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

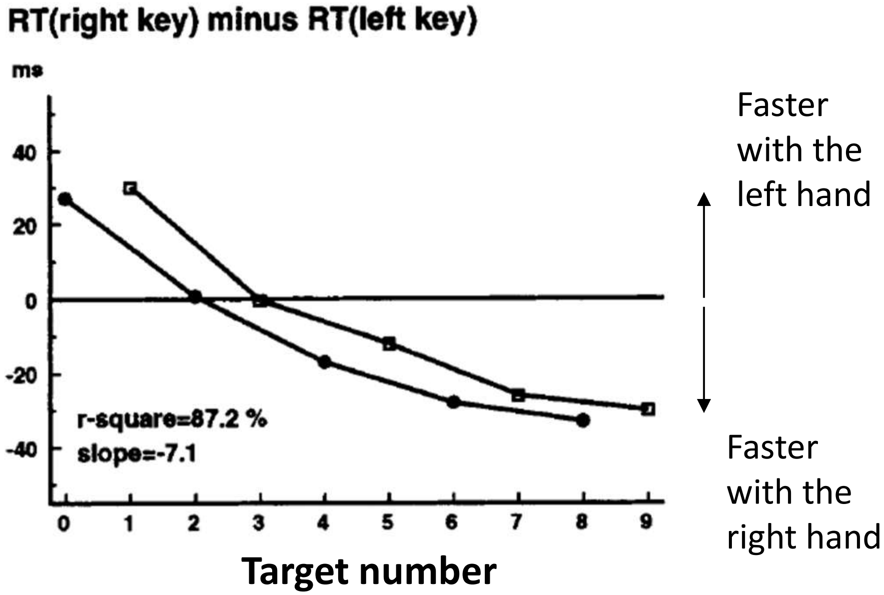
Cours n°3 bis

Mécanismes cérébraux de la correspondance entre le nombre et l'espace

Brain mechanisms of the mapping between numbers and space

Conclusions on number - space mappings

The mapping of numerical quantities onto space is an essential component of most graphics.



Fortunately, it is relatively **intuitive**:

- Many cultures invented measurement of space by numbers
- Intuitions of number-space mapping are present in
  - Remote cultures
  - Infants
  - Even non-human animals (chicks, monkeys, bees)

Even the **directionality** of the mapping is intuitive:

- SNARC effect : small numbers = left, larger numbers = right
- a left-to-right bias already exists in non-human animals and infants.

The **scale** seems to be initially compressive, and move to linear with education.

Today : What are the neural mechanisms of this mapping?

This mapping is probably due to the tight relations between **neural representations of number and space in the parietal lobe**.

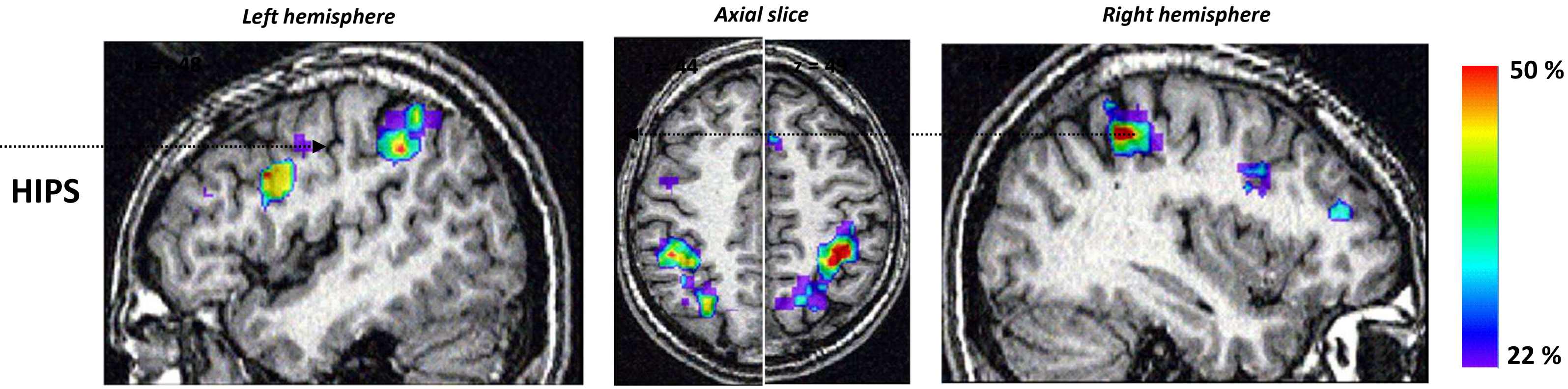
It **must** be tightly respected in graphics, for both efficiency and ethics reasons.

What is the place for the SNARC in the brain ?

"Just the place for a Snark!" the Bellman cried, As he landed his crew with care;
Supporting each man on the top of the tide By a finger entwined in his hair.
"Just the place for a Snark! I have said it twice: That alone should encourage the crew.
Just the place for a Snark! I have said it thrice: What I tell you three times is true."

the Bellman

A hypothesis:
the SNARC effect may occur due to overlapping activations for number sense and for space in the horizontal segment of the intraparietal sulcus (HIPS)



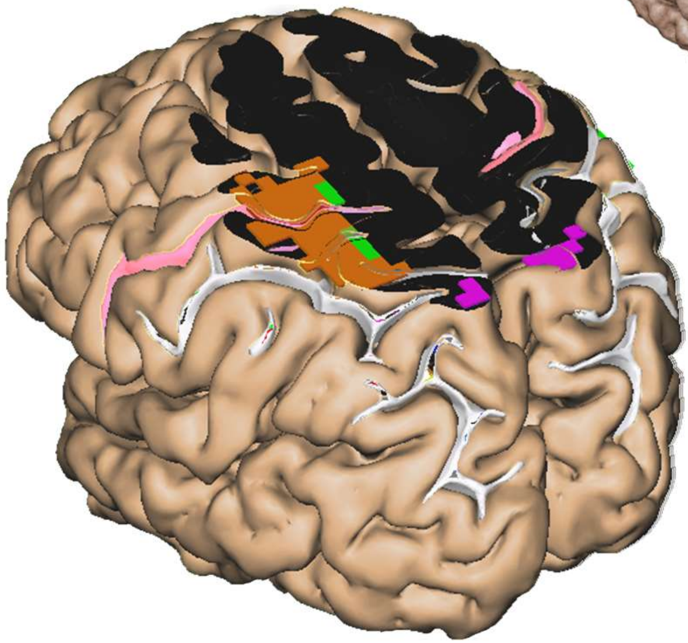
- All numerical tasks activate this region
  (e.g. addition, subtraction, comparison, approximation, digit detection…)
- This region fulfils two criteria for a semantic-level representation:

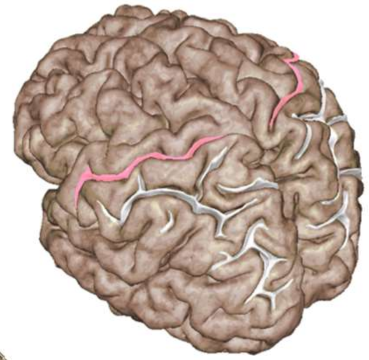
-It responds to number in various formats (Arabic digits, written or spoken words), more than to other categories of objects (e.g. letters, colors, animals…)
-Its activation varies according to a semantic metric (numerical distance, number size)

Dehaene, S., Piazza, M., Pinel, P., & Cohen, L. (2003). *Cognitive Neuropsychology*

An array of numerical and spatial areas around the intraparietal sulcus

- Calculation only
- Calculation and Language
- Grasping only
- Manual tasks
- Visuo-spatial tasks
- Attention only
- Saccades only



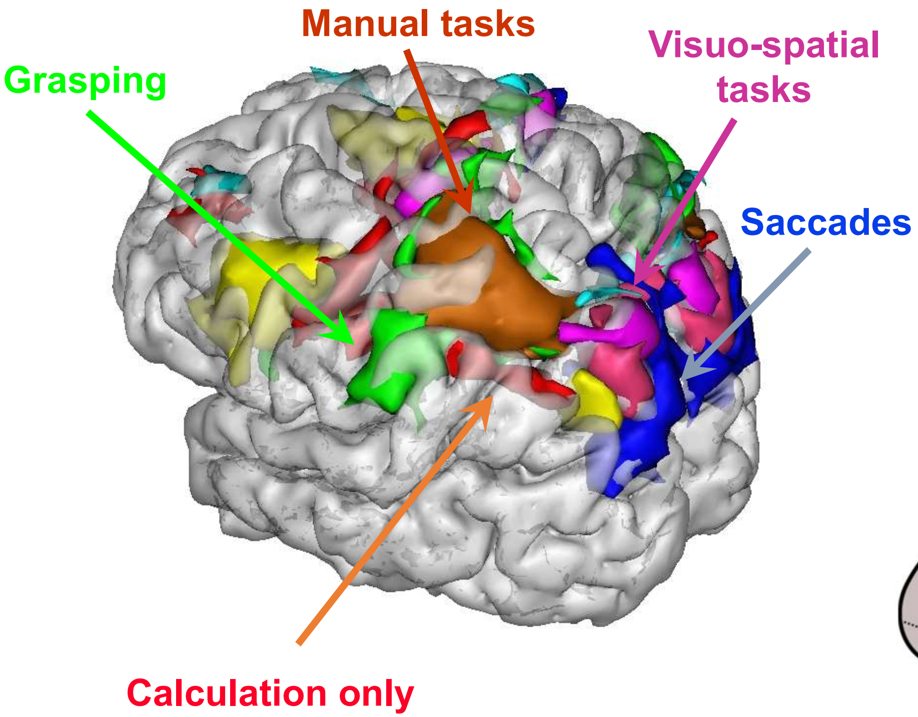


Simon, O., Mangin, J. F., Cohen, L., Le Bihan, D., & Dehaene, S. (2002). *Neuron, 33*(3), 475-487.

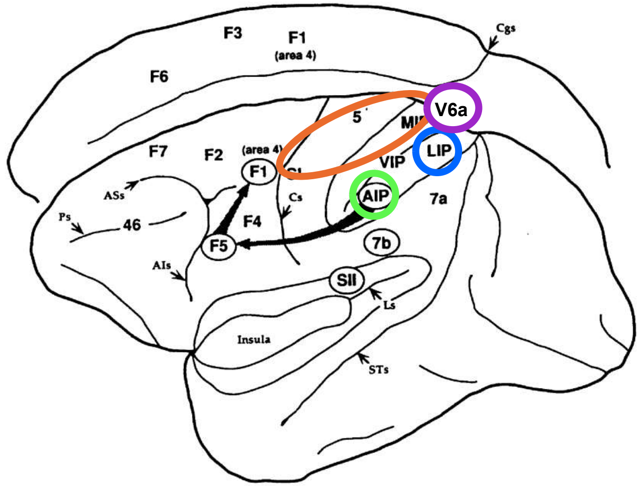
The intraparietal region:
a crucial site for number and space in the human and monkey brain

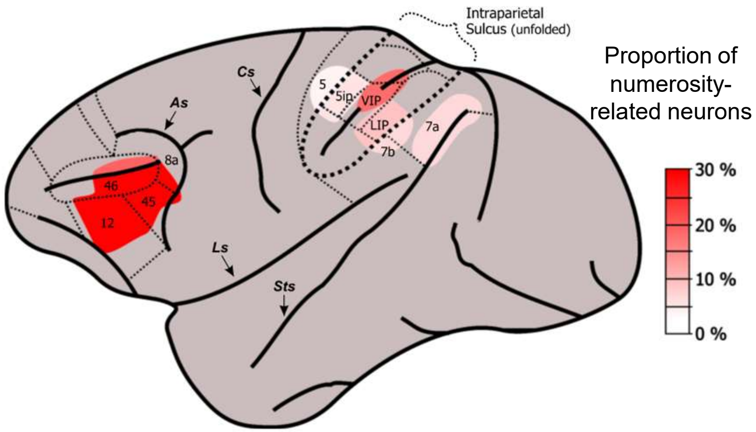
Simon et al, *Neuron 2002;* Nieder et al., *Science* 2002, *PNAS* 2004

Human brain



Macaque monkey





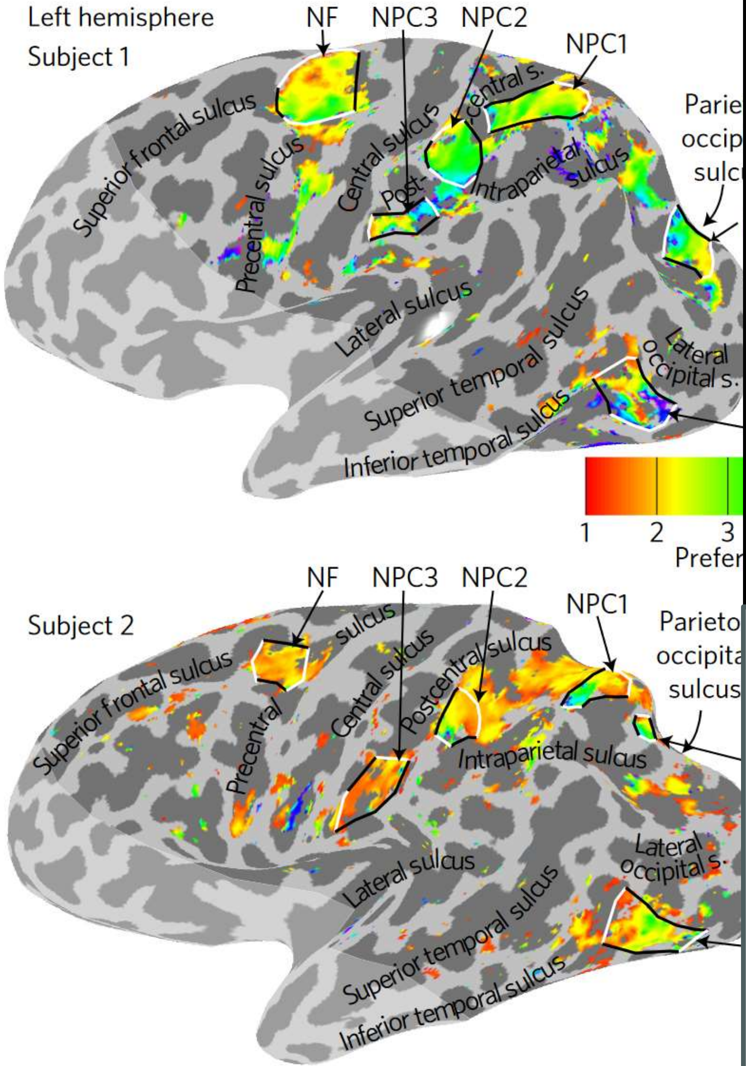
Topographic maps for number, object size, and attended location in parietal cortex

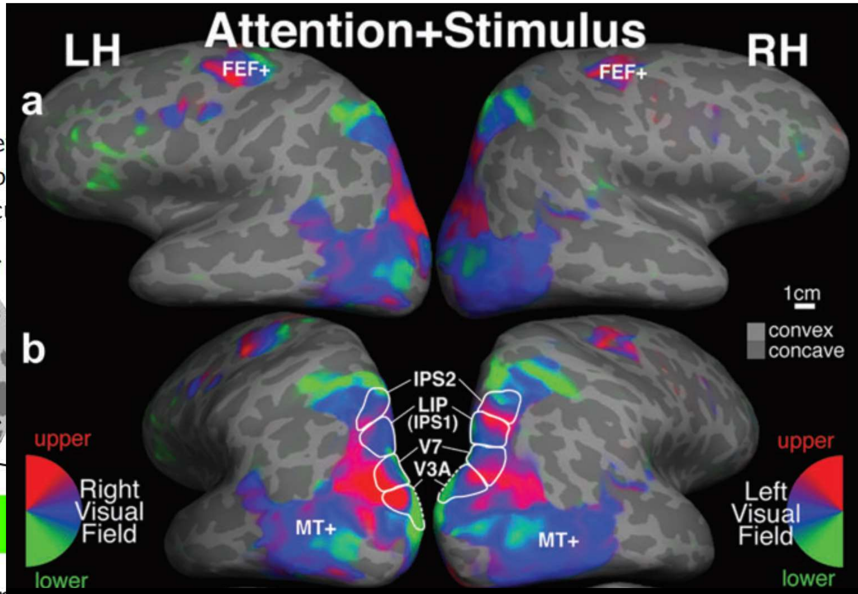
Harvey, B. M., & Dumoulin, S. O. (2017). A network of topographic numerosity maps in human association cortex. *Nature Human Behaviour*, *1*(2), Article 2. https://doi.org/10.1038/s41562-016-0036

Harvey, B. M., Klein, B. P., Petridou, N., & Dumoulin, S. O. (2013). Topographic Representation of Numerosity in the Human Parietal Cortex. *Science*, *341*(6150), 1123-1126. https://doi.org/10.1126/science.1239052

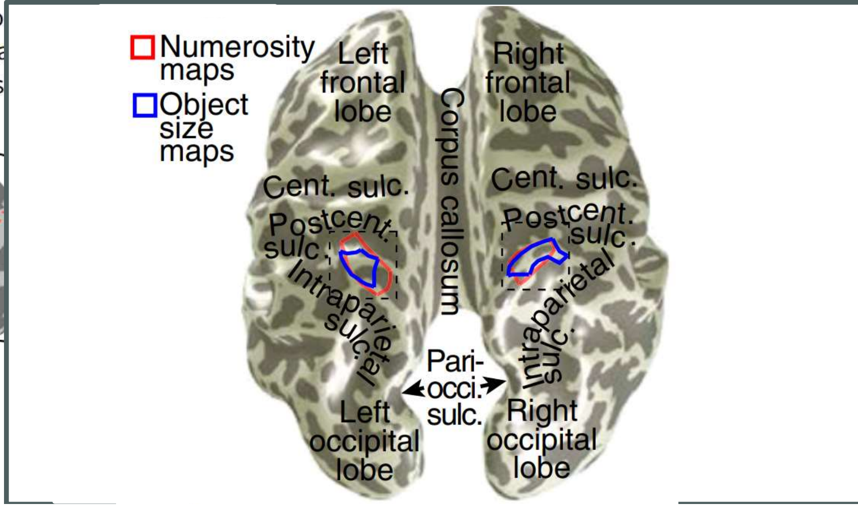
Overlap with the representation of object size:

Harvey, B. M., Fracasso, A., Petridou, N., & Dumoulin, S. O. (2015). Topographic representations of object size and relationships with numerosity reveal generalized quantity processing in human parietal cortex. *Proceedings of the National Academy of Sciences*, 112(44), 13525-13530. https://doi.org/10.1073/pnas.1515414112





