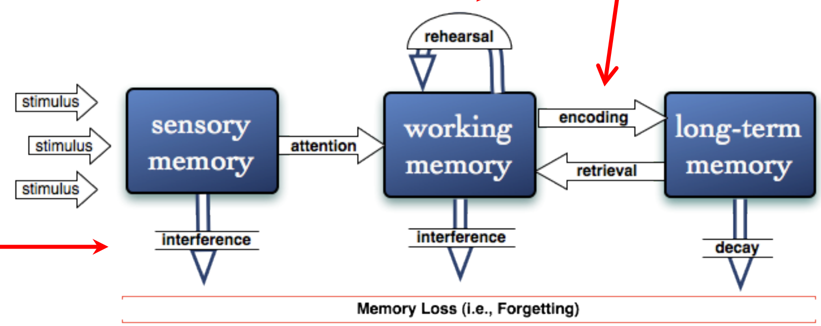
- Encoding should rely on features that can easily be decoded
- Often, easier said than done! The devil is in the details

Visual & cognitive systems

- A simplified model: Three stages

How to preserve info?

How is info lost?

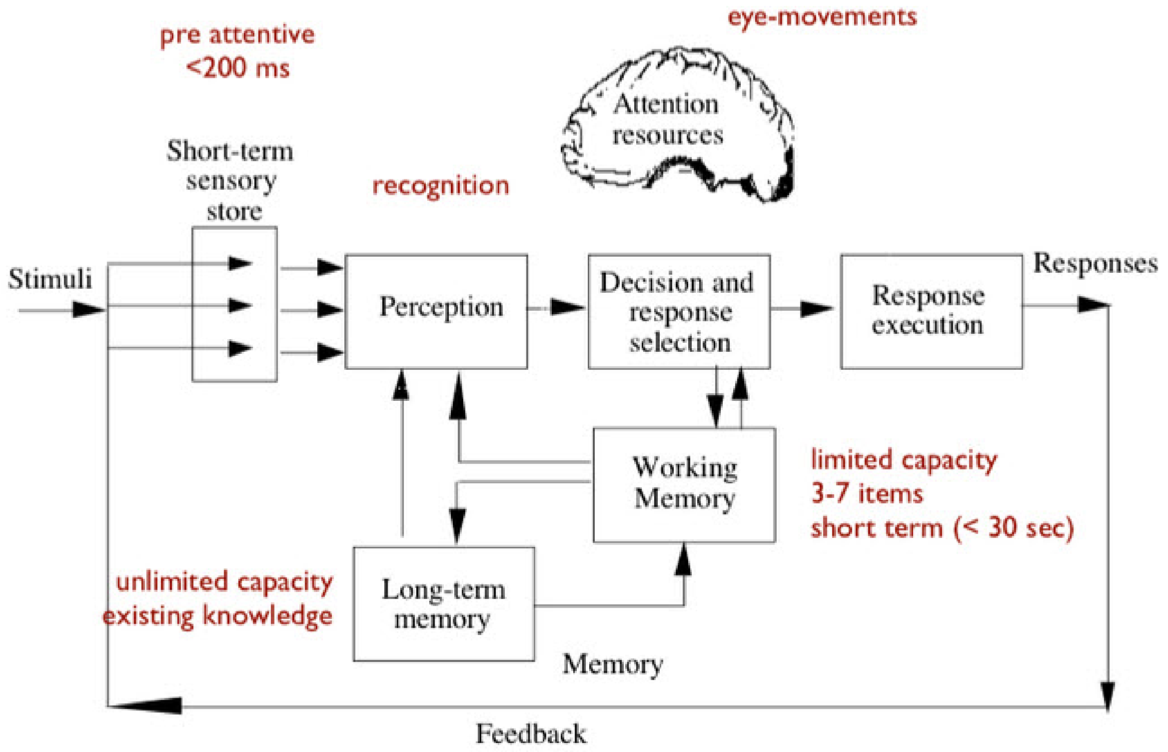


- Sensory (iconic) memory
  - pre-attentive, automatic, feature detection
  - massively parallel, short duration, easily fooled
- Working memory
  - requires attention, limited capacity (~ 4-6 "chunks")
- Long-term memory
  - real-world knowledge, unlimited capacity

Perception & cognition

Another coarse distinction:

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

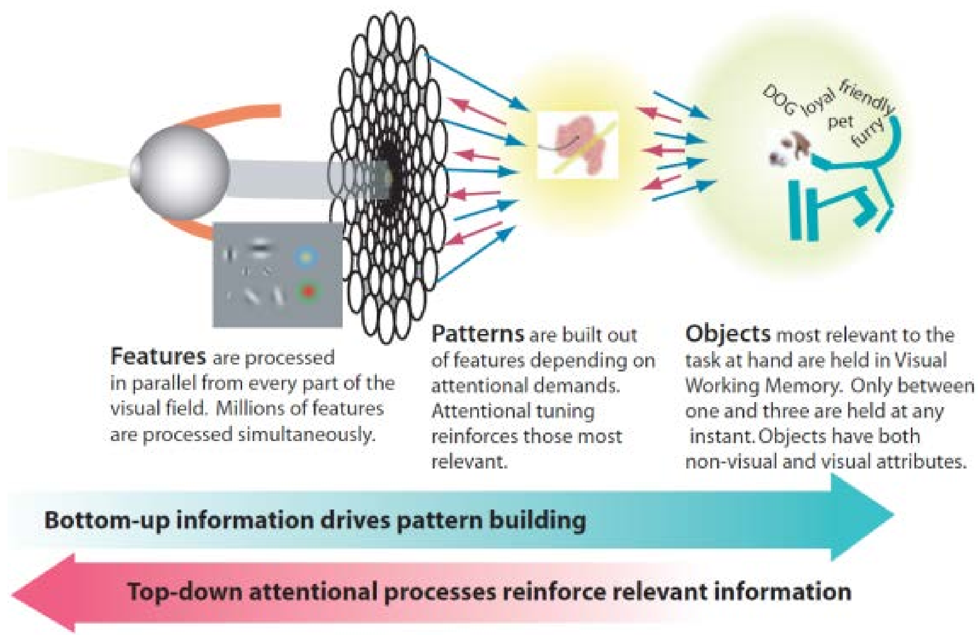


A nice scientific or textbook diagram
But where is cognition?

Based on slide from G. Grinstein

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

How many 5s in this display?

1561321203658413076510374627
4173127527327592732990709742
1703707774179527931749270973
4019743217909370945179279417

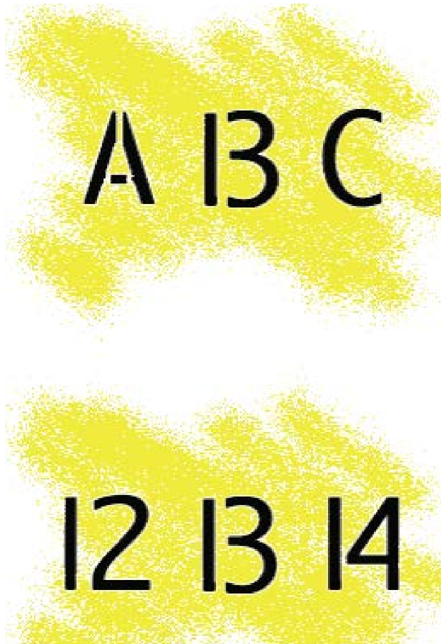
Numerals differ only in shape, and are high-level symbols
You have to literally scan them **all** & count the 5s.
The distinction of color is immediate & **pre-attentive**
You only have to scan & count the 5s.

This is why color is an important visual attribute for a categorical variable in graphs

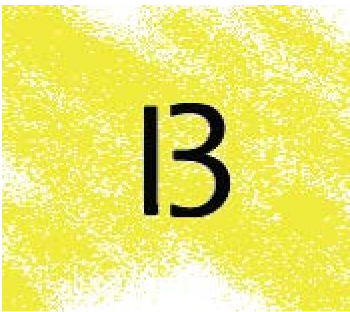
Perception: Top-down

What is in this scene?

What is the middle character?



What here?



An ambiguous figure!

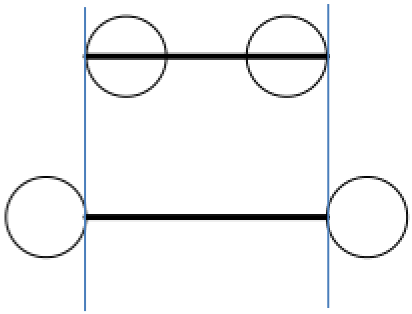
What is the middle letter in each word?

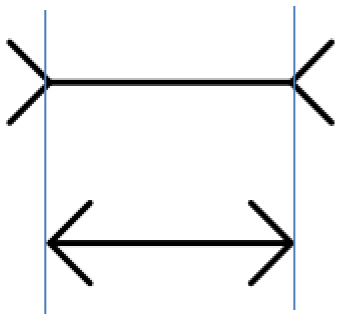
All of these are demonstrations of the role of expectations (top-down) in determining what we “see”

Illusions: Length

Surrounding context matters in judging the size of objects.

Which line is longer? Or are they the same?



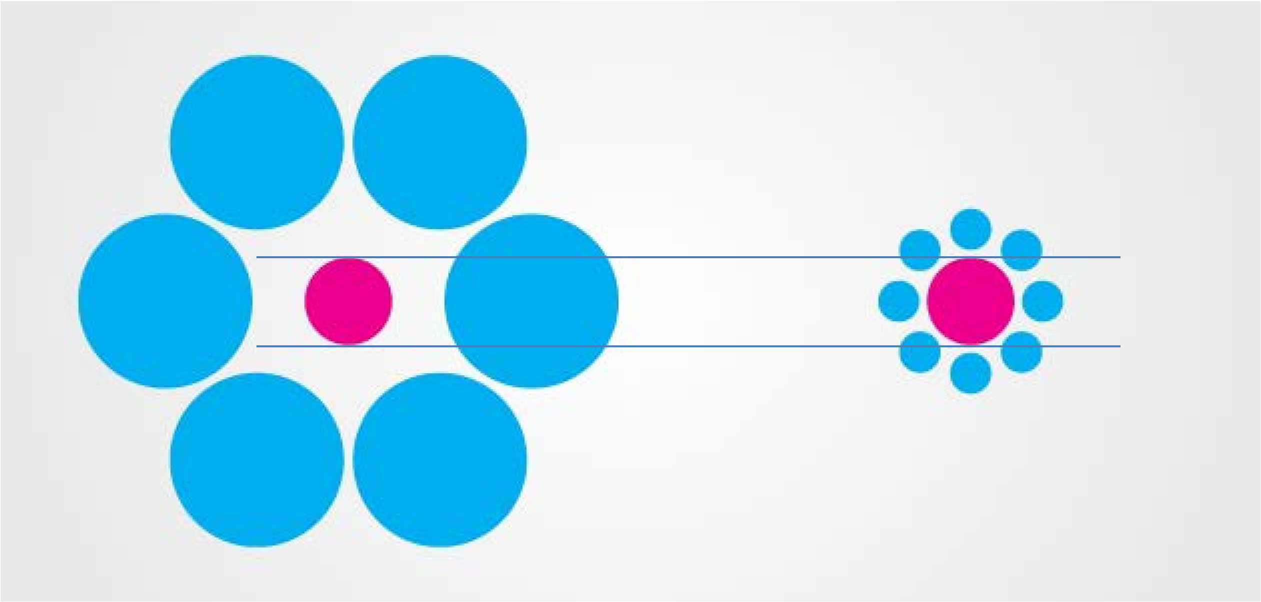


Surrounding context pulls perception of length in its direction
This is the famous Müller-Lyer illusion

Illusions: Area

Surrounding context matters in judging the size of objects.

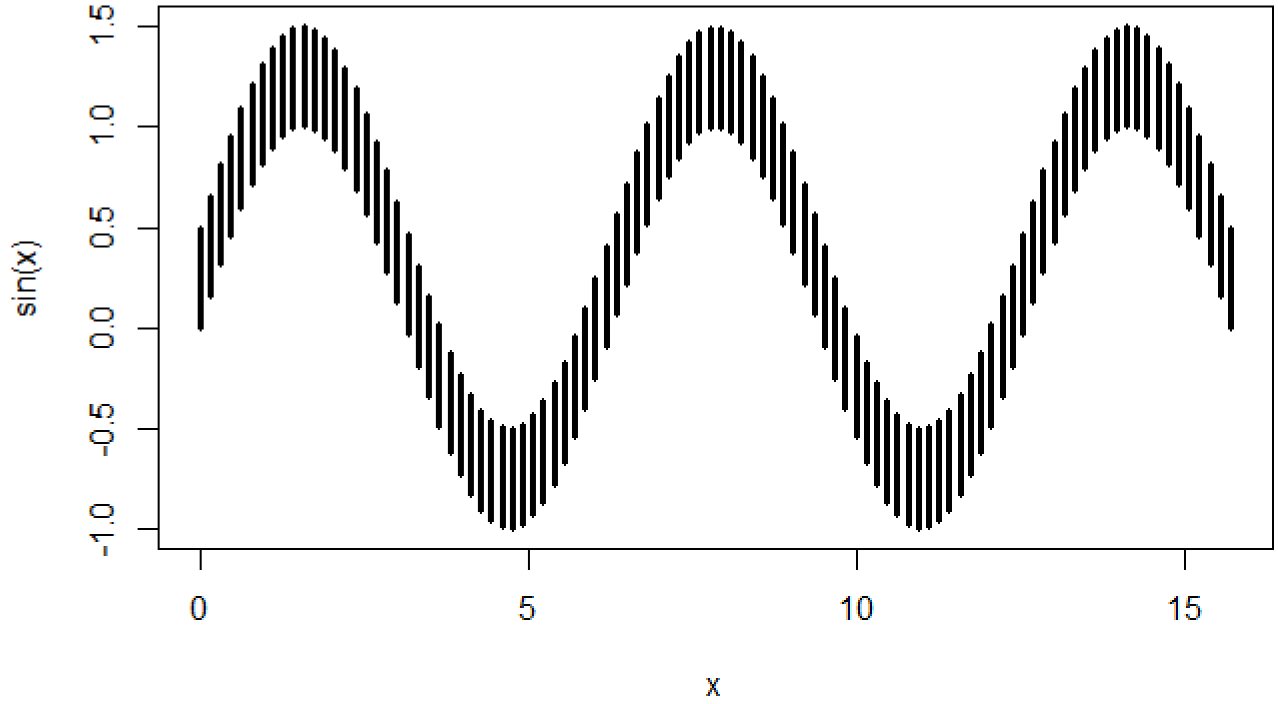
Which red circle is larger? Or are they the same?



