



Data Visualization

Foundational Concepts and Theories

IT 7113 Data Visualization

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<http://idi.kennesaw.edu/it7113/>

<https://www.edocr.com/v/e6ql9njin/jgzheng/data-visual-foundation>

Overview



Data visualization is a cross disciplinary field which has its theoretical roots in human information behavior and cognitive science. This lecture notes summarize some of the major theories and concepts that support our data visualization developments.

Some brief understanding of these concepts can broaden our knowledge of the field. We are not going to dive deeply in these theories but will focus more on their practical implications, which can be used to guide our data visualization designs and dashboard developments.

The foundational theories and concepts covered in this lecture notes:

- Representing data - data visualization process
 - Visual mapping
 - Visual attributes/variables/properties (SCOPeS)
 - Visual perception and cognition
- Presenting data
 - Pre-attentive processing
 - Gestalt principles



Data Visualization Process

- Generally, visualization can assist human (making things easier) in processing information on shaping attention, memorizing, understanding, learning, and communicating.
- Why and how exactly can visualizations help? Let's examine the Data Visualization Process first and see how visualizations impact human perception and cognition (some explanations from cognitive science, psychology, and physiology studies)

The Visualization Process

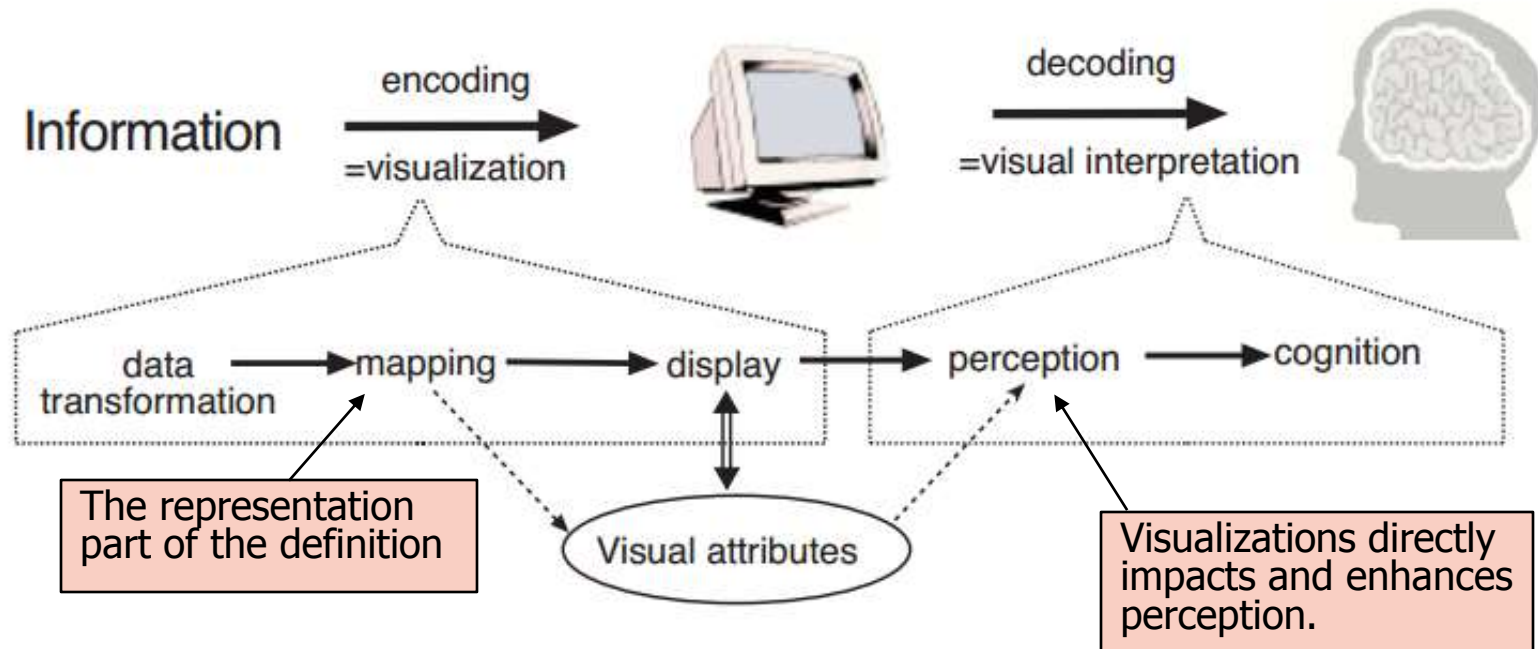


Figure 1: The visualisation process.

Extended reading:

A survey, classification and analysis of perceptual concepts and their application for the effective visualisation of complex information

<http://dl.acm.org/citation.cfm?id=1082104>

Visual Mapping (Encoding)



- Mapping is the process of connecting visuals to data (meanings) – the representation part

Visual mapping = data + visual



The + here indicates some kind of defined associations between the data and visuals

- The mapping (encoding) should be appropriate and fitting to the data and the story to tell

Three Elements of Visual Mapping



- There are three elements to define for a data/information visualization
 - Spatial substrate
 - Graphical (visual) elements
 - Graphical properties (visual variables/properties)

[Key reading] The Three Elements of Visual Mapping for Information Visualization
<https://www.interaction-design.org/literature/article/visual-mapping-the-elements-of-information-visualization>

The Spatial Substrate



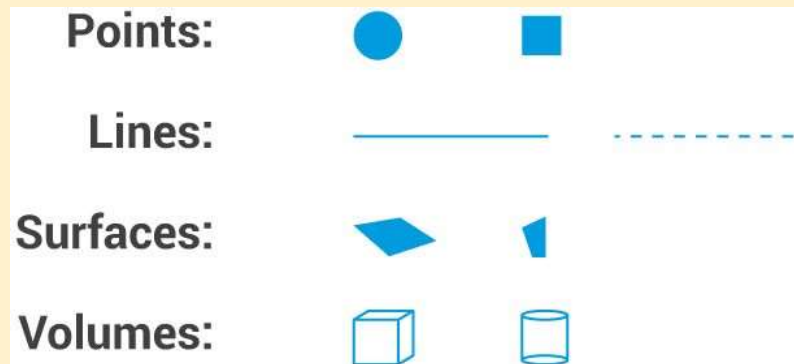
- The spatial substrate is the space in which we're going to create the visualization.
- Most data/information visualization takes place in 2-dimension spaces
 - Or 3D simulation (static or interactive) on a 2D display
- It is possible to create and project real 3-dimensional representations in 3D spaces with the help of new technologies like VR/AR
- Most of time we are designing data visualizations targeting desktop/laptop computer screens typically ranging from 12 inch to 27 inches.
 - More mobile devices are used to view data visualizations
 - Also on larger and even super size screens

