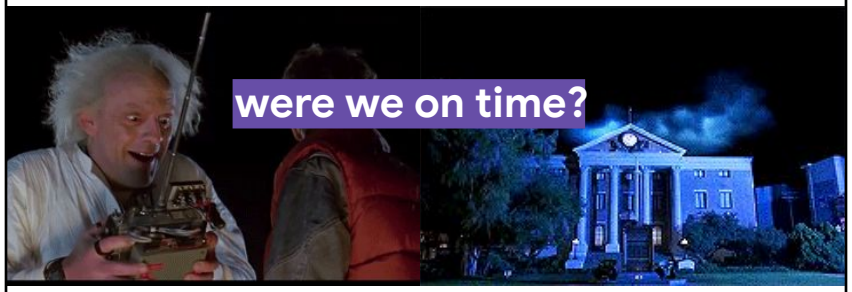
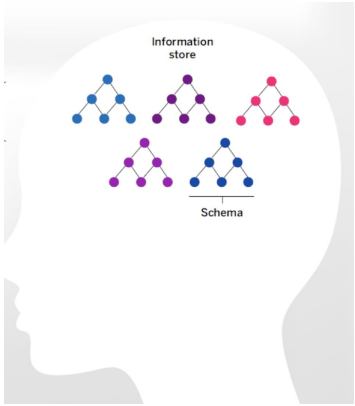
visual perception

the powers & handicaps
of the human visual system



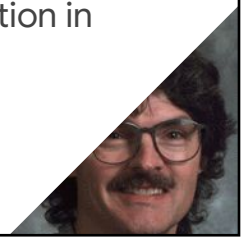
Objectives

- ❑ Understand the information processing shortcuts our brains make
- ❑ Understand the limitations & bugs in our brains software
- ❑ Learn the basic building blocks for data visualizations
- ❑ Learn how to subtly guide your audiences focus and understanding



“ A visualization is more effective than another visualization if the information conveyed by one visualization is more readily perceived than the information in the other visualization.”

Jock Mackinlay
Author, information designer and professor.
Knight Chair in Visual Journalism at the University of Miami.

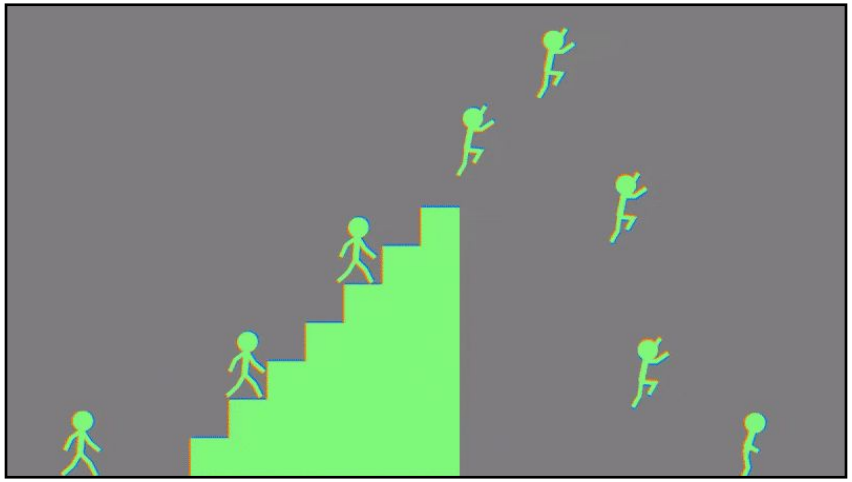


Human Perception and the Visual System

1. **Visual Advantages:** Making Sense of Too Much Data
2. **Information Processing:** features and patterns in the visual system.
3. **Encoding:** five primary means of effectiveness among visual attributes

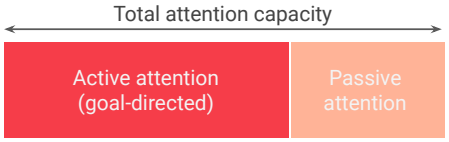
why vision? strengths & weaknesses

why vision? strengths & weaknesses



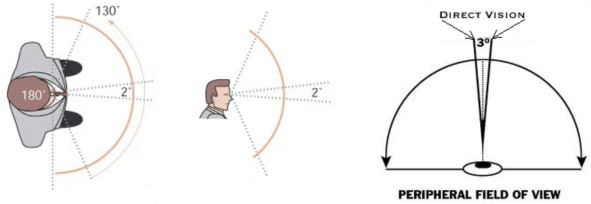
> On average, people hear or read 100,000 words a day. And studies have shown that ___% of what we learn is forgotten within 24 hours.
>
> —Forbes, "How To Be Unforgettable" (March 2013)

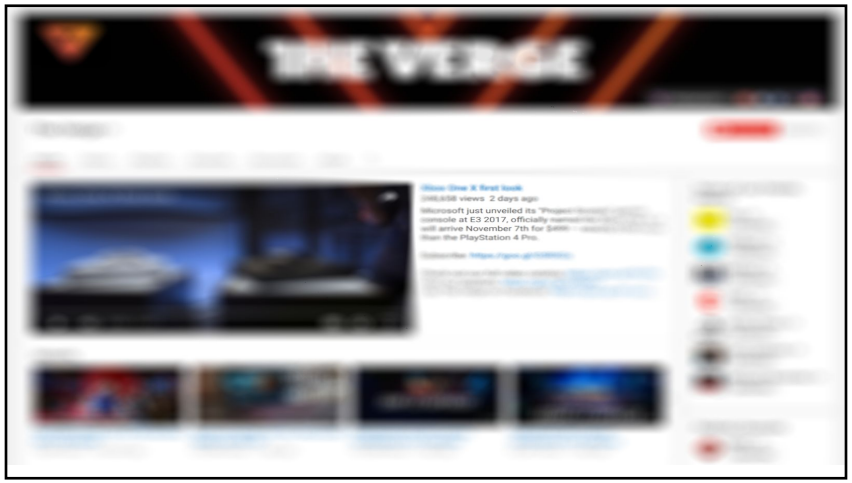
Attention | has its limits...

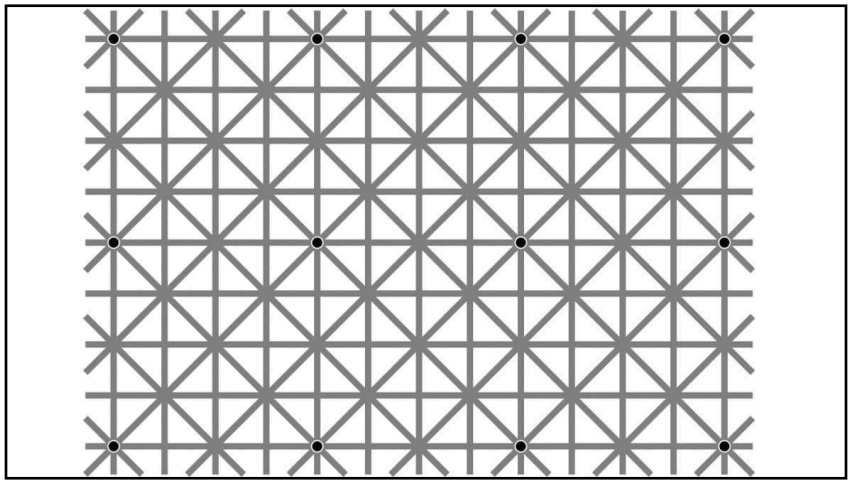


...and so does vision.

Vision | Our hardware doesn't process everything

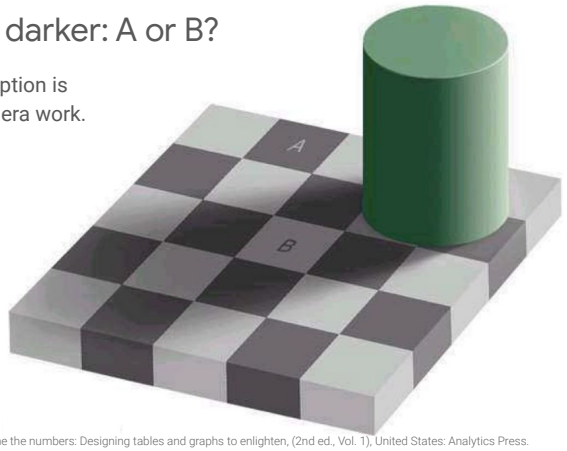






Which is darker: A or B?

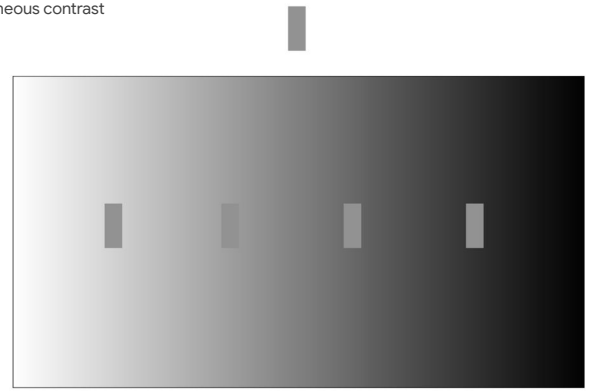
Visual perception is
not just camera work.