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

Illusions: Difference

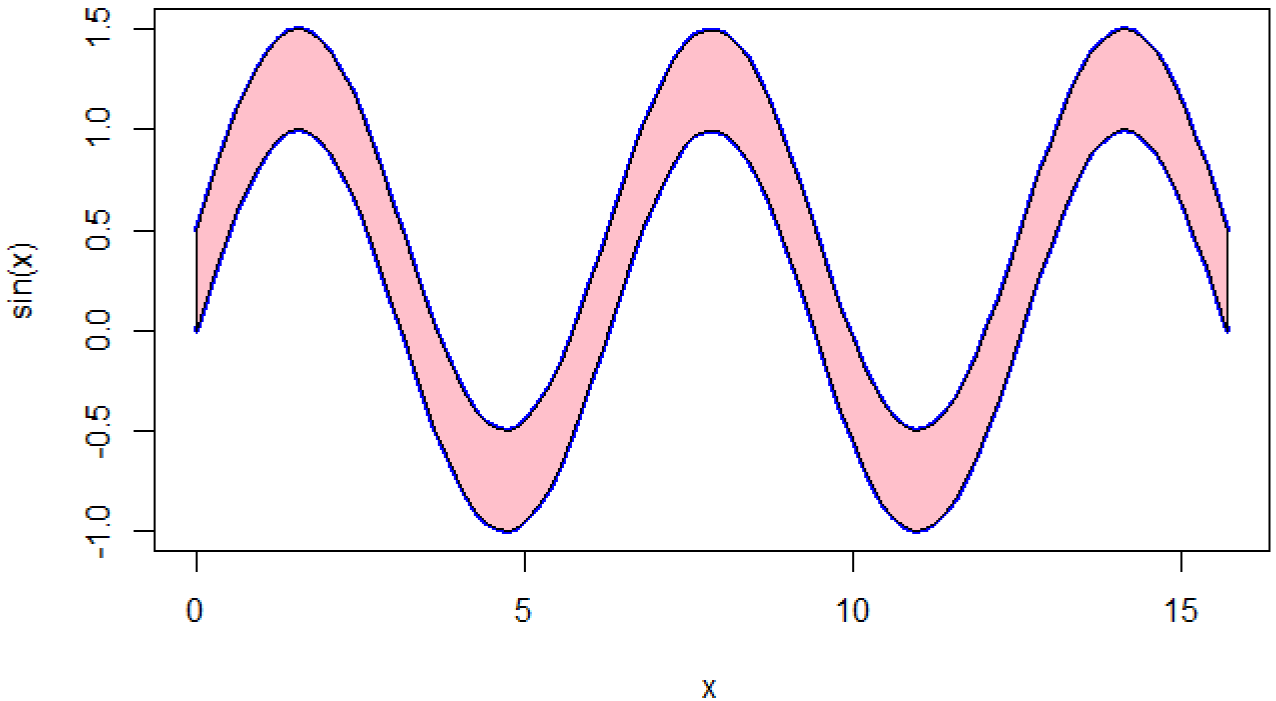
Which of the bars are longer? Or, are they all the same length?




```
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

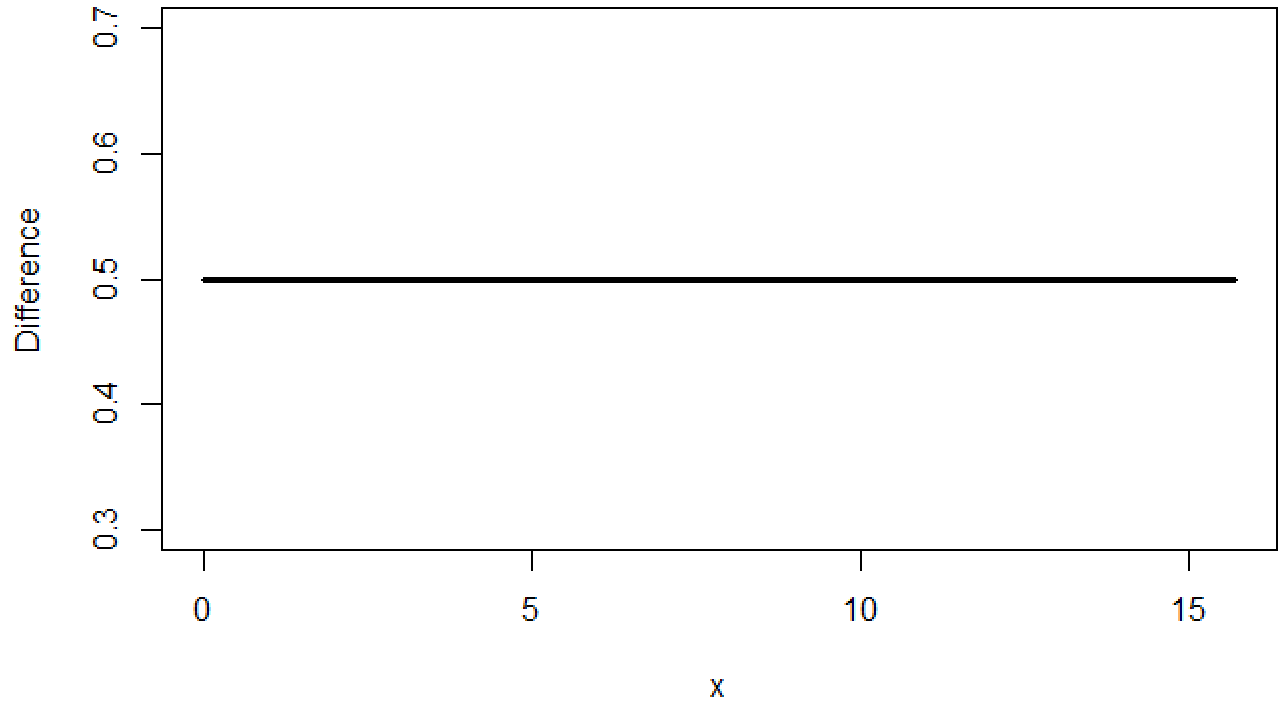
Where are differences between curves are larger? Or, are they all the same?



This is sometimes called the “sine illusion”

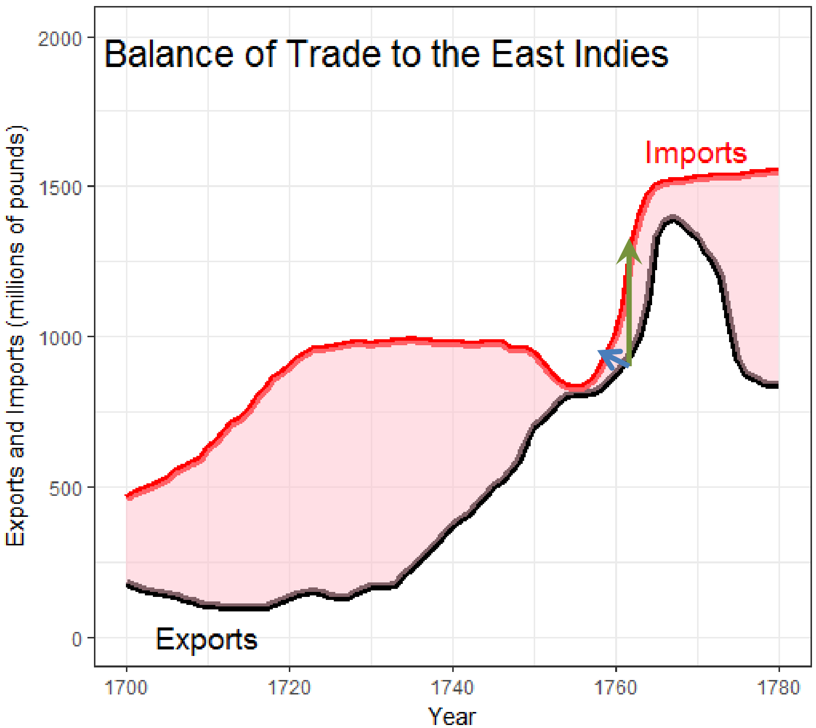
Illusions: Difference

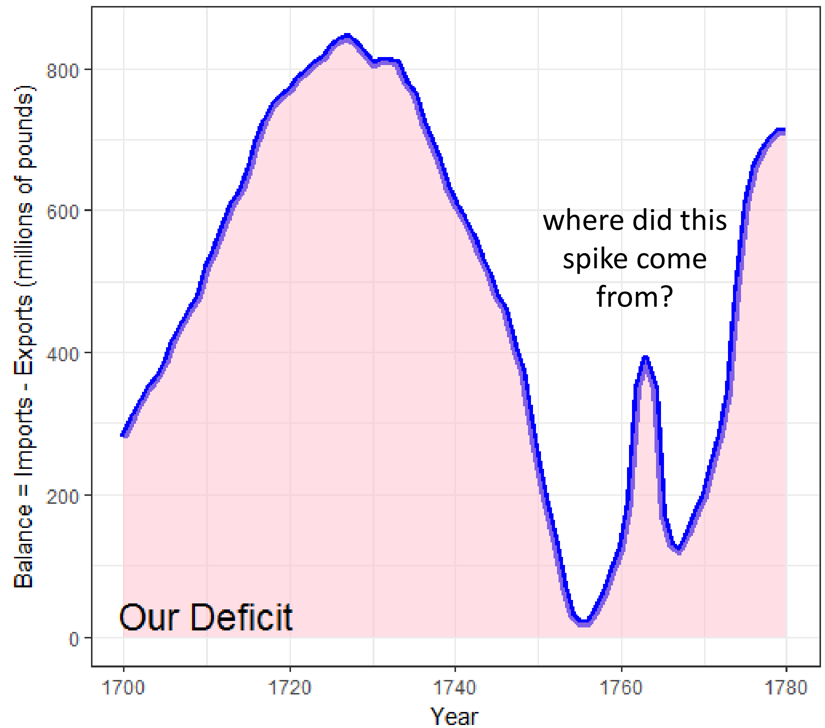
Plotting the difference directly gives the answer.



Distances between curves

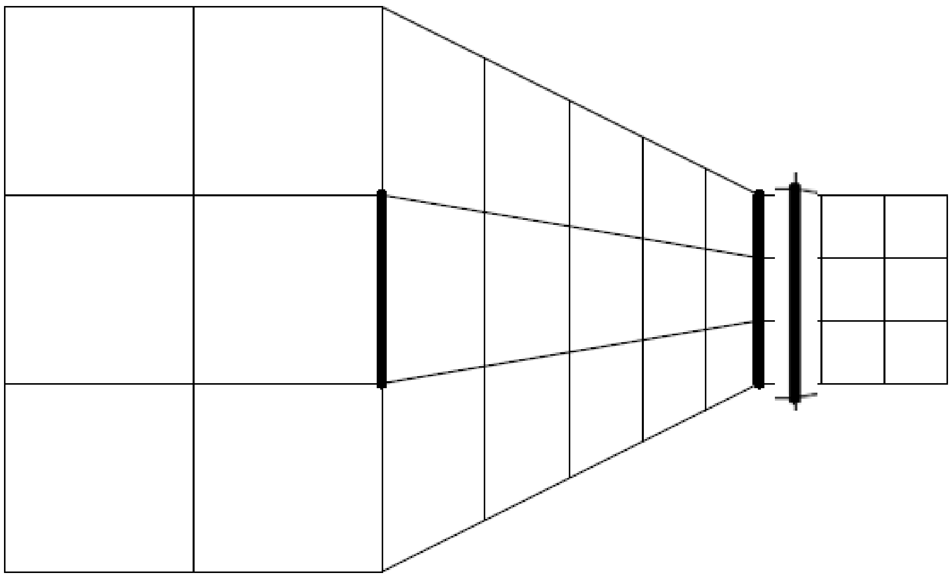
Playfair didn't know that judgments of distance between curves are biased
We tend to see the perpendicular distance rather than the vertical distance



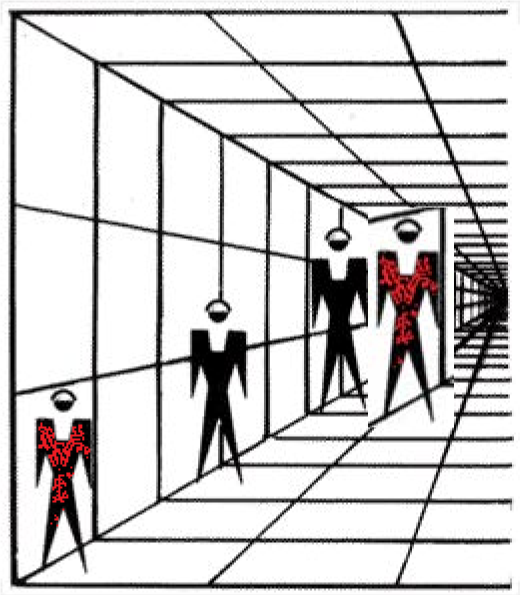


Illusions: Perspective

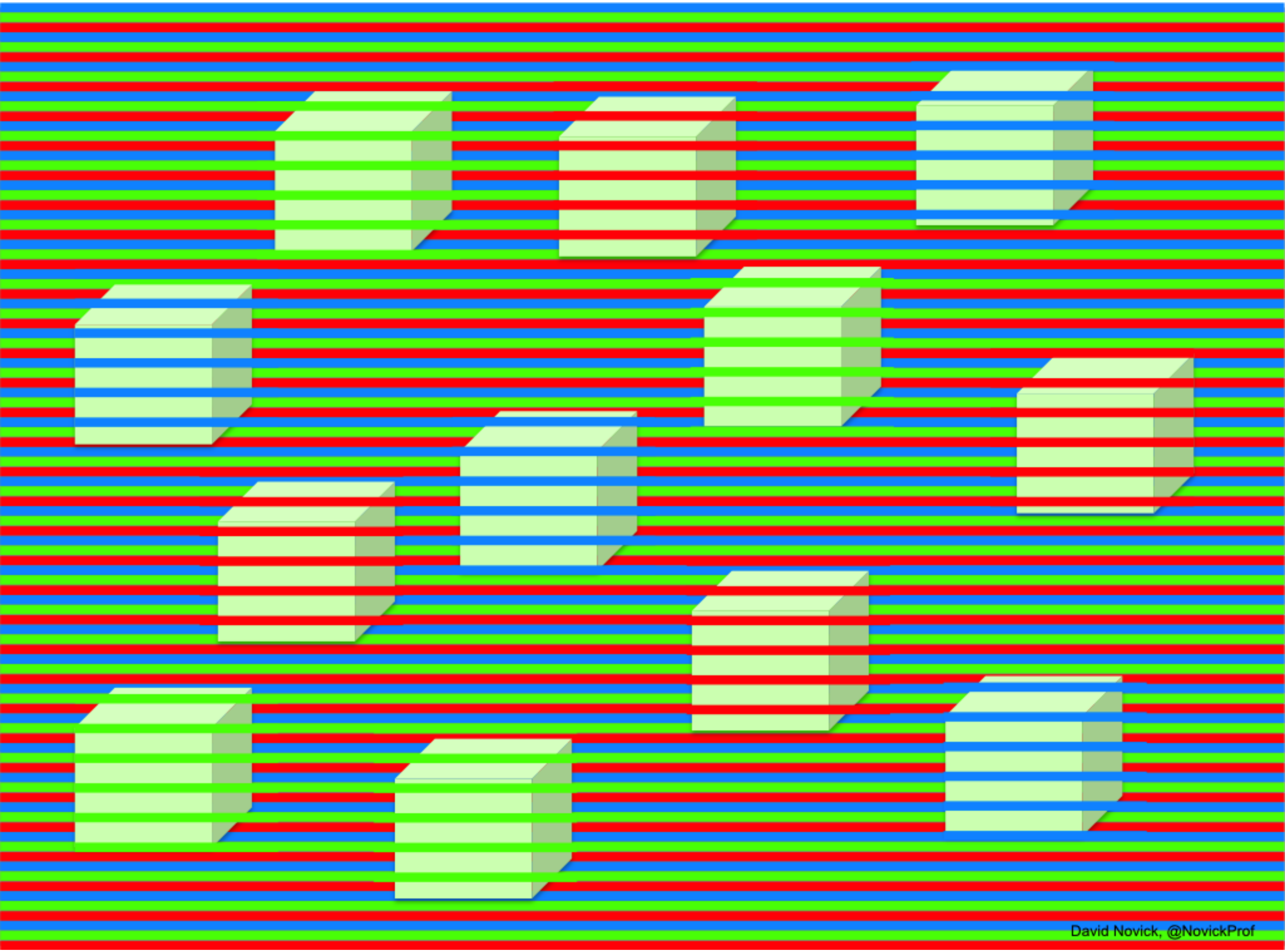
Which **thick** line is longer? Or, both the same?



Which figure is tallest?
Or, all the same?

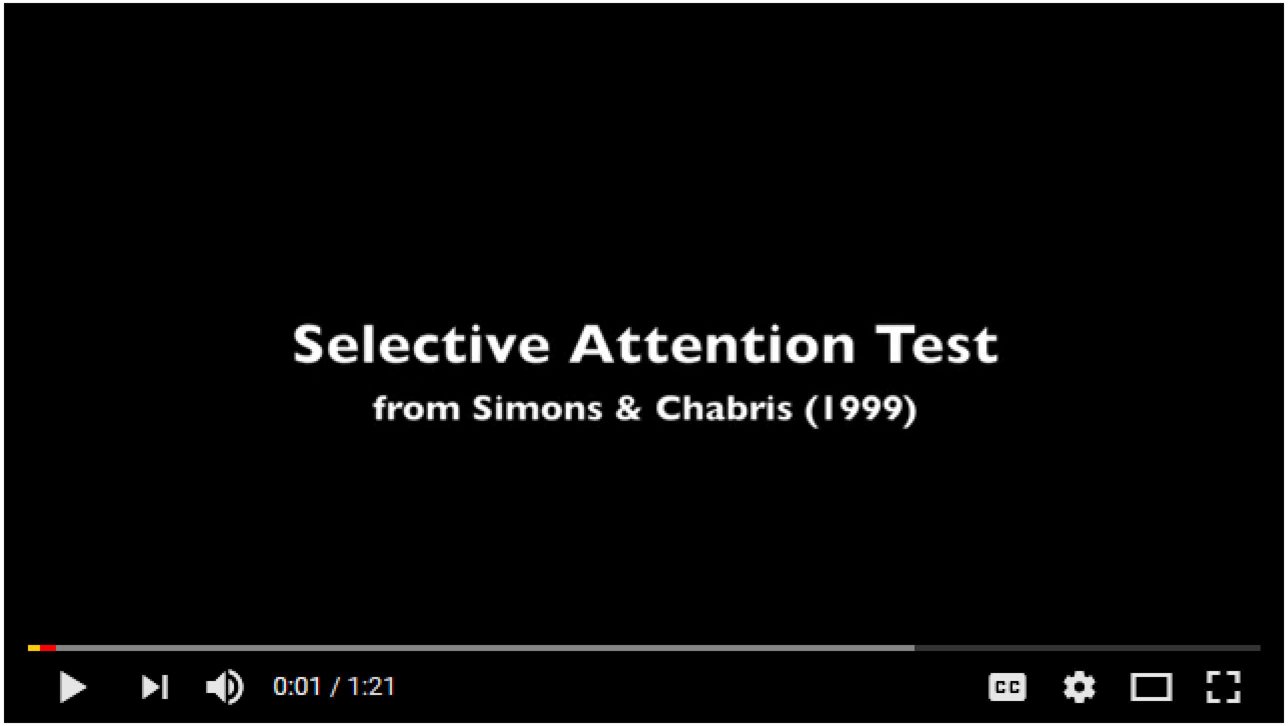


This is often called the Ponzo illusion: We judge the size of real-world objects relative to their background.



David Novick, @NovickProf

Selective attention



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

Magnitude estimation

How large are transport accidents?
How much bigger than non-transport accidents?

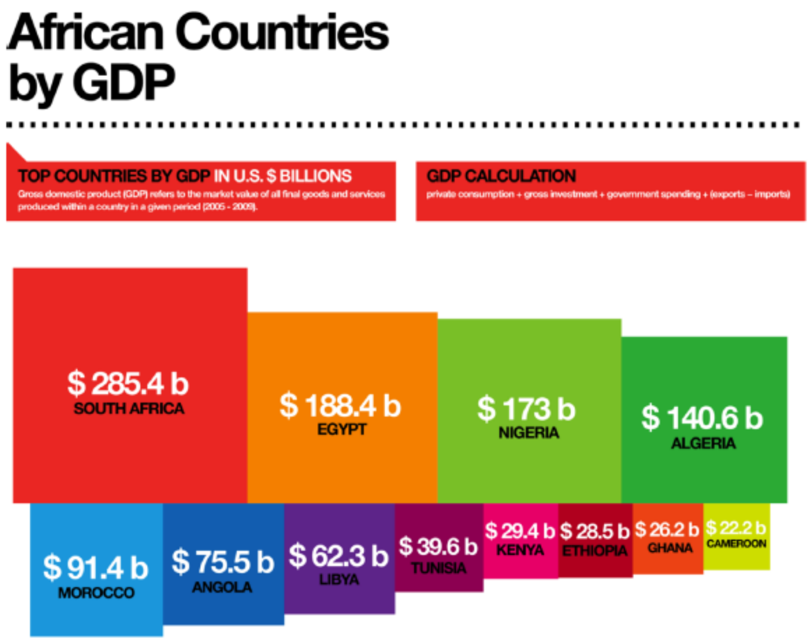
transport

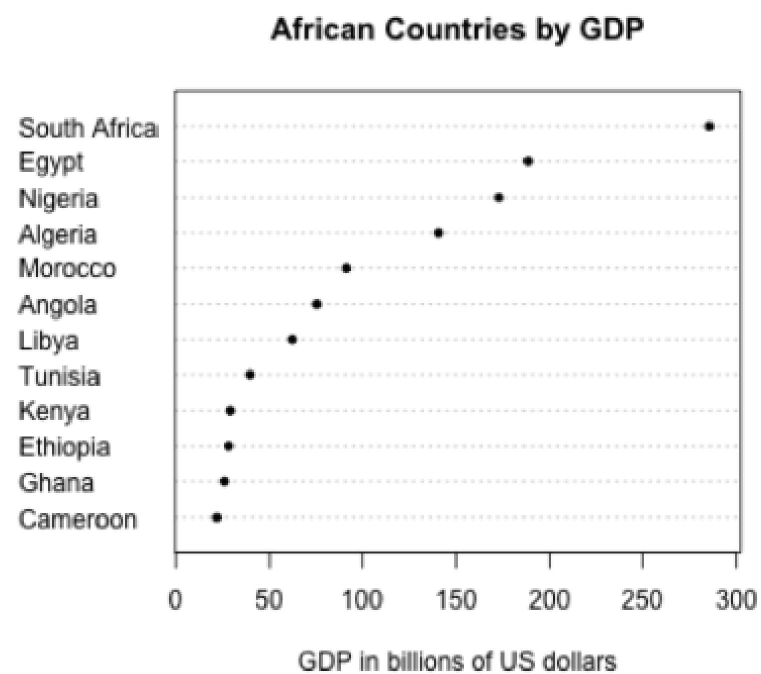
non-transport