Visual Elements



- Visual (or graphical) elements will appear in the spatial substrate. They represent data items or entities.
- Visual elements are the basic building blocks in a visualization (a chart or a diagram).
- The most fundamental abstract elements are:

- Points
- Lines
- Surfaces
- Volumes

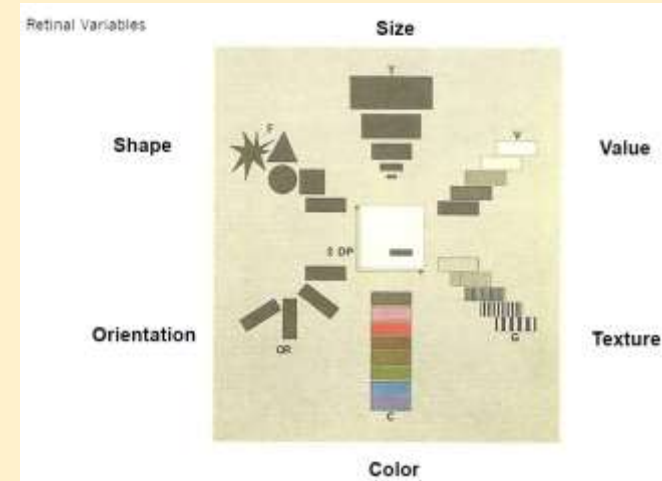


- More complex elements can be built (combined) upon the basic elements. Together they can represent almost anything in a visualization.

Visual Properties: SCOPeS



- Visual property, or attribute, or variable, is the “decoration” applied to visual elements to represent data values
 - http://wiki.gis.com/wiki/index.php/Visual_Variables
 - <https://blogs.ifgi.de/digital-cartography/symbols/visual-variables/>
- A visual property is used to encode different values of a particular dimension of data
 - Multiple visual variables can be used together to represent multiple dimensions of data
- There are six basic visual properties - easier to be remembered as “SCOPeS” – my term.
- Motion can be added on top of these basic visual properties: speed, moving direction, flicker/flash pattern
 - <http://metrocosm.com/global-immigration-map/>



Bertin's Original Visual Variables in his book *The Semiology of Graphics* (Jacques Bertin, 1967)

Size
Color
Orientation
Position
Texture
Shape

Refer to the lecture notes “Visual Encoding with SCOPeS Visual Variables/Properties”

<https://www.edocr.com/v/631d1wpb/jgzheng/SCOPeS>

The Mapping/Encoding



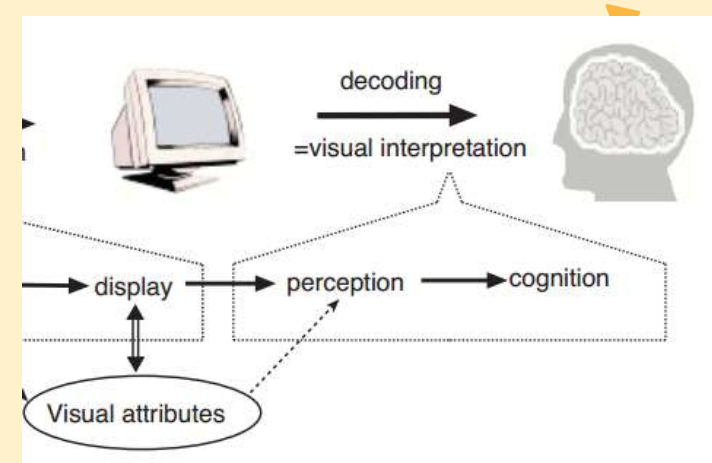
- The value of a data item is mapped to the value of a particular visual property based on the types of data

Continuous quantitative data	Numerical values. Example: sales amount, age, height, etc.
Ordinal data	Discrete data, but with an order; often qualitative (for example month in a calendar year, age groups) but can be quantitative (ranked).
Nominal	The data is a collection of non-numerical and non-ordered data (discrete): categorical. Example: departments in the college

- For example:
 - Sales amount can be mapped to the length of a rectangular bar.
 - Each company (nominal) is mapped to a specific color.
- Some properties can be more effectively represent values of certain data types than others

Visual Interpretation

- This is the interpretation and comprehension of the visualization that happens in human brain
 - Physiological: perception, spatial vision, working memory
 - Psychological: cognition, thinking, deduction, logic, experience, culture, knowledge
- It goes through two phases
 - Perception (perceptual processing): instinct, immediate
 - Cognition (cognitive processing): slower, more deliberate



Extended learning: see a video tutorial for some details: <https://www.coursera.org/lecture/dataviz-design/cognitive-vs-perceptual-design-distinction-gulX3>

Perception

A picture is worth
1000 words (clicks)

- Perception is the organization, identification, and interpretation of sensory information in order to represent and understand the presented information, or the environment.
 - <https://en.wikipedia.org/wiki/Perception>
- Perception happens in the brain, through three types of memories
- Visualizations directly, and can greatly, enhance the perception and response speeds
 - Therefore, it shapes people's attention

