

# Data Visualization

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VISUAL PERCEPTION

Tea Tušar, Data Science and Scientific Computing, Information retrieval and data visualization

## Outline

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Motivation

Attention and memory

Visual encoding

- Channel accuracy
- Channel discriminability
- Channel salience (pop-out)
- Channel separability
- Grouping

Visual order

# Motivation

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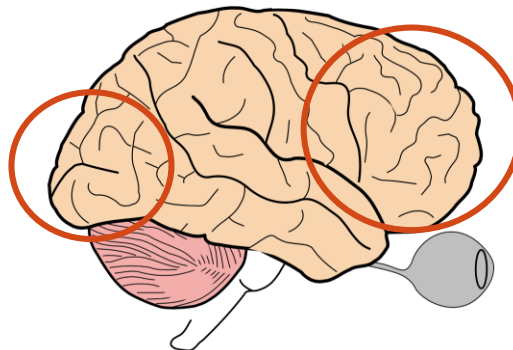
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## Why does visualization work?

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### Perception vs. cognition

Seeing (visual perception) is extremely fast and efficient



Thinking (cognition) is much slower and less efficient

Data visualization is effective because it shifts the balance between cognition and perception to take fuller advantage of the brain's abilities

<http://civicmedia.info/resources/stephen-few-data-visualization-for-human-perception>

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# Understanding visual perception

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One might think that the quality of a visualization is a matter of **subjective taste**



But visual perception follows specific rules derived from **how the brain works**

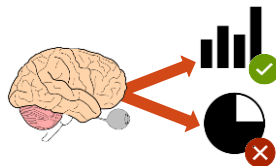


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# Understanding visual perception

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Understanding visual perception enables to make **informed decisions** about visualization design



The space of possibilities is huge – you need something to guide you in the choices you make

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Next, two examples ...

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And you will read this last

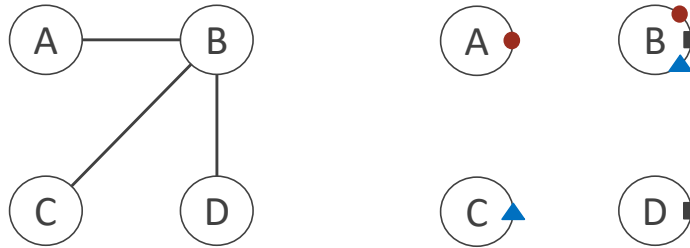
**You will read  
this first**

And then you will read this

Then this one

Which is easier to understand?

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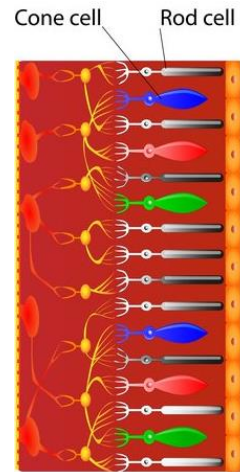
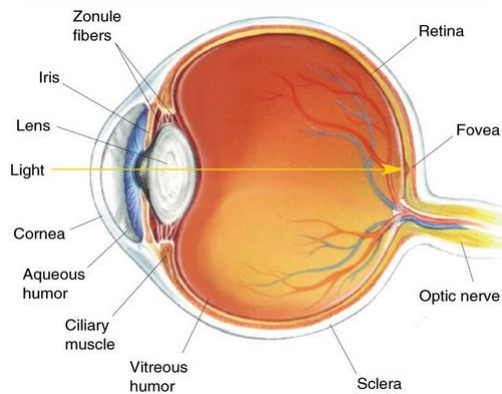
9

Attention and  
memory

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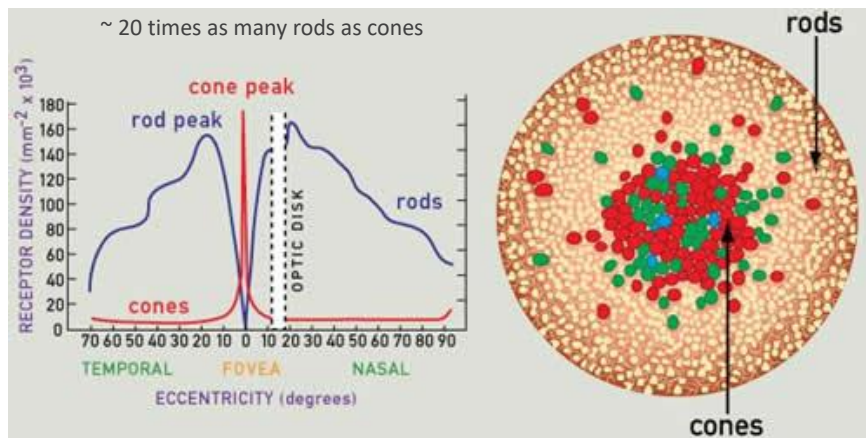
# Human eye anatomy



<https://www.webrn-maculardegeneration.com/rods-and-cones.html>

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# Rods and cones (photoreceptors)



<http://www.webexhibits.org/causesofcolor/1G.html>

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## Blind spot

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## Filling in the blanks

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*We don't see images with our eyes, we see them  
with our brains.*

Stephen Few

*The eye is not a camera*

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## Filling in the blanks

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<https://en.wikipedia.org/wiki/File:FoveatedLandscape.png>

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## Filling in the blanks

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### Saccadic eye movement

- Fast eye movement to sample the area around the focus of attention
- Eyes in continual motion (series of fixations of connected by saccades – about 3 per second)



What we perceive is the sum of the input that has been received in the last few fixations (things don't disappear when we blink)

[https://en.wikipedia.org/wiki/File:This\\_shows\\_a\\_recording\\_of\\_the\\_eye\\_movements\\_of\\_a\\_participant\\_looking\\_freely\\_at\\_a\\_picture.webm](https://en.wikipedia.org/wiki/File:This_shows_a_recording_of_the_eye_movements_of_a_participant_looking_freely_at_a_picture.webm)

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## Filling in the blanks



<https://petapixel.com/2019/07/31/this-black-and-white-photo-uses-color-grid-lines-to-trick-your-brain/>