Retinotopic maps: Saygin & Sereno 2008

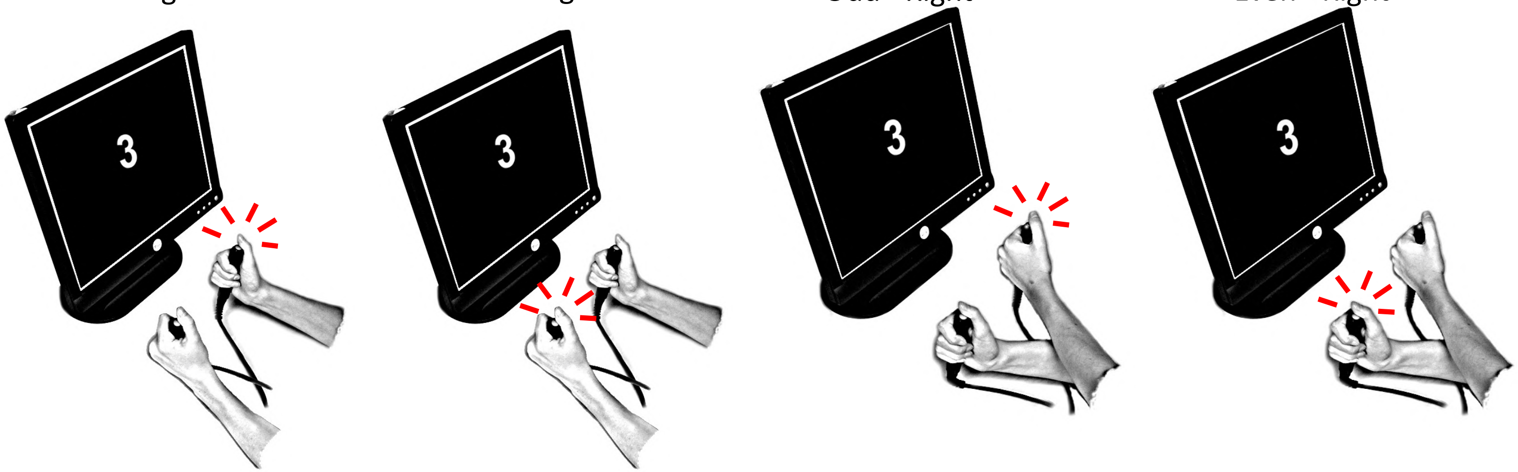


Ed Hubbard

Hunting the SNARC with fMRI

Hubbard, Pinel & Dehaene, 2006, unpublished manuscript

1. Parity judgment task



Three orthogonal factors: Hand (left or right); Side of space (left or right); Size of number (small or large)

2. Saccade Paradigm

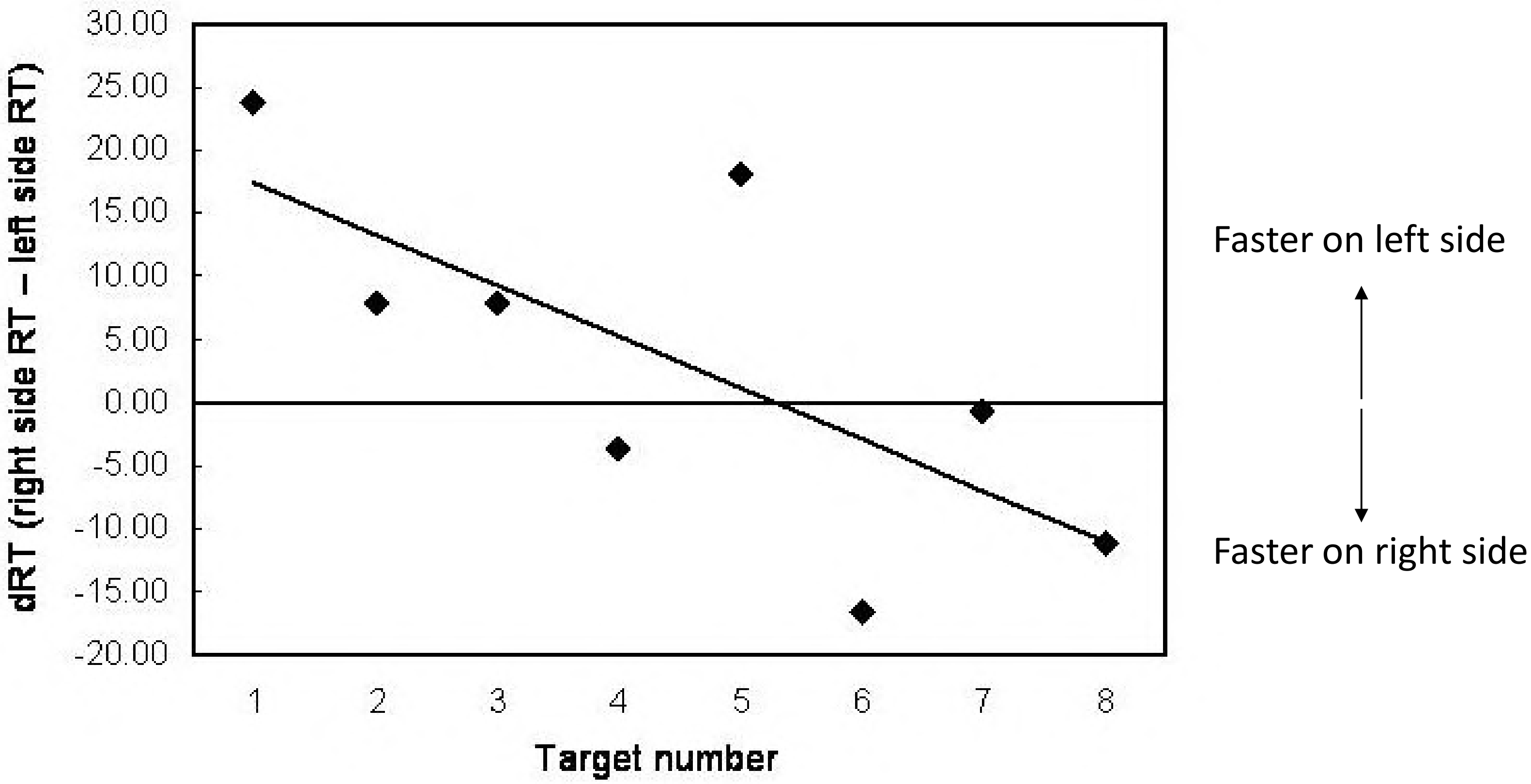
One factor: Saccade direction (left or right)

3. Arithmetic localizer

Activation to subtraction problem (spoken or written) relative to matched non-numerical sentences

Behavioral data collected during fMRI

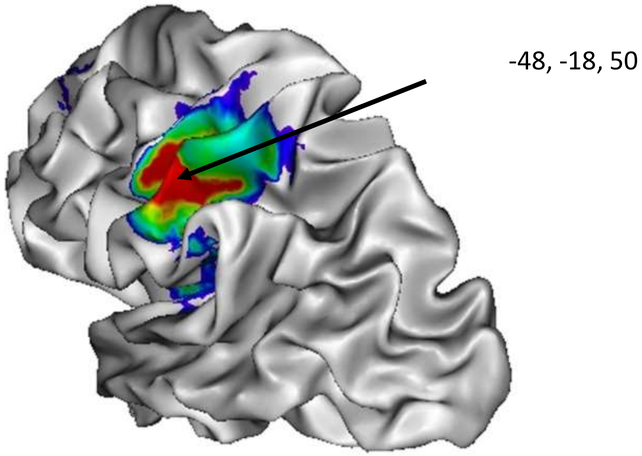
- replication of the SNARC effect
- association with side of space
no association with hand



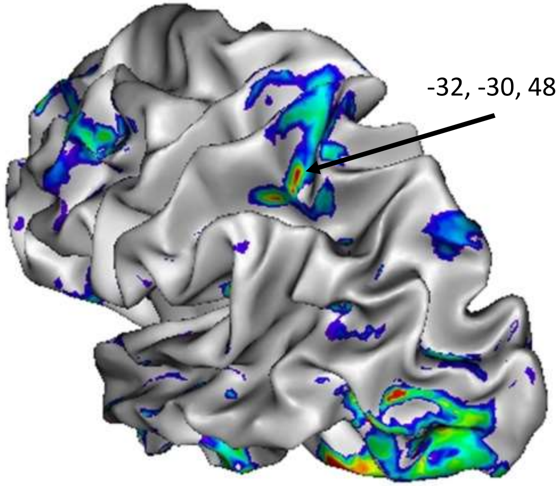
Hubbard, Pinel & Dehaene, 2006

Space and number: Definition of four parietal regions of interest (ROI)

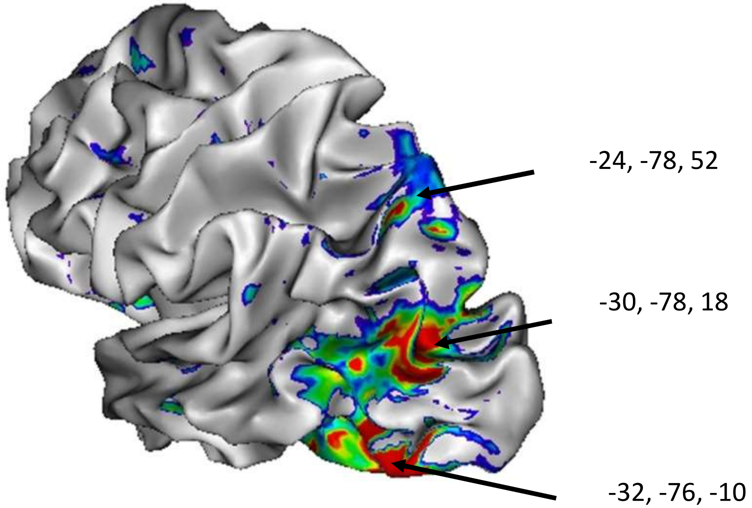
RESPONSE HAND
Right > Left Hand



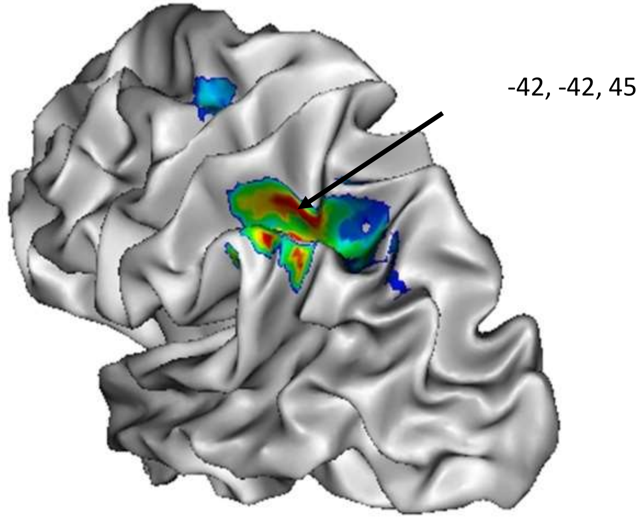
RESPONSE SPACE
Right > Left
Response Side



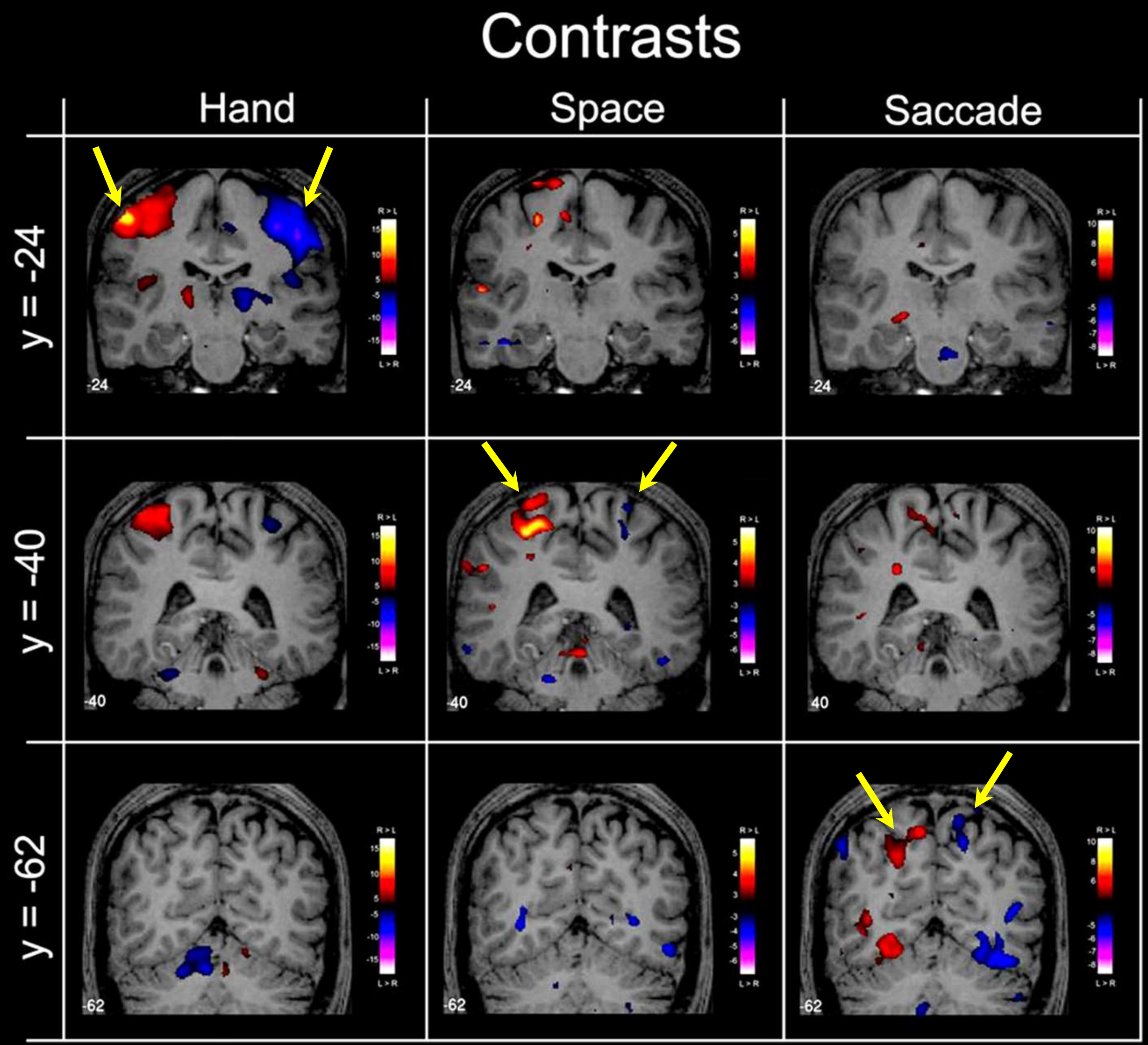
SACCADE SIDE
Right > Left Saccades



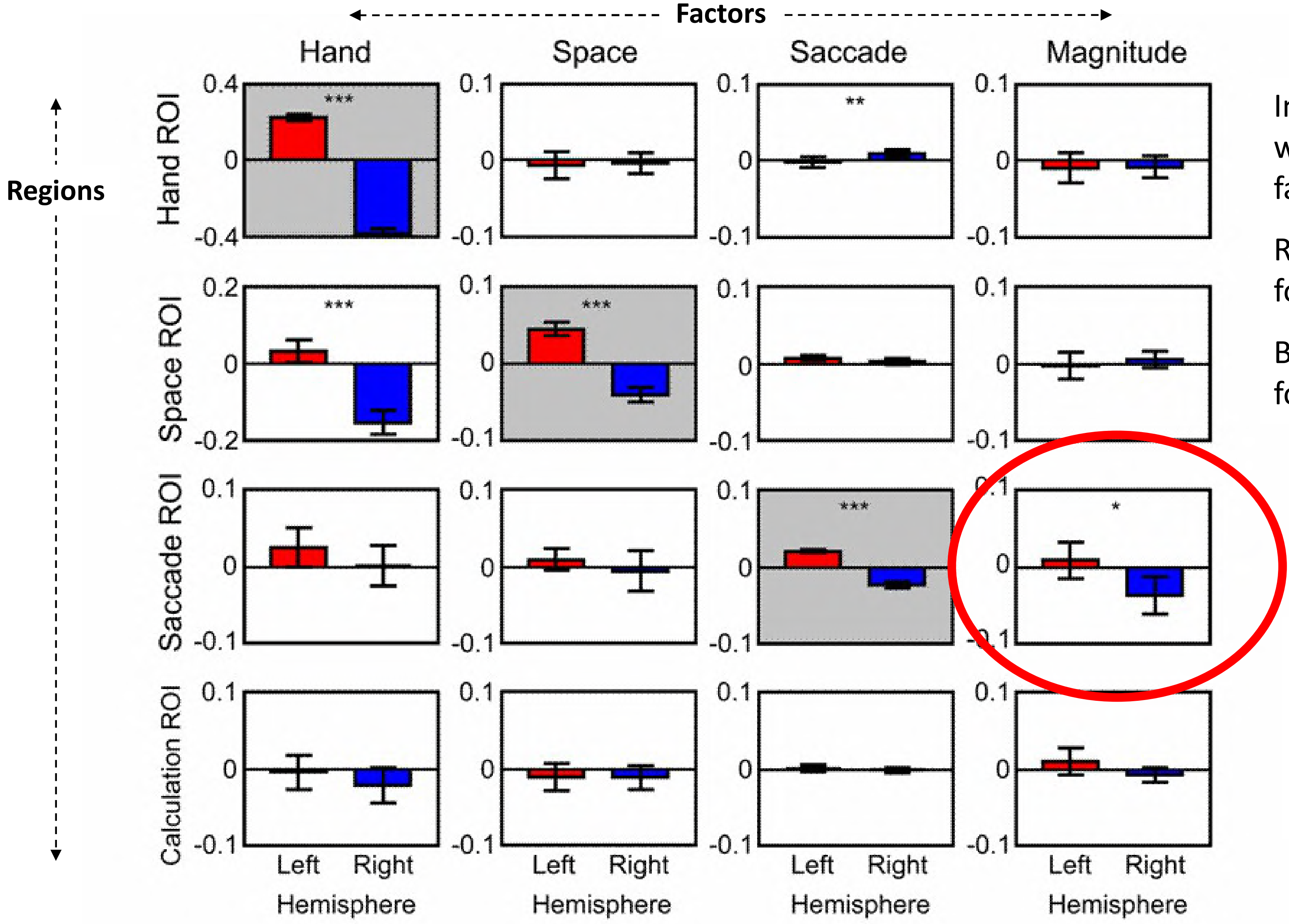
CALCULATION
Calculation (A+V)
– Sentences



three coronal slices



Only the saccade ROI, in posterior parietal cortex, generalizes to small vs large numbers



In each region, left and right, we plot the effect of each factor (right- left, large - small)

