Information Visualization
PERCEPTION and COLOR

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Let’s do an experiment …

What is Color?

= the set of **perceptions** elicited by the spectral distribution of light

Color Vision

- What we call color is generated by the visual brain
- There is no one to one relationship between the colors seen and wavelengths

Functions of Color Perception

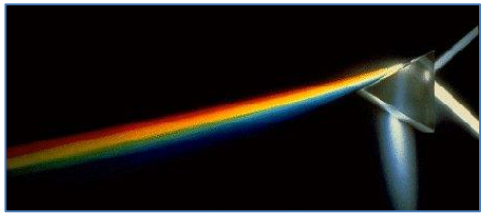
Color helps us to:

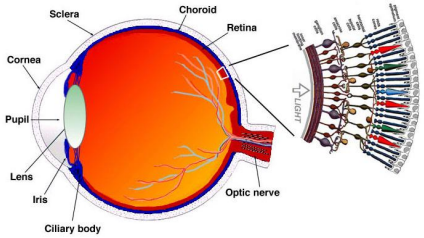
- Identify things
- Classify things

Through

- Grouping
- Background segregation

How do we describe color?





"Yellow"

Physical World

Lights, surfaces, objects

Visual System

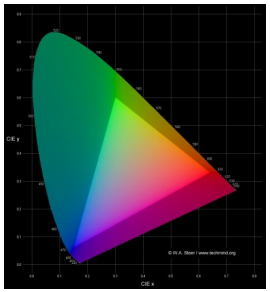
Eye, optic nerve, visual cortex

Mental Models

Red, green, brown

Bright, light, dark, vivid, colorful, dull

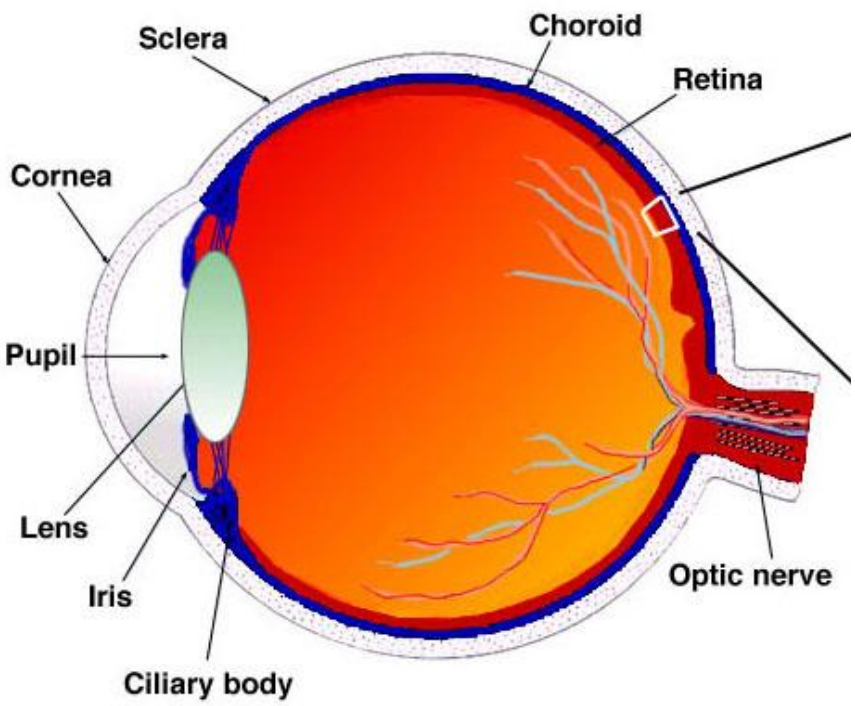
Warm, cool, bold, blah, attractive, ugly, pleasant, jarring



Color Models

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

Physical World→**Visual System**

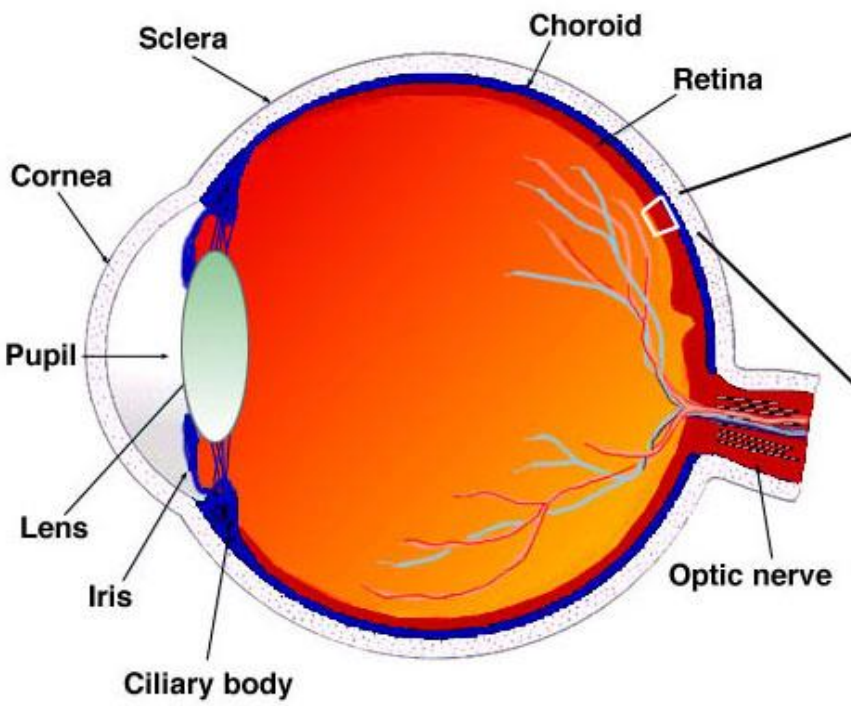


Retina is stimulated by three factors:

- illumination (light source)
- reflectance (from object)
- transmittance (atmosphere)

Simple Anatomy of the Retina, Helga Kolb

Physical World→**Visual System**



You **do not** see individual photons or light waves

- 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

Example: Lightness vs. Luminance

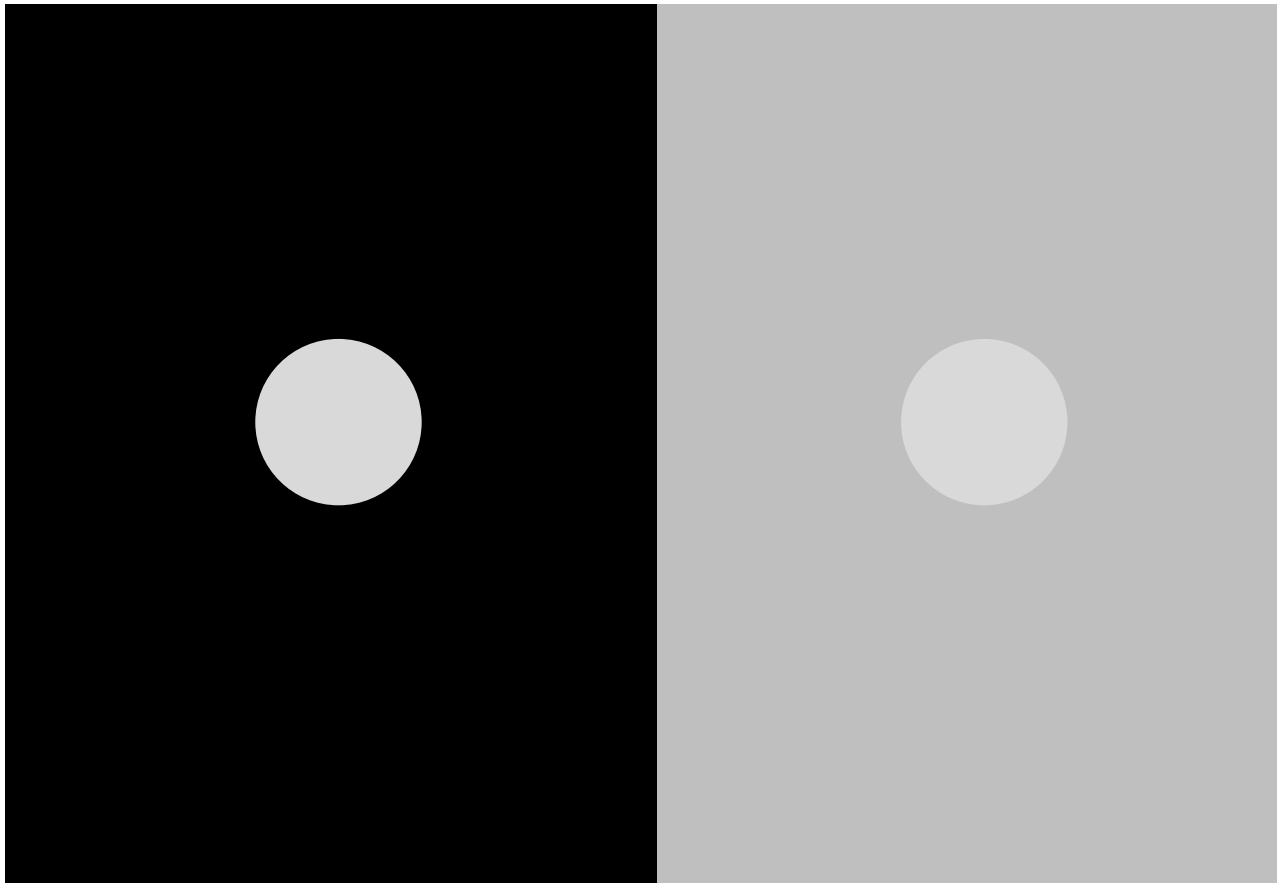
- LUMINANCE: an objective measurement of light intensity per unit area (e.g. cd/m2; physical)

- LIGHTNESS: a subjective impression of the intensity of light reflected from on object surface (no units; psychophysical)

Lightness experiment

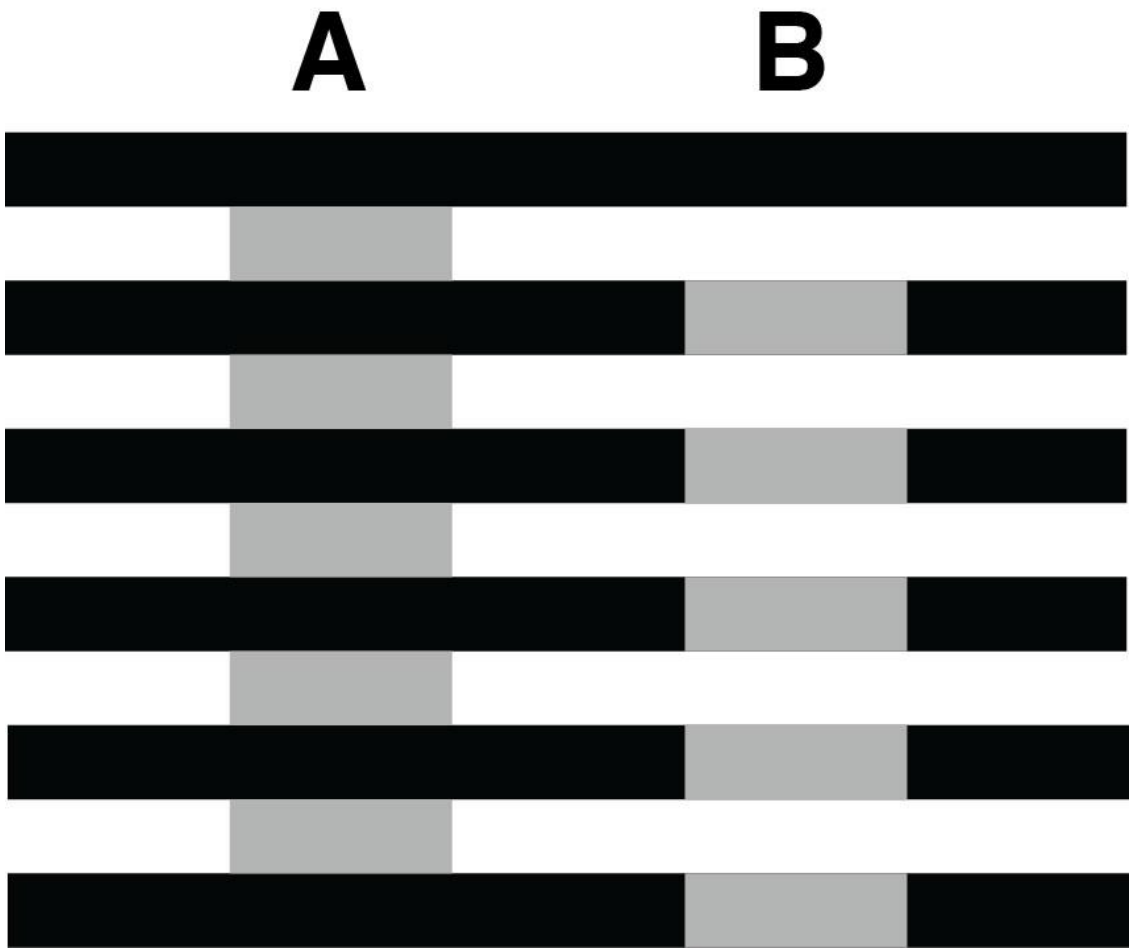
The two circles are physically the same

Lightness experiment



The two circles are still physically the same, but the lightness you perceive is not

White’s illusion: the opposite effect



A is surrounded by more black but seems darker than B, which is surrounded by more white

The Cornsweet Edge

As a result of two gradients, but why does this happen?

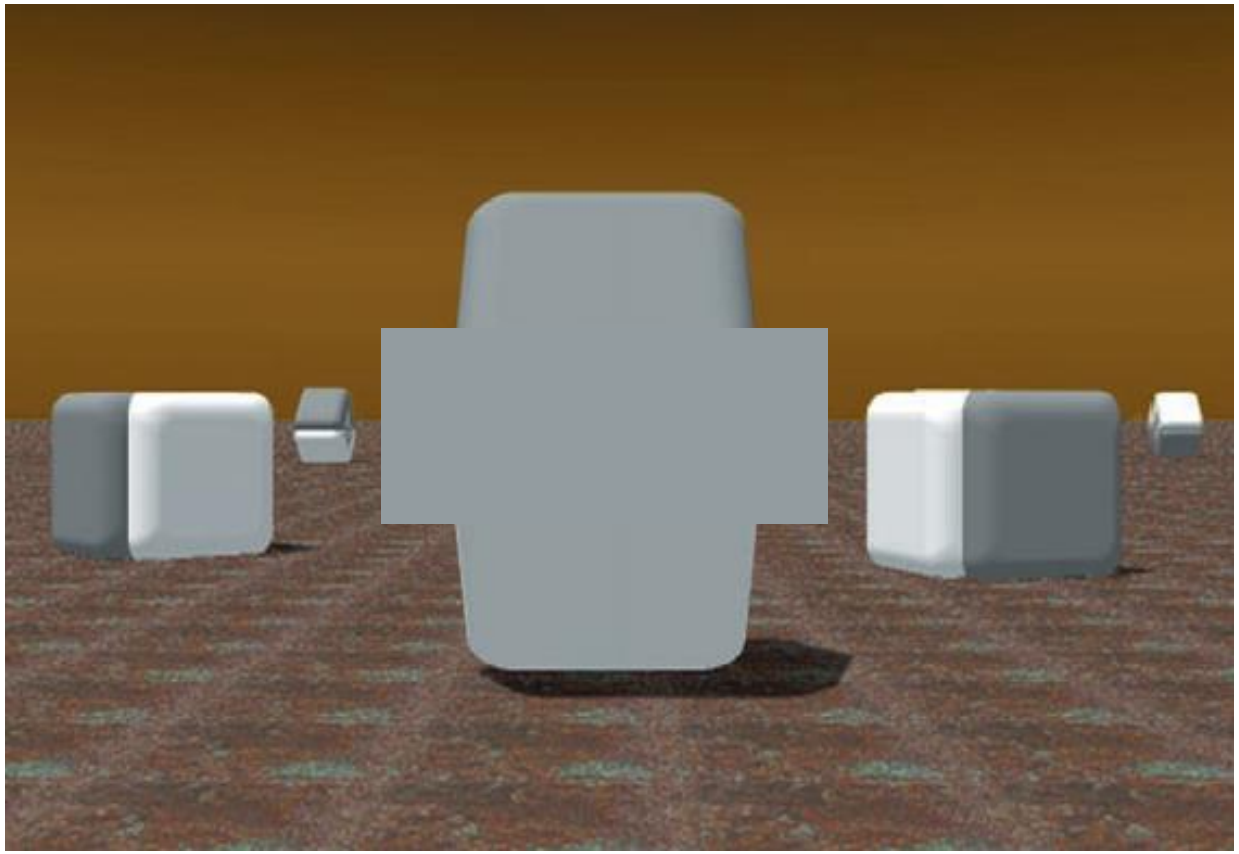


Image source: The Journal of Neuroscience, October 1, 1999, 19(19):8542–8551 An Empirical Explanation of the Cornsweet Effect.

WHAT IS GOING ON?

The Inverse Problem

- What the retina receives as input (stimulus) is a combination of photons/light waves
  - From illumination sources
  - From reflectance of objects
  - From transmittance through objects
- How do we know who contributed what?

→ We have learned what the relationships are between the physical world and our perceived information are, to solve this problem

WHAT IS COLOR?

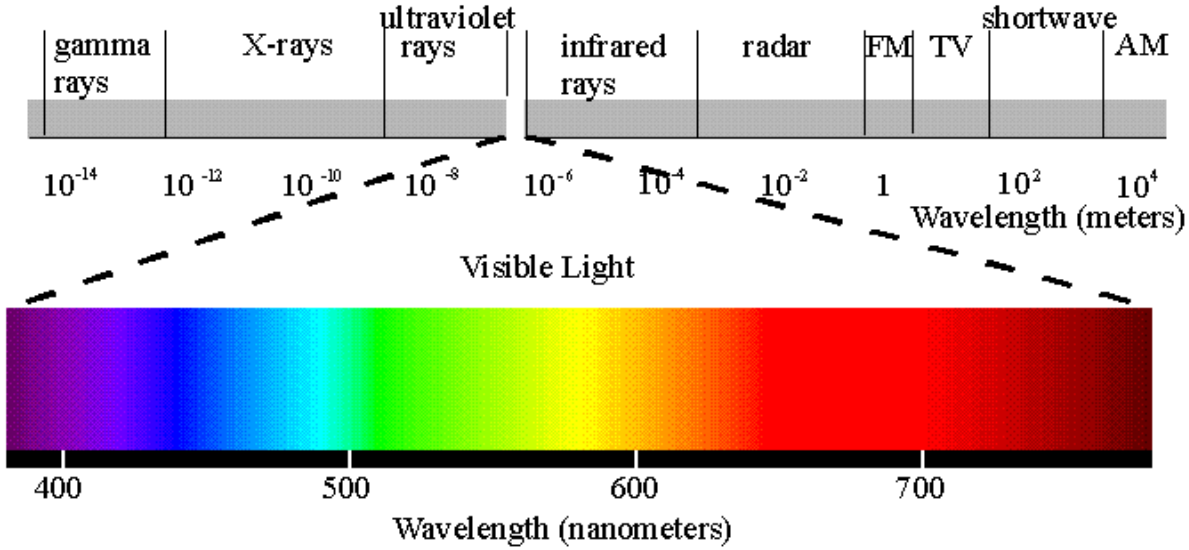
Some definitions

Physical measurement:
the relative intensities of wavelengths in light measured with a spectrophotometer

Psychophysical measurement:
report of the color seen by a normal subject, typically made by comparison

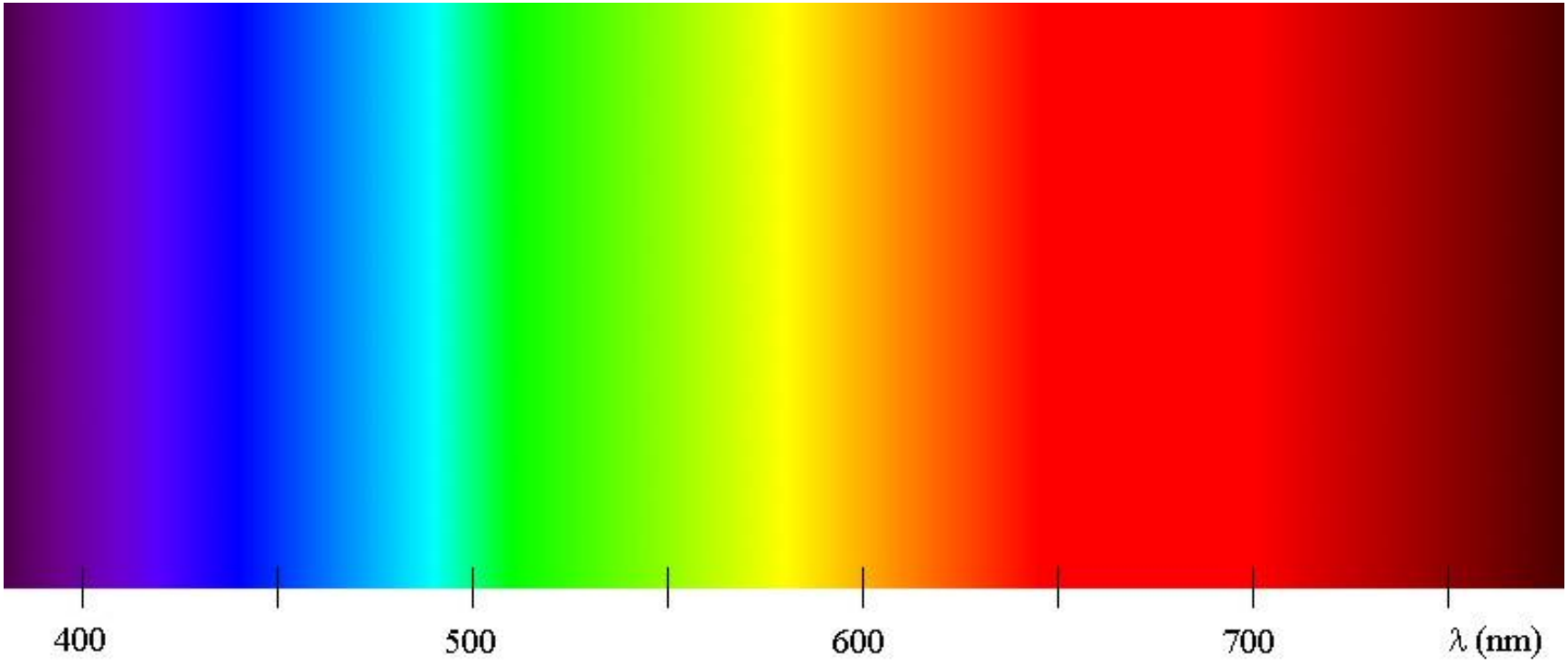
Physical World – The Nature of Light

We have evolved to see a range of wavelengths: ~400 - 700nm

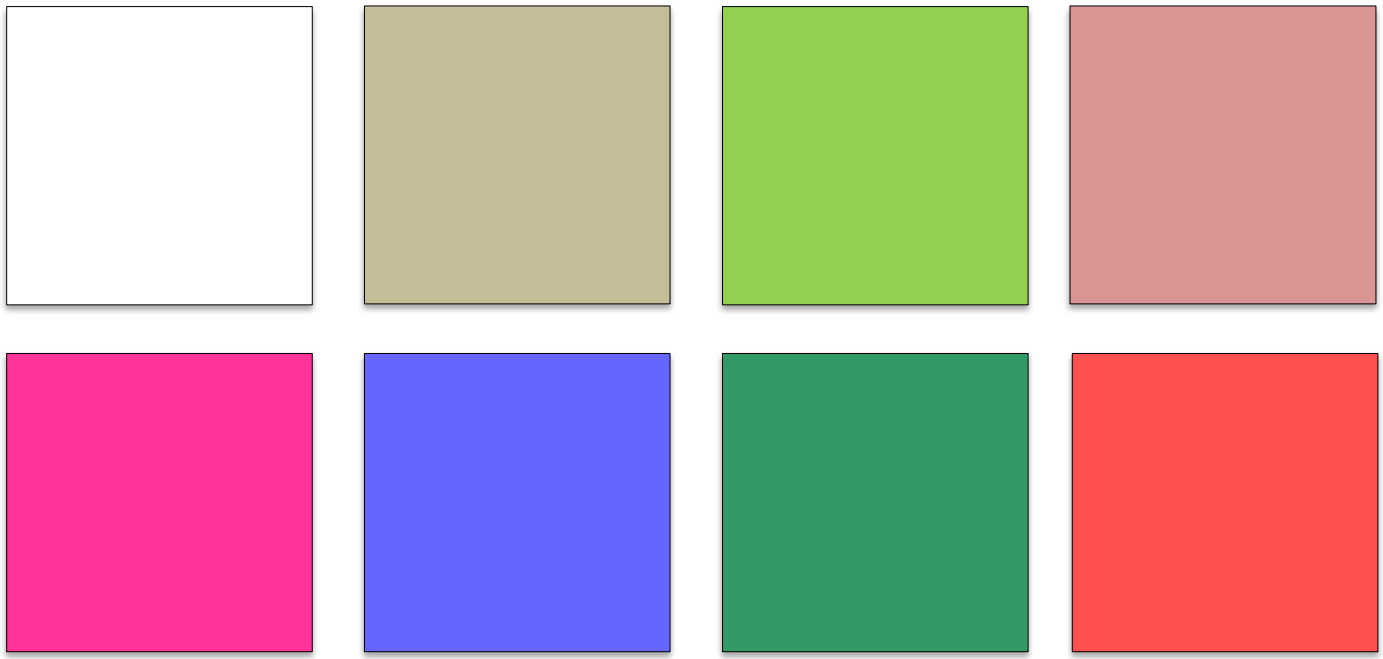


Light of a single wavelength is *monochromatic*

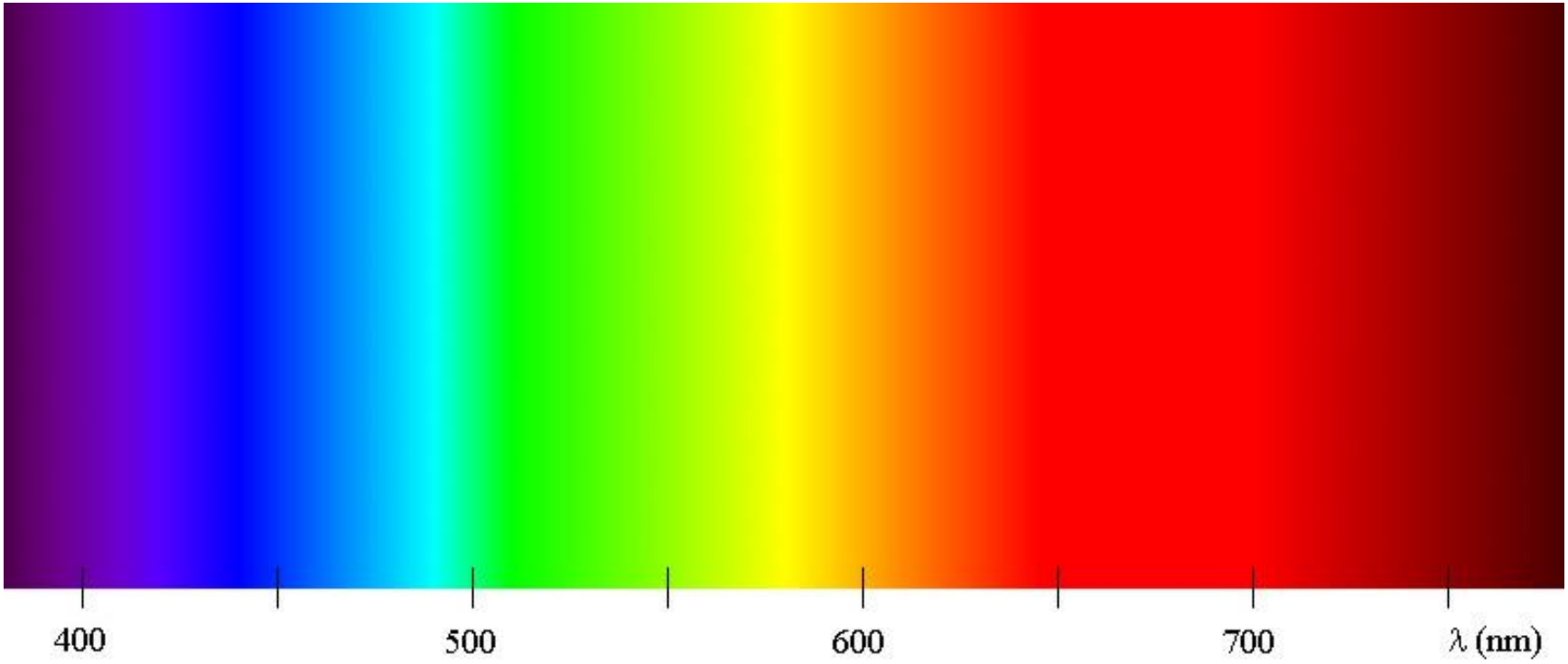
What do you notice?