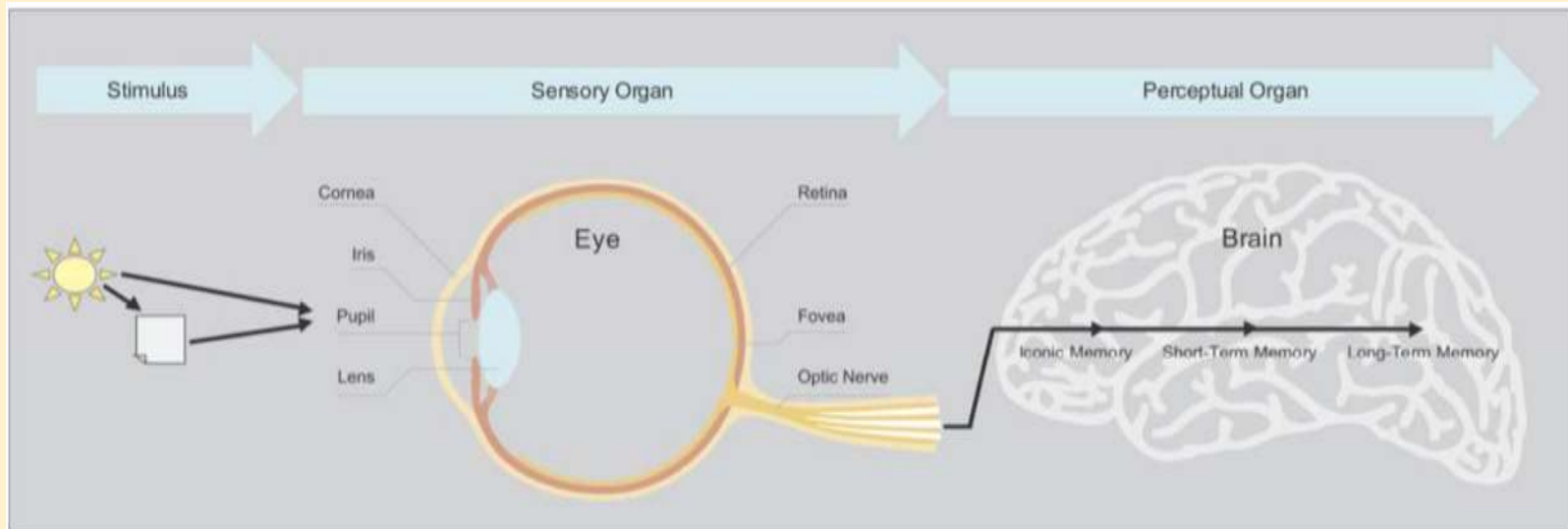


Image from: https://www.perceptualedge.com/articles/ie/visual_perception.pdf

Sensory Memory



- Visual sensory memory is often known as iconic memory.
- Sensory visual memories are the raw information that the brain receives (via the optic nerve) from the eye. We store and process sensory memories automatically – that is without any conscious effort to do so.
- Sensory memories are stored for tiny time periods. They are typically retained for less than 500 milliseconds.
- The processing of sensory information is called preattentive processing (e.g. it happens prior to our paying attention to the information). It is a limited form of processing which does not attempt to make sense of the whole image received but rather to a small set of features of the image.
- Reference
 - <https://www.interaction-design.org/literature/article/the-properties-of-human-memory-and-their-importance-for-information-visualization>

Extended reading about visual perception:

<http://www.users.totalise.co.uk/~kbroom/Lectures/3gs.htm>

Cognition



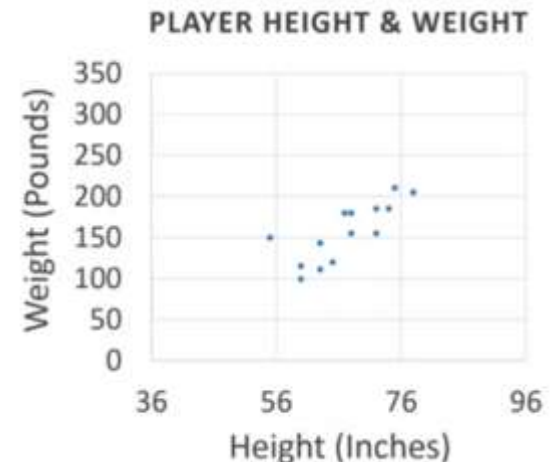
- Cognition is the comprehension of perceived information and relate to long term experience and knowledge for understanding
- Needs long term memory support, with existing knowledge and experience, and often cultures (for example, meaning of colors like red and green).
- Eventually, perception impacts cognition and supports higher-level behaviors based on cognition (such as making decisions)
- For example:

System 1 is the perception system, where visualized objects and patterns are noticed.

System 2 is the cognition system, where a decision is needed based on knowledge and experience.

System 1:
Notice dot near
cluster of other dots

System 2:
Hmmm...
is that dot an outlier
worthy of investigation?





Presenting Data

- The way to present data also has practical influences on people's perception.
- A well-presented data visualization can greatly help the perception and ease short term memory load.
- Two theories or principles help explain in more details on the perception and their impact on cognition:
 - 1. Pre-attentive processing**
 - 2. Gestalt principles**

Pre-Attentive Processing



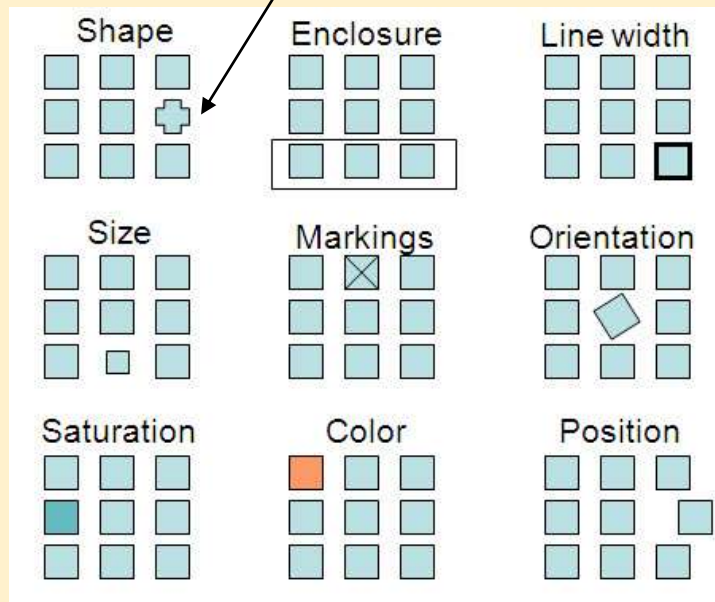
- Any visual processing of that item prior to the act of selection can be called “preattentive”.
 - Wolfe et. al. 2010 <https://www.researchgate.net/publication/245623481>
- Preattentive processing happens even before perception (or at least the very early part of perception), e.g., it happens prior to our paying attention to the information.
- It is a limited form of processing (of sensory memory) which does not attempt to make sense of the whole image received but rather to a small set of features of the image.
- Preattentive processing can help to rapidly draw the focus of attention to a target with a unique visual feature (i.e., little or no searching is required in the preattentive case).
 - Healey, 2005, <https://www.csc2.ncsu.edu/faculty/healey/PP/index.html>
- The technique is commonly used in many fields involving visual designs, including:
 - UX/UI and interaction design
 - Data/information visualizations (charts, maps, dashboards)
 - Web design, product design, shelf display, painting, etc.

