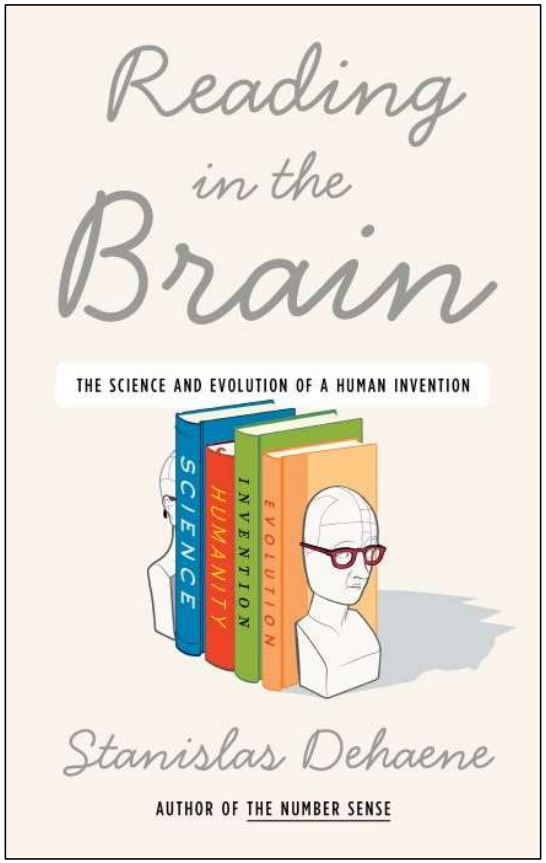


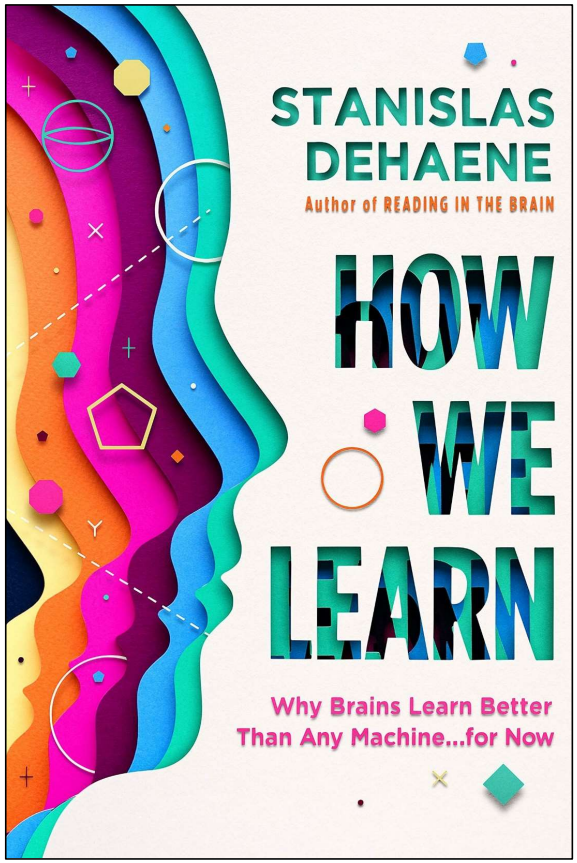
How we learn

The main principles of brain plasticity and learning

Stanislas Dehaene

Collège de France, Paris

and NeuroSpin Center, Saclay, France



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NeuroSpin

France

1. Brain plasticity

- How does the brain change with learning?
- How do nature AND nurture combine during learning?
- An example of cortical recycling : the acquisition of reading

2. Learning to learn

- The four pillars of learning, and how to exploit them

Two paintings by Nico, a gifted young artist

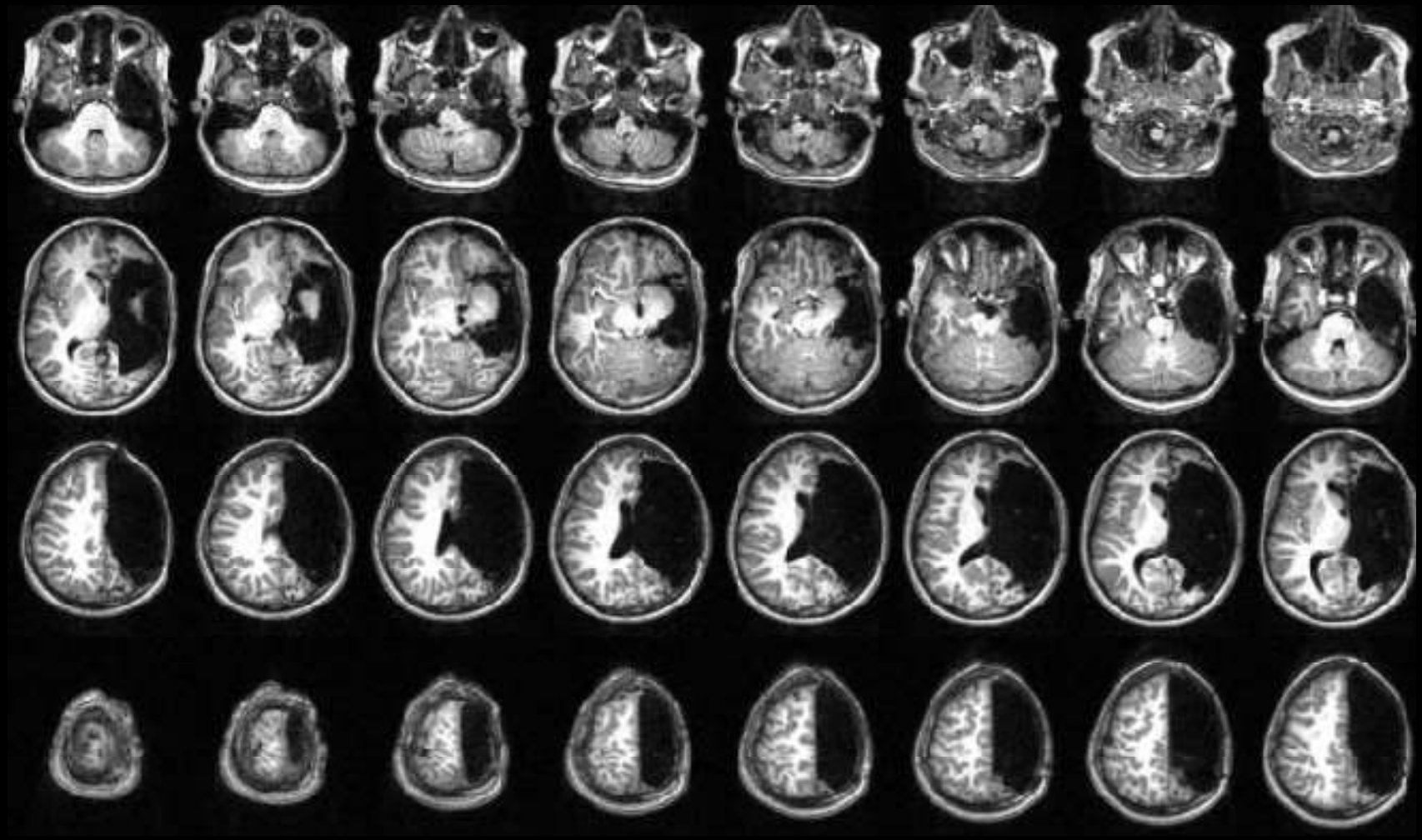
« The art of fencing »

« Butterflies »

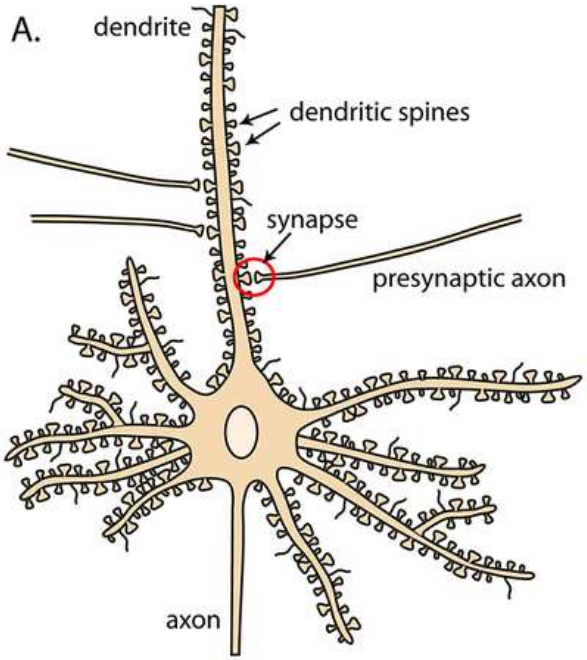
“Impression Soleil Levant” by Claude Monet, copied during a trip to Paris

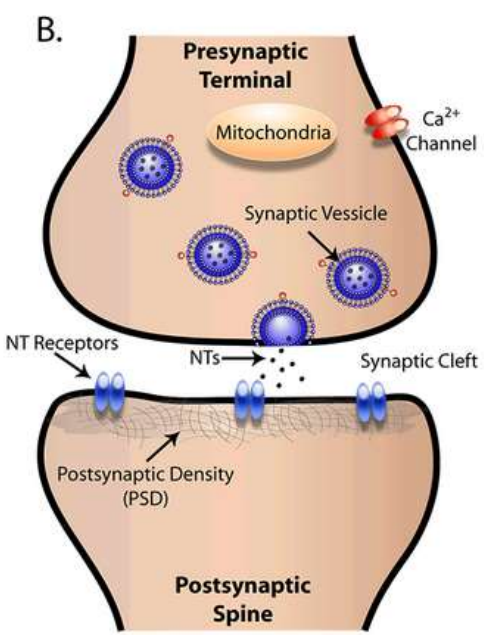
Half a brain is enough ! An immense message of hope for education

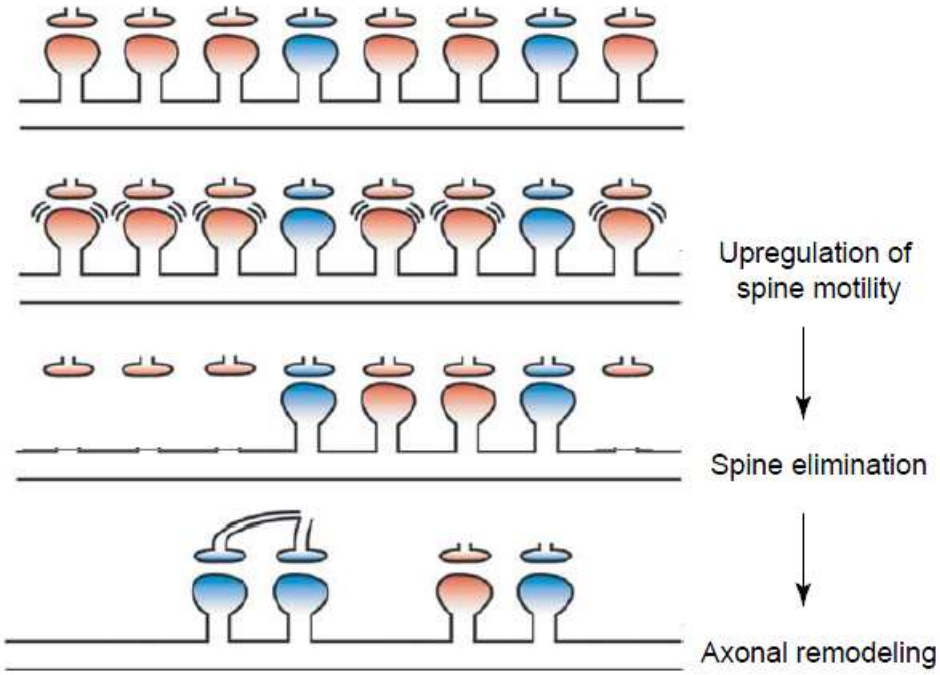
Nico’s brain



What is brain plasticity ?







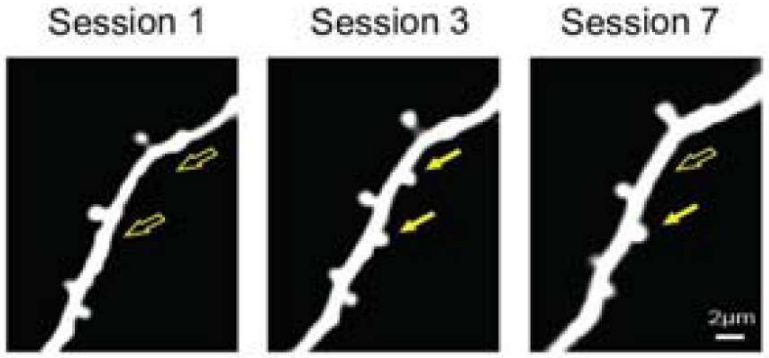
Smrt & Zhao. Frontiers in Biology 2010

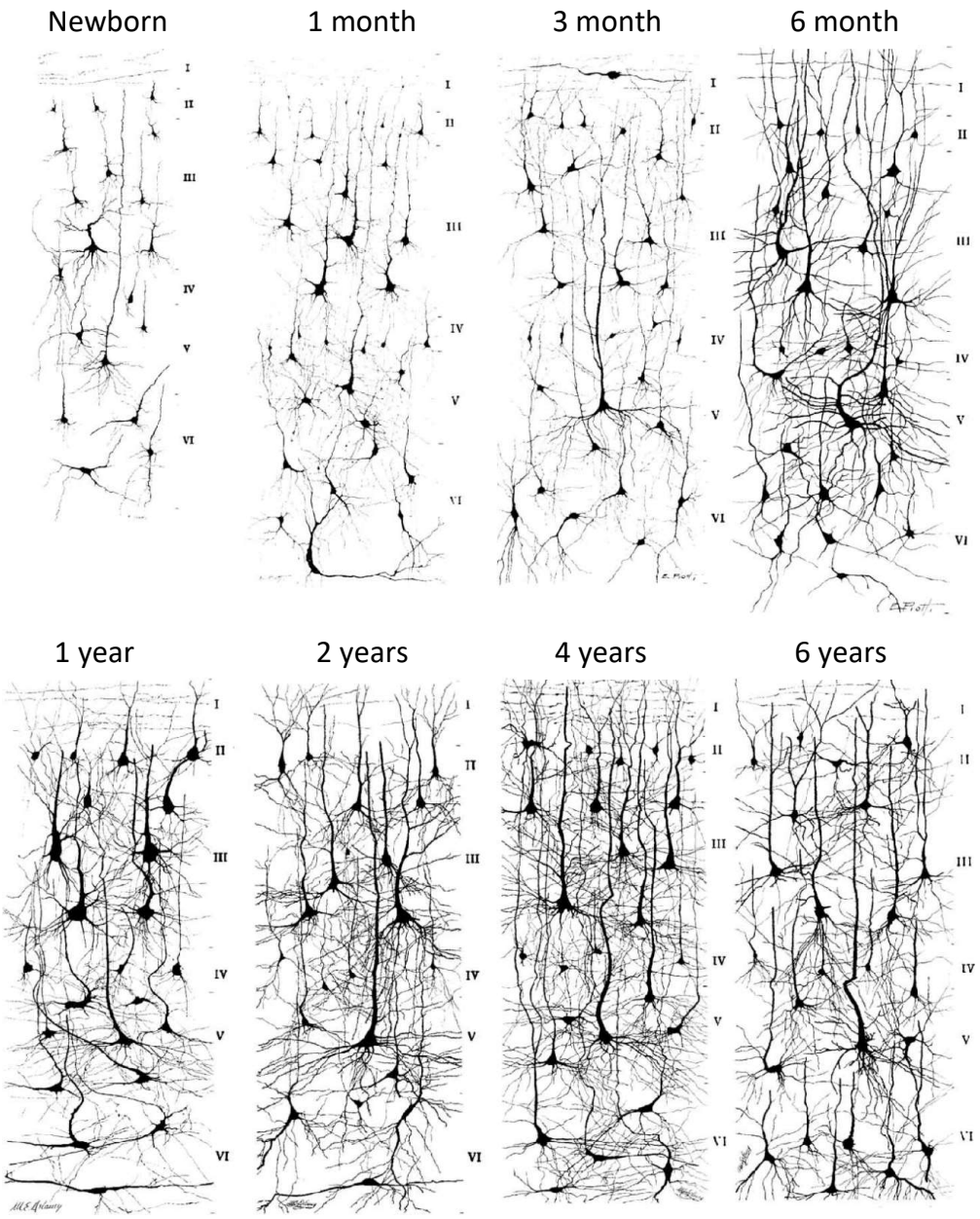
Many experiments show that learning rests primarily on the reinforcement and selective elimination of synapses, which form a memory trace of our experiences and affect the tuning of our neurons.

