Information Visualization
PERCEPTION and COLOR

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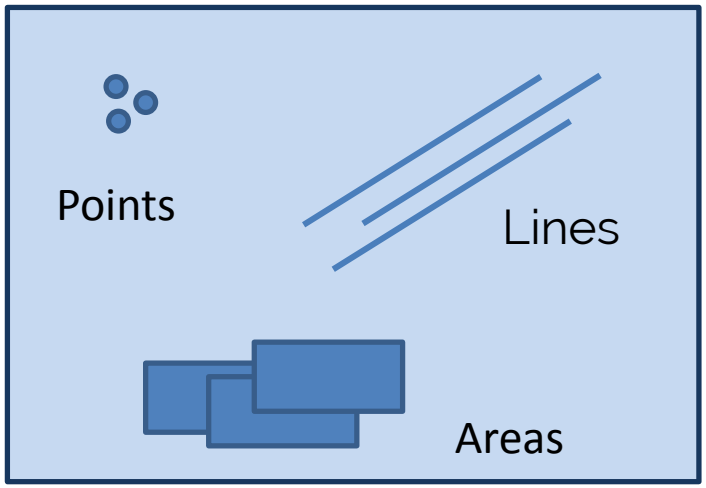
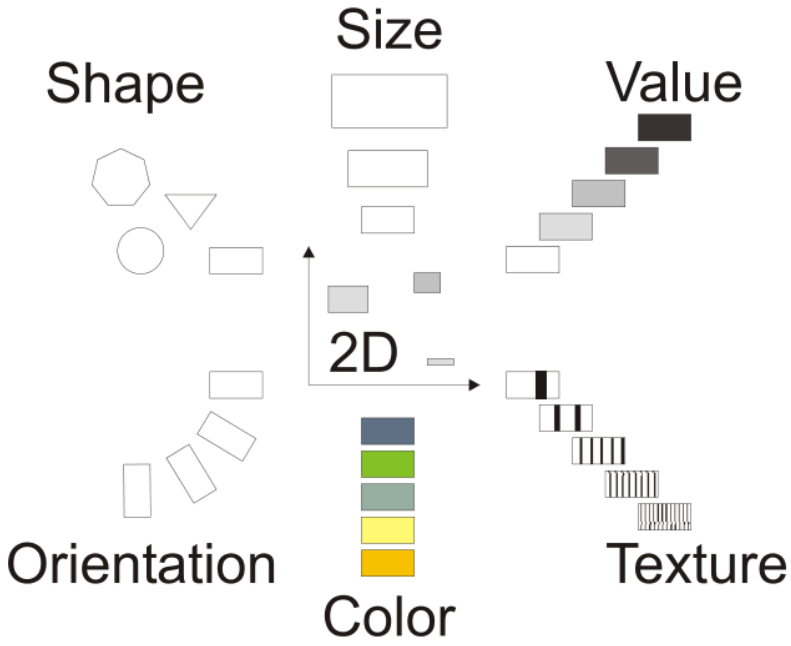
Recap

In Lecture 1 you learned about the basic components of visualization:

- marks and visual variables





and others

Summary

- You know the main building blocks are **marks**
- Marks are modified by **visual variables**
- Visual variables have **specific characteristics**
- These influence how the data will be **perceived**

Today you will

- Learn details about the **perception of color** and a few **other visual encodings**
- See that the vision system is **quicker and better** at detecting certain visual encodings

WHAT IS COLOR?

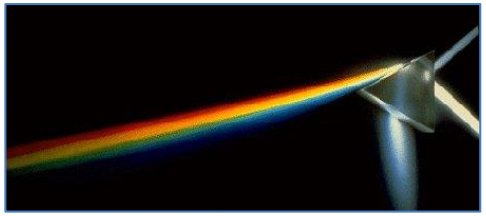
Let's do an experiment ...

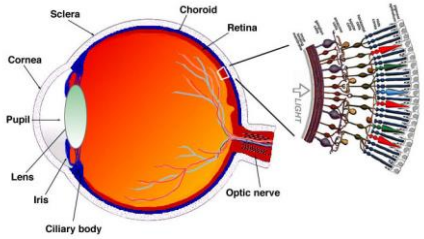
Let's do an experiment ...

What is Color?

- color is a **human reaction** to light (change)

What is Color?





"Yellow"

Physical World

Lights, surfaces, objects

Visual System

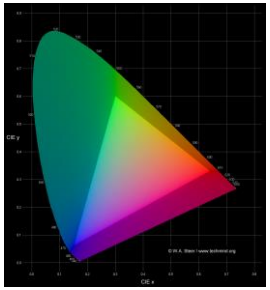
Eye, optic nerve, visual cortex

Mental Models

Red, green, brown

Bright, light, dark, vivid, colorful, dull

Warm, cool, bold, blah, attractive, ugly, pleasant, jarring

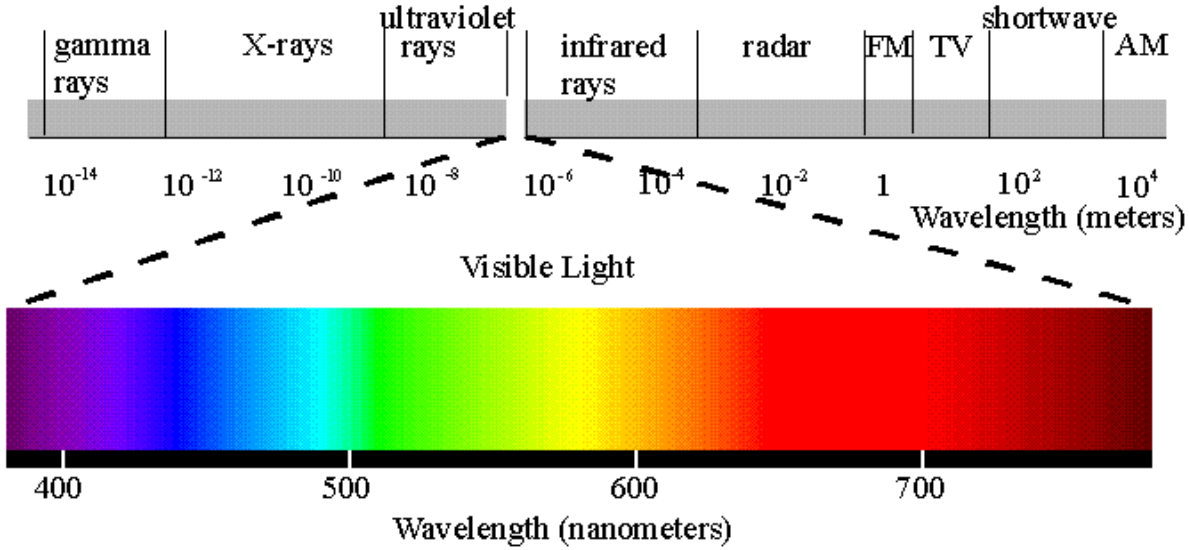


Color Models

RGB, CMYK, CIE XYZ, CIE Lab HSV/HSB, …

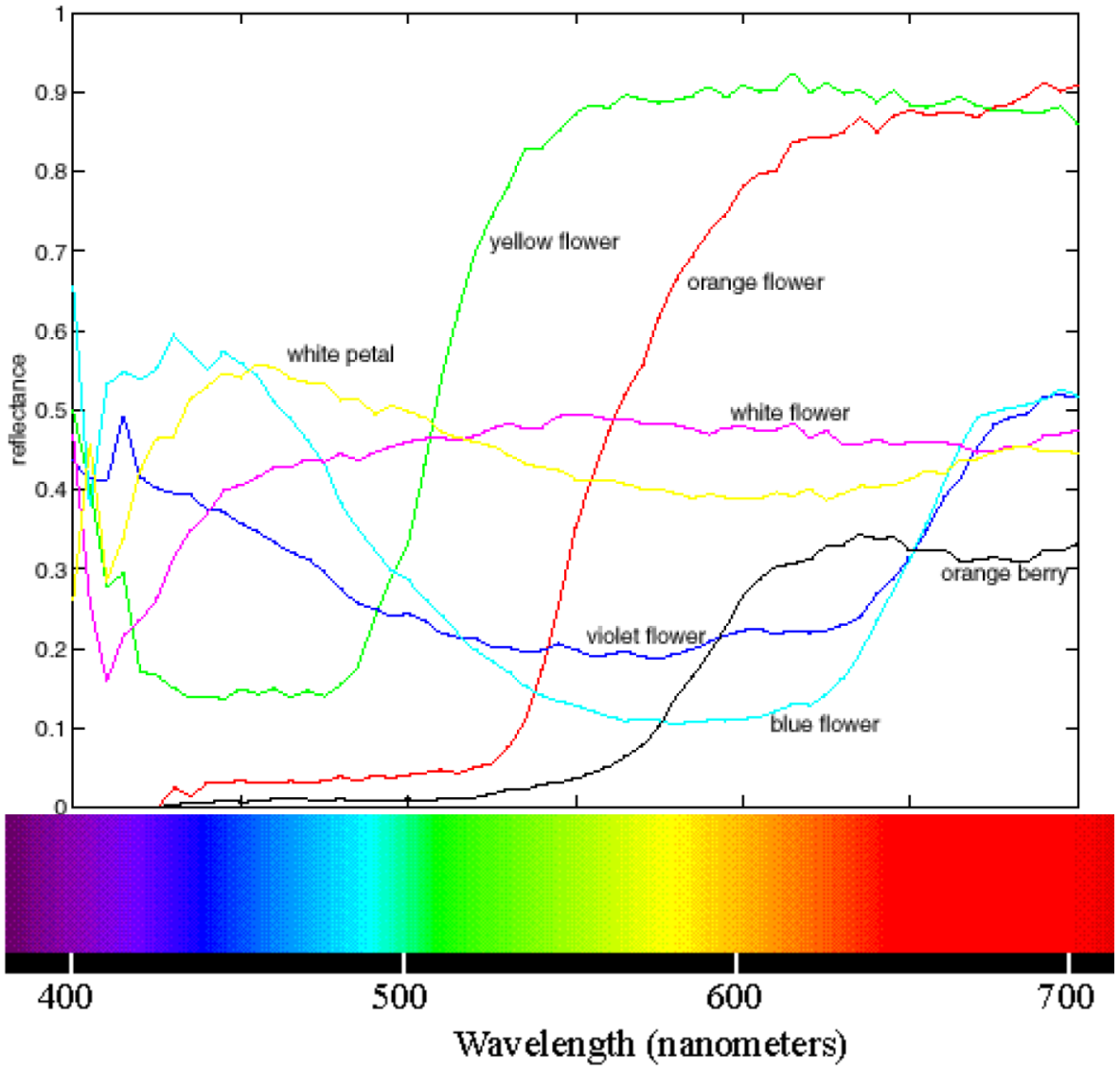
Physical World

Light is radiation in a range of wavelengths: 370–730nm

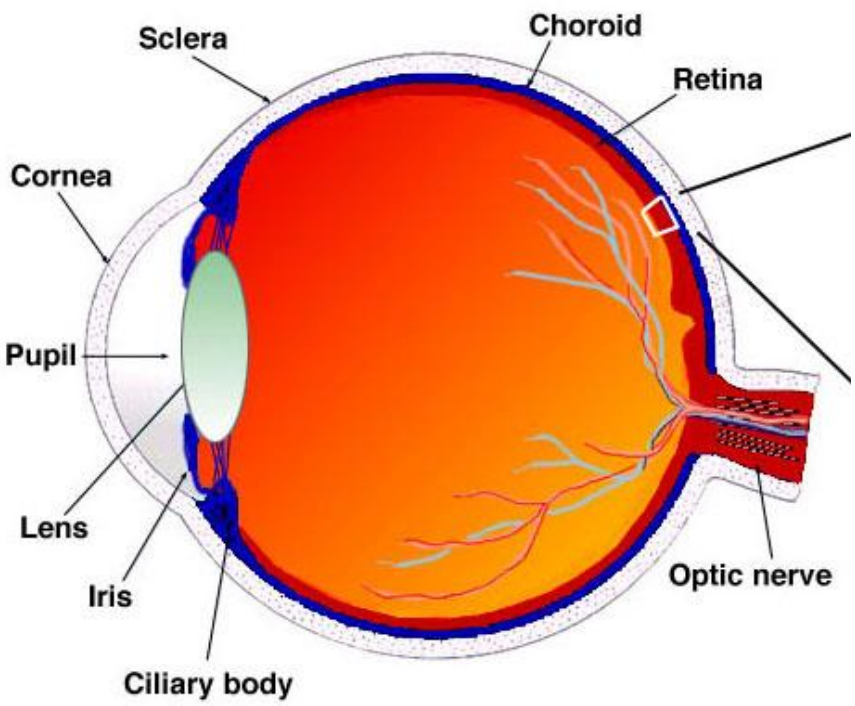


Light of a single wavelength is *monochromatic*

Most colors are not monochromatic



Physical World→**Visual System**

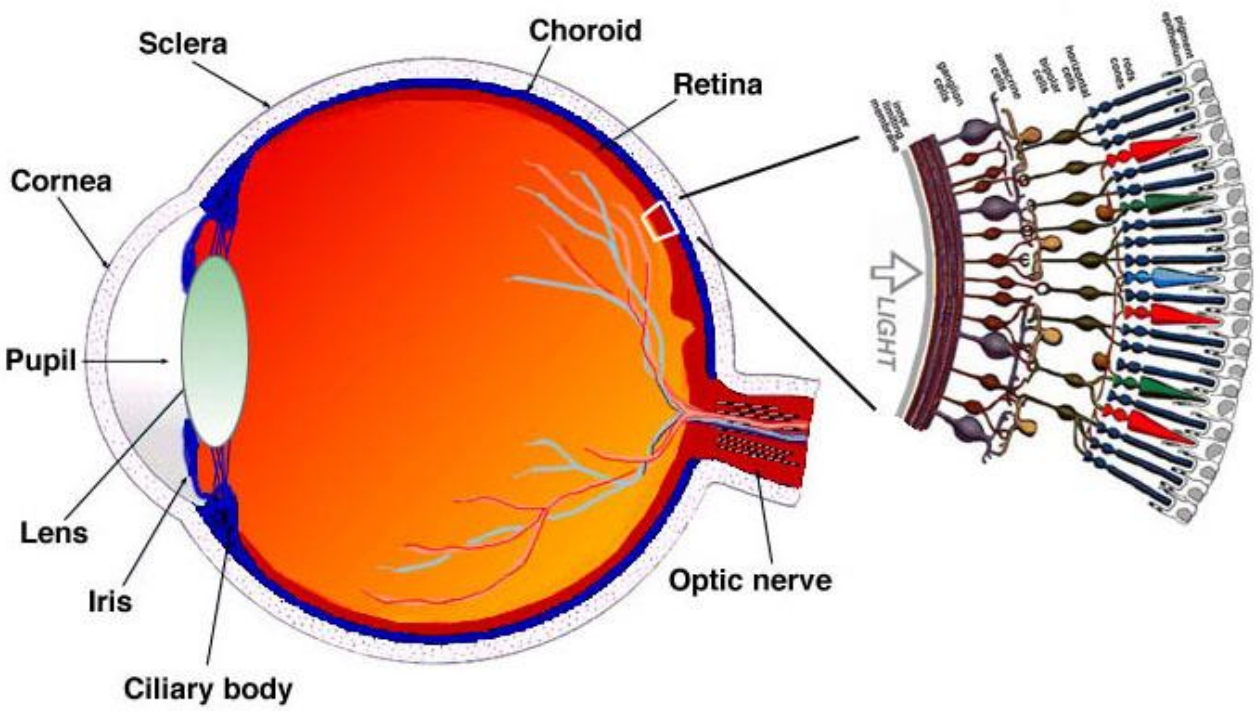


You **do not** see the spectrum of light

- Eyes make limited measurements
- Eyes physically adapt to circumstance
- You brain adapts in various ways
- Weird stuff happens

Simple Anatomy of the Retina, Helga Kolb

Physical World→**Visual System**



Rods

No color (sort of)

All over the retina

More sensitive

Cones

Three different kinds of “color receptors”

Mostly in the center

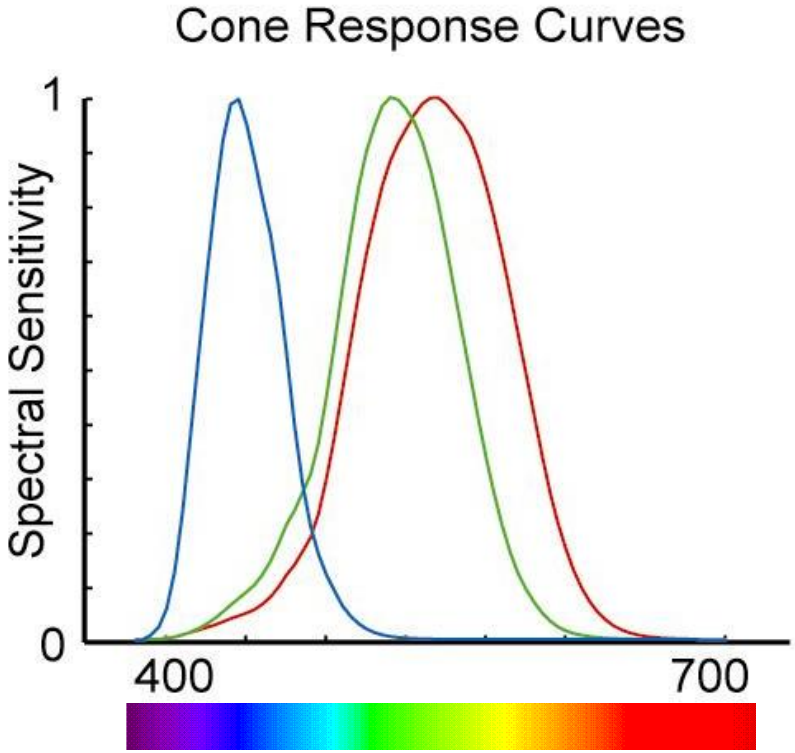
Less Sensitive

Simple Anatomy of the Retina, Helga Kolb

Cone response

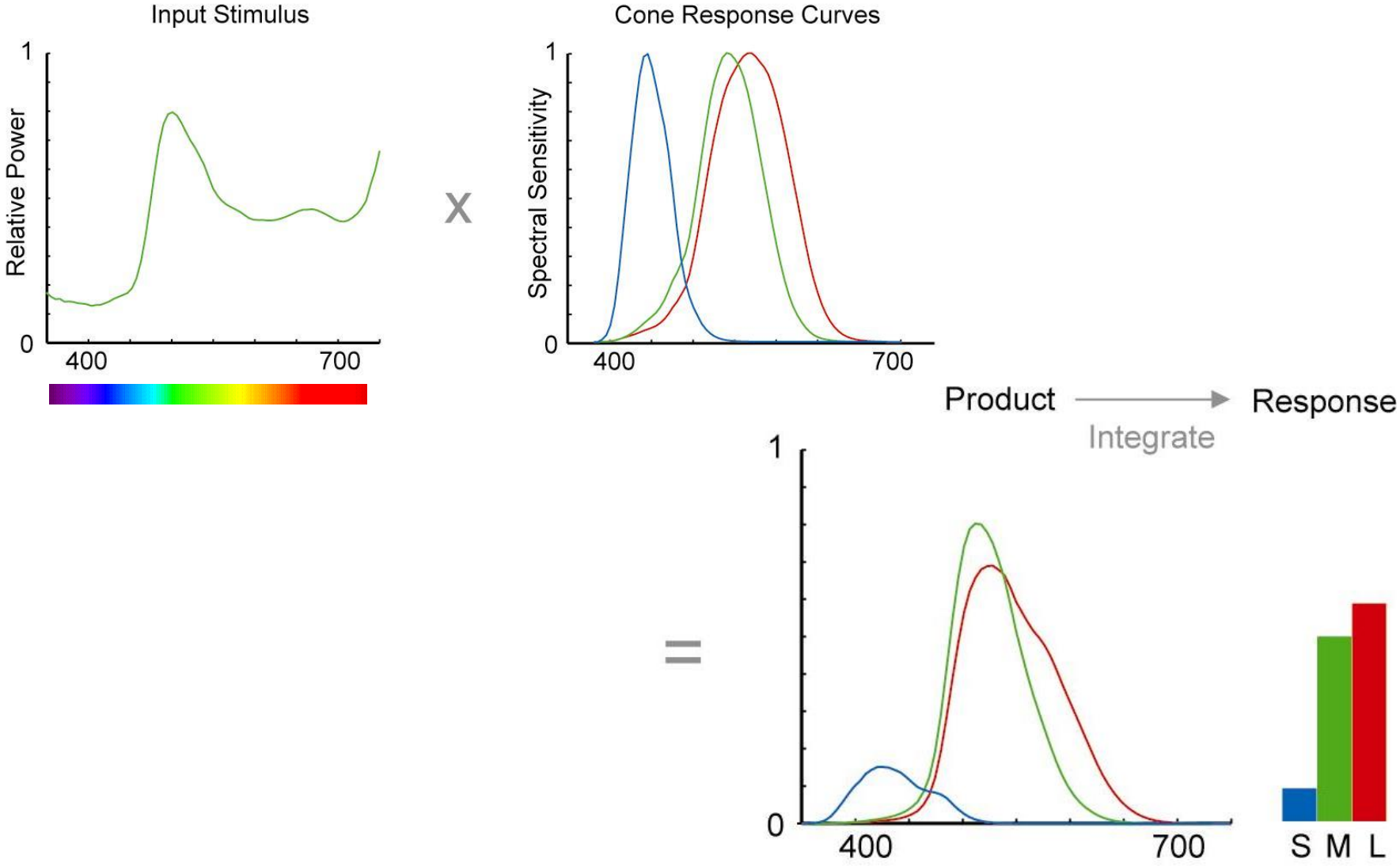
LMS (Long, Middle, Short) cones

Sensitive to different wavelengths



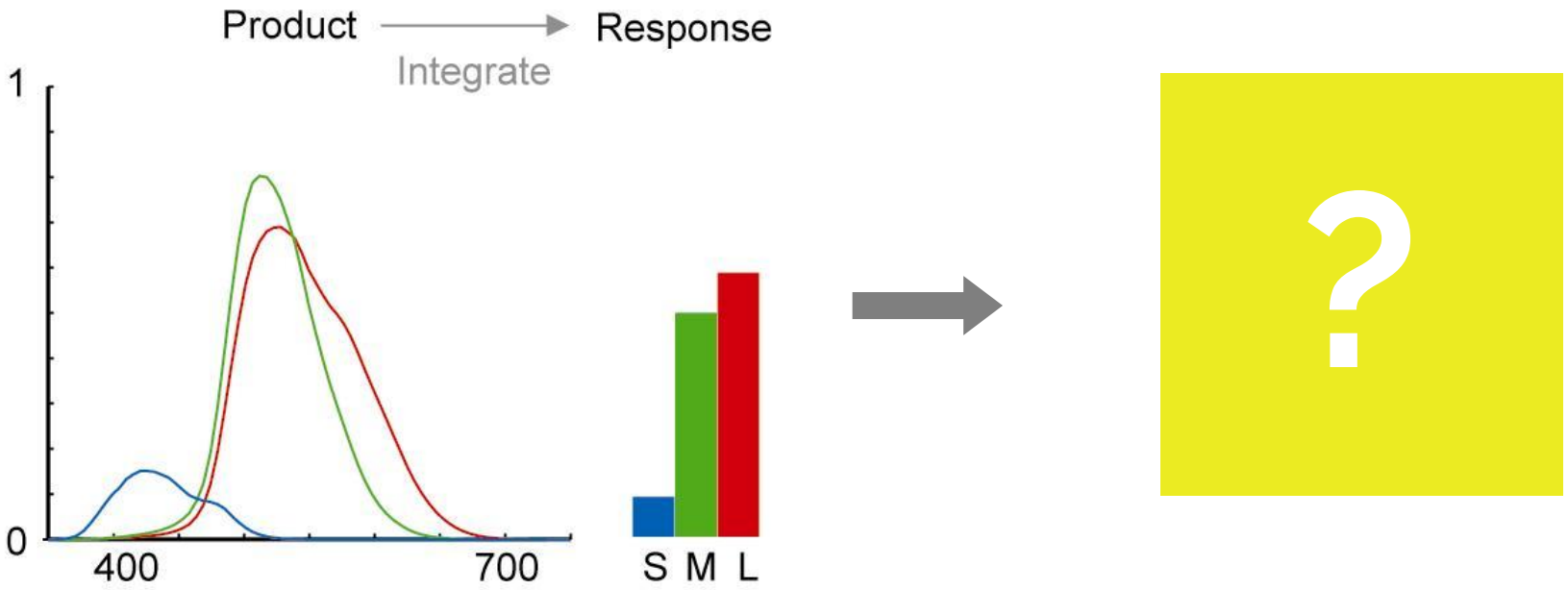
A Field Guide to Digital Color, Maureen Stone

Cone response



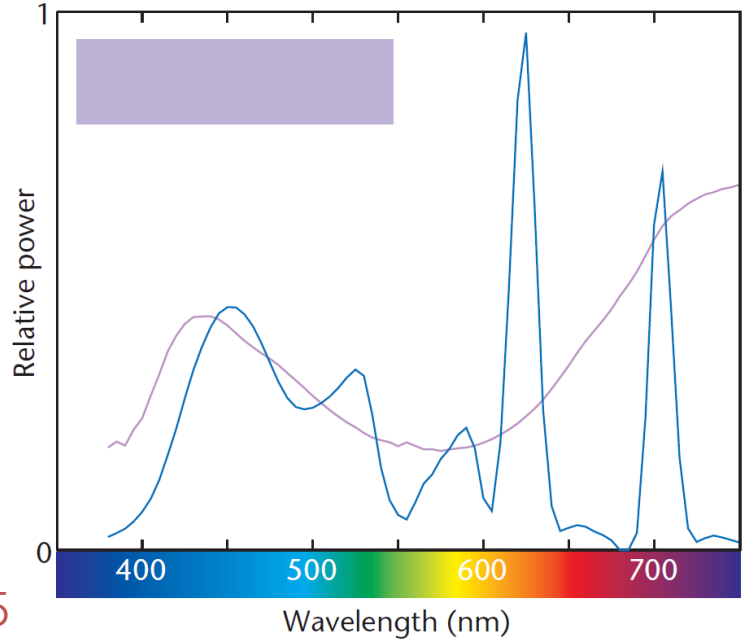
A Field Guide to Digital Color, Maureen Stone

Visual System → Color Models



Two Principles of Color Perception

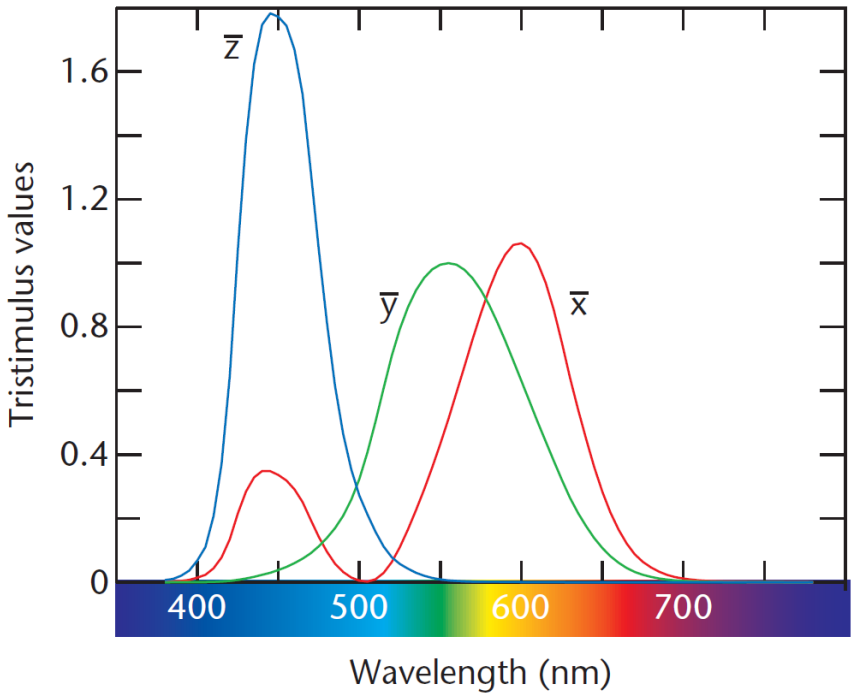
- **trichromacy**:
  representation of all spectral distributions possible with **three values** without information loss (w.r.t. the visual system)
  → essential for CS!
- **metamerism**:
  different spectra exist that produce the same trichromatic response



Stone 2005

XYZ Color Model

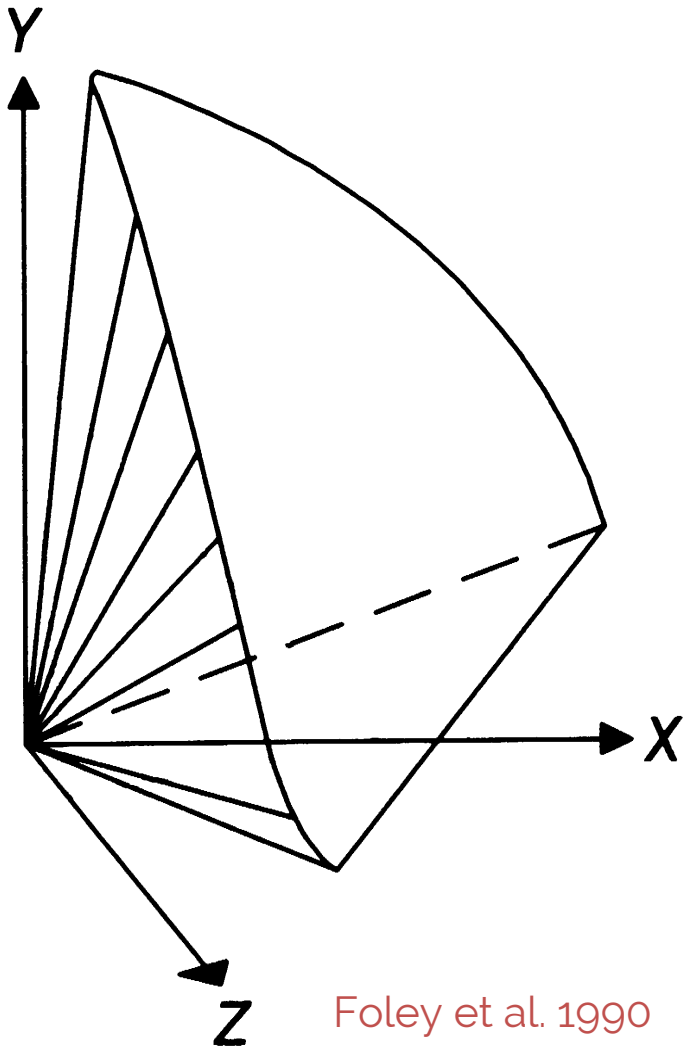
- definition of three primary colors: X, Y, Z
  - color-matching functions are non-negative
  - Y follows the standard human response to luminance, i.e., the Y value represents perceived brightness
  - can represent all perceivable colors
- mathematically derived from color matching experiments



Stone 2005

XYZ CIE Color Space

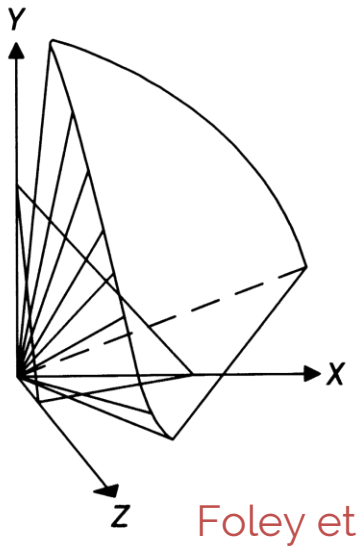
- plotting XYZ space in 3D
- all colors that are perceivable by humans form a deformed cone
- *X*, *Y*, and *Z*-axes are outside this cone

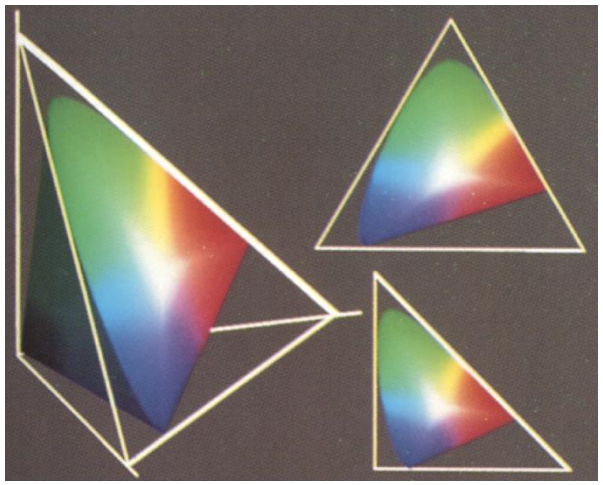


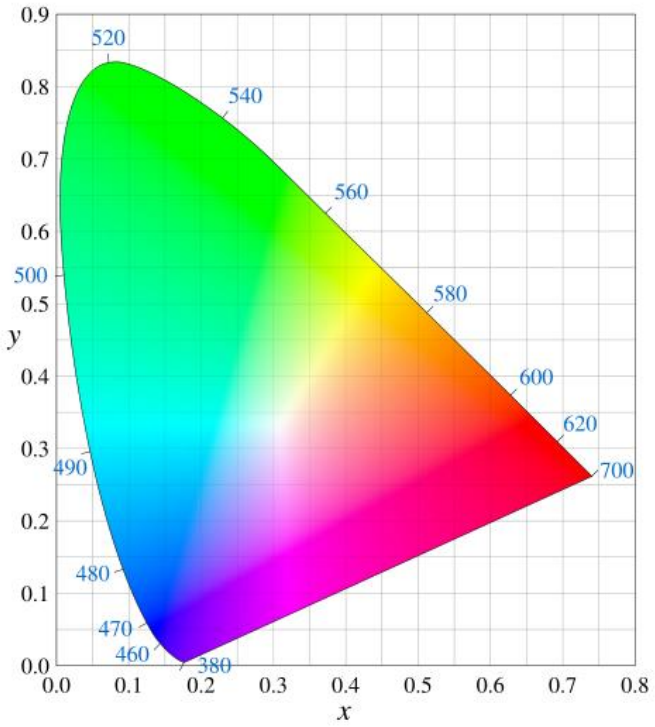
Foley et al. 1990

CIE Chromaticity Diagram

- projection of XYZ space onto X+Y+Z = 1 (to factor out a color's brightness):
  x = X/(X+Y+Z) y = Y/(X+Y+Z)
- monochromatic colors on upper edge



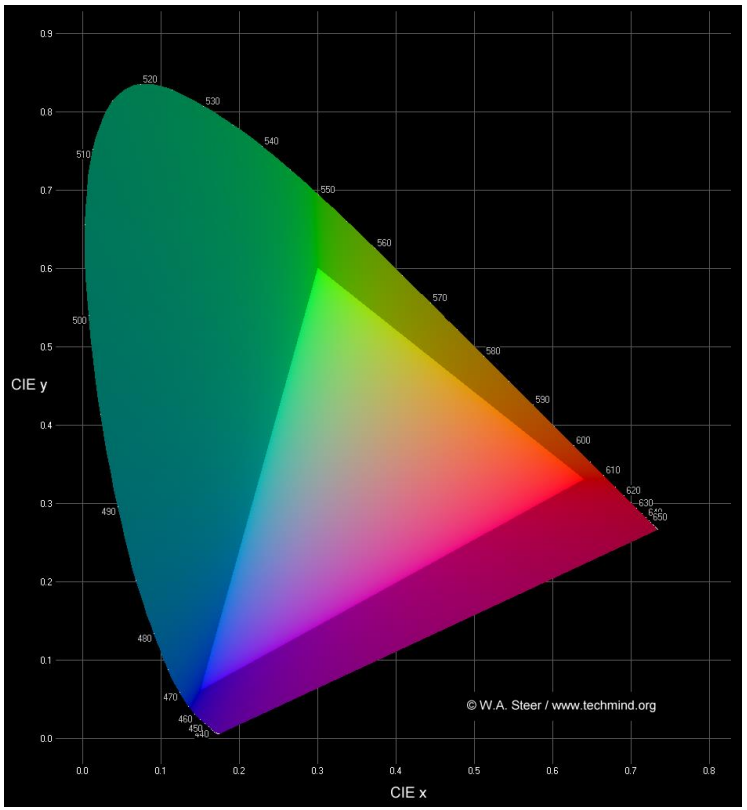




Foley et al. 1990

Color Gamut

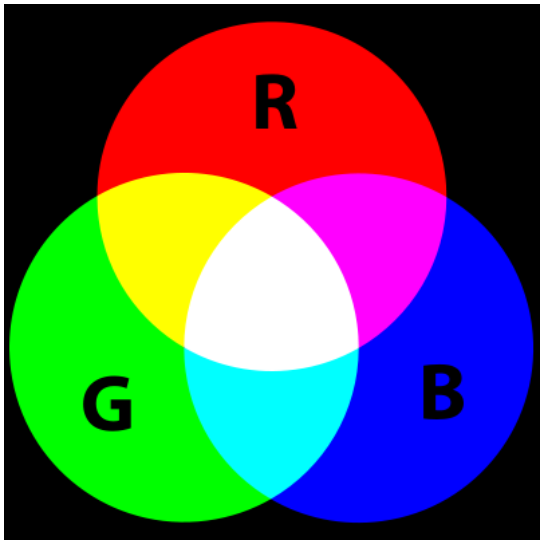
- color gamut: the area of colors in the CIE chromaticity diagram that can be created by adding together colors from the base colors
- if two colors are added, resulting color lies on straight line between them
- RGB shape: triangle

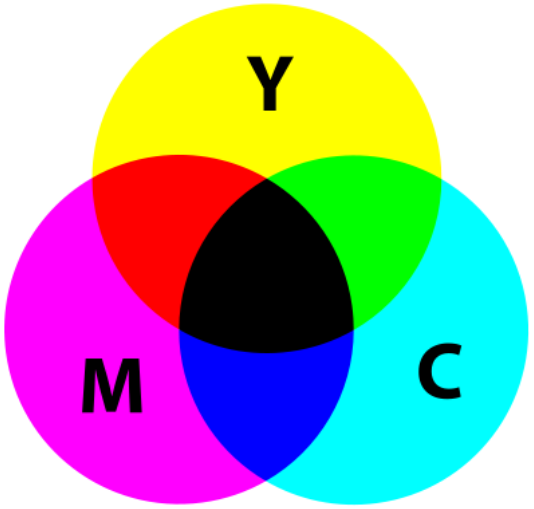


http://www.techmind.org/

Other Color Models: RGB & CMYK

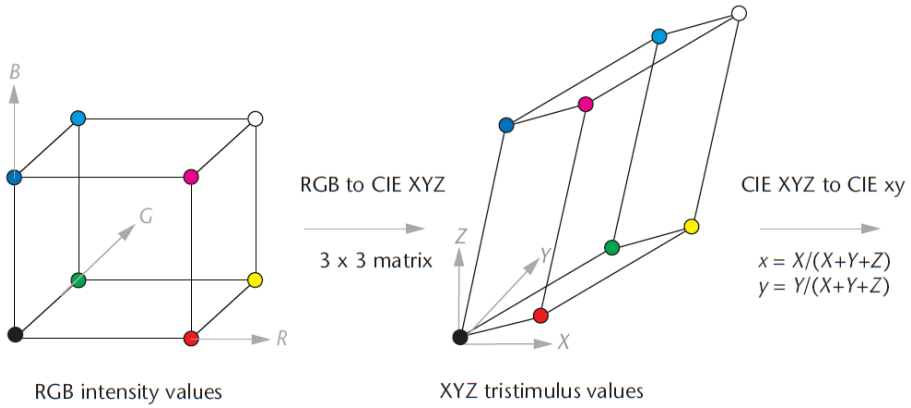
- (physical) color mixing depends on color production process
  - light emission: additive mixing (CRTs etc.): **RGB model**
  - light absorption: subtractive mixing (printing process): **CMY(K) model**





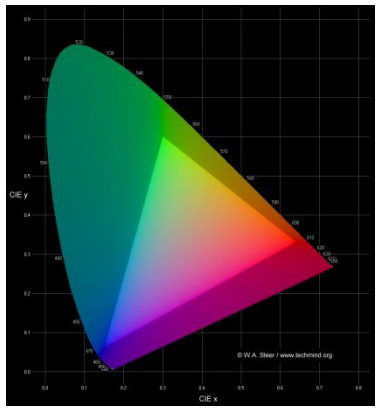
RGB and XYZ

- RGB to XYZ conversion



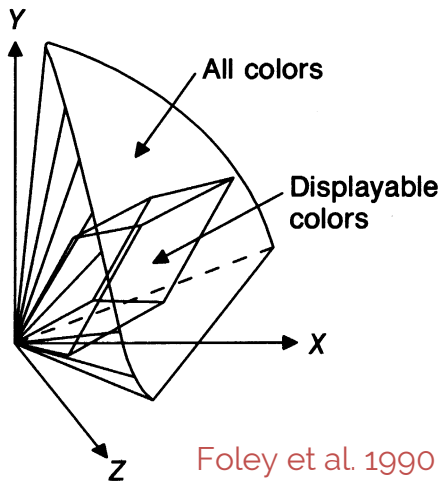
RGB intensity values

XYZ tristimulus values



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

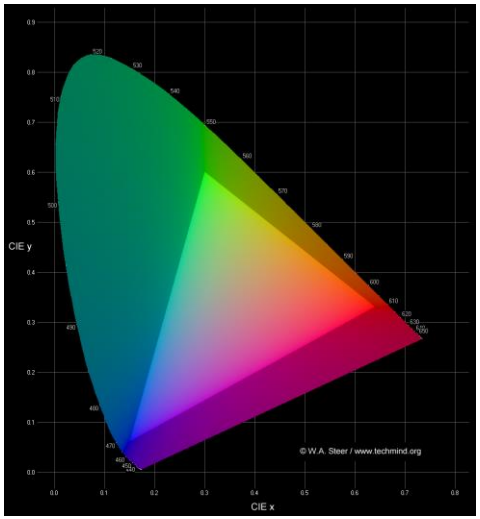
- RGB space: distorted cube
- black: origin of XYZ and projection center
- RGB projected to triangle



Foley et al. 1990

Can RGB Represent All Visible Colors?