Applying Preattentive Processing in Visual Attention (Salience)



- Basic technique: using contrast to differentiate the part that needs to draw attention
 - <http://kenhirakawa.com/significance-of-contrast/>
 - <https://www.coursera.org/lecture/dataviz-design/strategic-use-of-contrast-sDV6C>
- SCOPeS visual properties are commonly used in pre-attentive visual design

Some examples by using various distinctive visual properties



Extended reading:

“What shall we do with the preattentive processing stage”

<https://www.researchgate.net/publication/245623481>

More examples in “Perception in Visualization” by Christopher Healey

<https://www.csc2.ncsu.edu/faculty/healey/PP/index.html>

Preattentive Example: Color

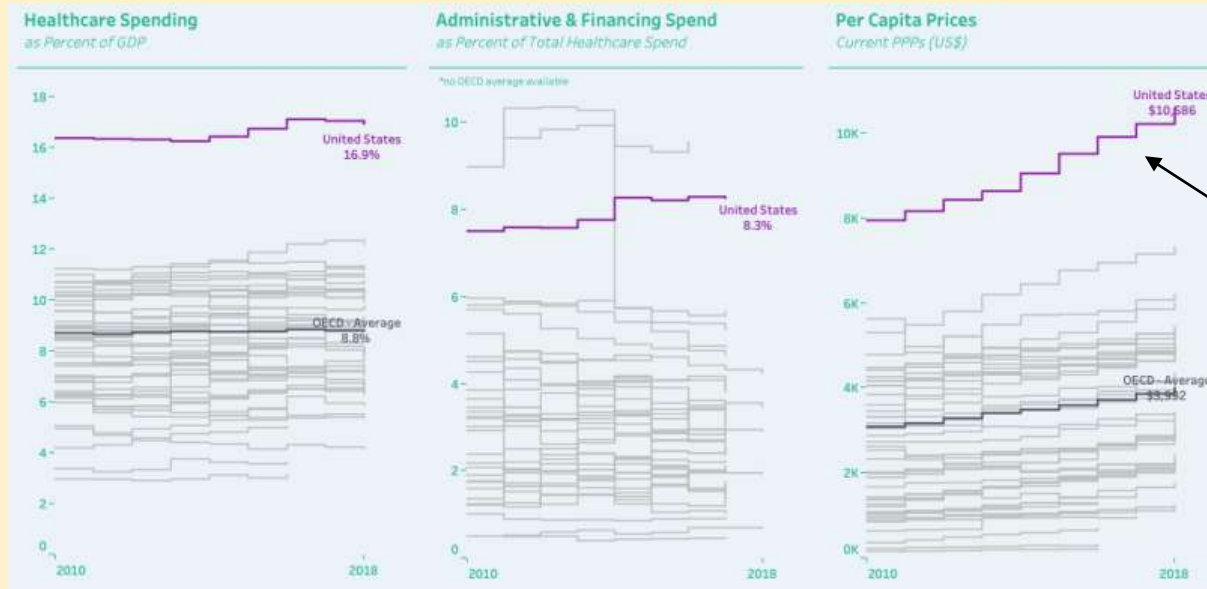


- Using bright colors for attention

Brighter green/red indicates higher percentages.



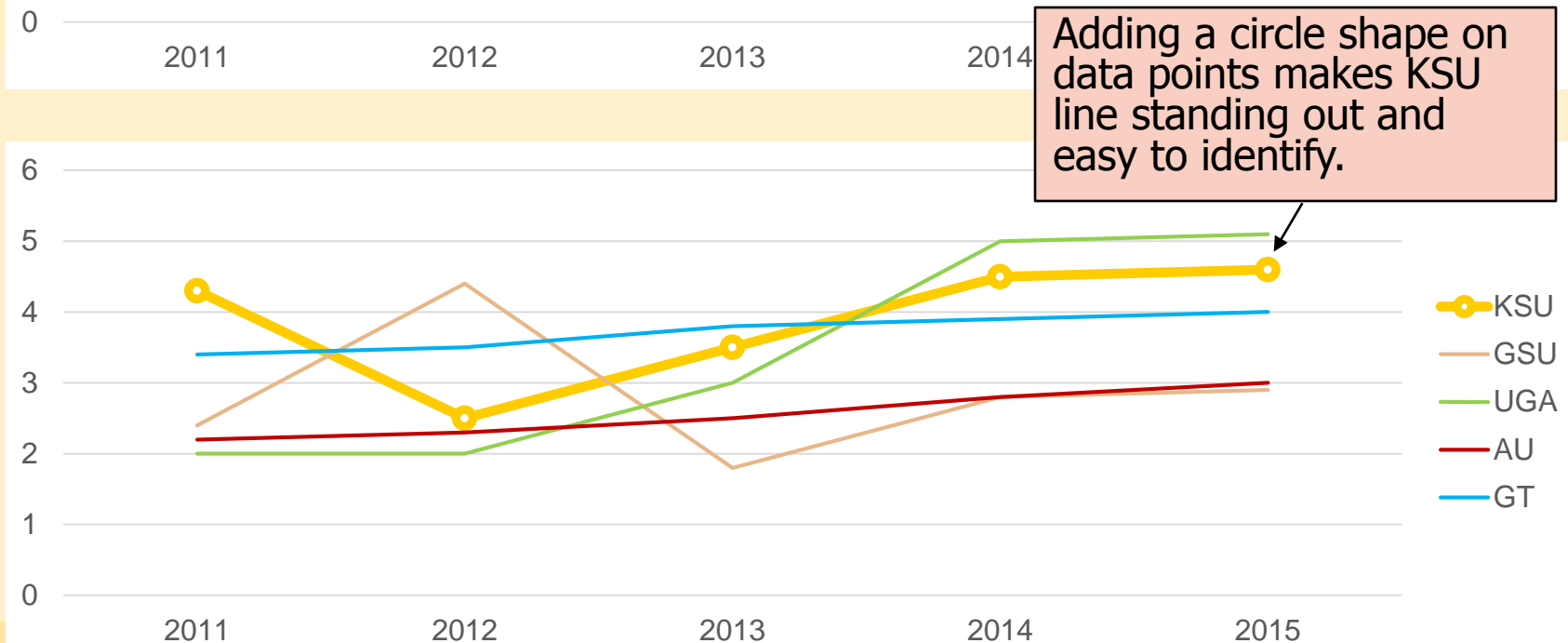
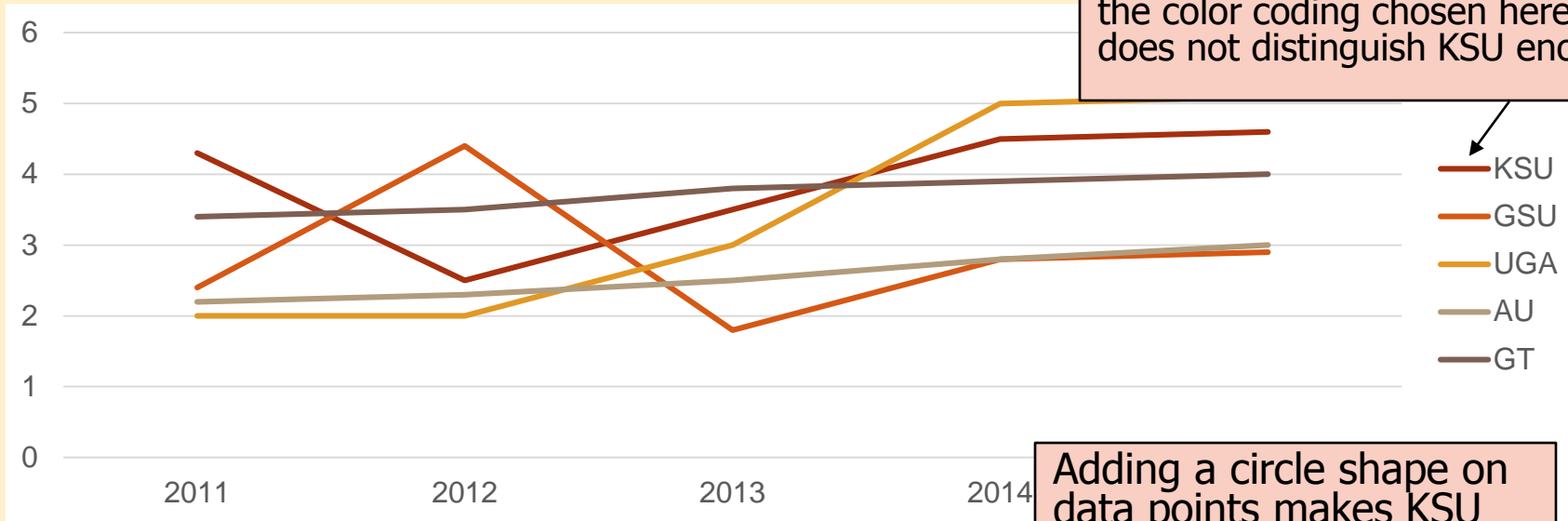
<https://finviz.com/map.ashx>