Neuronal activity (or its absence) selectively modulate synapse stability.

Synapses can rearrange on a fast time scale: dendritic spines come and go !

Learning also rests on changes in axonal branching, myelination, and even cell internal parameter changes.





Early childhood: a privileged period for brain plasticity

In the first years of life, the jungle of axonal and dendritic trees is exuberant.

In the brain of a two-year old, there is approximately twice as many synapses as in the adult !

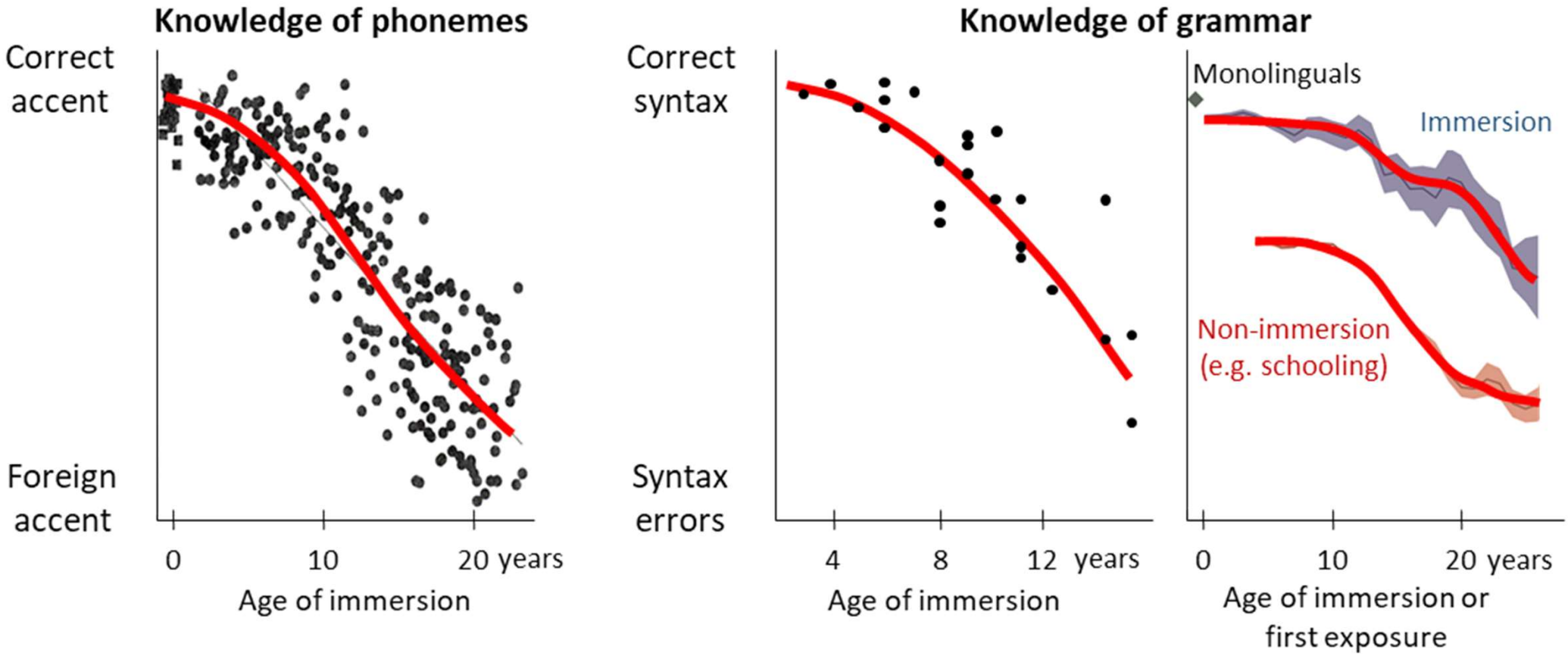
Synapses do not just grow: they form and retract under the influence of neuronal activity.

A neuronal Darwinian process (Jean-Pierre Changeux):

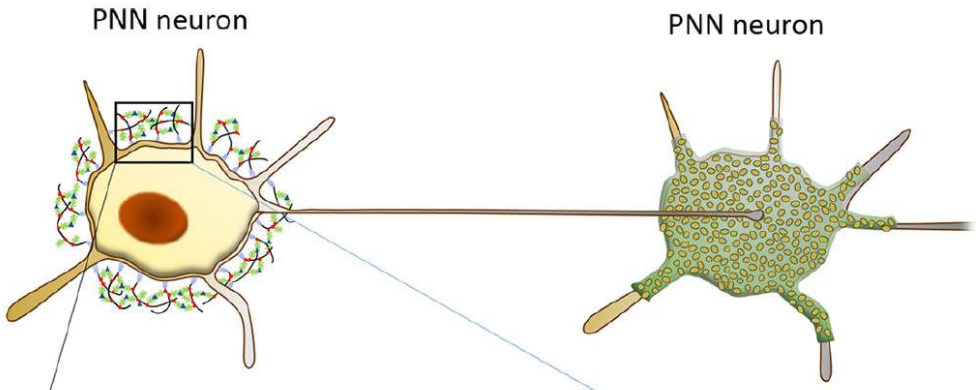
- Useful synapses are maintained and multiplied
- Counterproductive synapses are eliminated

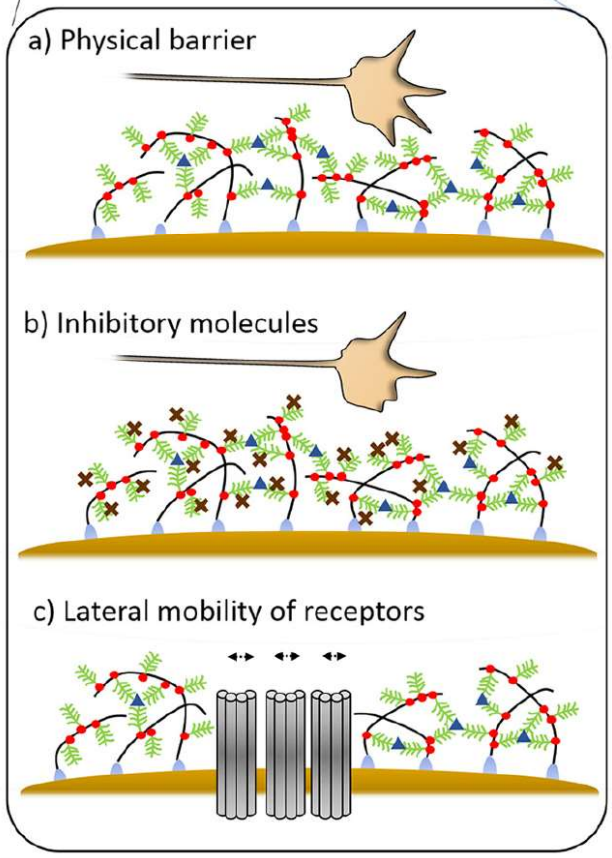
Learning is much easier at an early age

Example: the acquisition of a second language

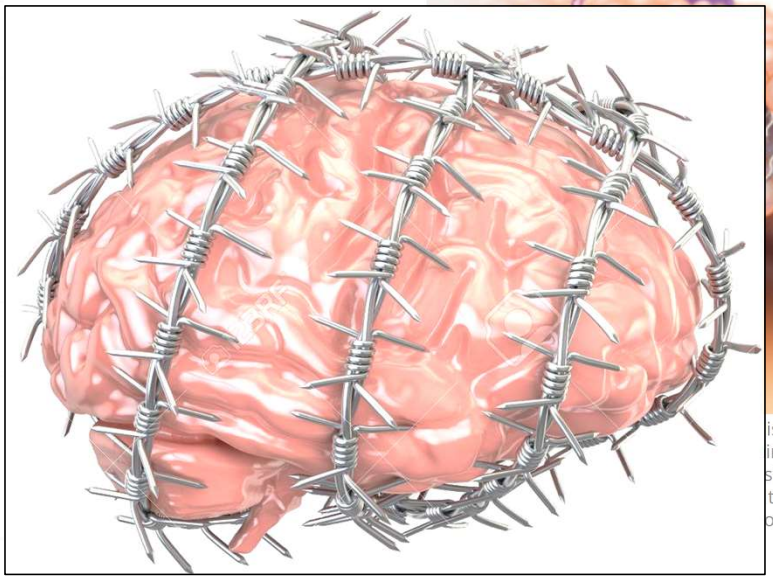


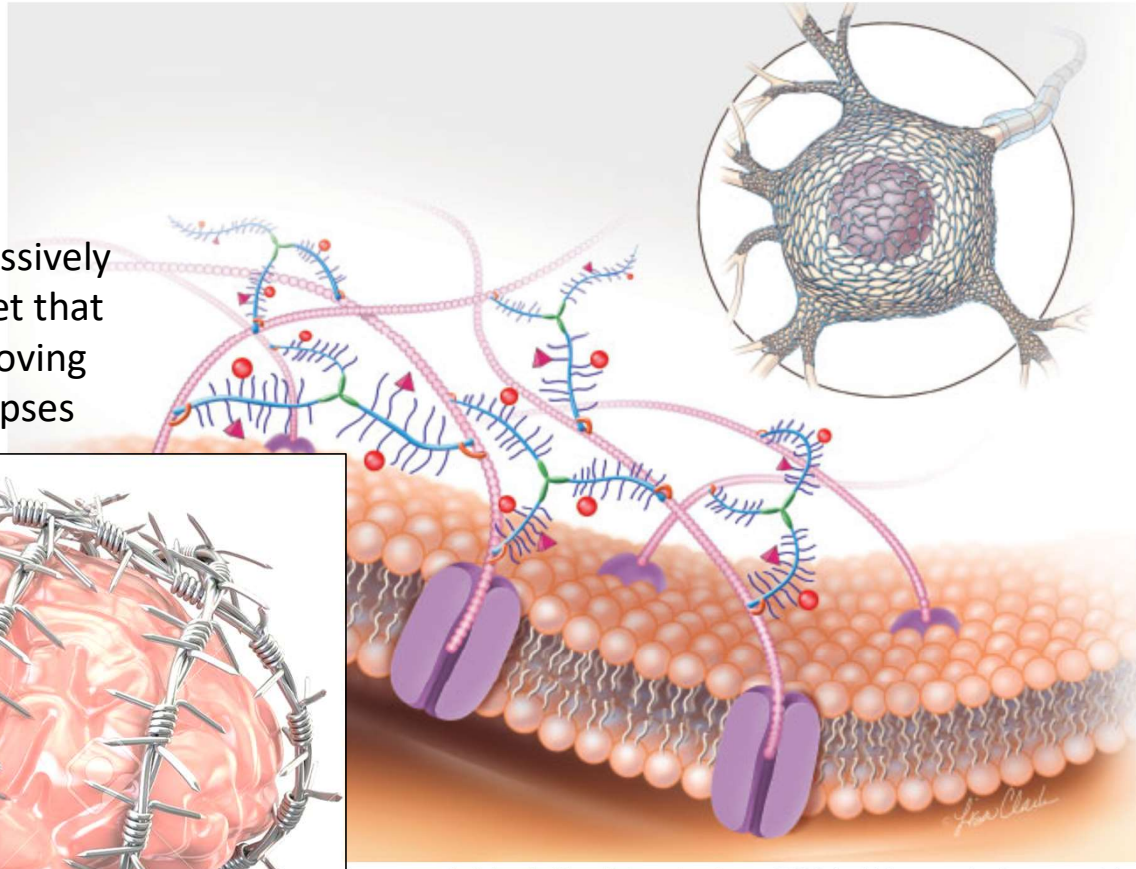
Why does brain plasticity diminish during development?





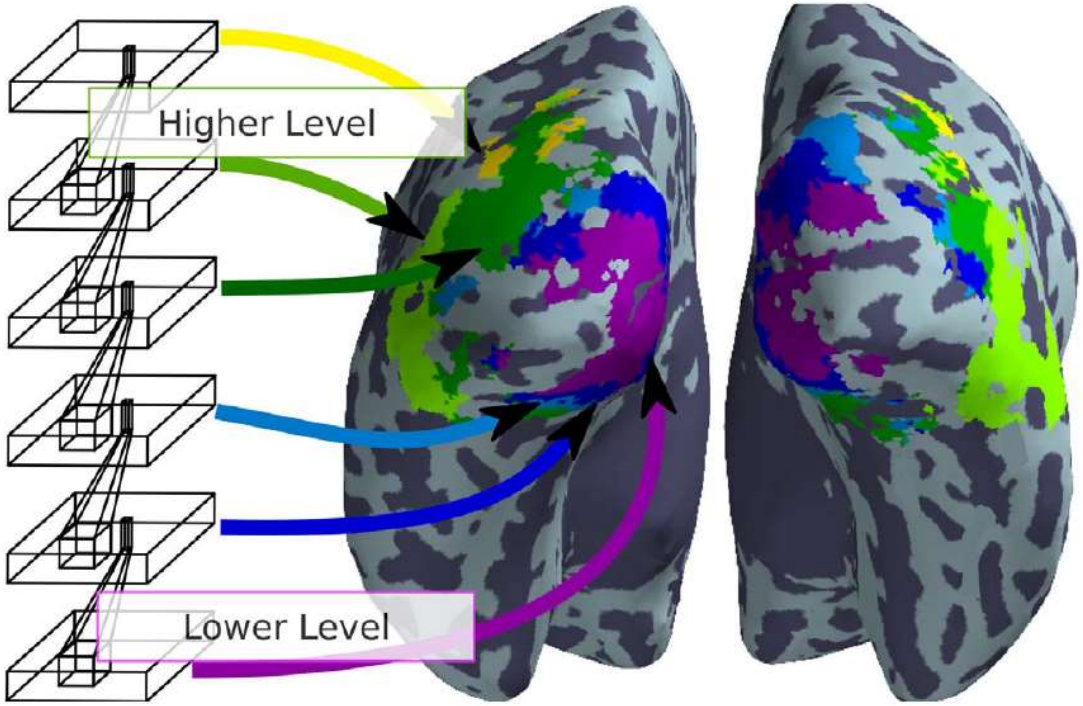
Neurons become progressively surrounded by a rigid net that prevents them from moving and forming new synapses

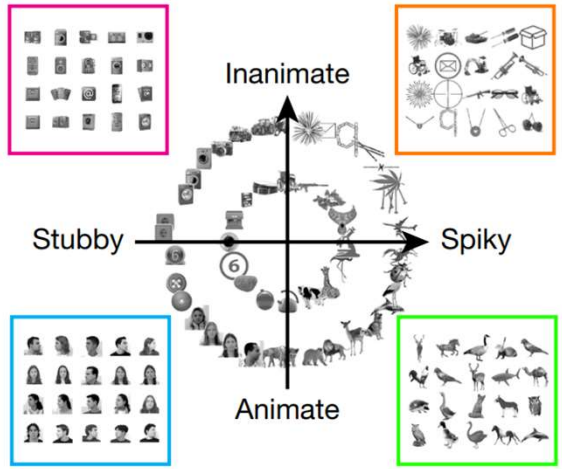


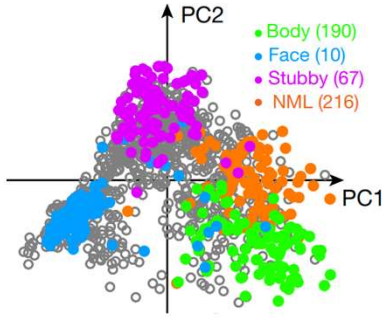


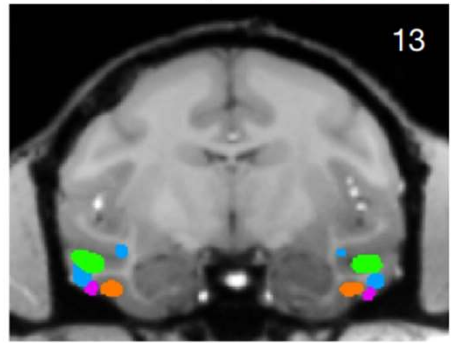
is composed of chondroitin sulfate proteoglycans (CSPGs), which are made of a core protein
ins (dark purple). CSPGs bind to hyaluronic acid (pink balls), which is secreted by membrane-
stabilize the interaction between hyaluronic acid and CSPGs. Sema3A and Otx2 (pink
to the sugar chains of the CSPGs. Tenascin-R (green) acts as a cross-linking protein among
omolecular assembly of the PNN.