http://www.science4all.org/article/colors/



Monochromatic colors

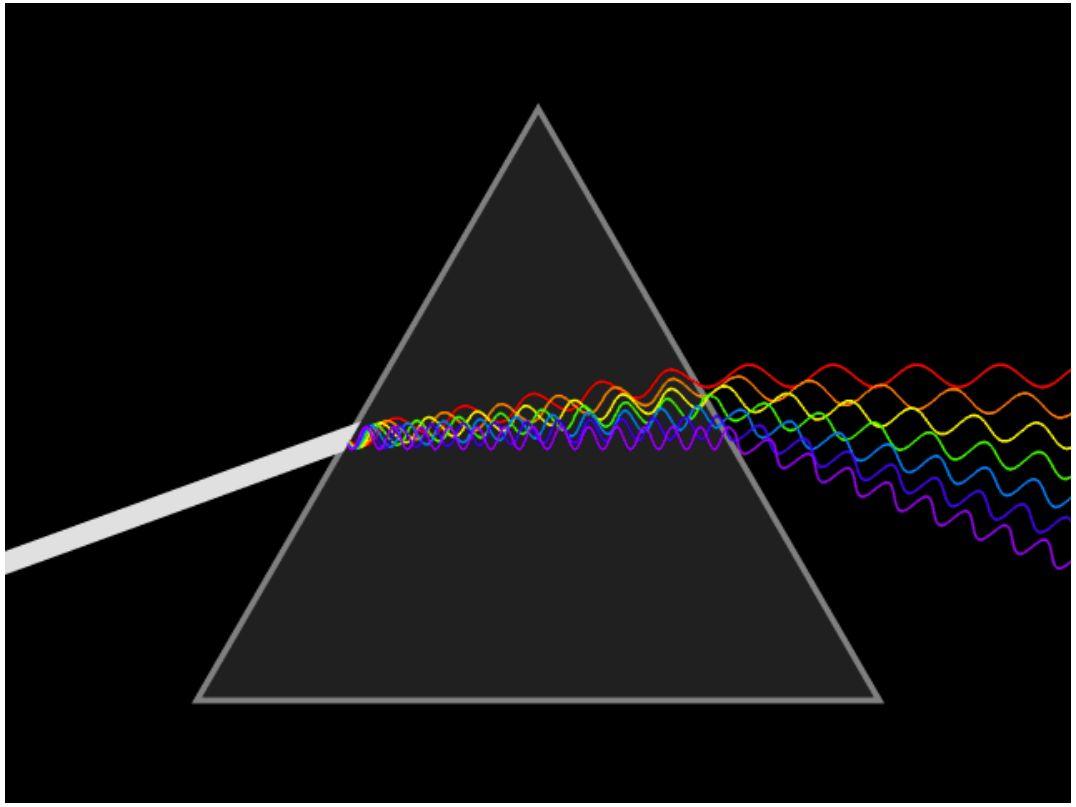


Can be obtained with one or more rays of light with a single wavelength

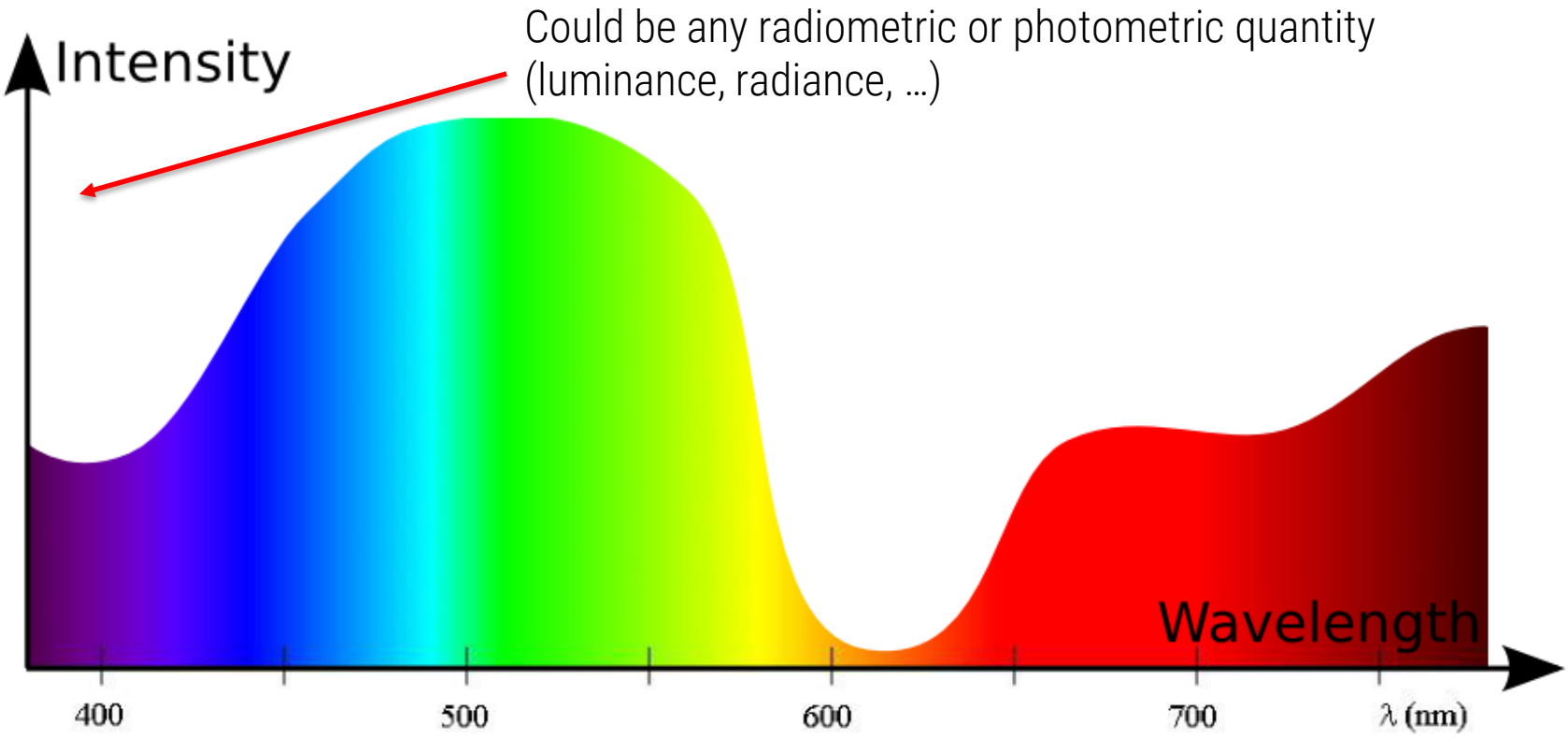
http://www.science4all.org/article/colors/

BUT…

Light rays are typically composed of multiple wavelengths



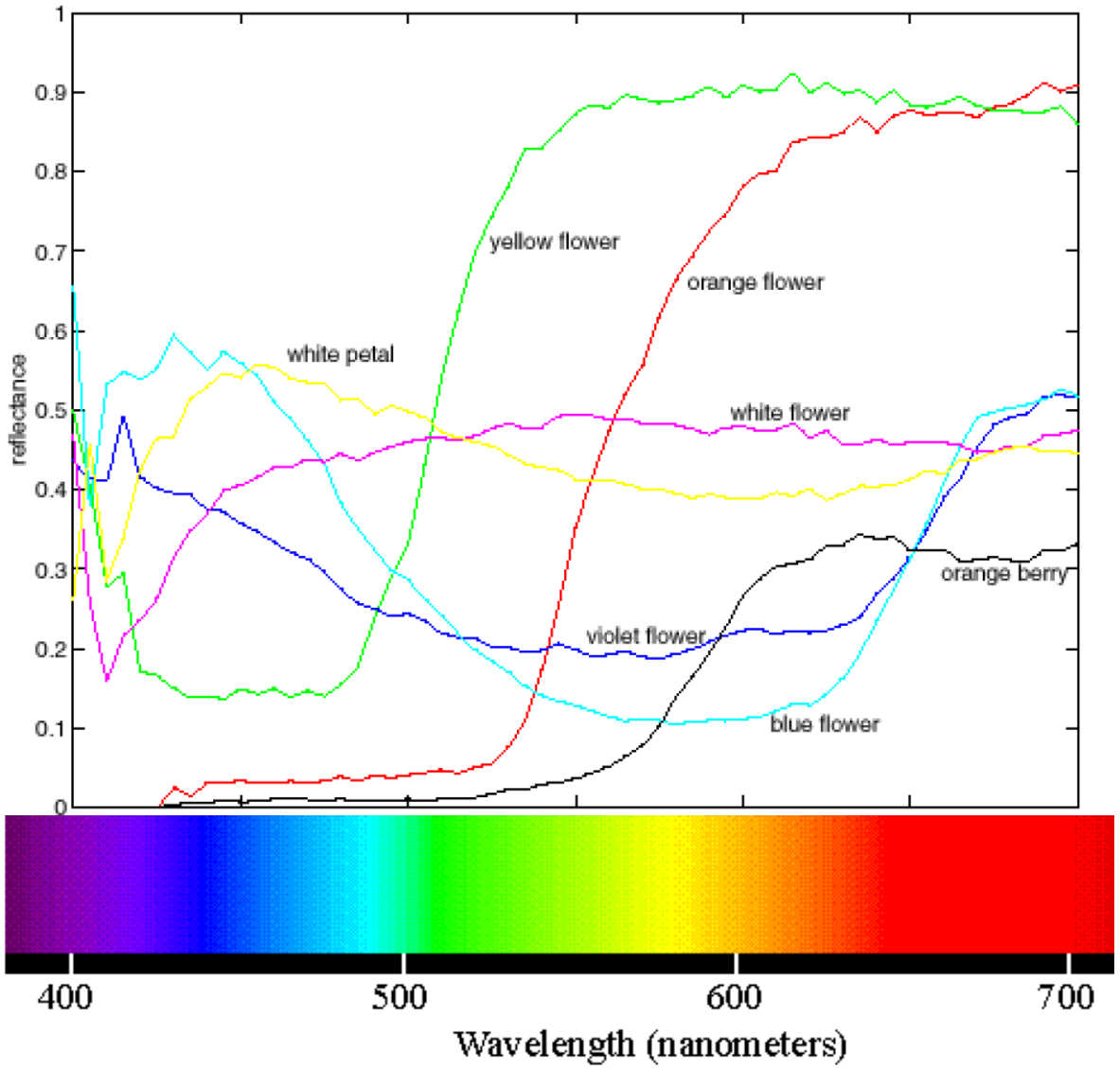
How do we describe a beam of light?



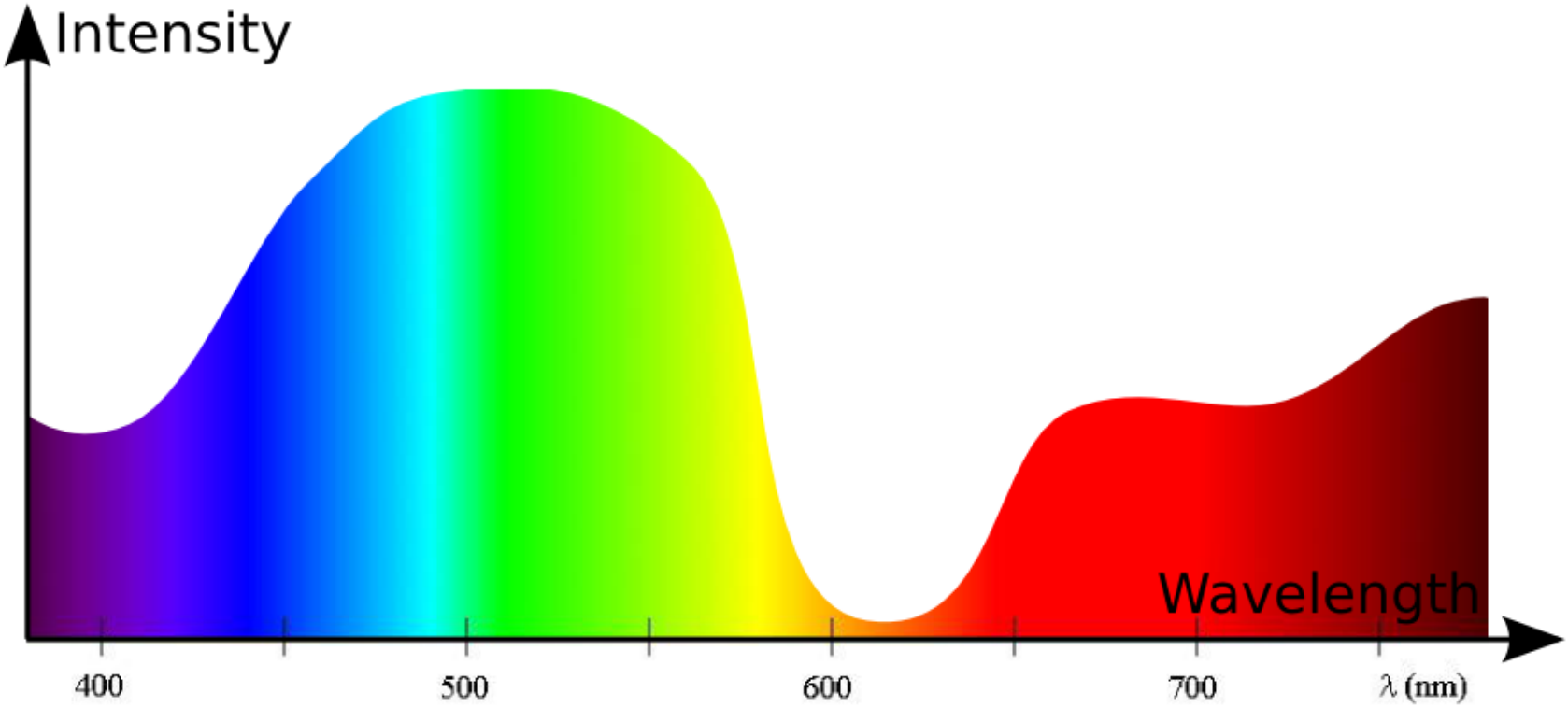
spectral power distribution (SPD)

http://www.science4all.org/article/colors/

Non-monochromatic color spectra



How do we know which color this would be?



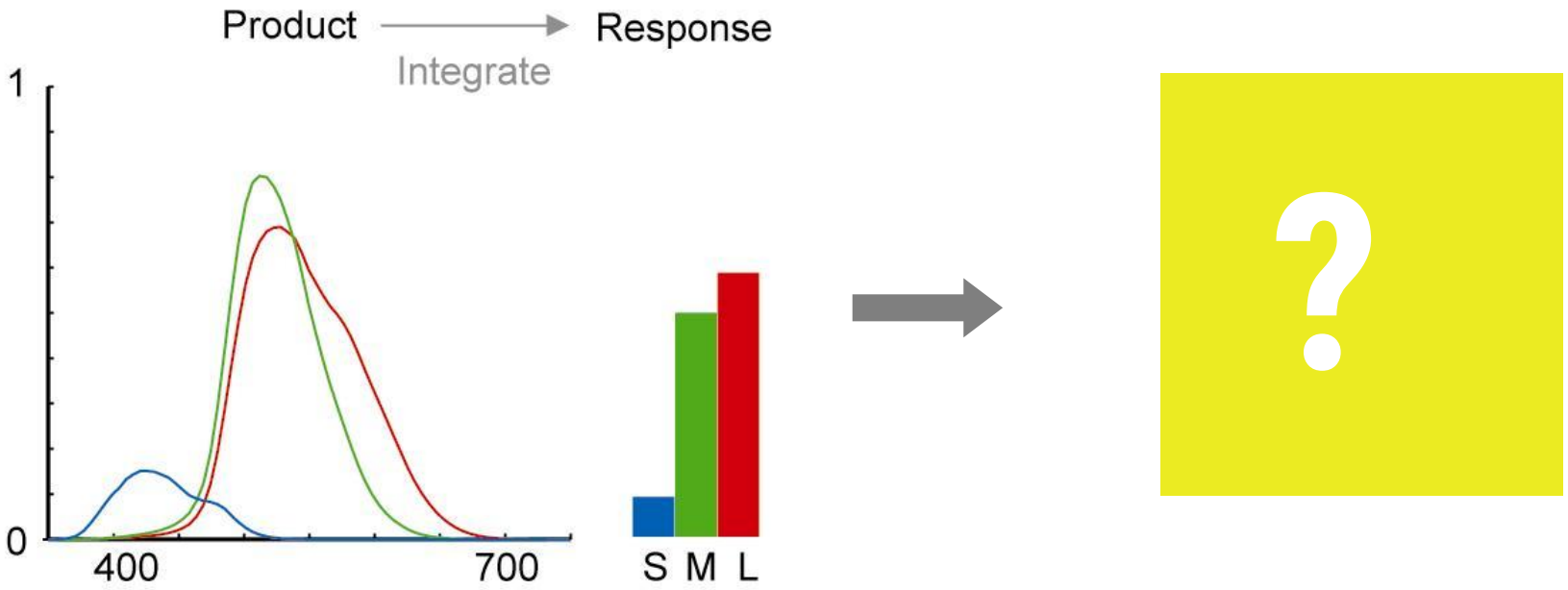
http://www.science4all.org/article/colors/

Physically speaking

If you want to see different wavelengths at different energies across the spectrum

→ you need to have multiple photo receptors that can be compared

Visual System → **Color Models**



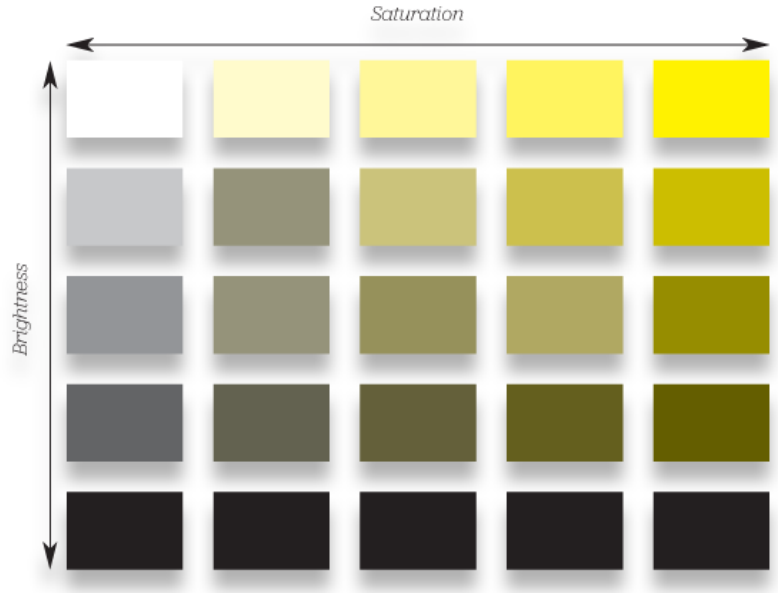
This is the color the eye sees

This is not necessarily the color the brain sees!

HOW TO DESCRIBE COLOR PERCEPTION

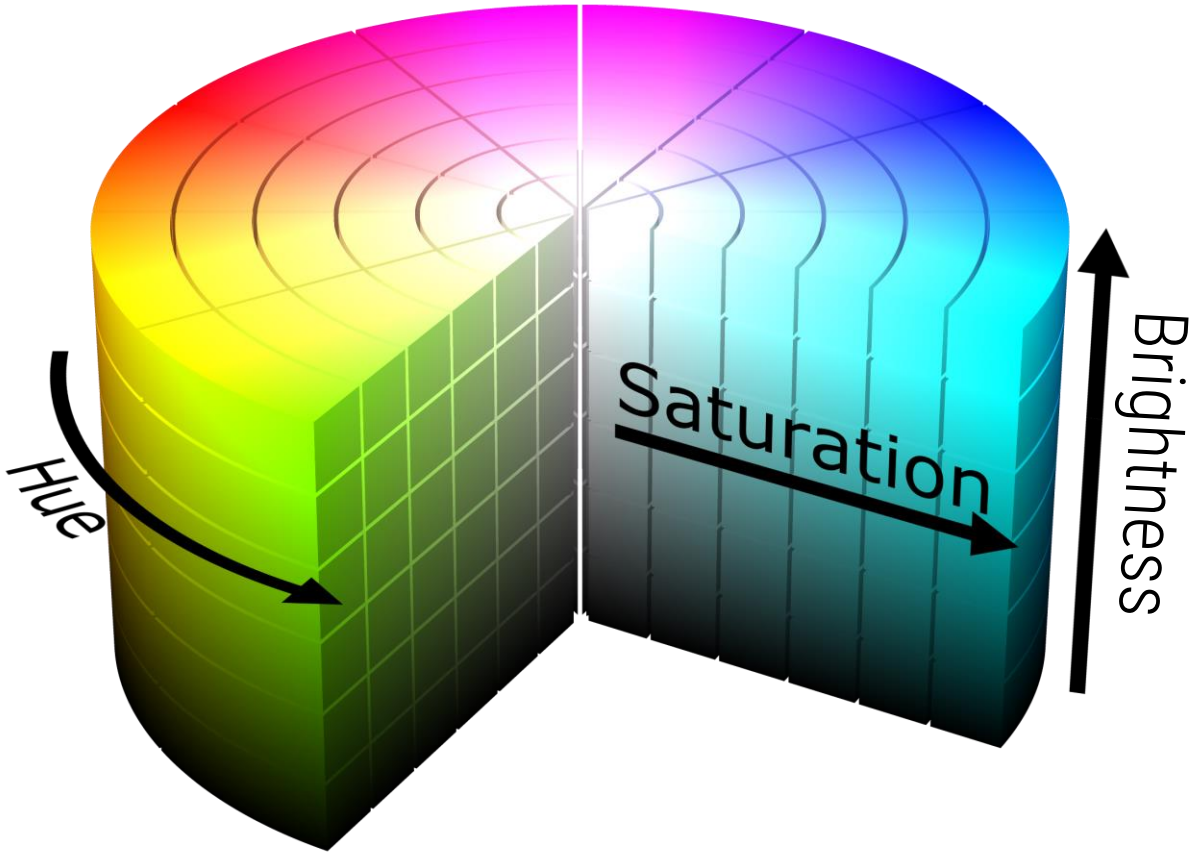
Color Terms

- Hue: Color we see (red, green, blue, …)
- Saturation: degree to which hue differs from neutral gray
- Lightness/Brightness: the intensity of a colored surface or source



https://designingfortheweb.co.uk/images/compare.png

Color Spaces



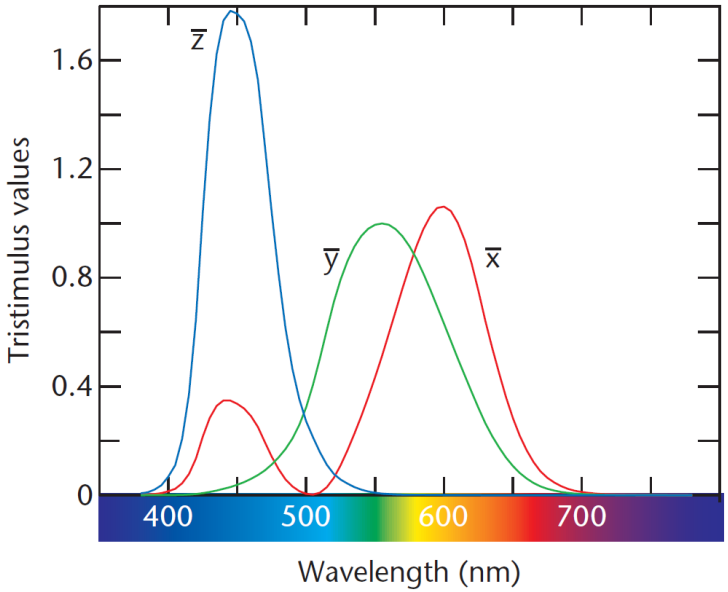
XYZ Color Model

- created by the International Commission on Illumination (CIE) in 1931
- Derived from color perception experiments
  - Relates physical wavelengths to physiologically perceived colors in human color vision.
- Seldom used directly but acts as a basis for color descriptions and transformations

XYZ Color Model

definition of three primary colors: X, Y, Z

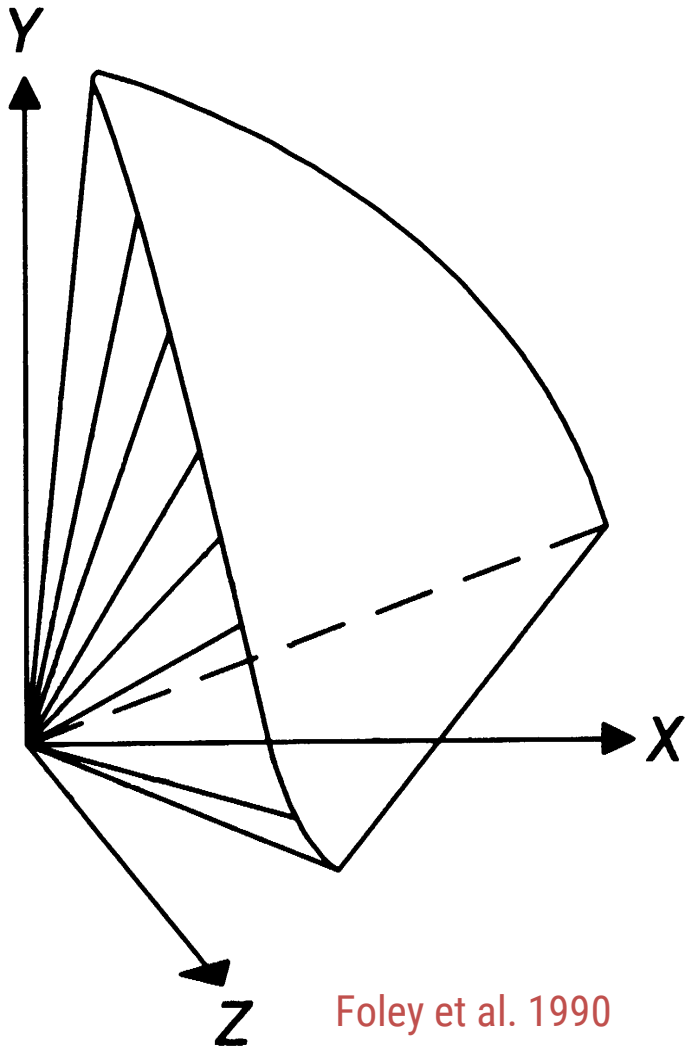
- color-matching functions (the numerical description of the chromatic response of the *observer)*
  - here non-negative
- Y follows the standard human response to luminance, i.e., the Y value represents perceived brightness
- can represent all perceivable colors



Stone 2005

XYZ CIE Color Space

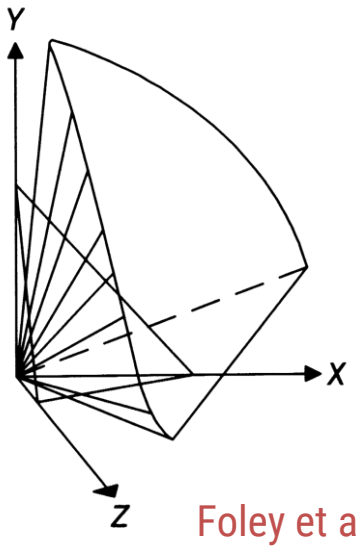
- plotting XYZ space in 3D
- all colors that are perceivable by humans form a deformed cone
- *X*, *Y*, and *Z*-axes are outside this cone

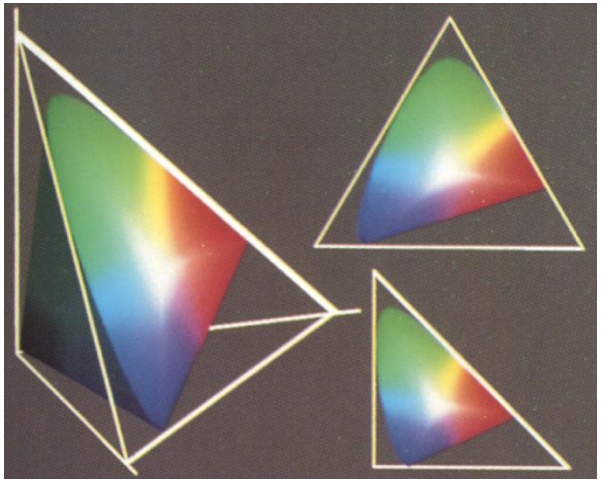


Foley et al. 1990

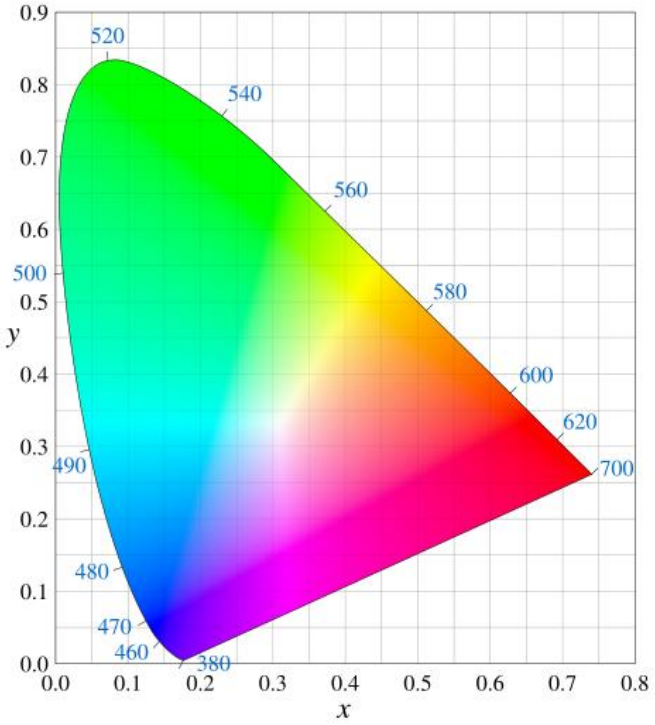
CIE Chromaticity Diagram

- 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 curved boundary



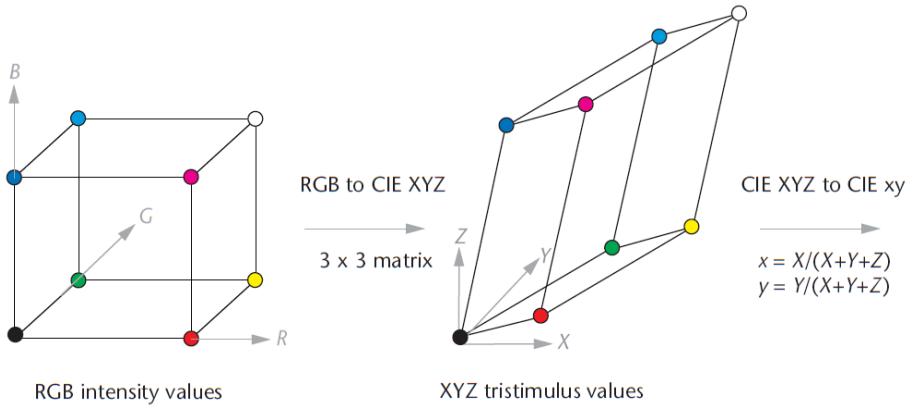


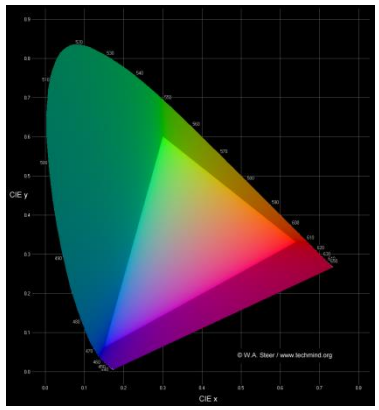
Foley et al. 1990



RGB and XYZ

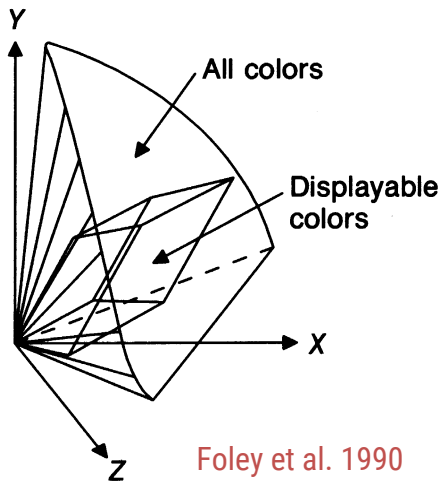
- RGB to XYZ conversion





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

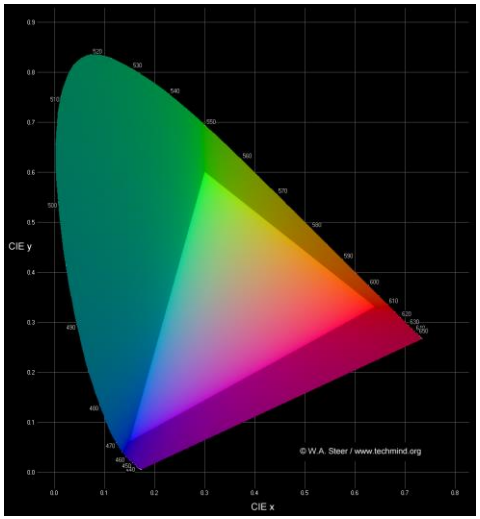
- RGB space: distorted cube
- black: origin of XYZ and projection center
- RGB projected to triangle



Foley et al. 1990

Can RGB Represent All Visible Colors?