Few, S. 2012. Show me the numbers: Designing tables and graphs to enlighten, (2nd ed., Vol. 1), United States: Analytics Press.

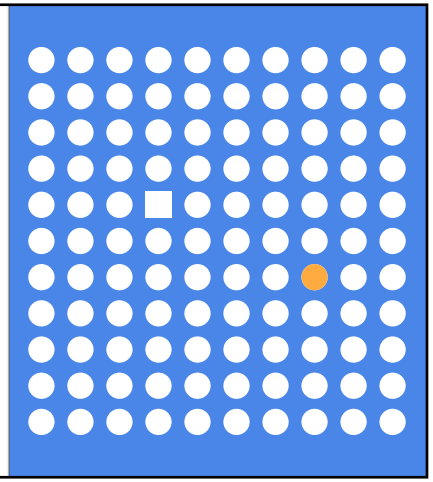
Context affects what we see.

Simultaneous contrast



Perception is sometimes serial and slow and sometimes parallel and immediate.

Our brains are programmed to detect these differences.



How many 9s can you count in this sequence?

Look-up tasks and reading text must be processed serially and slowly;

19845763251975214933524739
153187411935178400937052 92
09075289715006246219170310
75857317068271370907321710
70137031810571903710671097

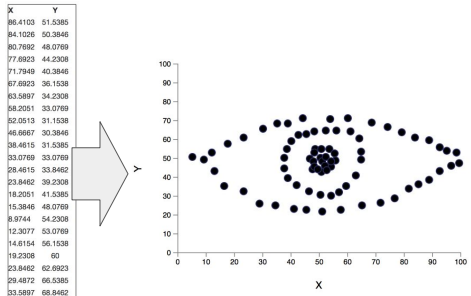
Graphical information does not (Few 2012).

What trends can you see in two columns of data?

Vision comprises

70%

of our sensory receptors



Other Senses?

sound:

1. lower bandwidth and different semantics
2. overview not supported
3. subjective experience of sequential stream

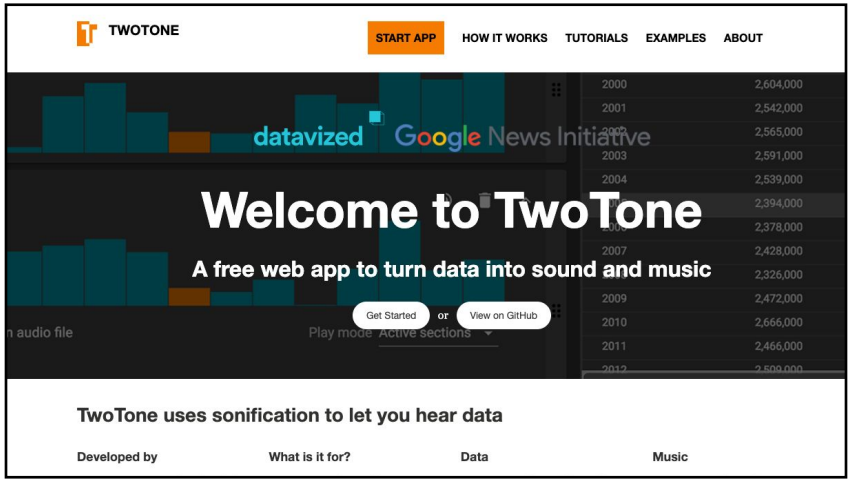
touch/haptics:

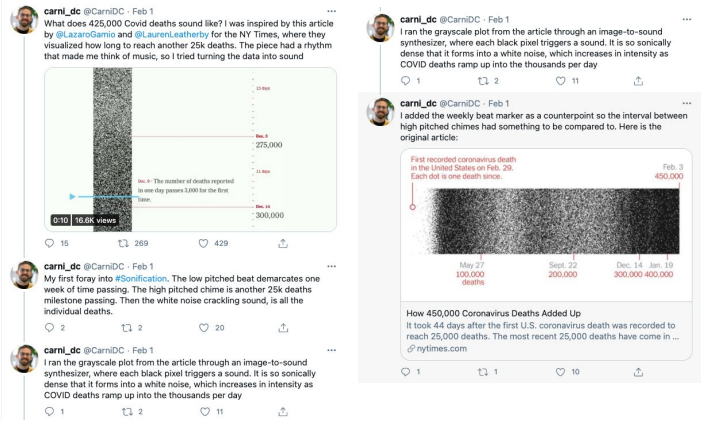
1. impoverished record/replay capacity
2. only very low-bandwidth communication thus far

taste, smell:

1. no viable record/replay devices

Munzner, T. (2009). Visualization. In P. Shirley & S. Marschner (Eds.), Fundamentals of Computer Graphics (Third Edit, pp. 675–707). https://doi.org/10.1.1.154.7671

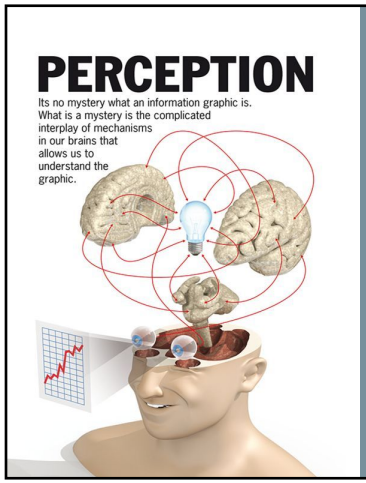




Hear the data : https://twitter.com/i/status/1356267828874256387

Three limitations of **vision**

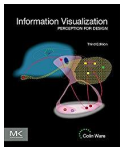
1. **Computational Capacity** (time, memory)
2. **Display Capacity** (resolution, screen size)
   a. information density: a measure of the amount of information encoded versus the amount of unused space (Tufte, 2001)
3. **Human Perceptual/Cognitive Capacity** (memory, attention)
   a. limited working memory: susceptibility to 'change blindness' (Simons, 2000)
   b. limited vigilance: degradation of search task performance (Ware 2000)



and the human visual system

> Why should we be interested in visualization? Because the human visual system is a pattern seeker of enormous power and subtlety.
>
> The eye and the visual cortex of the brain form a massively parallel processor that provides the highest-bandwidth channel into human cognitive centers... However, the visual system has its own rules. We can easily see patterns presented in certain ways, but if they are presented in other ways, they become invisible...
>
> If we can understand how perception works, our knowledge can be translated into rules for displaying information... if we disobey the rules, our data will be incomprehensible or misleading.

Ware, C. 2012. Information visualization: perception for design, Waltham, MA



The Visual System

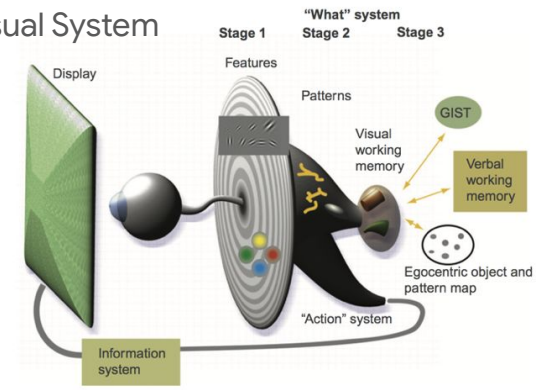
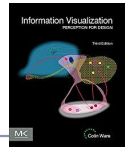
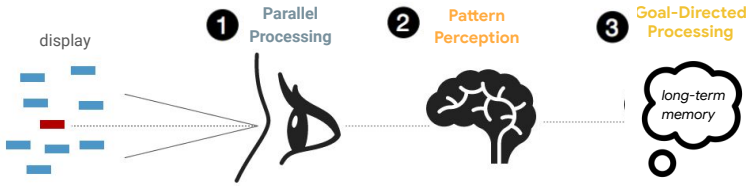


Figure 1.11 A three-stage model of visual information processing.

Ware, C. 2012. Information visualization: perception for design, Waltham, MA



information processing | the "what system"



features

Processed rapidly and simultaneously, from the whole field of vision

Elements of Highest Salience
"What stands out the most at first glance?"

patterns

Processed slower and serially, from our visual queries

(visual working) memory

Processed in sequence, related to the task

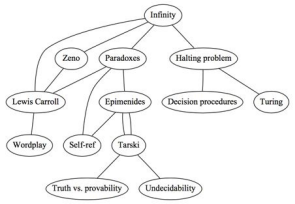
Elements of Most Relevancy
"What is most important to me?"
"What is top of mind for me at the moment?"

