

## Graphical Perception



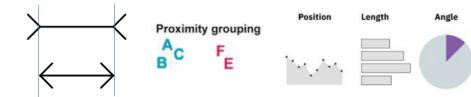
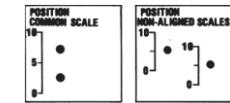
Michael Friendly  
Psych 6135

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



## Topics

- Perception & Cognition
  - Encoding, decoding
  - Top-down vs. bottom-up processing
- Perceptual aspects
  - Illusions
  - Gestalt factors
  - Accuracy of decoding
- Cognitive aspects
  - Memory
  - Color

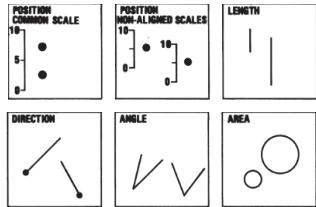


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## Graphical Perception

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

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

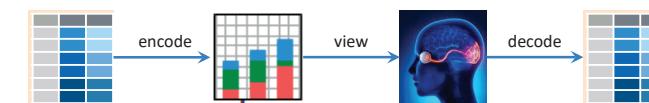


- What determines the ability of graph viewers to:
  - Make **comparisons** (which is larger?)
  - **Estimate** a magnitude?
  - See **patterns**, trends, unusual features?

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## 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

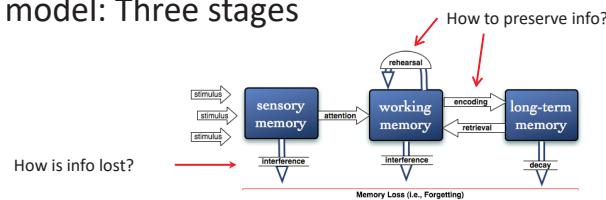


- Encoding should rely on features that can easily be decoded
- Often, easier said than done! The devil is in the details

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# Visual & cognitive systems

- A simplified model: Three stages



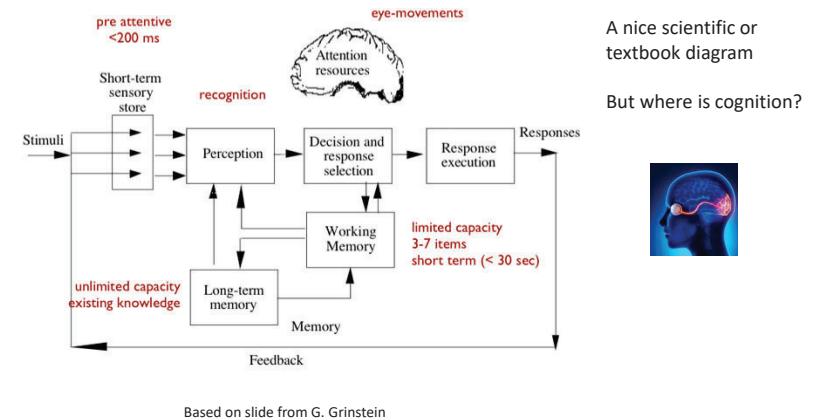
- Sensory (iconic) memory**
  - pre-attentive, automatic, feature detection
  - massively parallel, short duration, easily fooled ("thinking fast")
- Working memory**
  - requires attention, limited capacity (~ 4-6 "chunks")
  - memory aids: rehearsal; imagery
- Long-term memory**
  - real-world knowledge,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

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# Perception vs. cognition

Another coarse distinction:

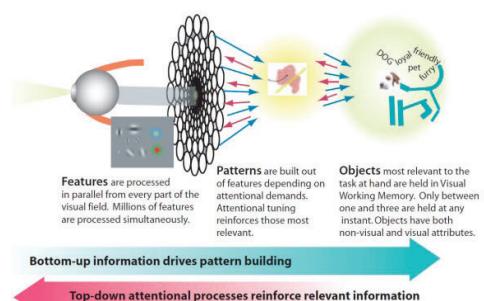
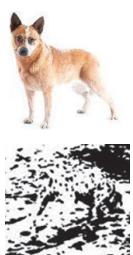
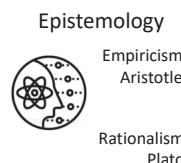
- Perception:** Processing of the signals coming in: what you **“see”**
- Cognition:** How you **understand** and **interpret** what you see



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# 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”



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# 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.

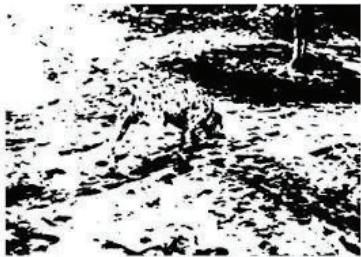
The distinction of **color** is immediate & **pre-attentive**  
You only have to scan for 5s & count them.

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

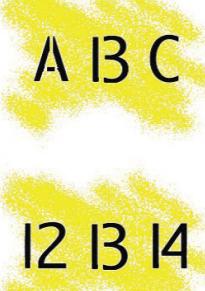
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## Perception: Top-down

What is in this scene?



What is the middle character?



What here?



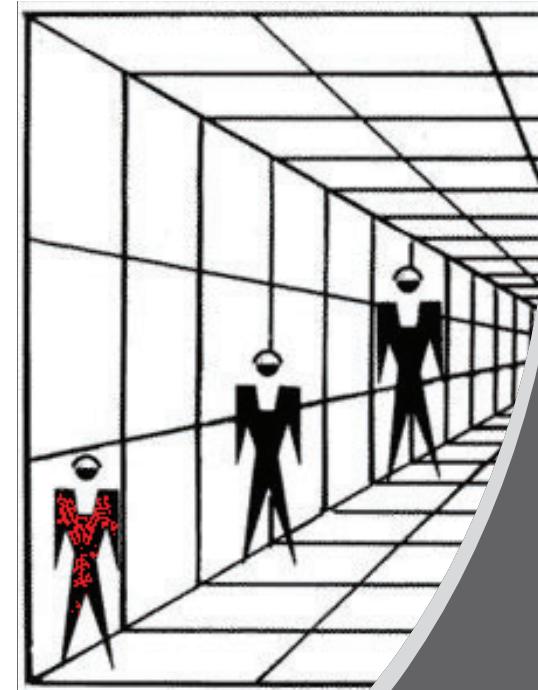
An ambiguous figure!

What is the middle letter in each word?

TAE CAT

All of these are demonstrations of the role of **expectations** (top-down) in determining what we "see"  
Gregory ('70): perception as **constructive**, depends on prior knowledge

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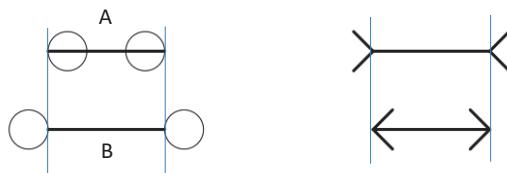
## Illusions: The Eye-Brain Barrier

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?

