Data Exploration & Visualization

Module 3

Perception & Cognition

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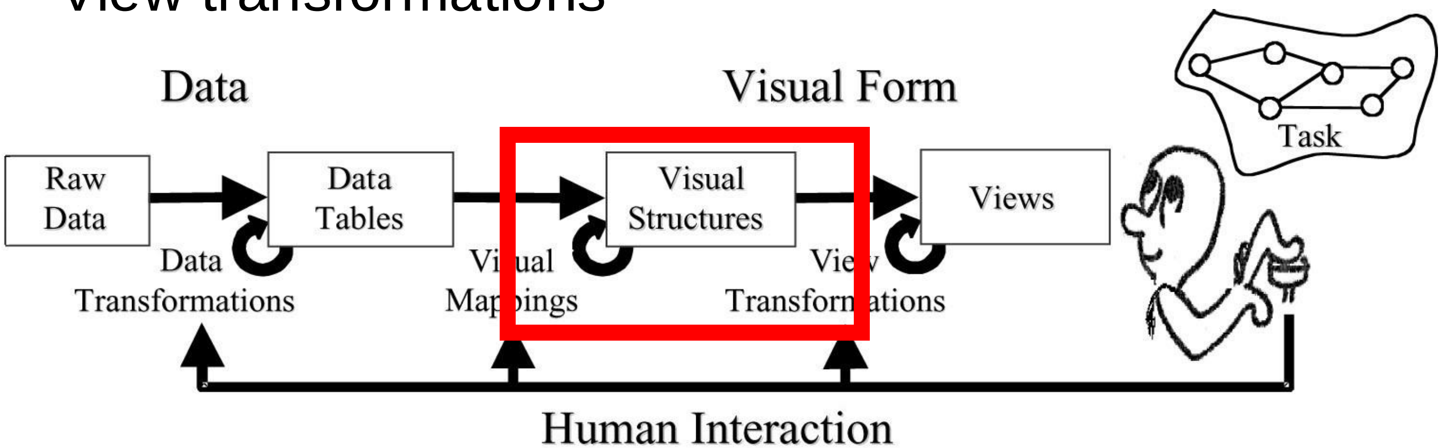
Visualization Process

- Information visualization reference model
  - Data transformations
  - Visual mappings
  - View transformations



Raw Data: idiosyncratic formats
Data Tables: relations (cases by variables) + meta-data
Visual Structures: spatial substrates + marks + graphical properties
Views: graphical parameters (position, scaling, clipping, …)

Credit: Stuart, Mackinlay, Shneiderman, 1999

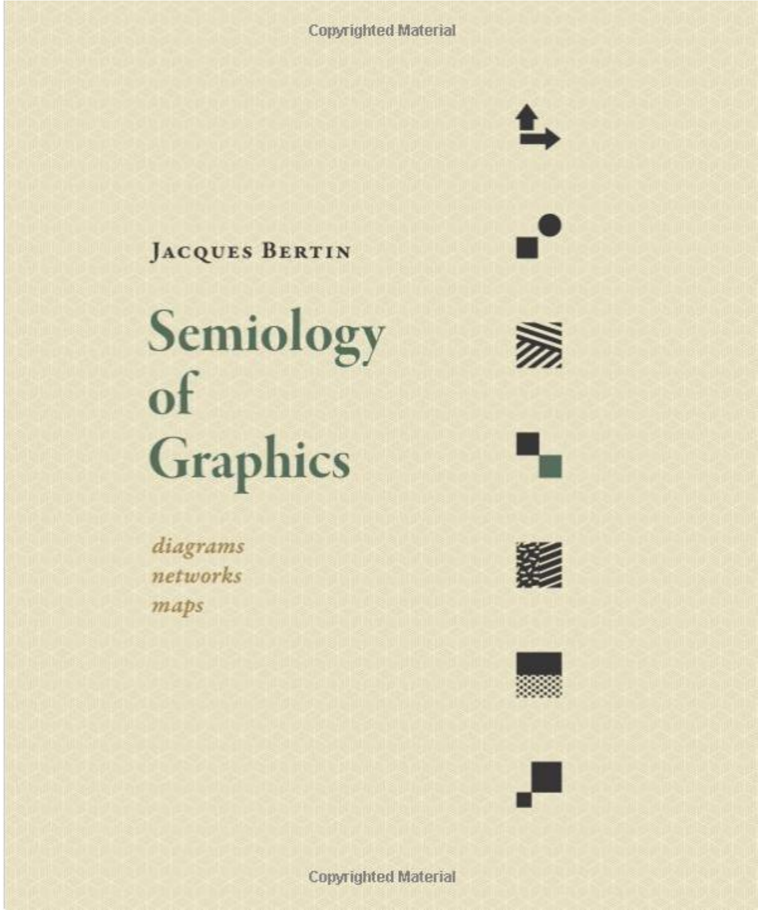
Data Exploration & Visualization

Module 3: Perception & Cognition

- Visual Channels
  - Pre-attentative visuals
  - Feature conjunction
- Just noticeable difference
  - Weber's law
  - Stevens' power law
- Gestalt theory

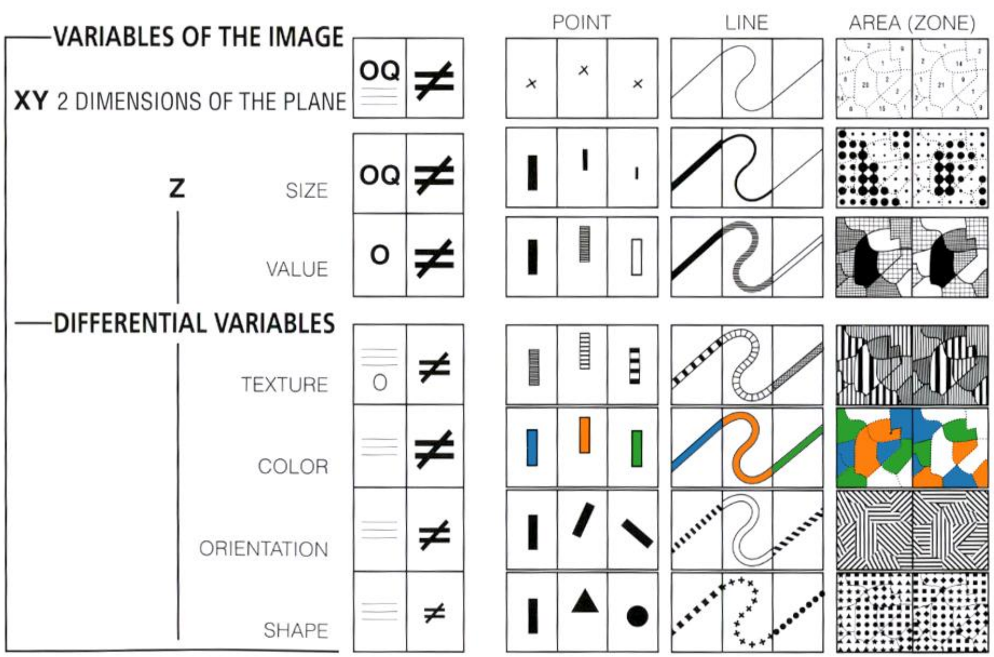
Semiology of graphics

- Bertin's *Semiology of Graphics* defined what visualization is.
  - It is the mapping of data features to visual features
- Given this definition, we can then discuss:
  - What are data elements?
    - Numbers, text, locations, etc.
  - What are visual elements?
    - Colors, points, lines, size, etc.
  - How do we do the mapping?
    - Numbers -> Position



Semiology of graphics

- Geometric primitives: **marks**
  - Points, lines, areas, volumes
- Attributes: visual/retinal variables (**channels**)
  - Parameters control mark appearance
  - [x, y]
    - Position
  - [z]
    - Size, shape,
    - Greyscale, color
    - Texture, orientation
- Data types
  - Nominal, ordinal, quant

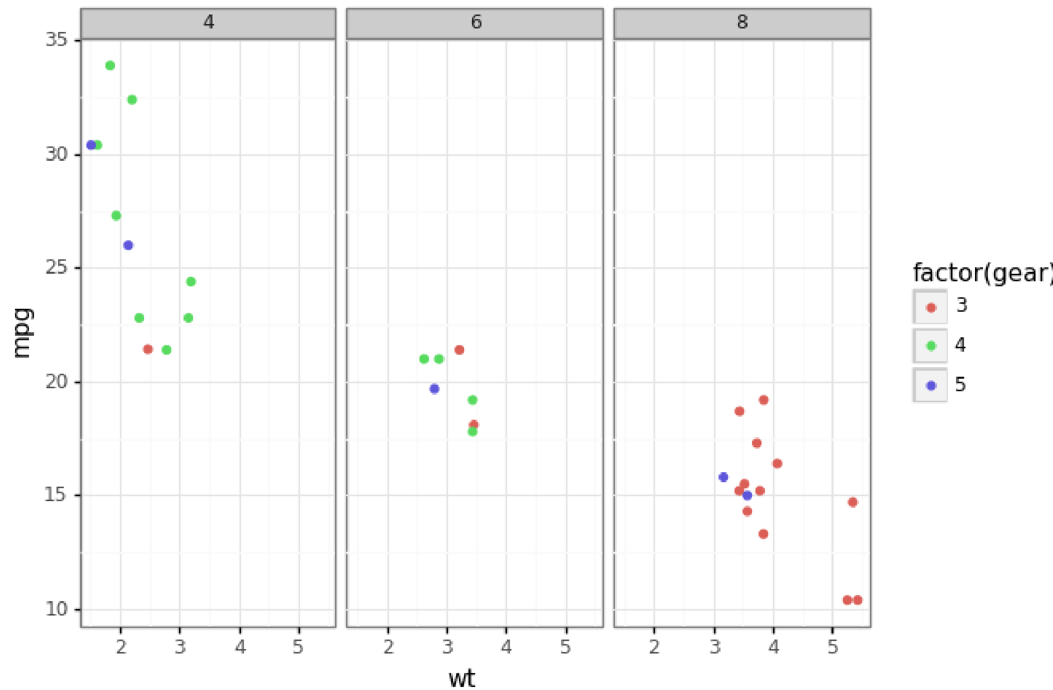


Grammar and languages

- “*Grammar of Graphics*,” Wilkinson, 1999
  - First proposed a grammar for constructing layered visualizations
  - Concepts include:
    - Data, Scale, Geometry, Coordinates, Facets, and Aesthetics, etc.
- “*ggplot2*,” Wickham, 2005
  - A visualization library in R
  - Implemented the *Grammar of Graphics*
    - Made modifications to focus more on the layers
    - “*A Layered Grammar of Graphics*,” Wickham, 2010

ggplot2

```
(ggplot(mtcars,
        aes('wt', 'mpg',
            color='factor(gear)'))
        + geom_point()
        + facet_wrap('~cyl')
        + theme_bw())
```

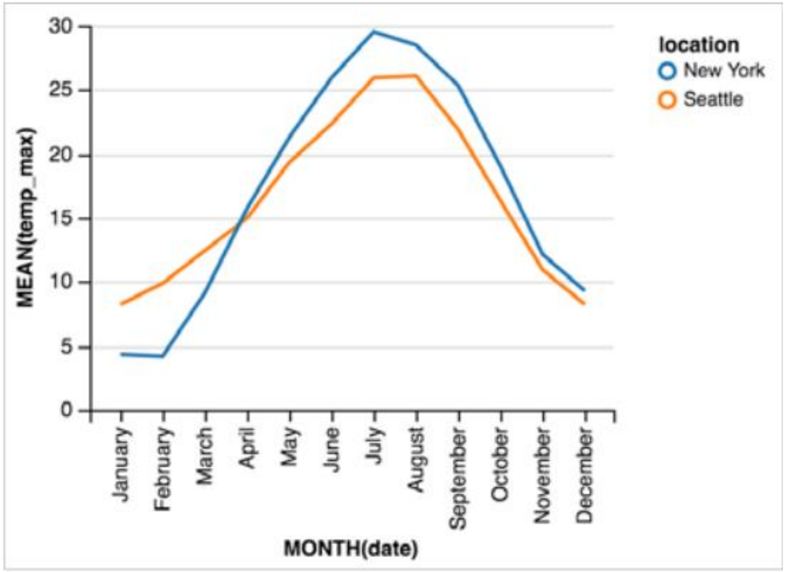


	name	mpg	cyl	disp	hp	drat	wt	qsec	vs	am	gear	carb
0	Mazda RX4	21.0	6	160.0	110	3.90	2.620	16.46	0	1	4	4
1	Mazda RX4 Wag	21.0	6	160.0	110	3.90	2.875	17.02	0	1	4	4
2	Datsun 710	22.8	4	108.0	93	3.85	2.320	18.61	1	1	4	1
3	Hornet 4 Drive	21.4	6	258.0	110	3.08	3.215	19.44	1	0	3	1
4	Hornet Sportabout	18.7	8	360.0	175	3.15	3.440	17.02	0	0	3	2

D3, Vega, Vega-lite

- Outside of the *R*, Jeff Heer (Univ. of Washington) has been working on a similar effort but for web-based development
  - Flare (2005), Heer. (Note: Written in Java)
  - Protovis (2009), Bostock and Heer
- D3.js (2011), Bostock and Heer
  - Key feature: maps data to SVG elements
- Vega (2015), Satyanarayan et al.
  - Key feature: a specification based language
- Vega-Lite (2016), Satyanarayan et al.
  - Key feature: makes interactivity a first-class citizen

```
{
  "data": {
    "url": "data/weather.csv",
    "formatType": "csv" },
  "mark": "line",
  "encoding": {
    "x": {
      "field": "date",
      "type": "temporal",
      "timeUnit": "month" },
    "y": {
      "field": "temp_max",
      "type": "quantitative",
      "aggregate": "mean" },
    "color": {
      "field": "location",
      "type": "nominal" }
  }
}
```



Example Vega-lite language and visualization

Goal of visualization

- Visualization motivation:
  - Recording, communication, analysis
- Finding patterns is key to visualization.
- Example Tasks:
  - Patterns showing groups?
  - Patterns showing structure?
  - What patterns are similar?
- How should we organize information on the screen?