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?





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.

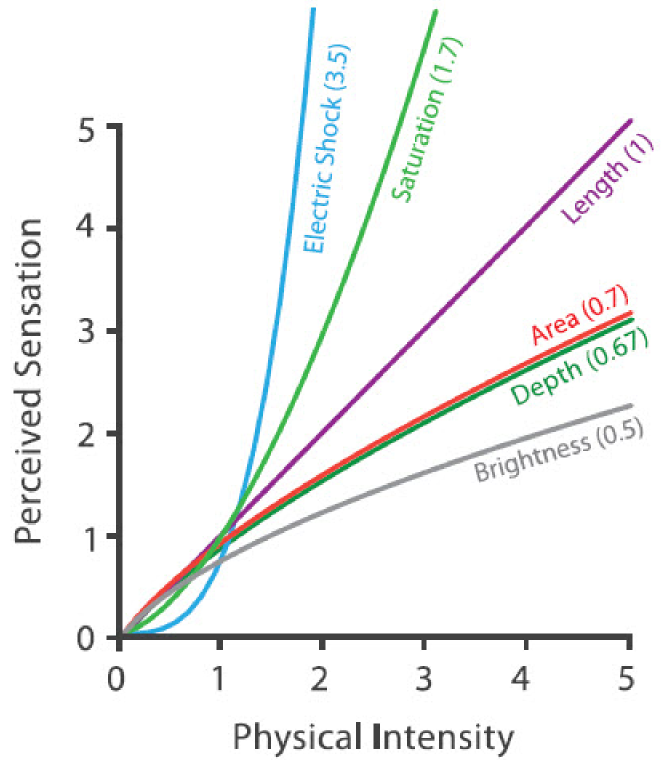


Fig. 5.7 from: Munzner, *Visualization Analysis & Design*

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

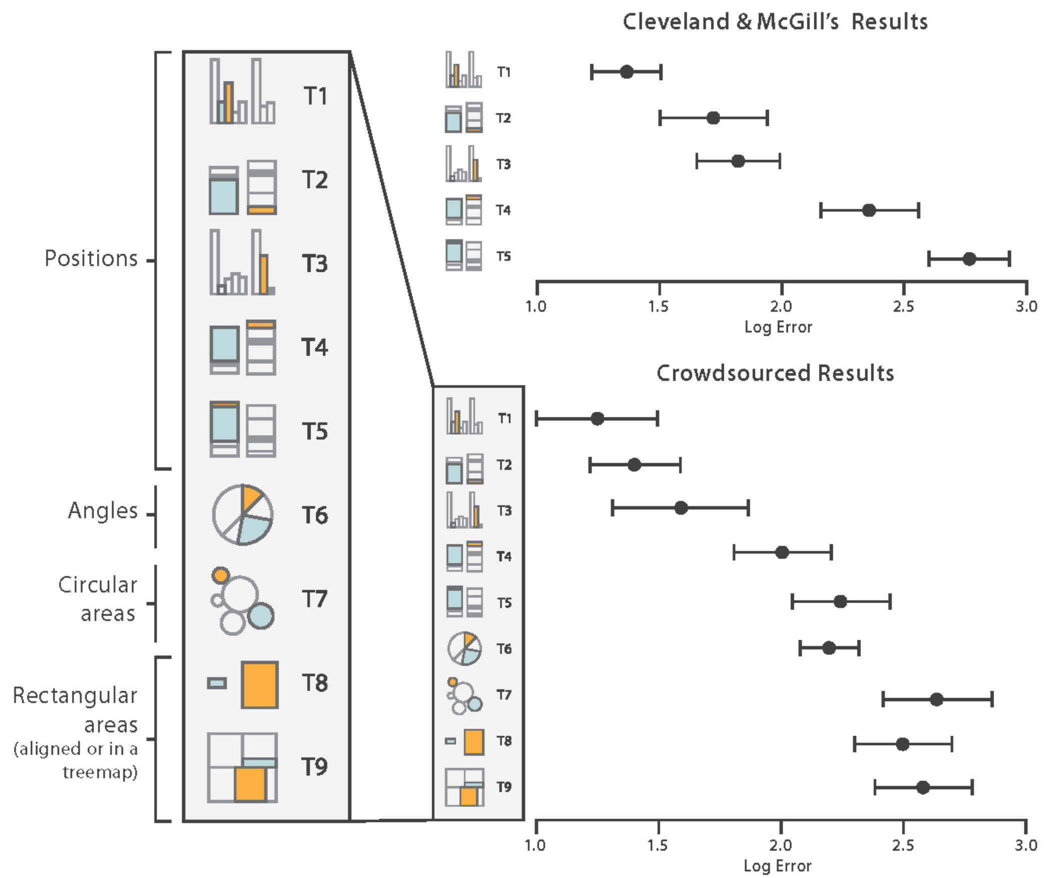


Fig. 5.8 from: Munzner, *Visualization Analysis & Design*

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

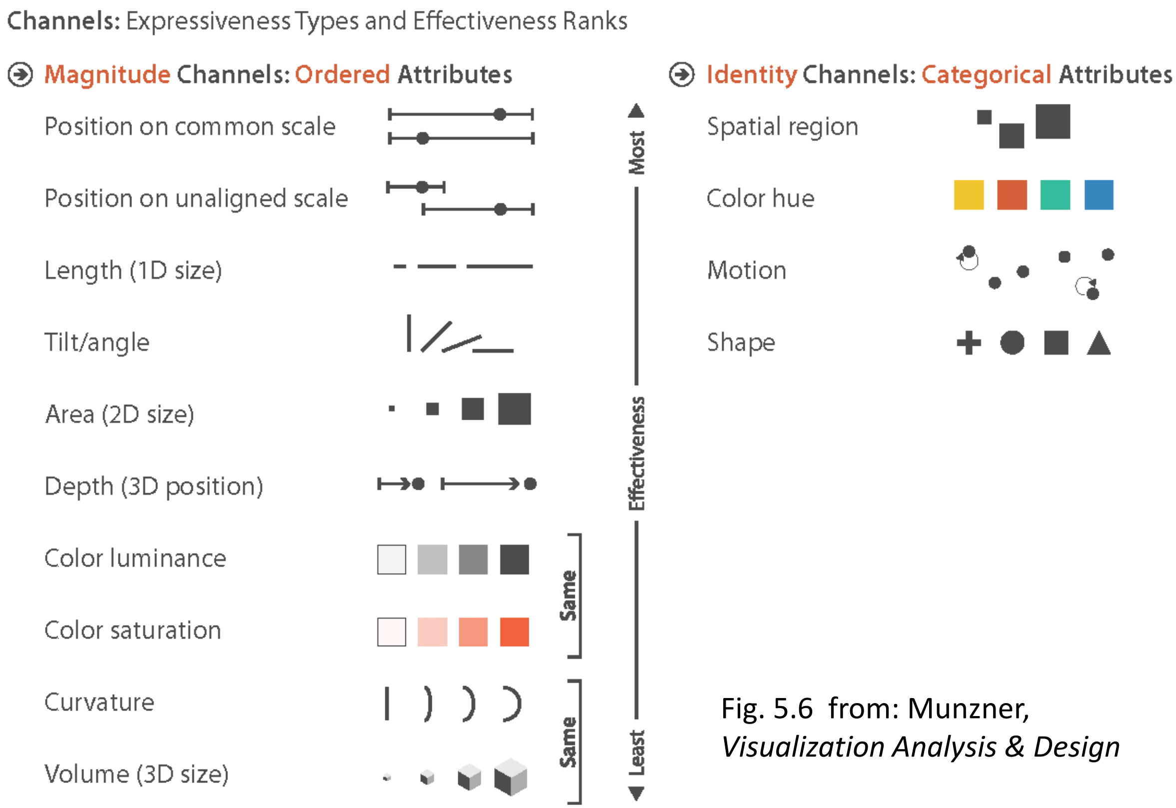


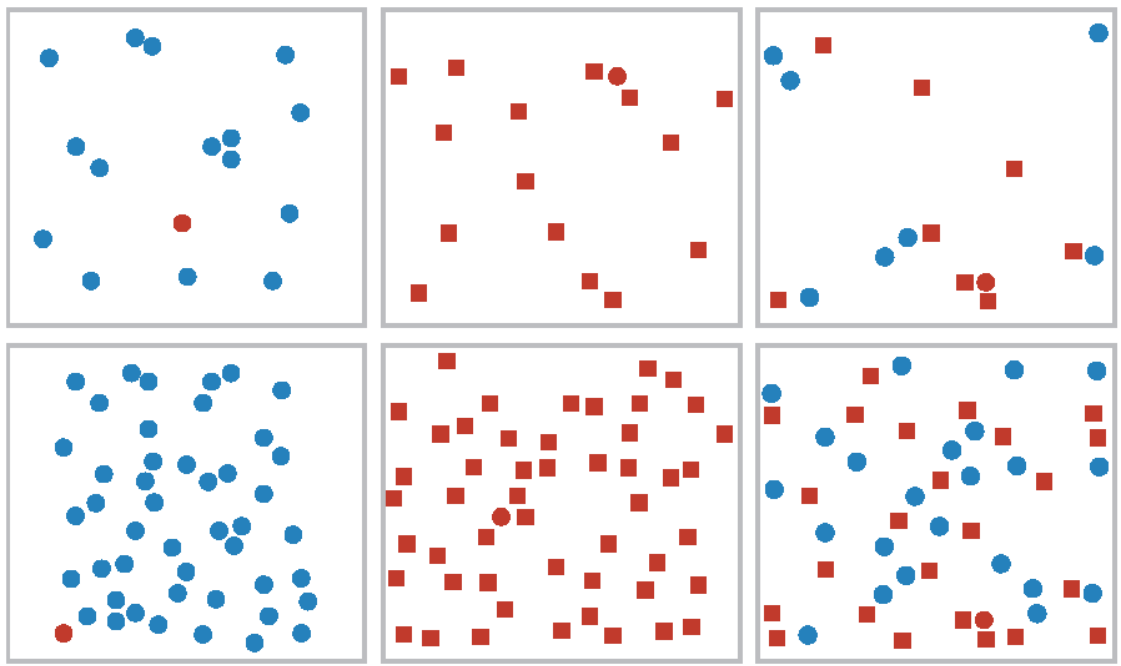
Fig. 5.6 from: Munzner, *Visualization Analysis & Design*

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

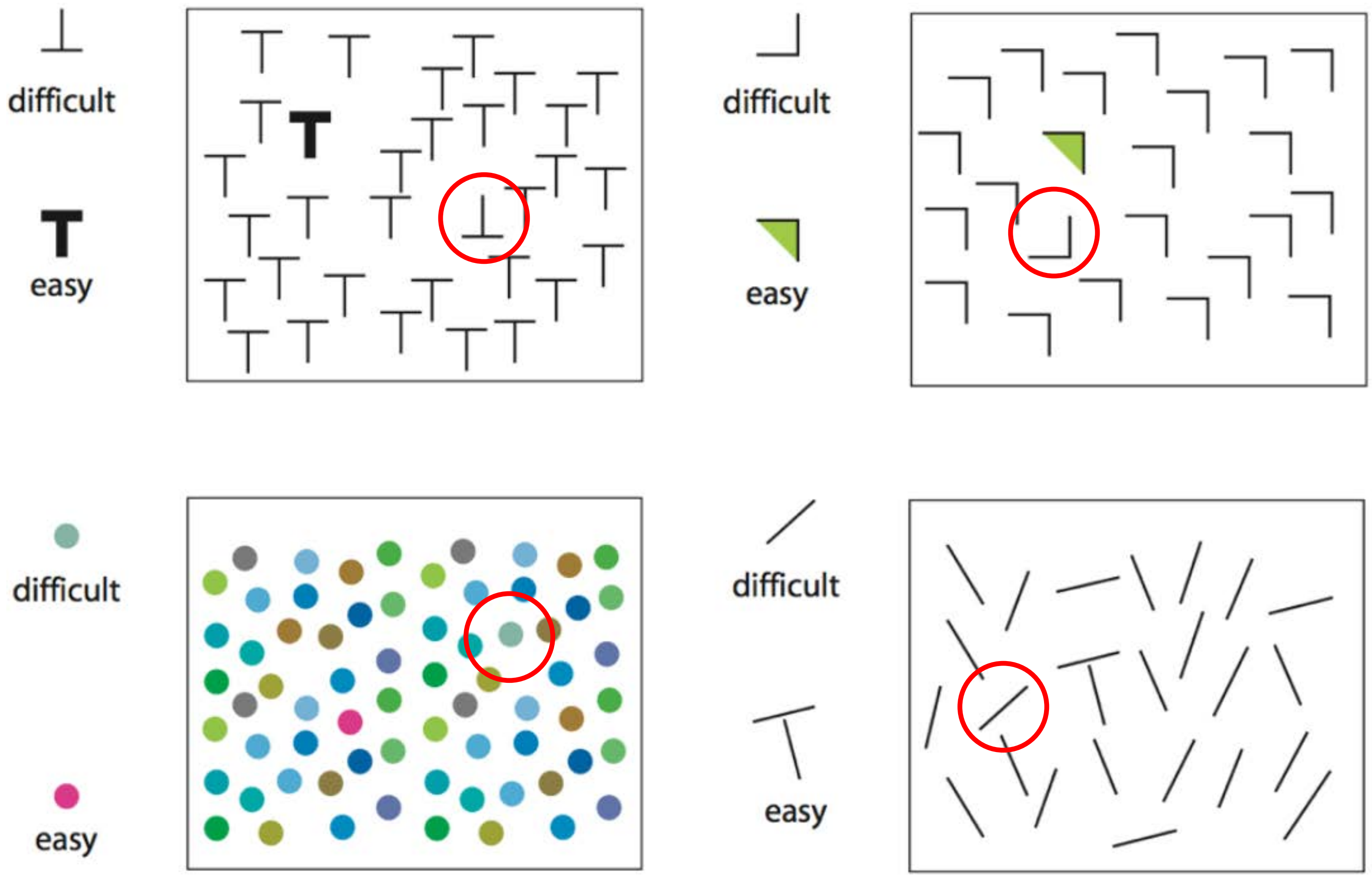
Sometimes called
“popout” effect.
Not a good term.



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

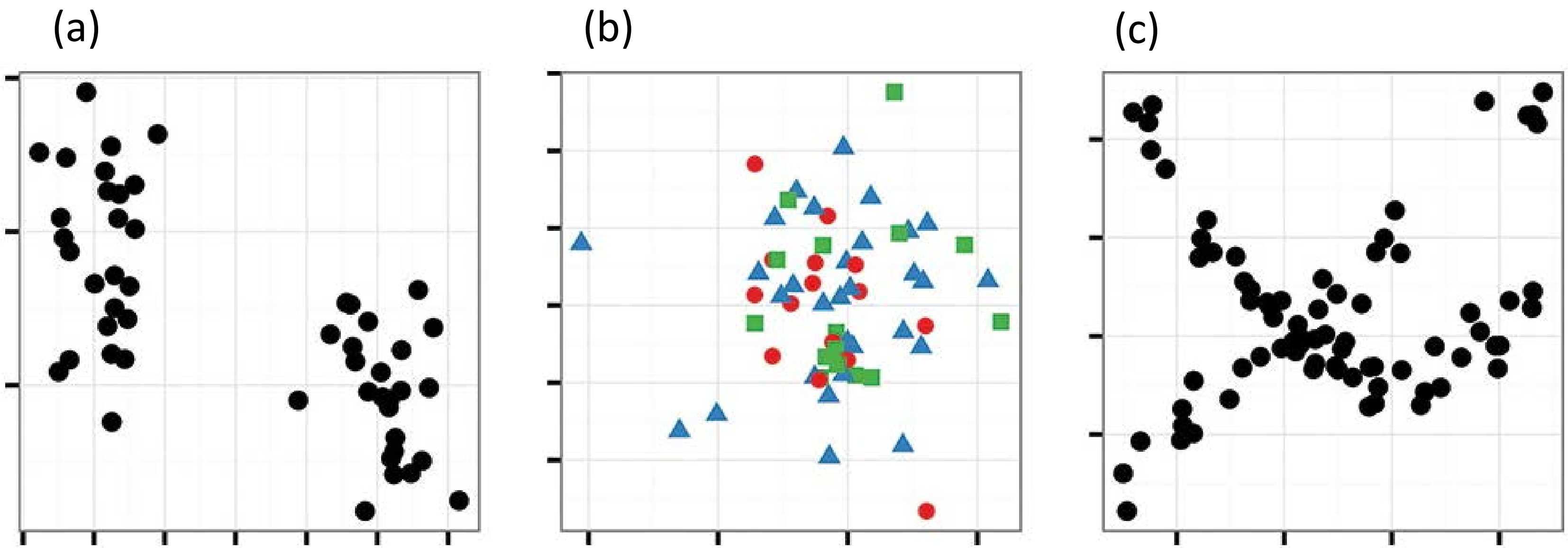
- Best to show quantitative variables with position or length
- Bar charts:
  - Best encoding via length $\rightarrow$ start at 0
  - Avoid stacked bars (not aligned), where possible
- Dot charts:
  - Best encoding via position along a scale $\rightarrow$ start at 0
- Frequency data:
  - area/color encoding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

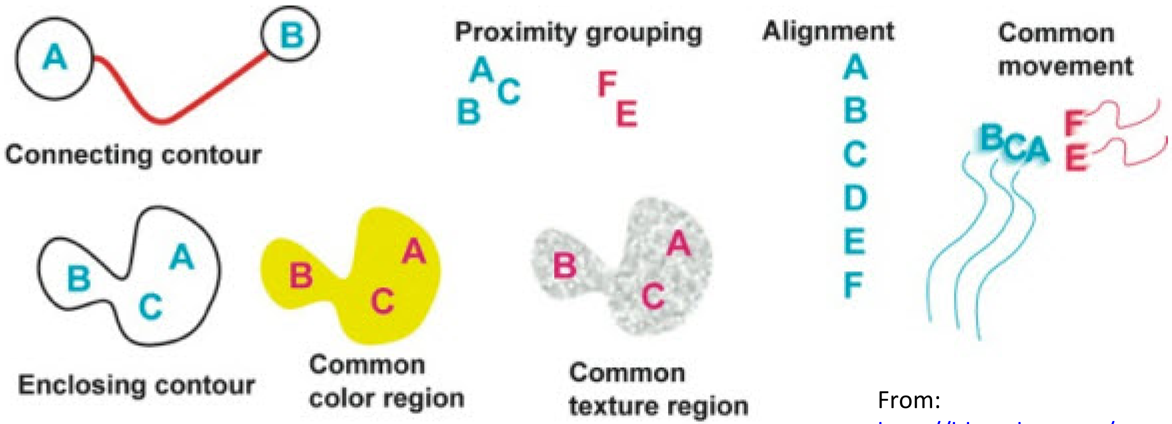
Gestalt principles

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



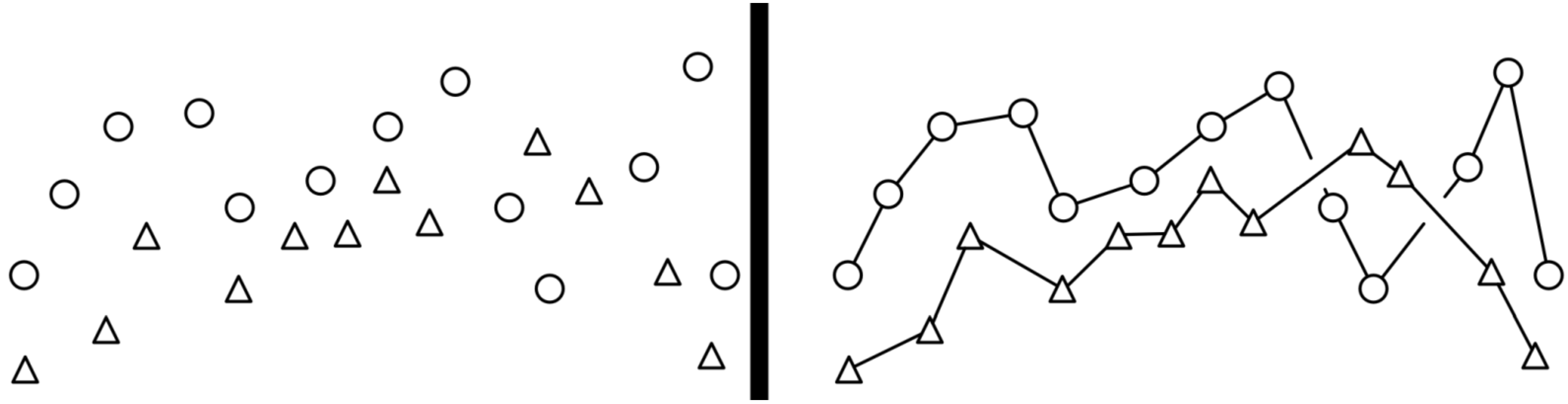
Gestalt principles

More gestalt ideas



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

Why lines are good in time series graphs

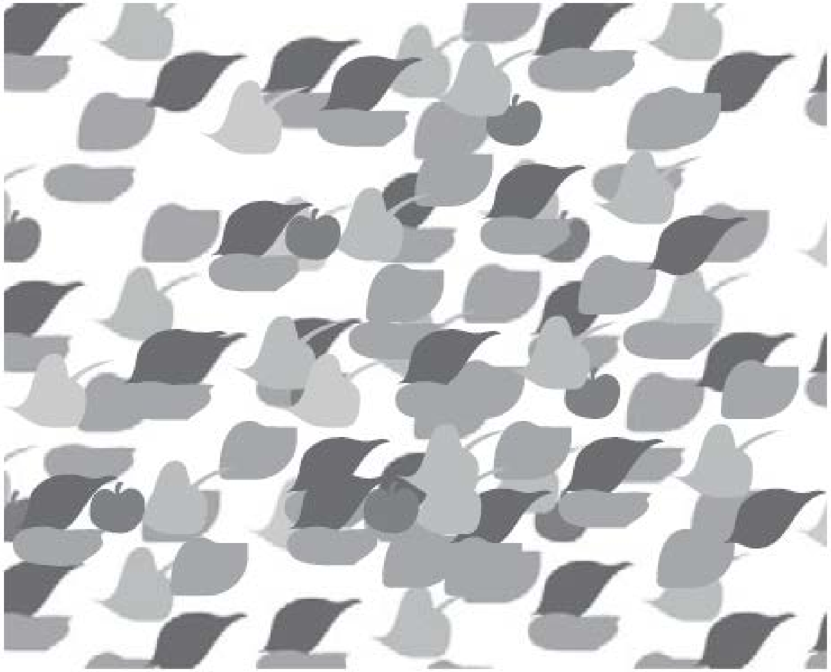


