Visual perception

Data Management and Visualization

SoftEng
http://softeng.polito.it

VISUAL INTEGRITY

Principles of integrity

PUC

- Proportionality
  - Representation as physical quantities should be proportional to the represented numbers
- Utility
  - Graphical element should convey useful information
- Clarity
  - Labeling should counter graphical distortion and ambiguity

Proportionality

PUC

- The magnitude of visual attributes should represent faithfully the magnitude of measures
- They should allow
  - Discrimination: are they different?
  - Comparison: which is larger?
  - Magnitude Assessment: how much larger?

Lie Factor

PUC

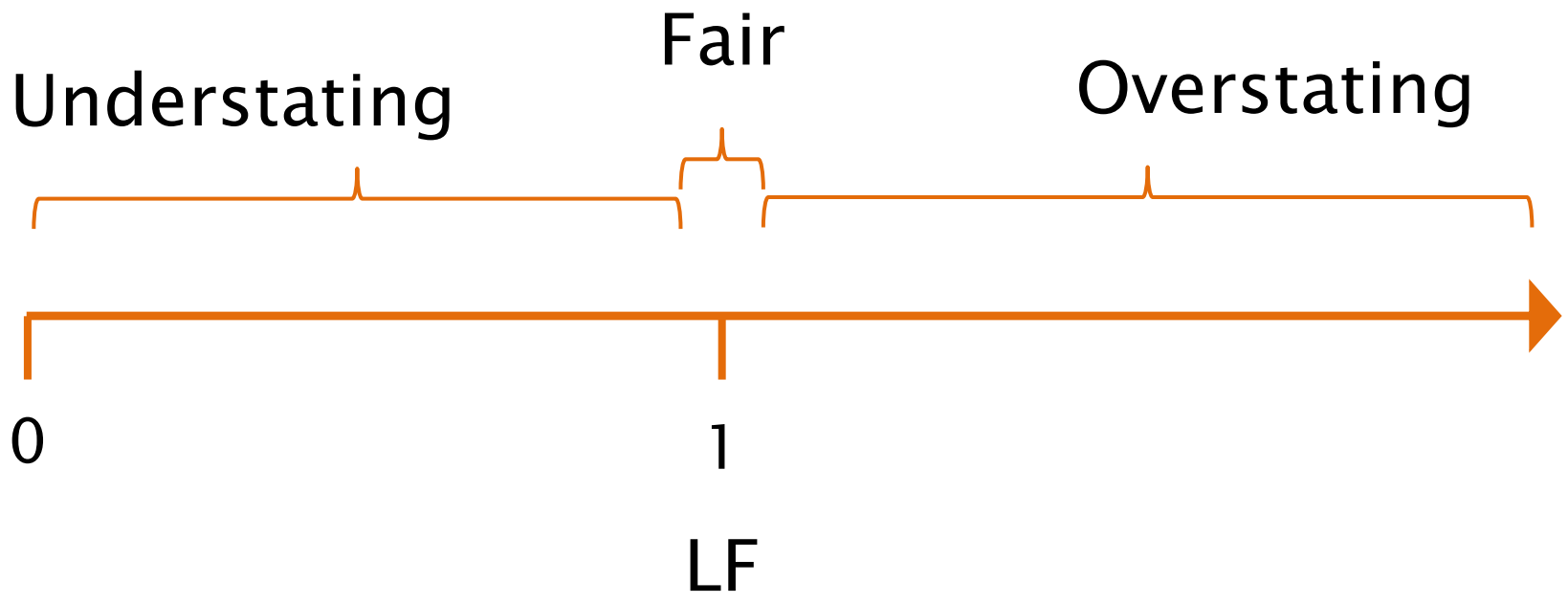
$$LF = \frac{\text{size of effect shown in graphic}}{\text{size of effect in data}}$$

- Overstating
  - LF $>$ 1 $\Leftrightarrow$ Log(LF) $>$ 0
- Understating
  - LF $<$ 1 $\Leftrightarrow$ Log(LF) $<$ 0
- Fair
  - LF $=$ 1 $\Leftrightarrow$ Log(LF) $=$ 0

Lie Factor

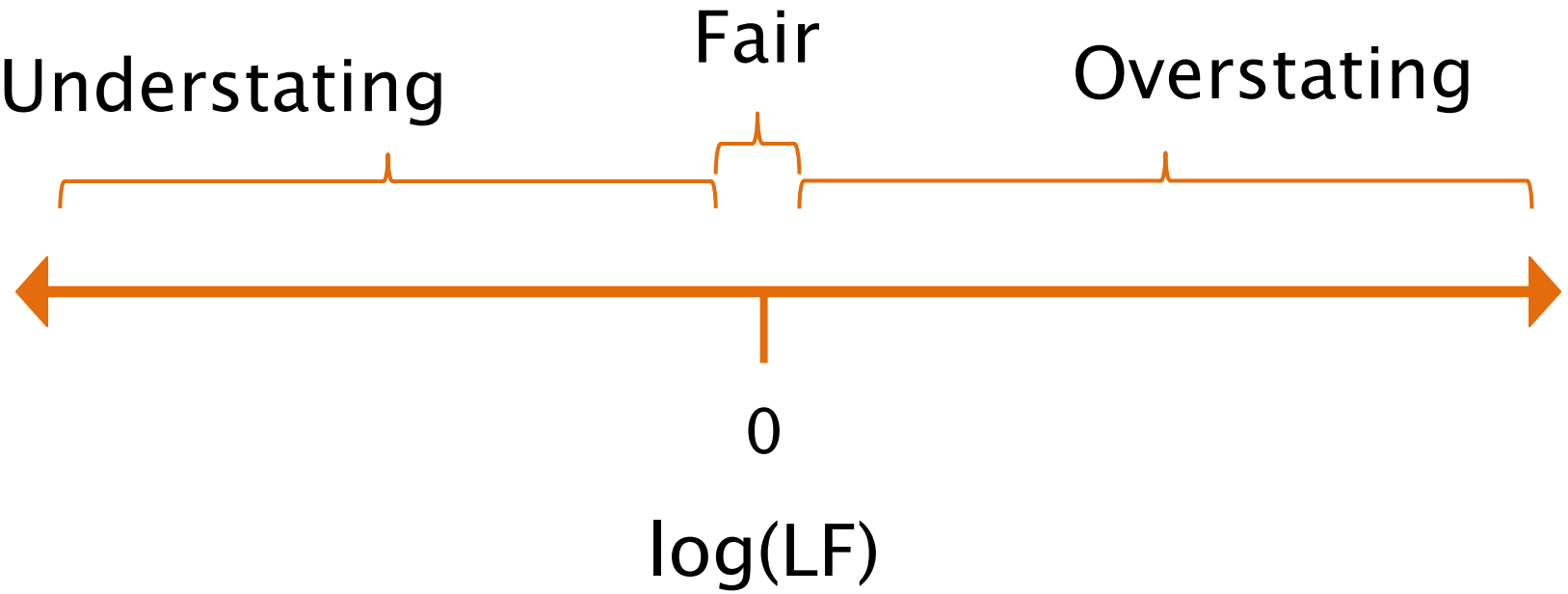
PUC

$$LF = \frac{\text{size of effect shown in graphic}}{\text{size of effect in data}}$$

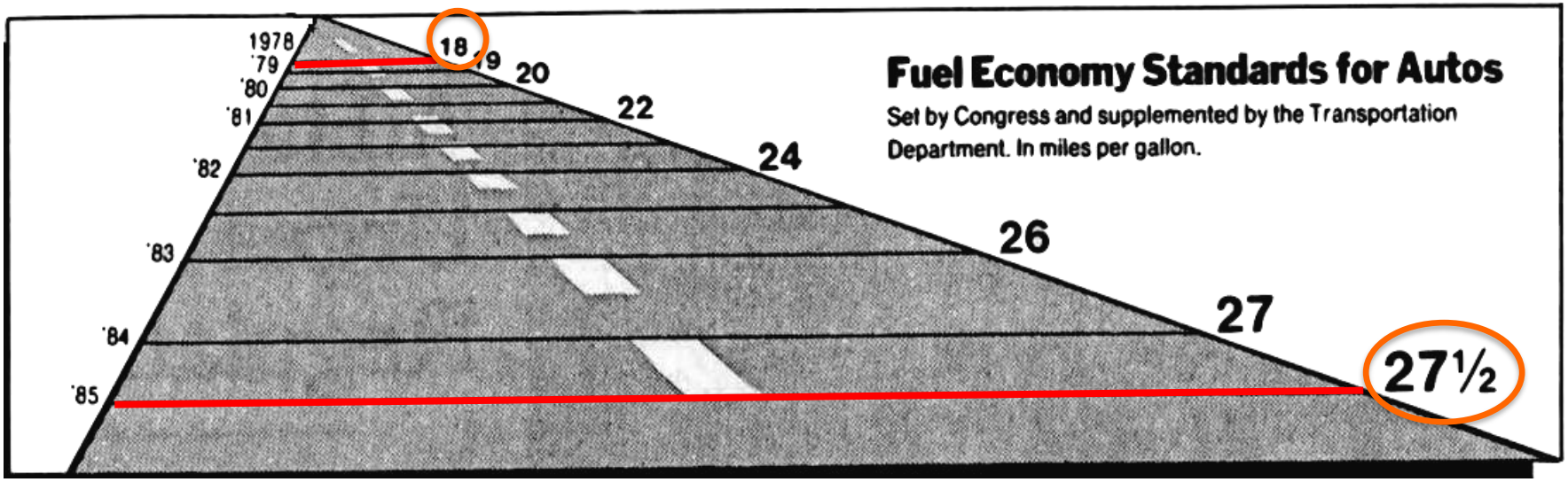


Lie Factor

$$LF = \frac{\text{size of effect shown in graphic}}{\text{size of effect in data}}$$



Lie Factor

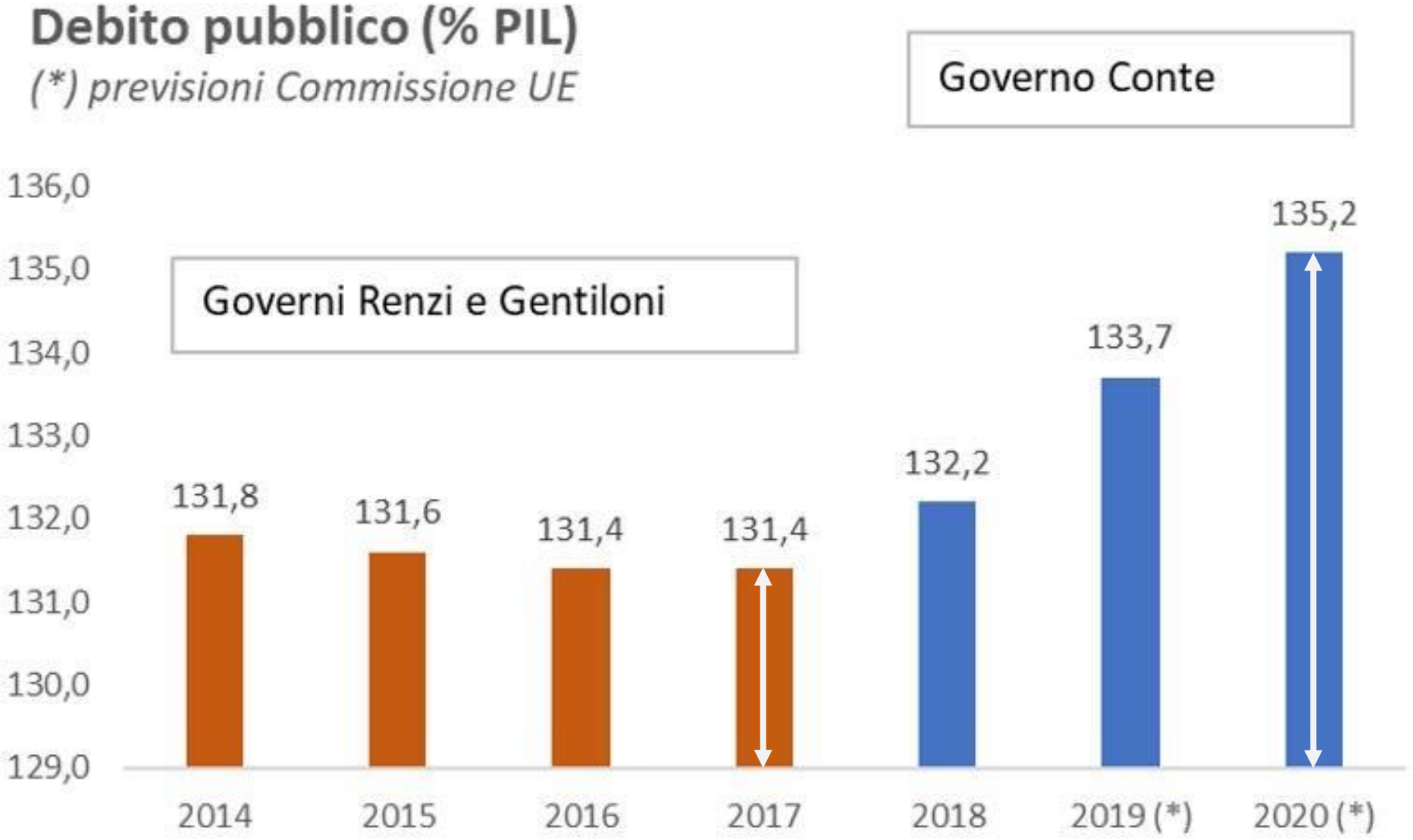


$$\frac{18.7}{2.2} = 8.5 \text{ on graphic} \qquad \frac{27.5}{18} = 1.52 \text{ in data}$$

$$LF = 8.5 \,/\, 1.52 = 5.59$$

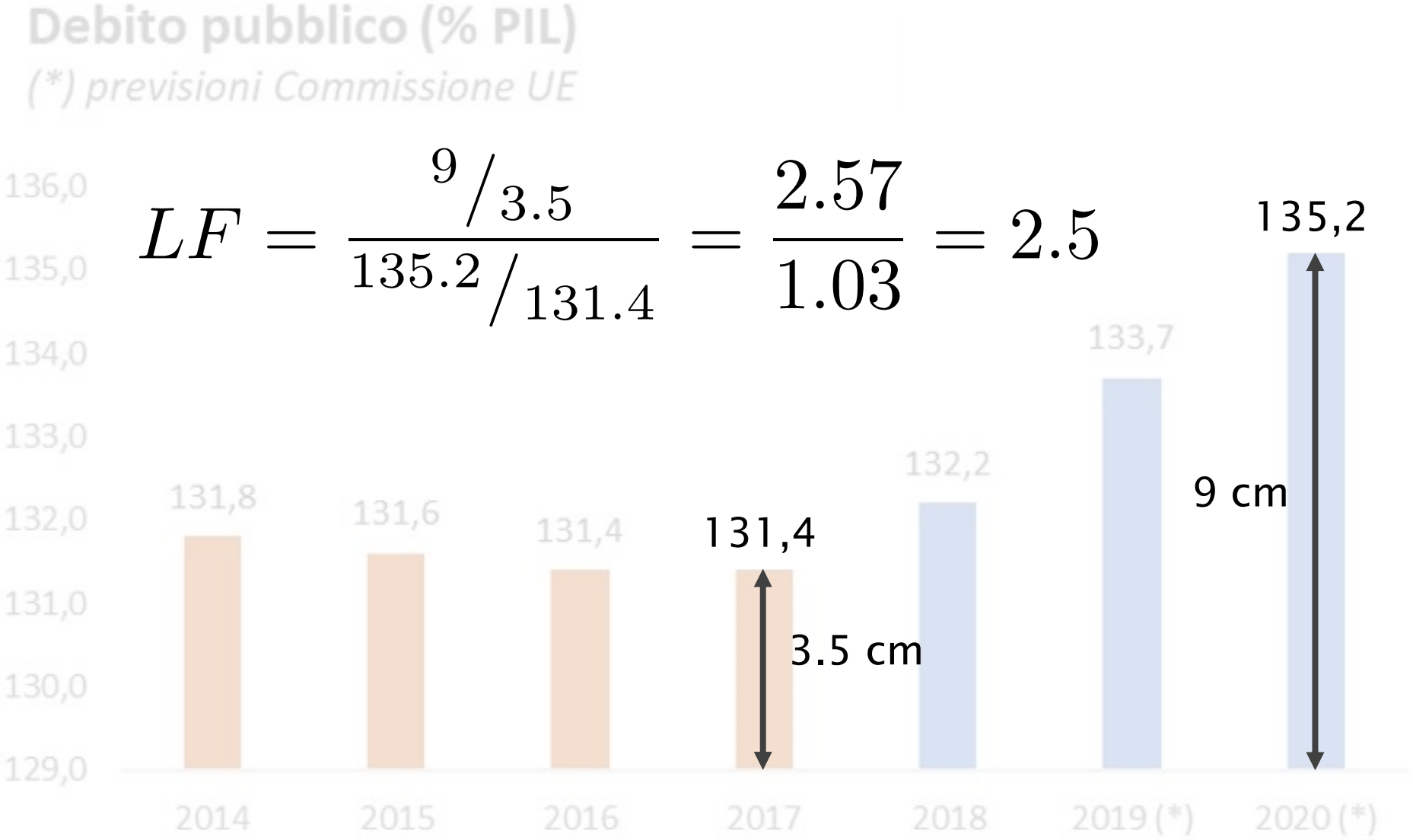
Example

PUC


Debito pubblico (% PIL)
(*) previsioni Commissione UE
Governo Conte
Governi Renzi e Gentiloni
136,0
135,0
134,0
133,0
132,0
131,0
130,0
129,0
131,8
131,6
131,4
131,4
132,2
133,7
135,2
2014
2015
2016
2017
2018
2019 (*)
2020 (*)

