Cours 2024-2025:

La perception des graphiques:
un nouvel exemple de recyclage neuronal
The perception of graphics : a new example of neuronal recycling

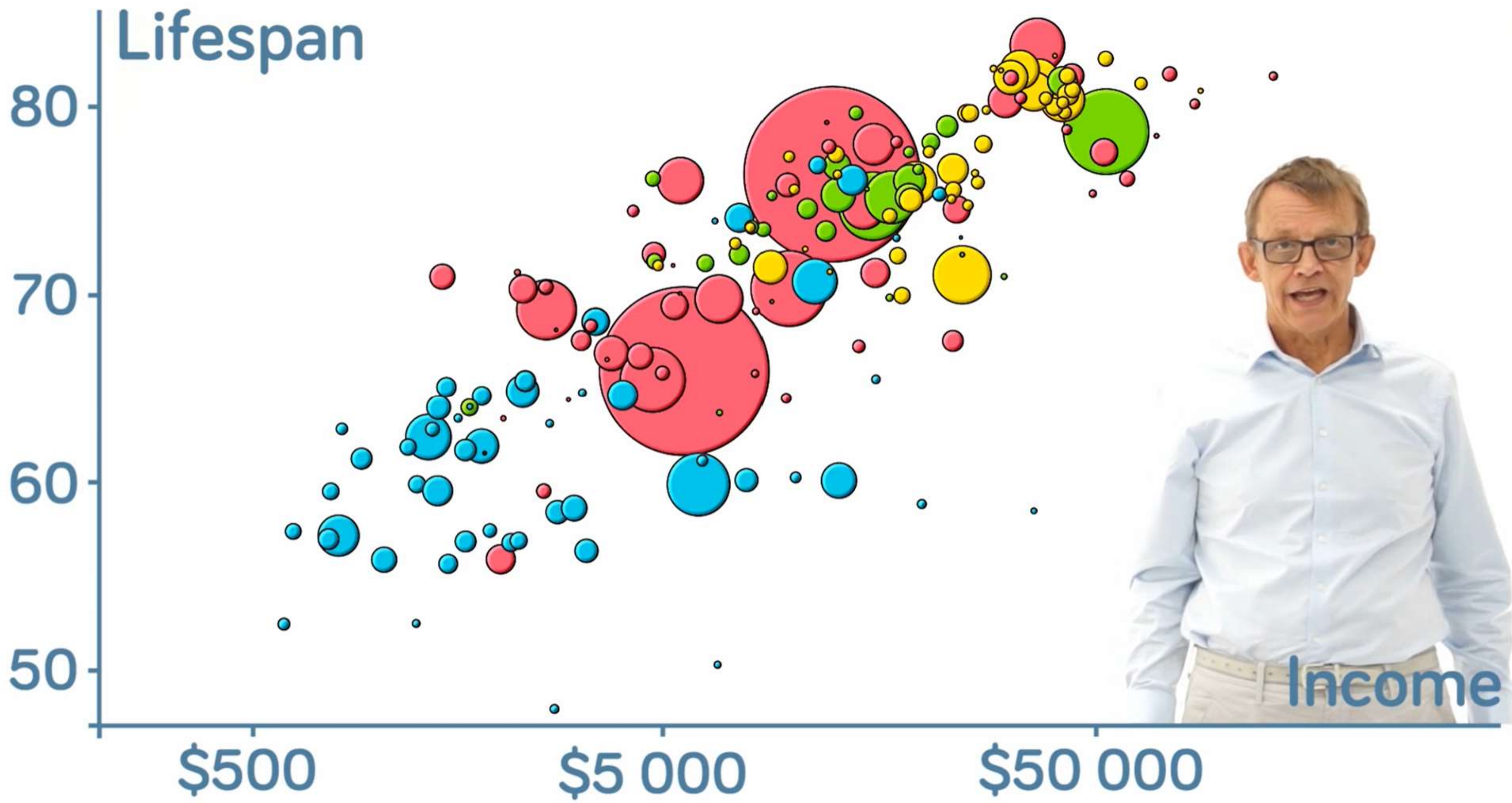
Stanislas Dehaene
Chaire de Psychologie Cognitive Expérimentale

Cours n°2

Etapes cognitives de la perception, de la compréhension et du design des graphiques

Cognitive stages in graphics perception, comprehension and design

What makes graphs so illuminating and useful ?
What successive processes are involved in deciphering them ?



World Health Chart | Gapminder

Hans Rosling, physician and data scientist, author of *Factfulness*

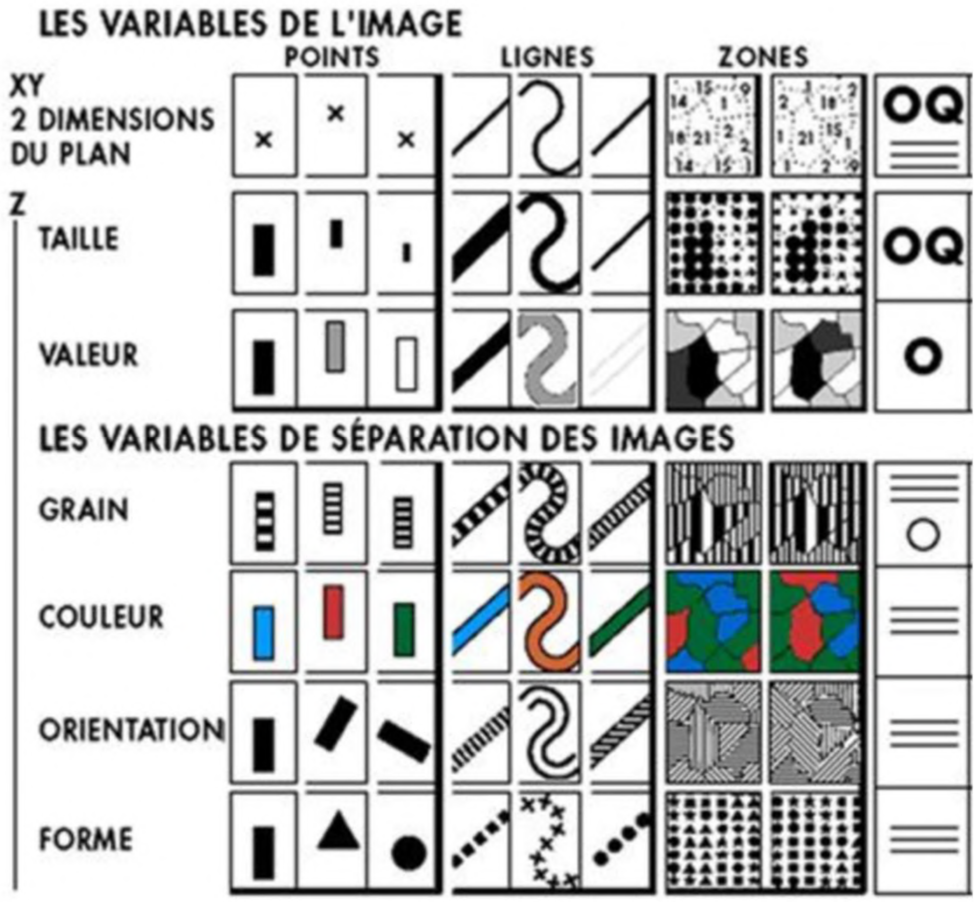
What is a graphic?

Pinker, S. (1990). A Theory of Graph Comprehension. In *Artificial Intelligence and the Future of Testing*. Psychology Press.

Cf Bertin (1967); or Pinker (1990):

« Each graph tries to communicate to the reader

- a set of n-tuples of values on n mathematical **scales**,
- using objects whose **visual dimensions** (i.e., length, position, lightness, shape, etc.) correspond to the respective scales
- and whose values on each dimension (i.e., an object's particular length, position, and so on) correlate with the values on the **corresponding scales**."

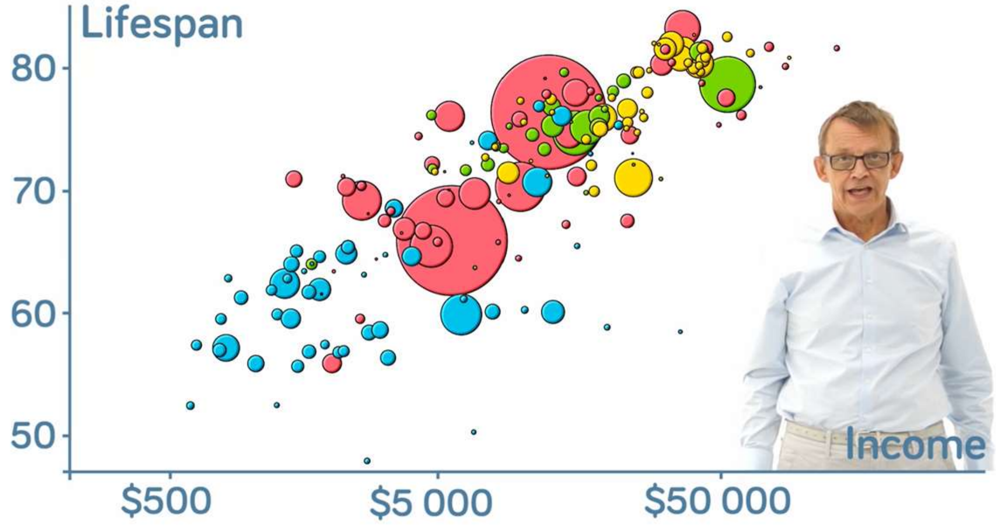


What are the necessary stages in the comprehension of graphics?

Pinker, S. (1990). A Theory of Graph Comprehension. In *Artificial Intelligence and the Future of Testing*. Psychology Press.

Bertin's ideas (1967) are summarized by Pinker (1990):

- « Internal identification » : determine which dimensions of variation in the graphic are relevant to its content, and how each dimension maps onto a different variable (x position, y position, angle, radius, color, shape…)
- « External identification »: identify, via alphanumeric labels, the referents of the symbols on the graphic (e.g. real-world measures; say age and weight).
- « Perception of correspondence » : Use the particular levels of each such dimension to draw conclusions about the referents.



Those conclusions can be

- absolute (Lifespan is ~60-70 years for countries with an average yearly income of 5000$)
- or relational (e.g. lifespan increases with income).

We may thus distinguish two stages in graph comprehension:

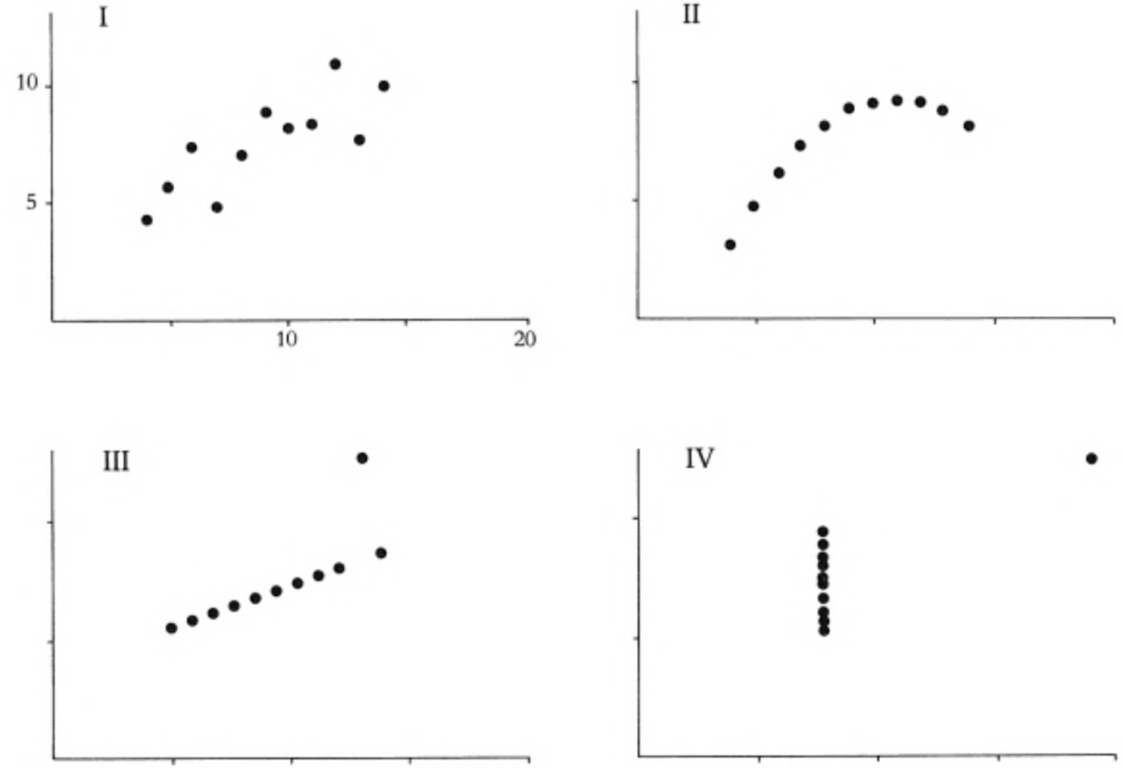
- **Perceptual stage** (Bertin's internal identification) : the objects on the page are parsed, relevant ones are attended and encoded.
  - Extraction of trends in the curves or dots
  - Grammar of graphics : identification of the axes, the legend, the title, and their inter-relations.
- **Conceptual stage** (Bertin's external identification): the objects' relevant dimensions are coded as numbers and their meaning is evaluated.
  - Comprehension of what the dimensions mean (what kind of data : categorical, ordinal, additive or ratio scales)
  - Number to line correspondence, and understanding of the scale (linear, logarithmic)

Why plot the data? Because graphics recycle our visual system’s capacities for efficient parallel processing and abstraction

Here are four data pairs with the same means and regression lines. Can you figure out how they behave?