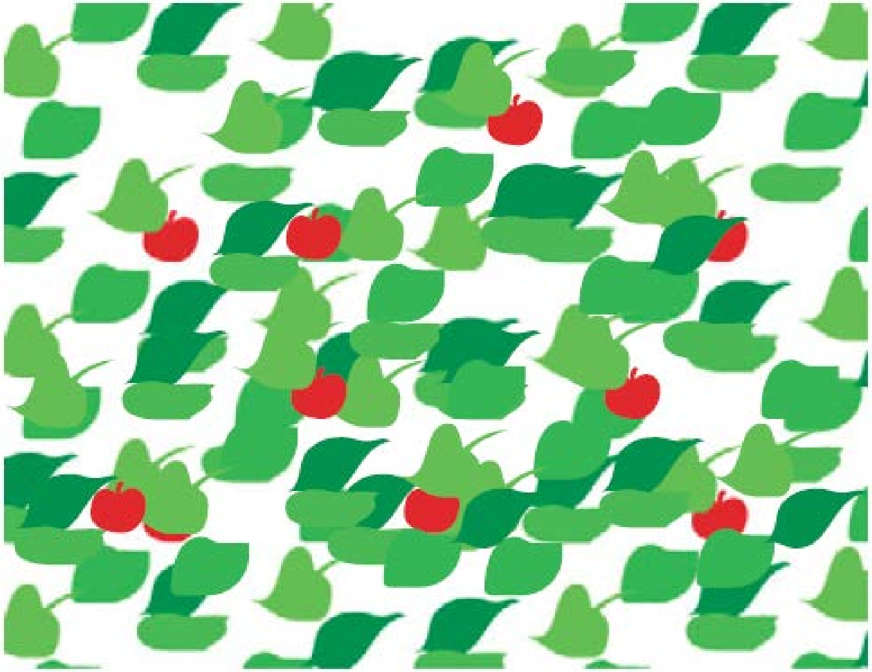
Color: Functions in data graphics

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





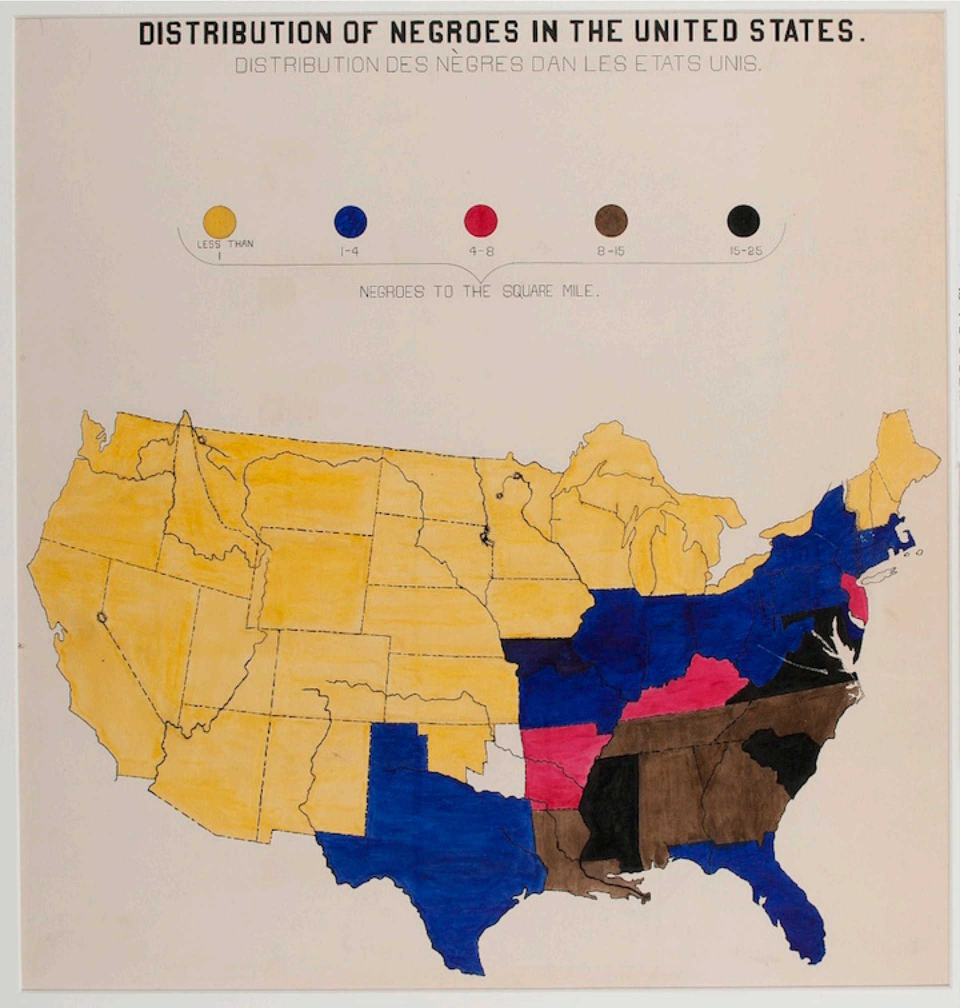
From: Colin Ware, *Information Visualization: Perception for Design*

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.

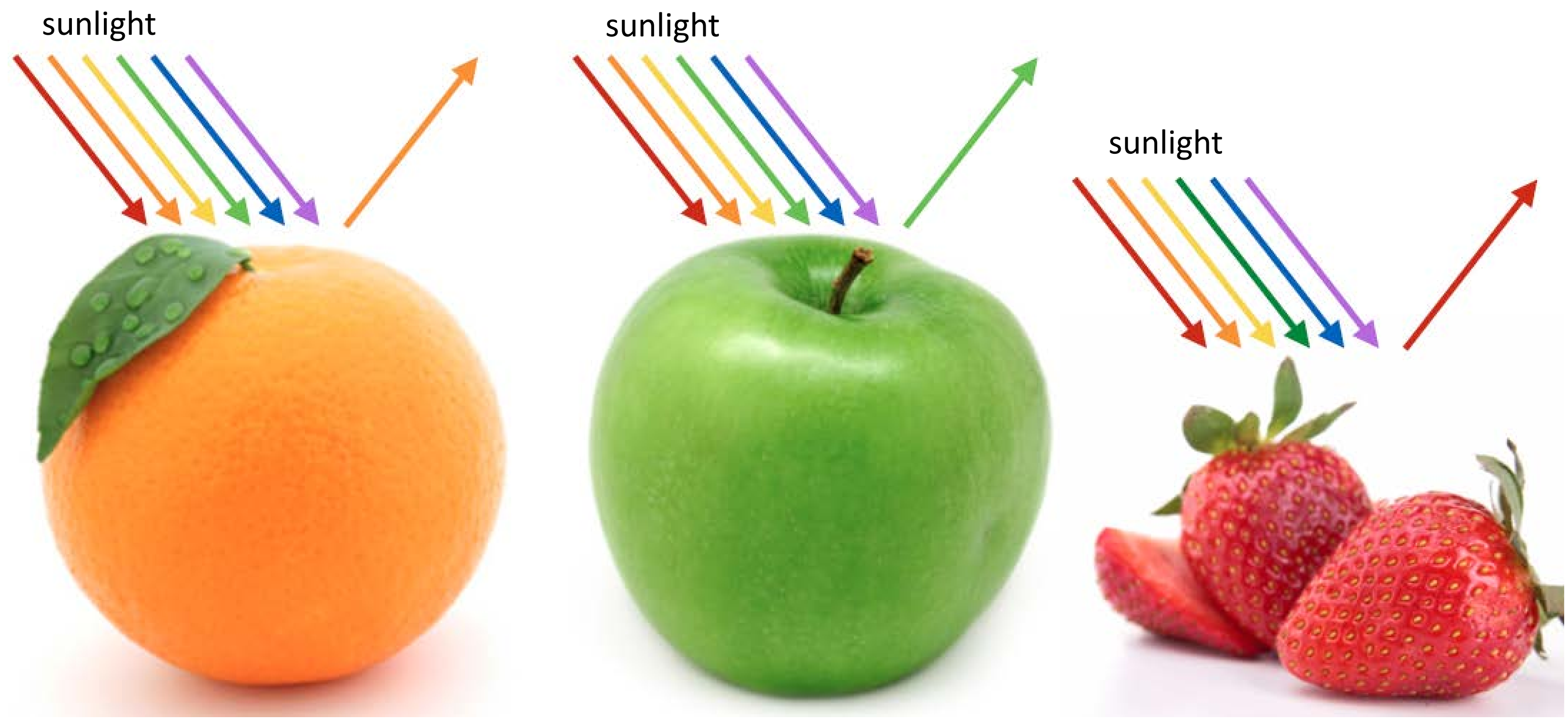
Q: Are there more Negroes per sq. mile in Texas or Louisiana?



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

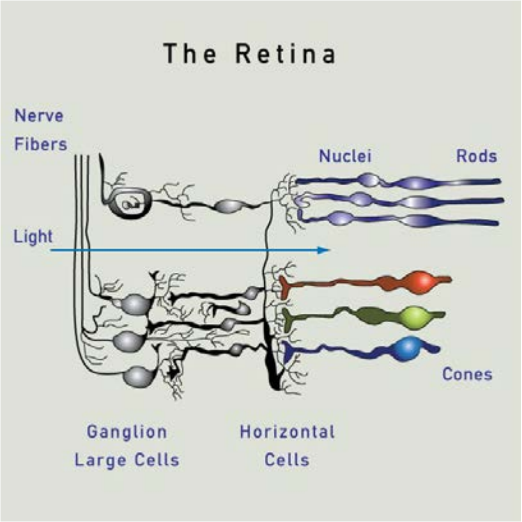
Color: Aspects in data graphics

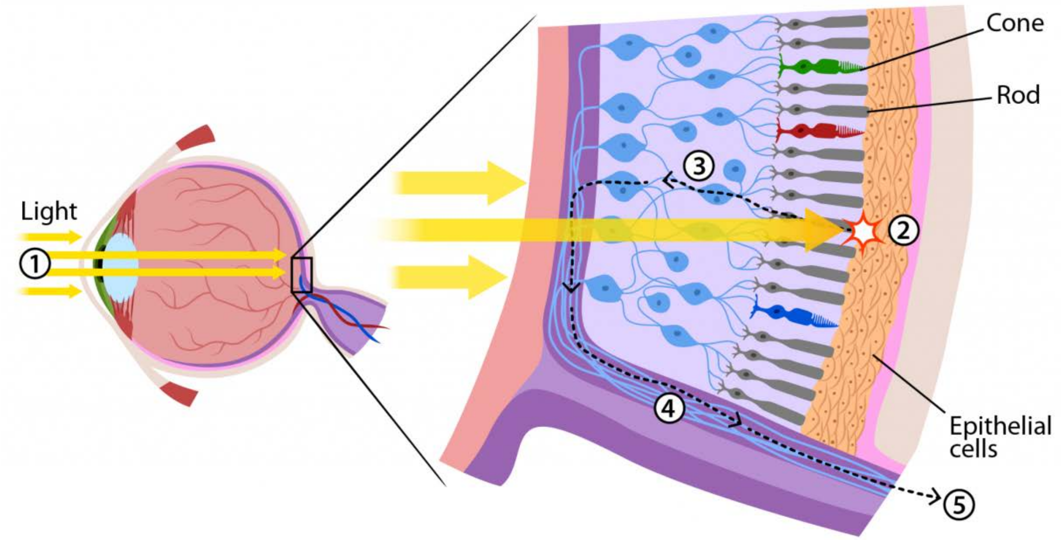
- Perception: trichromatic theory
  - How the eye sees color
- Color spaces:
  - RGB (additive), CMYK (subtractive)
  - HSV, HCL: perceptually based
- Color palettes for computer graphics
  - ColorBrewer: sequential, diverging, qualitative
  - Color-blind safe ?
  - Photocopy safe ?
- Transparency

Perception: The human eye

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

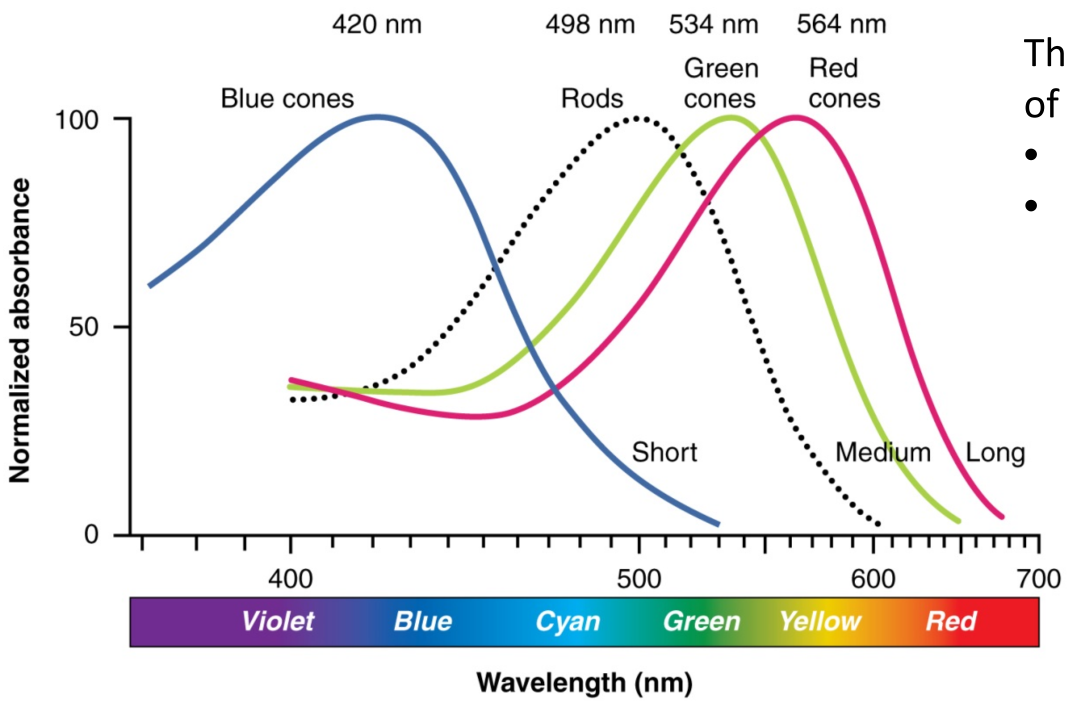
It is of interest to see the wide variety of ways this is conveyed in scientific diagrams:





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



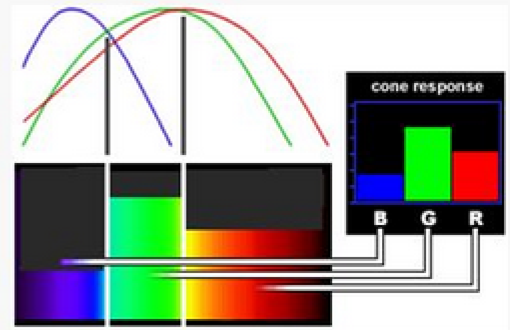
This figure also stimulates questions of scientific visualization

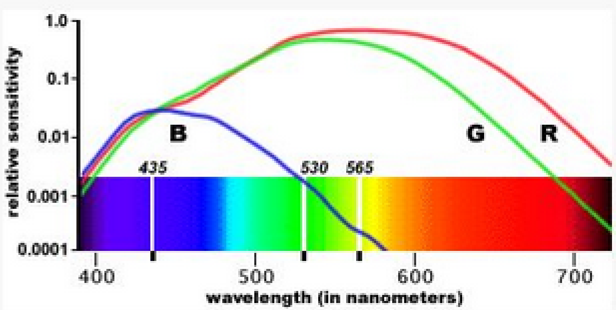
- Rods & cones are "normalized"
- Are they all equal in what we see?

Perception: color sensitivity

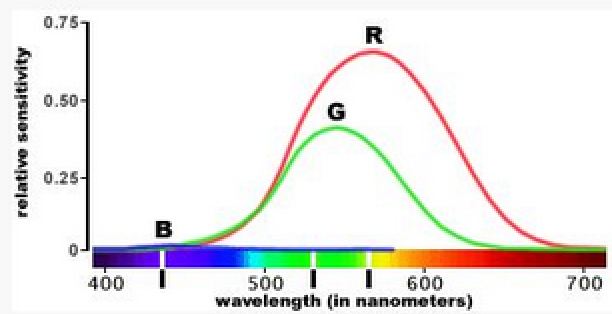
This slide, found at http://slideplayer.com/slide/6329532/ shows color sensitivity on three different scales