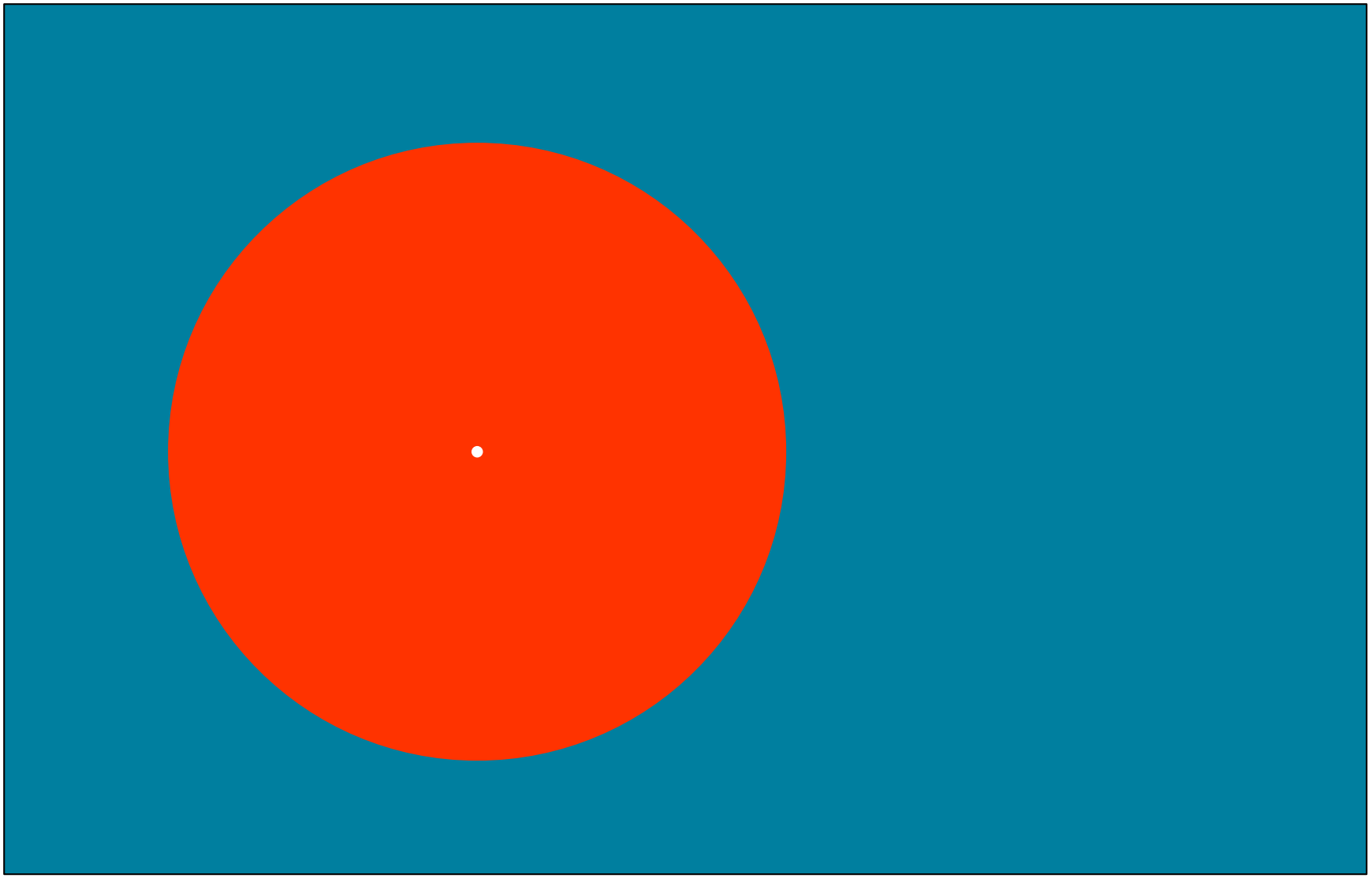
- no, because all colors form horseshoe shape in CIE chromaticity diagram and RGB gamut is triangular



http://www.techmind.org/

- But my shiny new 30" UHD OLED is state-of-the-art, it can surely show all colors!"
- → Let's see a color that it cannot show …

Let's see REAL cyan ...



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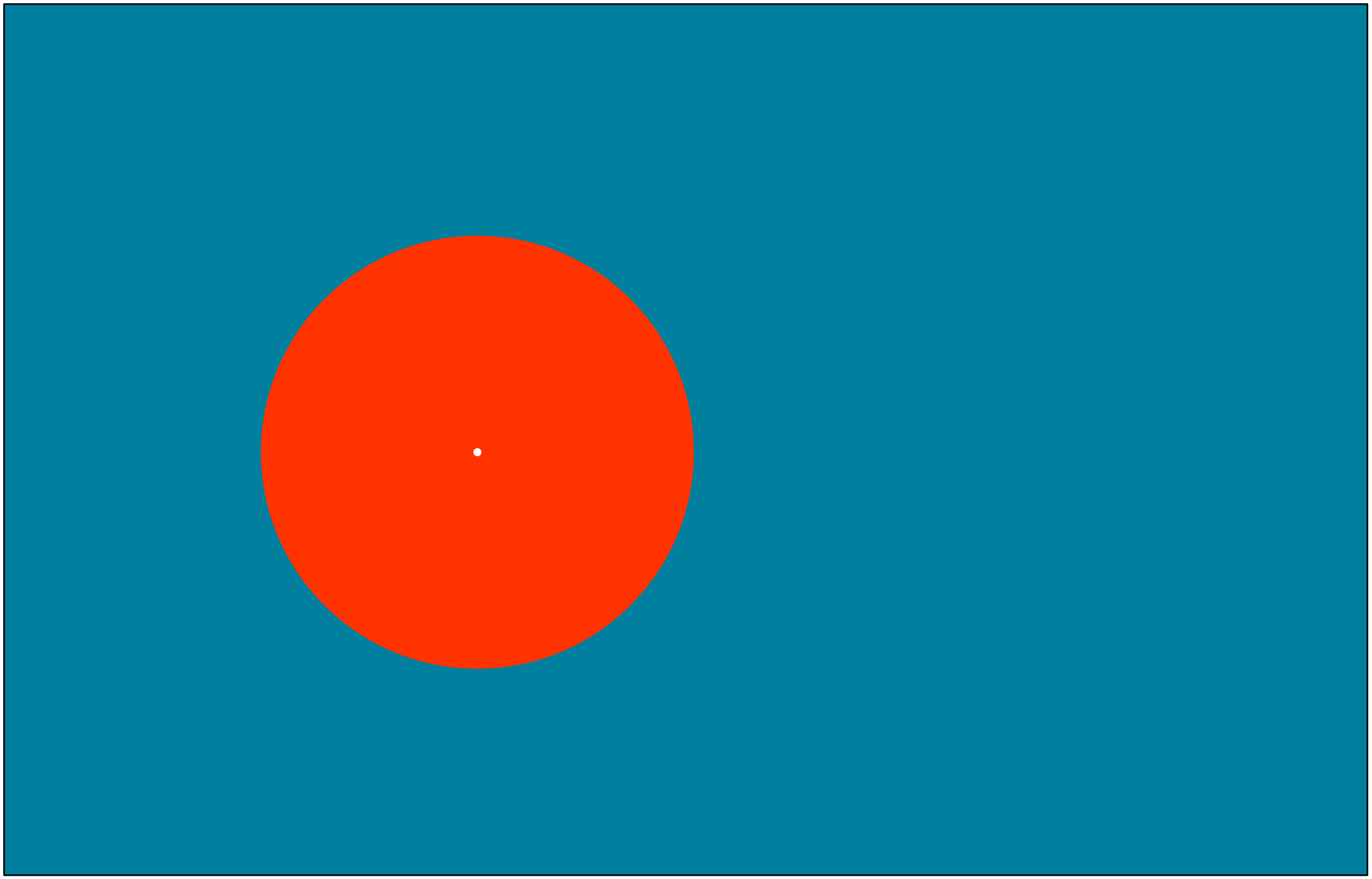

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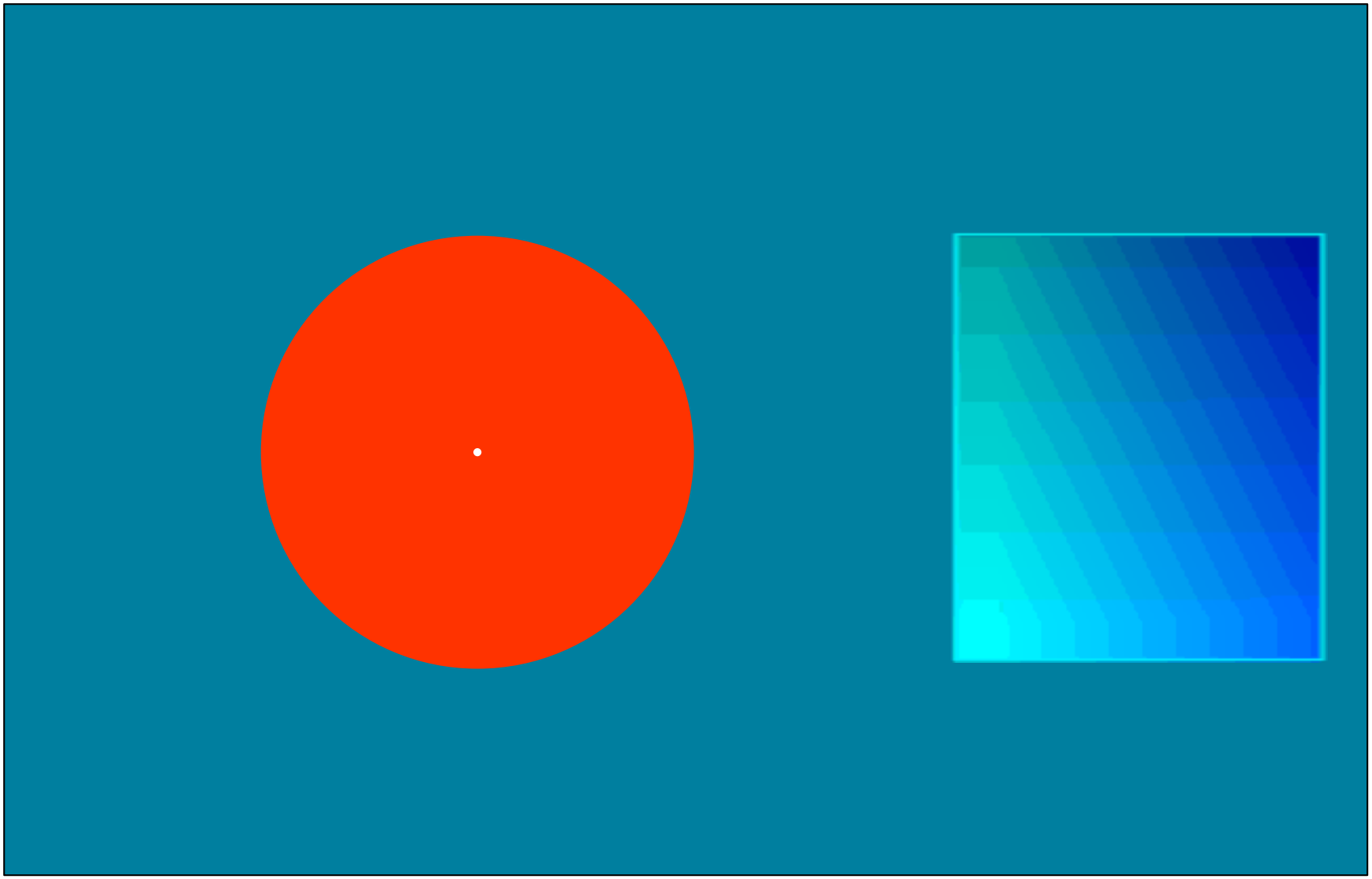
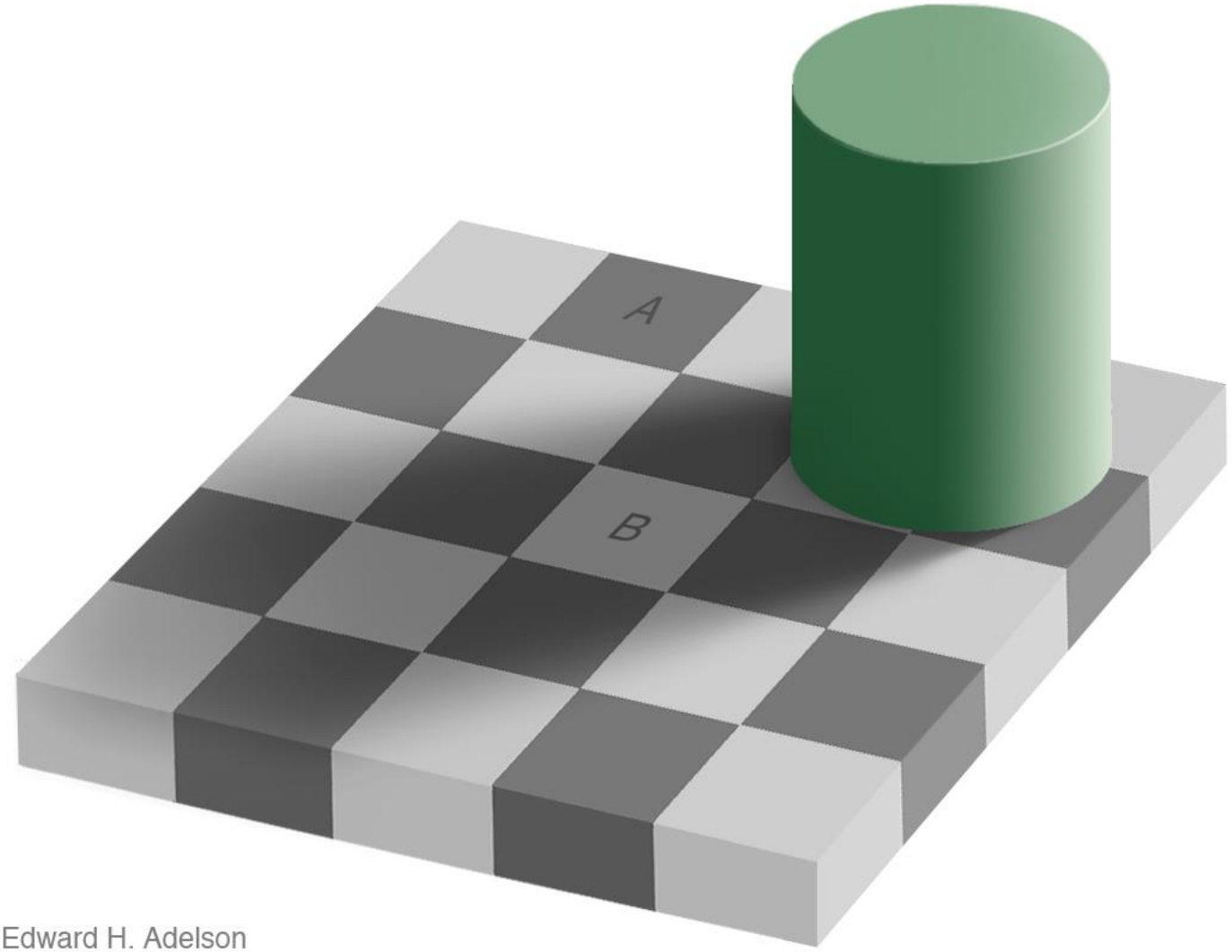


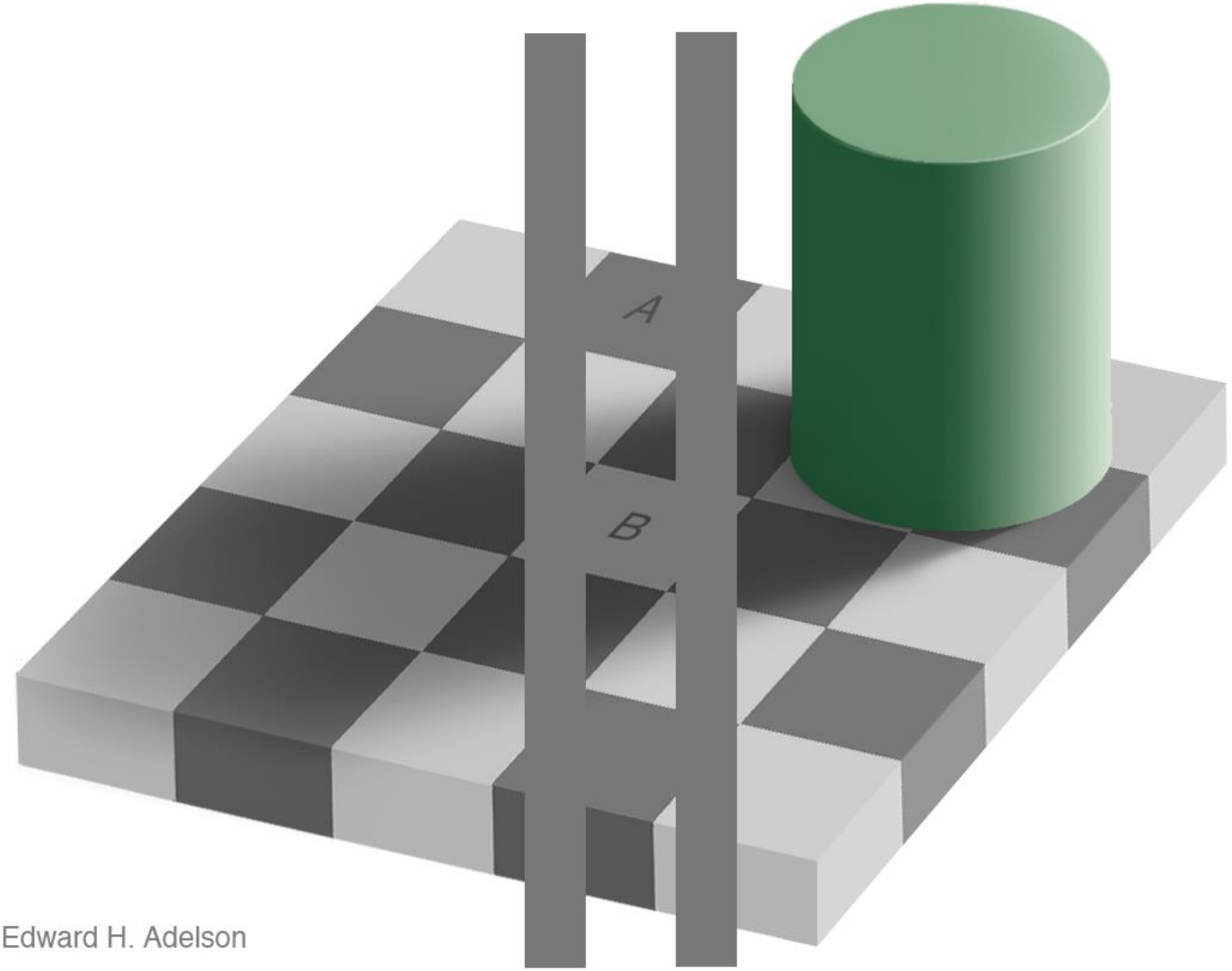
Visual System ➞ Color Perception



Edward H. Adelson

Slide adapted from Stone & Zellweger

Visual System ➞ Color Perception



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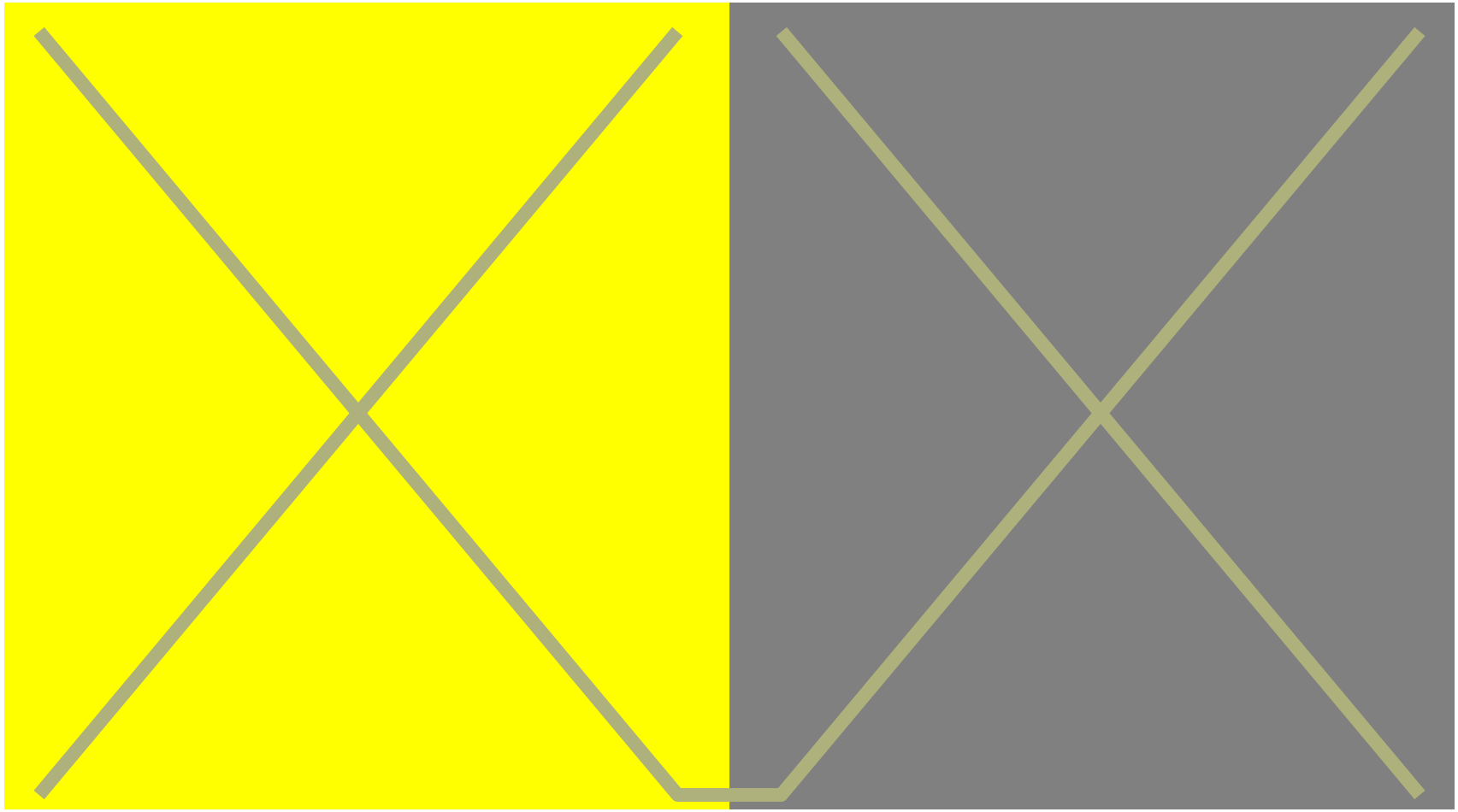
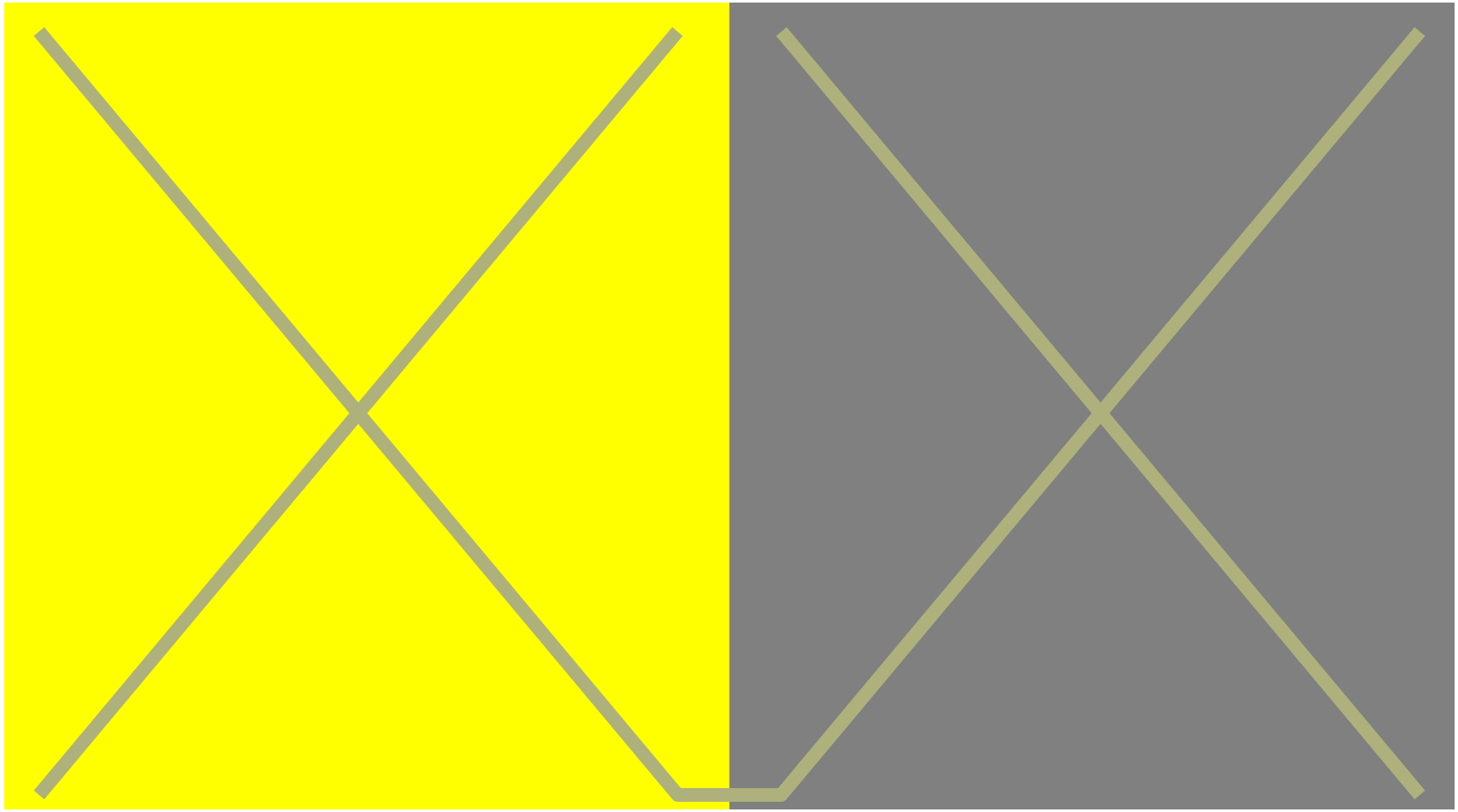
Visual System → Color Perception



Josef Albers

Simultaneous Contrast



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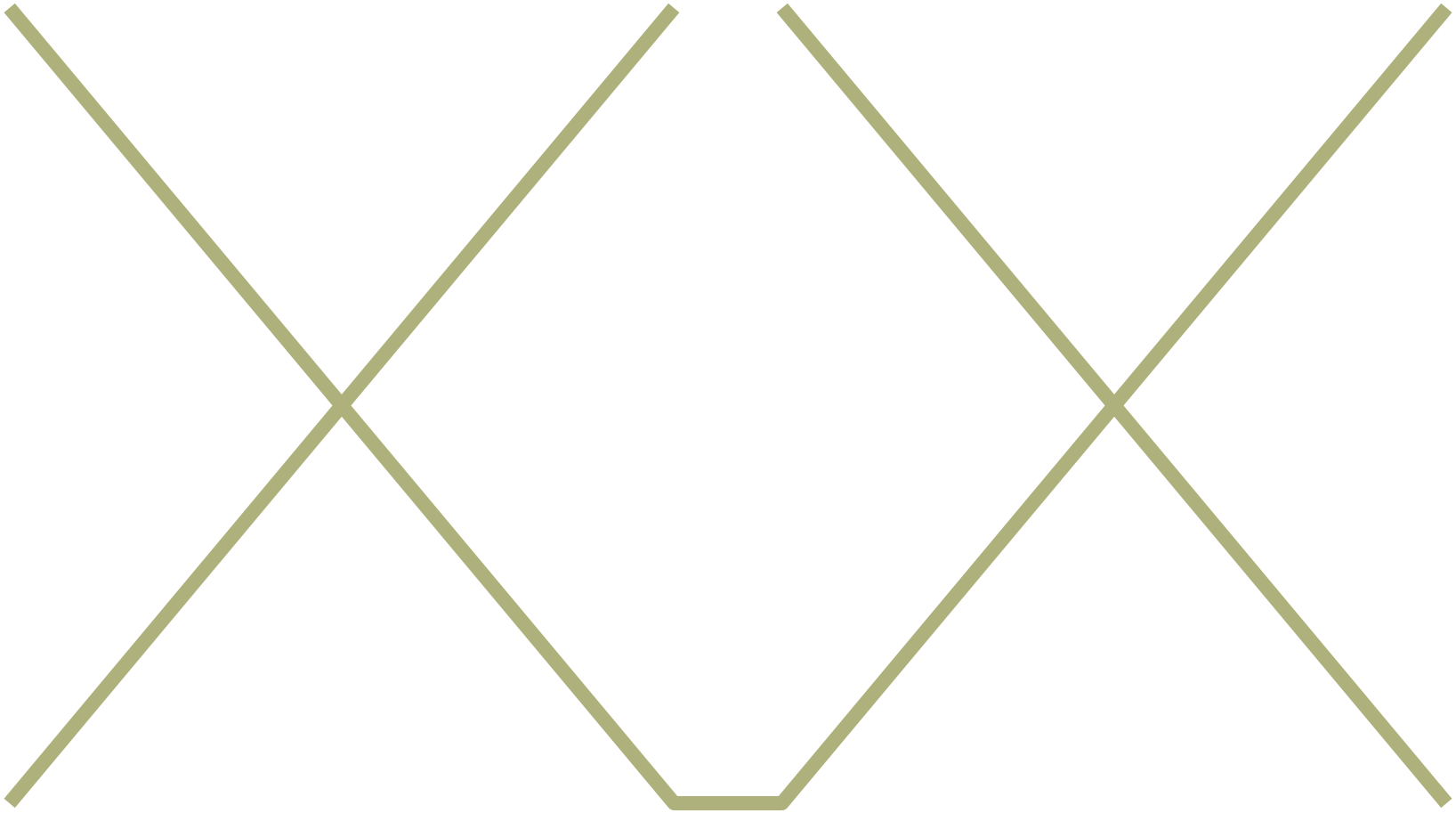

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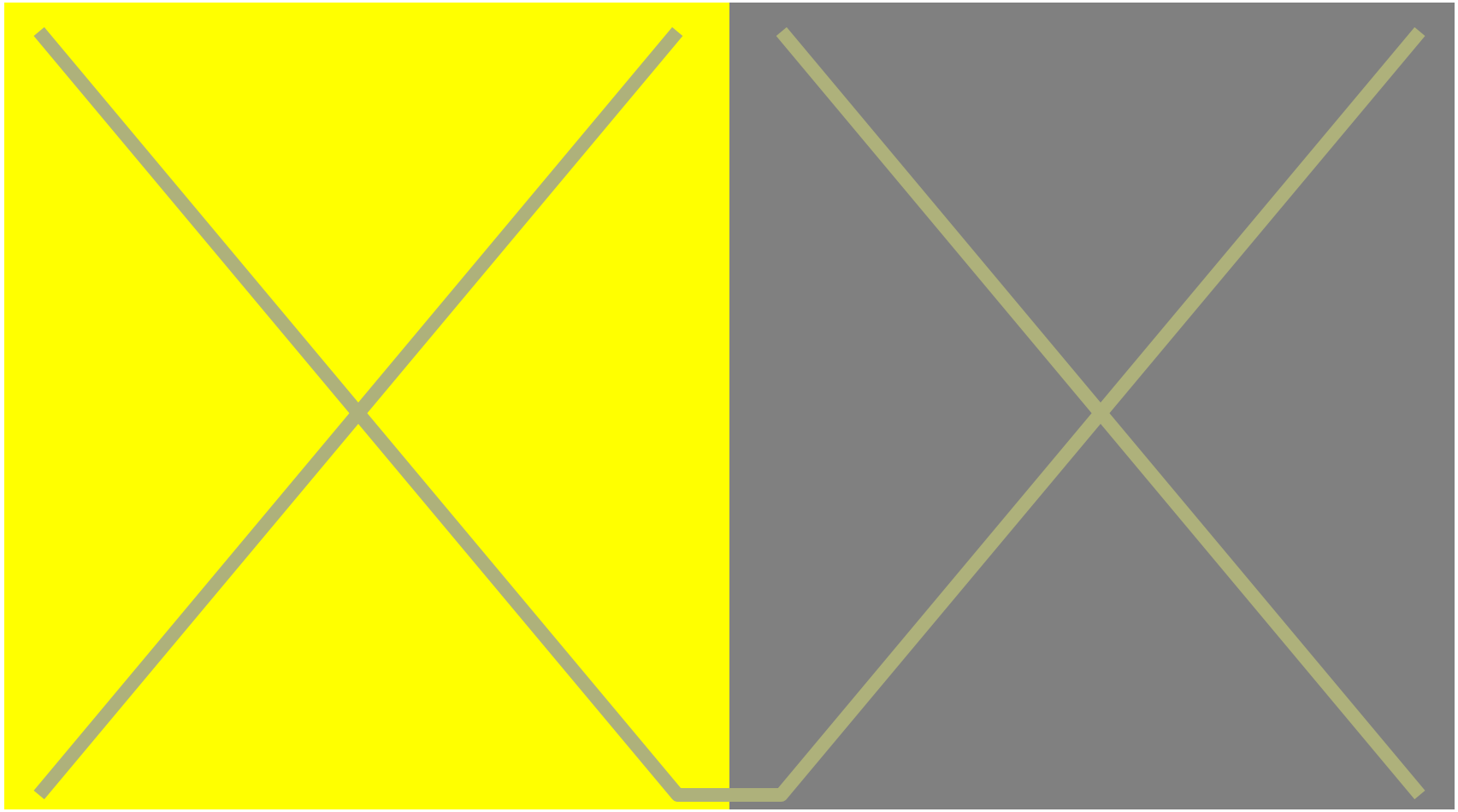
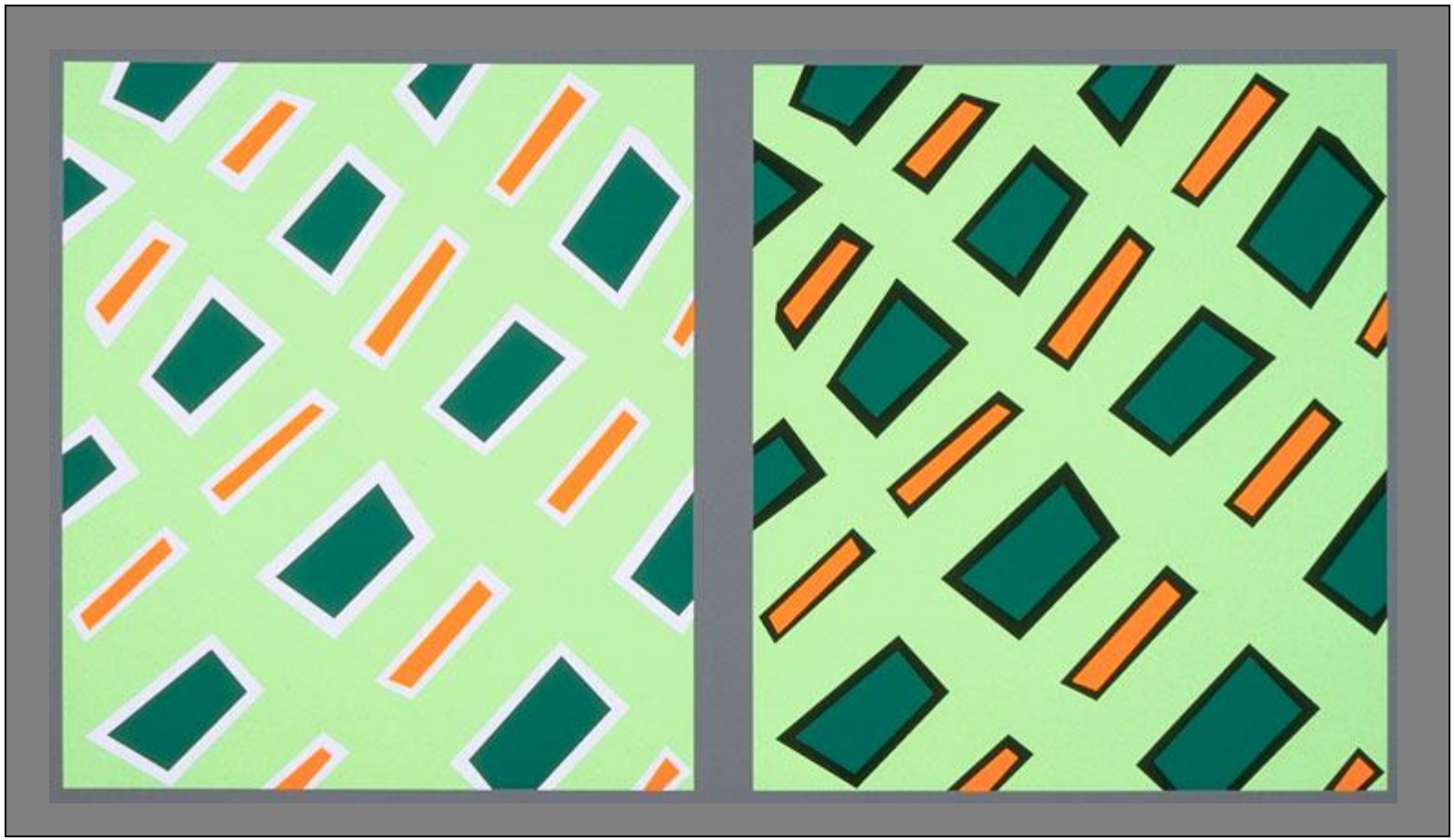


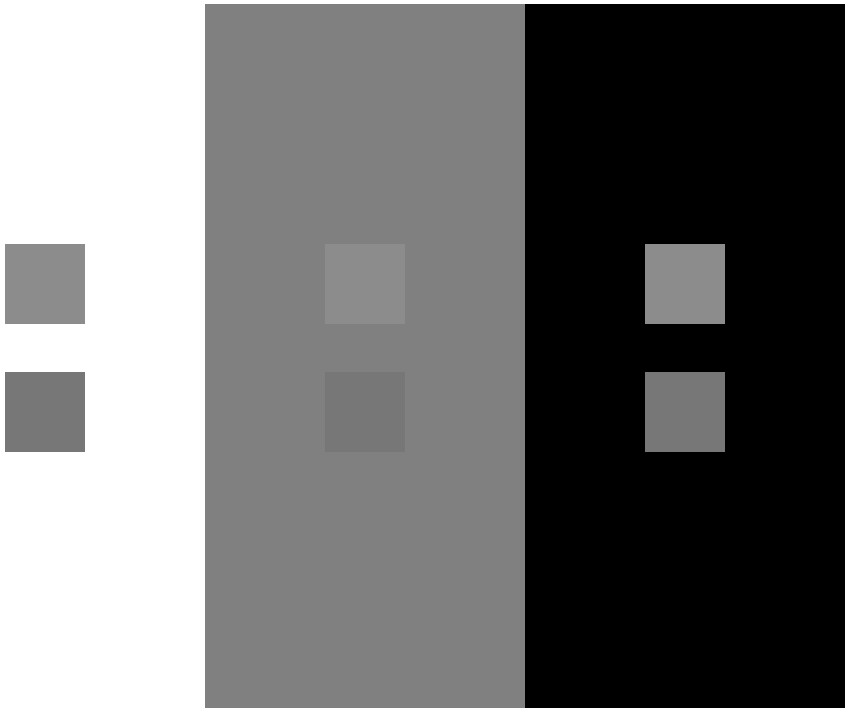
Josef Albers

Bezold Effect



Crispening

Perceived difference depends on background



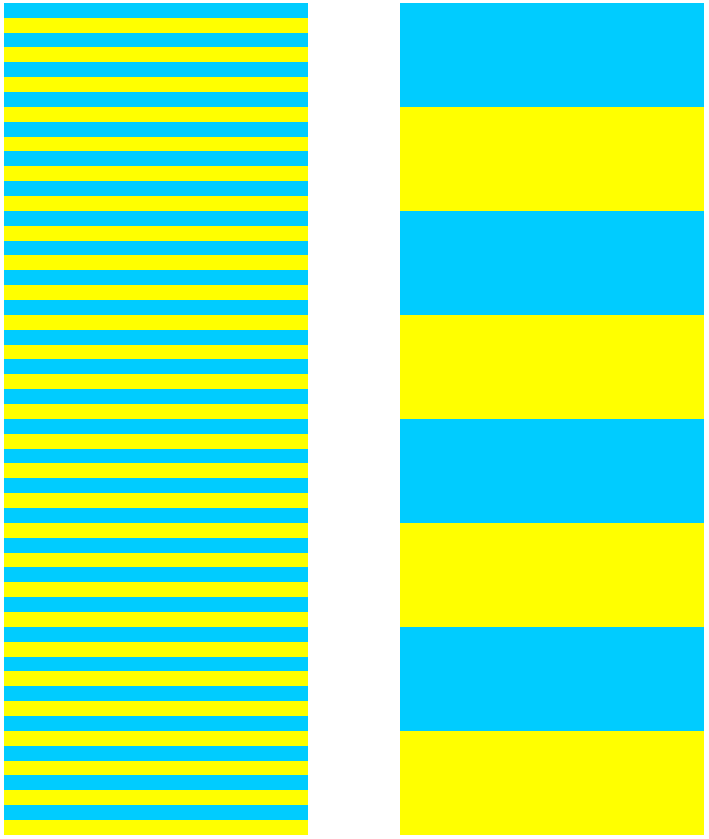
From Fairchild, *Color Appearance Models*

Spreading

Spatial frequency

- The paint chip problem
- Small text, lines, glyphs
- Image colors

Adjacent colors blend



Redrawn from *Foundations of Vision*

Color Perception ➞ Color Naming

What color is this?