Red indicates more activation for the right / large,

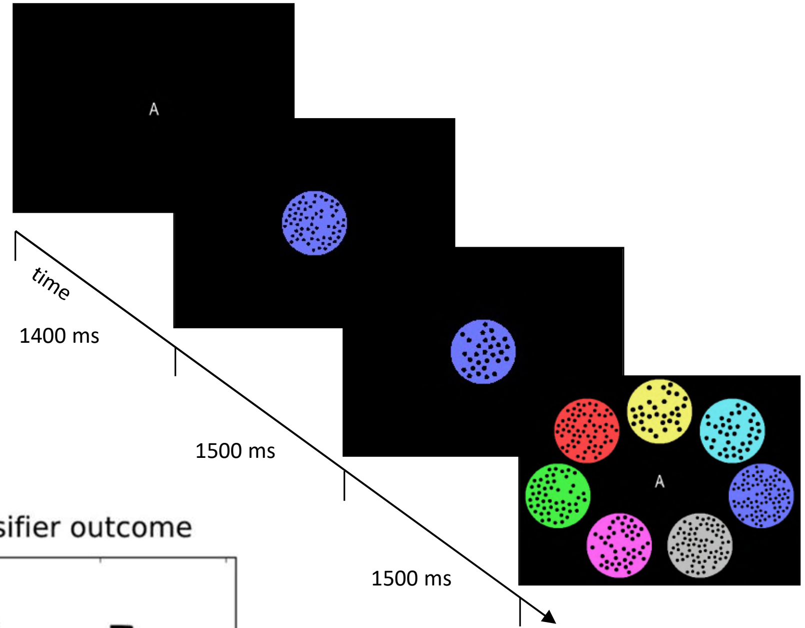
Blue indicates more activation for left / small

Cross-talk from the number code in the intraparietal sulcus to the spatial code, at or around area LIP, may explain the SNARC effect

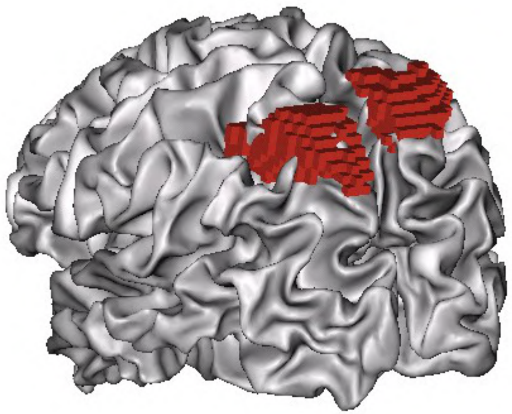
Cross-talk between number and space during calculation

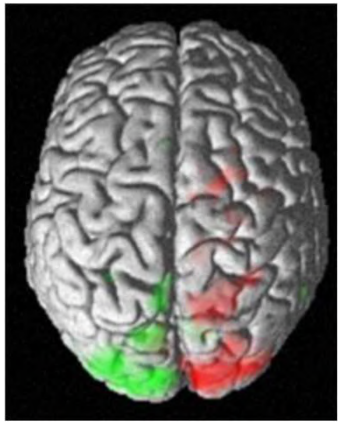
Knops, Thirion, Hubbard & Dehaene, *Science*, 2009

Test block: Addition / Subtraction



Training block: eye movements

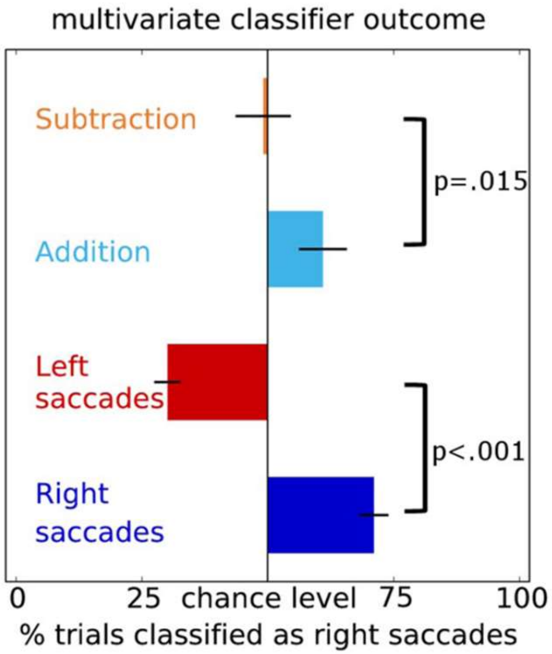




A decoder was trained to predict eye movements to the left (red) vs. to the right (green)

The decoder predicts novel left or right trials with ~70% accuracy on average (range: 56%-85%).

Classification is above chance (p<0.05) in 14/15 subjects.



The same decoder generalized to symbolic or non-symbolic calculation :

The distinction between left and right eye movements can also be used to distinguish subtraction from addition

(with Arabic or Dot notation)

Implications of the SNARC effect and other congruity effects for graphics (1)

All humans prefer small quantities to appear on the left, and large quantities on the right.

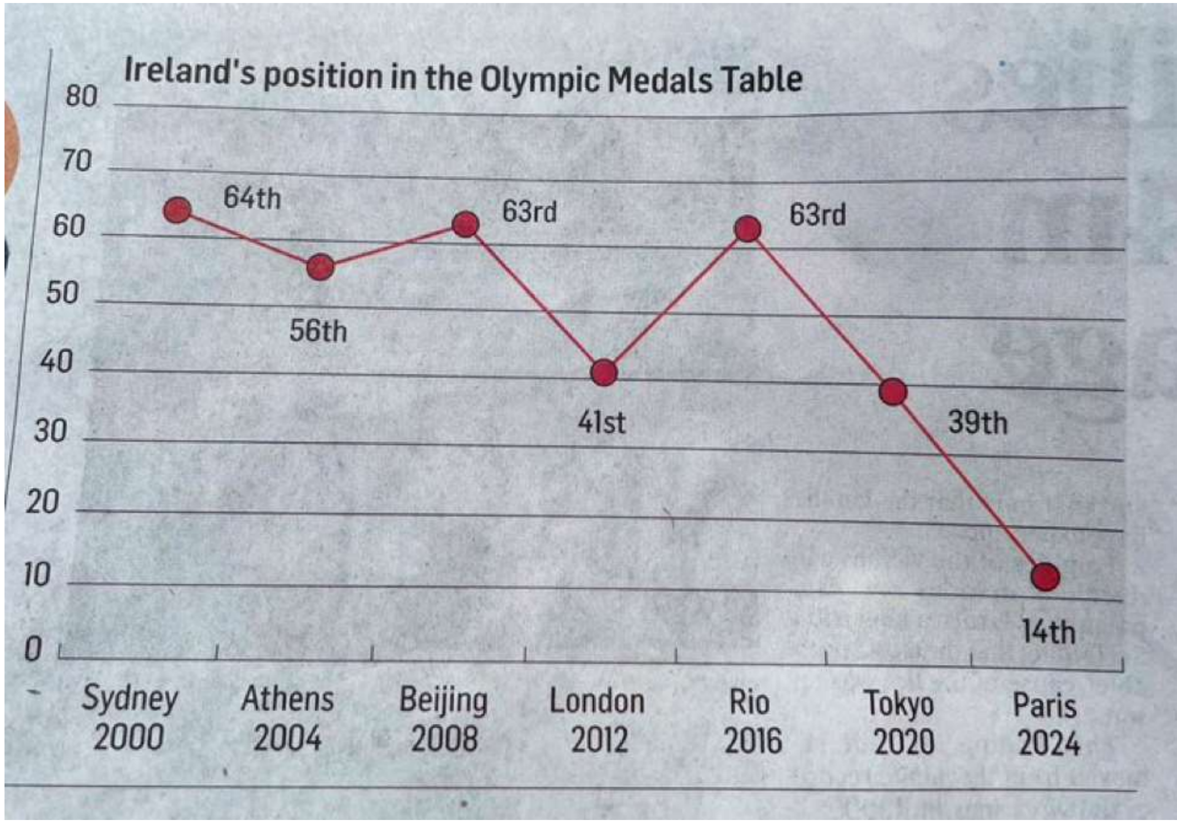
Don't contradict it in your graphics or other designs!

The SNARC effect is just one example of the general **congruity** effect : processing of two dimensions is easier when the dimensions are congruent with each other (e.g. the Stroop effect: blue red green versus blue red green)

Don't use smaller bars or smaller symbols for larger dimensions

Take into account other implicit associations, e.g.

- Up = good, down = bad
- Warm colors = front ; cold, blueish colors = back (Kosslyn, 2006)
- Cultural conventions, e.g. green = yes ; red = no



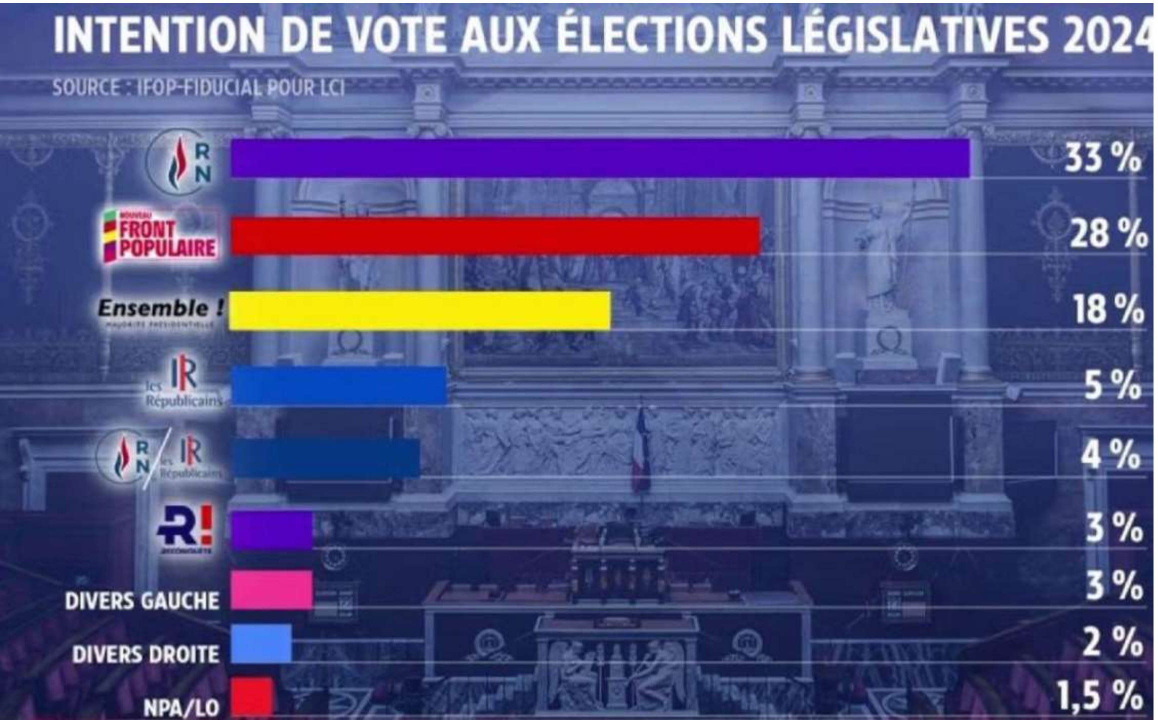
Implications of the linear vs logarithmic number line for graphics

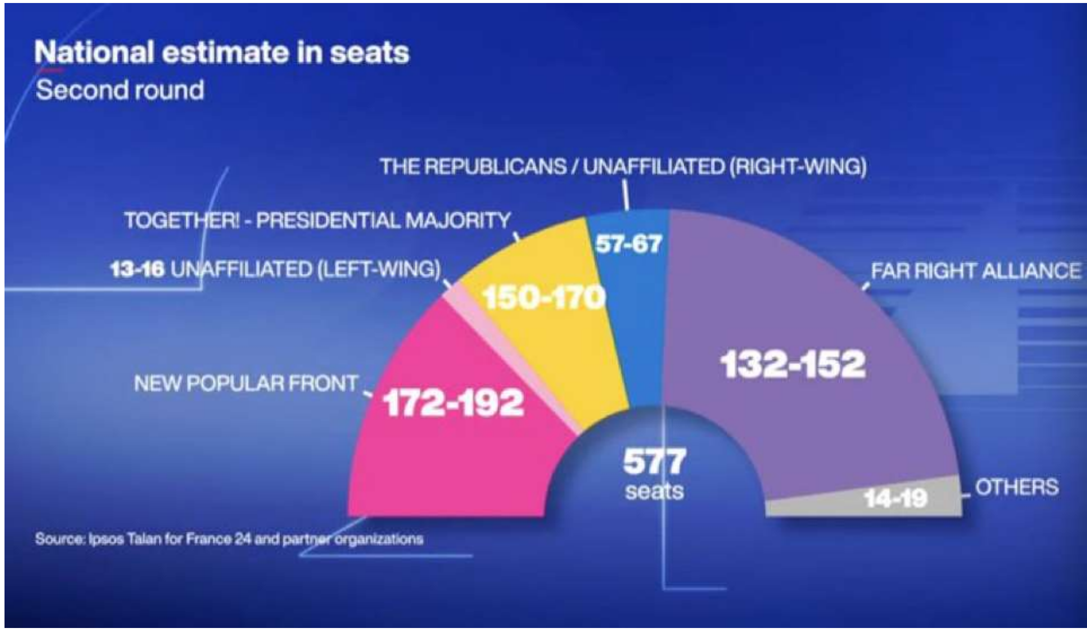
All humans can understand both linear and logarithmic scales.

Educated humans expect a **regular spatial** arrangement to reflect a regular spacing of the corresponding variable.

Consequence: don't mess up with scales! Graph readers expect them to be regular.

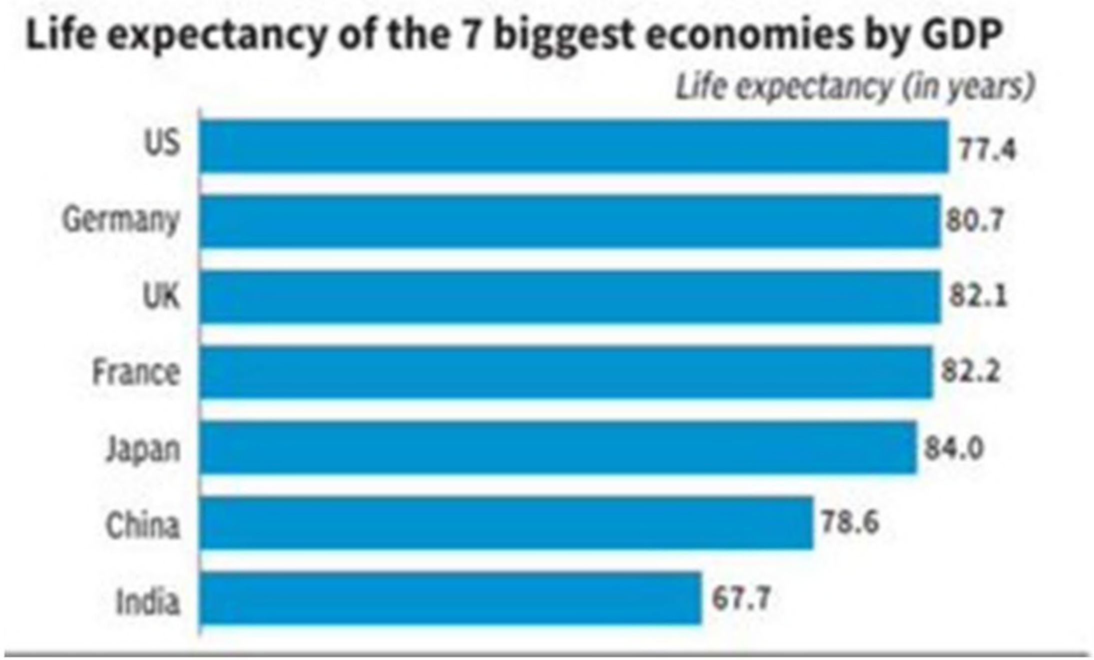
This advice may seem obvious, but counter-examples abound (voluntary or involuntary…):

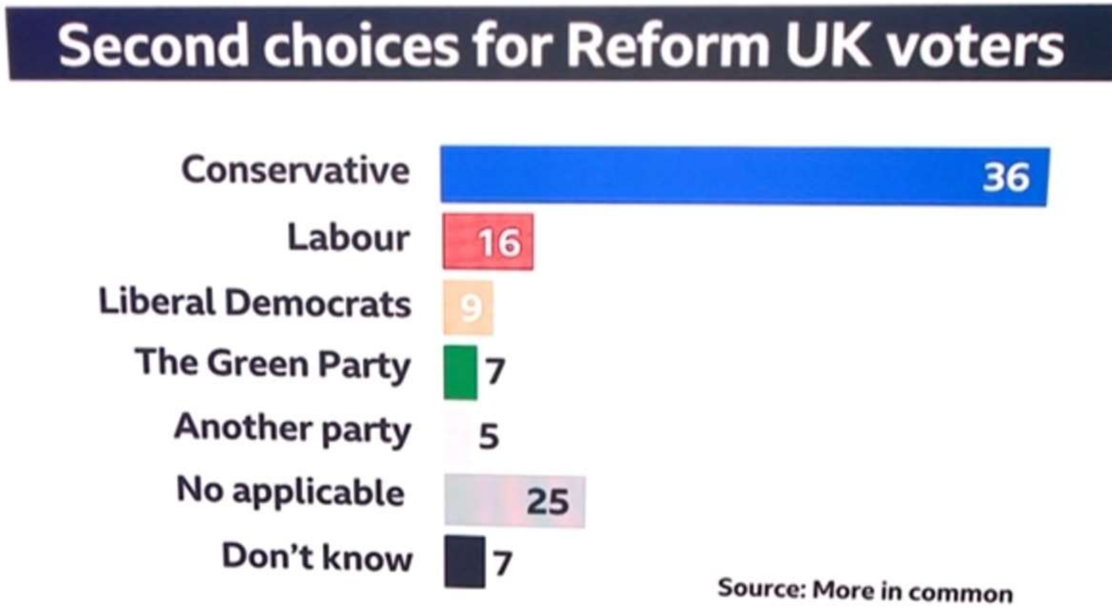




« Graph Crimes »: dramatic examples of lack of graphicacy

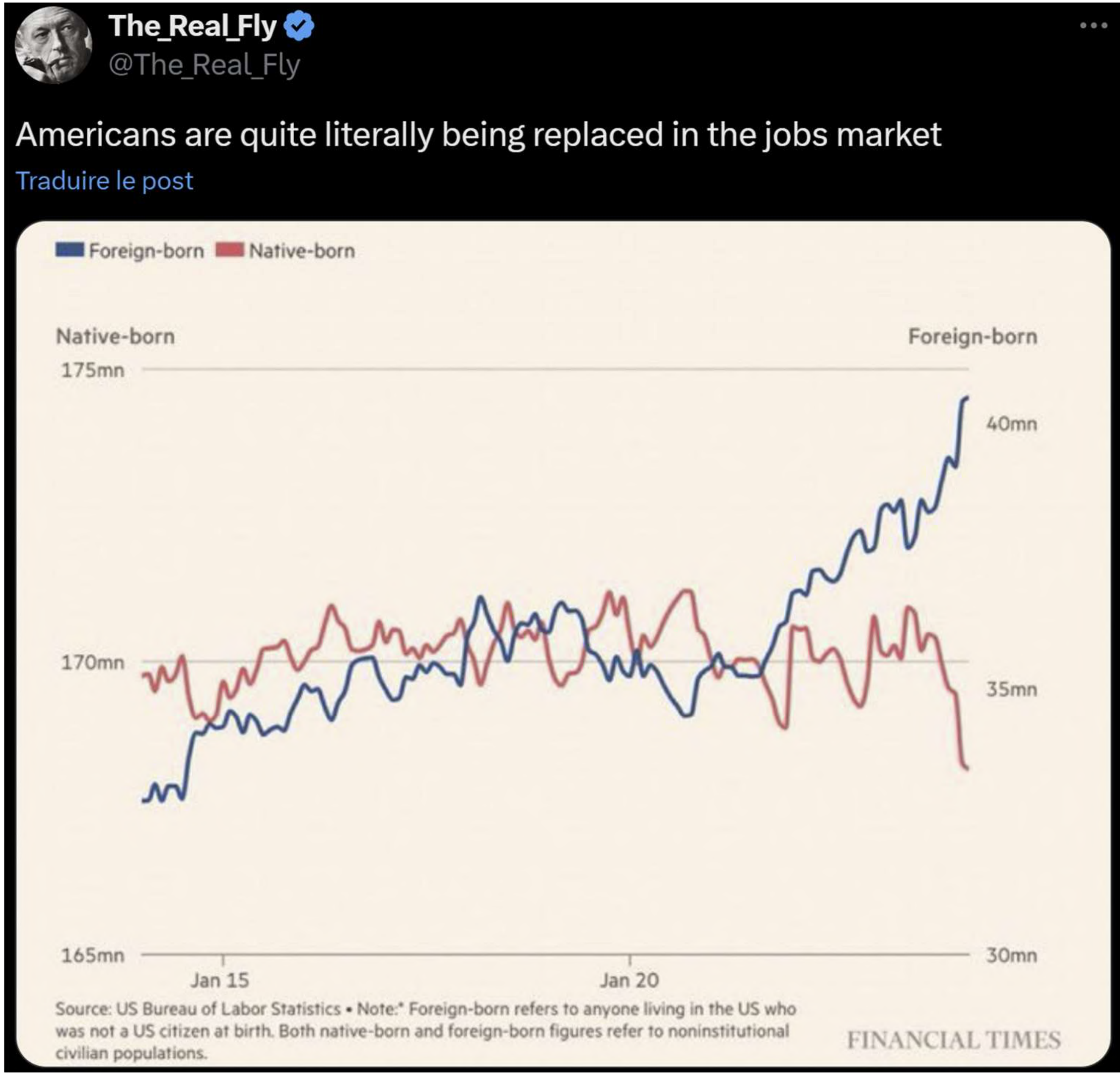
The manipulation of scales is very frequent in the media.
Education to media should probably teach students specifically about it.