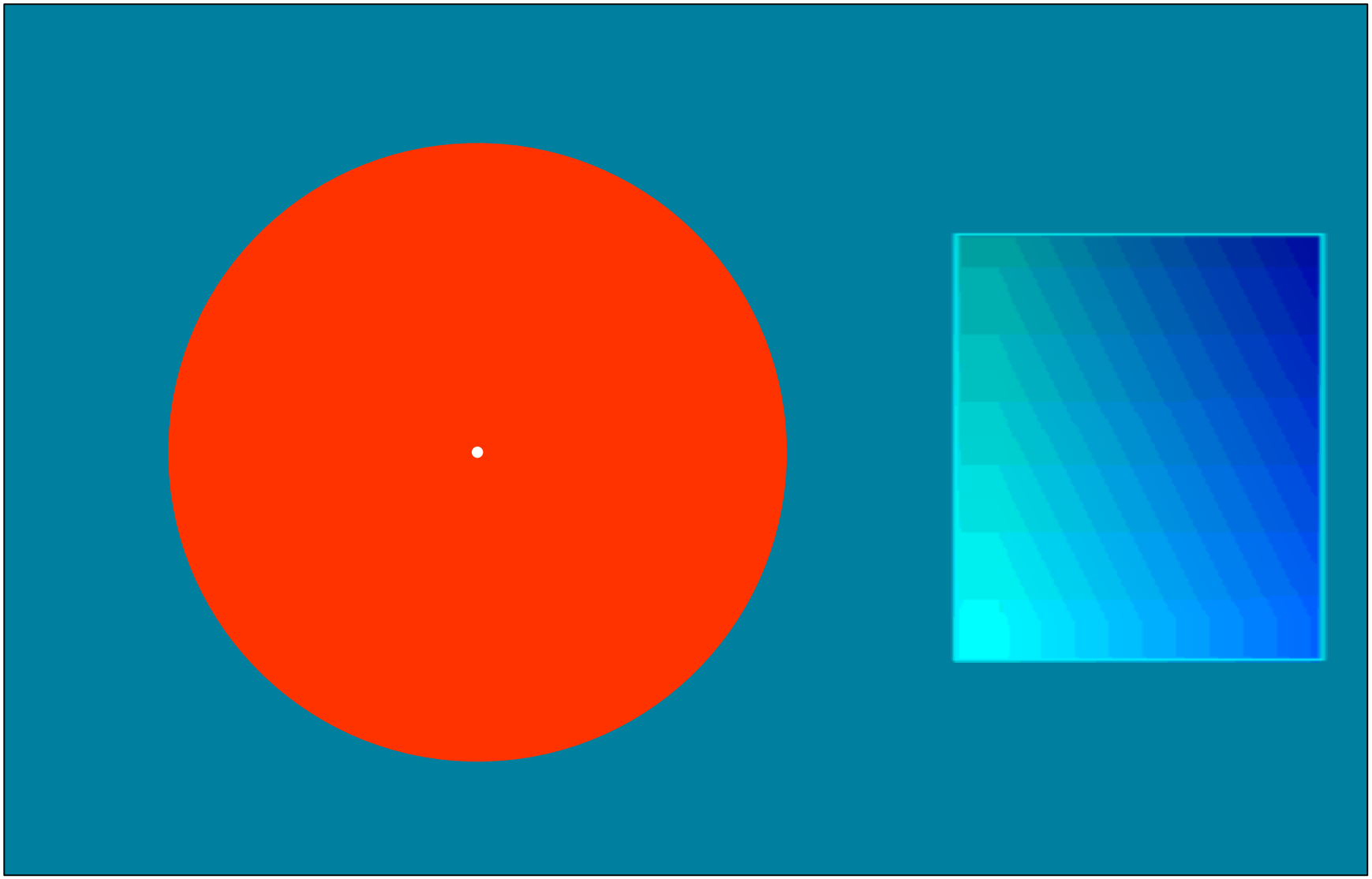
- no, because all colors form horseshoe shape in CIE chromaticity diagram and RGB gamut is triangular



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 …



THE STRANGE WAYS WE EXPERIENCE COLOR…

Color Perception → **Color Naming**

What color is this?

"Yellow"

Color Perception → **Color Naming**

What color is this?

“Blue”

Color Perception → **Color Naming**

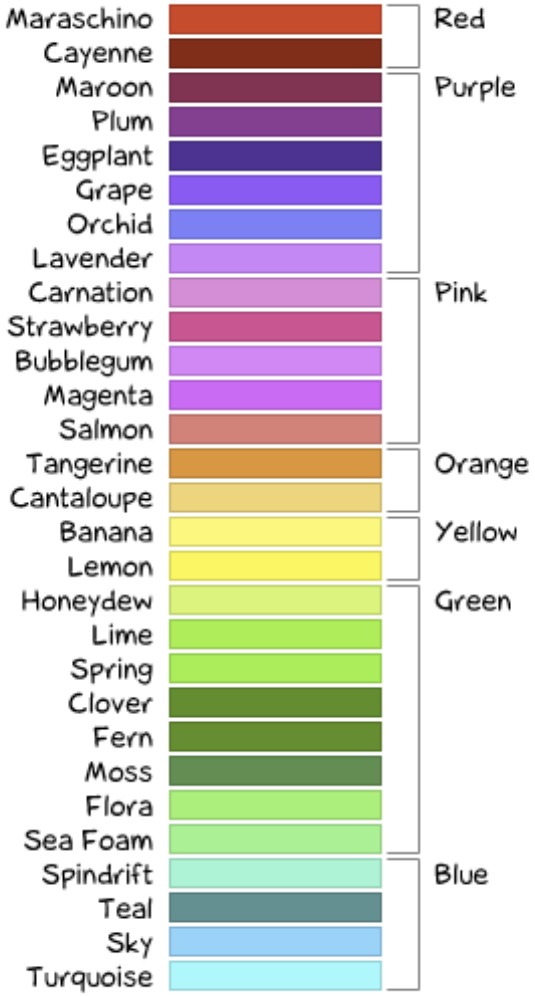
What color is this?

"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

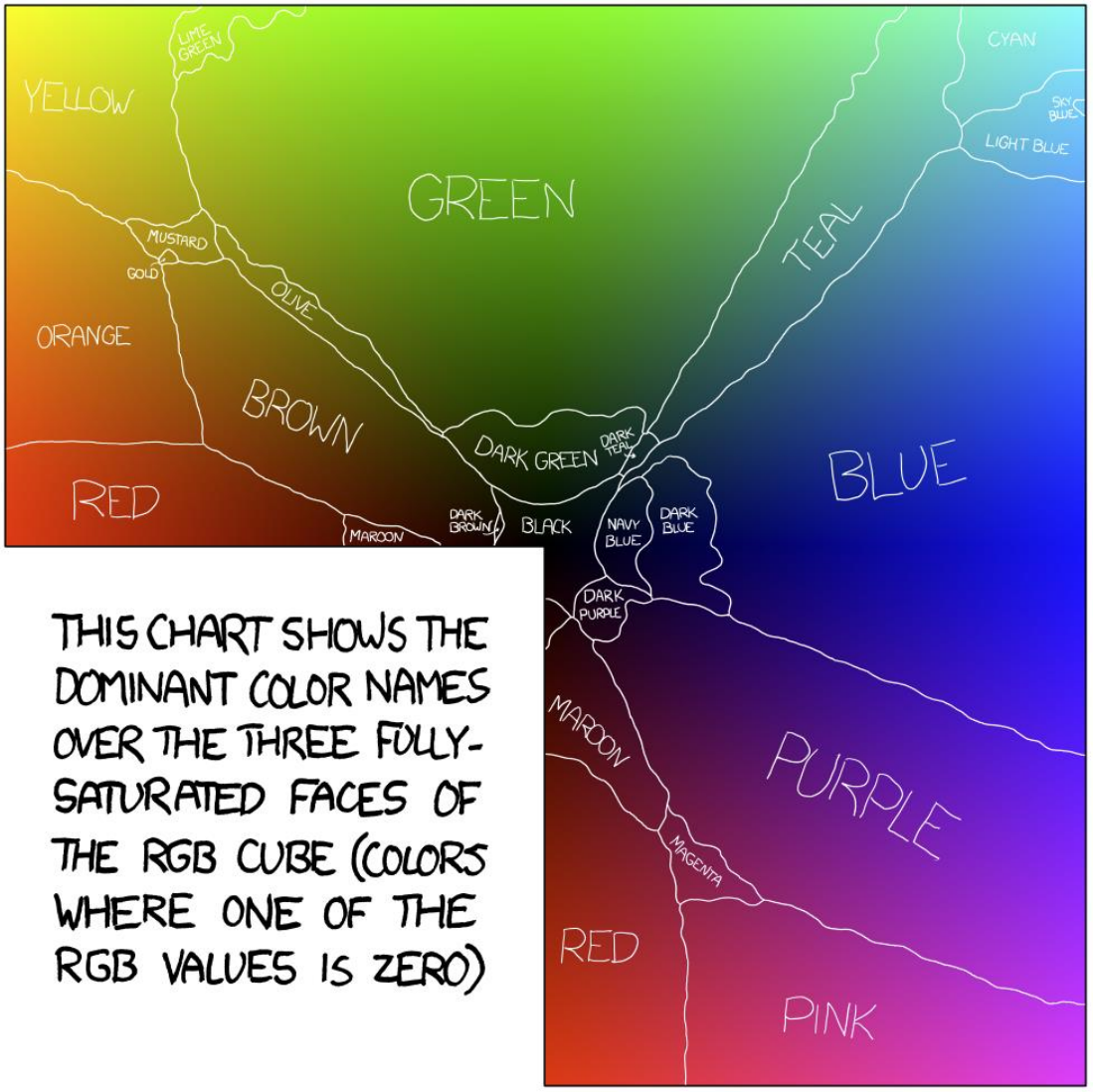
http://blog.xkcd.com/2010/05/03/color-survey-results/

Color according to XKCD

Color Naming

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

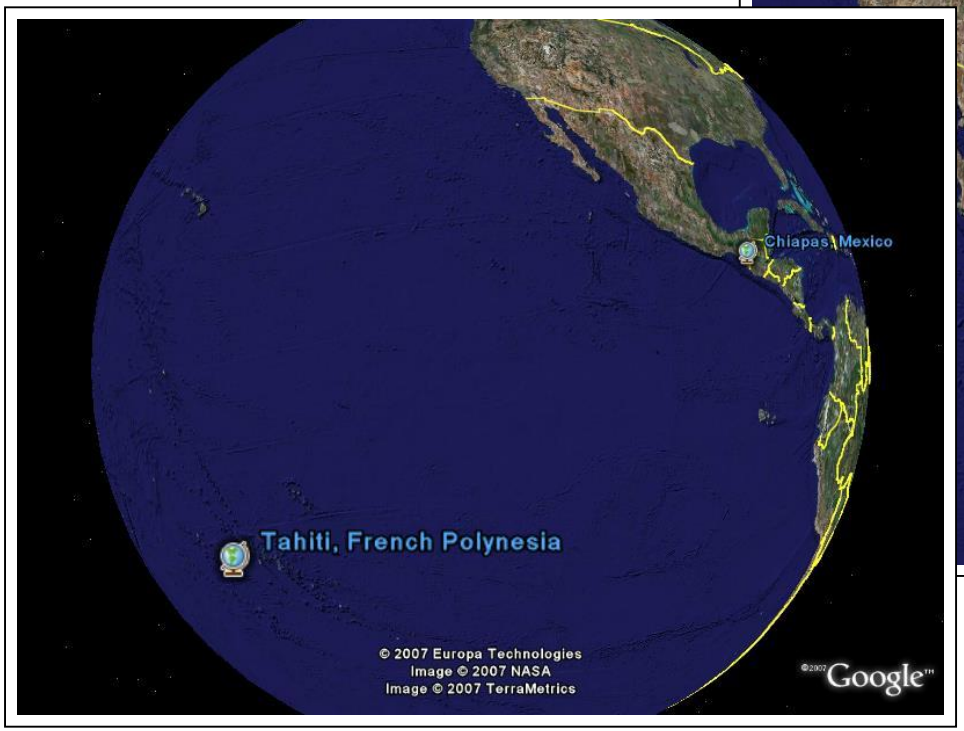
Are there natural boundaries?



xkcd

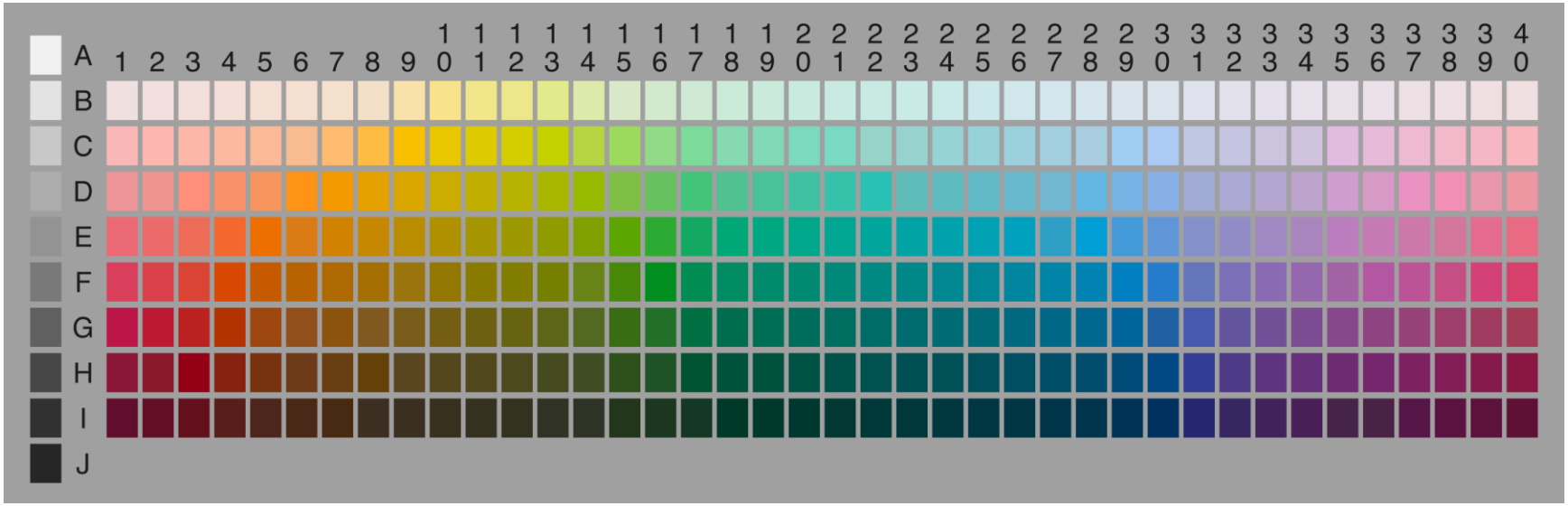
Basic Color Terms

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



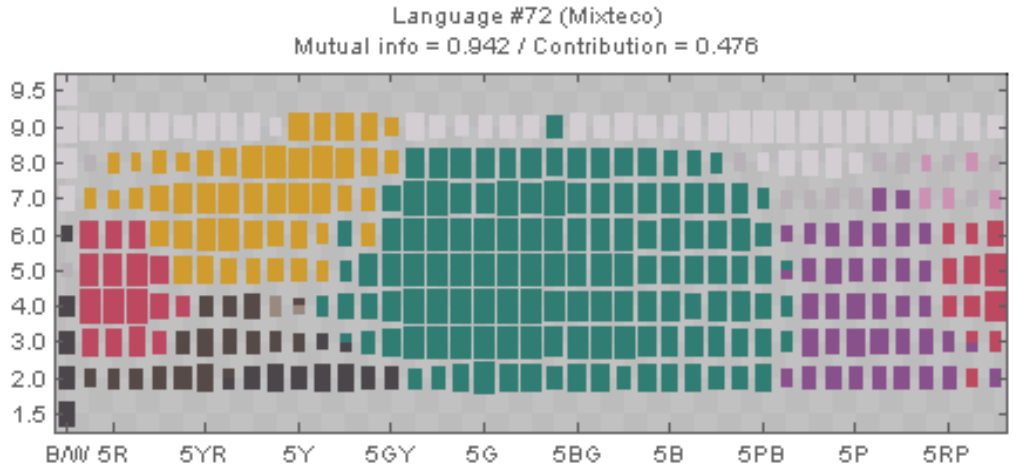
World Color Survey

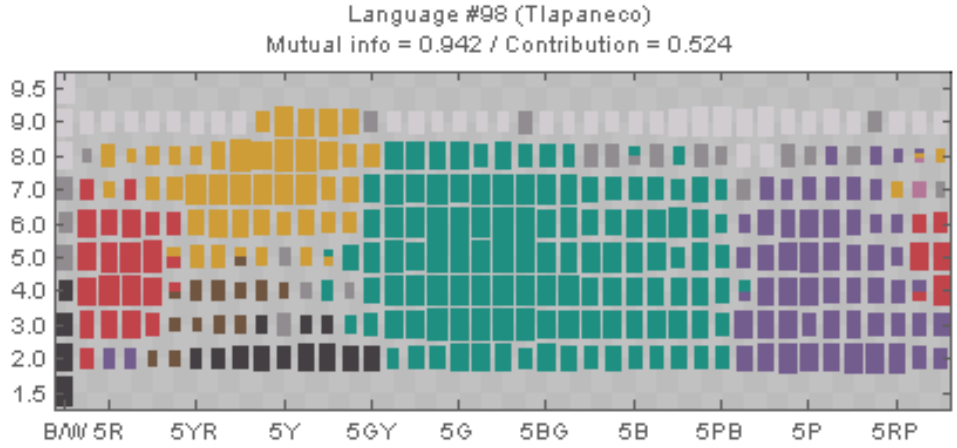
Surveyed 2616 speakers of 110 languages using 330 different color chips



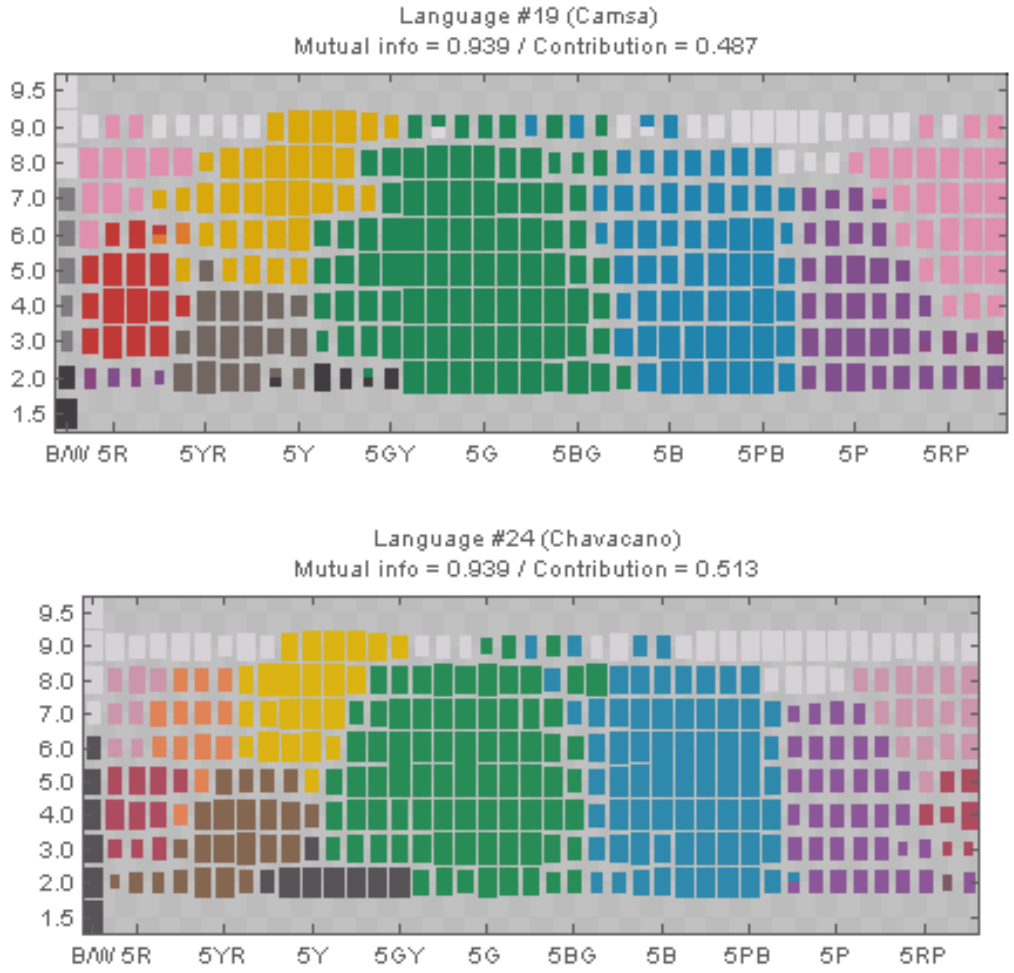
see also: http://wals.info/feature/132A?tg_format=map#2/32.5/153.5

Results from WCS (Mexico)





Results from WCS (South Pacific)

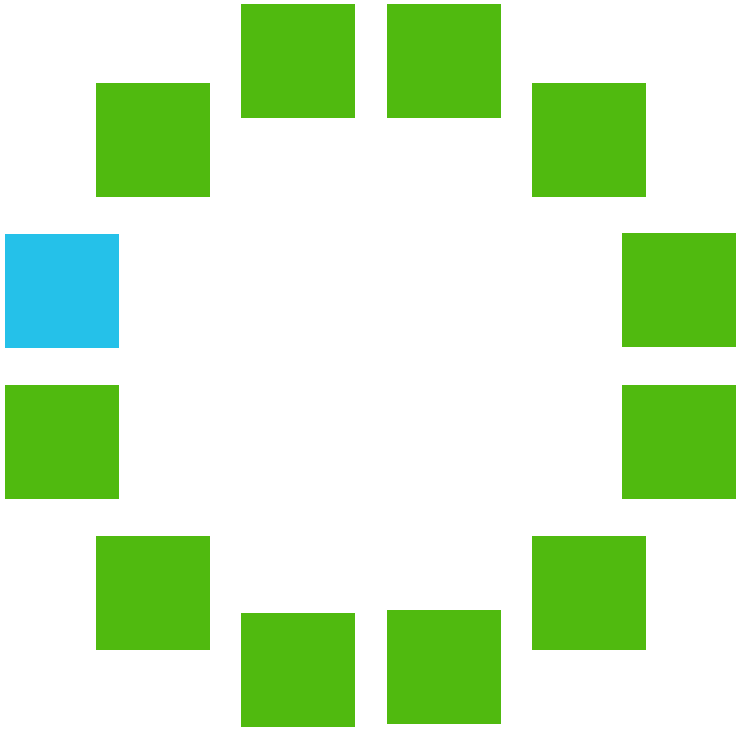


But language-color interaction

- 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?

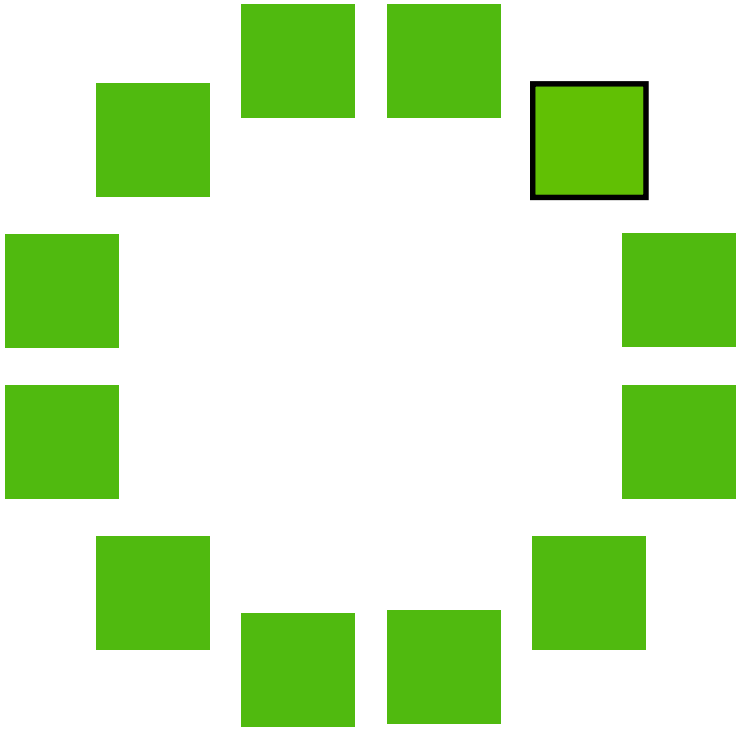


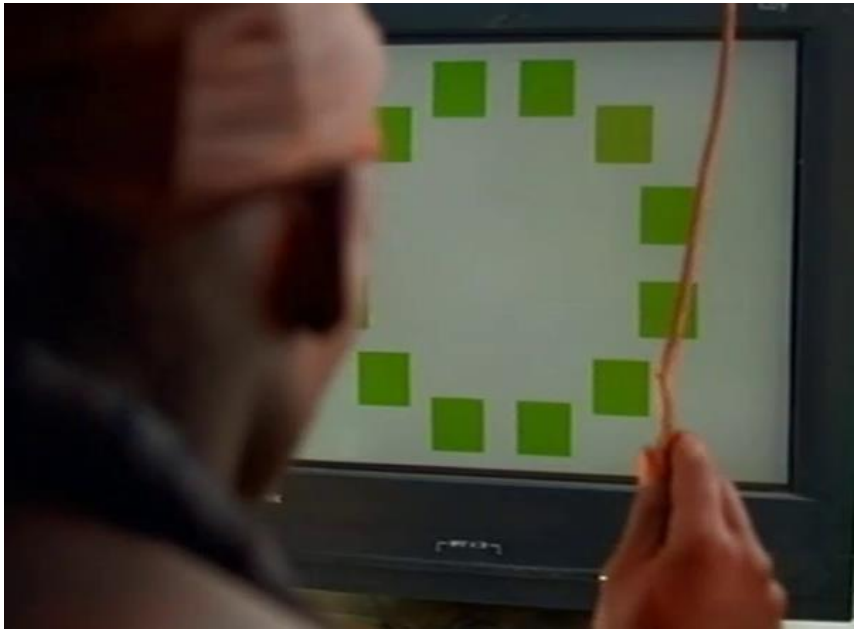
© BBC

difficult to impossible for Himba people

But language-color interaction

- experiment: how long to find a differing color?

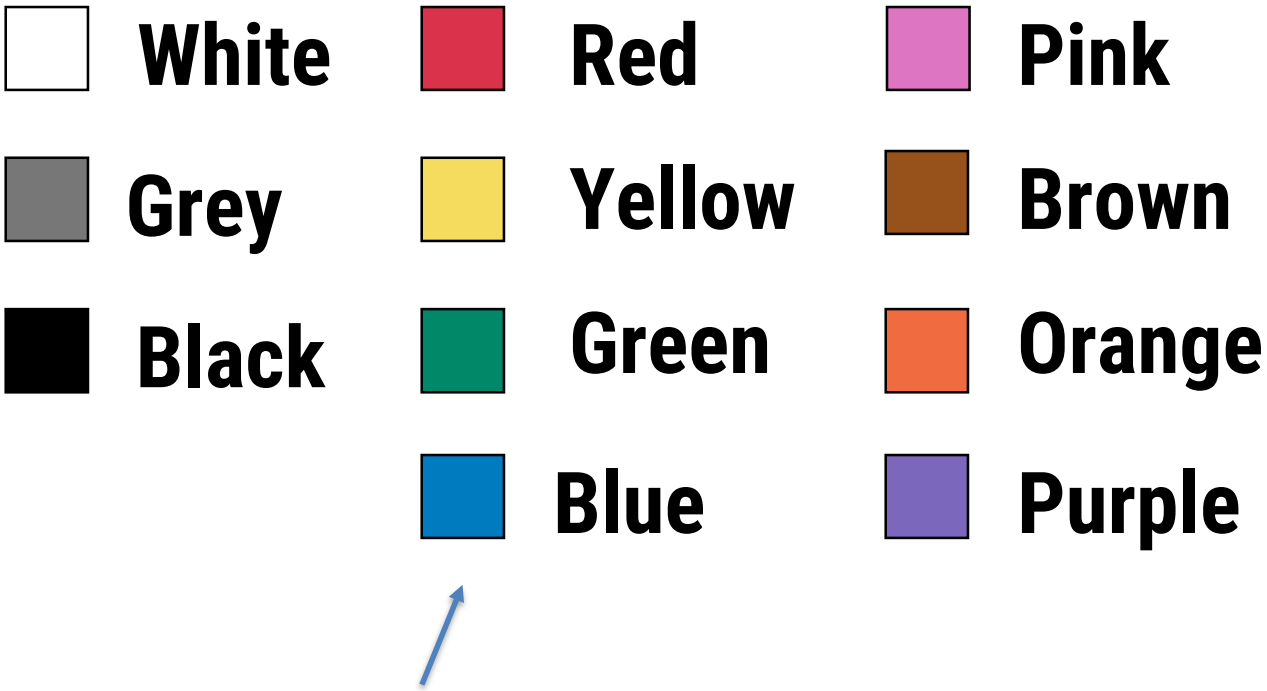




easy for Himba people: different words for both types of green

Universal (?) Basic Color Terms

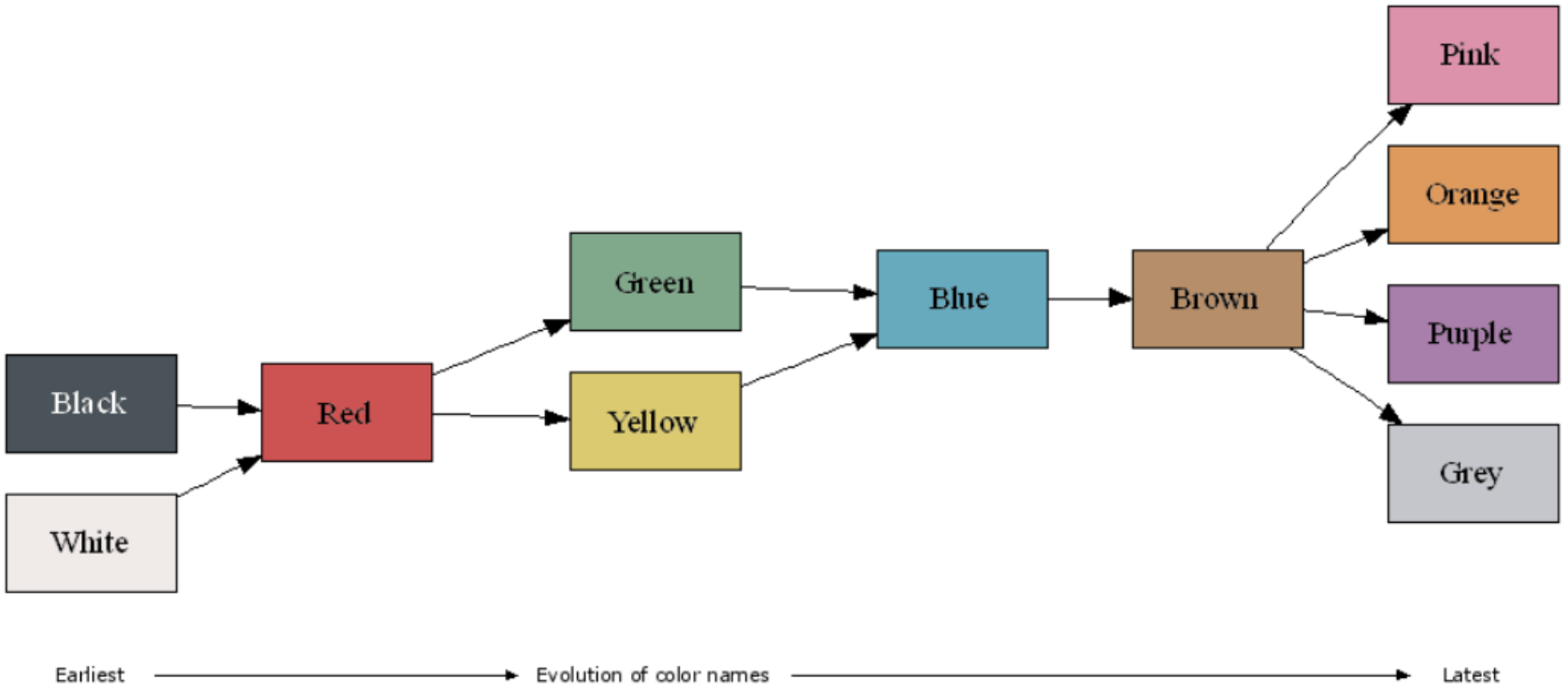
Basic color terms recur across languages