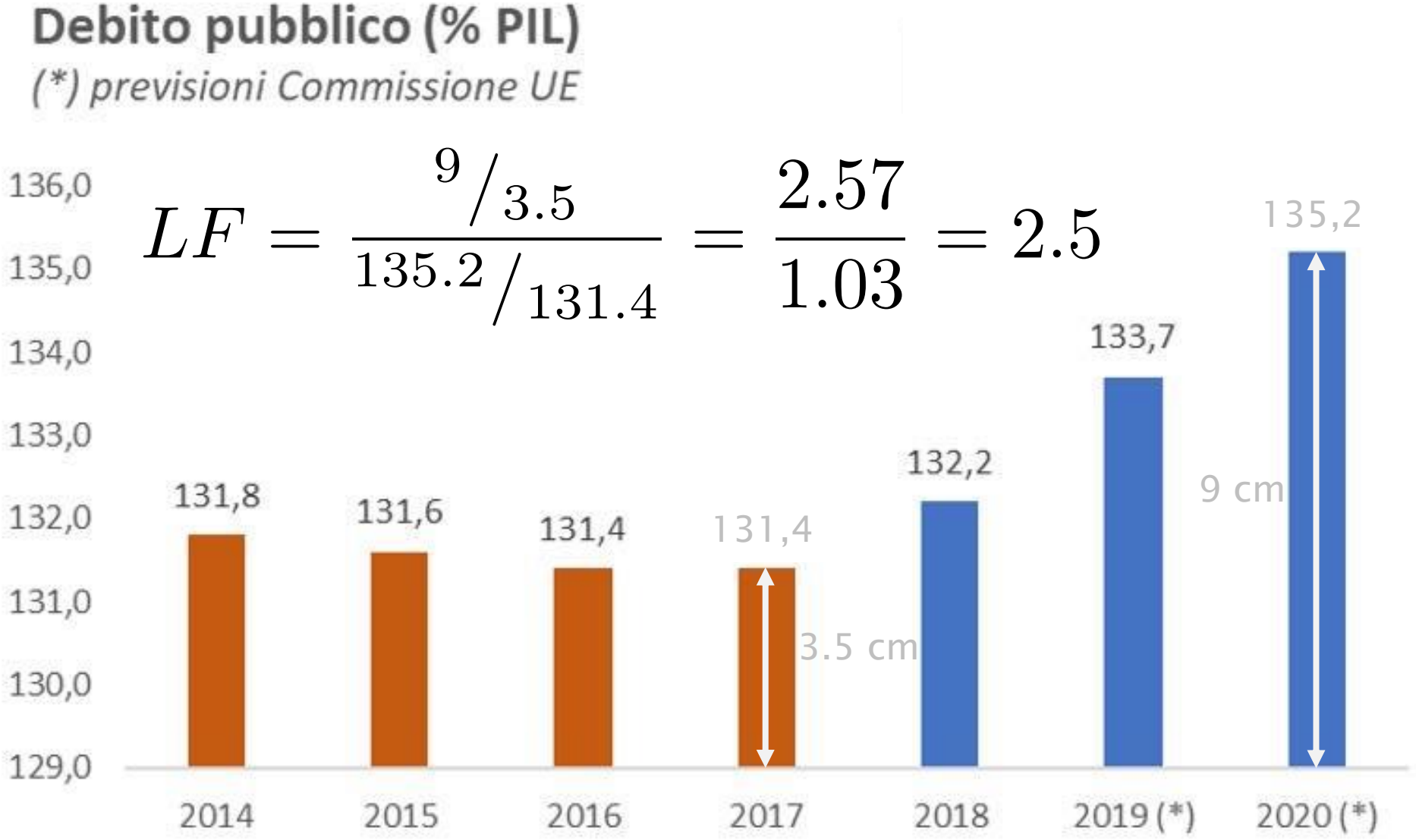
Example – Lie Factor

$$LF = \frac{{}^{9}/_{3.5}}{{}^{135.2}/_{131.4}} = \frac{2.57}{1.03} = 2.5$$

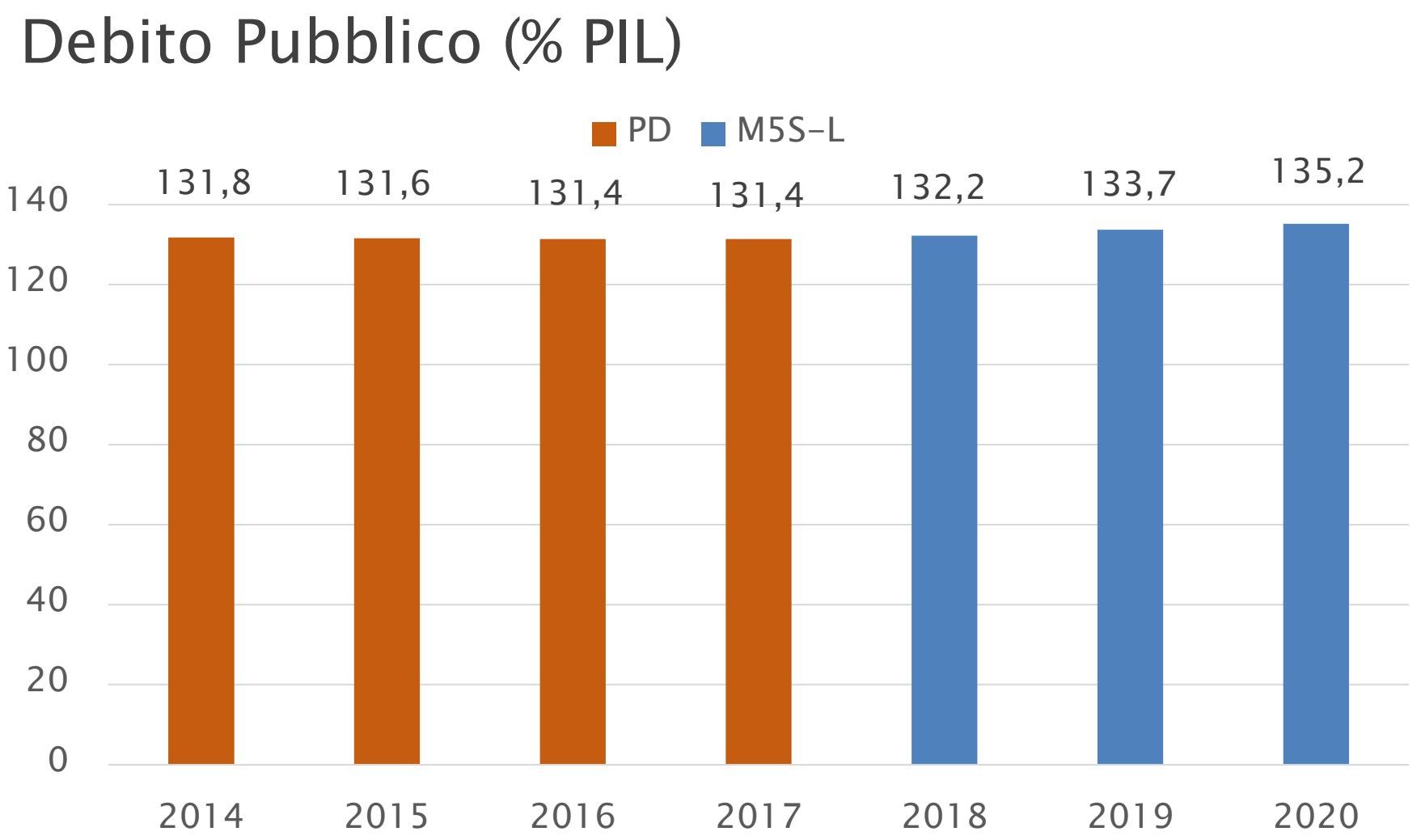


Example – Lie Factor

PUC

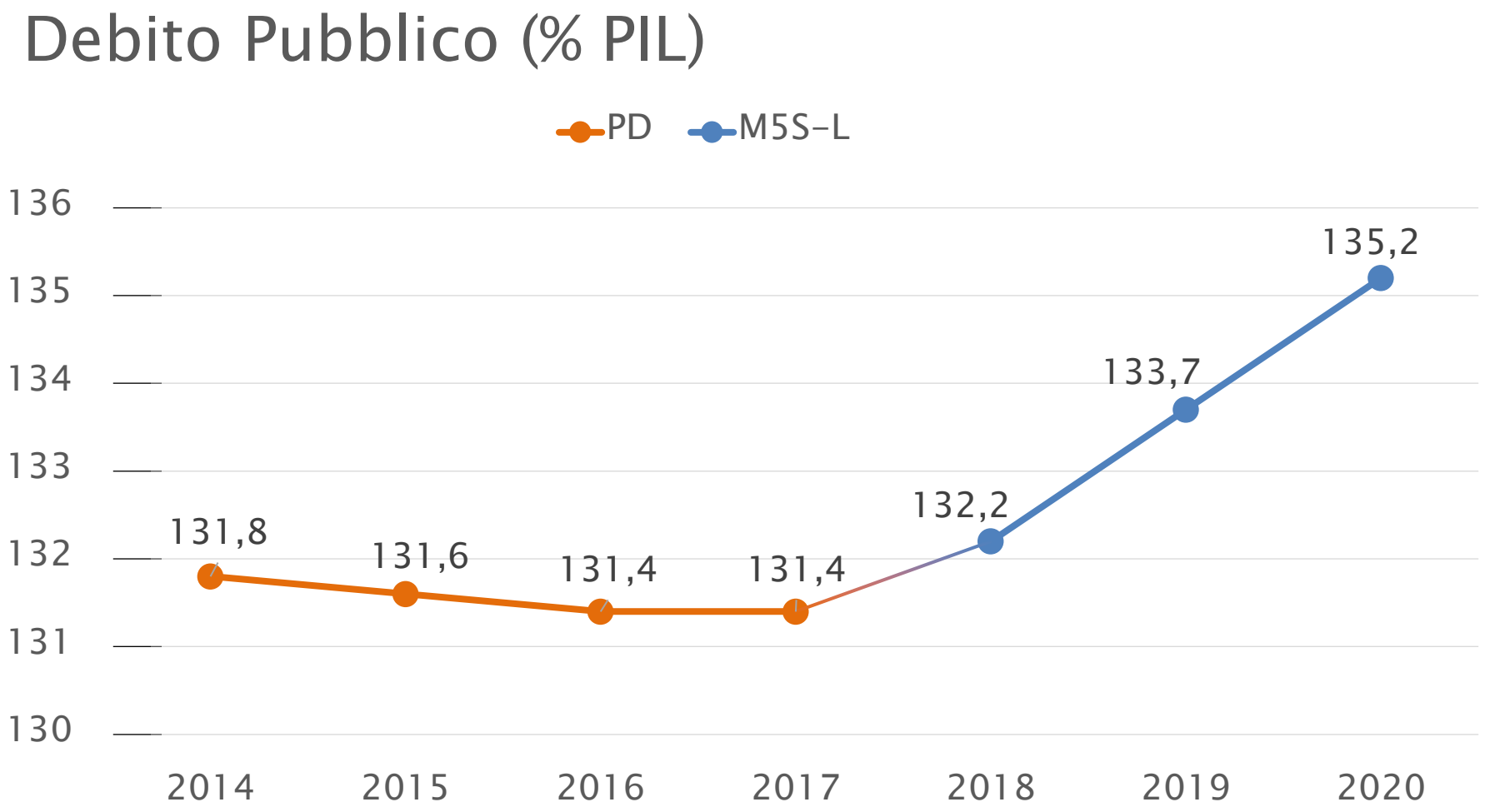


Example – Redesign



Example – Redesign

PUC



Guidelines for design

- Keep the physical Lie Factor = 1
- Limit the perceptual Lie Factor as much as possible

Utility

PUC

- Every element should convey useful information
- Unnecessary visual objects or attributes distract from the message
  - Different attributes trigger a search for a rationale (e.g. random colors)

Data-ink

PUC

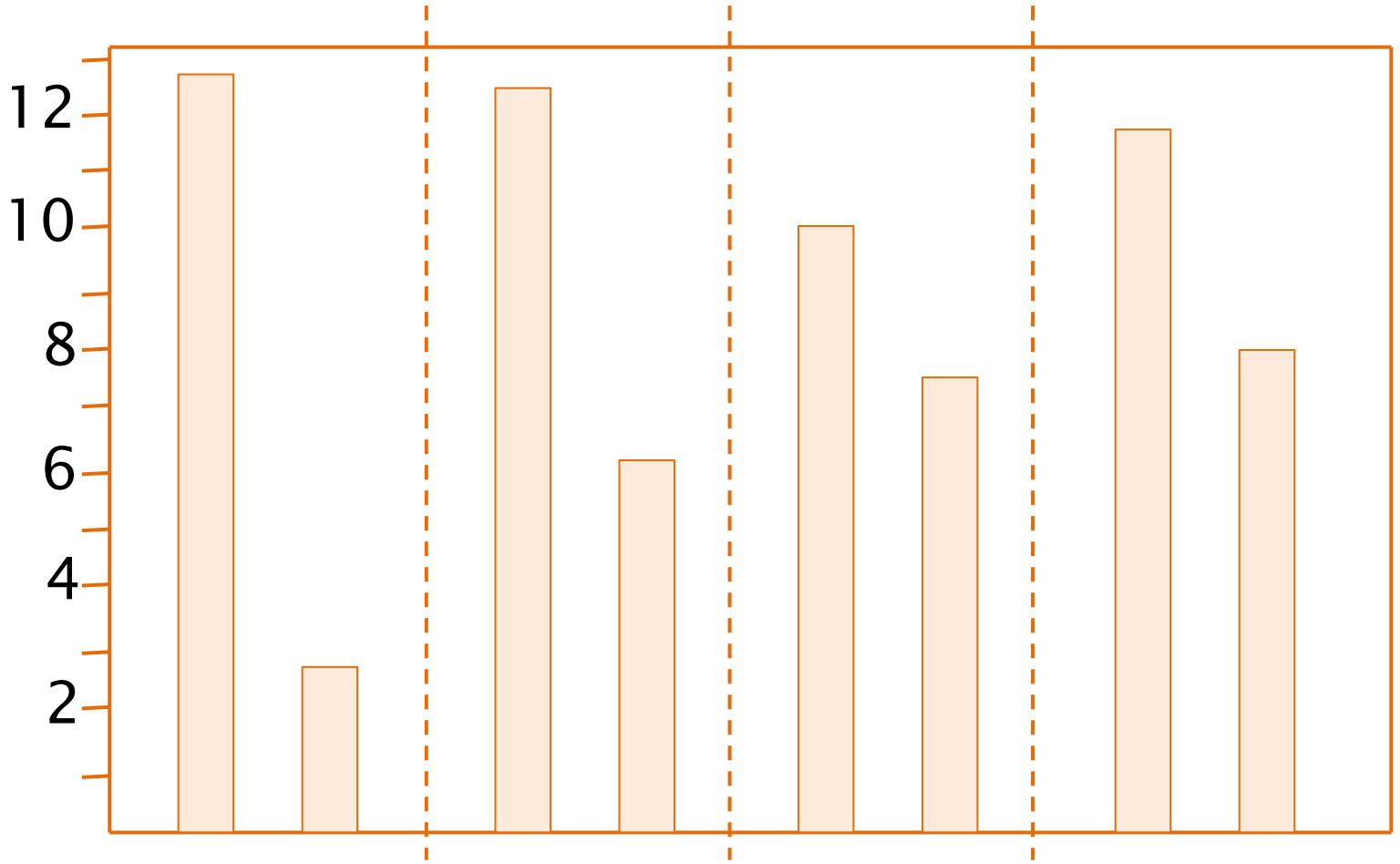
$$\text{Data-ink ratio} = \frac{\text{data ink}}{\text{total ink used to print the graphic}}$$

- Proportion of a graphic's ink devoted to the non-redundant display of data information
  - Or:

$$1 - \frac{\text{ink that can be erased without loss of information}}{\text{total ink used to print the graphic}}$$

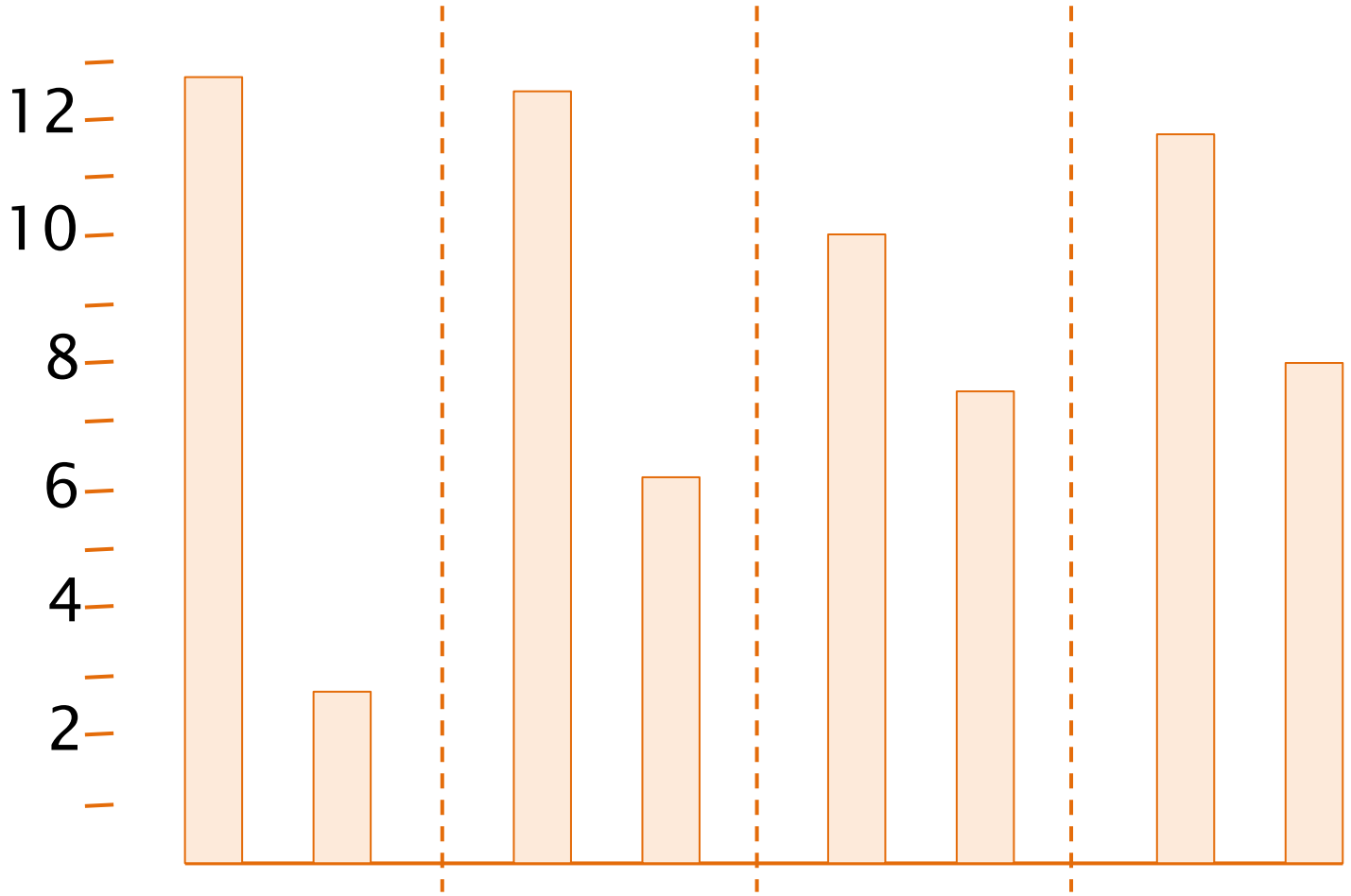
Data-ink

PUC



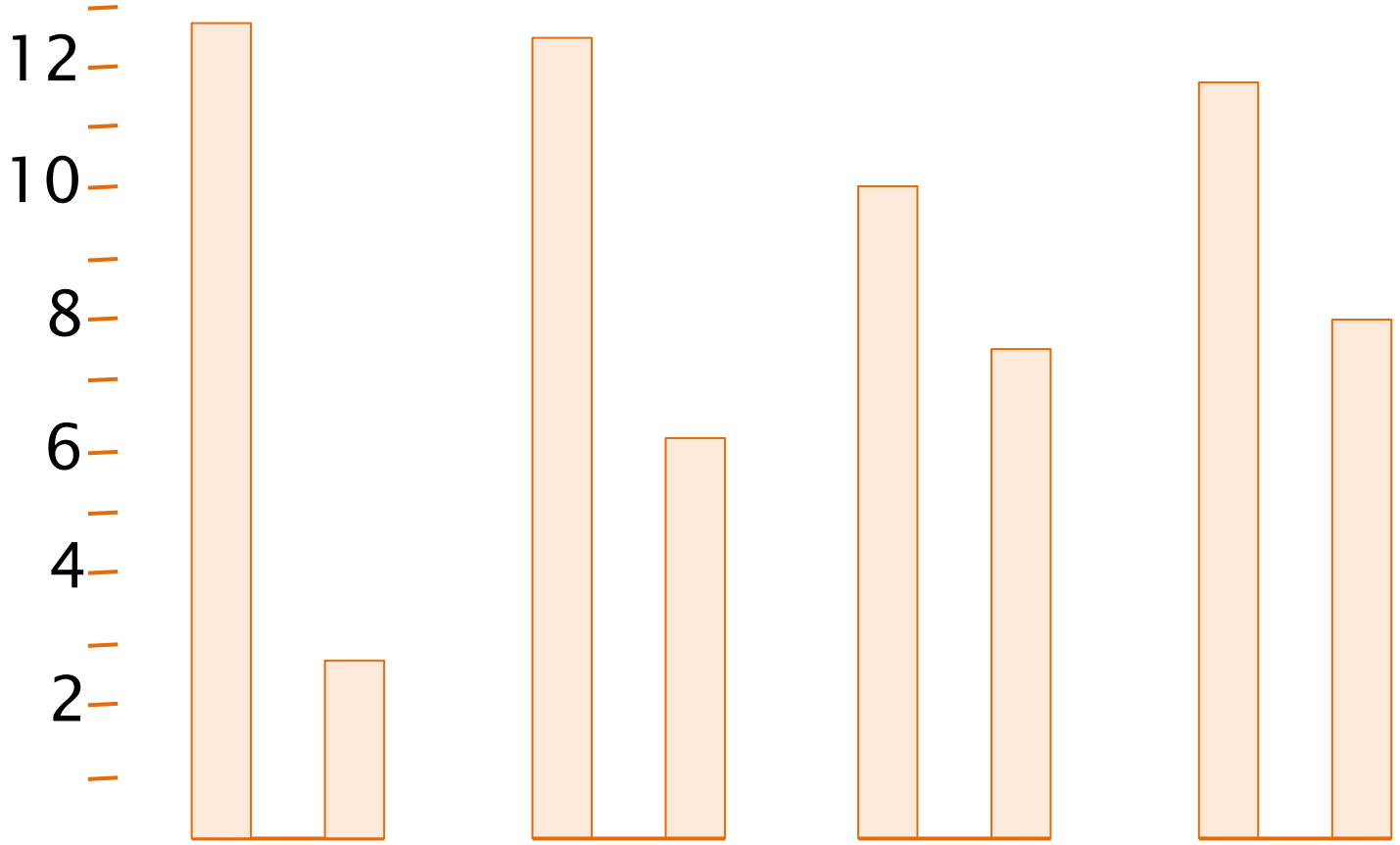
Data-ink

PUC

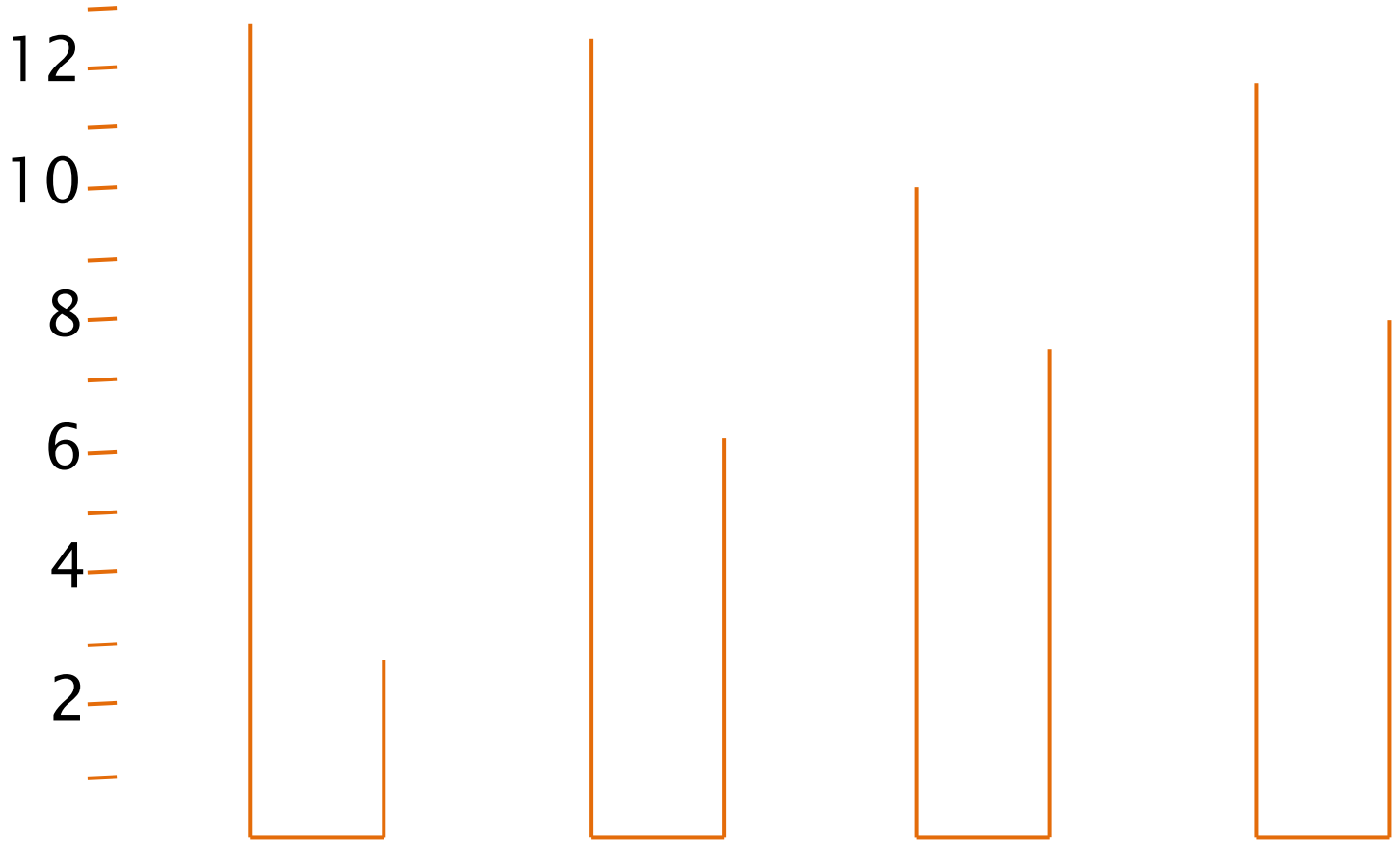


Data-ink

PUC



Data-ink



Tufte's proposed redesign

Guidelines for design

PUC

- Maximize data-ink ratio
  - Erase non-data-ink
  - Erase redundant data-ink
- "Within reason"

Above all else show the data

E.Tufte

Use of contrast

PUC

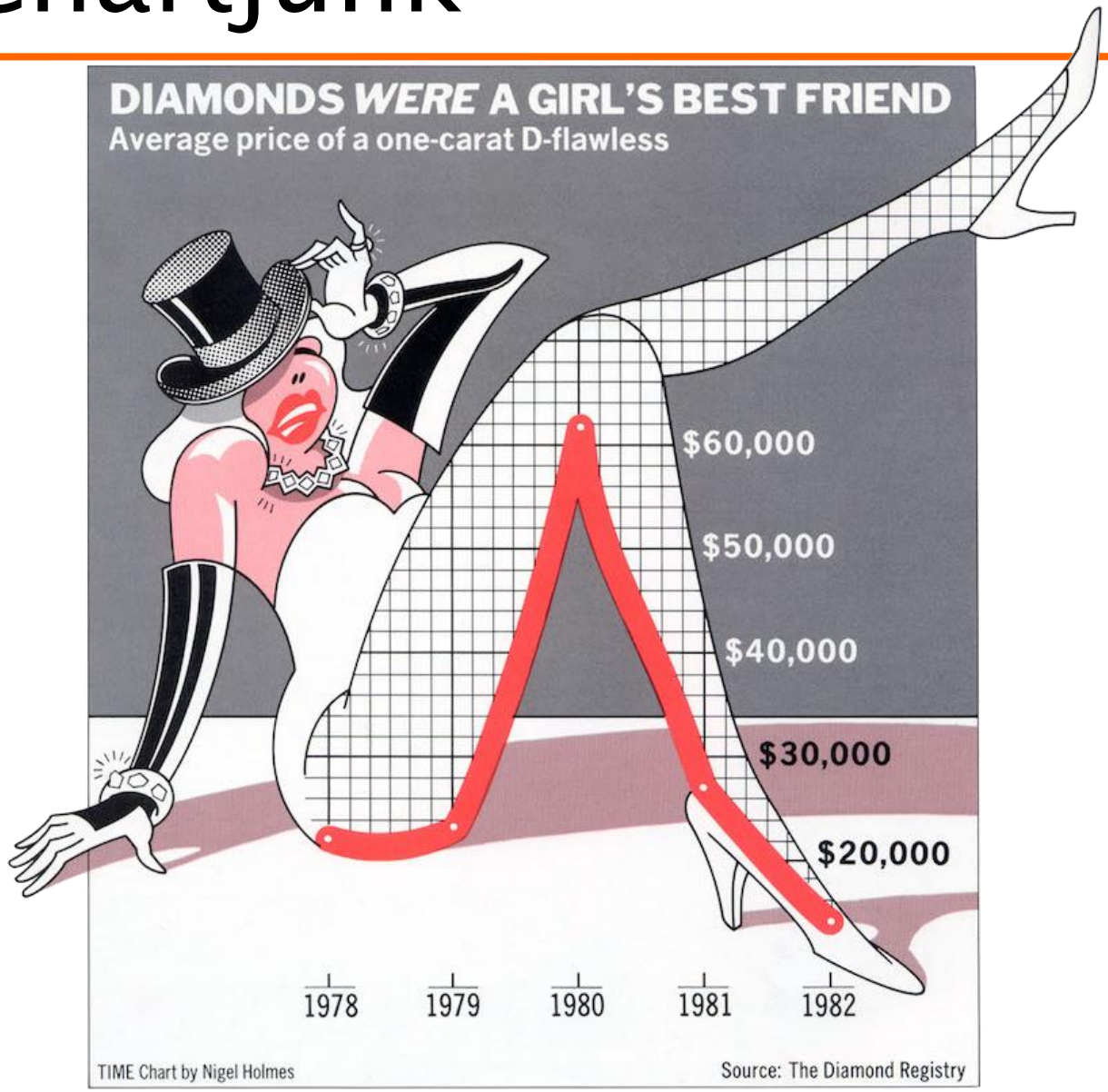
- Include differences corresponding to actual differences
- Effective when one item is different in a context of other items that are the same
  - Bright saturated color among mid colors