Using synaptic plasticity, artificial neural networks capture the early stages of brain activity







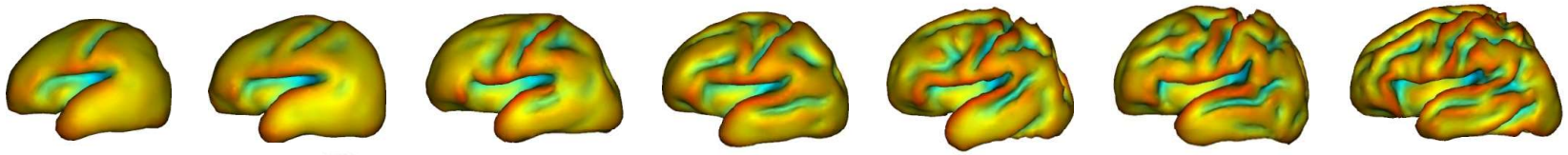


Eickenberg, M., Gramfort, A., Varoquaux, G., & Thirion, B. (2017). Seeing it all : Convolutional network layers map the function of the human visual system. *NeuroImage*, *152*, 184-194. https://doi.org/10.1016/j.neuroimage.2016.10.001

Yamins, D. L., Hong, H., Cadieu, C. F., Solomon, E. A., Seibert, D., & DiCarlo, J. J. (2014). Performance-optimized hierarchical models predict neural responses in higher visual cortex. *PNAS*, *111*(23), 8619-8624.

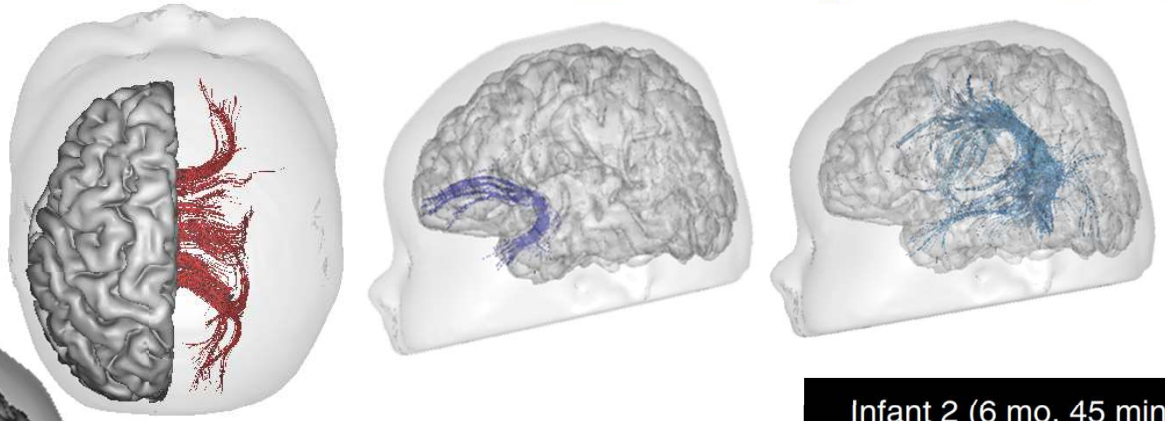
Doris Tsao
Bao et al, Nature 2020

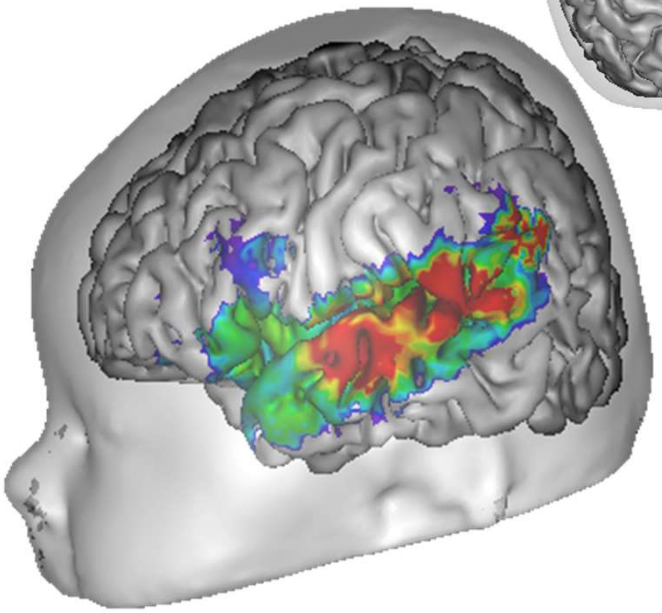
In the real brain, learning is not based on a « blank slate » or a random network : The infant's brain is highly structured from birth



The brain is **organized from birth**.

All major bundles of connections are in place

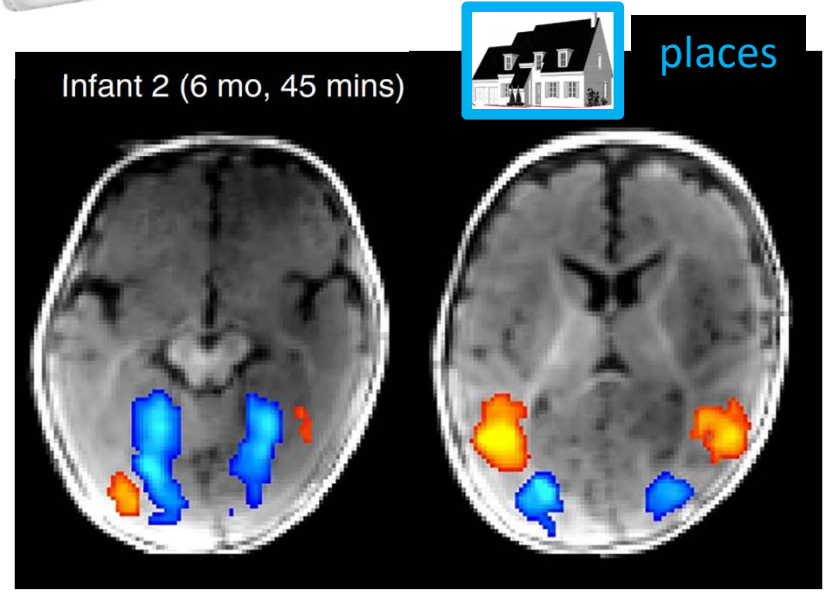




Specialized circuits are already active, for instance for

- **Spoken language**
- **Vision**

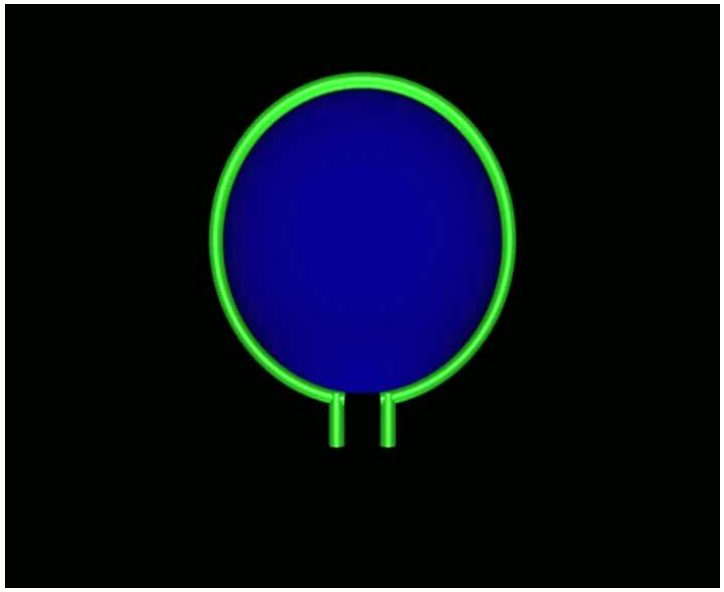
Babies possess « **core knowledge** » for numbers, space, probabilities, objects, people….



An example of early competence: Arithmetic intuitions in infants

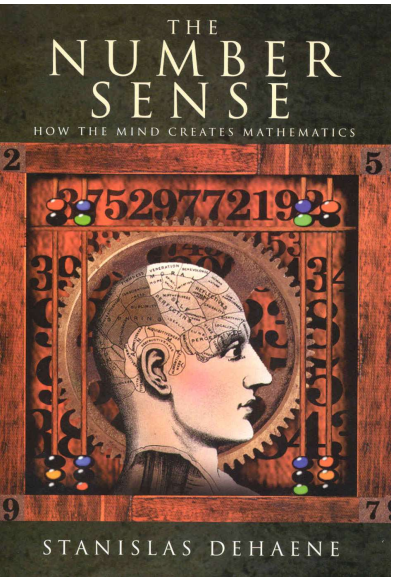
Babies of a few month of age discriminate numbers and react to violations of the laws of **arithmetic** and **probability**.

When 5 +5 does not make 10….



…infants look longer at such impossible events

K. McCrink, K. Wynn, L. Bonatti, F. Xu, E. Spelke…

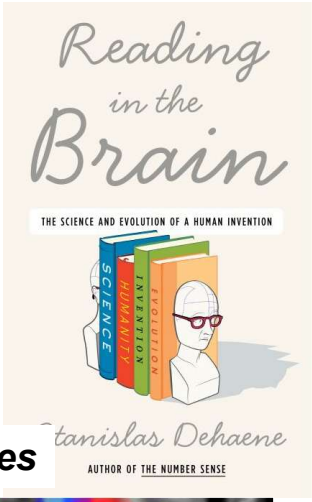


Neuronal recycling in humans

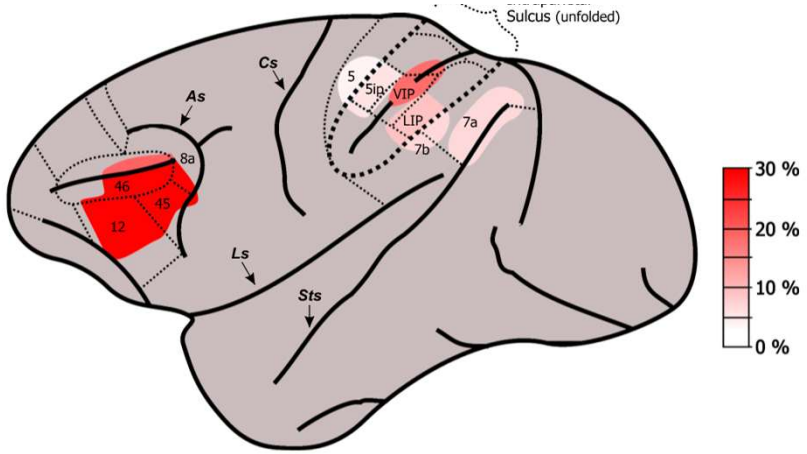
Cultural inventions such as Arabic numerals or the alphabet **repurpose** or **recycle** the pre-organized neural circuits that we inherit from our evolution.

Through **symbols**, these pre-existing representations, become (1) **discrete** and precise, and (2) capable of entering into **nested recursive expressions**.

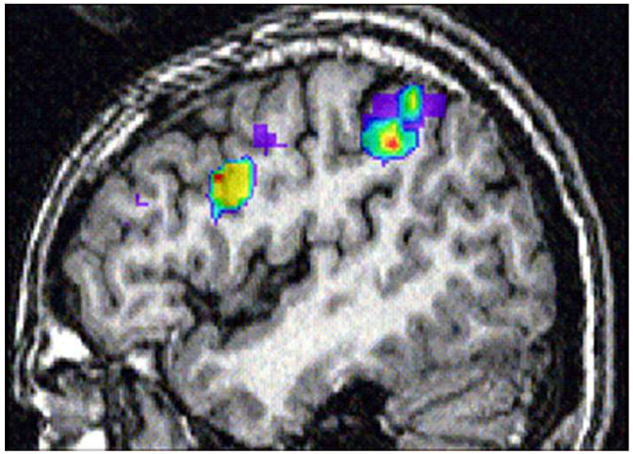
Recycling the ventral visual pathway for **reading**