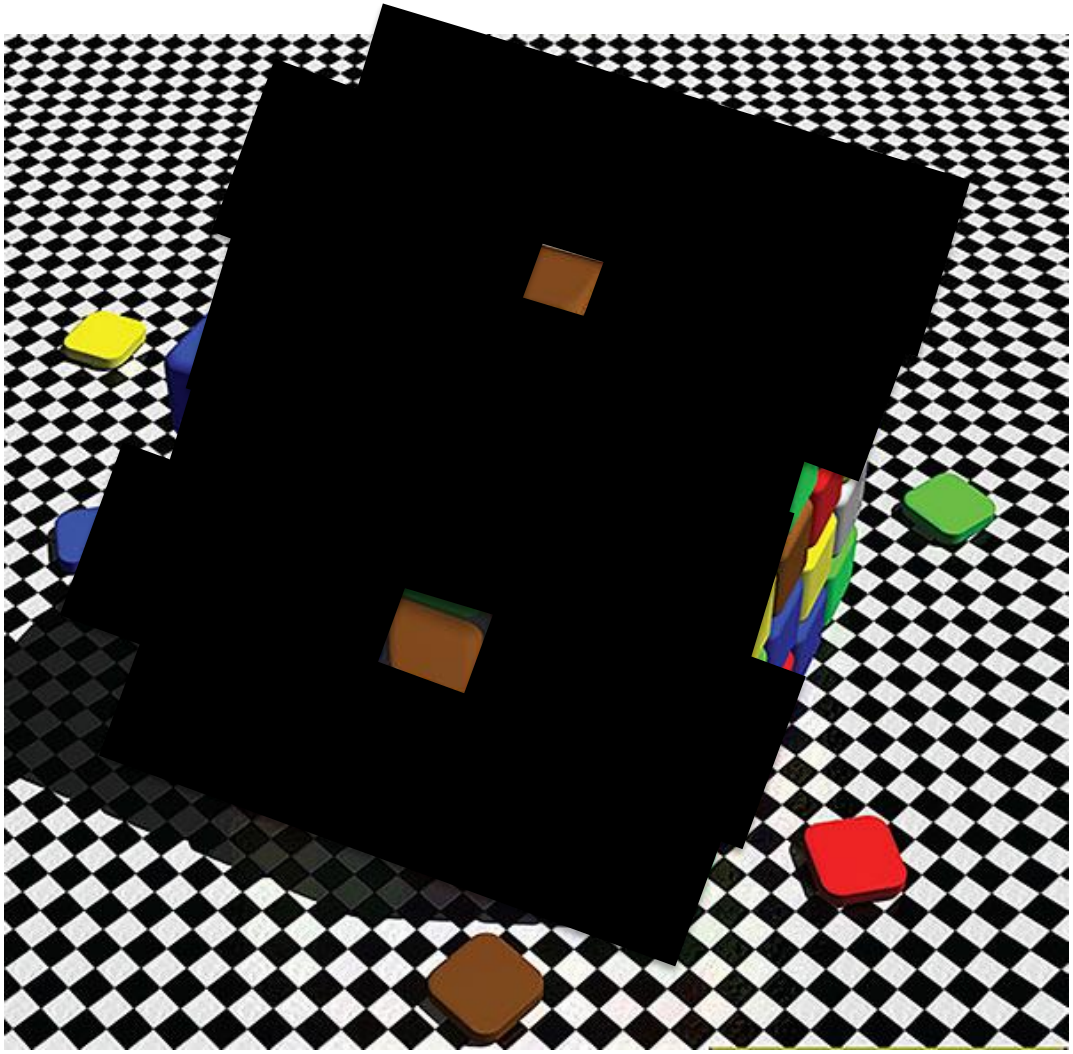
Interesting factoid: Cartographers found out that they need 4 unique hues to unambiguously distinguish all areas on an arbitrarily complex map

Evolution of Basic Color Terms

Proposed universal evolution of color names across languages.



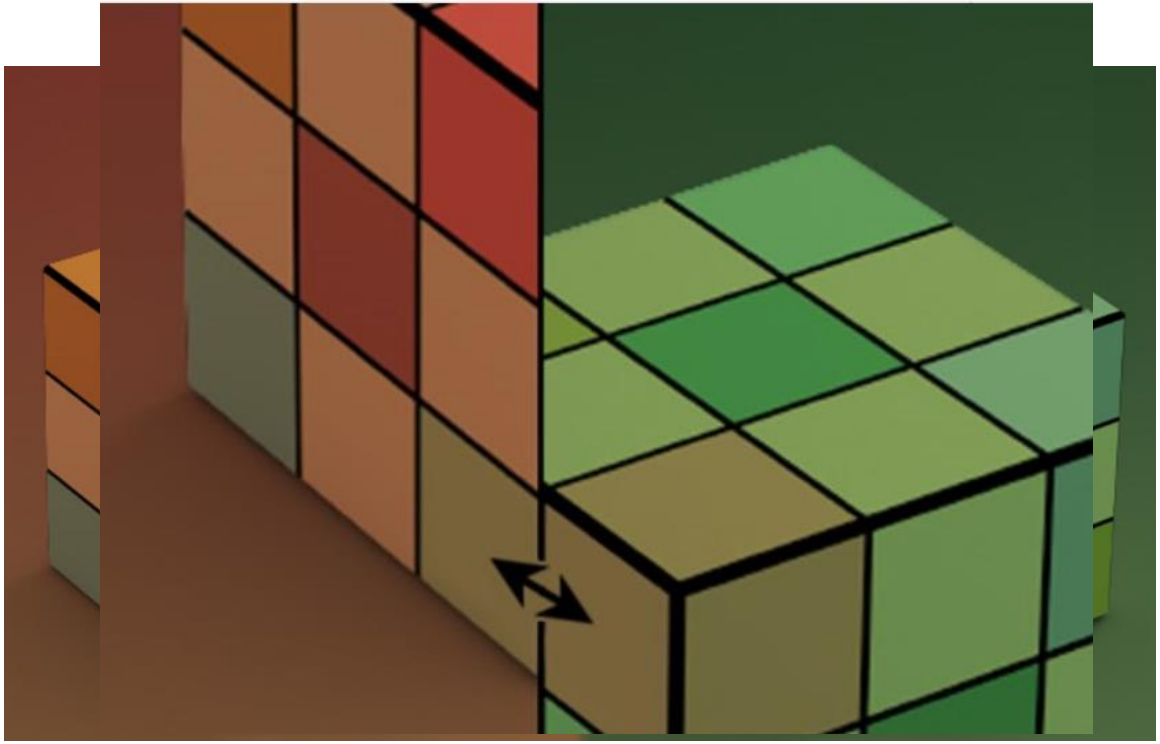
Some other color usage problems



This one is called COLOR CONTRAST: the same spectral input can appear as a different color

Color Constancy

- Background color and lighting have a big effect on how we see color
- Two different color spectra may look identical



CONCLUSION

- Color vision (just like brightness) does not correspond to physical measurements

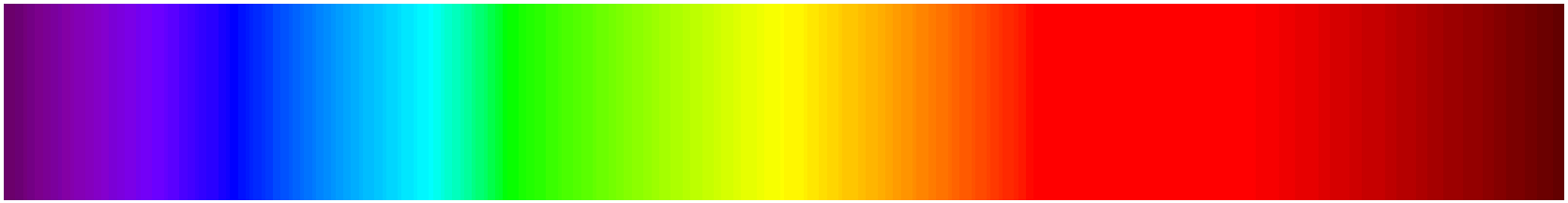
- Be mindful in how you apply color in your computer-generated scenes!

COLOR FOR VISUALIZATION

Why are color choices important?

Example: The Rainbow Color Scale

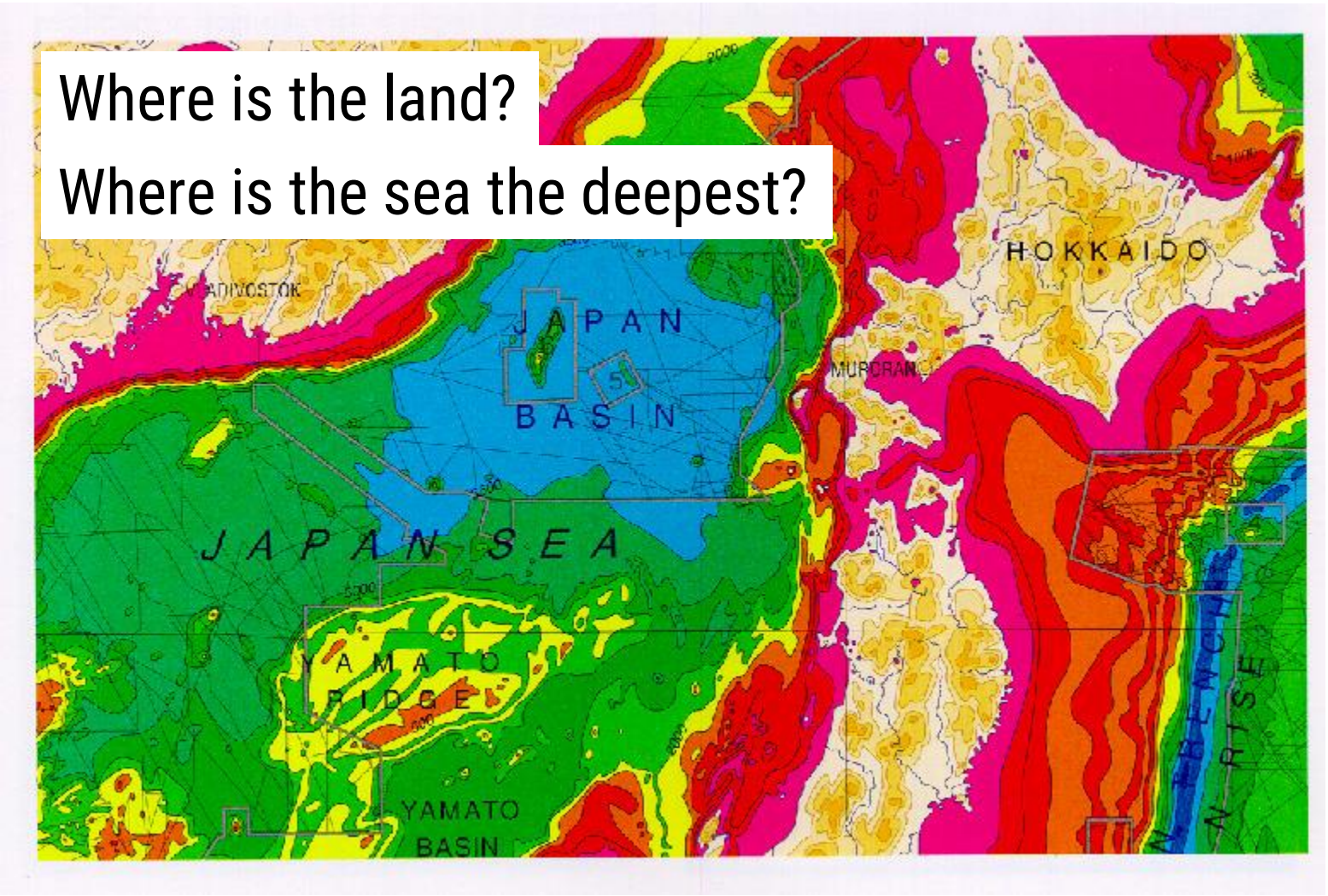
- Represent data by varying hue across (approximately) the full range of visible wavelengths
- One of the most common color scales in use today



And it's (usually) a huge mistake!

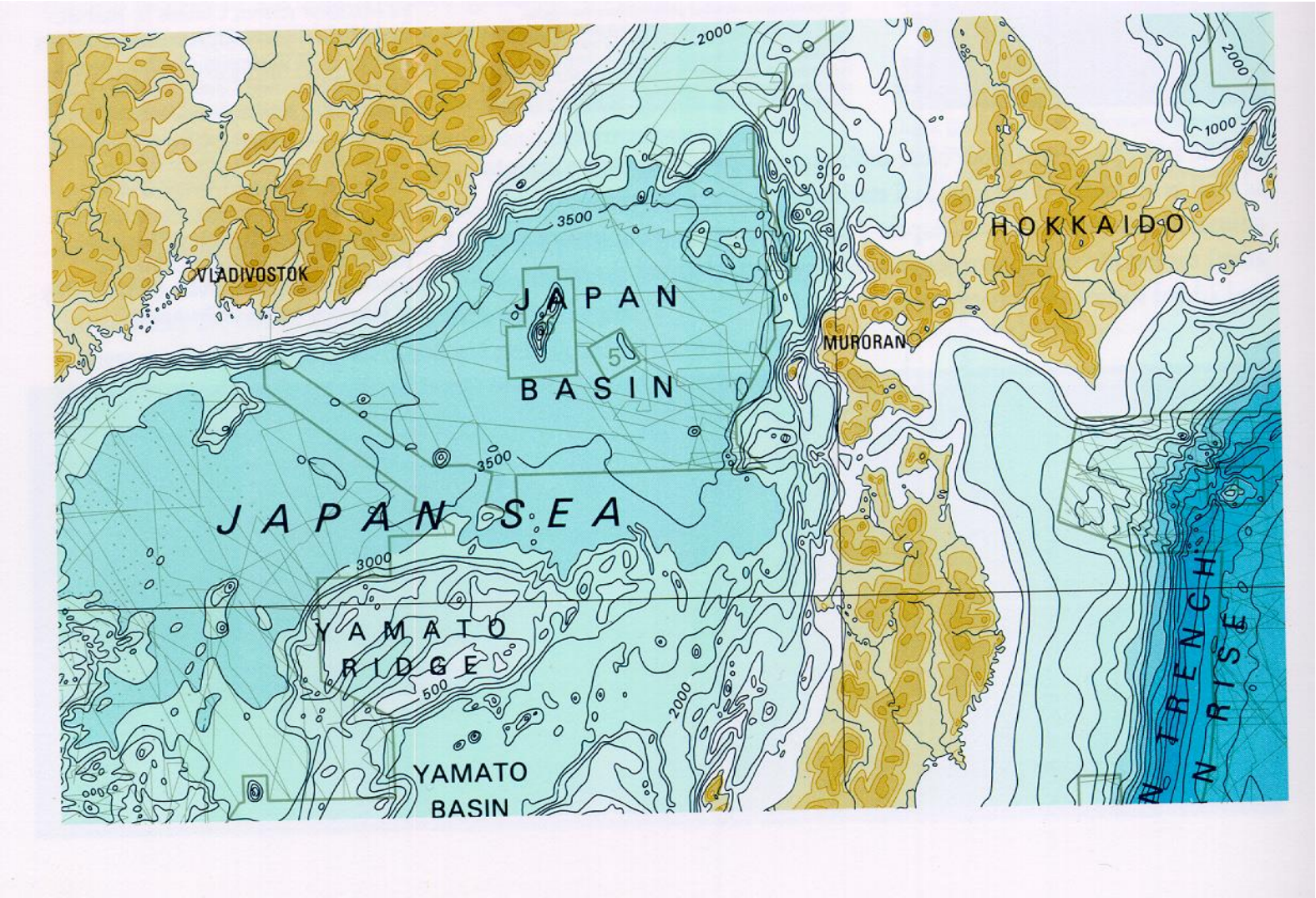
General Bathymetric Chart of the Ocean

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

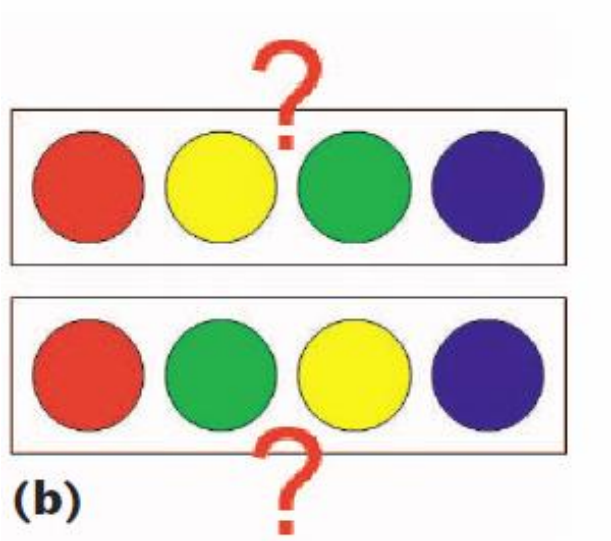


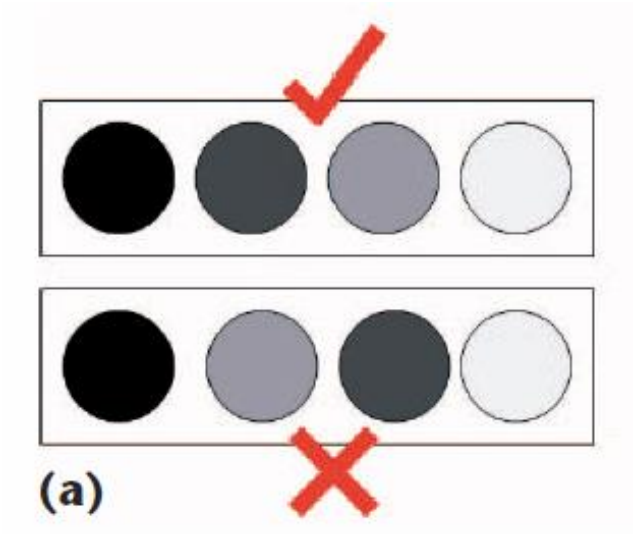
General Bathymetric Chart of the Ocean

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

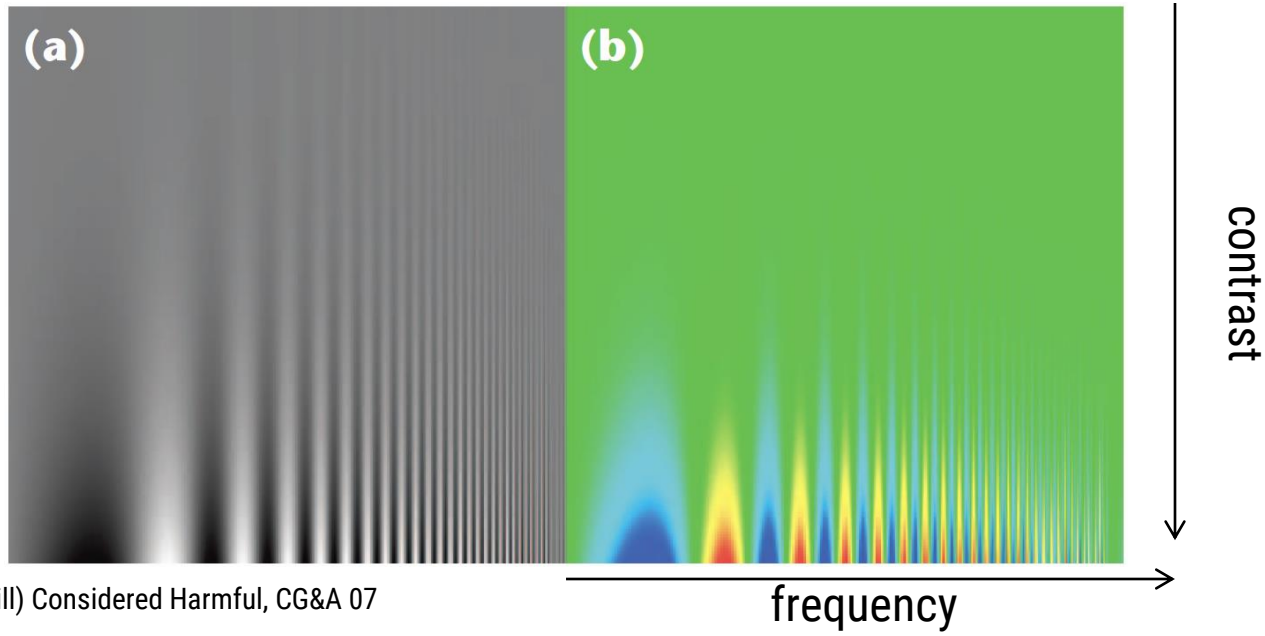
- Increases luminance (value) from dark to light
- Is perceptually ordered

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

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

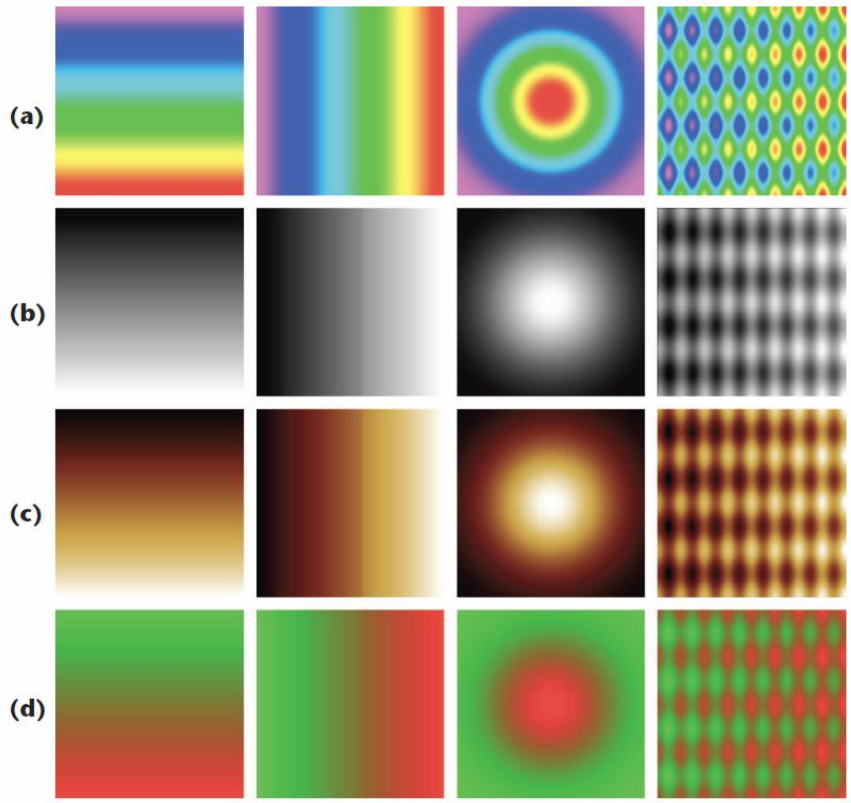


From: Rainbow Color Map (Still) Considered Harmful, CG&A 07

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

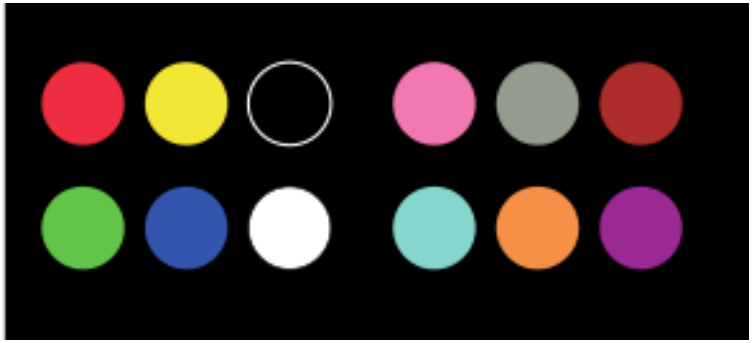
isoluminant green-red scale

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

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

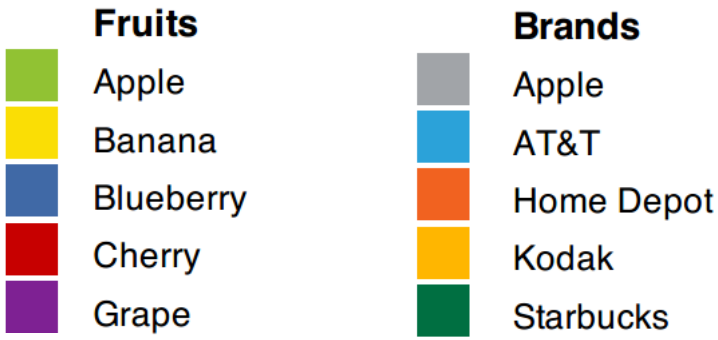
Using Color to Label

(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

CONTRAST

You can make this work if you consider value

CONTRAST

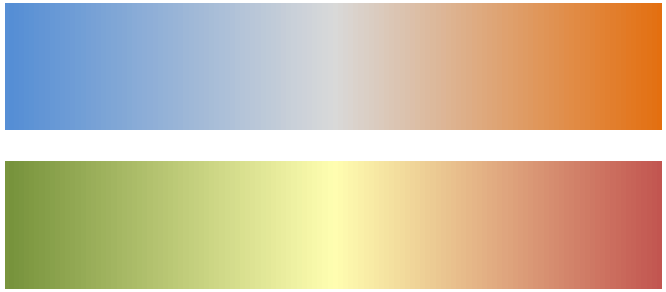
Using Color for Scales

(For ordinal or quantitative data)

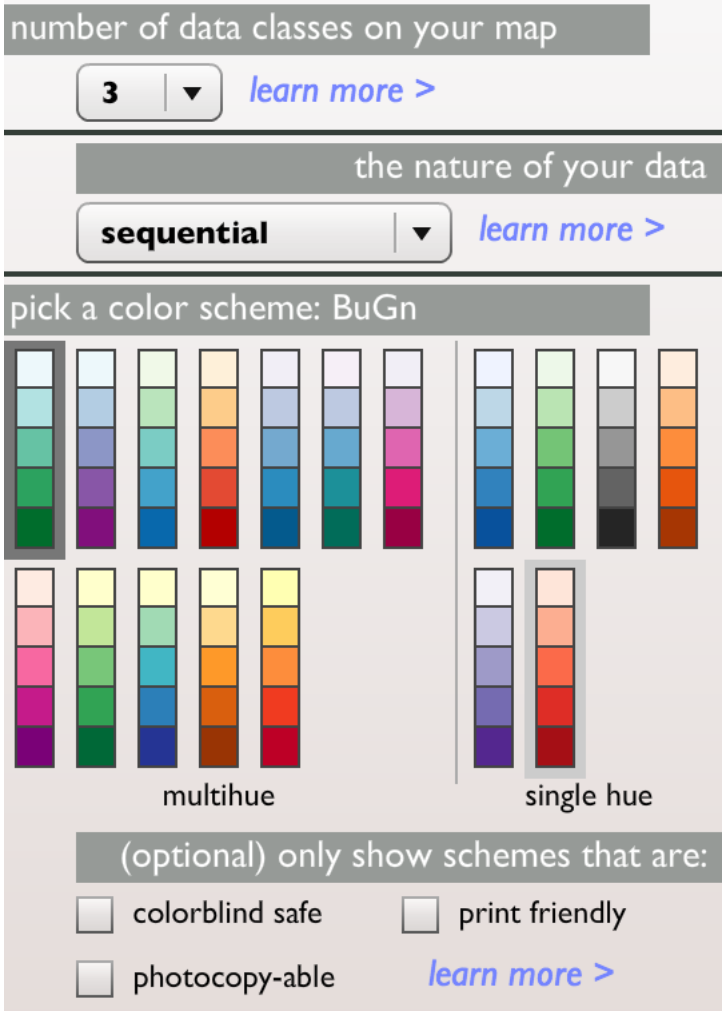
Use a scale that varies **lightness** in addition to color

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



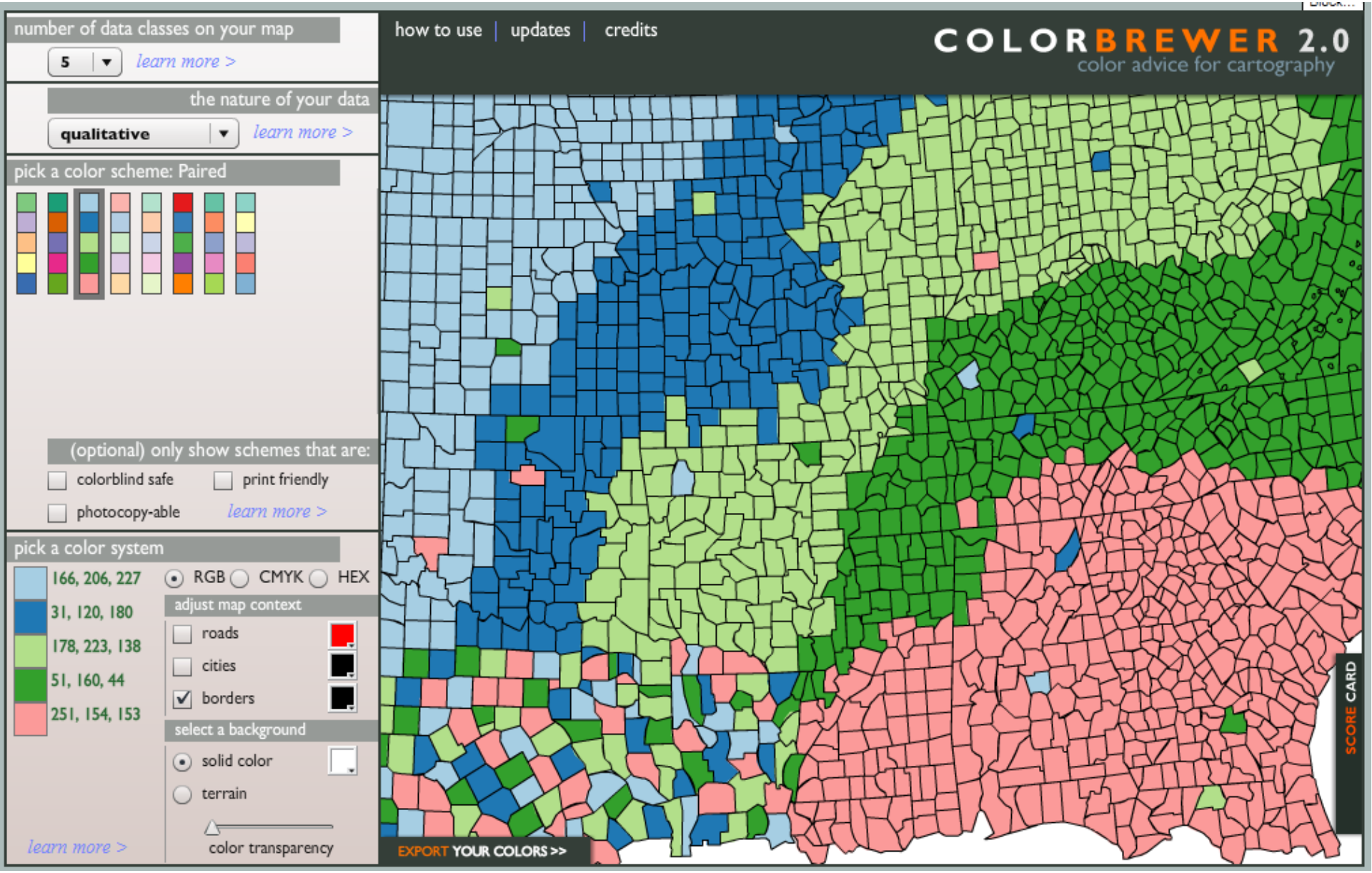
ColorBrewer



Highly recommended!