- 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

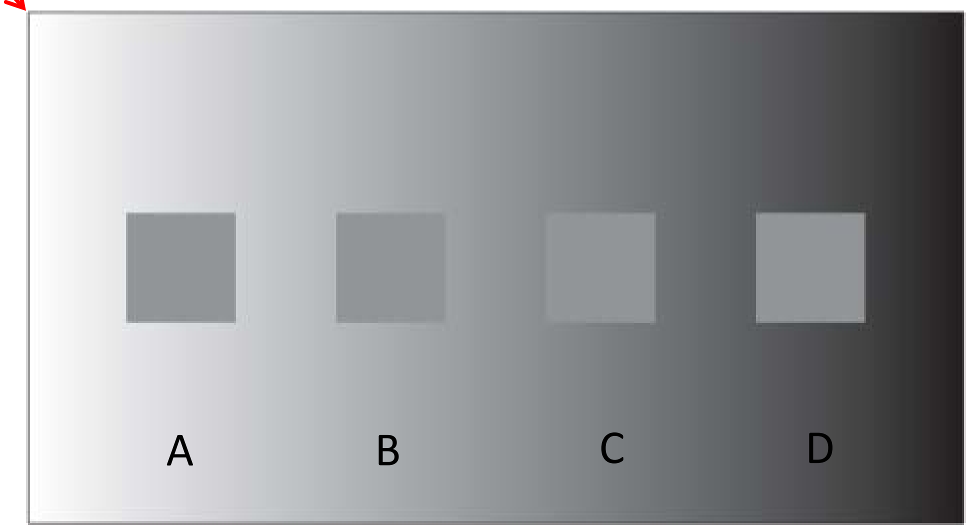
Perception: Contrast

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?

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

gray square



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.

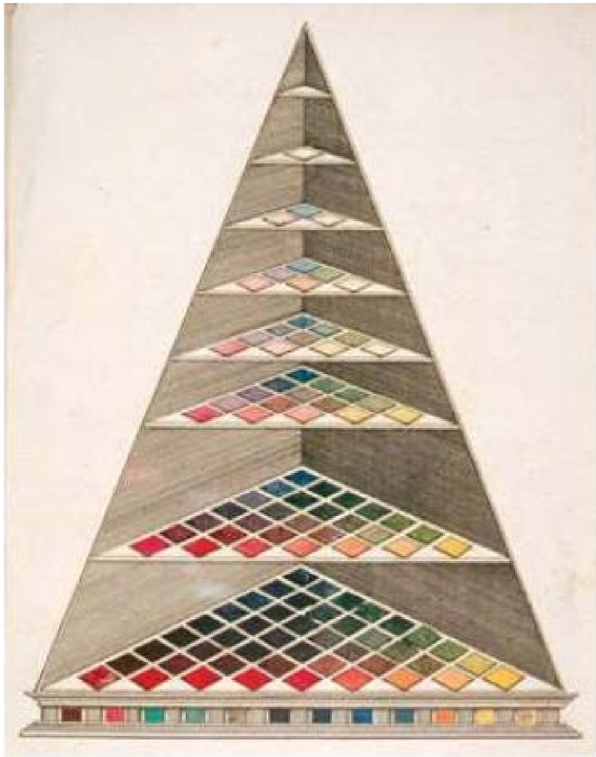
TIP: For presentations, light text on a dark background is often preferred.
I don't do this, because I'm also concerned with printing slides.
(With LaTeX Beamer, it is easy to have separate setups for presentation & print)

Early color theory

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

Introduces the idea of color "primaries"

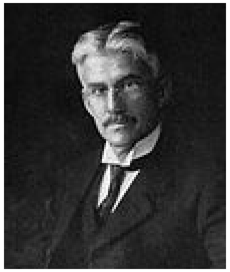
Johannes Lambert (1772) – A color pyramid, composed of 7 layers

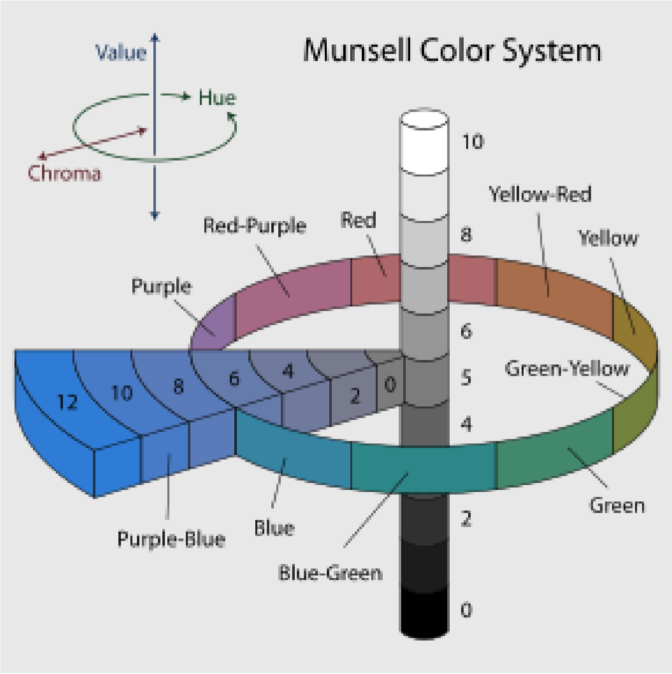


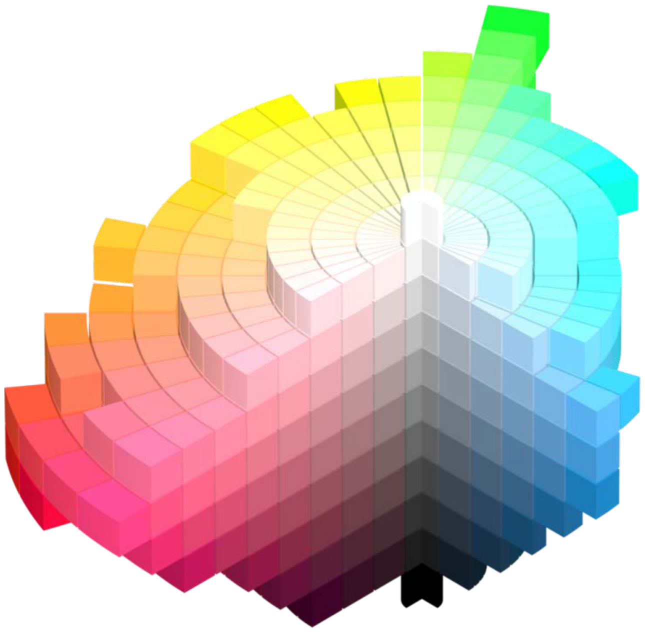
Introduces the idea of color saturation

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

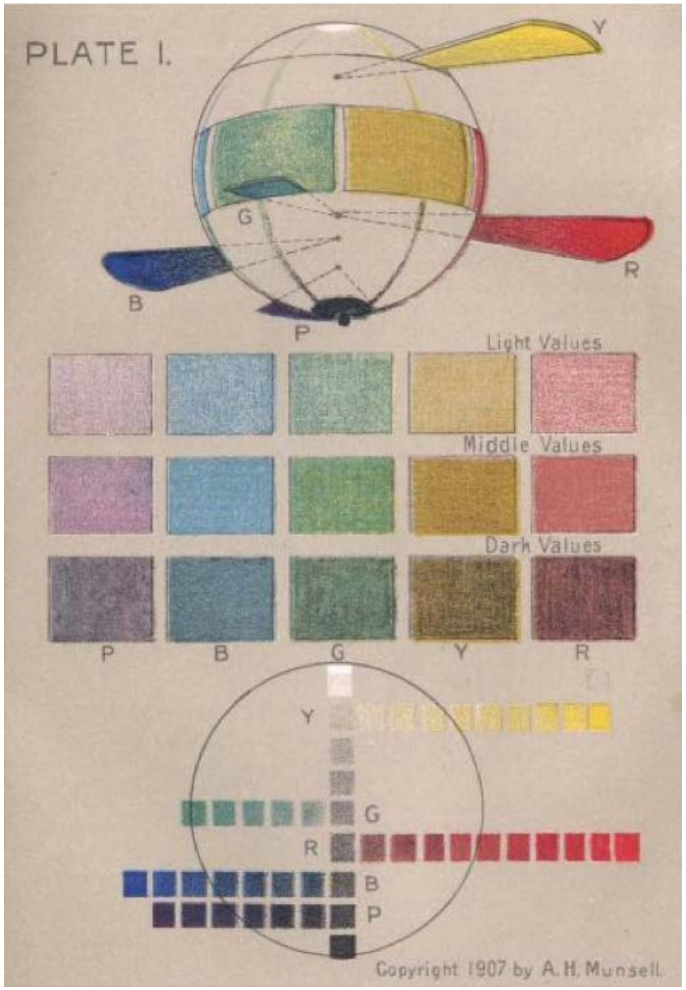


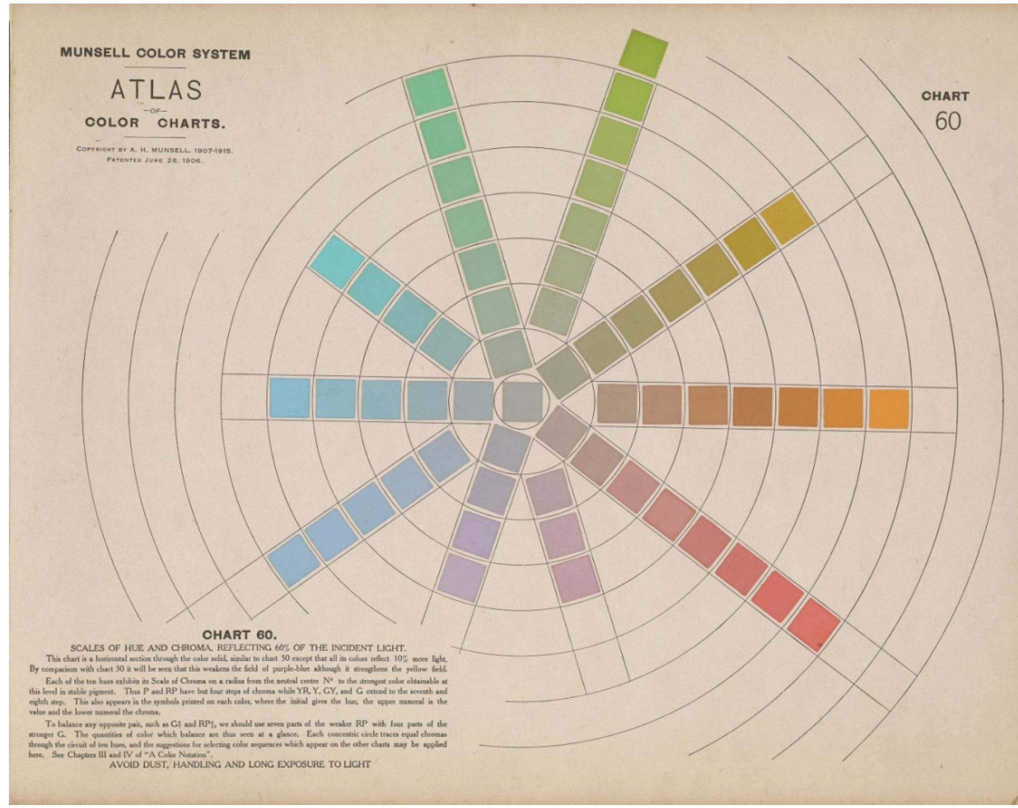




By SharkD - CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=8401562

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



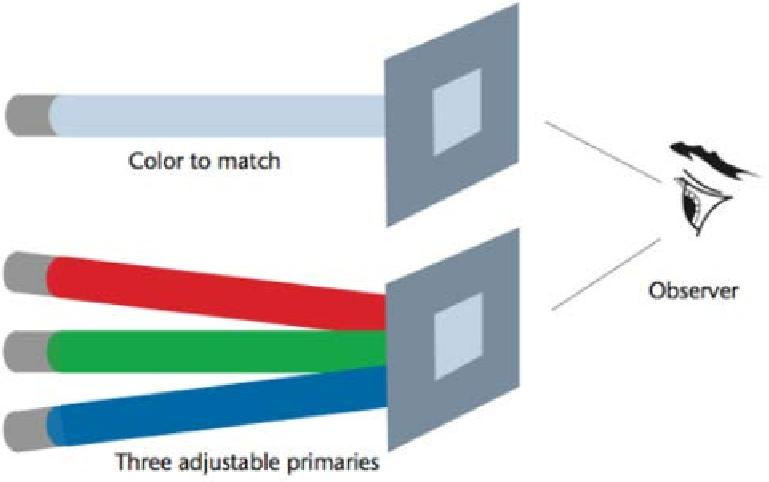


CIE color space

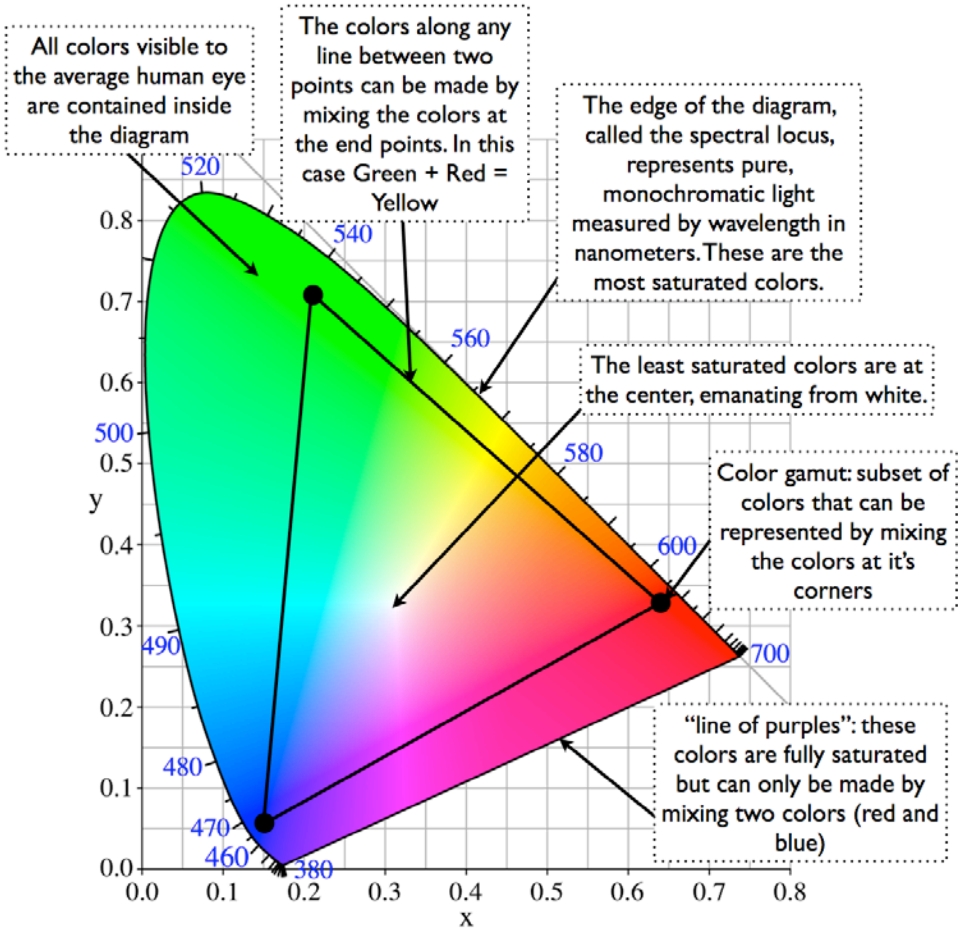
- How do we know about the perceptual properties of colors, taking spectral sensitivity into account?

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