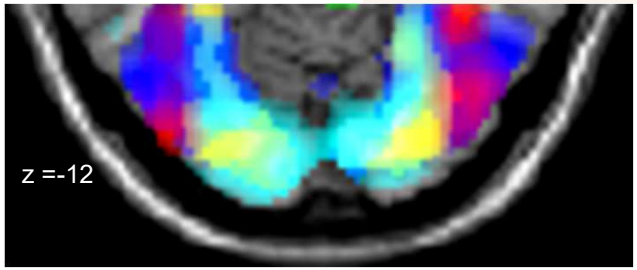
Number sense in the **monkey** brain



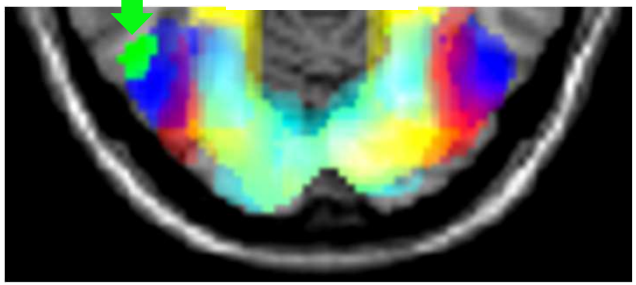
Symbolic arithmetic in the **human** brain



illiterates

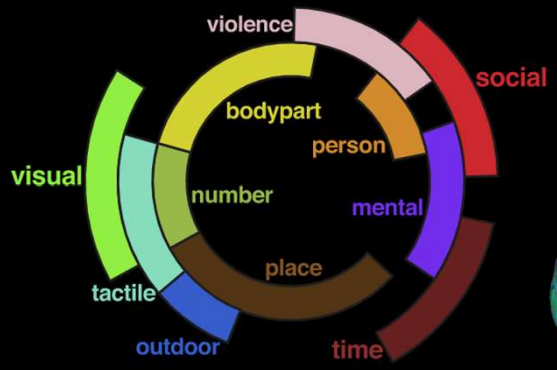


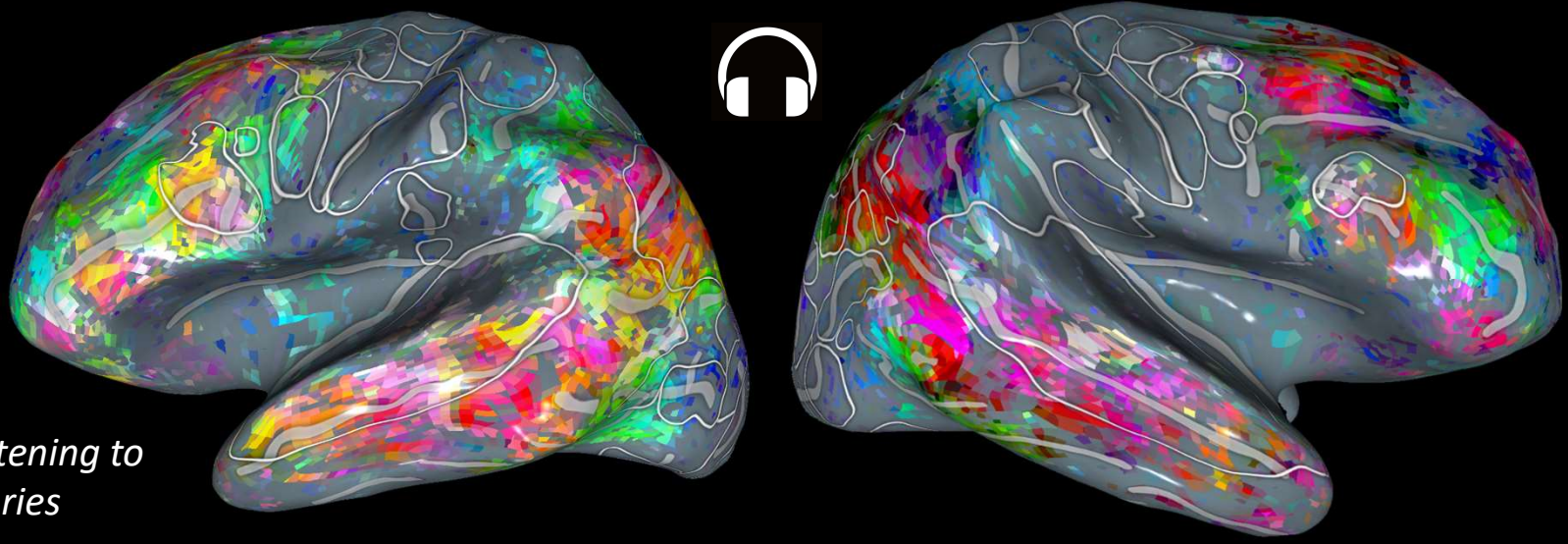
Literates



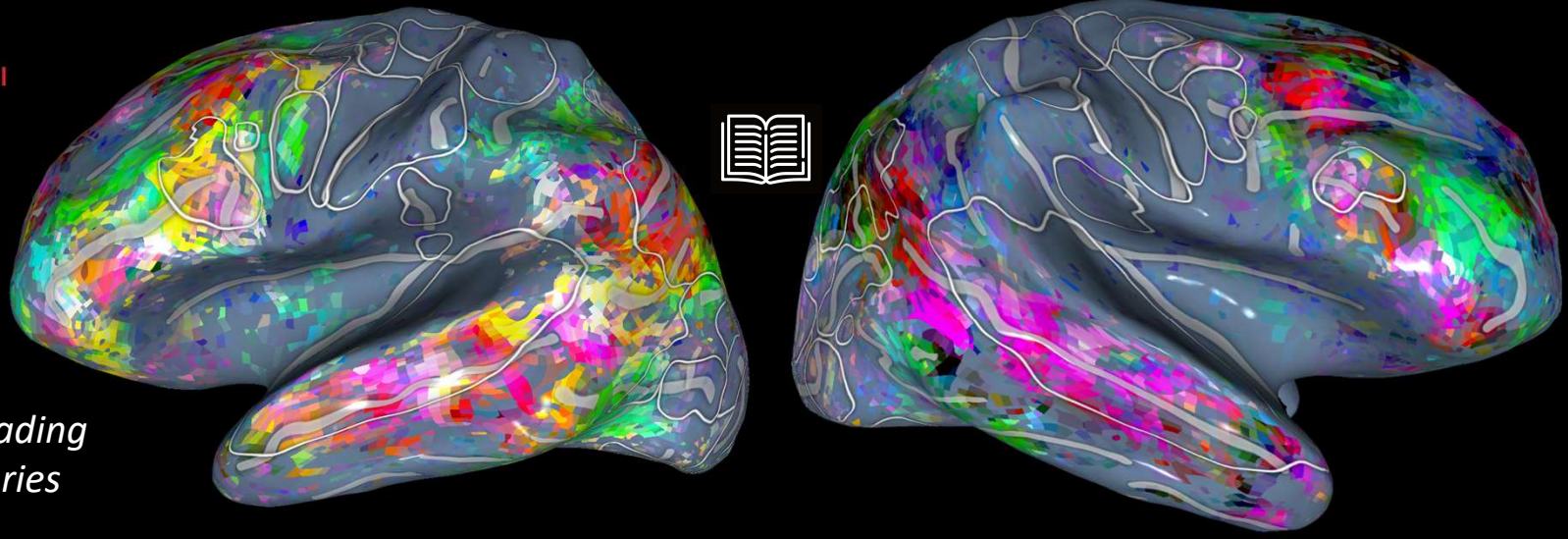
In expert adult readers, written and spoken language converge onto the very same brain areas for

meaning





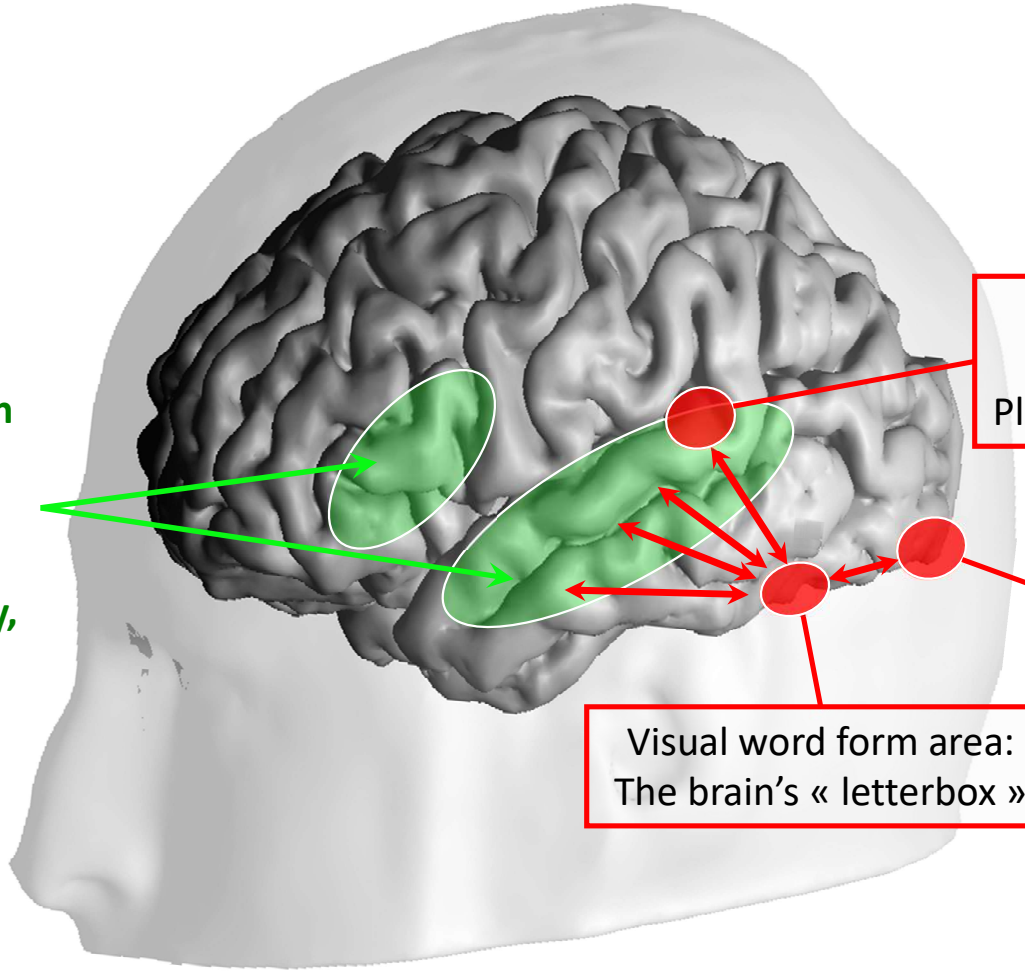
Listening to stories



Reading stories

Deniz, Nunez-Elizalde, Huth, & Gallant (2019). Journal of Neuroscience

Reading recycles pre-existing visual and language brain circuits



Transformations due to
Learning to read

Regions involved in spoken language:

Phonology, Lexicon Syntax, Meaning

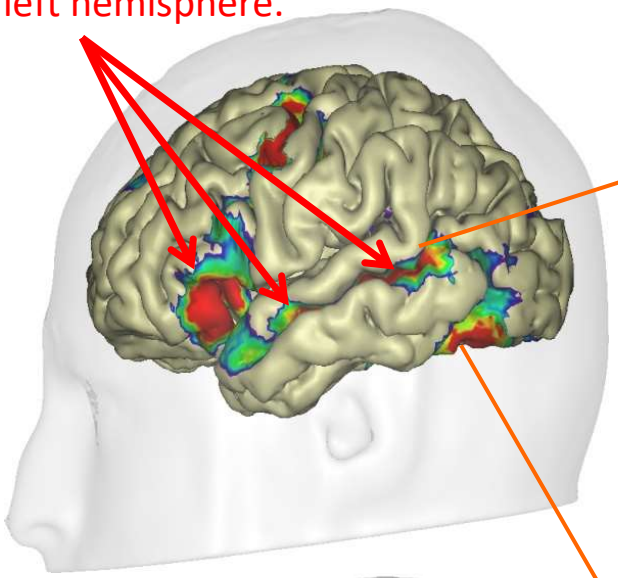
Phonemic representation Planum temporale

Visual cortex

Visual word form area: The brain's « letterbox »

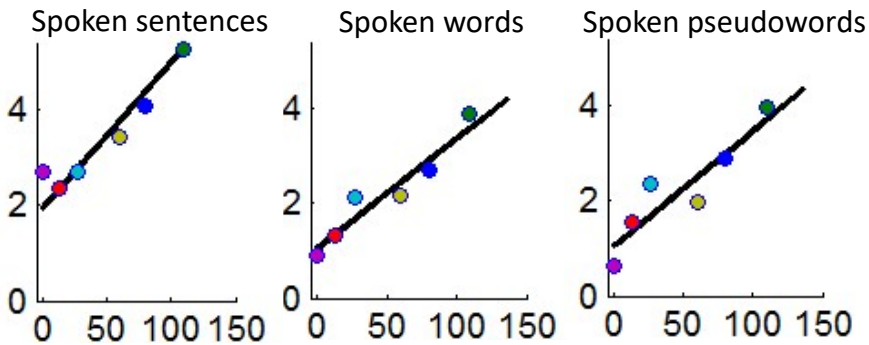
The main brain changes induced by reading acquisition

Reading gives access, through **writing**, to all **spoken language** areas of the left hemisphere.

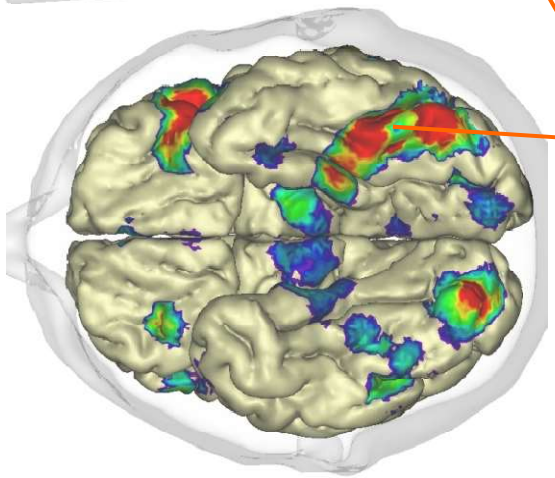


Reading develops the **phonological areas** of the brain. The left planum temporale increases its response to speech, and **phonological awareness** increases.

Auditory activation to

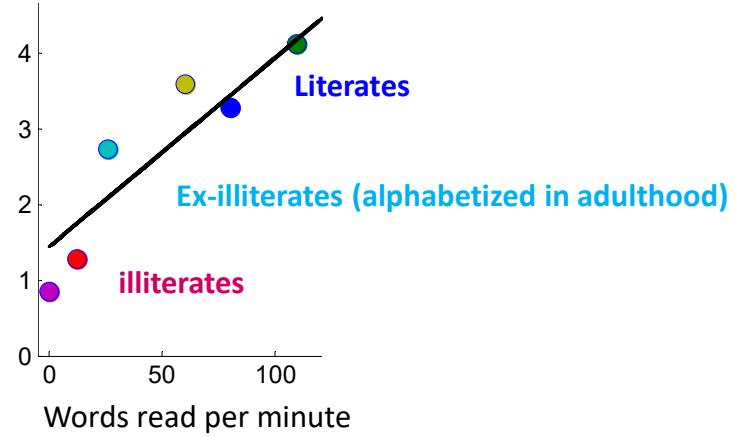


Reading reinforces the connections between those two systems.



Reading develops the **visual areas of the brain.** In particular, the **visual word form area** in the **left occipito-temporal sulcus** specializes for written words

Visual activation to written words



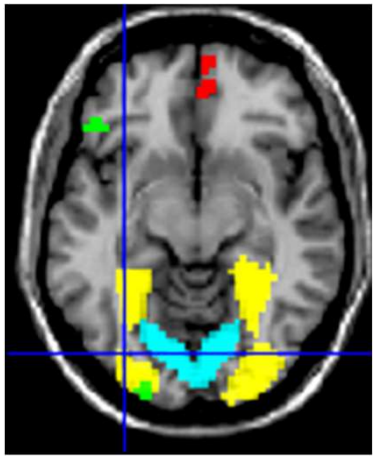
Dehaene et al., Science 2010; Dehaene et al., Nature Reviews in NeuroScience, 2015

What changes in young children as they learn to read?