Chartjunk

PUC

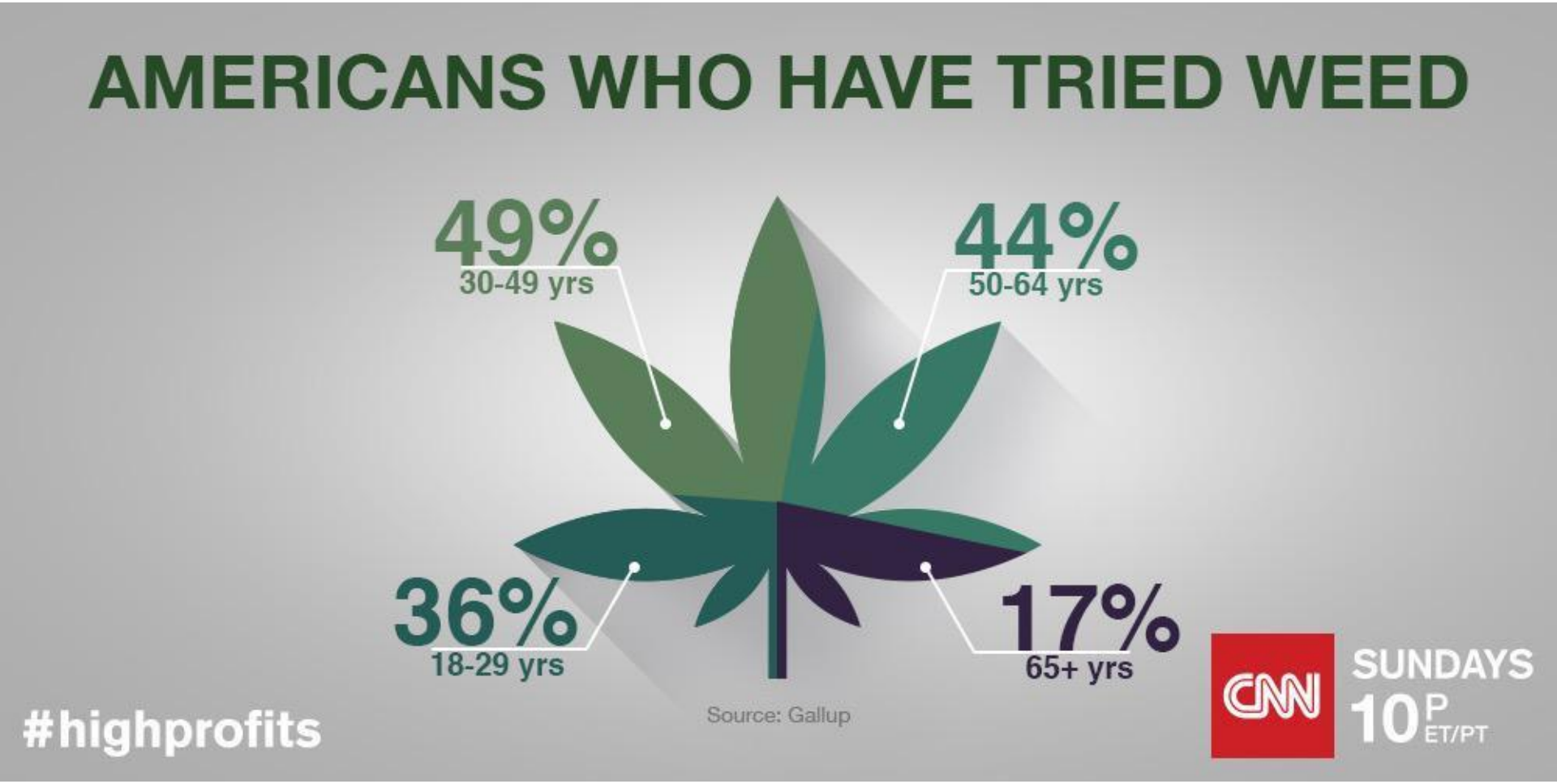
- The presence of unnecessary elements that distract or hide the message conveyed by the diagram

Chartjunk



Nigel Holmes:
http://nigelholmes.com

Chartjunk


AMERICANS WHO HAVE TRIED WEED
49%
30-49 yrs
44%
50-64 yrs
36%
18-29 yrs
17%
65+ yrs
Source: Gallup
#highprofits
CNN
SUNDAYS
10P ET/PT

Clarity

PUC

- Visual encoding and layout should make perception tasks easy and effortless
- Textual and support elements should provide effective support to understanding the information
- Any variation in the graph should represent useful information otherwise it is noise obfuscating the message

Clarity

PUC

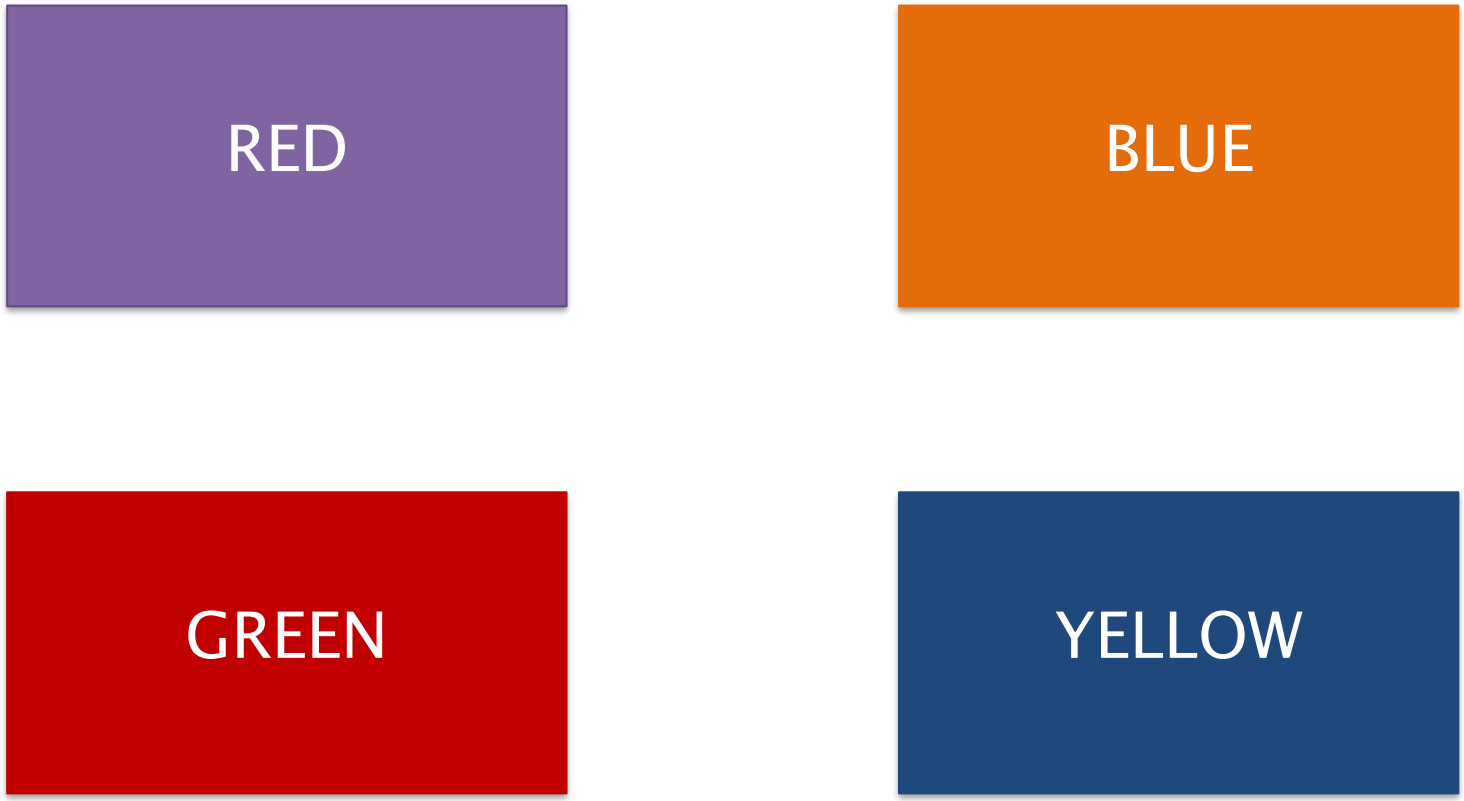
- Textual elements should provide effective support to understanding
  - Hierarchical
    - Size and position reflects importance
  - Readable
    - Large enough
  - Horizontal
  - Close to data (avoid legends)
- Always label the axes

Colors

PUC

- Get it right in black and white
- Use medium hues or pastels
  - Bright colors distract and tire out
- Use color only when needed to serve a particular communication goal

Cognitive Dissonance



Detection and Separation

PUC

Efficiency and efficacy of perception tasks is affected by:

- Detection

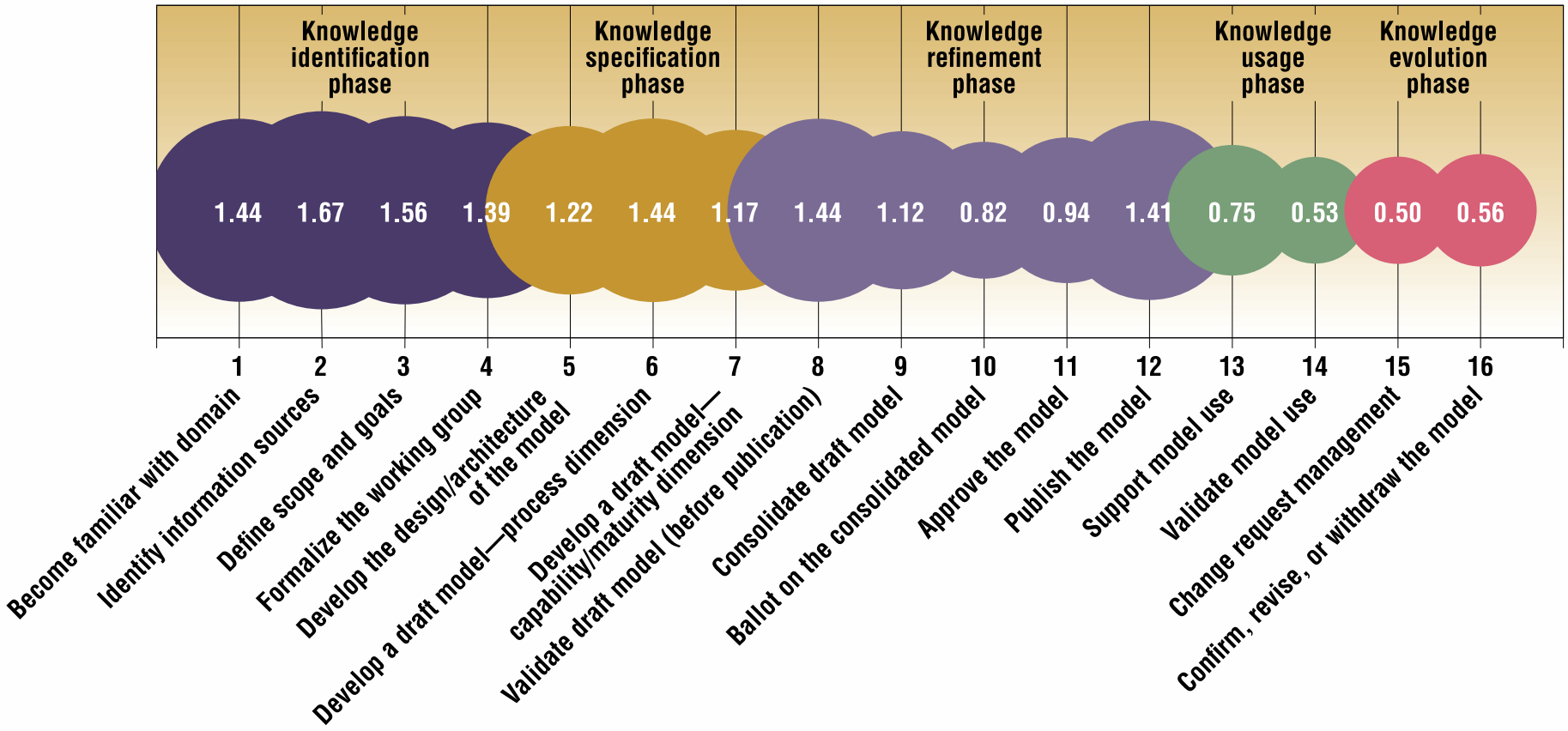
  The capability to visually identify the objects that represent the data to be compared

- Separation

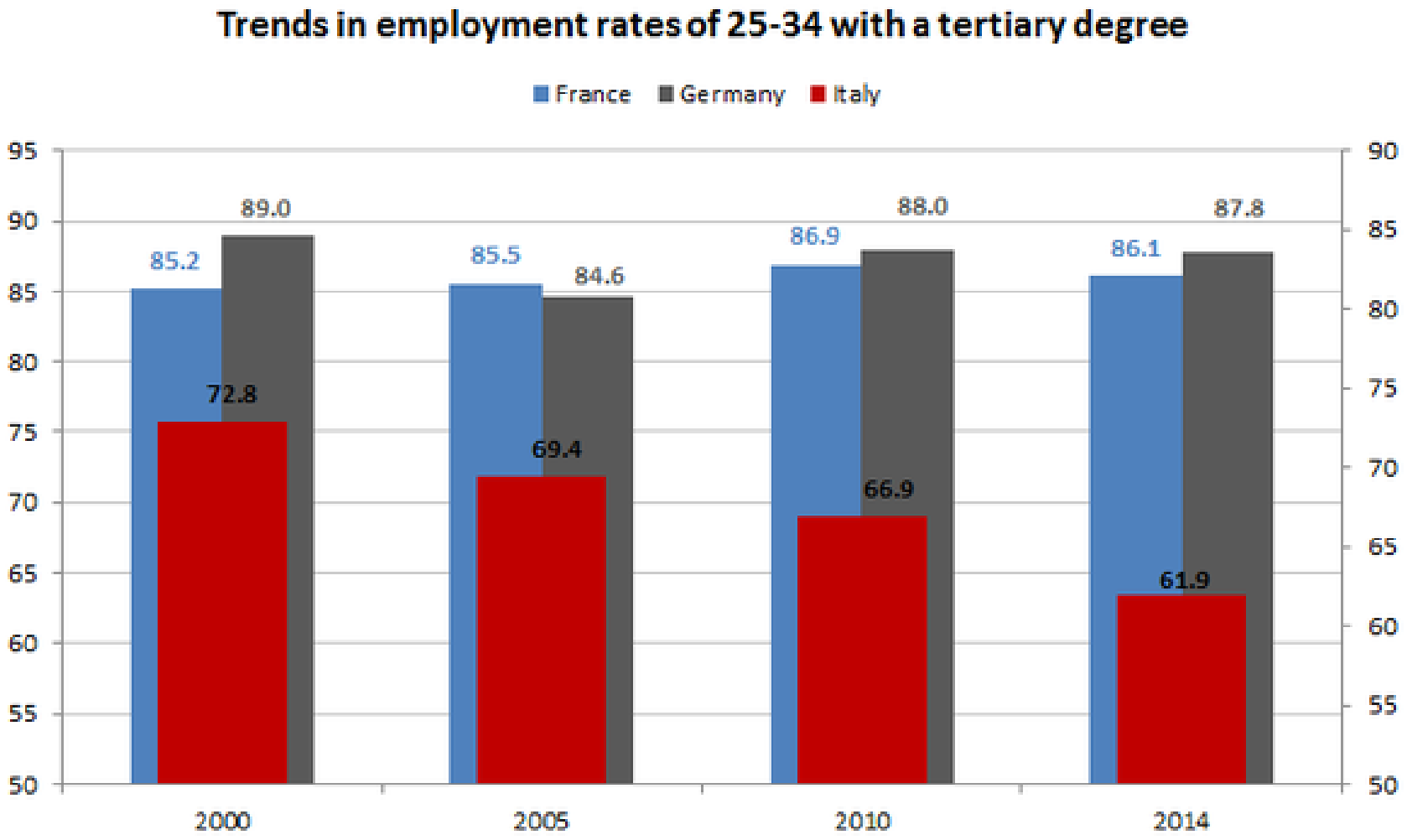
  The distance between the objects to be compared

  - affects negatively the accuracy

Clarity


Knowledge identification phase
Knowledge specification phase
Knowledge refinement phase
Knowledge usage phase
Knowledge evolution phase
1.44
1.67
1.56
1.39
1.22
1.44
1.17
1.44
1.12
0.82
0.94
1.41
0.75
0.53
0.50
0.56
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
Become familiar with domain
Identify information sources
Define scope and goals
Formalize the working group
Develop the design/architecture of the model
Develop a draft model—process dimension
Develop a draft model—capability/maturity dimension
Validate draft model (before publication)
Consolidate draft model
Ballot on the consolidated model
Approve the model
Publish the model
Support model use
Validate model use
Change request management
Confirm, revise, or withdraw the model

Example


Trends in employment rates of 25-34 with a tertiary degree
France
Germany
Italy
95
90
85
80
75
70
65
60
55
50
90
85
80
75
70
65
60
55
50
85.2
89.0
72.8
85.5
84.6
69.4
86.9
88.0
66.9
86.1
87.8
61.9
2000
2005
2010
2014

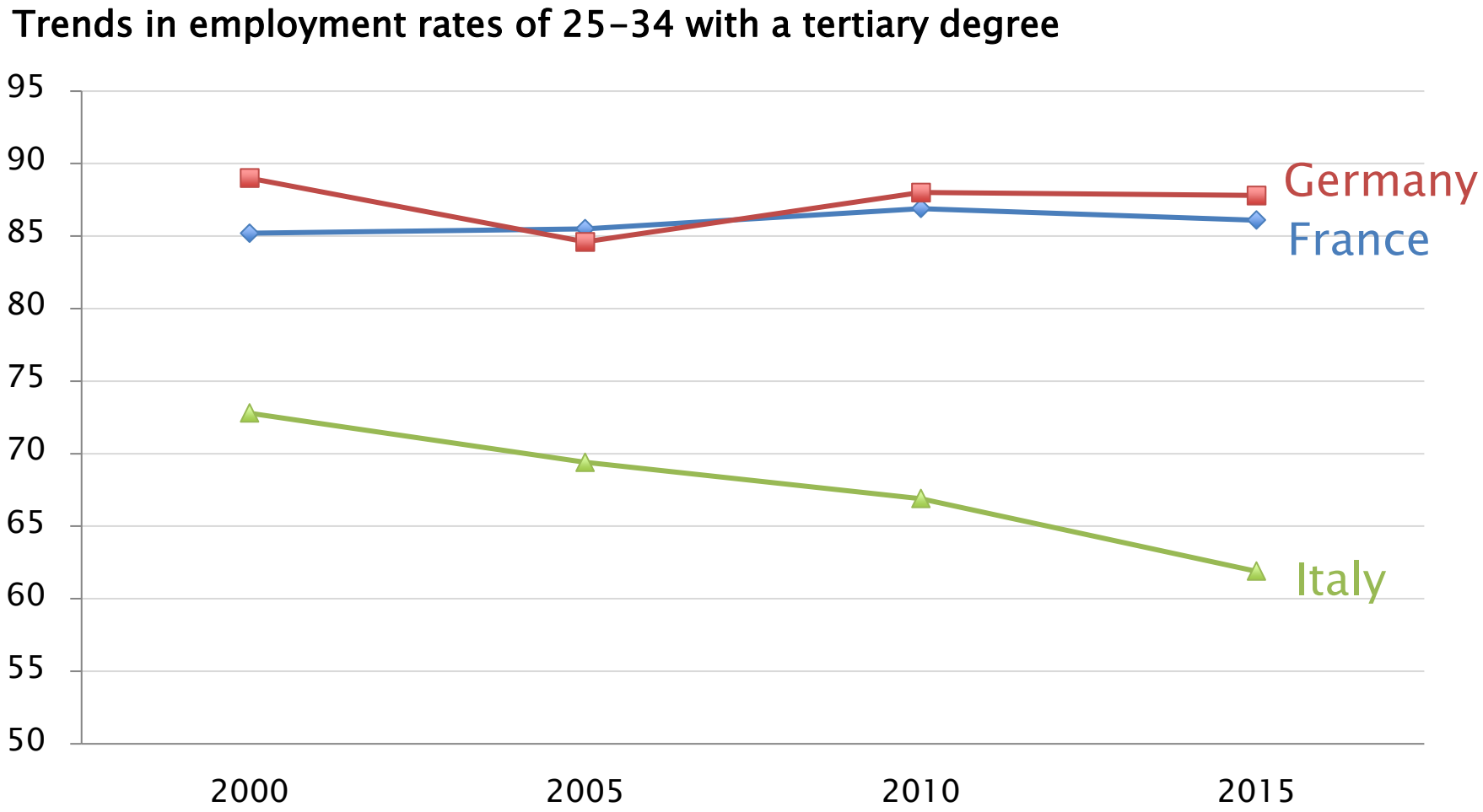
Analysis

- Proportionality
  - Due to non-zero base bars, it has a large lie factor (2.2):
    - ratio of real values: 87.8 : 61.9
    - ratio on graph: 37.8 : 11.9
- Utility
  - Most elements appear useful
  - X-axis ticks can be removed
  - Y grid could be made less prominent

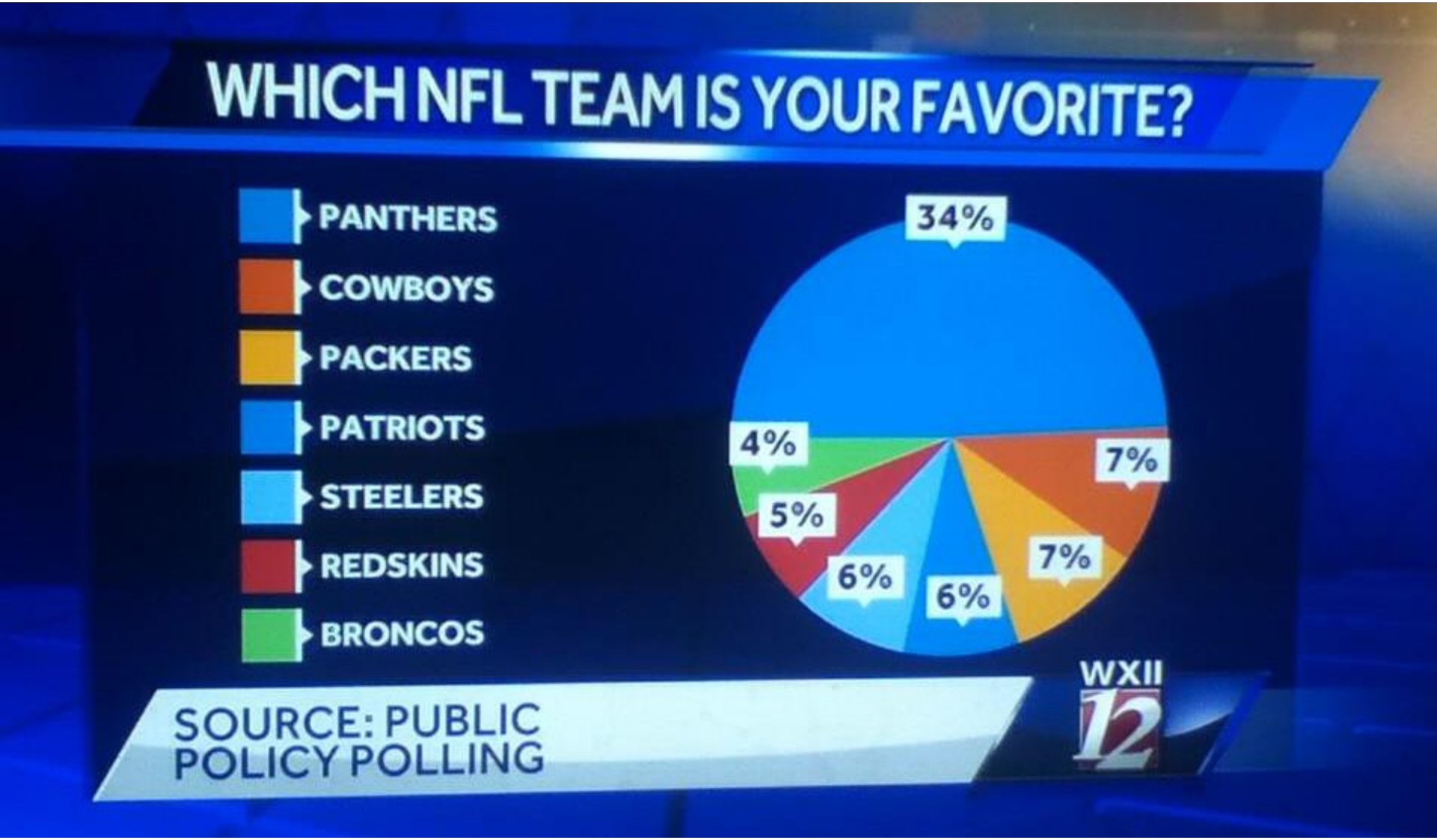
Analysis

- Clarity
  - It uses a dual scale that confuses and makes very hard a visual comparison of the values and further distorting the compared values.
  - The dual scale is not mentioned anywhere and it is not clear which values refer to which scale.
  - In general the usage of bars is not the most appropriate visual representation if the goal is to show a trend or evolution in time.