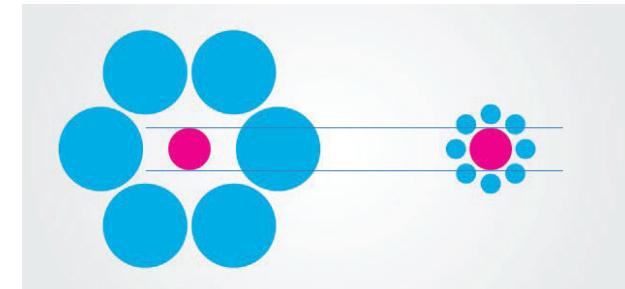


Surrounding context pulls perception of length in its direction  
This is the famous **Müller-Lyre** illusion

## Illusions: Area

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

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



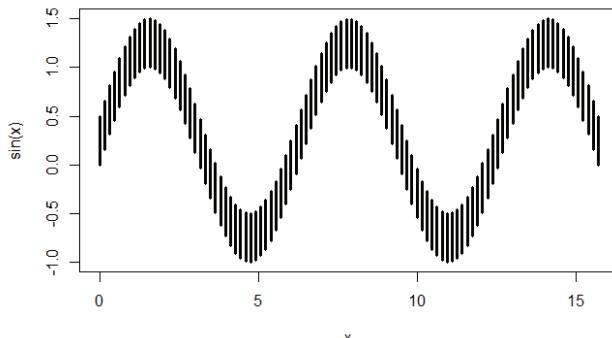
Surrounding **context** pulls perception of area against the background  
This is often called the **Ebbinghaus** illusion or the **Tichener** illusion

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## Illusions: Length

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



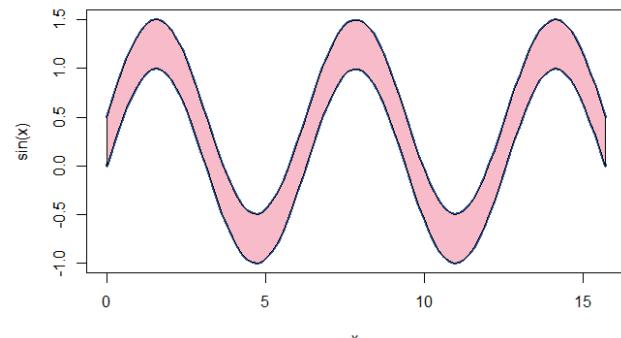
R code:

```
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)
```

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## Illusions: Difference

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



This is sometimes called the “sine illusion”

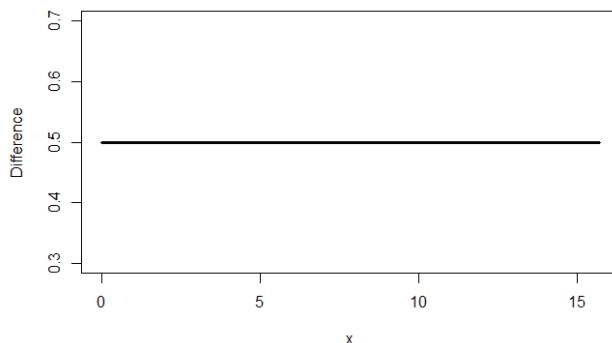
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## Illusions: Difference

Plotting the difference directly gives the answer.



OMG!

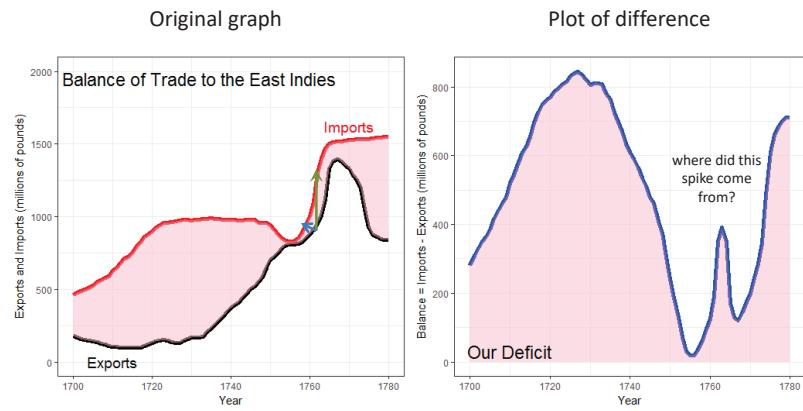


Why does this matter?

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## Distances between curves

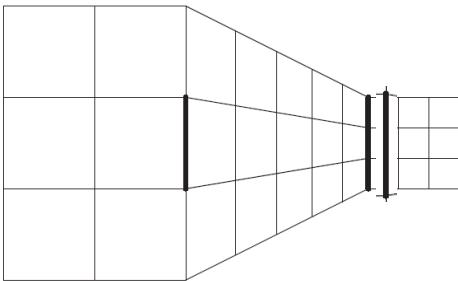
Playfair didn't know that judgments of distance between curves are **biased**  
We tend to see the **perpendicular** distance rather than the **vertical** distance



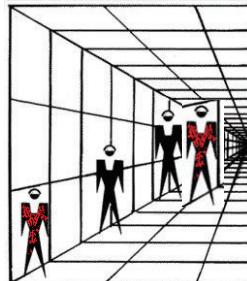
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## Illusions: Perspective

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



Which figure is tallest?  
Or, all the same?



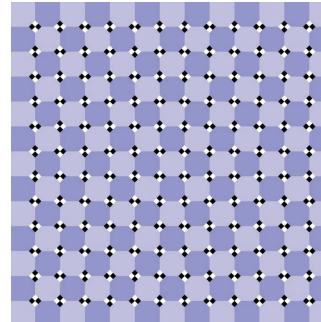
This is often called the **Ponzo** illusion: We judge the **size** of real-world objects relative to their **background** and **perspective**.

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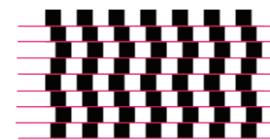
## Context illusions: Lines, shapes

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

Are the squares straight or tilted?



Are the pink lines straight or curved?



Does the rectangle change in darkness?

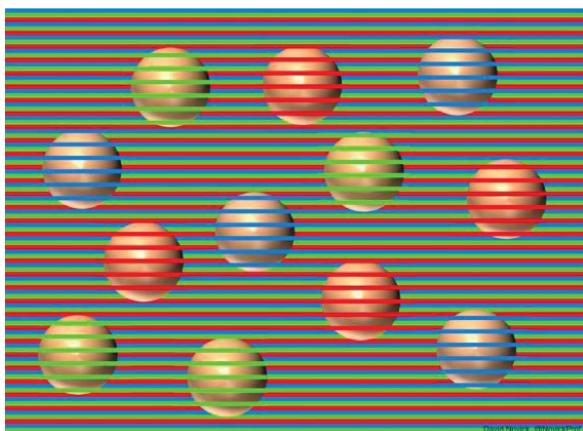


It is hard not to be fooled by these!

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## Context illusions: Color

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

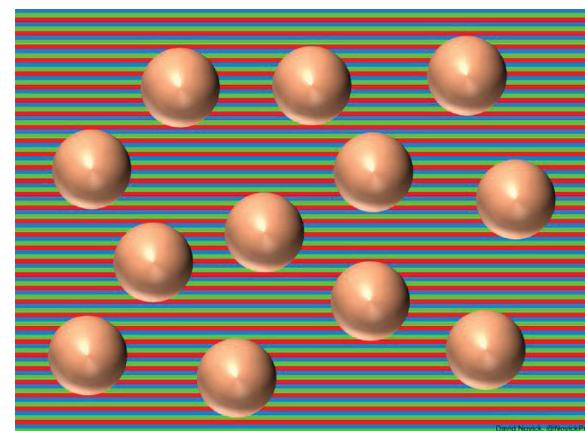


<https://twitter.com/novickprof/status/1139342022551191553>

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## Context illusions: Color

Removing the foreground stripes shows them all the **same**  
(Munkern illusion: perception of color is influenced by neighborhood)



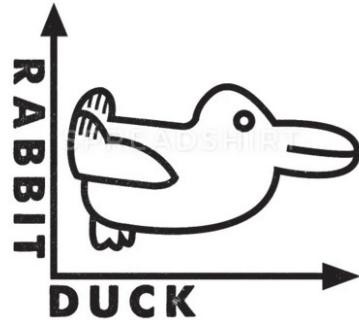
More examples: <http://engineering.utep.edu/novick/colors/>

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## 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?