Information Visualization: Perception for Design (Ware, 2013)

A **high-bandwidth channel** to brain

Visualization allows people to offload cognition to the perceptual system, using carefully designed images **as a form of external memory**.

Infinity - Lewis Carroll
Infinity - Zeno
Infinity - Paradoxes
Infinity - Halting problem
Zeno - Lewis Carroll
Paradoxes - Lewis Carroll
Paradoxes - Epimenides
Paradoxes - Self-ref
Epimenides - Self-ref
Epimenides - Tarski
Tarski - Epimenides
Halting problem - Decision procedures
Halting problem - Turing
Lewis Carroll - Wordplay
Tarski - Truth vs. provability
Tarski - Undecidability



Keeping track of relationships between topics is hard using memory and cognition...

But when we substitute them with perception, this allows us to understand relationships quickly.

Munzner, T. (2009) 'Visualization', in Shirley, P. and Marschner, S. (eds) Fundamentals of Computer Graphics. Third Edit, pp. 675–707. doi: 10.1.1.154.7671.

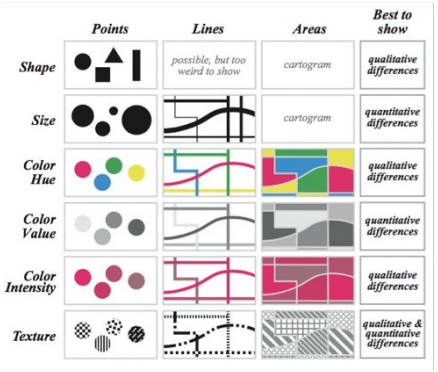
breaking down elements we see in parallel

Visual Encoding

Visual Encoding is the way in which data is mapped to visual structures. Typically, by mapping data items to visual marks and data attributes to visual channels in a principled way.

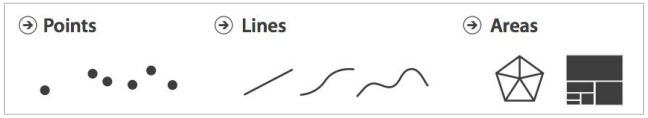
Every visualization can be described as a set of mappings:

- From data items to visual **marks**.
- From data attributes to visual **channels**.



Jacques Bertin, 'Semiologie Graphique', 1967

Marks

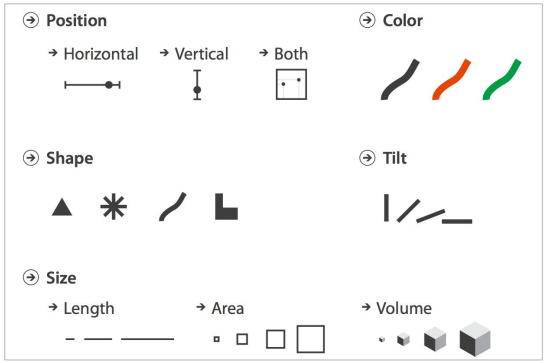


Marks are the basic visual objects/units that represent data objects visually.

Munzner, T. (2009) 'Visualization', in Shirley, P. and Marschner, S. (eds) Fundamentals of Computer Graphics. Third Edit, pp. 675–707. doi: 10.1.1.154.7671.

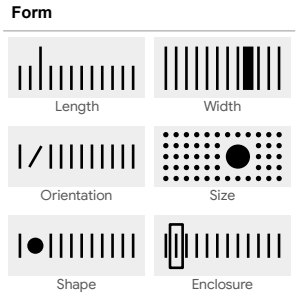
Channels

Visual channels are visual variables we can use to represent characteristics of these objects.



Munzner, T. (2009) 'Visualization', in Shirley, P. and Marschner, S. (eds) Fundamentals of Computer Graphics. Third Edit, pp. 675–707. doi: 10.1.1.154.7671.

From parallel to **pre-attentive processing**



Parallel Processes: when the visual image is broken into elements of color, form, and motion.

Pre-attentive processing (attributes) theory is applied to critical issues of making **one data object distinct from another**. Pre-Attentive Processing decides what will get conscious processing first - A subconscious accumulation of information that is filtered and processed for what is important.

Information Visualization: Perception for Design (Ware, 2013)

Five Forms of Channel Effectiveness

1. **Accuracy**: How accurately values can be estimated.
2. **Popout:** How easy it is to spot some values from the rest.
3. **Discriminability**: How many different values can be perceived.
4. **Separability:** How much interaction there is with multiple encodings.
5. **Grouping:** How good a channel is in conveying groups.

Munzner, T. (2009) 'Visualization', in Shirley, P. and Marschner, S. (eds) Fundamentals of Computer Graphics. Third Edit, pp. 675–707. doi: 10.1.1.154.7671.

accuracy

how accurately values can be estimated.

Graphical Perception

Visual encoding and elementary perceptual tasks.

→ *When we (the designers) visualize data, we encode the quantitative information across visual variables: shapes, color, position, etc. The viewers then have to decode that information.*

http://info.slis.indiana.edu/~katy/S637-S11/cleveland84.pdf

Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods

WILLIAM S. CLEVELAND and ROBERT McGILL*

The subject of graphical methods for data analysis and for data presentation needs a scientific foundation. In this article we take a few steps in the direction of establishing such a foundation. Our approach is based on *graphical perception*—the visual decoding of information encoded on graphs—and it includes both theory and experimentation to test the theory. The theory deals with a small but important piece of the whole process of graphical perception. The first part is an identification of a set of *elementary perceptual tasks* that are carried out when people extract quantitative information from graphs. The second part is an ordering of the tasks on the basis of how accurately people perform them. Elements of the theory are tested by experimentation in which subjects record their judgments of the quantitative information on graphs. The experiments validate these elements but also suggest that the set of elementary tasks should be expanded. The theory provides a guideline for graph construction: Graphs should employ elementary tasks as high in the ordering as possible. This principle is applied to a variety of graphs, including bar charts, divided bar charts, pie charts, and statistical maps with shading. The conclusion is that radical surgery on these popular graphs is needed, and as replacements we offer alternative graphical forms—*dot charts, dot charts with grouping*, and *framed-rectangle charts*.

KEY WORDS: Computer graphics; Psychophysics.

1. INTRODUCTION

Nearly 200 years ago William Playfair (1786) began the serious use of graphs for looking at data. More than 50 years ago a battle raged on the pages of the *Journal of the American Statistical Association* about the relative merits of bar charts and pie charts (Eells 1926; Croxton 1927; Croxton and Stryker 1927; von Huhn 1927). Today graphs are a vital part of statistical data analysis and a vital part of communication in science and technology, business, education, and the mass media.

Still, graph design for data analysis and presentation is largely unscientific. This is why Cox (1978) argued, "There is a major need for a theory of graphical methods" (p. 5), and why Kruskal (1975) stated "in choosing, constructing, and computing graphical methods we have little to go on but intuition, rule of thumb, and a kind of master-to-apprentice passing along of information. . . . there is neither theory nor systematic body of experiment as a guide" (p. 28–29).

There is, of course, much good common sense about how to make a graph. There are many treatises on graph construction (e.g., Schmid and Schmid 1979), but practice has been uncovered (e.g., Tufte 1983), graphic designers certainly have shown us how to make a graph appealing to the eye (e.g., Marcus et al. 1980). statisticians have thought intensely about graphical methods for data analysis (e.g., Tukey 1977; Chambers et al. 1983), and cartographers have devoted great energy to the construction of statistical maps (Bertin 1973; Robinson, Sale, and Morrison 1978). The ANSI manual on time series charts (American National Standards Institute 1979) provides guidelines for making graphs, but the manual admits, "This standard . . . sets forth the best current usage, and offers standards 'by general agreement' rather than 'by scientific test'" (p. iii).

In this article we approach the science of graphs through human graphical perception. Our approach includes both theory and experimentation to test it.

The first part of the theory is a list of elementary perceptual tasks that people perform in extracting quantitative information from graphs. In the second part we hypothesize an ordering of the elementary tasks based on how accurately people perform them. We do not argue that this accuracy of quantitative extraction is the only aspect of a graph for which one might want to develop a theory, but it is an important one.

The theory is testable; we use it to predict the relative performance of competing graphs, and then we run experiments to check the actual performance. The experiments are of two types: In one, once the graphs are drawn, the evidence appears so strong that it is taken prima facie to have established the case. When a strong effect is perceived by the authors' eyes and brains, it is likely that it will appear to most other people as well. In

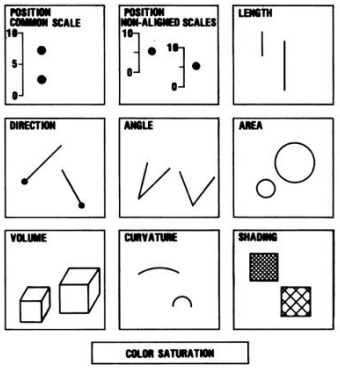
* William S. Cleveland and Robert McGill are statisticians at AT&T Bell Laboratories, Murray Hill, NJ 07974. The authors are indebted to John Chambers, Ram Gnanadesikan, David Krantz, William Kruskal, Colin Mallows, Frederick Mosteller, Henry Pollak, Paul Tukey, and the JASA reviewers for important comments on an earlier version of this article.