Redesign


Trends in employment rates of 25-34 with a tertiary degree
95
90
85
80
75
70
65
60
55
50
2000
2005
2010
2015
Germany
France
Italy

Case study


WHICH NFL TEAM IS YOUR FAVORITE?
PANTHERS
COWBOYS
PACKERS
PATRIOTS
STEELERS
REDSKINS
BRONCOS
34%
7%
7%
6%
6%
5%
4%
SOURCE: PUBLIC POLICY POLLING
WXII 12

Assessment

- Question:
  - Is there one (or more) question addressed by the visualization?
- Data:
  - Is the data quality appropriate?
- Visual Integrity:
  - Are the visual features appropriate?

Visual Integrity

- Proportionality:
  - Are the values encoded in a uniformly proportional way?
- Utility:
  - All the elements in the graph convey useful information?
- Clarity:
  - Are the data in the graph identifiable and understandable (properly described)?

Question

- What are the most popular/favorite NFL teams in our audience?
- …

Data

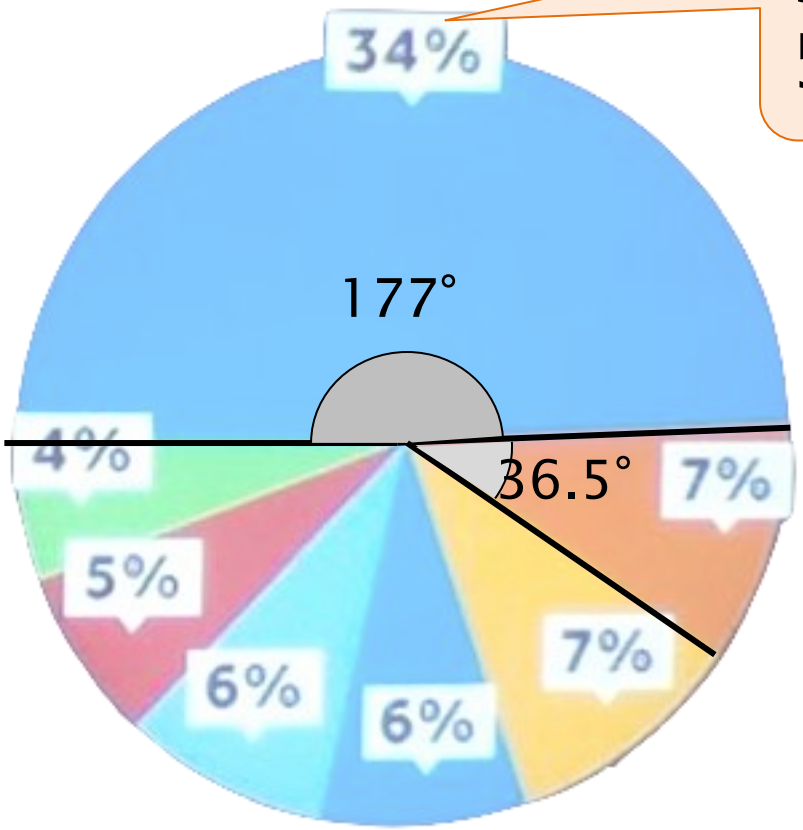
WXII-TV is an NBC-affiliated television station serving North Carolina: home of Panthers

Team	Preferences
Panthers	34%
Cowboys	7%
Packers	7%
Patriots	6%
Steelers	6%
Redskins	5%
Broncos	4%
Total:	69%

Full data

Team	Preferences
Panthers	34%
Cowboys	7%
Packers	7%
Patriots	6%
Steelers	6%
Redskins	5%
Broncos	4%
Other	31%
Total:	100%

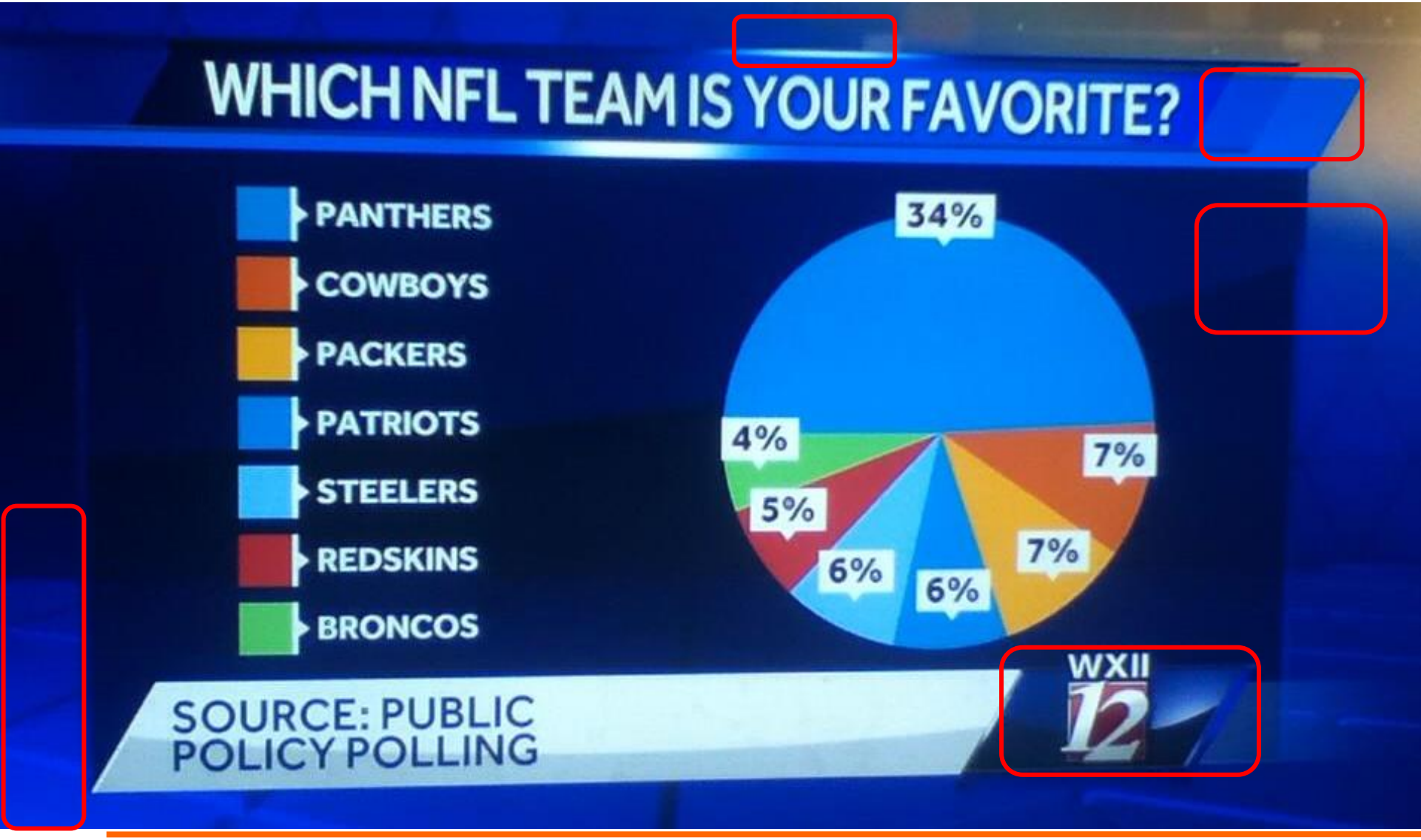
Integrity – Proportionality



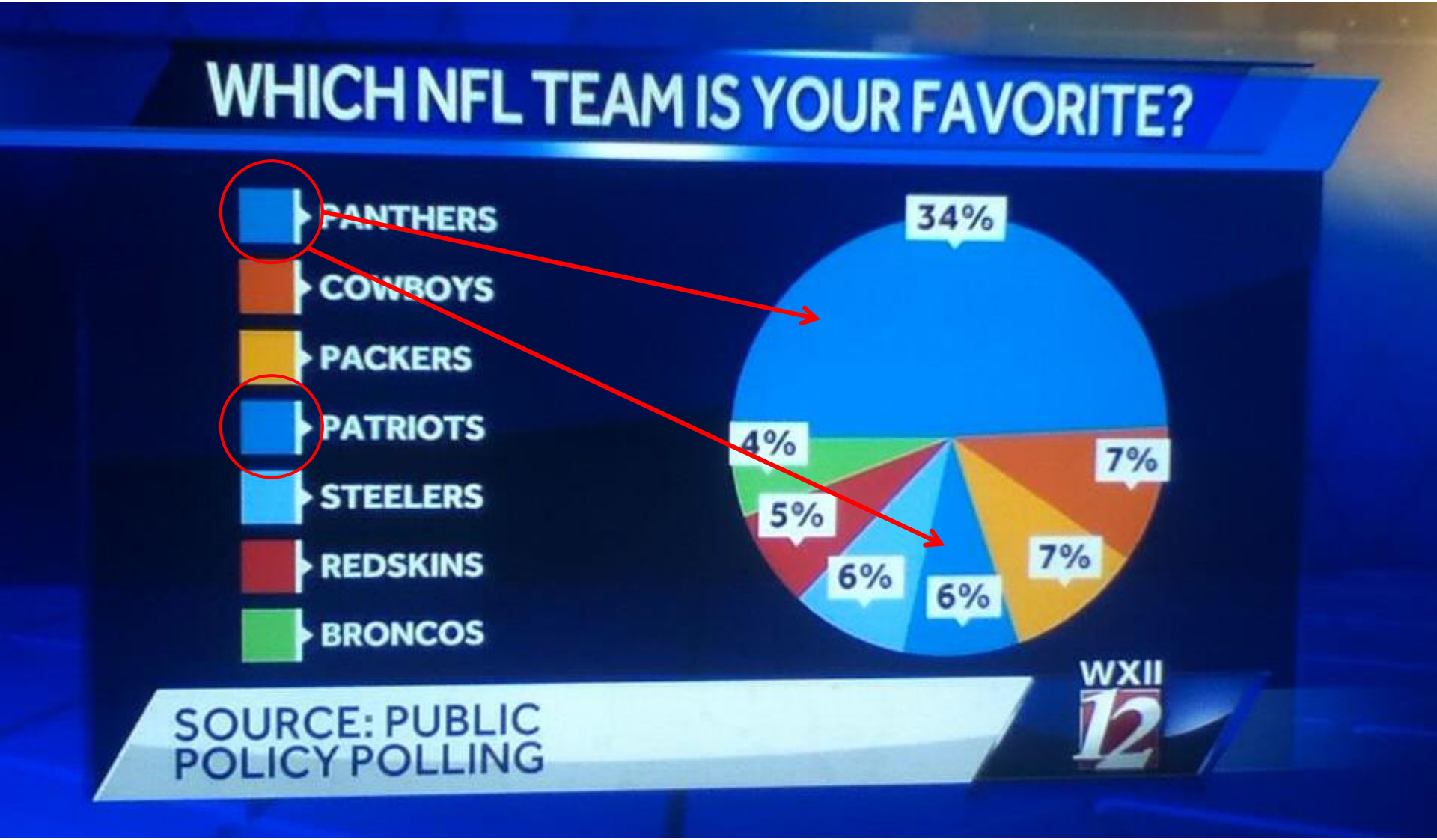
34% corresponds to 50% of the pie!

177/36.5 = 4.8
34/7 = 4.8

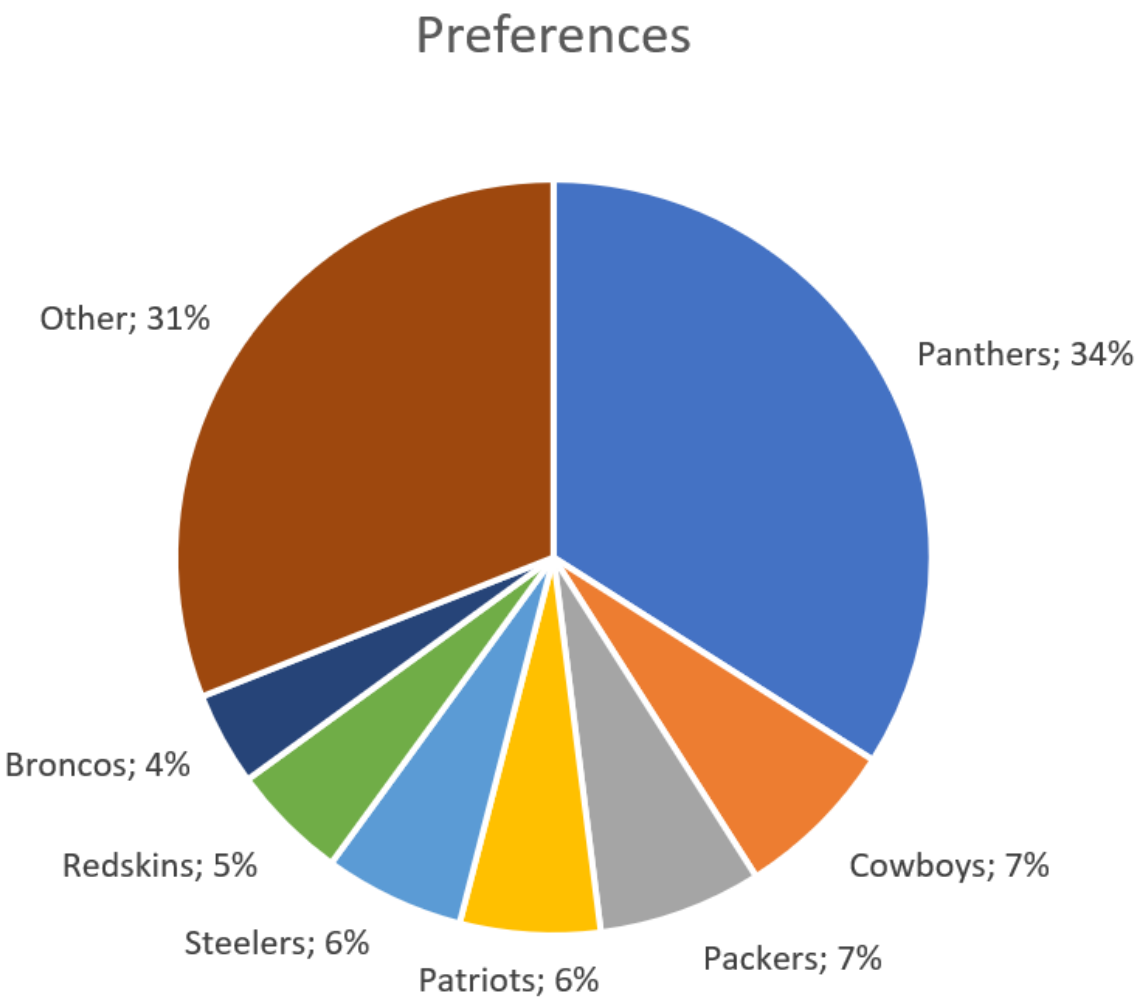
Utility


WHICH NFL TEAM IS YOUR FAVORITE?
PANTHERS
COWBOYS
PACKERS
PATRIOTS
STEELERS
REDSKINS
BRONCOS
34%
7%
7%
6%
6%
5%
4%
SOURCE: PUBLIC POLICY POLLING
WXII 12

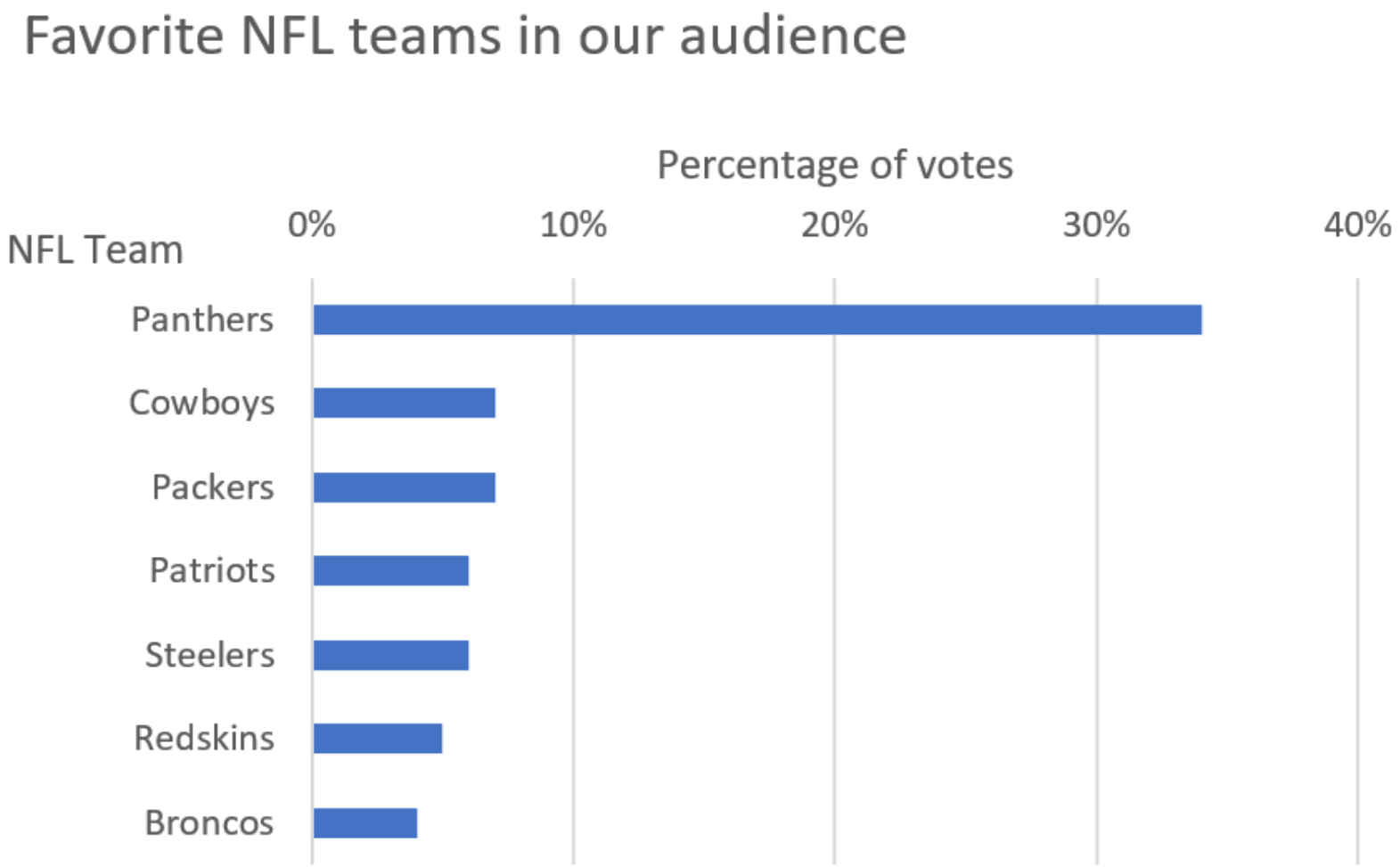
Clarity


WHICH NFL TEAM IS YOUR FAVORITE?
PANTHERS
COWBOYS
PACKERS
PATRIOTS
STEELERS
REDSKINS
BRONCOS
34%
7%
7%
6%
6%
5%
4%
SOURCE: PUBLIC POLICY POLLING
WXII 12

Redesign #1

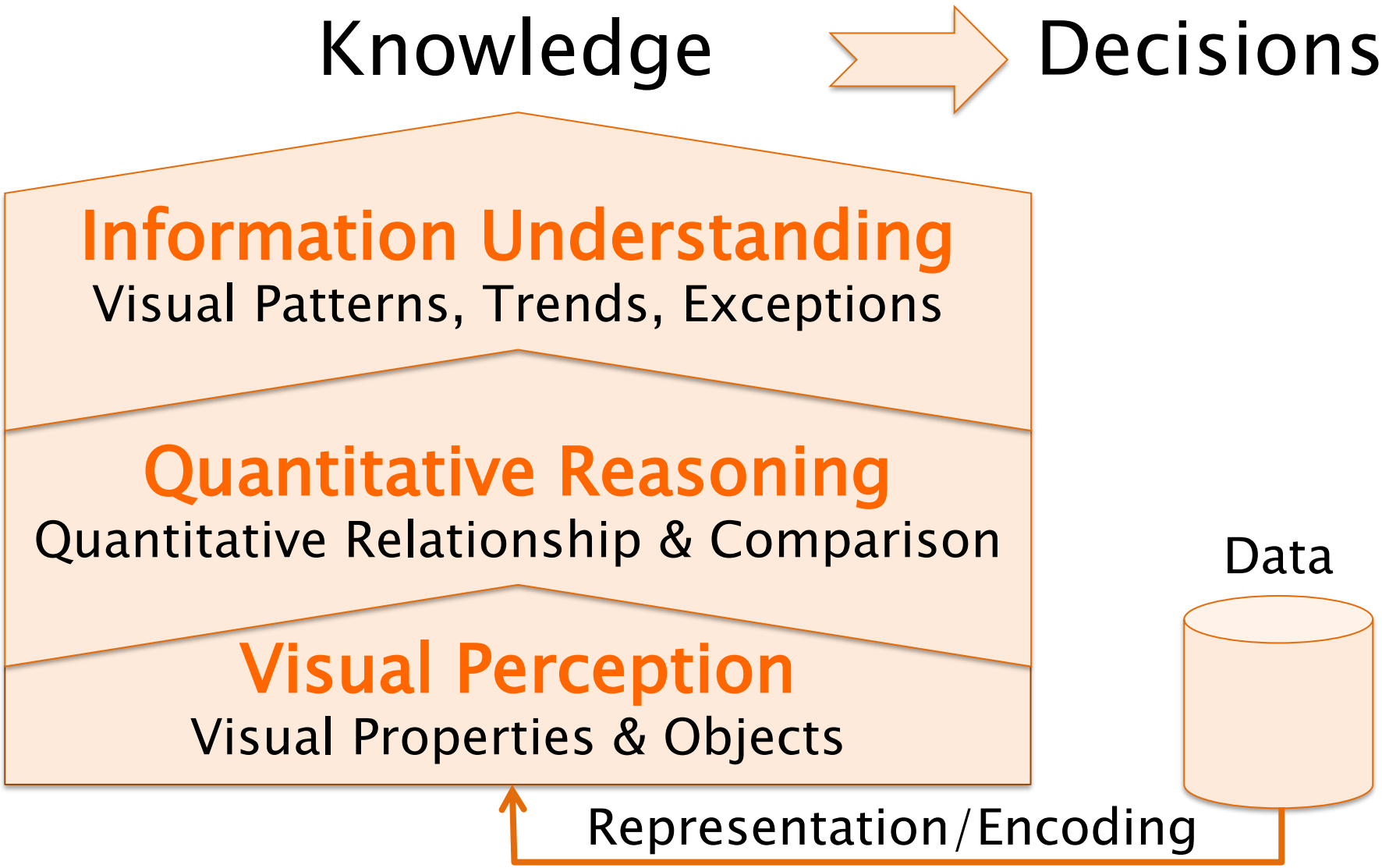

Preferences
Other; 31%
Panthers; 34%
Broncos; 4%
Redskins; 5%
Cowboys; 7%
Steelers; 6%
Patriots; 6%
Packers; 7%