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).

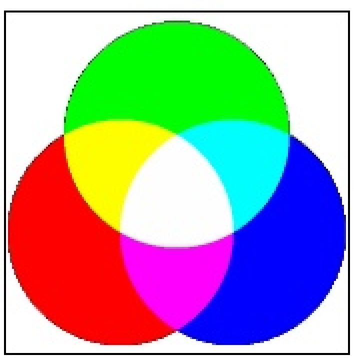
There are eventually a variety of CIE color spaces (CIElab, CIEluv, …) and lots of formulas for converting among them.

Color space: RGB & CMYK

Enter technology: how to produce color?

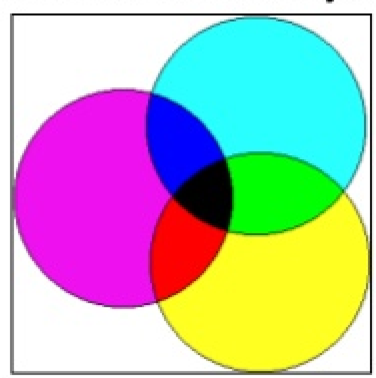
- RGB:
  - Combine light: R + G + B = white
  - Used in computer monitors, TV, film
- CMYK:
  - Combine ink: Cyan + Magenta + Yellow = Black
  - Used in color laser printers, the print industry

Additive colour system



Mixture of primary light colours-
White

Subtractive Colour System



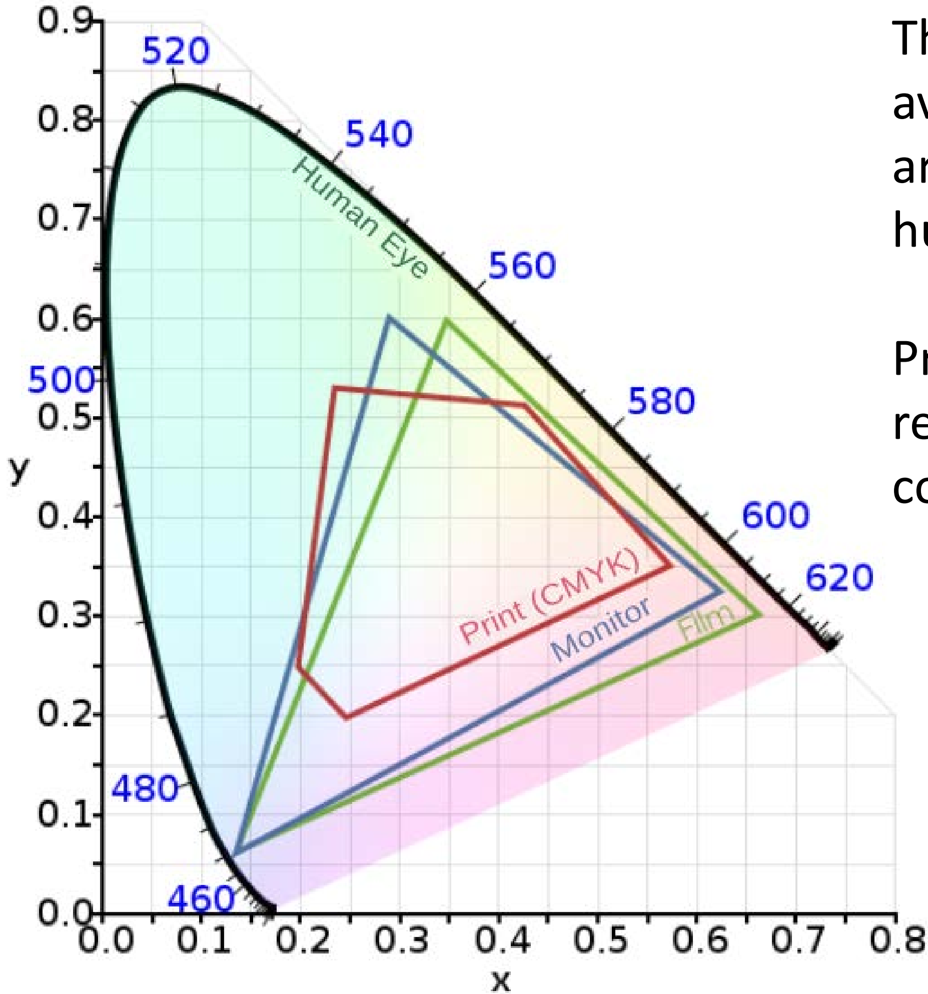
Mixture of primary pigment colours
Black

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

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	183	158
23	bisque4	#8B7D6B	139	125	107
24	black	#000000	0	0	0
25	blanchedalmond	#FFEBCD	255	235	205

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

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

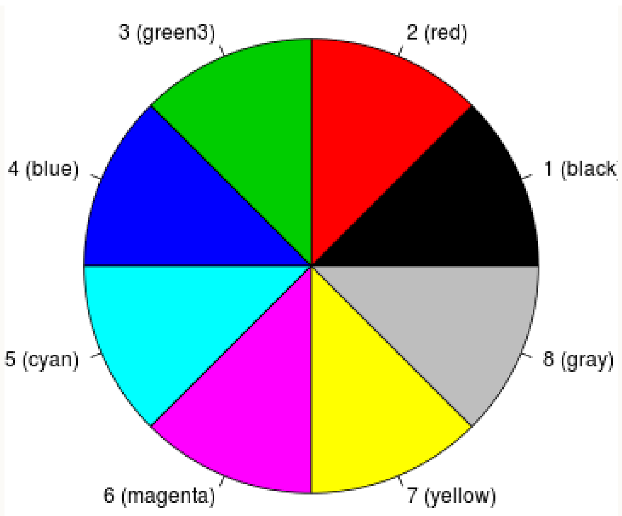
76	darkgoldenrod1	#FFB90F	255	185	15
77	darkgoldenrod2	#EEAD0E	238	173	14
78	darkgoldenrod3	#CD950C	205	149	12
79	darkgoldenrod4	#8B6508	139	101	8
80	darkgray	#A9A9A9	169	169	169
81	darkgreen	#006400	0	100	0
82	darkgrey	#A9A9A9	169	169	169

See: http://research.stowers.org/mcm/efg/R/Color/Chart/ for R color charts

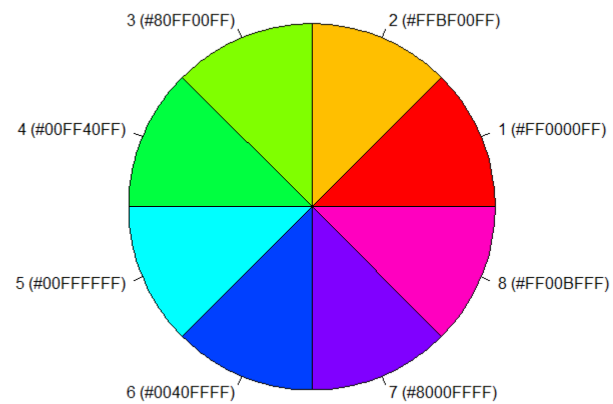
Software: palettes

- 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)
```