© Journal of the American Statistical Association
September 1984, Volume 79, Number 387
Applications Section

Grammar of Graphics

Data Visualizations are made up of visual variables that have rules for which ways they work together.

→ Visualizations in which objects are positioned on a common scale (bar graphs, line graphs) allow for more accurate judgements - Cleveland & McGill (1984)

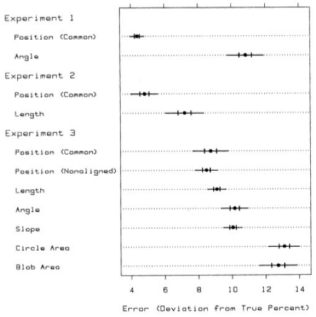


Hierarchy of perceptual tasks, or forms of encoding

Cleveland & McGill 1984 study:

1. Encoded data onto spatial forms / properties
2. Asked participants to estimate sizes
3. Ranked chart types according to accurate judgements.

Cleveland & McGill advocated for the charts based on common scales (top of the hierarchy) such as the dot plot.

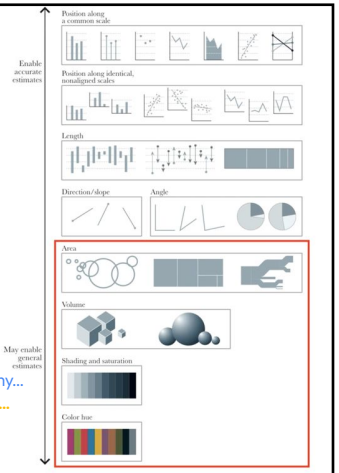


not all charts are created equal

For precise comparisons, communicate with:

1. **Position** along a common scale (scatterplot, line)
2. **Position** on nonaligned scales (e.g. SPLOM)
3. **Length** (ar chart)
4. **Angle & Slope** are a tie (pie chart)
5. **Area** (bubbles)
6. **Volume, density, and color saturation [tie]** (heatmap)
7. **Color hue** (newsmap)

→ **Align your chart-choosing compass** with this general hierarchy...
→ **But, remember there are good times to use the 'poorer' choices...**



Cleveland & McGill, 'Graphical Perception: Theory, experimentation and application to the development of graphical methods'", 1984

Attributes | Dimensionality of Data

Visual encoding: methods for coding data so it can be perceptually integrated or separated

Dataset

	1	2	3	>3
A				
B				
C				


Univariate


Bivariate

Trivariate

Multivariate

Data Attributes

	Categorical Data (Nominal)	Categorical Data (Ordinal)	Quantitative Data (All)
Characteristics	qualitative categories that are not 'orderable' nor computable	Anything that can inherently be ordered, but not computed	anything that can be counted, added together or subtracted
Examples	 Apple, Orange, Banana Japanese, Chinese, Korean	 S / M / L / XL Low / Medium / High Tuesday/Wednesday/Thursday	 Length of Running Route Number of Years experience

Discernibility of Attributes

Most Accurate

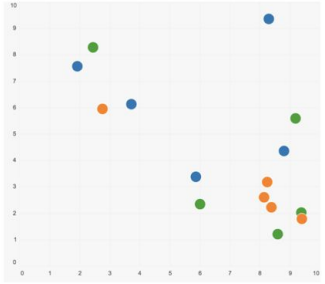
Least Accurate

Categorical (Nominal)	Categorical (Ordinal)	Quantitative (All)
Position	Position	Position
Color Hue	Density	Length
Texture	Color Saturation	Angle
Connection	Color Hue	Slope
Containment	Texture	Area
Density	Connection	Volume
Color Saturation	Containment	Density
Shape	Length	Color Saturation
Length	Angle	Color Hue
Angle	Slope	Texture
Slope	Area	Connection
Area	Volume	Containment
Volume	**Shape**	**Shape**

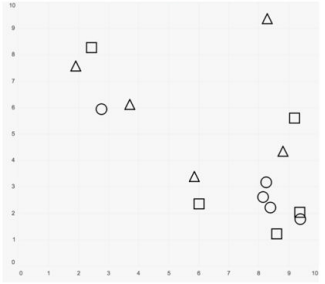
Which is better?

If your task is to discern between **categorical** data:

Color



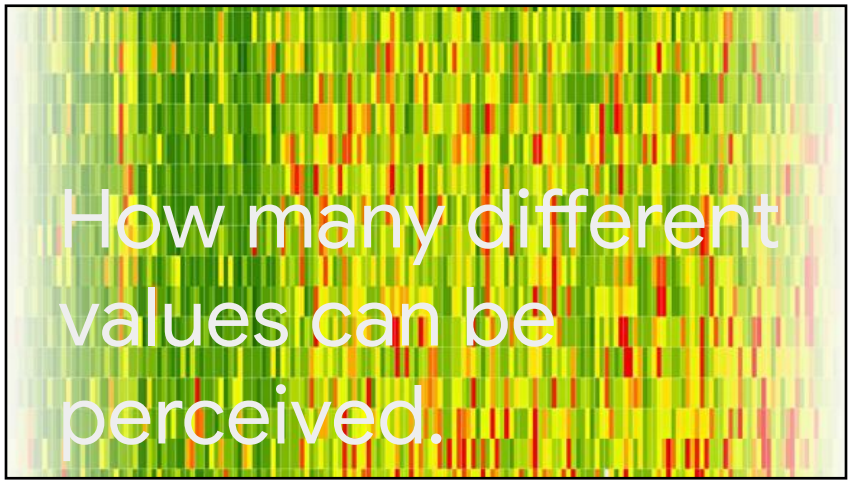
Shape



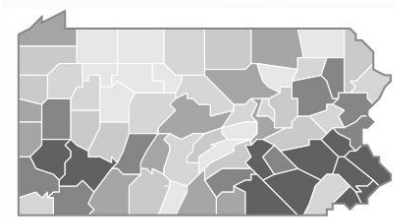
tical Academy

discriminability

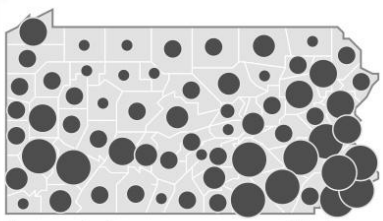
How many different values can be perceived.



Lightness vs. Size



darker means more, lighter less



larger circles mean more, smaller less

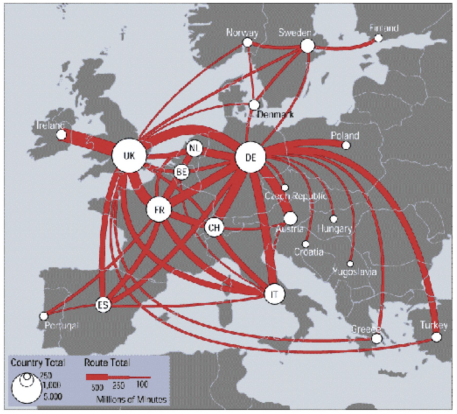
http://makingmaps.net/2007/08/28/perceptual-scaling-of-map-symbols/

Binning

Discriminability must be sufficient for number of attribute levels to show.

How many usable steps?

line width = few bins



[mappa.mundi.net/maps/maps_014/telegeography.html]

Veras, R., & Collins, C. (2019). Discriminability tests for visualization effectiveness and scalability. IEEE transactions on visualization and computer graphics, 26(1), 749-758.