Redesign #2


Favorite NFL teams in our audience
Percentage of votes
0%
10%
20%
30%
40%
NFL Team
Panthers
Cowboys
Packers
Patriots
Steelers
Redskins
Broncos

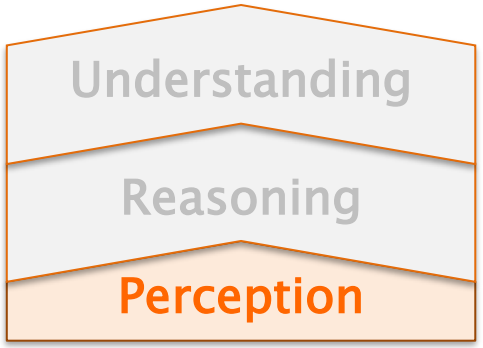
VISUALIZATION PIPELINE

Visualization Pipeline



Visual Perception

- Any variable (measure) must be visually encoded, i.e. we need to identify:
  - Visual object to represent entity
  - Visual attribute to represent the measure



Example

Votes received by four candidates in recent elections

Candidate	Votes	Proportion
Sergio	197800	50.09%
Alberto	140545	35.59%
Giorgio	53748	13.61%
Valter	2759	0.70%

http://www.comune.torino.it/elezioni/2019/regionali/presidente/citta/

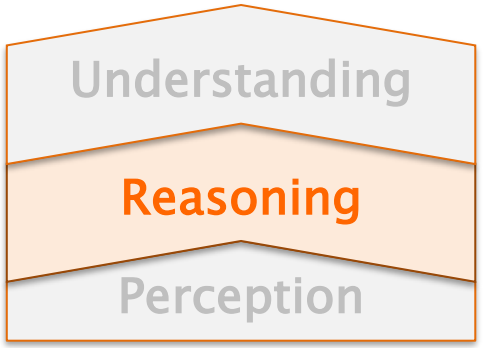
Encoding

- Visual object: line
- Visual attribute: length

Visual Reasoning

Layout and visual attributes allow:

- Discrimination
  - Distinguish visual objects or group of –
- Comparison
  - Place visual objects in order
- Magnitude assessment
  - Evaluate the (relative) magnitude of visual objects



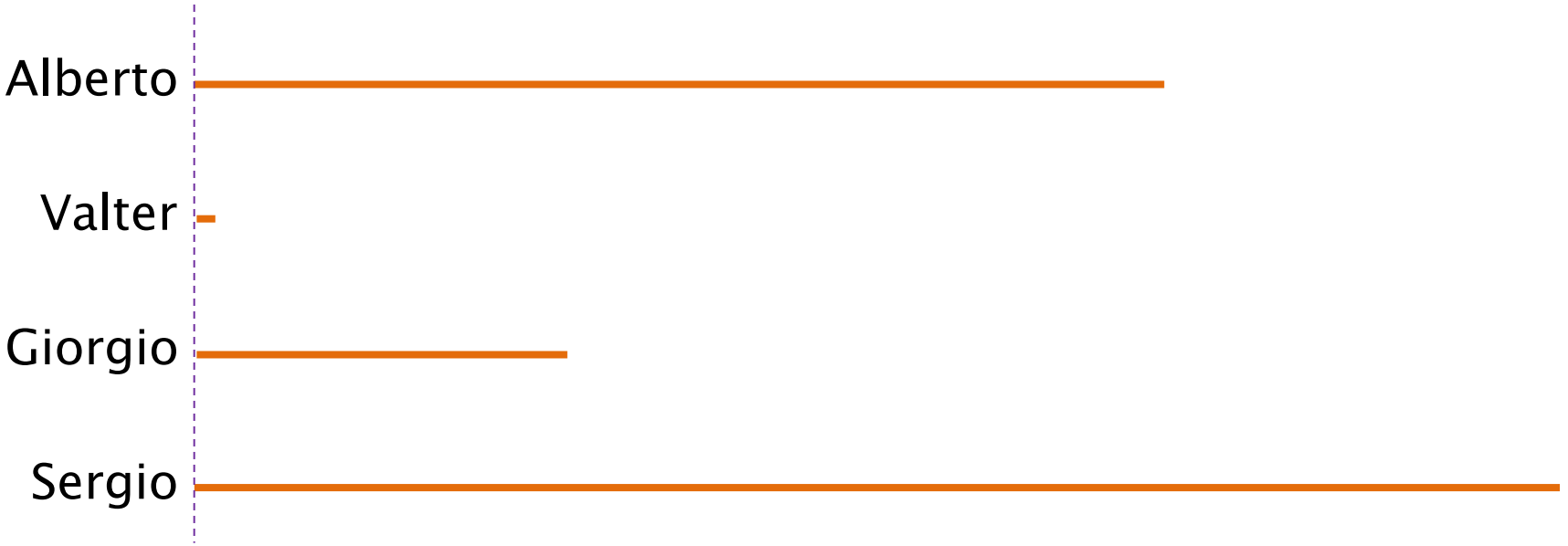
Reasoning

Reasoning

- Discrimination

Reasoning

- Comparison

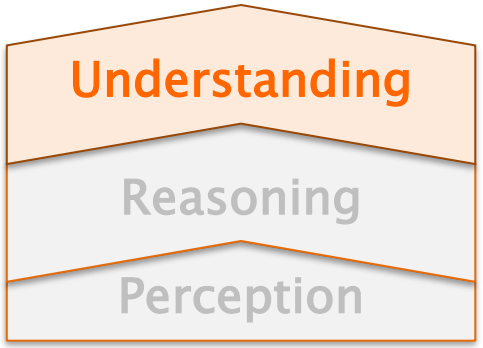


Reasoning

- Assessment

Understanding

- Variation within quantitative measures
  - Distribution
  - Deviation
  - Correlation
- Variation within category
  - Ranking
  - Part-to-whole
  - Time
  - Space
- Multivariate



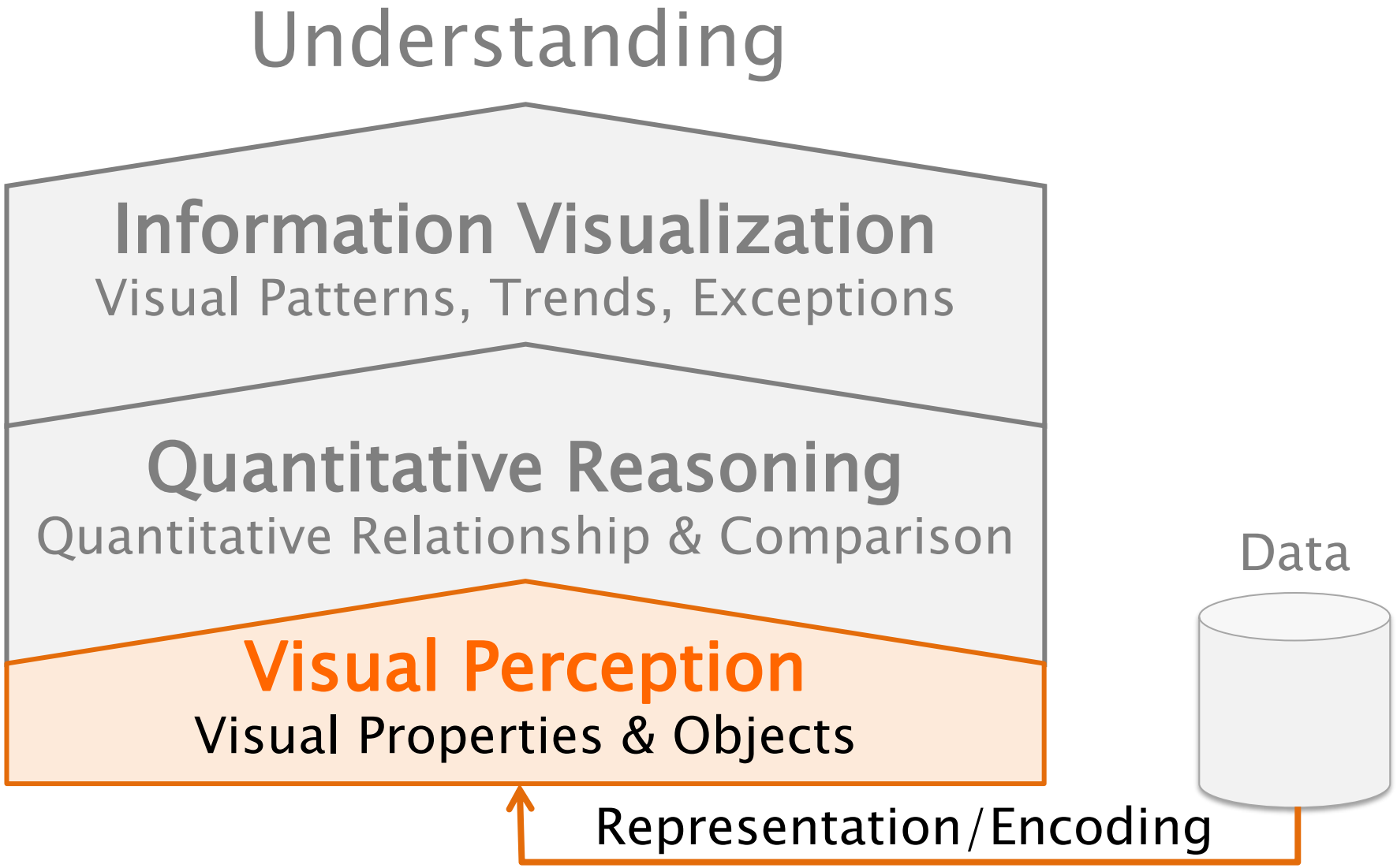
Understanding

Understanding

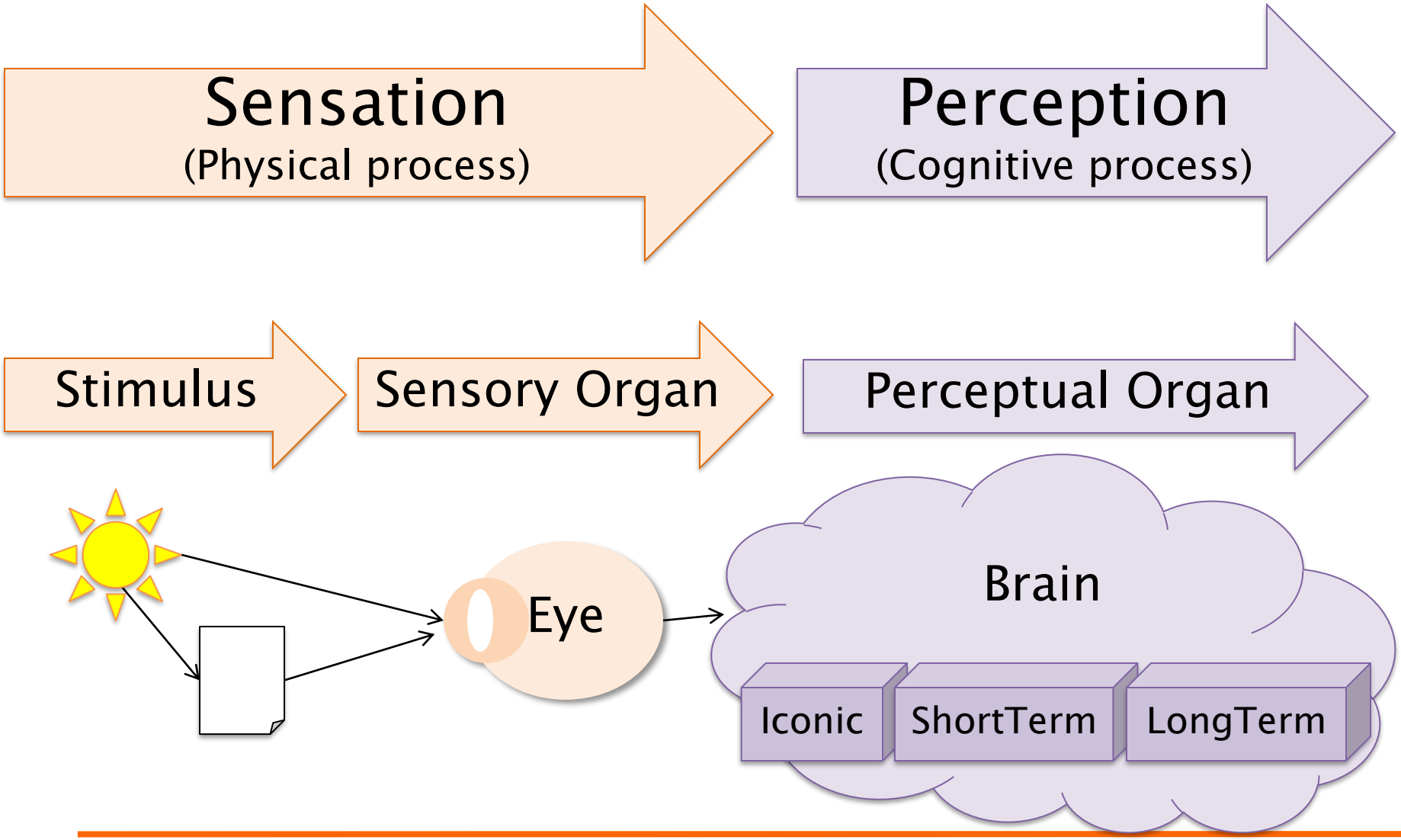
- Ranking

VISUAL PERCEPTION

Data Visualization



Visual perception



Memory Hierarchy

- Iconic memory (visual sensory register)
  - Pre-attentive processing
  - Detects a limited number of attributes
- Short-term memory (working memory)
  - Store visual chunks
  - Limited number
- Long-term memory
  - Store high-level knowledge

Simplified Model

- The three levels of memory represent a simplified model
  - does not correspond to “real” physical brain structure
- Useful to explain a few phenomena
  - The 7 ± 2 rule
  - Change blindness

Change blindness

http://www2.psych.ubc.ca/~rensink/flicker/download/index.html

Change blindness

http://www2.psych.ubc.ca/~rensink/flicker/download/index.html

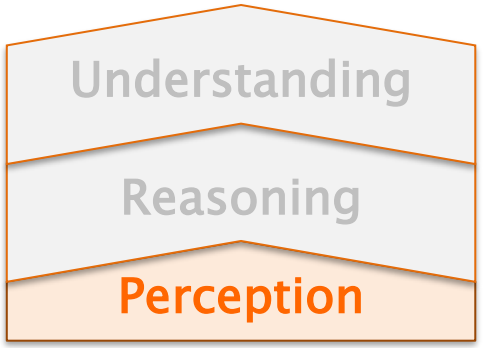
Pre-Attentive Attributes

5 7 8 4 9 8 3 1 1 0 6 8 8 2 1 1 5 2 6 6 5
9 5 1 8 4 6 8 4 9 3 0 4 5 3 4 9 2 5 8 5 8
5 0 5 4 6 2 6 5 7 3 7 8 6 5 3 7 2 6 3 1 5
5 8 6 6 8 3 7 6 5 0 9 6 3 4 6 1 9 5 6 6 4
1 6 7 3 9 9 2 8 3 4 0 3 5 1 6 3 5 3 9 3 4
8 6 9 7 5 4 2 4 7 4 9 5 8 5 3 0 7 6 0 6 7
0 3 1 5 3 2 3 5 6 7 2 8 9 8 5 3 7 8 8 2 4
5 5 3 4 8 1 5 6 2 3 5 5 1 2 1 0 8 7 2 6 3
7 4 3 8 4 8 2 6 7 9 5 6 2 3 6 7 8 0 8 3 6
4 9 5 6 7 2 2 2 8 3 1 1 0 1 8 6 2 6 2 1 4

Pre-Attentive Attributes

Encoding

- Encoding is the key to enable visual perception
  - Visual object to represent entity
  - Visual attribute to represent the measure
- Two main types
  - Quantitative (different properties)
  - Categorical (ordinal or not)



Pre-Attentive attributes

Category	Attribute
Form	Orientation Length/distance Line width Size Shape Curvature Added marks Enclosure
Color	Hue Intensity
Spatial position	2-D position
Motion	Flicker Direction Speed

Perception task

Visual attributes allow:

- Discrimination
  - Distinguish visual objects
- Comparison
  - Place visual objects in order
- Magnitude assessment
  - Evaluate the (relative) magnitude of visual objects

Just noticeable difference

- Given a physical dimension (length, brightness, etc.) x
- *d* is the just noticeable difference if:
  - difference between *x* and *x+d* is perceivable
  - but not smaller differences
- *d* depends on many factors:
  - Subject
  - Environment
  - Physical dimension

Weber's law

- Just noticeable difference *d* is:

$$d_p(x) = k_p \cdot x$$

- Where
  - x: dimension
  - $d_p(x)$: just noticeable difference
  - k_p: constant
    - Subjective
    - Environmental

Consequences of Weber's law

- It is easier to compare lengths that differ by a large percentage
- The same difference is easier to notice between smaller measures
  - More likely to be larger than just noticeable difference

$$x < y \implies d_p(x) < d_p(y)$$

- Length of non-aligned objects is harder to compare
  - Double comparison

Non-aligned objects lengths

Non-aligned objects lengths

- Additional references may help comparison
  - They provide alternative possible comparisons
- If lengths range between 0 and a maximum (L), e.g. percentages
- Comparing l_1 and l_2 (close to L) that differ by a small amount d
  - Difference $L-l_1$ vs. $L-l_2$ easier to notice than l_1 vs. l_2

Stevens's law

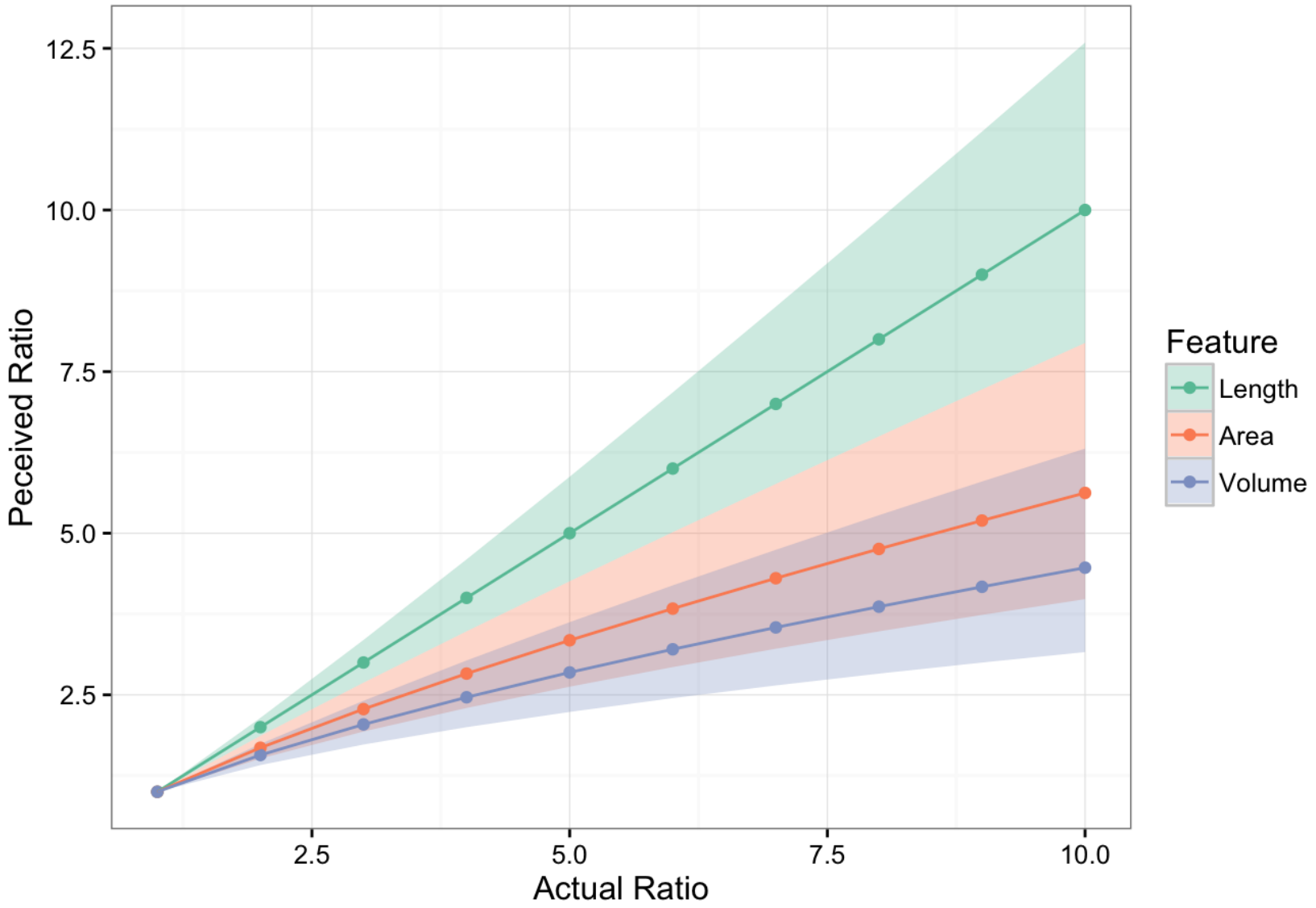
- Perceive scale (magnitude ratio)

$$p(x) = c \cdot x^{\beta}$$

- Where β depends on spatial dimension
  - 1D: Length → β in [0.9, 1.1]
  - 2D: Area → β in [0.6, 0.9]
  - 3D: Volume → β in [0.5, 0.8]

Stevens S. S. (1975). Psychophysics, John Wiley & Sons.