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## Catalog of visual/auditory illusions

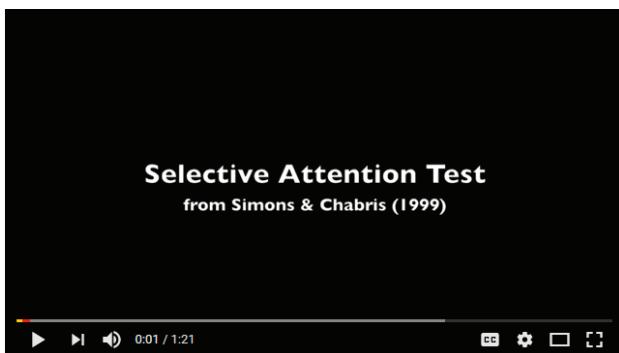
<https://www.illusionsindex.org/illusions>

A large collection of illusions with references to research studies.



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## Selective attention



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

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

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## 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**.

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## Area vs. length judgments

Easy: Which is larger— South Africa or Egypt?

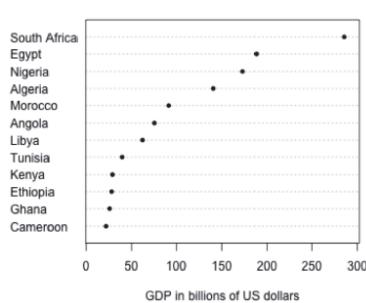
Harder: How much larger is South Africa than Egypt? (% or ratio)

### African Countries by GDP



Judgments here based on area

### African Countries by GDP



Judgment here based on position along a scale

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## Theory: 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: most accurate ( $p \approx 1$ )
  - area, depth: sub-sensitive ( $p < 1$ )
  - electric shock: hyper-sensitive ( $p > 1$ )
- But: graph perception is not always a matter of estimating **magnitudes**.

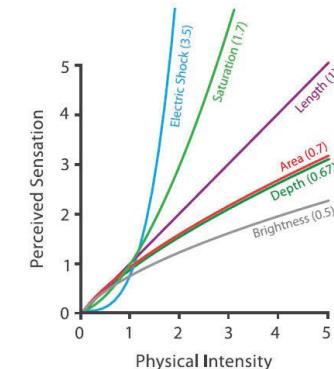


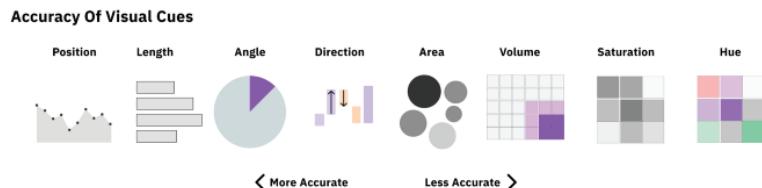
Fig. 5.7 from: Munzner, *Visualization Analysis & Design*

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## Practice: Scale of accuracy

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

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



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

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## 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

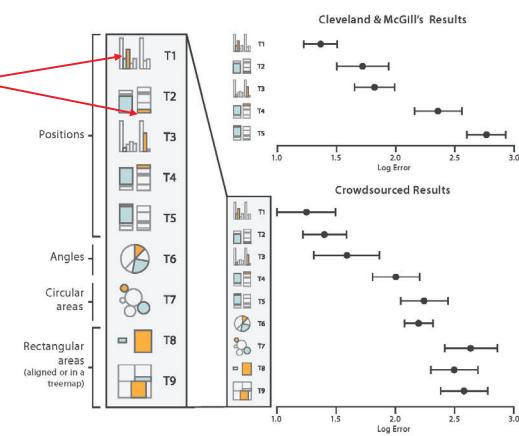


Fig. 5.8 from: Munzner, *Visualization Analysis & Design*

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## Encodings: Types & ranks

Based on this, Munzner (2015) proposes a ranking of visual attributes for **ordered** & **categorical** variables in data displays, with different **channels**

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

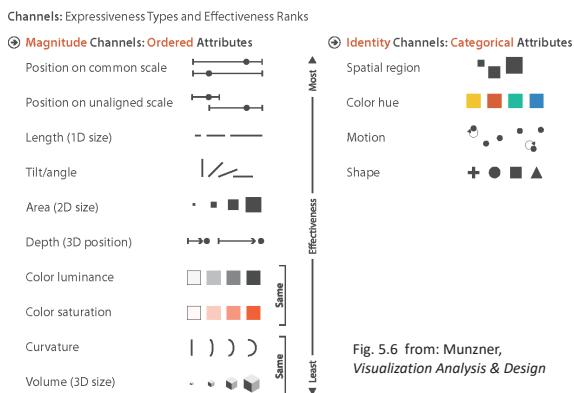


Fig. 5.6 from: Munzner,  
Visualization Analysis & Design

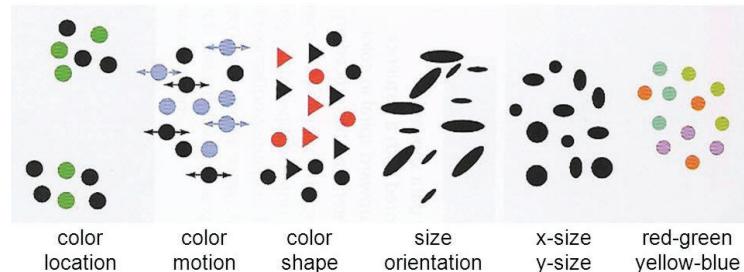
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## Integral & separable encodings

- 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 →



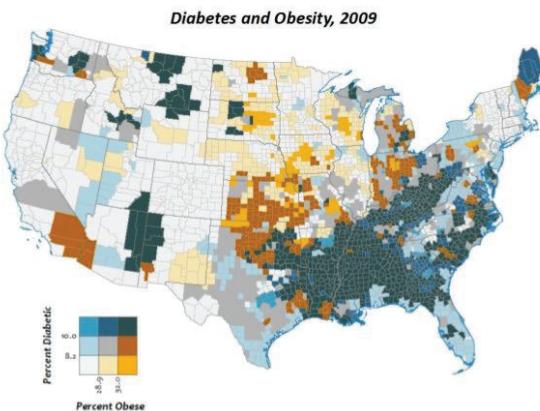
From: Ware, *Information visualization: Perception for Design*

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## 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**

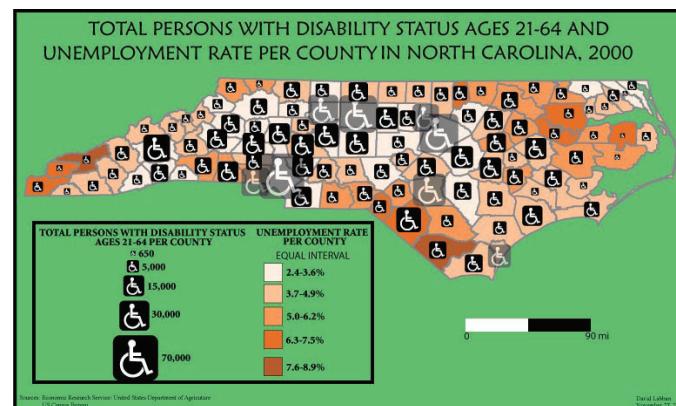
The eye is attracted to the positive correlation between these dark (blue, red) vs. light color

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## 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)



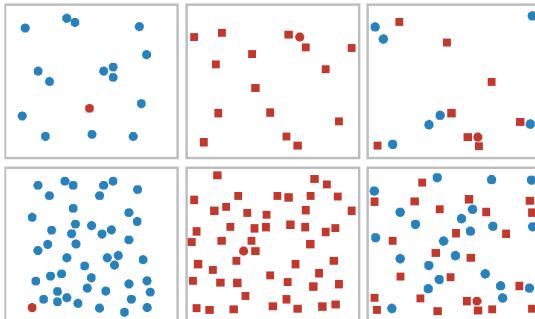
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## Anomaly detection

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.