Plotting the data immediately reveals their characteristics – not only the central tendency, but also the shape of the relationship (e.g. quadratic downwards), the noise level, the presence of outliers…

	1		2		3		4	
	X	Y	X	Y	X	Y	X	Y
	10.0	8.04	10.0	9.14	10.0	7.46	8.0	6.58
	8.0	6.95	8.0	8.14	8.0	6.77	8.0	5.76
	13.0	7.58	13.0	8.74	13.0	12.74	8.0	7.71
	9.0	8.81	9.0	8.77	9.0	7.11	8.0	8.84
	11.0	8.33	11.0	9.26	11.0	7.81	8.0	8.47
	14.0	9.96	14.0	8.10	14.0	8.84	8.0	7.04
	6.0	7.24	6.0	6.13	6.0	6.08	8.0	5.25
	4.0	4.26	4.0	3.10	4.0	5.39	19.0	12.50
	12.0	10.84	12.0	9.13	12.0	8.15	8.0	5.56
	7.0	4.82	7.0	7.26	7.0	6.42	8.0	7.91
	5.0	5.68	5.0	4.74	5.0	5.73	8.0	6.89
Mean	9.0	7.5	9.0	7.5	9.0	7.5	9.0	7.5
Variance	10.0	3.75	10.0	3.75	10.0	3.75	10.0	3.75
Correlation	0.816		0.816		0.816		0.816	



From Tufte’s *The visual display of quantitative information*; after Anscombe, “Graphs in statistical analysis”, Am Stat (1973).

Why is a graphic worth a thousand words? A theoretical analysis

Larkin, J. H., & Simon, H. A. (1987). Why a Diagram is (Sometimes) Worth Ten Thousand Words. *Cognitive Science*, *11*(1), 65-100.
https://doi.org/10.1016/S0364-0213(87)80026-5

"When they are solving problems, human beings use both internal representations, stored in their brains, and **external representations**, recorded on a paper, on a blackboard, or on some other medium."

The invention of external representations vastly enhances the computing power of the human brain. Cf Zhang, J., & Norman, D. A. (1995). A representational analysis of numeration systems. *Cognition*, *57*, 271-295.

Two kinds of external representations can be distinguished:

"1. In a **sentential representation**, the expressions form a **sequence** corresponding, on a one-to-one basis, to the sentences in a natural-language description of the problem. Each expression is a direct translation into a simple formal language of the corresponding natural language sentence.

2. In a **diagrammatic representation**, the expressions correspond, on a one-to-one basis, to the components of a diagram describing the problem. Each expression contains the information that is **stored at one particular locus in the diagram**, including information about relations with the adjacent loci.

"the diagrammatic representation **preserves explicitly the information about the topological and geometric relations** among the components of the problem, while the sentential representation does not."

In computer science, the format of data representation dramatically changes the ease with which certain computations can be performed.

E.g. Can you multiply the number 2878 by 10? And by 2 ? What about 100101000100 in binary notation ?

Two representations can be **informationally equivalent** yet differ in their **computational efficiency.**

"In general, the **computational efficiency** of a representation depends on all three of these factors (data structure, program, attention management)

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3 kinds of processes contribute to the formation of mental programs.

1. Search

Search can be vastly more efficient when data is in graphic form – we can move the eyes or even just our attention to any point in 2D space, guided by feature-based or object-based attention (compare, say, to a single-tape Turing machine).

2. **Recognition**

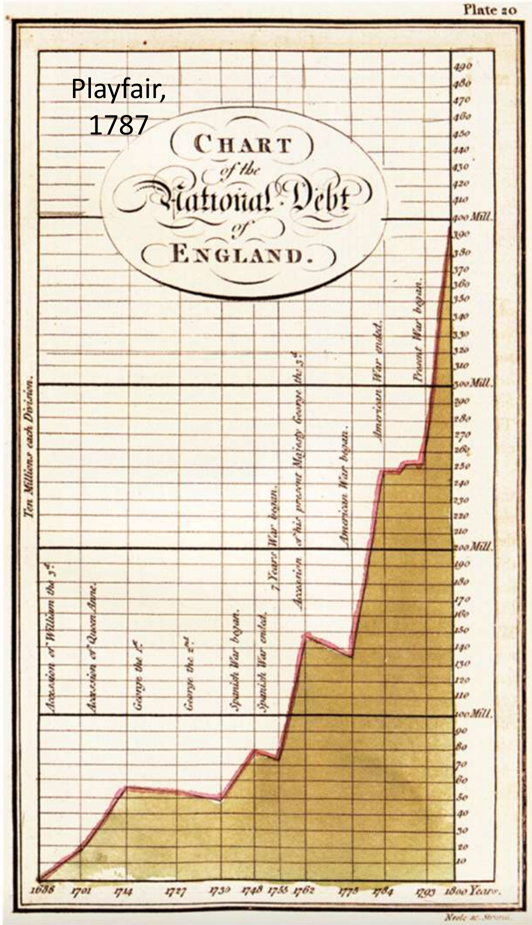
The visual system is extremely efficient at

- recognizing tens of thousands of items (legends, symbols…).
- recognizing the orientation of a curve or scatter plot, and even its curvature and organization – which would be impossible if the same data was presented as text or as a table.

Such recognition requires training -- just like learning to read the alphabet.

3. **Inference**

In the somewhat old-fashioned framework of Larkin & Simon, inference is performed through the application of “production rules” that “activate” when their conditions are matched. This matching process can be facilitated by the graphics format.



“The major difference in a diagrammatic representation, we believe, is difference in recognition processes.”

Larkin & Simon speak primarily of physics and math diagrams, but their thinking also applies to data graphics.

Why is a graphic worth a thousand words? A theoretical analysis

Larkin, J. H., & Simon, H. A. (1987). Why a Diagram is (Sometimes) Worth Ten Thousand Words. *Cognitive Science*, *11*(1), 65-100. https://doi.org/10.1016/S0364-0213(87)80026-5

The authors illustrate their ideas with some math problems such as:

"1. Two transversals intersect two parallel lines and intersect with each other at a point x between the two parallel lines.

2. One of the transversals bisects the segment of the other that is between the two parallel lines.

3. Prove that the two triangles formed by the transversals are congruent."

It is indeed almost impossible to solve this problem without first drawing a diagram. The authors show this formally by evaluating the size of the combinatorial space that would have to be explored by an algorithm with pure "logical rule matching" – and show that attention can be oriented much more efficiently using the diagram.

Interesting, pure language-based problem solving was the approach initially taken by Large Language Models (LLMs).

I asked the problem to ChatGPT 4o (July 30th 2024) and of course it failed.

ChatGPT first assigns labels ABCDX to the key points.

Then it writes a simple but runnable Python program that draws the diagram.

It obviously doesn't "use" the diagram, however – for instance it fails to "see" that AXC is NOT a line !

Conclusion: **a graphic can guide the recognition of relevant patterns and rules.**

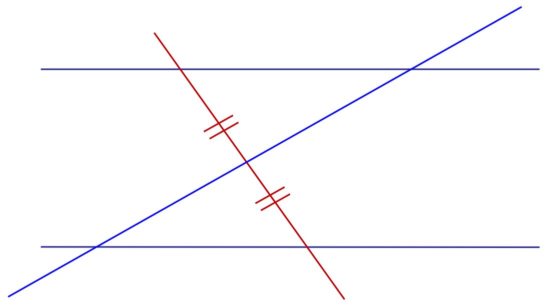


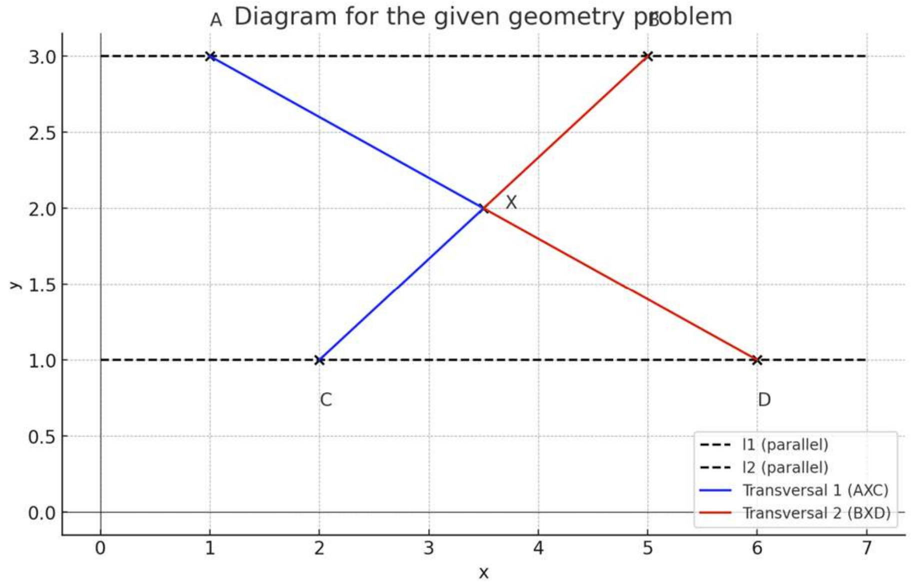
Diagram Creation:

•Draw two parallel lines ℓ1 and ℓ2.

•Draw two transversals that intersect these parallel lines and each other at a point X between ℓ1 and ℓ2.

•Label the points where the transversals intersect ℓ1 as A and B, and where they intersect ℓ2 as C and D.

•Assume transversal AXC bisects the segment BD of the other transversal between ℓ1 and ℓ2.

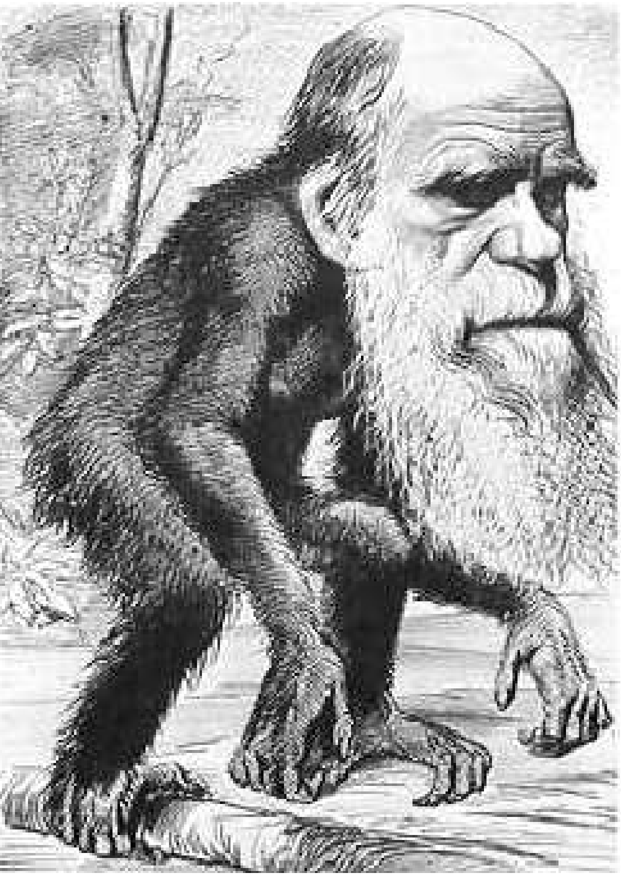


A proposal : Graphics perception provides a new instance of neuronal recycling

Graphics are a recent cultural invention – similar to the alphabet, Arabic number notation, or musical notation.

They cannot rely on specialized brain systems, specifically evolved for graphic comprehension.

Rather, they must rely on pre-existing perceptual and cognitive systems – but ones that learning and education may repurpose or **recycle.**



Dehaene, S. (2005). Evolution of human cortical circuits for reading and arithmetic : The “neuronal recycling” hypothesis. In S. Dehaene, J. R. Duhamel, M. Hauser, & G. Rizzolatti (Éds.), *From monkey brain to human brain* (p. 133-157). MIT Press.
Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron*, *56*(2), 384-398.

Four key postulates of the neuronal recycling hypothesis

Human brain organization is subject to **strong anatomical and connectional constraints** inherited from evolution. Organized neural maps are present early on in infancy and bias subsequent learning.

New cultural acquisitions are only possibly inasmuch as they fit within this pre-existing architecture.

Each **cultural object** must find its **neuronal niche** -- a set of circuits that are sufficiently close to the required function and sufficiently plastic to be partially “recycled”.

As cortical territories dedicated to evolutionarily older functions are invaded by novel cultural objects, their prior organization is never entirely erased. Thus, **prior neural constraints exert a powerful influence** on **cultural forms**, their **acquisition** and their **adult organization**

The neuronal recycling hypothesis and its predictions

Dehaene, S. (2005). Evolution of human cortical circuits for reading and arithmetic : The “neuronal recycling” hypothesis. In S. Dehaene, J. R. Duhamel, M. Hauser, & G. Rizzolatti (Éds.), *From monkey brain to human brain* (p. 133-157). MIT Press.
Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron*, *56*(2), 384-398.

Neuronal recycling is conceptually similar to **exaptation** (S.J. Gould) or **tinkering** (*bricolage,* F. Jacob).

Why introduce a new term?

In order to emphasize a key difference: Cultural acquisitions take place **in developmental time, without any genetic change**.

Several specific predictions:

Cross-cultural invariants:

- in the cortical representation of cultural inventions

- in the structure of cultural systems.

Learning constrained by the amount of recycling:

The speed and ease of learning in children should vary with the complexity of the required cortical remapping.

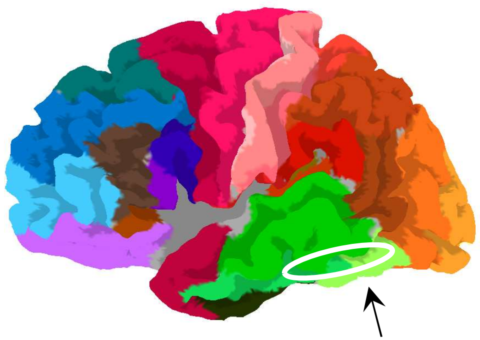
Gains, but also losses:

Education can lead to gains (generalization) but also to losses (cortical competition).