Visual attention

- Attention is the cognitive process of selectively concentrating on one aspect of the environment while ignoring other things
- Comprises a range of cognitive and perceptual processes
- One convenient (if perhaps simplistic) way to frame these is as top-down or bottom-up attention
  - Top down →“cognitive”, voluntary
  - Bottom-up → “perceptual”, involuntary
- Guideline for visualization design
  - How to make information visually distinct - to stand out

Change blindness

- Most of the time we are not “paying attention”

Demo from Ron Rensink: http://www.psych.ubc.ca/~rensink/flicker/

Change blindness

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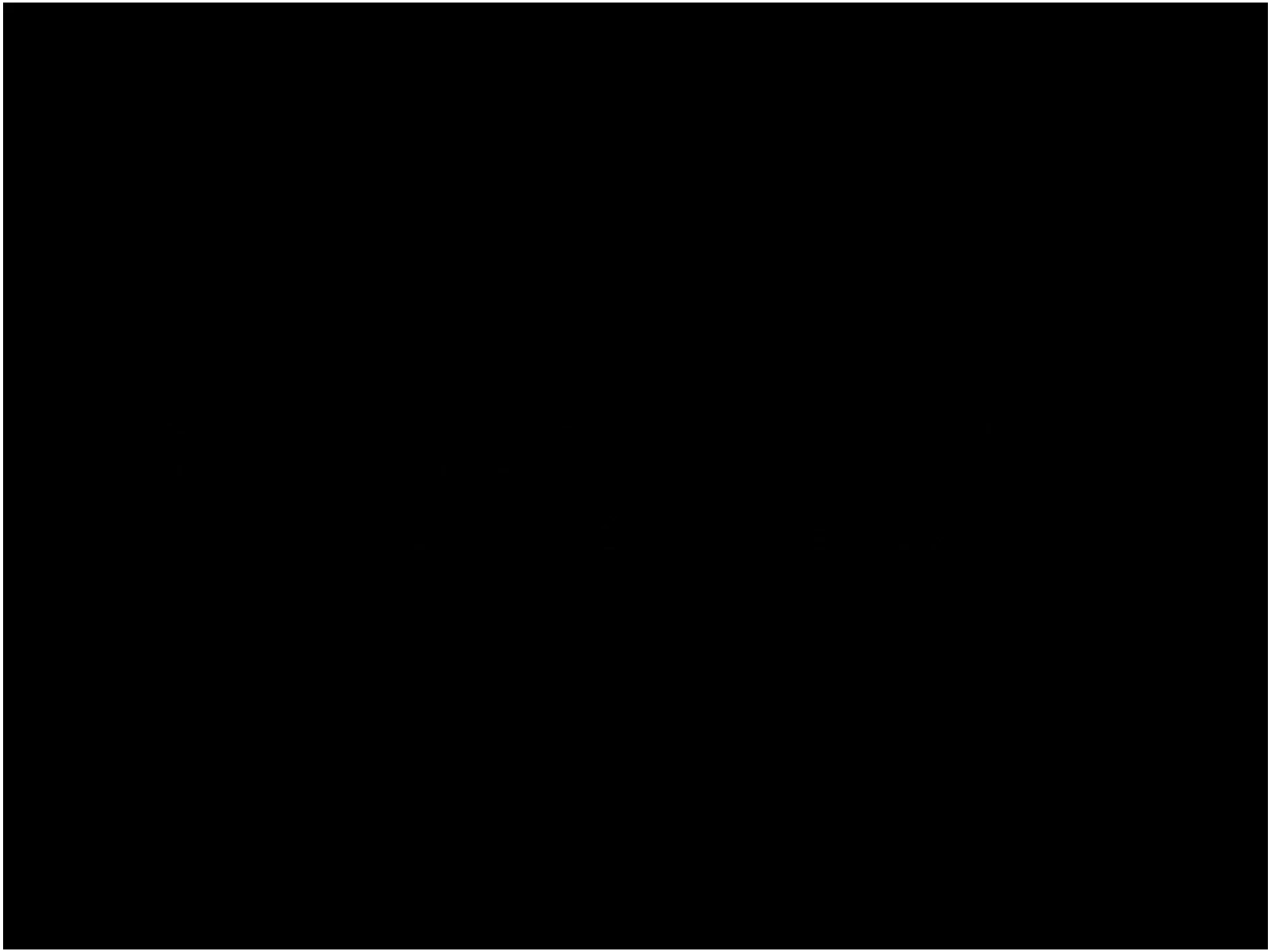
Selective attention test

- Scenario:
  - 3 people in *white* shirts
  - 3 people in *black* shirts
  - They pass basketballs around

- Task:
  - Keep a silent count of the number of passes made by the people in **White** shirts
  - **Don’t** count passes made by the people in black shirts

- Requirement: Attention!!!

Selective attention test



Selective attention test

- How many passes?
  - 15 times
- Did you see the gorilla?
  - Half of the people watched the video and counted the passes missed the gorilla
- Conclusion: We are missing a lot of what goes on around us, and that we have no idea that we are missing so much.

http://www.theinvisiblegorilla.com/gorilla_experiment.html

Preattentive processing

- The ability of the low-level human visual system to rapidly identify certain basic visual properties.
  - Without need for focused attention
  - Tasks completed in less than 200 to 250 ms
  - Parallel processing
- A limited set of visual elements are preattentive
  - What can be perceived immediately
  - What properties are good discriminators
  - What can mislead viewers
  - Differentiate items ‘at a glance’

Preattentive visual tasks

- Counting and estimation
  - How many elements of a certain type are present?
    - How many 3’s?
- Target detection
  - Is something there?
    - Where is the red circle?
- Boundary detection
  - Can the elements be grouped?
  - What associates them?
- Region tracking
  - Can we track one or more elements?

Counting task:
How many 3’s?

1281768756138976546984506985604982826762

9809858458224509856458945098450980943585

9091030209905959595772564675050678904567

8845789809821677654876364908560912949686

Counting task:
How many 3’s?

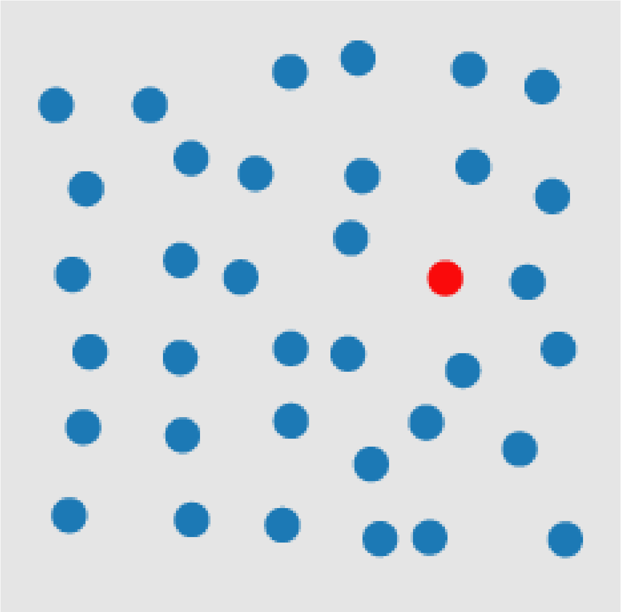
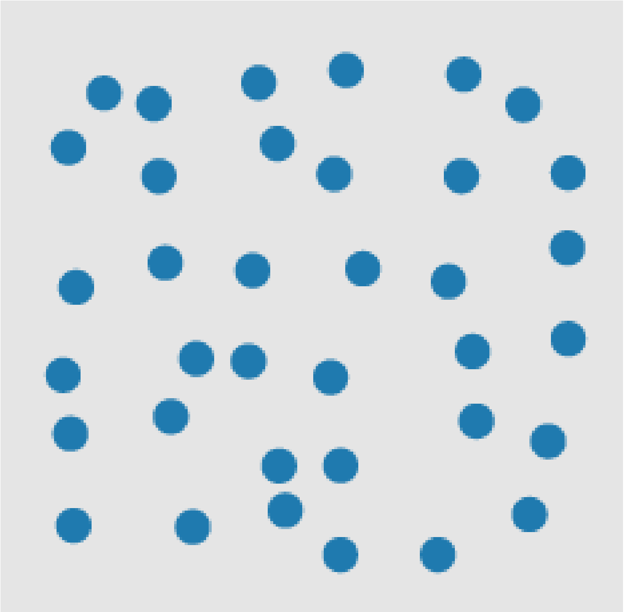
1281768756138976546984506985604982826762

9809858458224509856458945098450980943585

9091030209905959595772564675050678904567

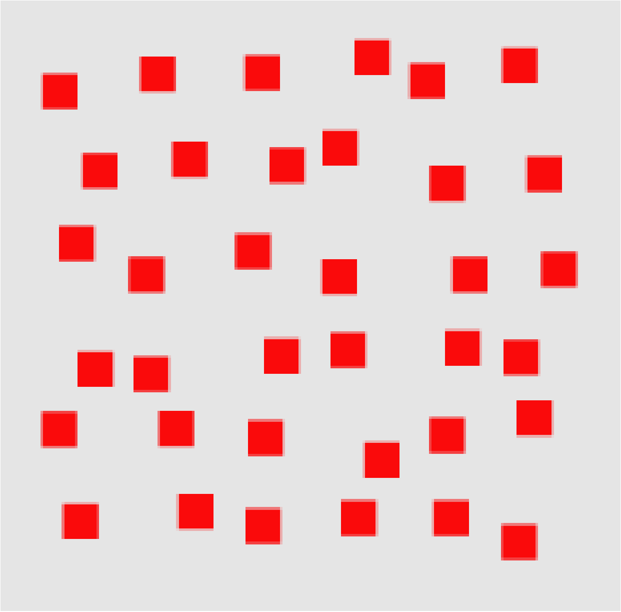
8845789809821677654876364908560912949686

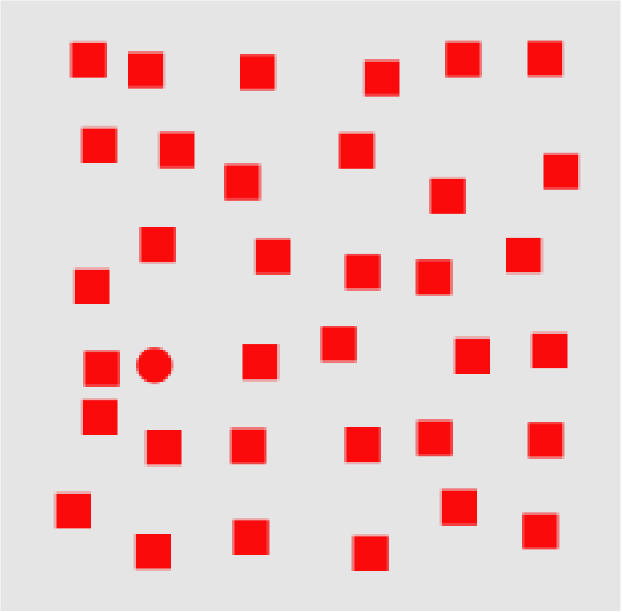
Detection task:
Where is the red circle?

The visual system identifies the target through a difference in hue

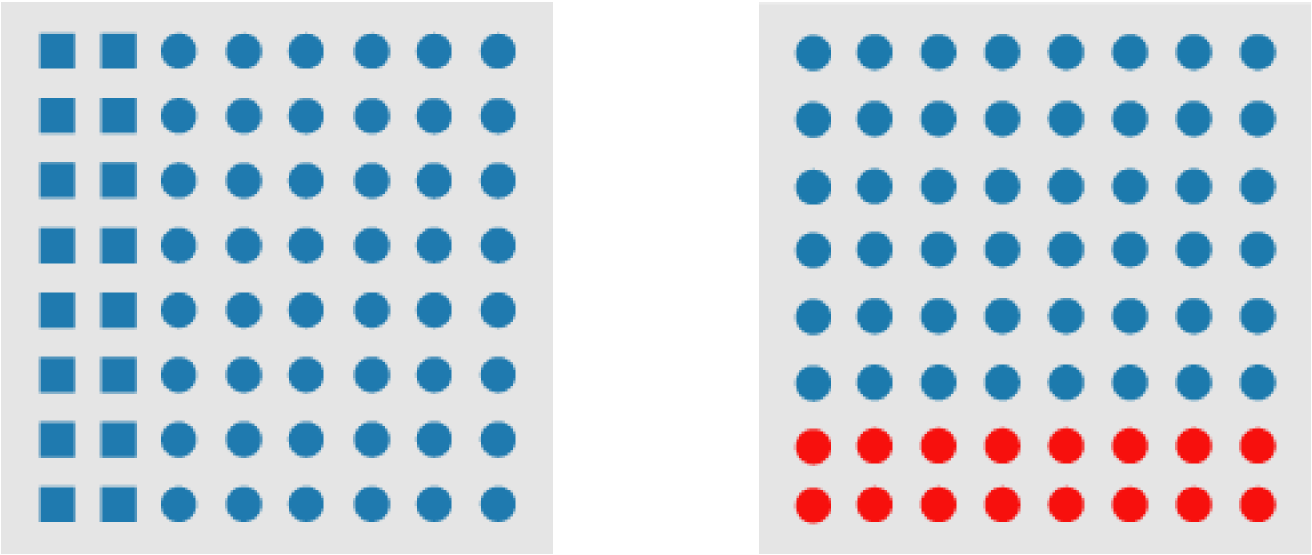
Detection task:
Where is the red circle?





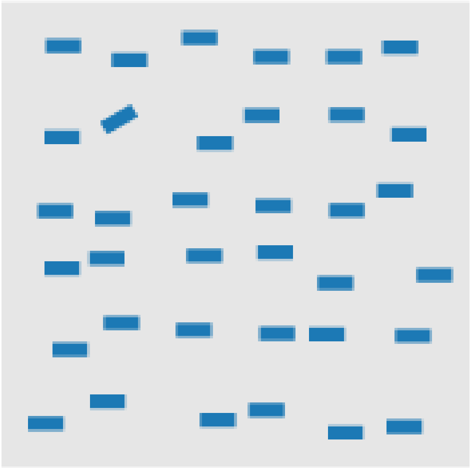
The visual system identifies the target through a difference in curvature (form)

Boundary task:
Where is the boundary?

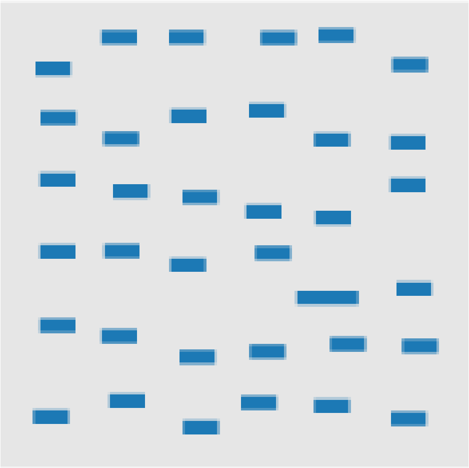


Form (left) and Hue (right) are preattentive features for boundary detection tasks.