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## Anomaly detection

For each display, find the anomaly shown at the left

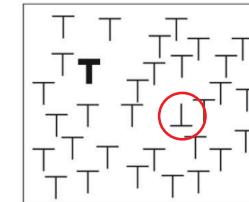
Color and shape: What is easy or hard depends on the background



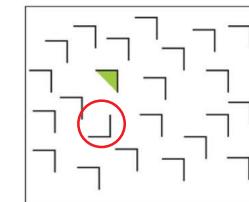
difficult



easy



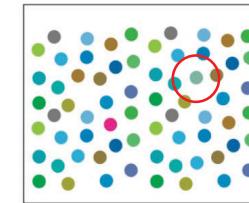
easy



difficult



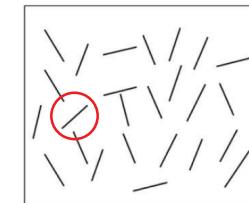
easy



difficult



easy



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## 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

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## 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

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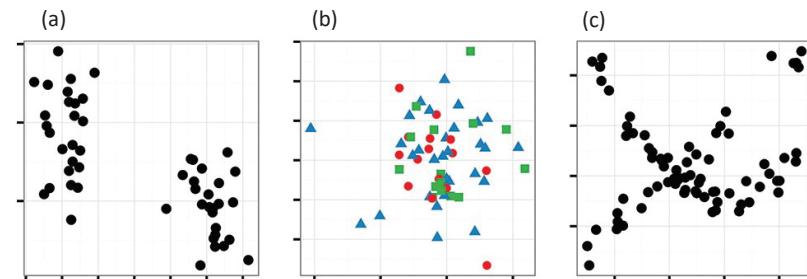
## Gestalt principles

- 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
  - **closure**: elements that make a meaningful whole belong together

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## Gestalt principles

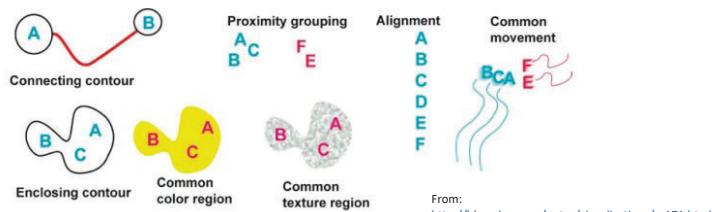
- (a) **proximity** creates impression of 2 groups
- (b) **similarity**: 3 groups via color & shape
- (c) **good continuation** gives impression of 2 groups



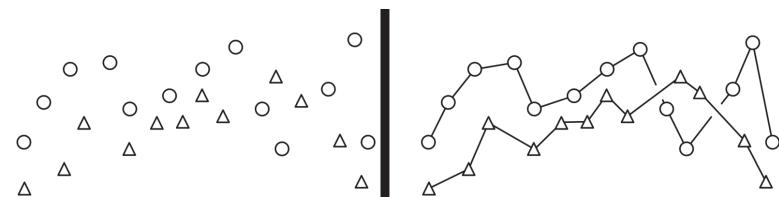
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## Gestalt principles

More gestalt ideas



Why lines are good in time series graphs



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## Closure

The Gestalt brain "wants" to make perception simpler by joining up disparate elements into coherent, meaningful wholes

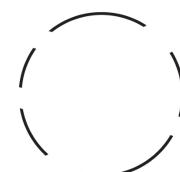
Logos: Empty space or a symbol?



Closure



5 arcs or a circle?



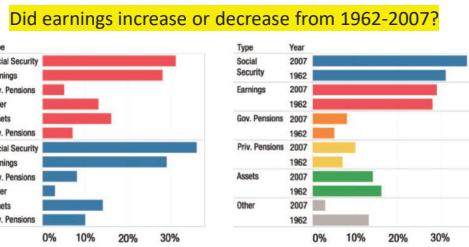
blobs or an animal?



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## Visual grouping & comparisons

Combination of color & proximity grouping → different visual comparisons are easier or harder



What was the most frequent baseball term?



- Comparisons in a word cloud:
- weakly controlled by **color**;
  - better controlled by **proximity**

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

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## Visual grouping & comparisons

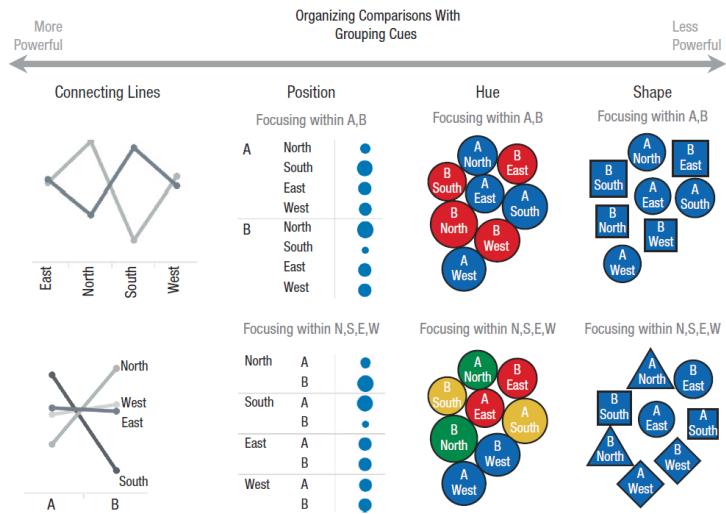
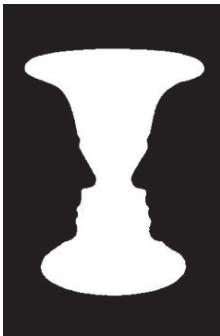


Fig. 8. Several grouping cues that can control how data values are compared. Connecting lines are particularly powerful cues, followed by proximity, color, and shape (Brooks, 2015).

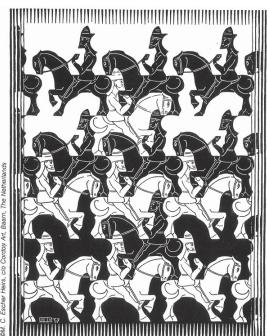
## Figure - Ground

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

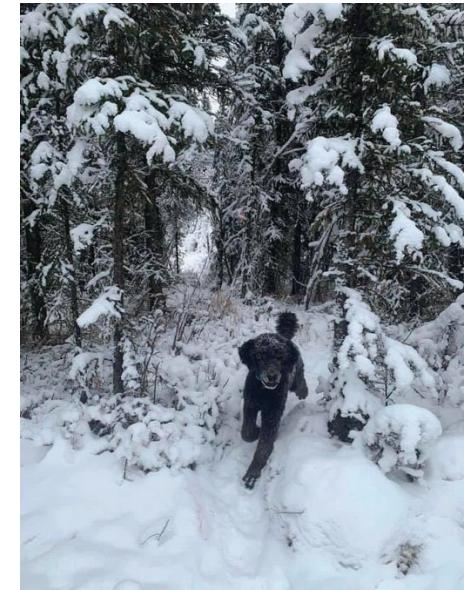
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## Ambiguous figures: Priming

Can you see the **poodle** in this scene?

What about the **man**?

**Semantic priming:** Suggestion increases likelihood of perception

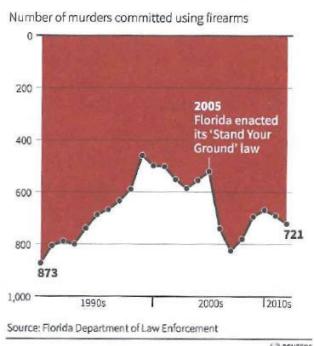


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## Figure - Ground

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

### Gun deaths in Florida

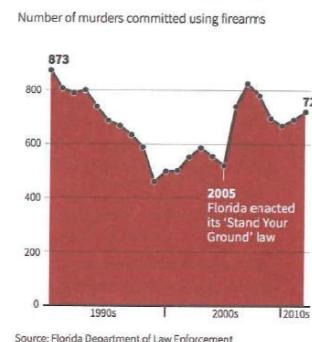


We tend to see 1999 & 2005 as high points

From: Andy Kirk, *Data Visualization: A Handbook for Data Driven Design*

A more conventional version of the same graph

### Gun deaths in Florida



Gun deaths increased after the 'Stand your ground' law

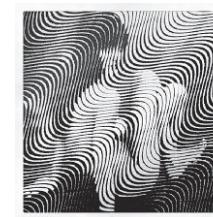
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## Discussion

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



What about this?