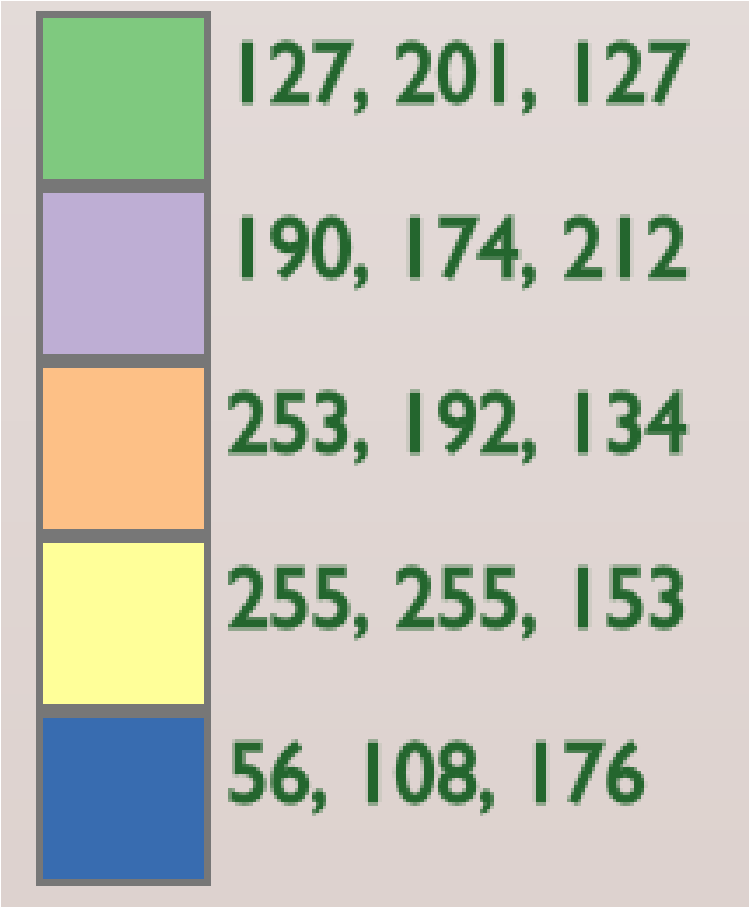
Designed originally for maps but will also work well for other types of visualizations

http://colorbrewer2.org/

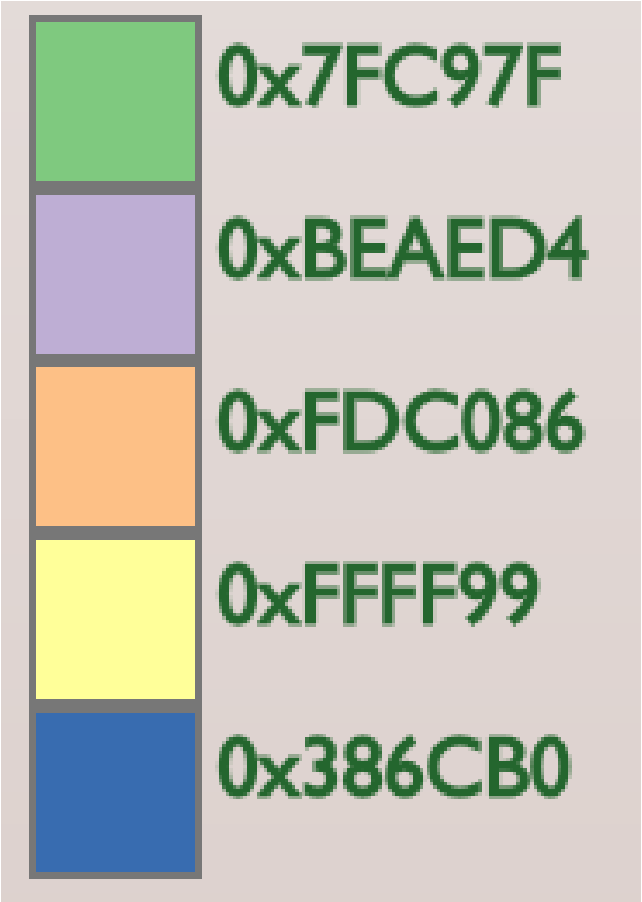


http://colorbrewer2.org/

ColorBrewer

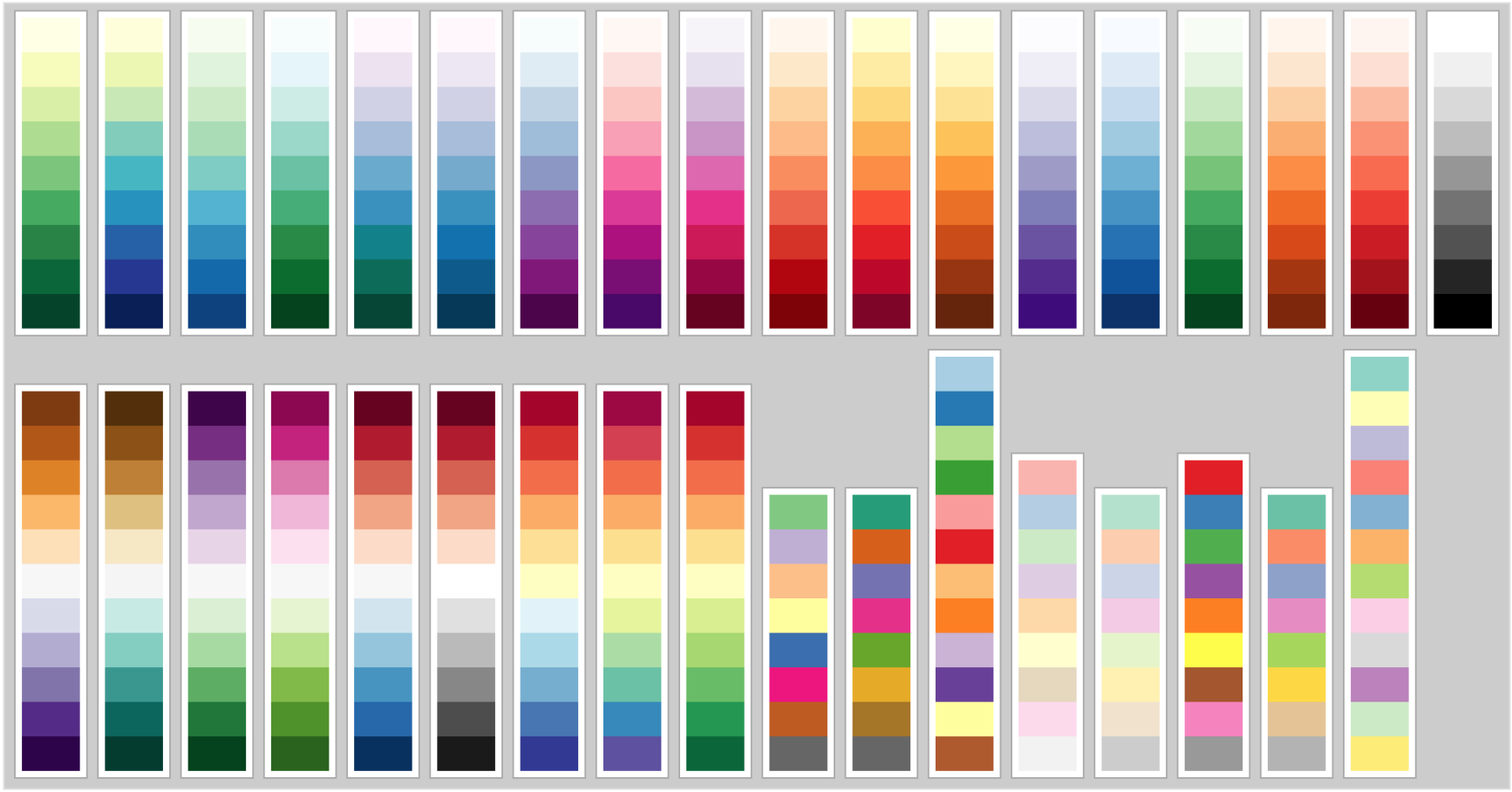


(RGB)



(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

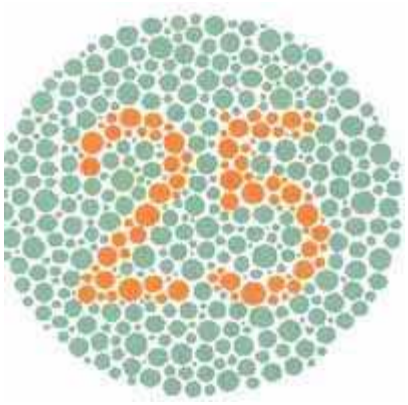
vormal color vision

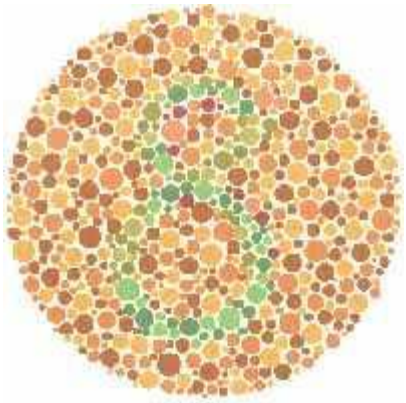
simulation of color contrast
for deuteranopic color vision
(green receptors absent)

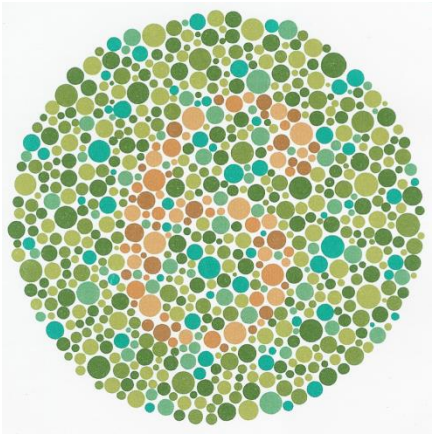
approx. 7% of male population color-deficient

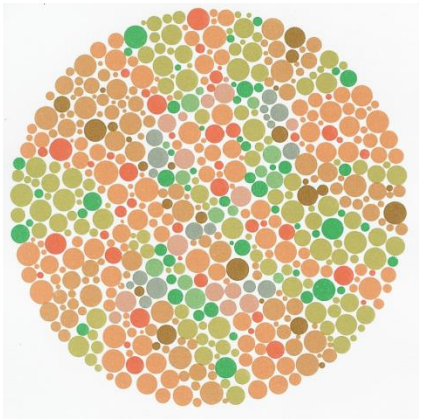
mostly red-green color deficiency (deuteranopia or protanopia) – but other forms exist as well

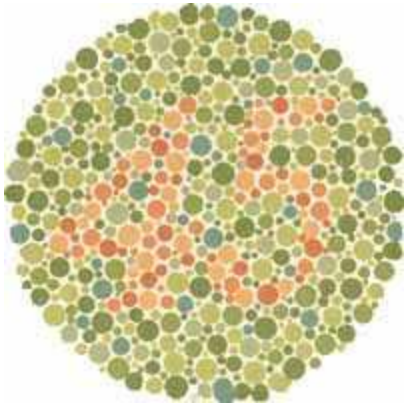
Color Deficiency Test (Ishihara Test)

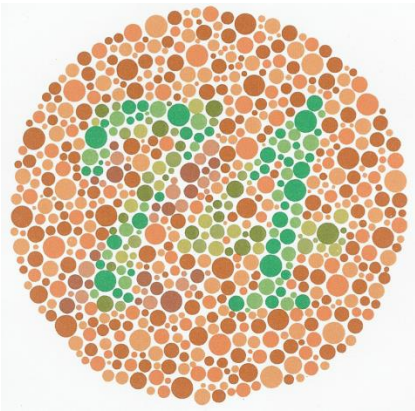






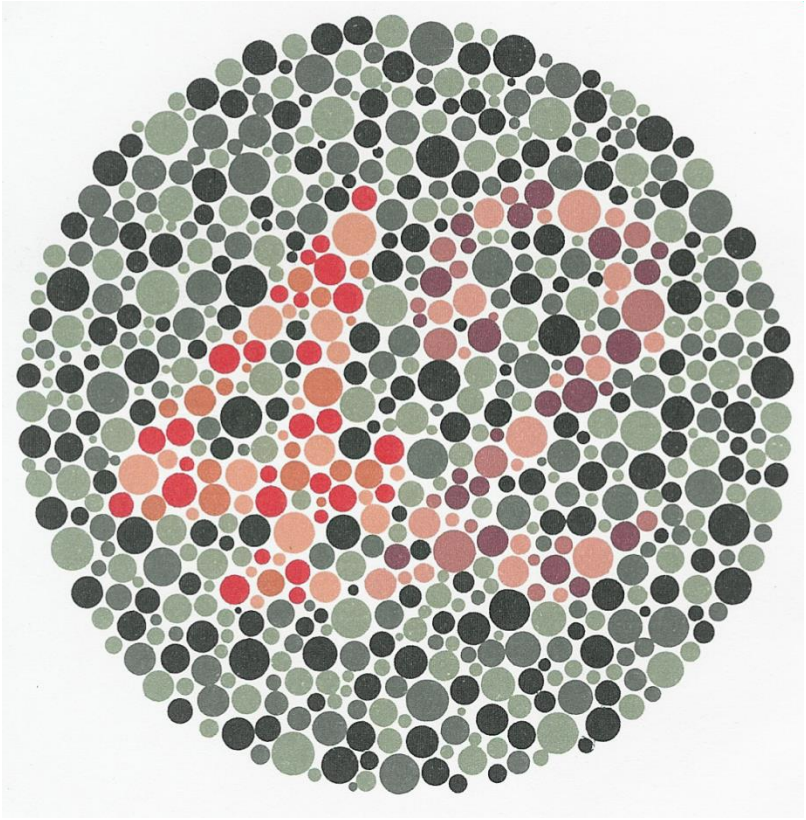


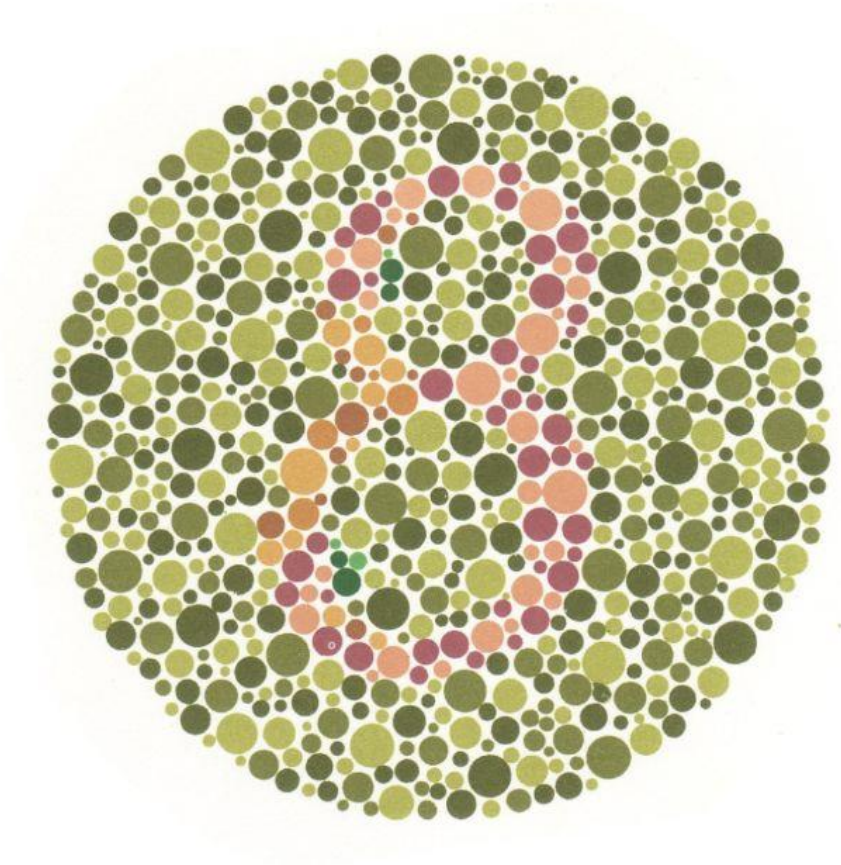




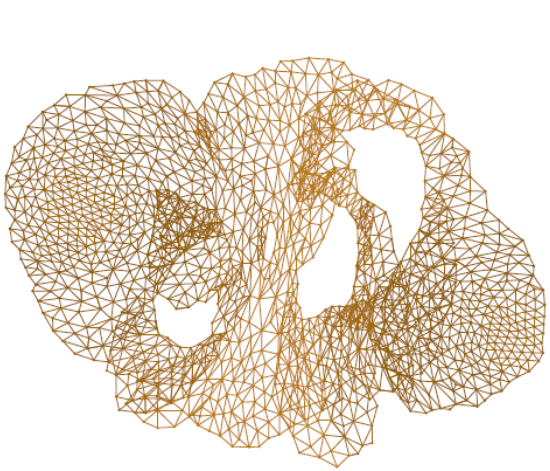
This likely won't work correctly here given the uncalibrated projector

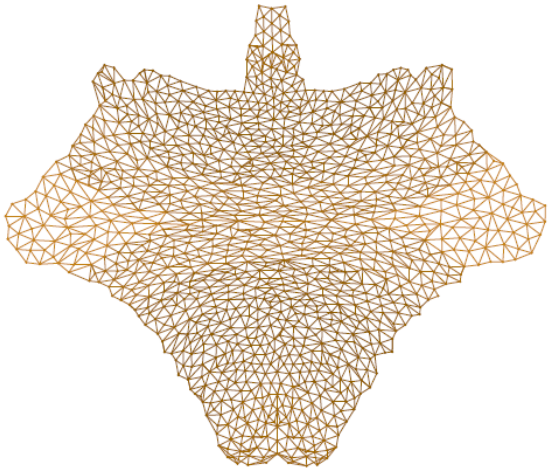
Color Deficiency Test

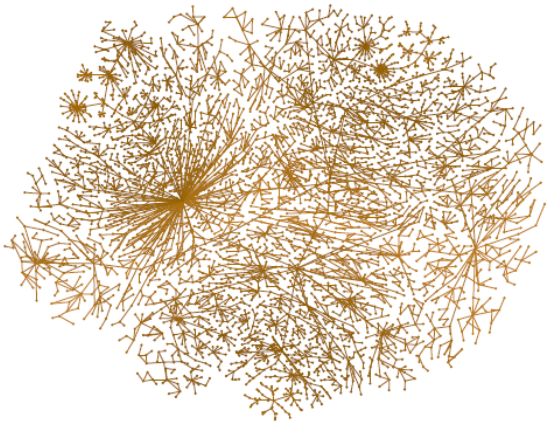


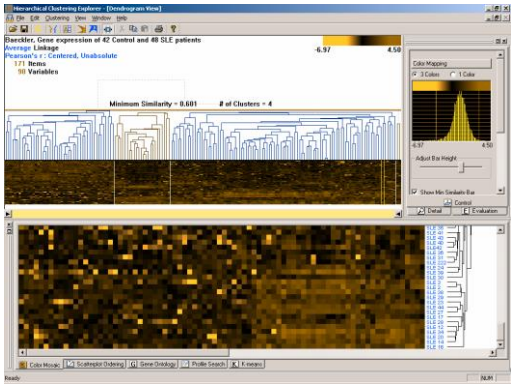


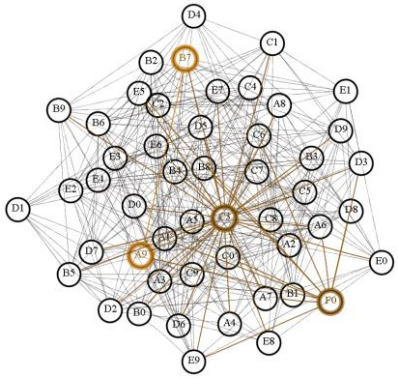
Examples from VIS/InfoVis 2004

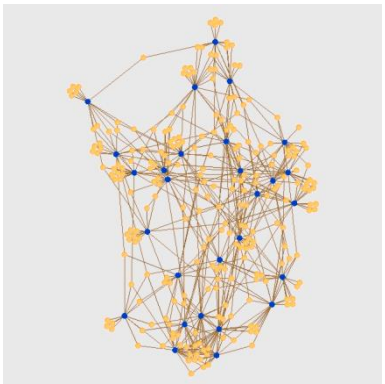




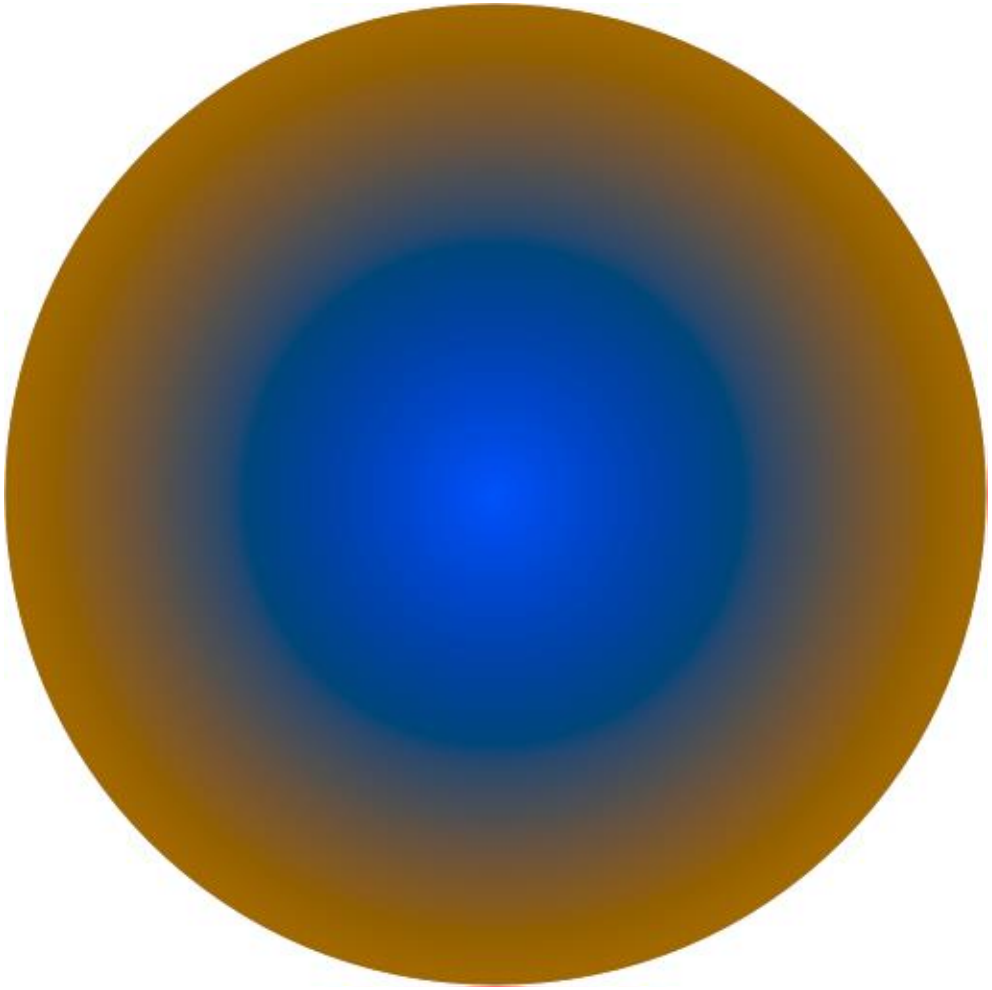






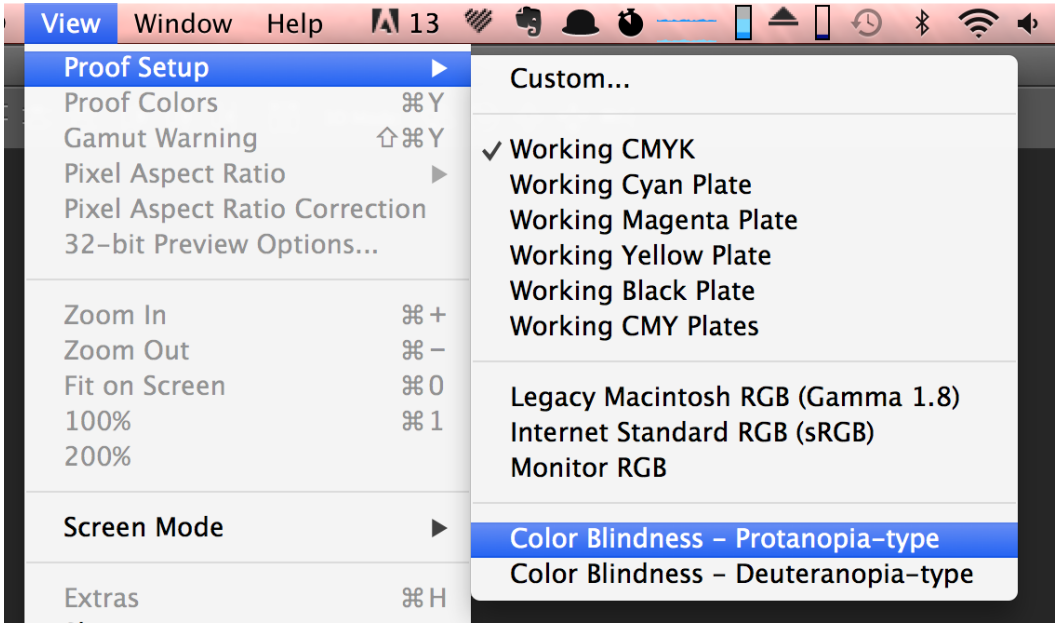


Better: Red-Blue Contrast



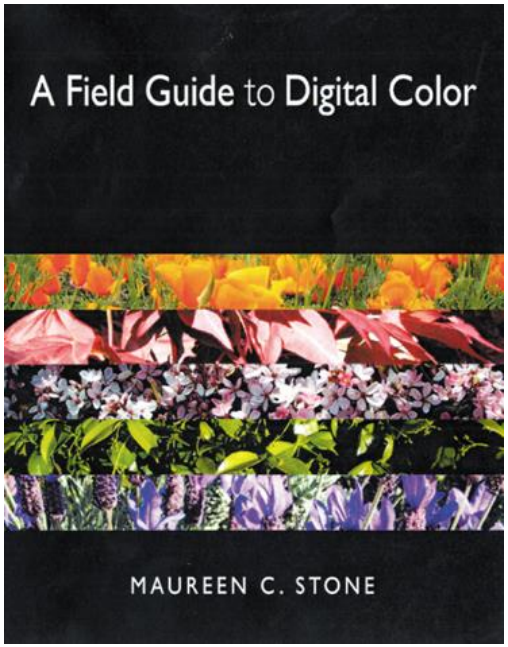
Check Your Visualizations!

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/

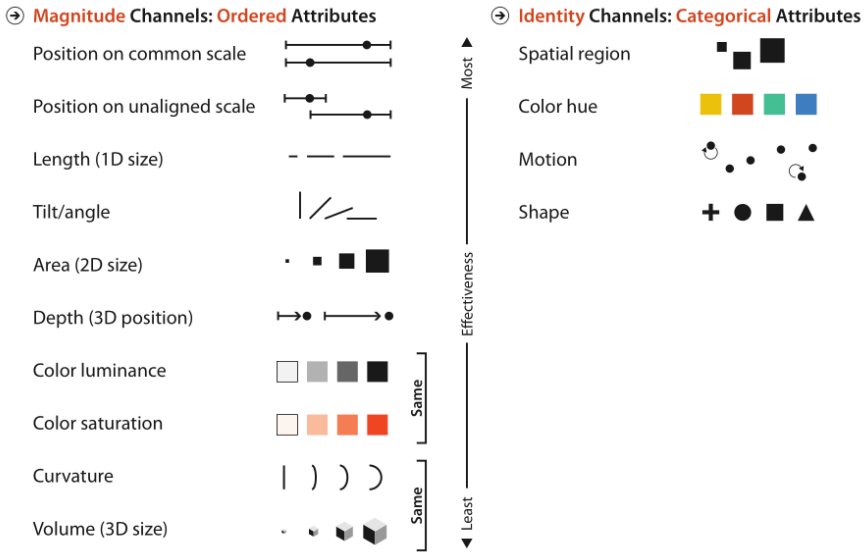
RadioLab “Colors”

WNYC Podcast

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

EFFECTIVENESS OF 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

how close is human perceptual judgement to some objective measurement of the stimulus?

1) ACCURACY

Elementary Graphical Perception Tasks

William S. Cleveland (1980s)

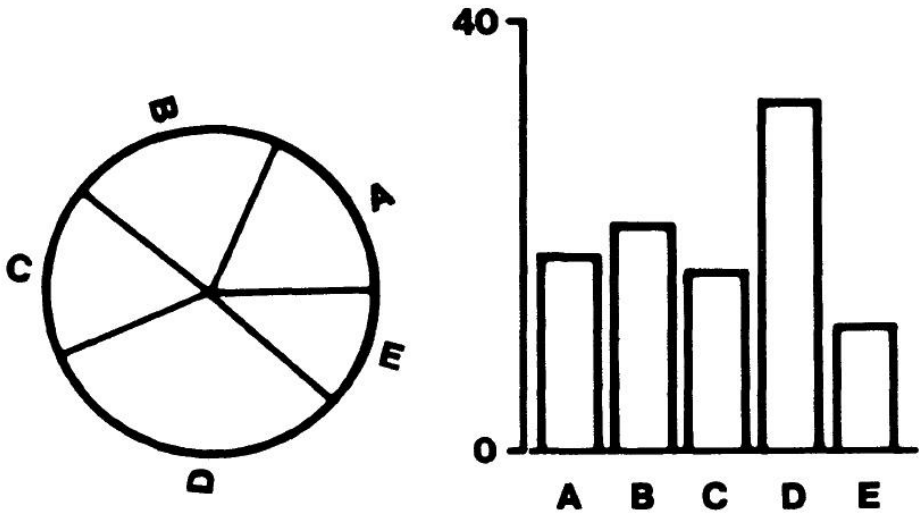


Figure 3. Graphs from position–angle experiment.