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## Attention

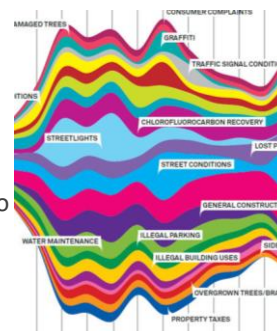
Visual perception is driven by our attention

Inattentional blindness

- We are blind to the things we do not pay attention to

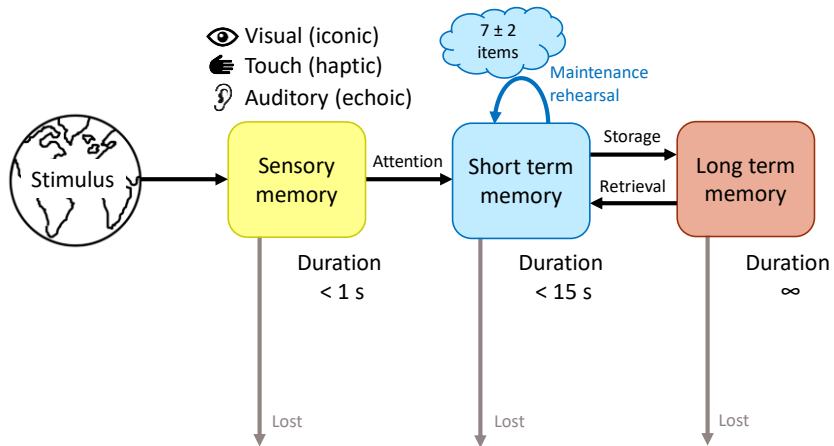
Implications for design

- Guide the attention of the viewer in a way that is useful for achieving the goal
- Be aware of how your design choices affect the attention of the user
- You don't want to inadvertently attract attention to unimportant information



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# Memory



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# Memory: Implications for design/presentation

Do not display more than  $7 \pm 2$  items/categories

The power of repetition: **Bing, Bang, Bongo**

- Introduce what you are going to tell the audience (**Bing**)
- Tell the audience (**Bang**)
- Summarize what you just told them (**Bongo**)

Be consistent (for example, always follow the same order) ▲●■



# Visual encoding

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# Visual encoding

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Mapping between data properties and graphical properties

Data attributes → Visual channels

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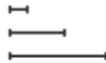
# Data attributes

## → Ordered

→ Ordinal



→ Quantitative



## → Categorical



# Visual channels

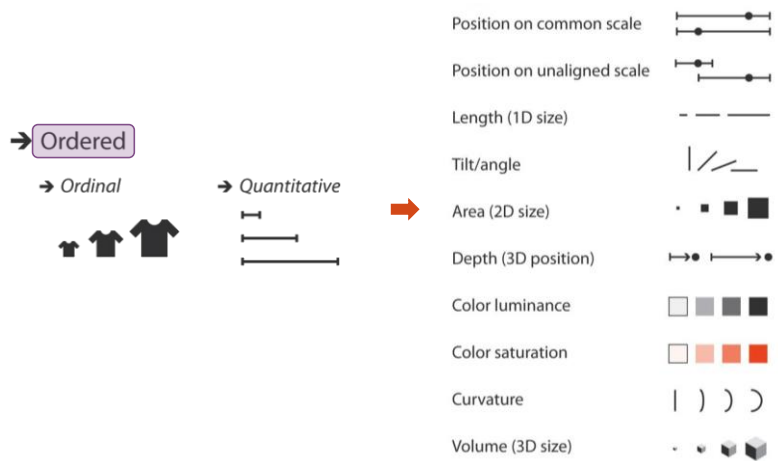
length (1D size)	— — —	colour hue	
angle	/ \	texture density	
curvature	) ) )	texture pattern	
shape	+ ● ■ ▲	position (2D)	
area (2D size)	• ■ ■ ■	depth (3D position)	
volume (3D size)	• ● ■ ■	motion	
lightness black/white	■ ■ ■ ■	blur/sharpness	
colour saturation	■ ■ ■ ■	containment	
transparency	■ ■ ■ ■	connection	

# Visual channels

## Channel properties

- **Expressiveness** – what can be expressed with a channel
- **Effectiveness** – how well it can be expressed

# Channels that can express order (magnitude channels)



## Channels that can express categories (identity channels)



T. Munzner. *Visualization Analysis & Design*. CRC Press, Boca Raton, 2014

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## Channel effectiveness

- Single channel
  - Accuracy (estimating magnitude)
  - Discriminability (number of values that can be distinguished)
- Multiple channels
  - Saliency or pop-out (attracting attention)
  - Separability (interference between channels)
  - Grouping (pattern formation)

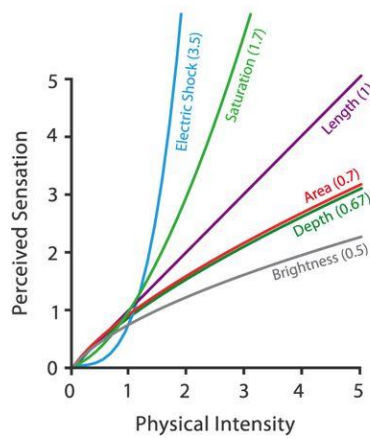
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# Channel accuracy

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# Channel accuracy

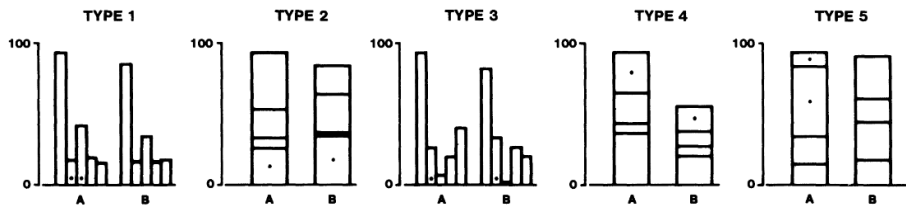
Steven's Psychophysical Power Law:  $S = I^N$



Published  
in 1957

# Channel accuracy

Experiments in graphical perception by Cleveland and McGill in 1983

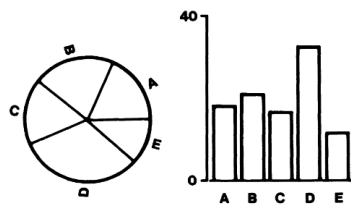


Which is smaller?  
How much smaller is it?

