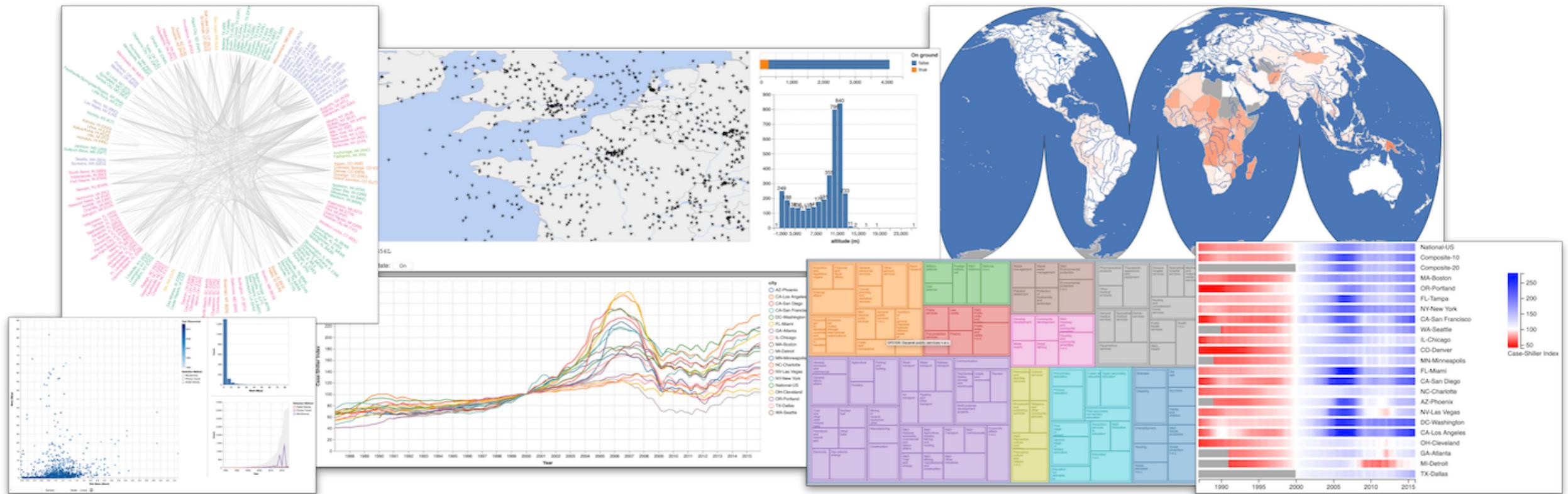


# Data Visualization

INF552 (2023-2024)

## Session 02 Fundamental Principles of Visual Perception for Visualization



# Individual Project - Milestone #1

- By session 03 (*i.e., Friday next week*), identify a dataset (or collection thereof) that you are interested in visualizing (based on your own interests).
- Validate it with me (just a sanity check to confirm feasibility) by uploading a short text description in the relevant Assignment on Moodle (will post a link to it on Slack).
- You can use the catalogs and search engines referenced on slide 6 of the course slide deck (INF552-2023-course-s01) to search for data, or use any other means.

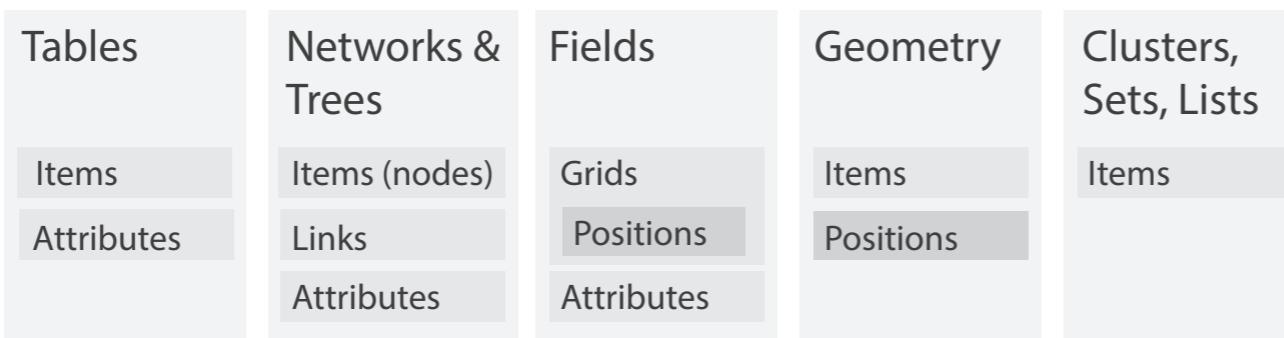
## Datasets

## Attributes

### → Data Types

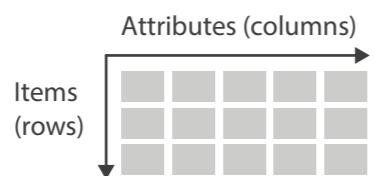
→ Items → Attributes → Links → Positions → Grids

### → Data and Dataset Types

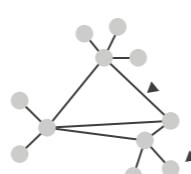


### → Dataset Types

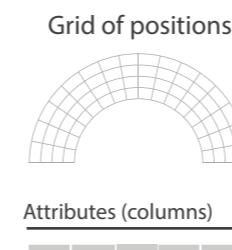
#### → Tables



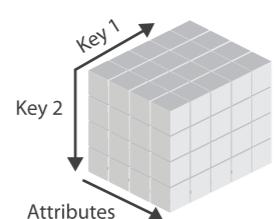
#### → Networks



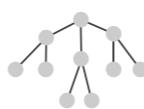
#### → Fields (Continuous)



#### → Multidimensional Table



#### → Trees



#### → Geometry (Spatial)



### → Attribute Types

→ Categorical



→ Ordered

→ Ordinal



→ Quantitative



### → Ordering Direction

→ Sequential



→ Diverging



→ Cyclic



*... we need to talk about data  
and dataset types.*

## Attributes

### Attribute Types

→ Categorical



→ Ordered

→ *Ordinal*



→ Quantitative



### Ordering Direction

→ Sequential



→ Diverging



→ Cyclic



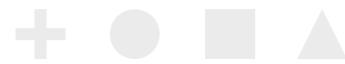
- or nominal (labels)
- can be counted
- examples:
  - fruits (apple, oranges, ...)
  - car makers (Audi, Renault, ...)
  - group membership
- operations:
  - =, ≠

A categorical scale divides items into classes that have no particular order.

## Attributes

### Attribute Types

→ Categorical



→ Ordered

→ *Ordinal*



→ Quantitative



### Ordering Direction

→ Sequential



→ Diverging



→ Cyclic



- can be counted, ordered
- examples:
  - 5-star rating scheme ( )
  - shirt sizes (XS, S, M, L, XL, XXL)
  - Likert scale
  - Military ranks
- operations:  
 $=, \neq, <, >$

An ordinal scale says nothing about the magnitude of differences between classes.

## Attributes

### Attribute Types

→ Categorical



→ Ordered

→ Ordinal



→ Quantitative



- can be counted, ordered, measured

*Ratio*

meaningful zero

- examples:
  - physical measurements: length, mass, luminance, temperature ( $^{\circ}\text{K}$ )...
  - financial indicators
- operations:  $=, \neq, <, >, - , +, \times, \div$

Items on an interval scale have an order and a relative distance between them.

### Ordering Direction

→ Sequential



→ Diverging



→ Cyclic



*Interval*

no clear zero, or an arbitrary one

- examples:
  - dates
  - lat/lon
  - temperature ( $^{\circ}\text{C}$  or  $^{\circ}\text{F}$ )
- operations:  $=, \neq, <, >, - , +$

Items on a ratio scale have an order and a distance to a non-arbitrary absolute zero.

Quantitative scales can be linear or logarithmic.

## Attributes

---

### → Attribute Types

→ Categorical



→ Ordered

→ *Ordinal*



→ Quantitative



### → Ordering Direction

→ Sequential



altitudes, speeds, ...

→ Diverging



temperature, elevation (terrain+bathymetry), profit & loss...

→ Cyclic



time measurements: hour of the day, month of the year, ...

# Why is this important?

- Because nominal, ordinal, and quantitative data are best expressed in different ways visually.
- Because the ordering direction will also have an influence on the choice of visual variable and its range.
- Because different data types are often associated with different tasks:
  - temporal data (comparison of events)
  - trees (understand parent-child relationships)
  - tabular data: identify correlations, understand distribution, ...
  - ...
- and the design space, again, is *enormous*.

→ Points



→ Lines



→ Areas



Marks are geometric primitives

### ④ Position

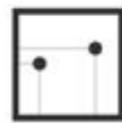
→ Horizontal



→ Vertical



→ Both



### ④ Color



### ④ Shape



### ④ Tilt



### ④ Size

→ Length



→ Area



→ Volume



Visual (encoding) channels control the appearance of marks

# Channels: Expressiveness Types and Effectiveness Ranks

## → 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)



## → Identity Channels: Categorical Attributes

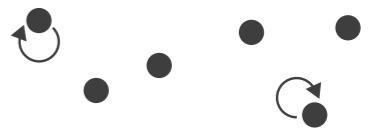
Spatial region



Color hue



Motion



Shape

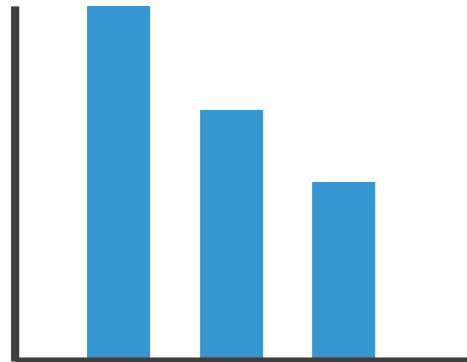


▲ Best

Effectiveness

▼ Least

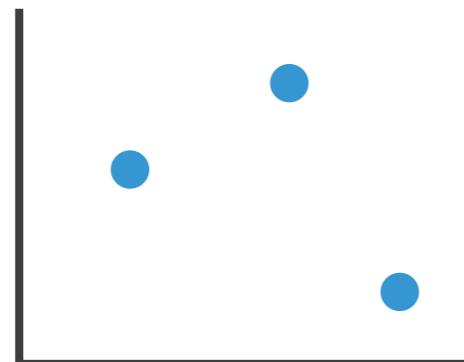
# Using marks and channels



Mark line

Vertical quantitative  
spatial position

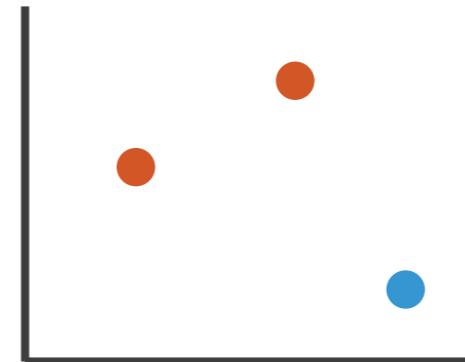
Horizontal categorical  
spatial position



Mark point

Vertical quantitative  
spatial position

Horizontal quantitative  
spatial position

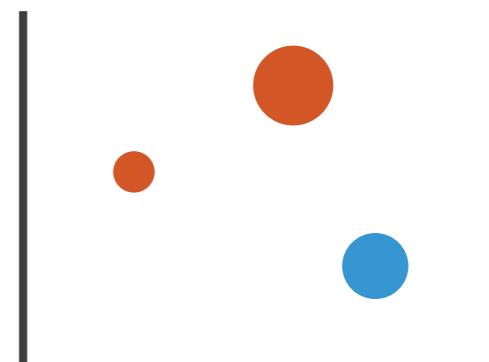


Mark point

Vertical quantitative  
spatial position

Horizontal quantitative  
spatial position

Color hue categorical



Mark point

Vertical quantitative  
spatial position

Horizontal quantitative  
spatial position

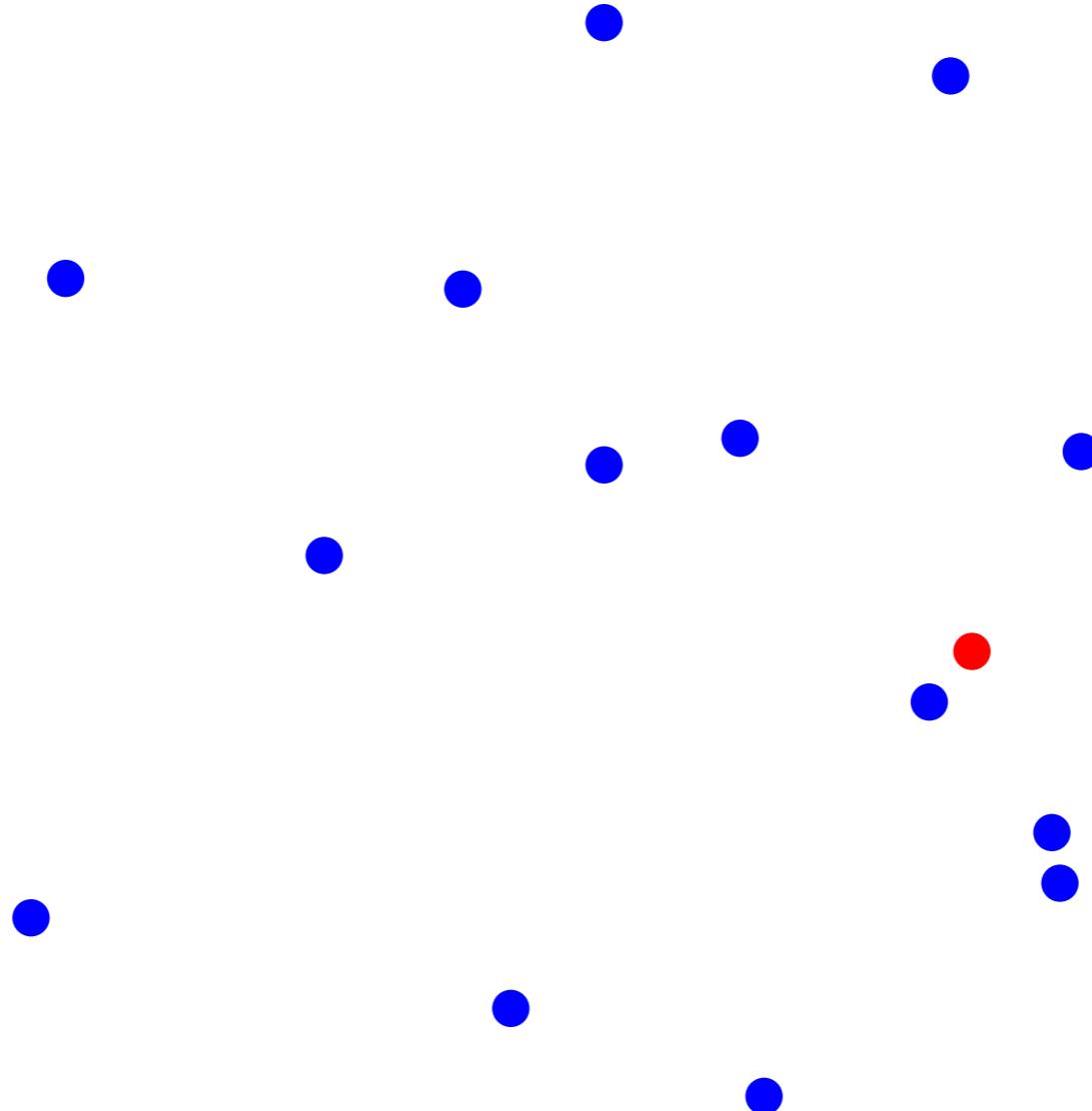
Color hue categorical

Size quantitative

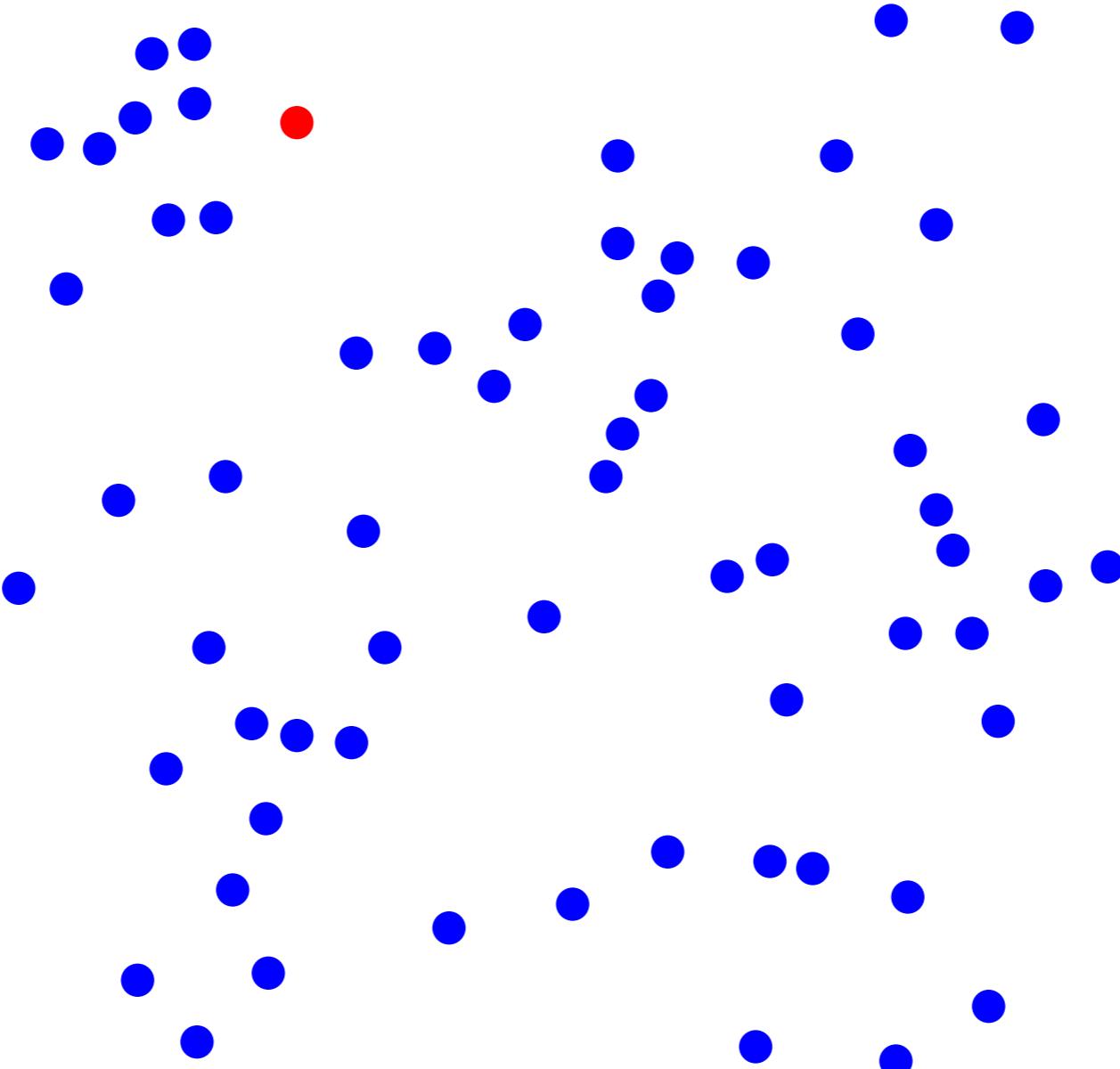
Assign variables of lesser importance to weaker visual channels.

(Variables that help interpret the data by giving context rather than enable making precise judgment.)