Applying the neuronal recycling hypothesis to **reading**

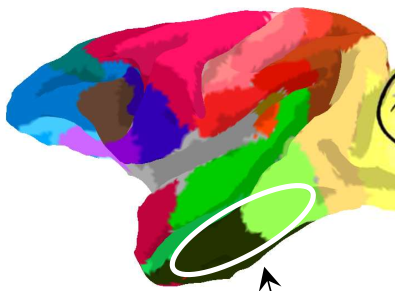
The inferotemporal cortex of *all* primates contains a pyramid of circuits for invariant shape recognition, which are recycled for letter and number recognition.

Human brain

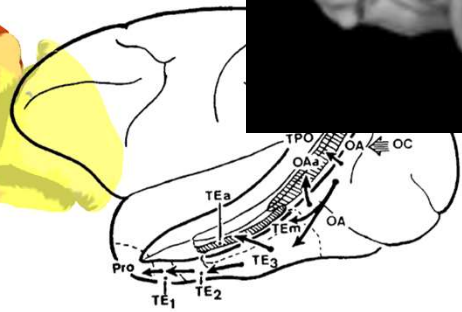


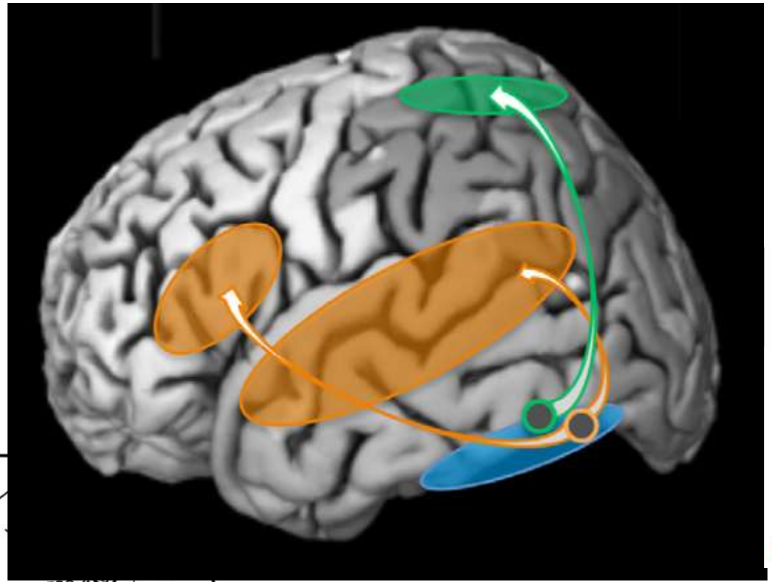
Visual recognition of objects, faces **and written words**

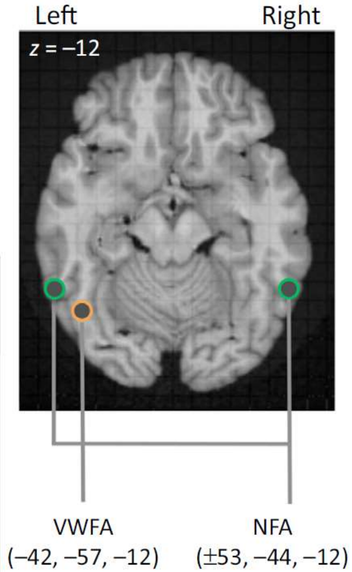
Macaque monkey

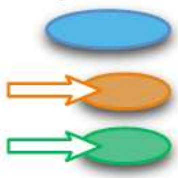


Visual recognition of objects and faces









Neurons in this region respond to an **alphabet** of shape descriptors.

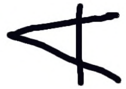
We adopted many of these shapes in our writing systems worldwide.

Letters compete for cortical territory with objects, faces…. And limbs (Nordt et al. 2021)

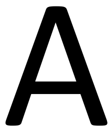
Lascaux

Proto-sinaitic

Phoenician



Greek / Latin



Letters and numbers land at distinct yet reproducible sites because these sites preferentially connect to language versus numerosity areas of the baby brain.

Saygin et al., with Gabrieli & Kanwisher (2016). Connectivity precedes function in the development of the visual word form area. Nature Neuroscience, 19(9), 1250-1255.

Applying the neuronal recycling hypothesis to graphics

What is recycled in the case of graphics?

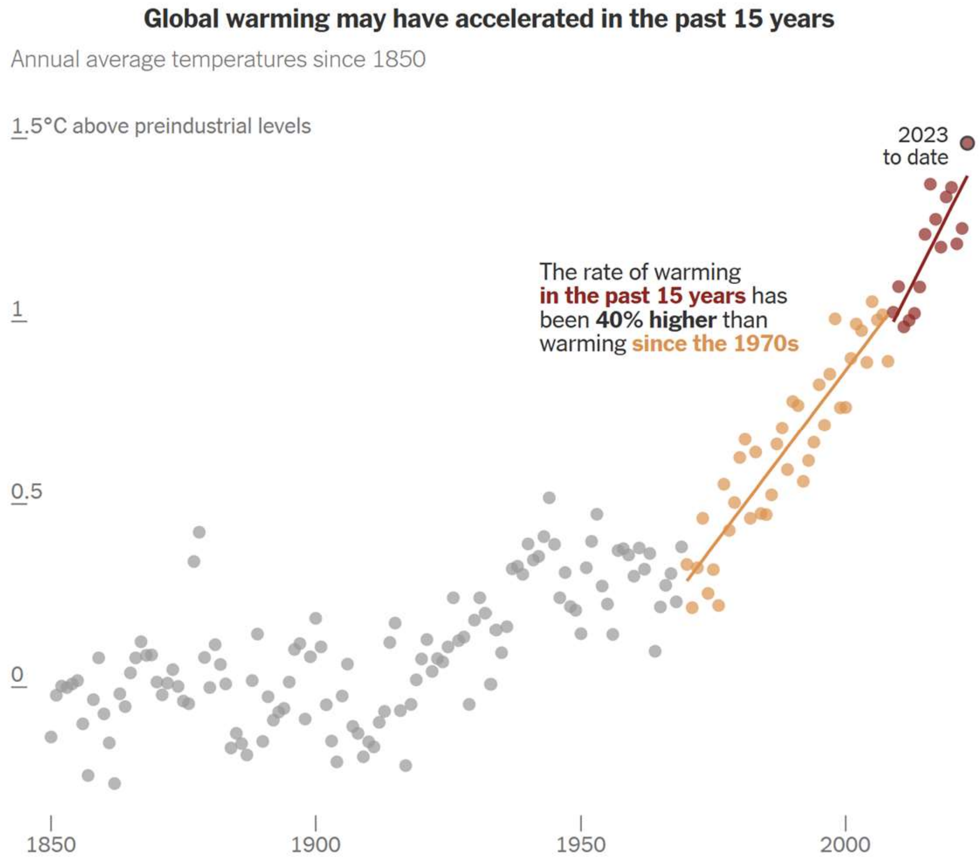
Our visual areas are extraordinarily efficient parallel processors.

Graphics transform data in a way that makes them easy to process by our visual processors.

This process is similar to the repurposing of GPUs (graphic processing units), initially developed for the ultrafast display of graphics in video games, and now best-sellers for all sorts of matrix computations, including AI.

The neuronal recycling hypothesis helps explain what makes a graphic efficient:

- **Parallel visual processing** is only possible if the data are displayed in different parts of **space**
- **Perception of the shape skeleton** is used to quickly perceive the linear or non-linear trend of the graphic, and to detect outliers (course 4).
- **Number-space mappings** allow space to convey any quantitative dimension (course 3).
  - **Spatial dimensions play a special role** in graphics – other dimensions such as color or texture can be used, but do not convey quantitative data as efficiently.
- **Feature-based attention** is used to select the items of a certain color.
- **Object-based attention** is used to select specific parts of the graph (a curve, the legend…).
- The **grammar of vision** allows us to parse the hierarchy of graphical elements.
- If needed, **serial routines such as curve-tracing** allows us to slowly inspect the data and use "system-2" thinking.



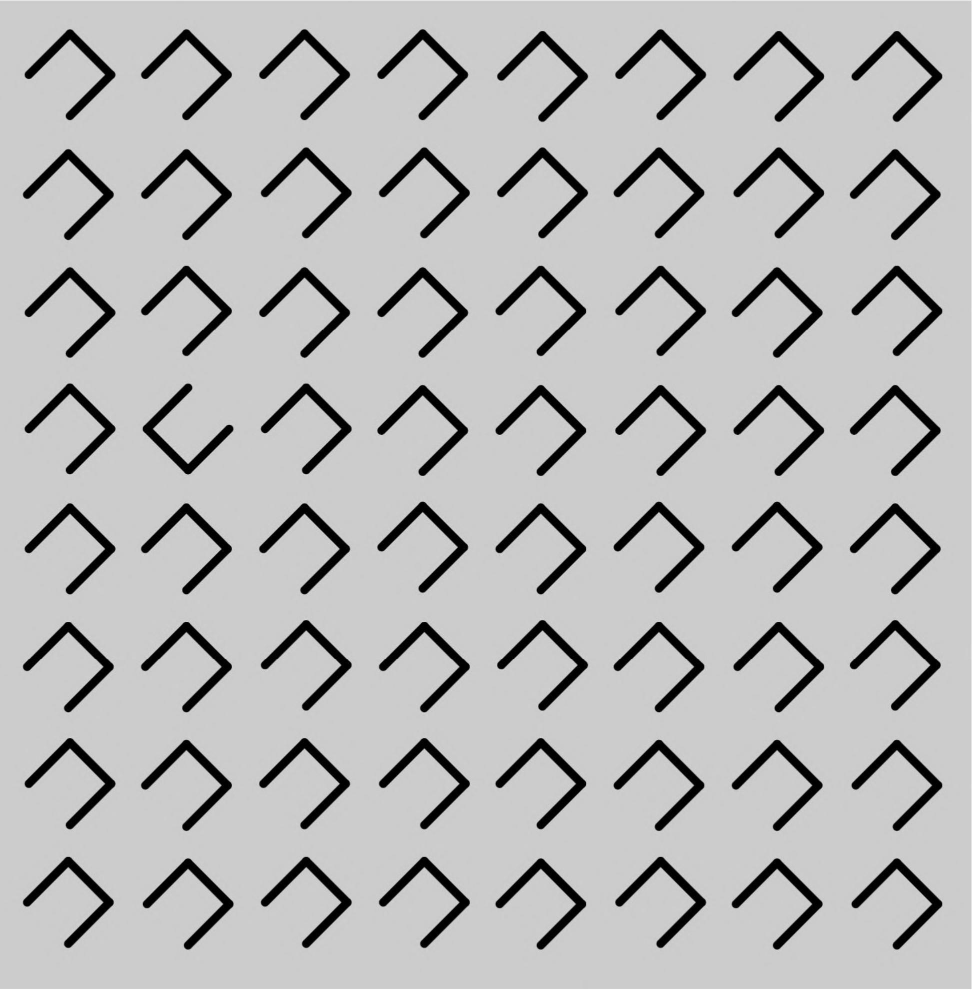
Parallel preattentive versus serial attention-dependent operations

Franconeri, S. L., Padilla, L. M., Shah, P., Zacks, J. M., & Hullman, J. (2021). The Science of Visual Data Communication : What Works. *Psychological Science in the Public Interest*, *22*(3), 110-161. https://doi.org/10.1177/15291006211051956

A major distinction in visual perception is between pop-out versus visual search.

Research by Anne Treisman (later extended by Daniel Kahneman into the system 1 / system 2 distinction), Jeremy Wolfe and many others.

Demonstrations:
https://michaelbach.de/ot/cog-popout/



Parallel preattentive versus **serial attention-dependent** operations

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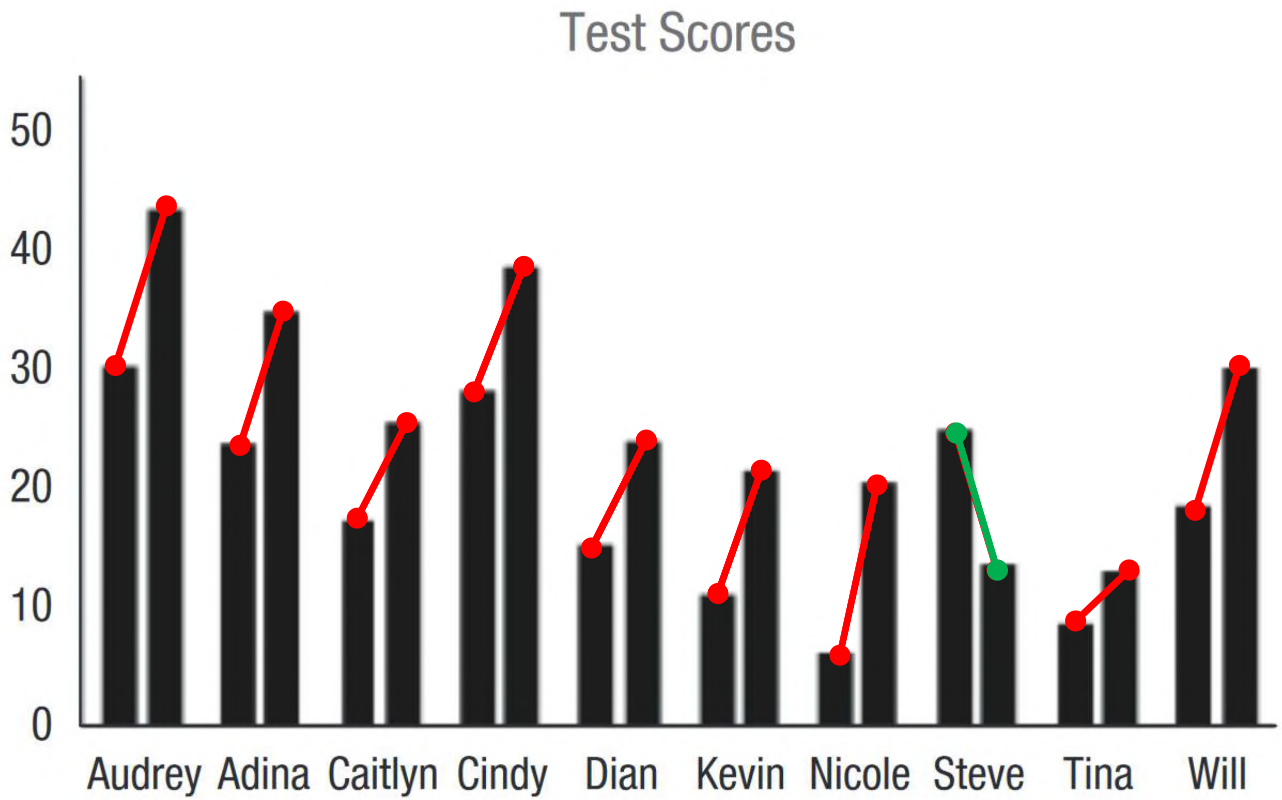
Graphics should **maximize parallel preattentive processing** and minimize the need for **serial search**.