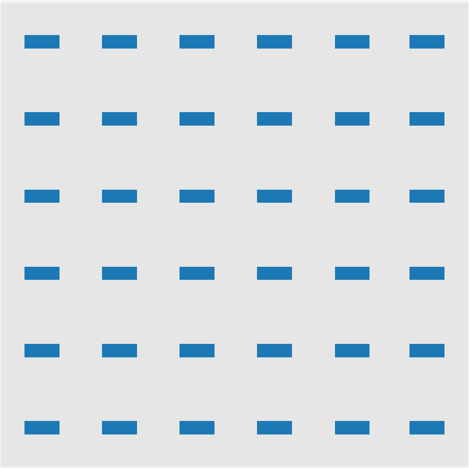
More preattentive features



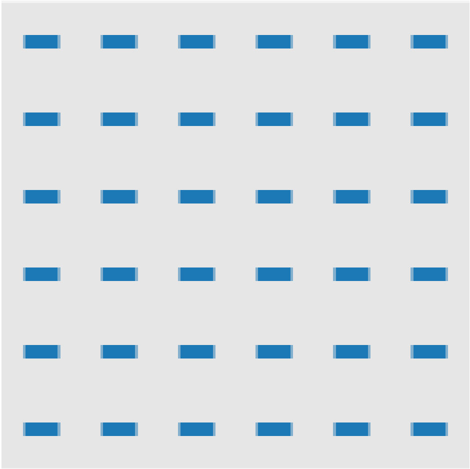
orientation



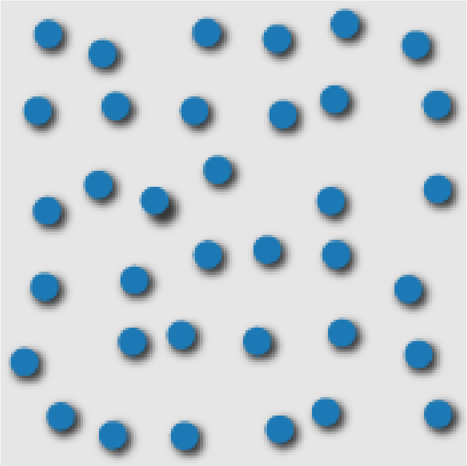
length



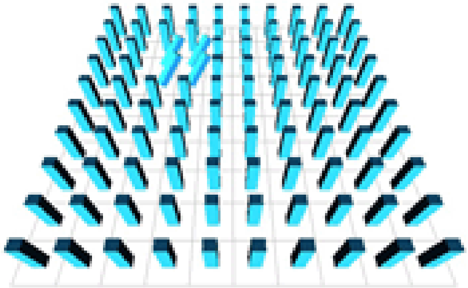
flicker



flicker



3D depth cue



3D orientation

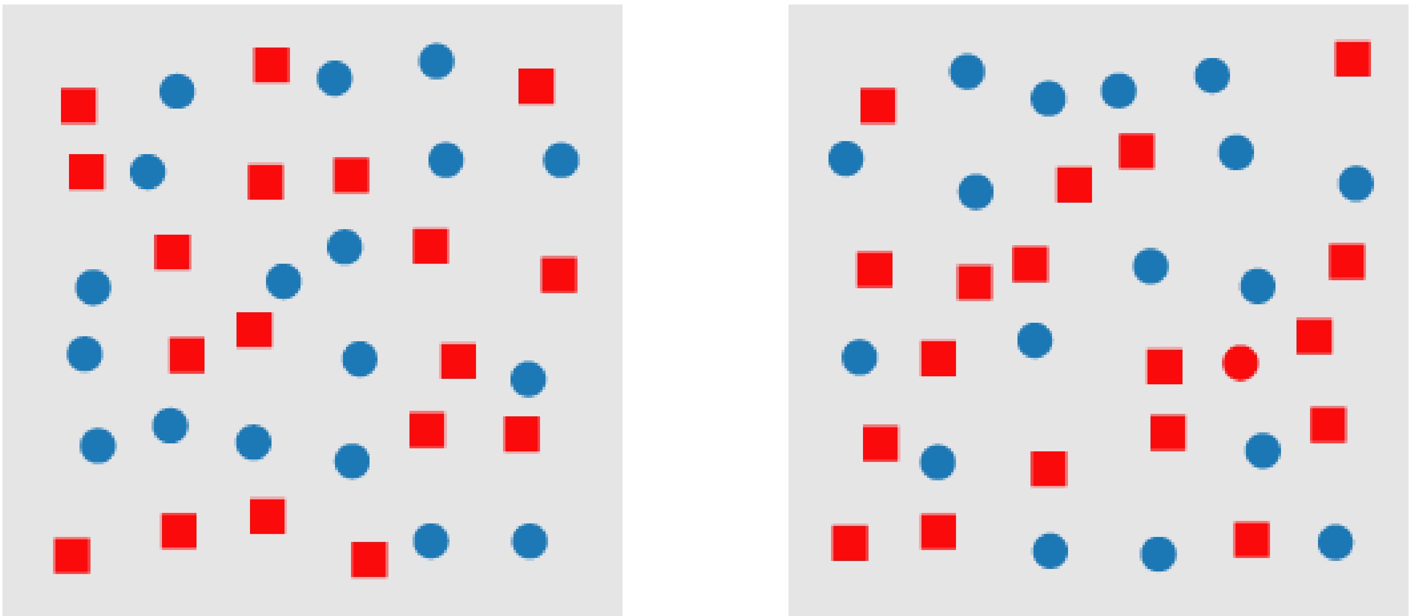
More preattentive features

- Form
  - Line orientation
  - Line length
  - Line width
  - Size
  - Curvature
  - Spatial grouping
  - Blur
  - Numerosity
- Color
  - Hue
  - Intensity
- Motion
  - Flicker
  - Direction of motion
  - Velocity of motion
- Spatial position
  - 2D position
  - Stereo depth
  - Shading

courtesy of https://www.csc2.ncsu.edu/faculty/healey/PP/index.html

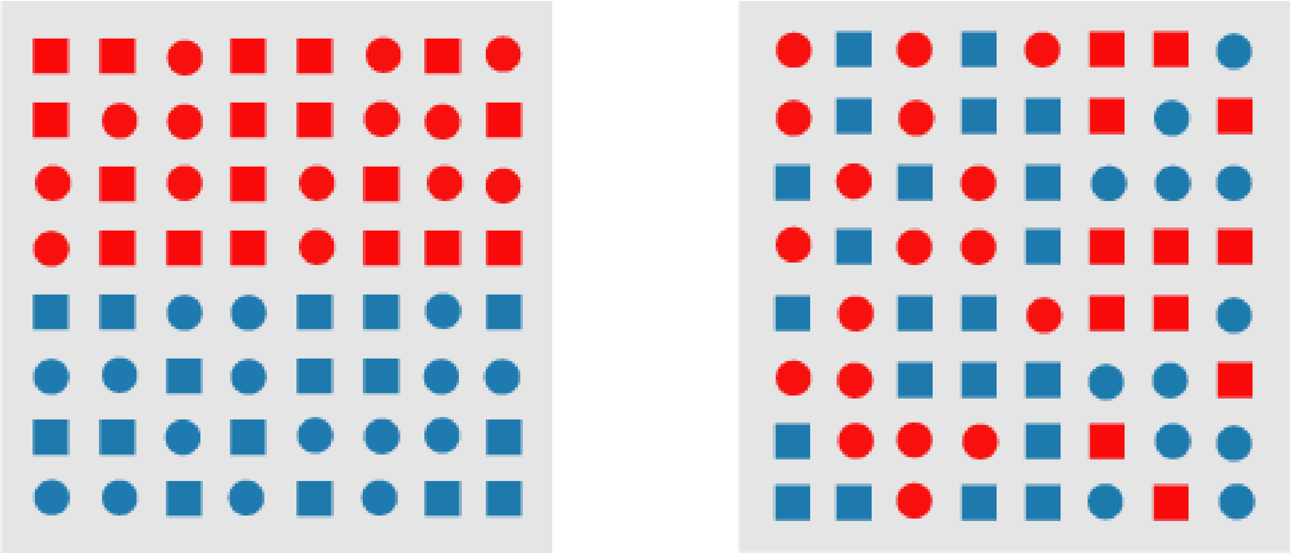
Beyond data visualization, do you know any scenario making use of pre-attentative visuals?

Feature conjunction



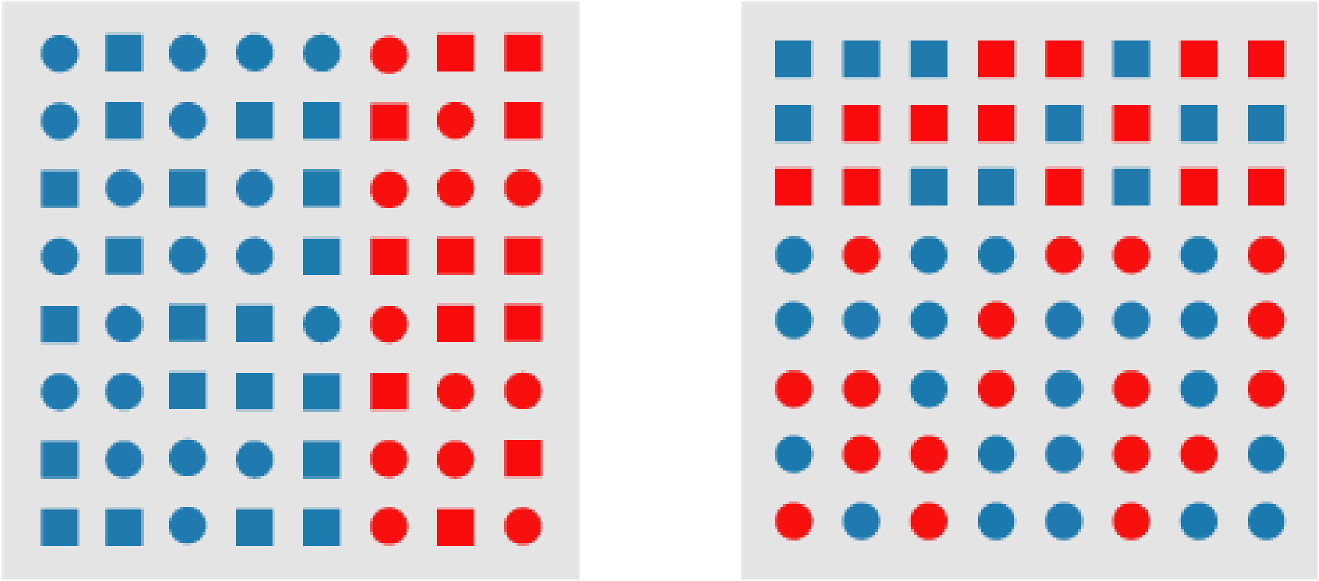
- Search for the red circle
- Not preattentive – must perform a sequential search
- Conjunction of features (hue and form)

Feature conjunction



- Identify group boundary
  - Left: unique feature hue is preattentive
  - Right: conjunction of features hue and form are non preattentive

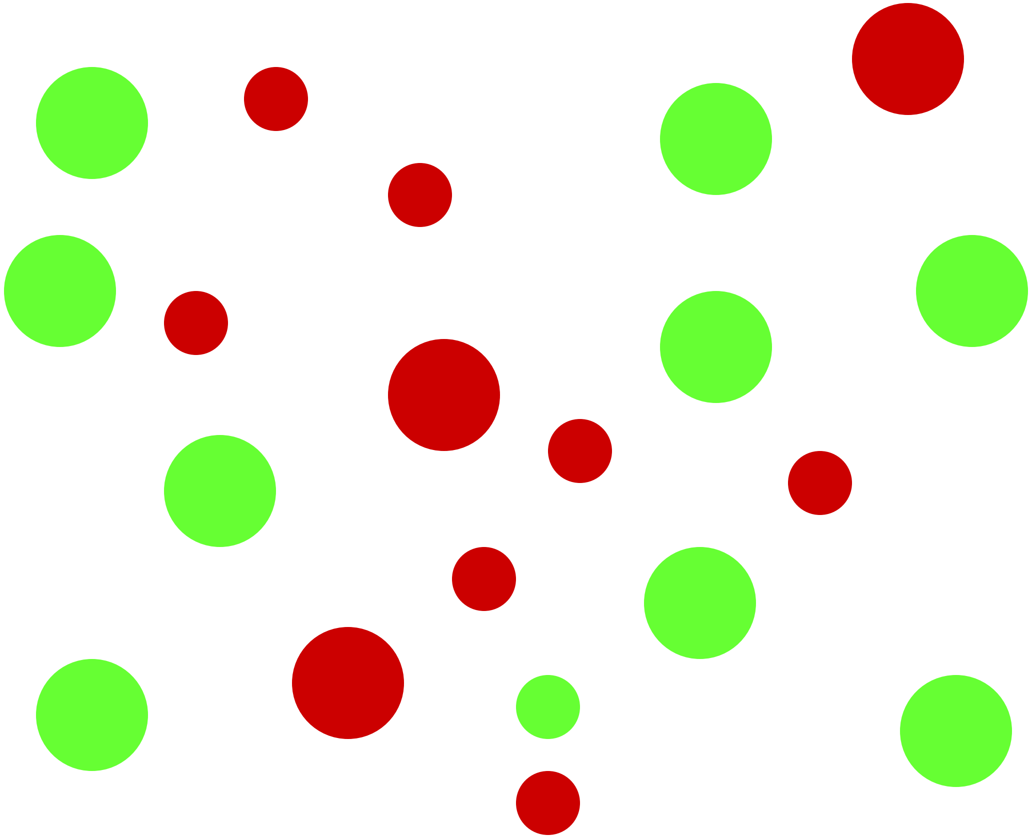
Feature conjunction



- Identify group boundary
  - Left: form randomly varies in the background, hue is preattentative
  - Right: hue randomly varies in the background, form is not preattentative

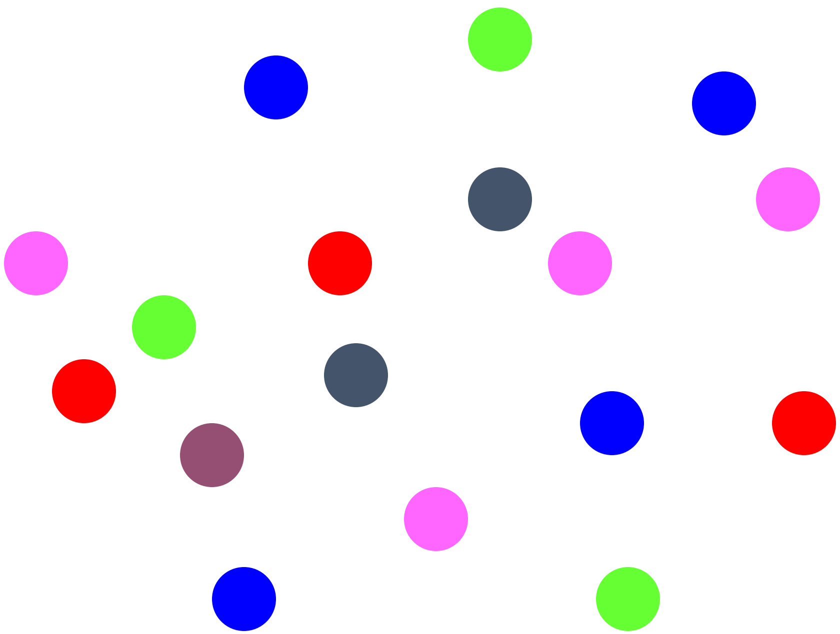
More examples

- Combinations do not pop out



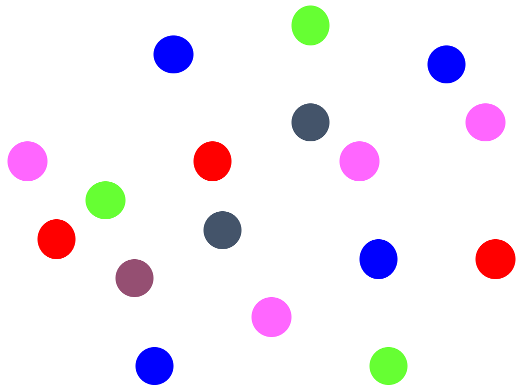
More examples

- Surrounded colours do not pop out



Distraction and clutter

- Pre-attentive symbols become less distinctive as the variety of distractors increases.
- Two factors are important in determining whether something stands out preattentively:
  - the **degree of difference** of the **target** from the **non-targets** (distractors), and
  - the **degree of difference** of the **non-targets** from **each other**.