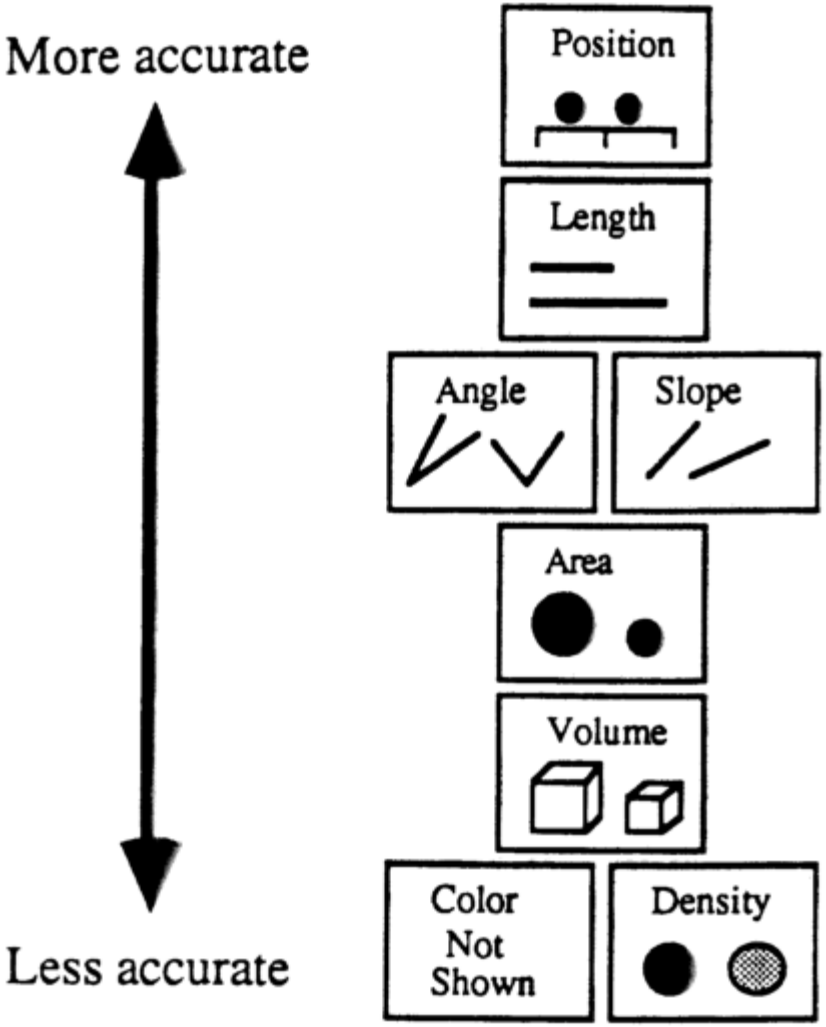
Performed **controlled experiments** to determine how effectively people could judge **changes in visual features**

Focus on **quantitative information**

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

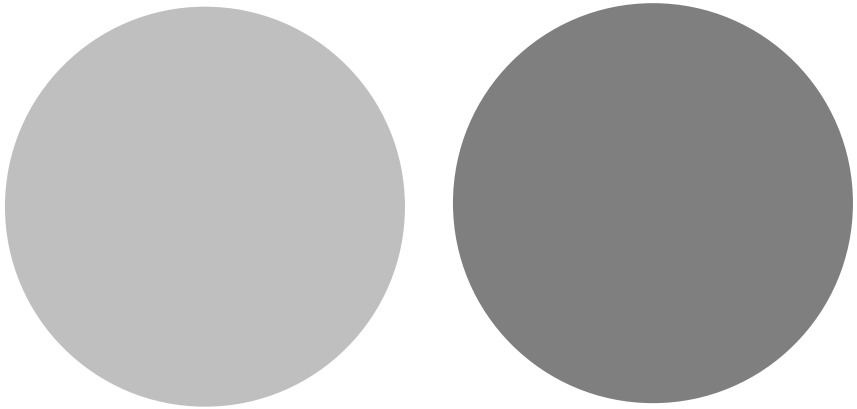
Elementary Graphical Perception Tasks

William S. Cleveland (1980s)



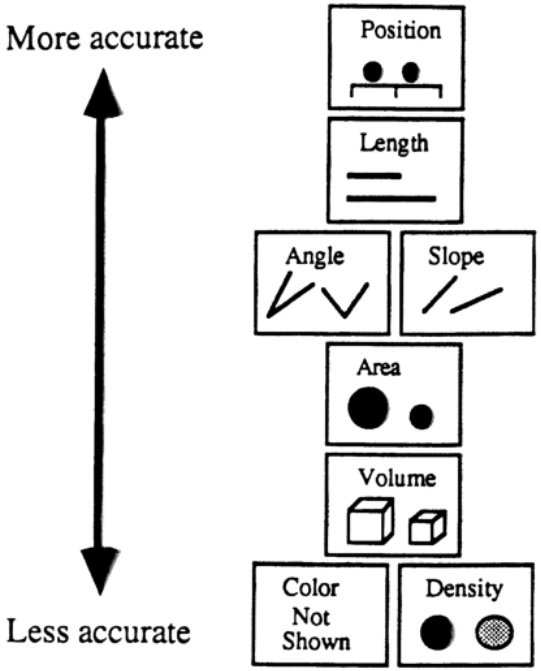
Color Value

What percentage in
value is the right from the left?



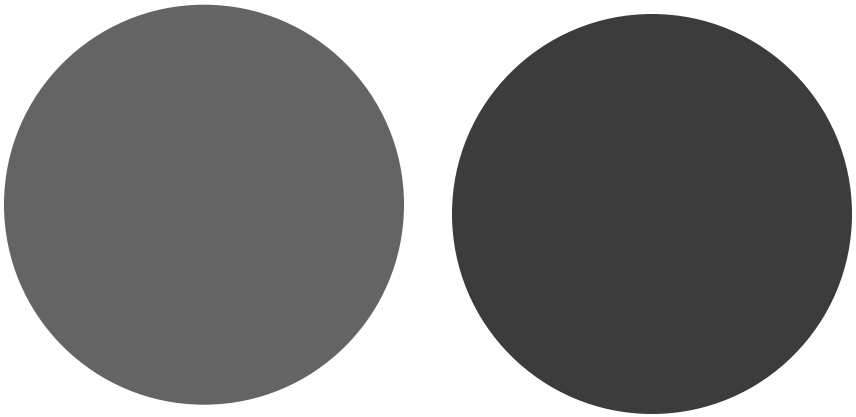
100%

66%

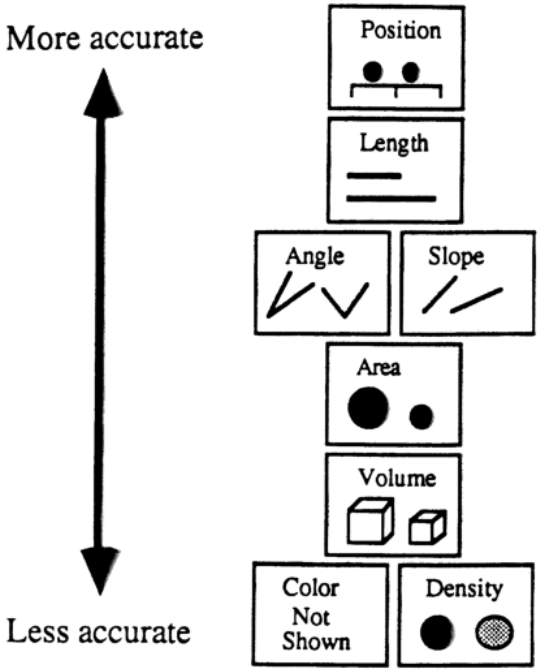


Color Value

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

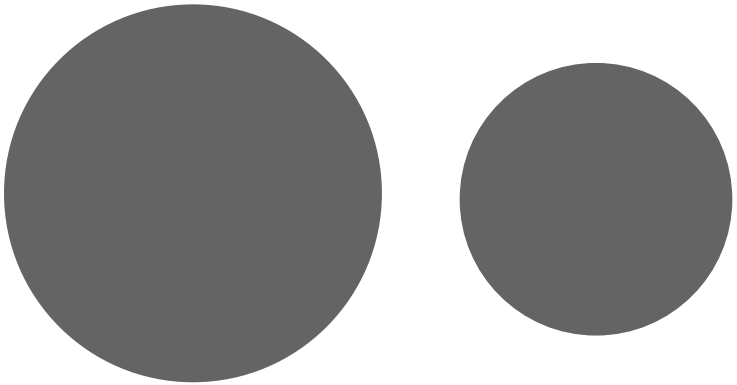


100% 60%



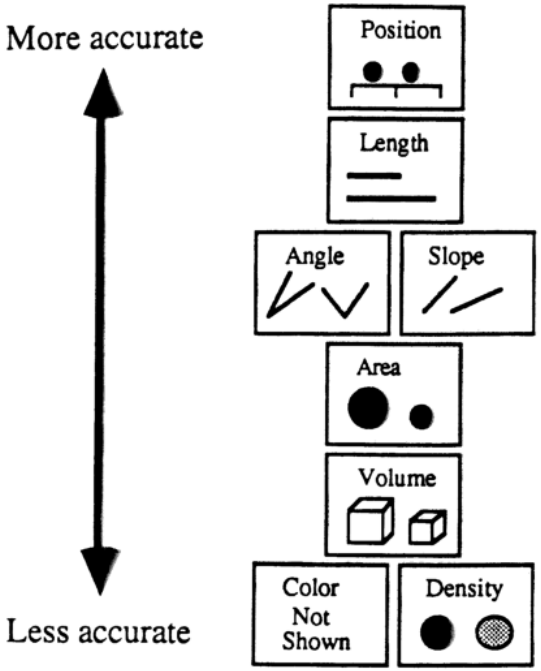
Area

What percentage in
size is the right from the left?



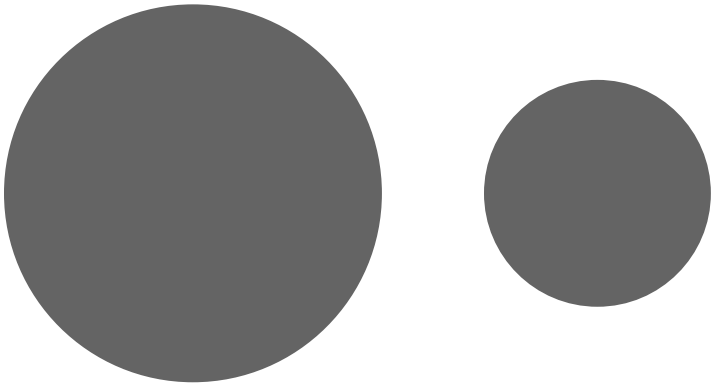
100%

52%



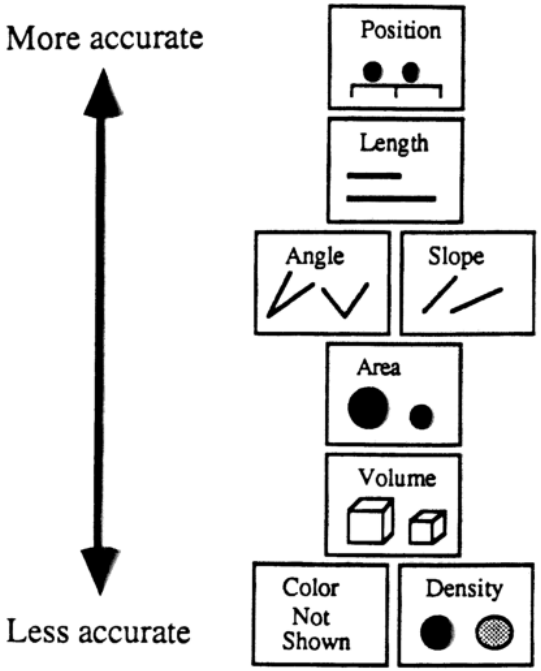
Area

What percentage in
size is the right from the left?



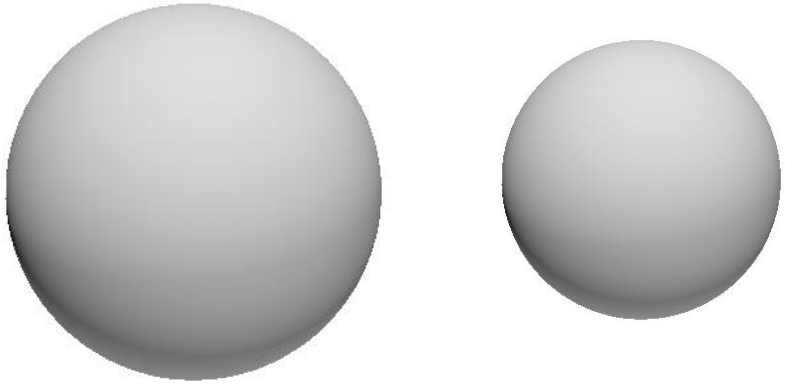
100%

36%



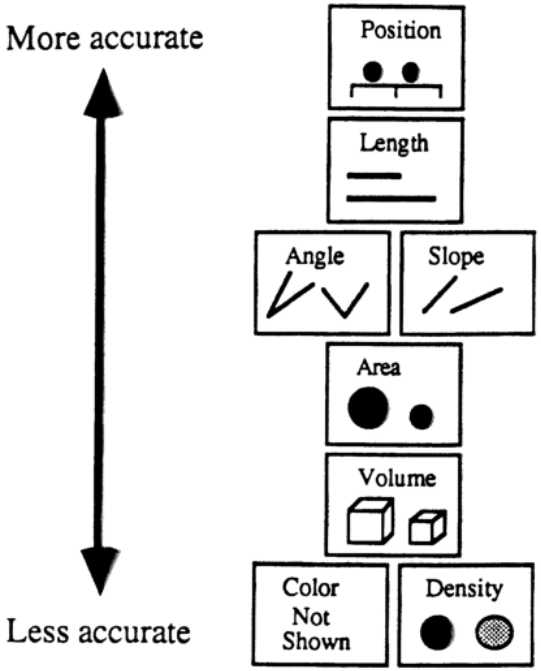
Volume

What percentage in
size is the right from the left?



100%

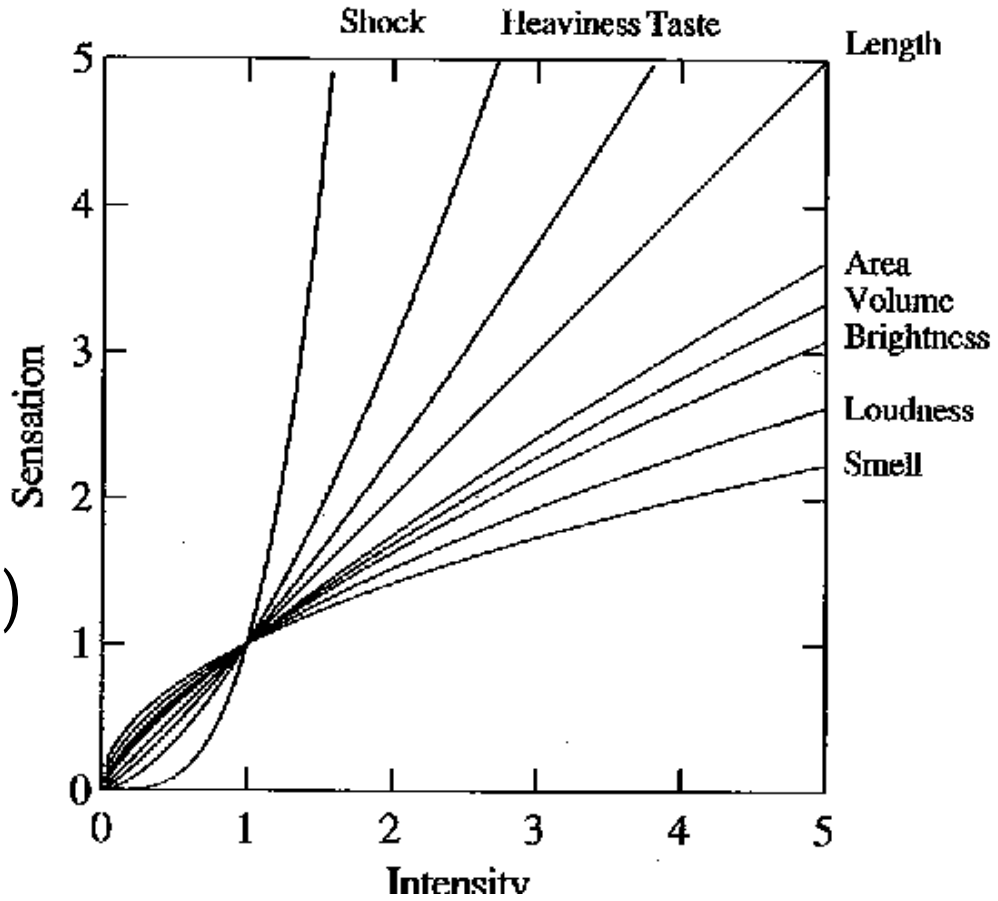
40%



Why are 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)

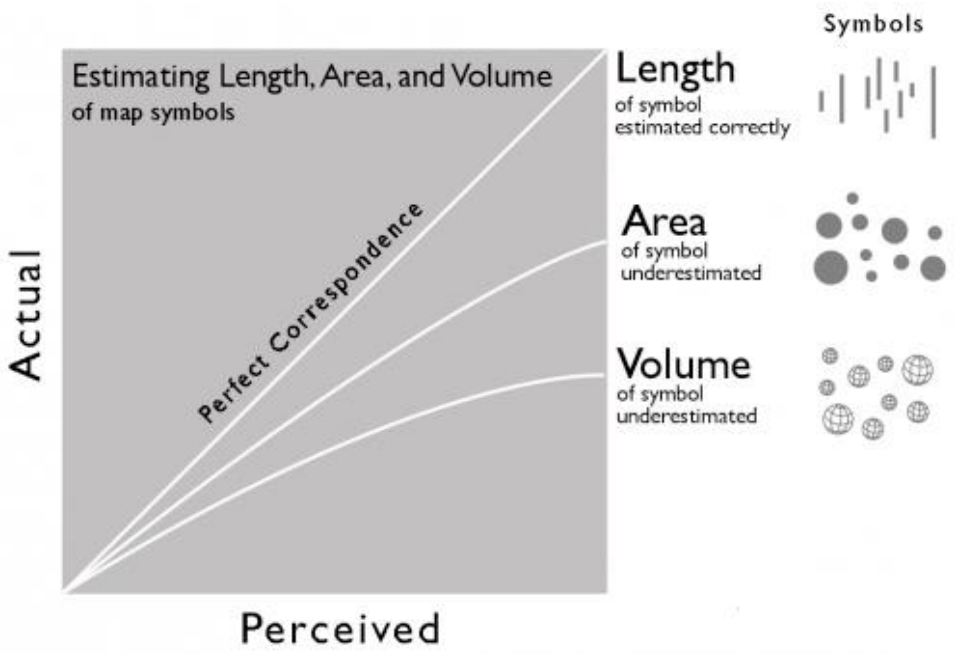


[Graph from Wilkinson 99, based on Stevens 61]

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/

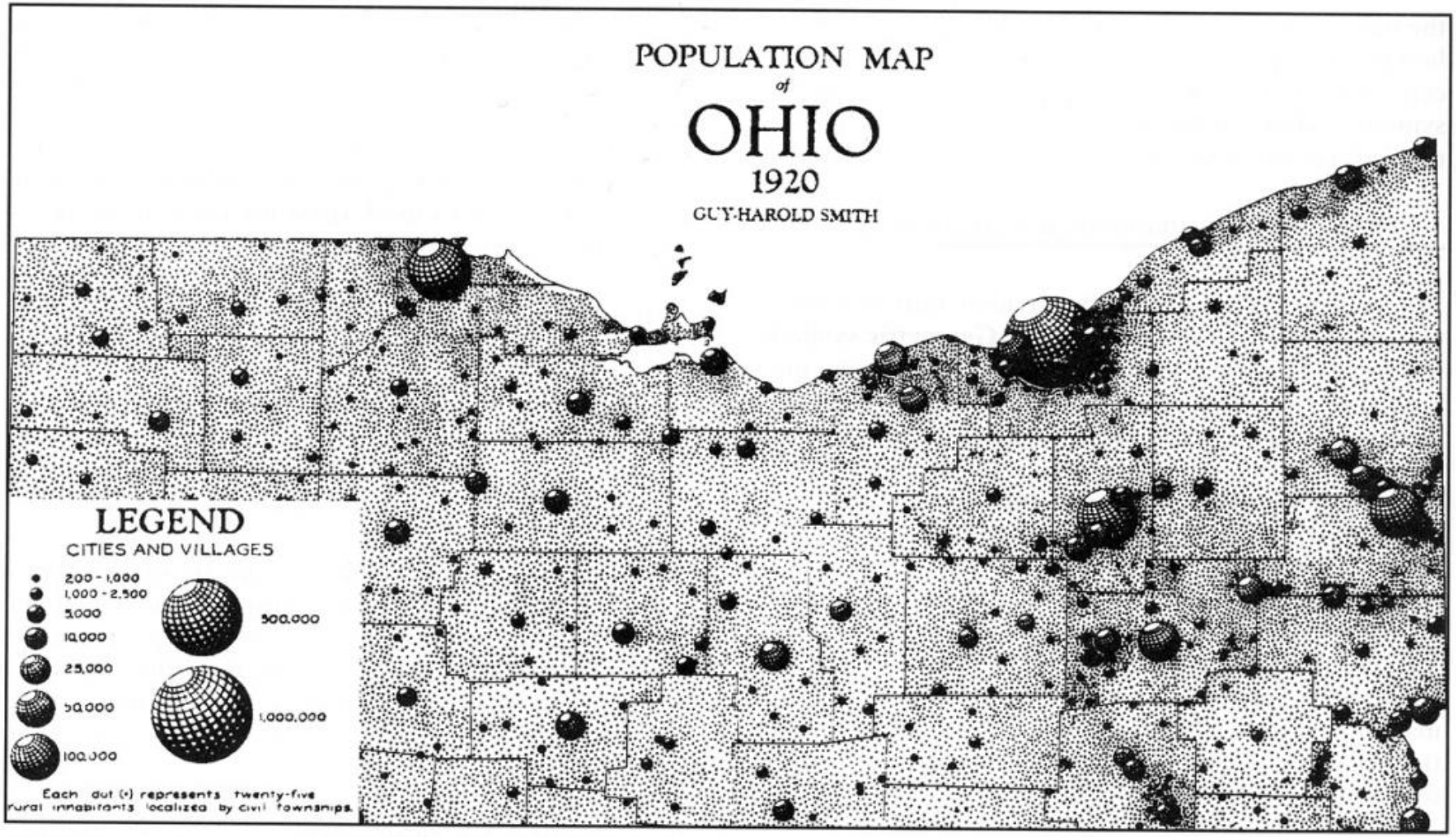
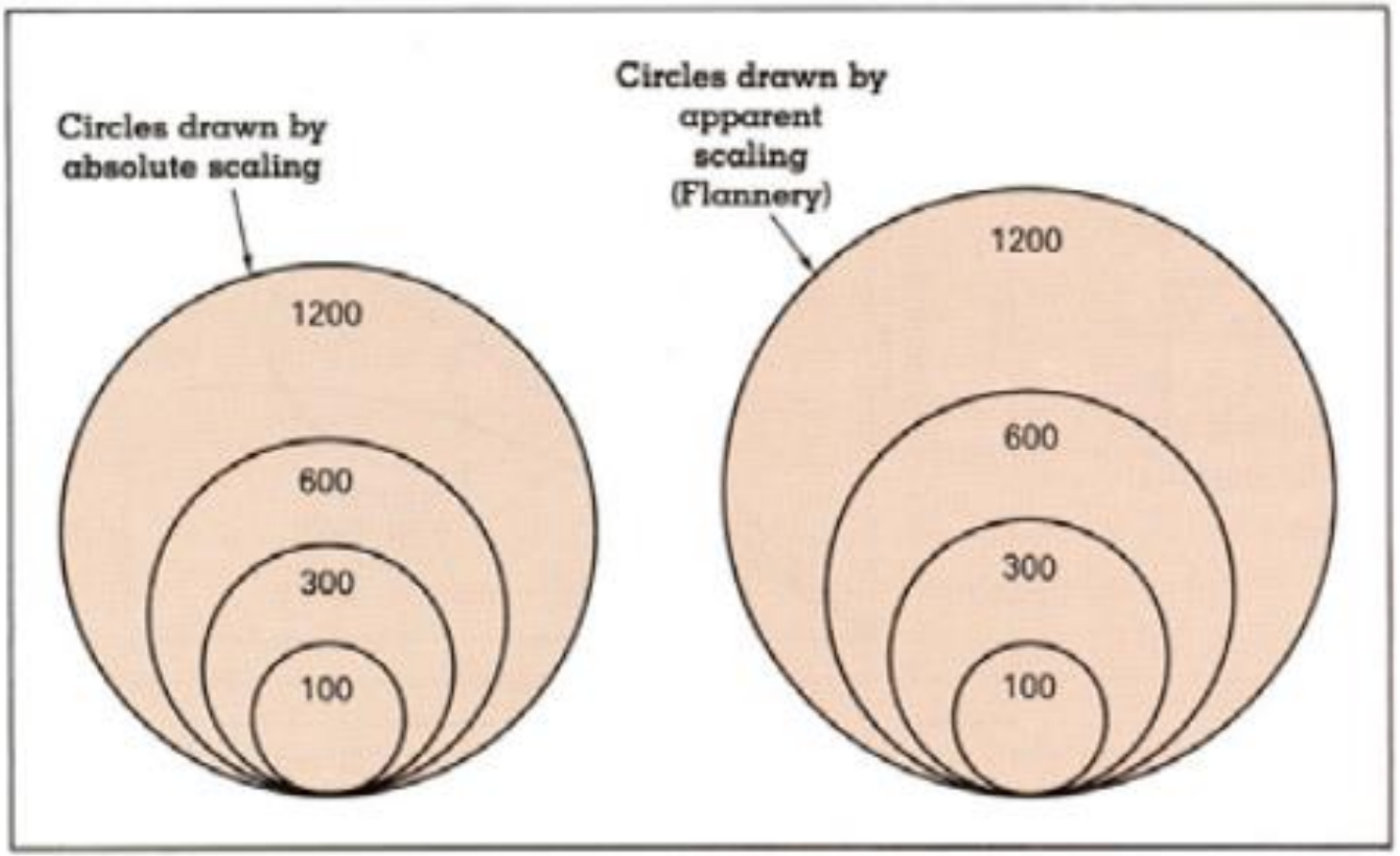


FIGURE 7.4. An eye-catching map created using three-dimensional geometric symbols. (After Smith, 1928. First published in *The Geographical Review,* 18(3), plate 4. Reprinted with permission of the American Geographical Society.)

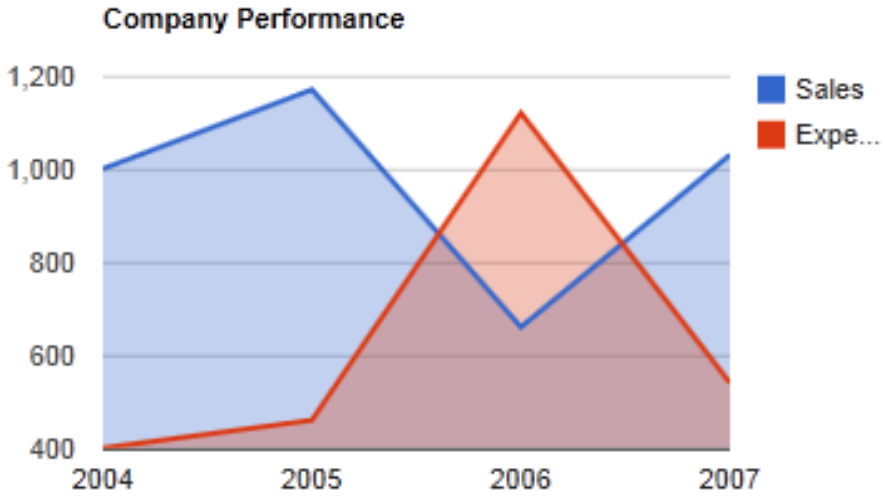


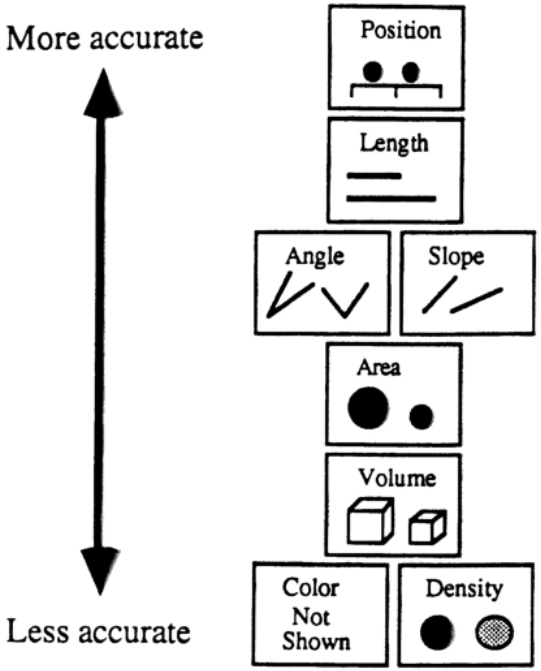
[Cartography: Thematic Map Design, Figure 8.6, p. 170, Dent, 96]

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

Area

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



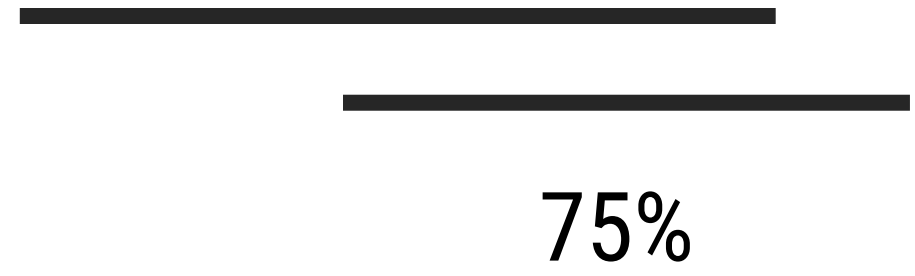


no idea – **this is very difficult**

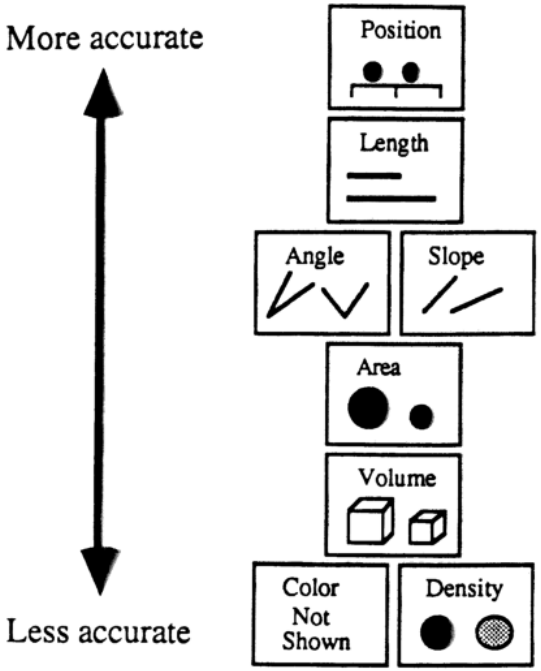
Length

What percentage in
length is the right from the left?