Brighter color highlights the key country and measure

<https://vizzendata.com/2019/12/18/using-preattentive-attributes-color-in-data-viz/>

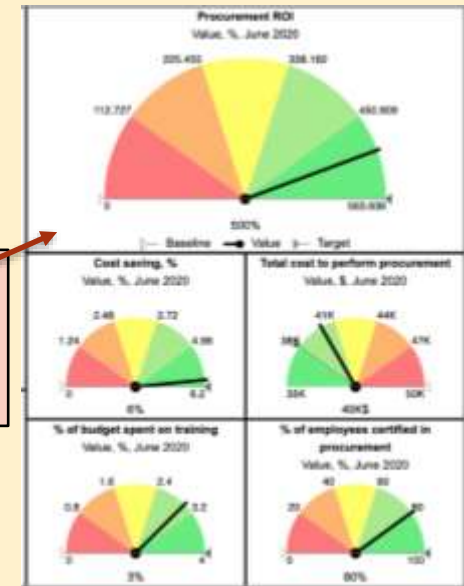
Preattentive Example: Shape



Preattentive Example: Size and Position



Center column (or top row) and big size chart indicates the most important metric.



<https://www.slideteam.net/maintenance-kpi-dashboard-showing-order-progress-and-backlog.html>

Good Resources on Preattentive



- Quick reference
 - https://infovis-wiki.net/wiki/Preattentive_processing
- Articles
 - “What shall we do with the preattentive processing stage”
<https://www.researchgate.net/publication/245623481>
 - “Perception in Visualization” by Christopher Healey
<https://www.csc2.ncsu.edu/faculty/healey/PP/index.html>
- Videos from UCD online course
 - <https://www.coursera.org/lecture/dataviz-design/pre-attentive-attributes-of-visualizations-GkLfQ>
 - <https://www.coursera.org/lecture/dataviz-design/color-as-a-pre-attentive-attribute-cdYql>
 - <https://www.coursera.org/lecture/dataviz-design/strategic-use-of-contrast-sDV6C>

Gestalt Principles of Perception



- Gestalt principles describes a set of ways how human perceives images and how visual information are identified and related from images.
 - These principles have profound implication on many fields involving visual designs, including:
 - UX/UI and interaction design
 - Data/information visualizations (charts, maps, dashboards)
 - Web design
 - Graphical design
 - Painting/Photography
 - Shelf display, catalog, form, etc.
 - See how it is applied in general visual designs
- <https://www.webfx.com/blog/web-design/gestalt-principles-applied-in-design/>

Basic Gestalt Principles



Proximity	Objects that are close together are perceived as a group.	
Similarity	Objects that share similar attributes (e.g., color or shape) are perceived as a group.	
Enclosure	Objects that appear to have a boundary around them (e.g., formed by a line or area of common color) are perceived as a group.	
Closure	Open structures are perceived as closed, complete, and regular whenever there is a way that they can be reasonably interpreted as such.	
Continuity	Objects that are aligned together or appear to be a continuation of one another are perceived as a group.	
Connection	Objects that are connected (e.g., by a line) are perceived as a group.	