Distractors

- For example, yellow highlighting of text works well if yellow is the only color in the display besides black and white
- but if there are many colors the highlighting will be less effective.

Integral vs. separable

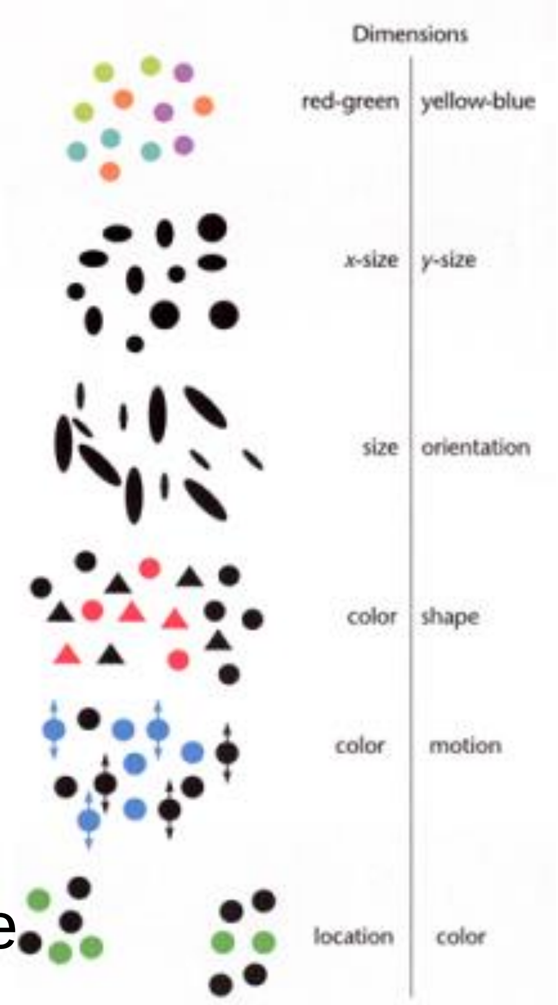
- How do the coding schemes work together?
  - Luminance variation is only real way of showing details
  - Colours must be chosen for dissimilarity
- *Integral* vs. *separable* visual dimensions
  - Integral: 2 or more features are processed holistically
    - Example: rectangle shape = width, height
  - Separable: make separate judgments about each dimension
    - Example: big red ball, size and colour are distinct
- Redundant coding: using separable dimensions to encode the same thing
- Interference: one visual attributes performance on the other

Integral vs. separable

- Many of visual elements are not independent
- Separable dimensions are orthogonal.
  - e.g., position is highly separable from color.
  - In contrast, red and green hue perceptions tend to interfere with each other.

Integral

Separable

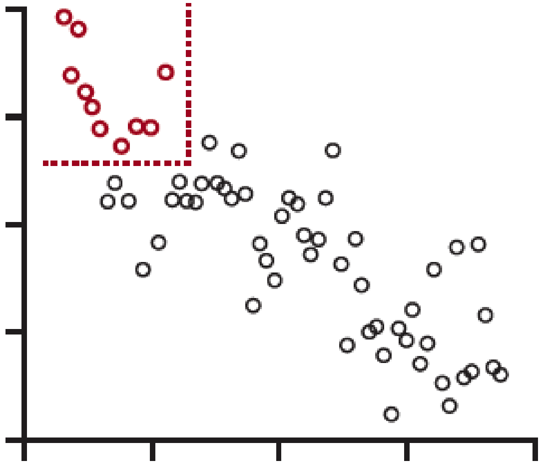


[Ware 2000]

Lessons for visualization design

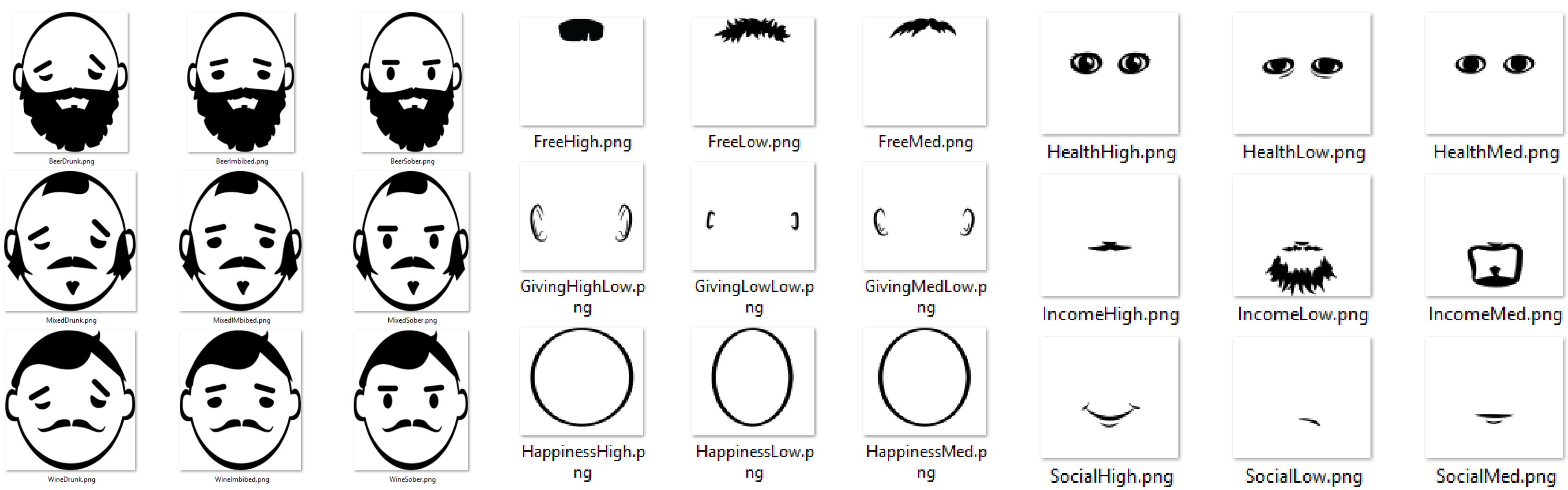
- Many visual elements are preattentative
  - Task dependent
  - Compound features can be non preattentative
    - When highlighting, choose one feature only
- To ensure that attention aligns with relevance in visuals used in visualization

Color name	RGB (1–255)
Black	0, 0, 0
Orange	230, 159, 0
Sky blue	86, 180, 233
Bluish green	0, 158, 115
Blue	0, 114, 178
Vermillion	213, 94, 0



Lessons for visualization design

- Tradeoffs in trying to display multivariate/high-dimensional data
  - Glyphs are frequently used for discrete multivariate data
    - Every time we use glyph, we sacrifice detail
    - Large glyphs == less details
    - Clear discrimination needs wider glyph spacing



Lessons for visualization design

- A critical issue for information display is whether more complex patterns can be preattentively processed.
- Coding with combinations of features requires *conjunction search*
  - Image that we wish to search for a gray square
  - Conjunction searches are generally not pre-attentive, although there are a few very interesting exceptions.
- Guidelines for highlighting
  - Adding marks to highlight is better than taking a mark away
  - Coding must stand out on some simple dimension
    - Color > simple shape = orientation, size
  - Use whatever graphical dimension is **least used** elsewhere

Data Exploration & Visualization

Module 3: Perception & Cognition

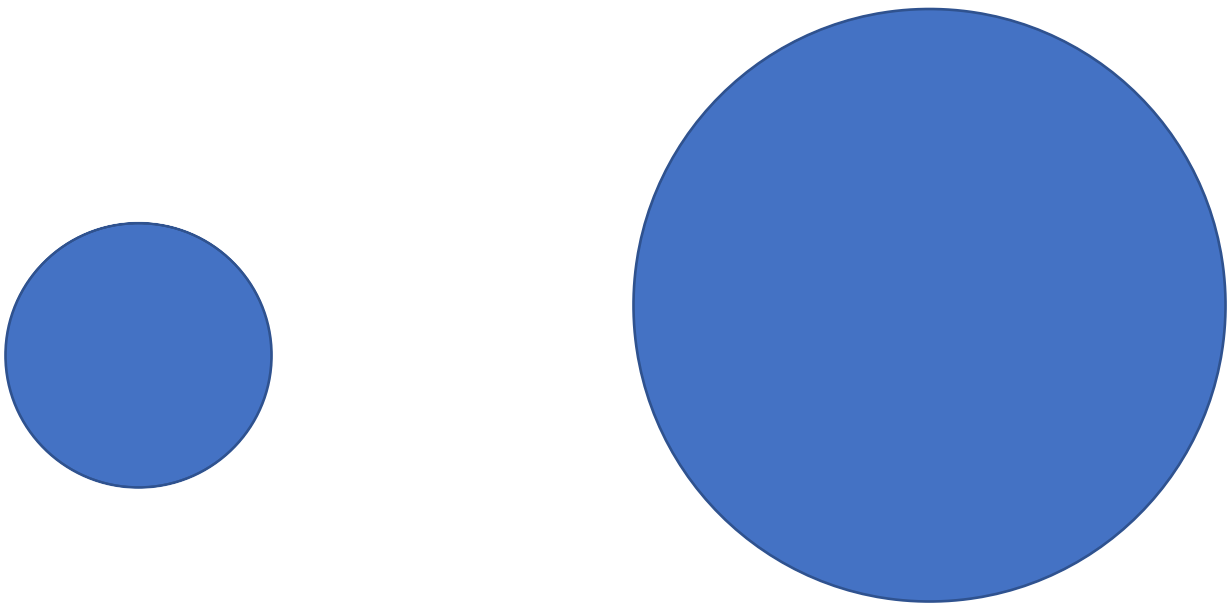
- Visual Channels
  - Pre-attentative visuals
  - Feature conjunction
- Just noticeable difference
  - Weber's law
  - Stevens' power law
- Gestalt theory

Magnitude estimation

- How much bigger is the lower bar?

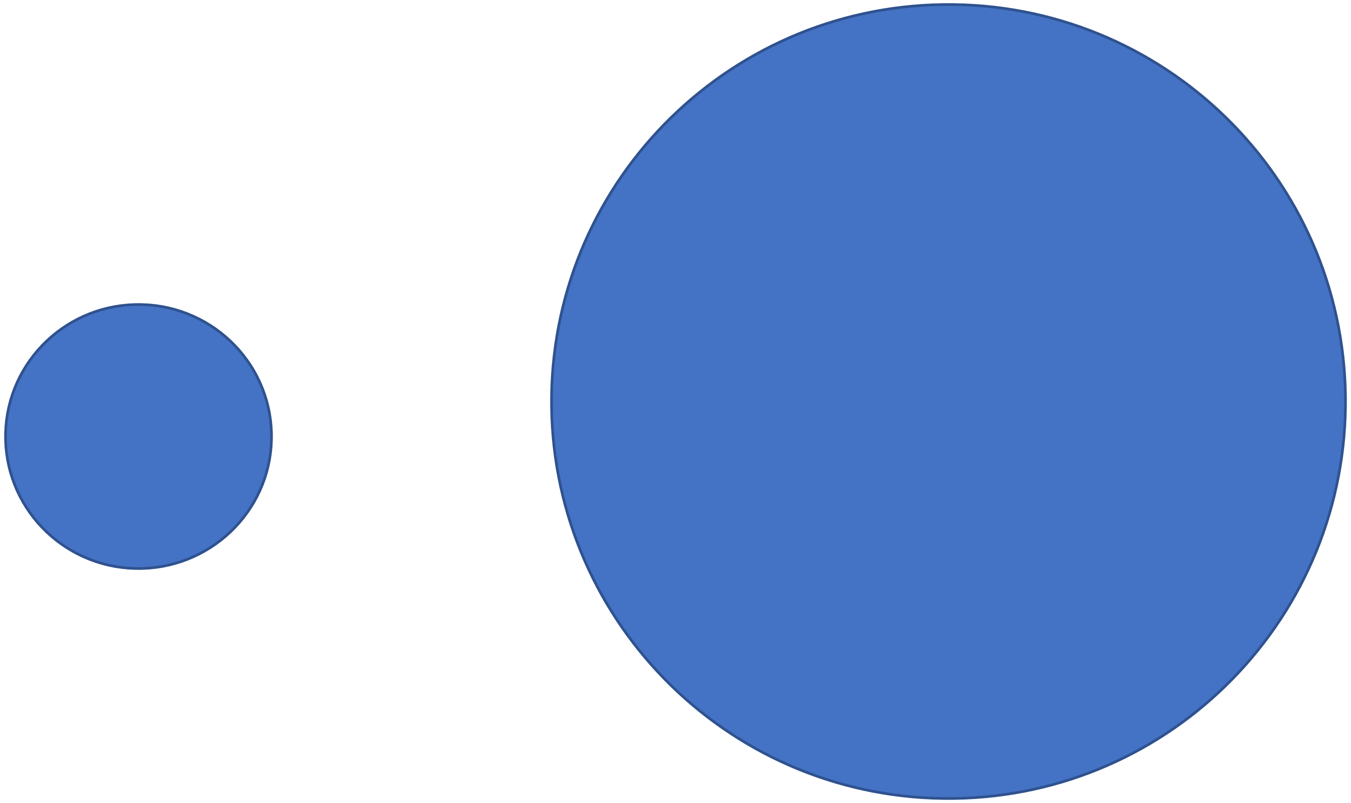
Magnitude estimation

- How much bigger is the right circle?