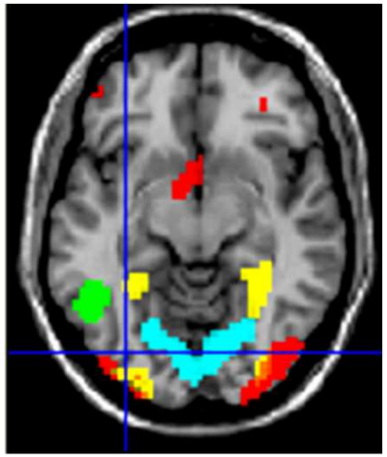
G. Dehaene-Lambertz, with Karla Monzalvo, C. Billard, S. Dehaene (NeuroImage, 2012)

The VWFA activation to strings emerges during reading acquisition and predicts reading scores

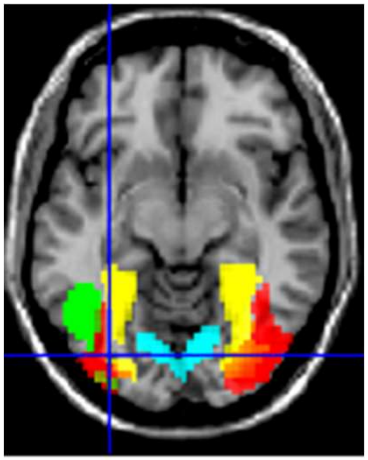
6 year-old
non-readers



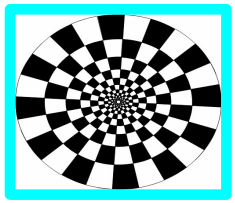
6 year-old
readers



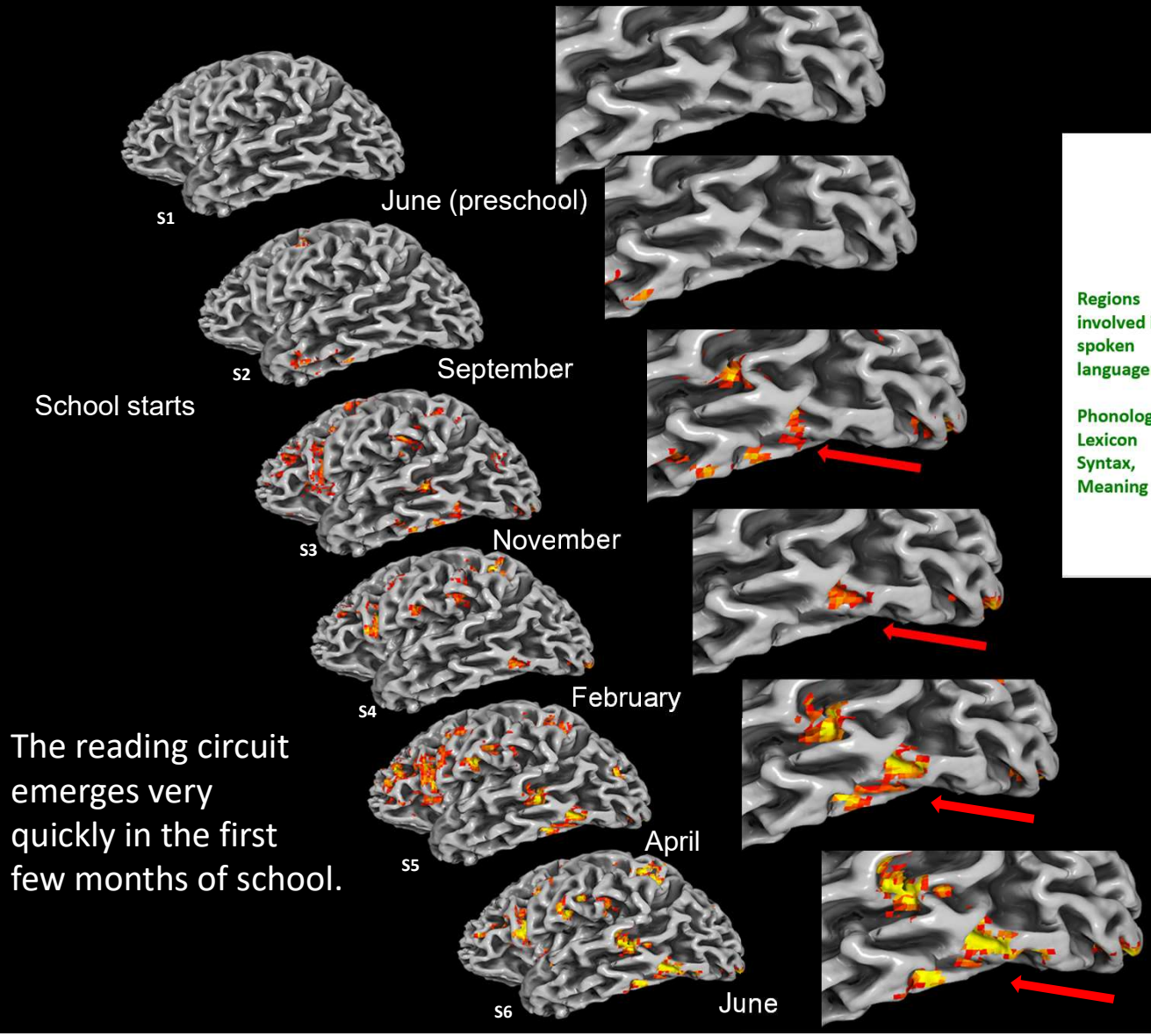
9 year-old
readers



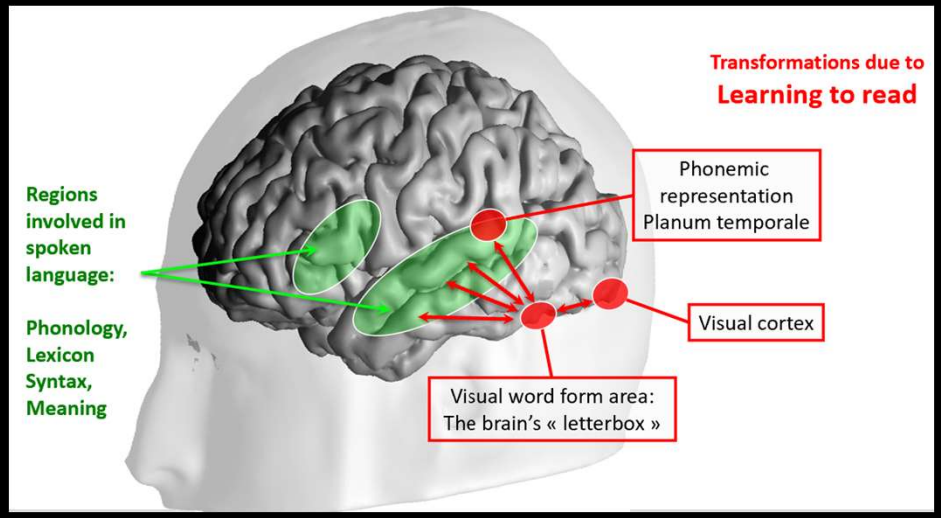
Words



Learning to read develops, in a few months, a specialized circuit for written words

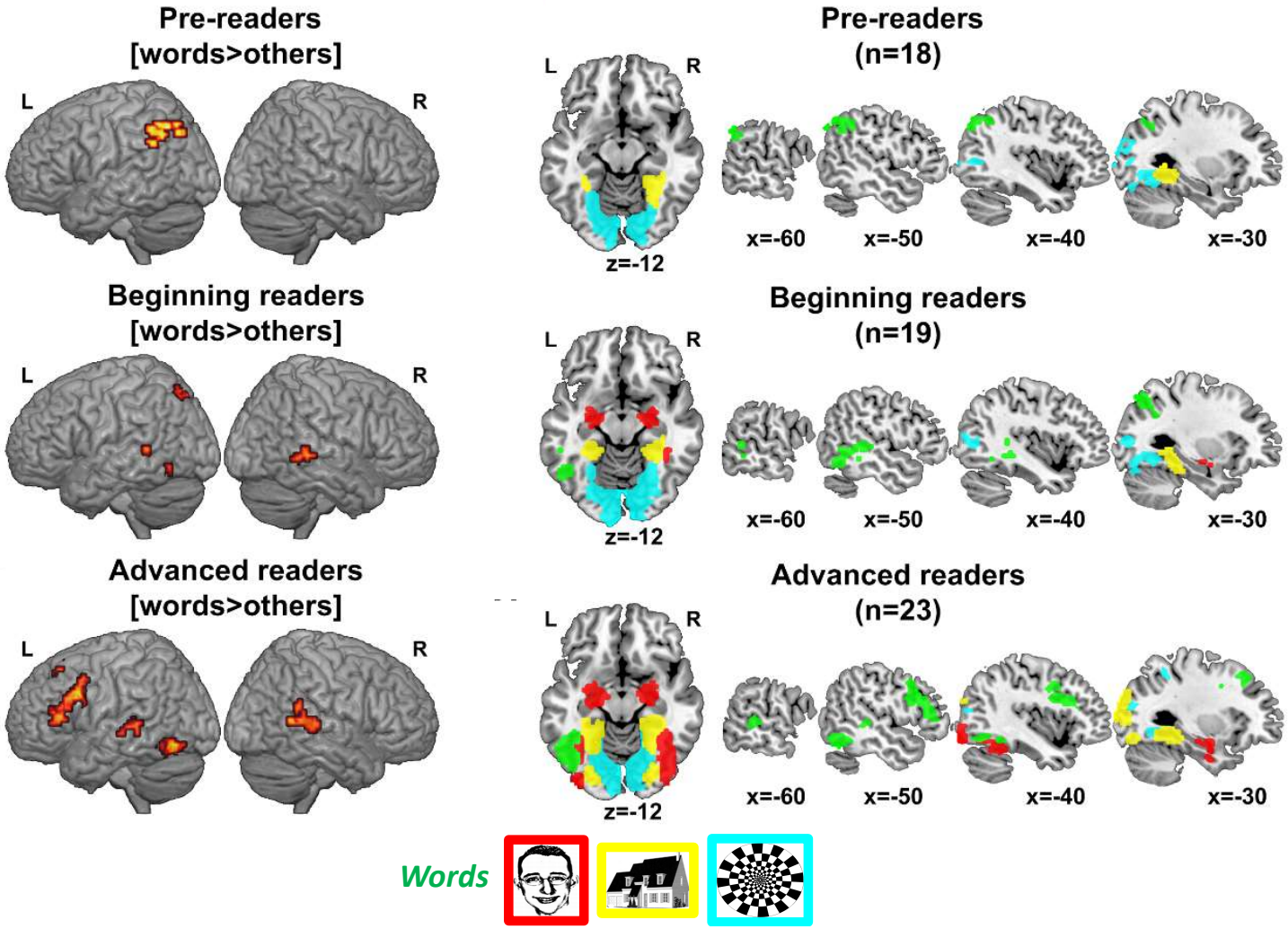


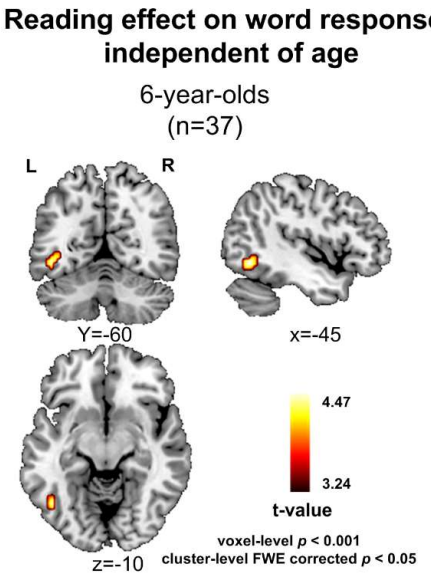
The reading circuit emerges very quickly in the first few months of school.

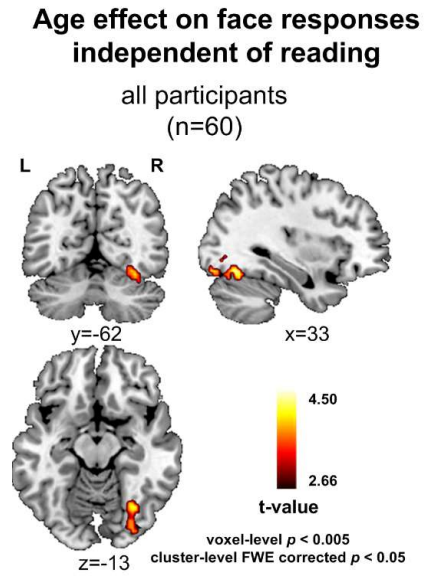


The emergence of the visual word form area depends on experience with reading, not age