Color Perception → Color Naming

"Yellow"

Color Perception ➞ Color Naming

What color is this?

Color Perception ➞ Color Naming

"Blue"

Color Perception ➞ Color Naming

What color is this?

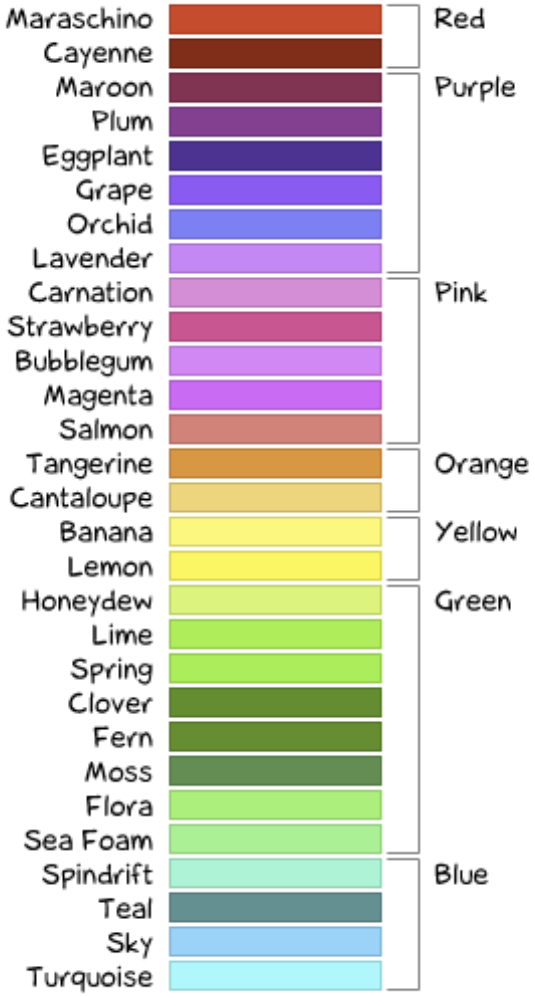
Color Perception ➞ Color Naming

"Teal ?"

"Turquoise ?" *"Blue-Green ?"* *"Sarcelle ?"*

Color according to gender?

Color names if you're a girl...



Color names if you're a guy...

Doghouse Diaries
"We take no as an answer."

Color according to XKCD

A crowdsourced color-labeling game

~5 million colors

~222,500 user sessions

http://blog.xkcd.com/2010/05/03/color-survey-results/

Color according to XKCD

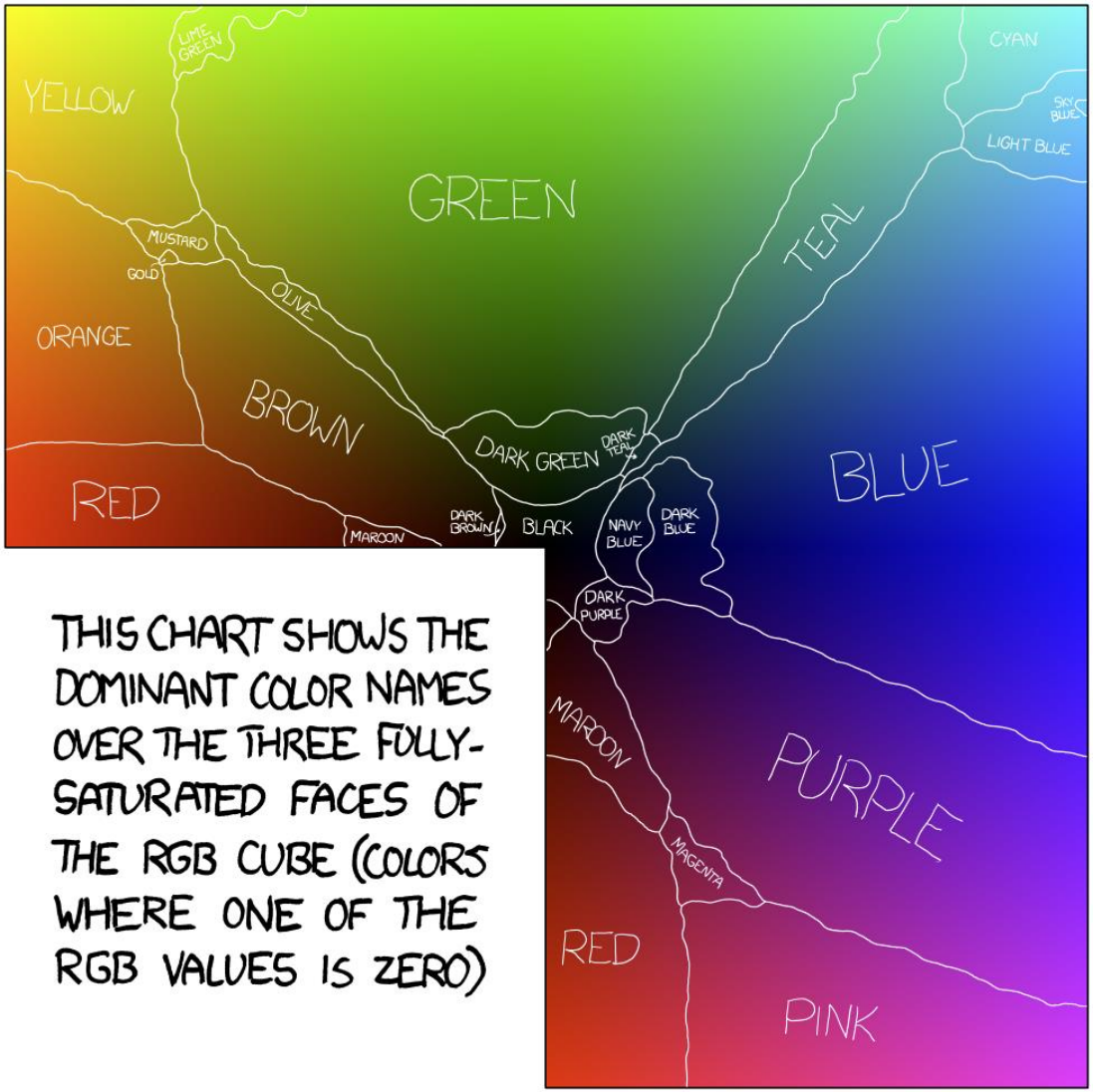
Color Naming

We associate and group colors together, often using the name we assign to the colors

Color Naming

We associate and group colors together, often using the name we assign to the colors

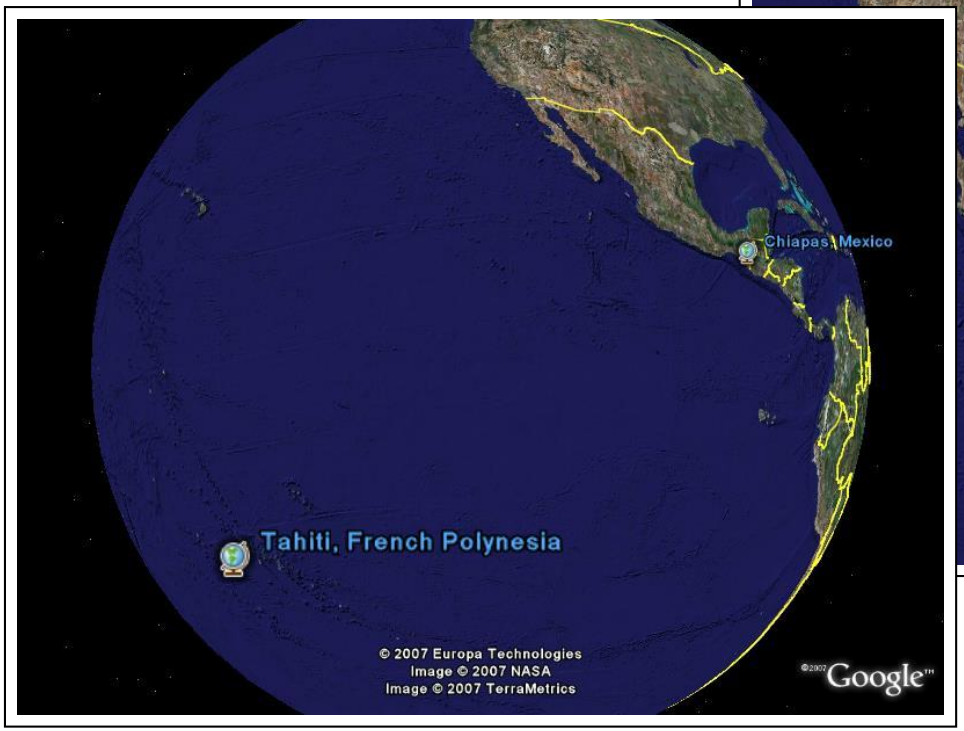
Are there natural boundaries?

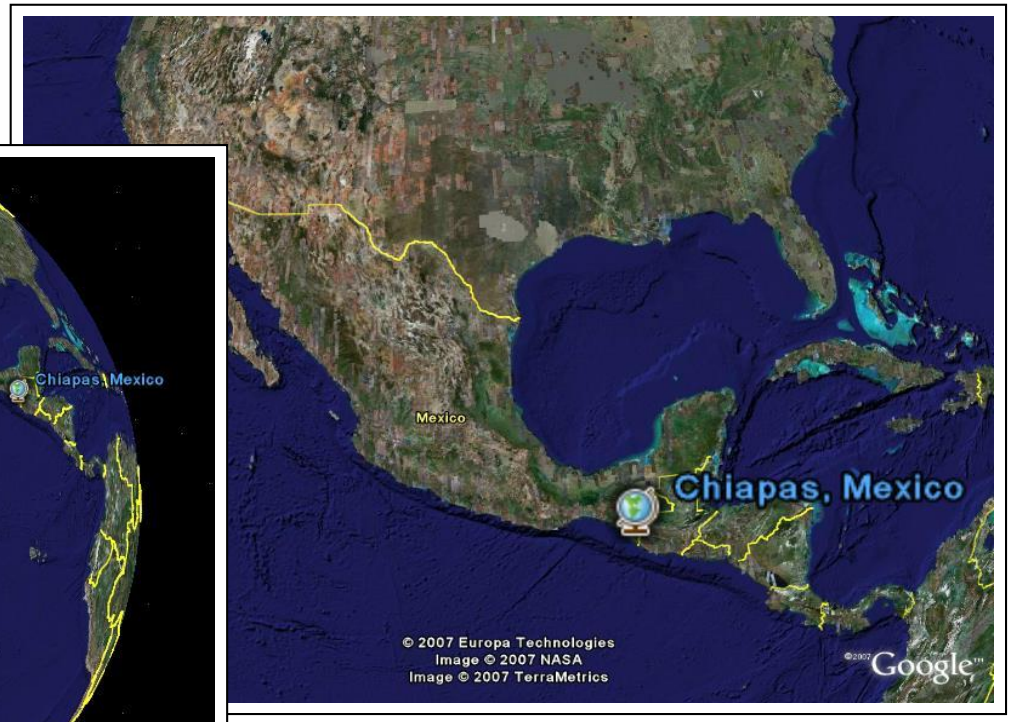


xkcd

Basic Color Terms

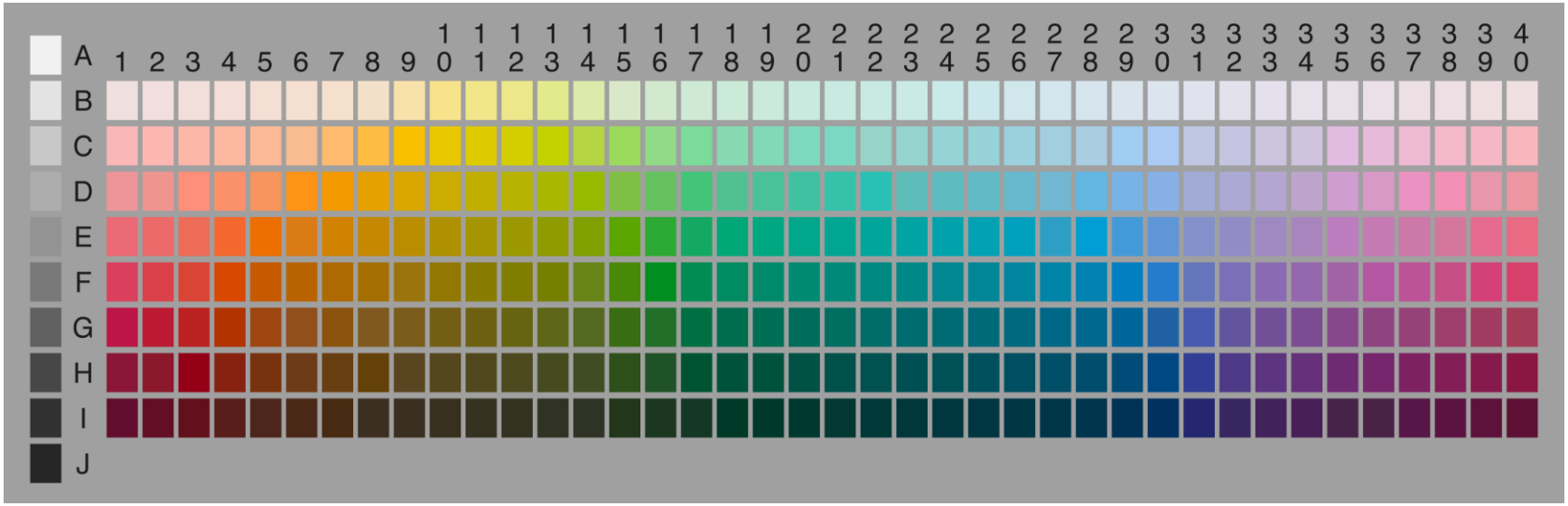
- Brent Berlin & Paul Kay 1969
- let's look at two specific places



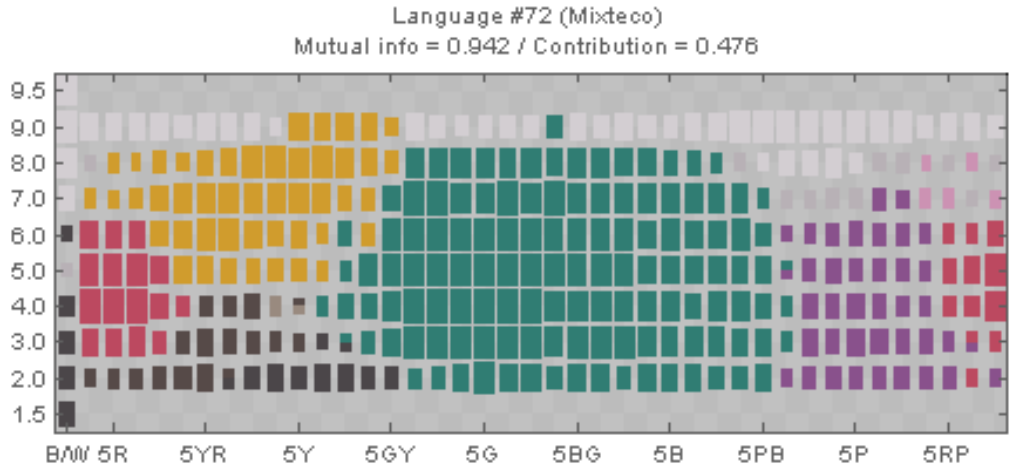


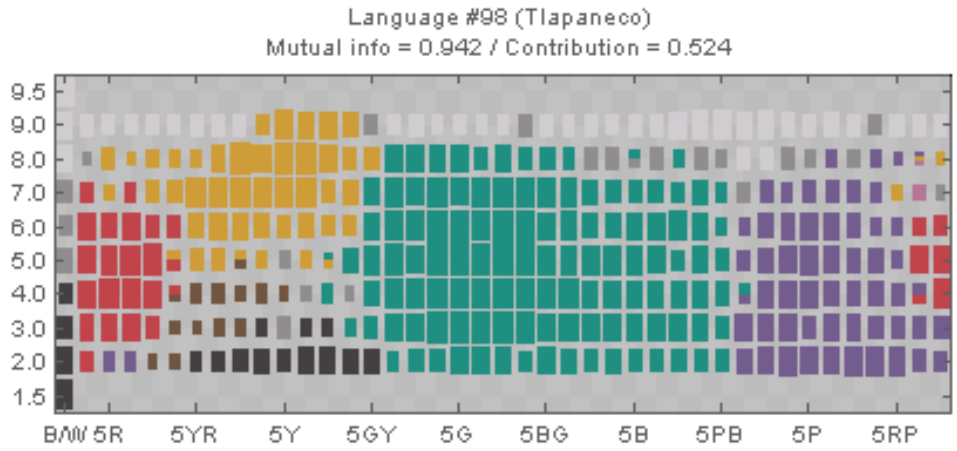
World Color Survey

Surveyed 2616 speakers of 110 languages using 330 different color chips

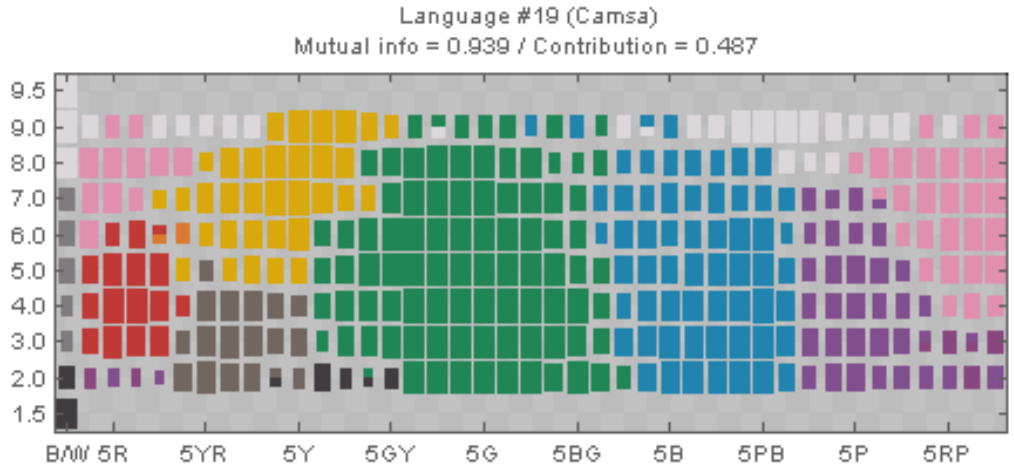


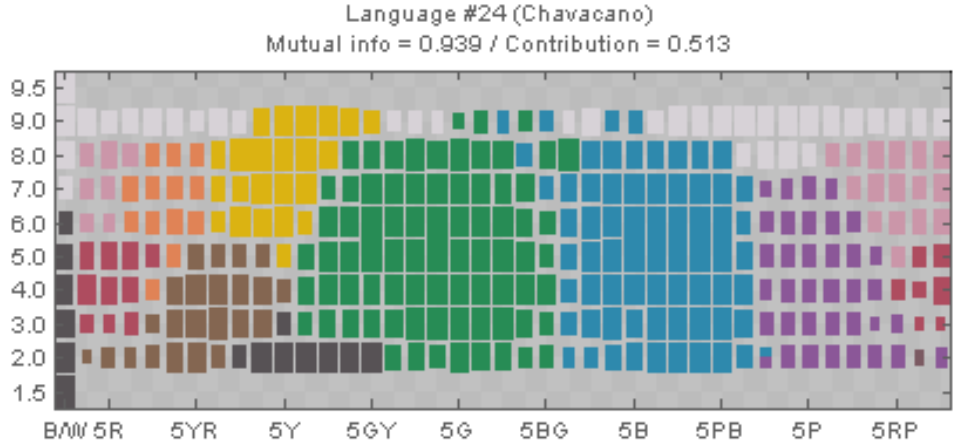
Results from WCS (Mexico)





Results from WCS (South Pacific)



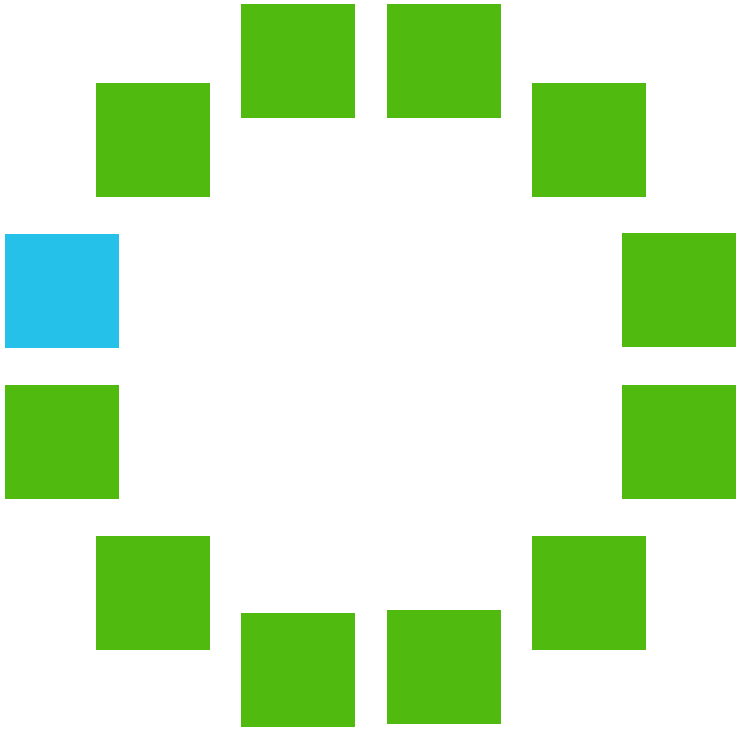


But language-color interaction

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

But language-color interaction

- experiment: how long to find a differing color?

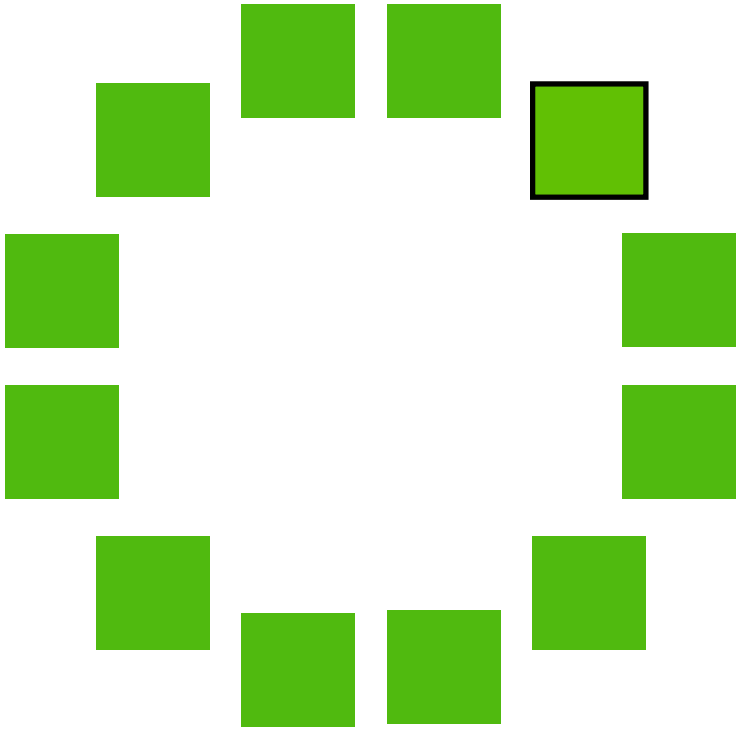


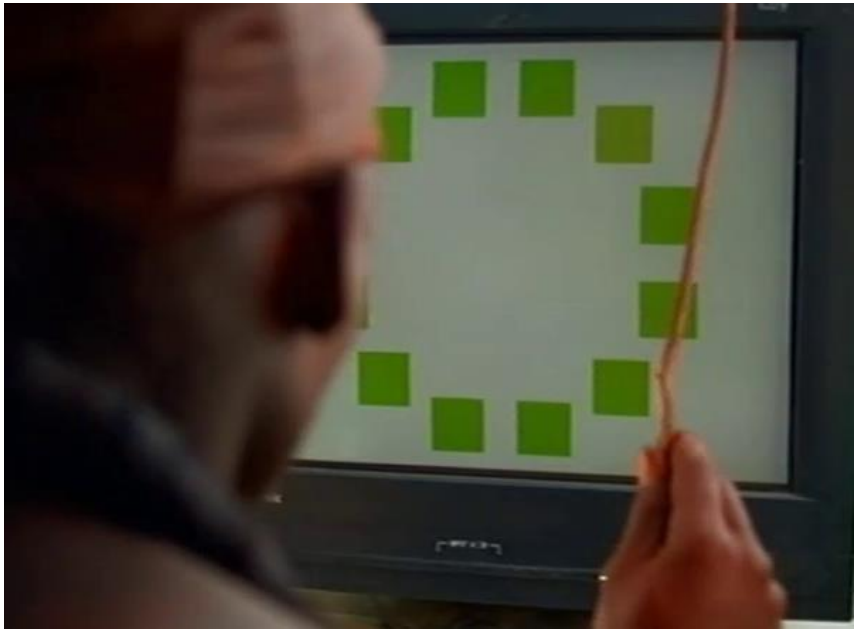
© BBC

difficult to impossible for Himba people

But language-color interaction

- experiment: how long to find a differing color?



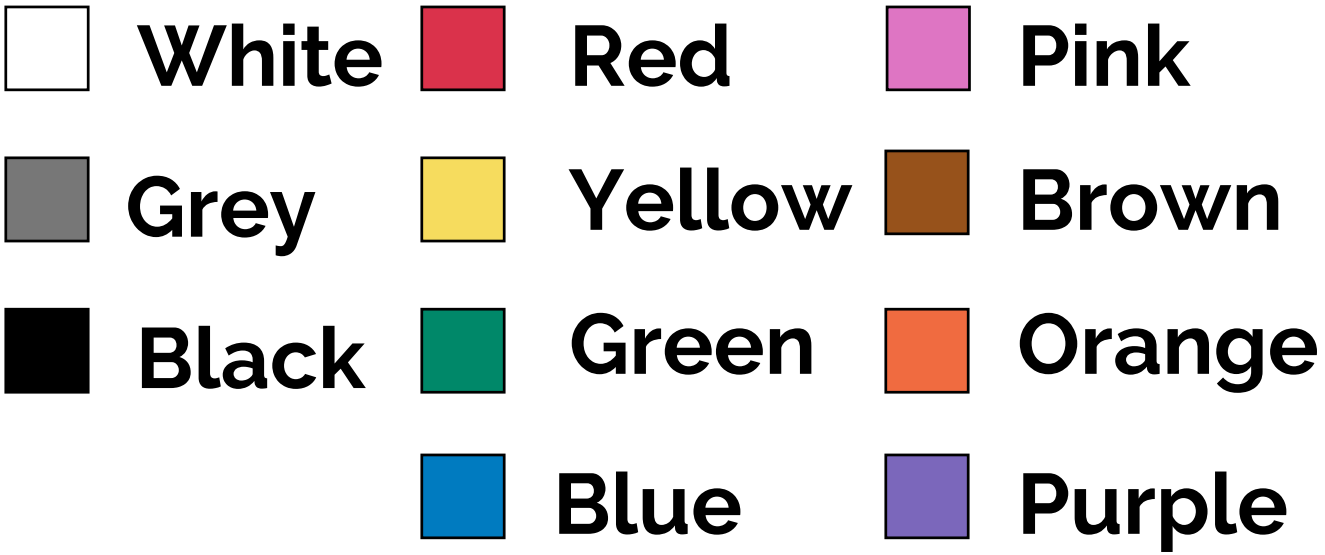


© BBC

easy for Himba people: different words for both types of green

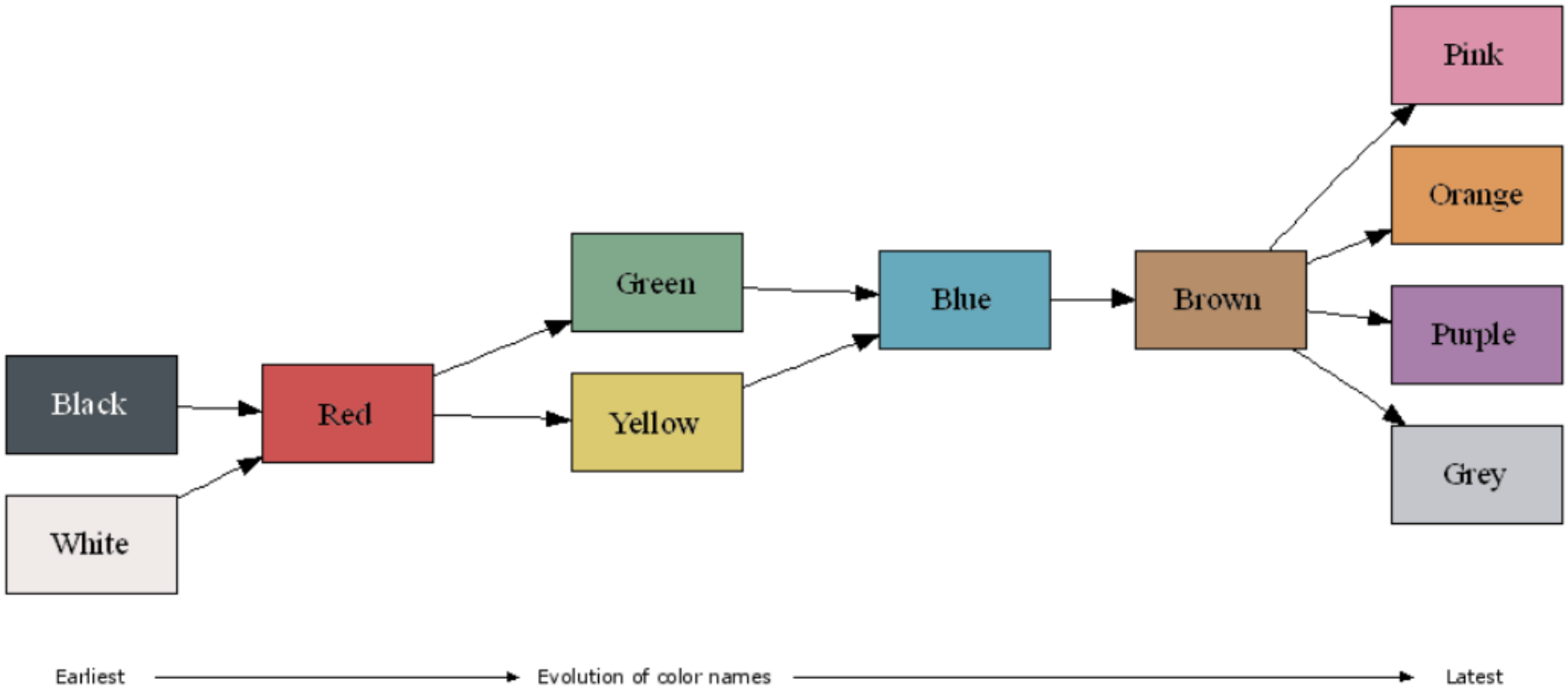
Universal (?) Basic Color Terms

Basic color terms recur across languages



Evolution of Basic Color Terms

Proposed universal evolution of color names across languages.

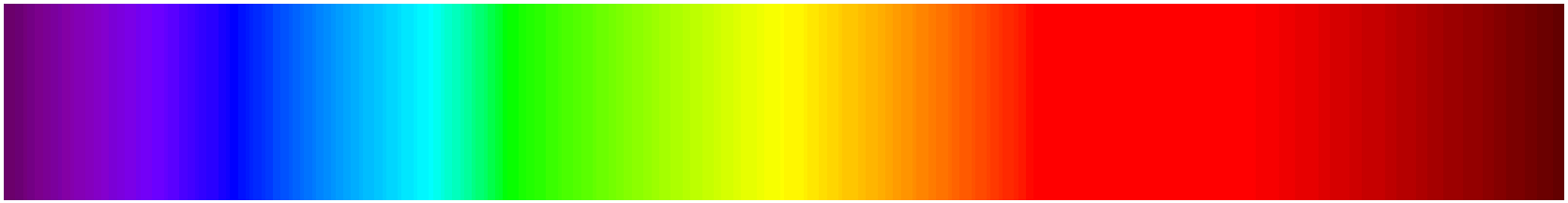


COLOR FOR VISUALIZATION

Why are color choices important?

Example: The Rainbow Color Scale

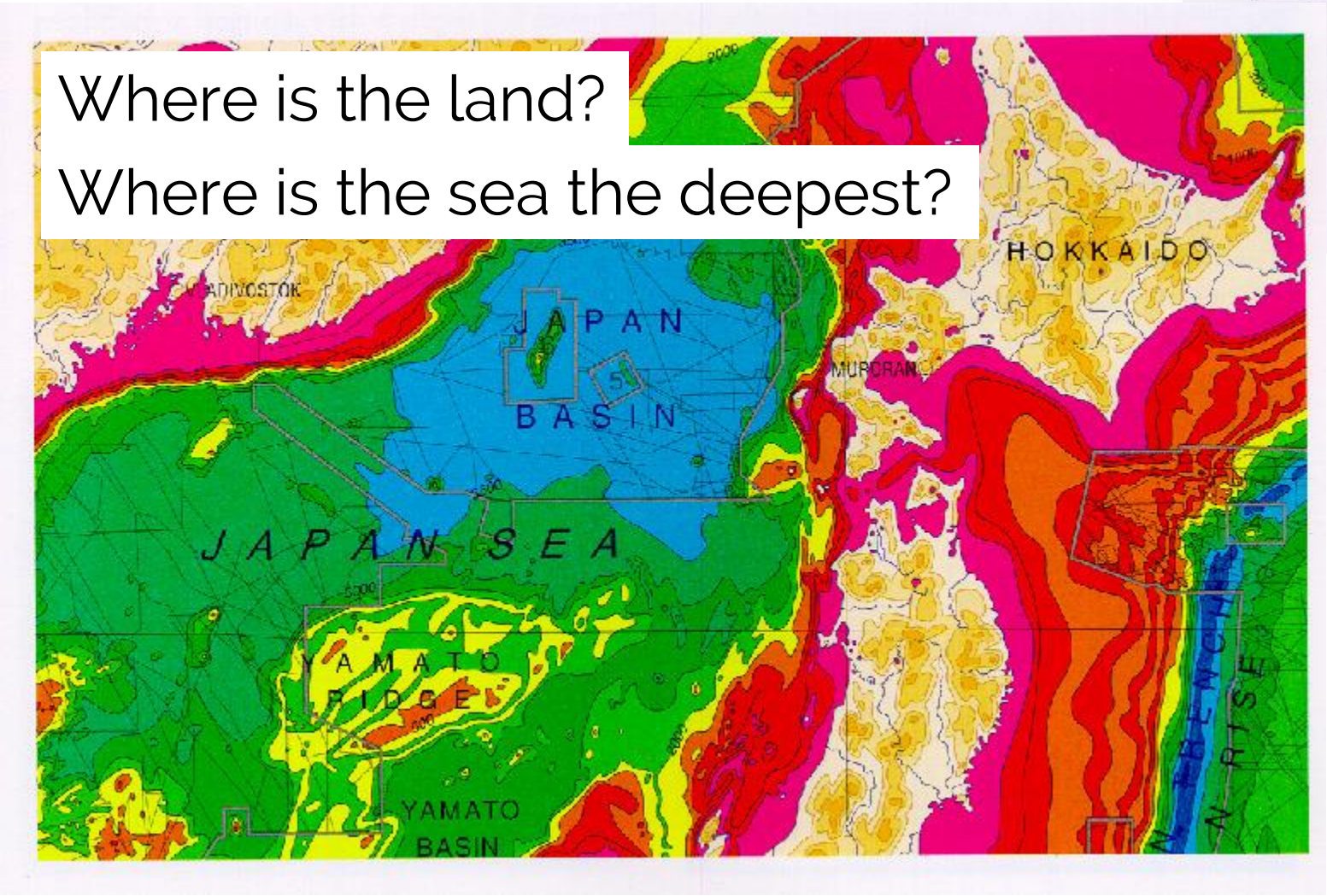
- Represent data by varying hue across (approximately) the full range of visible wavelengths
- One of the most common color scales in use today

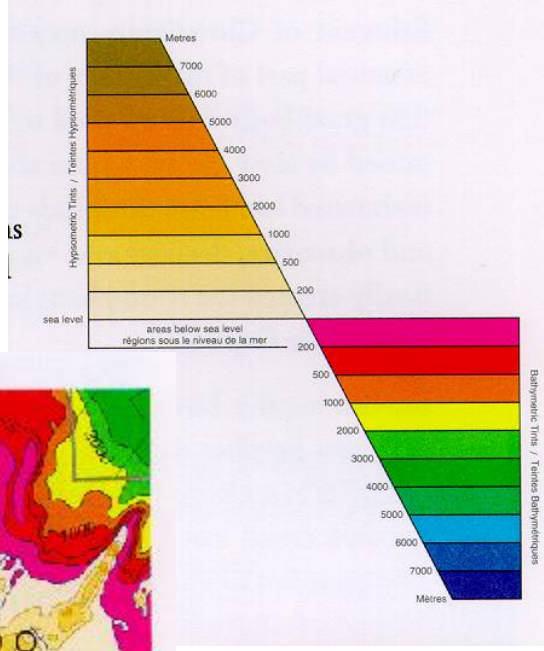


And it's (usually) a huge mistake!