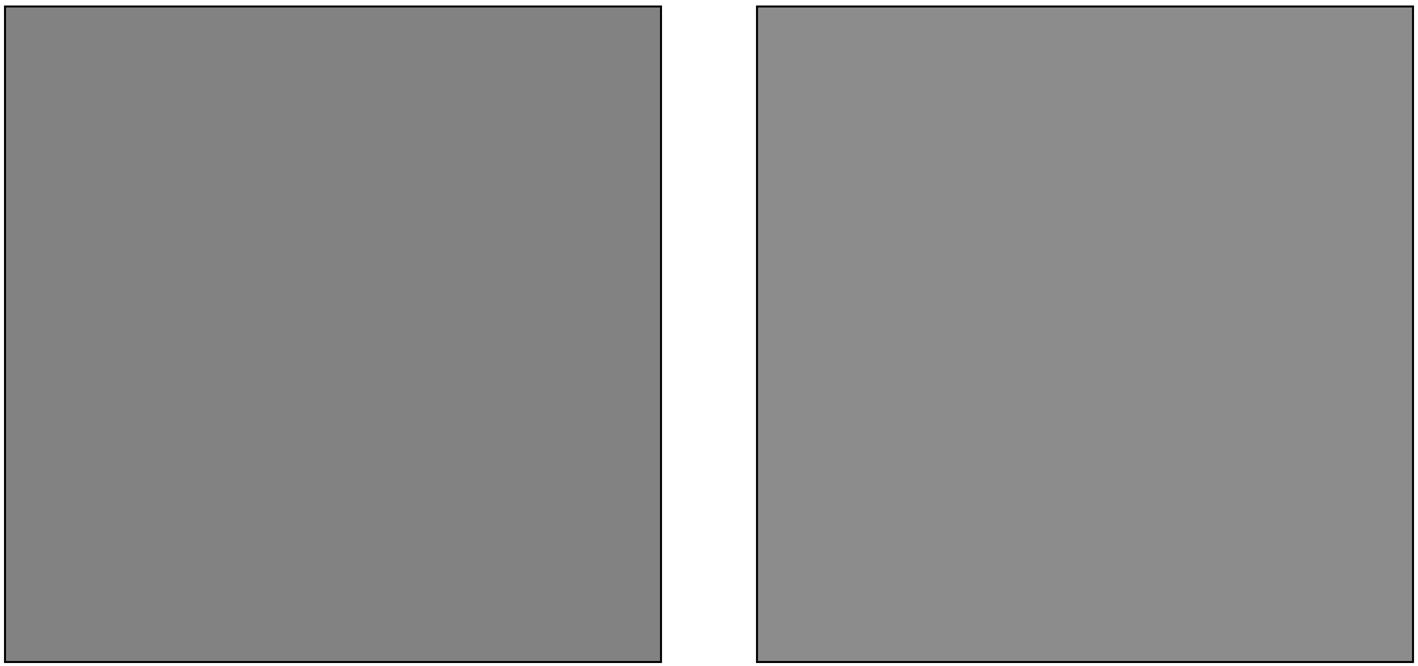
Magnitude estimation

- How much bigger is the right circle?



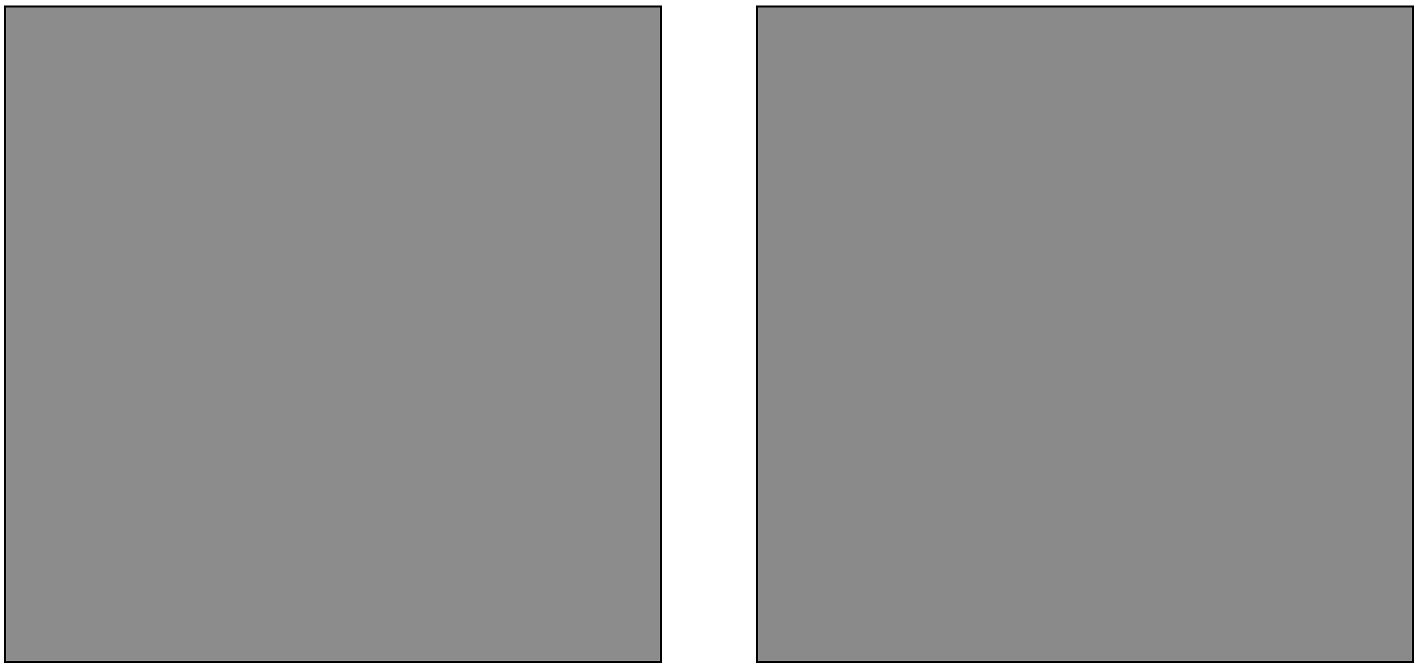
Color difference

- Which is brighter?



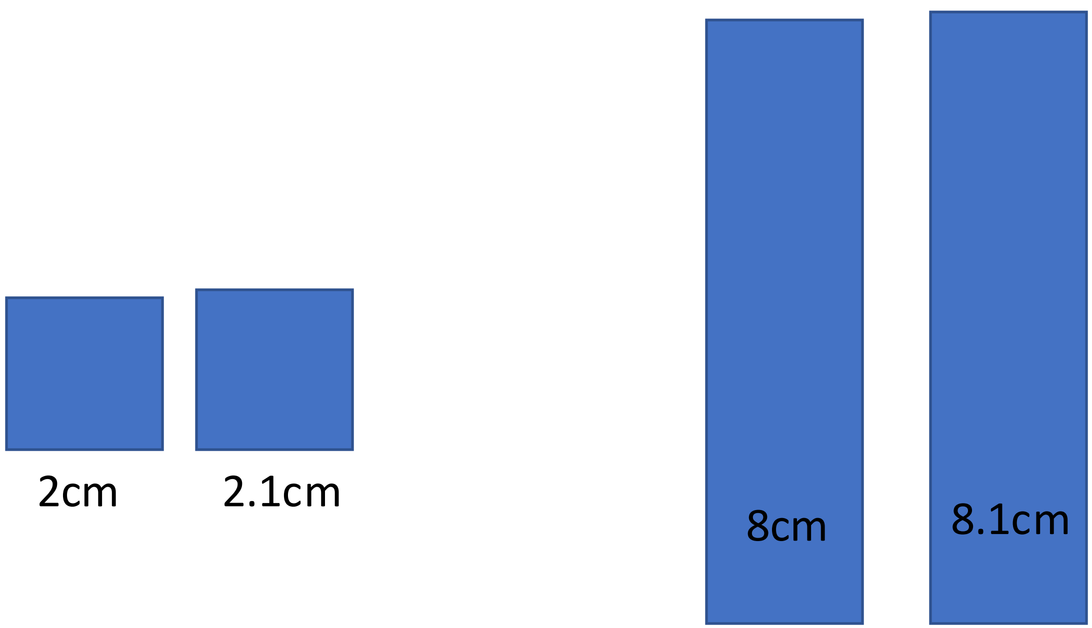
Color difference

- Which is brighter?



Just noticeable difference

- The minimum level a stimulus that needs to be changed in order for people to be able to perceive it.
  - ***S:*** the intensity of a particular stimulation (length, size, color, weight, density, etc.)



Weber's Law

- In the 1830's, Weber made measurements of the just-noticeable differences (JNDs) in the perception of weight and other sensations.

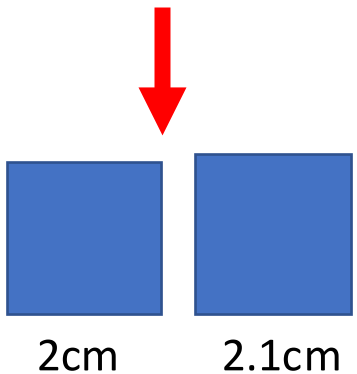
- For a range of stimuli, the ratio of the JND ΔS to the initial stimulus S was relatively constant:

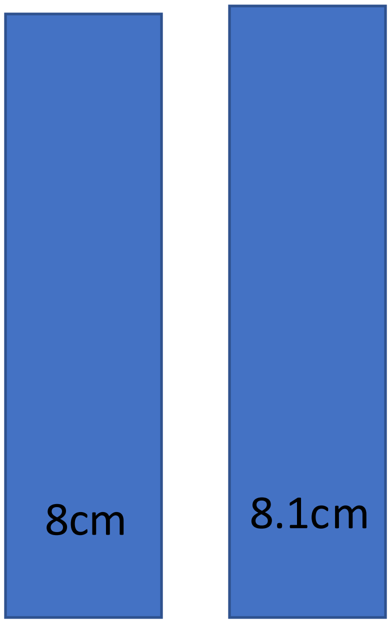
$$\Delta S / S = k$$

- For the same stimuli, *k is* ***constant***
- For different stimulus, *k* is ***different***

Weber's Law

More noticeable difference





S = 2cm
ΔS = 0.1cm

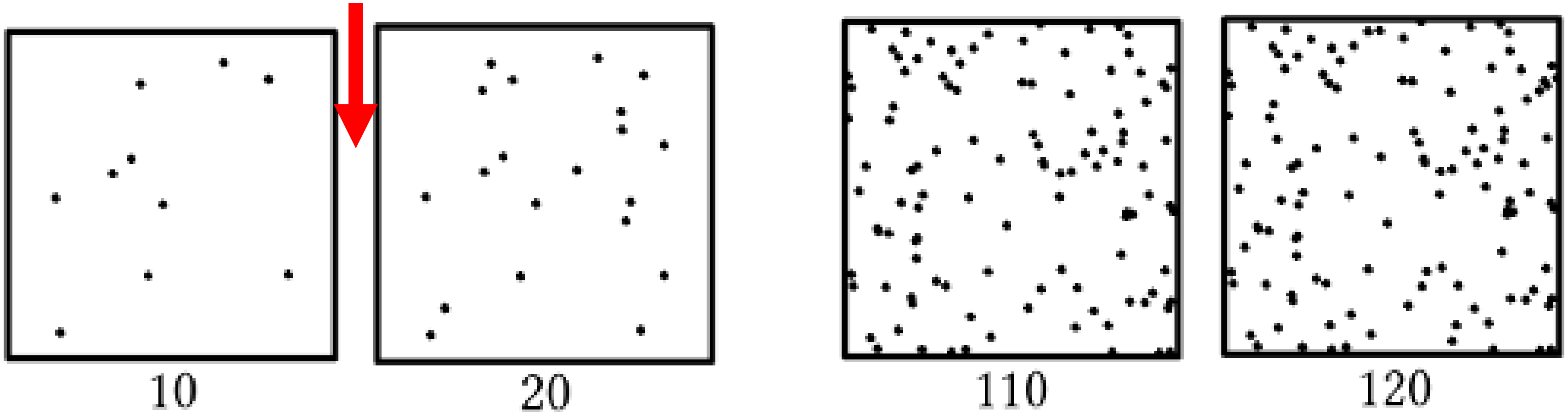
ΔS / S = 0.1cm / 2cm
= 0.05

S = 8cm
ΔS = 0.1cm

ΔS / S = 0.1cm / 8cm
= 0.0125

Weber's Law

More noticeable difference



S = 10

ΔS = 10

ΔS / S = 10 / 10

= 1

S = 110

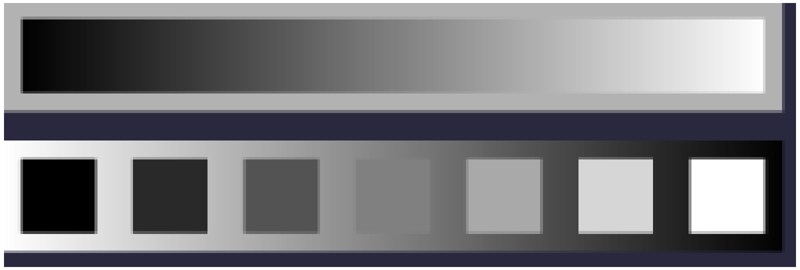
ΔS = 10

ΔS / S = 10 / 110

= 0.091

Weber's Law

- Most continuous variations in magnitude are perceived as discrete steps
  - Examples: color maps, font sizes



- Ratios more important than magnitude in stimulus detection
  - For example: we detect the presence of a change from 100 cm to 101 cm with the same probability as we detect the presence of a change from 1 to 1.01 cm