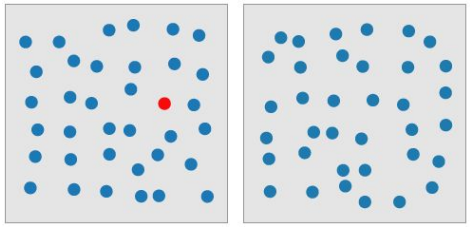
Implications for design:

- Do not overestimate the number of available bins - for most visual channels the number is surprisingly low.
- When you have too many categories find a way to group/bin the data further...
- ...or change channel! For example, you can often trade-off color with space.

popout

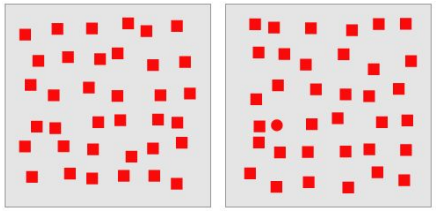
ease to which one can spot certain values from the rest

Popout (Preattentive Processing)

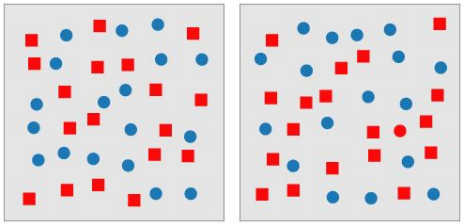


See interactive example here
http://www.csc.ncsu.edu/faculty/healey/PP/

Popout (Preattentive Processing)



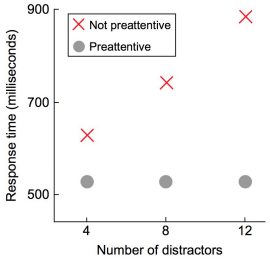
Serial Search



Pre-attentive processing occurs **automatically** and prior to conscious awareness

Rule for Perception

Use strong pre-attentive cues before weak ones where ease of search is critical (Ware 2000)



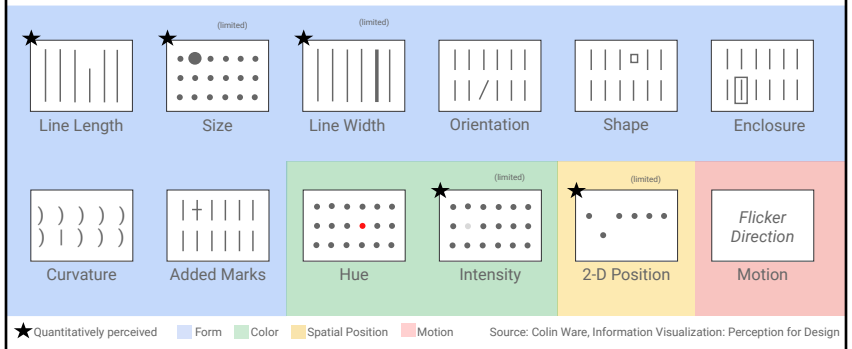
Information Visualization: Perception for Design (Ware, 2013)

What are other preattentive attributes?

snap poll

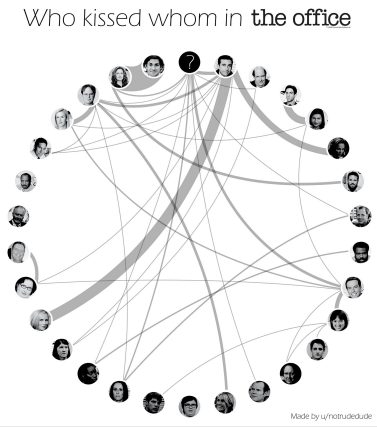
[1 min]

Preattentive attributes

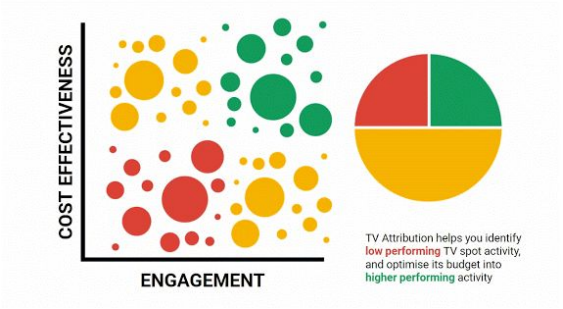


preattentive |
line width

"I never said **she** stole my money"



Preattentive attributes | Position & Motion

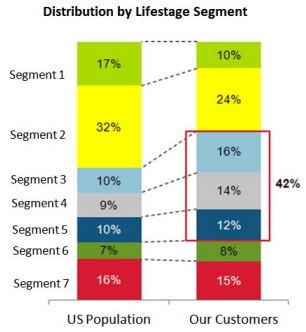


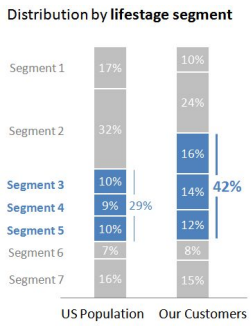
Implications for design

- do not encode data with too many non-spatial visual channels. (Max 3, maybe 4)
- If you want to encode data "holistically" (e.g., data encoded shapes) use integral dimensions, otherwise use separable dimensions.
- To direct attention (e.g., selection) use preattentive features.

practice your skills
[make a visualization better by applying what you've learned]

Exercise | use pre-attentive attributes strategically



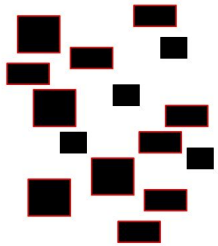


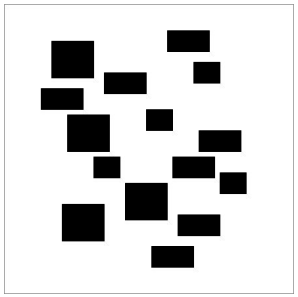
separability

How much interaction between multiple encodings.

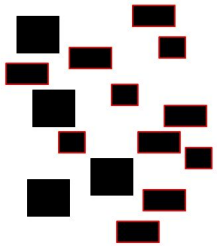
try to group these boxes by same width or height ...

Same Width



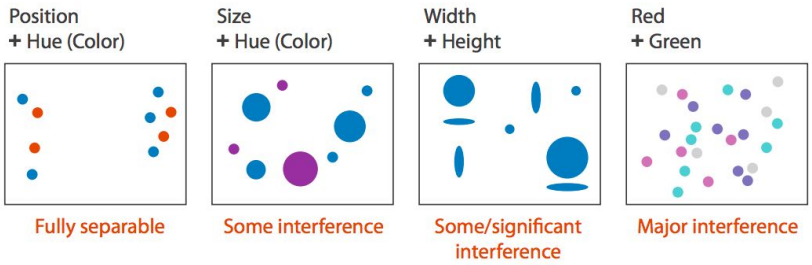


Same Height



It's hard! Because width and height interfere one to another

Separability

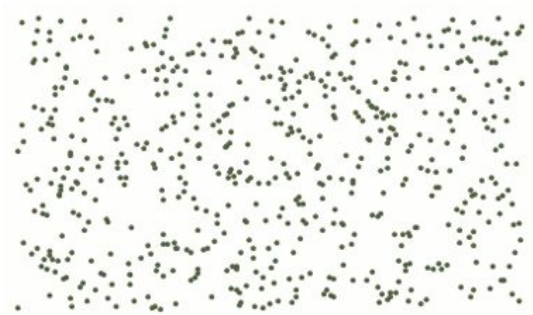


Break time!

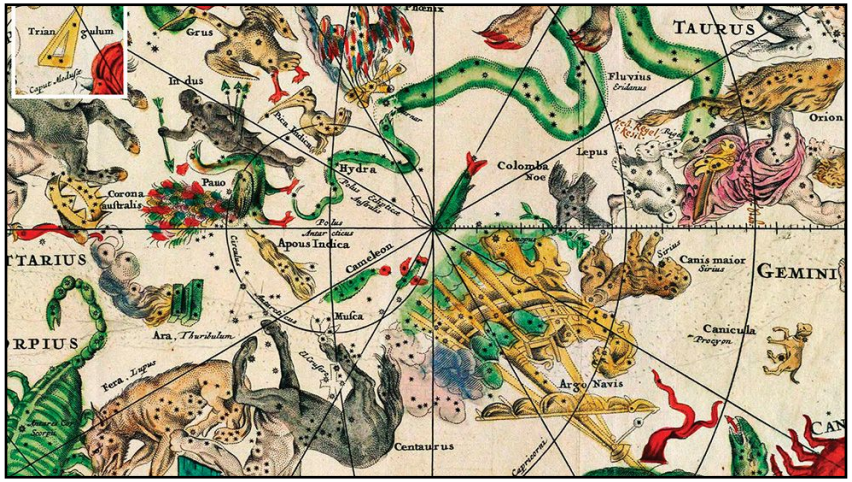
10:00

grouping

when the sum is greater than its parts



Camões, J. (2016). Data at Work: Best practices for creating effective charts and information graphics in Microsoft Excel (Voices That Matter)



we like to group stuff

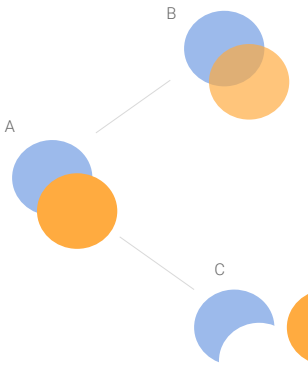
We are constantly grouping objects based on color, shape, direction, proximity, closure/enclosure;

We like shapes to be easy-to-process, simple, close, smooth, and symmetrical.

- → Take advantage of grouping laws to design better charts or dashboards.
- → But be wary of their negative impact: we shouldn't force the reader to see groups that aren't really there; and a simple shape isn't necessarily the right shape

Camões, J. (2016). Data at Work: Best practices for creating effective charts and information graphics in Microsoft Excel (Voices That Matter)

describe the shapes



What is behind the orange circle?