Whether parallel or serial processing is deployed may depend on the questions that we ask about the data.

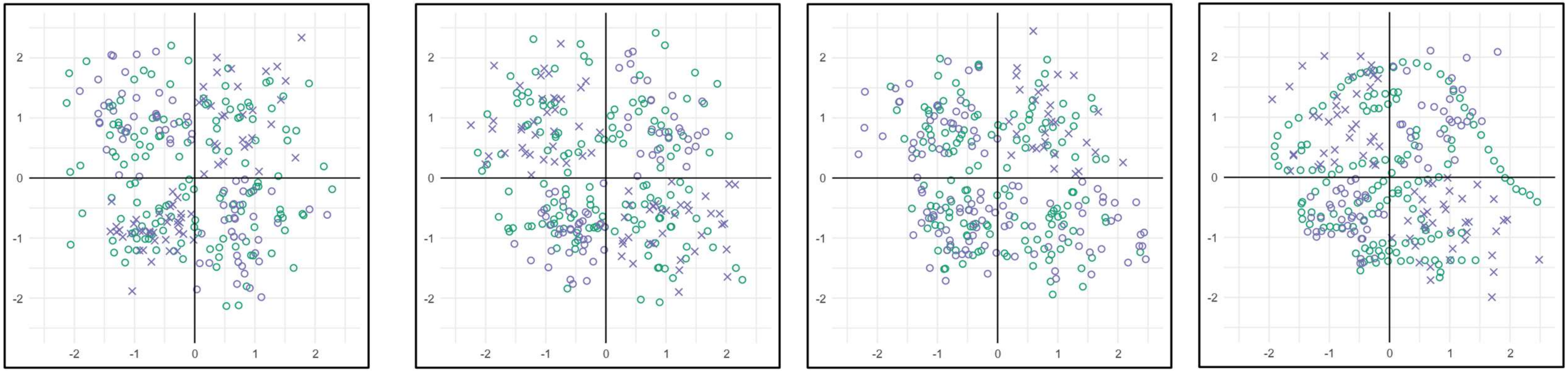
E.g. for the graphic at right:
- which student had the highest test score?
- Which student had a higher score on the first test than on the second?

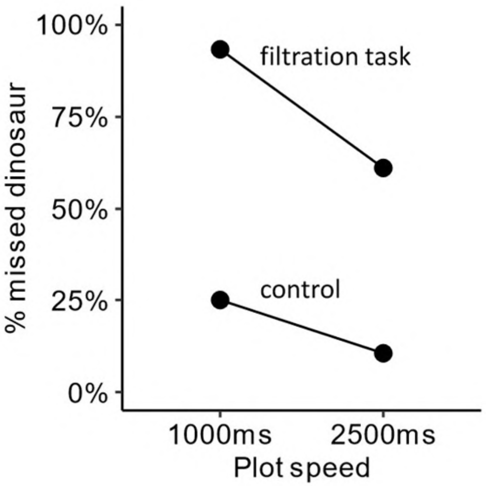
Designers should keep in mind what kind of questions will be asked from the data.



Attention is an extremely powerful factor in graphic reading

Your task is to attend to the blue X symbols, and decide if their trend is increasing, decreasing, or stable.





A vast majority of participants are unable to see the dinosaur.

A control condition show that the dinosaur is fairly visible in the absence of the filtering task.

Conclusions:

- Attention is an extremely powerful filter (both positive and negative)
- Don't assume that people can see what you easily see !
- This experiment is consistent with the idea that graphic perception involves a dorsal route and inhibits the ventral visual pathway for shape recognition .

Boger, T., Most, S. B., & Franconeri, S. L. (2021). Jurassic Mark : Inattentional Blindness for a Datasaurus Reveals that Visualizations are Explored, not Seen. *2021 IEEE Visualization Conference (VIS)*, 71-75. https://doi.org/10.1109/VIS49827.2021.9623273

The superiority of graphics also involves long-term memory retention

Ciccione, Caroti, Liu, Giardino, Pasquinelli & Dehaene, submitted

Lorenzo Ciccione

For large arrays, the superiority of graphics is easy to understand (speed of perception, facility of comprehension).

Several questions remain open:

- Are graphics useful **even for a very small number of data points**?
  - The idea of maximizing the data/ink ratio (Tufte) suggests that graphs are not needed when the number of data points is small – putting the data in a table or text may suffice.
  - However, graphs may also be easier to **remember** in pictorial form.

- Are graphics superior, not only for perception and comprehension, but also for long-term memory?
  - In this study, we ensure identical immediate perception and short-term memory, and study the impact on long-term memory.

An inconvenient truth (Al Gore), 2013
https://www.youtube.com/watch?v=-JIuKjaY3r4 at 3:29

Subjects were randomly divided into four groups, each consisting of the same 4 socio-economic topics to read in a different random order (40 seconds per topic).
Each topic could be presented in each of 4 formats.

In the long-term group, two hours later, a surprise memory test about these topics and their trends was proposed to subjects.

The questions were formulated as sentences with four possible choices (e.g. variable Y increased; decreased; stagnated; had a peak).

Crucially, the correct answer was presented using the exact same words used in the "text" condition.

In the short-term group, the same question was asked immediately after turning the page, plus two about

- The range of values of Y
- A specific value

1) ONLY TEXT

La consommation de pain en France depuis 1970

La consommation individuelle quotidienne moyenne de pain en France a diminué depuis les années 1970. En 1970, cette consommation quotidienne était de 184 grammes par jour et par habitant. Depuis, cette consommation par jour et par habitant est passée de 172 grammes en 1980, 160 grammes en 1990, 149 grammes en 2000 à 137 grammes en 2010. En 2020, cette consommation était de 128 grammes par jour et par habitant.

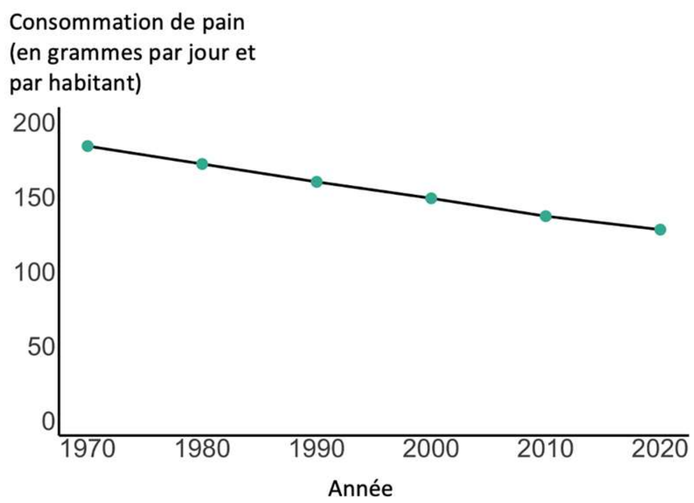
2) NUMERICAL TABLE

La consommation de pain en France depuis 1970

Année	Consommation de pain (en grammes par jour et par habitant)
1970	184
1980	172
1990	160
2000	149
2010	137
2020	128

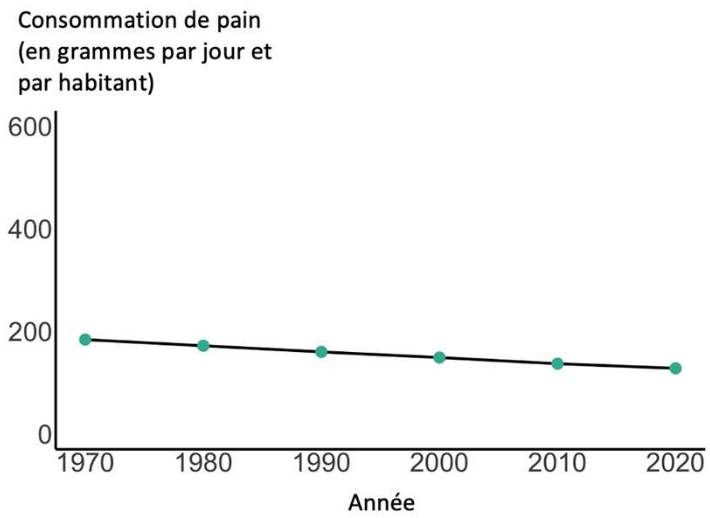
3) GRAPHIC

La consommation de pain en France depuis 1970



4) MISLEADING GRAPHIC

La consommation de pain en France depuis 1970

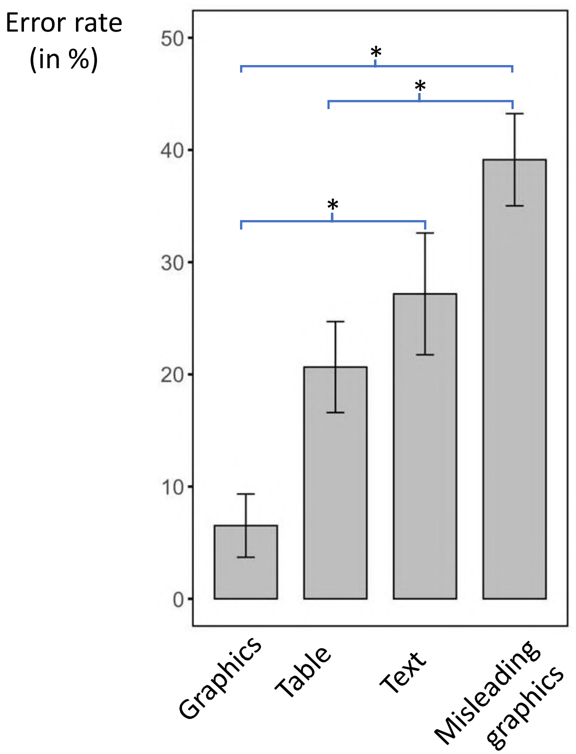


The superiority of graphics over text in long-term memory retention

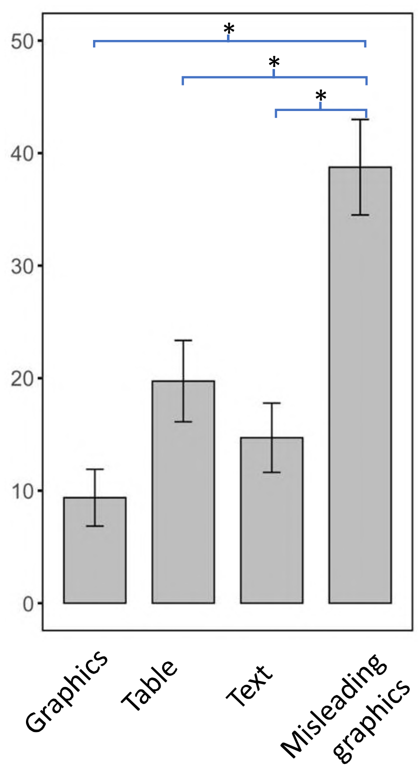
Ciccione, Caroti, Liu, Giardino, Pasquinelli & Dehaene, submitted

Recall of overall trend

Exp 1: 2 hours delay

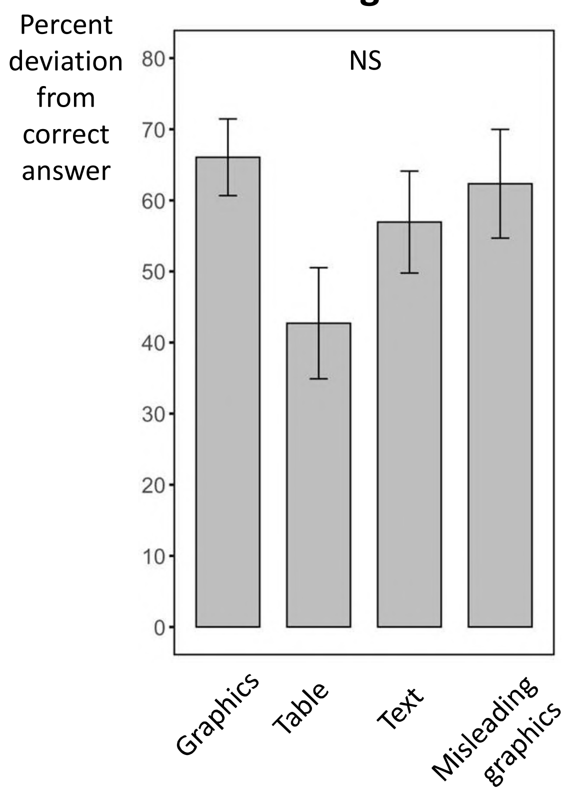


Exp 2: immediate

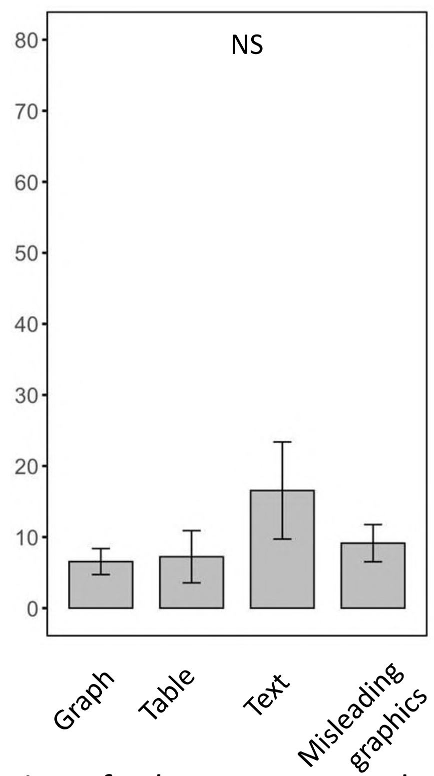


Immediate recall of numerical values

Range



Specific values



After two hours, the trend of a graph was remembered **much** better that any other presentation, including the same exact text.