Stevens' Power Law

$$s(x) = ax^b$$

s is the sensation

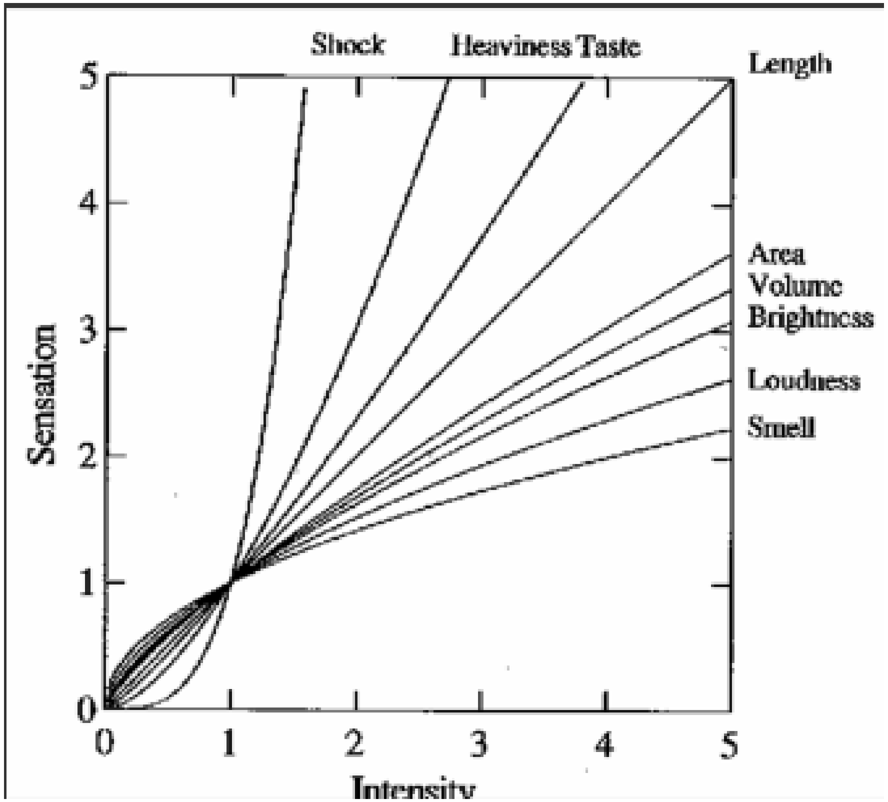
x is the intensity of the attribute

a is a multiplicative constant

b is the power

b > 1: overestimate

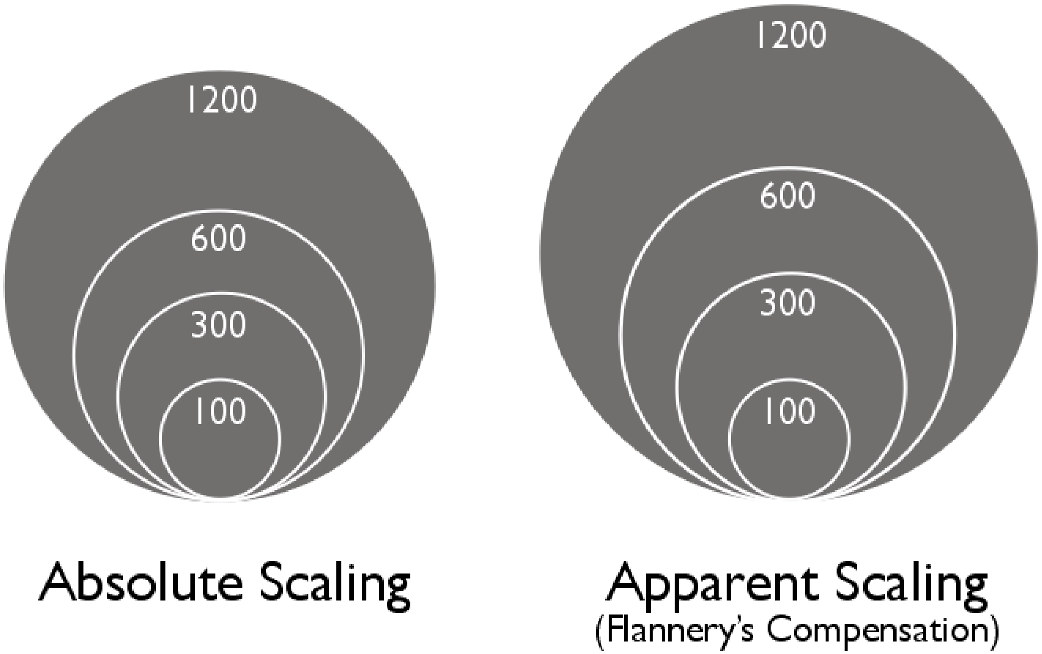
b < 1: underestimate



[graph from Wilkinson 99]

Stevens' Power Law

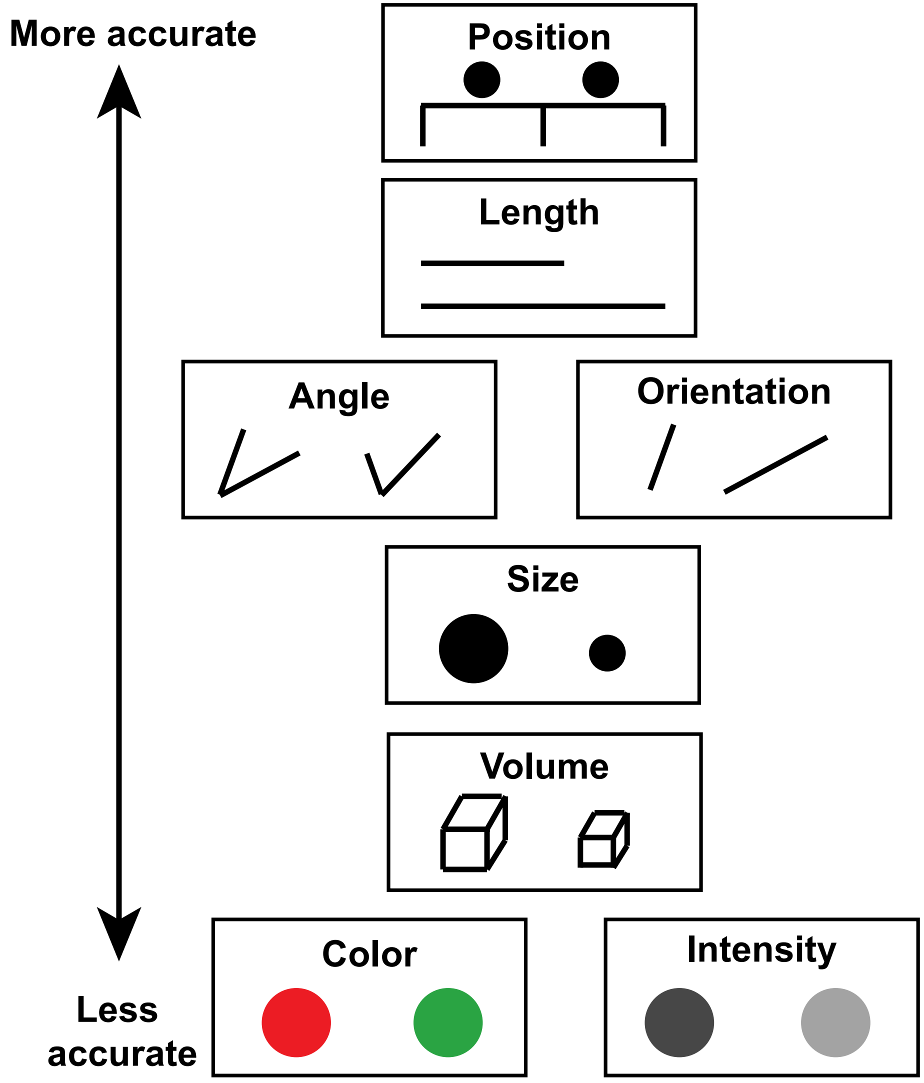
- Apparent magnitude scaling



$$S = 0.98A^{0.87}$$

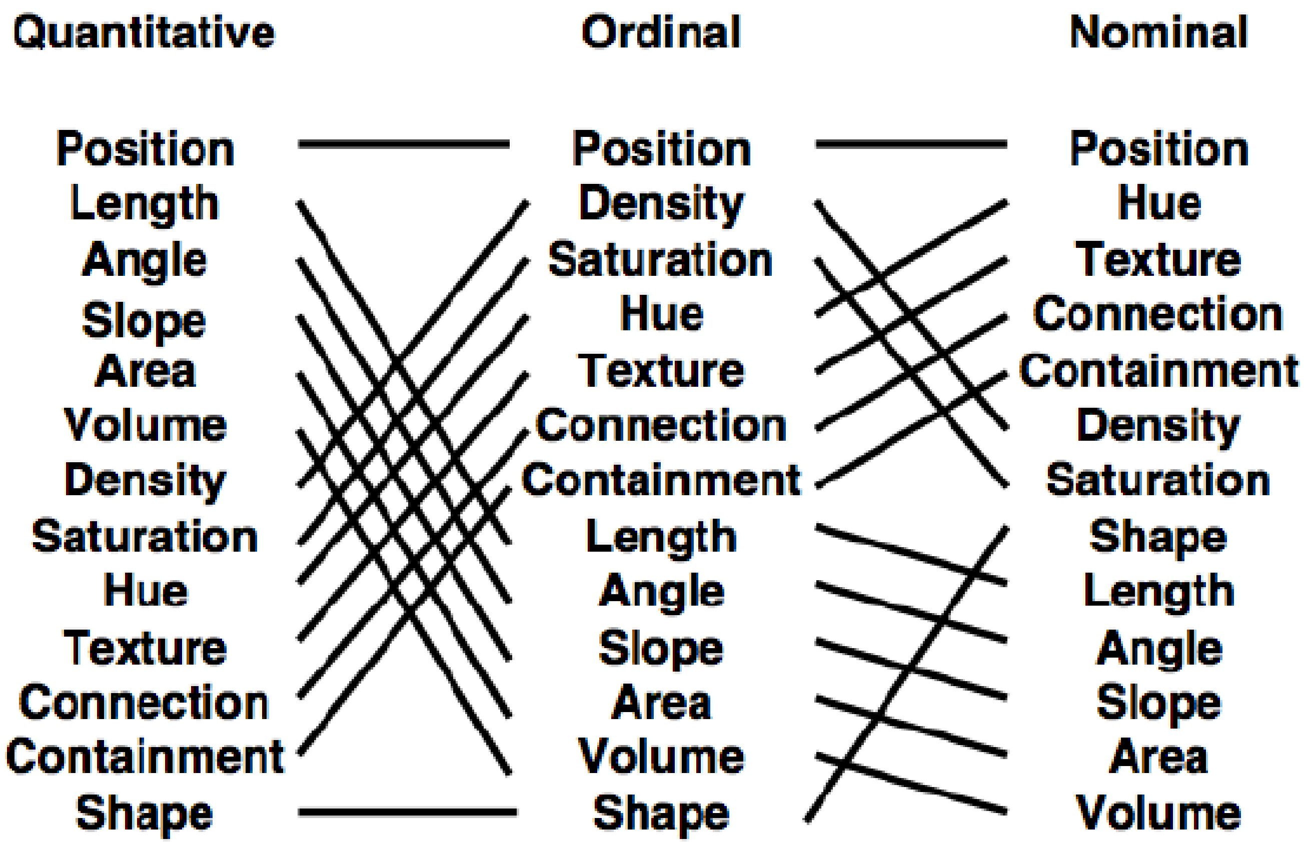
J. J. Flannery, The relative effectiveness of some graduated point symbols in the presentation of quantitative data, Canadian Geographer, 8(2), pp. 96-109, 1971

Relative magnitude estimation

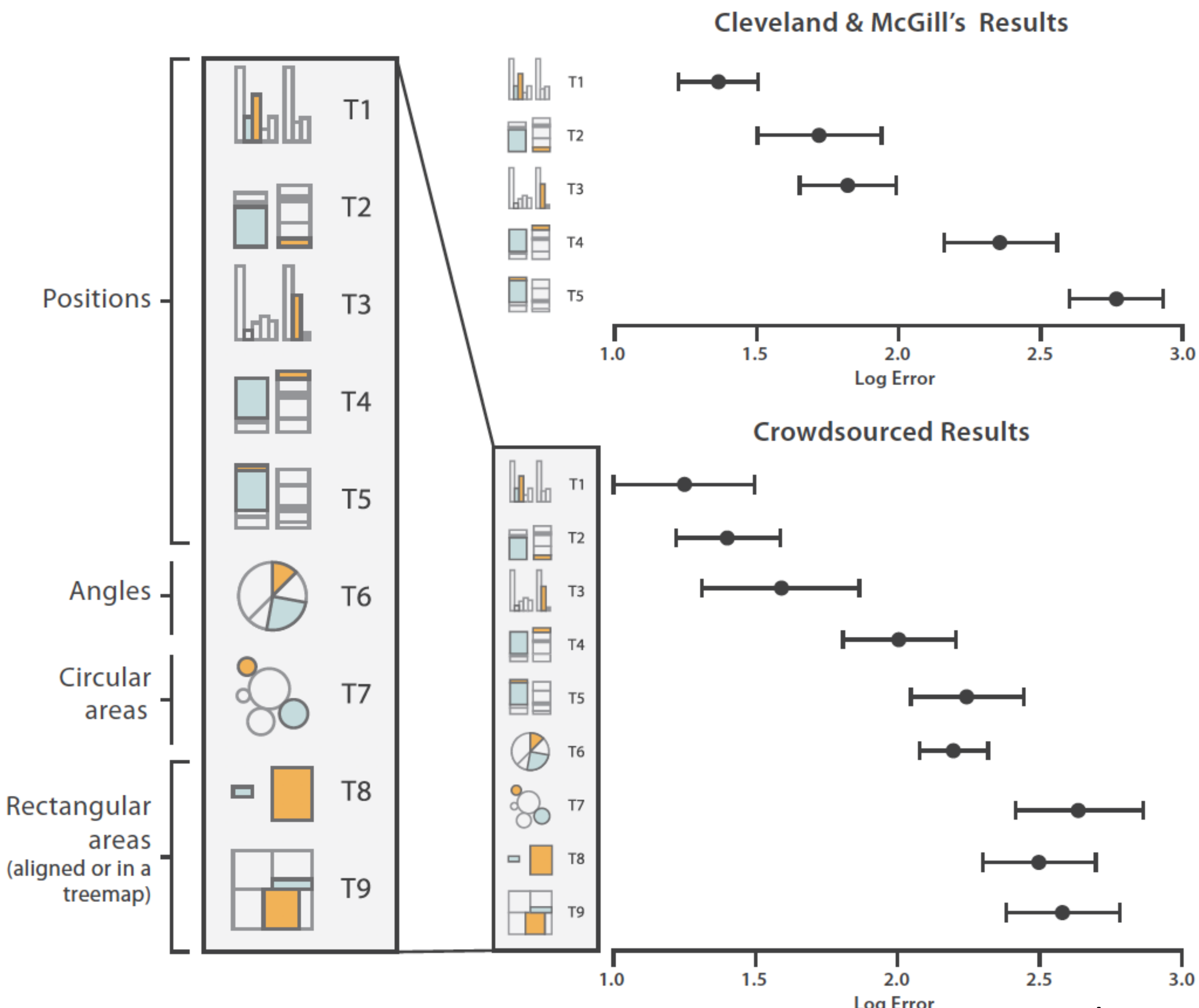


Accuracy of judgment

- Choices of visual variable dependent on different data types [Mackinlay, 1986]