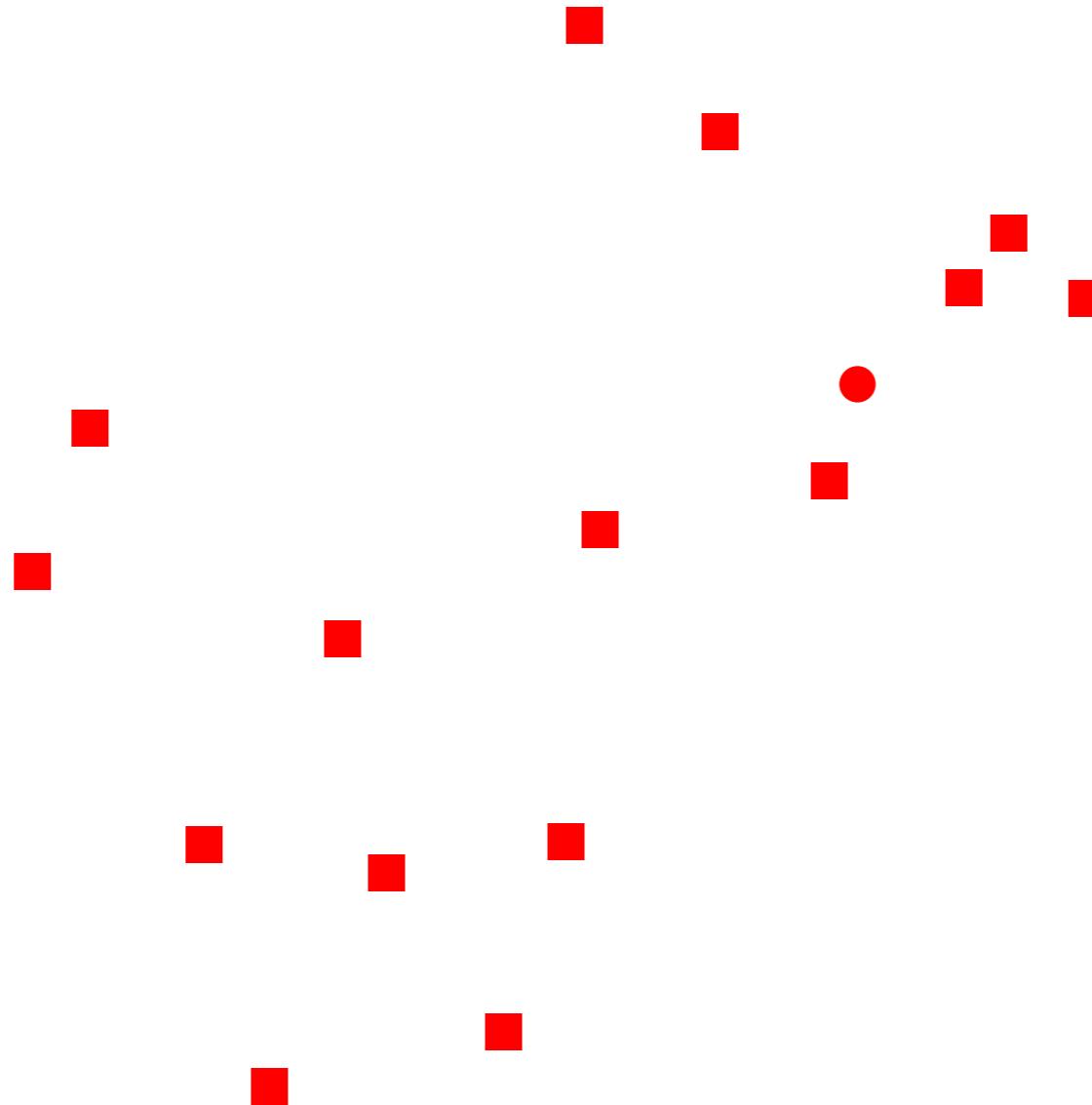
# Visual pop out



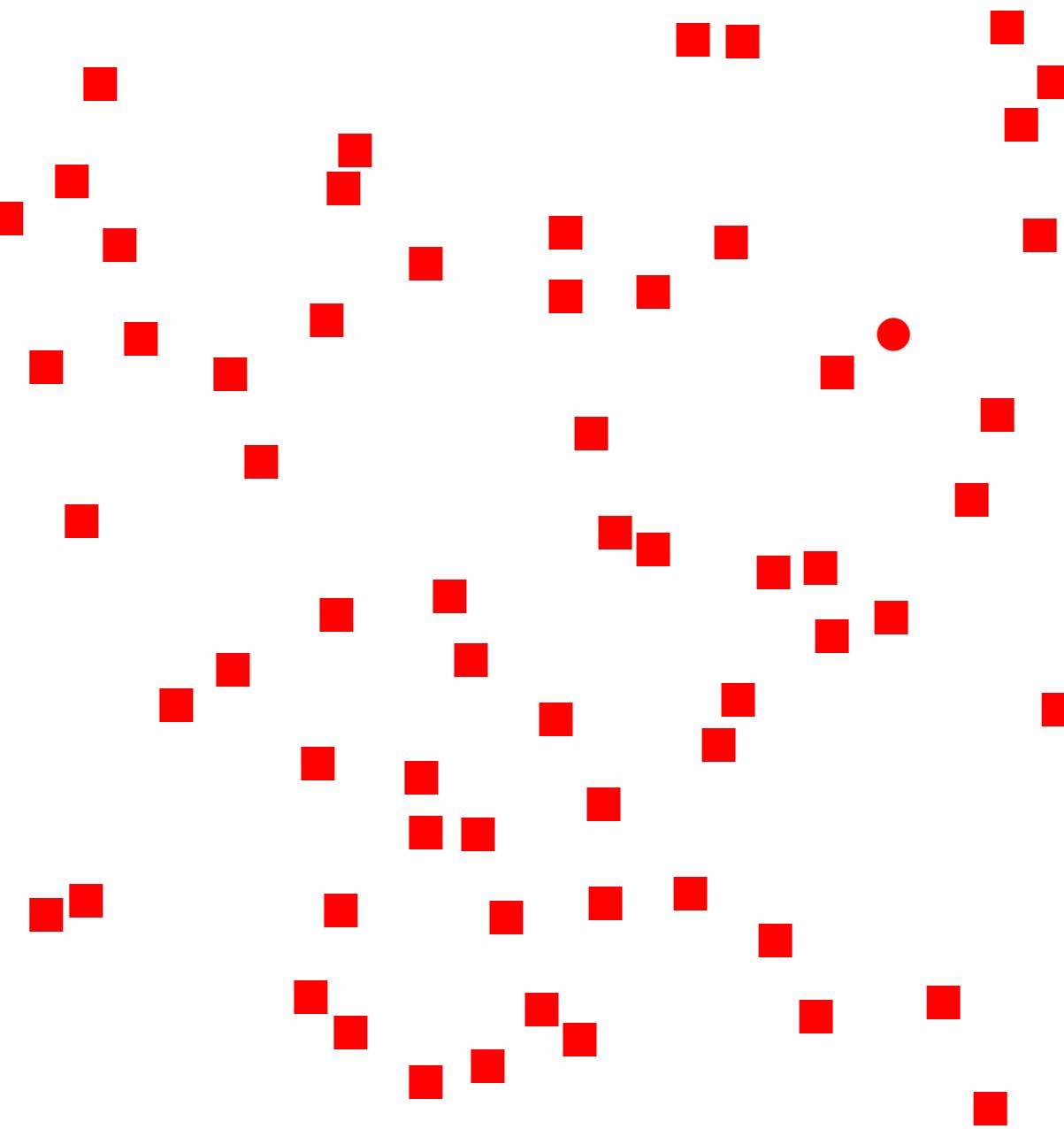
# Visual pop out



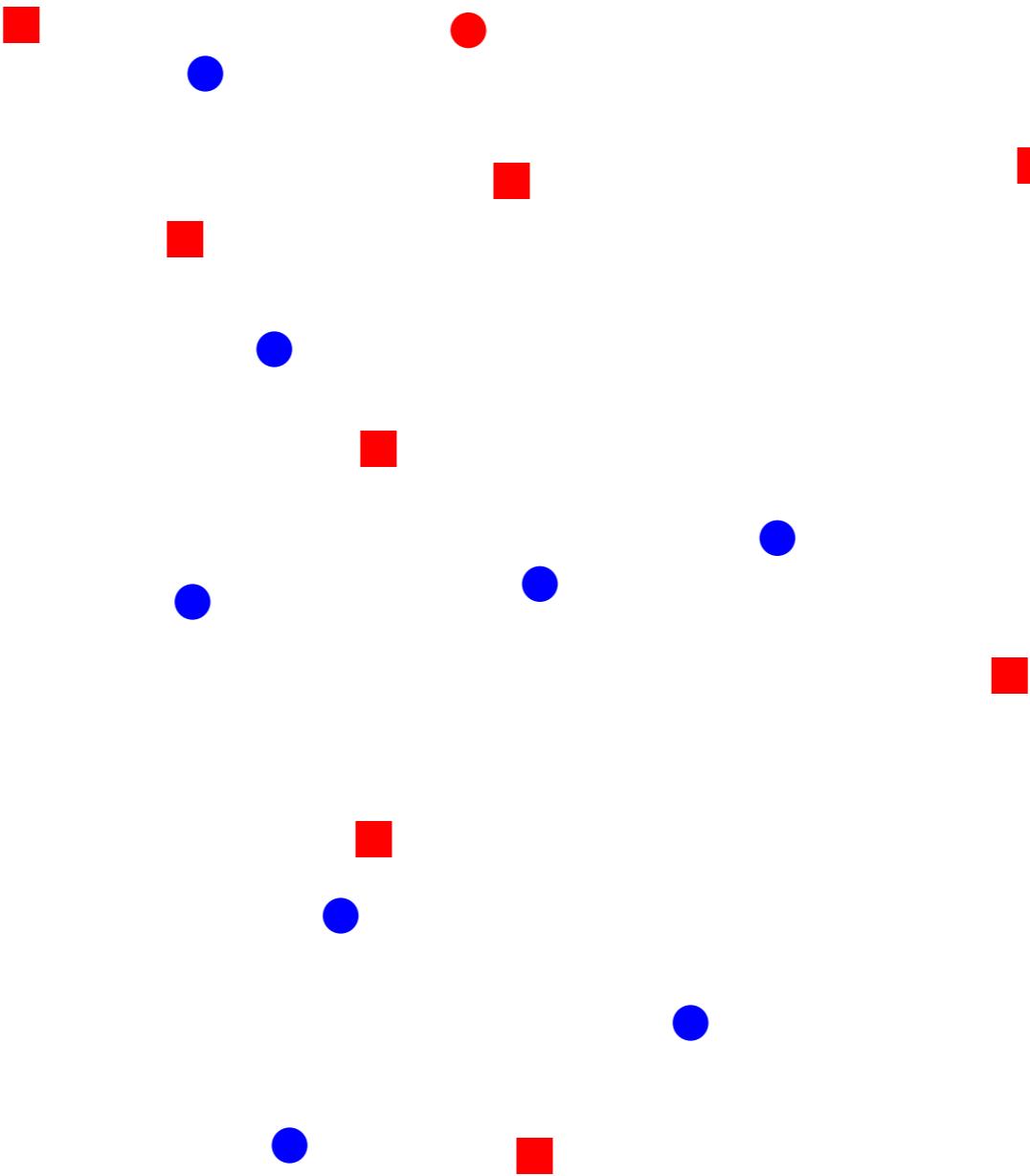
# Visual pop out



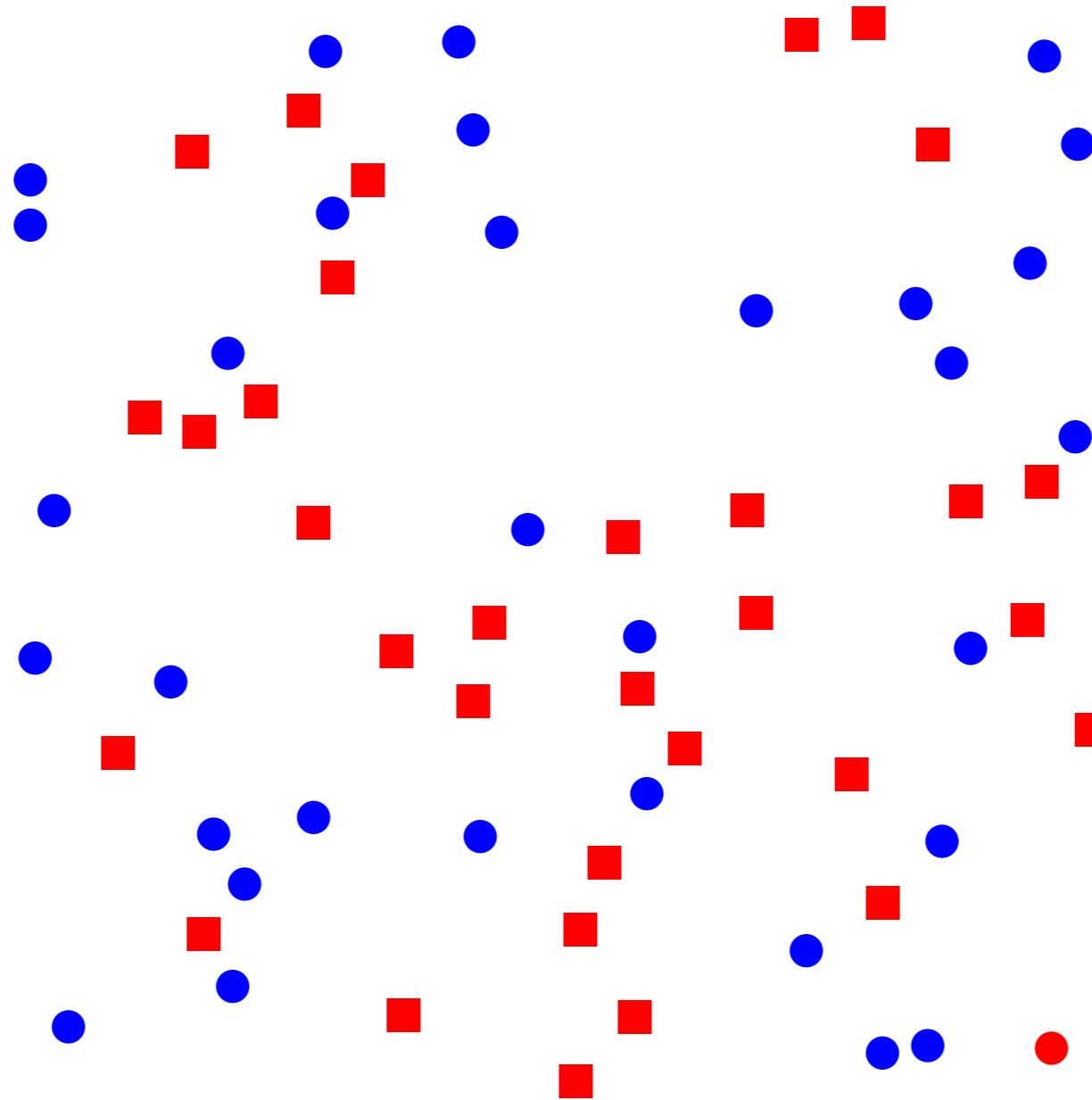
# Visual pop out



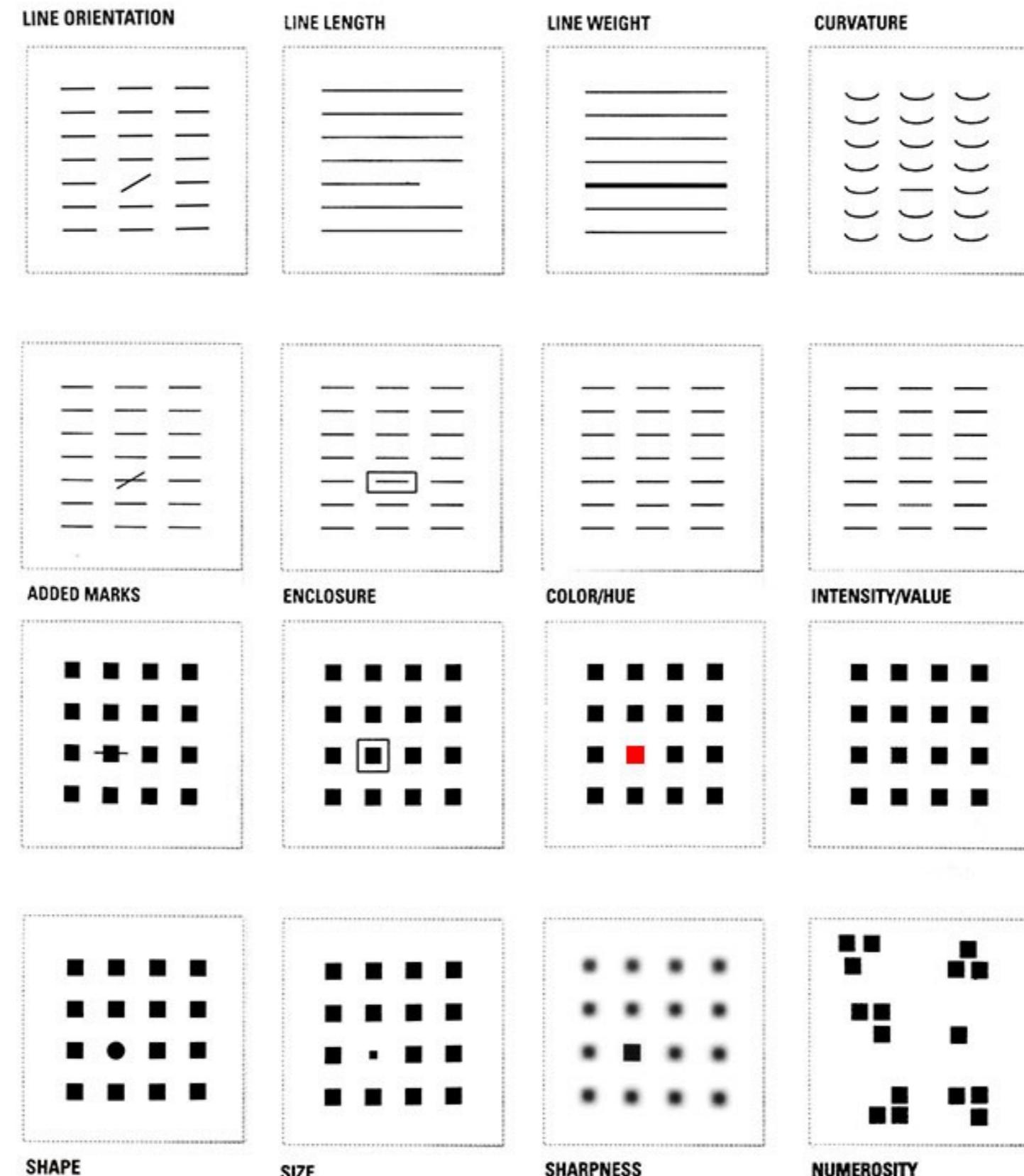
# Visual pop out



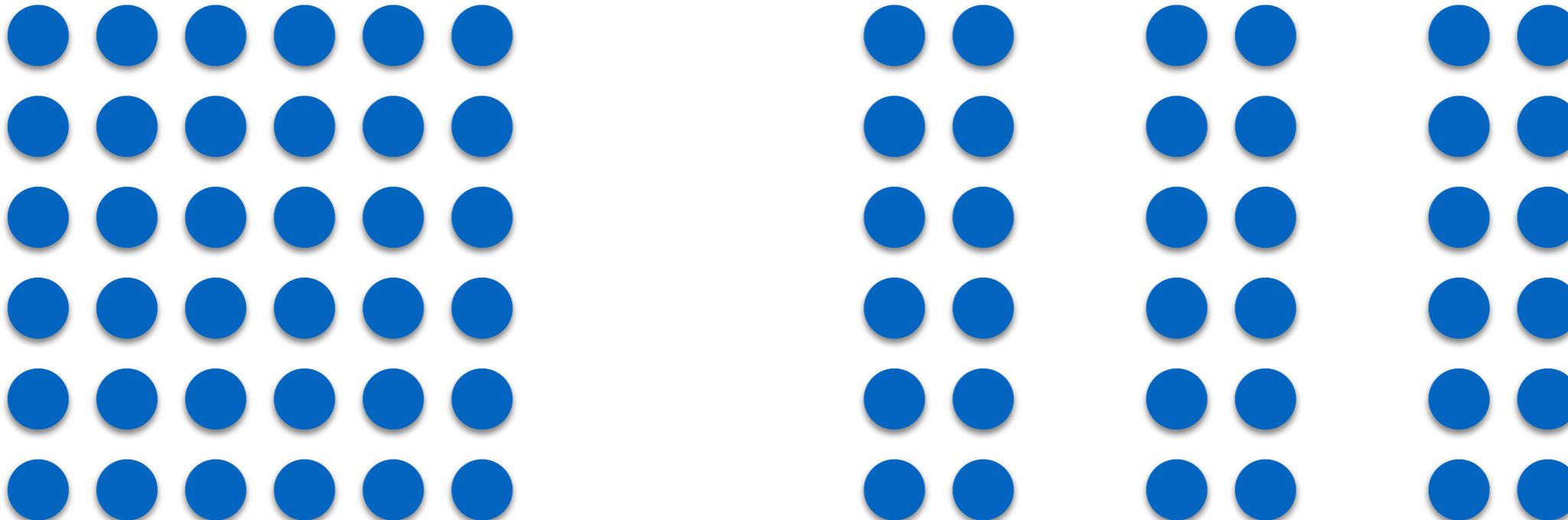
# Visual pop out



# Visual pop out

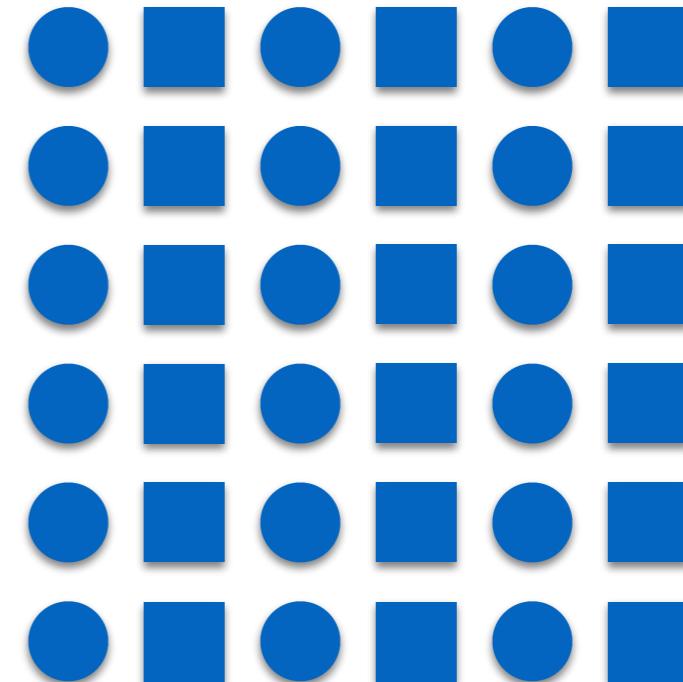
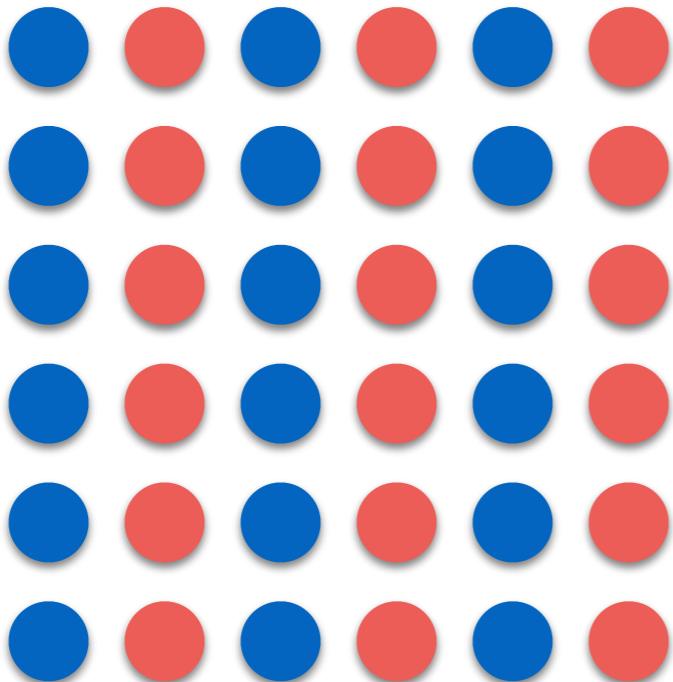


# Gestalt Laws of Perceptual Organization



**Law of proximity:** objects that are close together are likely to be perceived as a group.

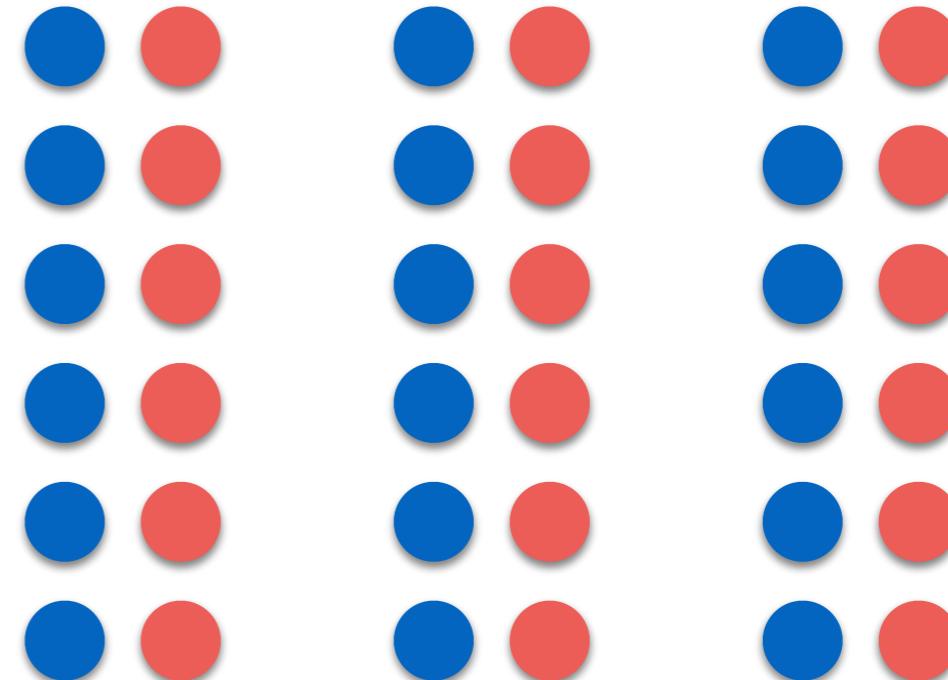
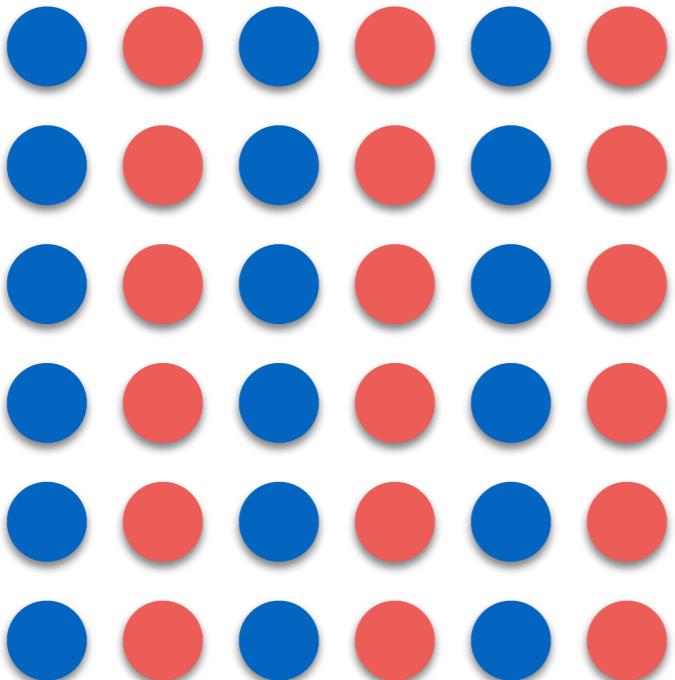
# Gestalt Laws of Perceptual Organization