Is there actually anything there?

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prägnanz

We like to make quick sense of things that would otherwise be upsettingly disordered.

The human eye tends to find simplicity and order in complex shapes.

→ This prevents us from being overwhelmed by information overload.

Google

Confidential + Proprietary

aka "Chunking"

Gestalt

how good a channel is in conveying grouped information

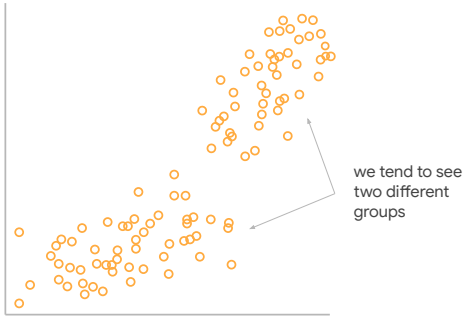
grouping laws

Proximity	Objects near each other
Similarity	Items similar to each other
Segregation	Enclosing objects (in order to override)
Connectivity	Following a smooth path
Continuity	Carrying on a pattern
Closure	Filling in the gaps

Proximity

Proximity

We tend to group data points that seem near each other and assume they share similar characteristics



Camões, J. (2016). Data at Work: Best practices for creating effective charts and information graphics in Microsoft Excel (Voices That Matter)

The Law of Proximity (position) is arguably the most important of all Gestalt Rules, since it tends to supersede all others (shape, color, size, etc)...

...Every person who's interested in **visual communication** should have a deep understanding of this principle."

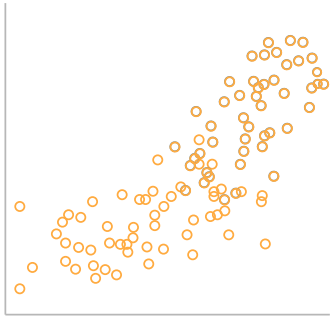
-- Manuel Lima

Similarity

Similarity

Items that are similar tend to then be grouped together.

Similarity can be achieved using basic elements such as shapes, colors, and size



Camões, J. (2016). Data at Work: Best practices for creating effective charts and information graphics in Microsoft Excel (Voices That Matter)

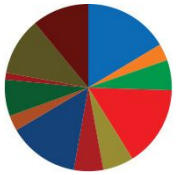
Similarity

Is particularly useful for grouping categories.

random color coding

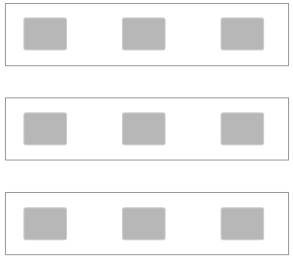
leveraging similarity

we see twelve independent slices



we see two segmented groups, blues and red-yellows, or cool and warm colors.

Segregation

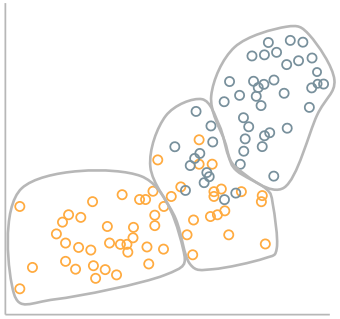


Segregation (aka enclosure, common area)

We see everything inside a drawn boundary as belonging to the same group

It can ever overpower other Gestalt Laws

E.g. Similarity < Enclosure



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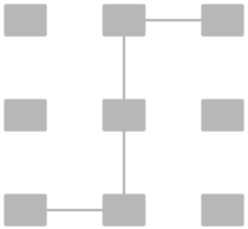
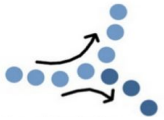
Connectedness

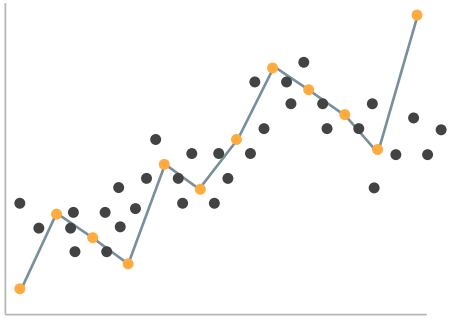


Connectivity

Connected data points are perceived as belonging to the same group



Can help audience avoid seeing non existent linear trends

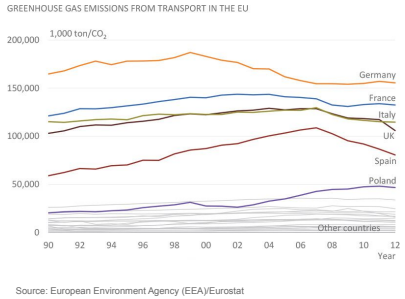


Camões, J. (2016). Data at Work: Best practices for creating effective charts and information graphics in Microsoft Excel (Voices That Matter)

Connectivity

is the basis of the line chart.

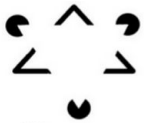
When it's important to not see the individual points but rather the links between them (most relevant in reading the chart).



Source: European Environment Agency (EEA)/Eurostat

Continuity

Continuity



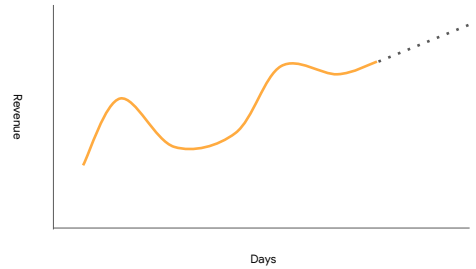
Closure

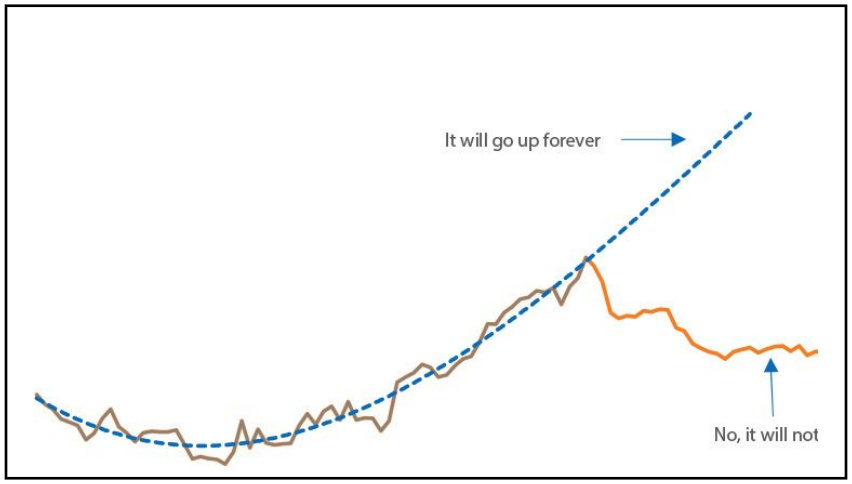
Common Fate

Continuity

We have a visual tendency to create continuous smooth paths

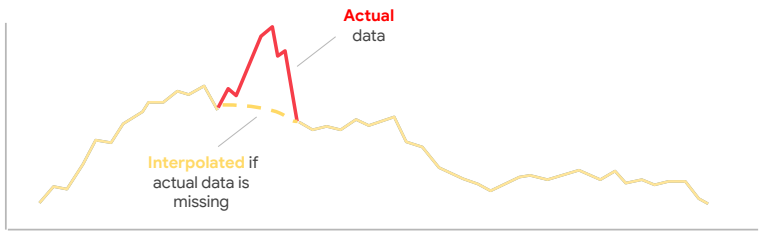
Especially with lines





Closure

Closure (continuity cont.)



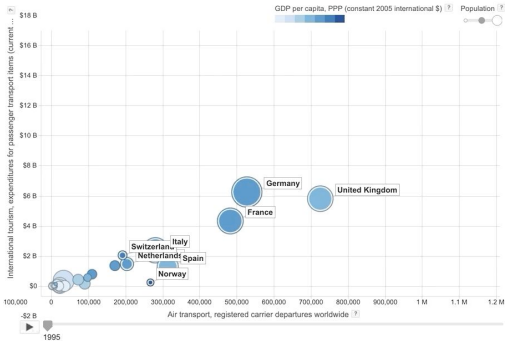
When some data are missing, we tend to make smooth transitions between data points.

Be careful - people might jump to the wrong conclusions.