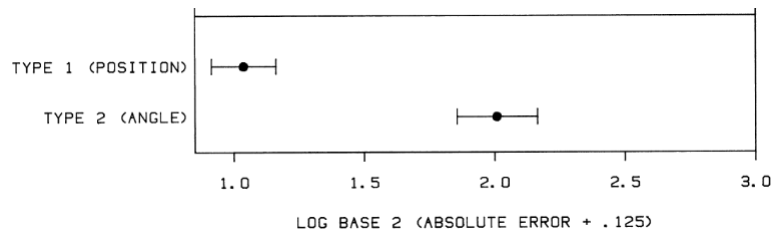
W. S. Cleveland, R. McGill. Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods. *Journal of the American Statistical Association*, 1984

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# Channel accuracy



How much bigger is  
B compared to A?

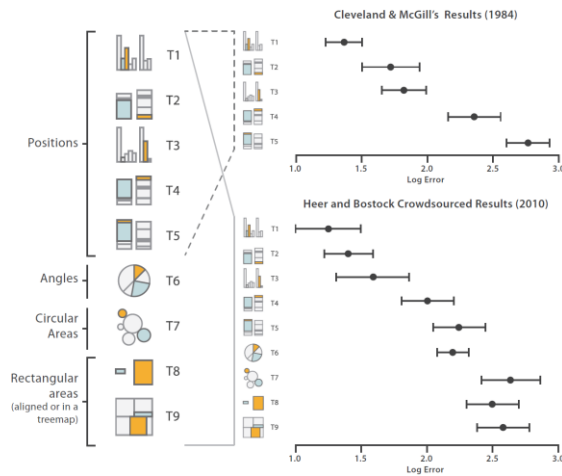


W. S. Cleveland, R. McGill. Graphical Perception: Theory, Experimentation, and Application to the Development of Graphical Methods. *Journal of the American Statistical Association*, 1984

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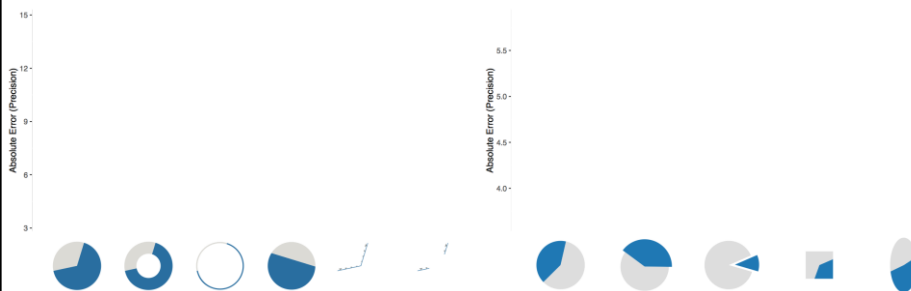
# Channel accuracy



E. J. Maguire. Systematising Glyph Design for Visualization, PhD Thesis, University of Oxford, 2014. 33

# Channel accuracy

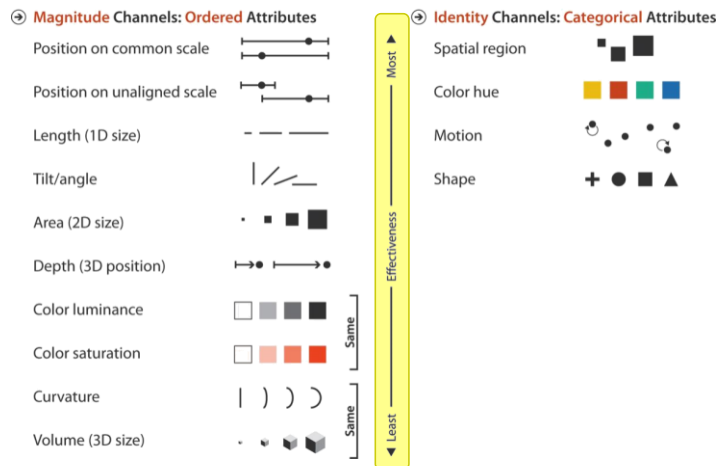
Recent experiments by Skau and Kosara show that pie charts are not read by angle



<https://eagereyes.org/blog/2016/an-illustrated-tour-of-the-pie-chart-study-results>

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# Channel accuracy: Implications for design



T. Munzner. *Visualization Analysis & Design*. CRC Press, Boca Raton, 2014

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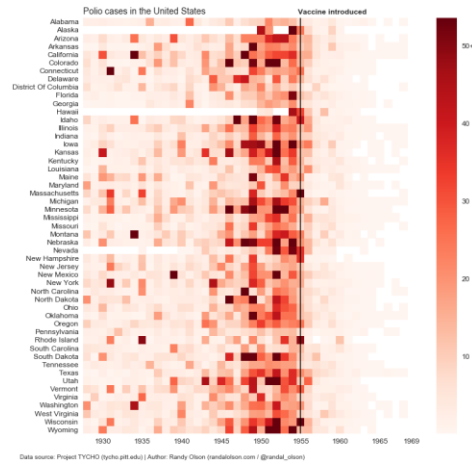
# Channel accuracy: Limitations

Specific to comparing and estimating magnitudes – not everything in data visualization is about magnitudes

Trade accuracy for something else, for example, scalability

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## Polio cases in the US



<http://www.randalolson.com/2016/03/04/revisiting-the-vaccine-visualizations/>

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## Channel discriminability

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# Channel discriminability

How many distinct values can be distinguished within a channel

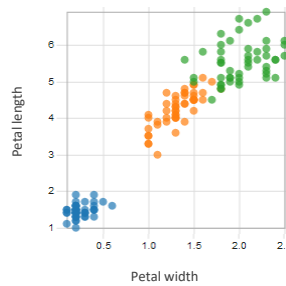
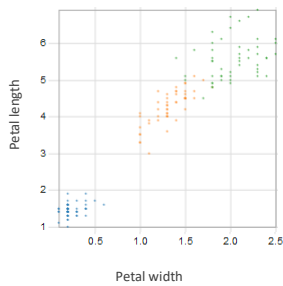
Discriminability depends on