X. Feng, S. Dehaene, G. Dehaene-Lambertz (*NeuroImage*, 2022)

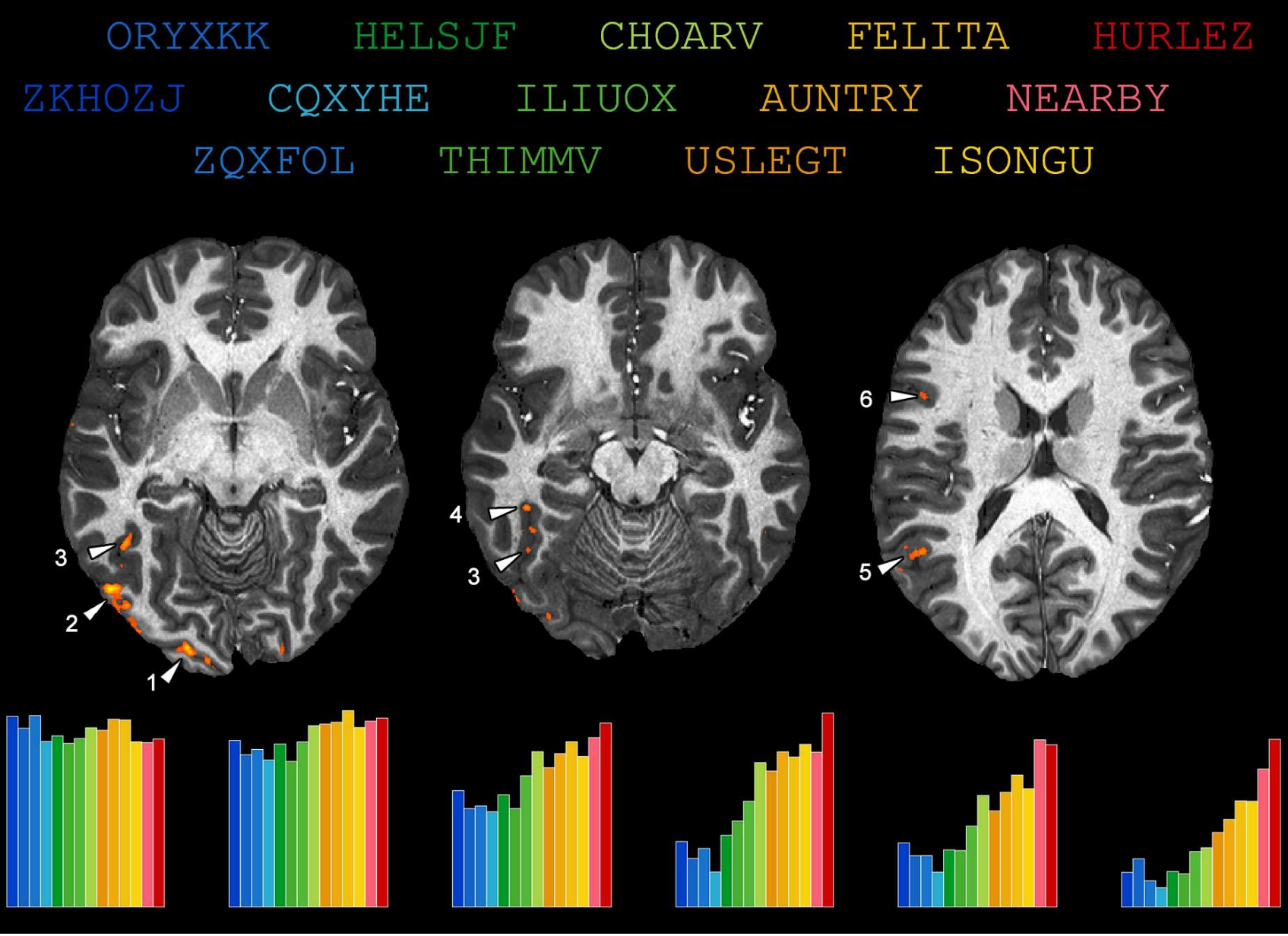


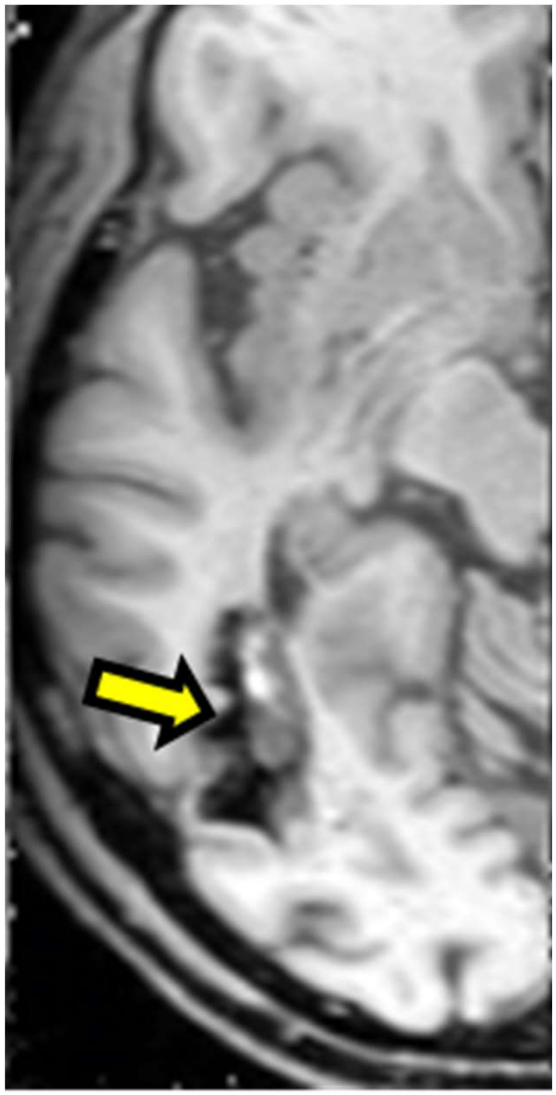




The brain as a statistician:

Visual areas compile the statistics of letters for all the languages we can read

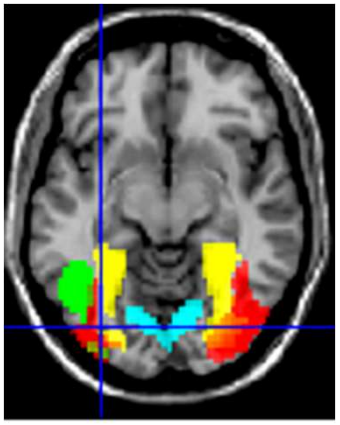




Alexia in the adult brain : brain plasticity is limited

Any of us could become ***alexic*** following a small brain lesion:

- **Reading impairment :** Every page looks like hebrew !
- **Vision is intact**
- **Spoken language and even writing can be intact**



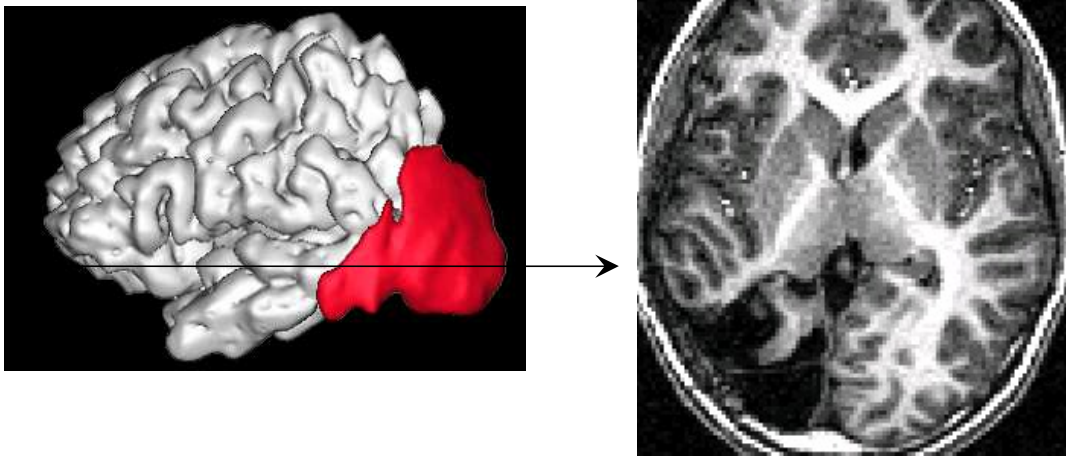
Words

We followed a pure alexic patient for 2 years:

- Very slow increase in reading speeding
- The patient remained a letter-by-letter reader
- No reappearance of the visual word form area

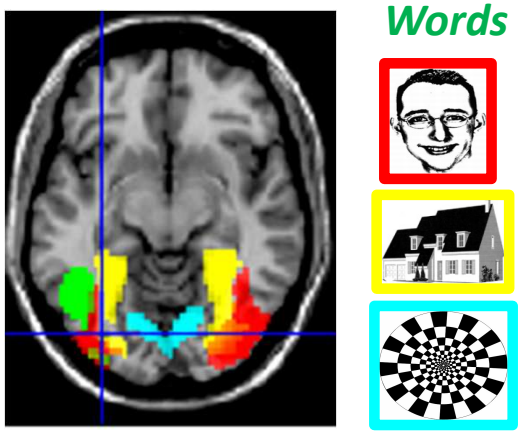
The child's brain reorganizes much more easily than the adult's

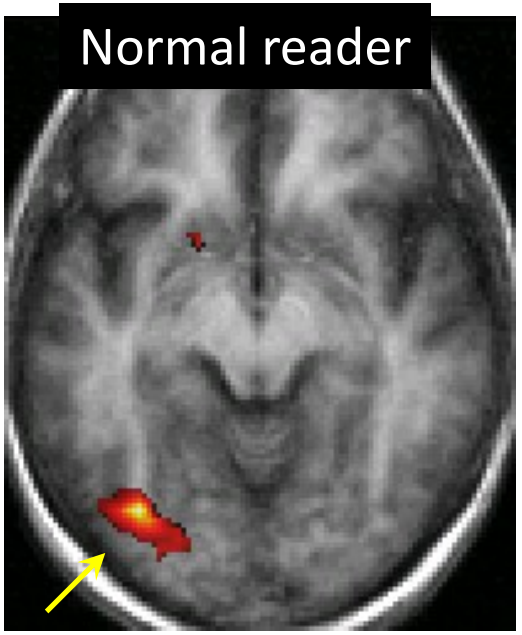
Cohen, L., Lehericy, S., Henry, C., Bourgeois, M., Larroque, C., Sainte-Rose, C., et al. (2004). Learning to read without a left occipital lobe: right-hemispheric shift of visual word form area. *Ann Neurol, 56*(6), 890-894.

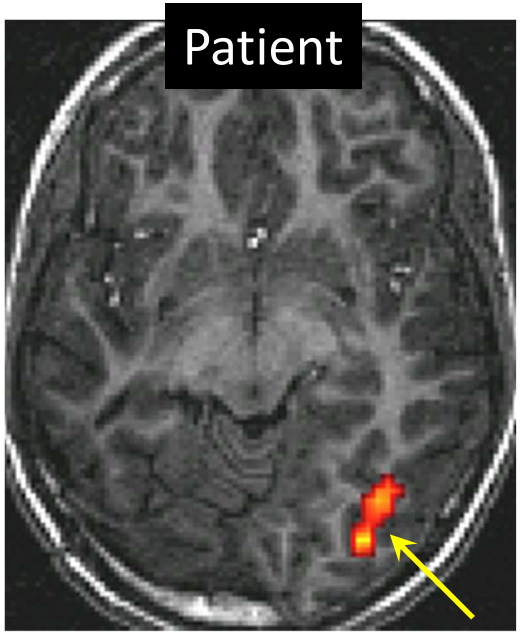


Surgical ablation of the left occipito-temporal region at the age of 4 (Sturge-Weber disease)

Scan at the age of 11 :
This child learned to read normally,
using the symmetrical region of the right hemisphere





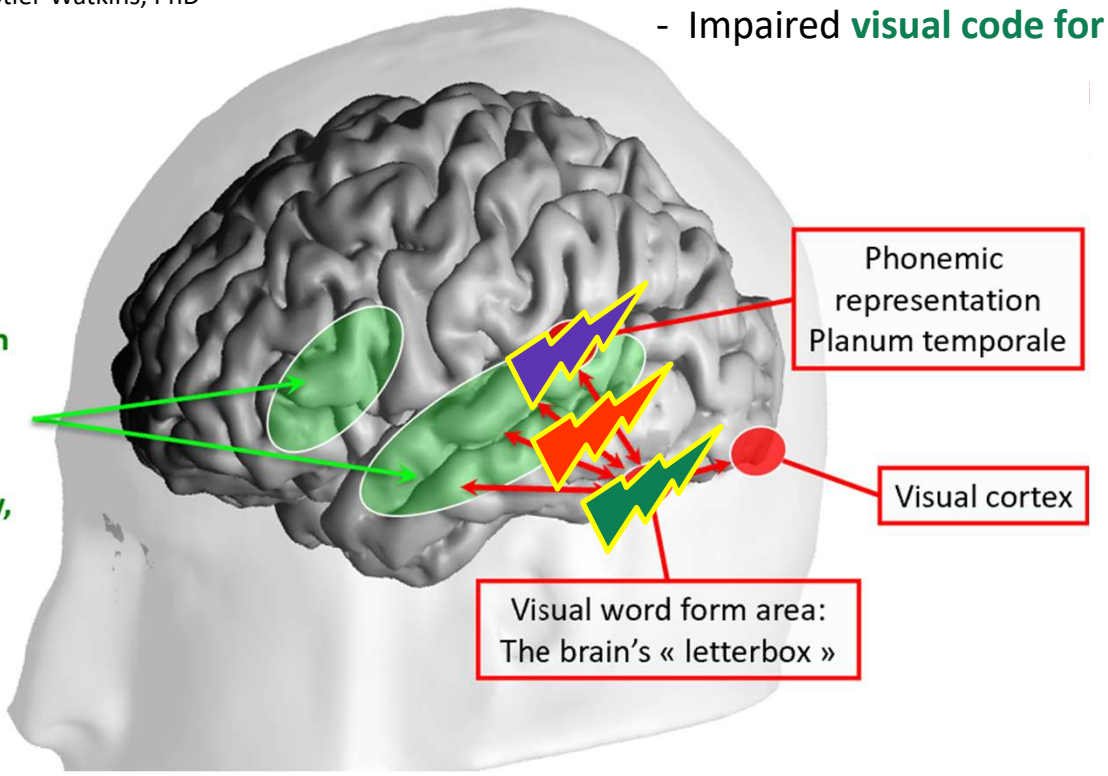


Cassandra Potier Watkins, PhD

Dyslexia*S* : Reading can fail at multiple stages including visual ones

Professor Naama Friedmann

Developmental dyslexia can arise from
- Impaired **phonology**
- Impaired **grapheme-phoneme conversion**
- Impaired **visual code for letters**



The proposed neural code can explain the two main types of **visual dyslexias**

- **Letter position dyslexia**

Imprecision in the neural code for letter position.

→ Letter transpositions :

FORM is read FROM

Those children can be helped by spacing and especially by finger tracking:

F O R M

- **Attentional dyslexia**

Inappropriate selection of a single word

→ M codes from two nearby words

FORM LE is read FARM POLE

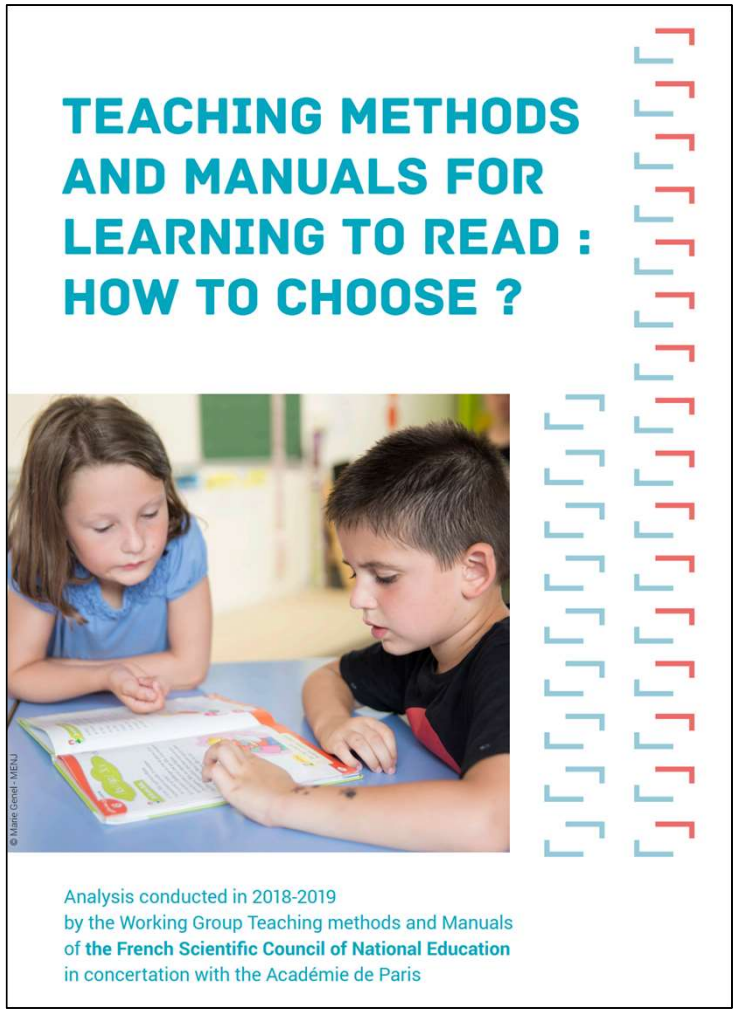
CONSEIL SCIENTIFIQUE DE L'ÉDUCATION NATIONALE

POUR L'ÉCOLE DE LA CONFIANCE

Review and **share** the evidence from scientific publications and international comparisons