In immediate recall, graphs were no different from tables or texts, although subjects could be misled by a wrong scale

With only 5 or 6 values, perception of values was as good with graphs as with other formats.
BUT… after 2 hours, even for small numbers of points, graphs leave a stronger memory trace.

Is a graphic always worth a thousand words?

After Kosslyn, S. M. (2006). *Graph Design for the Eye and Mind*. Oxford University Press, USA.

According to Kosslyn's review, it depends on the **task** that one is trying to solve, and the quality of the graphic.

"Umanath and Scamell (1988) compared a table to a bar graph and found that the graph was better for **recall of rank order** and pattern information, whereas the table was as good as the graph for specific point values

"Spence and Lewandowsky (1991) found that both pie and bar graphs were superior to a table when **relative values had to be compared**—even if only a few numbers were involved (counter to the suggestion of Tufte, 1983)"

"Moriarity (1979), Stock and Watson (1984), Nawrocki (1973), and Schwartz (1984) all found that participants performed better with graphics displays than with tables in **decision-making contexts**.

Graphs "reduce the effort of using specific mental processes and […] the amount of search necessary".

An important point: "Meyer, Shamo, and Gopher (1999) showed that **graphs are in fact more effective than tables when the data are not random".** Thus, laboratory tasks should not make use of random graphs.

"Umanath and Vessey (1994) found that graphs were better than tables when the participants had to use the data to **predict future events** (in this case, the probability that a company would go bankrupt). "

"Finally, for some tasks, graphs are particularly useful only if they distinguish between relatively important versus unimportant information, varying visual salience so that readers can immediately sort the grains of gold from the sand. […] Indeed, MacGregor and Slovic (1986) found that when a display **emphasized the relevant aspects of the data** in this decision-making task, it was more effective than a table."

"In short, although graphs are not always superior to tables, the bottom line—as I read it—is that graphs are more effective than tables **when relations among values are critical**".

Obviously the effectiveness of graphs and tables depends on the **quality of their design**. "If you want to convey both relations among data and absolute values, consider putting a few numbers in critical places on the graph".

How to maximizing readability: Critiques of Tufte's data / ink ratio hypothesis

Kosslyn (2006) stresses that a graphic should be designed with a specific reader and task in mind (cf Sperber's relevance theory)

On the **data** side, maximizing the amount of data is not necessarily a good idea. **Which** data to show or to omit must be carefully selected, based on how useful it is to the viewer.

- In general, one should avoid putting too much data on a graph.
- But there exceptions: geographical maps and other exploratory graphics that have a large variety of uses.

We may distinguish **communication** graphics, meant to convey a specific point, and **reference** graphics, meant to store and retrieve a very high density of information

On the **ink** side : it is a bad idea to remove elements that facilitate **fast grouping and parsing**. Kosslyn (2006): "These grouping effects sometimes require adding lines (e.g., to create symmetry). To obtain them, you will sometimes need to violate Tufte's (1983) recommendation […]. Carswell (1992a), in her review of the literature on graph reading, found little support for the importance of a high data:ink ratio. As Spence (1990) points out, contrary to this advice, more ink may allow people to read displays more quickly in some circumstances. For example, in one of his experiments Spence found that participants could compare two boxes faster than two vertical lines. **As a general rule, additional ink should be helpful if it completes a form, resulting in fewer perceptual units.**

Examples: putting a frame around the legend ; adding an arrow to point to a specific line or point.

Graphics design

Graphic design should maximize their utility and efficacy for the viewer.

Many books and sites make specific recommendations, e.g. ACCENT.

ACCENT Principles for effective graphical display

The essence of a graphic is the **clear communication of quantitative information**. The ACCENT principles emphasize, or *accent*, six aspects that determine the effectiveness of a visual display for portraying data.

- **Apprehension:** Ability to correctly perceive relations among variables. *Does the graphic maximize apprehension of the relations among variables?*
- **Clarity:** Ability to visually distinguish all the elements of a graphic. *Are the most important elements or relations visually most prominent?*
- **Consistency *(cohérence)*:** Ability to interpret a graphic based on similarity to previous graphics. *Are the elements, symbol shapes and colors consistent with their use in previous graphics?*
- **Efficiency:** Ability to portray a possibly complex relation in as simple a way as possible. *Are the elements of the graphic economically used? Is the graphic easy to interpret?*
- **Necessity:** The need for the graphic, and the graphical elements. *Is the graphic a more useful way to represent the data than alternatives (table, text)? Are all the graphic elements necessary?*
- **Truthfulness:** Ability to determine the true value represented by any graphical element by its magnitude relative to the implicit or explicit scale. *Are the graphic elements accurately positioned and scaled?*

From Michael Friendly, ACCENT Principles for effective graphical display (datavis.ca)
Adapted from: D. A. Burn (1993), "Designing Effective Statistical Graphs". In C. R. Rao, ed., *Handbook of Statistics*, vol. 9, Chapter 22.

Which perceptual channels are most effective ?

Munzner, T. (2014). *Visualization Analysis and Design* (1er édition). A K Peters/CRC Press.

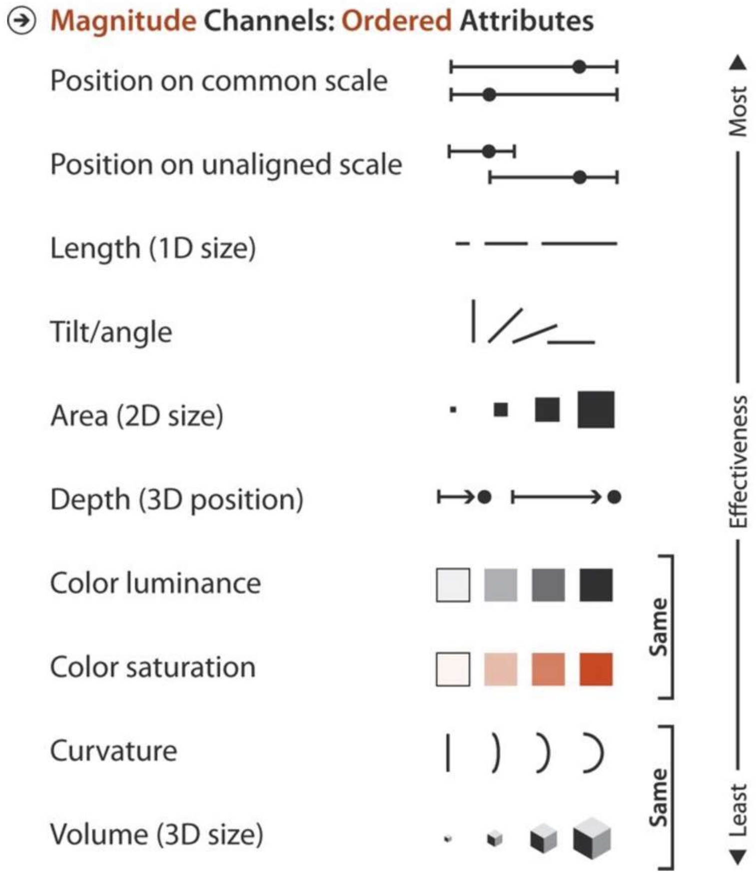
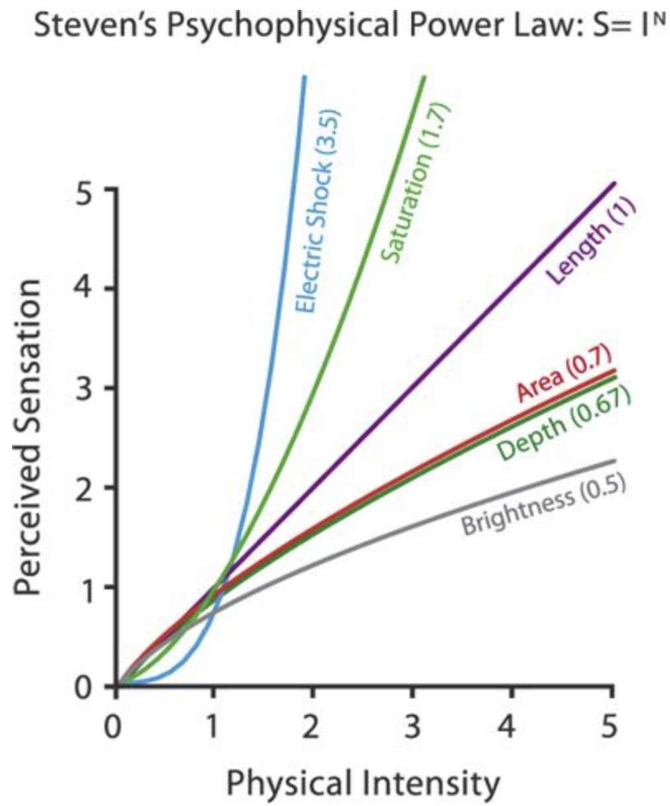


Figure 5.1. The effectiveness of channels that modify the appearance of marks depends on matching the expressiveness of channels with the attributes being encoded.

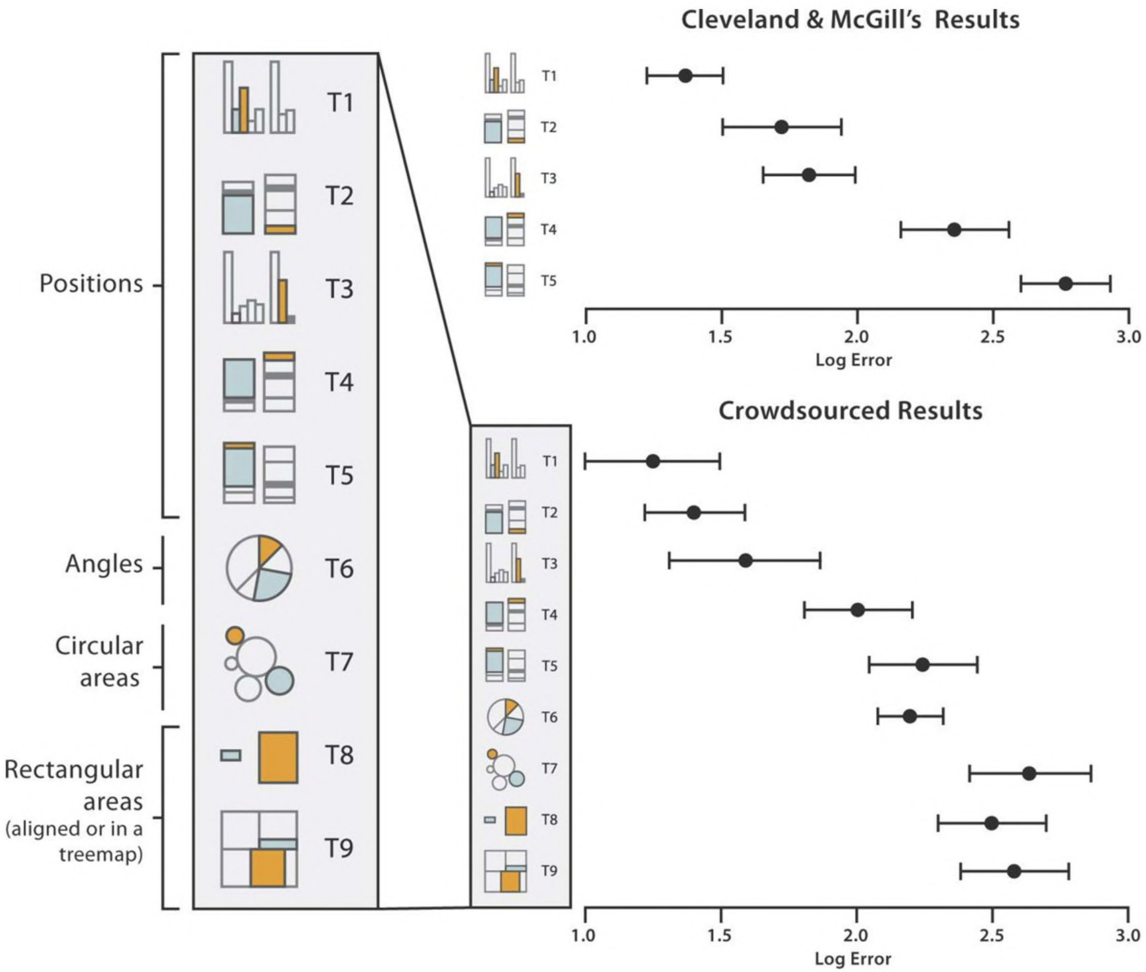
Munzner proposes a systematic ordering of perceptual channels to **faithfully convey magnitudes** and identities.