General Bathymetric Chart of the Ocean

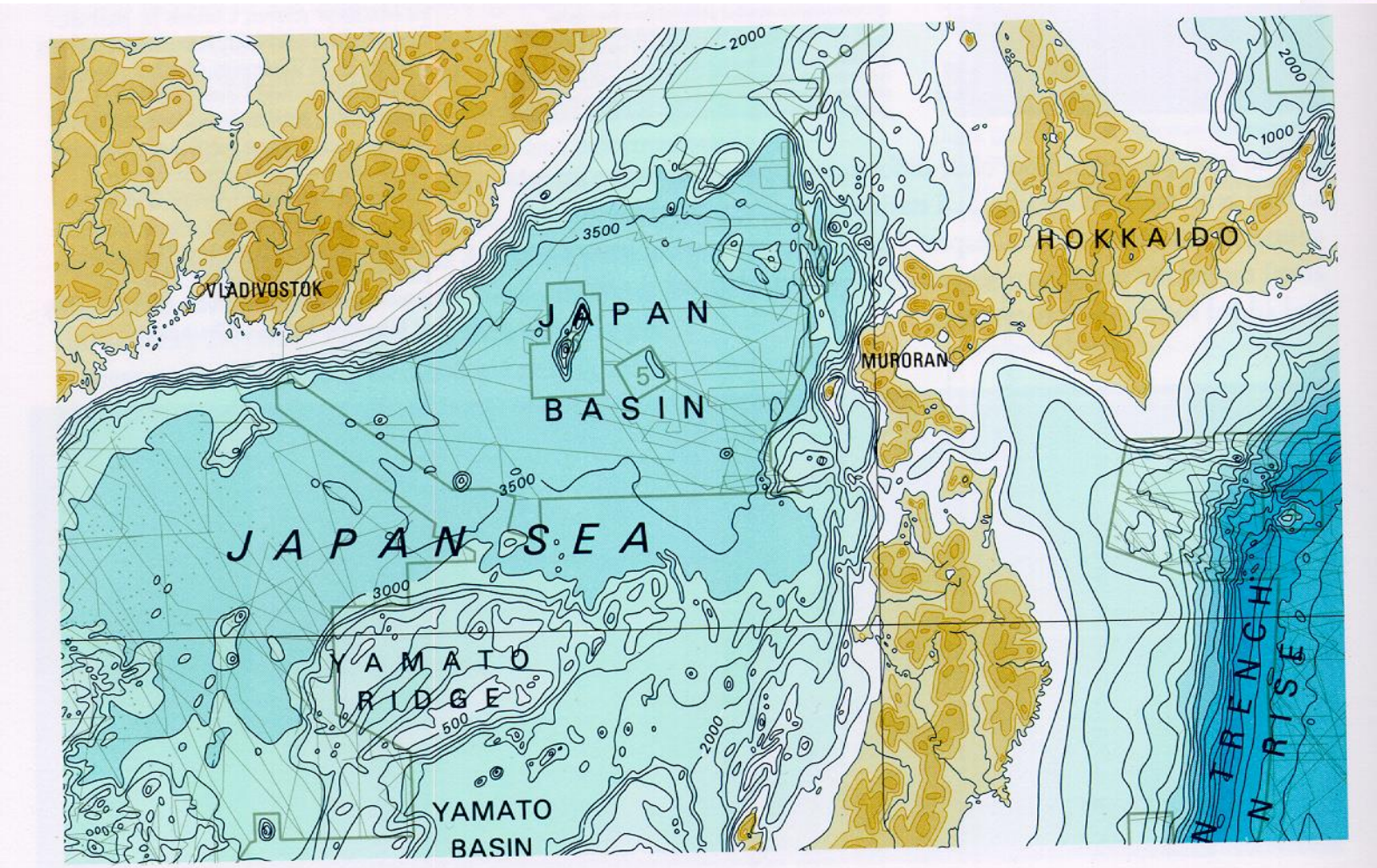
Every color mark signals:
longitude, latitude, sea/land, depth/altitude

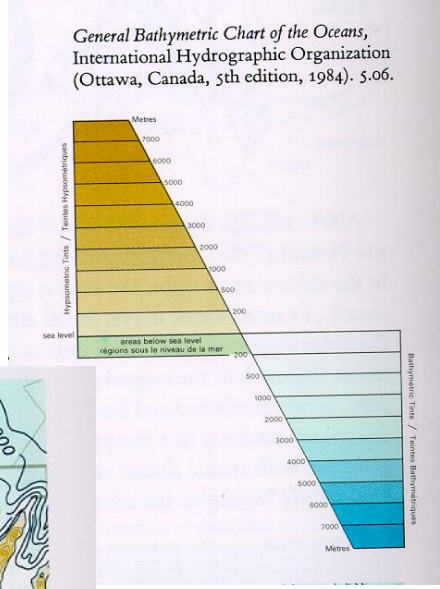




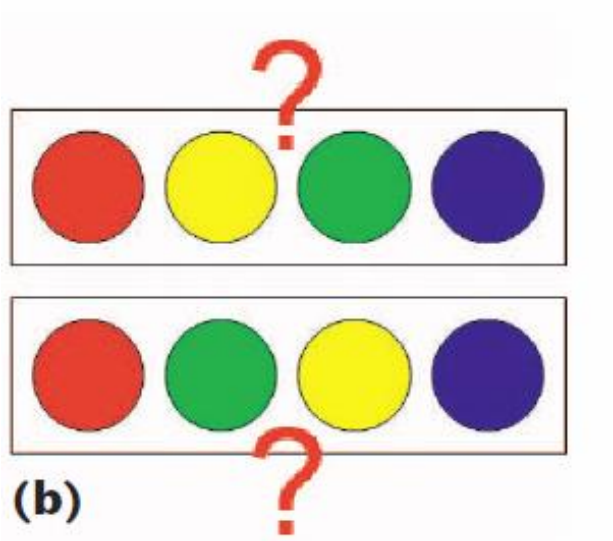
General Bathymetric Chart of the Ocean

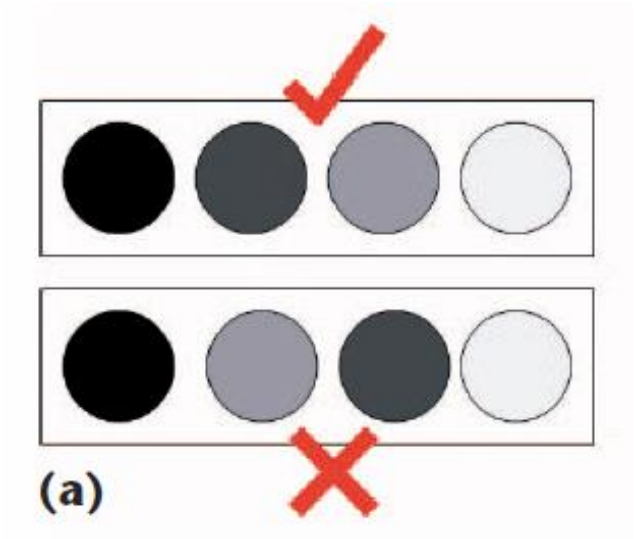
Now describe what kind of color scale was possibly used here





Perceptual Ordering





Rainbow Color Scale

- Is ordered by wavelength
- Is **not** perceptually ordered

Gray Scale

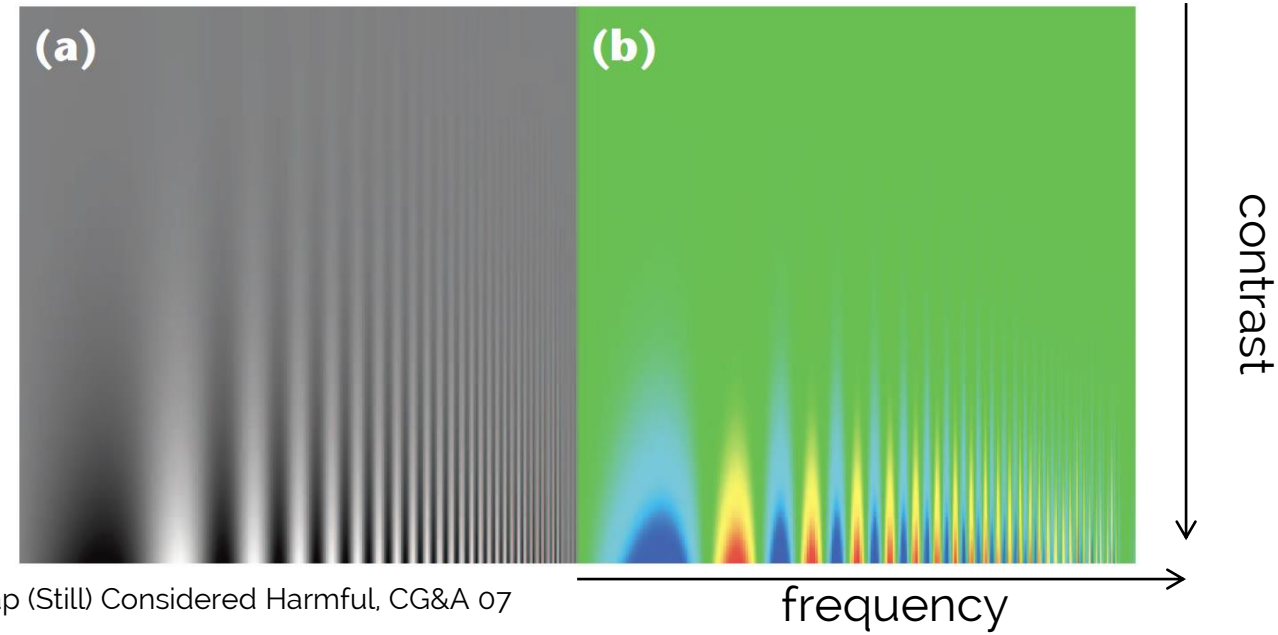
- Increases luminance (value) from dark to light
- Is perceptually ordered

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

Color Scale Luminance

Rainbow Color Scale

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

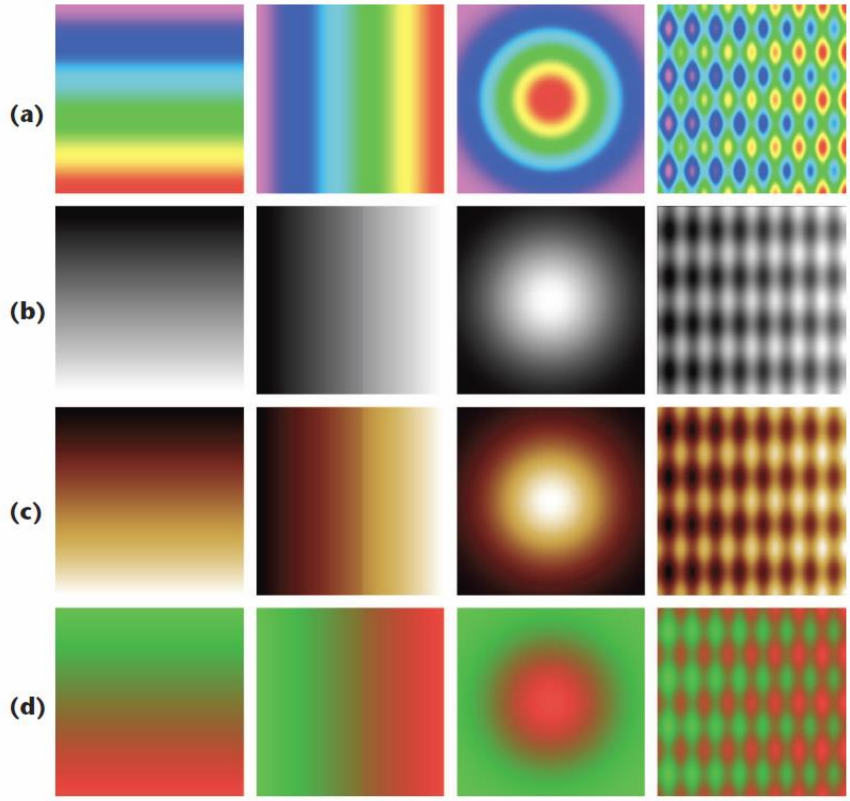


From: Rainbow Color Map (Still) Considered Harmful, CG&A 07

Color Scale Transitions

Rainbow color scale

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



rainbow color scale

gray scale

heated color scale

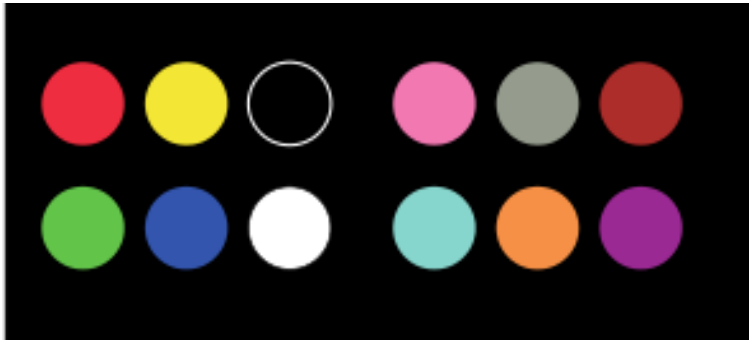
isoluminant green-red scale

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

HOW TO PICK COLORS

A Few General Rules

- Always have **high luminance contrast** between foreground and background
- Use **only a few distinct colors**



> 12 colors will likely not work
~5 colors recommended

From Ware, Information Visualization

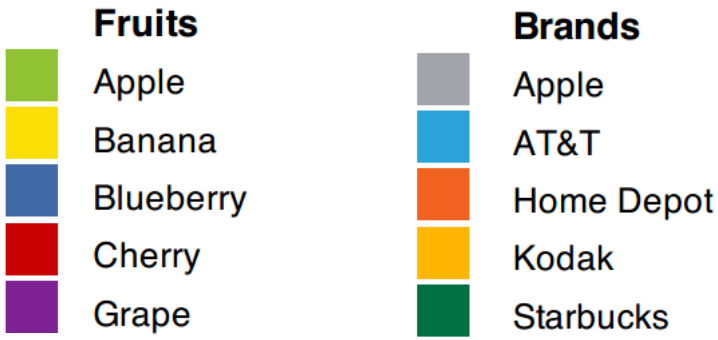
Using Color to Label

(For groups, categories, highlights, etc.)

Colors should be distinctive and named

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

Use cultural conventions & appreciate symbolism



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

Beware of bad interactions (red/blue etc.)

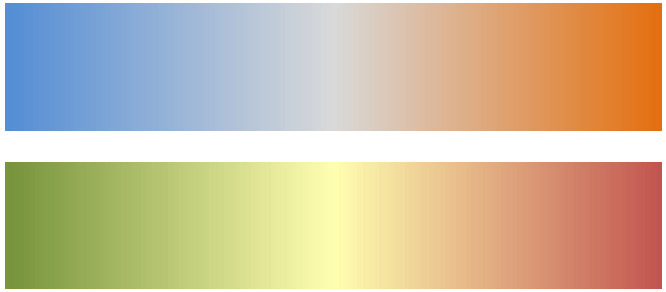
Using Color for Scales

(For ordinal or quantitative data)

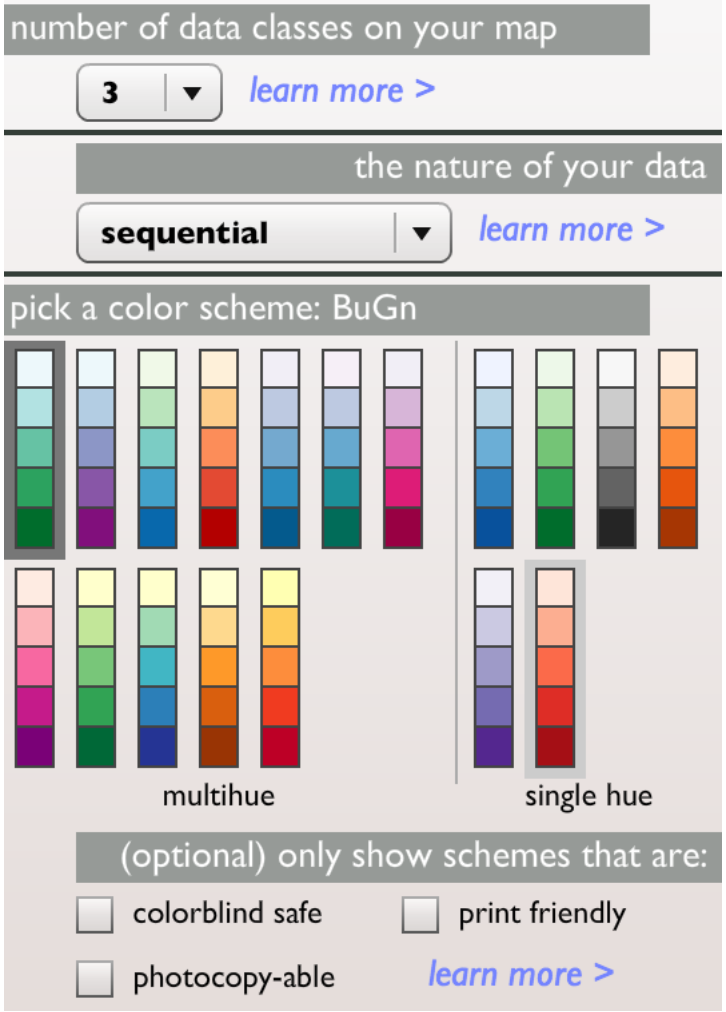
Use a scale that varies **lightness** in addition to color

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

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



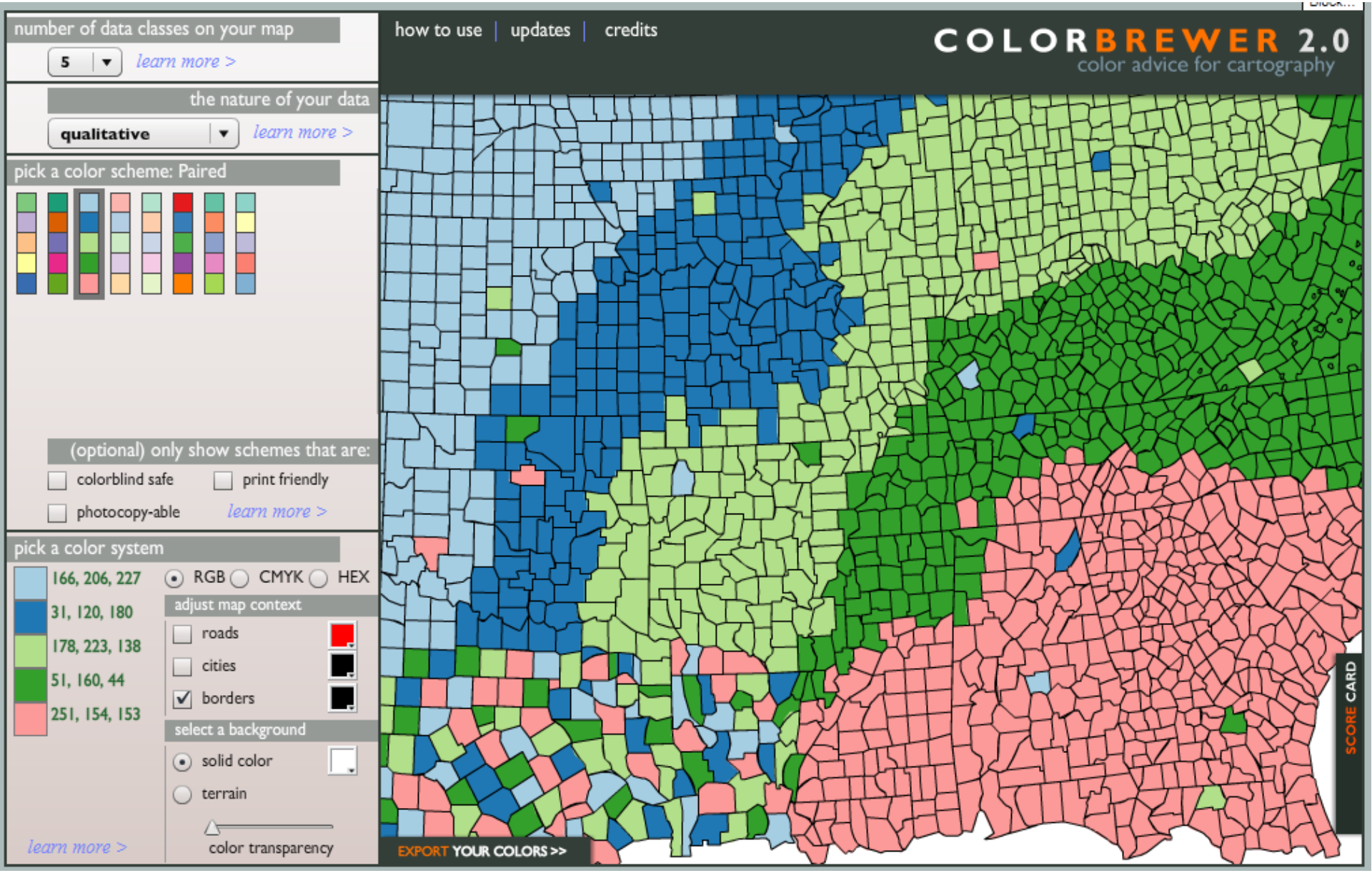
ColorBrewer



Highly recommended!

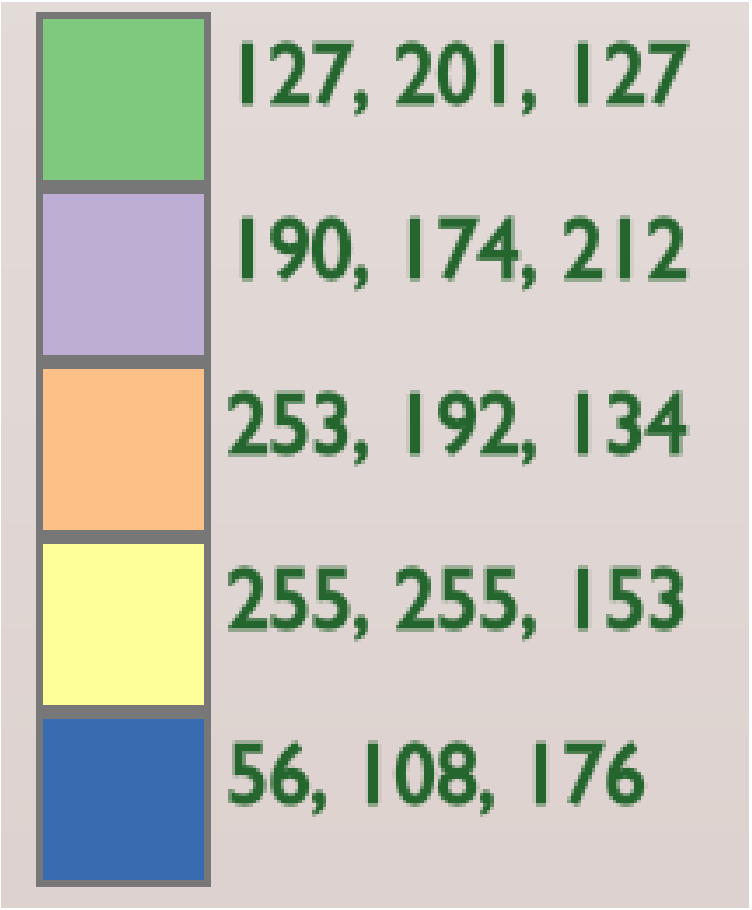
Designed originally for maps but will also work well for other types of visualizations

http://colorbrewer2.org/

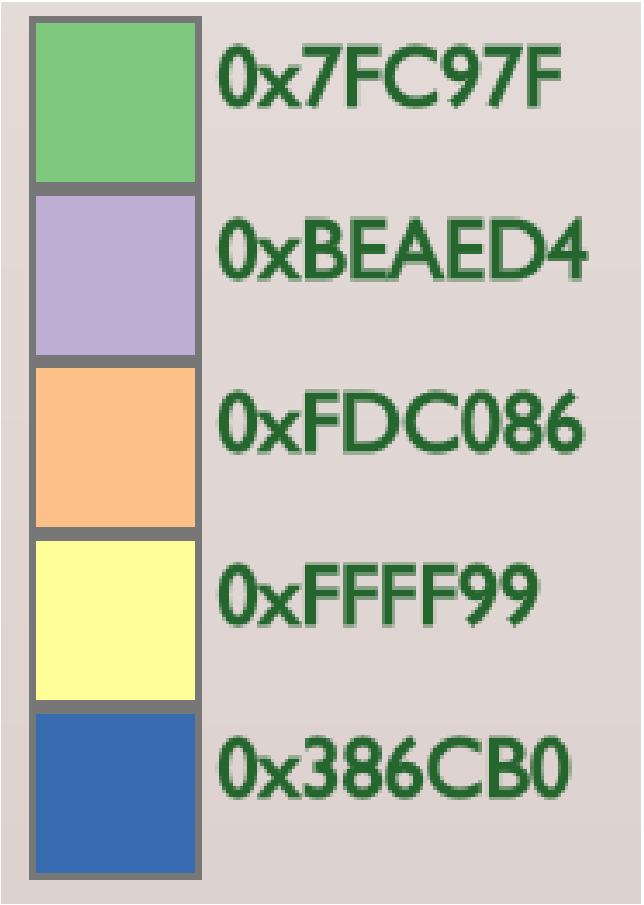


http://colorbrewer2.org/

ColorBrewer

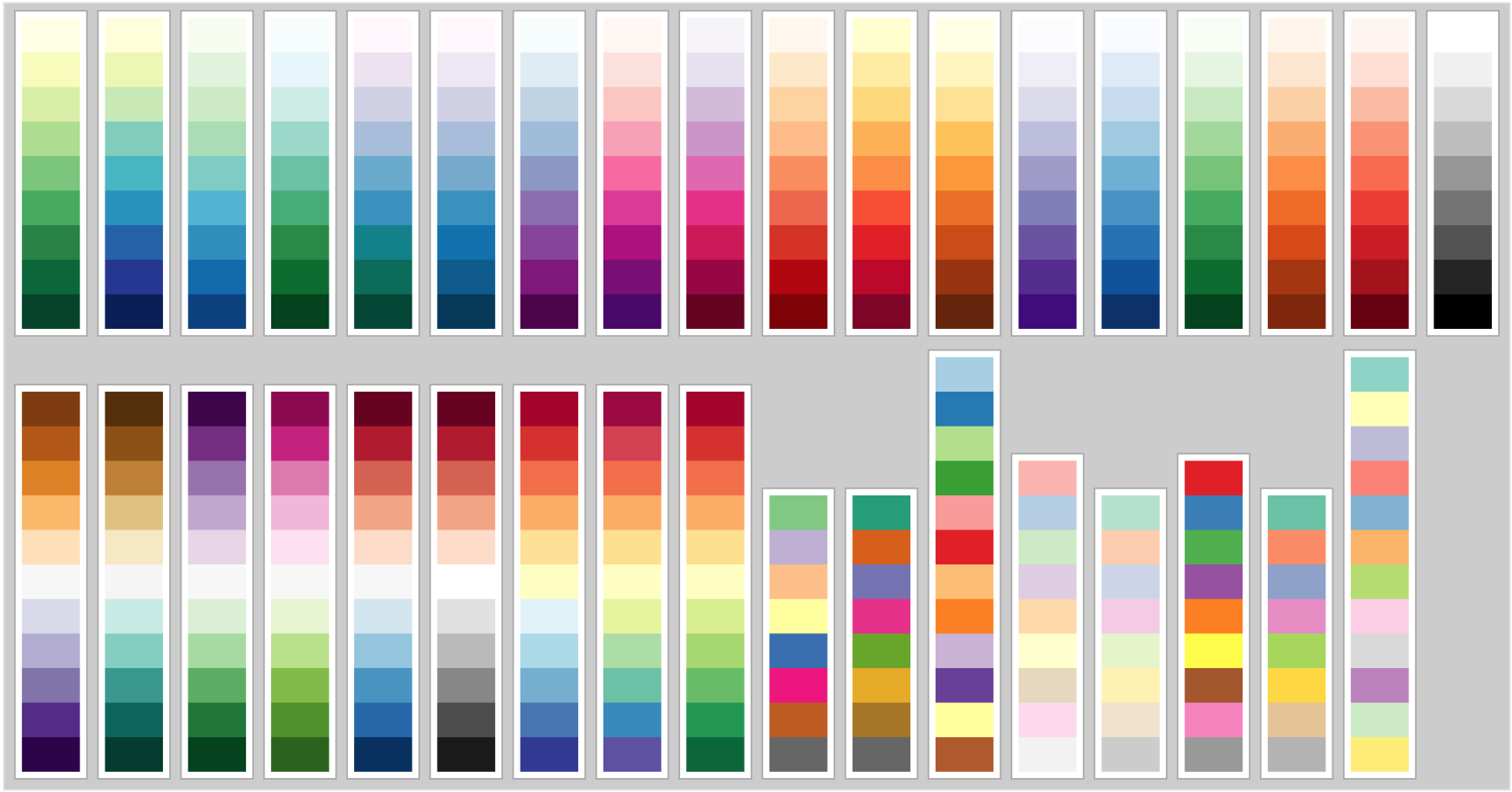


(RGB)



(Hex)

Every ColorBrewer Scale



For CSS and JavaScript (by Mike Bostock)

http://bl.ocks.org/mbostock/5577023

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

ONE WARNING ABOUT RED-GREEN

The following slides on the topic are adapted from Tobias Isenberg's

Color Vision Deficiency

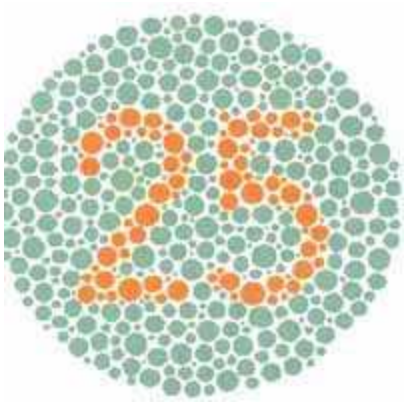
vormal color vision

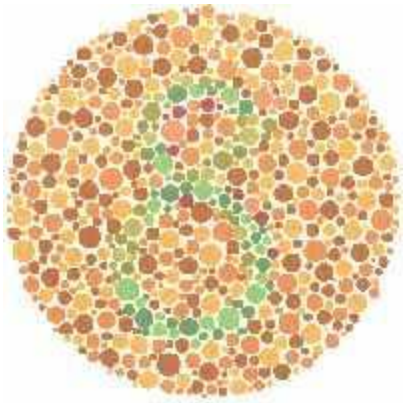
simulation of color contrast
for deuteranopic color vision
(green receptors absent)

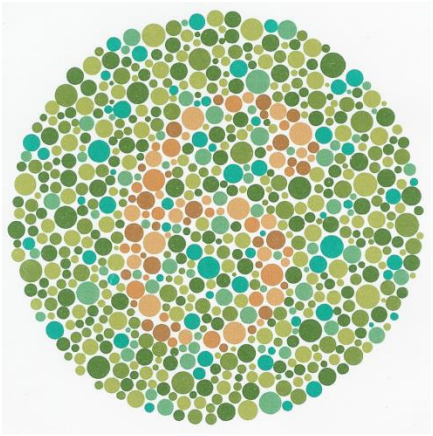
approx. 7% of male population color-deficient

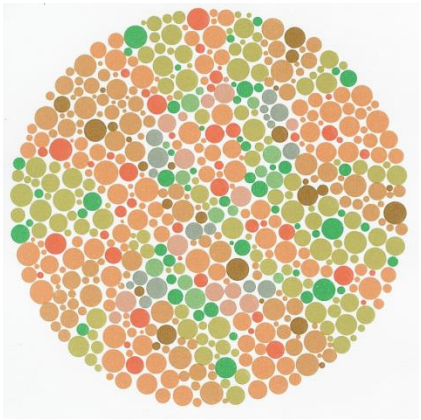
mostly red-green color deficiency (deuteranopia or protanopia) – but other forms exist as well

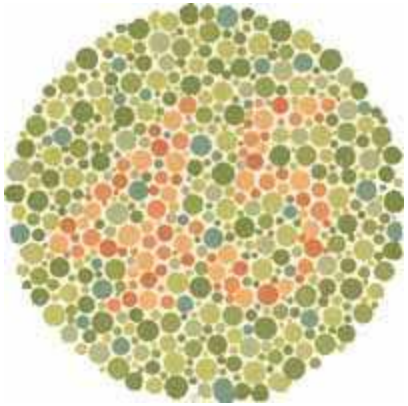
Color Deficiency Test (Ishihara Test)