Stevens's law



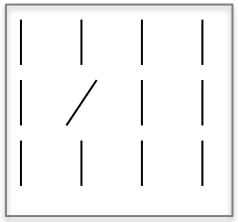
Stevens's law

Consequences

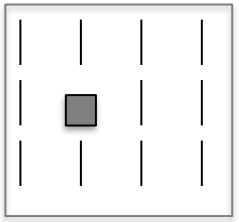
- Prefer comparing lengths
- Avoid comparison between areas
  - Except for ordinal measures
- Never-ever make volume comparisons

Attributes of form

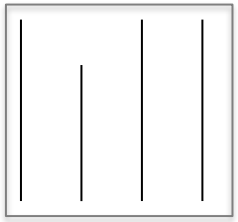
Orientation



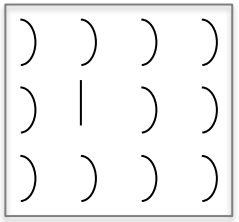
Shape



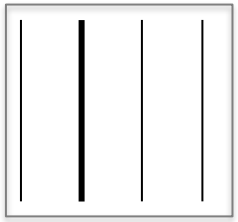
Line Length



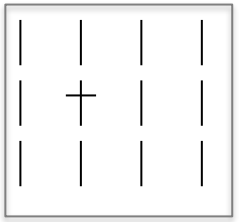
Curvature



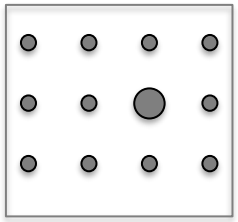
Line Width



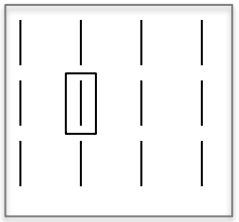
Added mark



Size

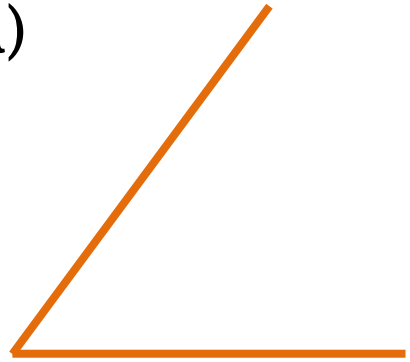


Enclosure

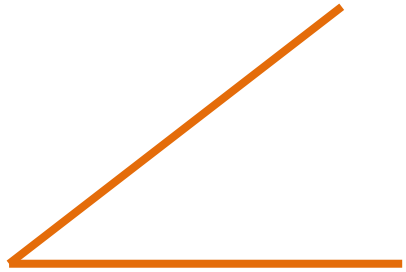


Orientation (angle or slope)

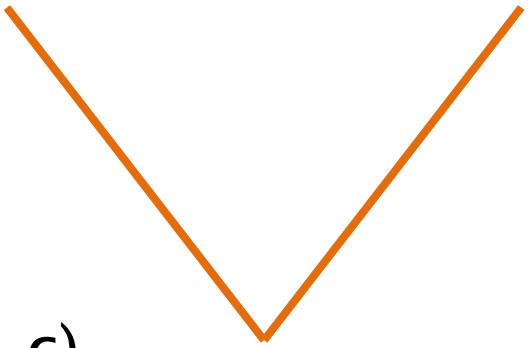
a)



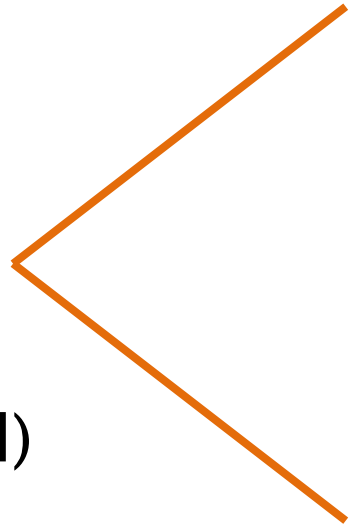
b)



c)

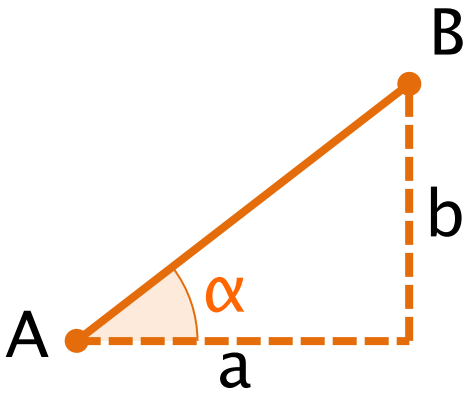


d)



Angle vs. Slope

- Slope of A–B is b/a
  - tan(α)
- Slope judgment typically falls back to an angle judgment
  - Given an error ϵ in the angle judgment
  - It is reflected in a slope error

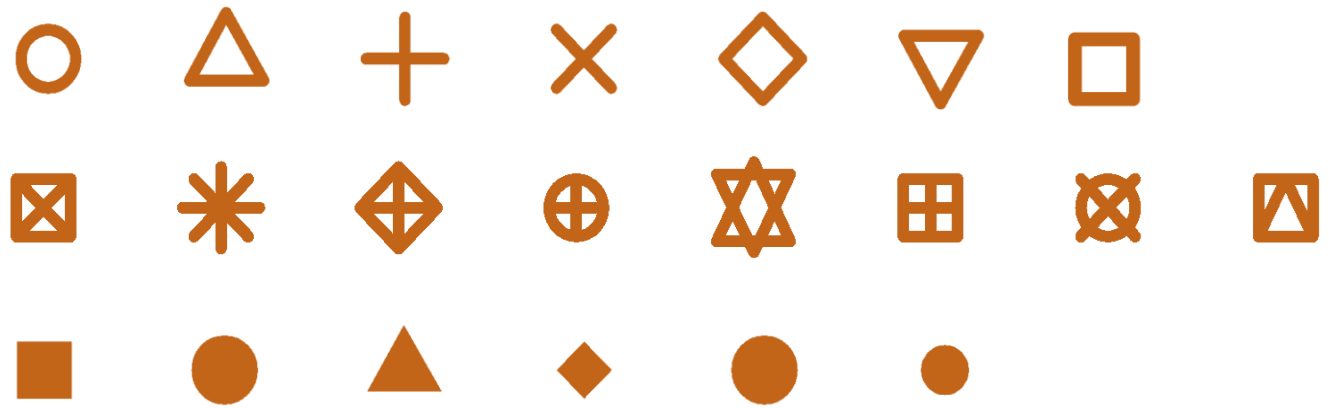


$$tan(\alpha + \epsilon) - tan(\alpha) = \epsilon \cdot tan'(\alpha) = \frac{\epsilon}{cos^2(\alpha)}$$

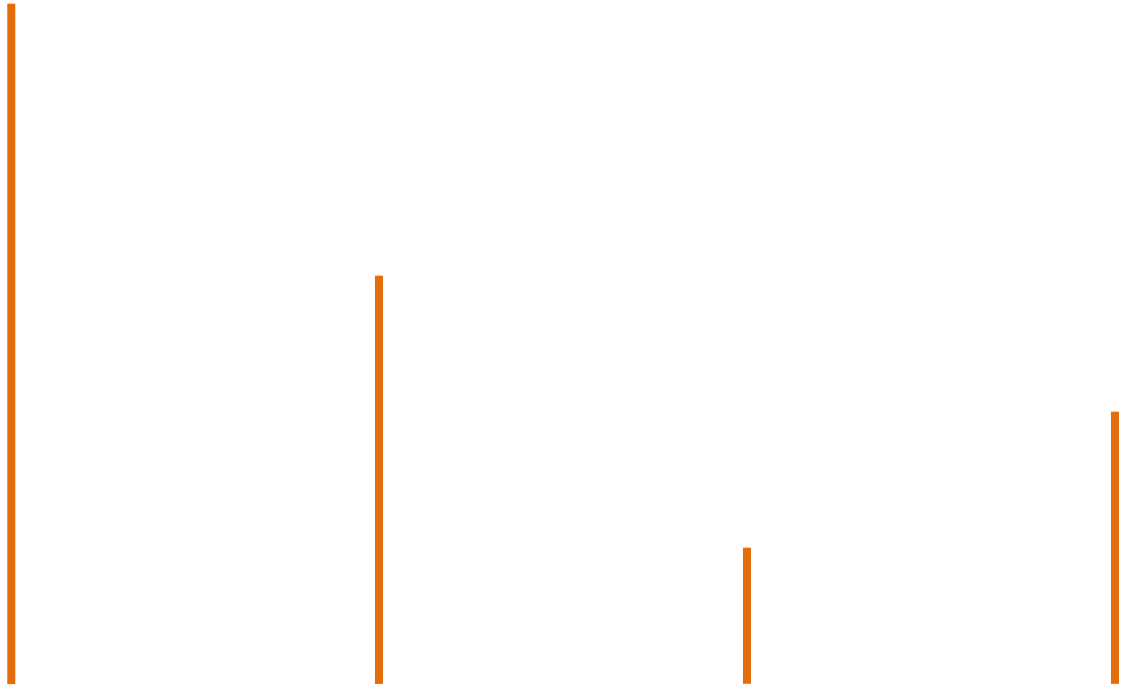
  - Getting infinite as α approaches to π/2

Shape

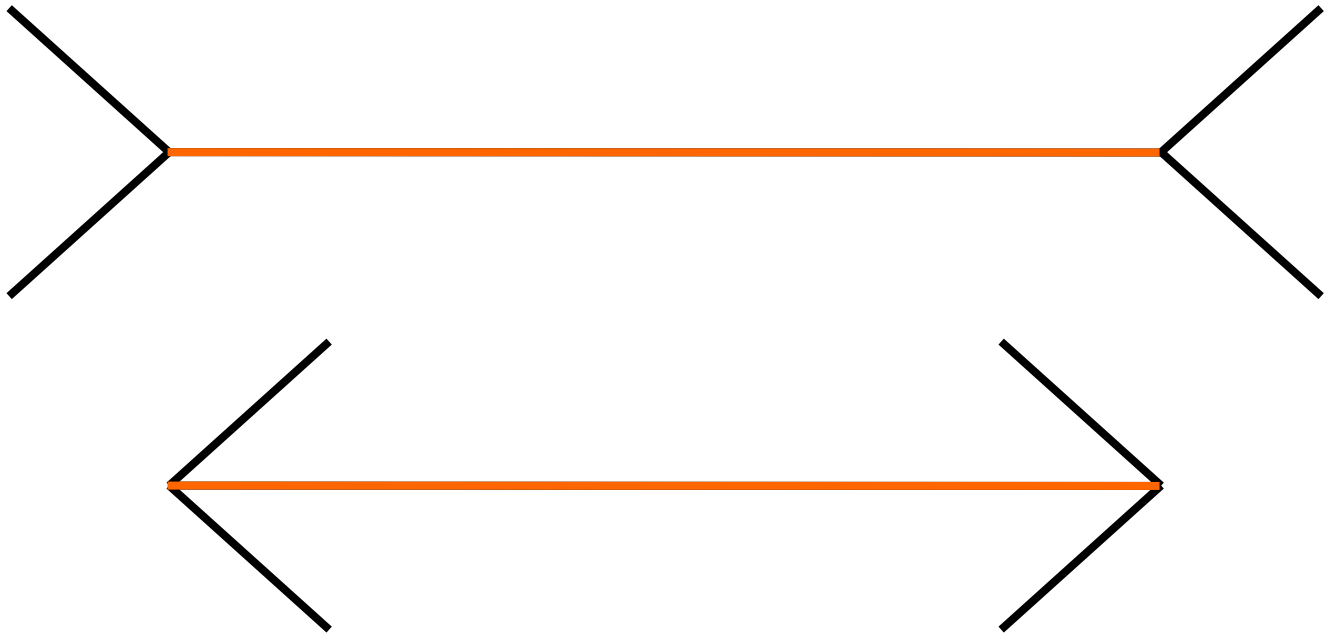
- There is no common quantitative semantics for the shapes
  - Unless they are characters…
    - Fill textures are shapes too



Length



Effect of context

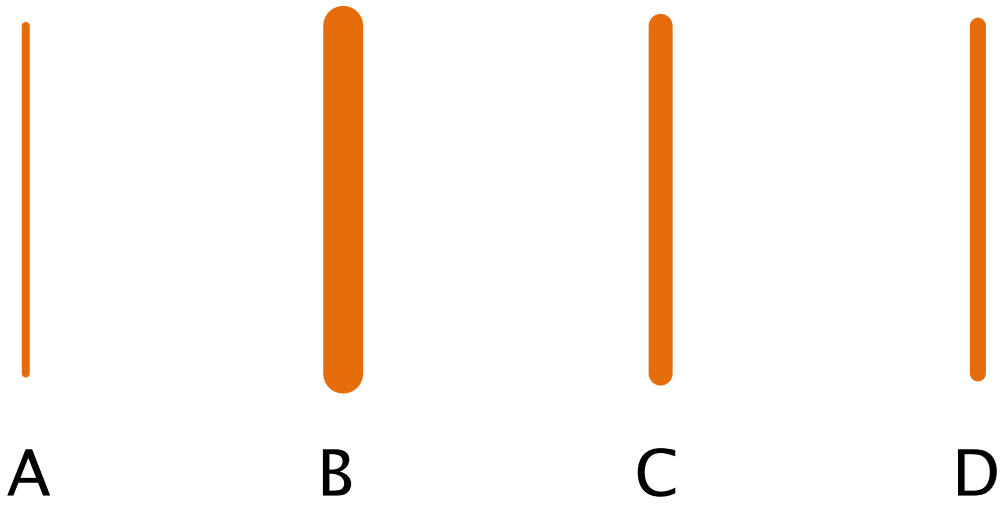


Curvature

- There is no common magnitude assessment for the curvature

Width

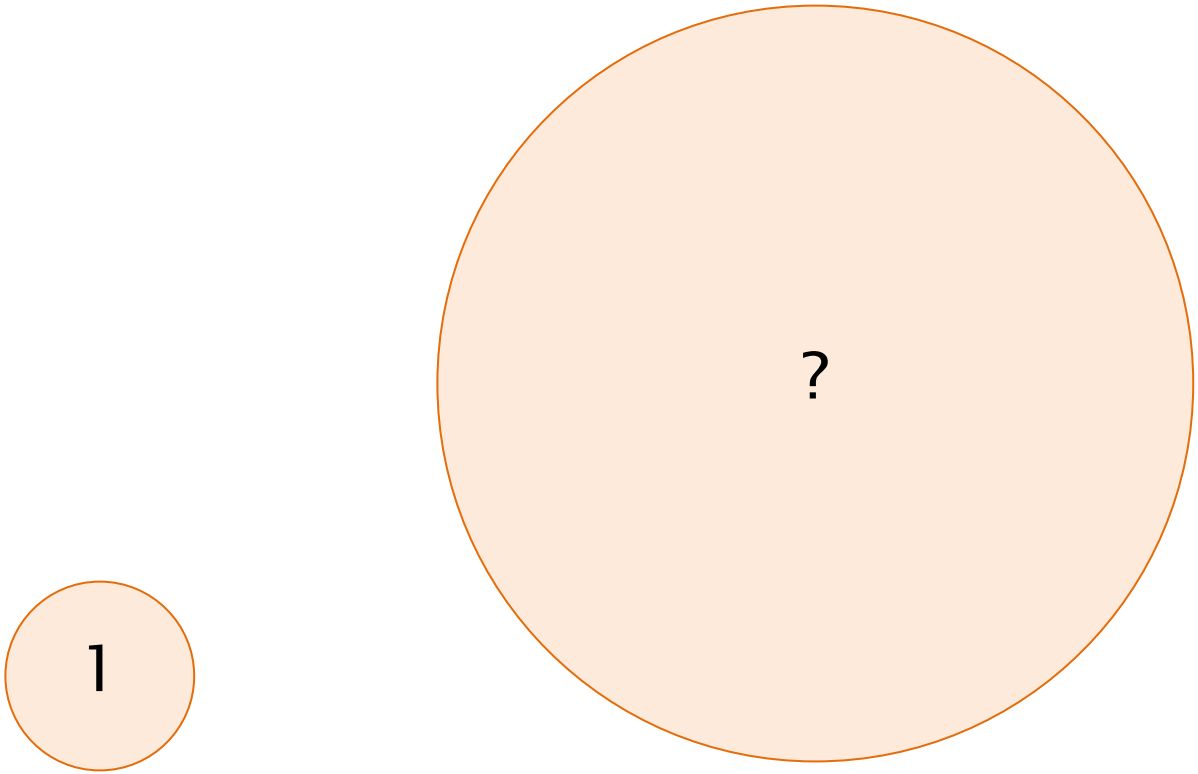
- Order can be identified
  - Difficult to appreciate actual magnitude



Mark

- No common quantitative semantics of marks
- Number of marks could encode a natural number
  - Harder to read than a cipher

Size / Area



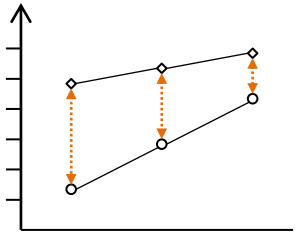
Enclosure

- No common quantitative semantics for enclosure
  - Except counting items enclosed

Spatial Position

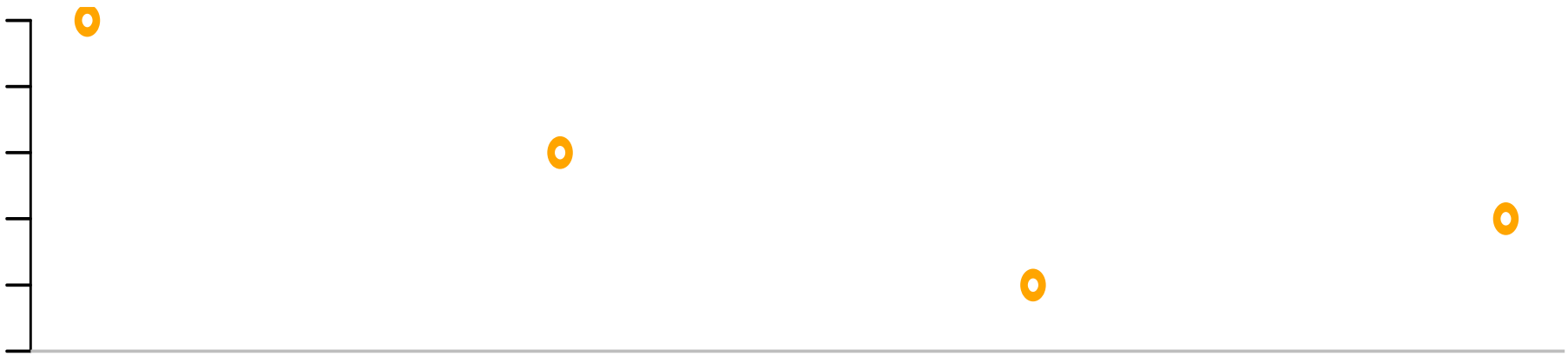
- Position along axis
  - Common scale
  - Distinct identical scales
    - Possibly un-aligned

- Distance

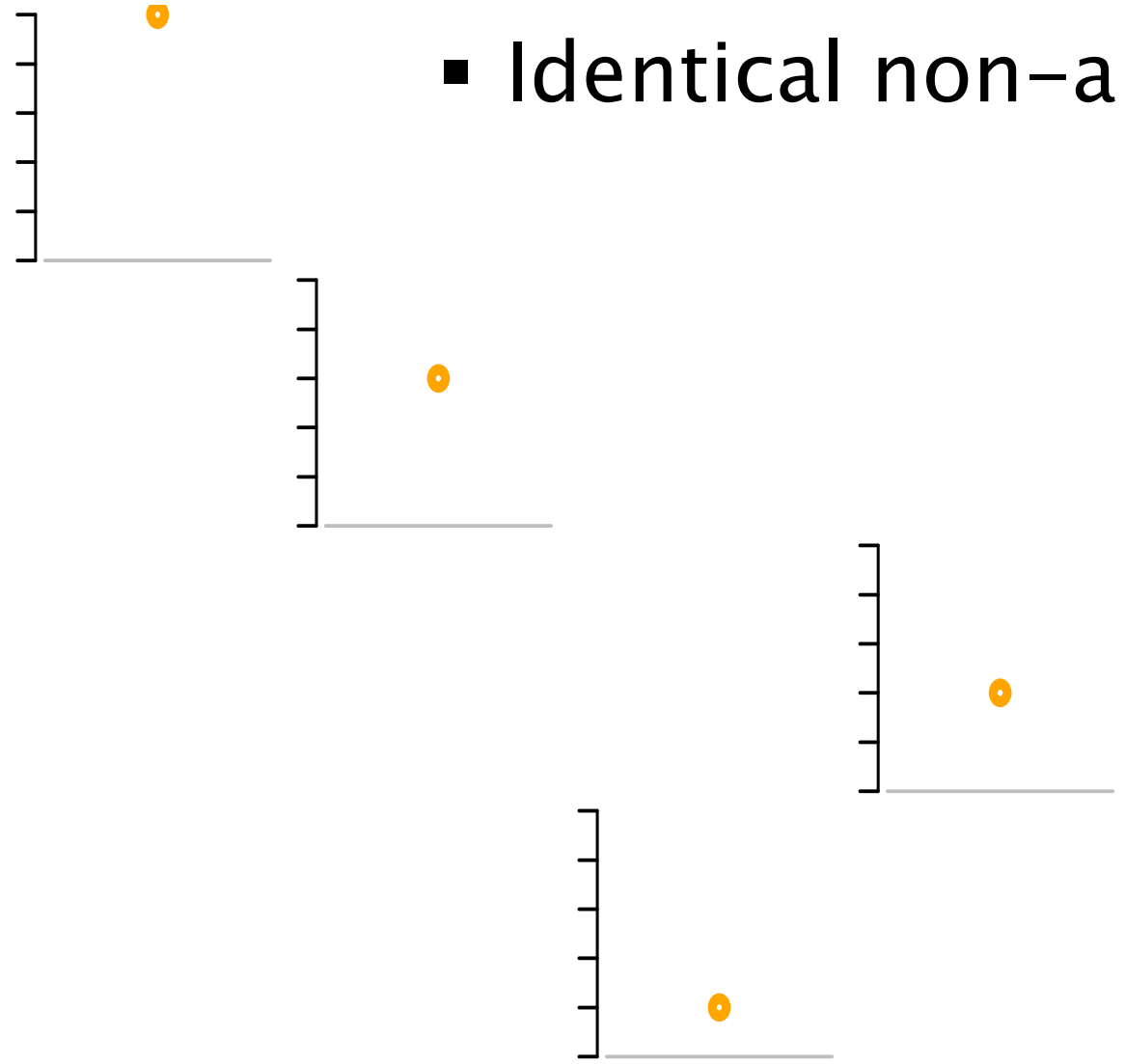


Position

- A common scale



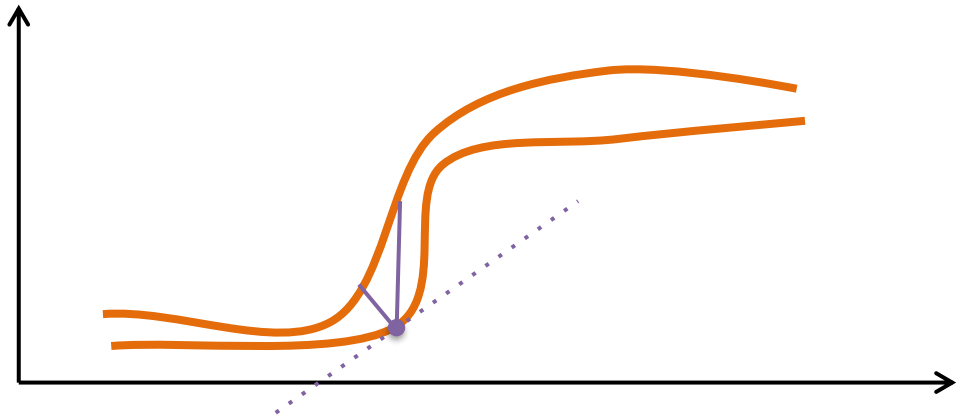
Position



- Identical non-aligned scales

Distance

- Points
  - Use length of imaginary connecting lines
- Lines
  - Distance orthogonal to tangent
    - Not what is meant in xy plots



Detection and Separation

Comparison is affected by:

- Detection
  - The capability to visually identify the objects that represent the data to be compared
- Separation
  - The distance between the objects to be compared
    - affects negatively the accuracy

Attributes of color

- Hue

- Saturation

- Intensity

  - Luminance
  - Value

Hue

- There is no common ordering semantics for hues
  - High spatial frequencies are perceived through intensity changes
  - Often perceived as separated into bands of almost constant hue, with sharp transitions between hues
- Nominal values can be represented by suitably spaced values