Top-down?  
Bottom-up?  
Gestalt?



or this?



or this?

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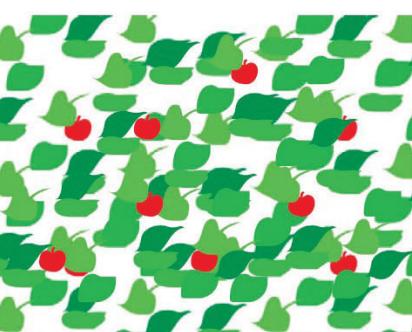
## Color: Functions in data graphics

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*

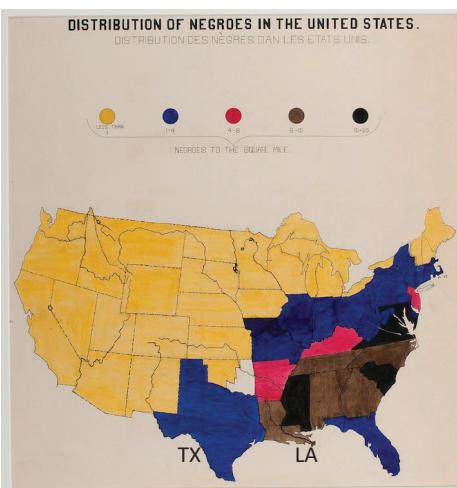
47

## Nice graphic, naïve about color

W.E.B. DuBois 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)?

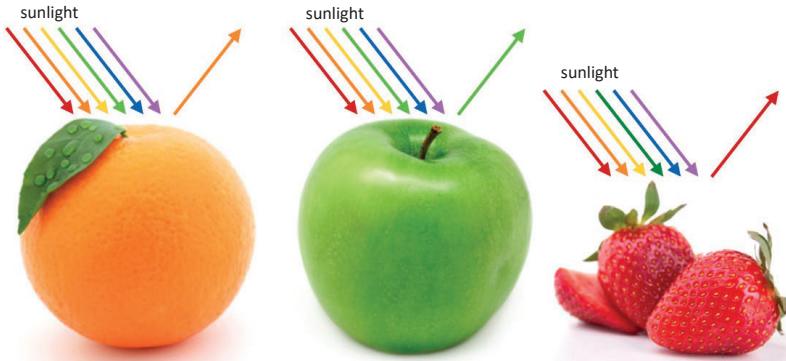


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## Object color

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



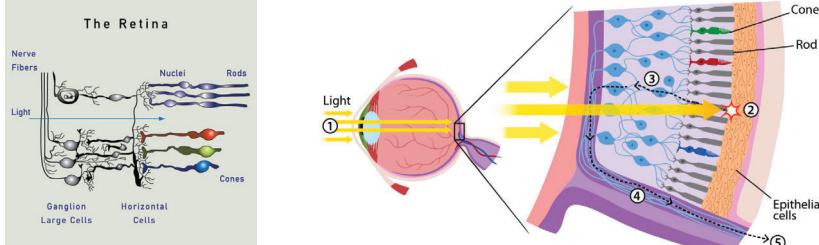
From: Miriah Meyer, lecture notes, cs6330

49

## Perception: The human eye

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

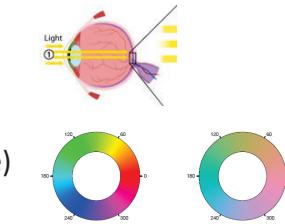
It is of interest to see the wide variety of ways this is conveyed in scientific diagrams:



51

## Color: Aspects in data graphics

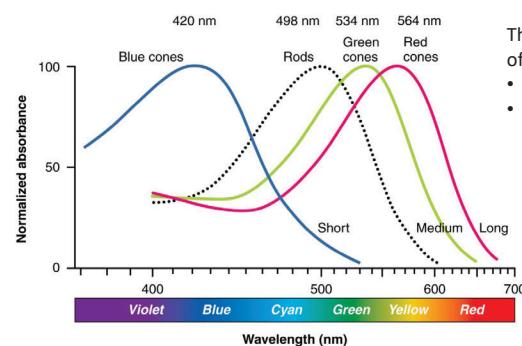
- Perception: trichromatic theory
  - How the eye sees **color**
- Color spaces:
  - RGB (additive), CMYK (subtractive)
  - HSV, HCL: perceptually based
- Color palettes for computer graphics
  - ColorBrewer: sequential, diverging, qualitative
  - Color-blind safe ?
  - Photocopy safe ?
- Transparency



50

## 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

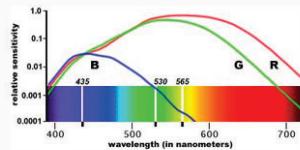
- Rods & cones are “normalized”
- Are they all equal in what we see?

52

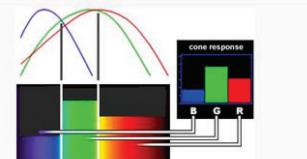
## Perception: color sensitivity

Color sensitivity, shown on three different scales

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



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

from: <http://slideplayer.com/slide/6329532/>

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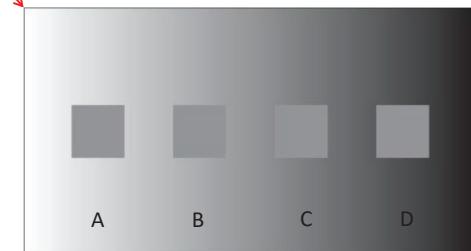
## Perception: Contrast

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



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

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## 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.

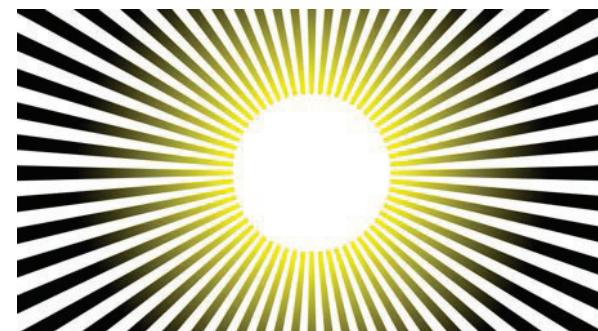
TIP: For presentations, light text on a **dark background** is often preferred.  
I don't do this, because I'm also concerned with printing slides.  
(With LaTeX Beamer, it is easy to have separate setups for presentation & print)

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## 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>

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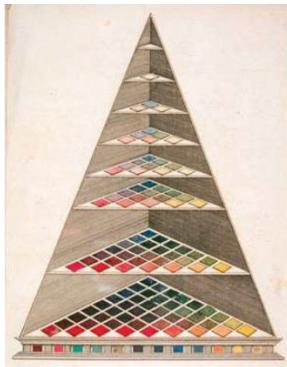
## Early color theory

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



Introduces the idea of color “primaries”

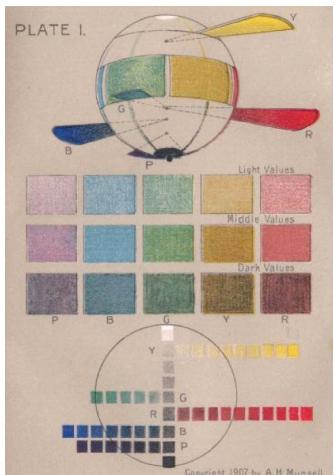
Johannes Lambert (1772) – A color pyramid, composed of 7 layers