100%



75%

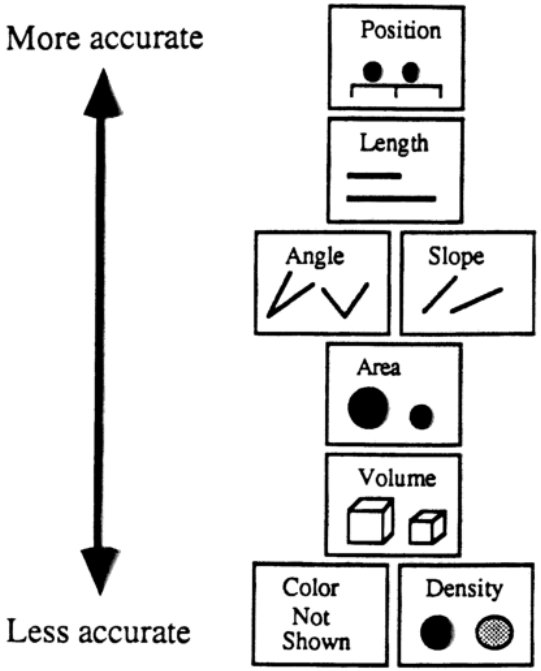


Length / Position

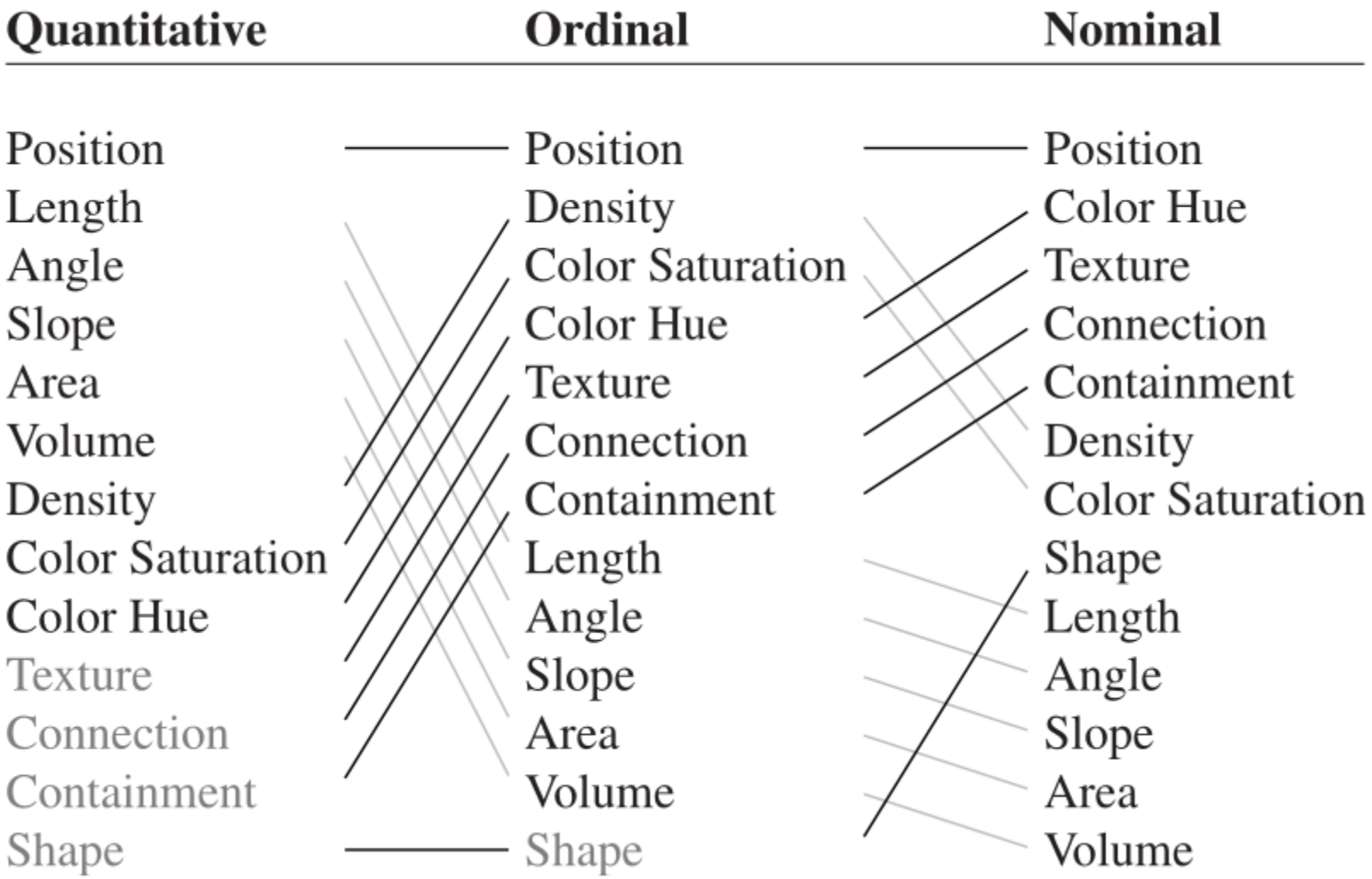
What percentage in
length is the right from the left?

100%

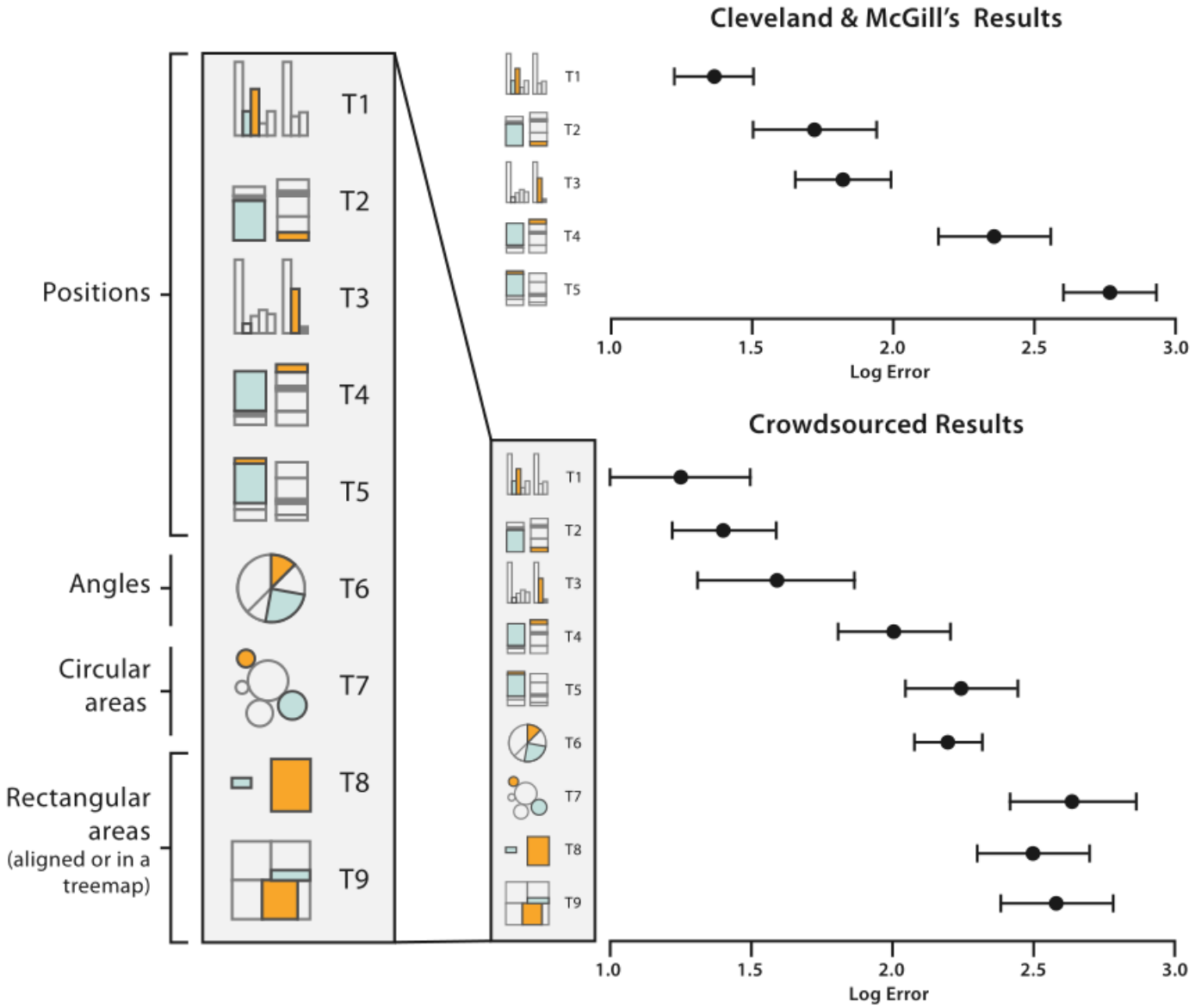
25%



Effectiveness of Data Encodings (Conjecture)



Mackinlay 1986



Jeffrey Heer and Michael Bostock. "Crowdsourcing Graphical Perception: Using Mechanical Turk to Assess Visualization Design." In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI), pp. 203–212. ACM, 2010. DOI 10.1145/1753326.1753357

Magnitude Channels: Ordered Attributes

- Position on common scale
- Position on unaligned scale
- Length (1D size)
- Tilt/angle
- Area (2D size)
- Depth (3D position)
- Color luminance
- Color saturation
- Curvature
- Volume (3D size)

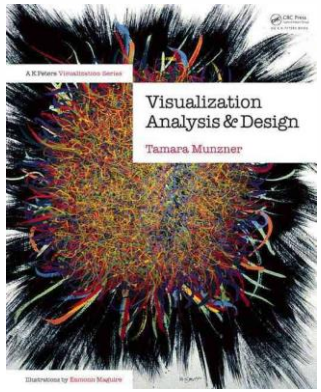
Most ▲ Effectiveness ▼ Least

Same (Color luminance, Color saturation)

Same (Curvature, Volume (3D size))

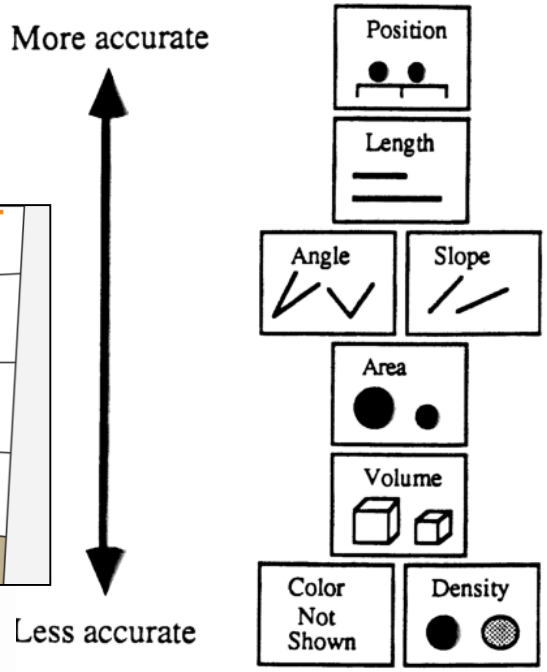
Identity Channels: Categorical Attributes

- Spatial region
- Color hue
- Motion
- Shape

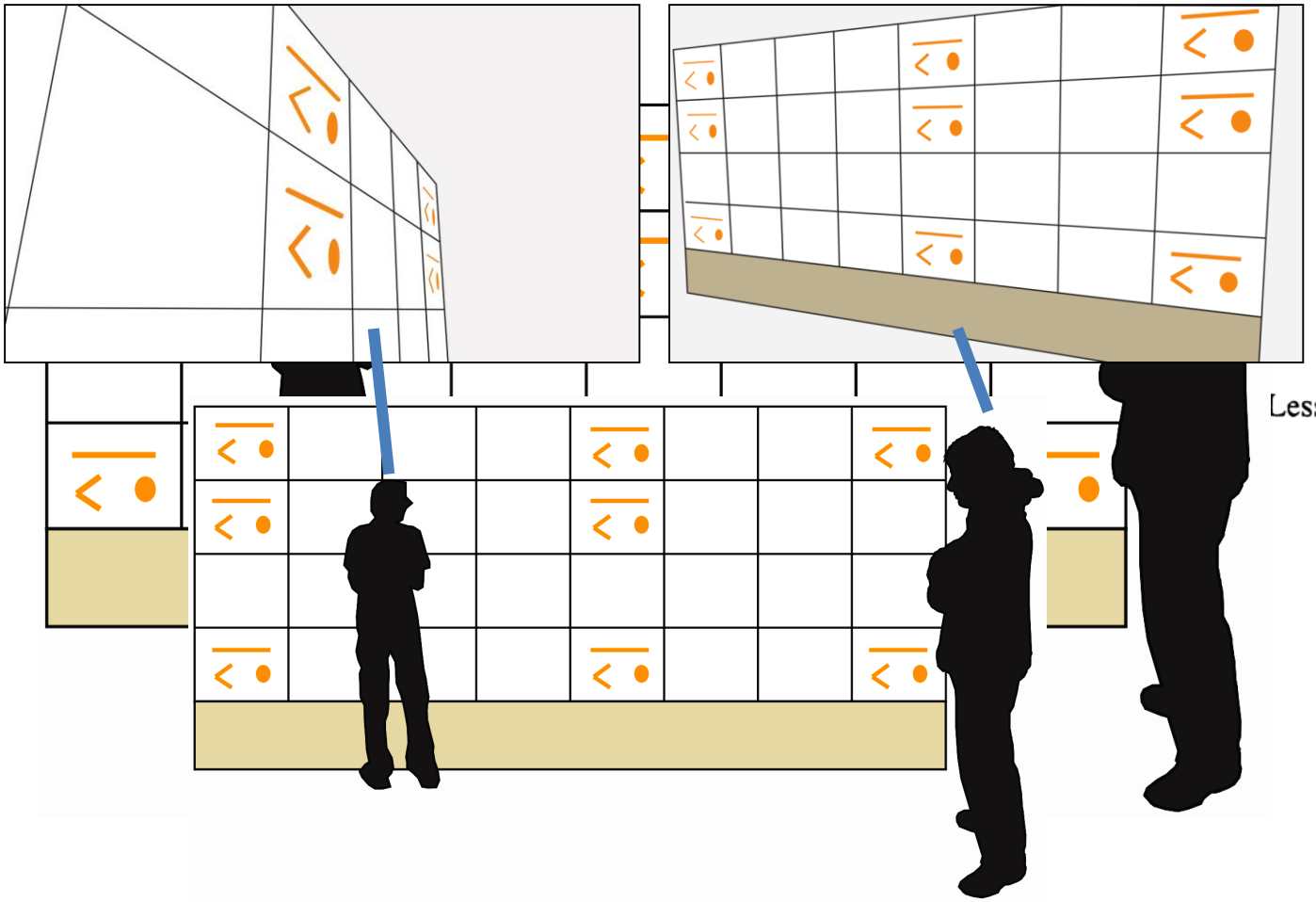


Elementary Graphical Perception Tasks

William S. Cleveland (1980s)



also beware of the physical presentation:



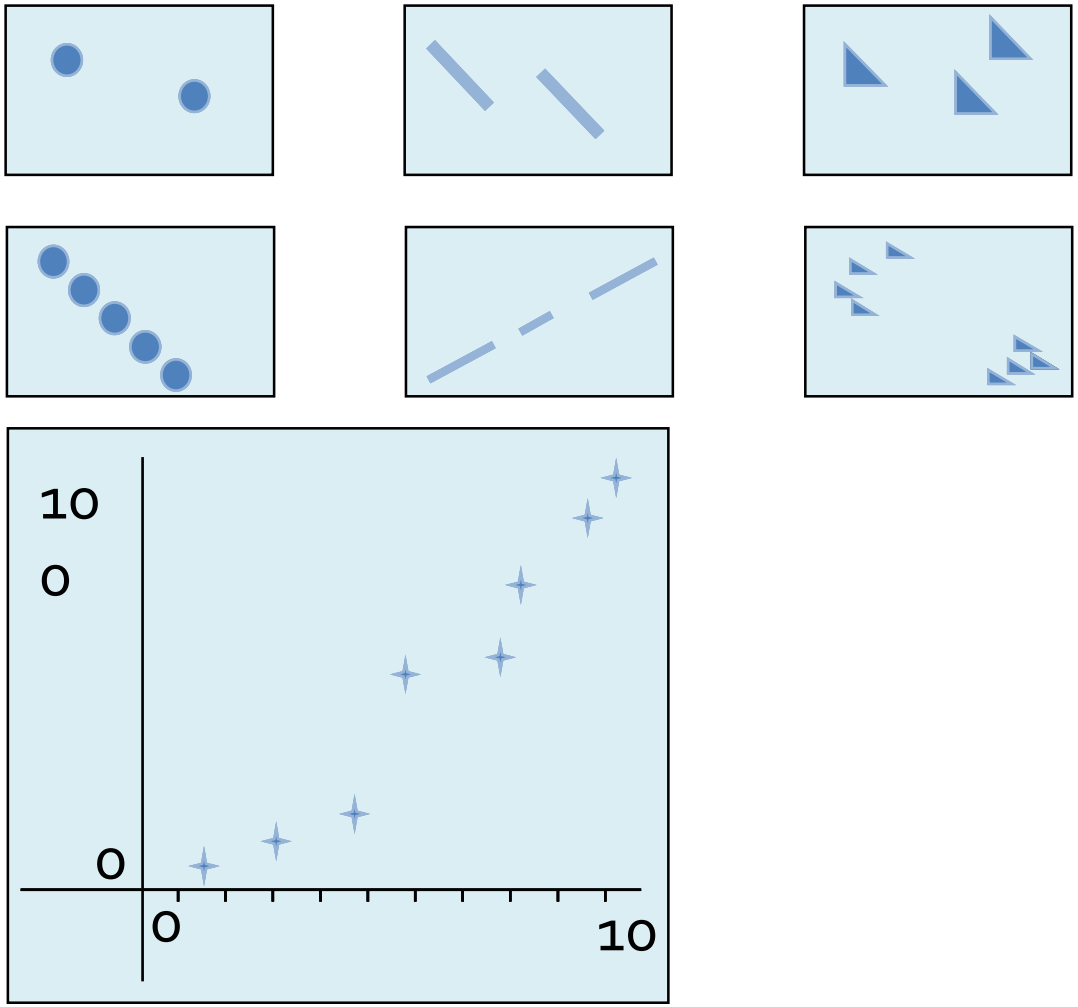
2) DISCRIMINABILITY

POSITION

Very high

Depends on:

* Resolution
* Visual acuity

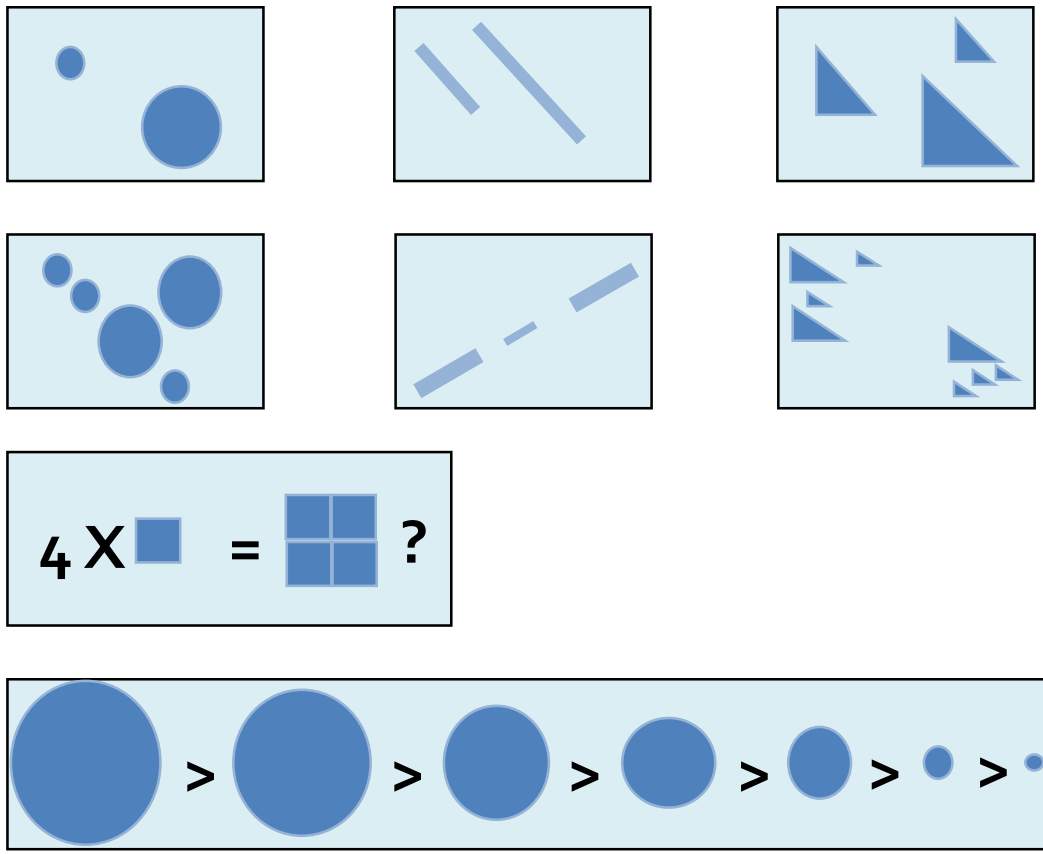


SIZE

Very high

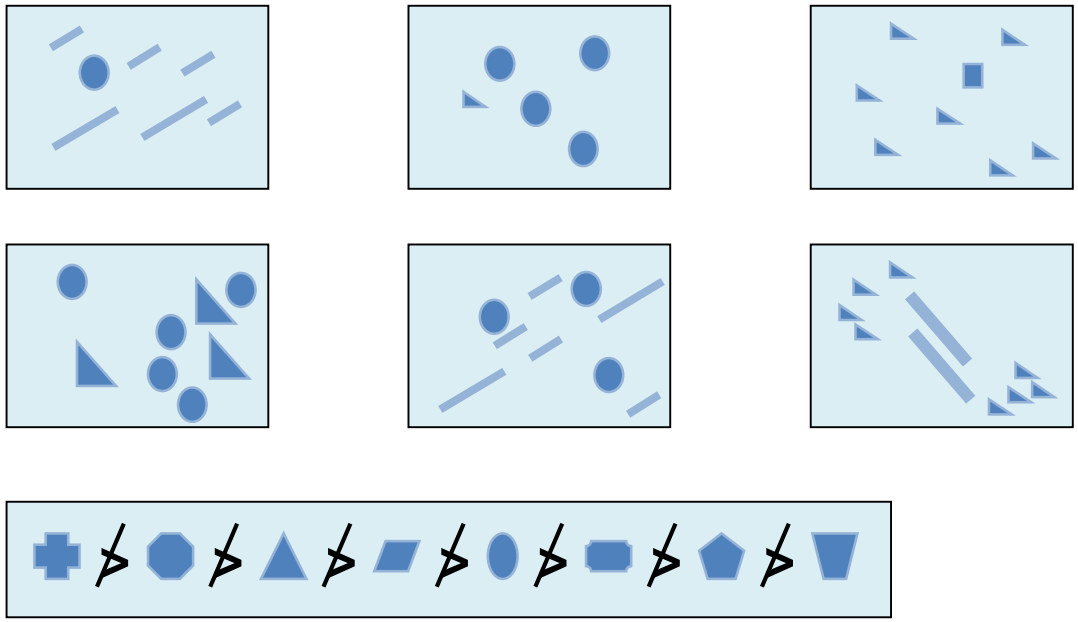
Depends on:

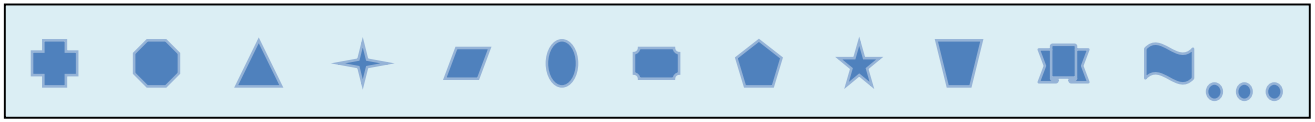
* Resolution
* Visual acuity



SHAPE

Theoretically infinite



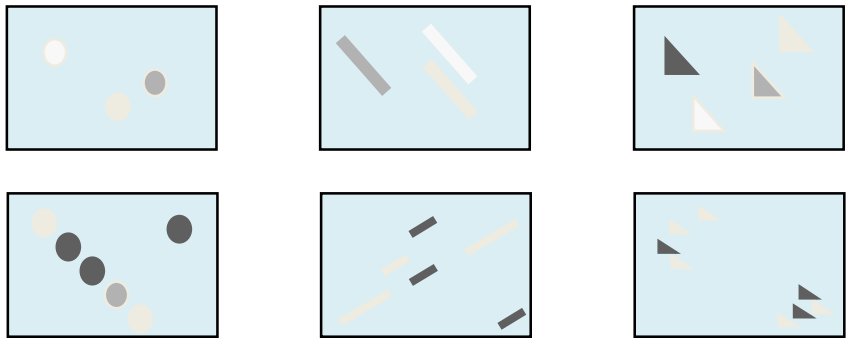


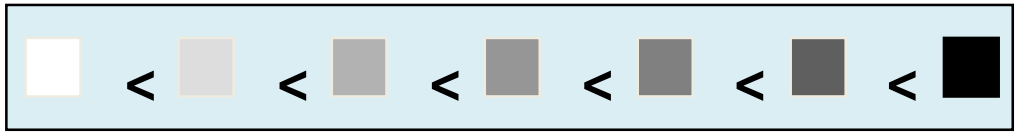
VALUE

Theoretically infinite
but practically limited

association and
selection ~ < 7

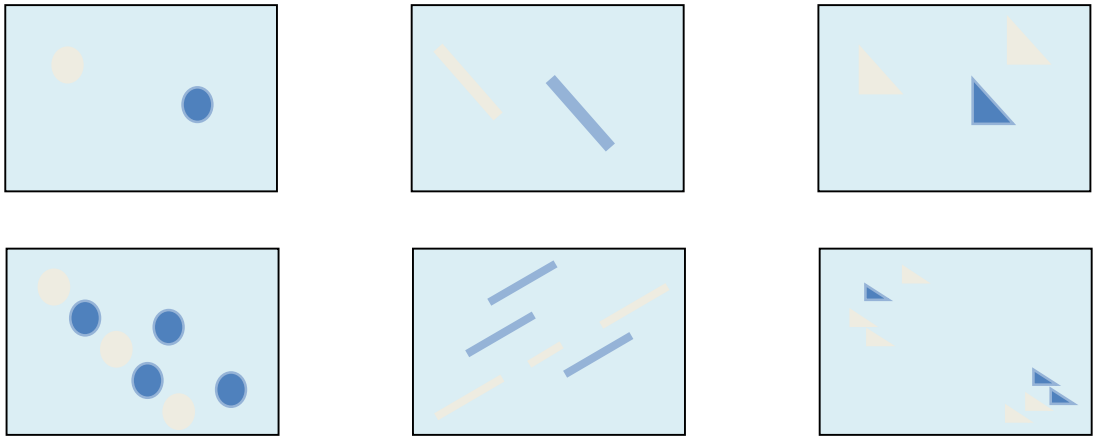
distinction ~ 10





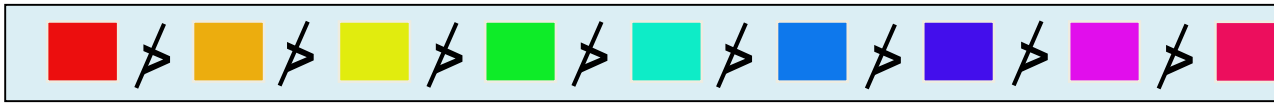
COLOR HUE

Theoretically infinite
but practically limited



association and
selection ~ < 7

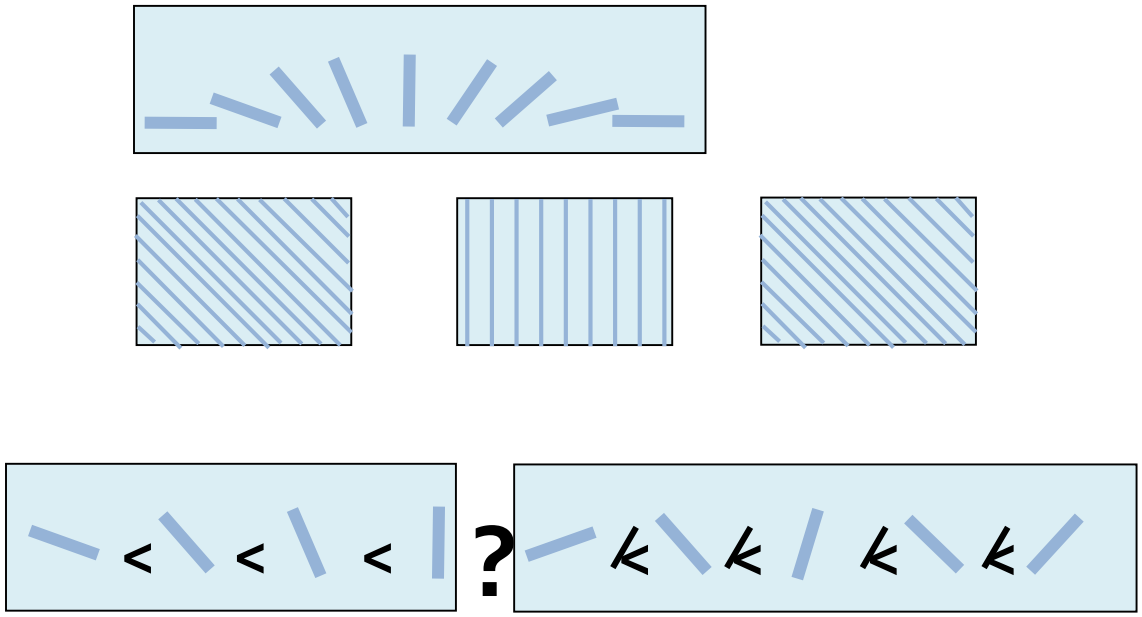
distinction ~ 10



ORIENTATION

Resolution dependent

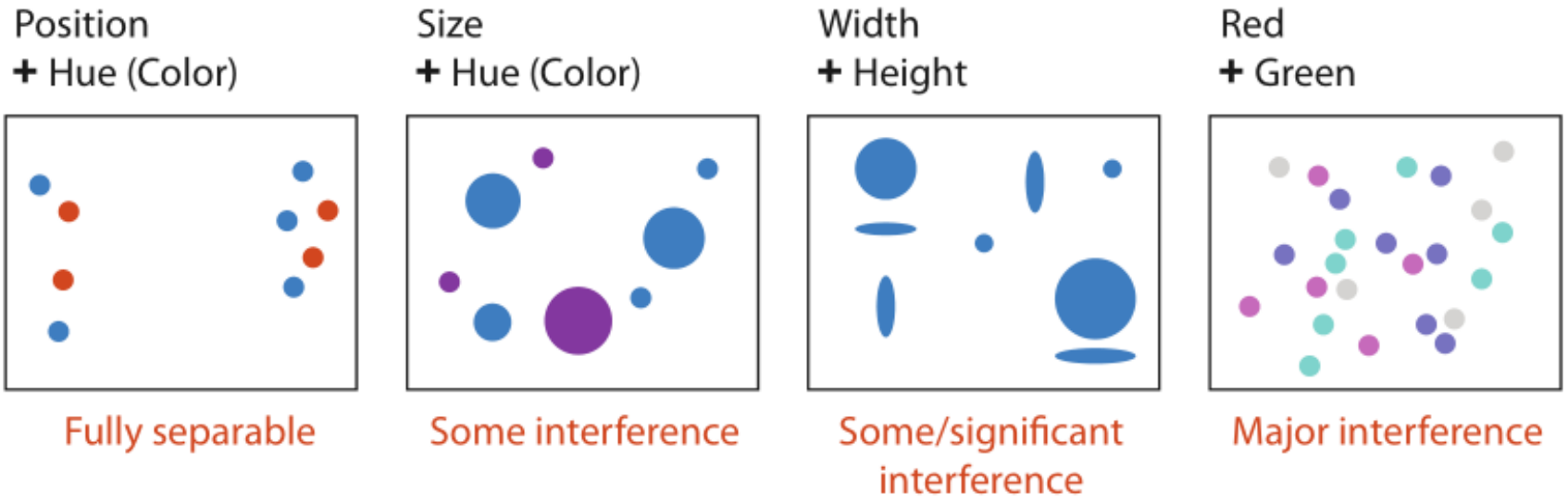
~5 in 2D; ? in 3D



3) SEPARABILITY

SEPARABILITY

There are dependencies and interferences between visual channels



a distinct item stands out from many others immediately

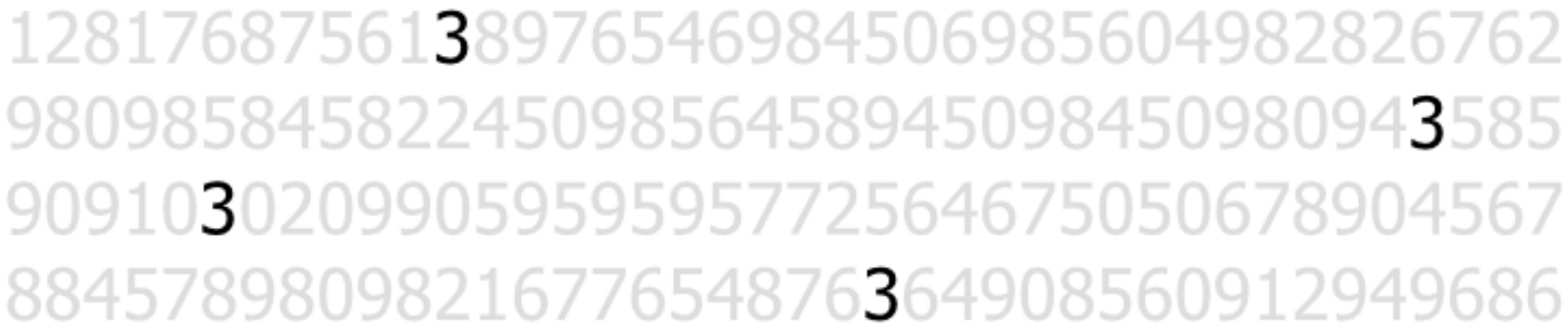
4) POPOUT

How many 3’s do you see?