« Graph Crimes »:

Another dramatic example of graphic manipulation



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The perception of graphics : a new example of neuronal recycling

Stanislas Dehaene
Chaire de Psychologie Cognitive Expérimentale

Cours n°4

La perception des tendances et des courbes

Perceiving trends and curves

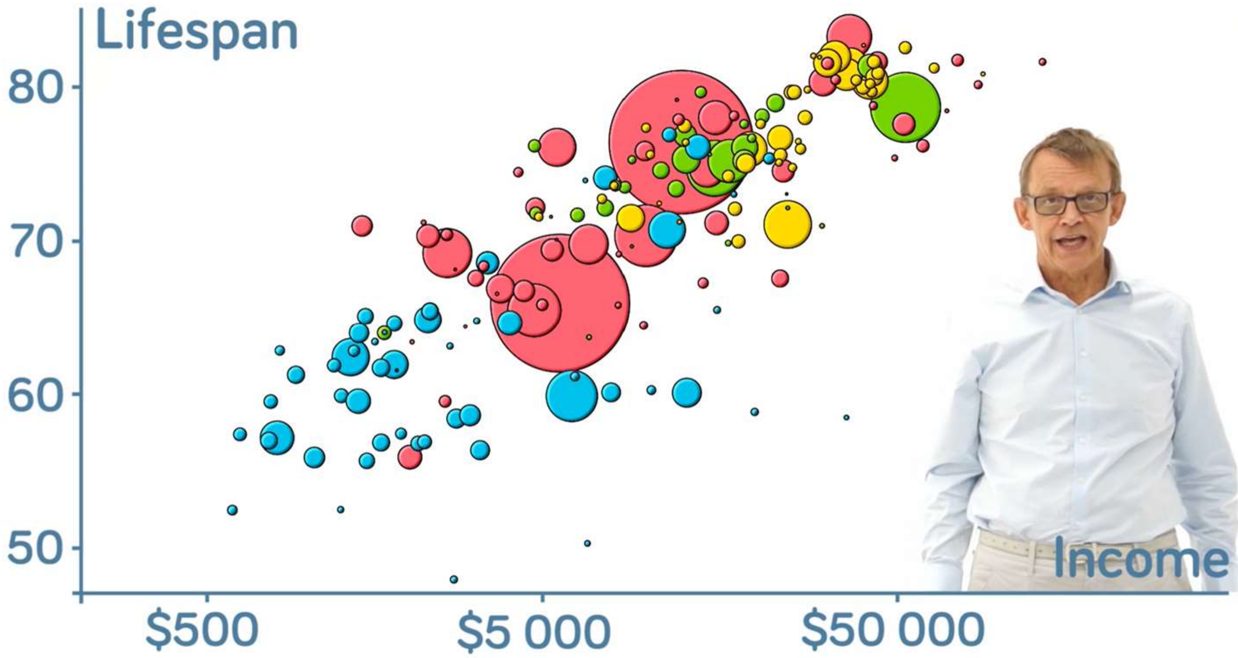
What are the necessary stages in the comprehension of graphics?

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

We may 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)



Trend judgment in the lab

Ciccione, L., & Dehaene, S. (2021). Can humans perform mental regression on a graph? Accuracy and bias in the perception of scatterplots. *Cognitive Psychology*, *128*, 101406.

Lorenzo Ciccione

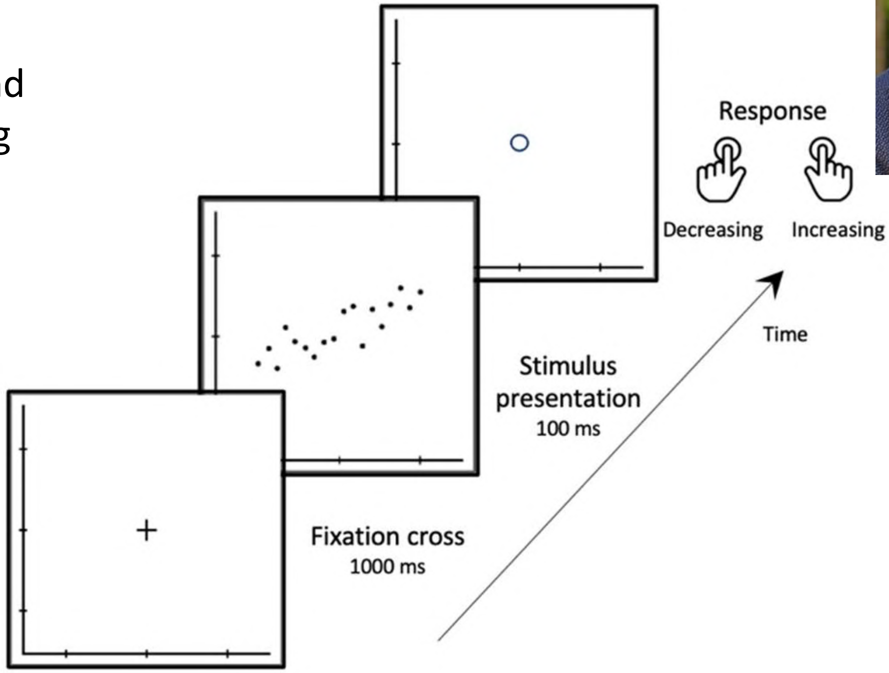
We designed a novel psychophysical task of trend judgment over noisy scatterplots to investigating human perception of statistics in graphics.

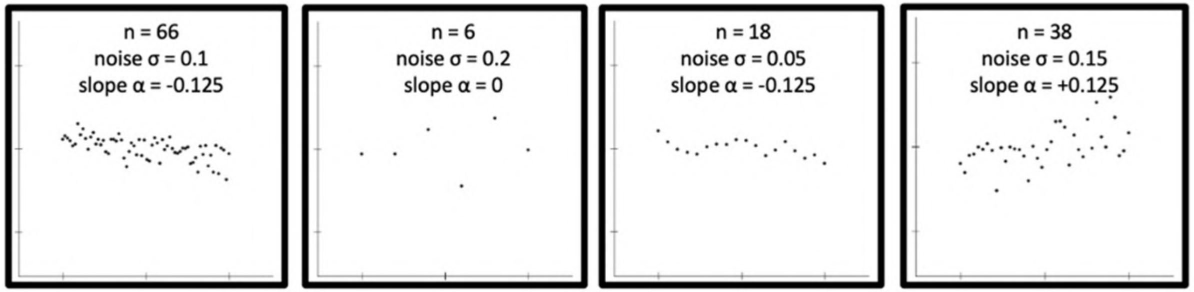
On each trial, participants are asked to decide whether the trend is increasing or decreasing.

The graph is generated according to the hypotheses underlying ordinary least squares regression (OLS) : x is fixed, and y is a linear function of x plus Gaussian noise.

We vary the key parameters:

- Slope
- Noise level
- Number of points





t-value = -6.08 | *t*-value = 0.33 | *t*-value = -2.81 | *t*-value = 3.6

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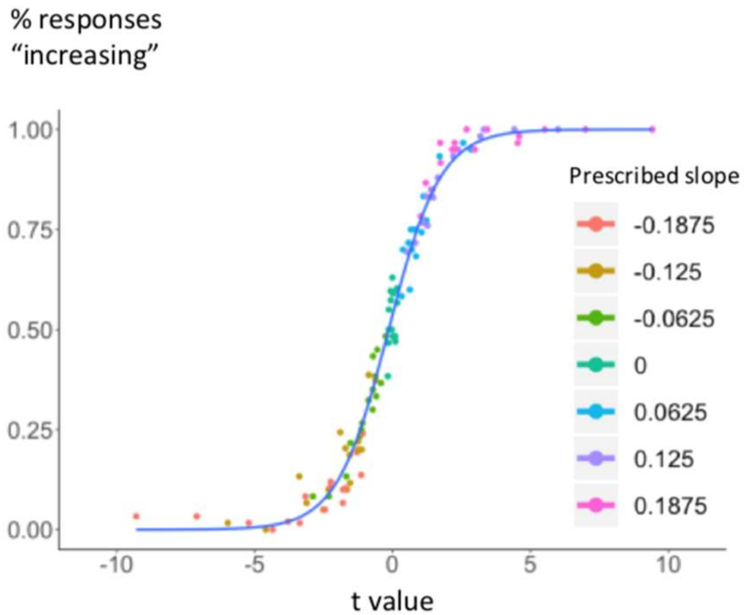
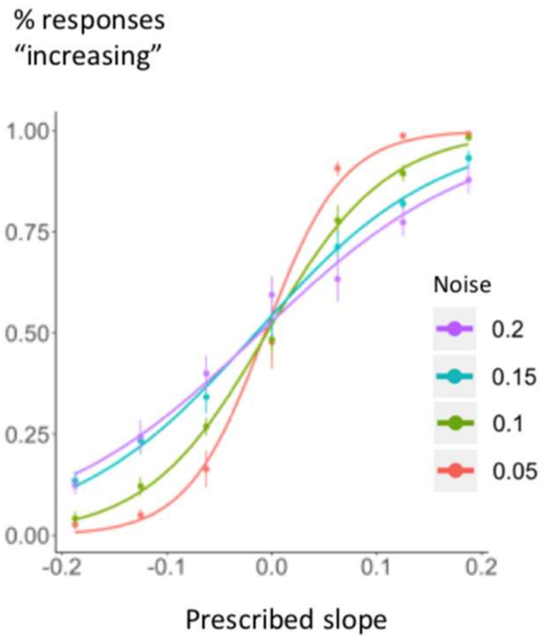
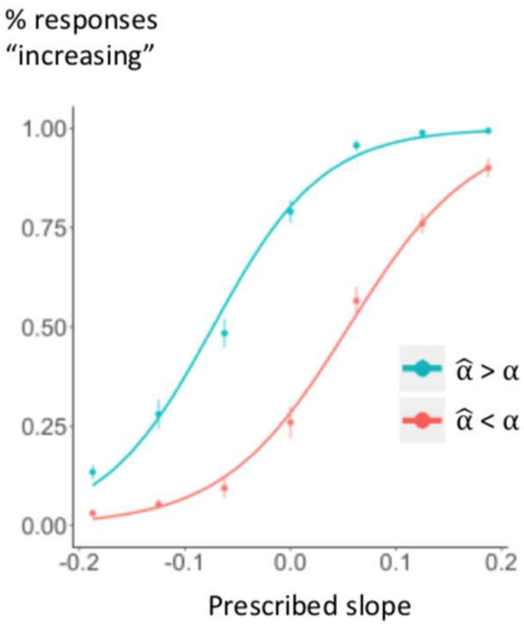
Ciccione, L., & Dehaene, S. (2021). Can humans perform mental regression on a graph? Accuracy and bias in the perception of scatterplots. *Cognitive Psychology*, *128*, 101406.

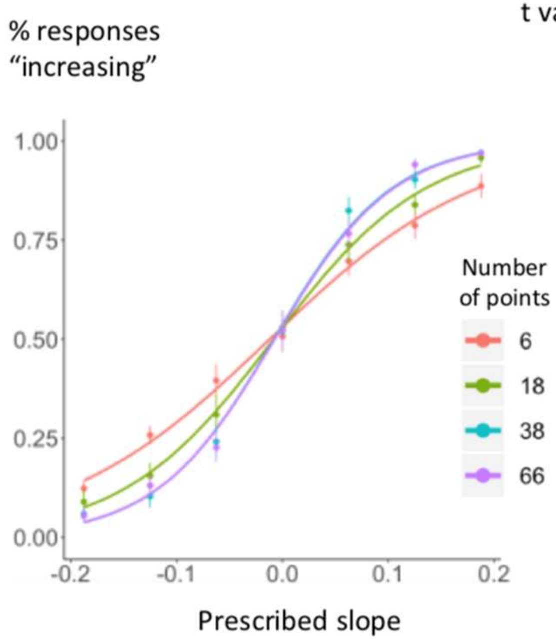


The results fully accord with what a statistician would do:

- Performance varies with slope and noise level
- The real slope, not the prescribed one, determines behavior
- Performance also varies with the number of data points
- All of these effects are subsumed by an effect of the t value of the graph (the value that a statistician would use!).







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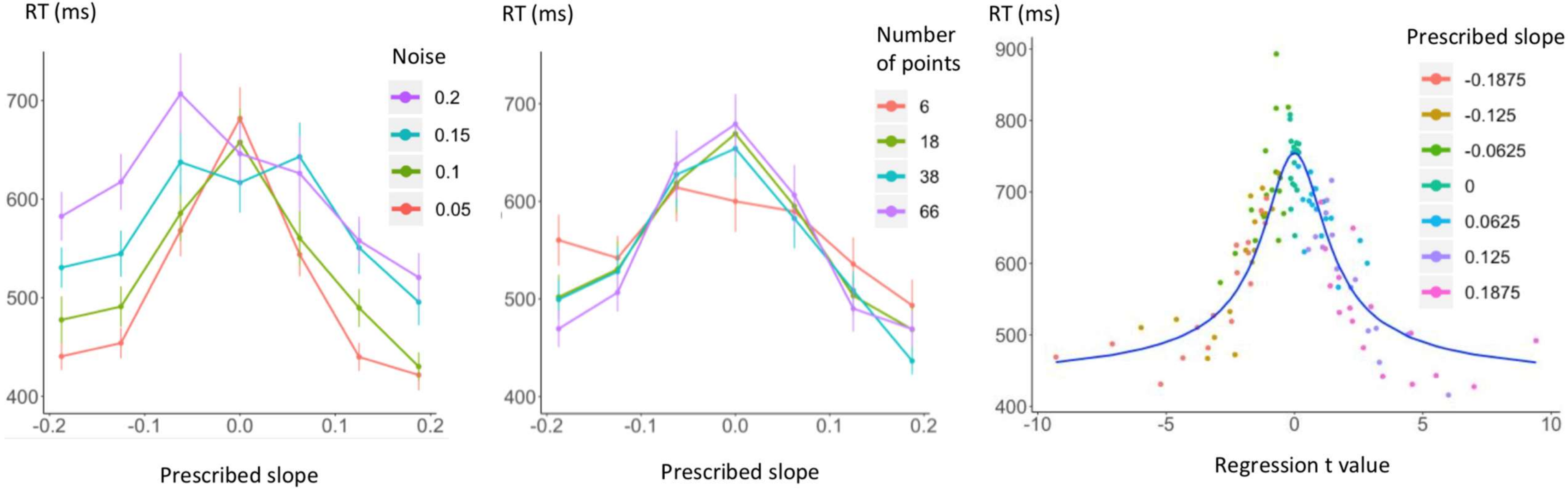
Similarly, response times vary with all these parameters, but in fact are **driven by the t value** only.

The effect of the number of points clearly excludes a serial process : **graph perception occurs in parallel across the entire dataset.**



Trend judgment outside the lab : a measure of graphicacy ?