**Law of similarity:** objects that look similar are likely to be perceived as a group.

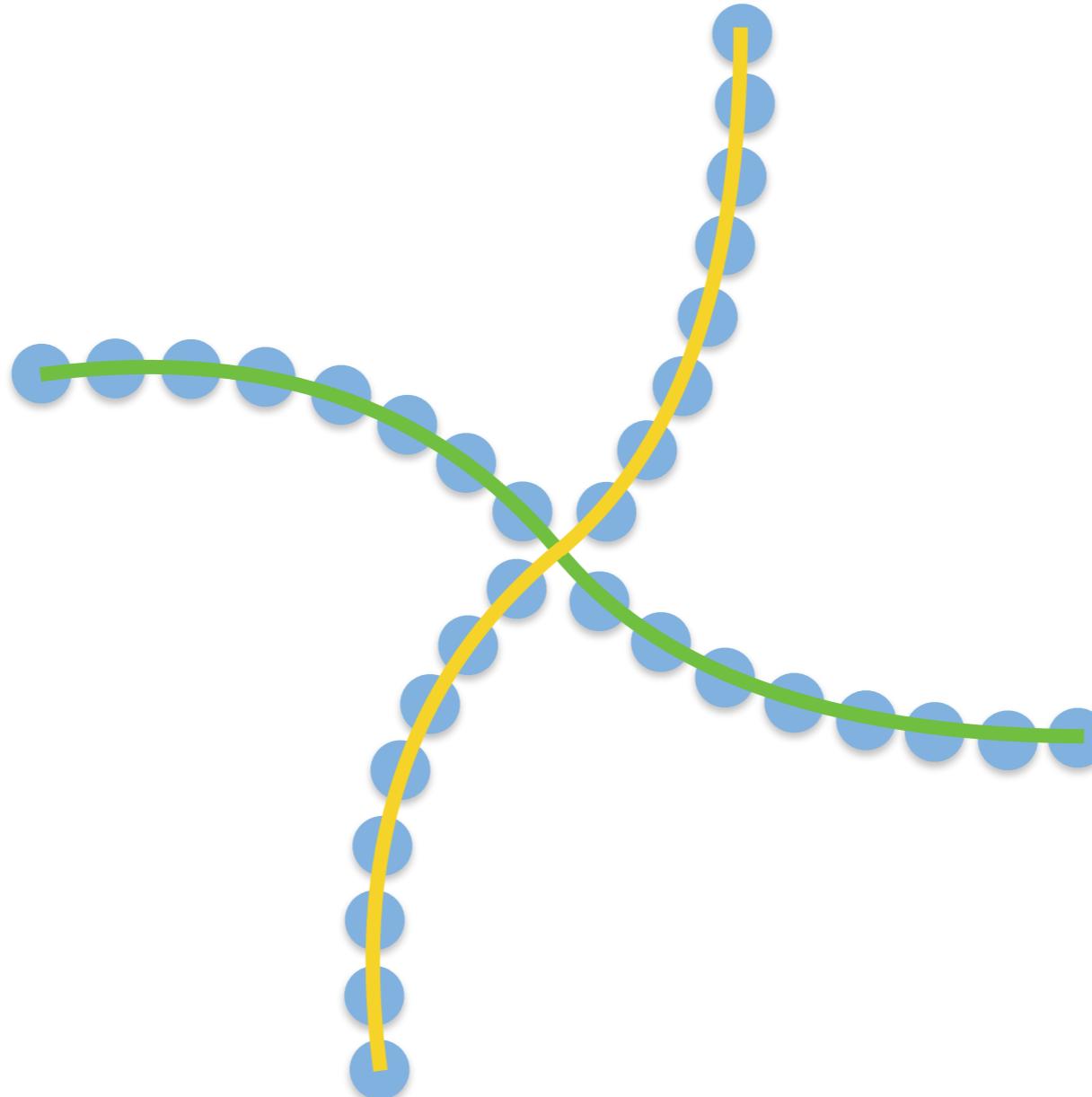
Similarity can occur in the form of color, shape, shading, etc.

# Gestalt Laws of Perceptual Organization



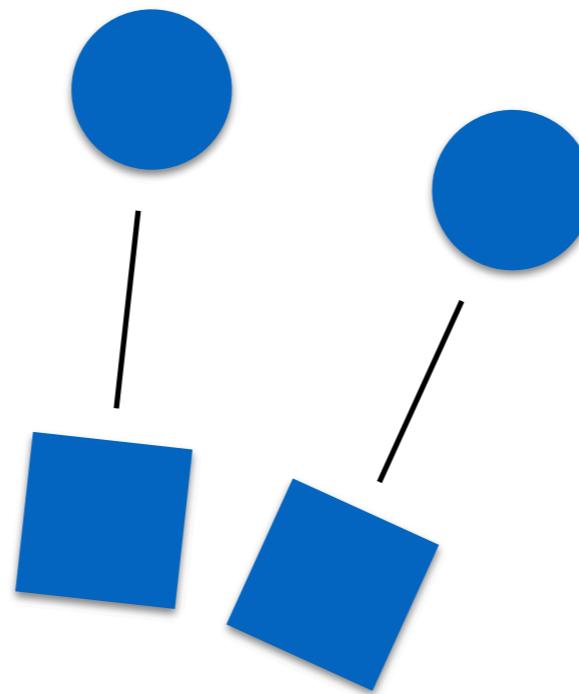
Proximity is stronger than color similarity

# Gestalt Laws of Perceptual Organization



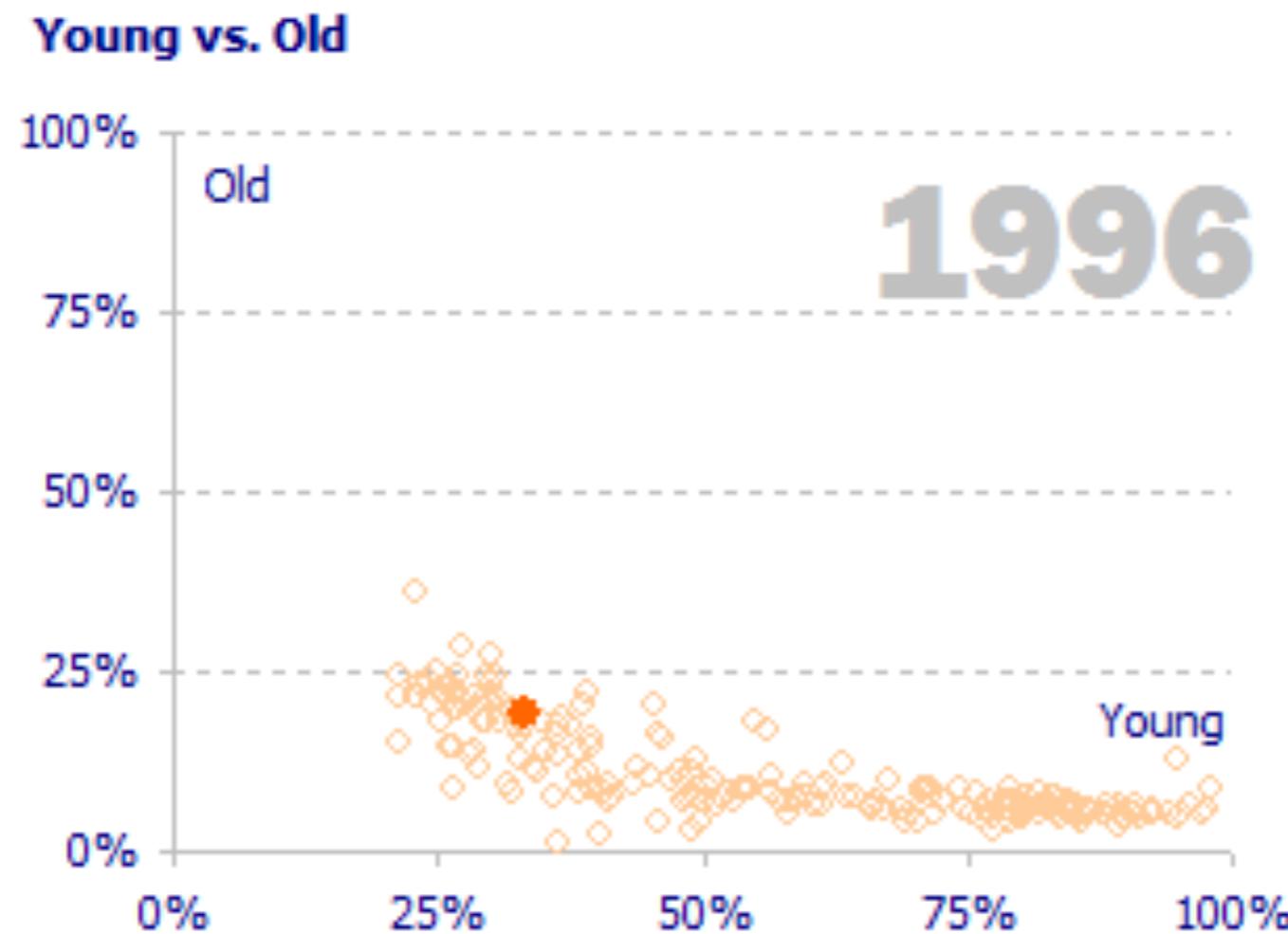
**Law of continuity:** objects that follow straight or curved lines without abrupt changes are perceived as belonging together. In cases where there is an intersection between objects, individuals tend to perceive the two objects as two single uninterrupted entities. Stimuli remain distinct even with overlap.

# Gestalt Laws of Perceptual Organization



**Law of Connectedness:** objects that are connected by lines are likely to be perceived as a group.  
This is true even if the resulting combinations are in conflict with other Gestalt laws.

# Gestalt Laws of Perceptual Organization



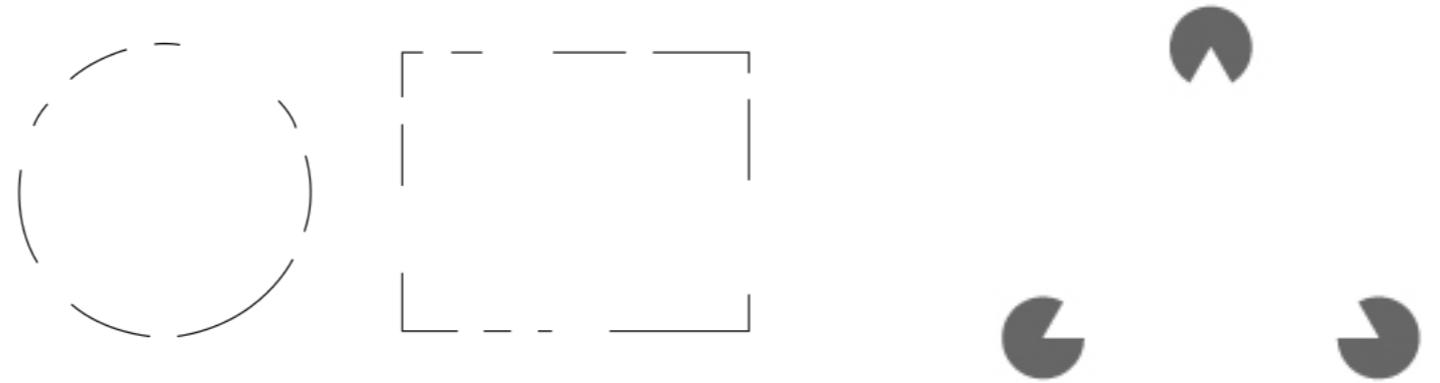
**Law of Common Fate:** objects that move together are likely to be perceived as a group.

Movement of elements of an object produce paths that individuals perceive that the objects are on.  
Objects that have the same trend of motion are perceived as being on the same path.

# Additional Gestalt Laws of Perceptual Organization

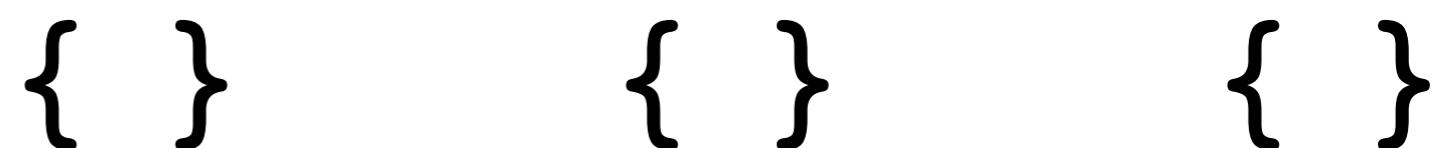
**Law of closure:** individuals perceive objects such as shapes, letters and images as being whole when they are not complete.

When parts of a whole picture are missing, our perception fills in the visual gap.



**Law of symmetry:** individuals perceive objects as being symmetrical and forming around a center point.

When two symmetrical elements are unconnected the mind perceptually connects them to form a coherent shape.



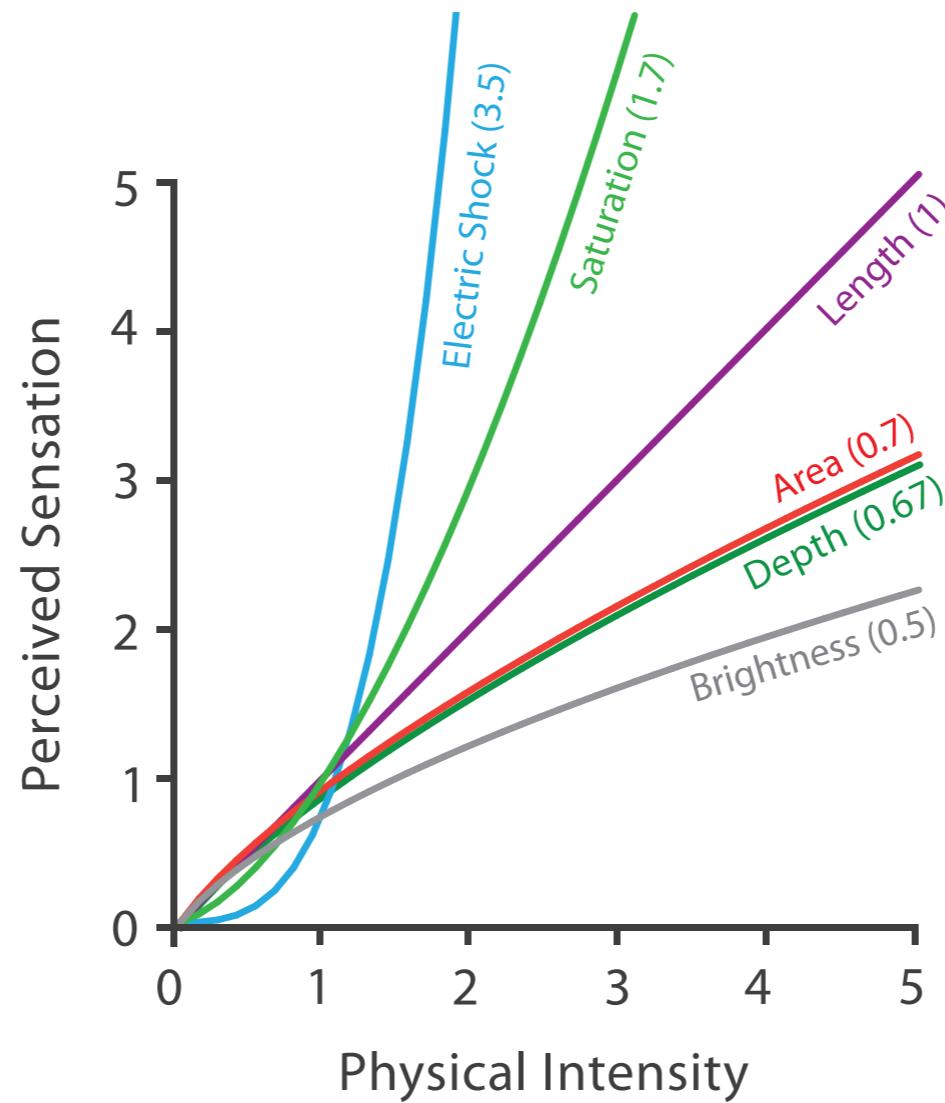
**Law of Good Figure / Prägnanz principle:** complex object are perceptually decomposed into simple geometries, based on the identification of regular, simple, orderly patterns.

Individuals eliminate complexity and unfamiliarity so they can observe a reality in its most simplistic form.



# Stevens' Psychophysical Power Law

Steven's Psychophysical Power Law:  $S = I^n$

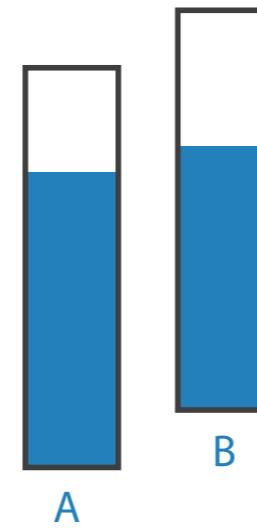


# Relative vs. absolute judgements

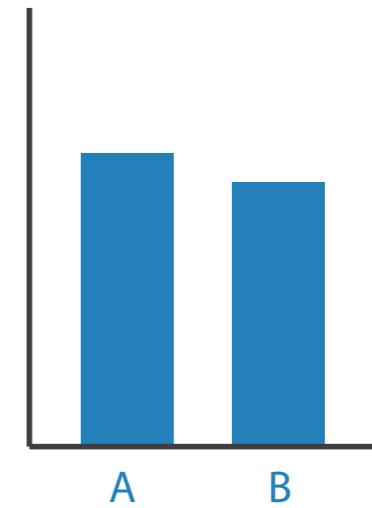
- Our perceptual system mostly operates with relative judgements, not absolute ones.
- Accuracy increases with common frame/scale and alignment.



*Length*



*Position along  
unaligned  
common scale*



*Position along  
aligned  
common scale*

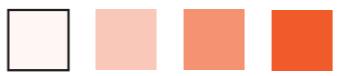
# Characterizing visual variables

- **Selective (related to visual popout):**  
Can this variable allow us to spontaneously differentiate/isolate items from groups?
- **Associative:**  
Can this variable allow us to spontaneously put items in a group?
- **Ordered:**  
Can this variable allow us to spontaneously perceive an order?
- **Quantitative:**  
Is there a numerical reading obtainable from changes in this variable?
- **Length, or rather, Discriminability (resolution):**  
Across how many changes in this variable are distinctions possible?
- **Accuracy:**  
Can we make accurate judgments about this variable in terms of perception?
- **Separability vs. Integrality:**  
Are two (or more) variables interfering with each other?