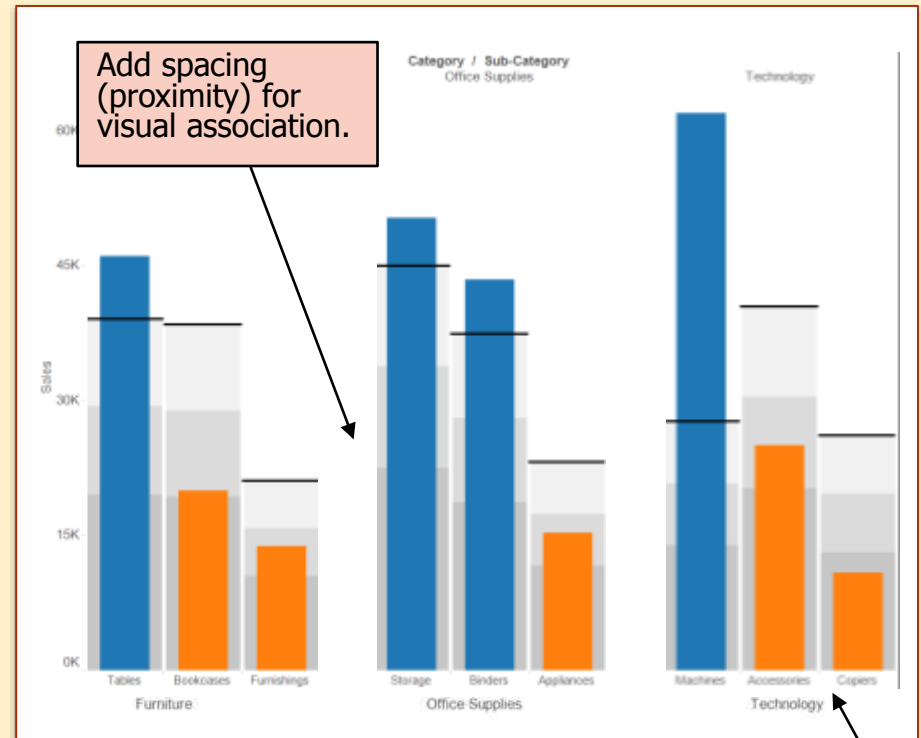
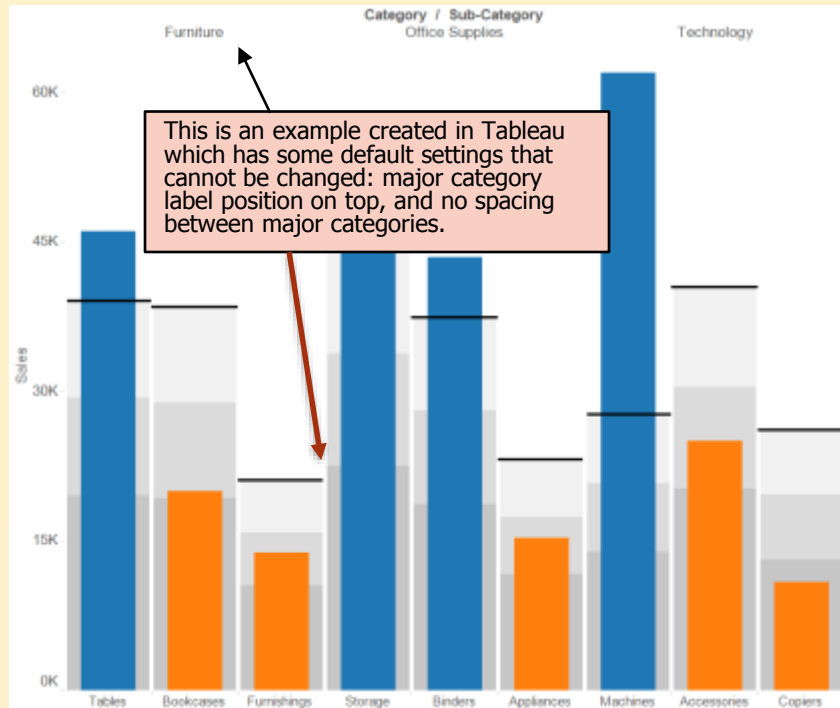
Table from:

<https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/data-visualization-for-human-perception>

More readings:

<https://www.interaction-design.org/literature/topics/gestalt-principles> (with a video)

Applying Gestalt: Proximity



Put category name closer to the subcategory names.

Note: Tableau does not have an inherent setting to define spacing between the panes and category label position in a view. We must hack it.

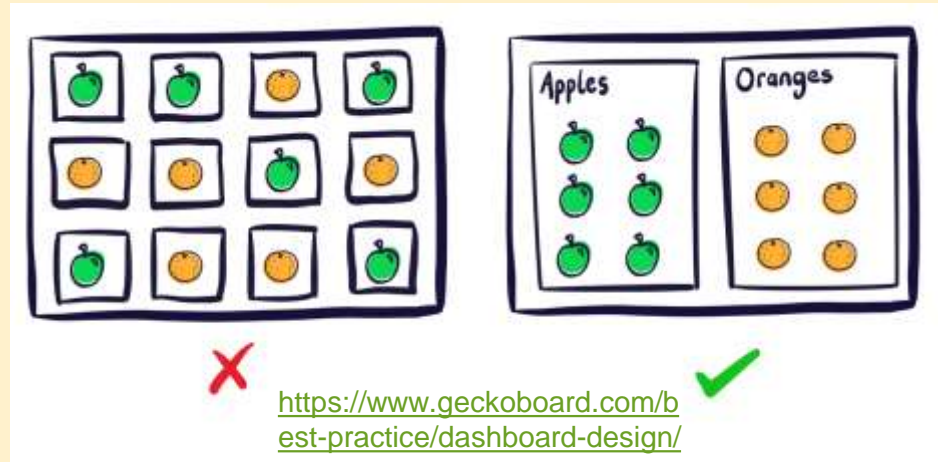
- <https://senturus.com/blog/tableau-tip-add-space-between-groups-of-bars-in-charts/>
- <https://community.tableau.com/thread/140692>