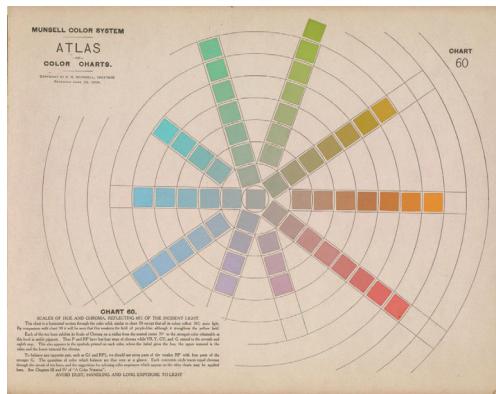
Introduces the idea of color saturation

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



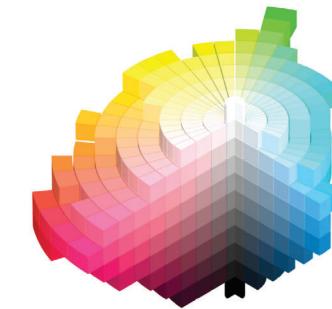
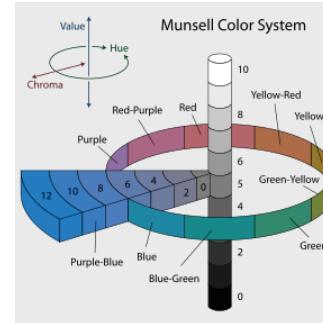
Copyright 1907 by A. H. Munsell.



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## 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



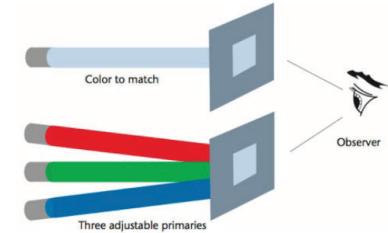
By SharkD - CC BY-SA 3.0,  
<https://commons.wikimedia.org/w/index.php?curid=8401562> 58

## CIE color space

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

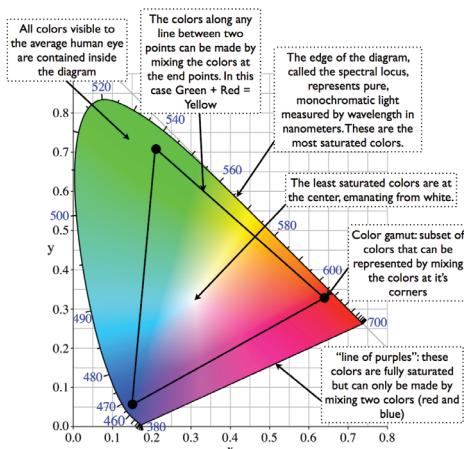
Experiments used a **color-matching** task:

- 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



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## 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.

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## 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



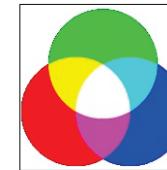
**Caution:** R, SAS, SPSS use RGB by default

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

Some software offer useful tools for this:

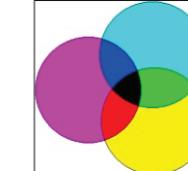
- Adobe Acrobat Pro
- ImageMagik

### Additive colour system



Mixture of primary light colours-  
White

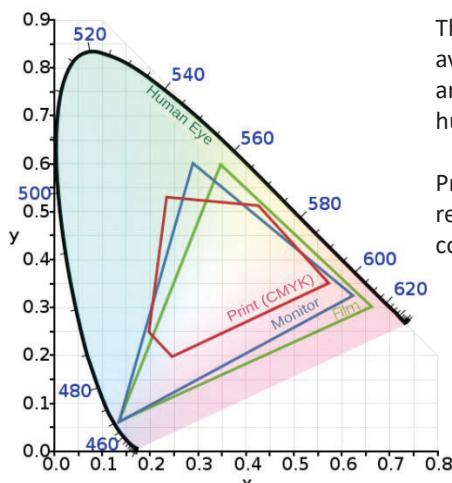
### Subtractive Colour System



Mixture of primary pigment colours  
Black

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## 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.

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## Color in DataViz Design

There are several commonsense rules & guidelines for use of color in statistical graphics, maps & info vis



From: Alicja Gosiewska, Data Visualization Techniques, <https://bit.ly/3RZWw0t>

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## 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	#FFB4C4	255	228	196
20 bisque1	#FFB4C4	255	228	196
21 bisque2	#EED5B7	238	213	193
22 bisque3	#CD979E	205	182	159
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	42	224
32 brown	#8A5A5A	165	42	42
68 cyan	#00FFFF	0	255	255
69 cyan1	#00FFFF	0	255	255
70 cyan2	#00EEFF	0	238	255
71 cyan3	#00CCFF	0	205	255
72 cyan4	#00BFFF	0	139	255
73 darkblue	#00008B	0	0	139
74 darkcyan	#00BFFF	0	139	139
75 darkgoldenrod	#8B8A0B	194	134	11
76 darkgoldenrod1	#FFB90F	255	105	15
77 darkgoldenrod2	#EBAD0B	238	173	14
78 darkgoldenrod3	#CD950C	205	149	12
79 darkgoldenrod4	#8B650B	139	101	9
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

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## 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



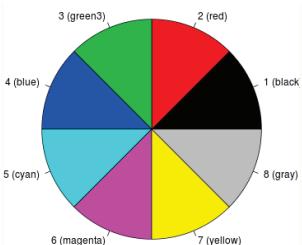
*Every time you are forced to say "#008B8B" or "cyan4" a puppy dies somewhere*  
-- MF, 2018

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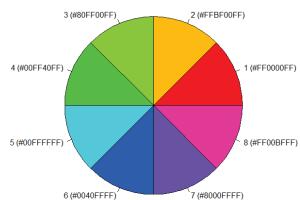
## Software: palettes