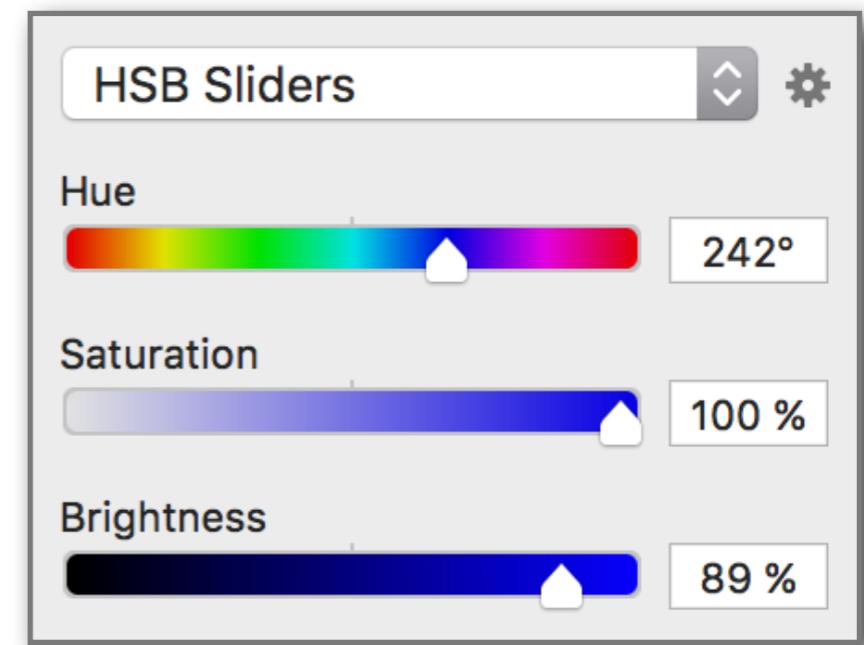
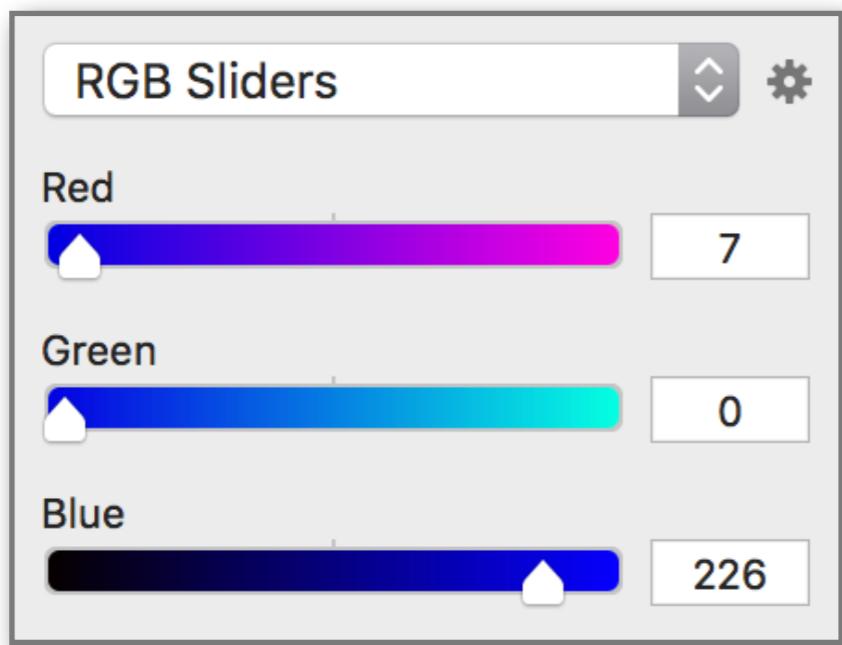
Color hue



Color saturation



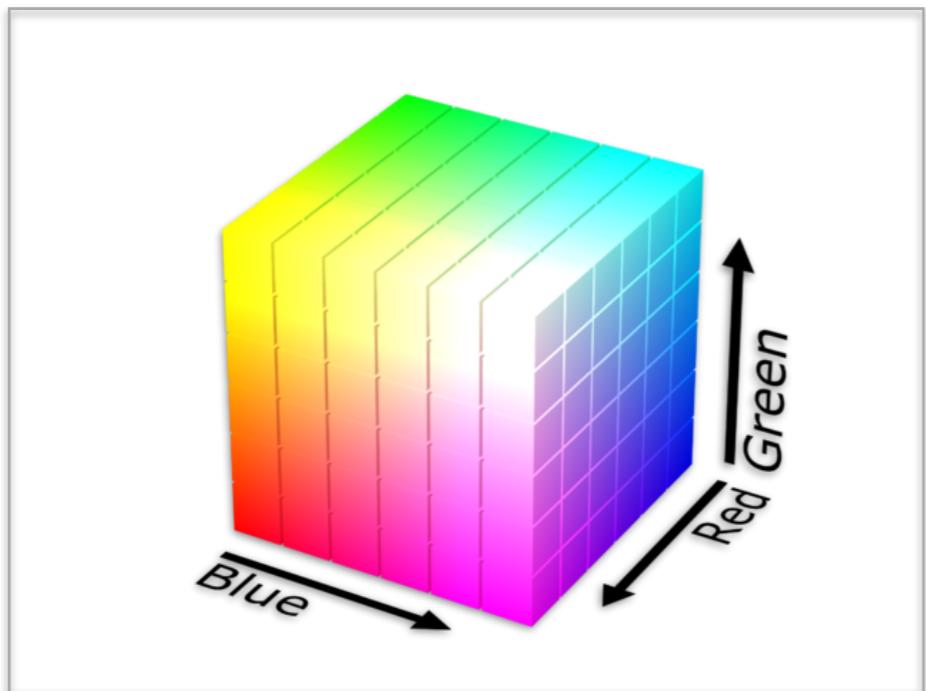
Color luminance



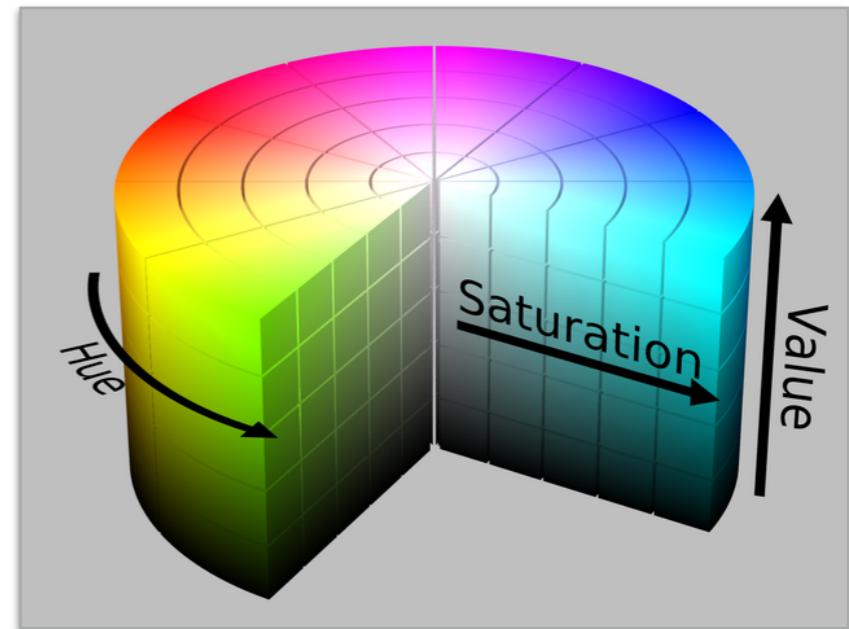
Color hue 

Color saturation 

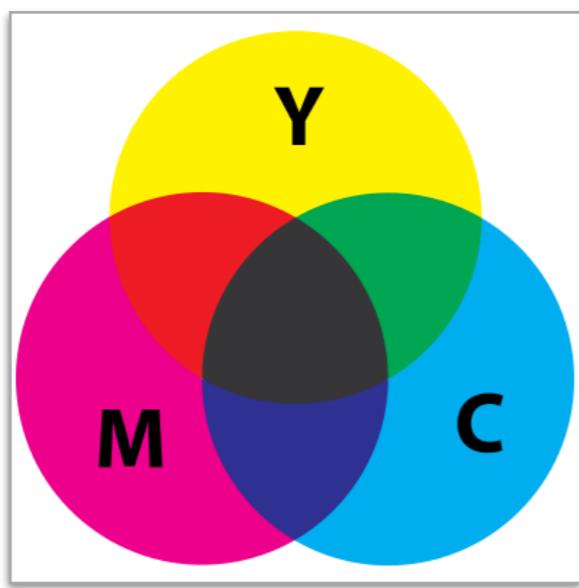
Color luminance 



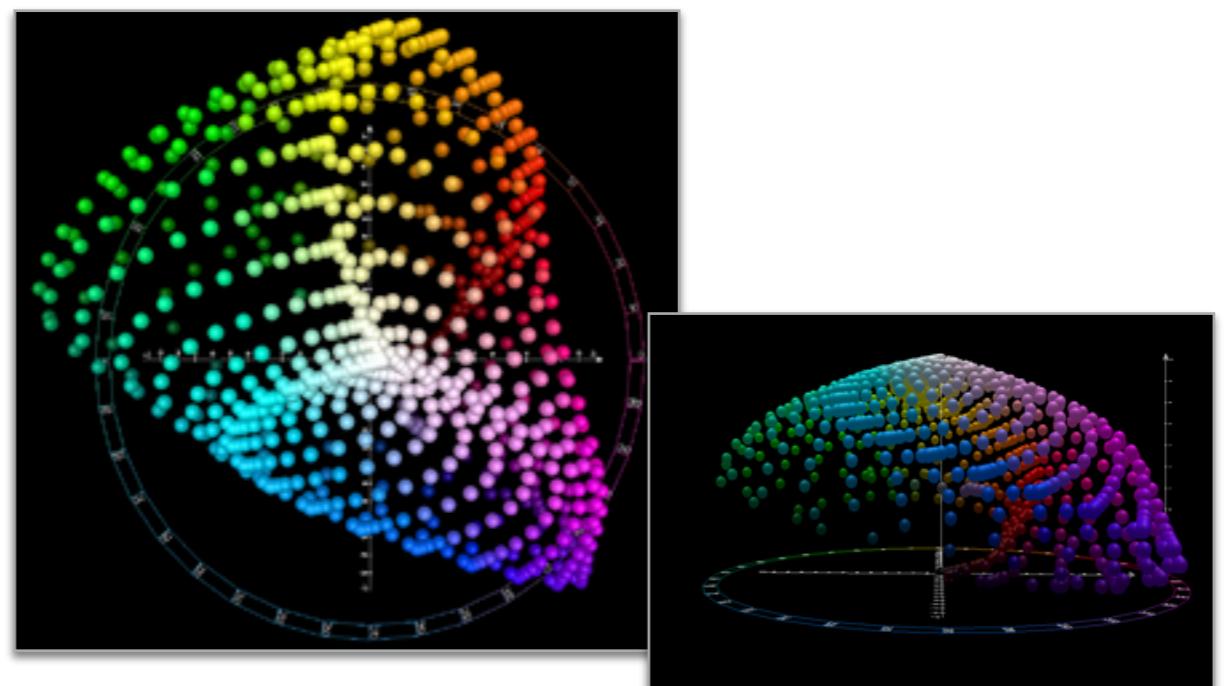
RGB



HSV

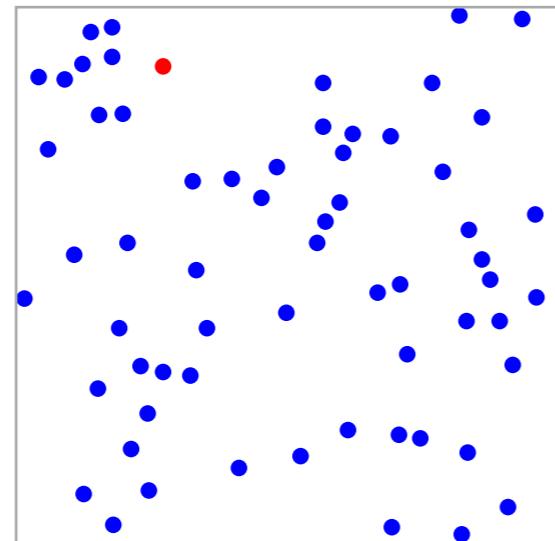


CMYK

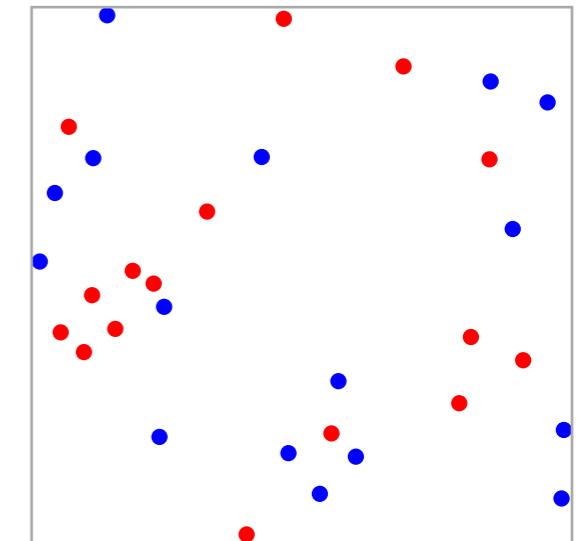


CIE L\*a\*b and L\*C\*h

- Selective: ✓



- Associative: ✓



- Ordered: ✗



- Quantitative: ✗

- Discriminability (resolution):

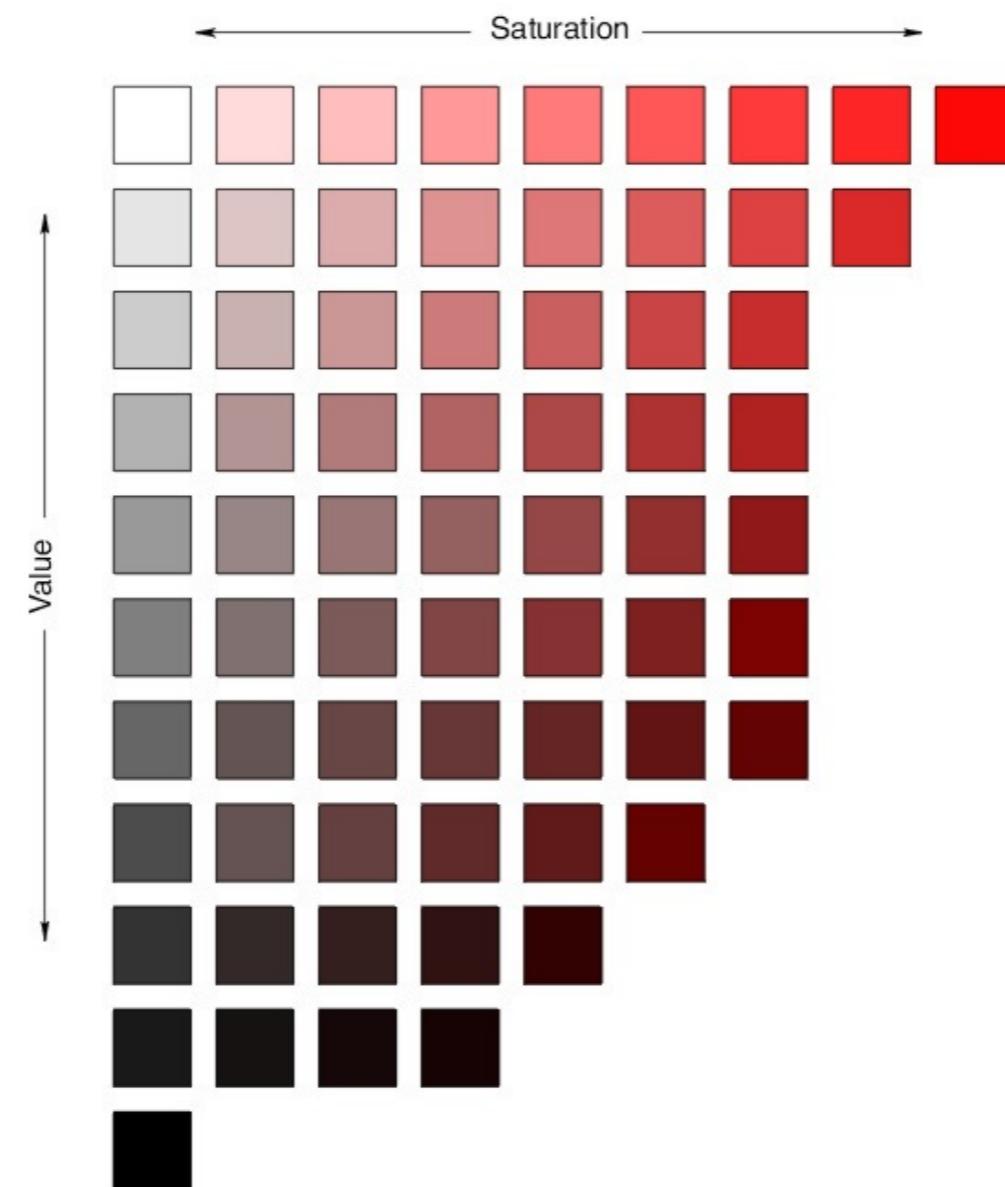
- in theory:  $\infty$

- in practice:  $\leq 7$  for selection and association,  $\leq 10$  for distinction **but...**

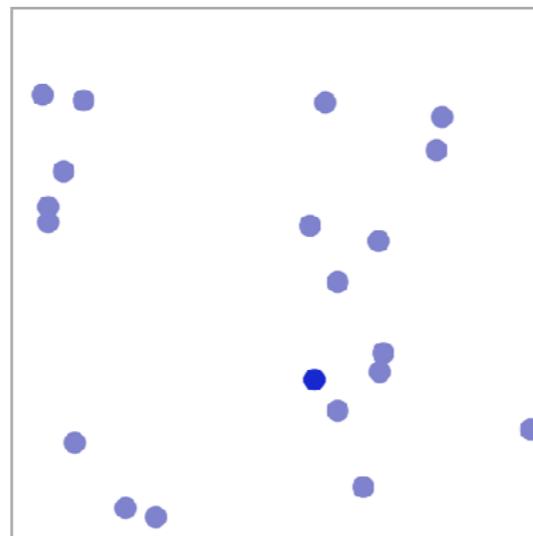
Color saturation



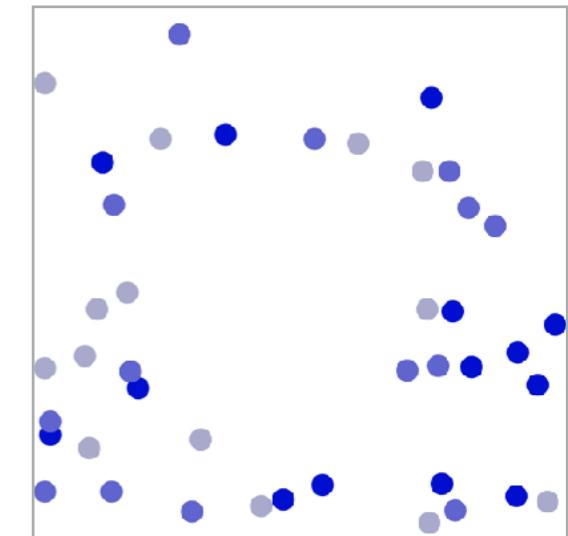
Color luminance



- Selective: ✓



- Associative: ✓



- Ordered: ✓

$$\square \leq \square \leq \square \leq \square$$

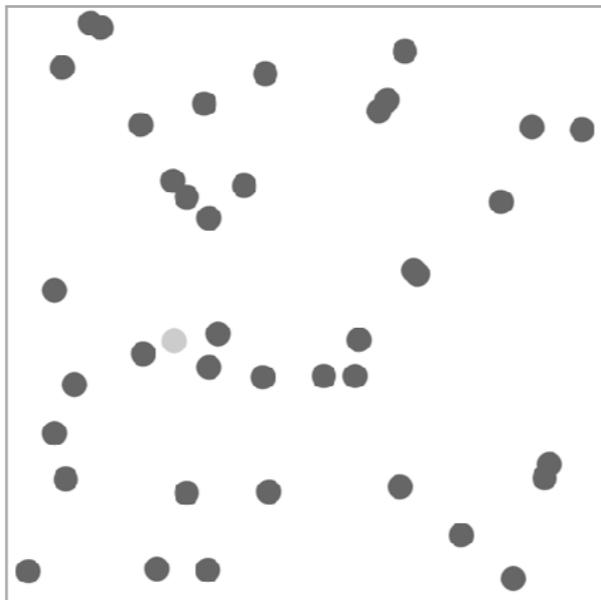
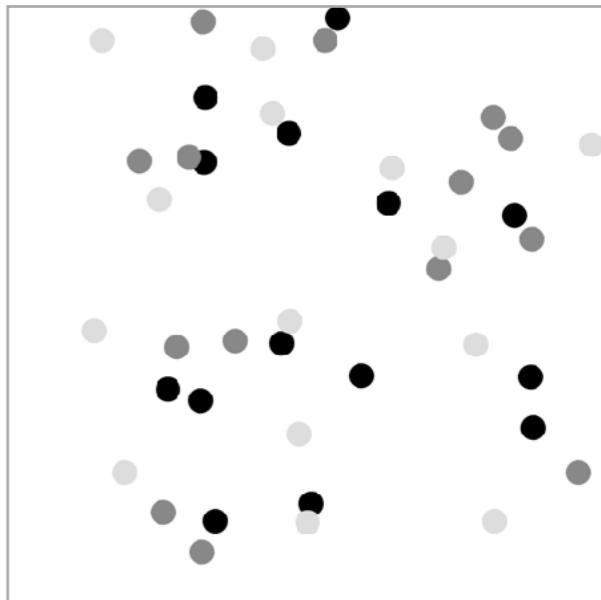
(will often be  $<$ , but depends on the semantics)

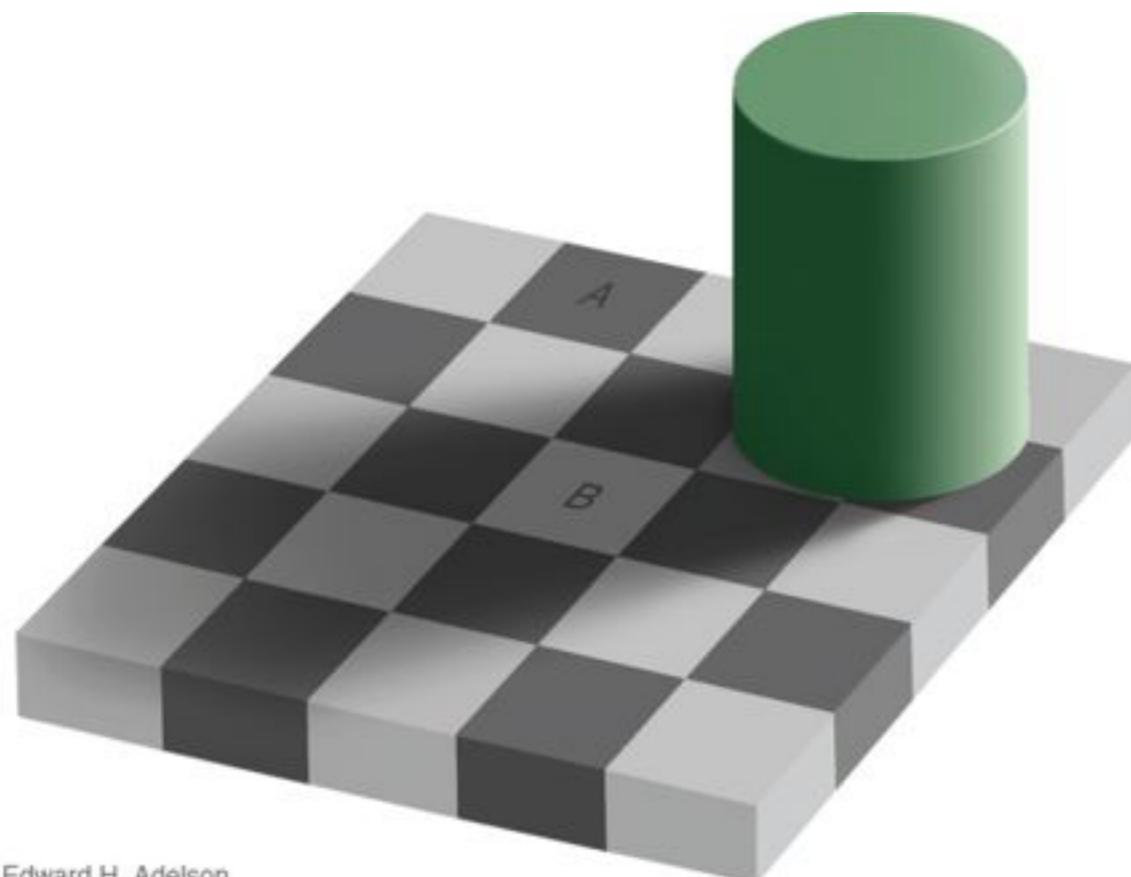
- Quantitative: ✗

- Discriminability (resolution):

- in theory:  $\infty$

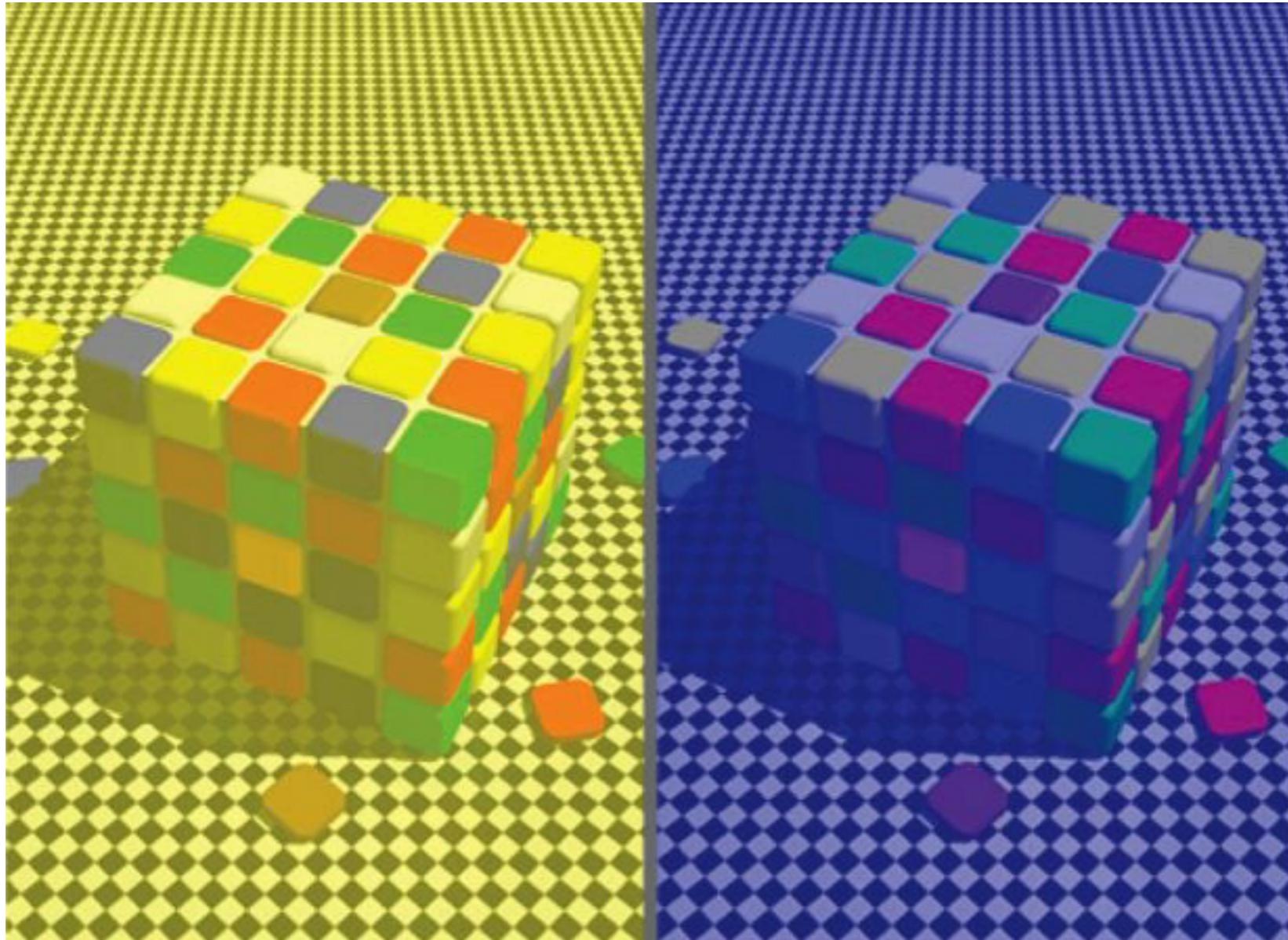
- in practice:  $\leq 7$  for selection and association,  $\leq 10$  for distinction

- Selective: ✓ 
- Associative: ✓ 
- Ordered: ✓  (highly depends on the semantics)
- Quantitative: ✗
- Discriminability (resolution):
  - in theory:  $\infty$
  - in practice:  $\leq 7$  for selection and association,  $\leq 10$  for distinction



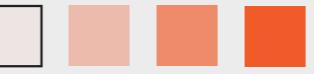
Edward H. Adelson

Luminance perception is based on relative, not absolute, judgements.