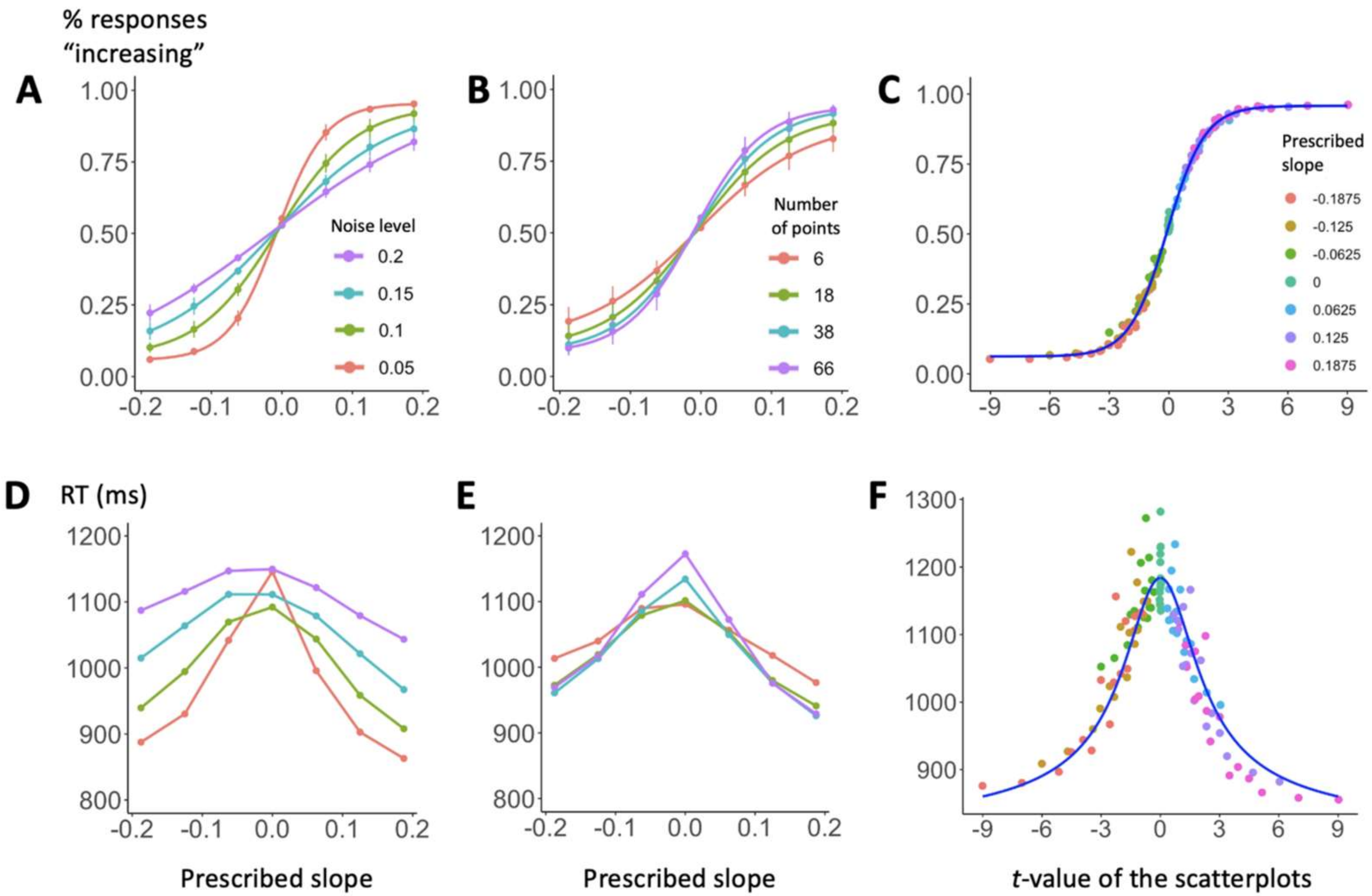
Ciccione, L., Sablé-Meyer, M., Boissin, E., Josserand, M., Potier-Watkins, C., Caparos, S., & Dehaene, S. (2023). Trend judgment as a perceptual building block of graphicacy and mathematics, across age, education, and culture. *Scientific Reports*

In the domains of literacy and numeracy, simple perceptual tests can be predictive of reading and mathematical abilities:
- Letter crowding is a correlate of reading fluency
- Comparison of non-symbolic numerosity is a correlate of mathematical abilities, and even a predictor of dyscalculia

We wondered whether the sensitivity of trend judgment could be used as a measure of graphicacy.

3943 adults from all around the globe participated in an on-line trend judgement task.

The average results beautifully replicated our previous work.



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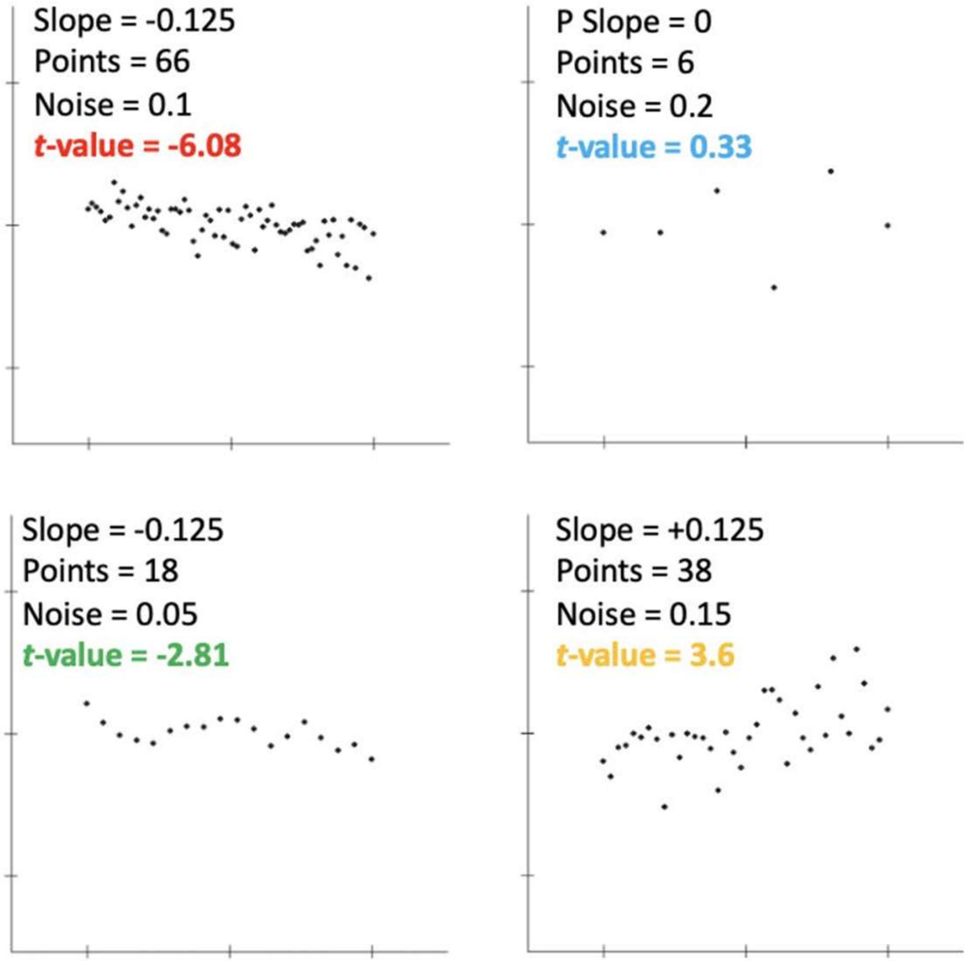
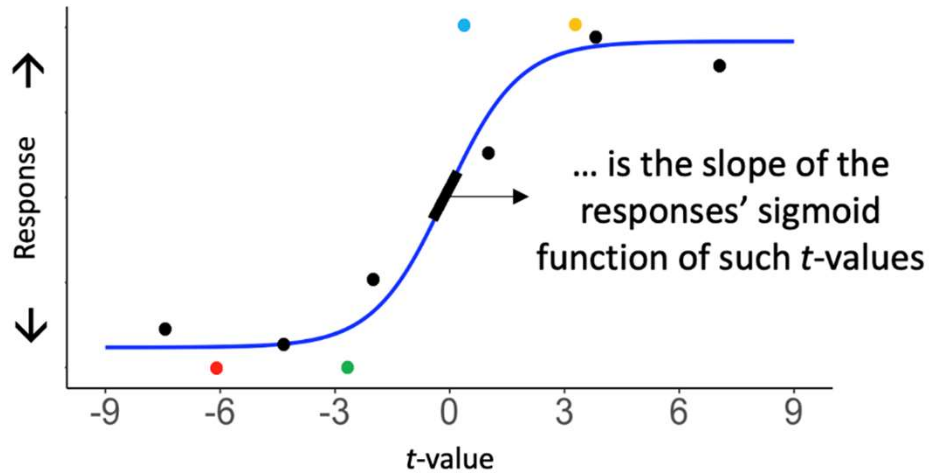


Different stimuli varied in their t value, i.e. the amount of evidence for a positive or negative trend in the graphic.

For each subject, we used logistic regression to obtain the slope of the sigmoid linking t value and response rate, thus estimating the **sensitivity of this participant to a graphic trend**.

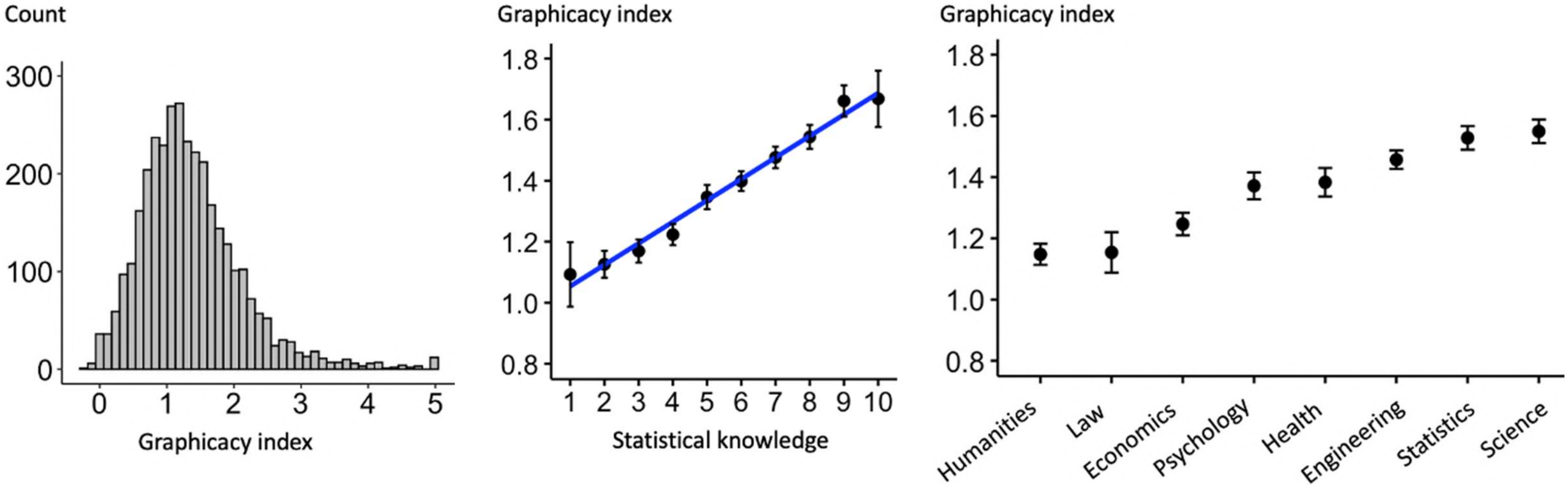
The regression was significant in 98.2% of participants.



Trend judgment as a perceptual building block of graphicacy

Ciccione, L., Sablé-Meyer, M., Boissin, E., Josserand, M., Potier-Watkins, C., Caparos, S., & Dehaene, S. (2023). Trend judgment as a perceptual building block of graphicacy and mathematics, across age, education, and culture. *Scientific Reports*

The median graphicacy index was 1.26, but there was a broad distribution around this value.
This variability was not "noise" : the index was stable within participants, both within a single run (1st 50 trials versus last 50 trials), r = 0.38) and across two separate runs, r=0.49). It can thus be reasonably estimated in a 6-minute test.
The graphicacy index correlated strongly with self-reported statistical knowledge (r=0.21) and math education (r=0.22), but not with language skills.
In graduate subjects, it varied with university discipline and also correlated with average math grades (r=0.24).
Reminder : correlation is not causation ! The relation between graphicacy and education might well be bi-directional.



Experts in graphicacy are probably attuned to specific graphic patterns

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

Kosslyn suggests that, as graphic readers, we become attuned to specific patterns, not just linear trends.

E.g. A cross between two lines signals an interaction between 2 variables (the effect of variable 1 depends on the level of variable 2).

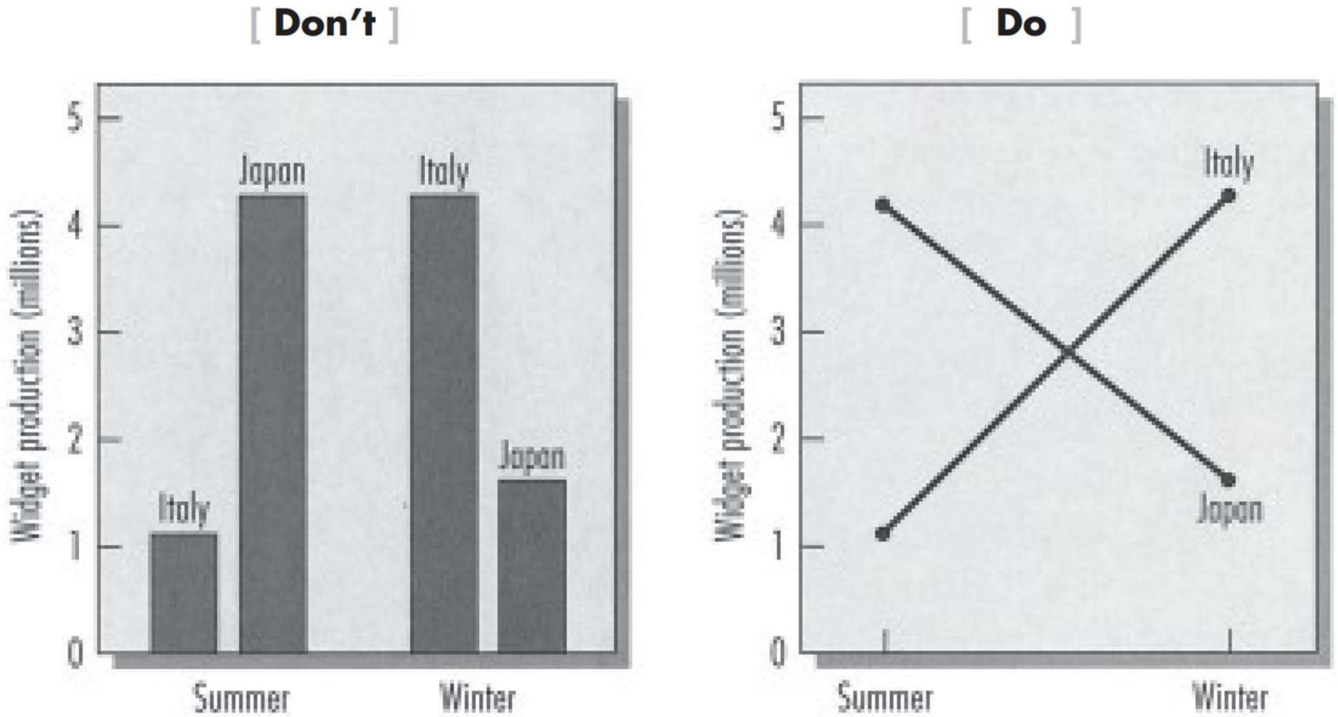


Figure 2.6. Experienced graph readers can interpret typical patterns of lines at a glance.

Another « Graph Crime », due to a reflex interpretation of graphic patterns

As we acquire graphic conventions, we may also fall into interpretative traps.

Igor Halperin · 2nd
Finance AI & Quant (FAIQ) Research
2d · Edited ·

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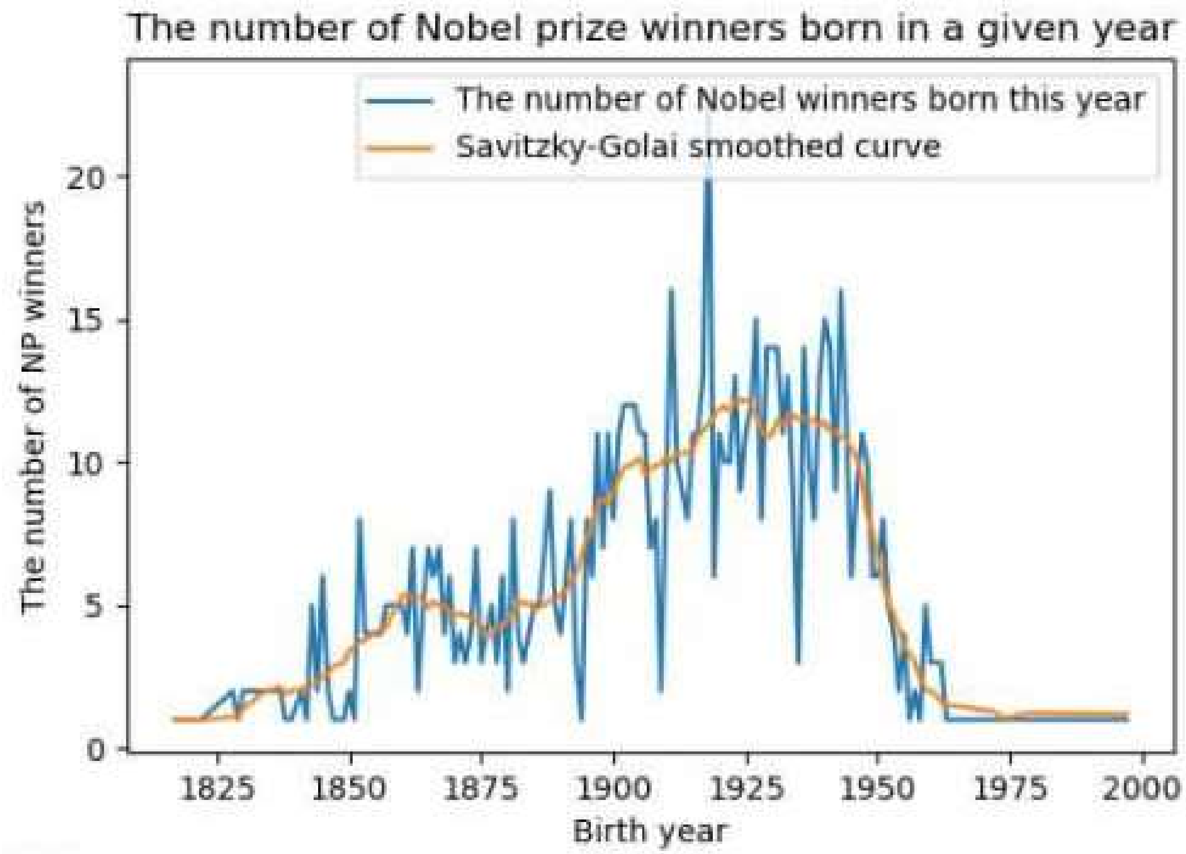
Are we getting dumber?
The figure below shows the number of Nobel Prize winners born in each year, along with its smoothed-out version. The trend is very pronounced: starting from approximately 1935, the number of future Nobel Prize winners born in each year is nearly monotonically decreasing. Using this statistics as a proxy to the dynamics of the average IQ of the human race, this data can be interpreted as supporting previous research that concluded that we are getting dumber (see https://lnkd.in/eQQbTNcC).

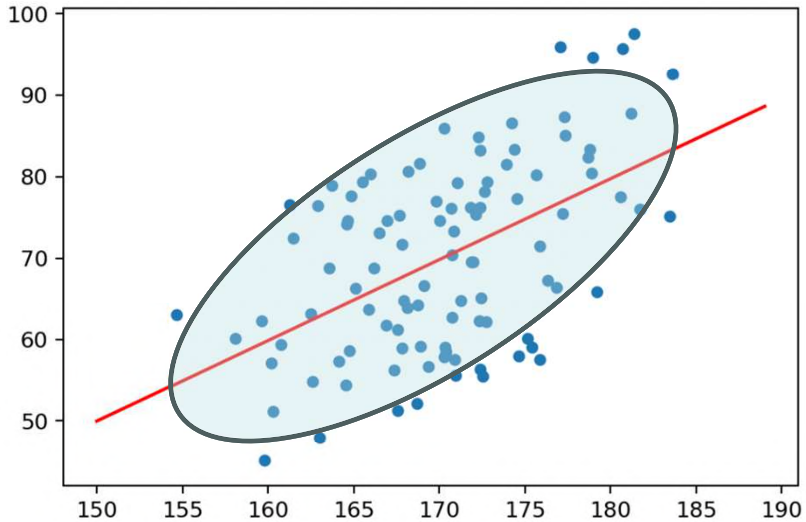
#science #datascience #society #NobelPrize



What visual abilities does graphic perception recycle ?