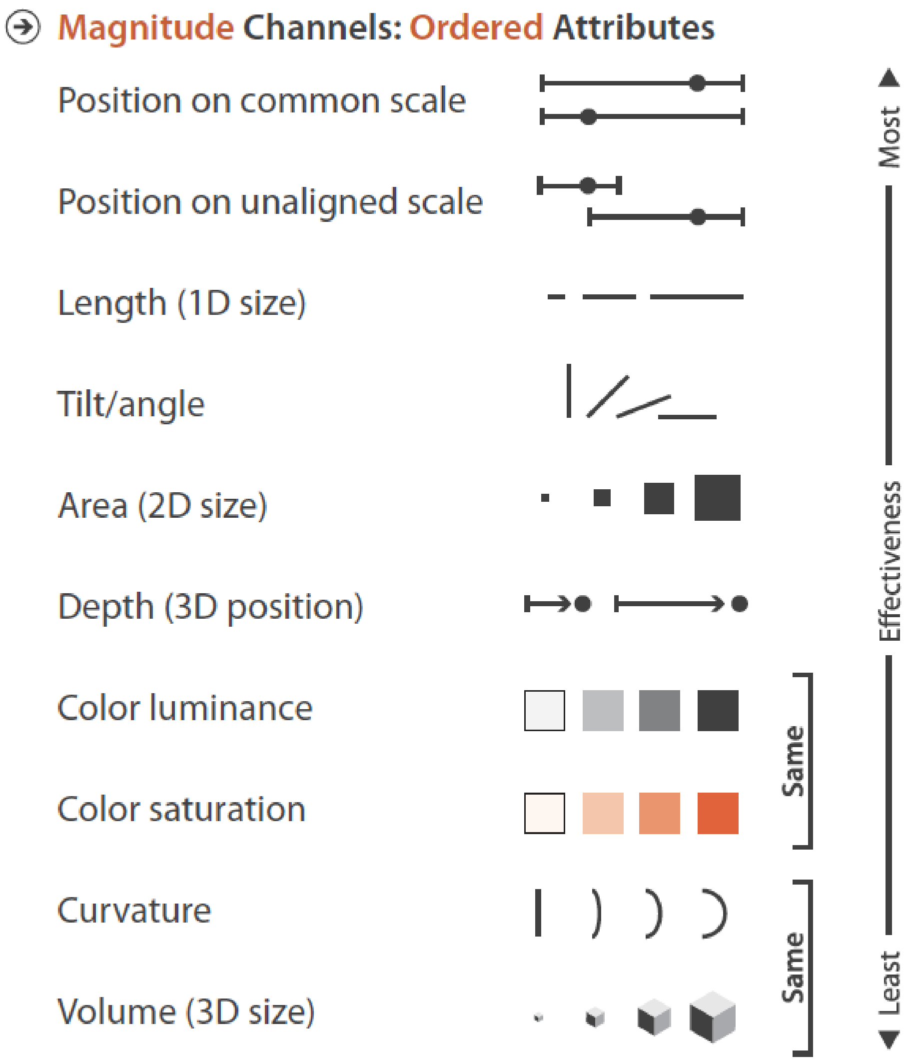


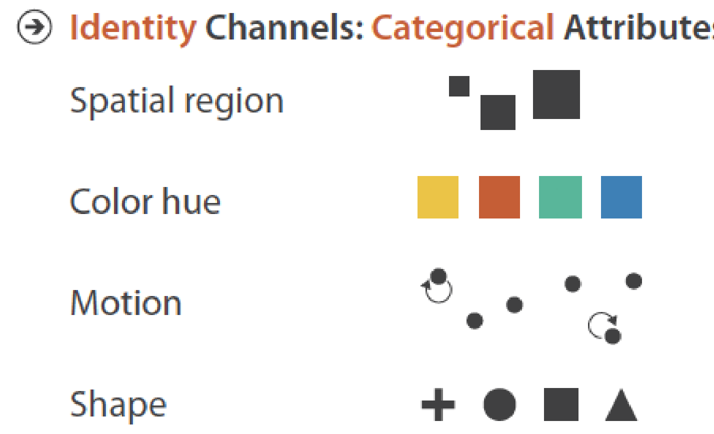
Graphical perception accuracy



Credit: Heer & Bostock

Effectiveness principle





- **Effectiveness principle**
  - Encode most important attributes with highest ranked channels

Credit: Tamara Munzner

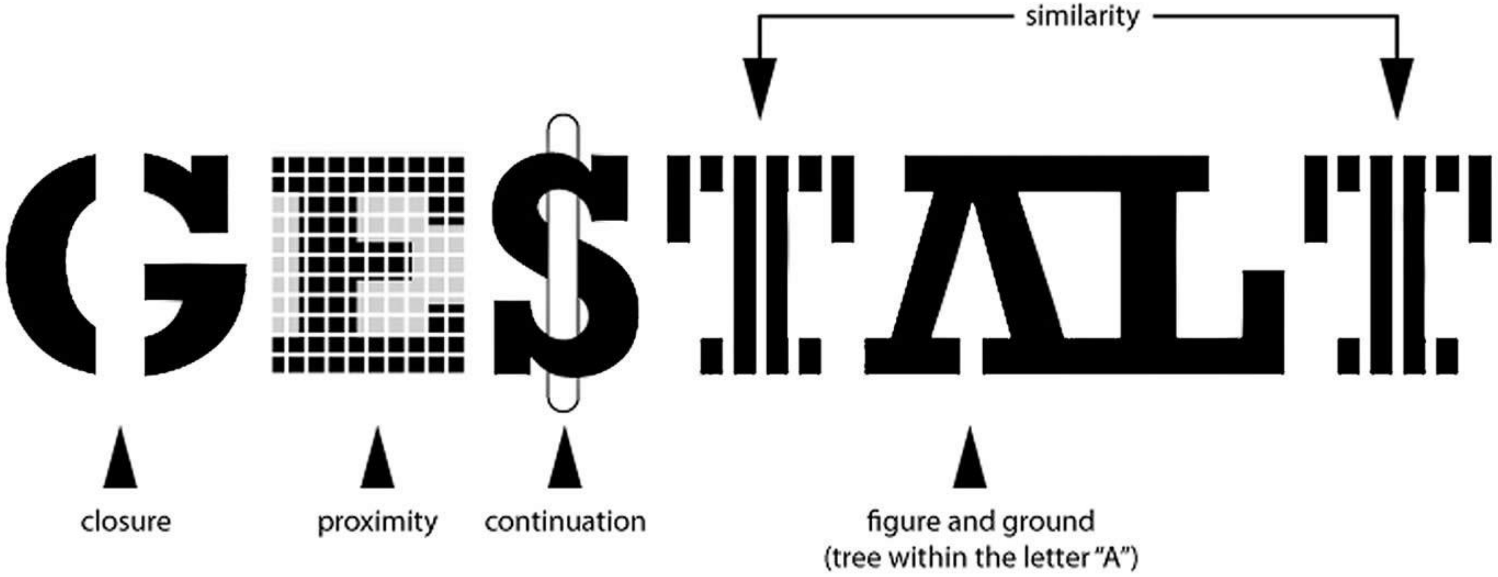
Data Exploration & Visualization

Module 3: Perception & Cognition

- Visual Channels
  - Pre-attentative visuals
  - Feature conjunction
- Just noticeable difference
  - Weber’s law
  - Stevens’ power law
- Gestalt theory

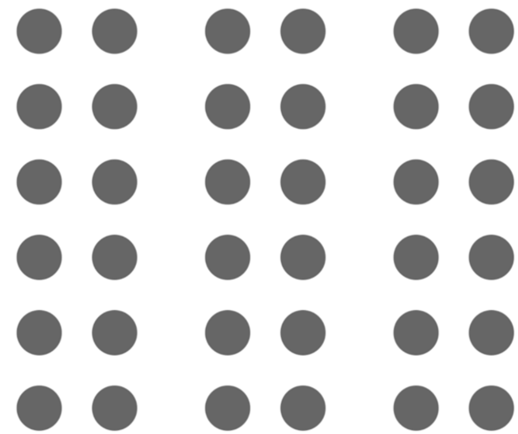
Gestalt theory

- Gestalt (German word – ‘the unified whole’), is interpreted as "pattern" or "configuration"
- The whole is more than the sum of its parts



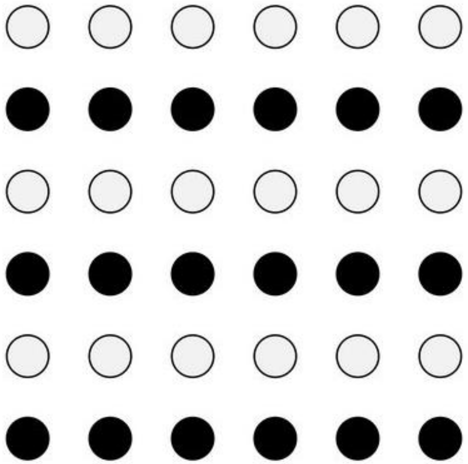
Law of proximity

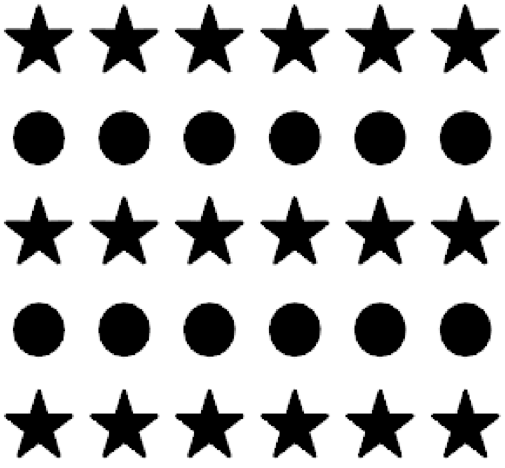
- The whole is more than the sum of its parts
  - Proximity: Objects or shapes that are close to one another are perceived to form groups.
  - Similarity
  - Continuity
  - Closure
  - Symmetry
  - Figure-ground



Law of similarity

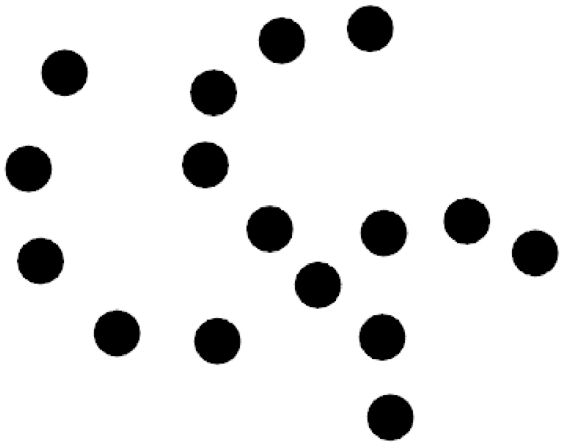
- The whole is more than the sum of its parts
  - Proximity
  - Similarity: Objects or shapes that are similar in shape, size, color, texture or value are perceived to belong together.
  - Continuity
  - Closure
  - Symmetry
  - Figure-ground

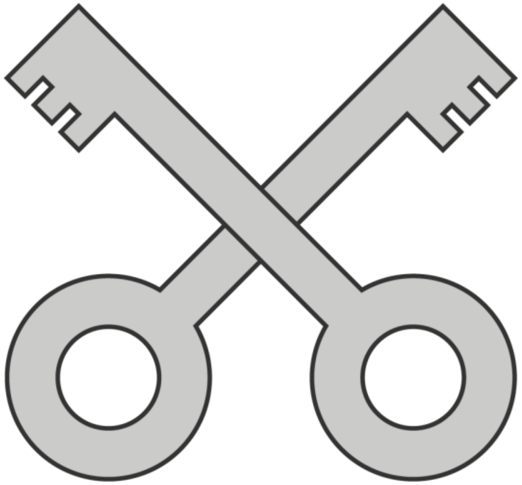




Law of continuity

- The whole is more than the sum of its parts
  - Proximity
  - Similarity
  - Continuity: Objects or shapes that are arranged in a line or a curve are perceived to be more related than those that are abrupt.
  - Closure
  - Symmetry
  - Figure-ground





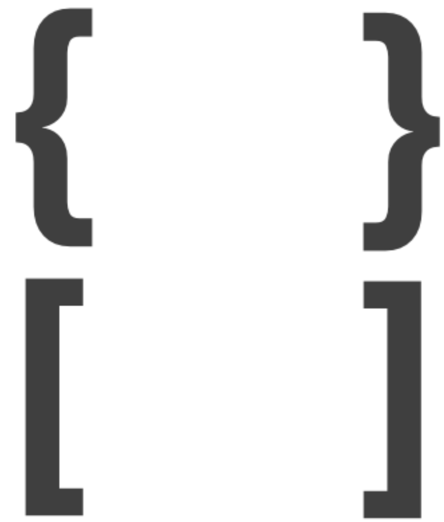
Law of closure

- The whole is more than the sum of its parts
  - Proximity
  - Similarity
  - Continuity
  - Closure: Figures or shapes that are incomplete or partially hidden are perceived to be complete as our brain automatically fill in the gaps.
  - Symmetry
  - Figure-ground

World Wide Fund for Nature

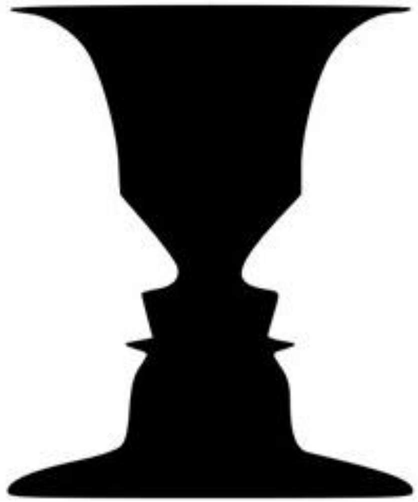
Law of symmetry

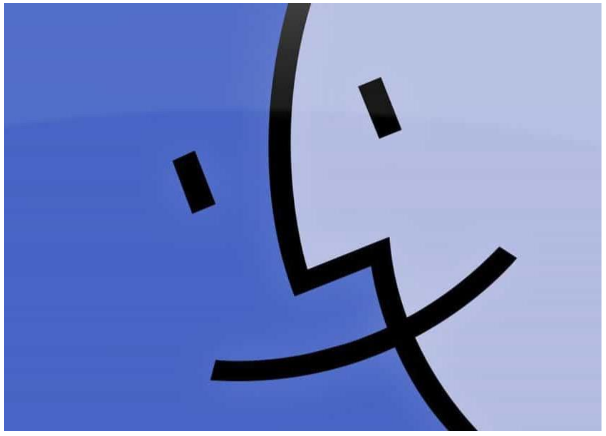
- The whole is more than the sum of its parts
  - Proximity
  - Similarity
  - Continuity
  - Closure
  - Symmetry: Objects or shapes that are symmetrical and forming around a center point are **{**perceptually pleasing**}**.
  - Figure-ground