Color perception is also relative to surrounding colors and depends on context. Both cubes have tiles that appear to be red.

Color hue 

Color saturation 

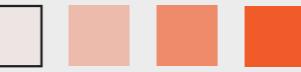
Color luminance 

# Sequential color scales

Variation in lightness is the most important parameter



Color hue 

Color saturation 

Color luminance 

# Sequential color scales

Variation in lightness is the most important parameter



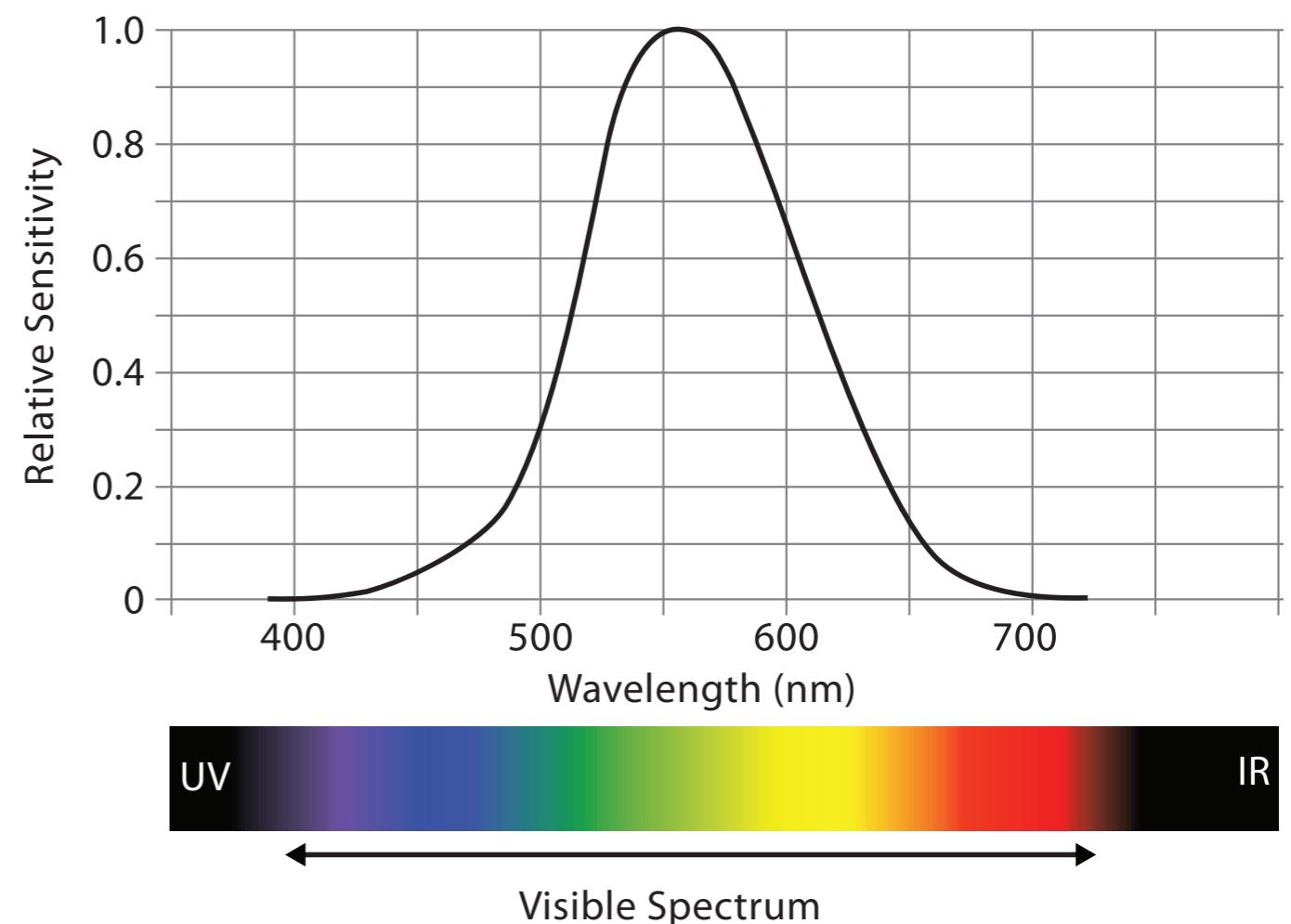
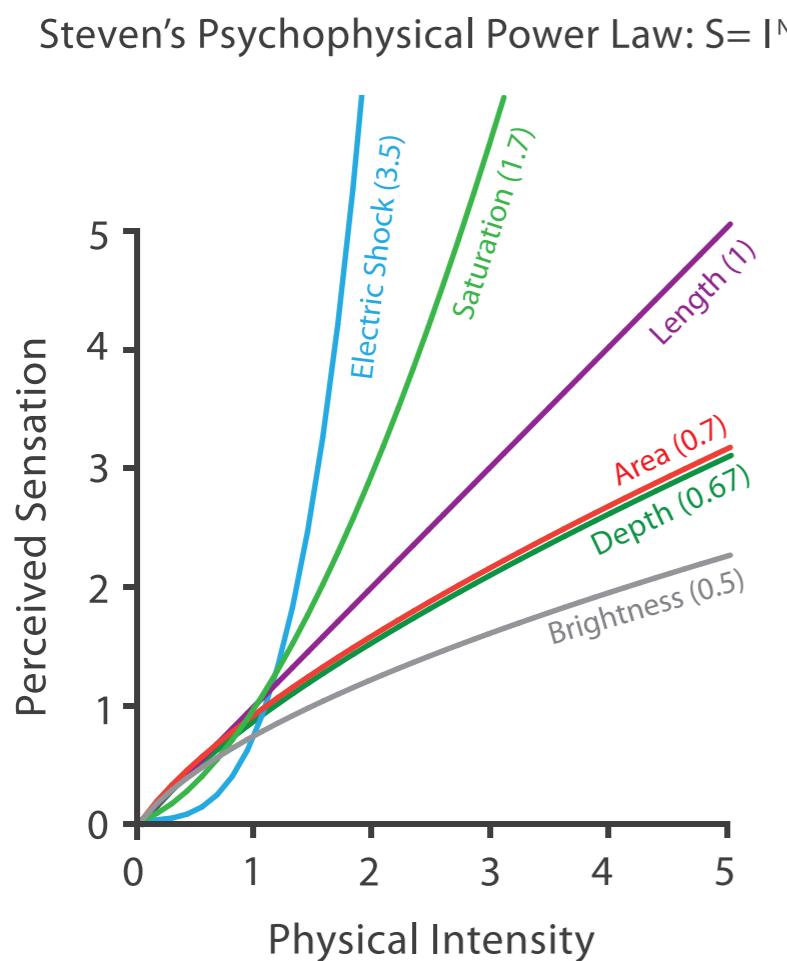
Varying the hue will provide further color contrast



# Photopic Spectral Sensitivity

More sensitive to changes at low light levels

More sensitive to green than red light, and even less sensitive to blue light



Color hue 

Color saturation 

Color luminance 

# Sequential color scales

Variation in lightness is the most important parameter



Varying the hue will provide further color contrast



Create *perceptually* linear variations. Counter example:

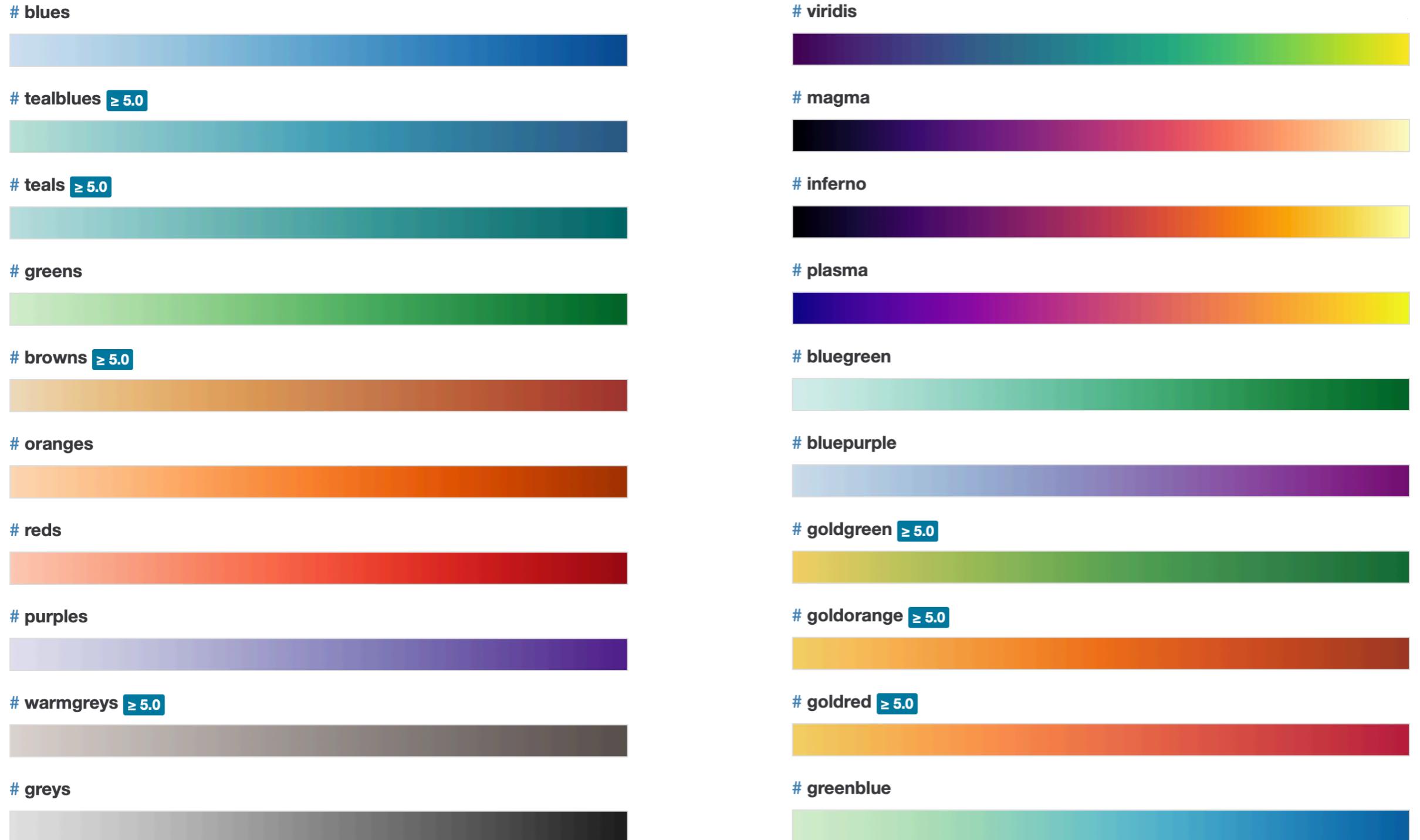


Color hue 

Color saturation 

Color luminance 

# Sequential color scales



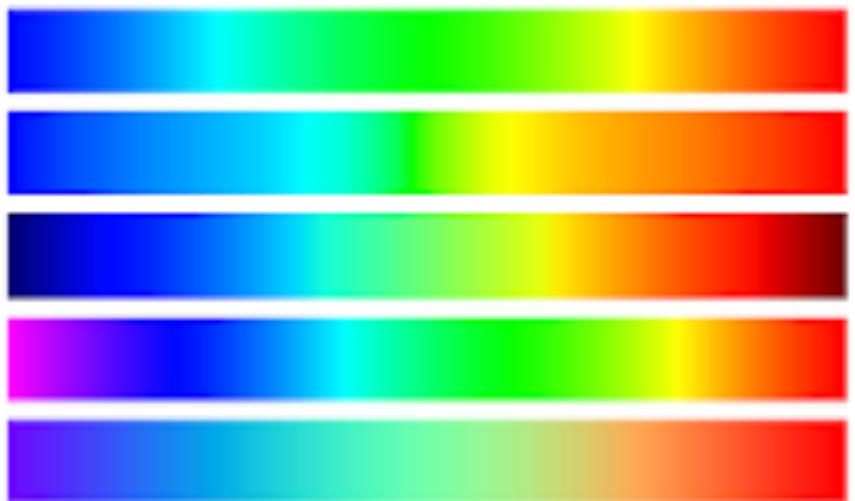
Color hue 

Color saturation 

Color luminance 

# Rainbow color scale(s)

We do not see it as ordered.



Luminance suggests depth (bright => peak)

Some scales are highly non-monotonic.

It tends to highlight arbitrary aspects of the data.

It makes us see categorical boundaries in  
otherwise continuous data (illusory discretization).

Color hue



Color saturation



Color luminance



# Bifurcated color scales

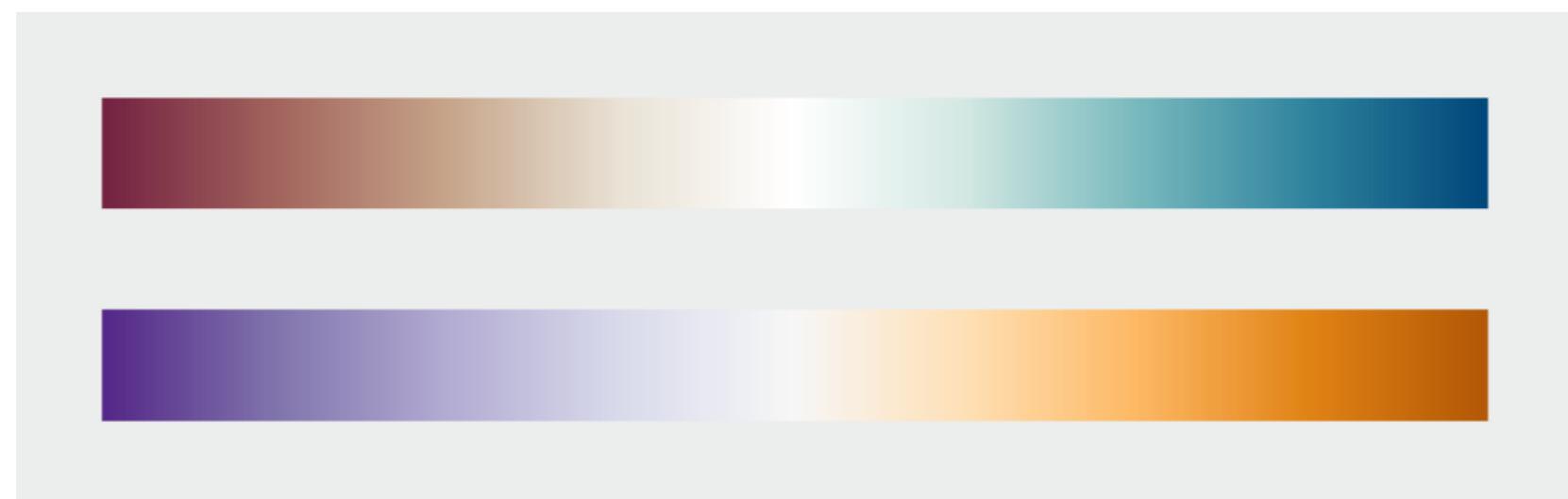
Divergent (or bipolar) data:

varies from a central value

implies a qualitative change as it crosses a threshold

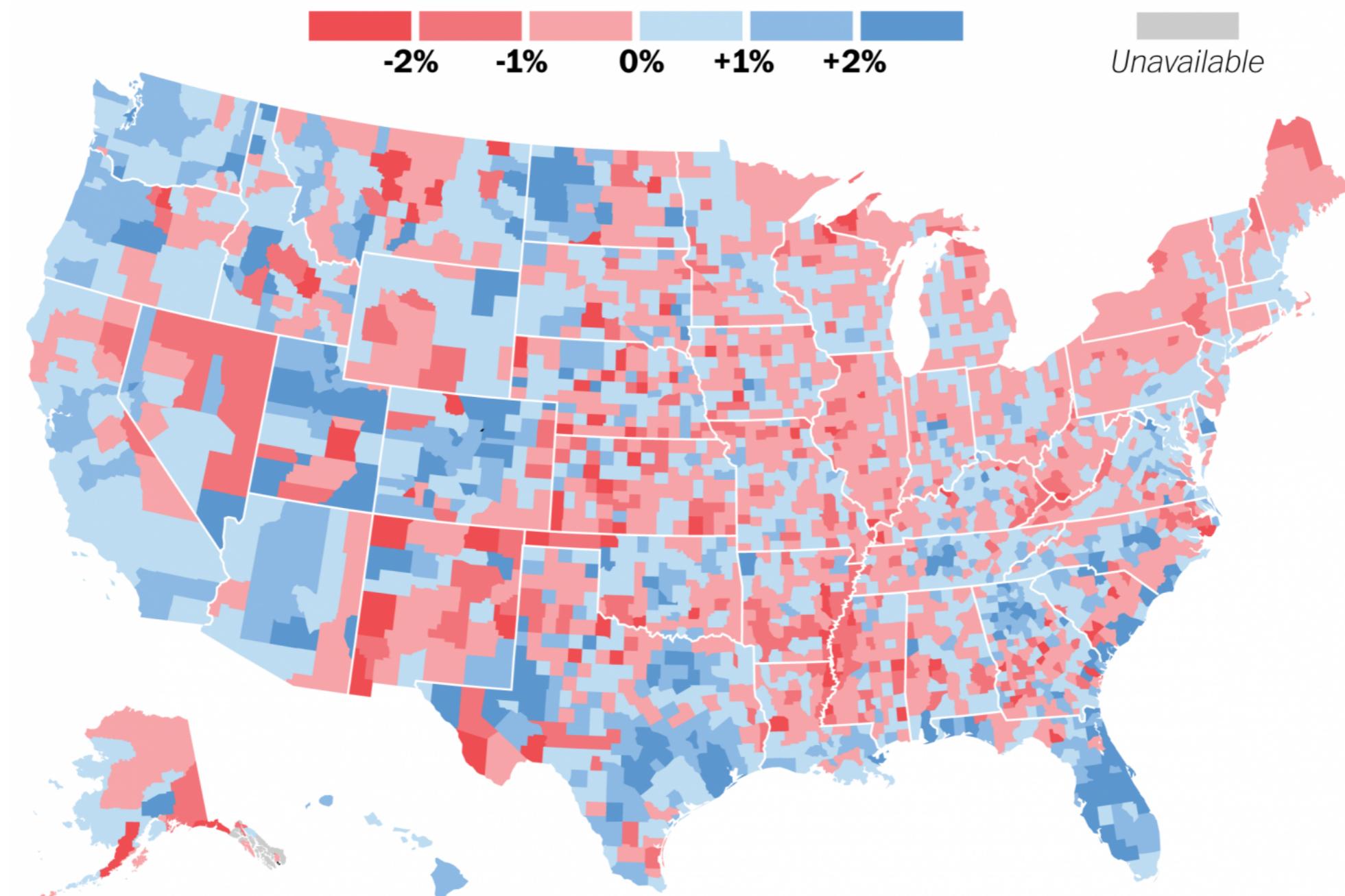
Best represented with a bifurcated color palette

neutral color at the center



## A year of population change

Percent change in population 2014 – 2015



---

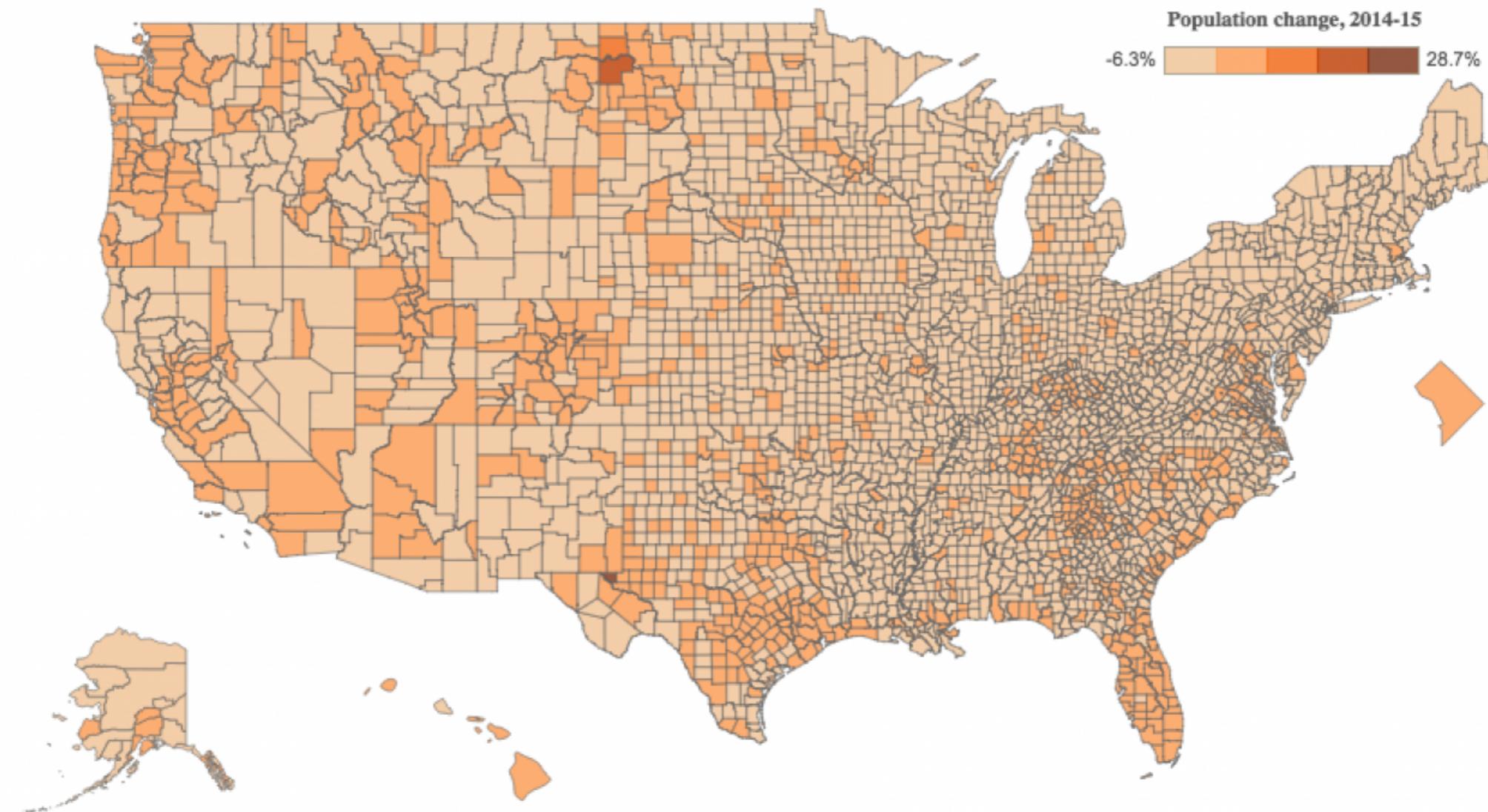
WAPO.ST/WONKBLOG

Source: U.S. Census Bureau

# Improper use of color (exact same data as previous map)

## Population Growth

Population growth slowed last year in some of the nation's most expensive counties, like those in California's Silicon Valley, and picked up in more affordable counties in the Sun Belt. Hover over counties for details.