Camões, J. (2016). Data at Work: Best practices for creating effective charts and information graphics in Microsoft Excel (Voices That Matter)

Common Fate

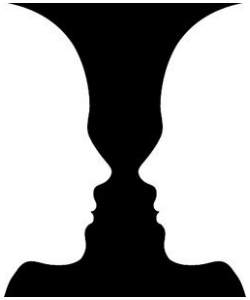
Data points in an animated chart are seen as a group if they move together.



https://covidspreadingrates.org/

Law of Figure/Grounding

We tend to see closed objects, objects seen as a unit, or objects that look smaller as the object that stands out from the amorphous background.



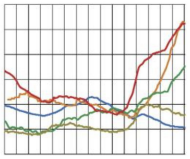
"Rubin's vase"

Figure/Ground

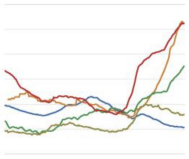
When clearly distinguished, helps focus attention on the relevant objects.

Lines in jail

so noisy that they compete with the data for the leading role.



Lines in the open



remain visible but work quietly

helping the reading and emphasizing the role of the data.

mini exercise applying principles

Gestalt

how good a channel is in conveying grouped information

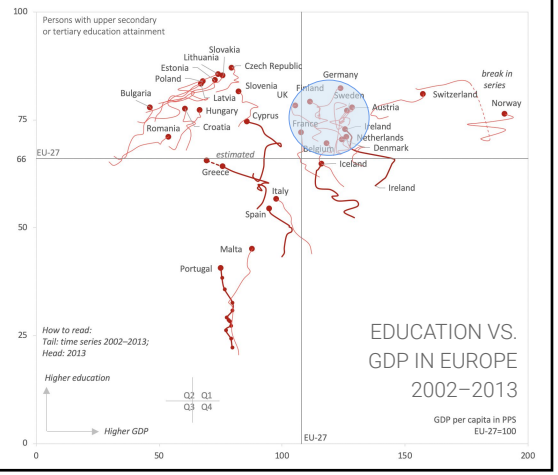
grouping laws

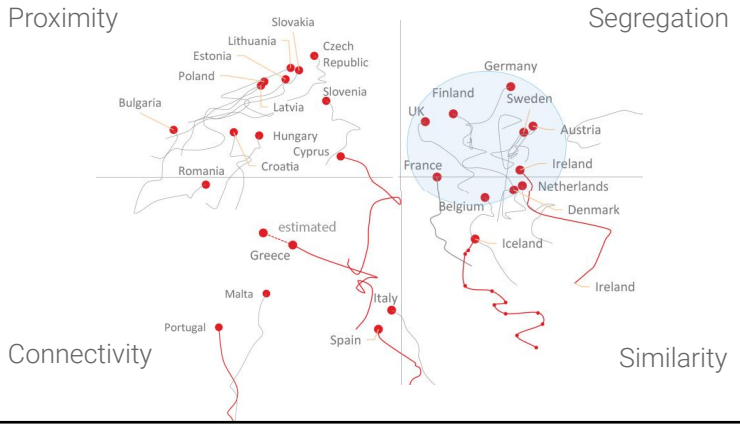
- **Proximity** Objects near each other
- **Similarity** Items similar to each other
- **Segregation** Enclosing objects (in order to override)
- **Connectivity** Following a smooth path
- **Continuity** Filling in the gaps
- **Closure** Carrying on a pattern

Exercise

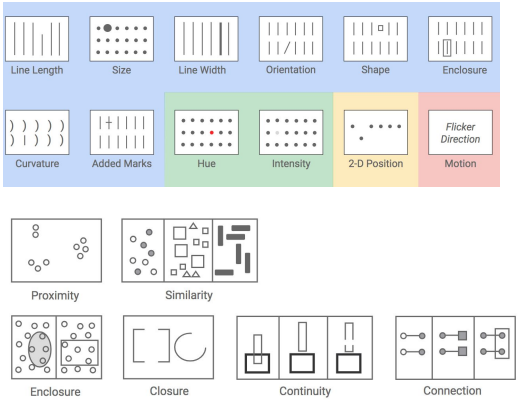
How many gestalt principles are at play in this scatterplot?

- **Proximity** Objects near each other
- **Similarity** Items similar to each other
- **Segregation** Enclosing objects
- **Connectivity** Following a smooth path
- **Continuity** Filling in the gaps
- **Closure** Carrying on a pattern





In sum:



3 simple but effective tools

Encoding Hierarchy
Use those decoded accurately

+

Pre-attentive Attributes
How draw the eye

+

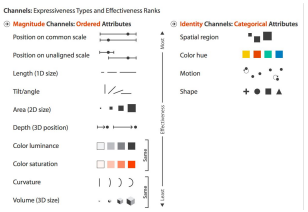
Gestalt Principles
How the brain groups things

=

Powerful experiences
You subtly control the flow and direction of the audiences focus and insights

Principles to Remember
Effectiveness & Expressiveness

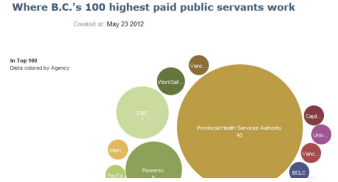
Effectiveness Principle:
The importance of the information should match the *salience* of the channel.



Expressiveness Principle: Visual information should express all and **only** the information in the data.

→ **Ordered data** should not appear as unordered.

→ **Unordered data** should not appear as ordered.

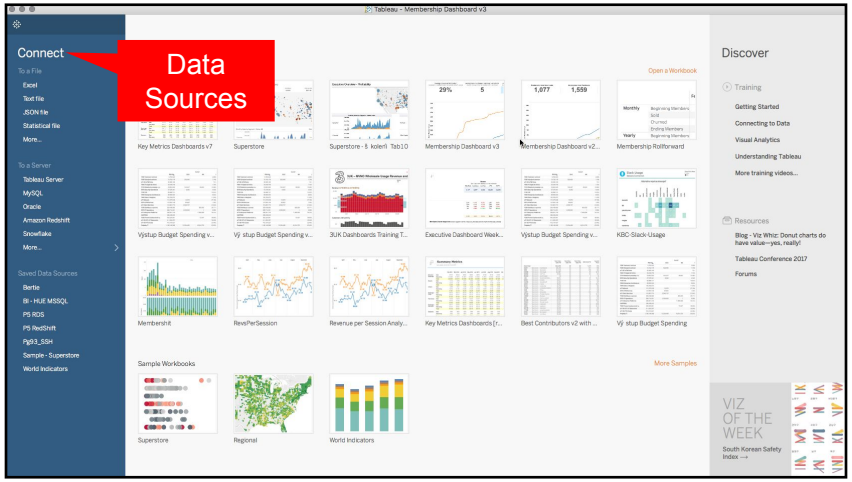


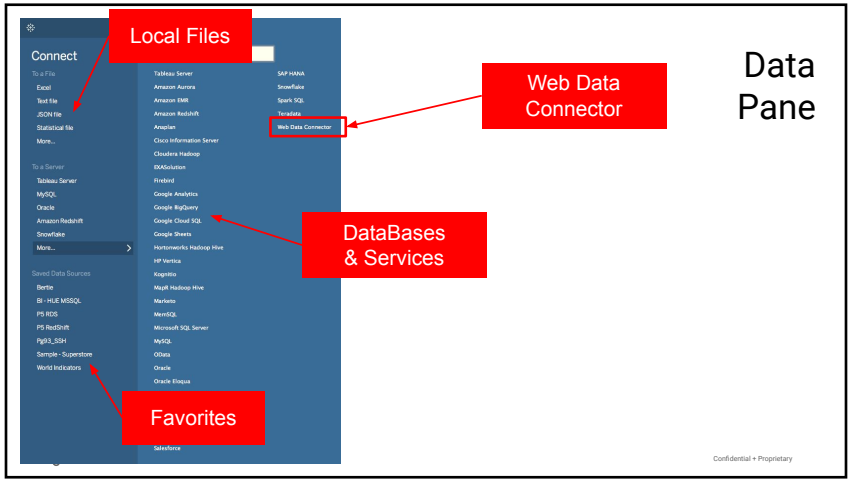
Munzner, T. (2009) 'Visualization', in Shirley, P. and Marschner, S. (eds) Fundamentals of Computer Graphics. Third Edit, pp. 675–707. doi: 10.1.1.154.7671.