- Channel properties (similar to accuracy)
- Size
- Spatial arrangement
- Cardinality



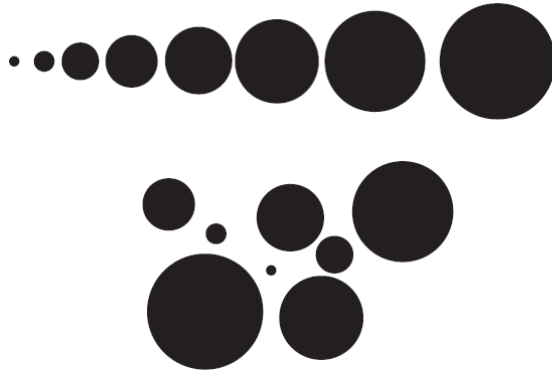
# Channel discriminability

The effect of size



# Channel discriminability

The effect of spatial arrangement



E. J. Maguire. Systematising Glyph Design for Visualization, PhD Thesis, University of Oxford, 2014. 41

# Channel discriminability

The effect of cardinality



E. J. Maguire. Systematising Glyph Design for Visualization, PhD Thesis, University of Oxford, 2014. 42

## Channel discriminability: Implications for design

Do not overestimate the number of values viewers can perceive/discriminate

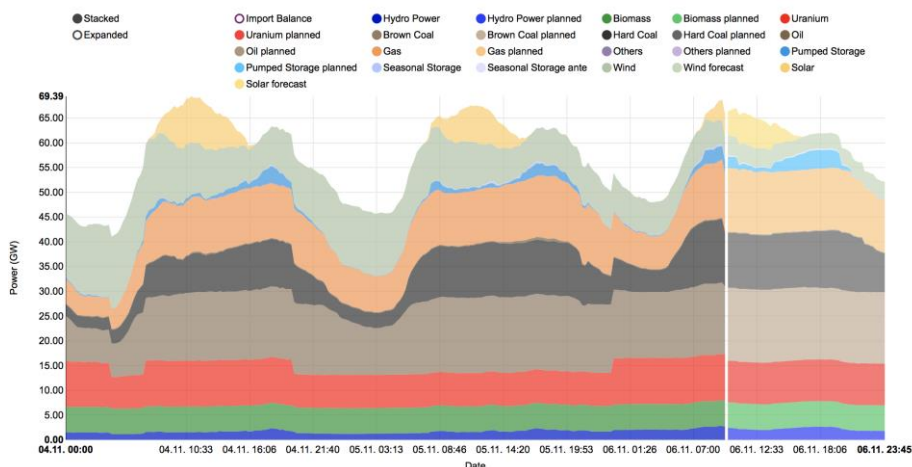
Short term memory limitation:  $7 \pm 2$  items (rather 5 than 9)

What to do in case of a large number of categories?

- Grouping (show groups of categories)
- Filtering (show only selected few)
- Faceting (use small multiples)

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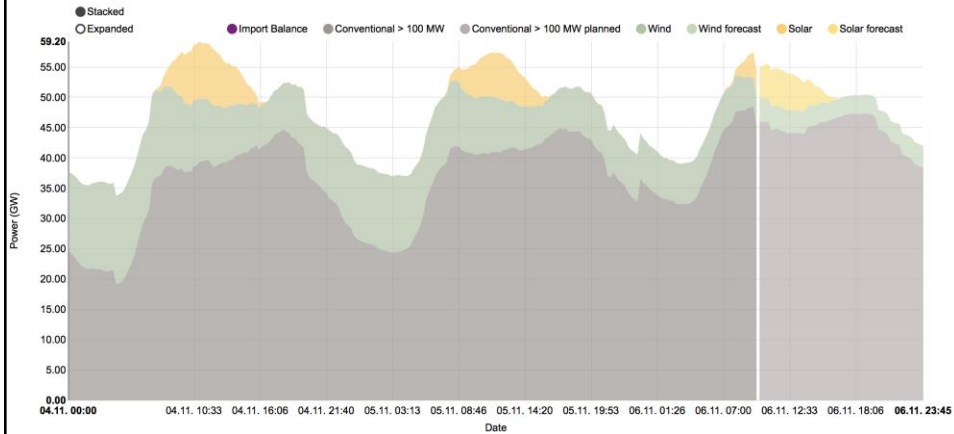
## Electricity production in Germany – all sources



<https://energy-charts.de/power.htm?source=all-sources&year=2019&week=45>

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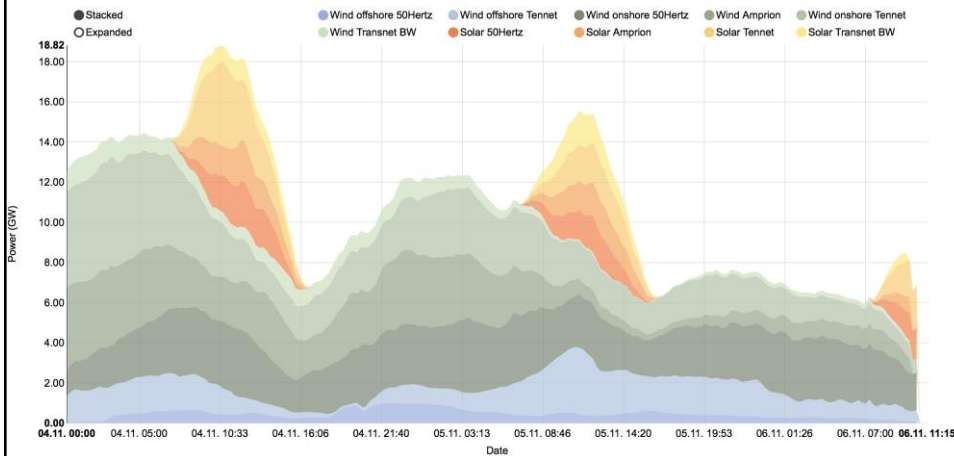
# Electricity production in Germany – grouped sources