128176875613897654698450698560498282676 2
980985845822450985645894509845098094358 5
909103020990595959577256467505067890456 7
884578980982167765487636490856091294968 6

From: Ware, Information Visualization using Vision to Think

How about now?

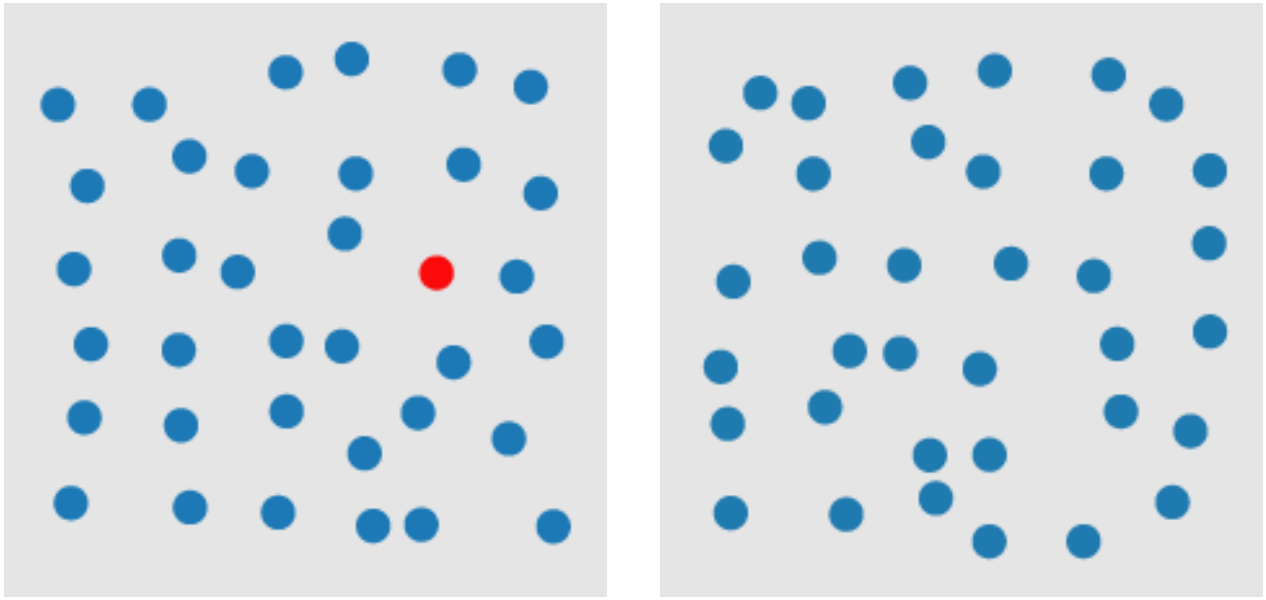


From: Ware, Information Visualization using Vision to Think

Visual encodings influence **preattentive** processing

DETERMINE IF A RED CIRCLE IS PRESENT

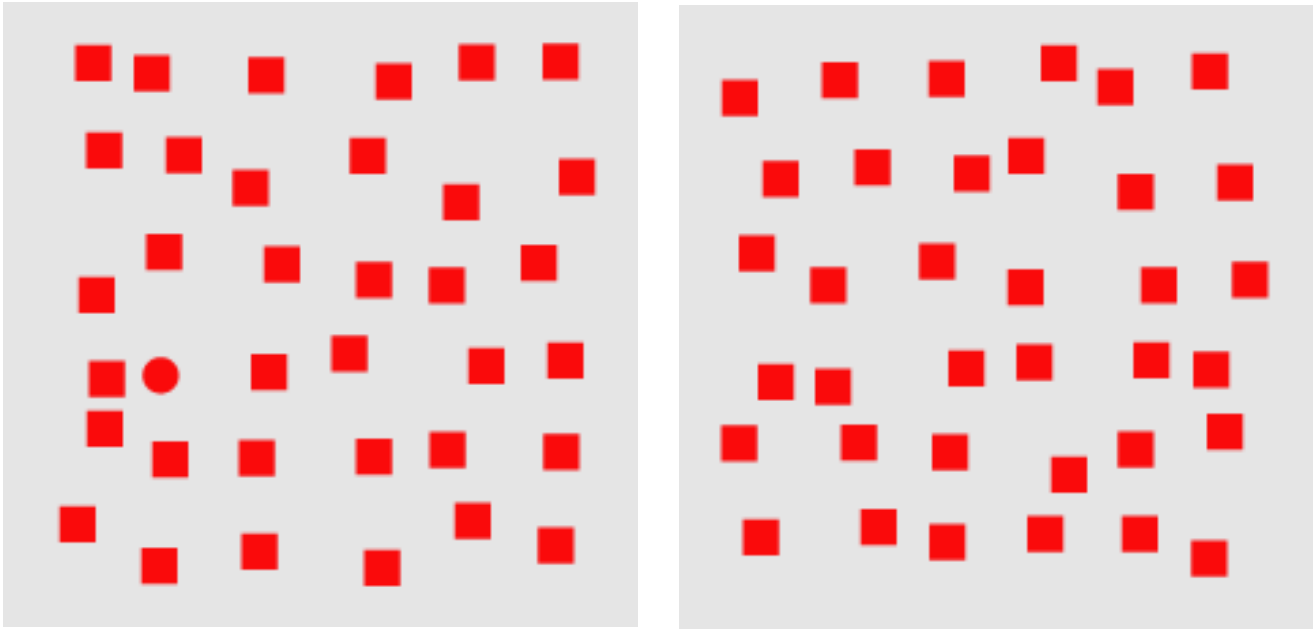
Hue



Hue pops out, no matter if we have 15 or 50 blue circles

From: Healey, Perception in Visualization

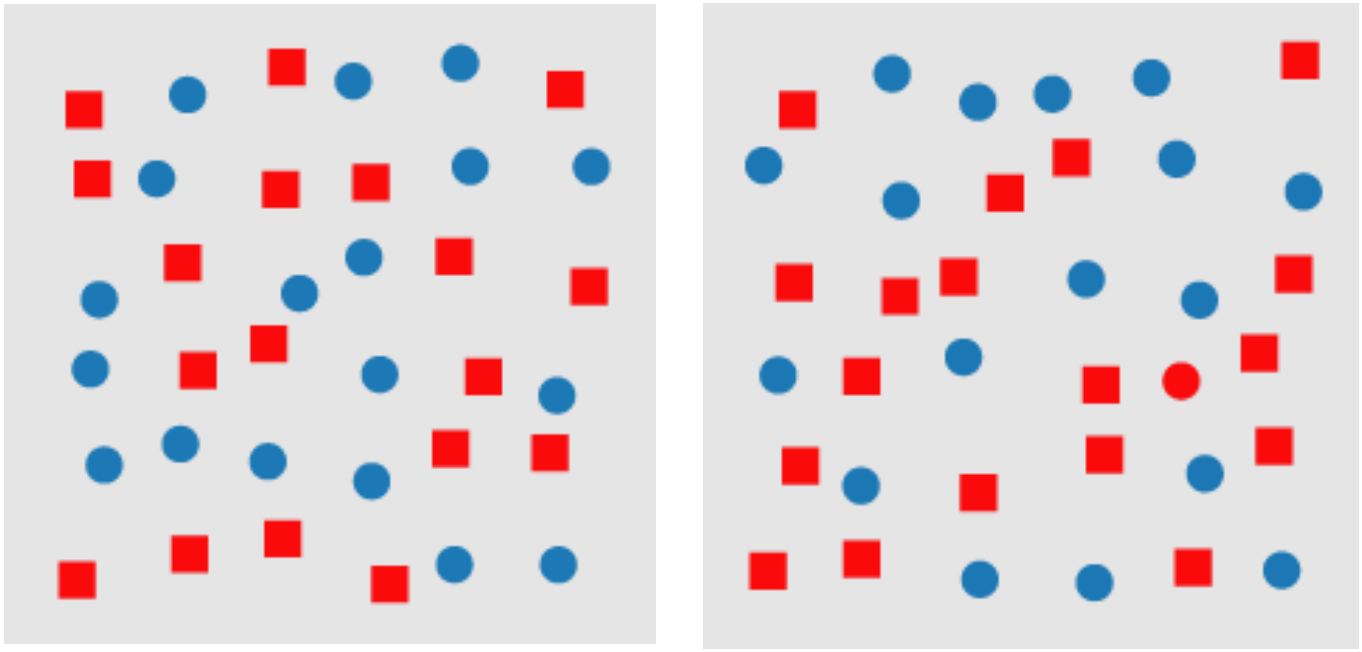
Shape



Yes, can be done quickly but a bit more slowly than before

From: Healey, Perception in Visualization

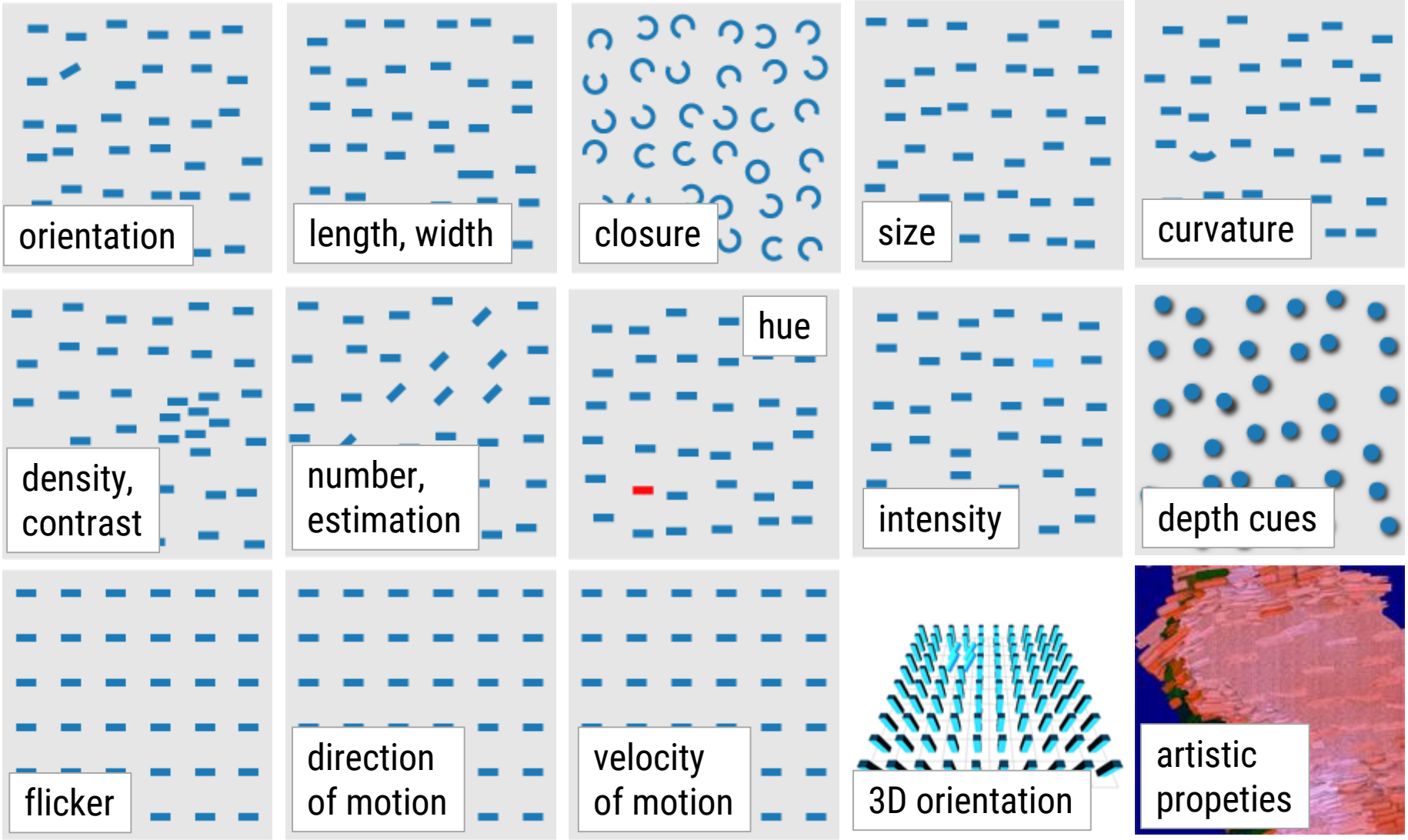
Hue and Shape



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

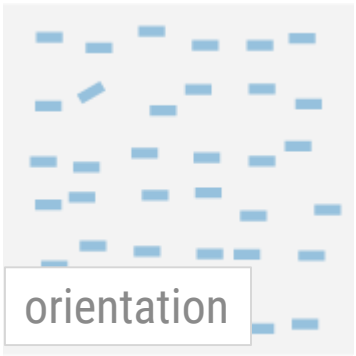
From: Healey, Perception in Visualization

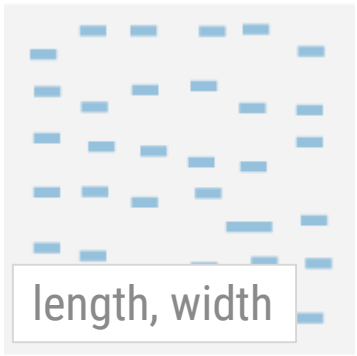
Channels that support popout (some)

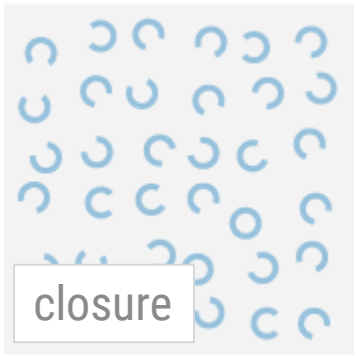


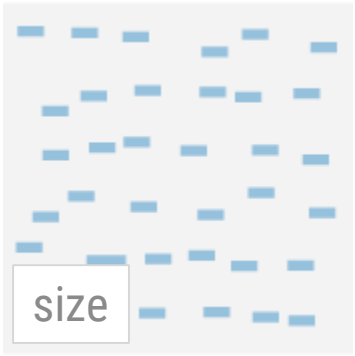
From: Healey, Perception in Visualization

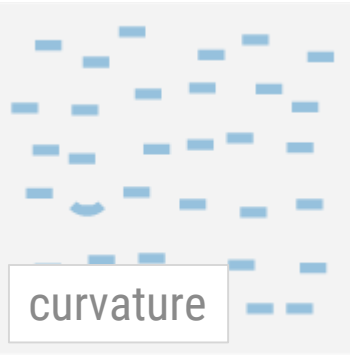
Channels that support popout (some)

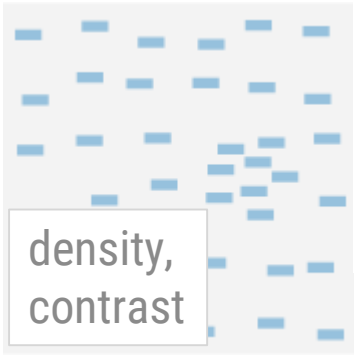




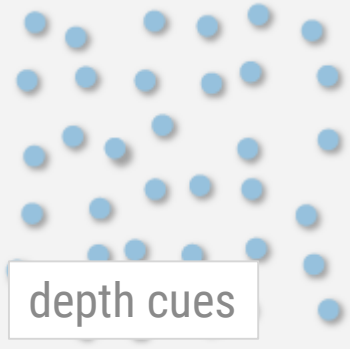


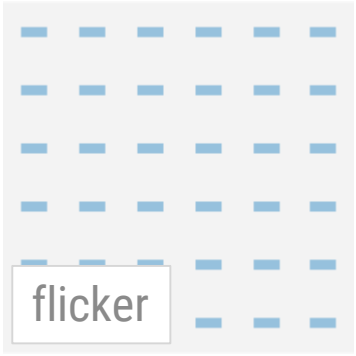


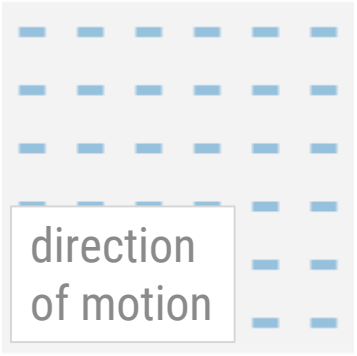


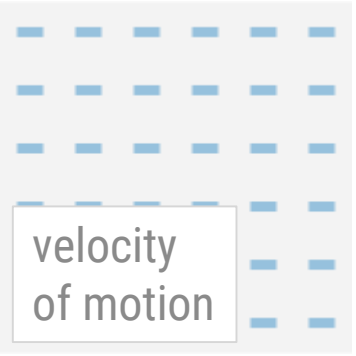


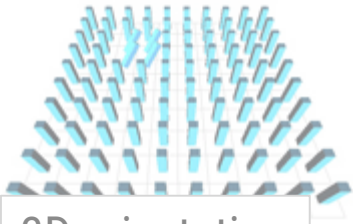
When designing visualizations, try to use channels that pop out to support the **most important tasks**.











From: Healey, Perception in Visualization

- Most pairs of channels do not support popout
  - A few do: space & color, motion & shape
- No popout possible with 3 or more channels
- Count on using popout for a single channel at a time

5) GROUPING

GROUPING

How do you show that items belong together effectively?

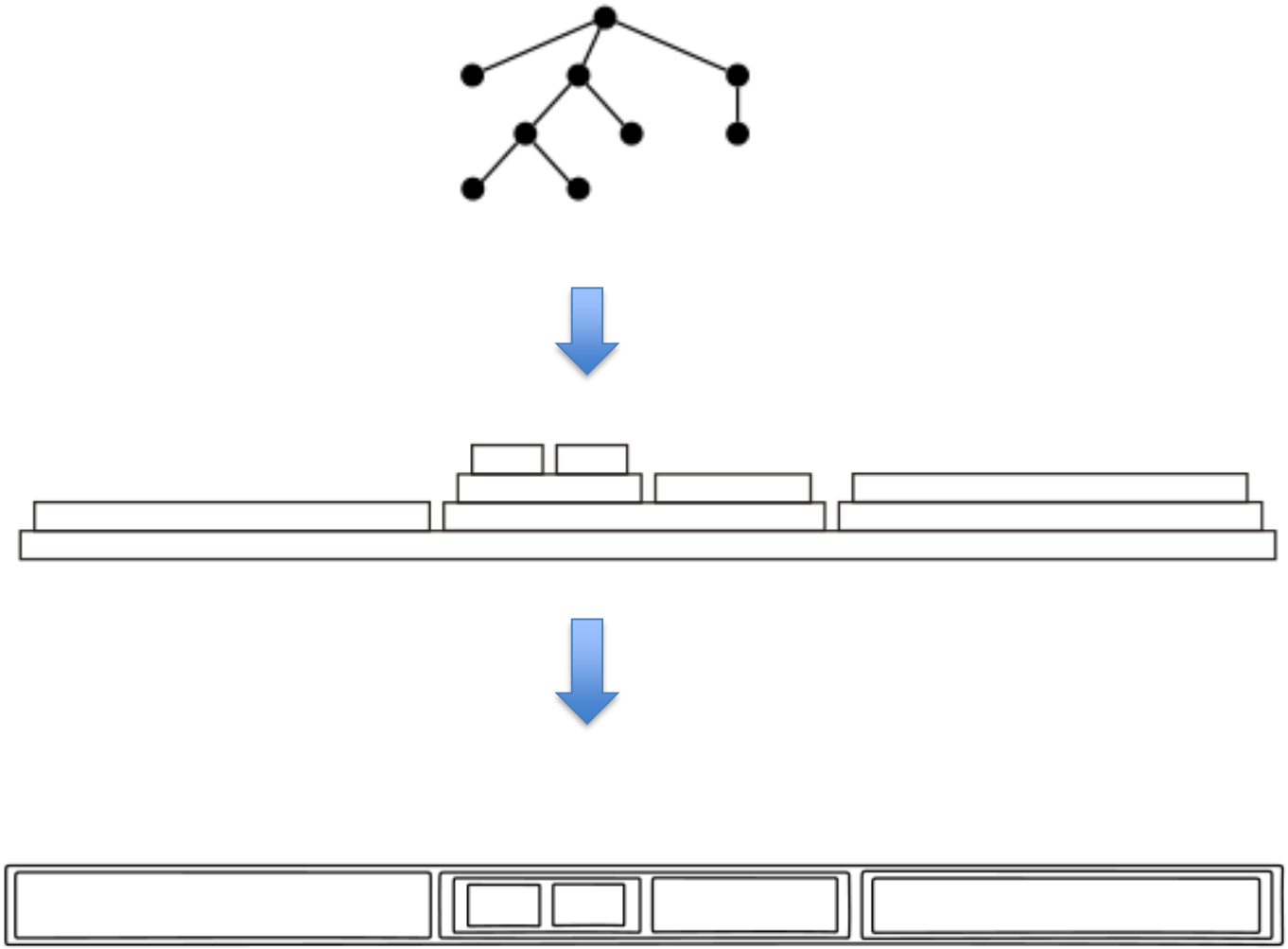
1+2) Explicit Links

Containment

Strongest cue

Connection

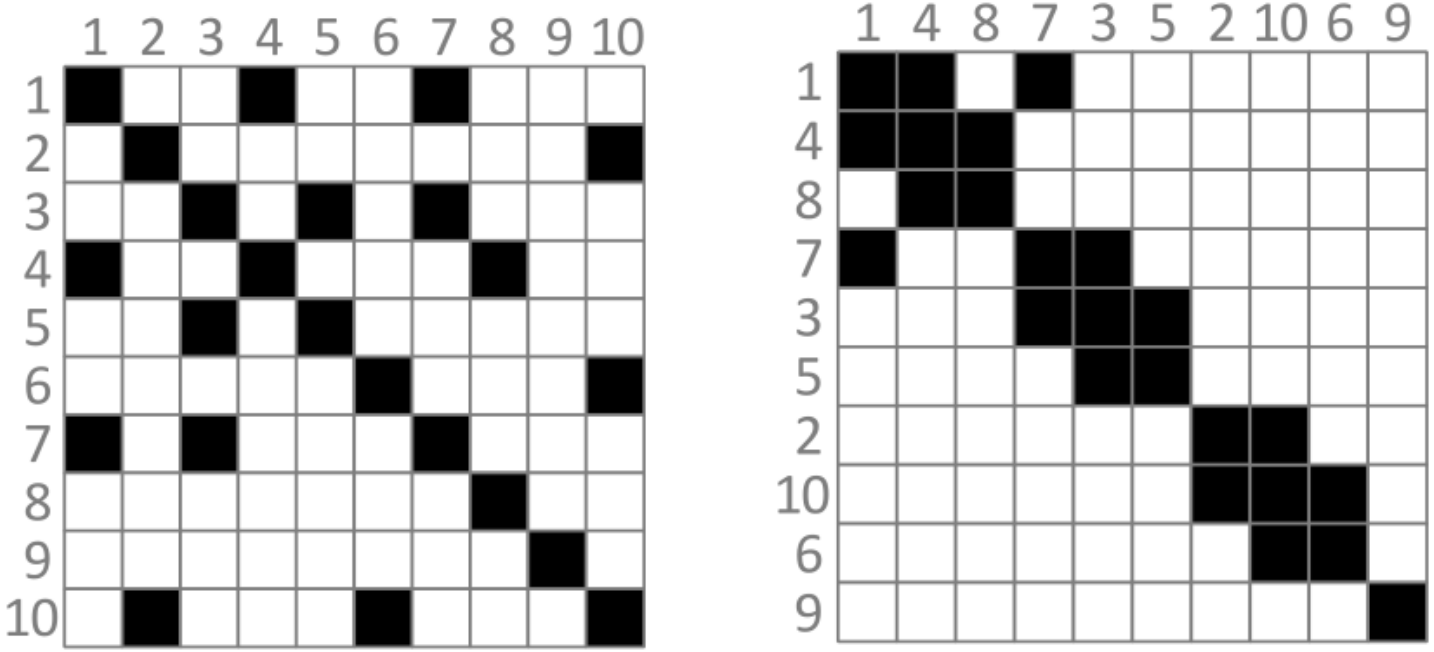
Second strongest cue



GROUPING

How do you show that items belong together effectively?

3) Proximity



Matrix Reordering Methods for Table and Network Visualization, June 2016, Computer Graphics Forum 35(3), DOI: 10.1111/cgf.12935

GROUPING

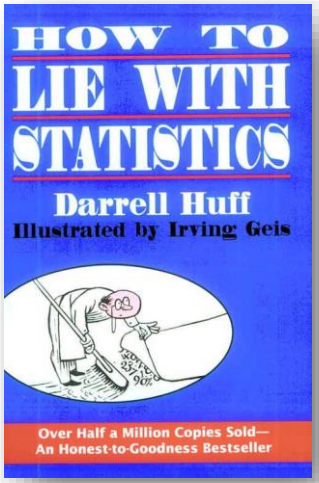
How do you show that items belong together effectively?

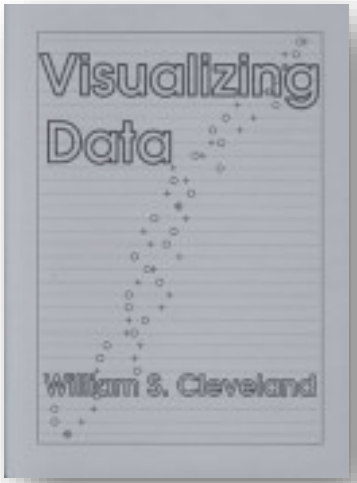
3) Categorical Channels

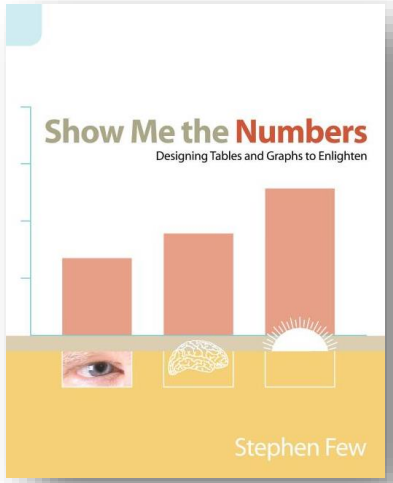
- Hue
- Motion
- Shape

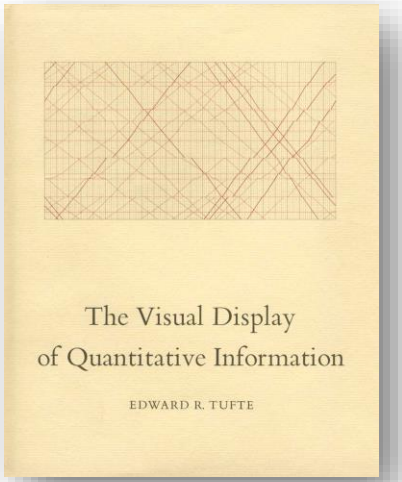
these are all difficult to use, be careful of interactions

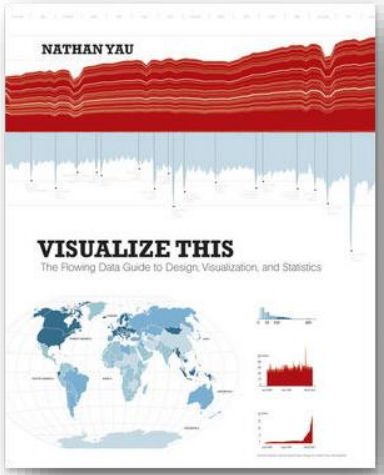
Many more useful guidelines!











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 (theoretically)**

Müller-Lyer Sinusoidal Waves

New variant by Gianni A. Sarcone

Though the **blue** and **red** segments seem to oscillate, they are always the **same length**! **Nothing moves except the arrows** at the endpoints of each color segment...