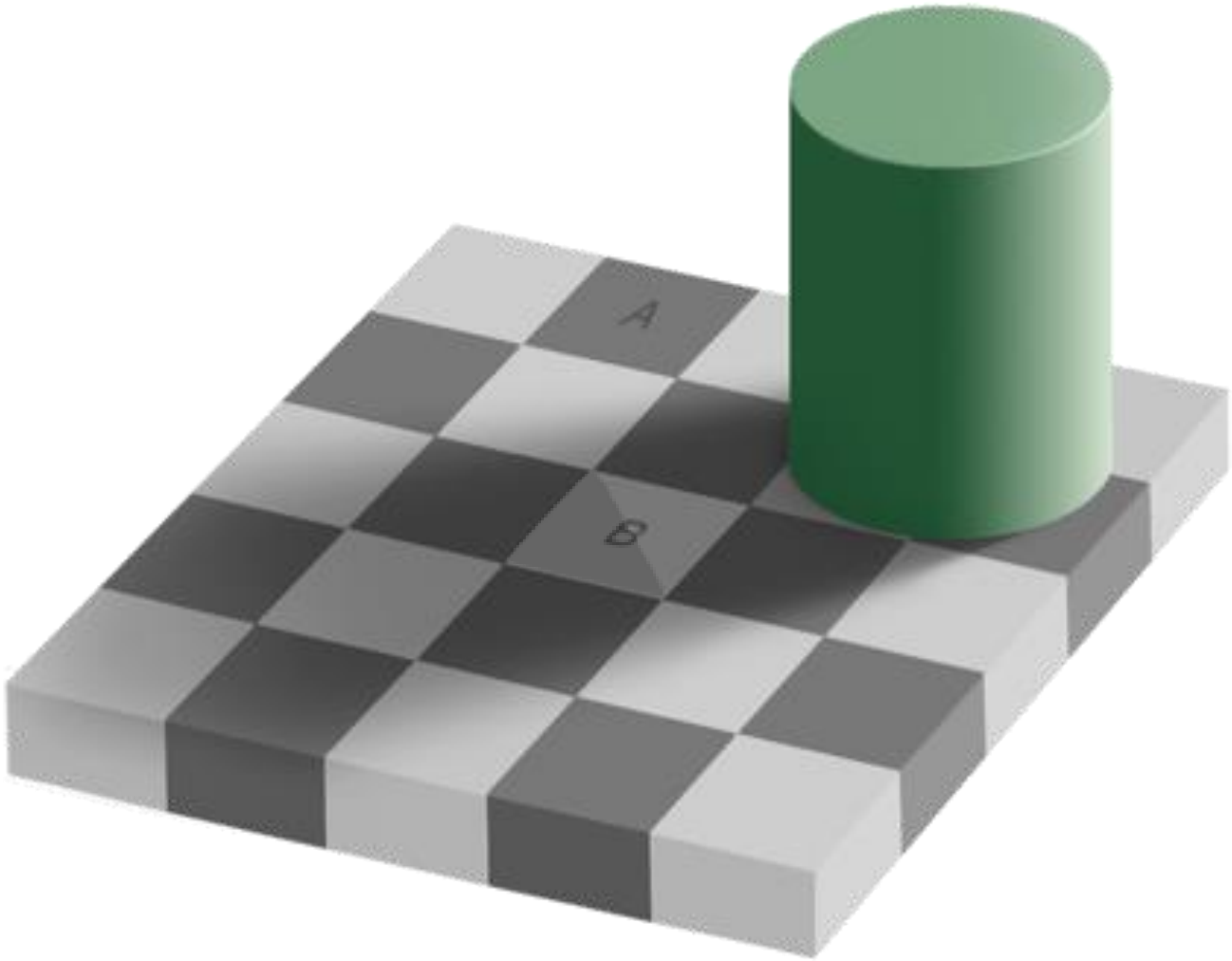
Intensity

- a.k.a. Luminance, Value
- Provides a perceptually unambiguous ordering
  - Context can affect accuracy

Saturation

- Perceptually difficult to associate an ordered semantics
  - Can be combined with hue to increase discrimination

Effect of Context



Effect of Context

- Use uniform background
  - To make distinct visual objects for the same feature look the same
- Use a background color that is contrasting enough with the visual objects' color
  - To make visual objects easily seen
- Avoid non-uniform background

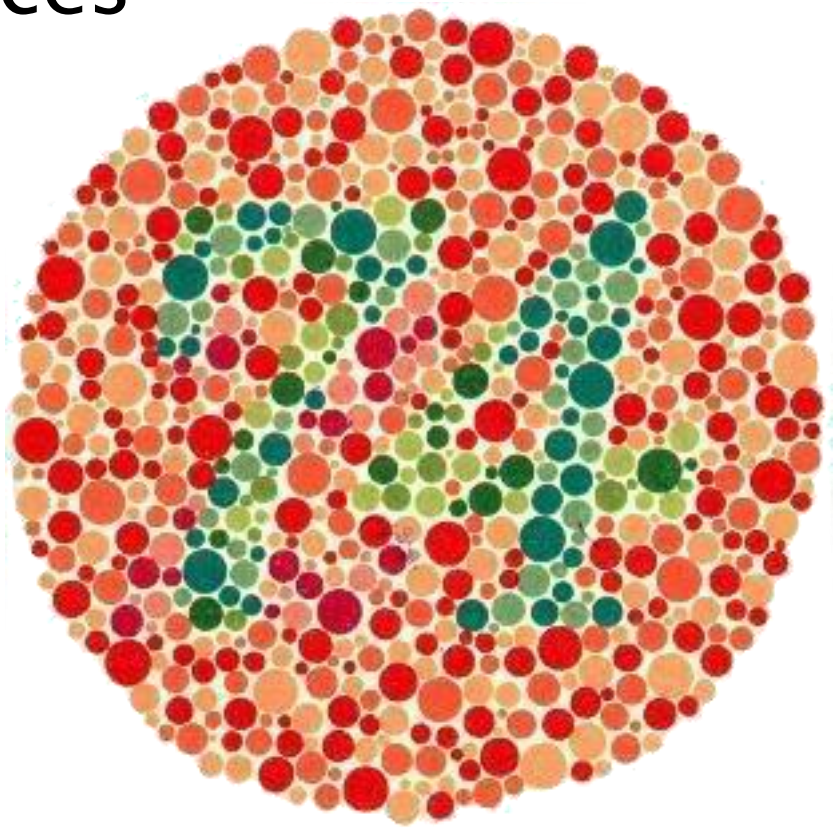
Color usage

- Ordinal measure should be mapped to increasing saturation and intensity
  - Avoid rainbow palette
- Use sequential or diverging palette
  - E.g.

  - http://colorbrewer2.org/

Color Blindness

- Inability to see colors or perceive color differences



http://www.color-blindness.com

Visual Encoding: Quantitative

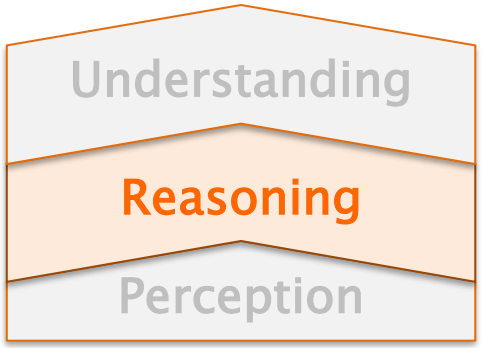
Object	Attribute
Point	Position (w.r.t. axis/axes)
Line	Length Position (w.r.t. axis/axes) Slope
Bar	Length
Shape	Size (area) Count

Visual Encoding: Categorical

Attribute	
Position	
Size	
Color	Intensity Saturation Hue
Shape	
Fill pattern	
Line style	

Ordinal

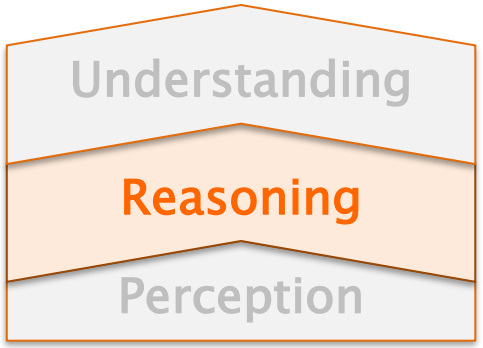
VISUAL REASONING



Graph layout

Layout and visual attributes allow:

- Discrimination
  - Distinguish visual objects or group of –
- Comparison
  - Place visual objects in order
- Magnitude assessment
  - Evaluate the (relative) magnitude of visual objects



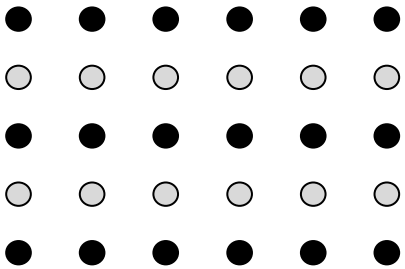
Gestalt principles

- Visual features that lead us to group visual objects together
  - Proximity
  - Similarity
  - Enclosure
  - Closure
  - Continuity
  - Connection

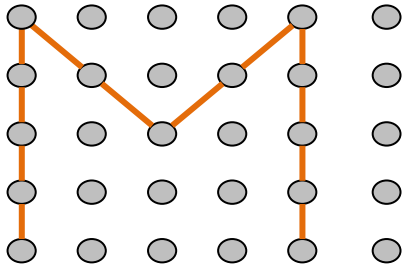
Gestalt principles

- Visual features that lead the viewer to group visual objects together

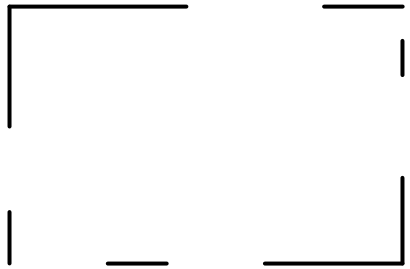
Similarity



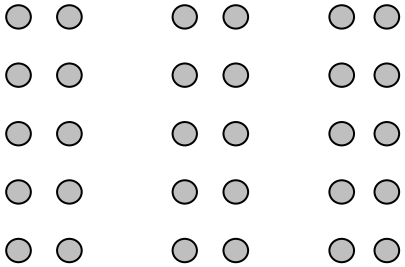
Connection



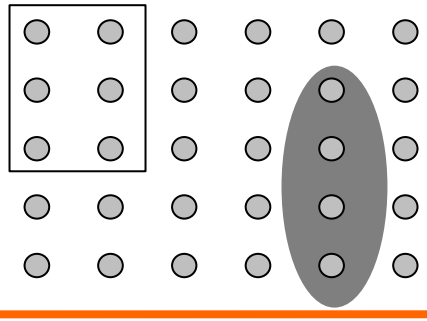
Closure



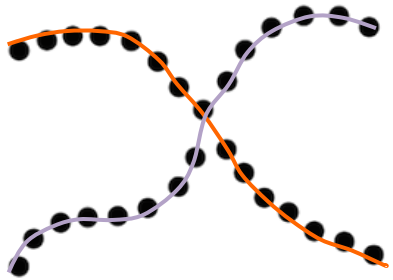
Proximity



Enclosure



Continuity



Gestalt principles

- Visual attributes/patterns that lead observer to group objects together
  - **Proximity**
  - Similarity
  - Enclosure
  - Closure
  - Continuity
  - Connection

Gestalt principles

- Visual attributes/patterns that lead observer to group objects together
  - Proximity
  - **Similarity**
  - Enclosure
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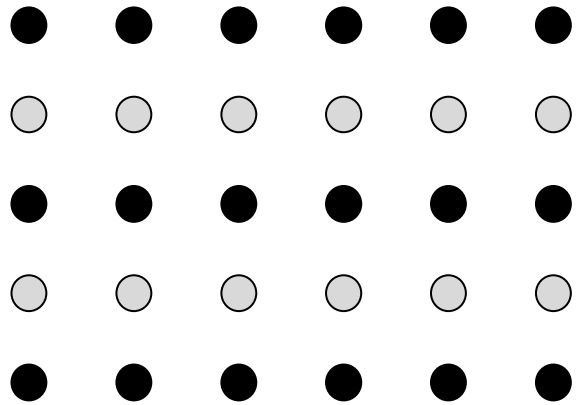
  - Continuity
  - Connection



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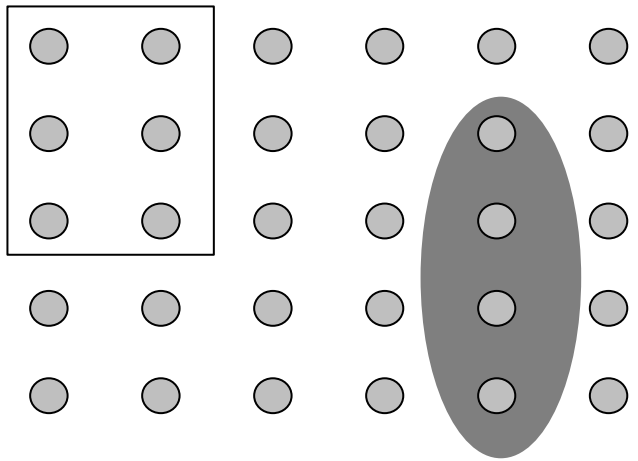

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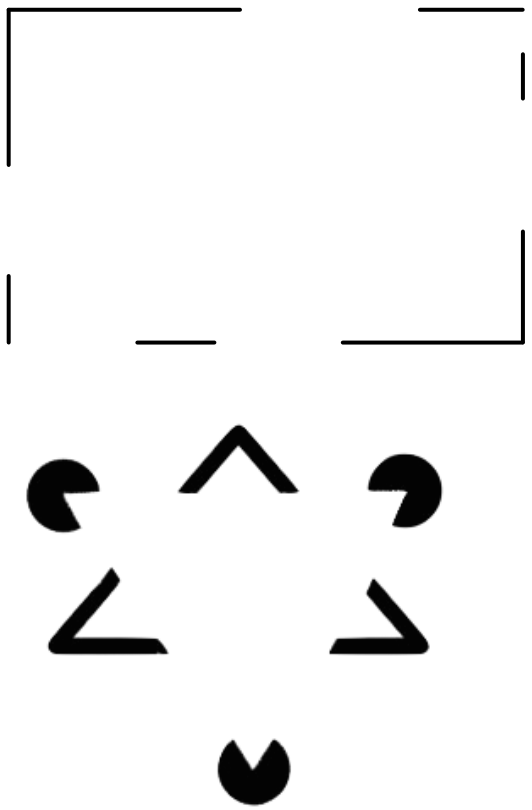

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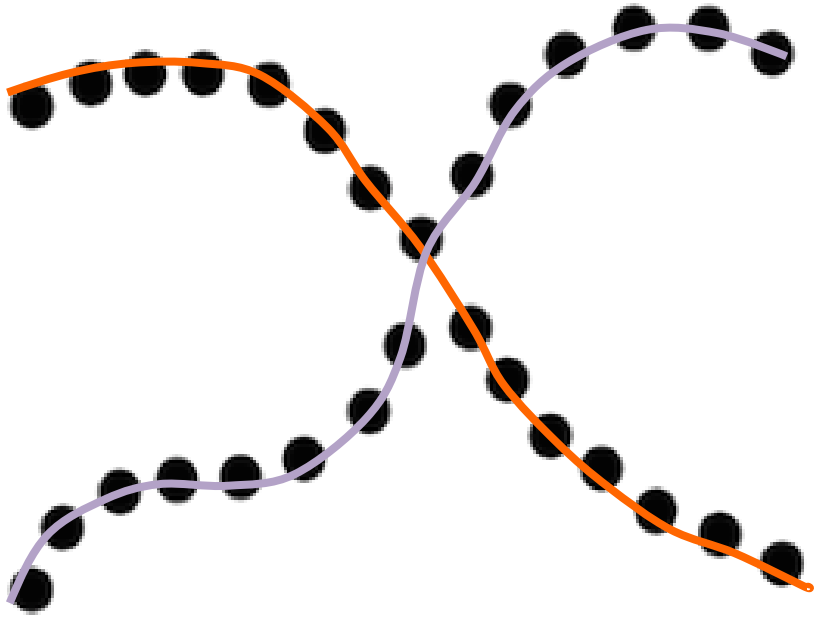

Gestalt principles

- Visual attributes/patterns that lead observer to group objects together
  - Proximity
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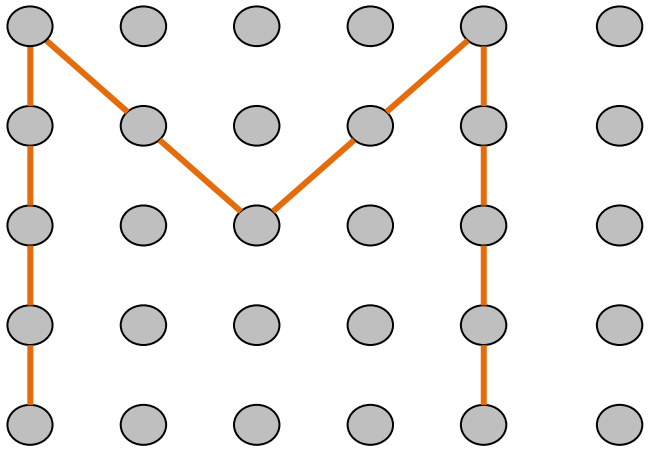
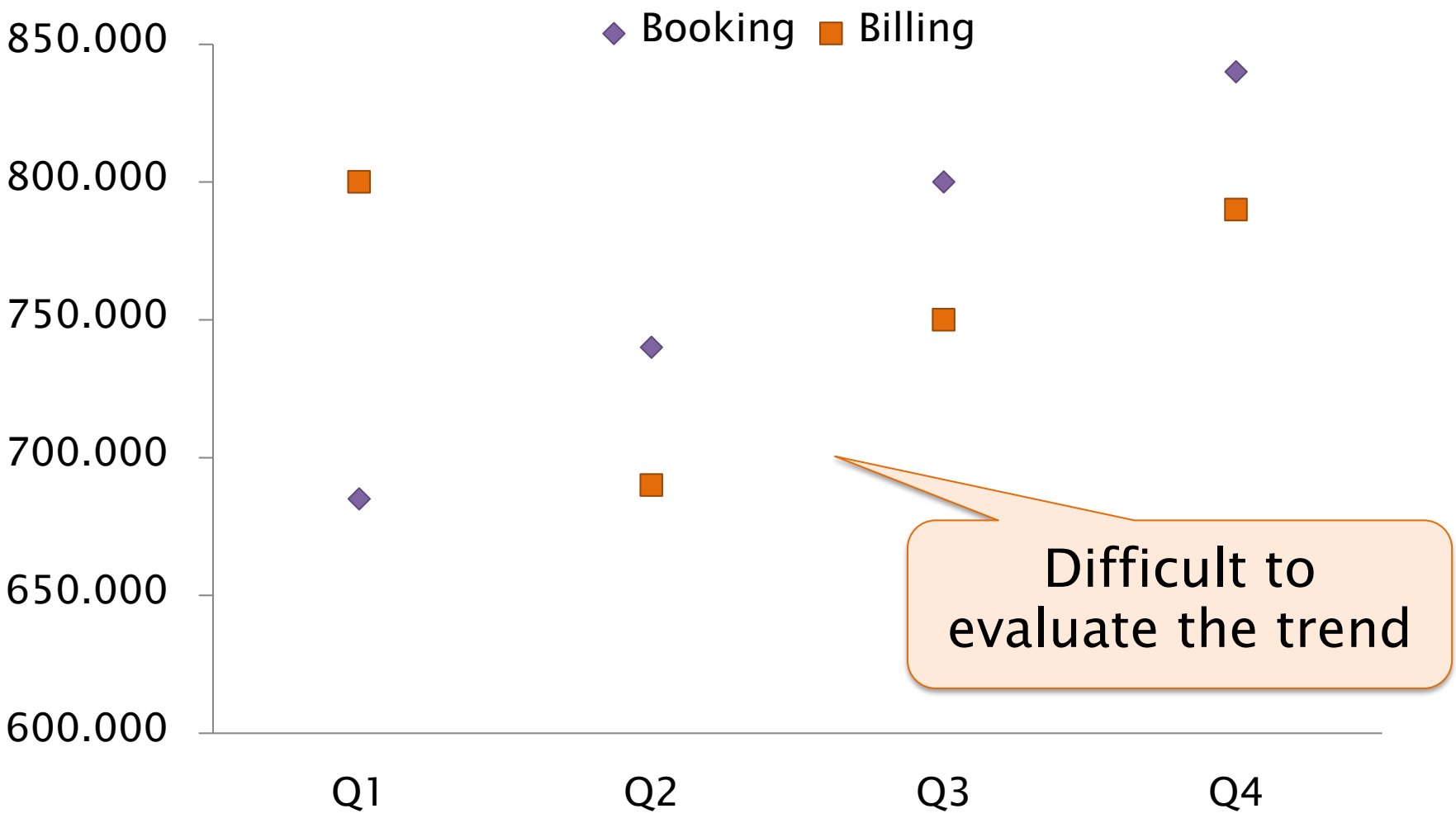
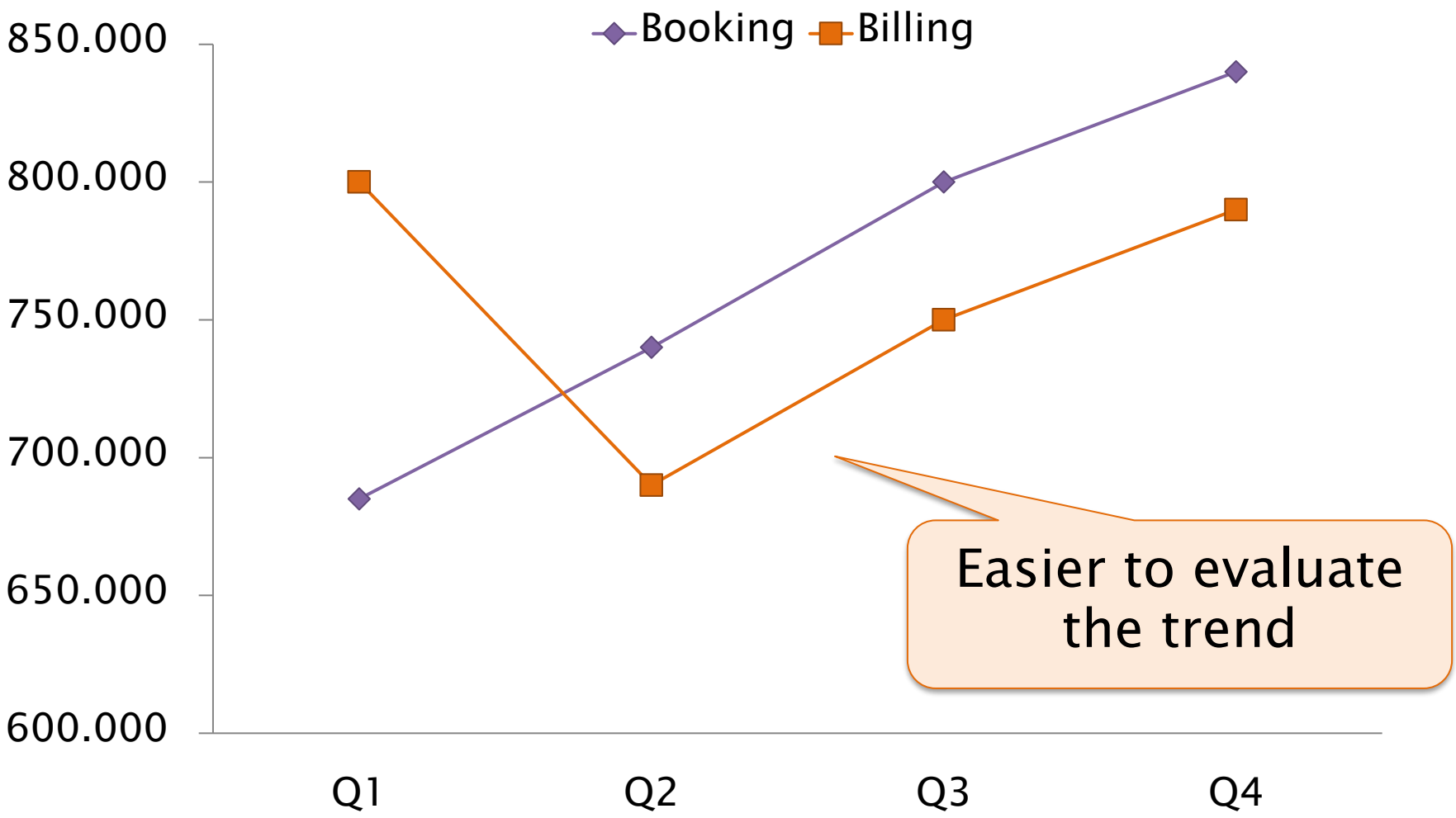
  - Continuity
  - **Connection**