Hypothesis: the perception of scatterplots relies on a pre-existing ability to identify the **principal axis** of objects (perhaps for the purpose of grasping)

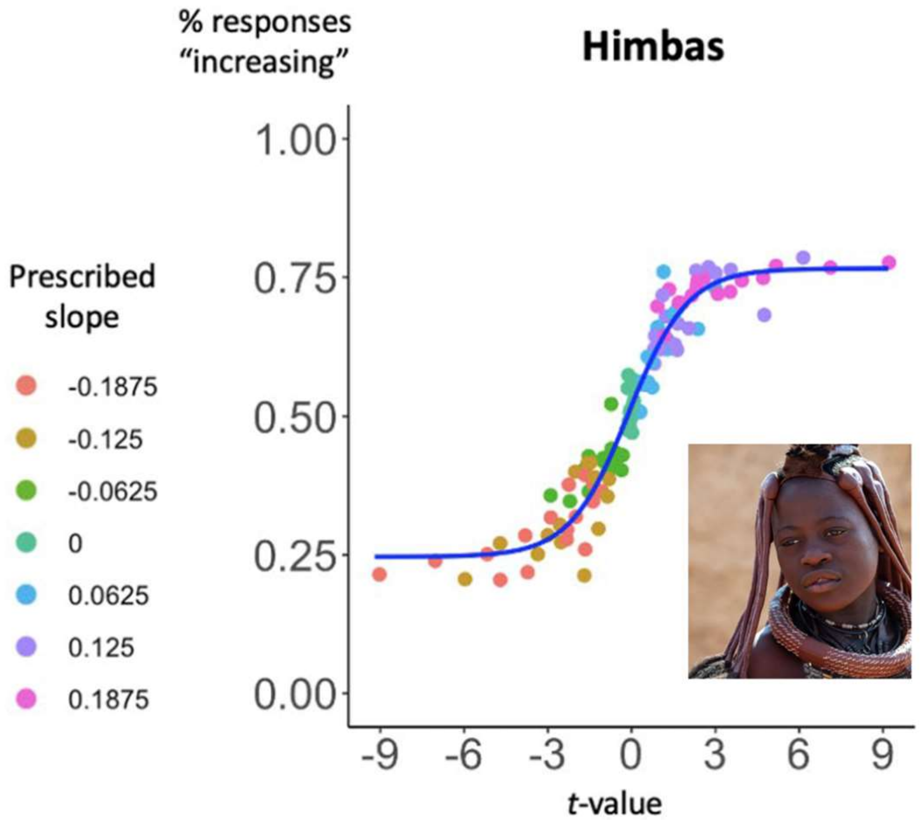
- Prediction 1. The perception of the central tendency in graphics is not just a skill learned at school. It should be **available early on in childhood and also in evolution, thus possibly in non-human primates.**
- Prediction 2. The participant's best-fitting line should correspond to the object's principal axis, which is **not** the least-squares line.
- Prediction 3. The perception of the central tendency in graphics should **recycle** brain areas involved in the perception of object orientation.

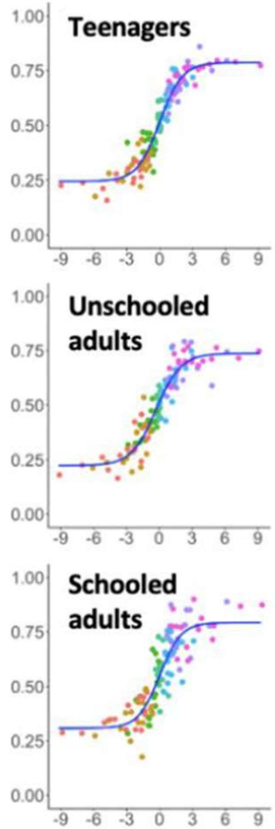


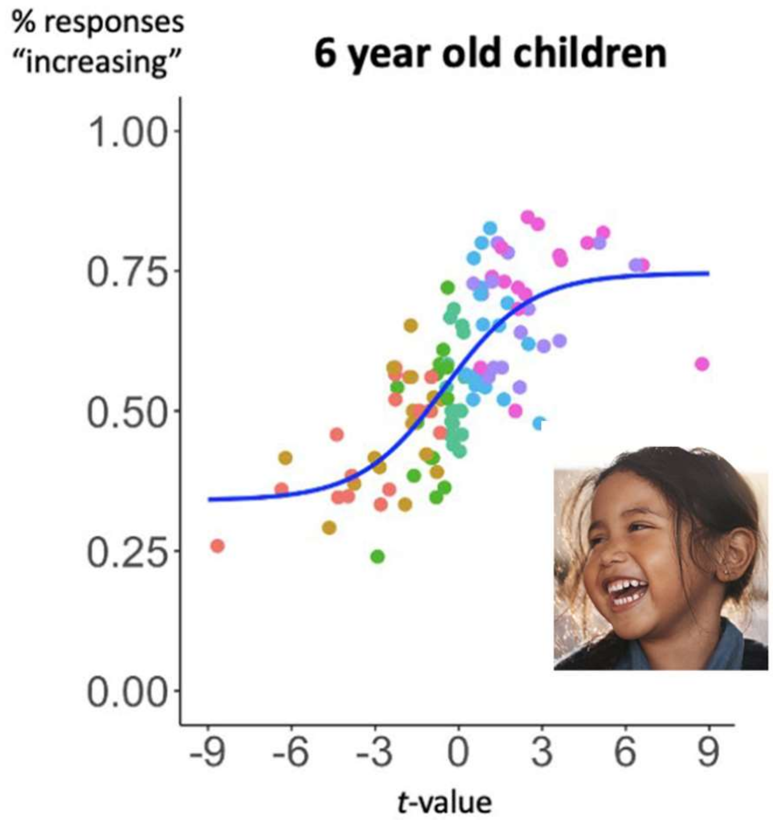
Trend judgment in subjects with limited access to formal education

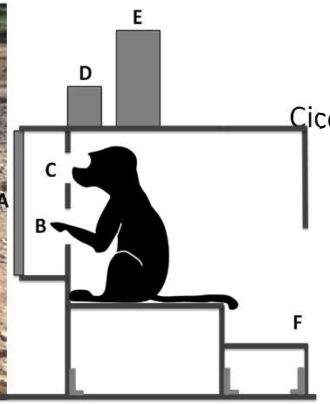
Ciccione, L., Sablé-Meyer, M., Boissin, E., Josserand, M., Potier-Watkins, C., Caparos, S., & Dehaene, S. (2023). Trend judgment as a perceptual building block of graphicacy and mathematics, across age, education, and culture. *Scientific Reports*

- Prediction 1. The perception of the central tendency in graphics is not just a skill learned at school. It should be **available early on in childhood.**





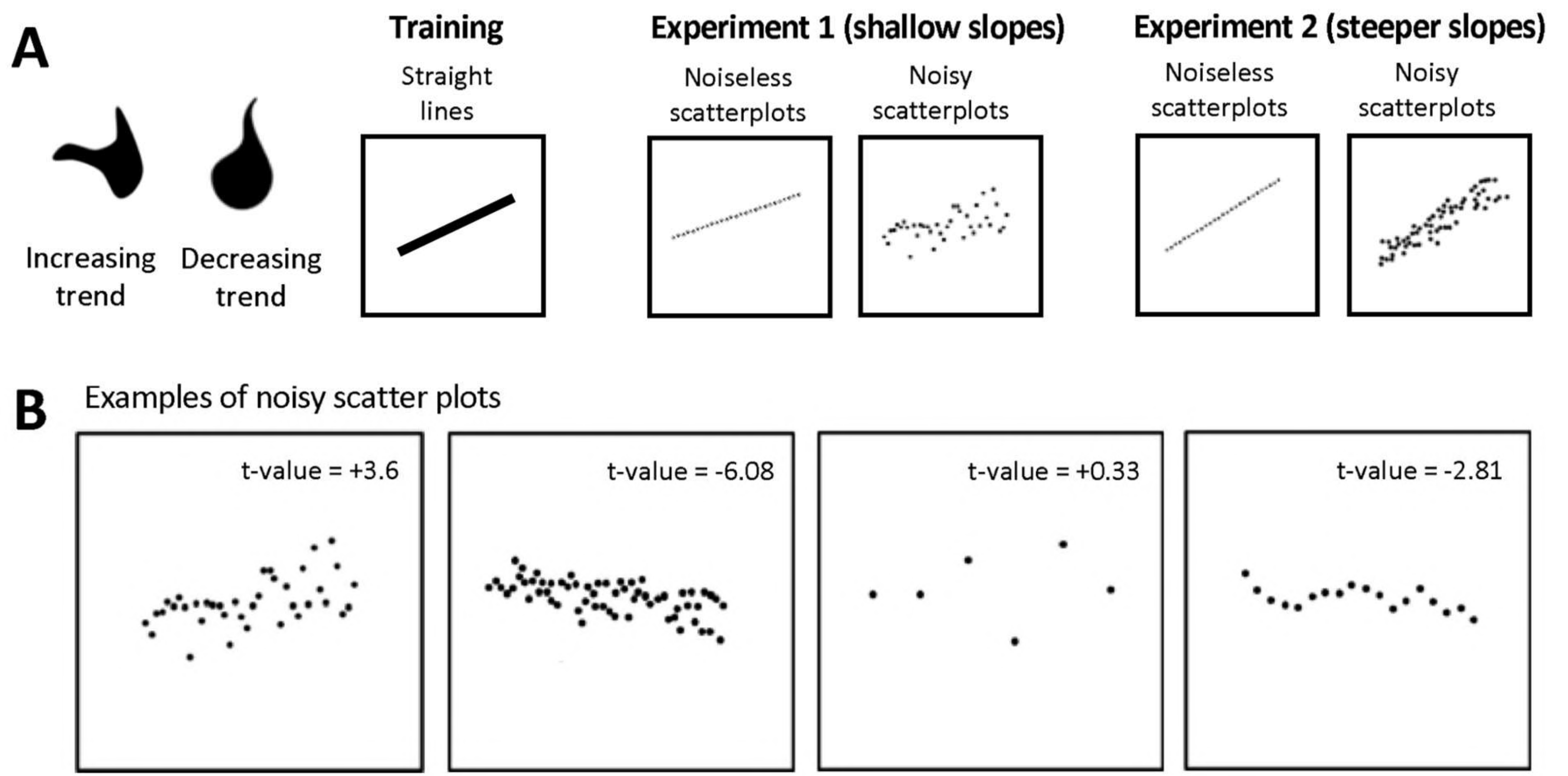




Trend judgment in baboons

Ciccione, L., Dighiero Brecht, T., Claidiere, N., Fagot, J., & Dehaene, S. (2024). The baboon as a statistician: Can non-human primates perform linear regression on a graph? *iScience*

- Prediction 1. The perception of the central tendency in graphics is not just a skill learned at school. It should be **available early on in childhood and also in evolution, thus possibly in non-human primates.**

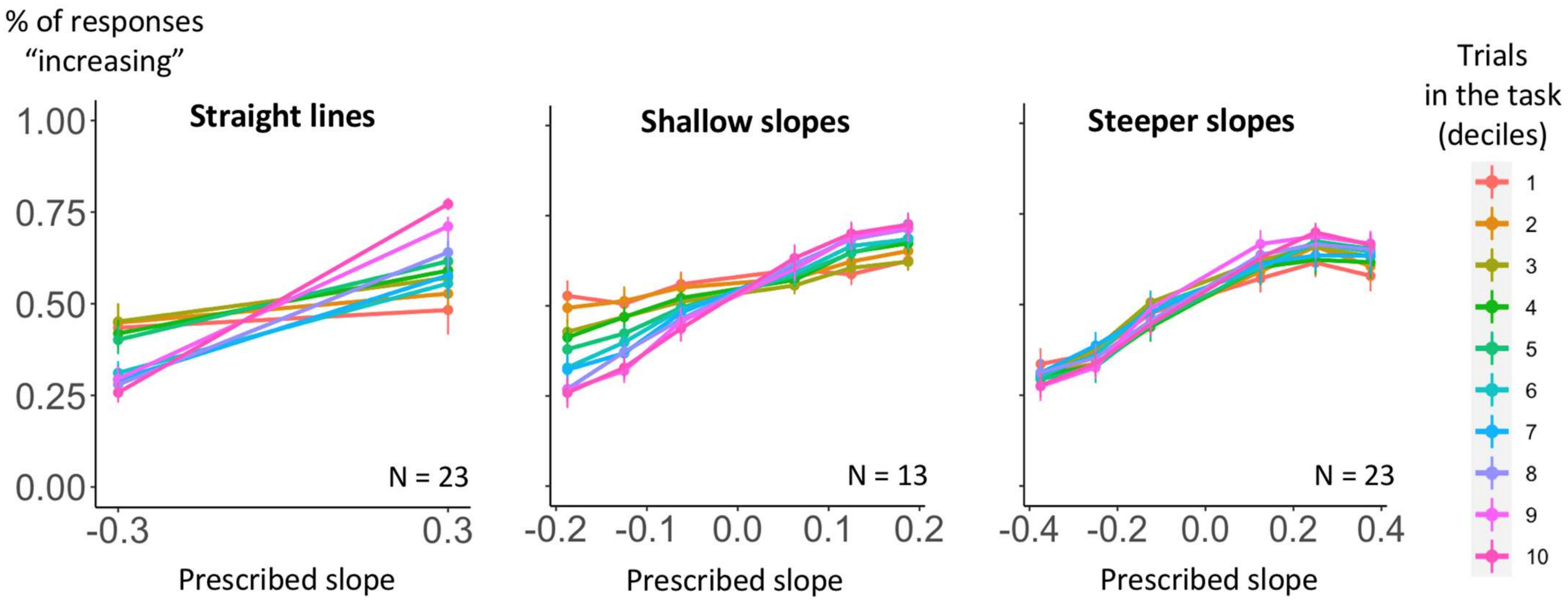


We trained baboons to attach two symbols to increasing and decreasing straight lines, then tested how they performed with scatterplots.

Trend judgment in baboons

Ciccione, L., Dighiero Brecht, T., Claidiere, N., Fagot, J., & Dehaene, S. (2024). The baboon as a statistician: Can non-human primates perform linear regression on a graph? *iScience*

On average, baboons learned the task with straight lines, but did not generalize much to scatterplots. However, they became way above chance with scatterplots, allowing us to probe the determinants of their behavior.

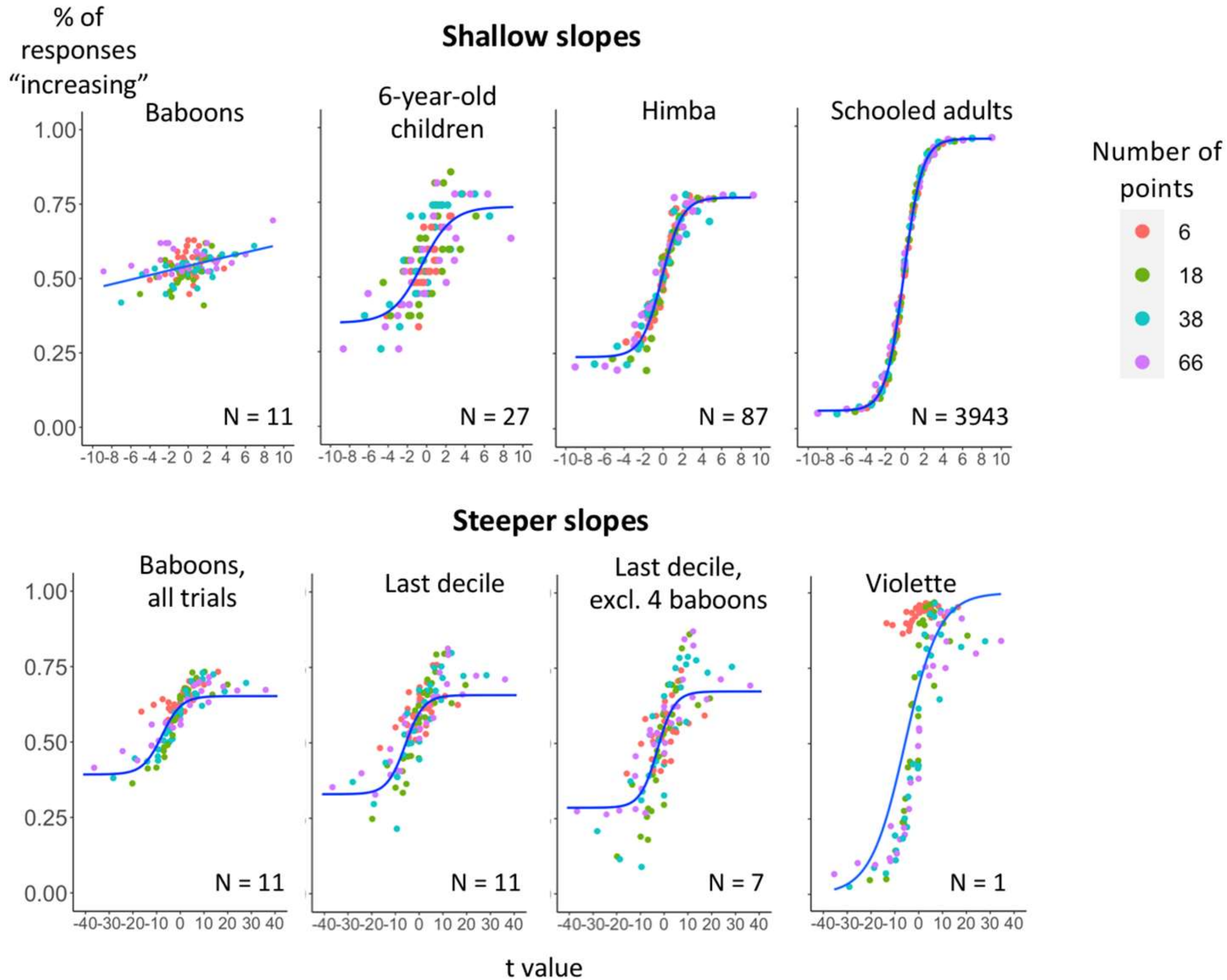


Trend judgment in baboons

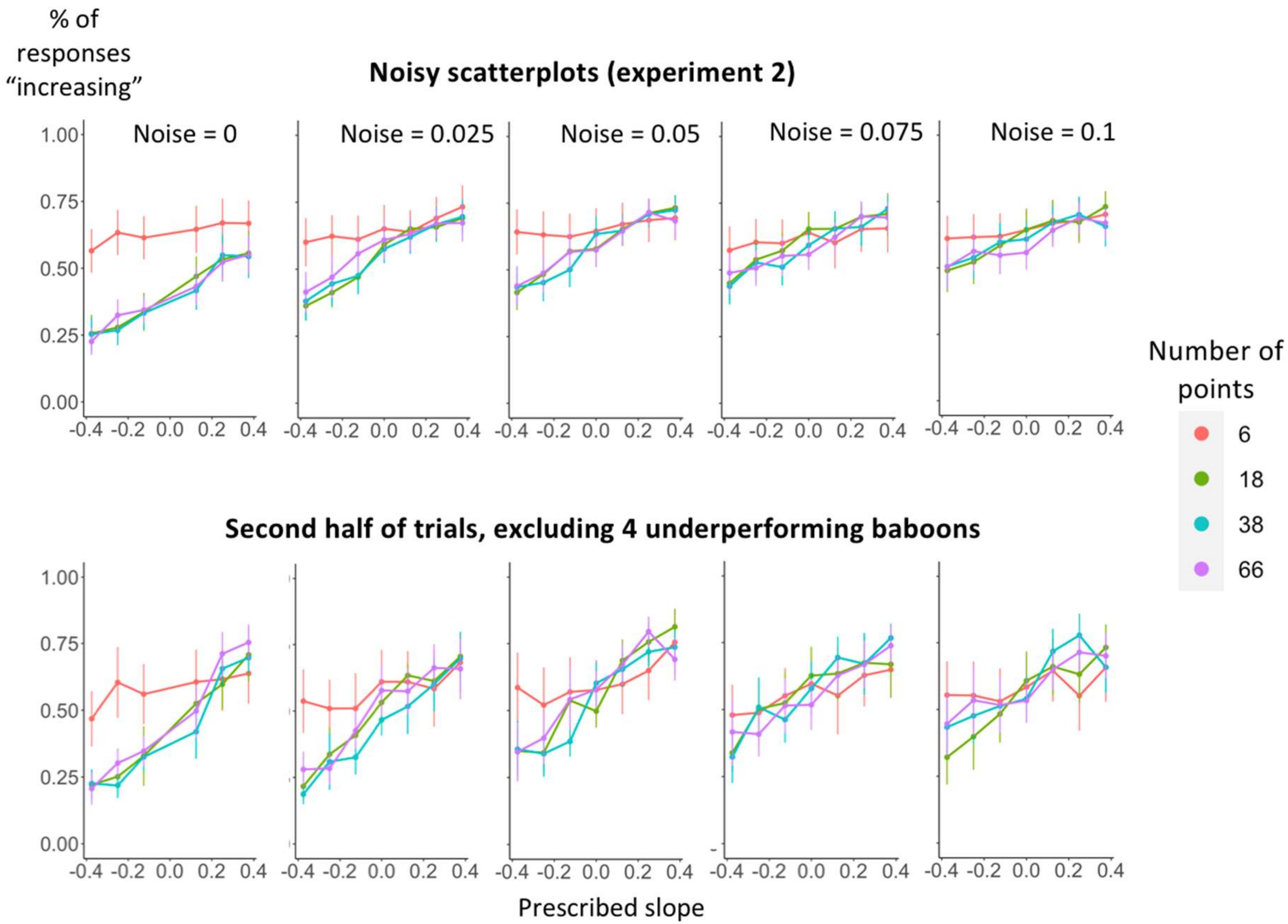
Ciccione, L., Dighiero Brecht, T., Claidiere, N., Fagot, J., & Dehaene, S. (2024). The baboon as a statistician: Can non-human primates perform linear regression on a graph? *iScience*