Perform randomized controlled experiments. Replace **opinions** with **facts**

The French scientific council for education: Reviews and tools for teachers

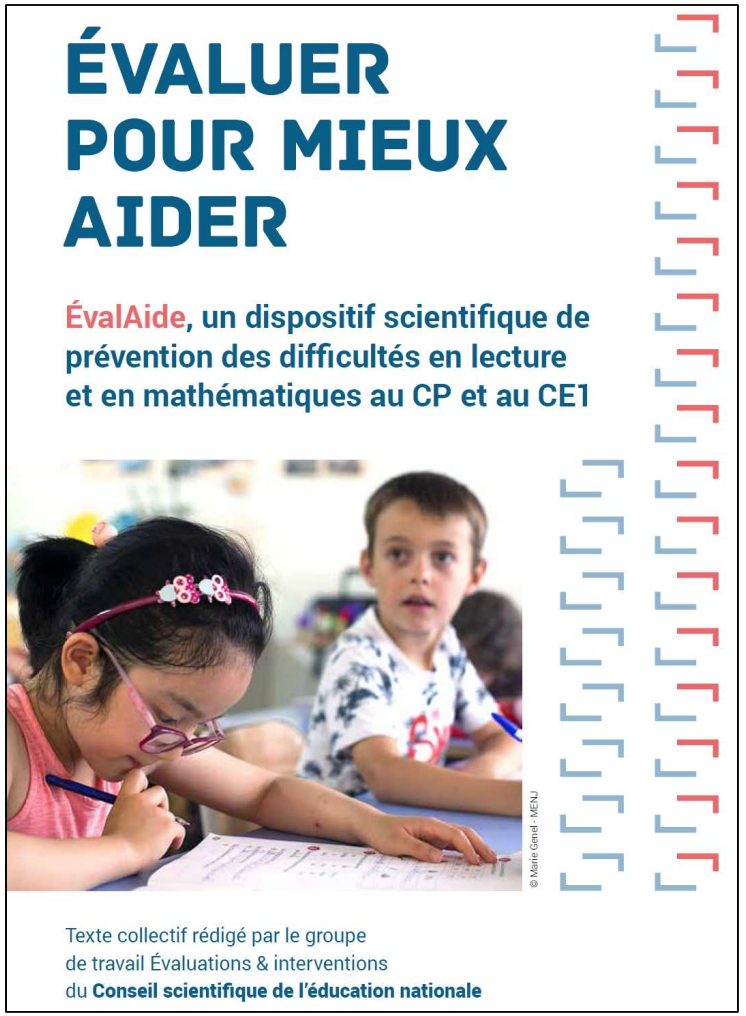


Choosing the best manual and teaching method for reading acquisition

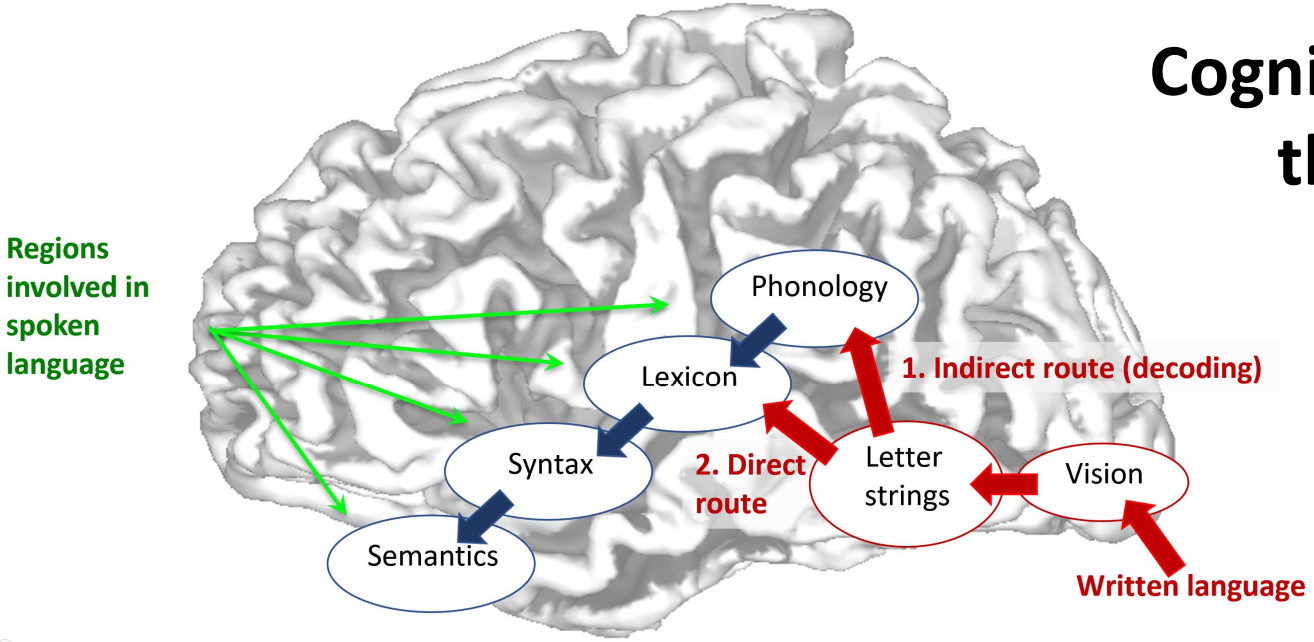
https://www.reseau-canope.fr/conseil-scientifique-de-leducation-nationale.html

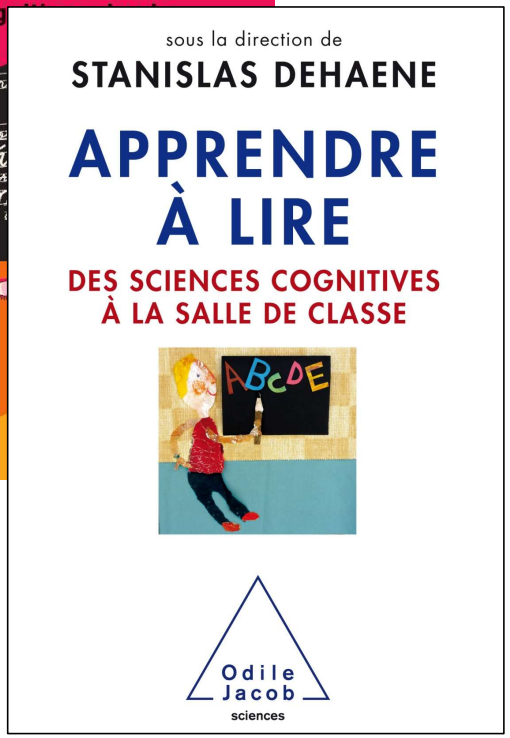
Evaluation and intervention:

All 730,000 children in France receive cognitive tests in phonology, spoken and written language, numeracy, and geometry



Cognitive neuroscience informs the teaching of reading





- On the basis of our growing understanding of the cognitive neuroscience of reading, we can outline the major pedagogical principles for reading acquisition:
- **Explicit teaching of grapheme-to-phoneme conversion rules ("phonics")**
- **With a systematic progression, based on the statistics of the language** (start with frequent, regular grapheme-phoneme mappings)
- **Careful guidance of visual attention** (left-to-right, systematic)
- Active learning, associating **reading *and* writing**
- Need to **automatize the word recognition process**

Please don't….

Show entire texts and ask to guess words

Ce matin, la maîtresse dit aux lutins : « Prenez votre crayon ! »

Rocololo sort son crayon d… trou… Mais le bout est tout rongé, tout grig… mordillé, tout mâchouillé.

— Qui a abîmé ce crayon ? d… aîtresse en fronçant les sourcils.

Rocololo baisse la tête.

Soudain, Turlututu crie : … est un p… rat qui l'a mordu ! Je l'ai vu. Il … dans son trou ! »

Tout les lutins éclatent de rire.

Show crazy, unreadable word shapes

Observe les parties en jaune du texte caché.

Train children to recognize « sight words » that they cannot decode yet

Le même mot

jaune

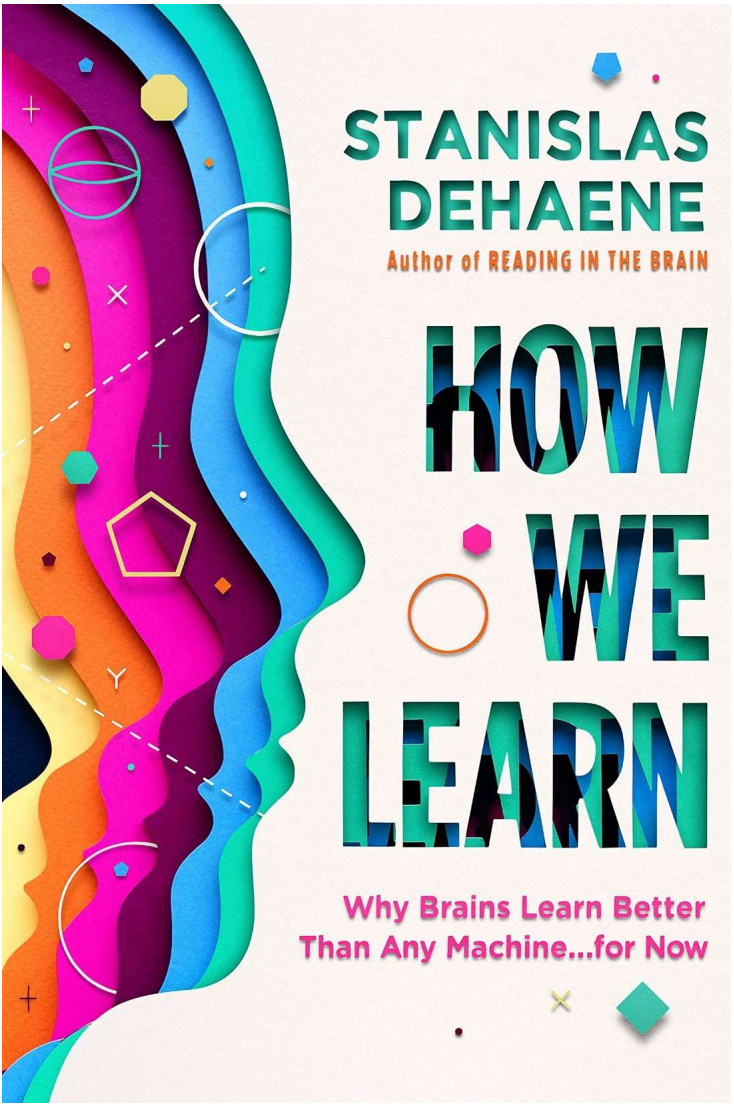
jaune

jean

jument

Teach children the phonetic alphabet !

Taking maximal advantage of our learning algorithms: The four pillars of efficient learning

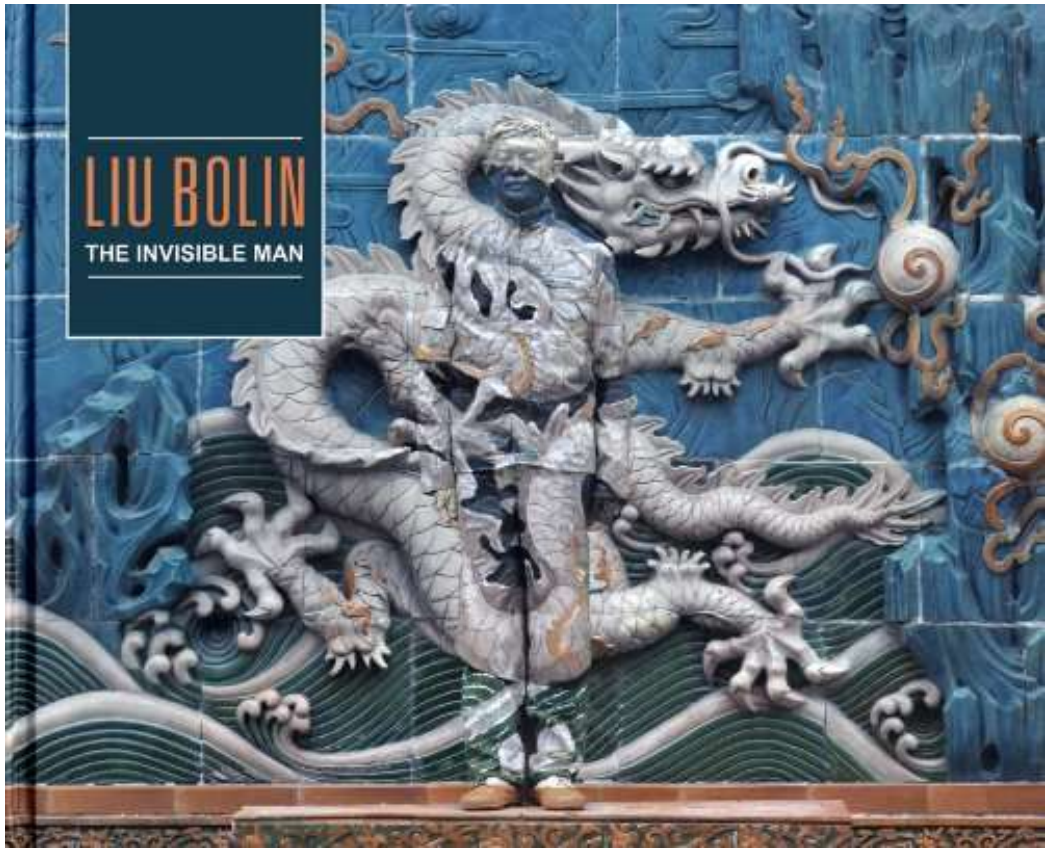


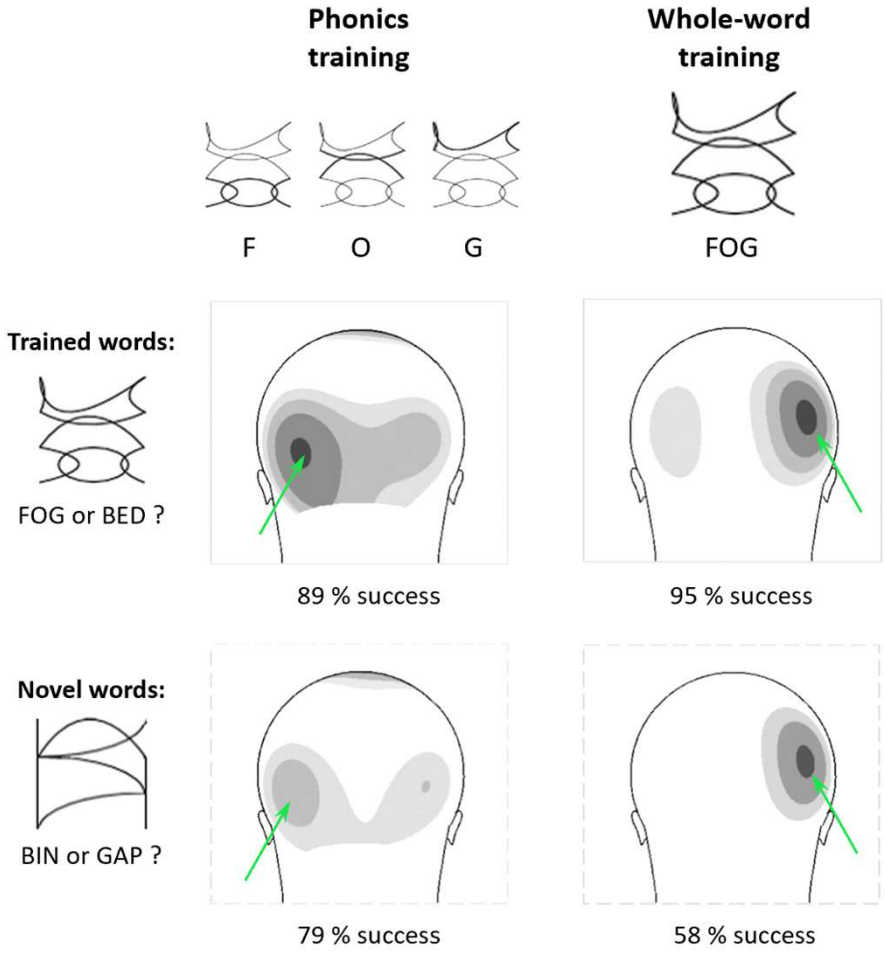
Cognitive neuroscience has identified at least four factors that determine the speed and ease of learning:

- **Attention**
- **Active engagement** (curiosity)
- **Feedback**
- **Consolidation**
  - Automatisation : transfer from conscious to unconscious
  - Sleep

1st Pillar of learning: Attention, a filter that determines what we see and what we learn

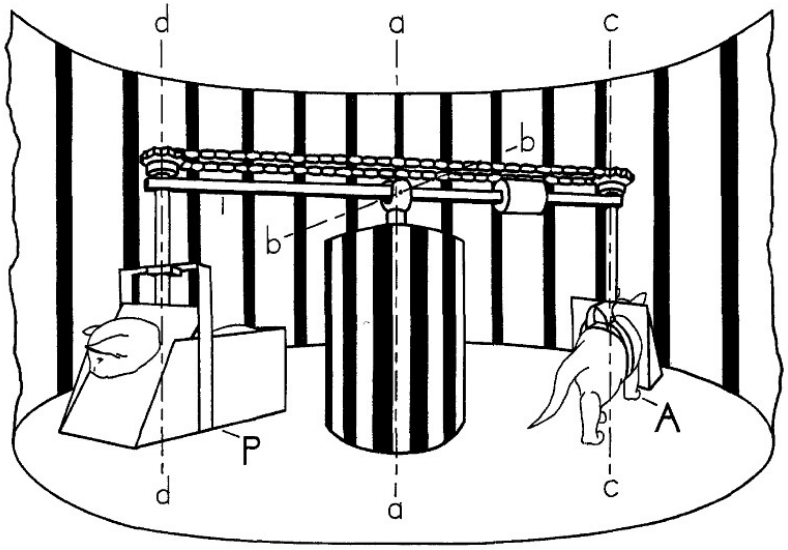
- Attention is a massive modulator of brain activity. It can facilitate learning but also, if misoriented, prevent it.
- Perhaps the greatest talent of a teacher consists in **channeling the child's attention** to the appropriate level.