<https://energy-charts.de/power.htm?source=all-sources&year=2019&week=45>

45

# Electricity production in Germany – filtered sources

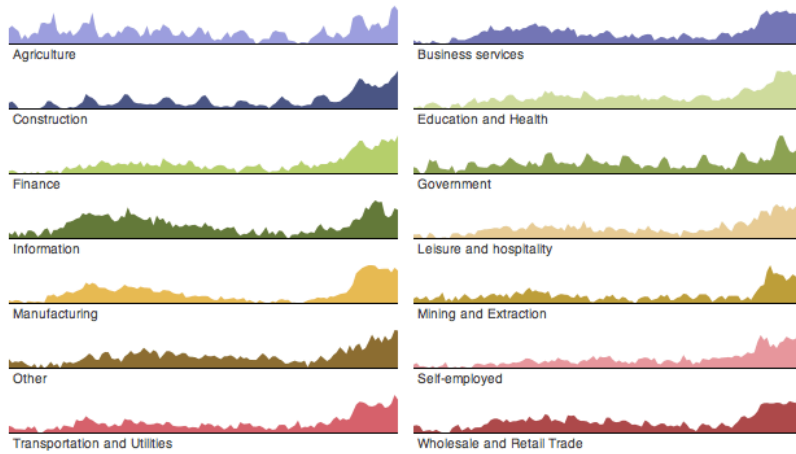


<https://energy-charts.de/power.htm?source=all-sources&year=2019&week=45>

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## Small multiples

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<https://homes.cs.washington.edu/~iheer/files/zoo/>

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## Channel salience

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## Channel salience (pop-out)

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Ability to stand out in a scene

Highly related to **preattentive processing**

- Uses sensory memory
- Happens automatically
- Tasks performed in less than 250 ms (faster than eye movement initiation)

Neurons in the brain are tuned to specific properties, called **preattentive attributes**

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## An example

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

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## An example

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

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## Another example

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How many cats do you see?

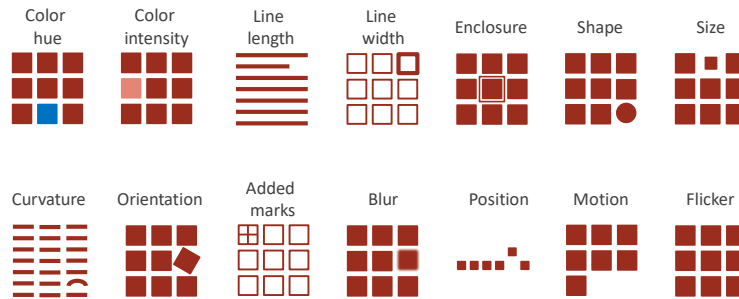


<https://twitter.com/vikkik88/status/1448850783928152074>

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## Preattentive attributes

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## Preattentive attributes

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Many attributes are asymmetric

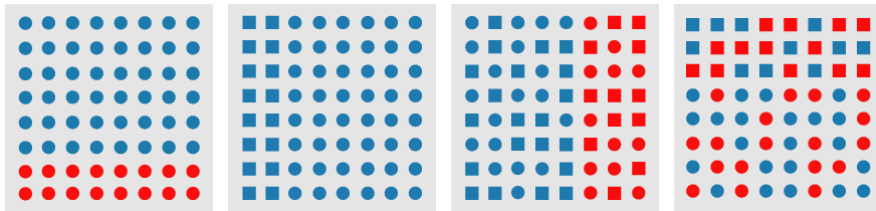


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## Preattentive attributes

Some attributes are stronger than others

- In boundary detection, color hue is stronger than shape

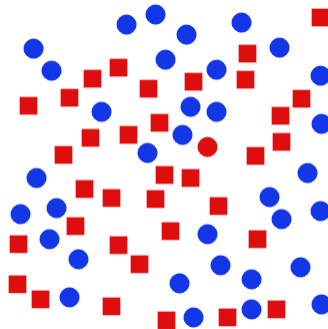


<https://www.csc2.ncsu.edu/faculty/healey/PP/>

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## Preattentive attributes

Conjunctions of two attributes often not preattentive



Preattentive conjunctions

- Space and color
- Motion and shape

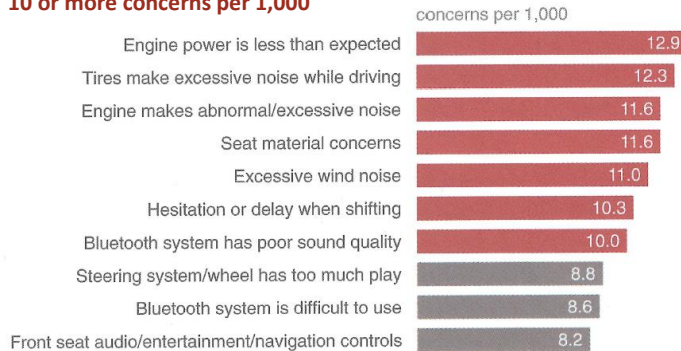
<https://www.csc2.ncsu.edu/faculty/healey/PP/>

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# Channel salience: Implications for design

Preattentive attributes can be used to draw attention

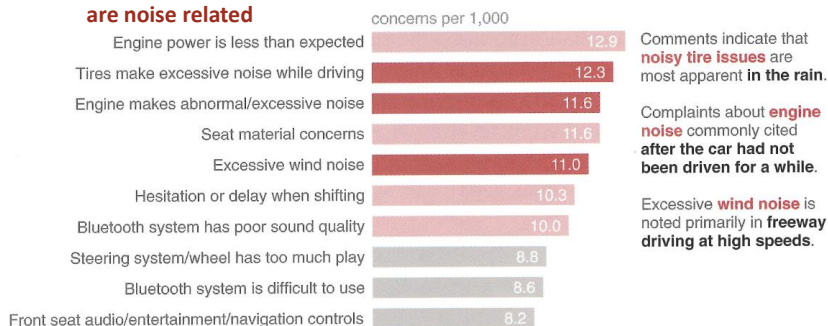
**7 of the top 10 complaints have  
10 or more concerns per 1,000**