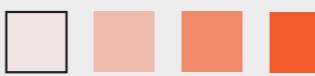


Stateline data visualization, April 2016 | Source: U.S. Census Bureau

Color hue



Color saturation

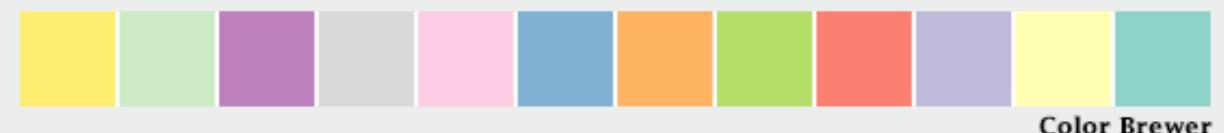


Color luminance

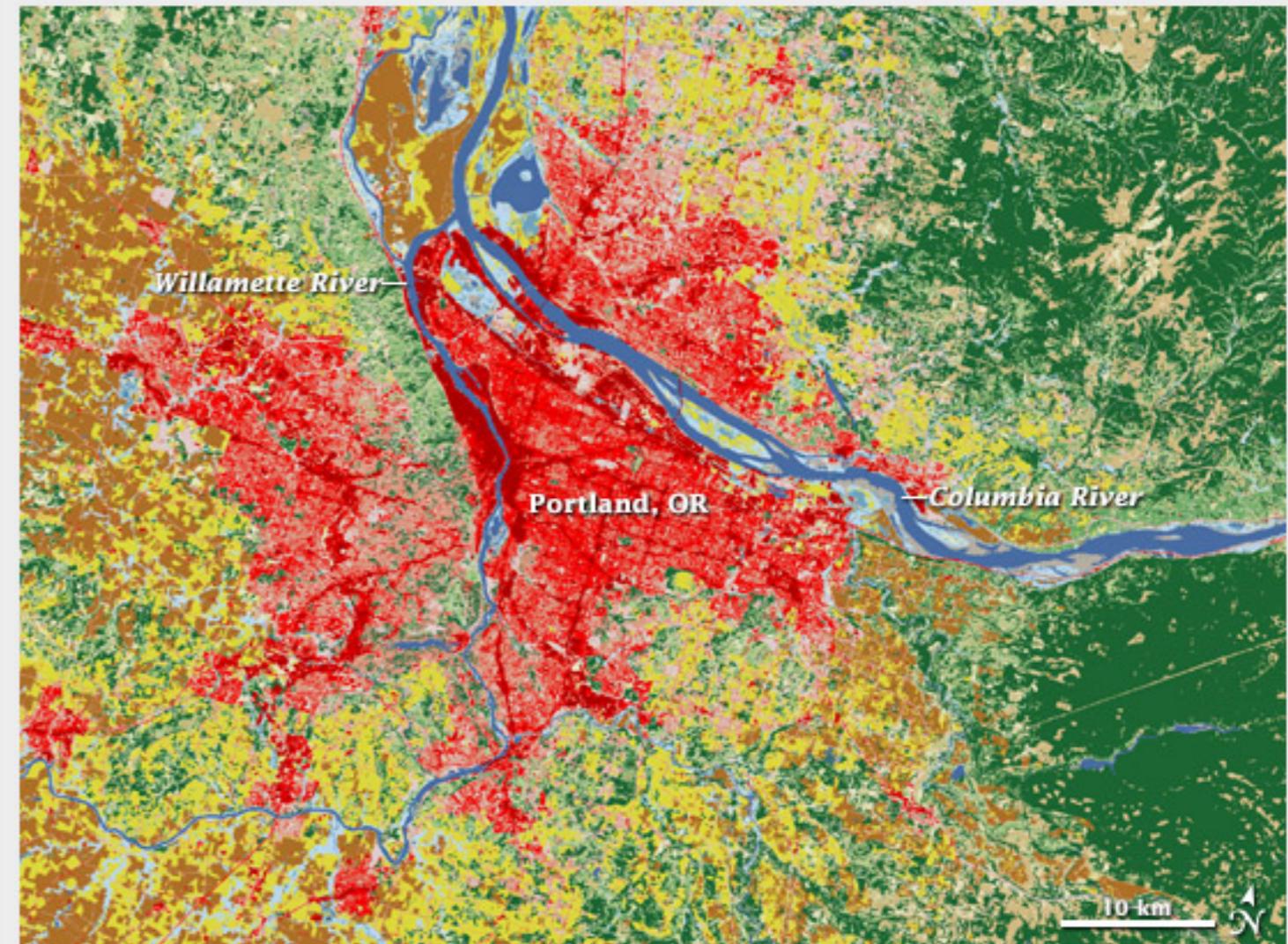


# Qualitative color schemes

Colors as distinct from one another as possible.



If too many categories, try to group them:



# Color Palettes for data visualization

Number of data classes: 6  
Nature of your data: sequential  
Pick a color scheme: Multi-hue, Single hue  
Only show: colorblind safe, print friendly, photocopy safe  
Context: roads, cities, borders  
Background: solid color, terrain, color transparency  
© Cynthia Brewer, Mark Harrower and The Pennsylvania State University  
Source code and feedback  
Back to Flash version  
Back to ColorBrewer 1.0

<http://colorbrewer2.org>

VIZ PALETTE By: Elijah Meeks & Susie Lu

PICK

Use Chroma.js Add Replace

EDIT

7 Colors Add #hex #rgb #hsl

GET

#1ee6f6 #d0d1e6 #a6bddb #74a9cf #2b8cbe #045a8d

<https://projects.susielu.com/viz-palette>

Colorghical Source

Generate

Background color: #f0f0f0  
Font color: #000000  
Number of colors: 5  
Charts made with Sera

Score importance: Perceptual Distance  
Name Difference, Pair Preference, Name Uniqueness

Color Population: No Color Deficiency - 96%, Deuteranomaly - 2.7%, Protanomaly - 0.66%, Protanopia - 0.59%  
Deuteranopia - 0.56%, Greyscale

Sample font Randomize Data Stroke: Dark, None

Select hue filters: 90°, 180°, 270°

Charts:

- [LCH(85,42,135)\*, "LCH(30,1f"]
- [LCH(85,42,135) + start]
- [LCH(30,16,-162) + start]
- [LCH(85,70,159) + start]
- [LCH(30,30,180) + start]
- [LCH(55,47,162)\*, "LCH(85,5i"]
- [LCH(55,47,162) + start]
- [LCH(85,57,165) + start]
- [LCH(30,25,169) + start]
- [LCH(85,21,-166) + start]
- [LCH(55,34,-117)\*]
- [LCH(55,34,-117) + start]

<http://vrl.cs.brown.edu/color>

# Color Palettes for UI design

MATERIAL DESIGN

Color > The color system > Tools for picking colors

Material System	300	#9575CD	300	#7985CB	300	#64B5F6
Introduction	400	#7E57C2	400	#5C6BC0	400	#42A5F5
Material studies	500	#673ABA	500	#3F51B5	500	#2196F3
Material Foundation	600	#5E35B1	600	#3949AB	600	#1E88E5
Foundation overview	700	#512DA8	700	#3039FF	700	#1976D2
Environment	800	#4527A0	800	#283593	800	#1565C0
Layout	900	#311B92	900	#1A237E	900	#0D47A1
Navigation	A100	#B388FF	A100	#8C9EFF	A100	#82B1FF
Color	A200	#7C4dff	A200	#536DFE	A200	#448AFF
The color system	A400	#651FFF	A400	#3D5AFE	A400	#2979FF
Applying color to UI	A700	#6200EA	A700	#304FFE	A700	#2962FF
Color usage	Light Blue 50	#E1F5FE	Cyan 50	#EOF7FA	Teal 50	#EOF2F1
Text legibility	100	#B3E5FC	100	#B2EBF2	100	#B2DFDB
Dark theme	200	#81D4FA	200	#80DEEA	200	#80CBC4
Typography	300	#4FC3F7	300	#4DD0E1	300	#4DB6AC
Sound	400	#29B6F6	400	#26C6DA	400	#26A69A
Iconography	500	#03A9F4	500	#00BCD4	500	#009688
Gloss	600	#039BE5	600	#00ACC1	600	#00897B

<https://material.io/design/color/#tools-for-picking-colors>

Adobe Color

CREATE EXPLORE TRENDS MY THEMES Sign In

Search with colors, moods or keywords like ocean, wine, moonlight, lucky, water...

GLOWING, GLOWING, GONE The Colors of Climate Crisis

View All Sources

Language: English Terms of Use Privacy User Forums Community Guidelines Copyright © 2019 Adobe. All rights reserved. AdChoices

<https://color.adobe.com/explore>

# Color vision deficiency

Trichromacy: response functions of cones to light waves - blue (S), green (M), red (L)

1 in 20 people suffer from some type of color vision deficiency:  
protanopia, deutanopia, or tritanopia, ...

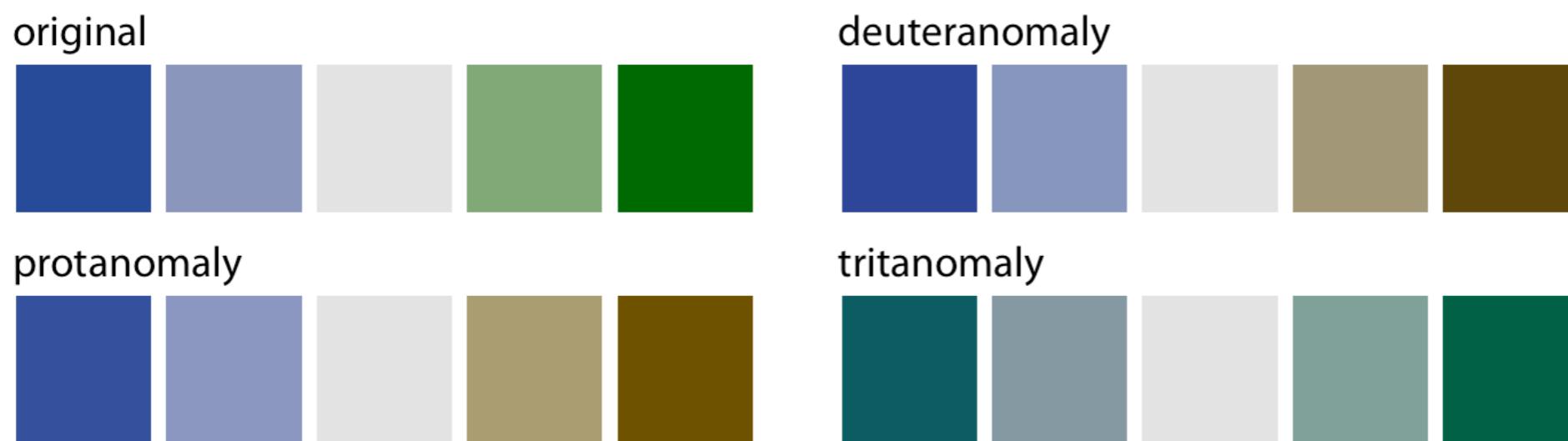
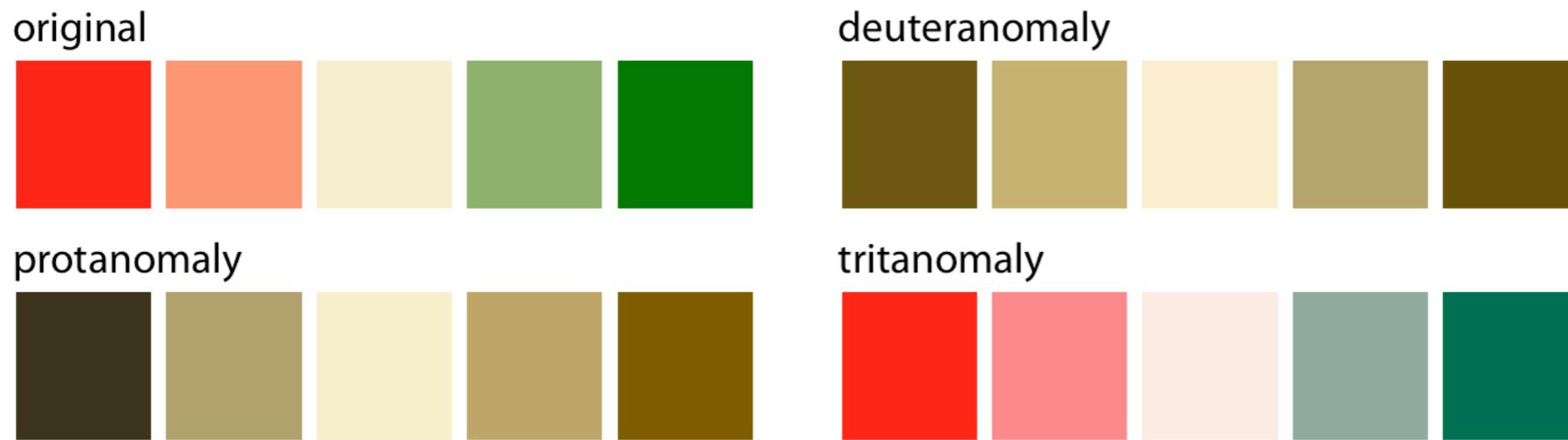
8% of men, 0.5% of women

Anomalies in the cone cells, which are responsible for detecting primary colors (red, green, blue)

Intentionally bad palette:

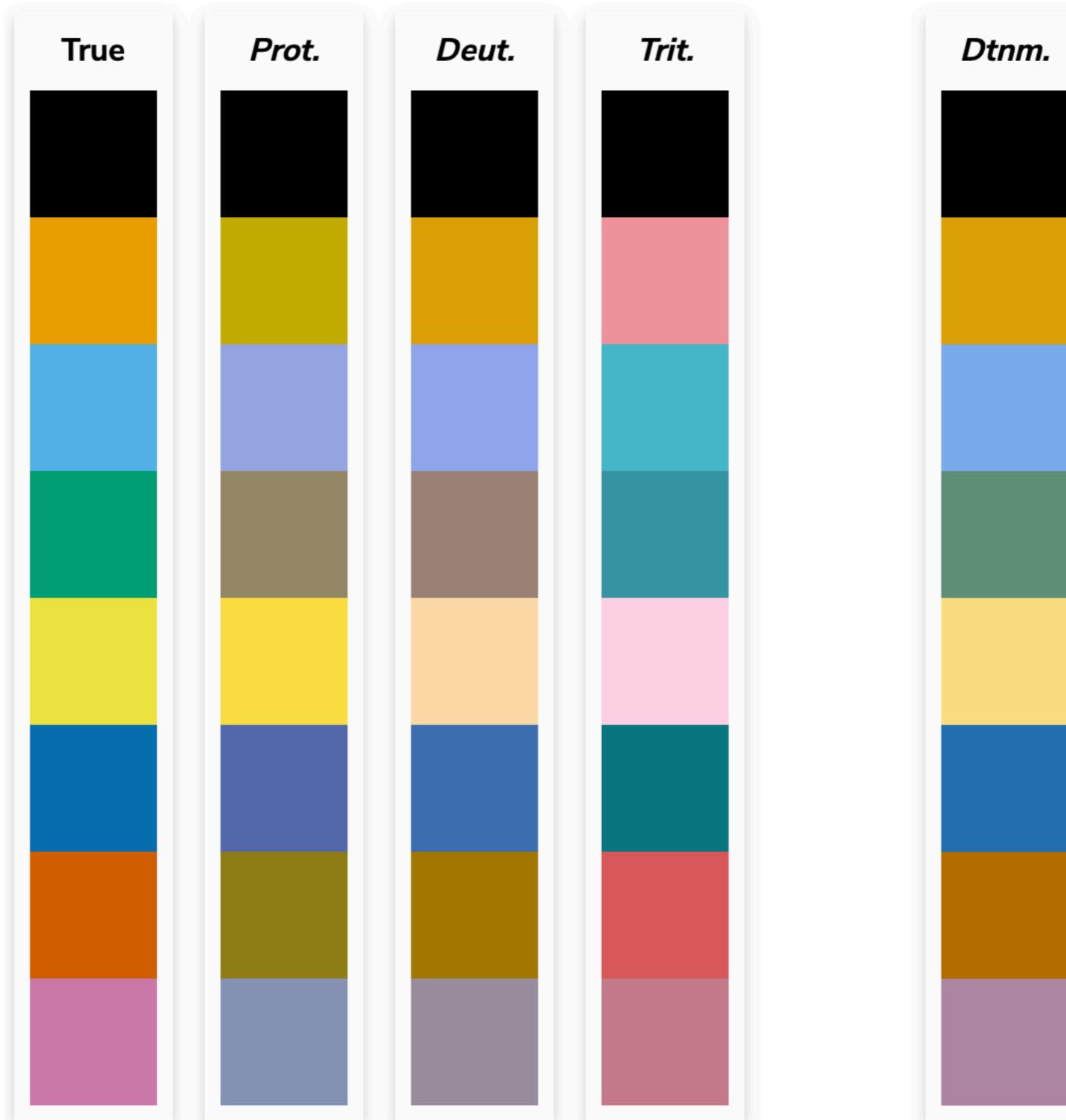


# Color vision deficiency



# Color vision deficiency

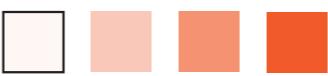
Conservative 7-color palette adapted for color blindness



Color hue



Color saturation



Color luminance

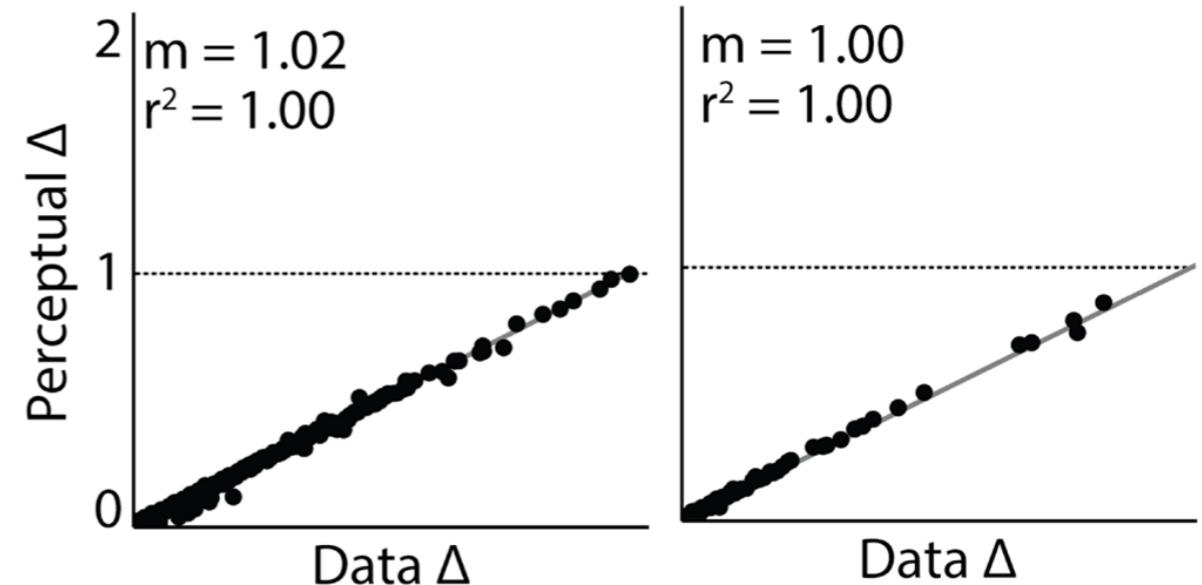
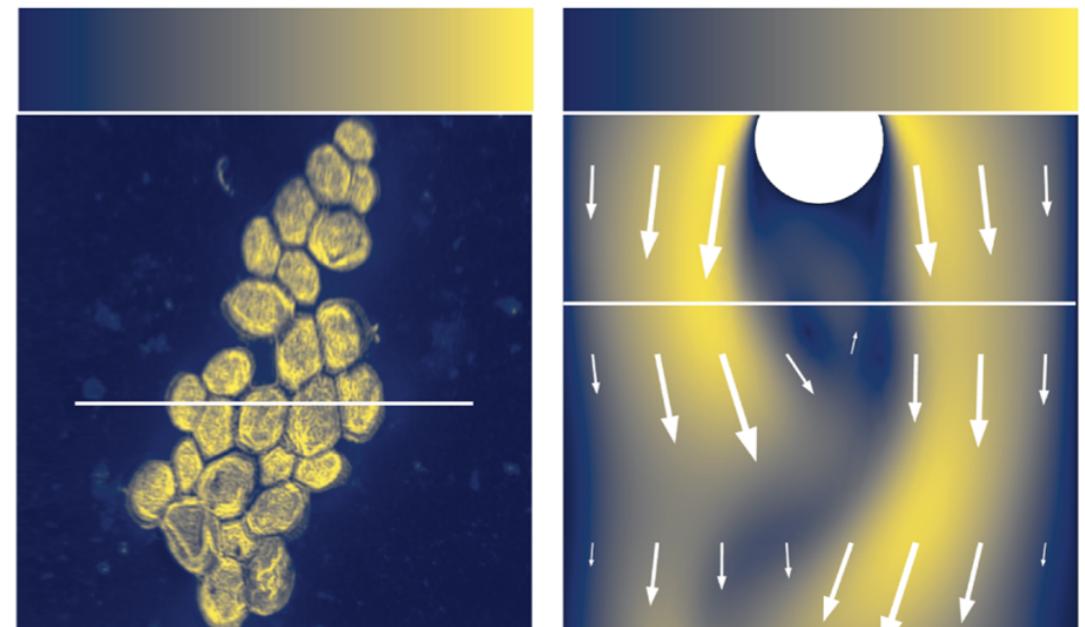