Performance was not very good, but it was determined by the t-test statistic – like in and human children and adults.

With training, performance became increasing driven by the t test, with a steeper slope – and some individual baboons performed just as well as humans!

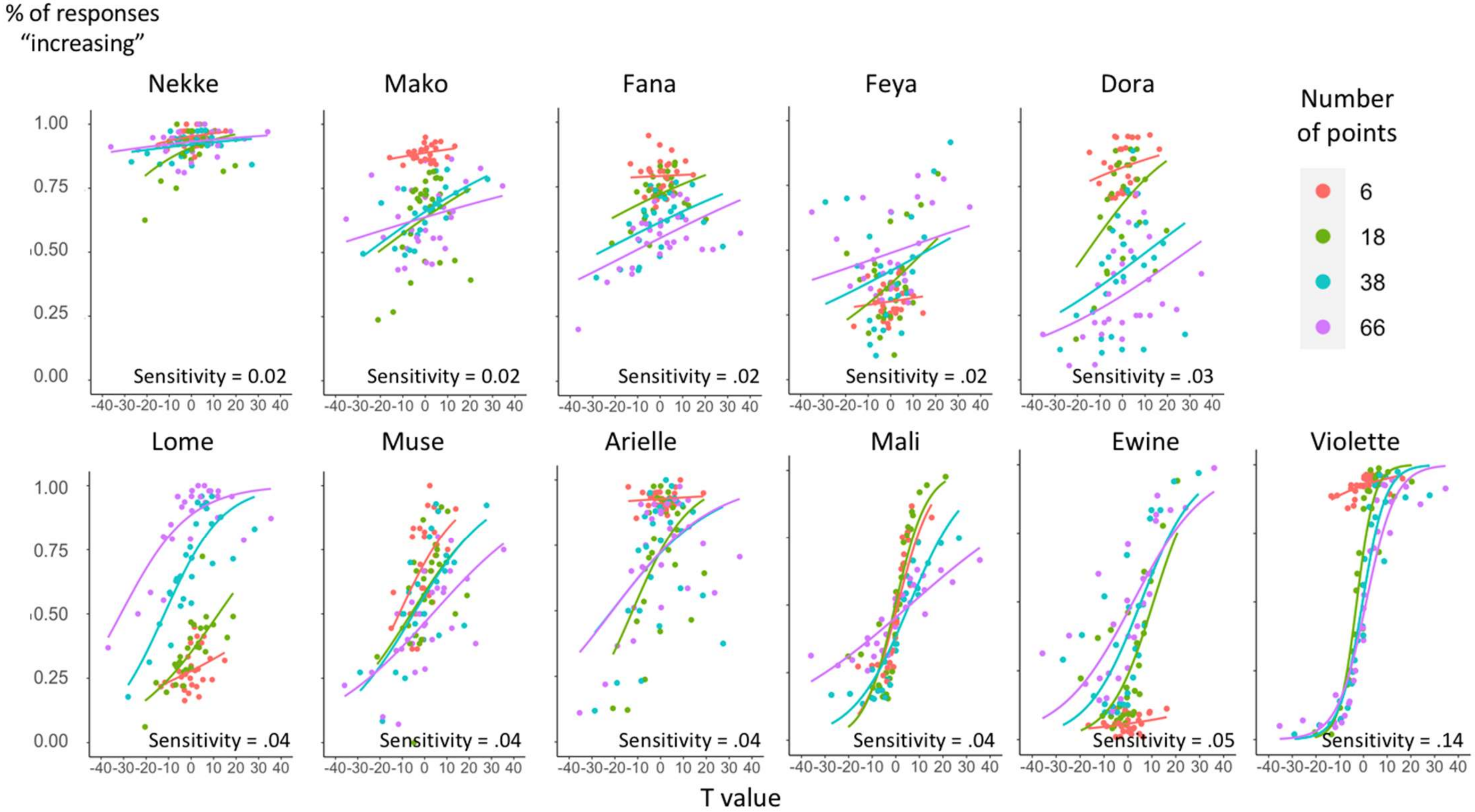


Baboons did not perform very well with scarce scatterplots (with only 6 data points).
→ Inability to understand that the task requires treating those points as a single "object" ?



Performance was highly variable across baboons.

- Some understood the task very well (bottom right)
- Many exhibited additional biases as a function of the number of dots.



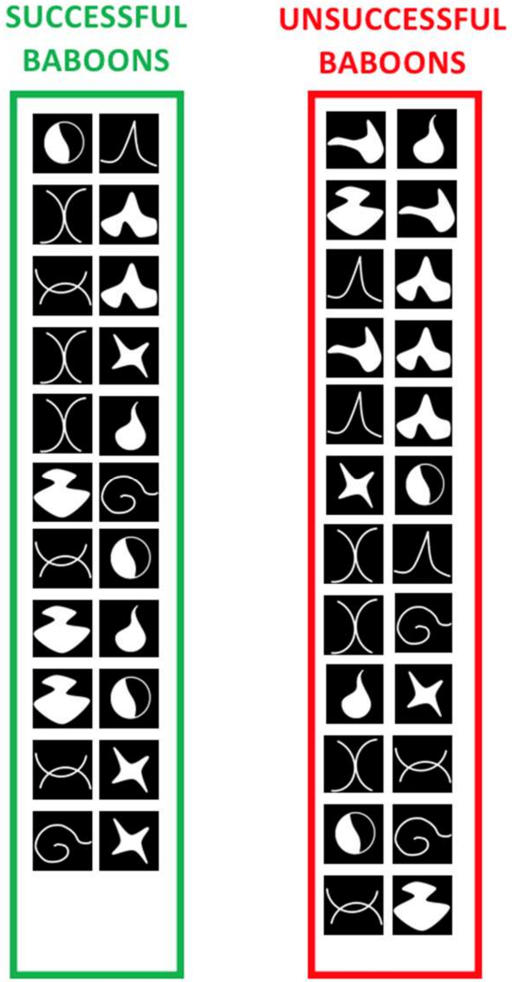
Trend judgment in baboons

Ciccione, L., Dighiero Brecht, T., Claidiere, N., Fagot, J., & Dehaene, S. (2024). The baboon as a statistician: Can non-human primates perform linear regression on a graph? *iScience*

Some of the variability could be accounted for by an irrelevant variable: the visual discriminability of the two symbols for "increasing" and "decreasing".

Conclusion:
- The perceptual component of graph perception is present in non-human primates.
- They can treat a discontinuous array of dots as a single "object" and assess its orientation.

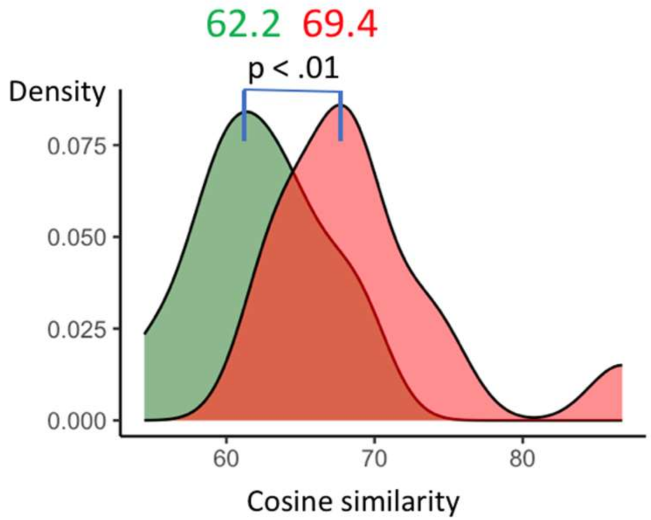
→ A new form of ensemble perception – not of the mean location or other average properties of the objects, but their correlation or covariance.



Based on CLIP (Contrastive Language-Image Pretraining) model.

1. Take the embeddings of each image.

2. Calculate the cosine similarity between the embeddings of the two images in the pair.

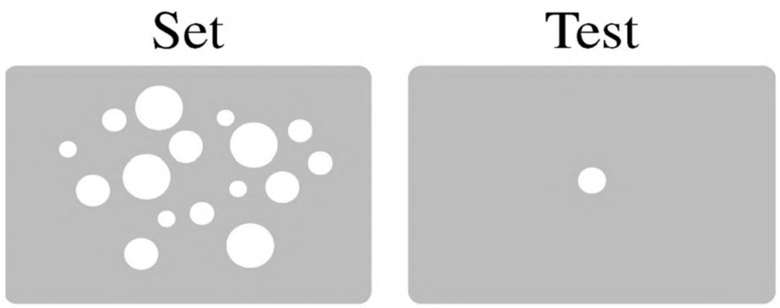


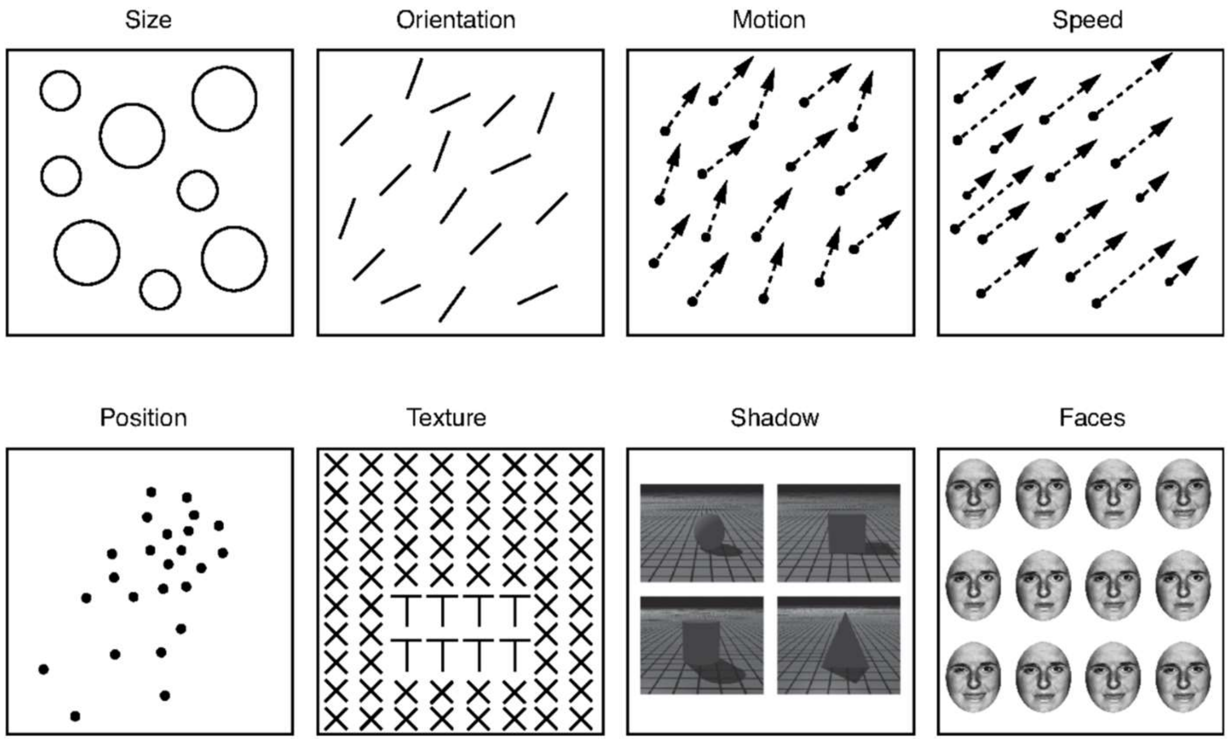
A side comment : Relation to ensemble perception

Ariely, D. (2001). Seeing Sets : Representation by Statistical Properties. *Psychological Science*, *12*(2), 157-162. https://doi.org/10.1111/1467-9280.00327

Graphic perception may be a special case where we compute over the **positions** of data points.

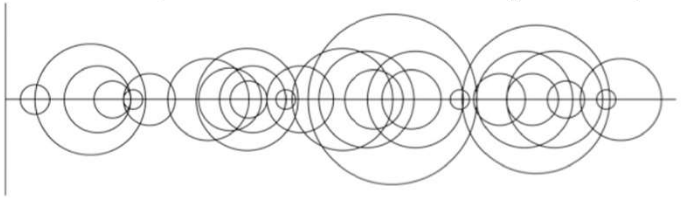
Remarkably, we can also **average** quantities conveyed by other parameters (size, orientation, motion)



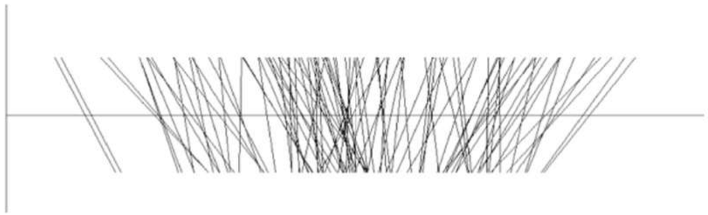


Whitney & Yamanashi, 2018

And even compute their correlations (Rensink, 2014, 2015):



a Second dimension represented by size

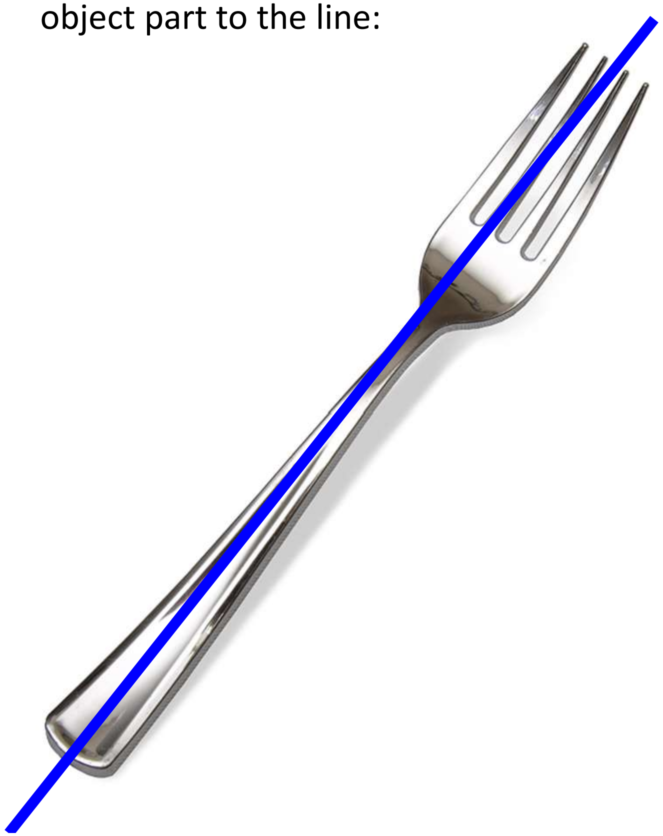


b Second dimension represented by orientation

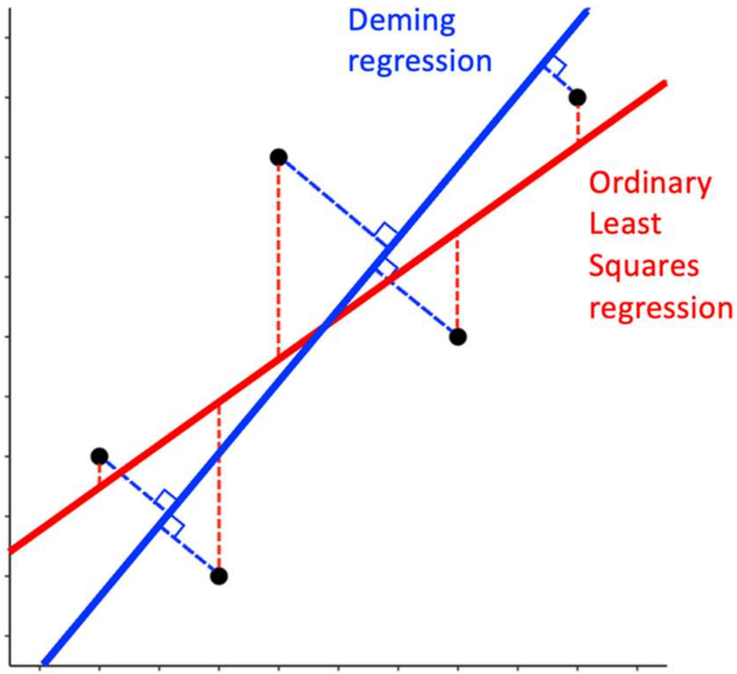
Prediction 2 : The principal axis of an object corresponds to Deming regression, not ordinary least squares

Ciccione, L., & Dehaene, S. (2021). Can humans perform mental regression on a graph? Accuracy and bias in the perception of scatterplots. *Cognitive Psychology*

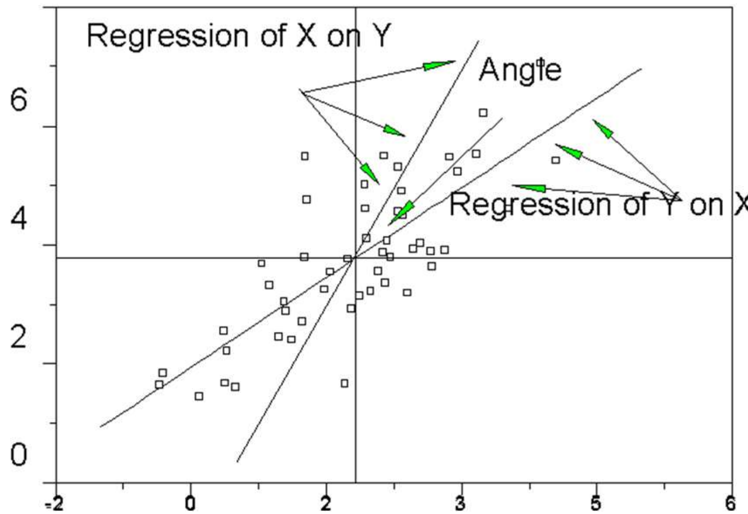
The principal axis of an object is defined as the line whose orientation minimizes the sum of the square distances of each object part to the line:



For a scatter plot, this corresponds to Deming regression, which differs from Ordinary Least Squares. The latter assumes y = a x + b + noise, and therefore minimizes the vertical distance to the line.