Applying Gestalt: Enclosure

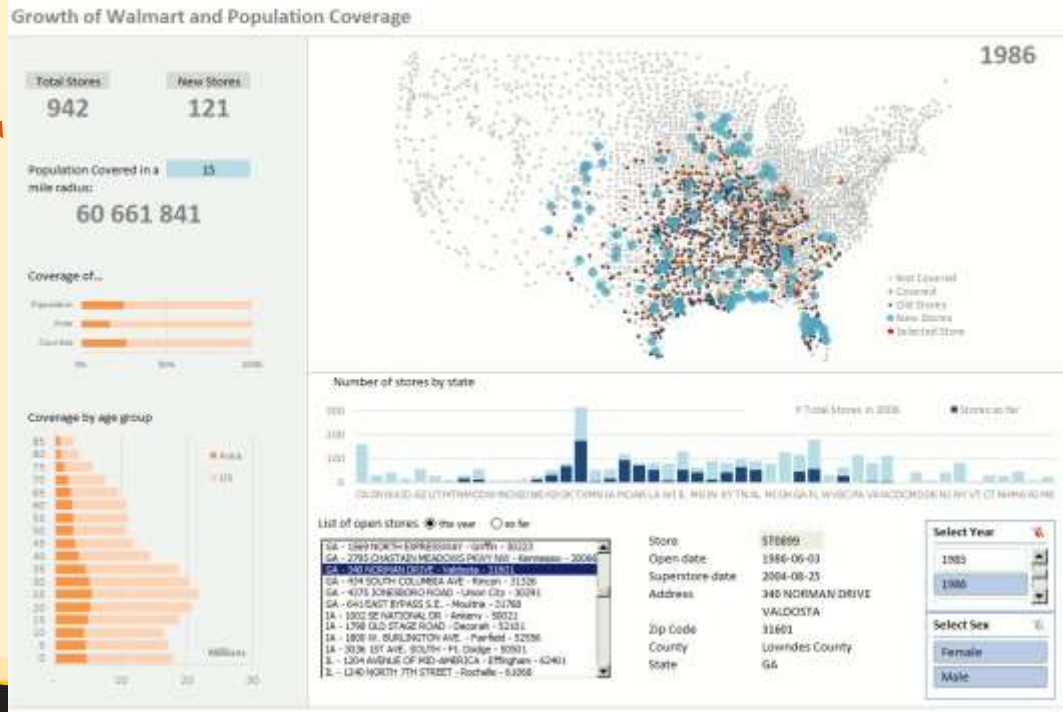


- Enclosure for grouping, applied to dashboards

Shaded side panel for summary information, which separates the details on the right



<https://www.geckoboard.com/best-practice/dashboard-design/>

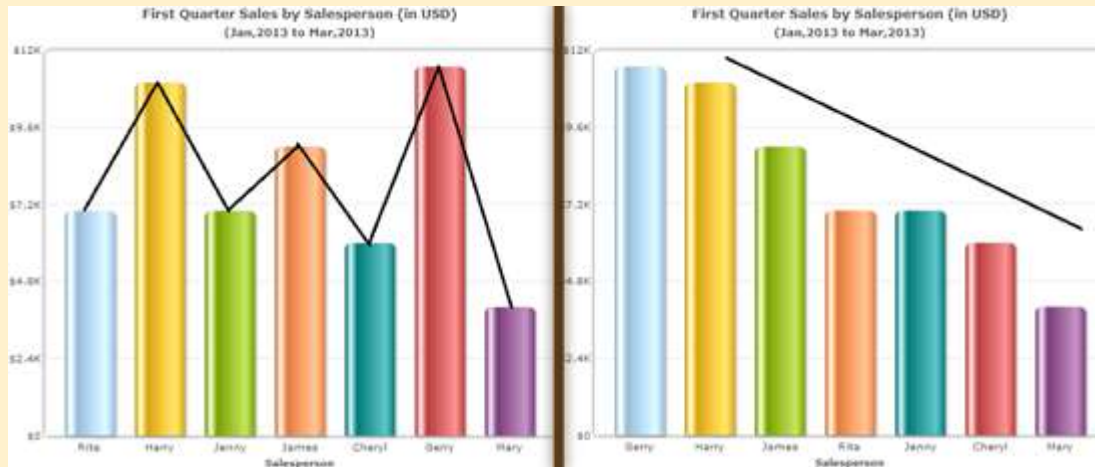


<http://www.excelcharts.com/blog/excel-dashboard-catchment-area/>

Applying Gestalt: Continuity



- The law of continuity states that our eyes instinctively group things that are aligned with each other. Let's go back to our "Sales by Salesperson" chart example. In the left chart below, there are abrupt directional changes.
- In the chart on the right below, the eyes follow a continuous path; it makes the whole chart more readable because of the continuous downward direction.



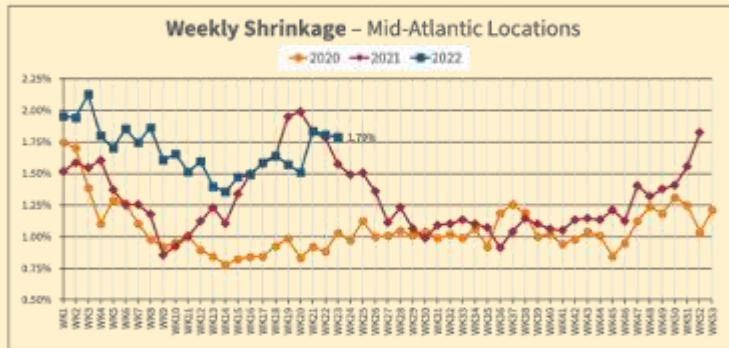
See more examples from
"How to Make Data
Visualization Better with
Gestalt Laws":
<https://www.webfx.com/blog/web-design/data-visualization-gestalt-laws/>

Case Study



- a multi-level makeover: simplifying a shrinkage report — storytelling with data