Multi-hue scheme with two colors that have a clear brightness hierarchy

Both color and brightness vary at a steady rate through the entire scale

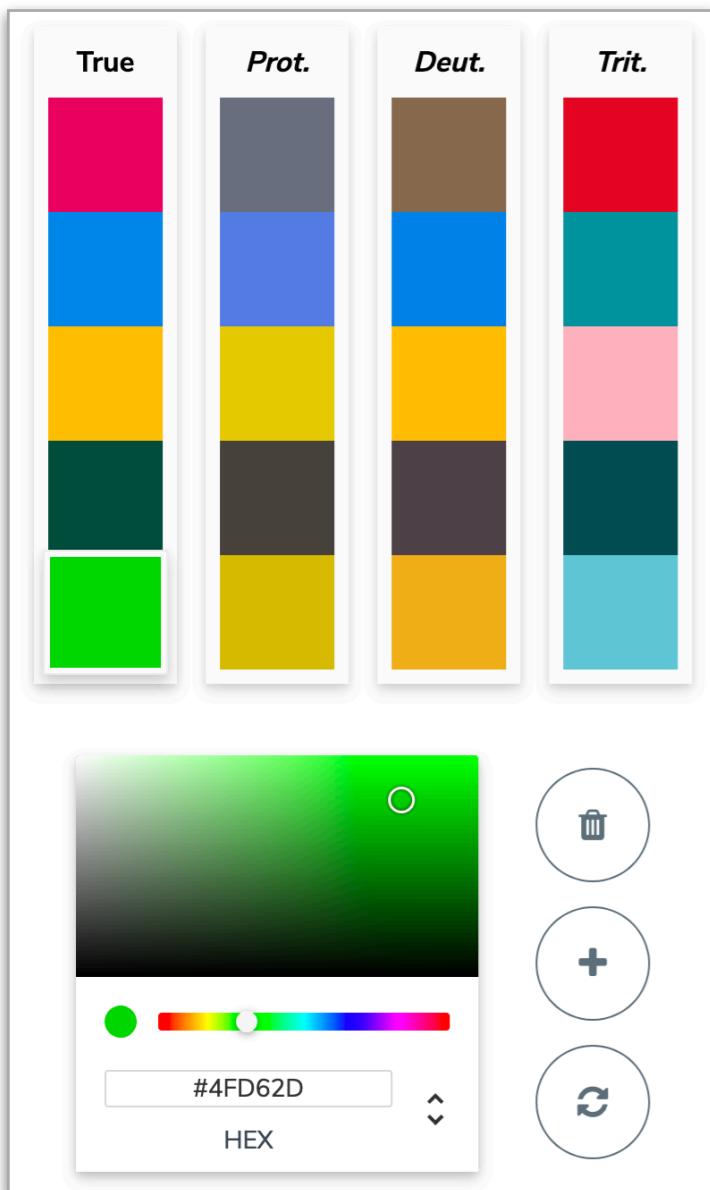
Perceptually consistent among people who are color blind and those with normal color vision.

a) NanoSIMS Overlay    b) Fluid Flow Overlay



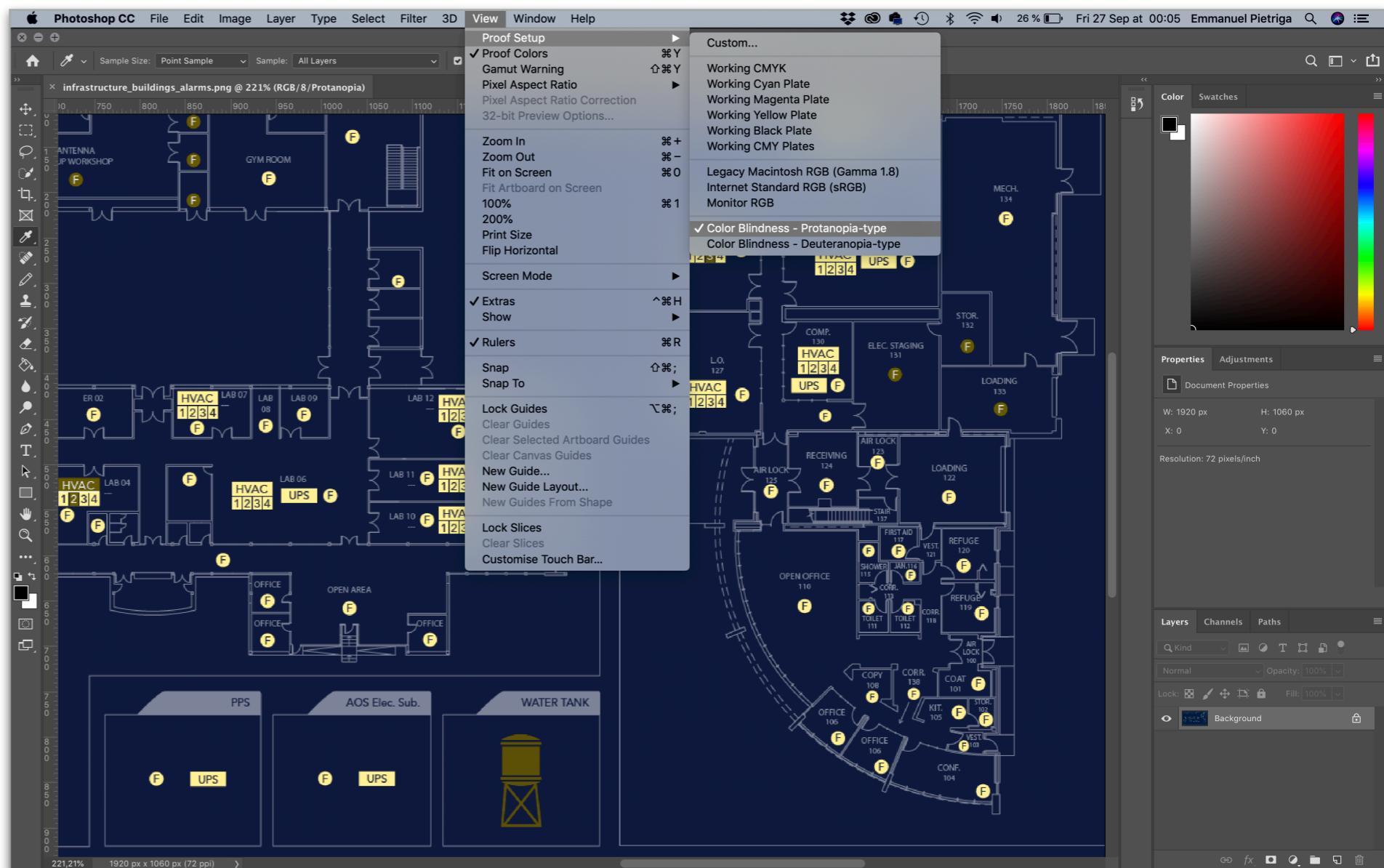
Nuñez JR, Anderton CR, Renslow RS (2018) Optimizing colormaps with consideration for color vision deficiency to enable accurate interpretation of scientific data. PLOS ONE 13(7): e0199239. <https://doi.org/10.1371/journal.pone.0199239>

# Color vision deficiency



Early design phase, use interactive tools like  
<https://davidmathlogic.com/colorblind/>

In later stages, tools such as Adobe Photoshop are convenient



# Color vision deficiency

## Live simulation in Chrome

ILDA - Software    x    +

ild.a.saclay.inria.fr/software.html

MapMosaic (Java / JOGL)  
Dynamic Layer Compositing for Interactive Geovisualization

Baia (Java / JOGL)  
Before-and-after Satellite Image Animation

UI Toolkits

ZVTM / ZUIST (Java)  
Zoomable User Interface Toolkit  
for desktop and ultra-high-resolution wall displays

Smarties (Android & Java or C++)  
Mobile interactive support  
to collaborative applications for wall displays

Elements    Console    Sources    »    fonts    E    :

html body

Styles    Event Listeners    DOM Breakpoints    Properties    Accessibility

Filter :hov .cls +

```
element.style { }
```

```
body { other than home.css:1
background-image: url(images/logo_ilda.svg);
background-repeat: no-repeat;
background-position: left top;
background-attachment: fixed;
background-size: 54px 38px; }
```

```
body { main.css:3 Filter
Console Animations What's New Rendering X }
```

margin 4
border -
padding -
866 x 2087.980 -
28

Plots frames per second, frame rate distribution, and GPU memory.

Scrolling performance issues

Highlight elements (teal) that can slow down scrolling, including touch & wheel event handlers and other main-thread scrolling situations.

Highlight ad frames

Shows borders around hit-test regions.

Emulate CSS media type

Forces media type for testing print and screen styles

No emulation ▾

Emulate CSS media feature prefers-color-scheme

Forces CSS prefers-color-scheme media feature

No emulation ▾

Emulate CSS media feature prefers-reduced-motion

Forces CSS prefers-reduced-motion media feature

No emulation ▾

Emulate vision deficiencies

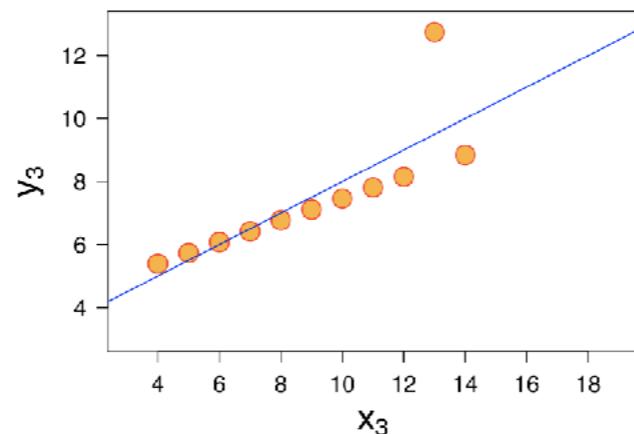
Forces vision deficiency emulation

No emulation ▾

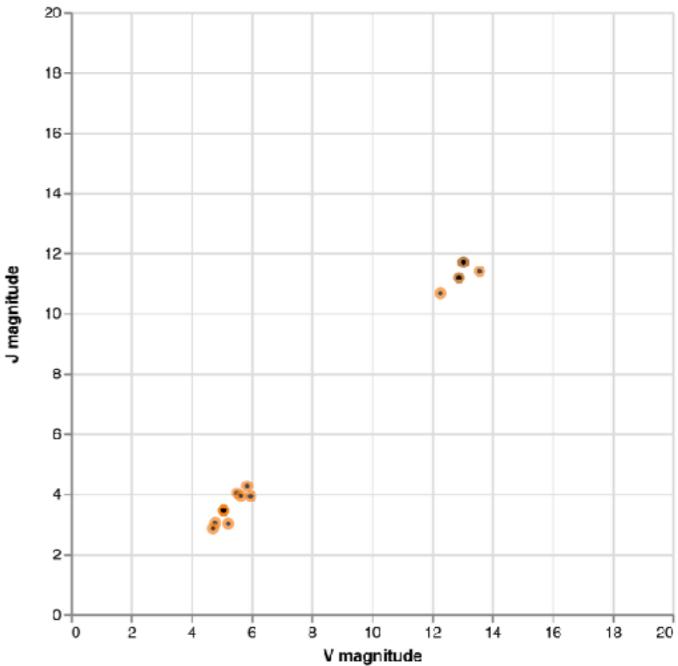
## Position



- Selective: ✓



- Associative: ✓



- Ordered: ✓



- Quantitative: ✓

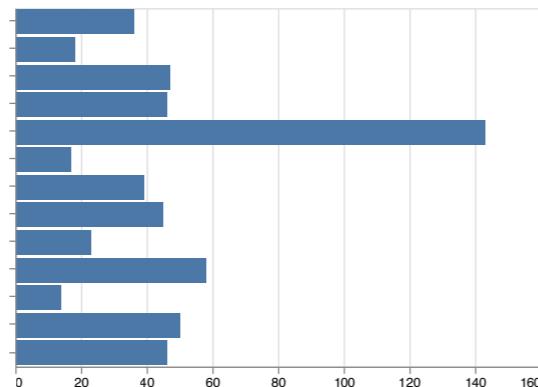
- Discriminability (resolution): ✓

- All the way down to individual pixels
  - Can make very accurate judgments

Length (1D size) - — —

Area (2D size) - ■ ■ ■

- Selective: ✓



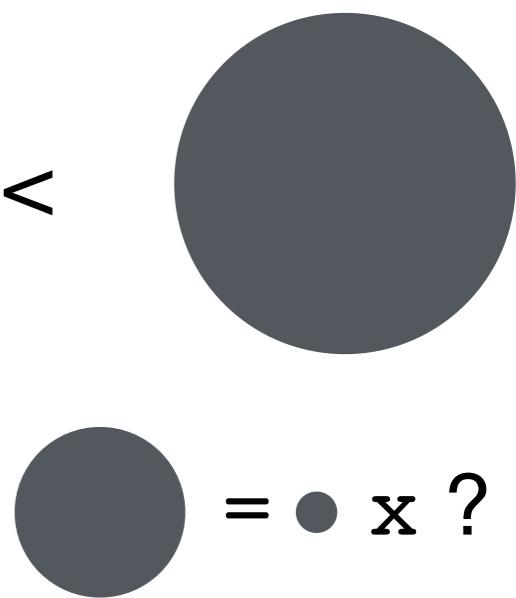
- Associative: ✓

- Ordered: ✓



- Quantitative: ✓

relative judgement  
quadratic for areas (amplifies differences)



- Discriminability (resolution):

- in theory:  $\infty$

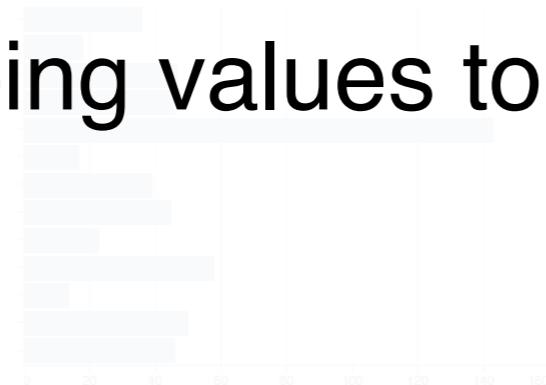
- in practice:  $\leq 5$  for selection and association,  $\leq 20$  for distinction

Length (1D size) - — —

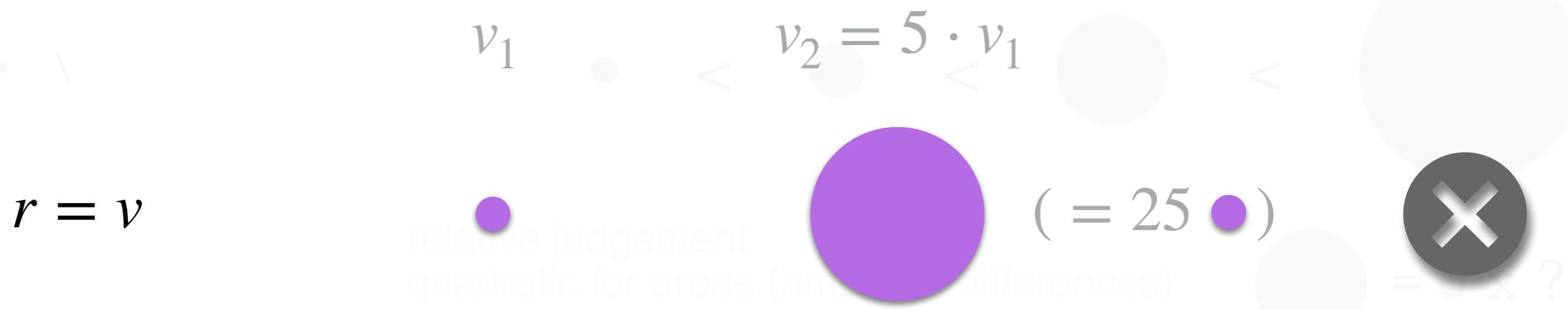
Area (2D size) · ■ ■ ■

## Properly mapping values to areas:

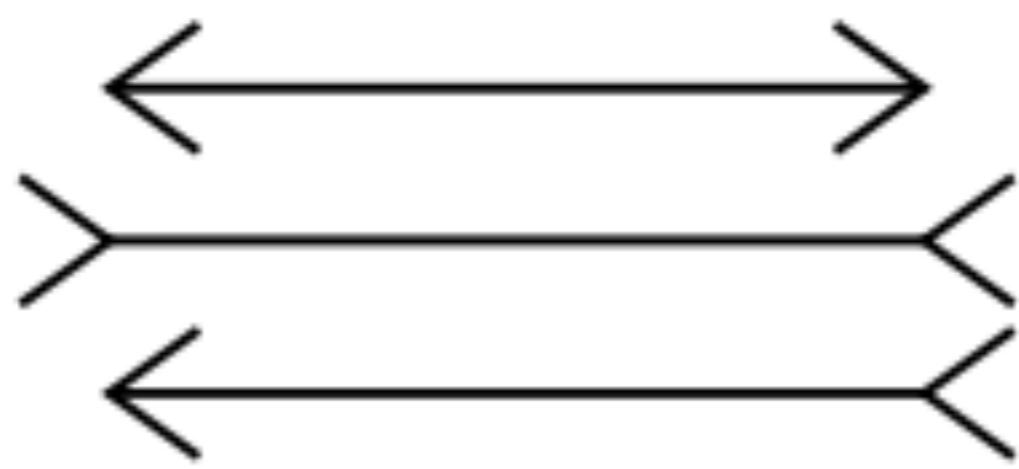
- Selective: ✓



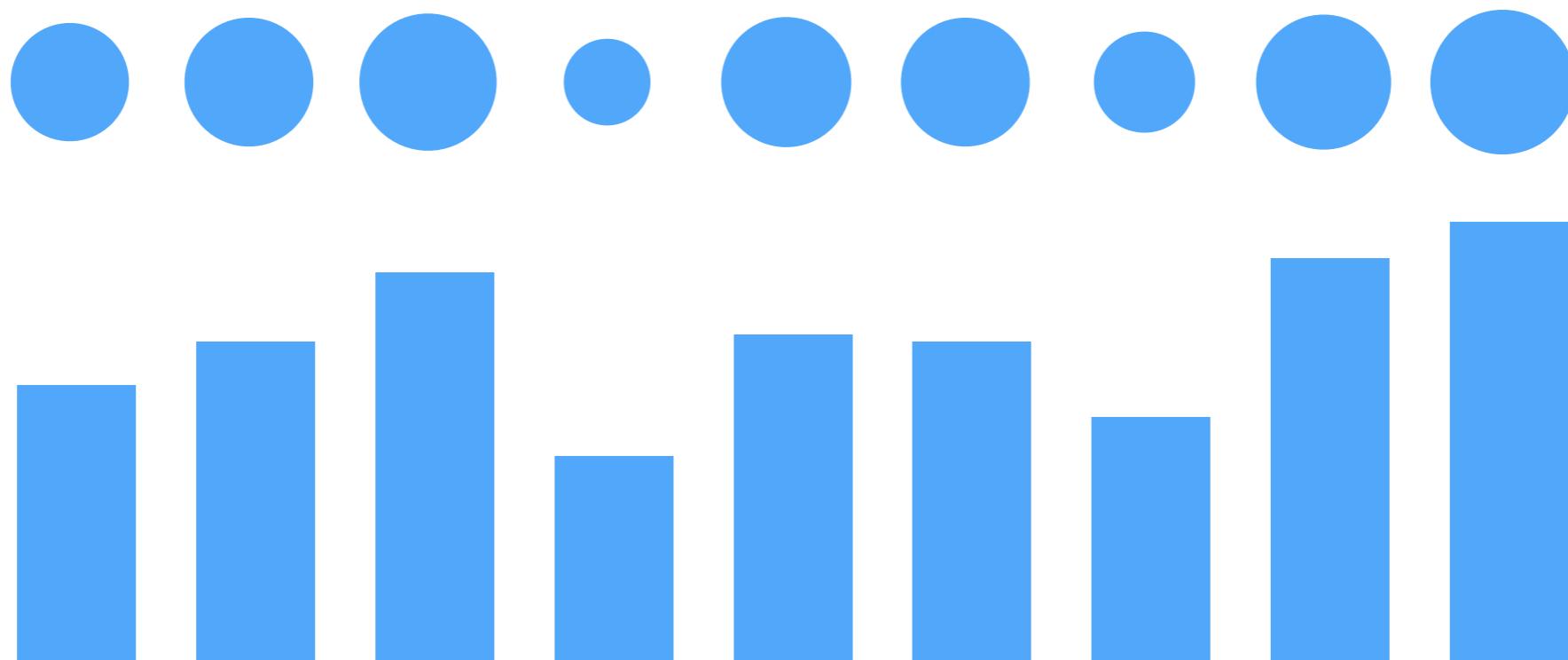
- Associative: ✓



$$r = \sqrt{v \cdot a} \quad (= 5 \text{ } \bullet) \quad \text{checkmark}$$

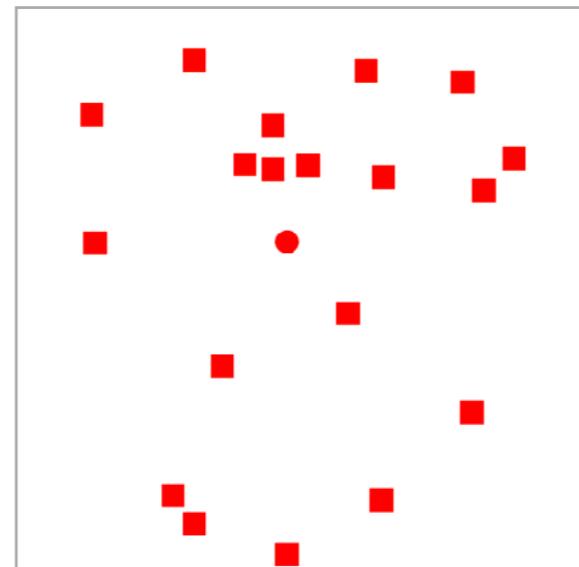


Length (1D size) - — VS. Area (2D size) · ■ ■■

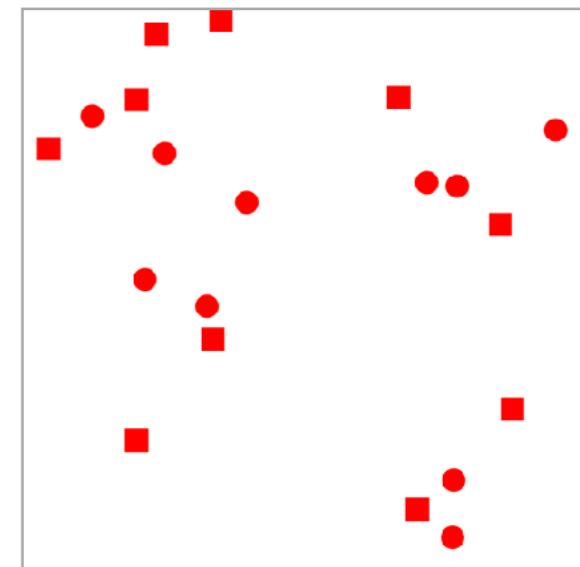


Shape + ● ■ ▲

- Selective: ✓



- Associative: ✓



- Ordered: ✗

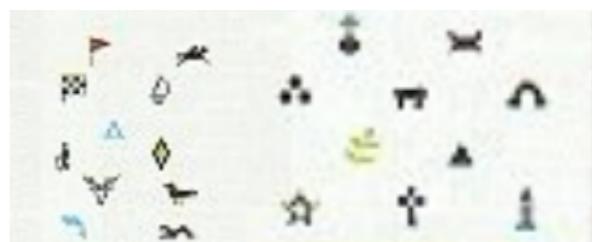


- Quantitative: ✗

- Discriminability (resolution): ✓

- in theory:  $\infty$

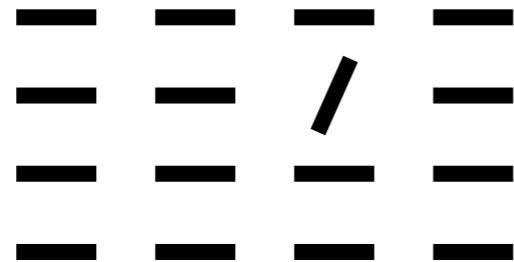
- in practice: a lot (enough, for most practical purposes)



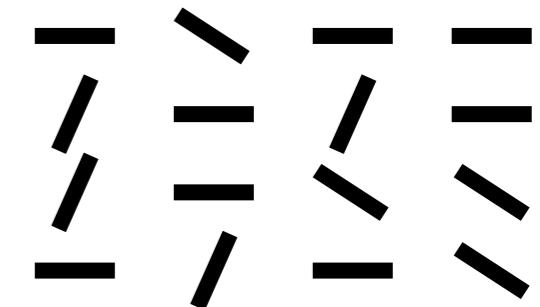
## Tilt/angle



- Selective: ✓



- Associative: ✓



- Ordered: ✗



- Quantitative: ✗

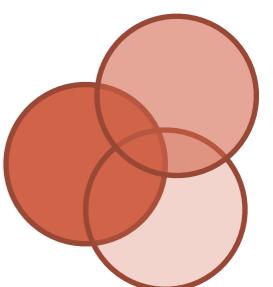
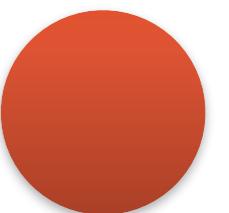
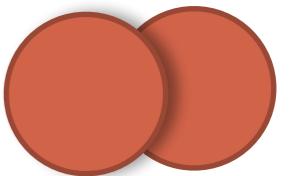
most of the time...