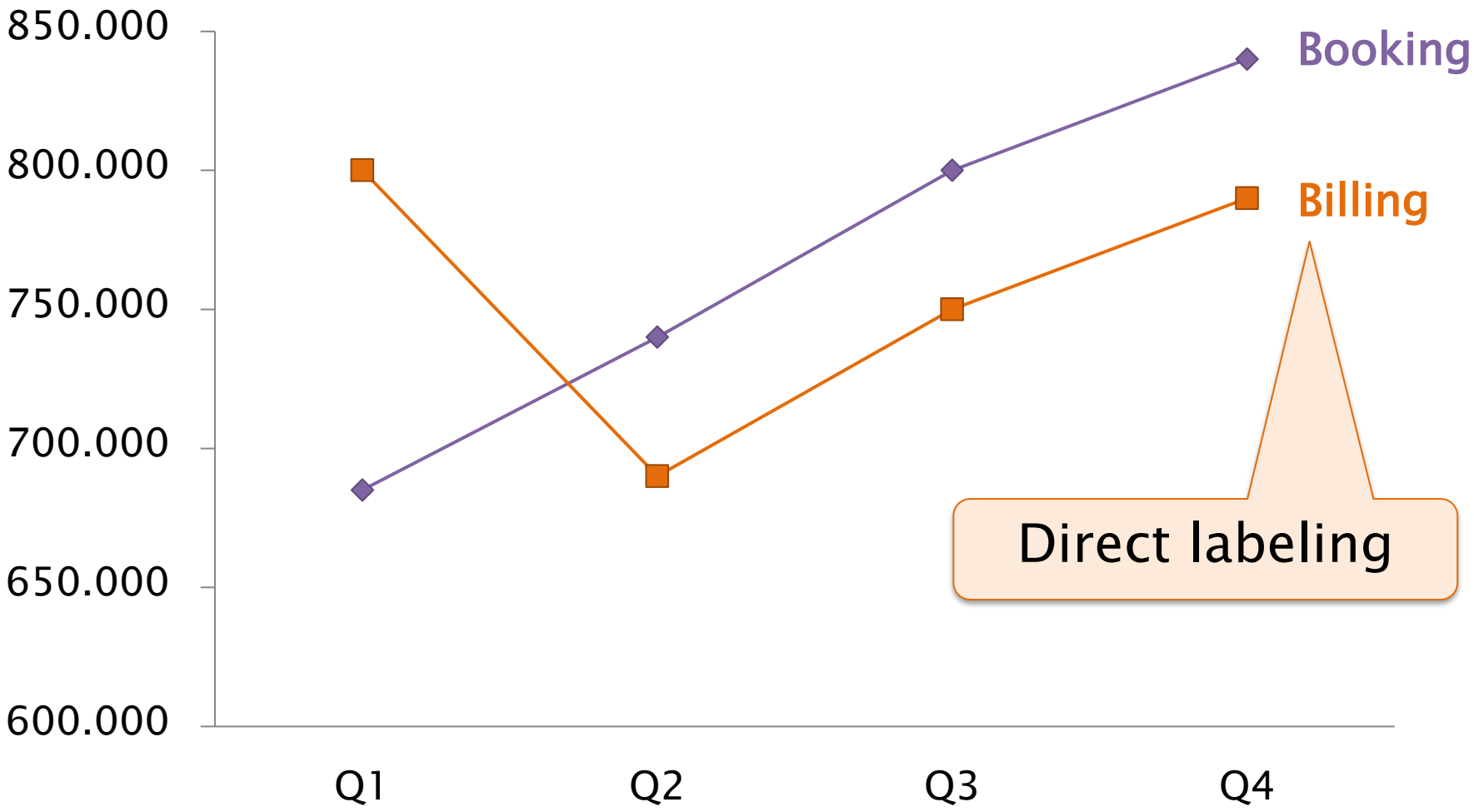
Similarity in Shape & Color



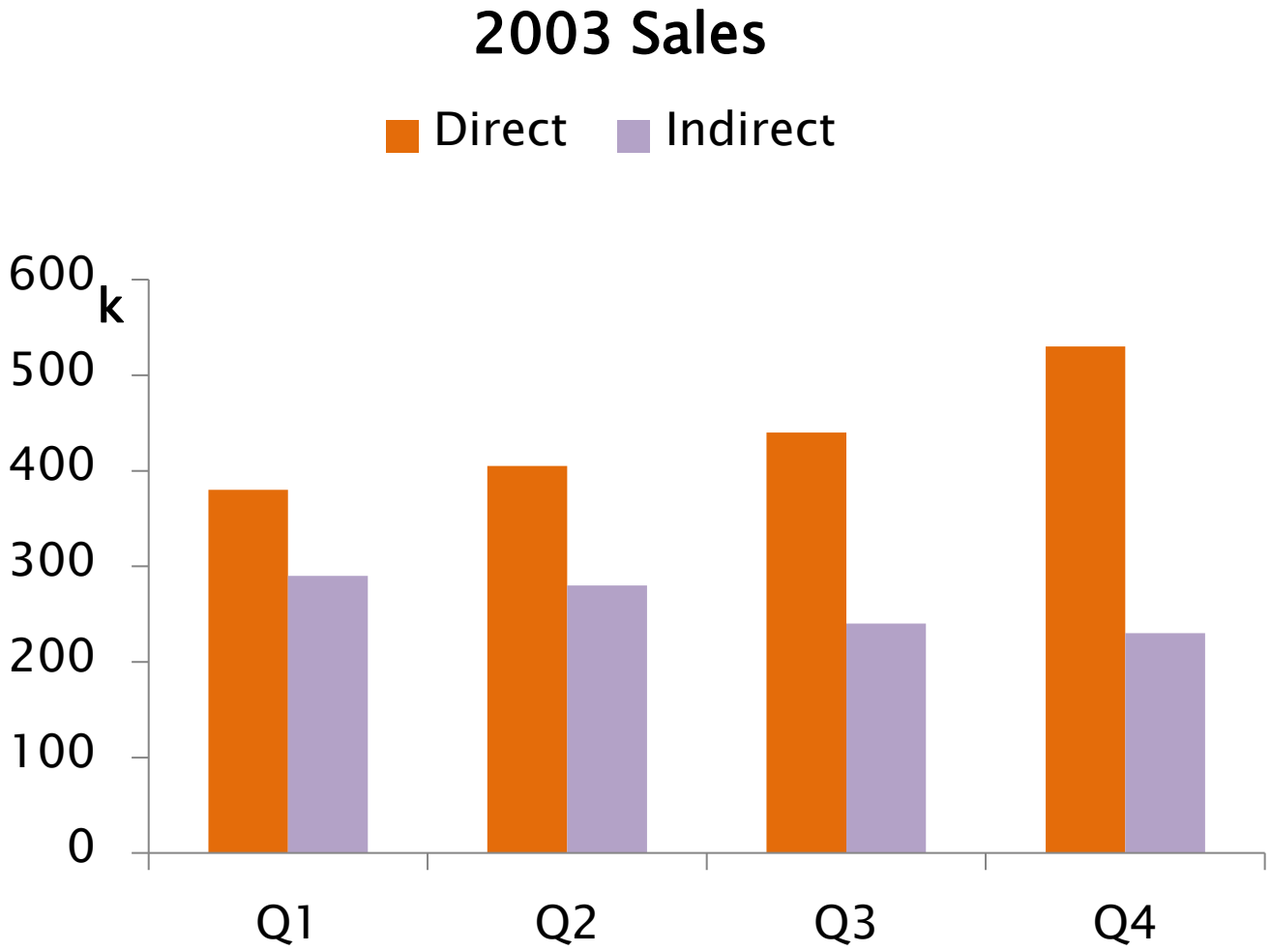
Similarity+Connection



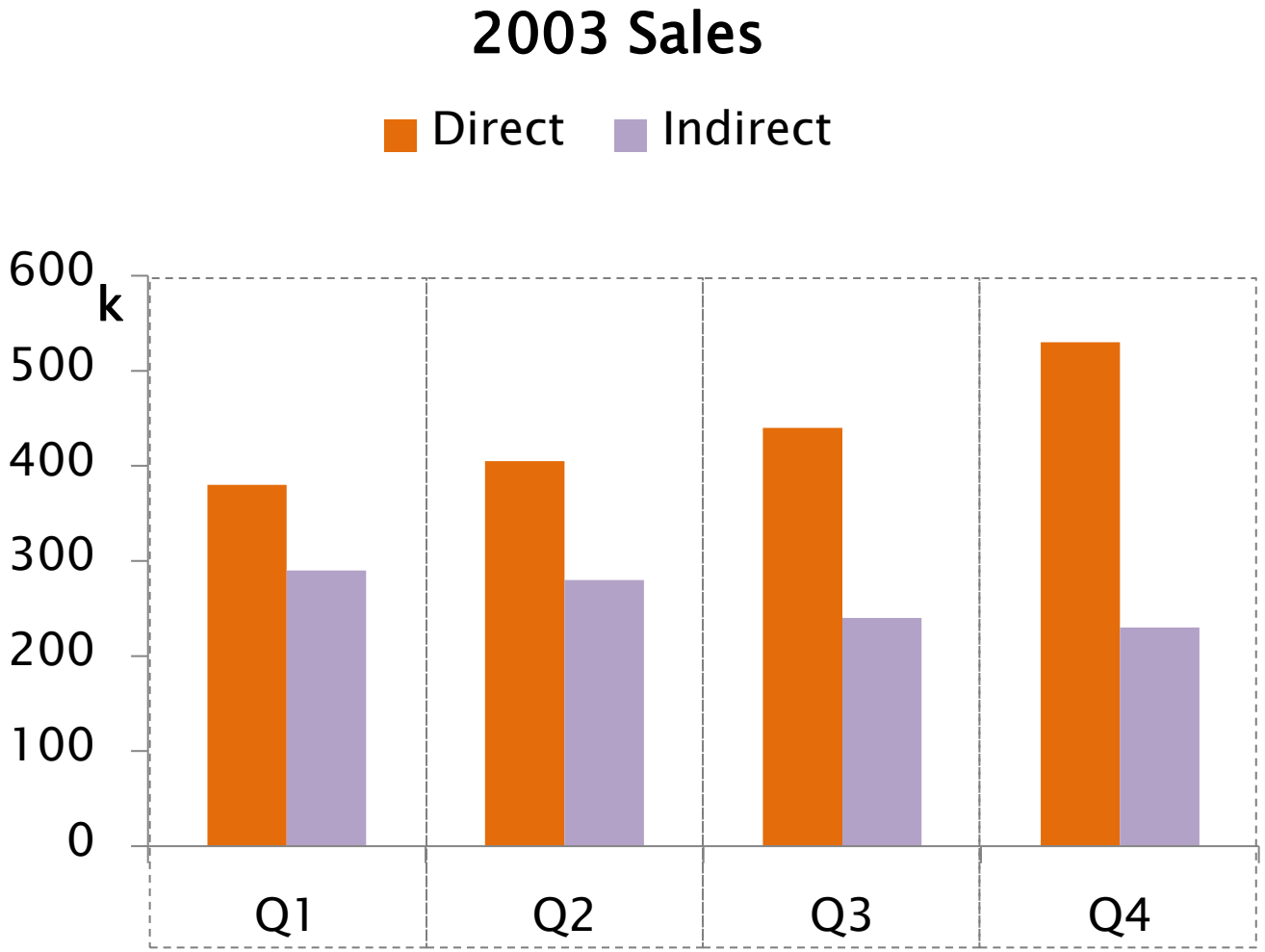
Similarity+Connection+Proximity



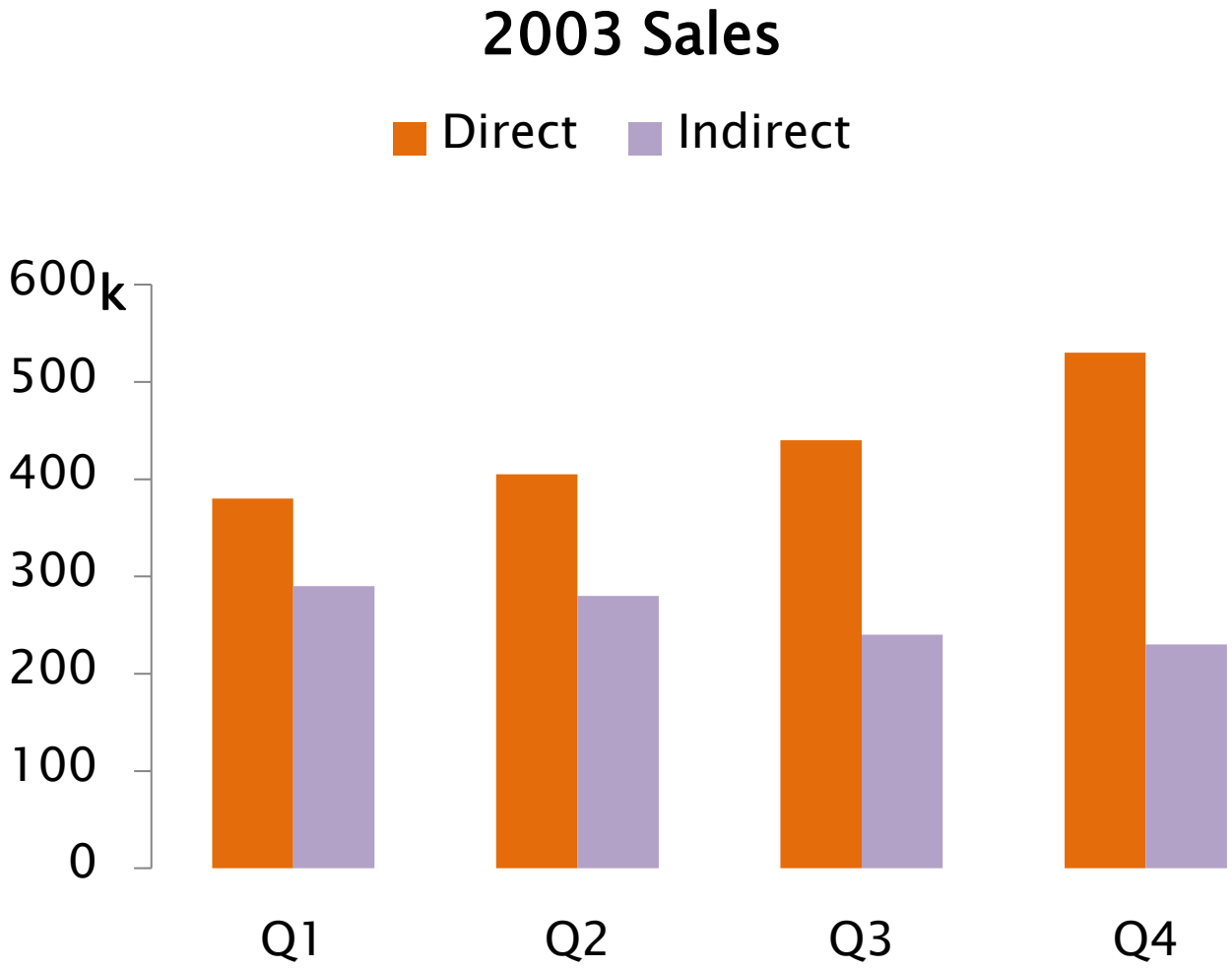
Similarity × Proximity



Similarity × Proximity & Enclosure



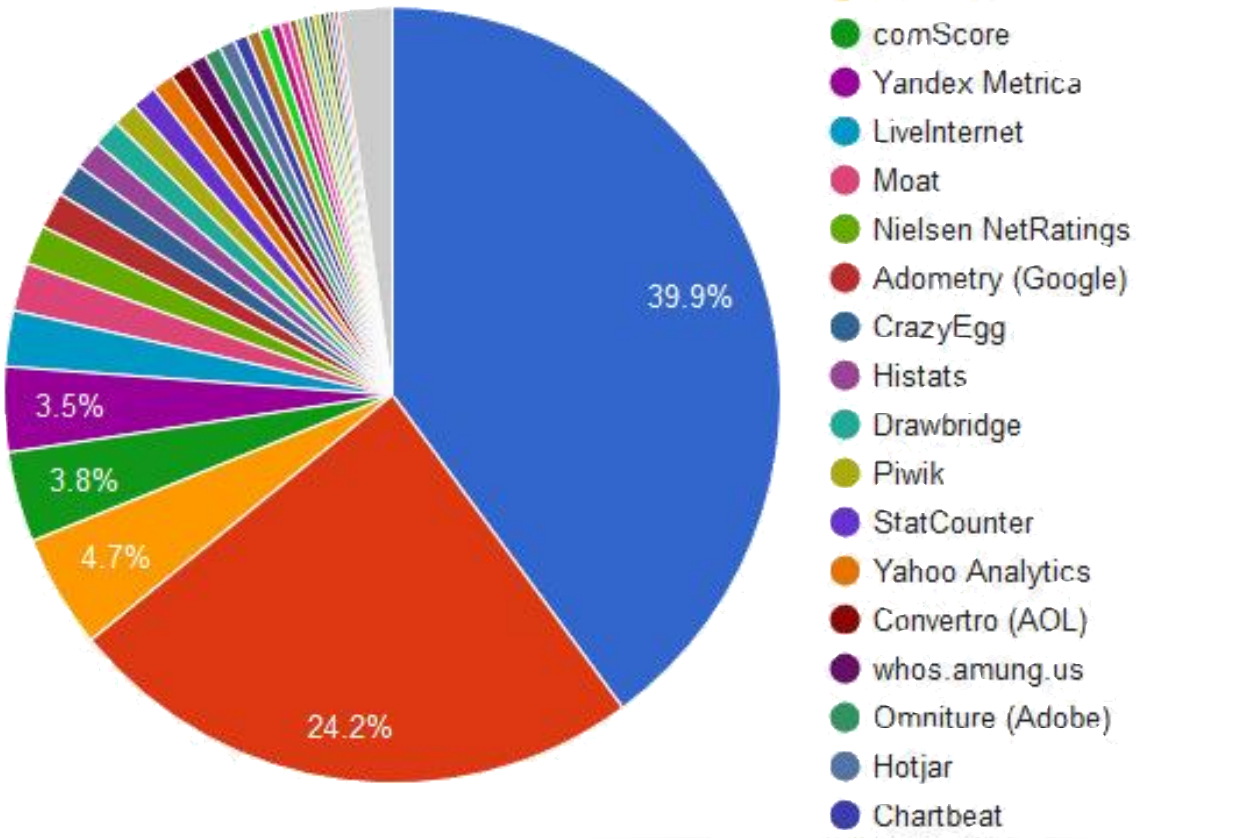
Continuity replaces axis



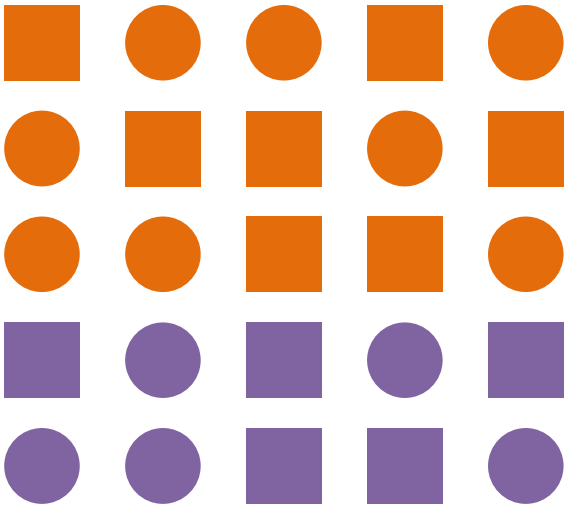
Distinct perceptions

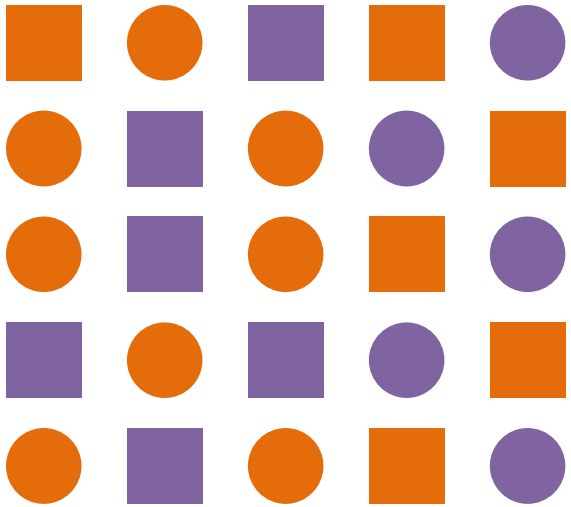
- The immediacy of any pre-attentive cue declines as the variety of alternative patterns increases
  - Even if all the distracting patterns are individually distinct from the target
  - For each single attribute no more than four distinct levels are discernible

Rainbow Pies

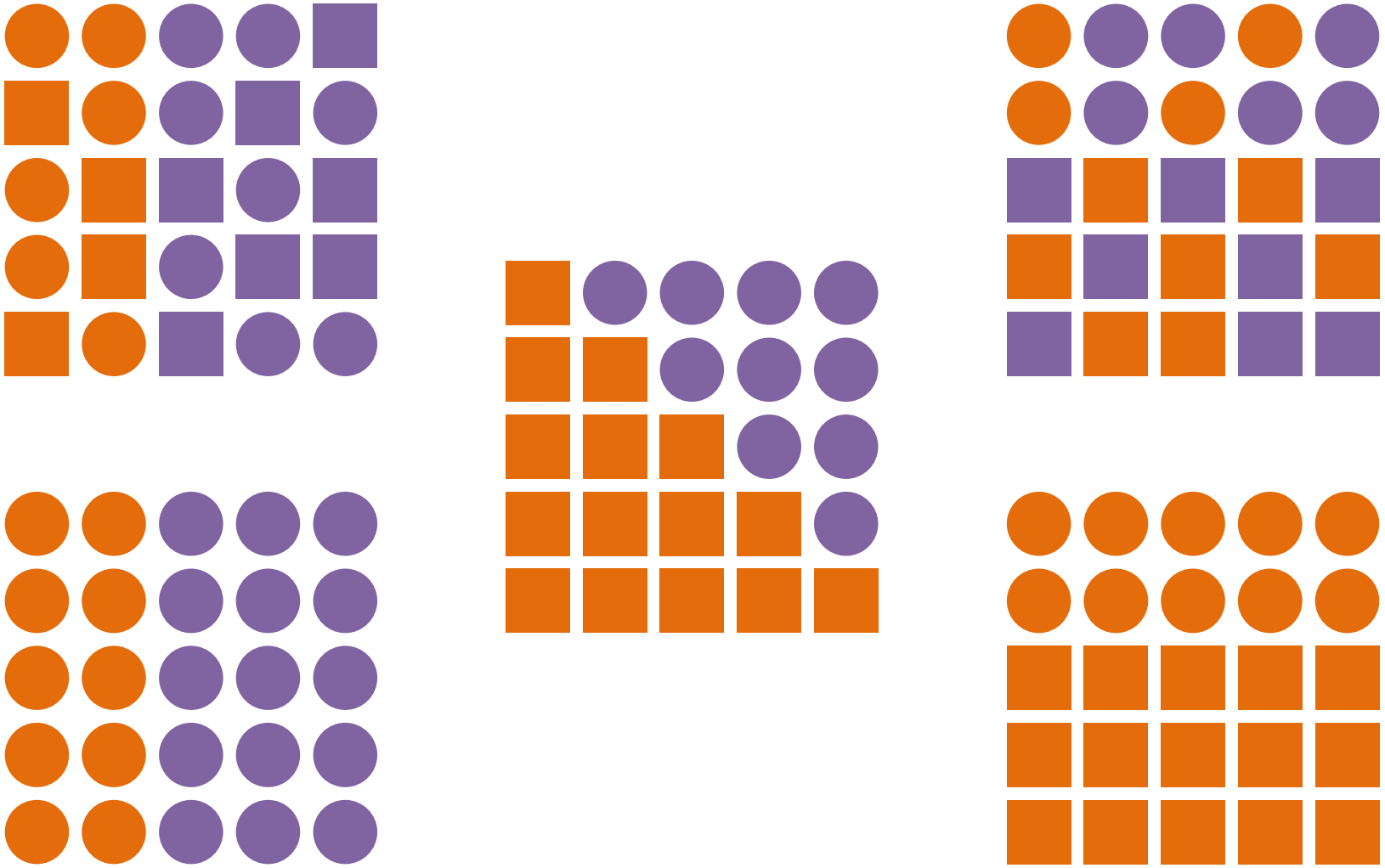


Attribute Interference





Attribute Interference



Cultural conventions

- Reading proceed from left to right and from top to bottom
  - At least in western culture
- What is at the top (on the left) precedes what is at the bottom (on the right) in terms of
  - Importance
  - Ordering
  - Time

Emphasis

Attribute	Tables	Graphs
Line width	Boldface text	Thicker lines
Size	Bigger tables Larger fonts	Bigger graphs Wider bars Bigger symbols
Color intensity	Darker or brighter colors	
2-D position	Positioned at the top Positioned at the left Positioned in the center	

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