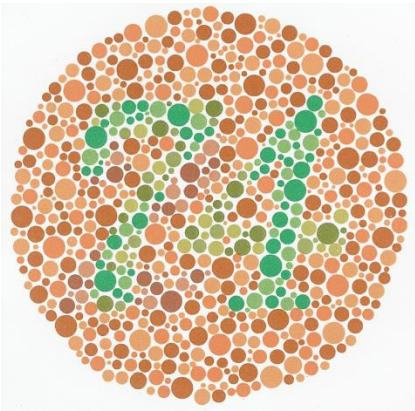




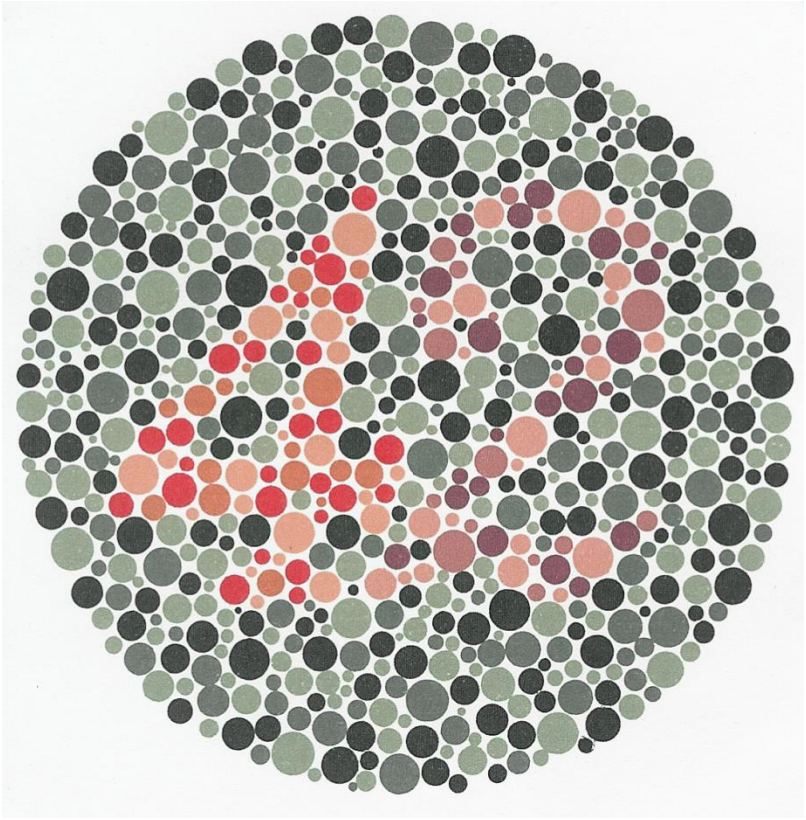


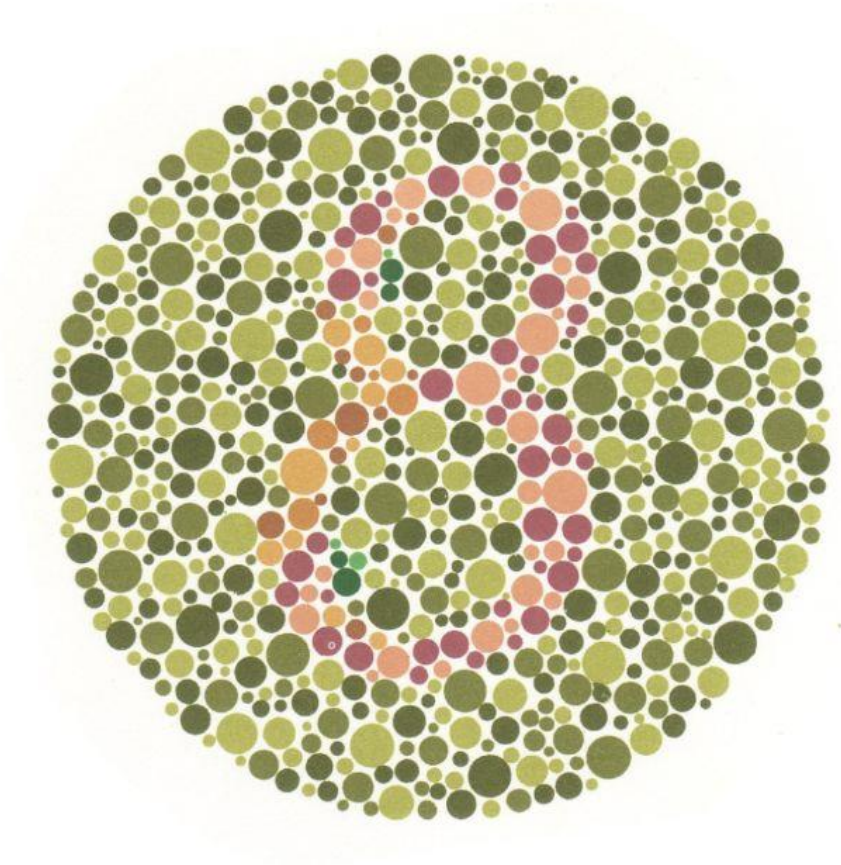




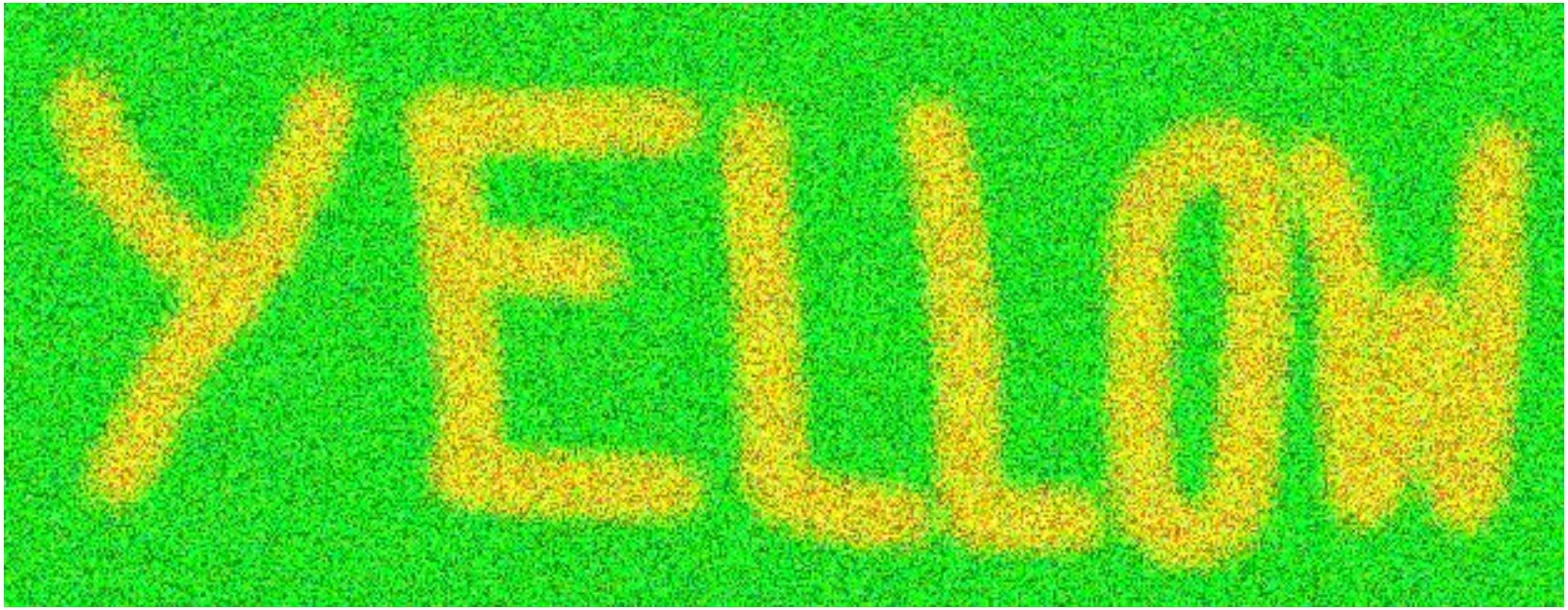


Color Deficiency Test

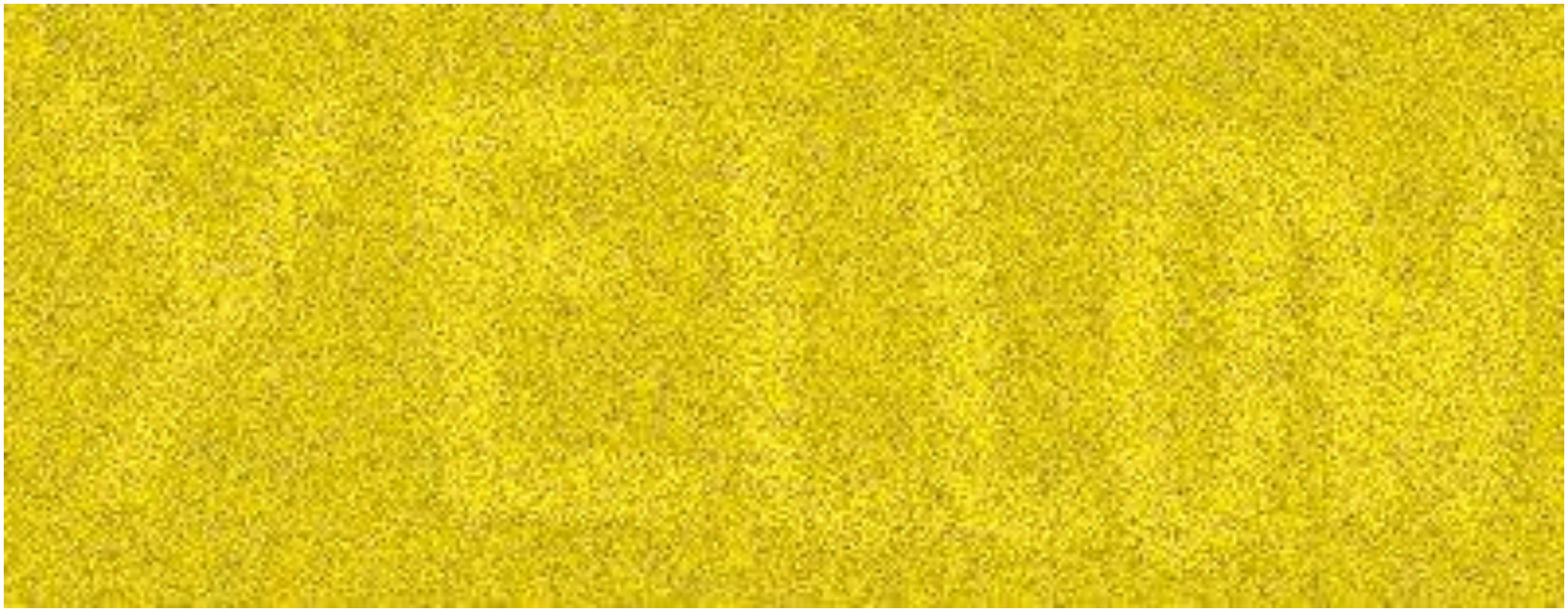




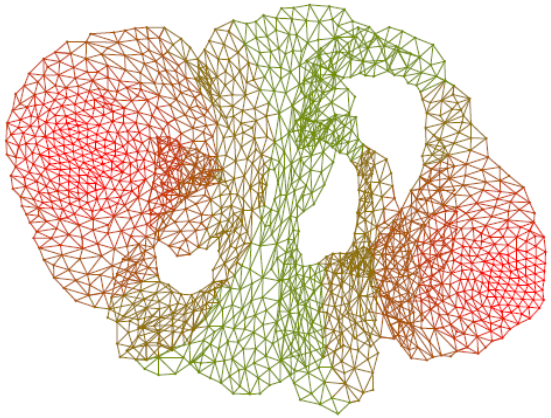
Color Deficiency

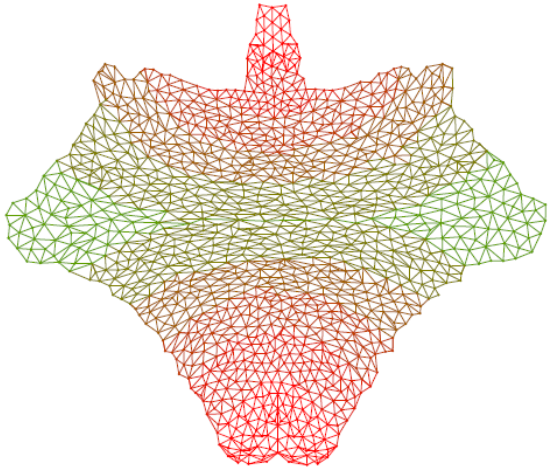


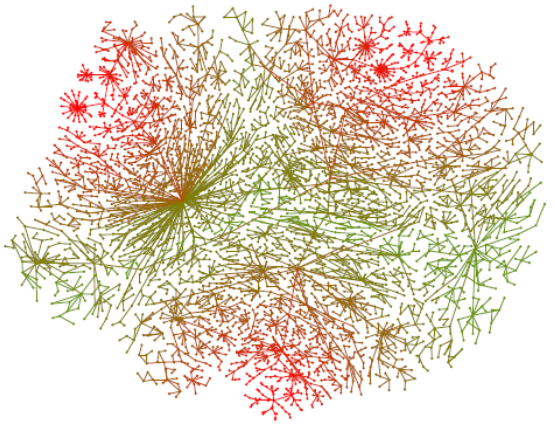
Color Deficiency

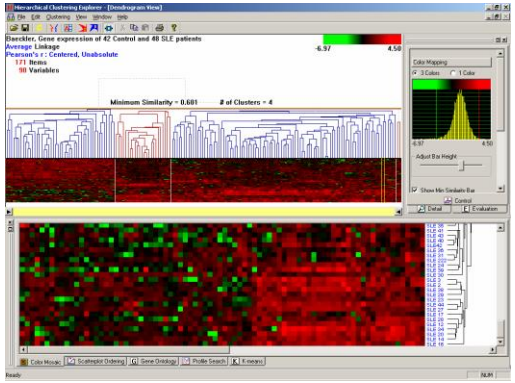


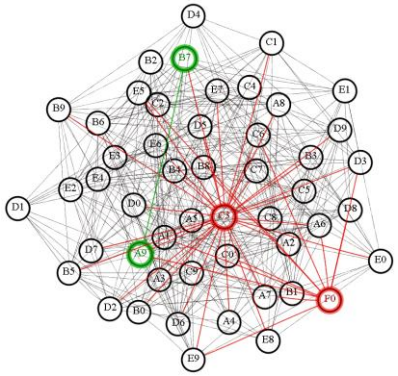
Examples from VIS/InfoVis 2004

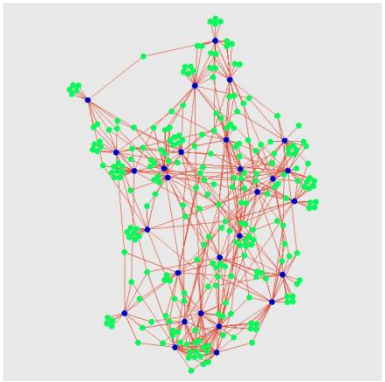


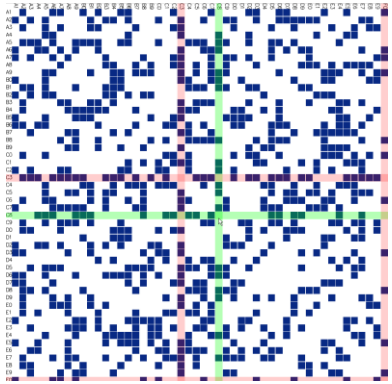




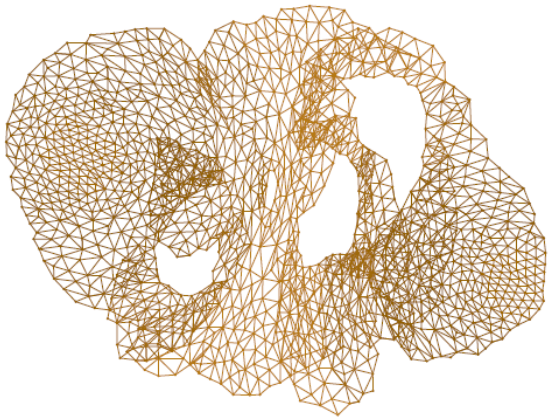


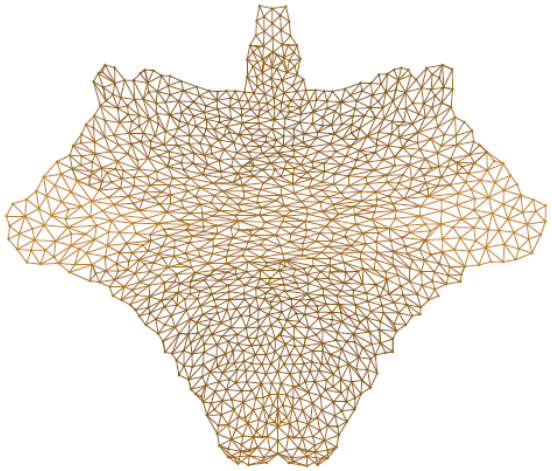


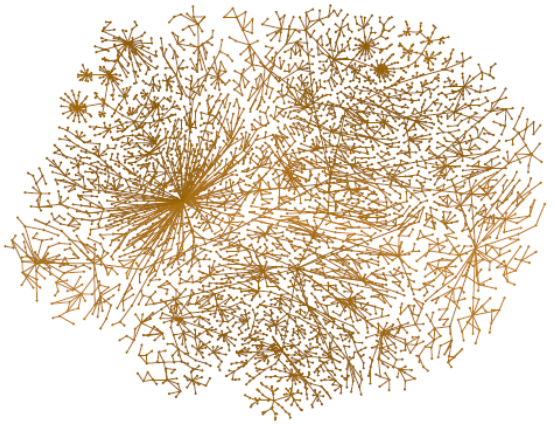


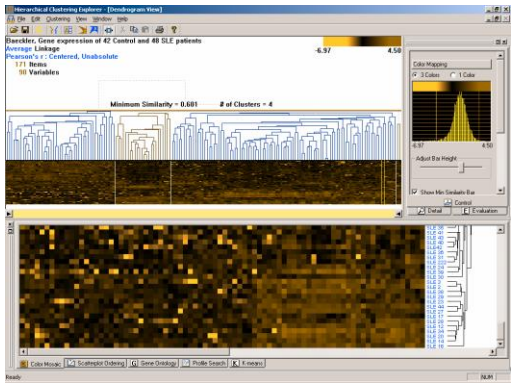


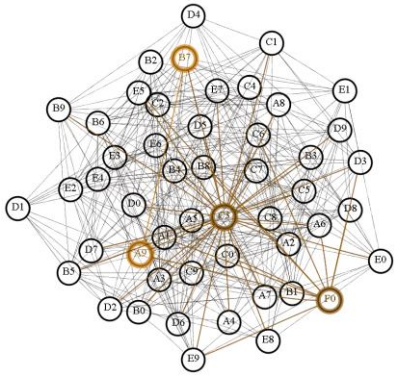
Examples from VIS/InfoVis 2004

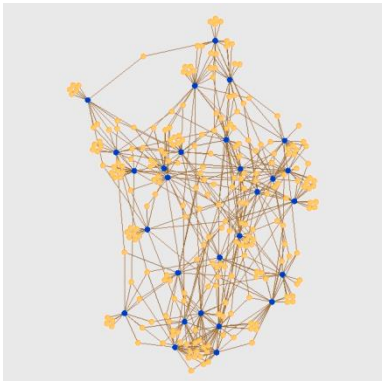




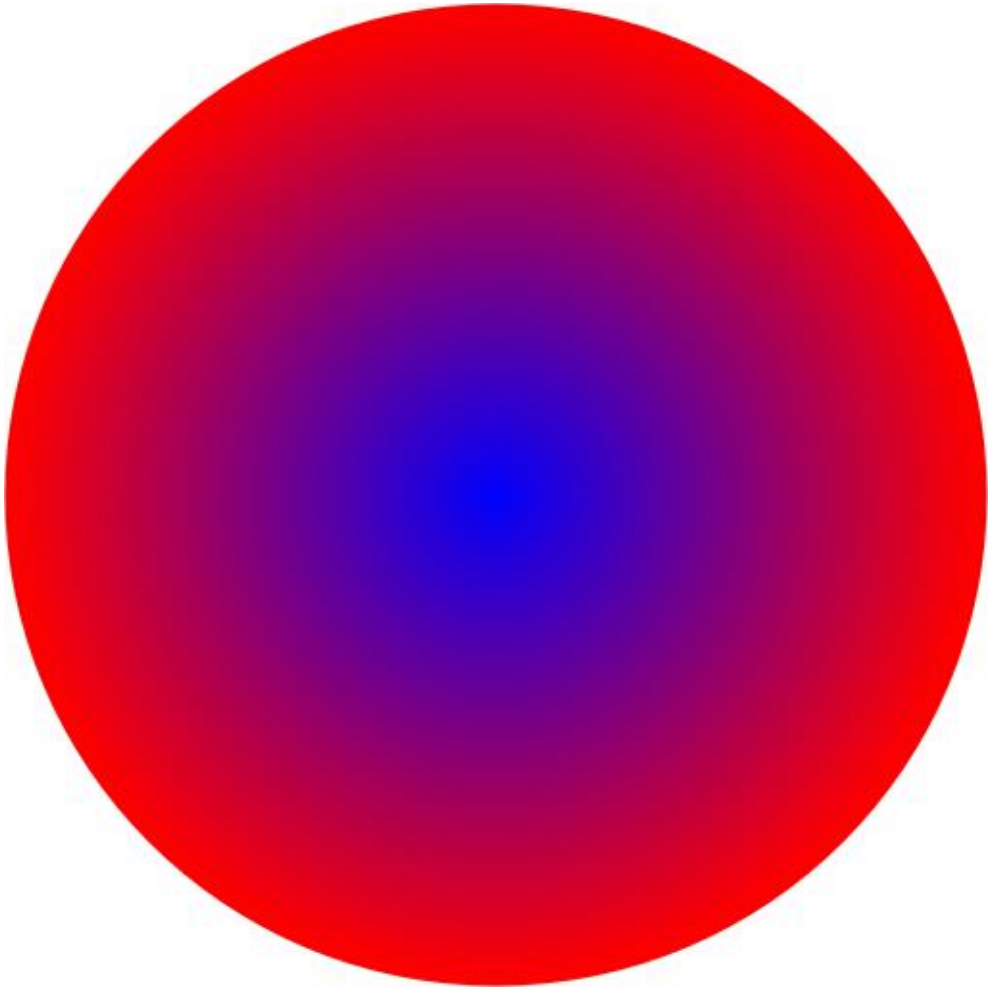




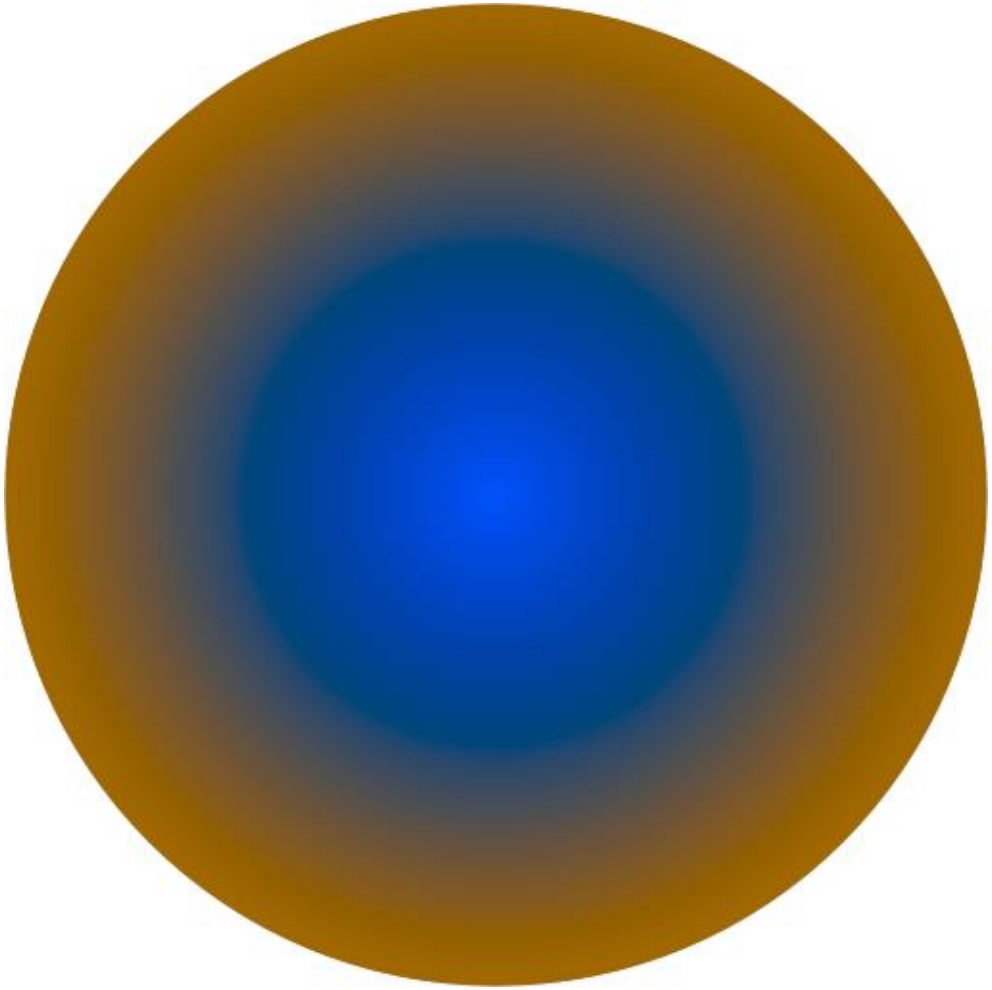




Better: Red-Blue Contrast

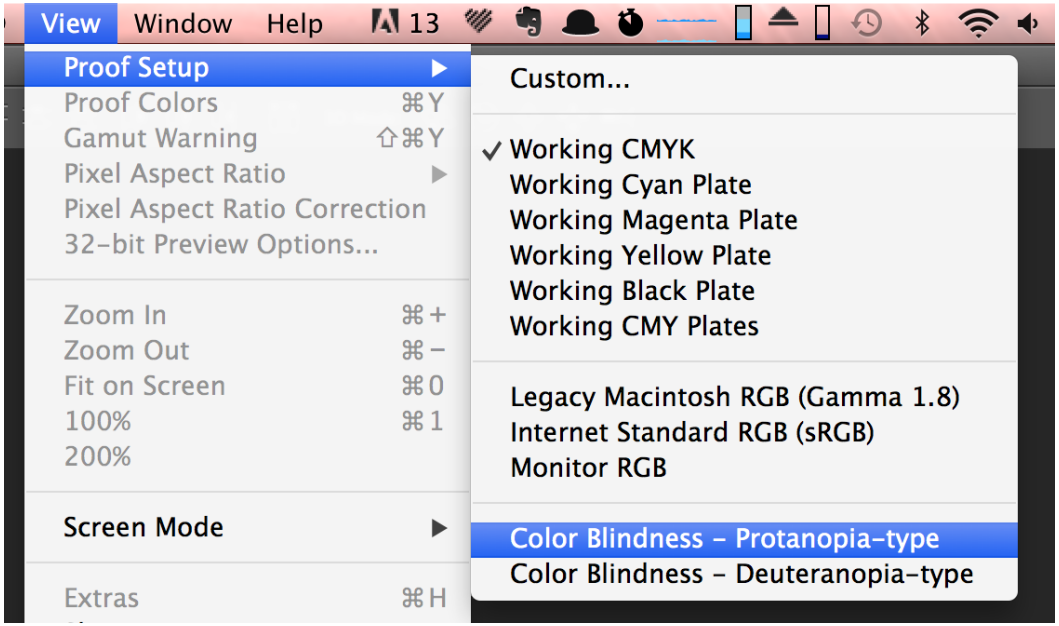


Better: Red-Blue Contrast



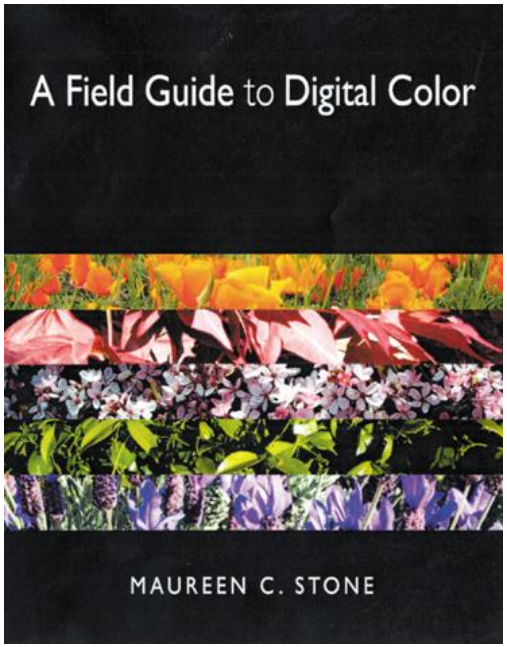
Check Your Visualizations!

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



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

Color Resources



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

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

Community Palette Sharing
http://www.colourlovers.com
http://kuler.adobe.com

(Fun) Color Resources!

Wired "The Crayola-fication of the World"

by Aatish Bhatia

http://www.wired.com/wiredscience/2012/06/the-crayola-fication-of-the-world-how-we-gave-colors-names-and-it-messed-with-our-brains-part-i/

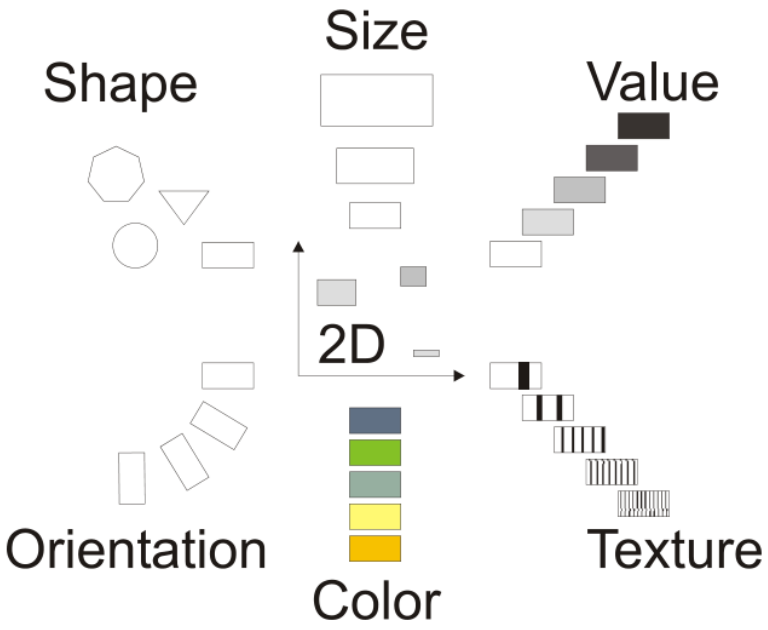
RadioLab "Colors"

WNYC Podcast

http://www.radiolab.org/story/211119-colors/

PERCEPTION OF OTHER VISUAL ENCODINGS

Perception of Visual Encodings



There are **lots** of possible visual encodings

Their **effectiveness** is related to how they are handled by our perceptual system

Elementary Graphical Perception Tasks

William S. Cleveland (1980s)

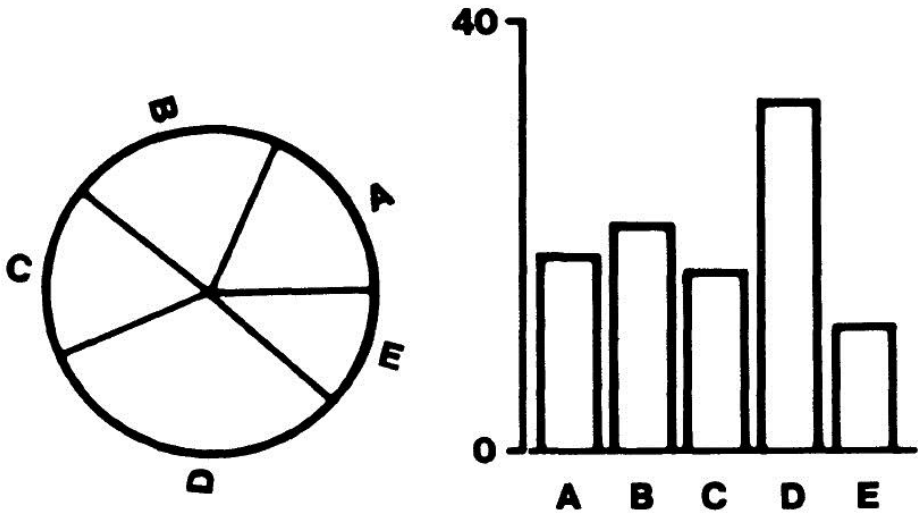


Figure 3. Graphs from position–angle experiment.

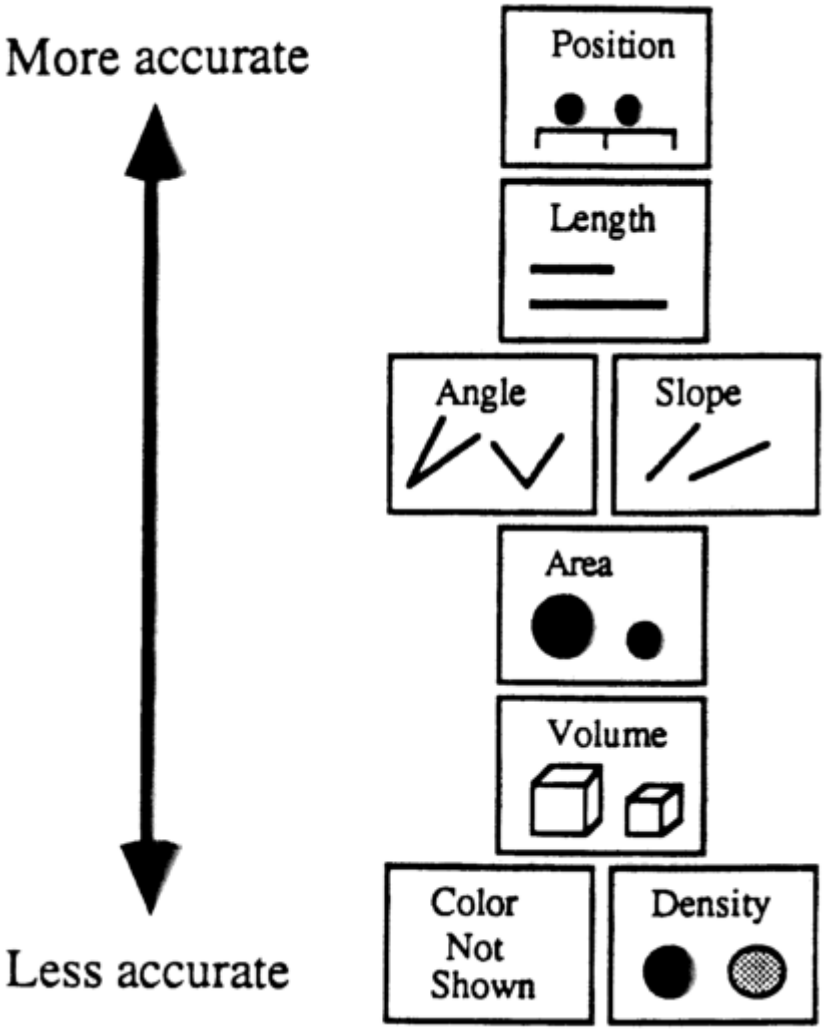
Performed **controlled experiments** to determine how effectively people could judge **changes in visual features**

Focus on **quantitative information**

Variables used: angle, area (size), color hue, color saturation, density (value), length, position, slope, volume

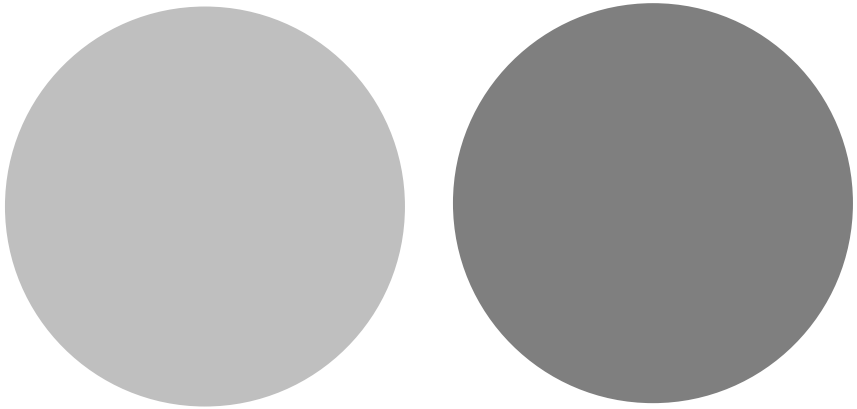
Elementary Graphical Perception Tasks

William S. Cleveland (1980s)

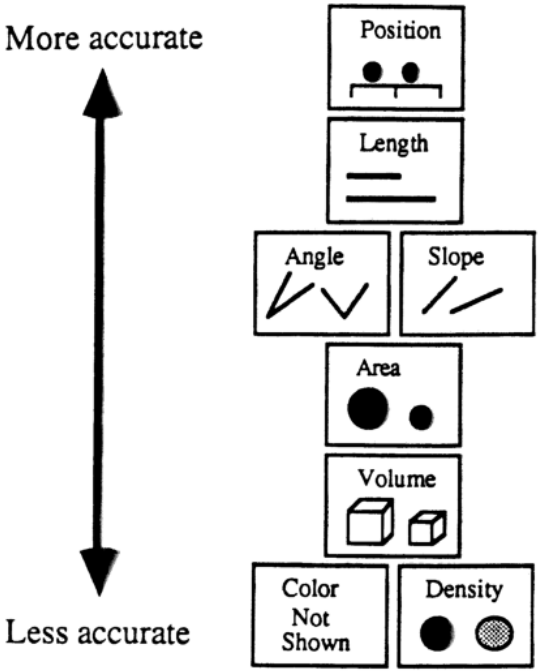


Color Value

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

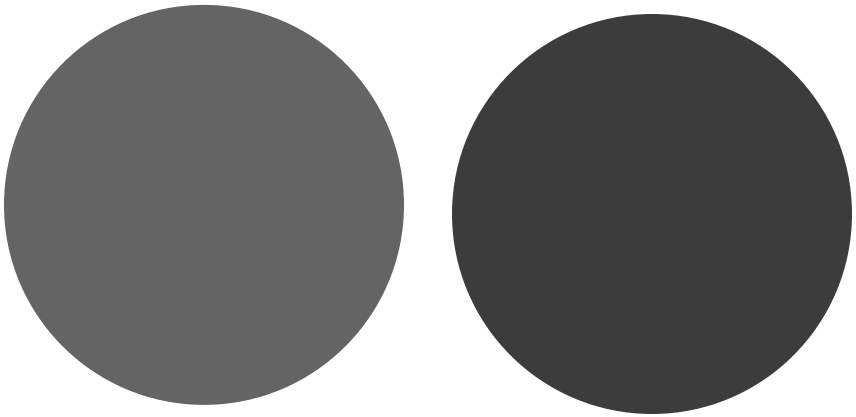


100% 66%

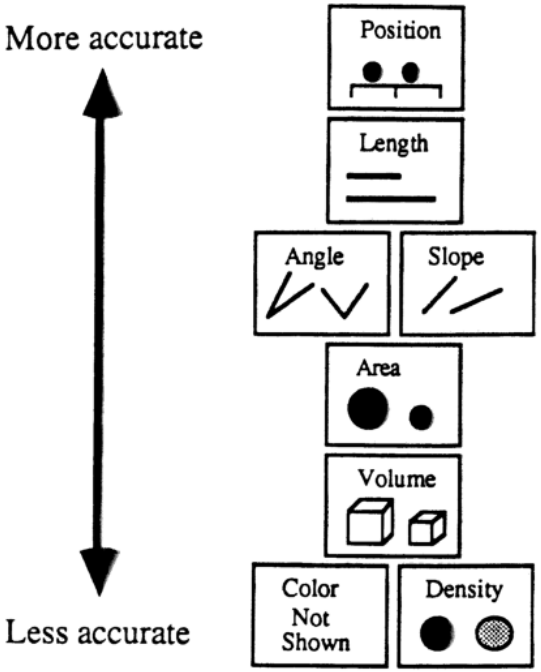


Color Value

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

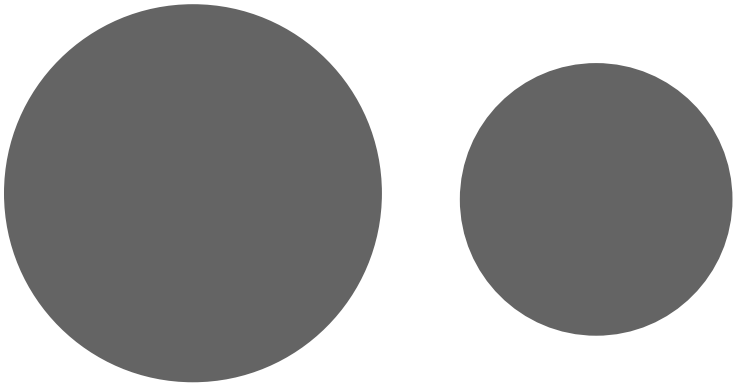


100% 60%

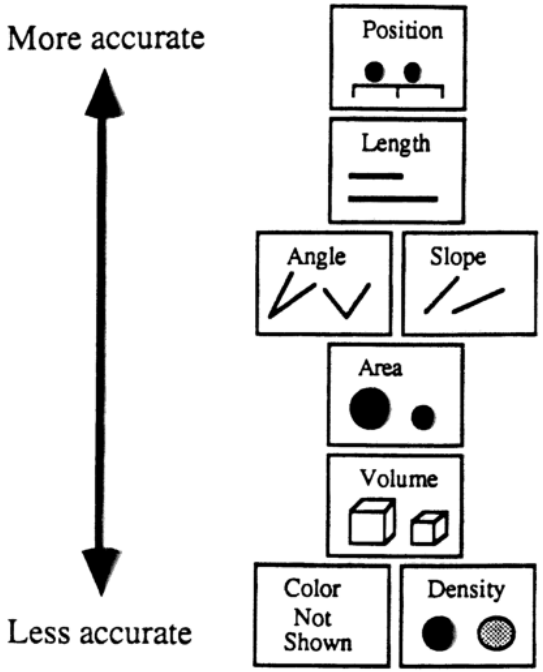


Area

- What percentage in size is the right from the left?

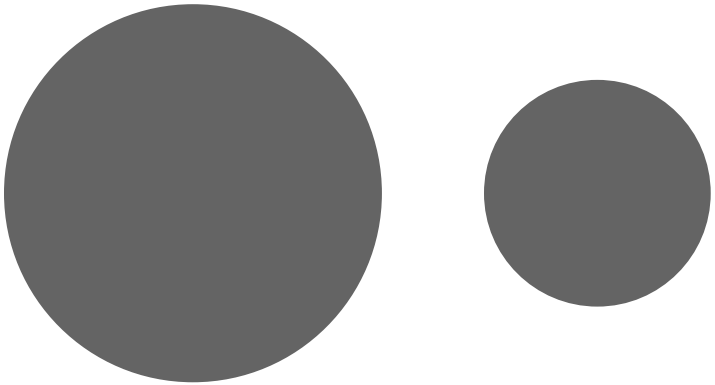


100% 52%

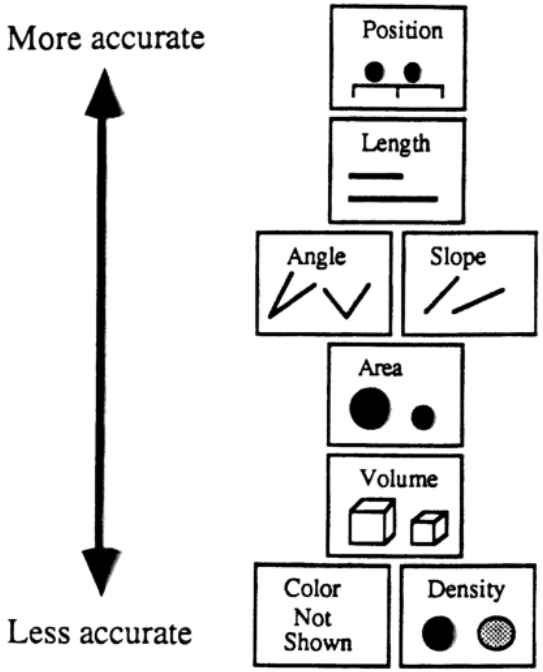


Area

- What percentage in size is the right from the left?