# Channel salience: Implications for design

Preattentive attributes can be used to create a visual hierarchy of information

**3 of the top 10 complaints  
are noise related**



## Channel salience: Implications for design

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Use color sparingly

Use gray for elements that are not that important

When you highlight one point, you make the other points harder to see

Do not use preattentive attributes in exploratory data analysis

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## Channel separability

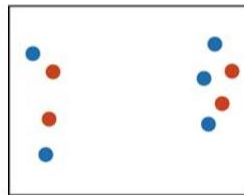
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## Channel separability

Amount of interference between channels

Position  
+ Hue (Color)



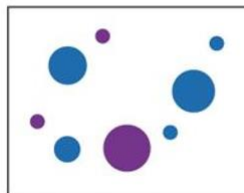
An example of  
separable channels

Fully separable

## Channel separability

Amount of interference between channels

Size  
+ Hue (Color)

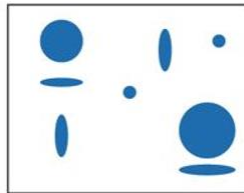


Some interference

## Channel separability

Amount of interference between channels

Width  
+ Height



An example of  
integral channels

Some/significant  
interference

## Channel separability

Amount of interference between channels

Red  
+ Green

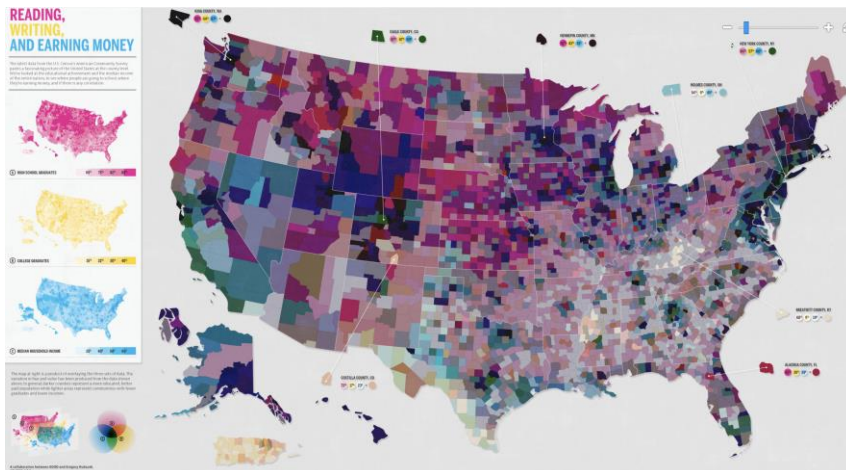


An example of  
integral channels

Major interference



## Are the richest Americans also the best educated?



<https://www.good.is/infographics/america-s-richest-counties-and-best-educated-counties#open>

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## Channel separability: Implications for design

Use **separable channels** when the audience should perceive **one variable at a time**

Use **integral channels** when you want a **holistic effect**

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# Grouping

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GESTALT LAWS

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## Gestalt laws

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Gestalt (German) = shape, form

Gestalt psychology aims to understand how individual visual objects are grouped to form a pattern

*The whole is other than the sum of its parts*

Kurt Koffka, Gestalt psychologist

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## Gestalt laws

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Proximity

Similarity

Connection

Enclosure

Closure

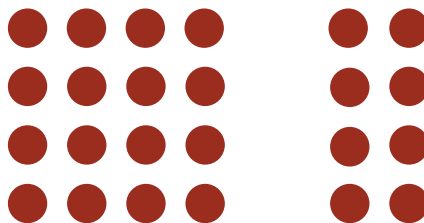
Figure/Ground

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## Gestalt law of Proximity

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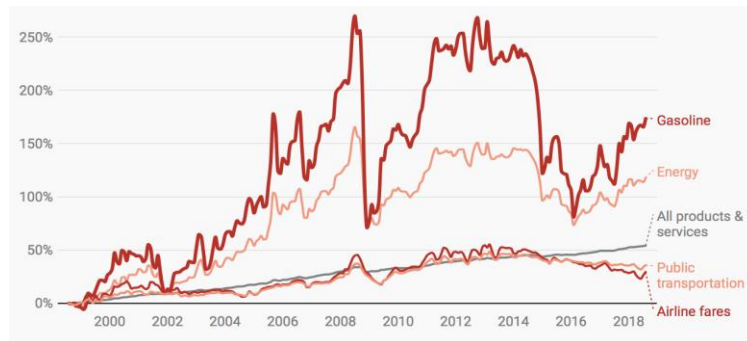
We perceive objects close to each other as belonging to a group



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## Gestalt law of Proximity: Implications for design

Place annotations close to the data

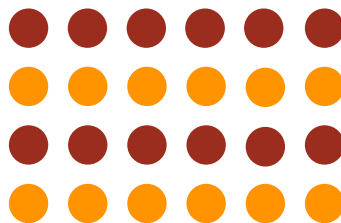


<https://blog.datawrapper.de/weekly47-cpi-dollars-for-college/>

71

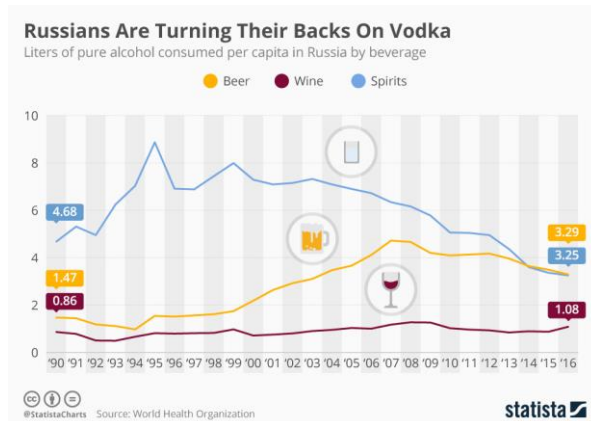
## Gestalt law of Similarity

We perceive similar objects as belonging to a group



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## Gestalt law of Similarity: Implications for design

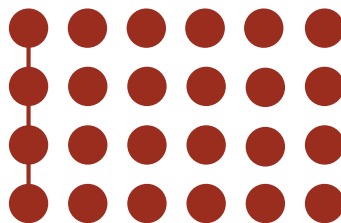


<https://www.statista.com/chart/15918/liters-of-pure-alcohol-consumed-per-capita-in-russia/>