It is, in part, due to Stevens' power law S = I^n, whose exponent should be closest to 1.

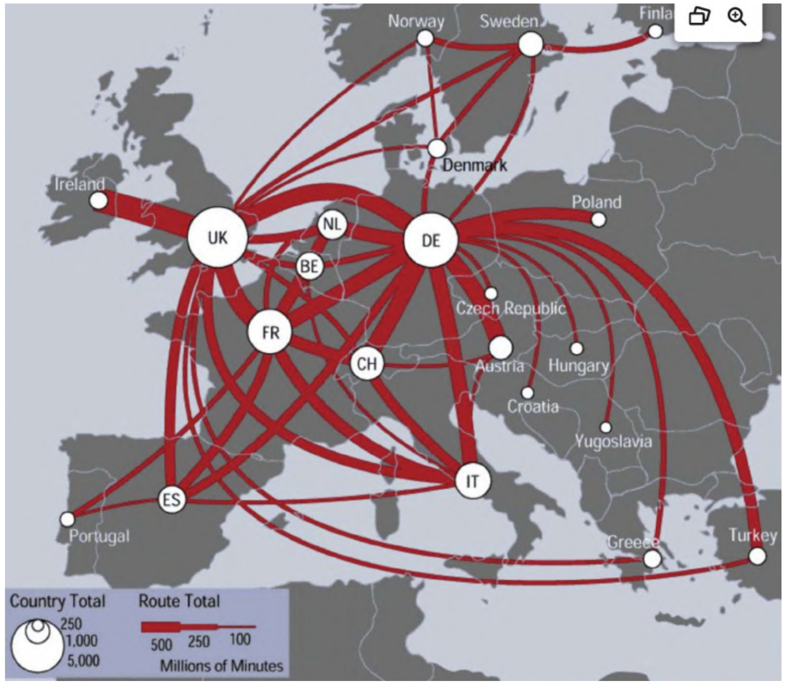


Which perceptual channels are most accurate and discriminable ?

Munzner, T. (2014). *Visualization Analysis and Design* (1er édition). A K Peters/CRC Press.
Following pionnering studies by Cleveland, W. S., & McGill, R. (1985). Graphical Perception and Graphical Methods for Analyzing Scientific Data. *Science*, *229*(4716), 828-833. https://doi.org/10.1126/science.229.4716.828 ; See also Franconeri et al. (2021) for a nice extensive review.



Another measure is **accuracy**, or the amount of error in the perception of magnitudes.
Position always comes on top, with best results achieved when the data is properly aligned and scaled by explicit axes.
A third key parameter is **discriminability**, which can be very limited (e.g. line thickness). Shapes must be carefully selected.

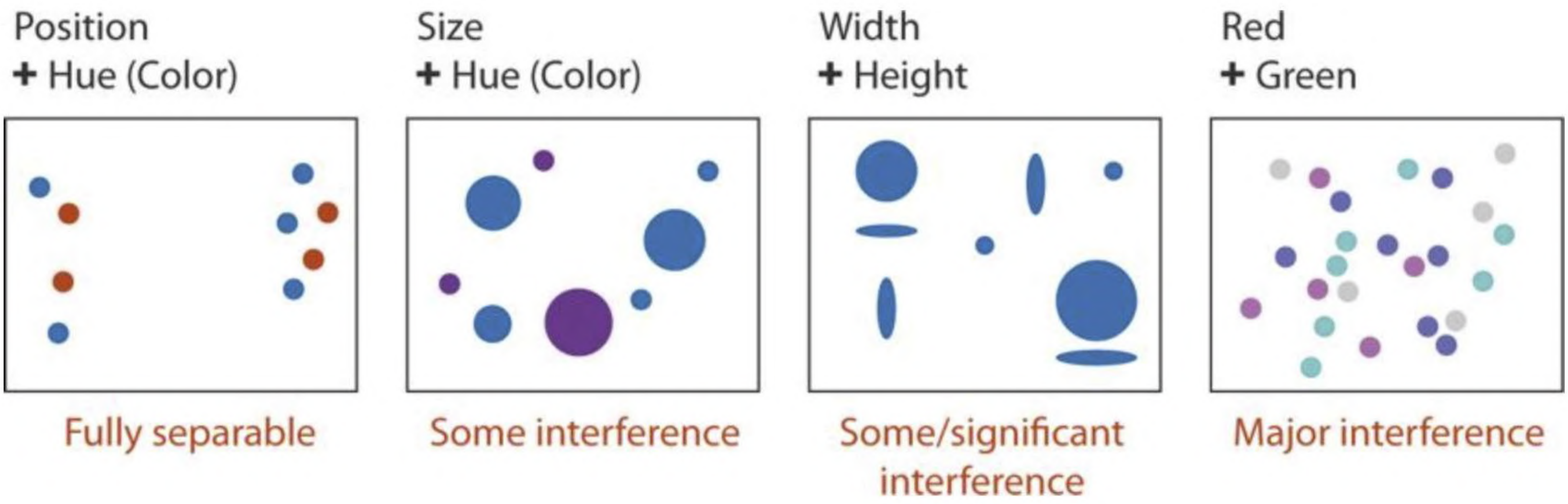


Which perceptual channels are separable ?

Munzner, T. (2014). *Visualization Analysis and Design* (1er édition). A K Peters/CRC Press.

When conveying multiple variables, another essential parameter is separability.

- x/y plots, such as scatterplots, provide fully separable access to two dimensions. Color is a third one.
- Other combinations create some interference



Which types of graphics yield the most accurate perception of proportions ?

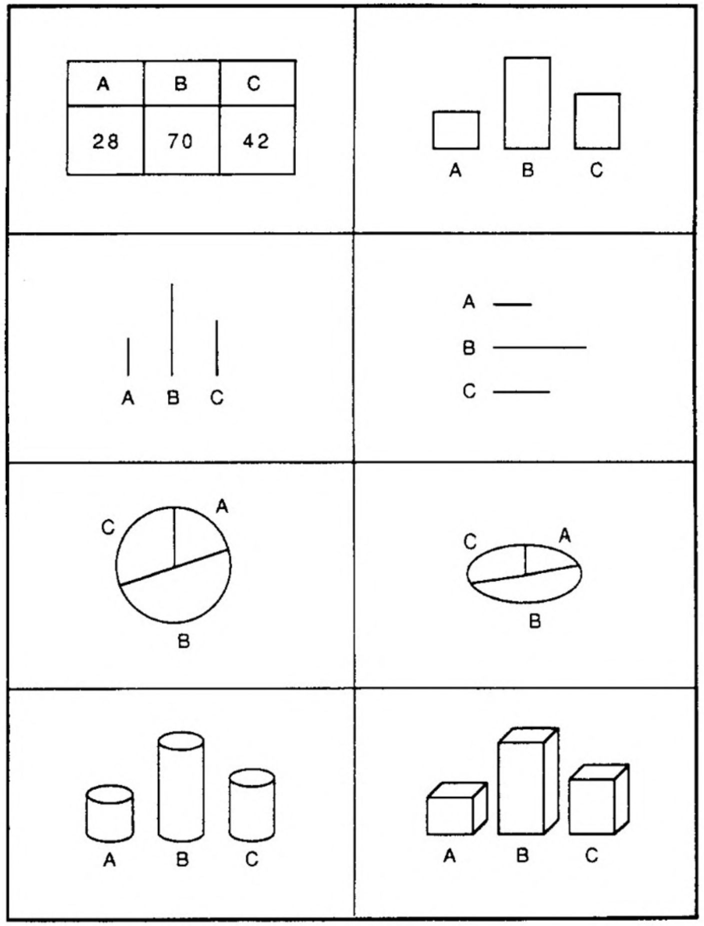


Figure 1. One table (top left) and seven graphs that display the same numerical data. The table elements are numbers. The graphical elements are bars, lines [vertical], lines [horizontal], pie slices, disk slices, cylinders, and boxes.

Spence, I. (1990). Visual psychophysics of simple graphical elements. *Journal of experimental psychology: Human perception and performance*, *16*(4), 683.

On each trial, participants must evaluate in which proportion a bar has been split into two.

Assuming that each quantity is represented internally according to Stevens' law $\phi = \alpha\Pi^{\beta}$

Then the response should be placed at position

$$P = \frac{\alpha\Pi^{\beta}}{\alpha\Pi^{\beta} + \alpha(1 - \Pi)^{\beta}}$$

$$= \frac{1}{1 + [(1 - \Pi)/\Pi]^{\beta}}$$

The closer the exponent beta is to 1, the more accurate the perception of proportions.

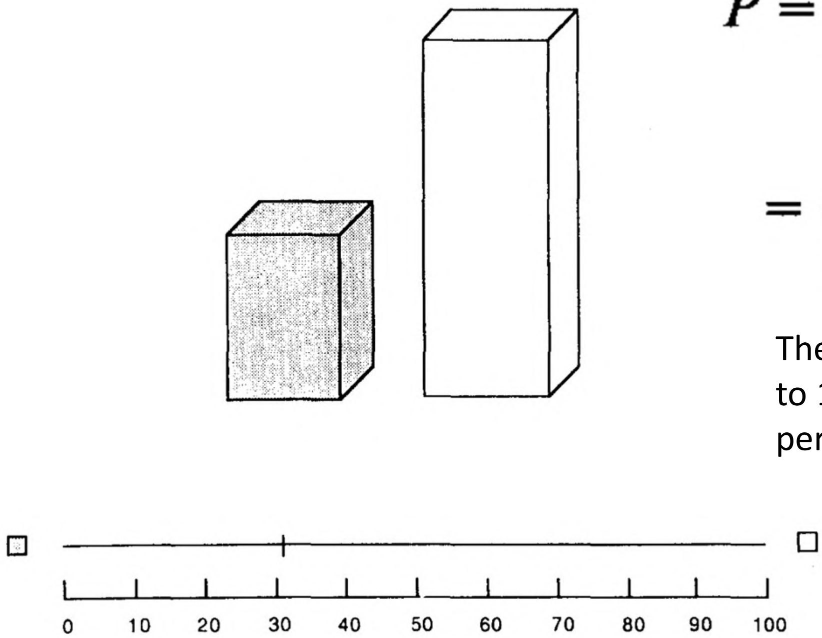


Figure 2. Task display. (Subject must position the cursor so that the horizontal line is divided in proportion to the apparent sizes of the elements, which are boxes in this example.)

Which types of graphics yield the most accurate perception of proportions ?

Spence, I. (1990). Visual psychophysics of simple graphical elements. *Journal of experimental psychology: Human perception and performance*, *16*(4), 683.

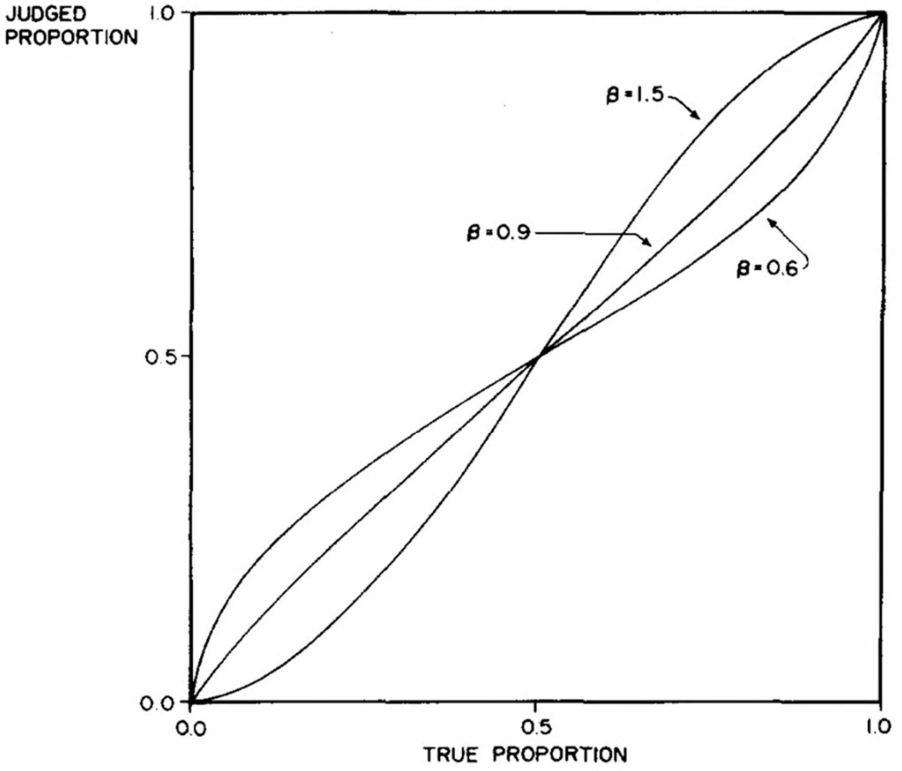
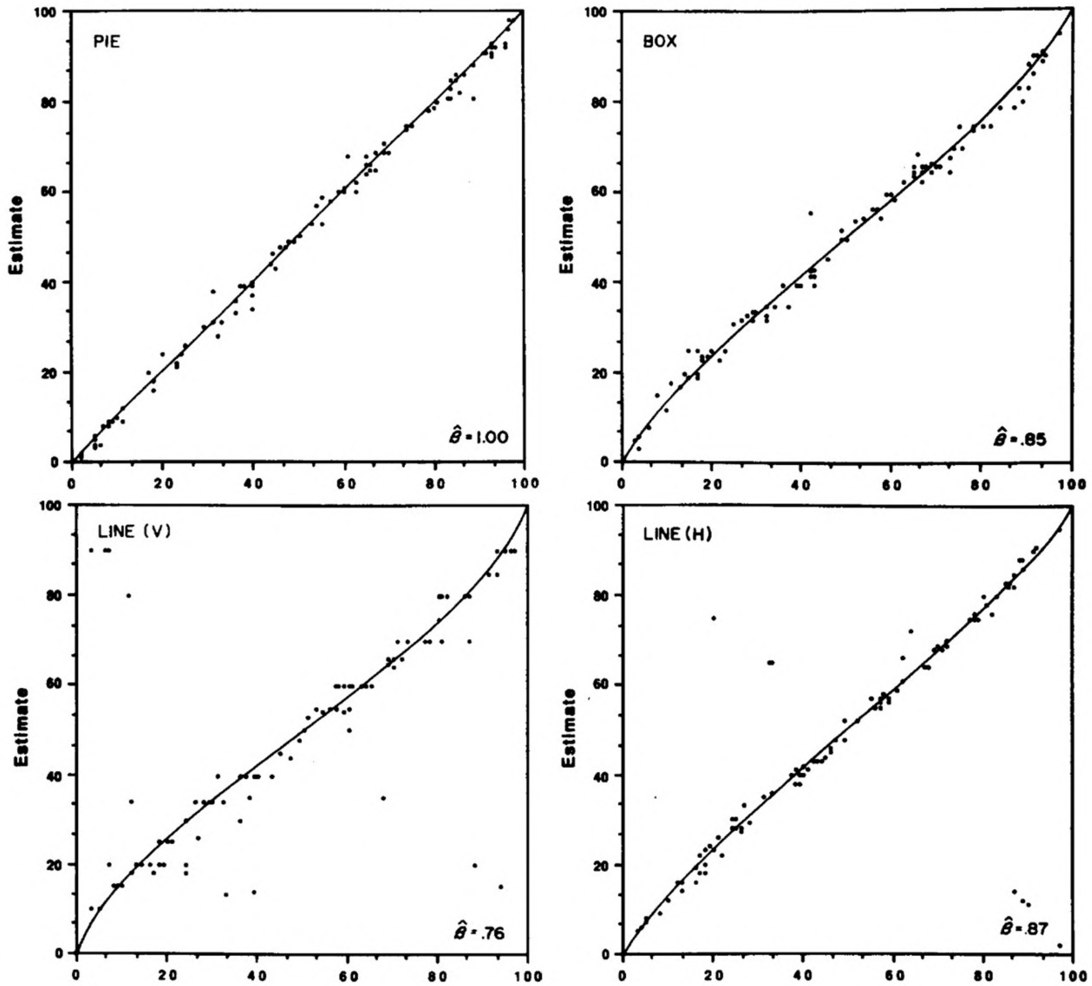