Key Takeaways

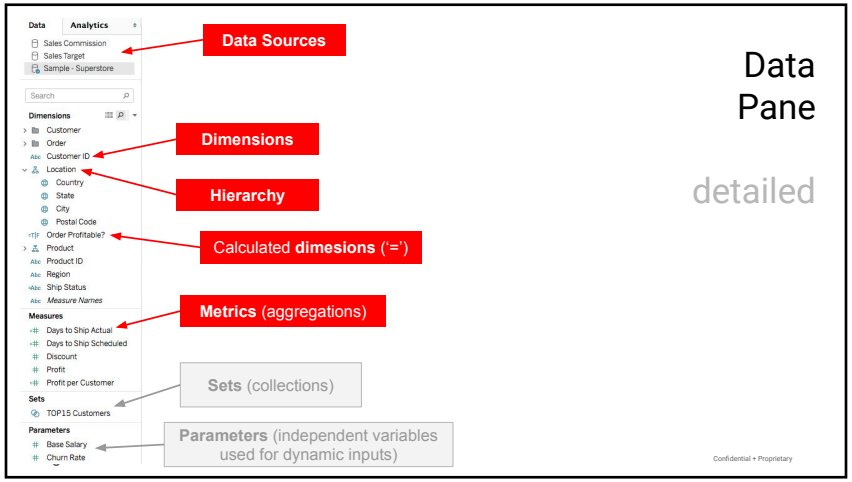
- Understanding how perception and the eye–brain system work affects data visualization in multiple ways, making your displays more effective while saving and optimizing cognitive resources.
- We have a small arc of visual acuity forcing us to constantly move our eyes from one point of fixation to the next (saccadic movement). Effective charts should minimize the need for this movement.
- We read some features of objects, like color, shape, or size, before others, just like we make quick sketches before drawing an image in more detail. This is called pre-attentive processing, and it's one of the reasons why visualization can be so effective at processing data.
- We can take more advantage of pre-attentive processing by making key objects more salient (giving them higher contrast to other objects or to the background), creating a hierarchy of relevance.

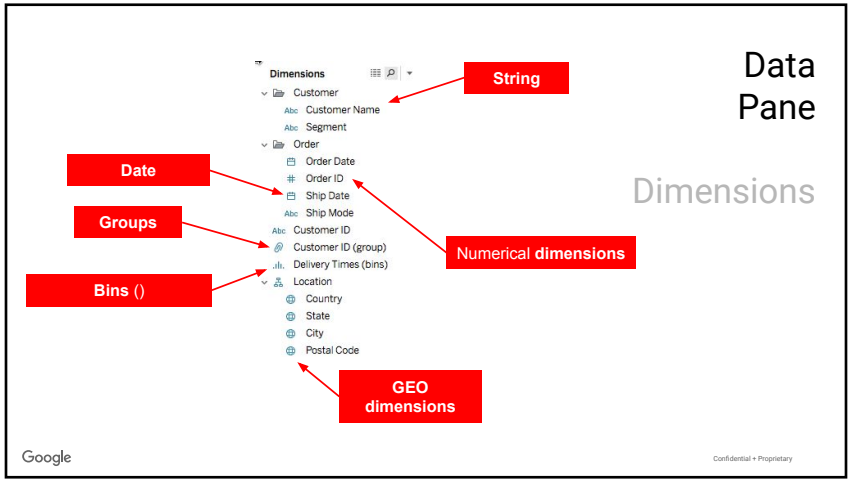
Lab session Exercise + Tableau Intro

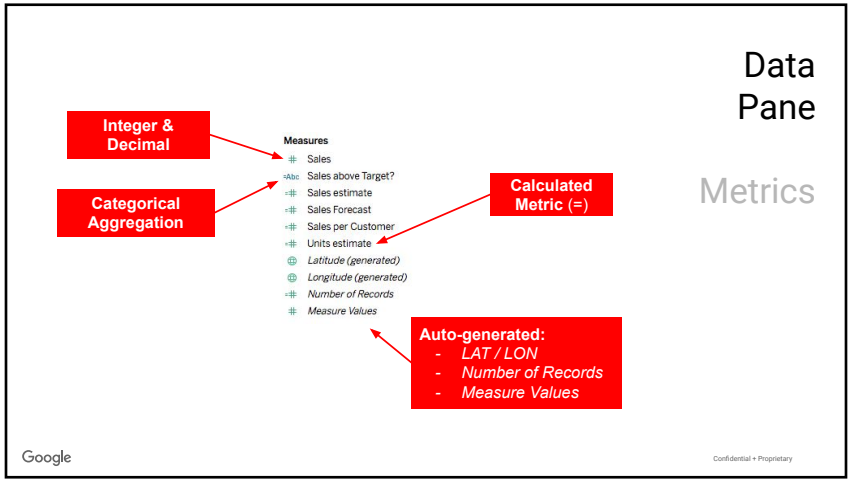


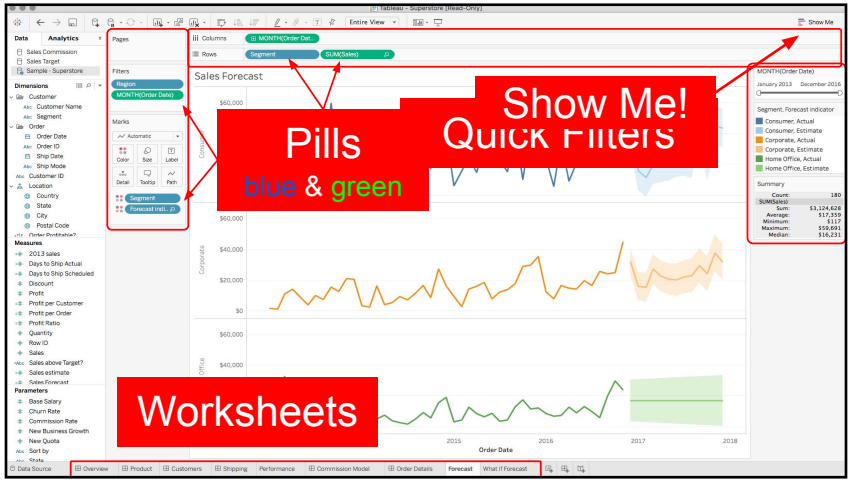



Data Pane


Data Sources
Dimensions
Hierarchy
Calculated dimesions ('=')
Metrics (aggregations)
Sets (collections)
Parameters (independent variables used for dynamic inputs)
Data Pane
detailed
Confidential + Proprietary

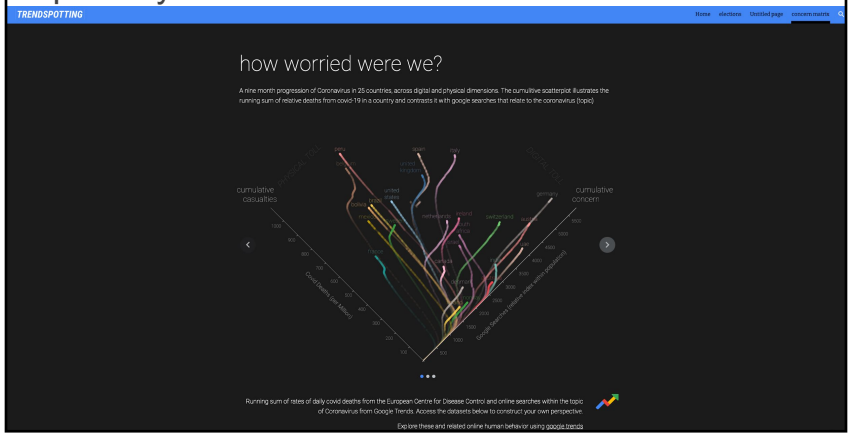

String
Date
Groups
Bins ()
Numerical dimensions
GEO dimensions
Data Pane
Dimensions
Google
Confidential + Proprietary


Integer & Decimal
Categorical Aggregation
Calculated Metric (=)
Auto-generated:
- LAT / LON
- Number of Records
- Measure Values
Data Pane
Metrics
Google
Confidential + Proprietary

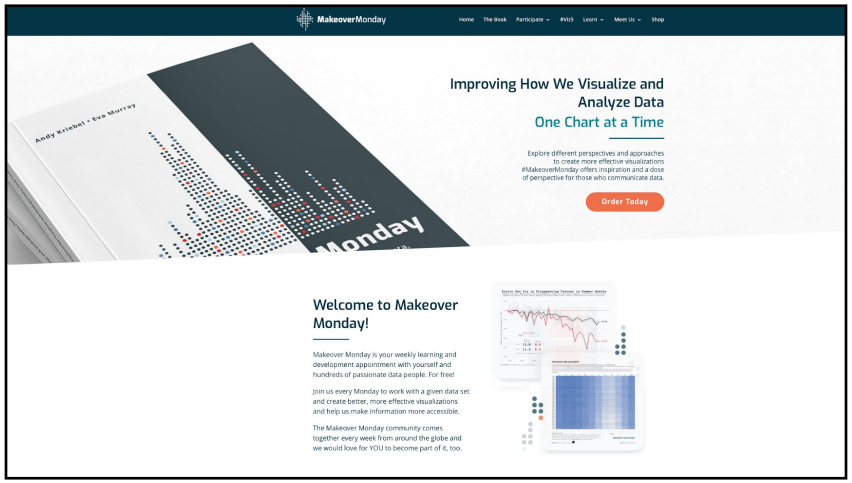


main exercise
tinyurl.com/
corona-concern

https://tinyurl.com/1ifvefce



next time
information
design workshop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