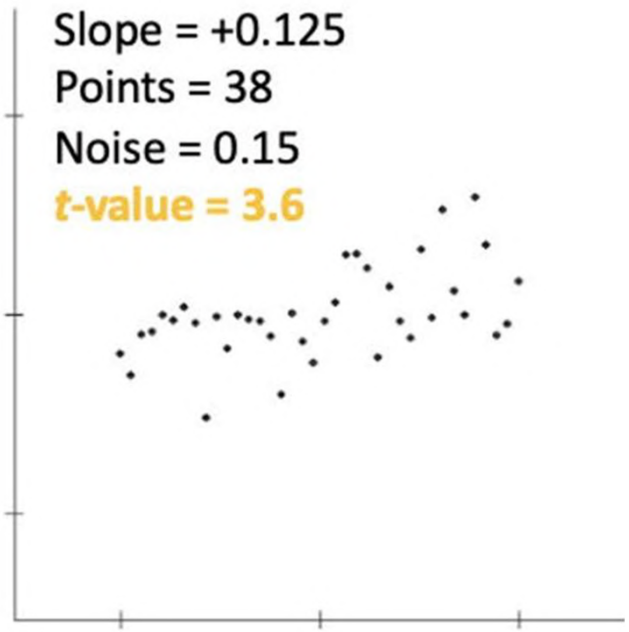
OLS regression provides unbiased estimates of the slope a and the intercept b, but it has some counterintuitive properties.
Notably, there are **two** regression lines, one for regressing Y on X, and one for regressing X on Y.
The regression coefficient r is the same for Deming and OLS.

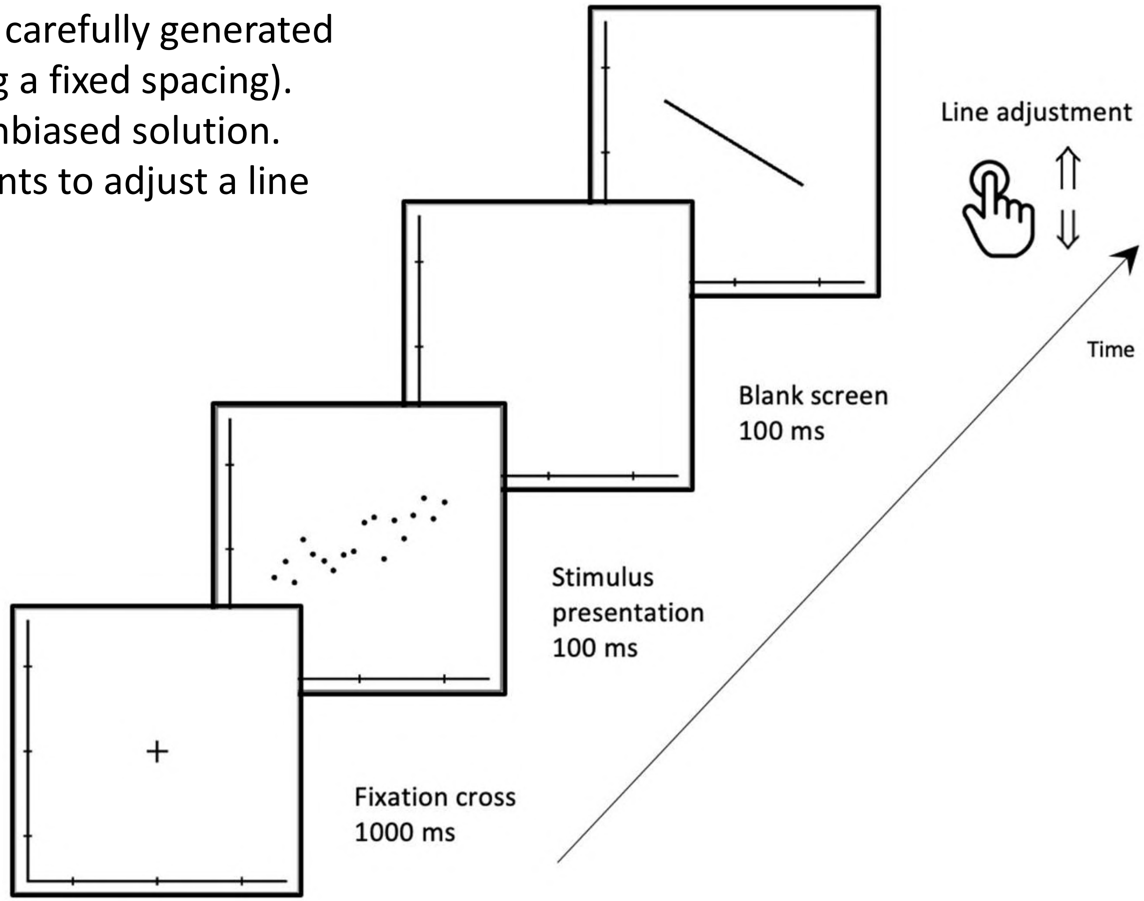


Evaluating the nature of the human regression line with a line adjustment task

Ciccione, L., & Dehaene, S. (2021). Can humans perform mental regression on a graph? Accuracy and bias in the perception of scatterplots. *Cognitive Psychology*

In this experiment, as in all previous experiments, we carefully generated graphics according to y = a x + b + noise (with x having a fixed spacing). Thus Ordinary Least Squares should be the optimal unbiased solution. After briefly flashing a scatterplot, we asked participants to adjust a line to the best fitting orientation.

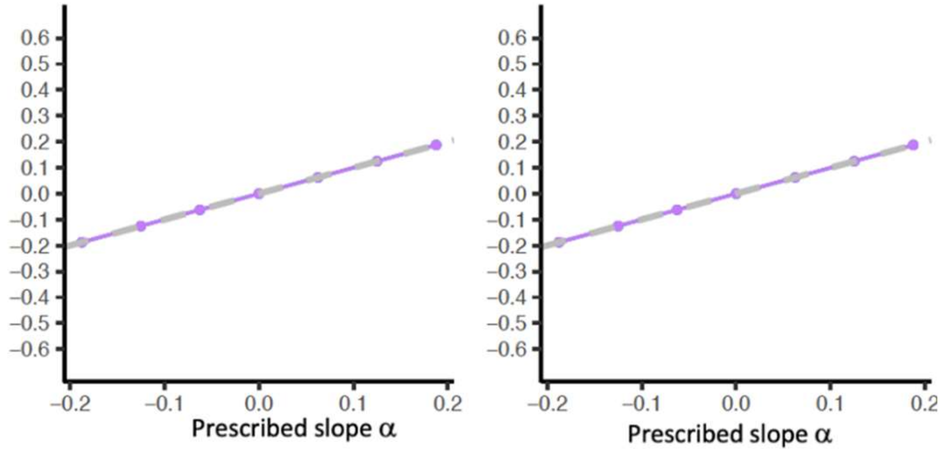




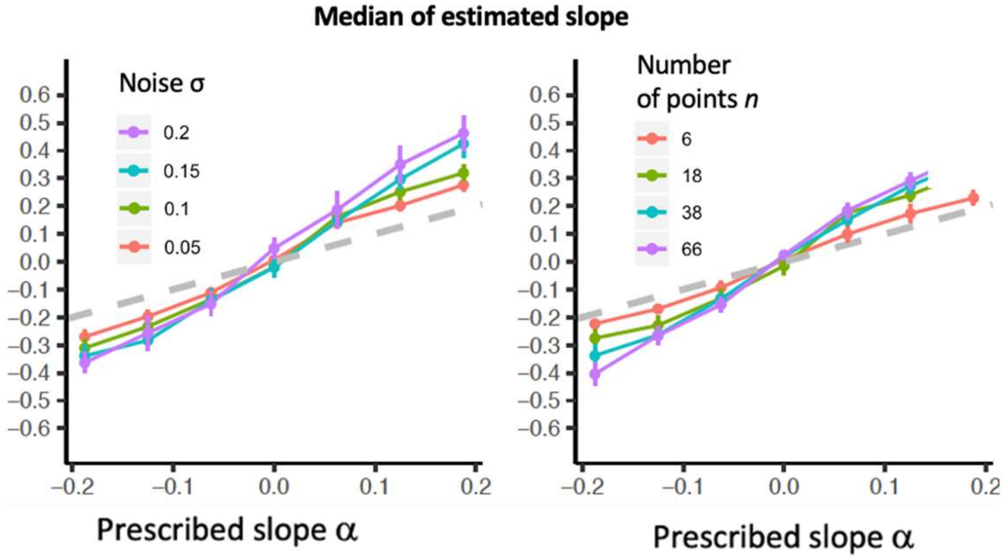
Line adjustment task

Ciccione, L., & Dehaene, S. (2021). Can humans perform mental regression on a graph? Accuracy and bias in the perception of scatterplots. *Cognitive Psychology*

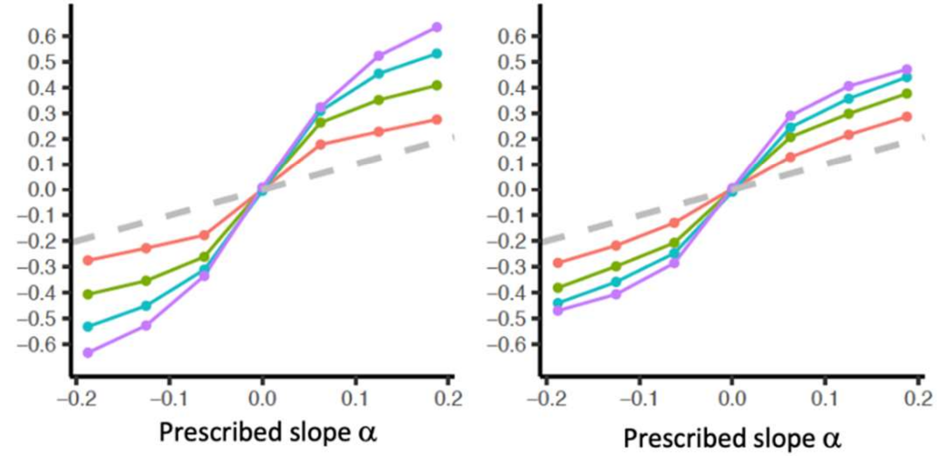
OLS



SUBJECTS



DEMING



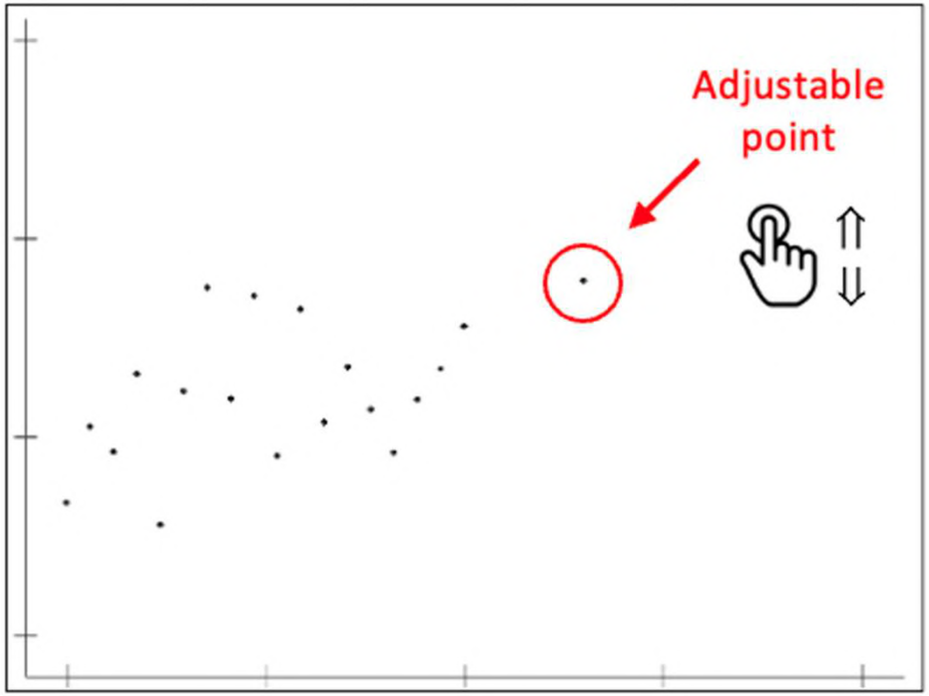
Results: the reported slope varied systematically with two parameters: the noise level and the number of points.

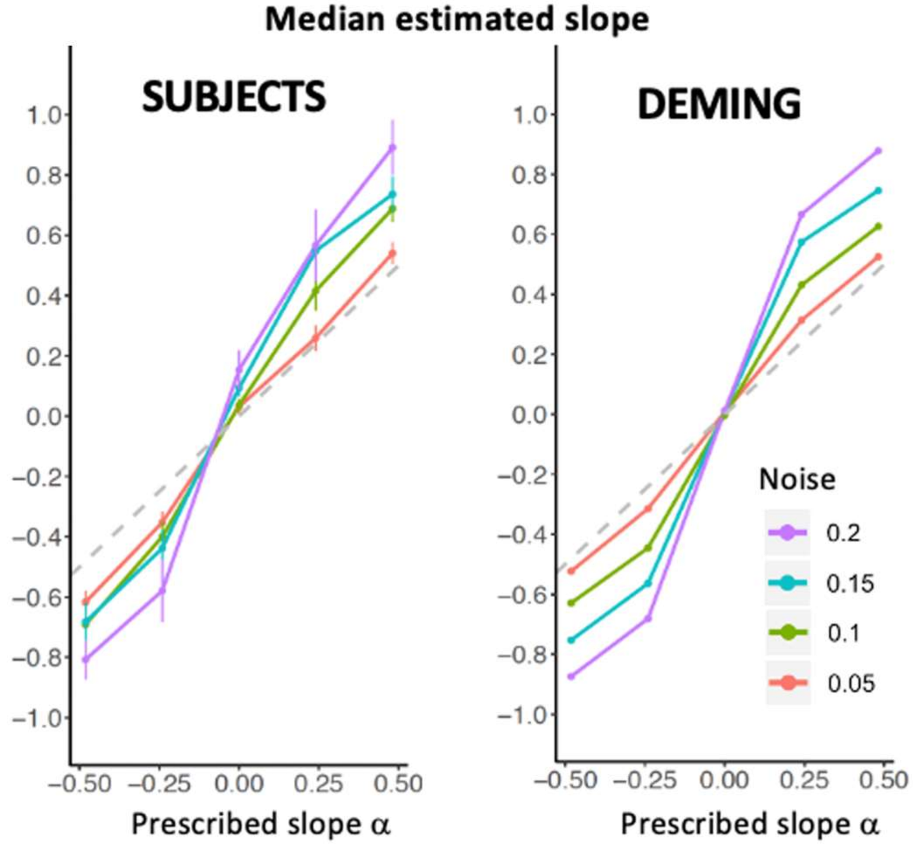
These variations were consistent with Deming regression, not ordinary least squares.

Extrapolation task

Ciccione, L., & Dehaene, S. (2021). Can humans perform mental regression on a graph? Accuracy and bias in the perception of scatterplots. *Cognitive Psychology*

Those results were replicated with a second method, a more implicit task where subjects extrapolated a regression by placing a dot.





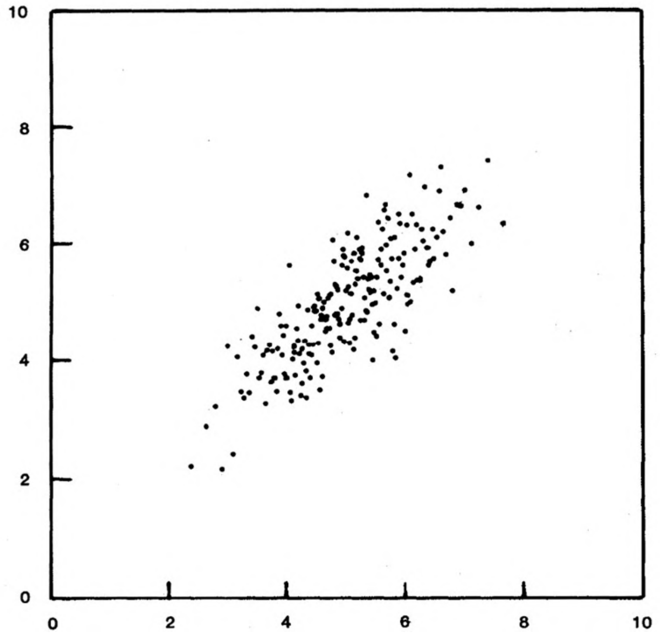
Conclusions

Subjects excel at quickly extracting statistics from a visual display:

- They can identify the **central tendency** (increasing or decreasing)

(we will see next week that they can partially reduce the influence of **outliers**).

- This capacity can be enhanced by **education**
- But is also present, in an **intuitive** manner, in children and even non-human animals
- Subjects compute the **principal axis** of a graph, not the Ordinary Least Squares regression line.



Next week : more tests of the neuronal recycling hypothesis

- Participants are influenced by the placement of the data relative to the size of the axes.
- All of these data may be explained by assuming that **they treat the multiple data points forming a scatterplot as an object** that they judge according to its skeleton and density.
- Brain imaging of graphic perception suggests a hypothetical two-step process:
    - Perceptual processing at or just anterior to Lateral Occipital Cortex (LOC)
    - Extraction of statistical parameters in IPS