- Discriminability (resolution): ✓

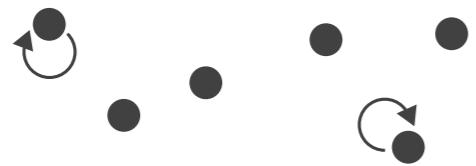
- ~ 5 in 2D
- ? in 3D

# Additional variables

- Depth (with shadows)
- Illumination (with gradients)
- Transparency (with alpha channel / compositing)
  - Can interfere with other color-based encodings
  - But also a great way to handle overlapping objects / dense regions
- Blur (sharpness)
  - Can be useful to guide attention
  - Uncertainty?



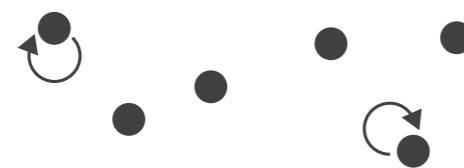
[Image Source: R. Kosara, Eagereyes, Feb 2011]



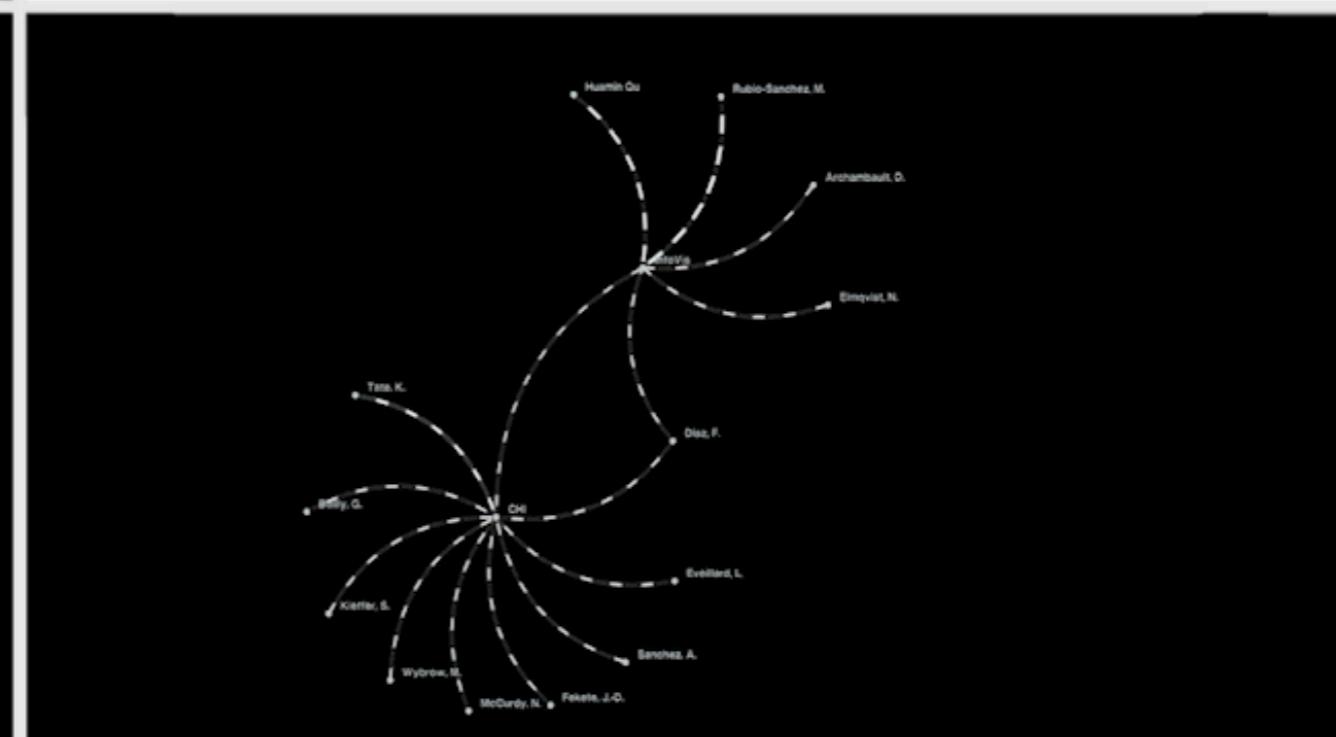
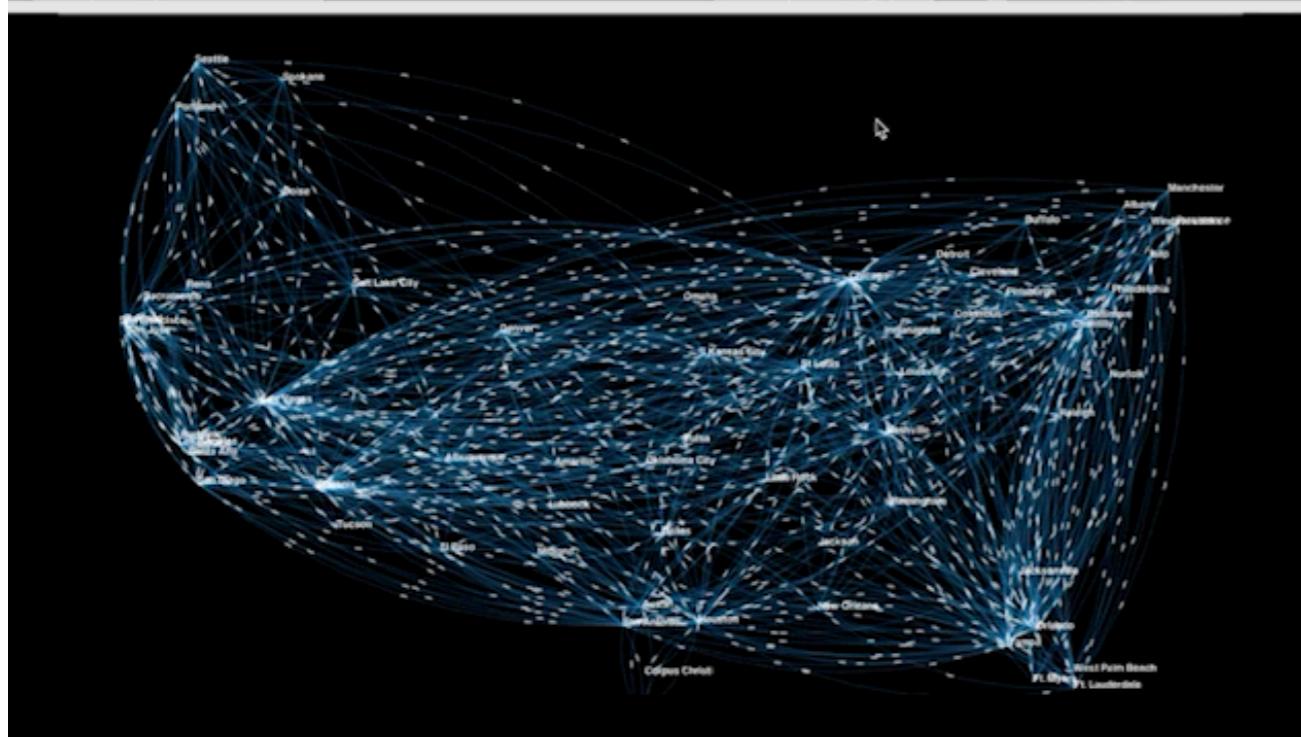
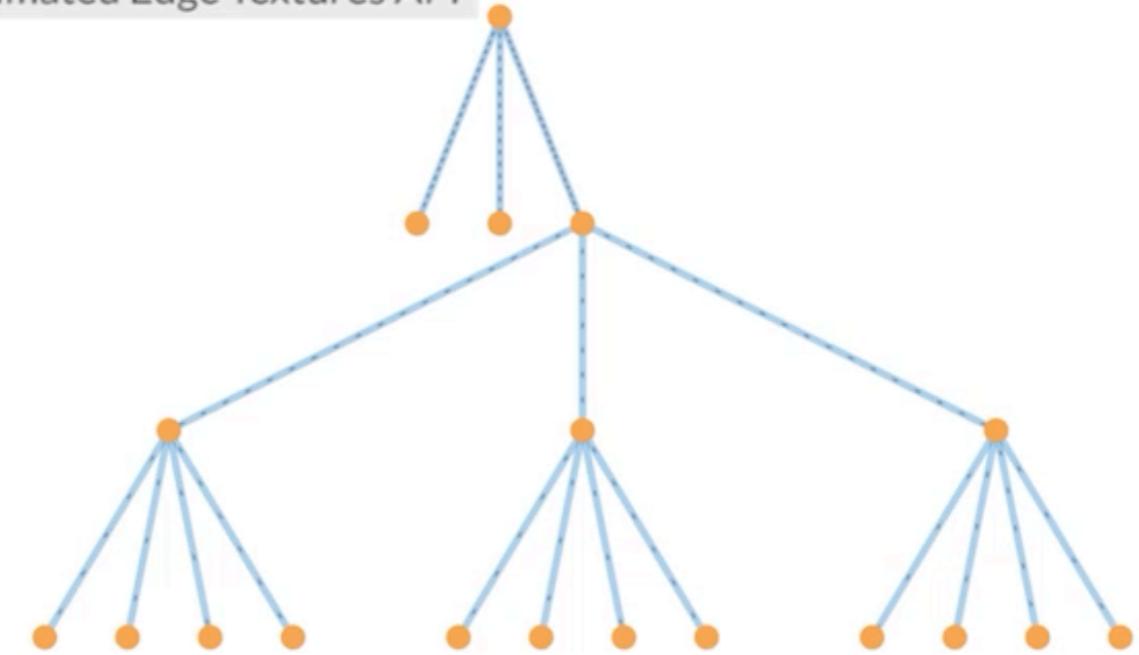
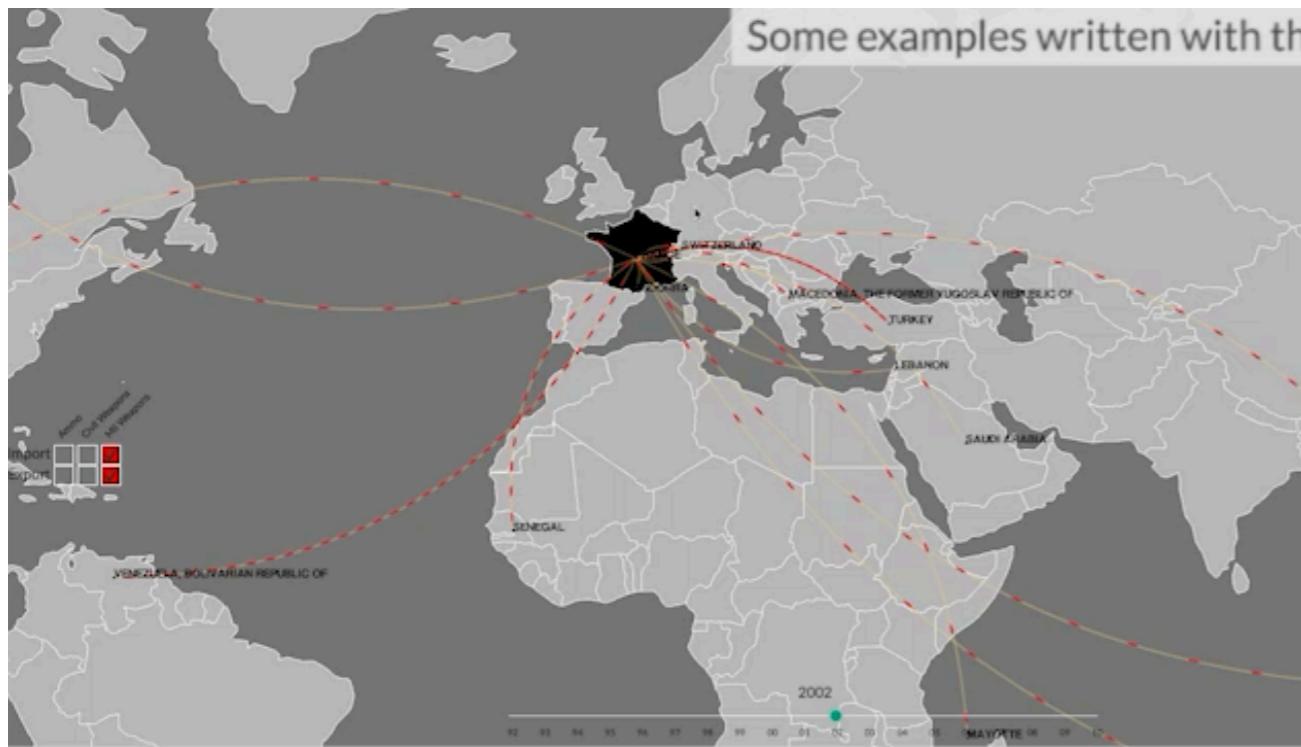
... and other types of animation

- **Motion**
  - direction, acceleration, speed, frequency, trajectory (e.g. wiggling to represent uncertainty)
- **Flicker**
  - frequency, rhythm, appearance/disappearance





... and other types of animation

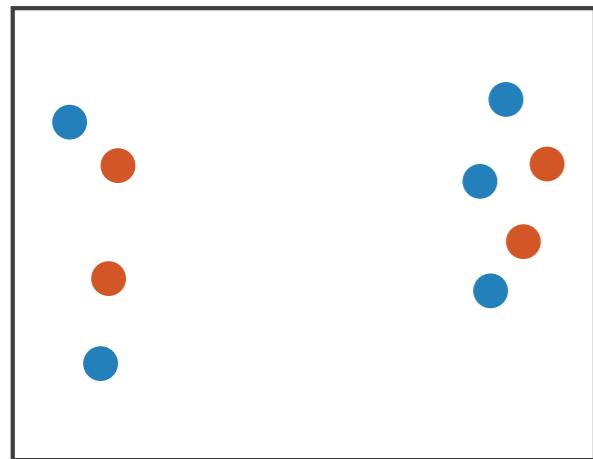


# Characterizing visual variables

- **Selective (related to visual popout):**  
Can this variable allow us to spontaneously differentiate/isolate items from groups?
- **Associative:**  
Can this variable allow us to spontaneously put items in a group?
- **Ordered:**  
Can this variable allow us to spontaneously perceive an order?
- **Quantitative:**  
Is there a numerical reading obtainable from changes in this variable?
- **Length, or rather, Discriminability (resolution):**  
Across how many changes in this variable are distinctions possible?
- **Accuracy:**  
Can we make accurate judgments about this variable in terms of perception?
- **Separability vs. Integrality:**  
Are two (or more) variables interfering with each other?

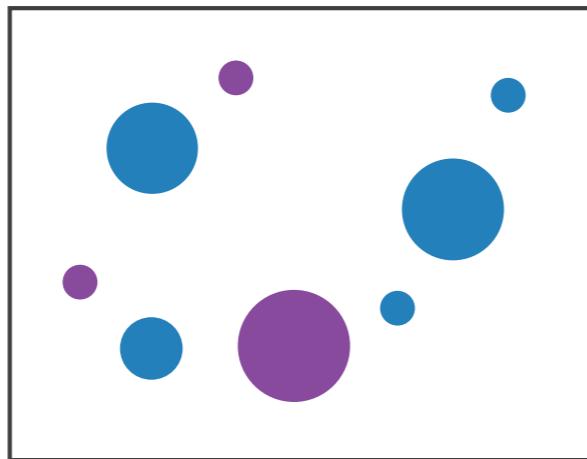
# Separability vs. Integrality, Selective Attention

Position  
+ Hue (Color)



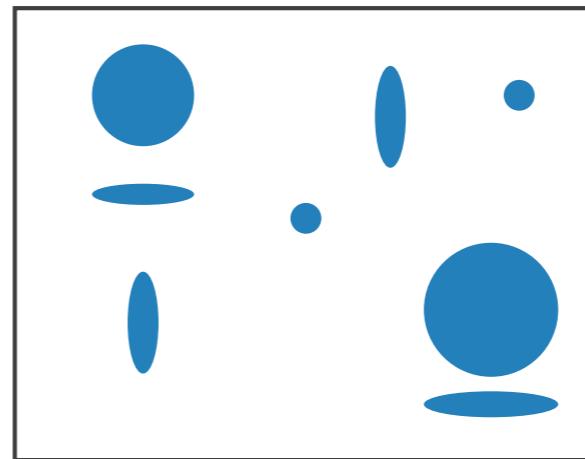
Fully separable

Size  
+ Hue (Color)



Some interference

Width  
+ Height



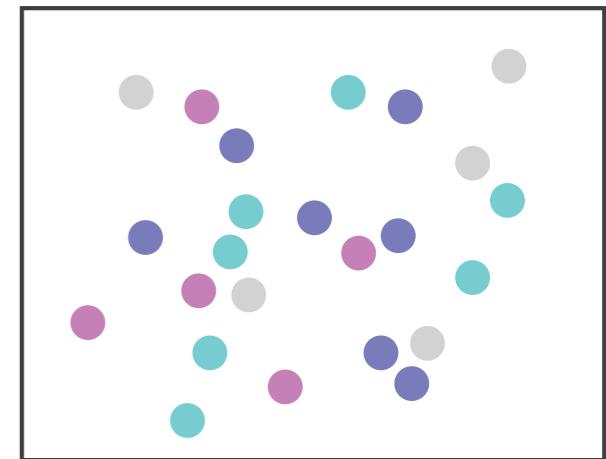
Some/significant  
interference

2 groups each

2 groups each

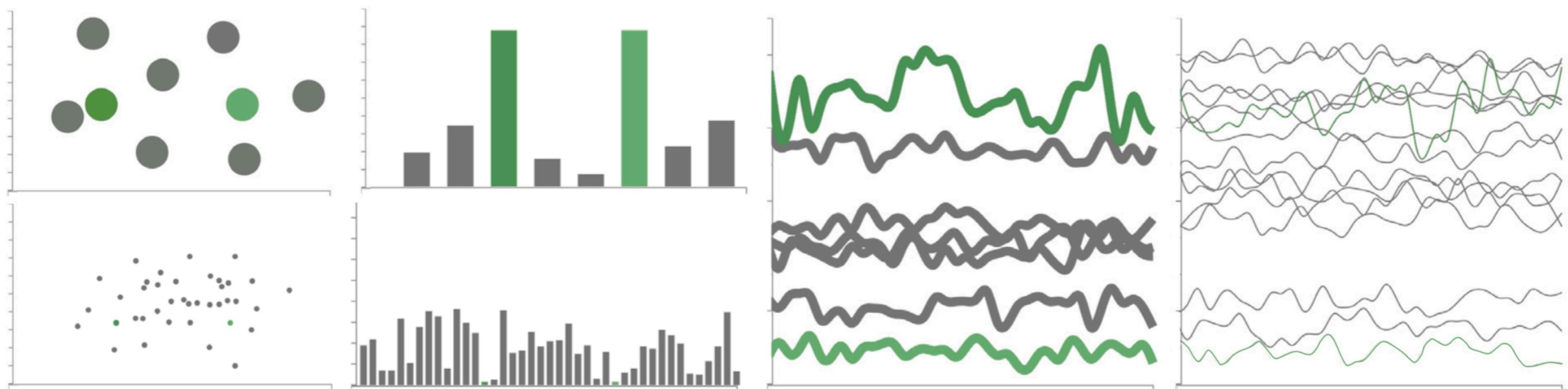
3 groups total:  
integral area

Red  
+ Green



Major interference

4 groups total:  
integral hue



[Danielle A. Szafrir. 2018. Modeling color difference for visualization design. *IEEE Trans. on Visualization and Comp. Graphics* 24, 1 (2018), 392–401.]

# Selective Attention and Emergent Features

Ability to attend to one stimulus while ignoring the confounding influence of others

Emergent features arise from the combination of two visual variables

Separable combination	minimal perceptual interference	
Integral combination	attention to individual variables is inhibited	
Configural combination	features arise when the combined variables are congruent	
Asymmetrical combination	interaction effects between the combined variables	