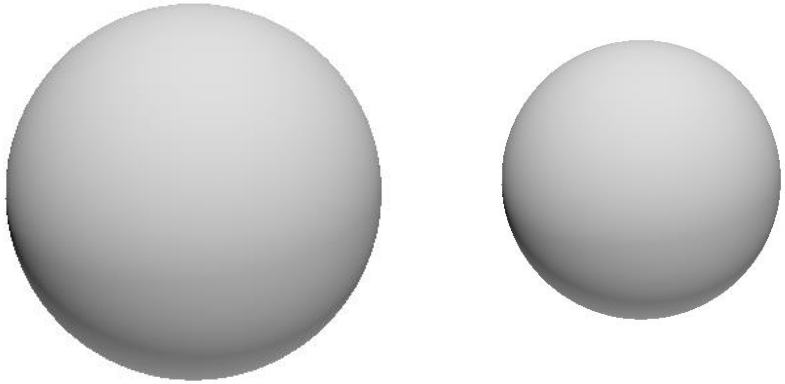


100% 36%



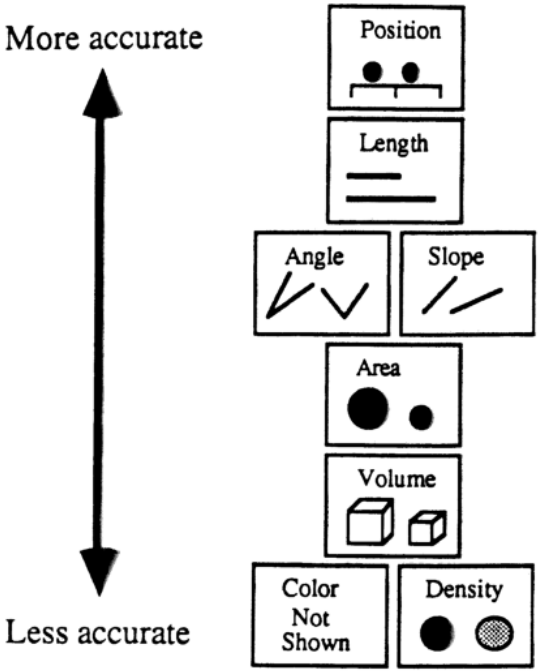
Volume

- What percentage in size is the right from the left?



100%

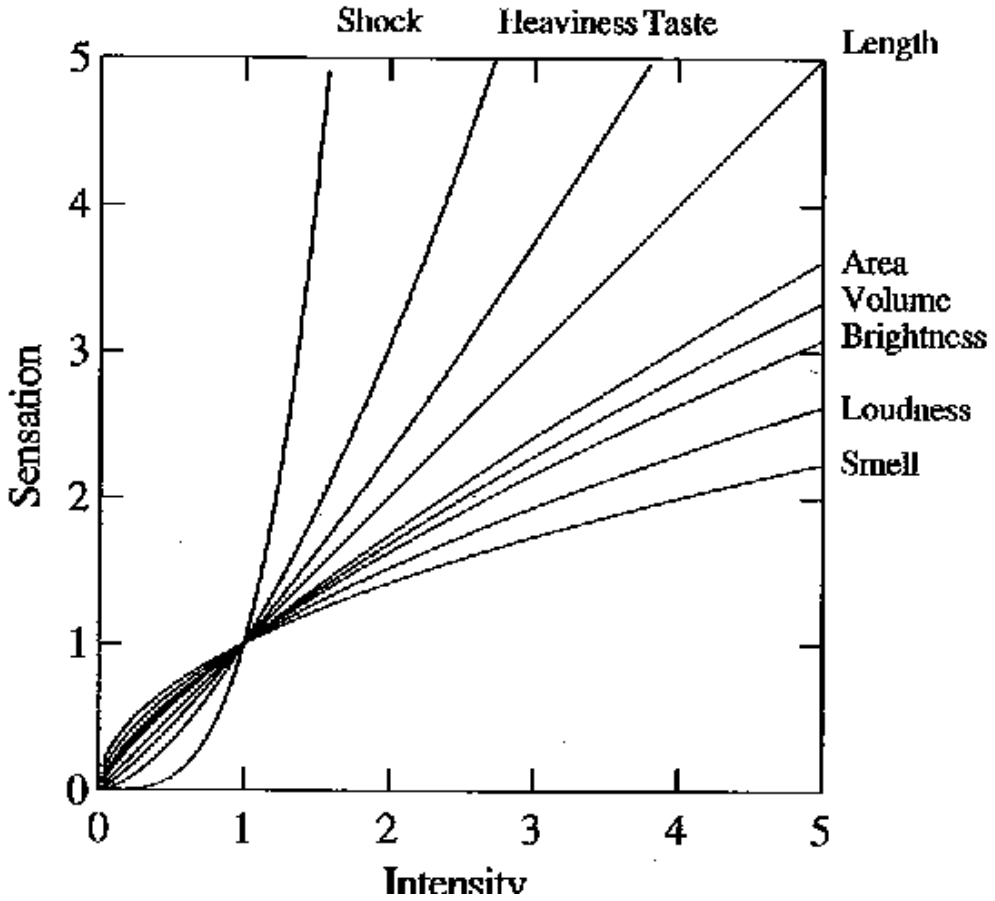
40%



Why people so bad at this?

Relationship between stimulus and perception **isn't always linear!**

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

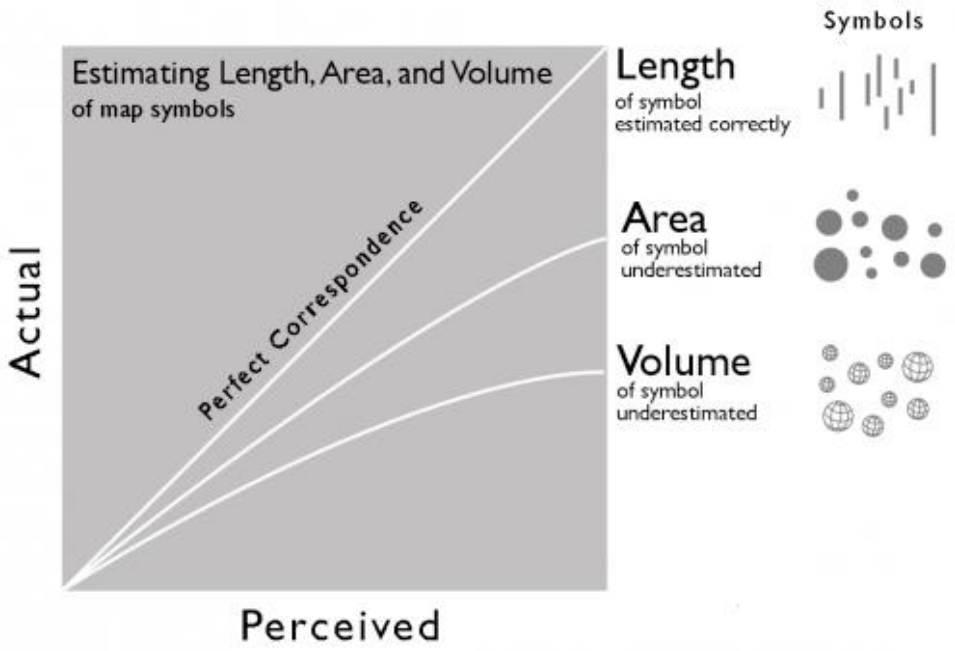


[Graph from Wilkinson 99, based on Stevens 61]

Perception

People tend to **correctly estimate lengths**

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



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

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

Volume **is even worse**!

http://makingmaps.net/2007/08/28/perceptual-scaling-of-map-symbols/

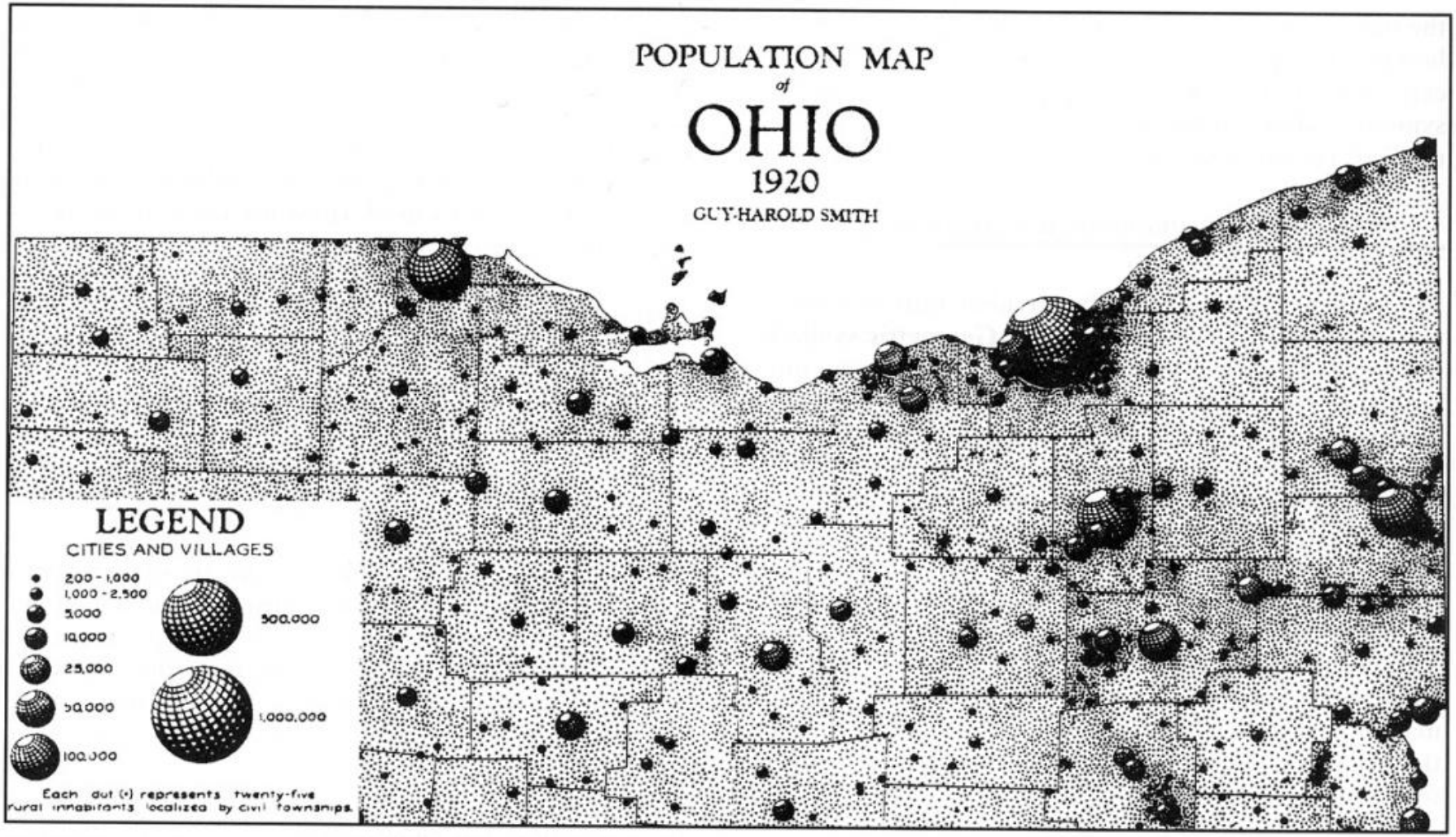
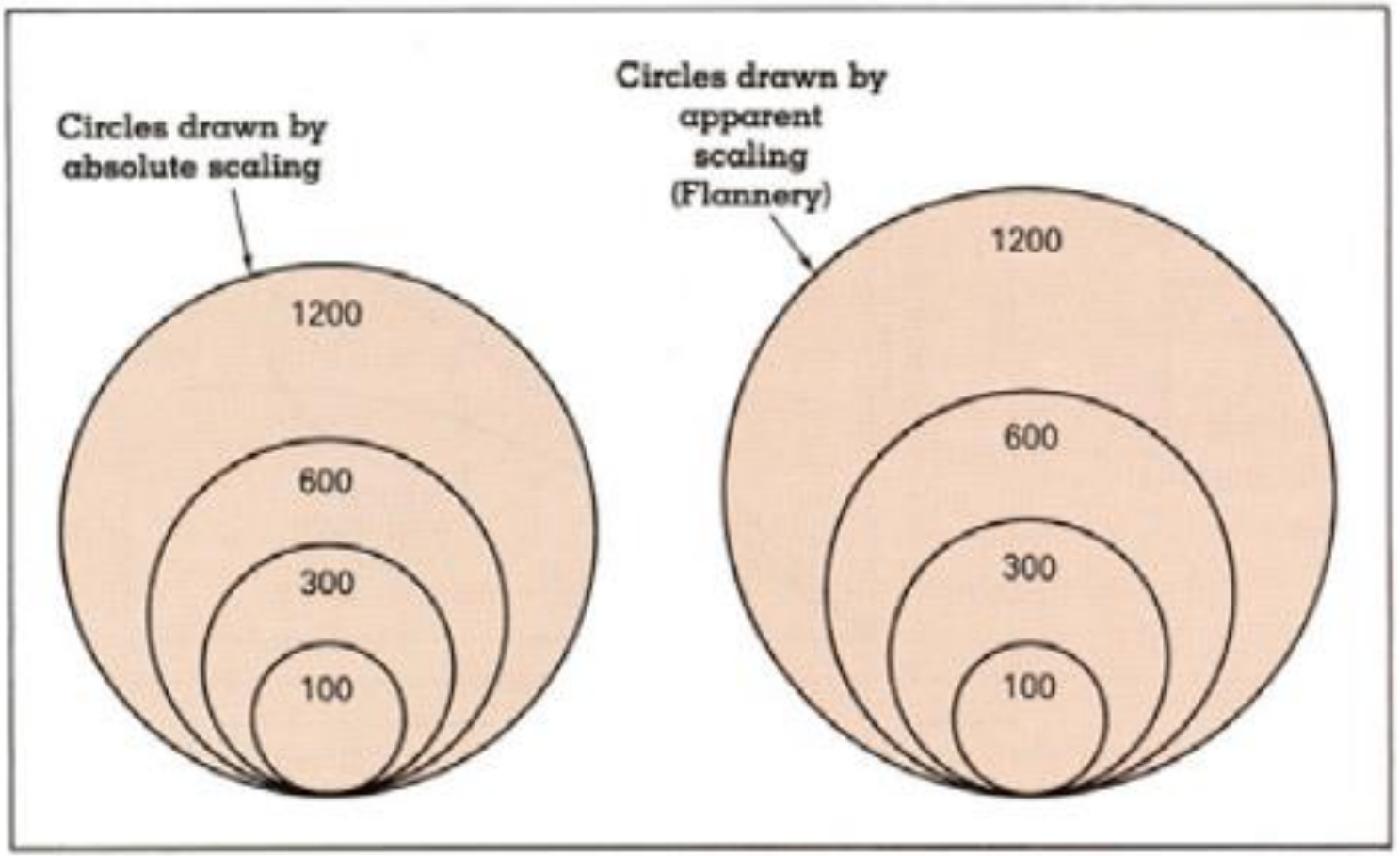


FIGURE 7.4. An eye-catching map created using three-dimensional geometric symbols. (After Smith, 1928. First published in *The Geographical Review,* 18(3), plate 4. Reprinted with permission of the American Geographical Society.)

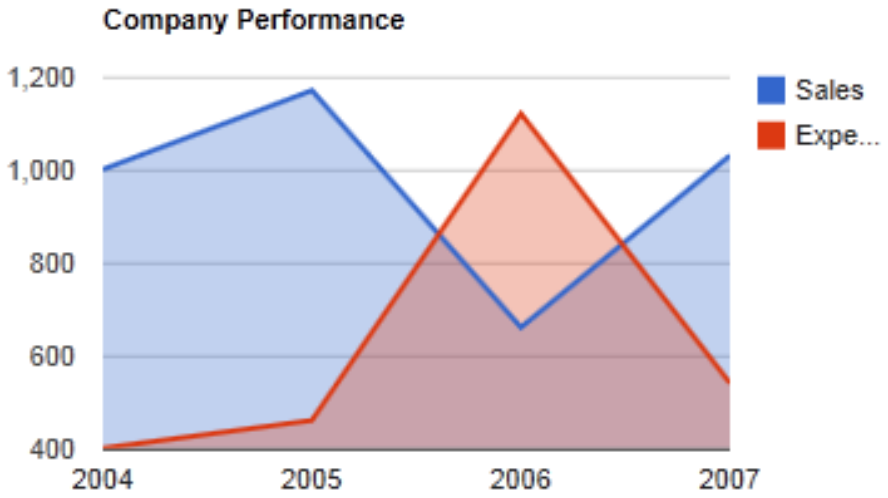


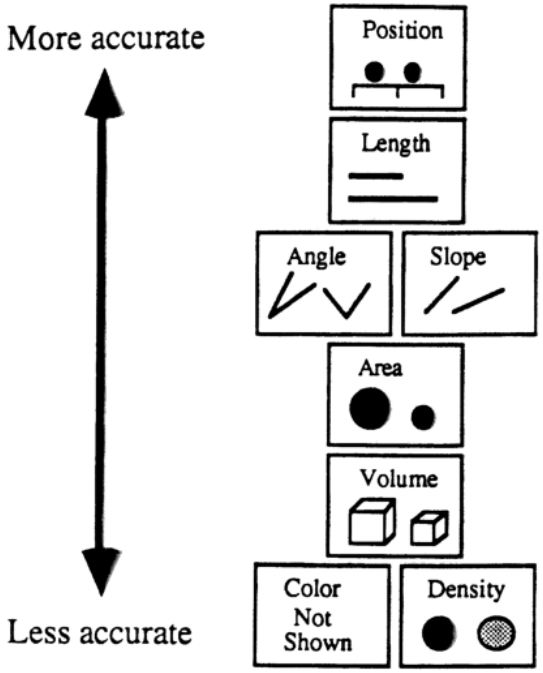
[Cartography: Thematic Map Design, Figure 8.6, p. 170, Dent, 96]

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

Area

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





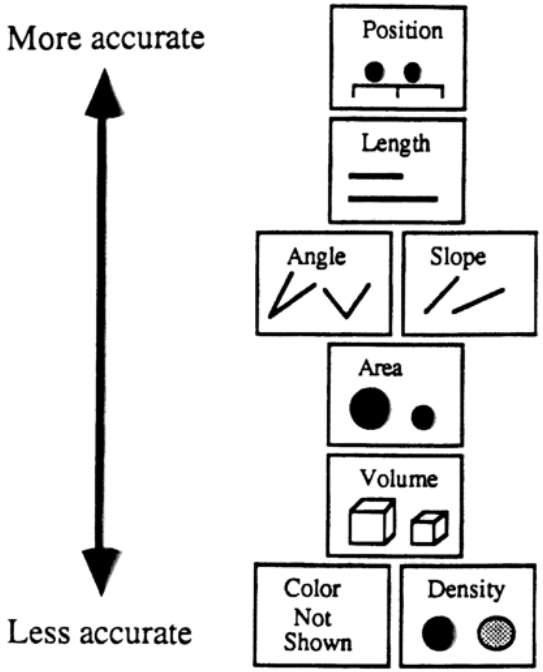
no idea – **this is very difficult**

Length

- What percentage in length is the right from the left?

100%

75%

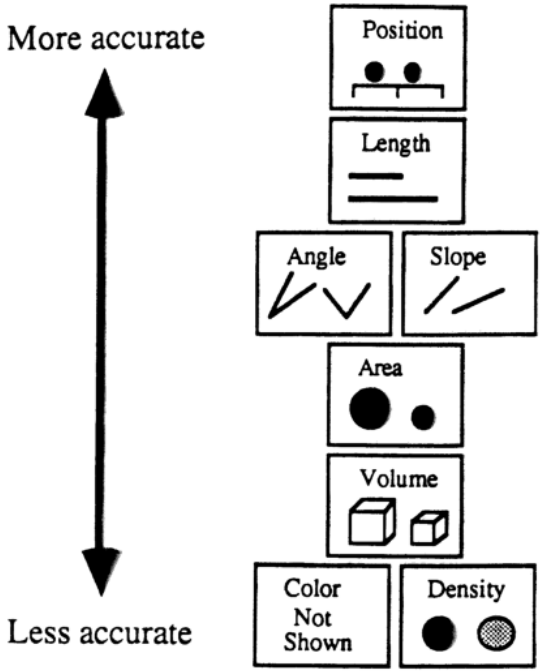


Length / Position

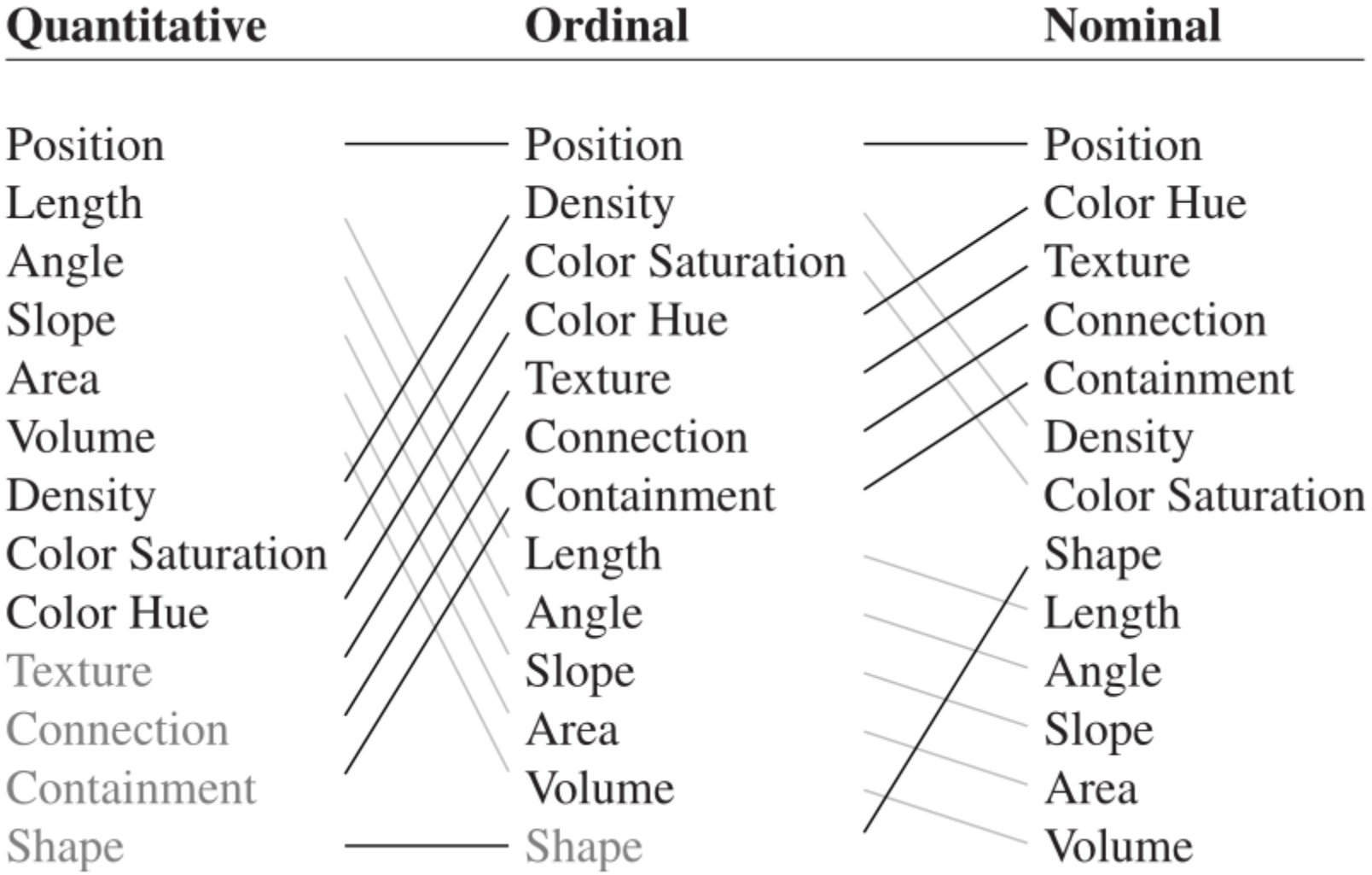
- What percentage in length is the right from the left?

100%

25%



Effectiveness of Data Encodings (Conjecture)

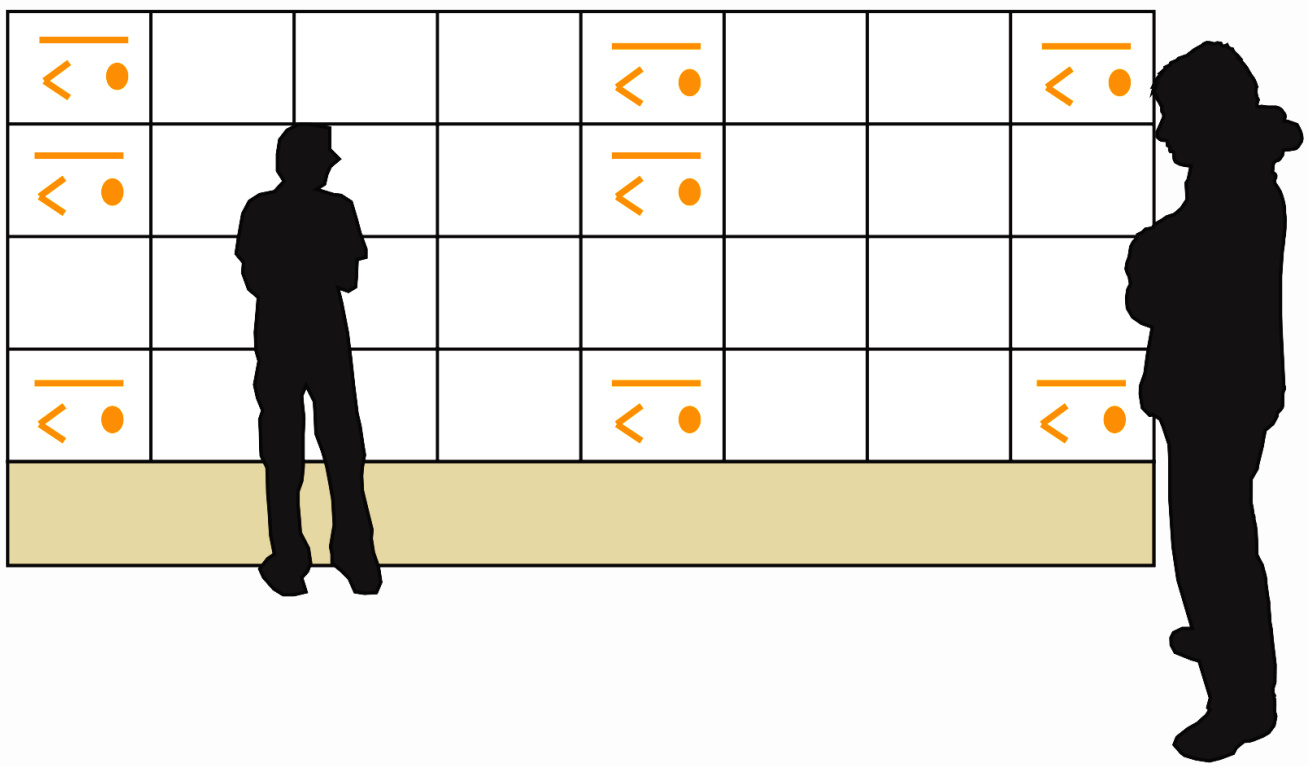


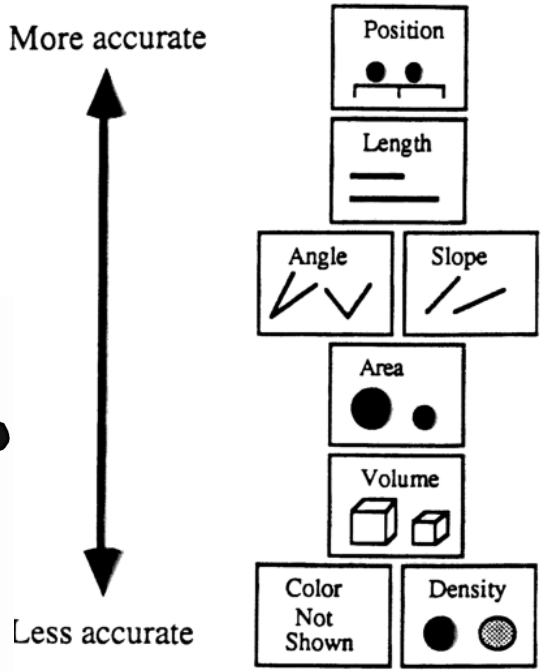
Mackinlay 1986

Elementary Graphical Perception Tasks

William S. Cleveland (1980s)

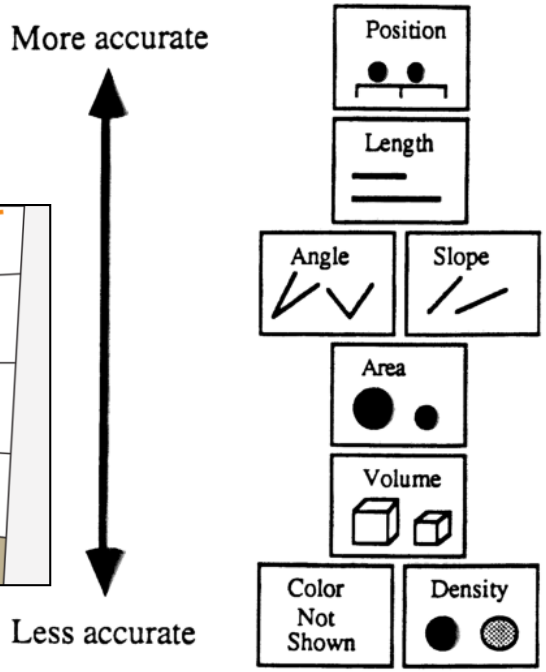
also beware of the physical presentation:



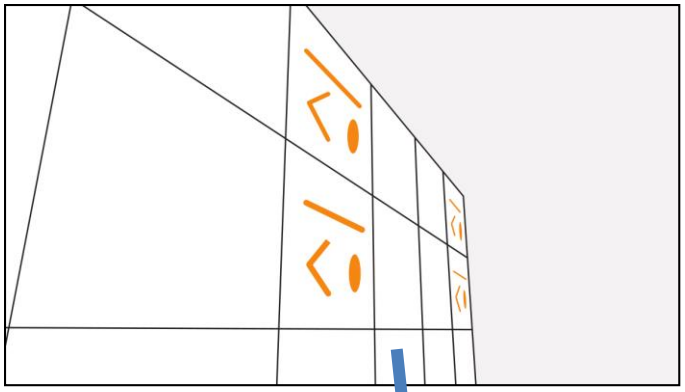


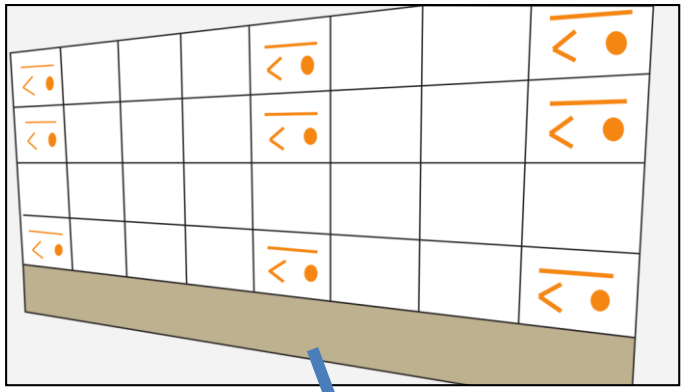
Elementary Graphical Perception Tasks

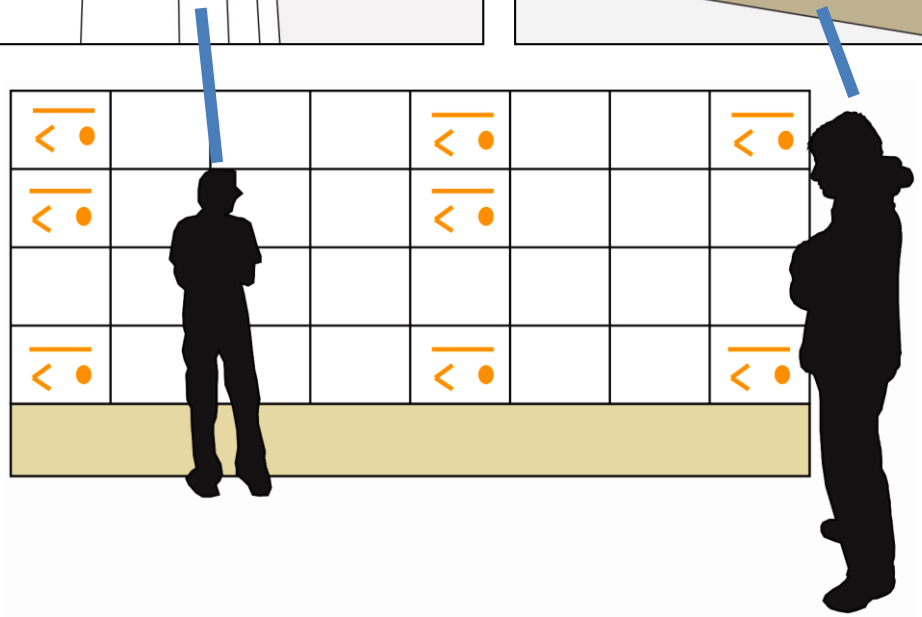
William S. Cleveland (1980s)



also beware of the physical presentation:

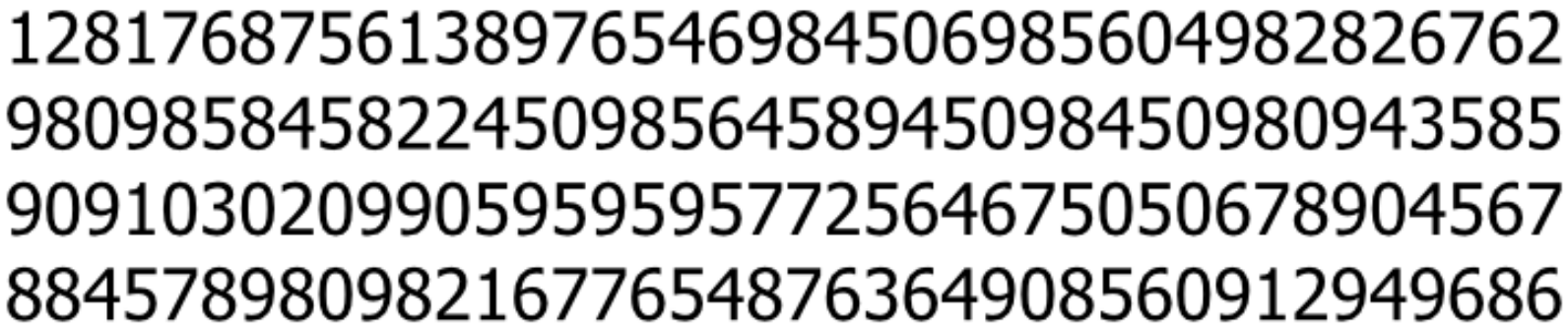






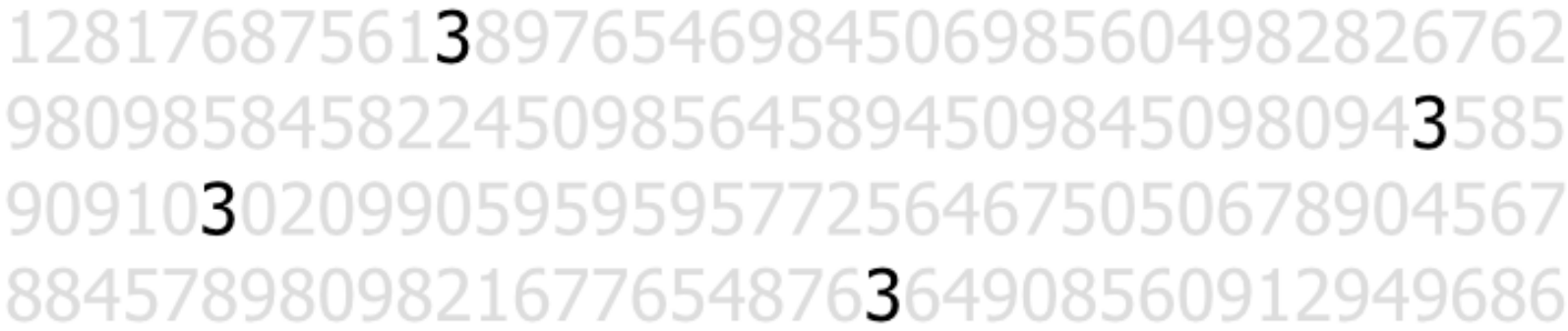
PREATTENTIVE PROCESSING

How many 3's do you see?



From: Ware, Information Visualization using Vision to Think

How about now?



From: Ware, Information Visualization using Vision to Think

Preattentive Processing

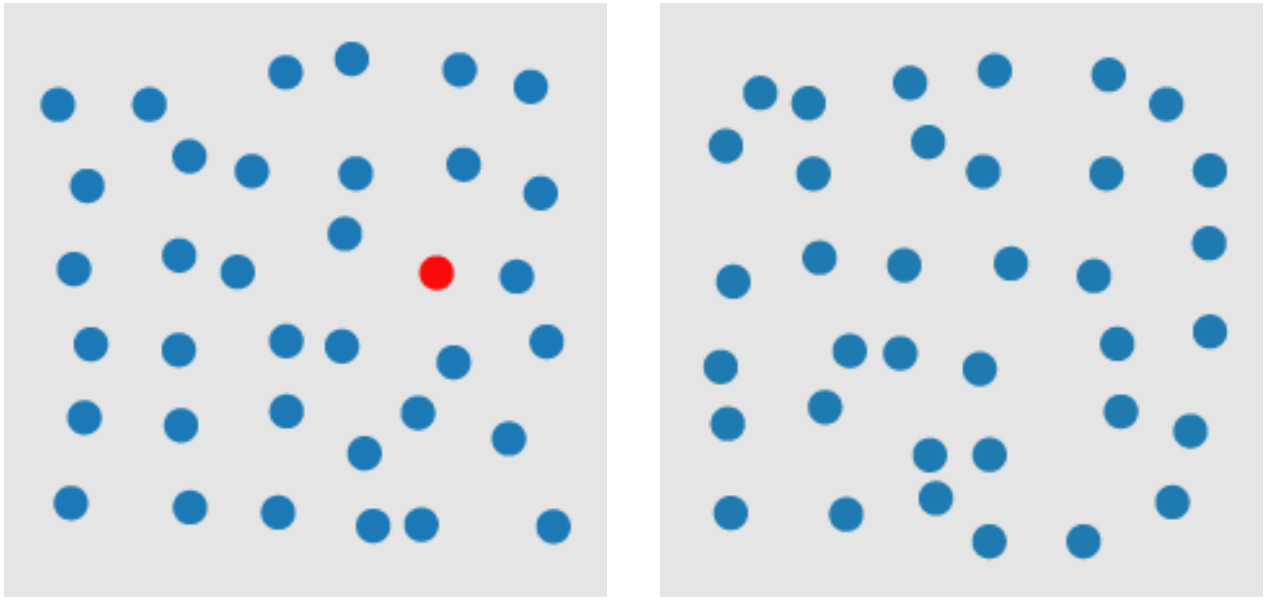
- Some stimuli can be perceived **without** the need for focused attention
- Generally within **200-250 ms**
- Seems to be done **in parallel** by the low-level vision system

Visual encoding has a **big** impact on this!