Figure 3. Three theoretical psychophysical functions for Stevens's exponents of 0.6, 0.9, and 1.5.



Which types of graphics yield the most accurate perception of proportions ?

Spence, I. (1990). Visual psychophysics of simple graphical elements. *Journal of experimental psychology: Human perception and performance*, *16*(4), 683.

Results:

- All exponents are not far from 1…. Surprisingly even for pie charts, which have a bad reputation.
- Judgements can be much faster for 3D and 2D objects, compared to simple lines – thus violating Tufte's rule.
- 2D and 3D features make chart elements more similar to real objects, thus facilitating their perception (neuronal recycling).
- Spence speculates that they may also make the graphic more attractive and thus enhance memory for the data.

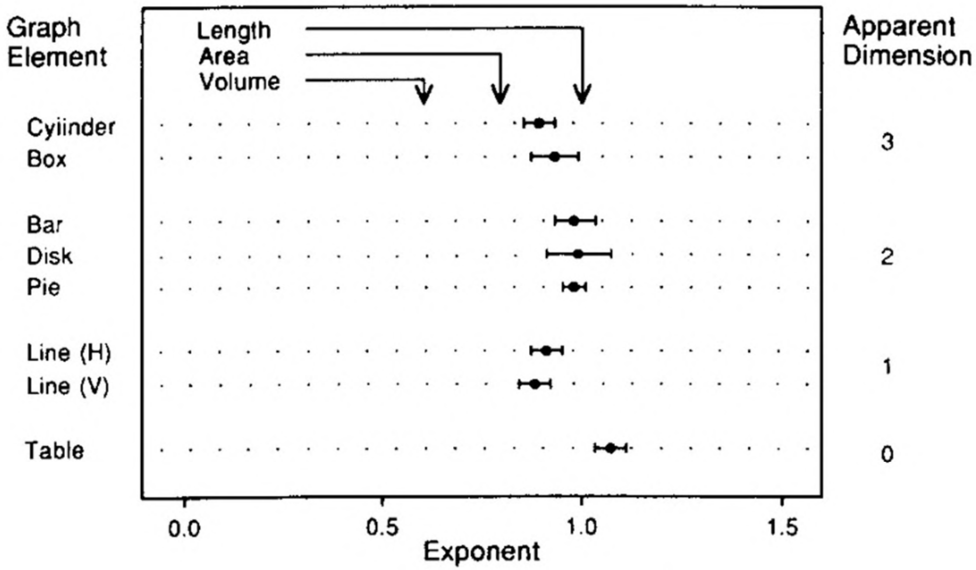


Figure 5. Dot chart with 95% confidence intervals showing the average exponent for each element.

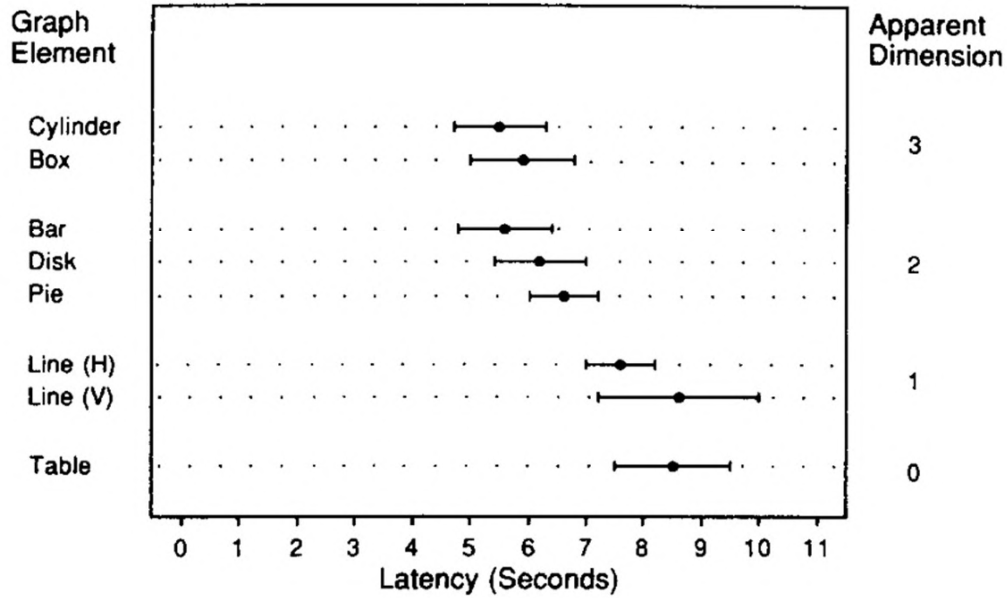
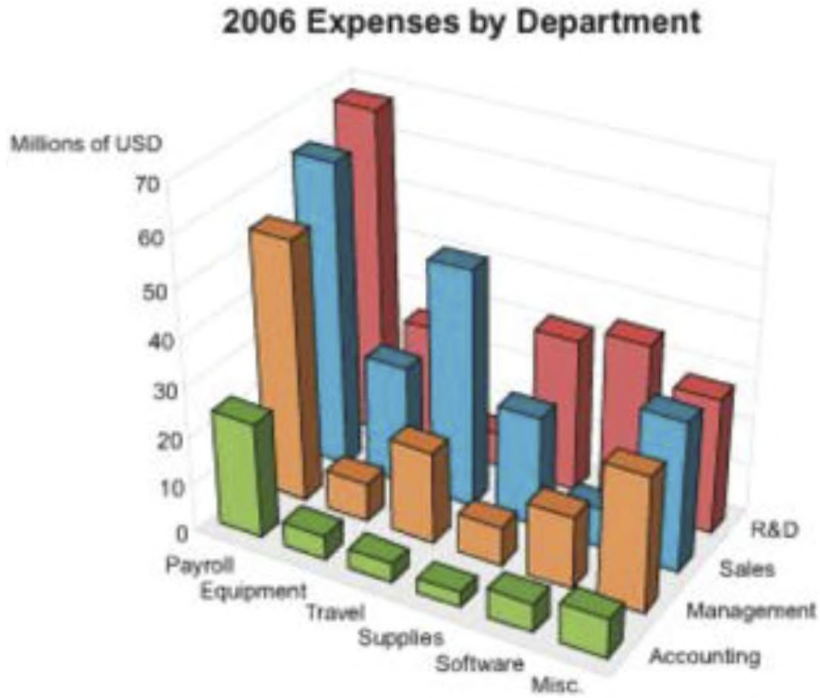


Figure 7. Dot chart with 95% confidence intervals showing the average latency (response time in seconds) for the elements.

Many other rules of thumb for graphics

Munzner, T. (2014). *Visualization Analysis and Design*. A K Peters/CRC Press.
Franconeri, S. L., Padilla, L. M., Shah, P., Zacks, J. M., & Hullman, J. (2021). The Science of Visual Data Communication : What Works. *Psychological Science in the Public Interest*, *22*(3), 110-161.



No unjustified 3D (for data; not for 3D computer-aided design)

- Visual perception always starts with a planar projection
- Depth is an imprecise inference from a 2D projection
- Occlusion hides information
- Perspective leads to data distortion

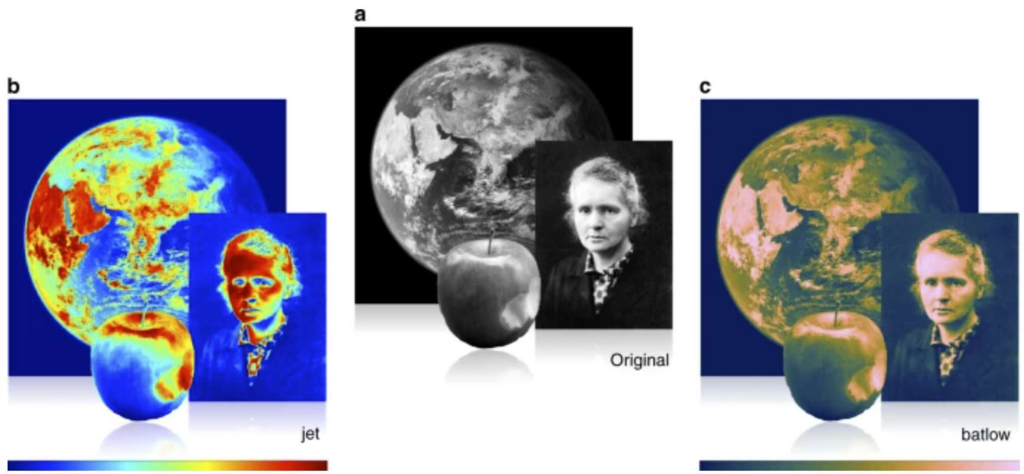
Eyes beat memory

- Make information explicit in simultaneously visible, parallel graphs, rather than animations
- Avoid change blindness (add arrows, etc.)
- Avoid acronyms

More generally, rely on the cognitive science of perception

- For instance, use scientifically designed color scales

(see resources at Crameri, F., Shephard, G. E., & Heron, P. J. (2020). The misuse of colour in science communication. *Nature Communications*, *11*(1), 5444. https://doi.org/10.1038/s41467-020-19160-7



The importance of titles and legends : Never use vertical writing

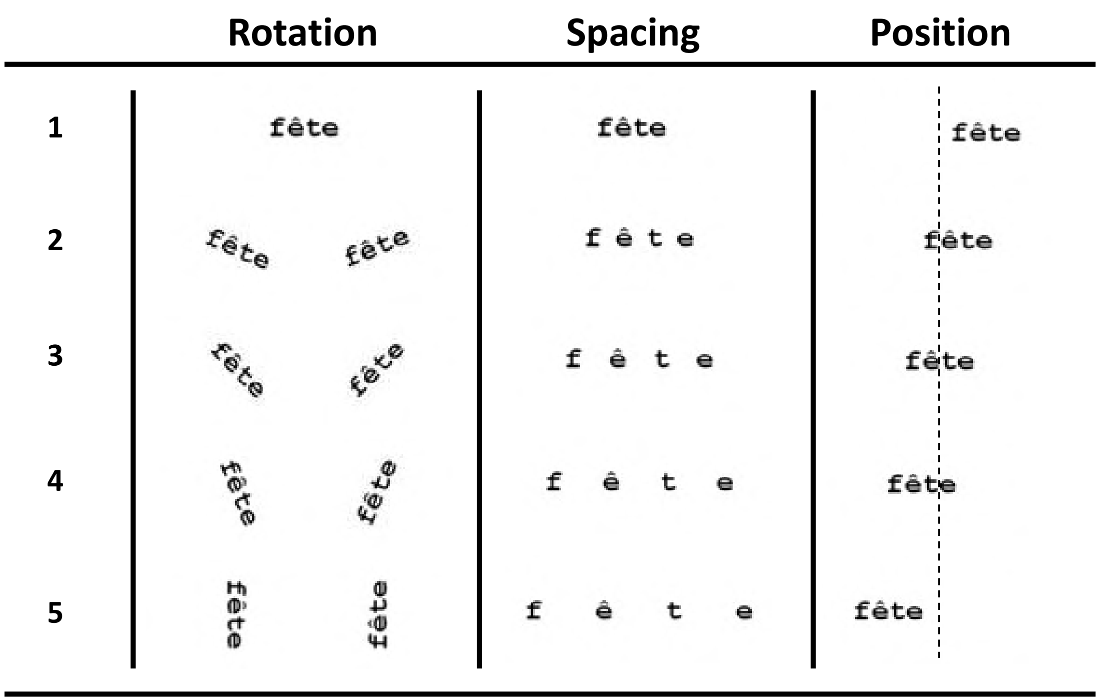
Cohen, L., Dehaene, S., Vinckier, F., Jobert, A., & Montavont, A. (2008). Reading normal and degraded words : Contribution of the dorsal and ventral visual pathways. *Neuroimage*, *40*(1), 353-366.