- 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)
```



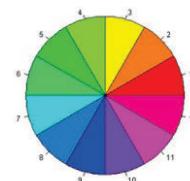
palette(rainbow(8)); pie(...)



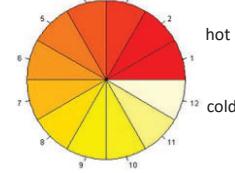
67

## R: basic palettes

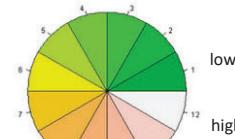
n < 12  
pie(rep(1, n), col=heat.colors(n))



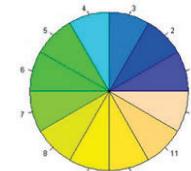
pie(rep(1, n), col=heat.colors(n))



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



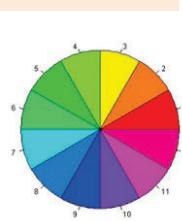
pie(rep(1, n), col=topo.colors(n))



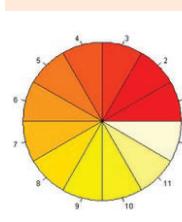
68

## R: basic palettes

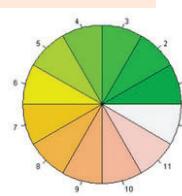
rainbow



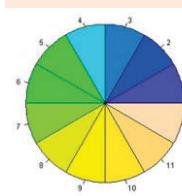
heat



terrain



topo



### Discussion Q:

- Which of these seem 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**

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## 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. A sidebar on the left allows setting the number of data classes (4), nature of data (sequential), and picking a color scheme (Multi-Hue). It also includes options for 'Only show' (colorblind safe, print friendly, photocopy safe), 'Context' (roads, cities, borders), and 'Background' (solid color, terrain). On the right, a map of the United States is colored according to a 4-class sequential scheme named 'BuGn'. Below the map, color swatches and their corresponding hex codes (#e7fcb1, #a52ea2, #66c2ad, #238b45) are listed.

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

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## 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

The screenshot shows the ColorBrewer 2.0 interface with the 'Nature of your data' set to 'diverging'. A 5-class 'RdBu' scheme is selected. The sidebar includes options for 'Only show' (colorblind safe, print friendly, photocopy safe), 'Context' (roads, cities, borders), and 'Background' (solid color, terrain). The map of the United States is colored using the 'RdBu' scheme, with red for lower values, white for the center, and blue for higher values. Below the map, color swatches and their hex codes (#e40020, #f4a532, #92c5de, #0571b0) are listed.

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>

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## palettes: ColorBrewer

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

The screenshot shows the ColorBrewer 2.0 interface with the 'Nature of your data' set to 'qualitative'. A 5-class 'Accent' scheme is selected. The sidebar includes options for 'Only show' (colorblind safe, print friendly, photocopy safe), 'Context' (roads, cities, borders), and 'Background' (solid color, terrain). The map of the United States is colored using the 'Accent' scheme, with various colors (green, purple, orange, yellow, blue) assigned to different categories. Below the map, color swatches and their hex codes (127,201,127, 190,174,212, 253,192,134, 255,255,153, 56,108,176) are listed.

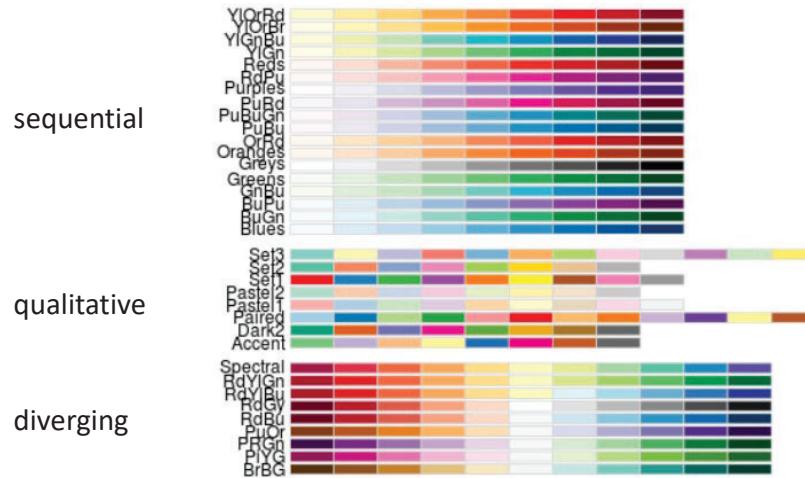
These are all available in the RColorBrewer package

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

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## palettes: RColorBrewer

RColorBrewer::display.brewer.all()



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## R: choose\_palette()

The colorspace package in R has an interactive palette widget.

It also provides functions for many kinds of color manipulations.

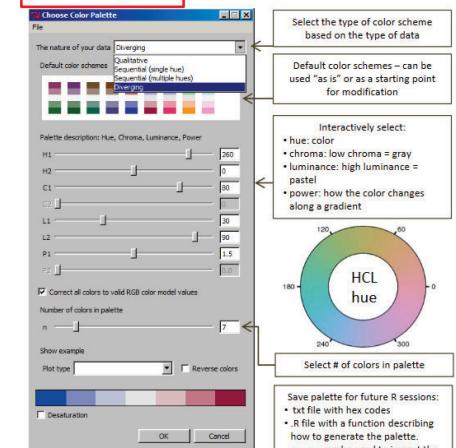
The R Color cheatsheet, by Malcolm Fraser is a goto source for all aspects of color in R:

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

## R color cheatsheet

Overview of colorspace palette selector

library("colorspace")  
pal <- choose\_palette()



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## Viridis palettes

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

Goals:

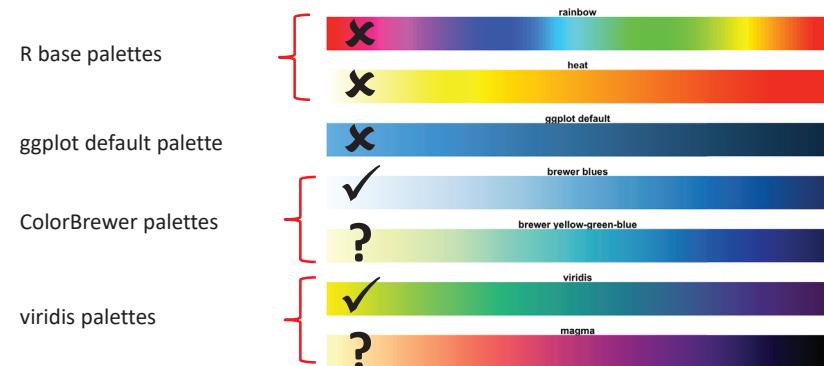
- **Colorful**, spanning as wide a palette as possible so as to make differences easy to see
- **Perceptually uniform**: values close to each other have similar-appearing colors and values far away from each other have more different-appearing colors
- **Robust to colorblindness**: these properties hold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

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## Comparing palettes

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

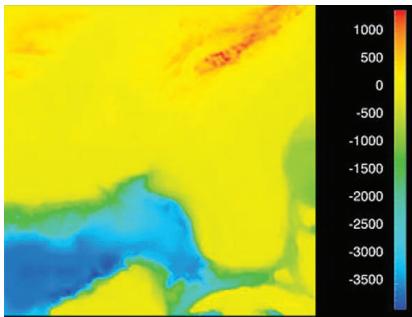


This is a bit tricky: ideally, we want a **wide range** of color

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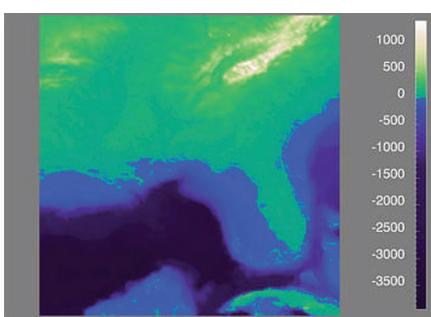
## Comparing palettes

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



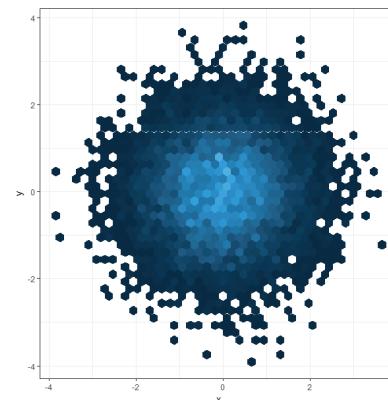
This color scheme was designed to reveal the essential topography of the map & to have perceptually equal elevation steps

From: <http://www.research.ibm.com/people/l/lloyd/color/color.HTM>

77

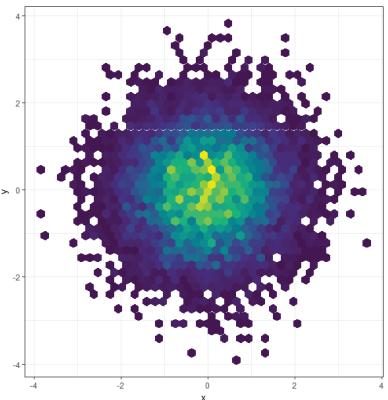
## Comparing palettes

ggplot 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
```

viridis default palette



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

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## Metbrewer palettes

Artistic palettes inspired by works at the Metropolitan Museum of Art in New York



Renoir

Nini in the Garden



VanGoghI

Cypresses, 1889, Vincent van Gogh



Cap Nègre, 1909, Henri-Edmond Cross



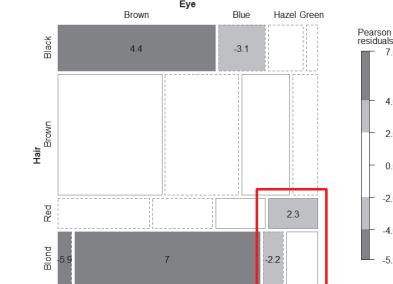
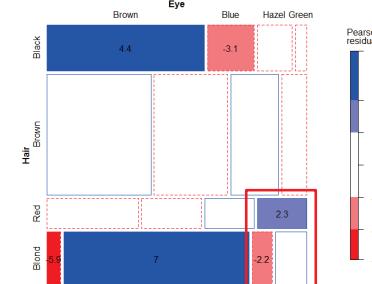
79