BEFORE



AFTER

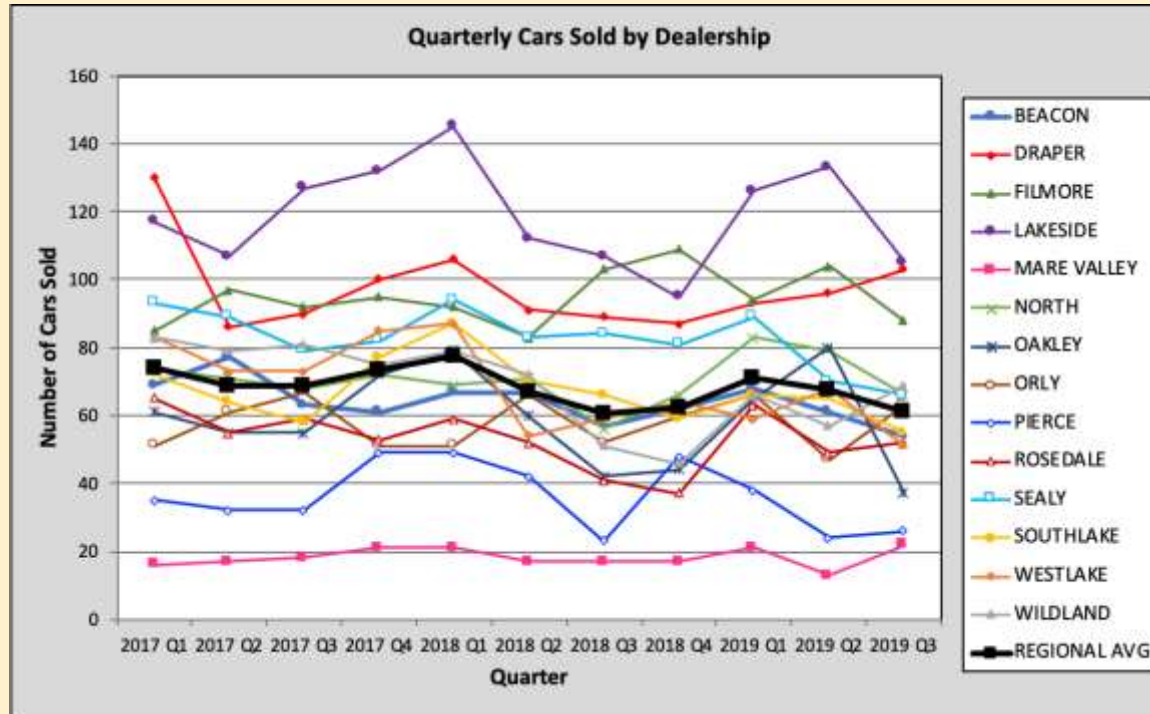
Weekly shrinkage across Mid-Atlantic locations is **back above our 2021 rate** for the first time in six weeks, and is **more than 0.5% worse than our goal for 2022**.

Mid-Atlantic | Shrinkage from all causes

2020 | 2021 | 2022



Let's Practice



- A better way to design this chart?

- <https://community.storytellingwithdata.com/exercises/one-little-changeand-a-redesign>

See more in “data vis cases and exercises 2”.

Good Resources on Gestalt



- Introduction

- <https://www.interaction-design.org/literature/topics/gestalt-principles> (with videos)
 - Part 1 <https://www.interaction-design.org/literature/article/the-law-of-similarity-gestalt-principles-1>
 - Part 2 <https://www.interaction-design.org/literature/article/laws-of-proximity-uniform-connectedness-and-continuation-gestalt-principles-2>
 - Part 3 <https://www.interaction-design.org/literature/article/the-laws-of-figure-ground-praeganz-closure-and-common-fate-gestalt-principles-3>
- <http://excelcharts.com/data-visualization-excel-users/gestalt-laws/>
- http://www.scholarpedia.org/article/Gestalt_principles
- <http://elijahmeeks.com/#essays>
- <https://www.smashingmagazine.com/2014/03/design-principles-visual-perception-and-the-principles-of-gestalt/>
- https://en.wikipedia.org/wiki/Principles_of_grouping
- <https://www.webfx.com/blog/web-design/gestalt-principles-applied-in-design/>

- Best practices

- <https://vizzendata.com/2020/07/06/utilizing-gestalt-principles-to-improve-your-data-visualization-design/>
- How to Make Data Visualization Better with Gestalt Laws: <https://www.webfx.com/blog/web-design/data-visualization-gestalt-laws/>

- Videos

- <https://www.coursera.org/lecture/dataviz-design/principles-of-visual-perception-TW6DT>
- <https://www.youtube.com/watch?v=ZWucNQawpWY>
- <https://www.youtube.com/watch?v=20N53khArXA>
- <https://www.youtube.com/watch?v=RWJSC1HU32c>
- <https://www.youtube.com/watch?v=dk7cXdjX2Ys>

Key Readings and Resources



- Visualization process
 - Visual Mapping – The Elements of Information Visualization: <https://www.interaction-design.org/literature/article/visual-mapping-the-elements-of-information-visualization>
 - The Properties of Human Memory and Their Importance for Information Visualization: <https://www.interaction-design.org/literature/article/the-properties-of-human-memory-and-their-importance-for-information-visualization>
- Visual Variables
 - <https://blogs.ifgi.de/digital-cartography/symbols/visual-variables/>
 - Visual Encoding with SCOPeS Visual Variables/Properties <https://www.edocr.com/v/631d1wpb/jgzheng/SCOPeS>
- Gestalt principles:
 - The Gestalt Principles <https://www.interaction-design.org/literature/topics/gestalt-principles> (with video)
 - How to Make Data Visualization Better with Gestalt Laws <https://www.webfx.com/blog/web-design/data-visualization-gestalt-laws/>

Additional Good Resources



- Perception
 - Tapping the Power of Visual Perception by Stephen Few
https://www.perceptualedge.com/articles/ie/visual_perception.pdf
 - Perception in Visualization: <https://www.csc2.ncsu.edu/faculty/healey/PP/>
- Data Visualisation - A Game of Decisions with Andy Kirk
<https://www.youtube.com/watch?v=GVkXbQOzKNs>
- Other relevant visual processing concepts and theories
 - https://en.wikipedia.org/wiki/Visual_thinking
 - https://en.wikipedia.org/wiki/Structural_information_theory
 - <http://fellinlovewithdata.com/guides/7-classic-foundational-vis-papers>
 - <http://www.users.totalise.co.uk/~kbroom/Lectures/3gs.htm>
 - Card, Mackinlay, and Sheniederman, “Readings in Information Visualization: Using Vision to Think”
https://www.researchgate.net/publication/220691172_Readings_in_Information_Visualization_Using_Vision_To_Think
- Video lessons on concepts (from Coursera by University of California, Davis)
 - Week 1
 - <https://www.coursera.org/lecture/dataviz-design/the-human-brain-and-data-visualization-X9IVx>
 - <https://www.coursera.org/lecture/dataviz-design/cognitive-vs-perceptual-design-distinction-gulX3>
 - Week 2
 - <https://www.coursera.org/lecture/dataviz-design/principles-of-visual-perception-TW6DT>
 - <https://www.coursera.org/lecture/dataviz-design/strategic-use-of-contrast-sDV6C>
 - <https://www.coursera.org/lecture/dataviz-design/pre-attentive-attributes-of-visualizations-GkLfQ>
 - <https://www.coursera.org/lecture/dataviz-design/color-as-a-pre-attentive-attribute-cdYqI>