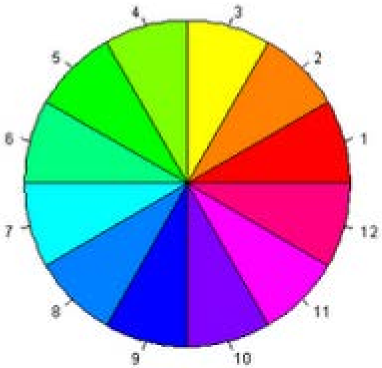


palette(rainbow(8)); pie(...)

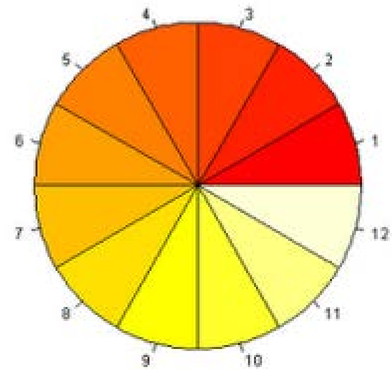


R: basic palettes

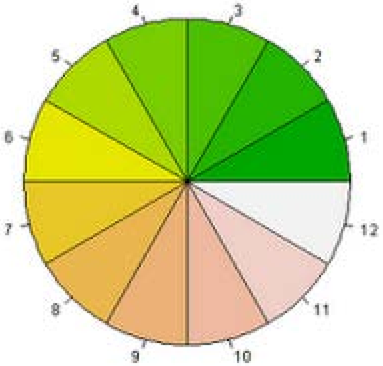
```
n <- 12
pie(rep(1, n), col=rainbow(n))
```



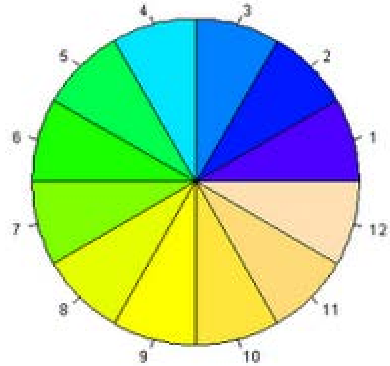

```
pie(rep(1, n), col=heat.colors(n))
```




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

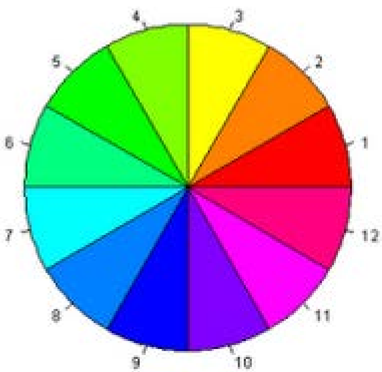



```
pie(rep(1, n), col=topo.colors(n))
```

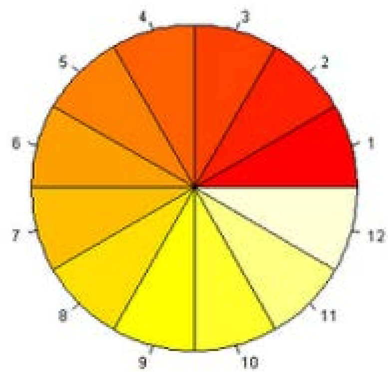


R: basic palettes

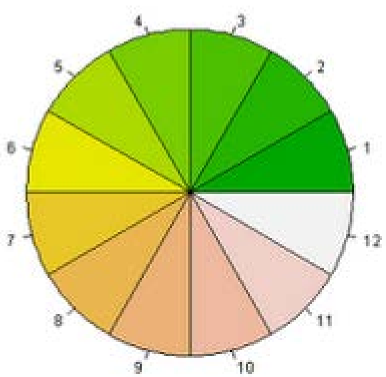
rainbow



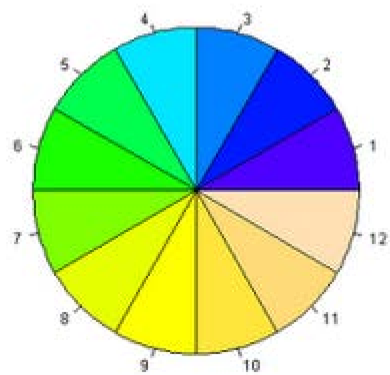
heat



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

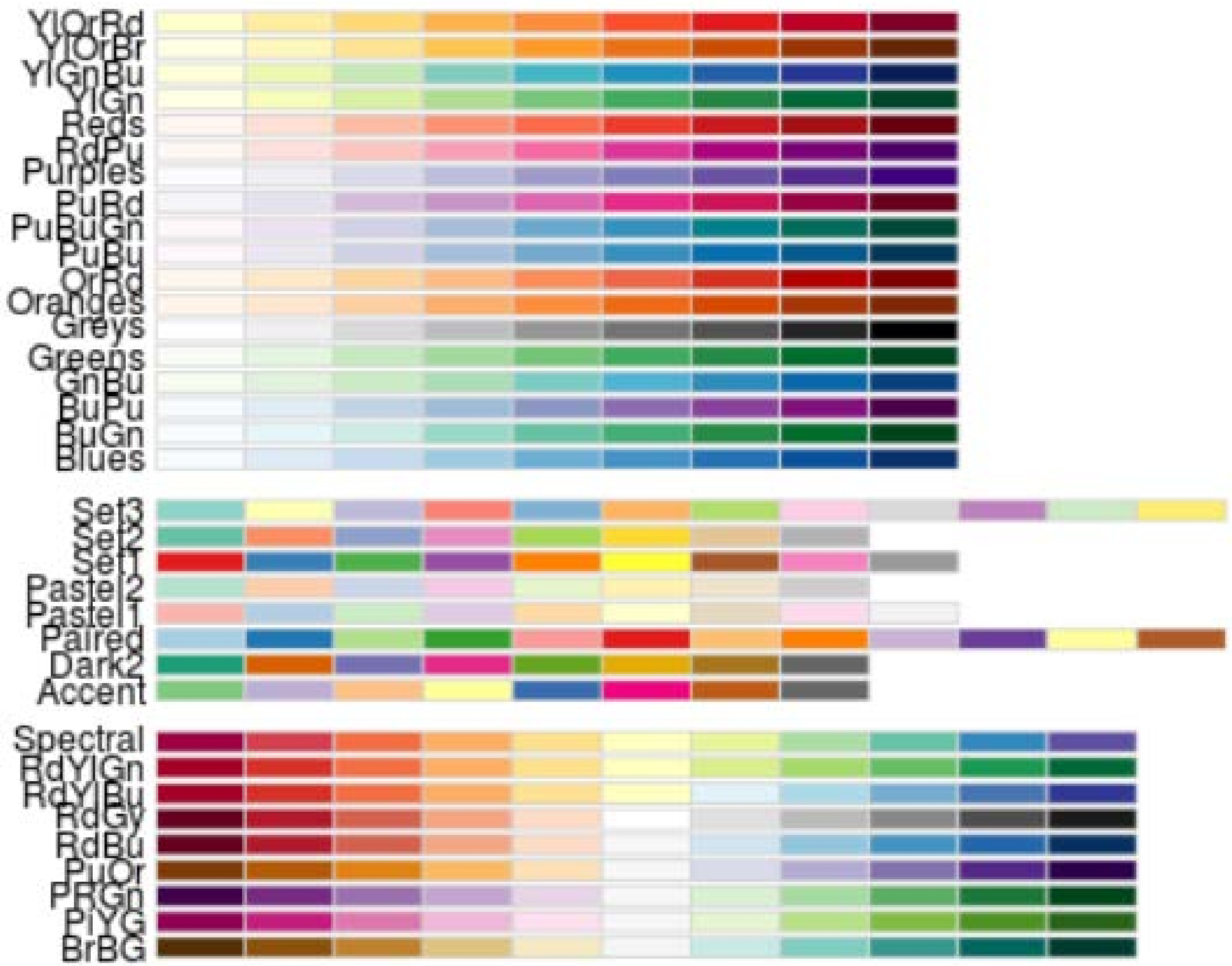
palettes: ColorBrewer

RColorBrewer::display.brewer.all()

sequential

qualitative

diverging

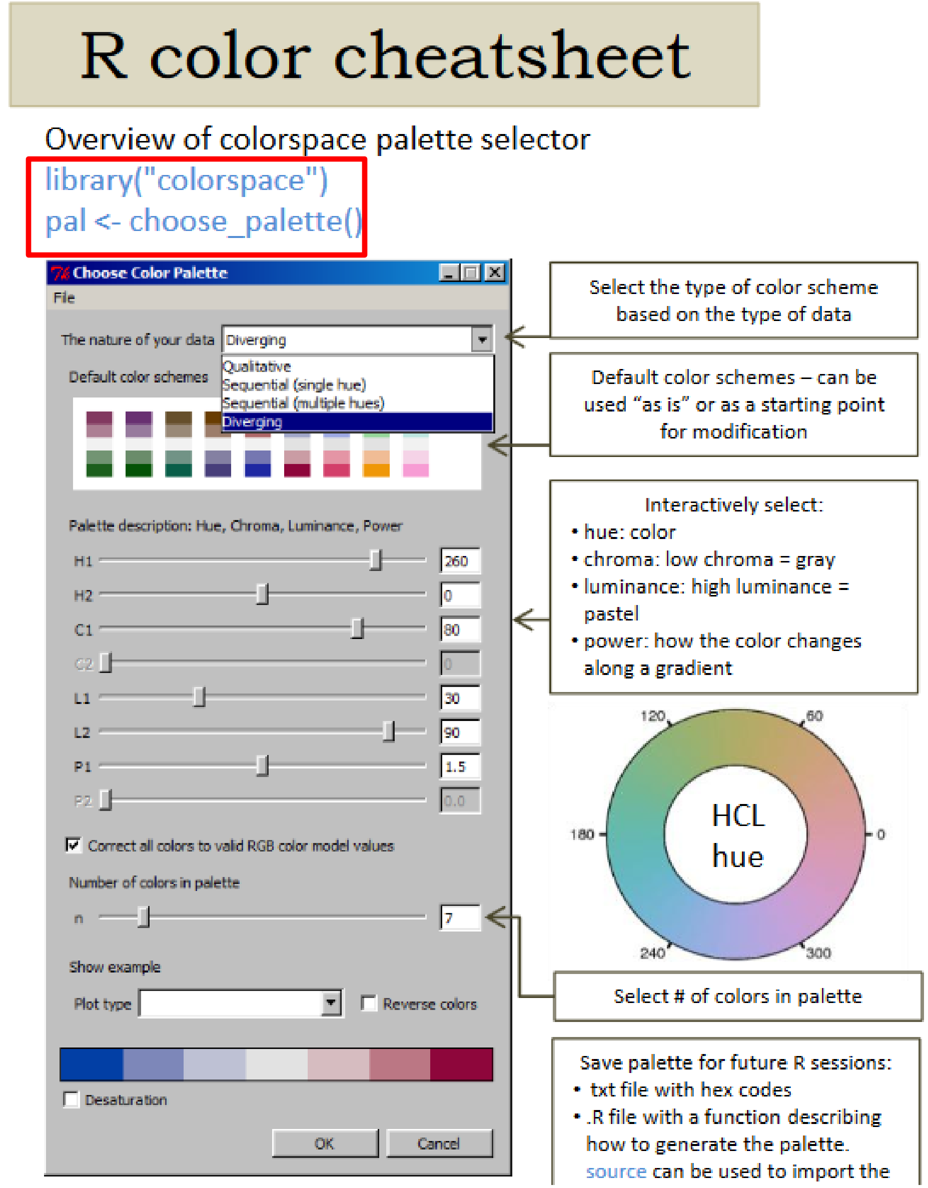


R: choose_palette()

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



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

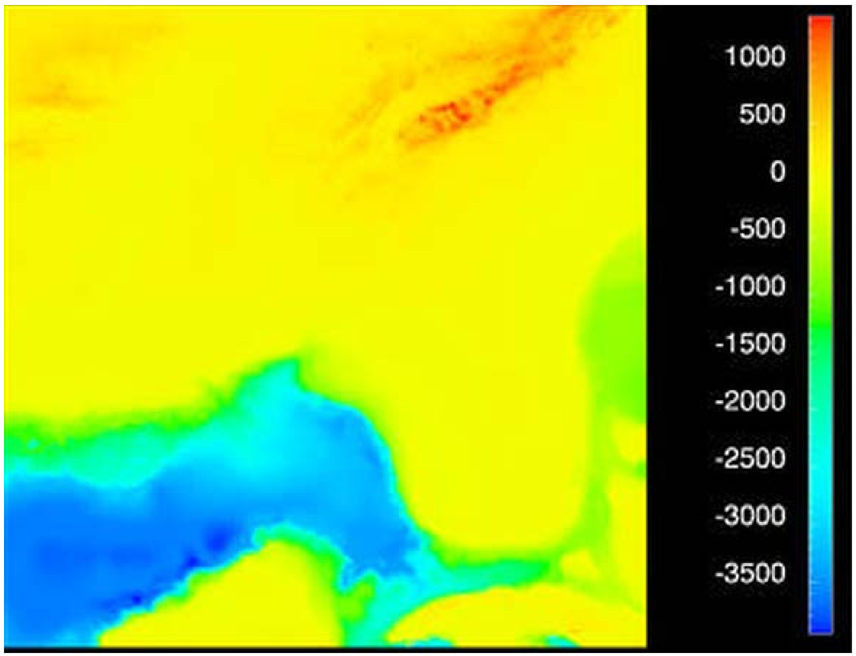
ColorBrewer palettes

viridis palettes

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

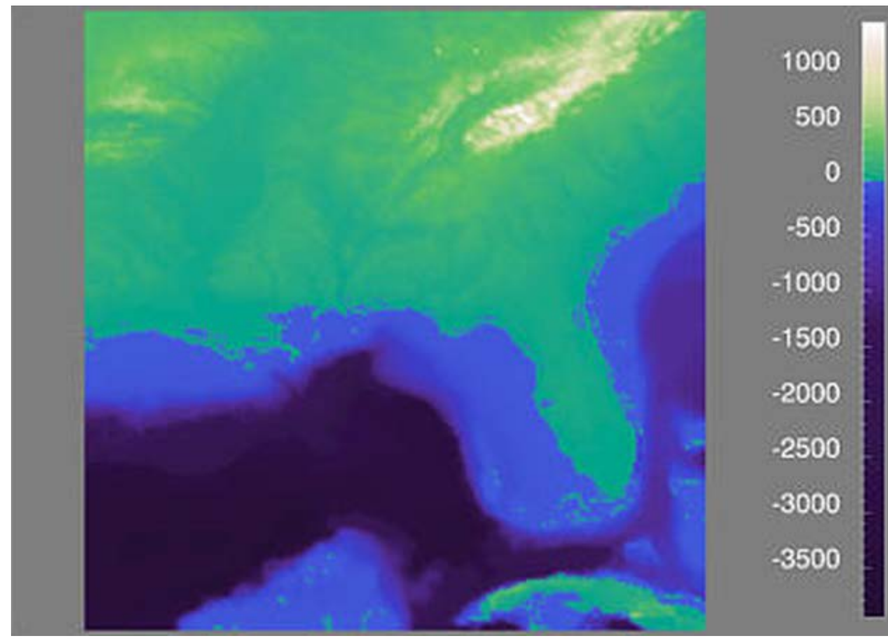
Comparing palettes

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

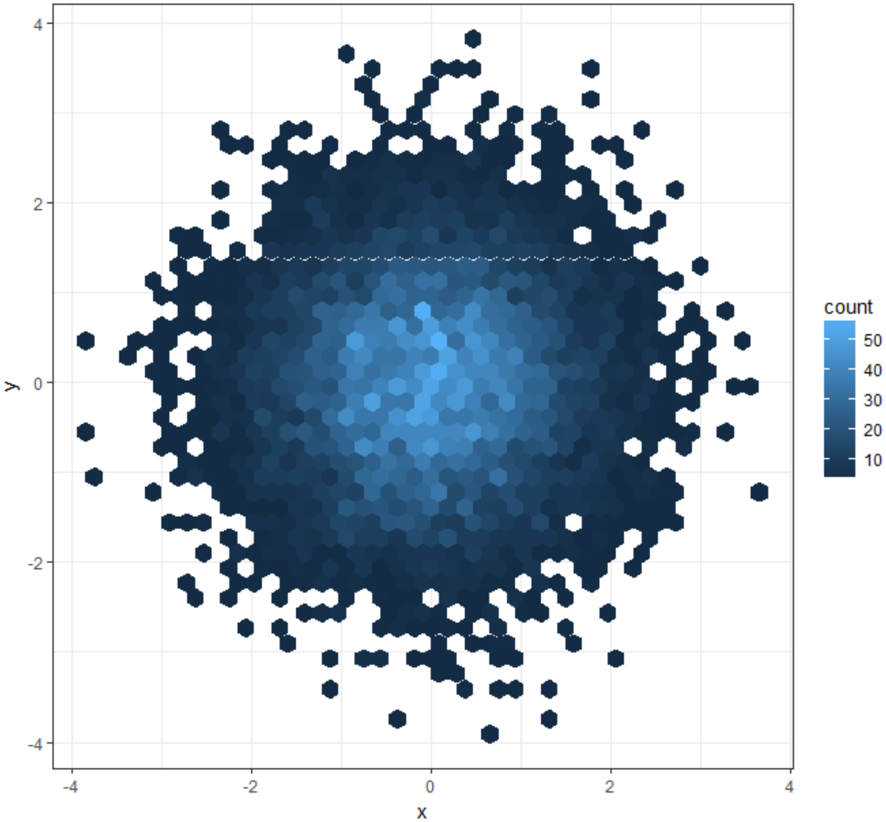


This color scheme was designed to reveal the essential topography of the map & to have perceptually equal elevation steps