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## Gestalt law of Connection

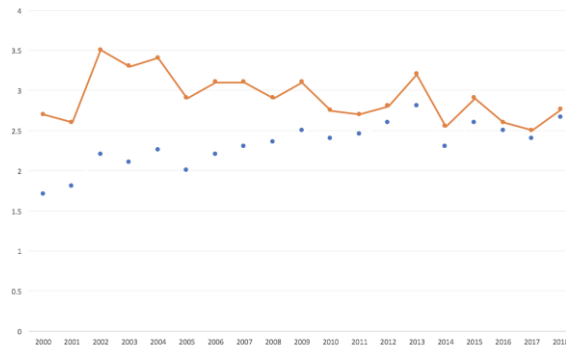
We perceive objects connected to each other as a single group



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## Gestalt law of Connection: Implications for design

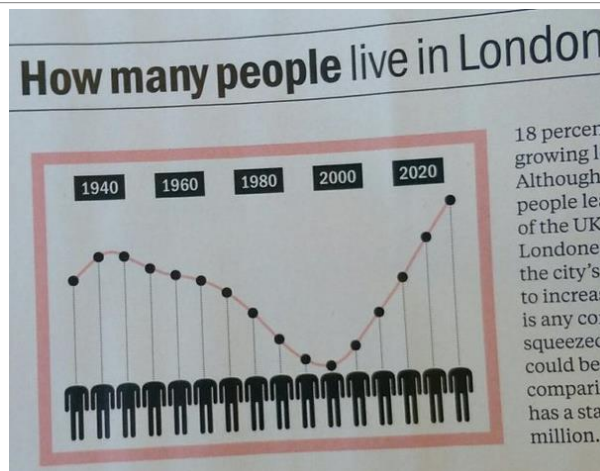
Use lines to show the data is in the same group



<http://daydreamingnumbers.com/concepts/gestalt-laws-data-visualization/>

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## Gestalt law of Connection: Implications for design

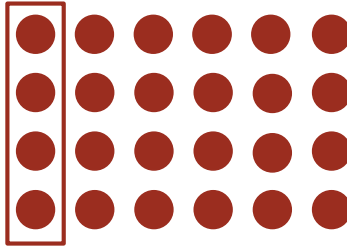


<https://twitter.com/mikebrondbjerg/status/1011560612055408640>

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# Gestalt law of Enclosure

We perceive physically enclosed objects as part of a group



# Gestalt law of Enclosure: Implications for design

Use enclosures to show groups



# Gestalt law of Enclosure: Implications for design

Bubble sets visualization



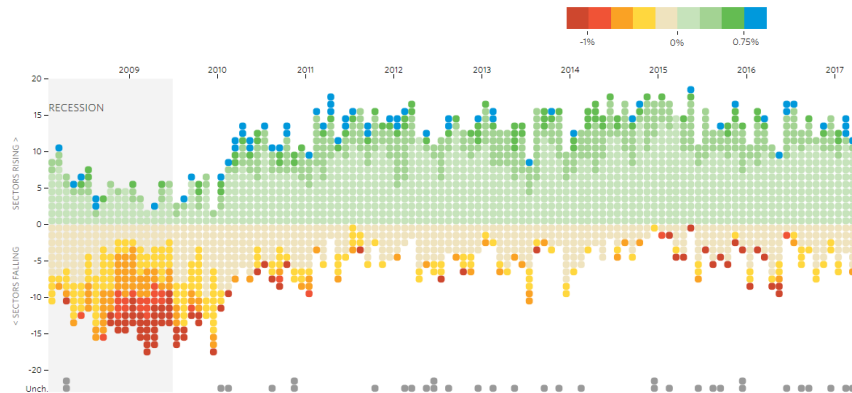
<http://vialab.science.uoit.ca/portfolio/bubblesets>

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# Gestalt law of Enclosure: Implications for design

**Winners and Losers: Job Gains and Losses** [Jump to National Unemployment](#)

Track the number of sectors gaining or losing jobs each month. Boxes are shaded based on percentage change from the previous month in each sector's payrolls.



<http://graphics.wsj.com/job-market-tracker/>

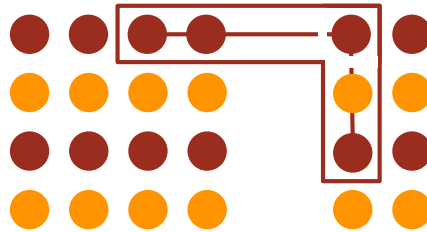
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## Hierarchy within grouping

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Similarity < Proximity < Connection & Enclosure

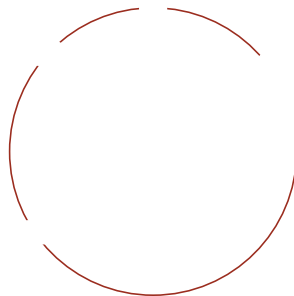


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## Gestalt law of Closure

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We perceive objects as being whole even when they are not complete

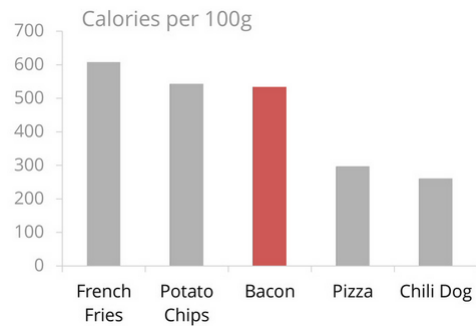


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## Gestalt law of Closure: Implications for design

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No need to draw chart borders



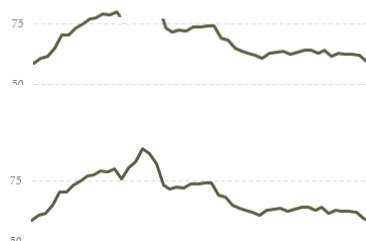
<https://www.darkhorseanalytics.com/blog/data-looks-better-naked>

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## Gestalt law of Closure: Implications for design