Visual encodings influence **preattentive** processing

DETERMINE IF A RED CIRCLE IS PRESENT

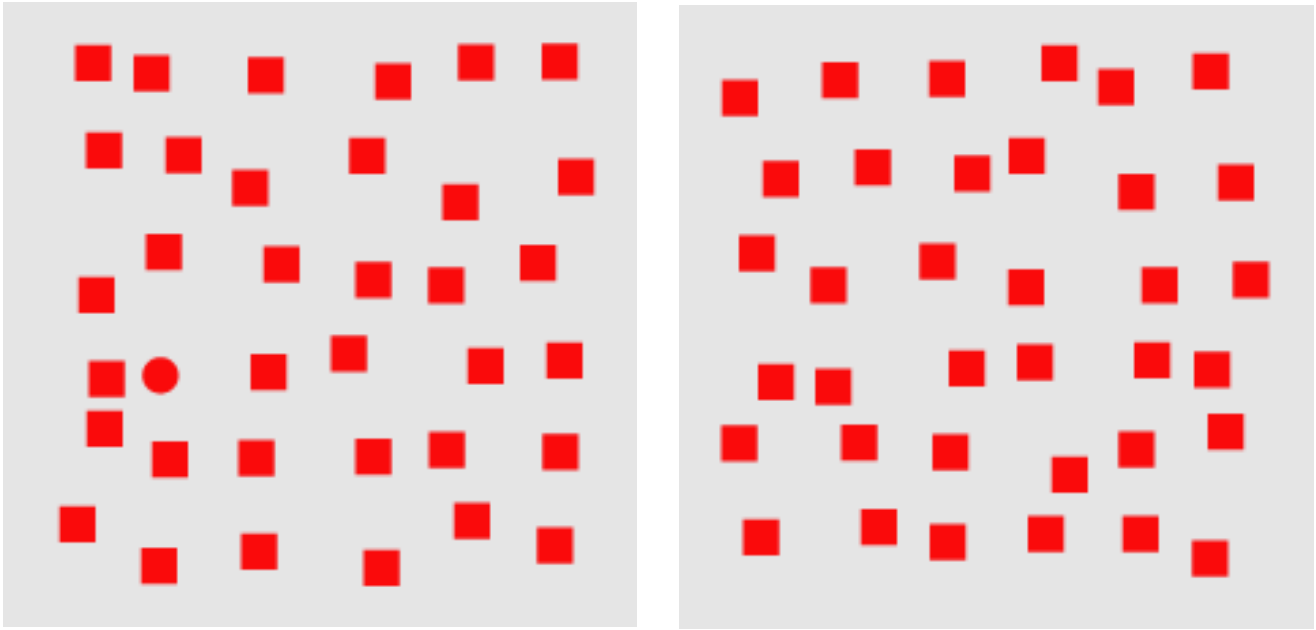
Hue



Yes, can be done preattentively

From: Healey, Perception in Visualization

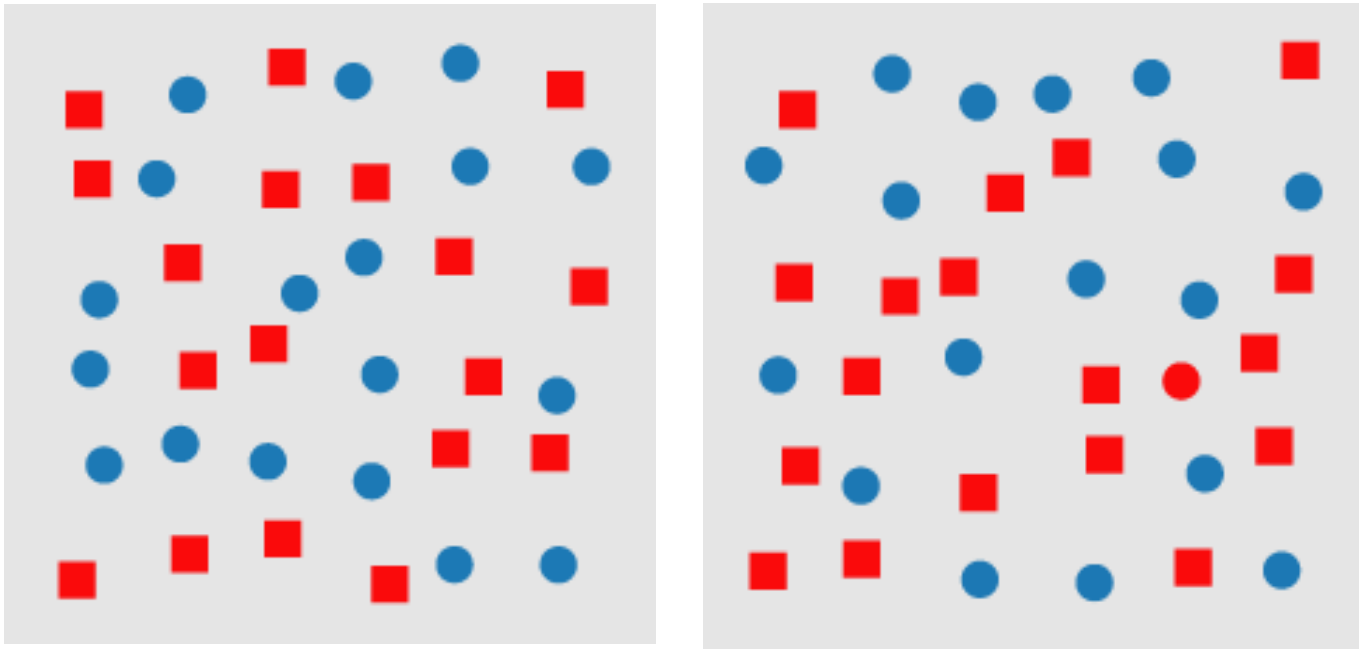
Shape



Yes, can be done preattentively

From: Healey, Perception in Visualization

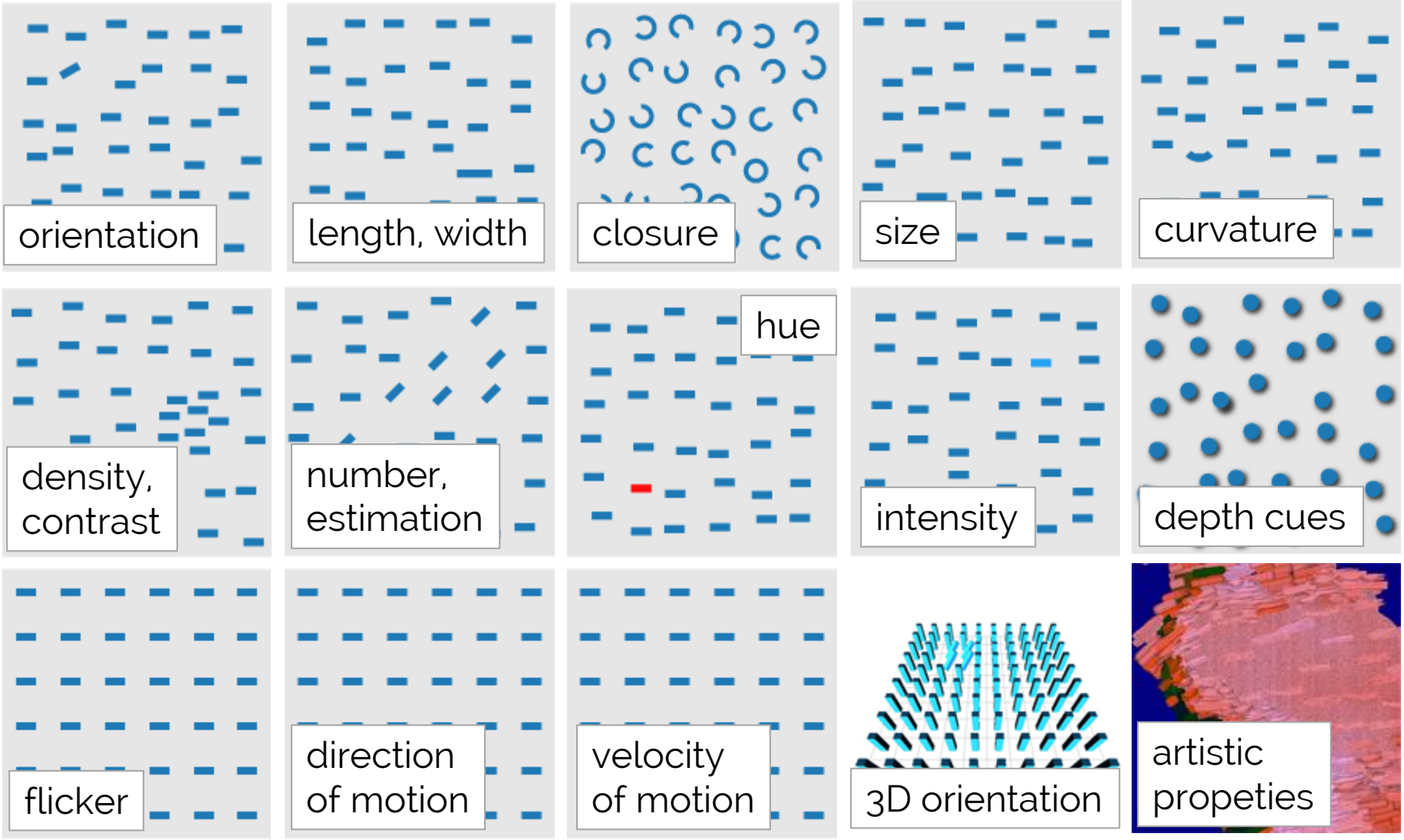
Hue and Shape



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

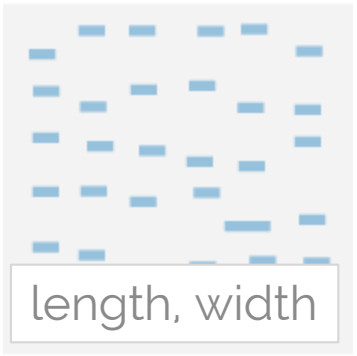
From: Healey, Perception in Visualization

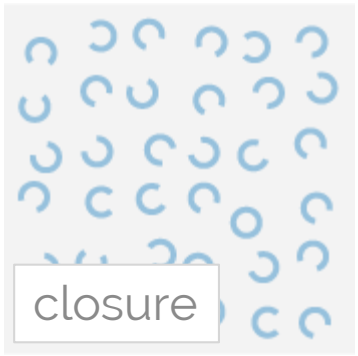
Preattentive visual features (some)

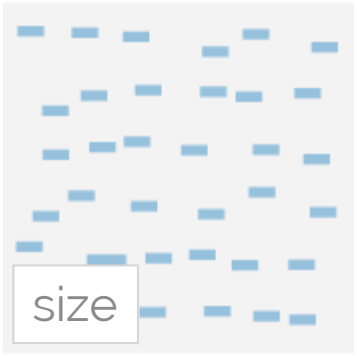


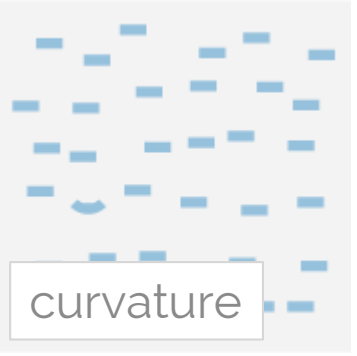
From: Healey, Perception in Visualization

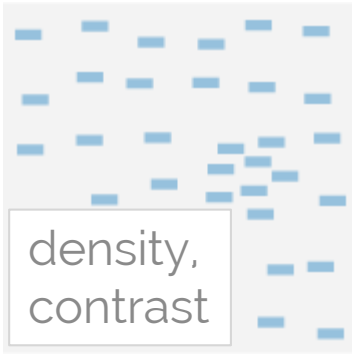
Preattentive visual features (some)



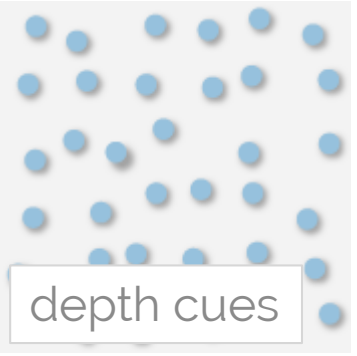


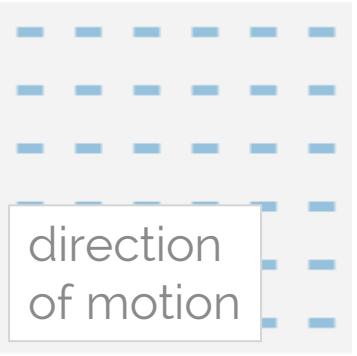


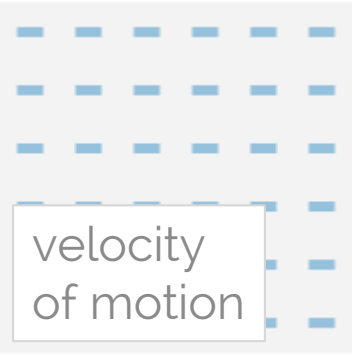


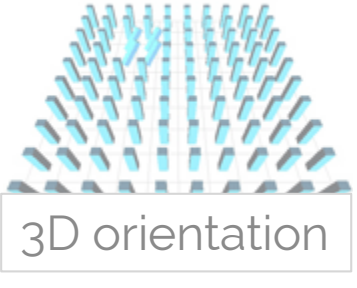


When designing visualizations, try to **use pre-attentive** features to support the **most important tasks**.



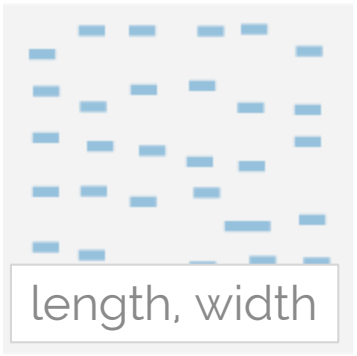


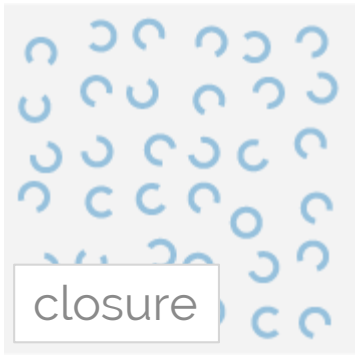


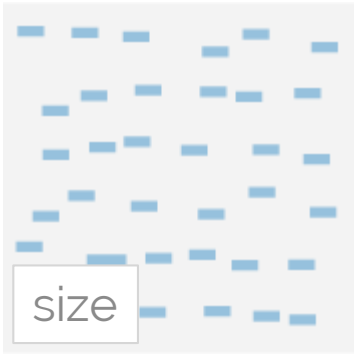


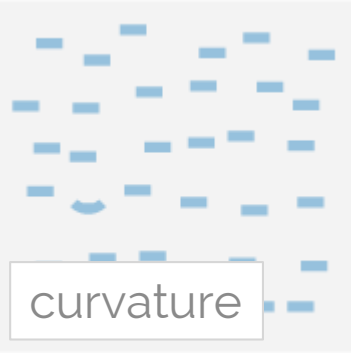
From: Healey, Perception in Visualization

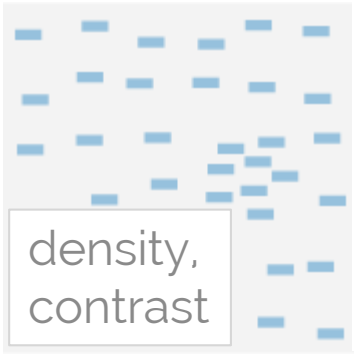
Preattentive visual features (some)





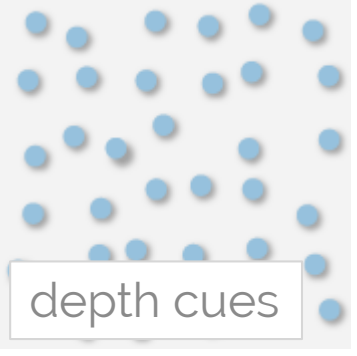


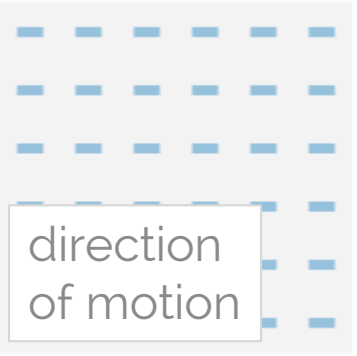


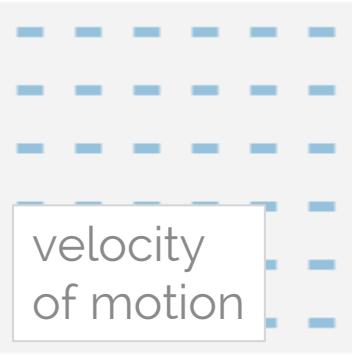


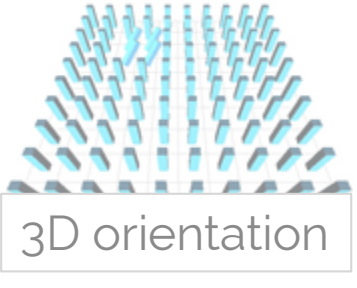
Avoid conjunctions that inhibit preattentive recognition.

(**Most conjunctions** are require search.)









From: Healey, Perception in Visualization

Applying what we know to

ASSESS VISUAL REPRESENTATIONS

Let's evaluate…

Car / Nation	USA	Japan	Germany	France	Sweden
Accord		x			
AMC Pacer	x				
Audi 5000			x		
BMW 320i			x		
Champ	x				
Chevy Nova	x				
Saab 9000					x

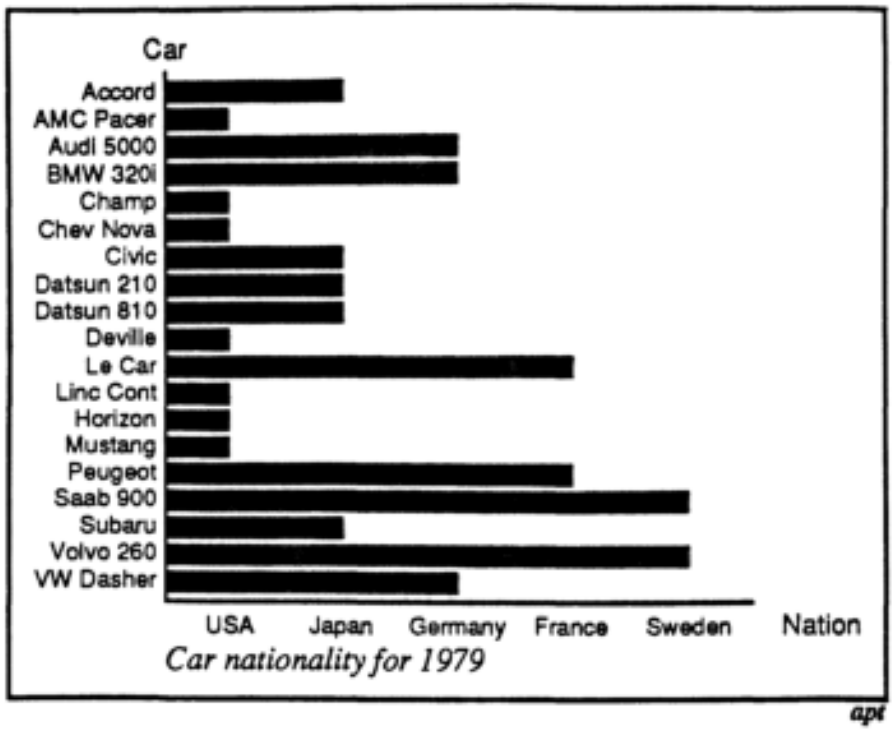
What kind of data are we looking at?

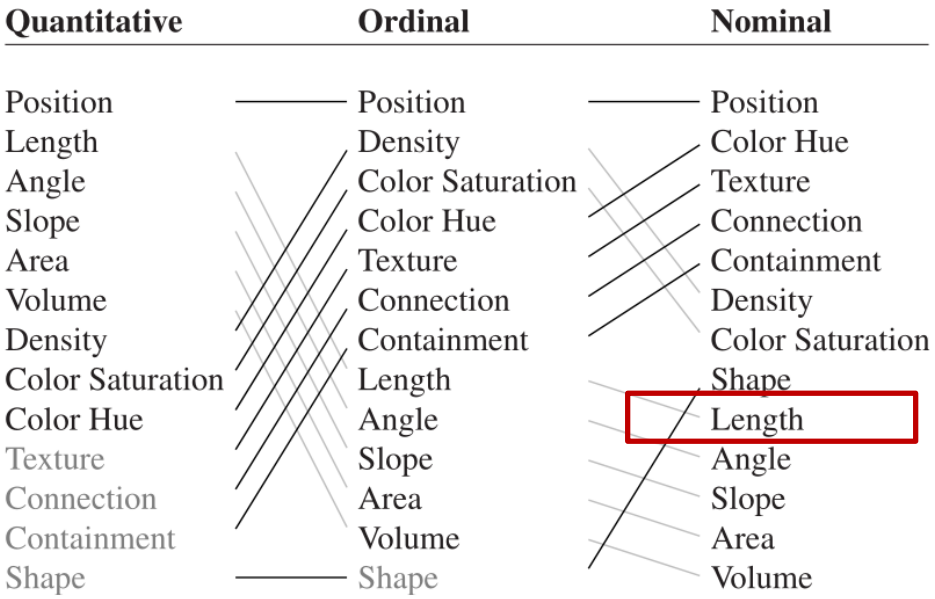
Nations: **Nominal**

Cars: **Nominal**

(Nation,Car): **Nominal**

Let's evaluate...

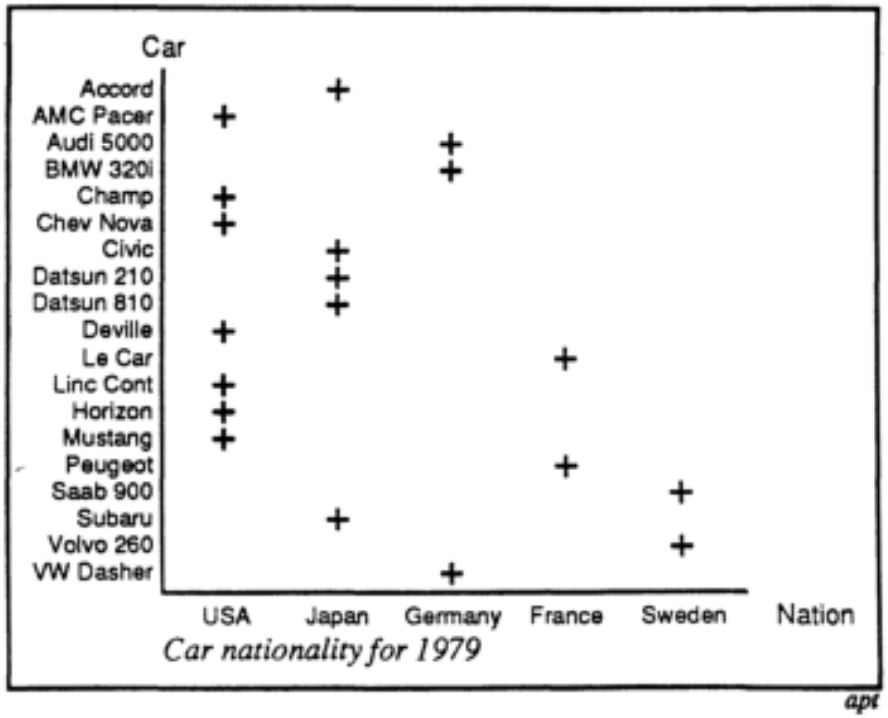


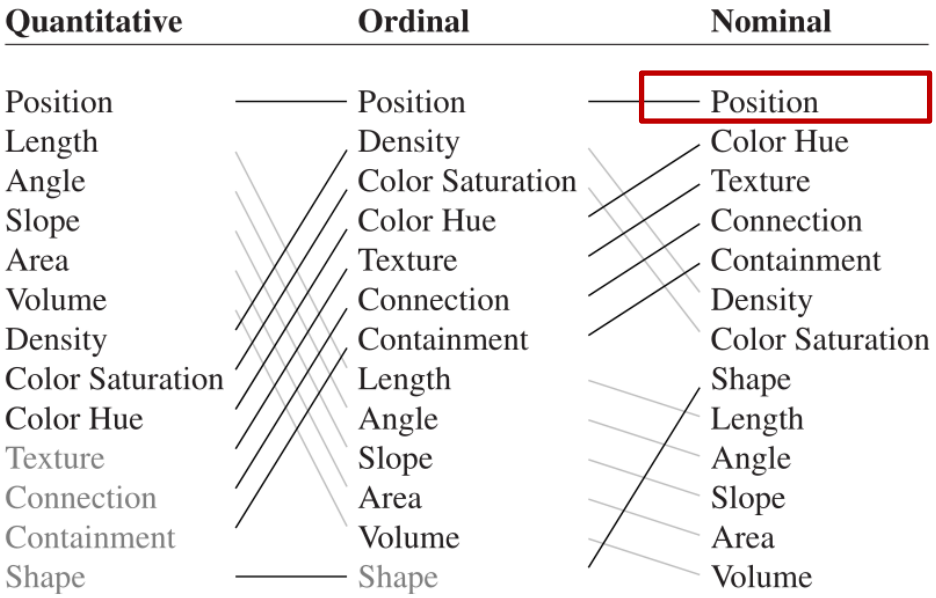


Problem:

Length of bar suggests an order or quantity (e.g. Swedish cars are better)

Let's evaluate...



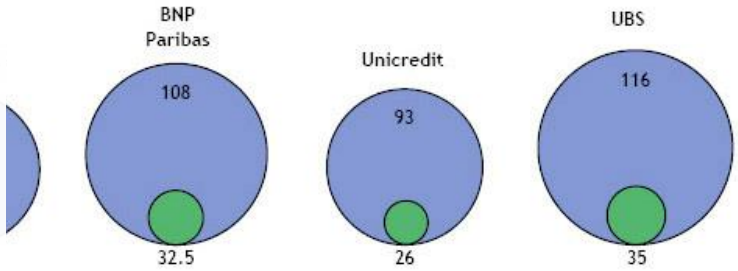


Better!

Let's evaluate…

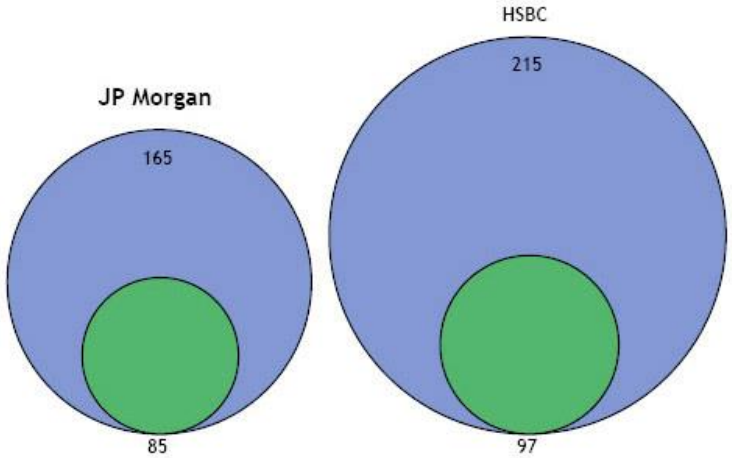
Market Capitalization =

What would it cost to buy all of a company's stock at the current price.



Compares 15 major banks on two dates:

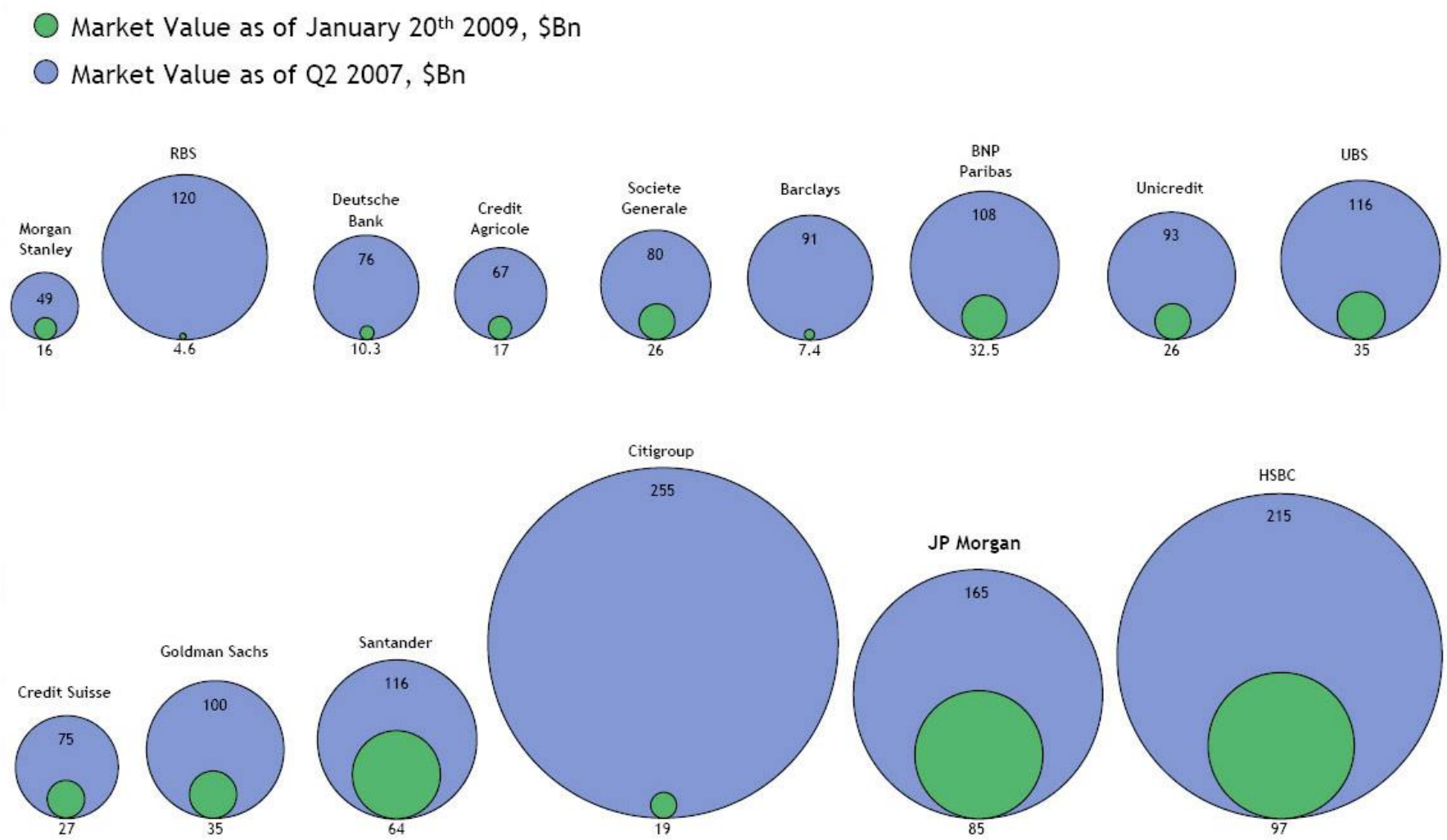
- January 20th, 2009
- Q2 2007 (before banking crisis hit)



Source: Bloomberg, Jan 20th 2009

Let's evaluate...

Banks: Market Cap



J.P.Morgan

Source: Bloomberg, Jan 20th 2009

Problems here?

We are not good at comparing areas.

(And the areas here are actually misleading!)

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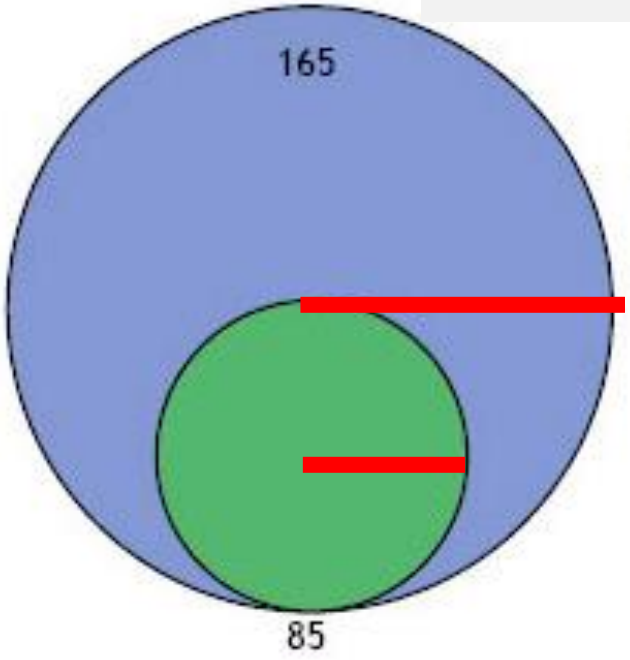
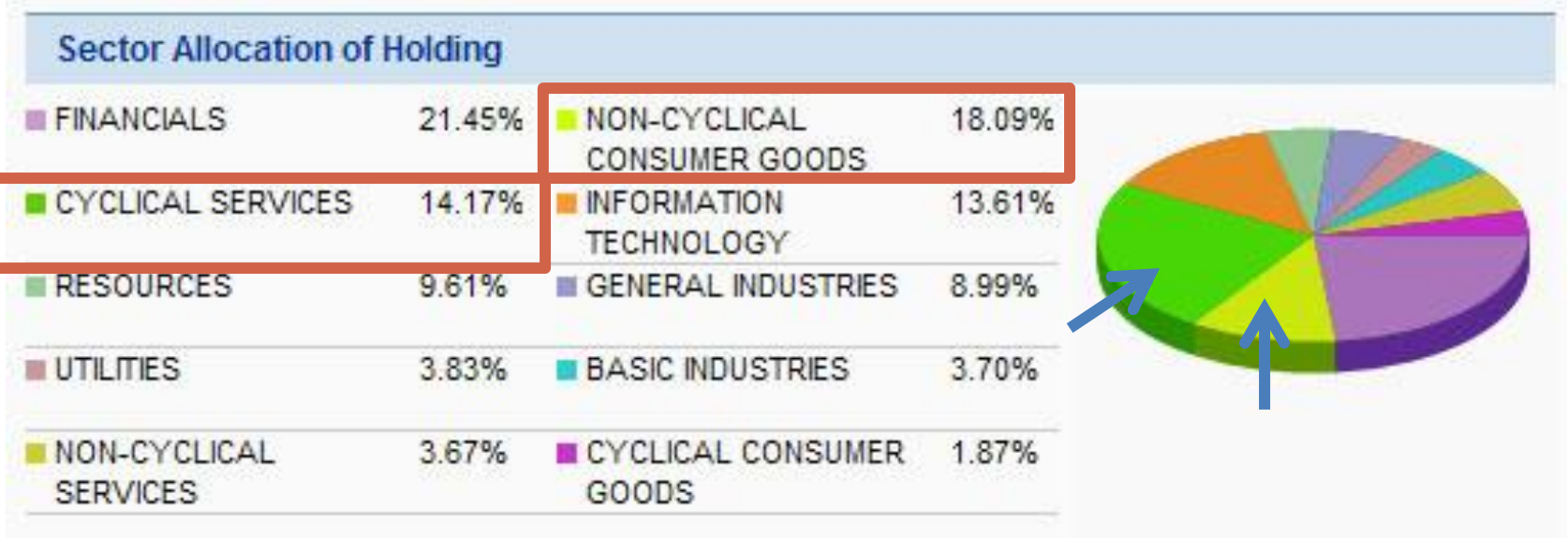


85 / 165 = ~50%

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

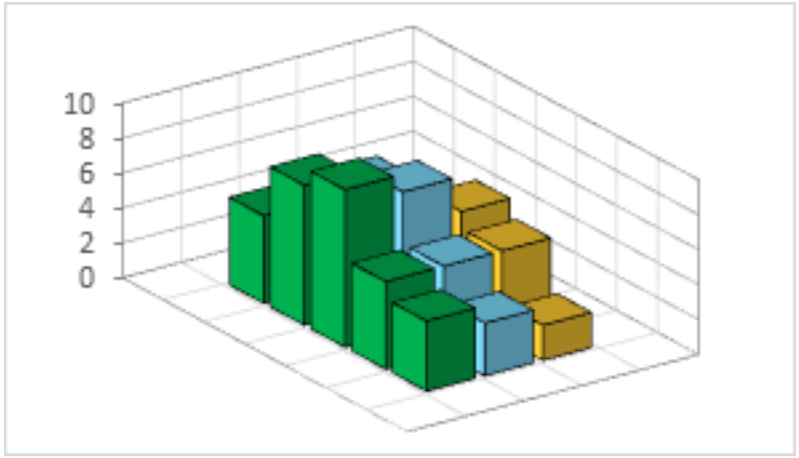
A bar chart would be better.

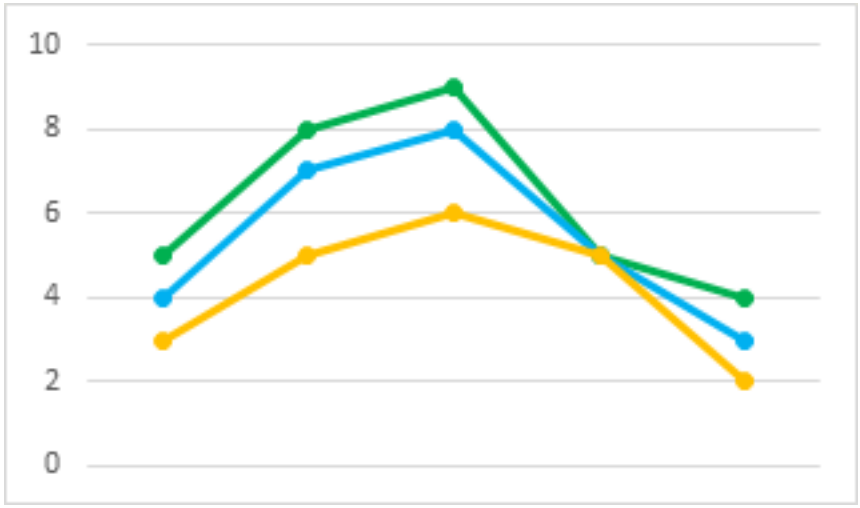
Problem here?



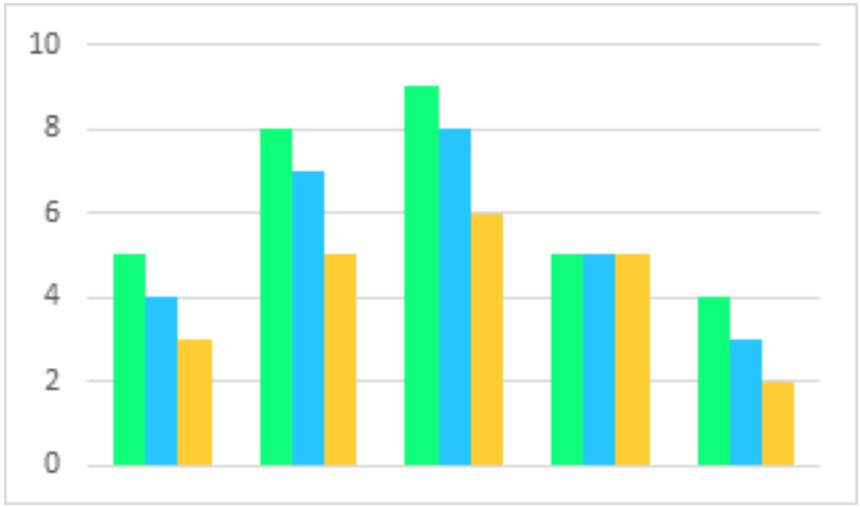
- There is likely a **bug or error** in the data
- Pie slices are difficult to compare by **area** or by **angle**
- **Similar colors** are difficult to distinguish
- **Perspective distortion** adds to the problem

Similarly…3D bar charts are not recommended



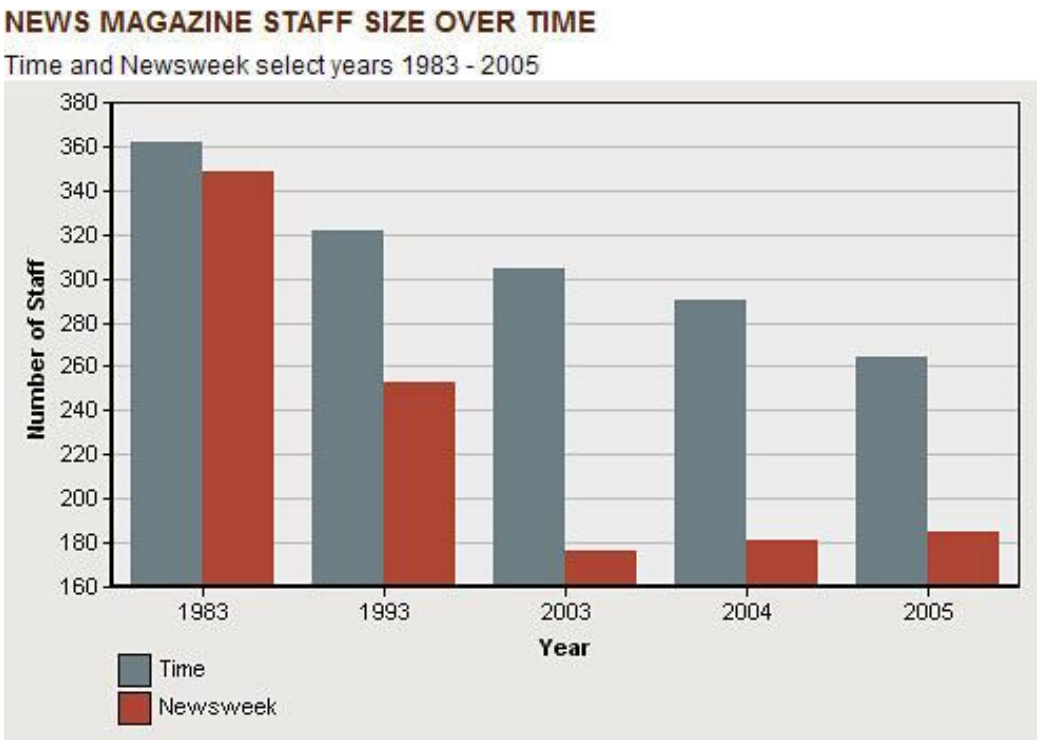


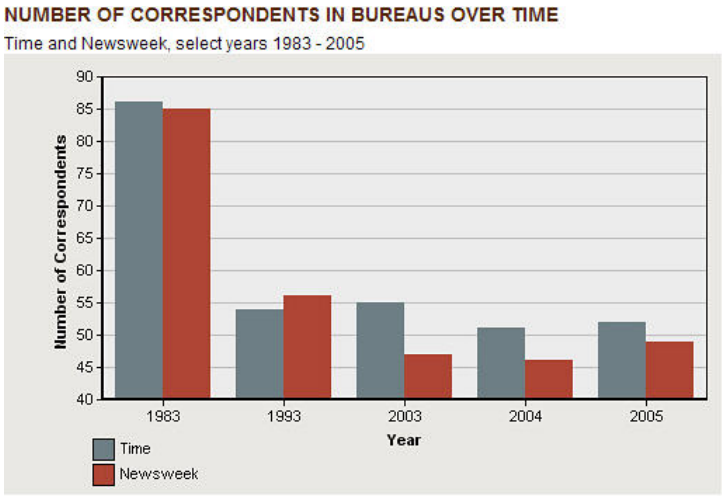
These are **much easier** to read & compare!