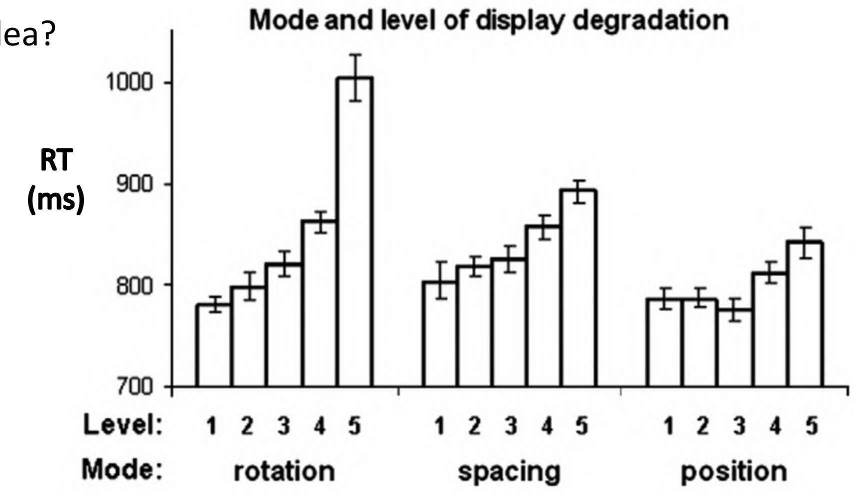
Especially on the Y axis, it is tempting to write the legend vertically – but is it a good idea?

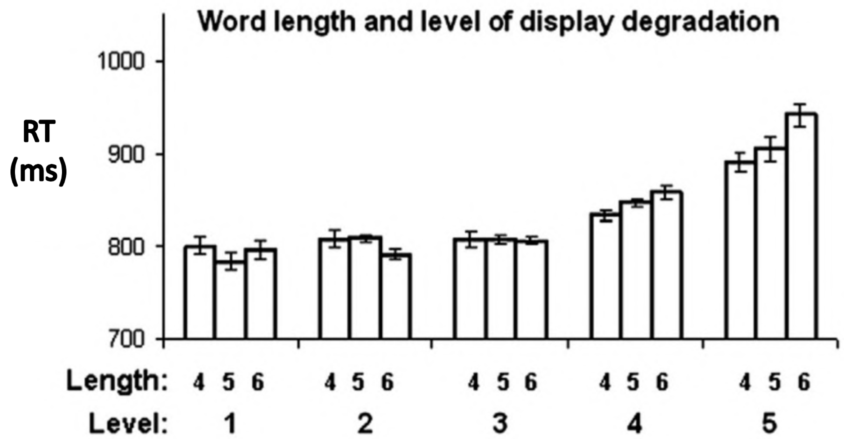
With Fabien Vinckier, we tested the impact of rotating, spacing or displacing words.

Behaviorally, reading is massively slowed, and an effect of word length emerges.

Three modes of word degradation





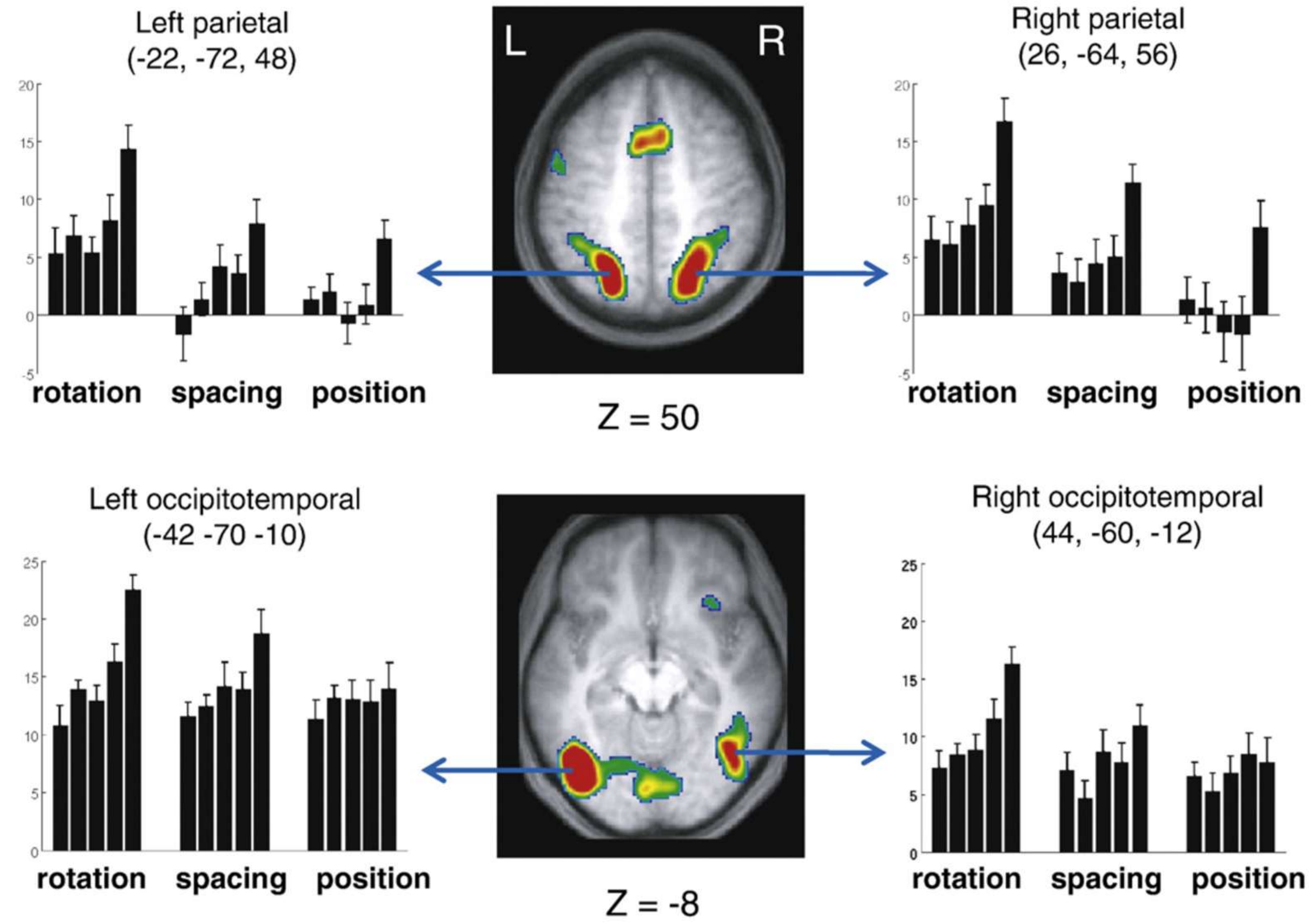


Why you should never use vertical writing

Cohen, L., Dehaene, S., Vinckier, F., Jobert, A., & Montavont, A. (2008). Reading normal and degraded words : Contribution of the dorsal and ventral visual pathways. *Neuroimage*, *40*(1), 353-366.

Sudden onset of parietal activation common to all three degradation modes, but particularly strong for rotated stimuli.

Amplification of activation in the posterior VWFA
(peaking at the putative location of letter detectors)



Why you should never use vertical writing

Vinckier, F., Naccache, L., Papeix, C., Forget, J., Hahn-Barma, V., Dehaene, S., & Cohen, L. (2006). “What” and “Where” in Word Reading : Ventral Coding of Written Words Revealed by Parietal Atrophy. *Journal of Cognitive Neuroscience*, *18*(12), 1998-2012.

Normal ventral pathway

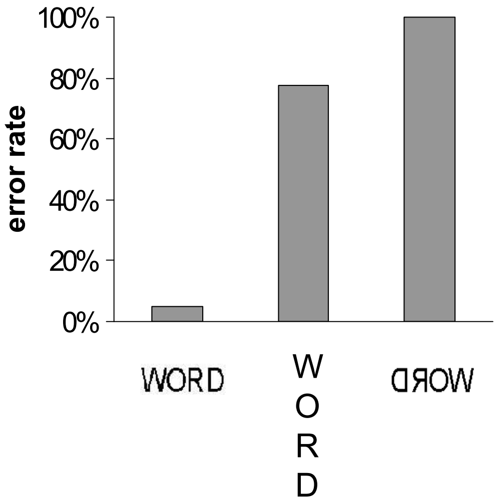
Impaired dorsal pathway

Following a bilateral parietal degeneration, the patient became unable to deploy attention serially in space (simultanagnosia).

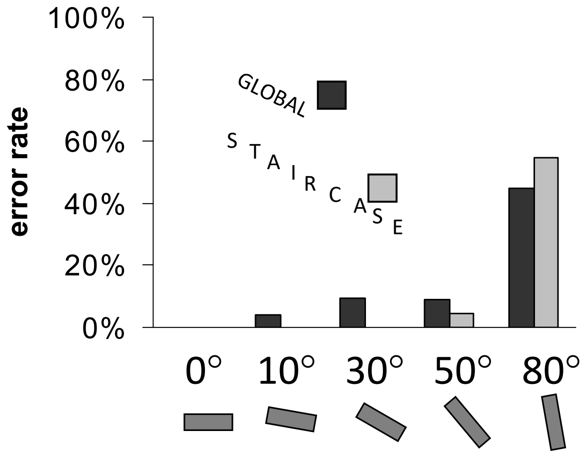
We used this case to exploit the limits of the isolated visual word form.

The results confirm that
- Normal reading is spared, doesn’t call upon the dorsal attention system
- Letter by letter reading becomes impossible
- Rotation poses a severe challenge to reading and requires a functional dorsal attentional pathway.

Orientation



Rotation angle



Conclusions

Graphics comprehension can be subdivided into

- A perceptual stage (internal identification)
- A comprehension stage (external identification)

Graphics are efficient because

- They **recycle** the **parallel processing** circuits in our visual cortex.
- They therefore permit the processing of **arbitrary data** by **recycling evolved circuits** for efficient visual perception.

In this way, graphics can be vastly superior to verbal or tabular form:

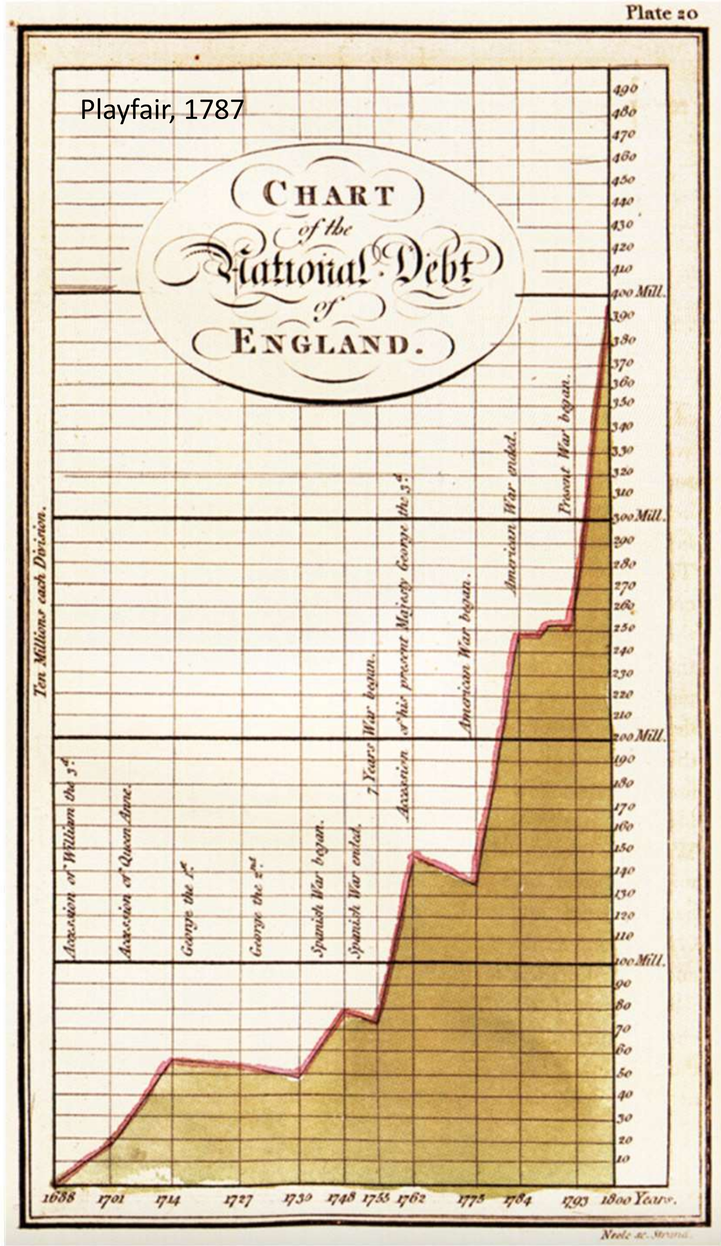
- in immediate comprehension
- in memory retention.

Good graphic design involves

- **maximizing fast, parallel readability**
- **minimizing the need for serial search**

Maximizing readability is not trivial:

- Leave enough “ink” to **easily parse** the graphic (contra Tufte)
- Select the most **efficient** dimensions to convey the corresponding scales (typically x and y locations, color, size)
- Avoid 3D, avoid calls to memory, vertical writing…



Playfair, 1787