## Color → B/W ?

Graphics designed in color often must 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)
```



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# 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 (1998–2013)

	1998–2002	2003–2009	2006–2010	2010–2013	2014–2016	Scale
Roads, streetscapes	30	33	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 (1998–2013)

	1998–2002	2003–2009	2006–2010	2010–2013	2014–2016	Scale
Roads, streetscapes	30	33	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

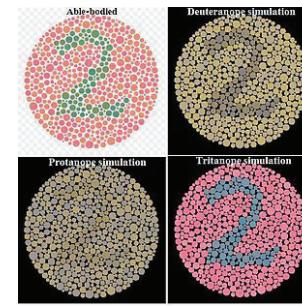
Background shading works equally well in color or B/W  
+ for visual design!

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/>

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# Colorblindness

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



- Protanopia (red deficient)
- Deutanopia (green deficient)
- Tritanopia (blue deficient)

Some form of red-green insensitivity is most common

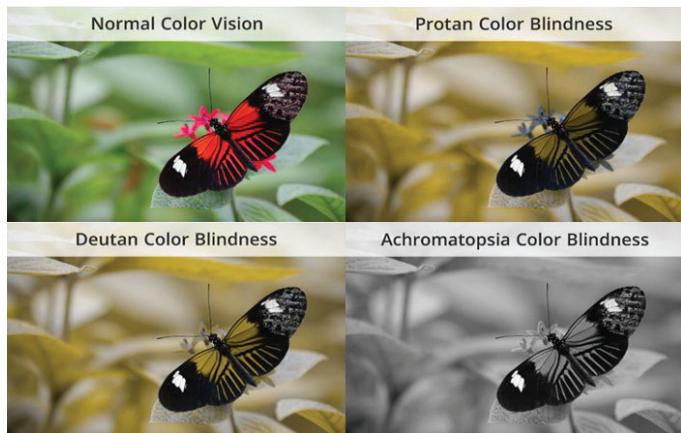
- about 6-8% of population
- more common in males

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

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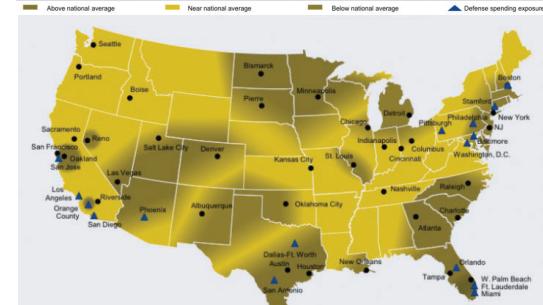
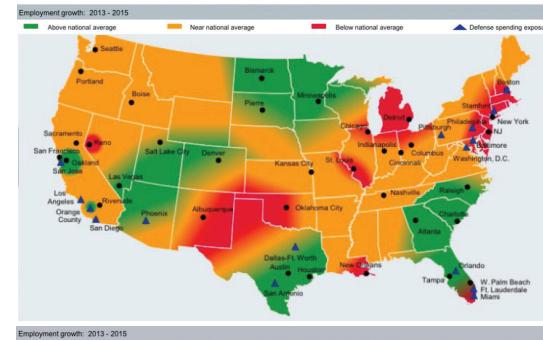
# Colorblindness

What an image looks like with various forms of color deficiency



Red-green colorblindness: -R (protan) ≈ -G (deutan)

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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

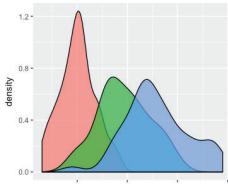
From: <http://www.mena-forum.com/category/u-s-a/>

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## colorblindr package

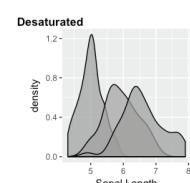
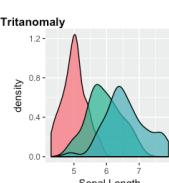
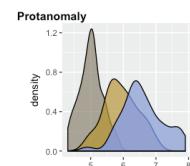
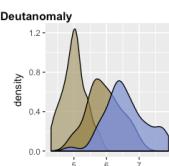
myfig



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

NB: The default ggplot colors aren't colorblind or B/W friendly

What would my graph look like to someone with color deficiency?  
colorblindr simulates a graph under various conditions



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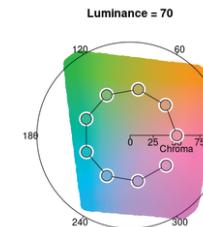


## colorspace 2.0-0



## A Toolbox for Manipulating and Assessing Colors and Palettes

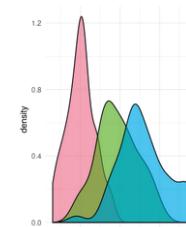
### Color spaces



### HCL-based palettes



### ggplot2 scales



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

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## 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

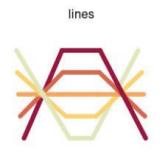
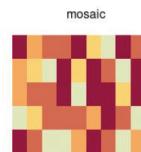
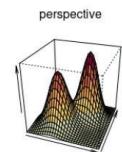
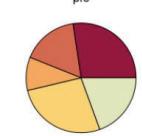
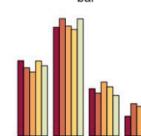
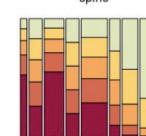
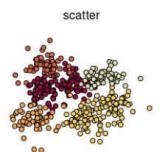
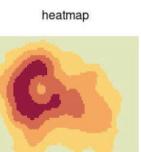
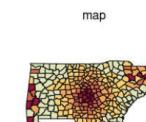
```
swatchplot(palette.colors(), cvd = TRUE)
```



## colorspace: demoplot()

See how color palettes work in different kinds of statistical displays

```
demoplot(sequential_hcl(5, "Heat"))
```



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## 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 (set your `palette()`)
- 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

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## 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

Images from: Stephen Few,  
[http://www.perceptualedge.com/articles/visual\\_business\\_intelligence/rules\\_for\\_using\\_color.pdf](http://www.perceptualedge.com/articles/visual_business_intelligence/rules_for_using_color.pdf)

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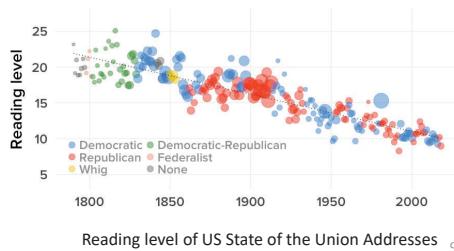
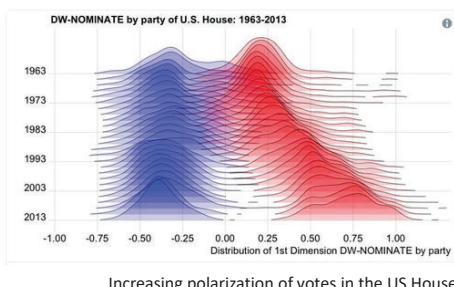
## Transparency

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?

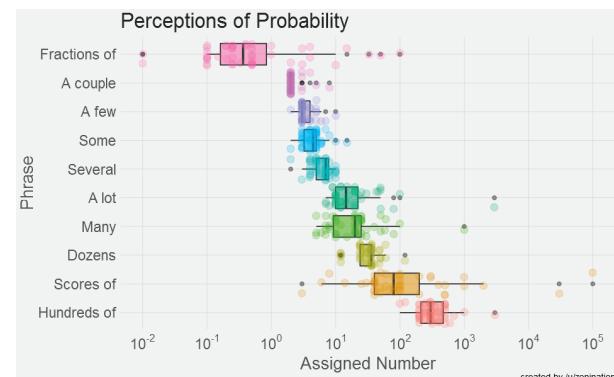


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## Transparency: Adding another layer

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>

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## 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