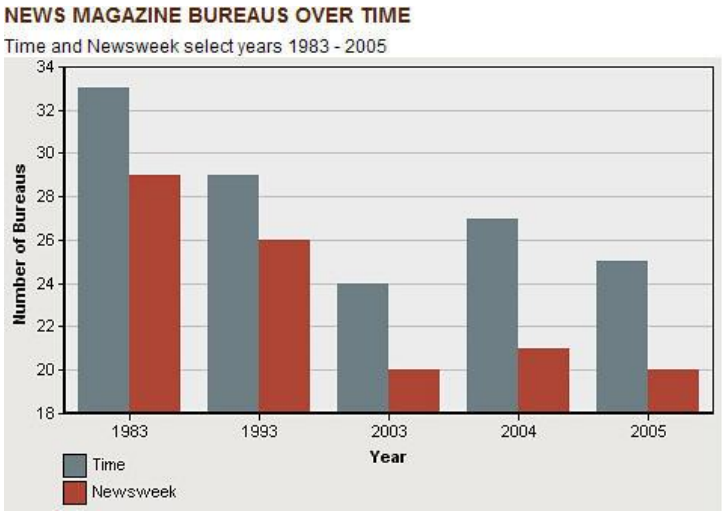


John Peltier http://peltiertech.com/WordPress/3d-bar-chart-alternatives/

Problem here?

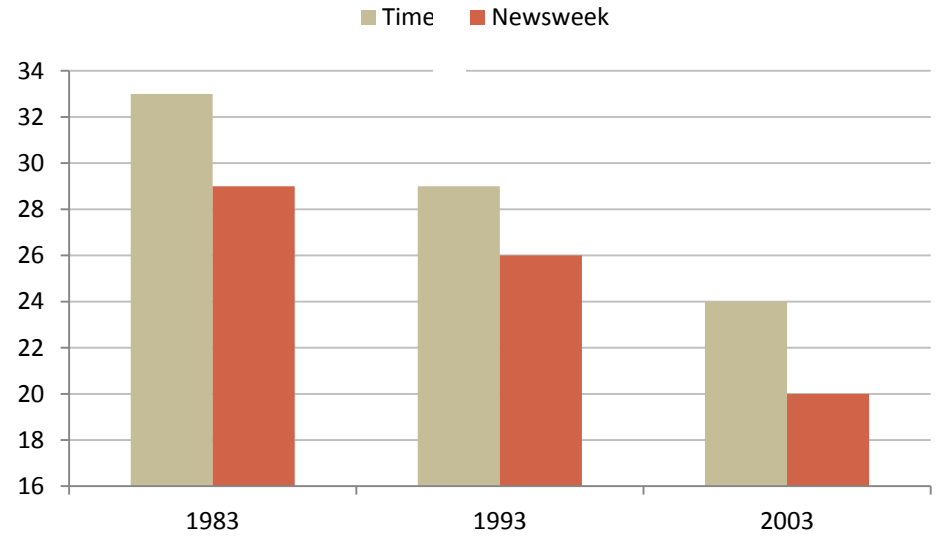


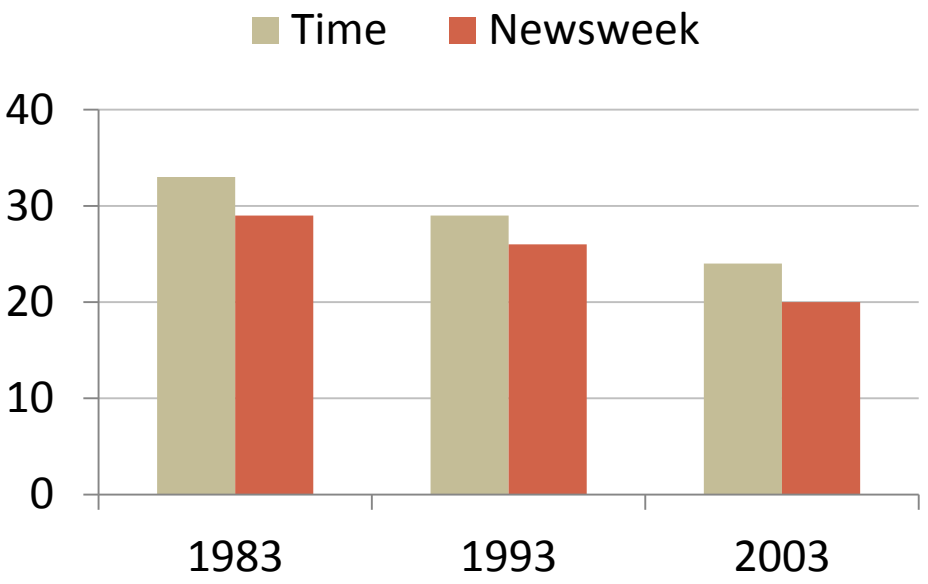




Journalism.org (via Stephen Few)

Length Comparison





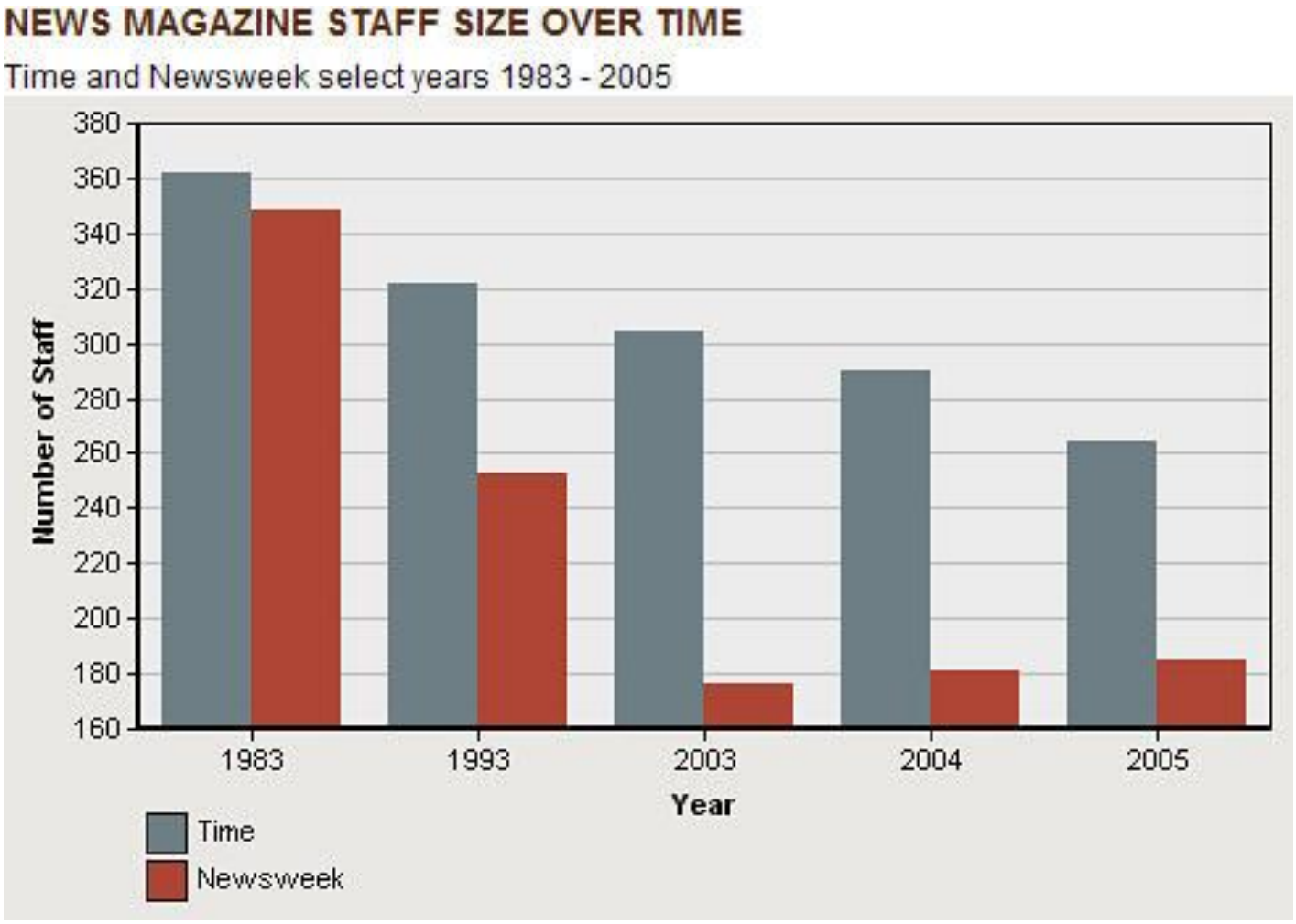
At first glance:

- A huge overall decline
- In 2003, Newsweek is 50% of Time

If we add a proper baseline at 0:

- The downward trend is less severe
- 2003: Newsweek is ~80% of Time

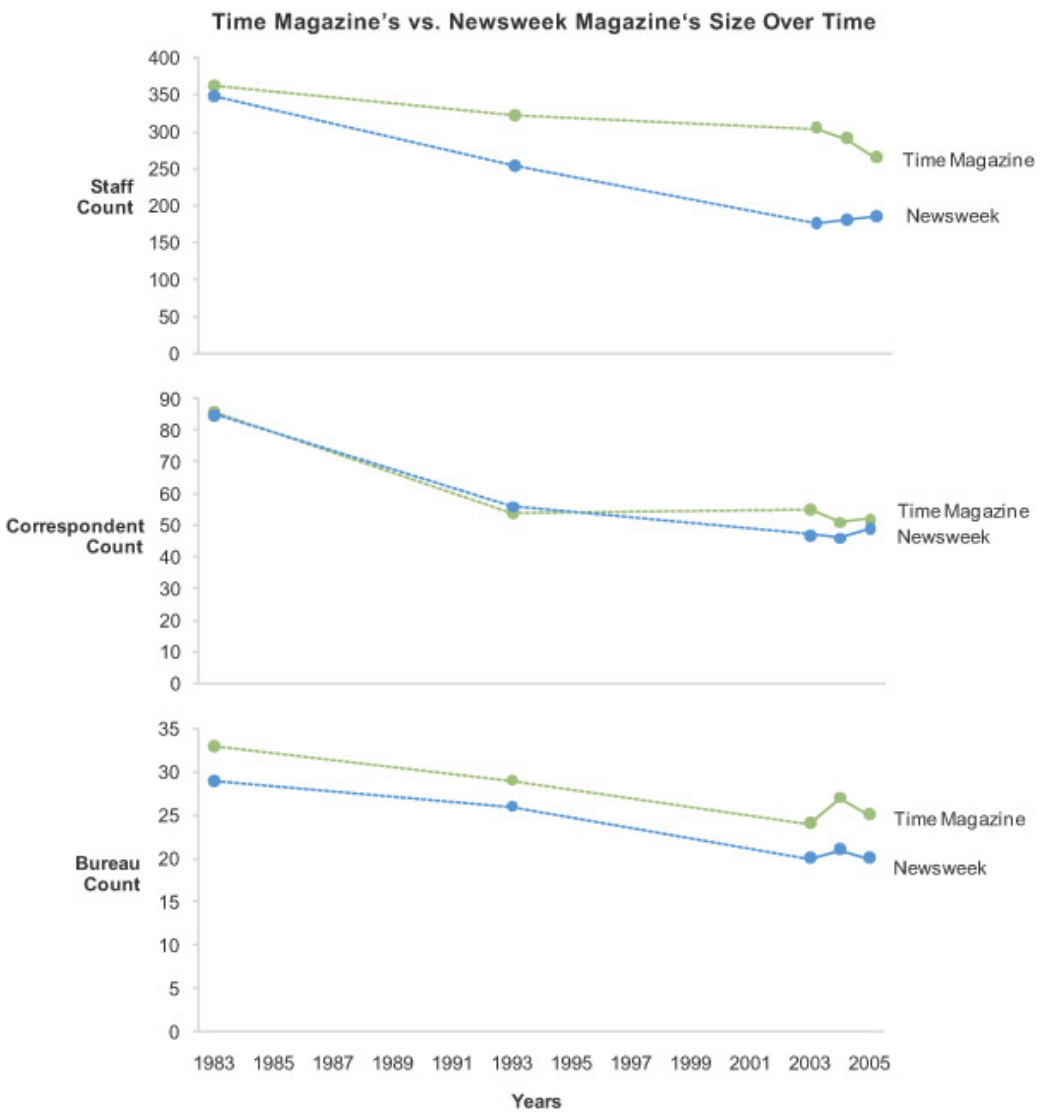
Moreover…



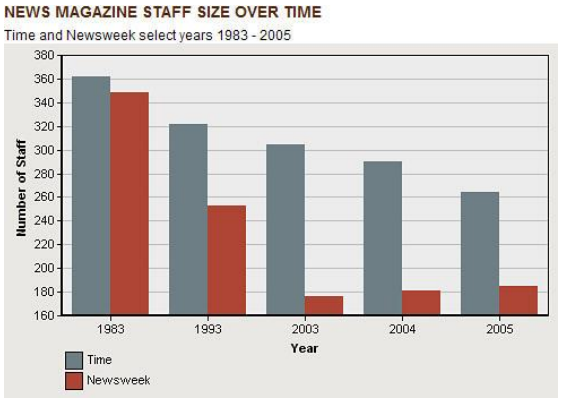
10 years each

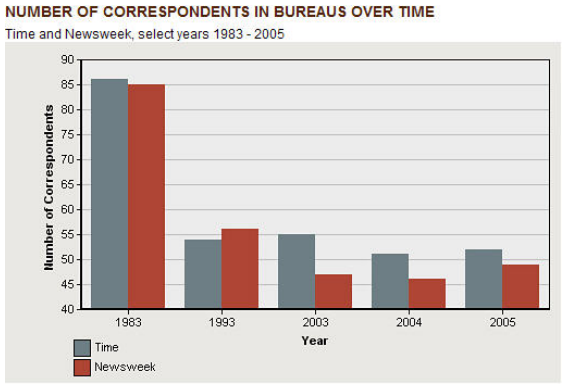
1 year each

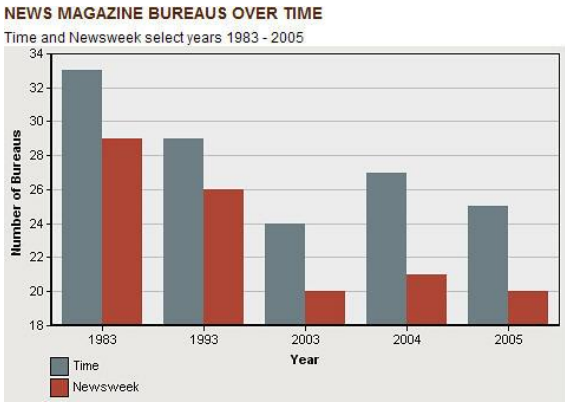
Redesign (by Stephen Few)



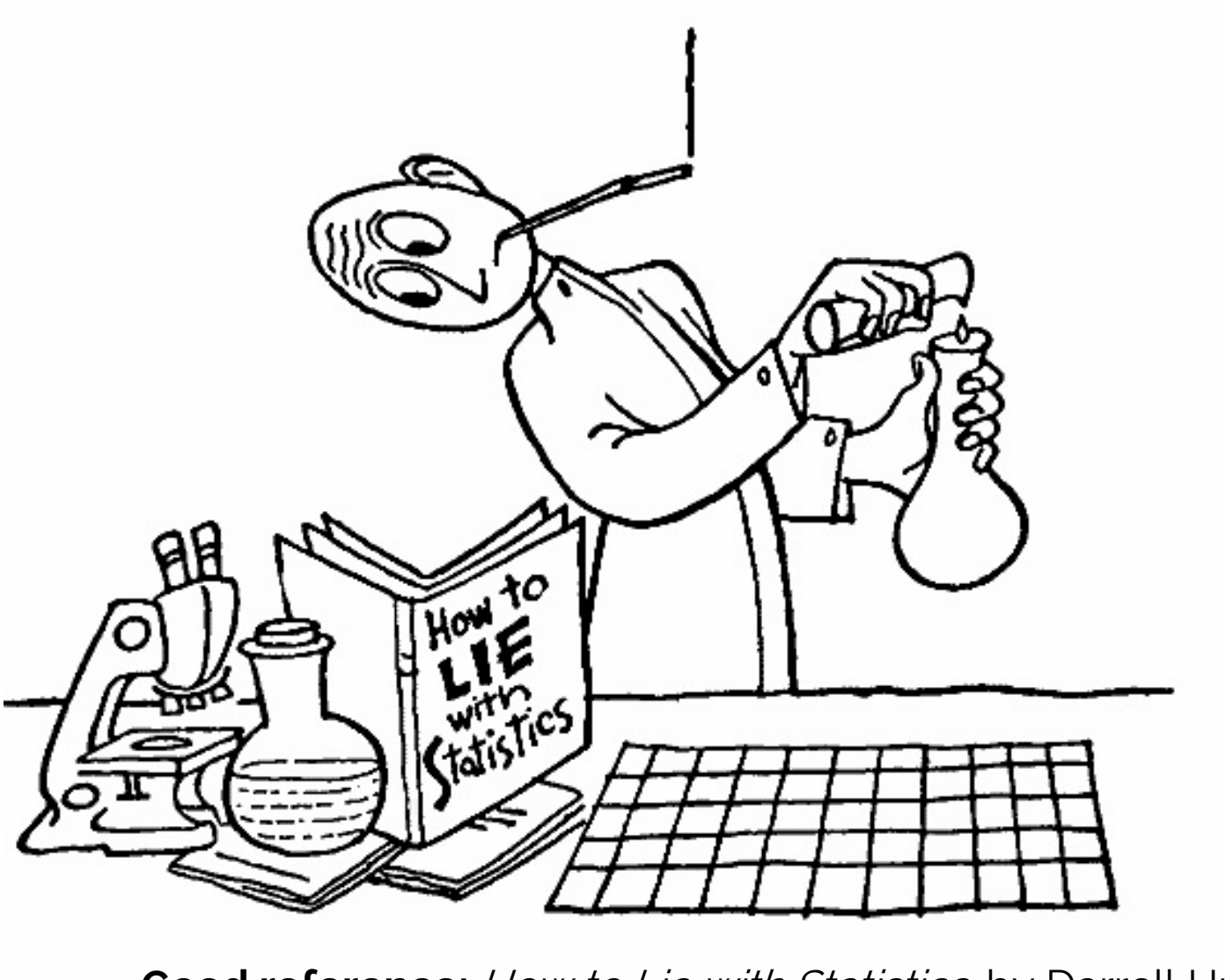
Note: A dashed line connecting two points indicates that there are years between the points for which values were not available. If the values were available, the shape of the lines might vary significantly.







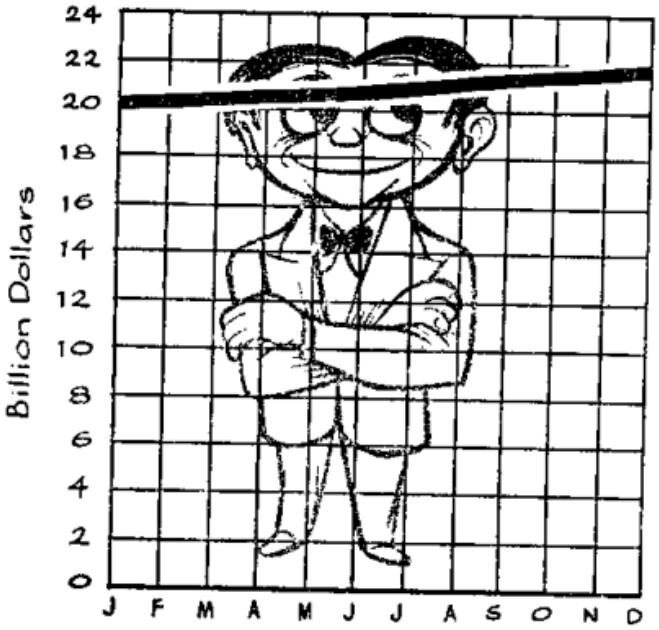
A few more (classic) guidelines!



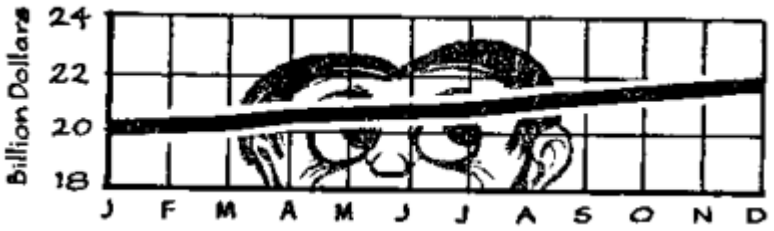
Good reference: *How to Lie with Statistics*, by Darrell Huff (1954)

Chart Rules

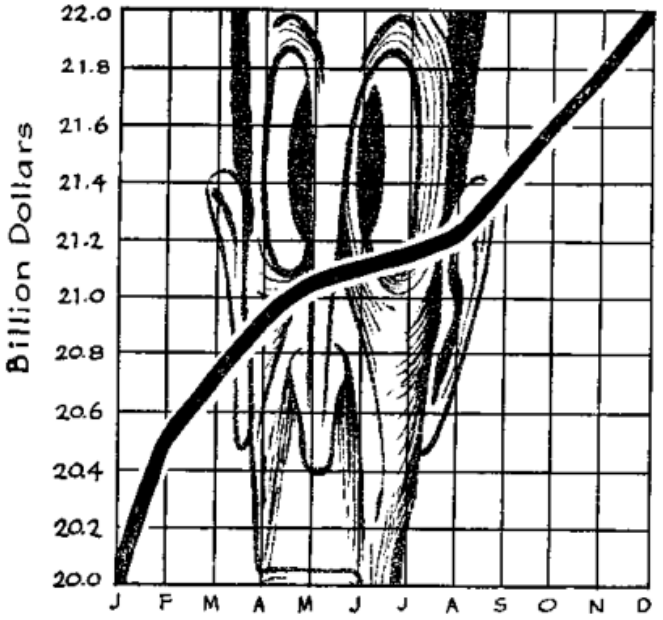
- Provide a proper baseline



A 10% increase. Good!



Already looks more impressive



Wow!

Chart Rules

- Provide a **proper baseline** & **label your axes**

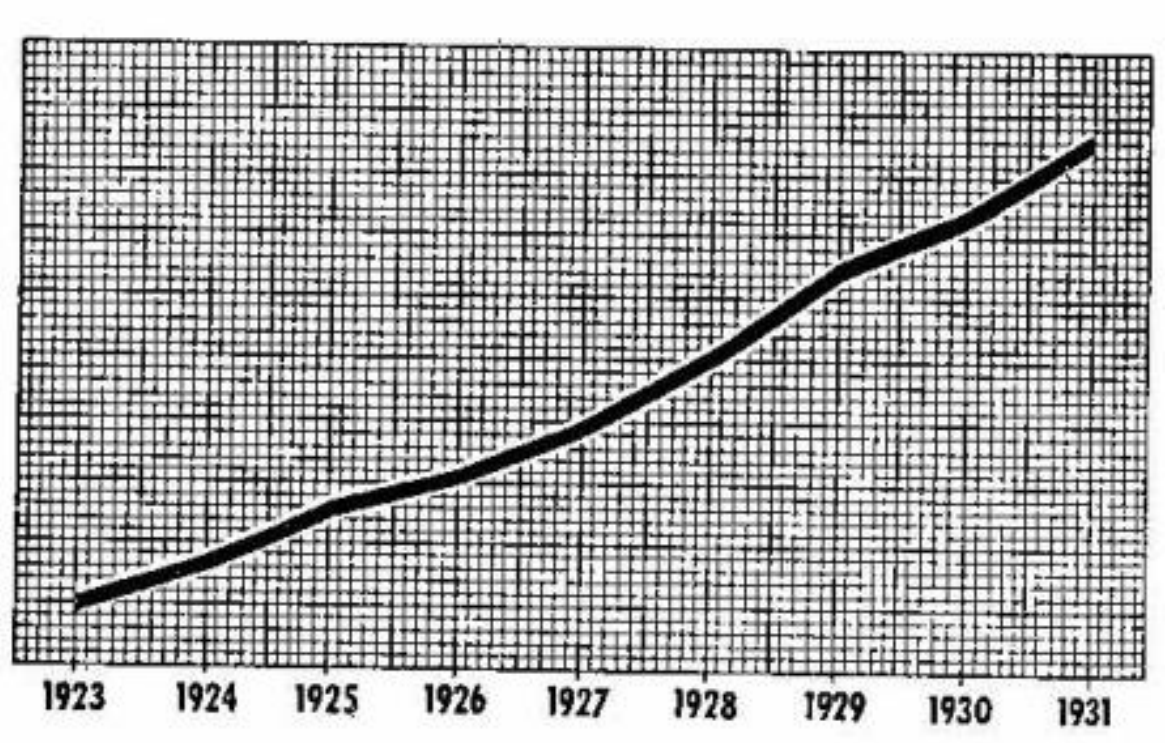
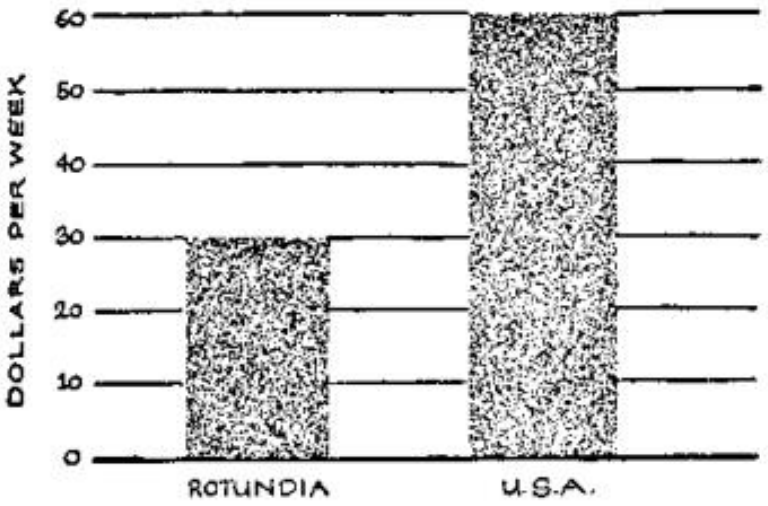


Chart Rules

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



Actual data

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

Impressive, but a lie!

Chart Rules

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

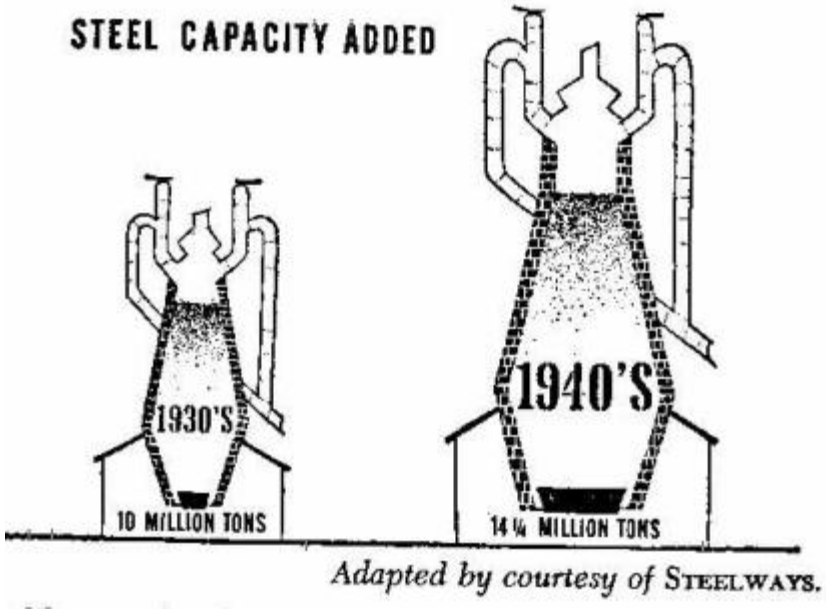


Chart Rules

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

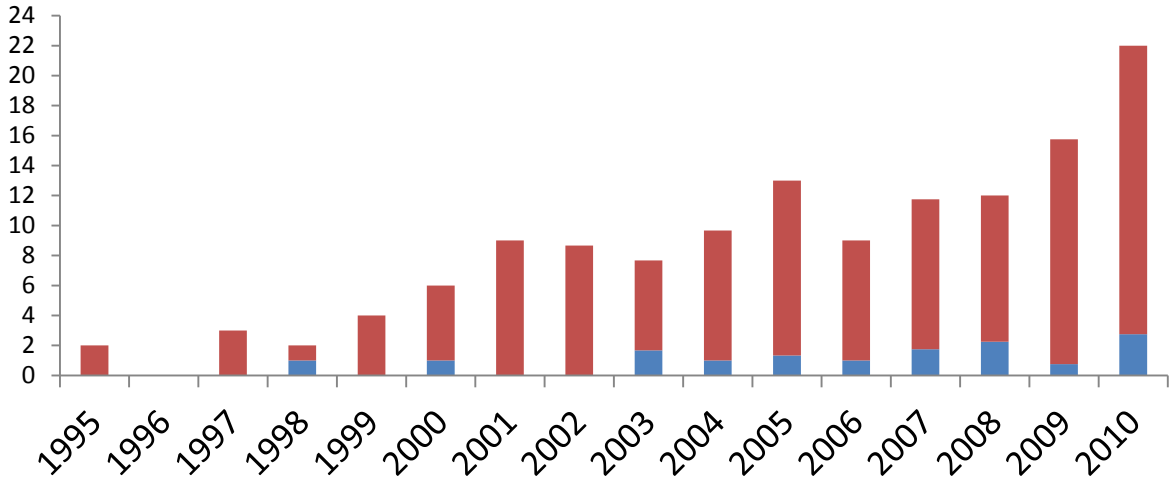


Chart Rules

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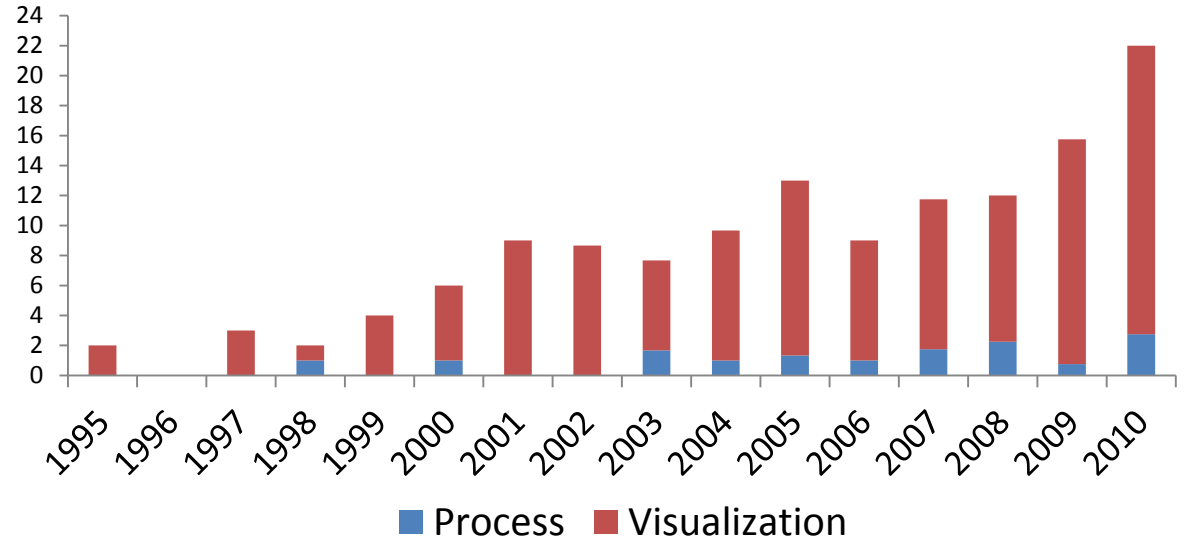
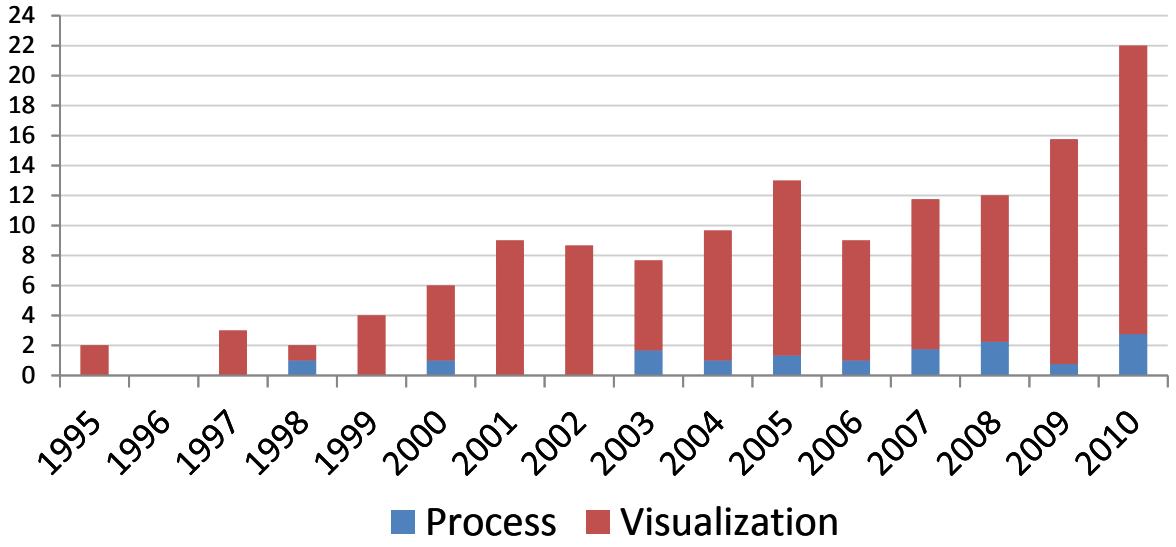
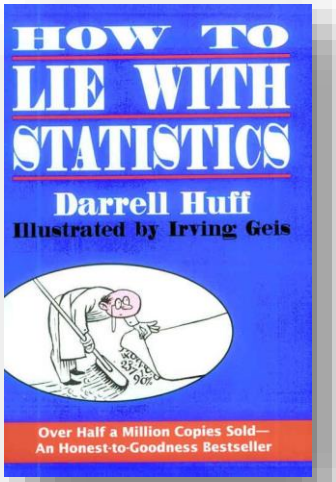


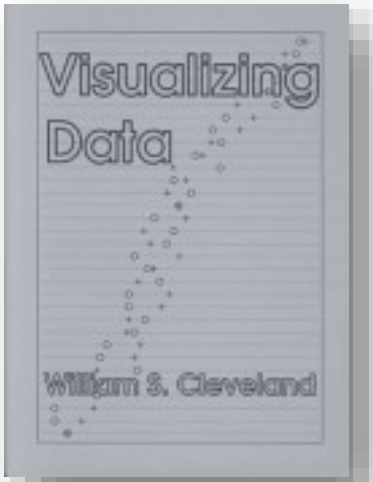
Chart Rules

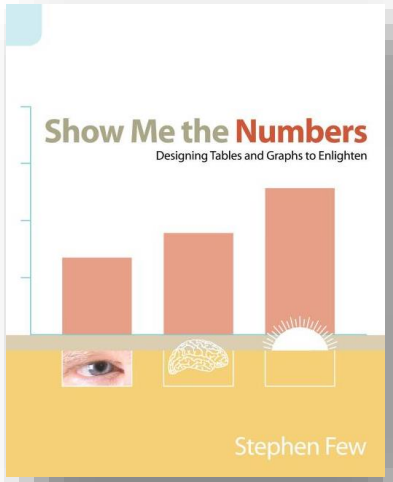
- Provide a **proper baseline** & **label your axes**
- Avoid **eye-candy**
- Avoid **area comparisons** whenever possible
- Provide **legends**
- **Grids help** – but make them subtle
  (about 20% opacity – **no black lines**)

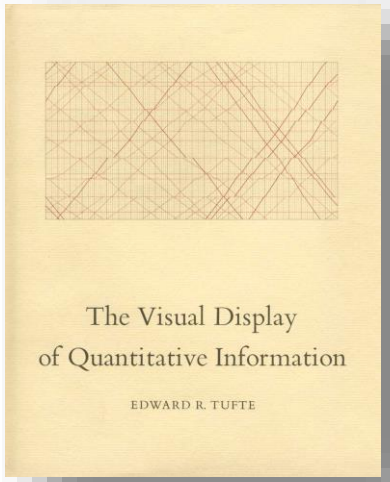


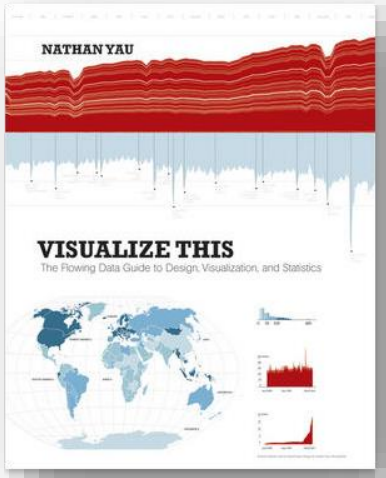
Many more useful guidelines!











Summary

Today you learned

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

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

Learned how to **critique visualizations**

For Your Projects

Apply what you learned about color

- Use **color judiciously**
- Pick good colors based on the **data and task**
  (e.g. Don't use a rainbow color scale unless you have a **very** good reason)
- Respect the **color blind**

Consider perception when choosing encodings

- Choose visual representations that **support your task** and don't **misrepresent the data**