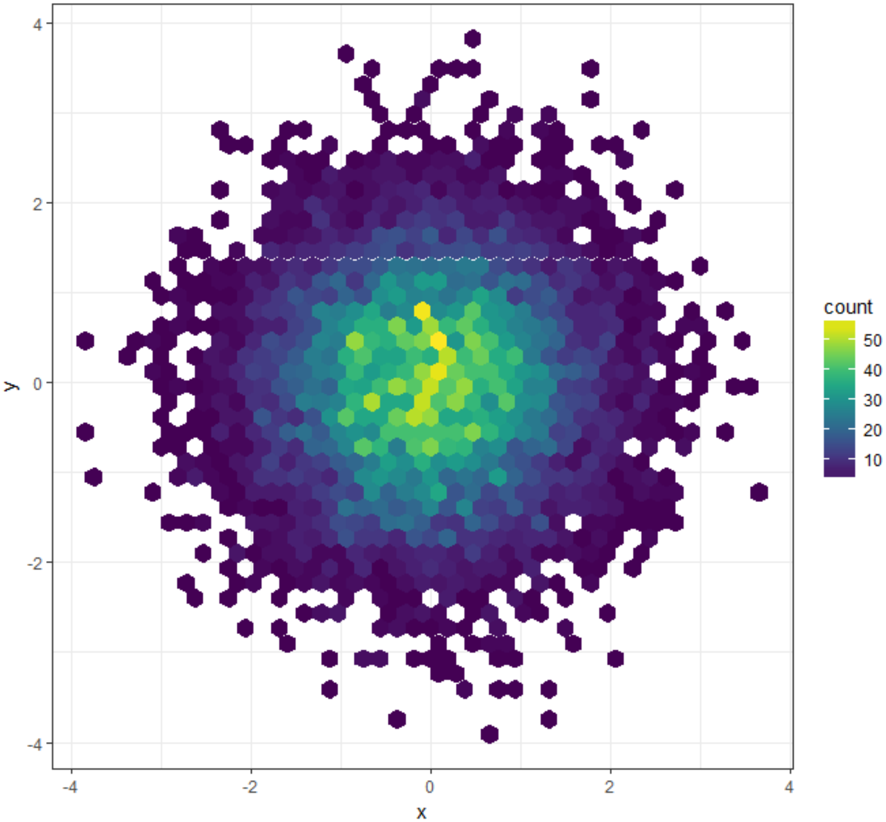
From: http://www.research.ibm.com/people/l/lloydt/color/color.HTM

Comparing palettes

ggplot default palette



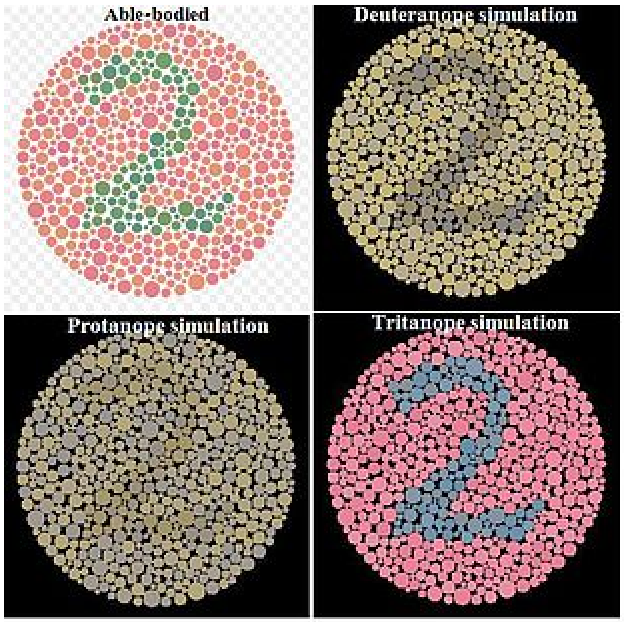
viridis default palette




```
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()
```

Colorblindness



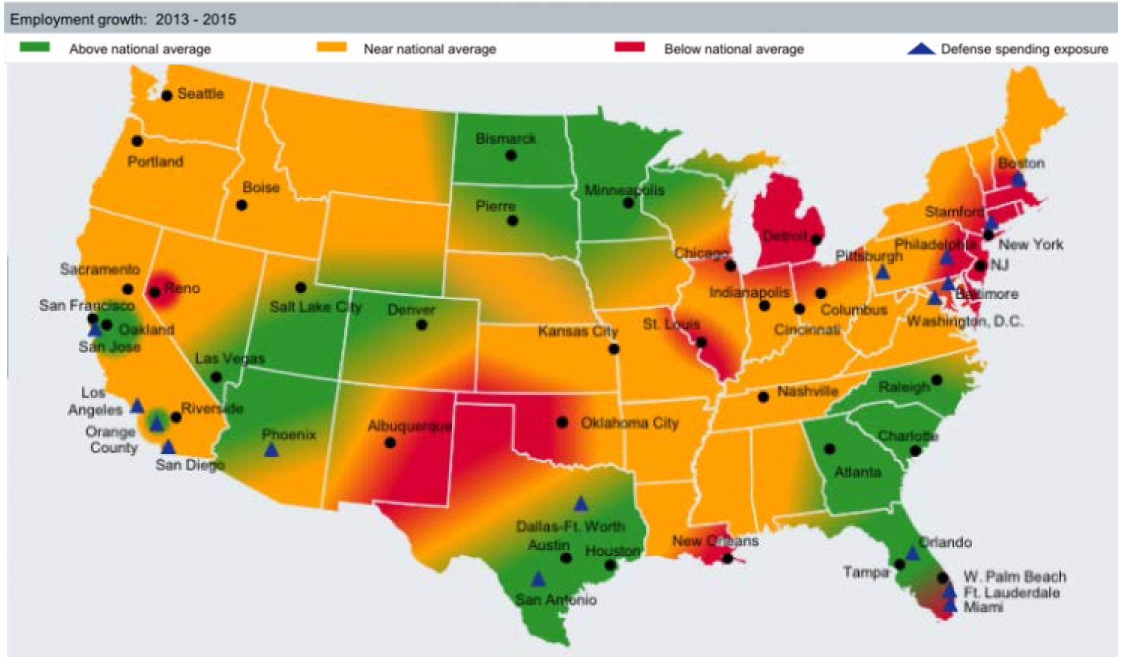
Most common forms are genetic, and involve a deficiency in one of the cone type sensitivities

- 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

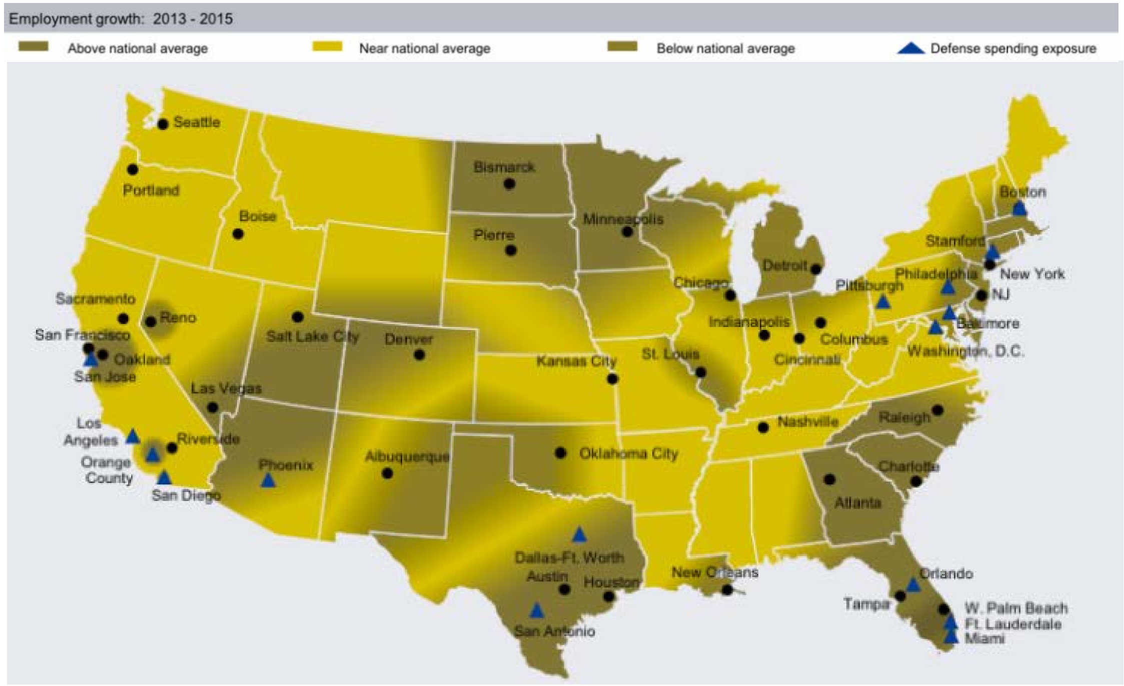
TIP: Avoid color scales with main variation between red & green



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

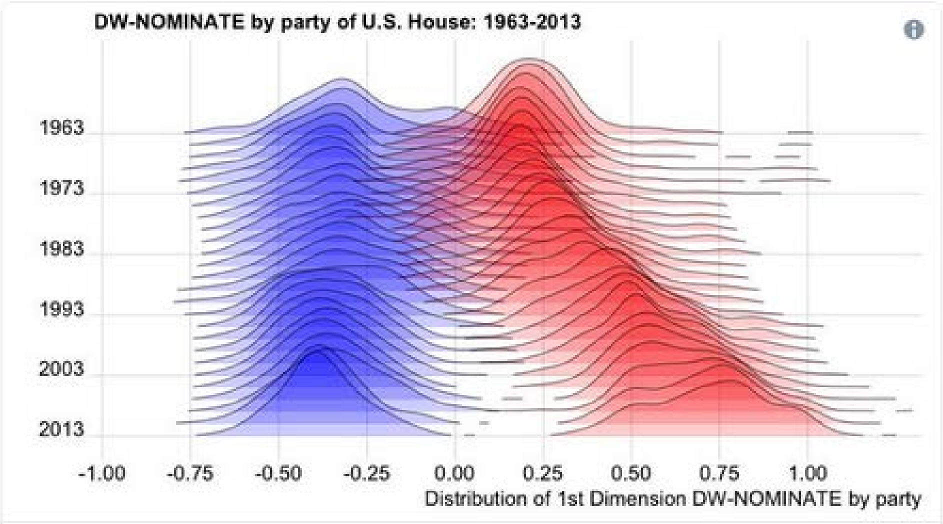
From: http://www.mena-forum.com/category/u-s-a/

Transparency

Colors can be made partially transparent, by adding an “alpha” channel,

$0 \le \alpha \le 1$ (opaque)

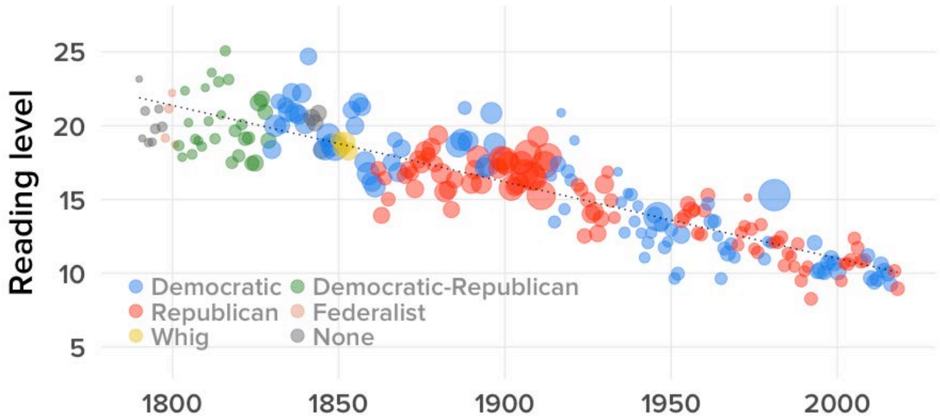
Filled areas combine to look more saturated
What do you see here?



Increasing polarization of votes in the US House

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

Different colors “blend”
What do you see here?

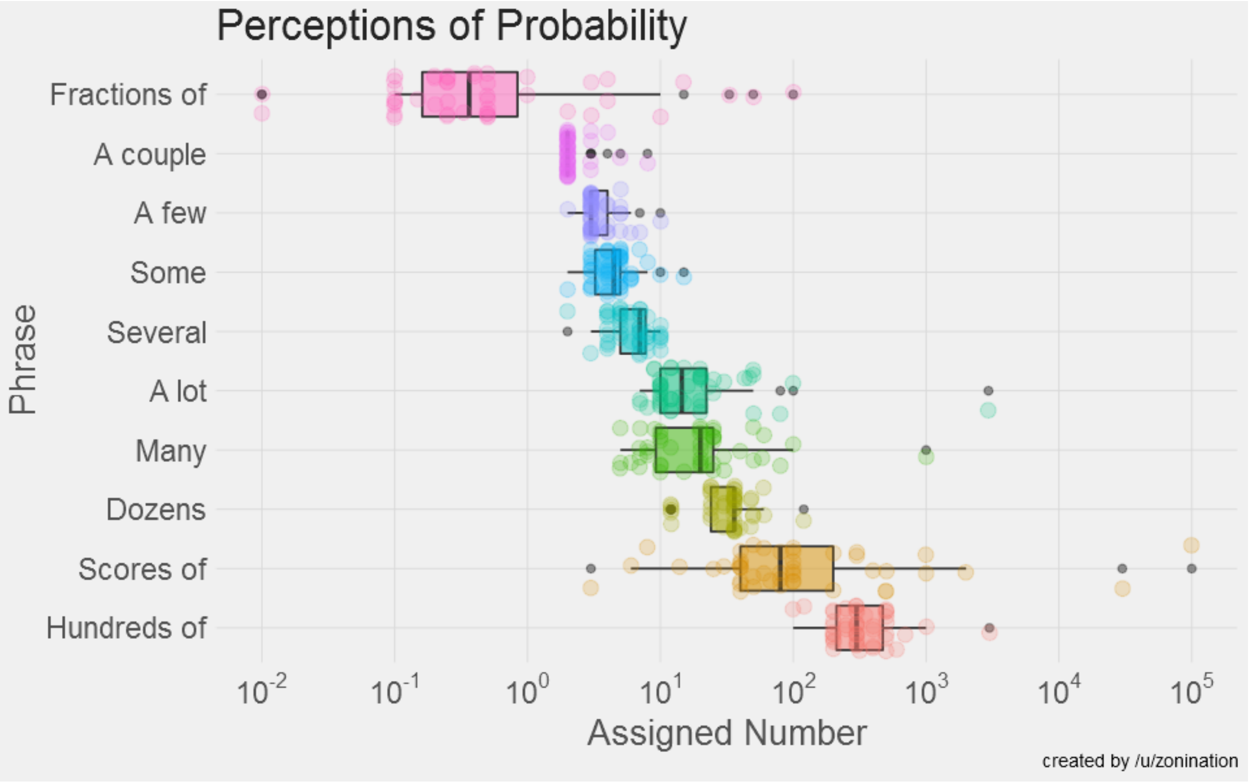


Reading level of US State of the Union Addresses

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?

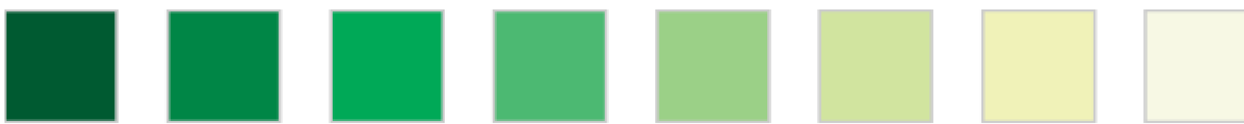


From: https://github.com/zonination/perceptions

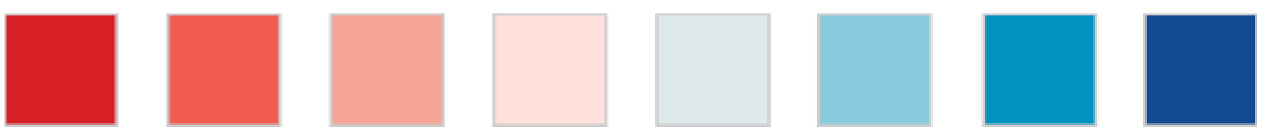
Color: Lessons

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

  - <u>Sequential</u>: use a small range of hues of varying intensity



  - <u>Diverging</u>: Use two sequential schemes, decreasing toward the middle



Images from: Stephen Few,
http://www.perceptualedge.com/articles/visual_business_intelligence/rules_for_using_color.pdf

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

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