Law of figure-ground

- The whole is more than the sum of its parts
  - Proximity
  - Similarity
  - Continuity
  - Closure
  - Symmetry
  - Figure-ground: Humans can distinguish an object (the **figure** of the rule) from background (the **ground**)



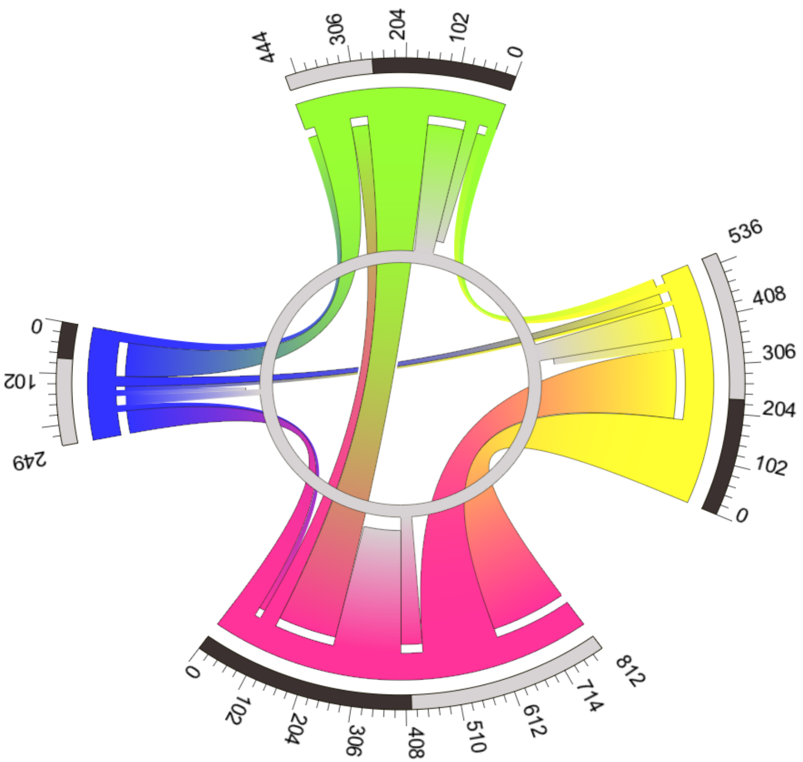


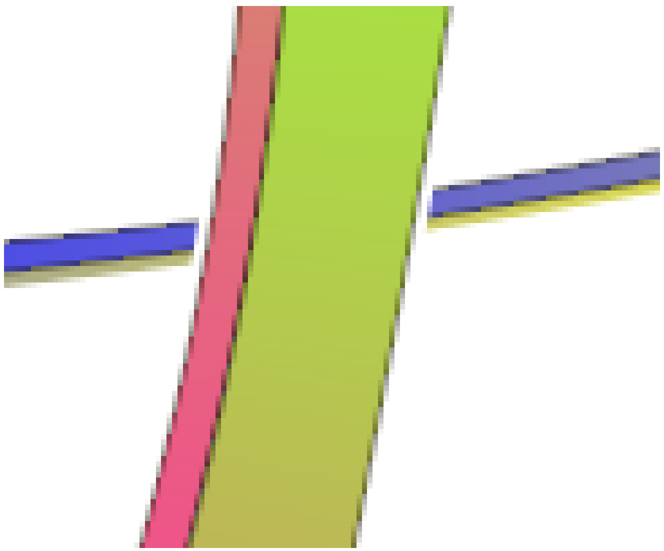
Application

- Charming China, Season 3

Examples for visualization design

- Interchange circos diagram
  - Haloes to reduce ambiguity caused by edge crossing

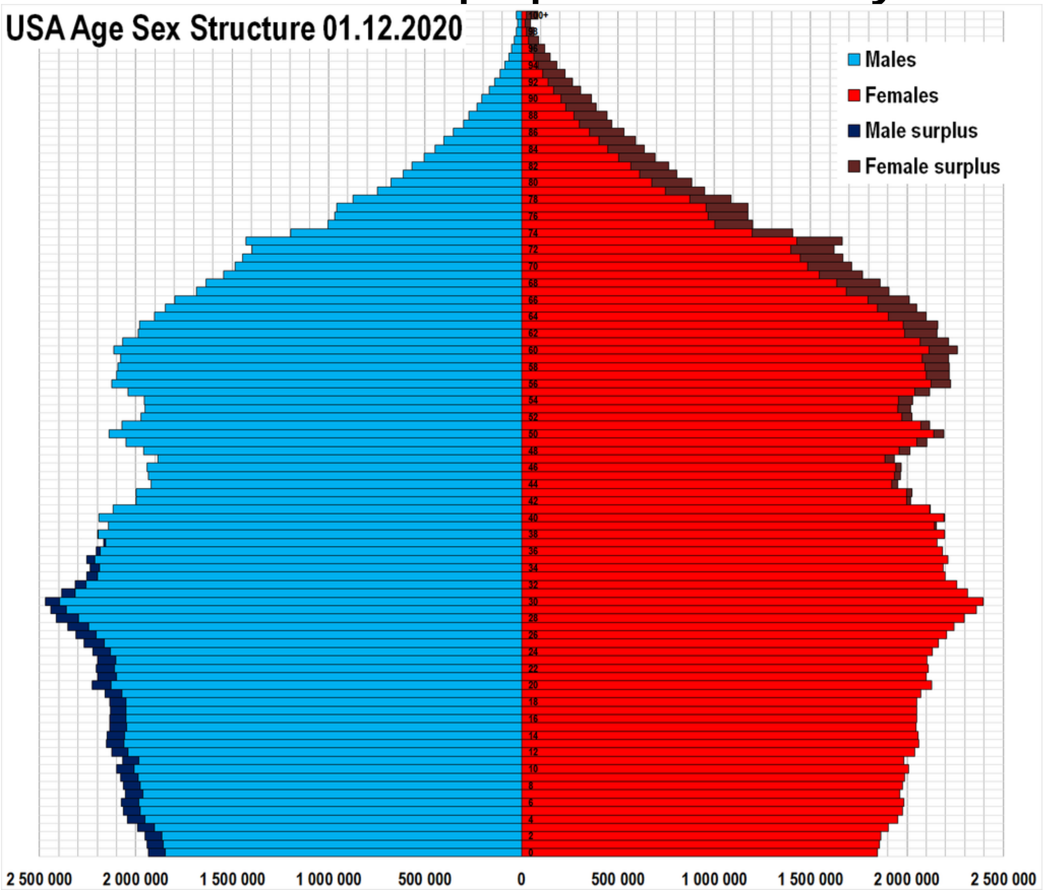




Credit: Zeng et al. 2013

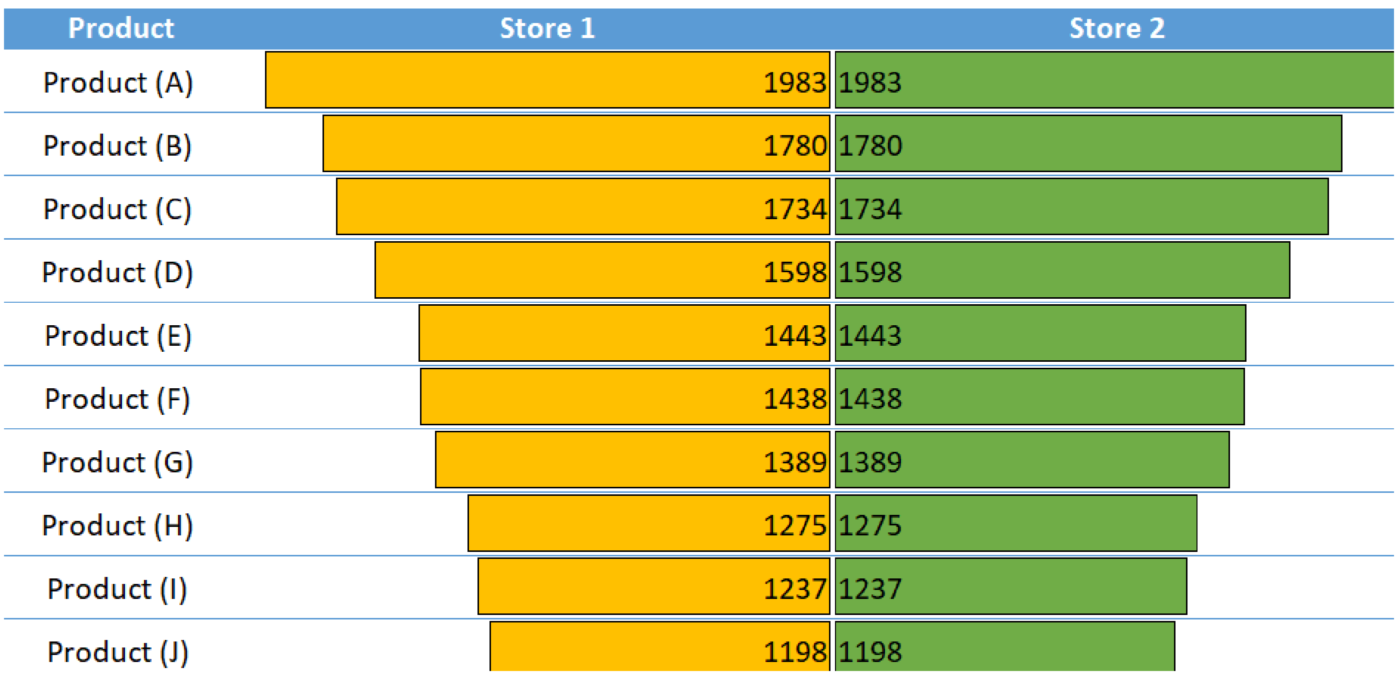
Examples for visualization design

- Population pyramid diagram
  - Arranges male/female population in symmetry



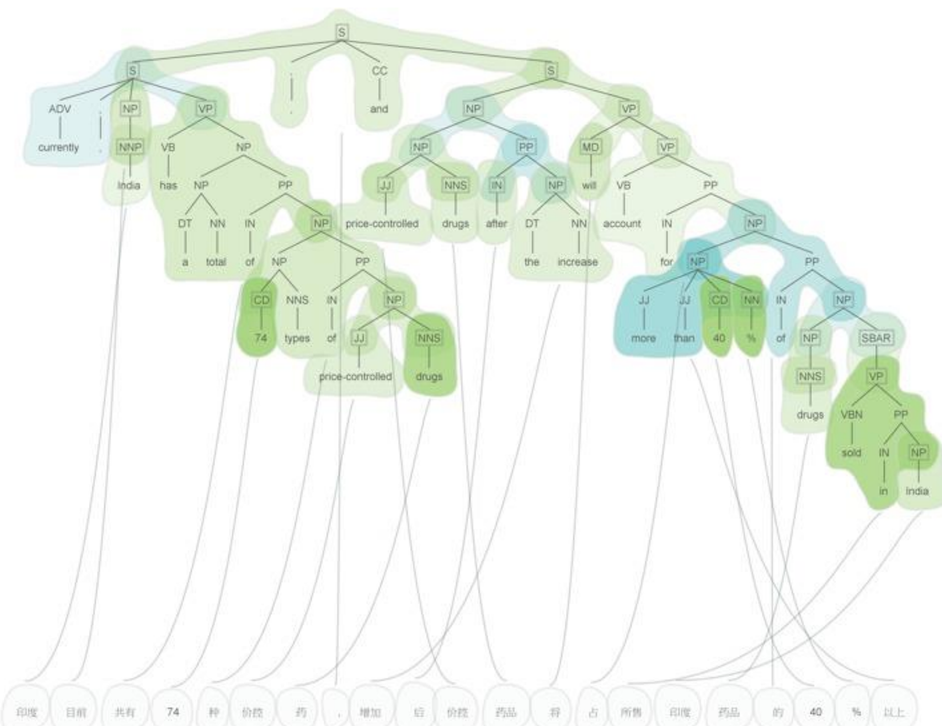
Examples for visualization design

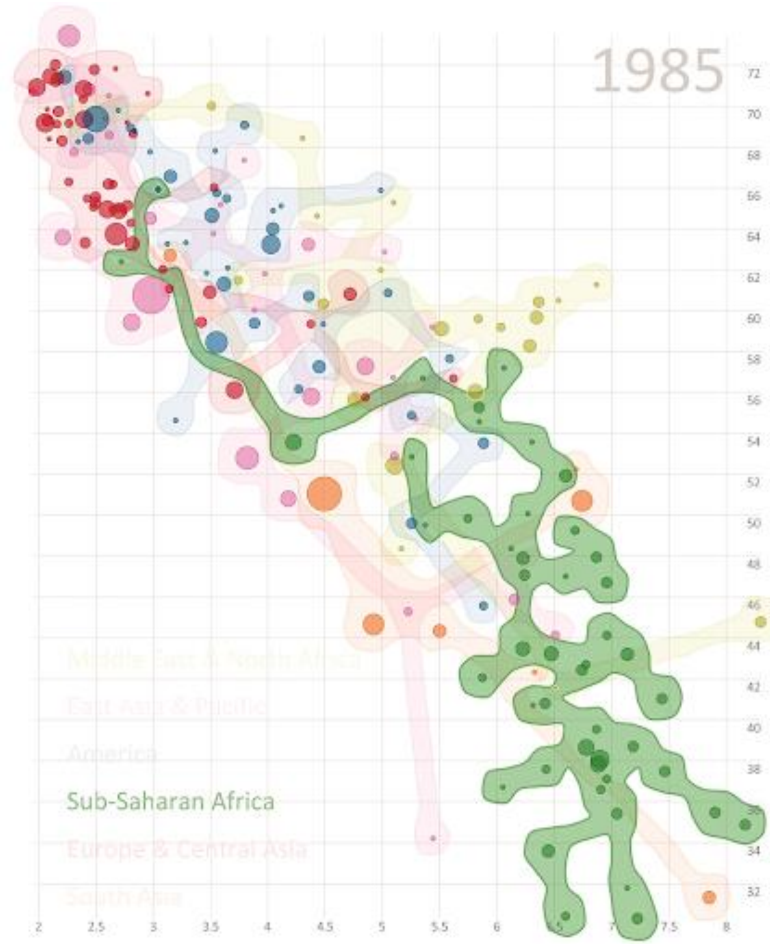
- Tornado plot
  - Bar charts arranged in symmetry
  - Make comparison easy
  - Useful for sensitivity analysis



Examples for visualization design

- Bubble sets
  - spatial organization
  - set membership relationship





Credit: Collins et al., 2009

Questions?