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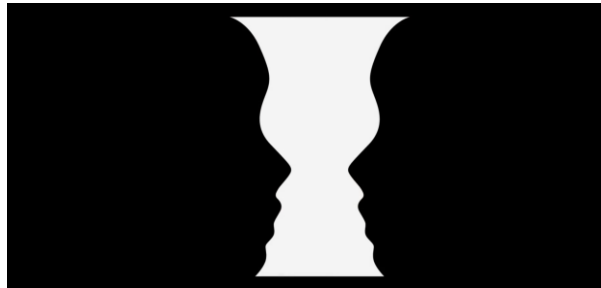
Be careful in case of missing values



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## Gestalt law of Figure/Ground

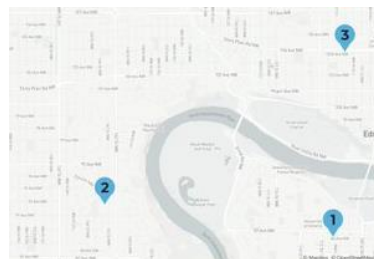
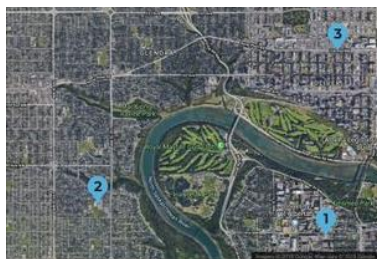
We perceive elements as either figure (element of focus) or ground (background)



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## Gestalt law of Figure/Ground: Implications for design

Color contrast and overlays can be used to discern the figure from the background

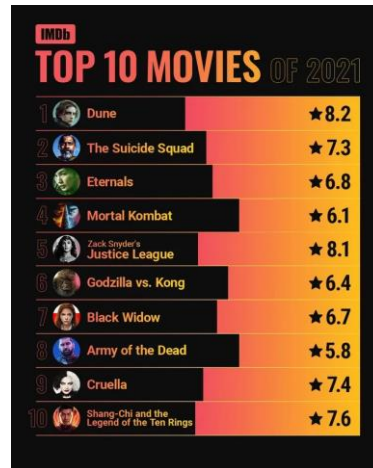


<https://twitter.com/cherdarchuk/status/140846611465594881>

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## Gestalt law of Figure/Ground: Implications for design

Which bar represents the data, the black one or the colored one?



<https://twitter.com/IMDb/status/146860009285320707>

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## Channel efficiency summary

### Accuracy

- Prioritize high ranking channels

### Discriminability

- Do not use more than 5-7 colors

### Salience (pop-out)

- Be mindful with how you direct attention

### Separability

- Use separable channels to perceive one variable at a time
- Use integral channels to obtain a holistic effect

### Grouping

- Be mindful of how visual elements form groups

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# Visual order

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# Visual order

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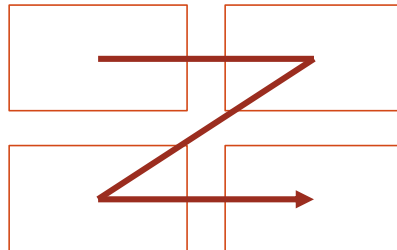
<https://twitter.com/flieldy/status/1384950048086282246>

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## Visual order

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The attention of people follows the Z shape



You should place the important things on the top (left) of the display

## Visual order

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All elements should be aligned – create clean vertical and horizontal ‘lines’ to establish a sense of unity and cohesion

Do not be afraid of white (empty) space – do not add more data (or stretch the graphics) to get rid of it

# Visual order

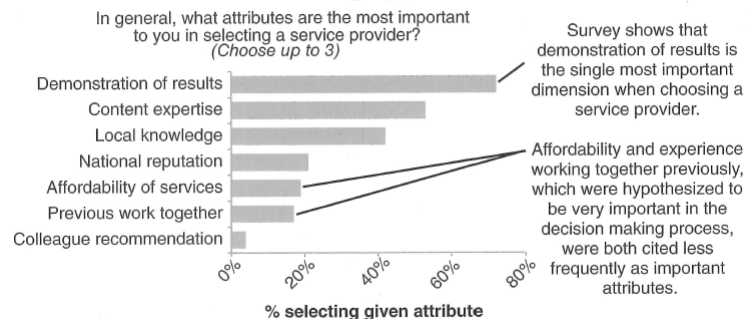
Stay away from diagonal components (especially text)

Text rotated by 45 degrees (in either direction) is 52% slower to read than normally oriented text

Text rotated by 90 degrees (in either direction) is 205% slower to read than normally oriented text

# Visual order – an example

## Demonstrating effectiveness is most important consideration when selecting a provider



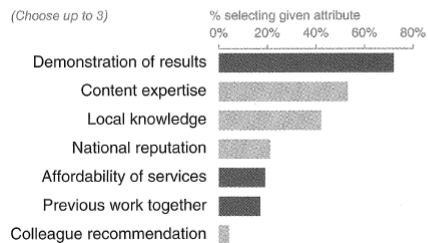
Data source: xyz; includes N number of survey respondents. Note that respondents were able to choose up to 3 options.

## Visual order – an example

**Demonstrating effectiveness** is most important consideration when selecting a provider

In general, **what attributes are the most important** to you in selecting a service provider?

(Choose up to 3)



Survey shows that **demonstration of results** is the single most important dimension when choosing a service provider.

**Affordability** and **experience working together previously**, which were hypothesized to be very important in the decision making process, were both cited less frequently as important attributes.

Data source: xyz; includes N number of survey respondents.  
Note that respondents were able to choose up to 3 options.

## Visual order

Pay attention to details

Avoid

- Too much centered text
- Diagonal components, especially text
- Too many things on a single display



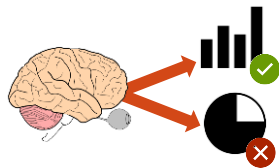
# Summary

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## How data visualization works

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The quality of visualizations  
is mostly not subjective

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## How data visualization works

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And you will read this last

**You will read  
this first**

And then you will read this

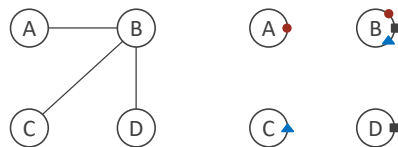
Then this one

Pop-out and  
visual order

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## How data visualization works

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Connection more  
powerful than  
similarity

10  
0