Yoncheva, Y. N., Blau, V. C., Maurer, U., & McCandliss, B. D. (2010). *Developmental Neuropsychology*, *35*(4), 423–445.

Pillars 2 and 3 :
active engagement and error feedback



A passive organism does not learn.

Learning is optimal when the student is **engaged**, **curious**.

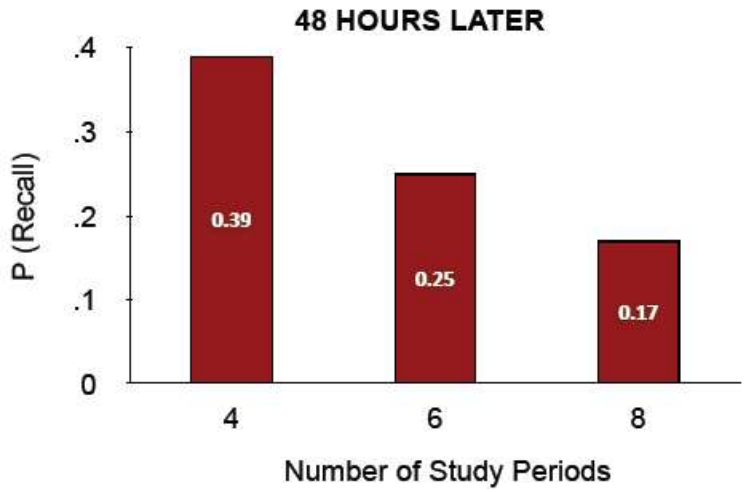
and when he receives precise **error feedback**.

An alternation of **attentive learning** and **testing** leads to optimal learning and retention.

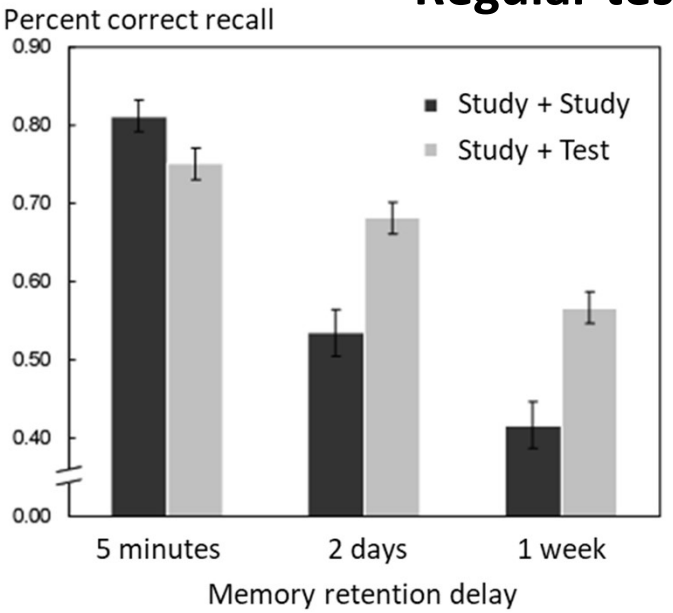
Is it better to study or test oneself?

ST ST ST ST	4 study, 4 test
ST SS ST SS	6 study, 2 test
SS SS SS SS	8 study, 0 test

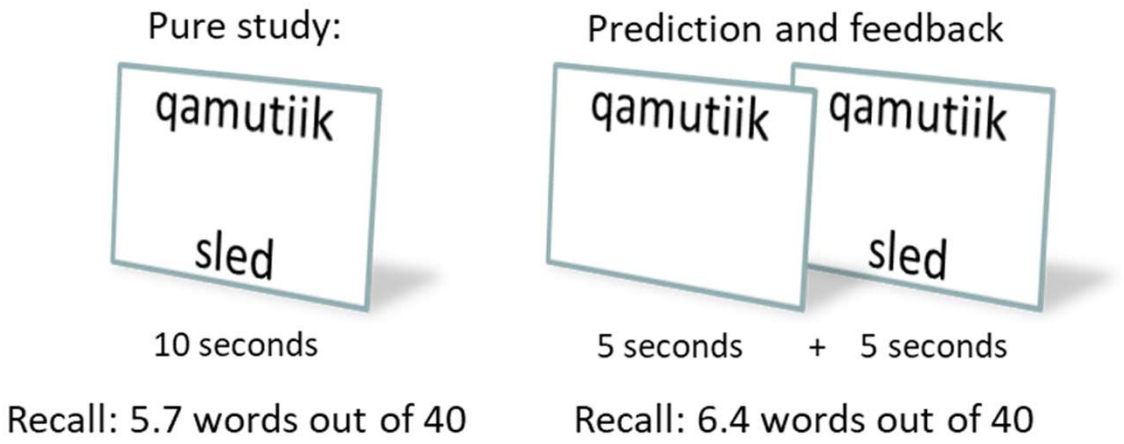
48 hours later, it's the number of test periods that counts.



The massive effect of retrieval practice : Regular testing maximizes long-term memory



Roediger, H. L., & Karpicke, J. D. (2006). Test-enhanced learning: taking memory tests improves long-term retention. Psychological Science, 17(3), 249–255.



Carrier, M., & Pashler, H. (1992). The influence of retrieval on retention. Memory & Cognition, 20(6), 633–642.

"Making learning conditions more difficult, thus requiring students to engage more cognitive effort, often leads to enhanced retention." (Zaromb, Karpicke et Roediger, 2010)

Neither the students nor the teachers correctly predicted this effect ! → need for **experimentation**

Pillar 4: Consolidation: Transfer from explicit to implicit knowledge

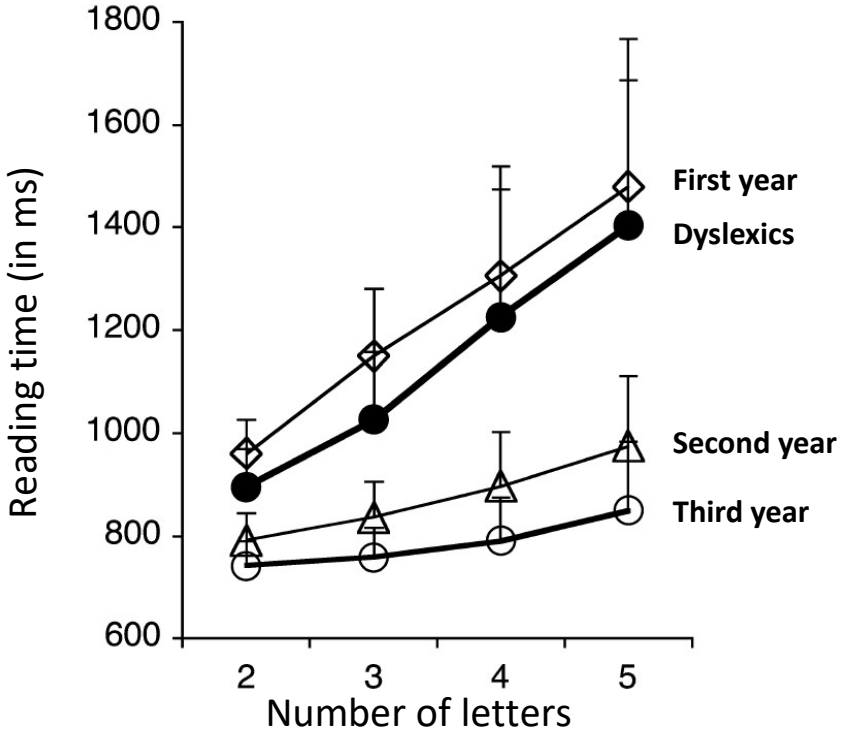
At the beginning of learning, prefrontal cortex is strongly activated:
Explicit, conscious, effortful processing

Progressively, **automatization** transfers the knowledge to non-conscious circuits, thus freeing the resources of prefrontal cortex for other tasks.

Example of reading:

Initially, children remember explicit grapheme-phoneme conversion rules, which they apply in a serial manner whenever they read a word → word length effect.

Later, decoding becomes more efficient and routinized.



Zoccolotti et al., 2005

Automatisation is essential:

Only when reading becomes fluid and automatic can the child focus on the meaning of a text.

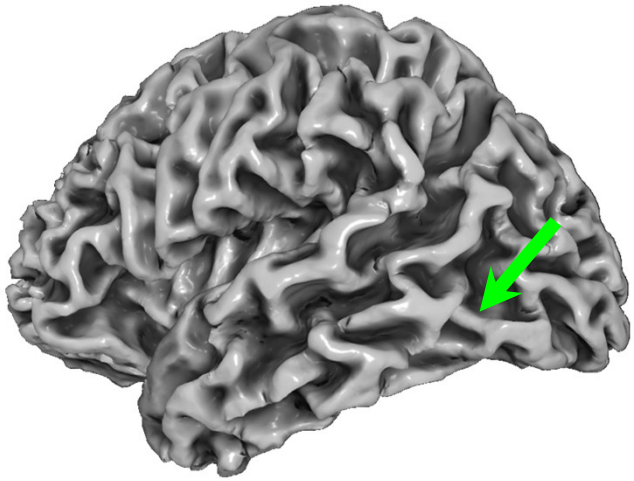
Let’s return to childhood…

“Zer har per apse no daize ov ouwur tchail dude wee livd so foo lee as zoze wee bee liv wee left weezout aving lived them, those we spent with a favorite book.”

Marcel Proust, ***On reading***

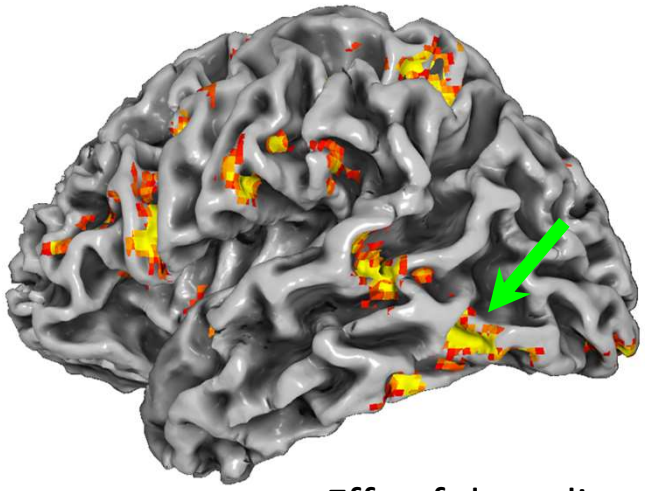
The development of reading in a single child

End of preschool

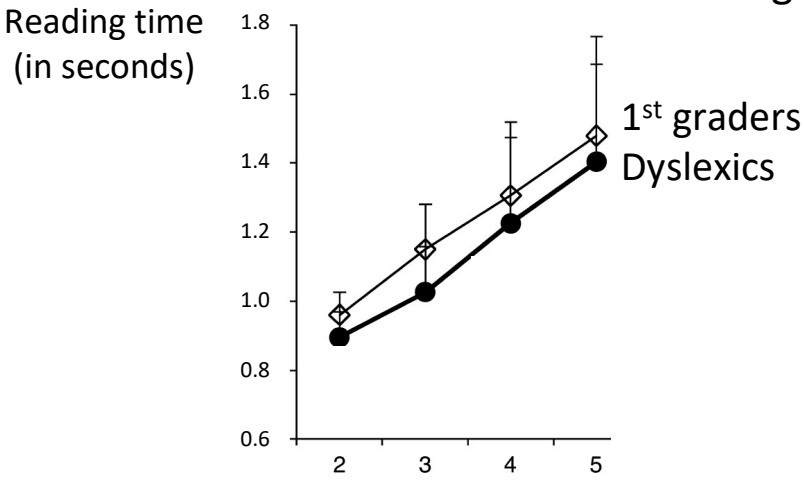


No reading

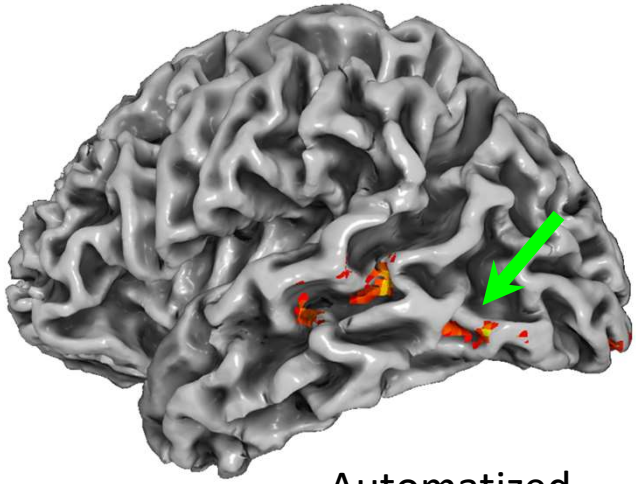
First grade



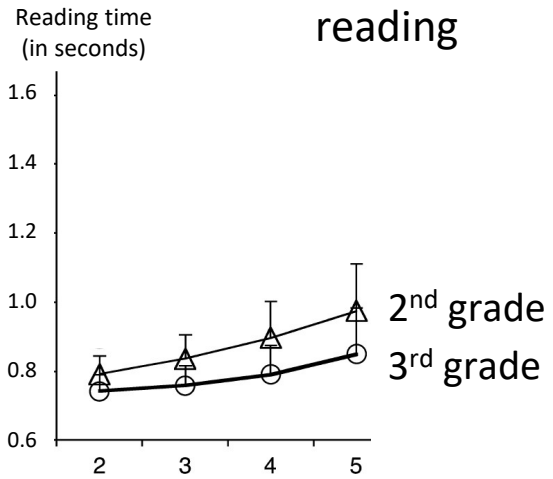
Effortful reading



End of second grade



Automatized reading



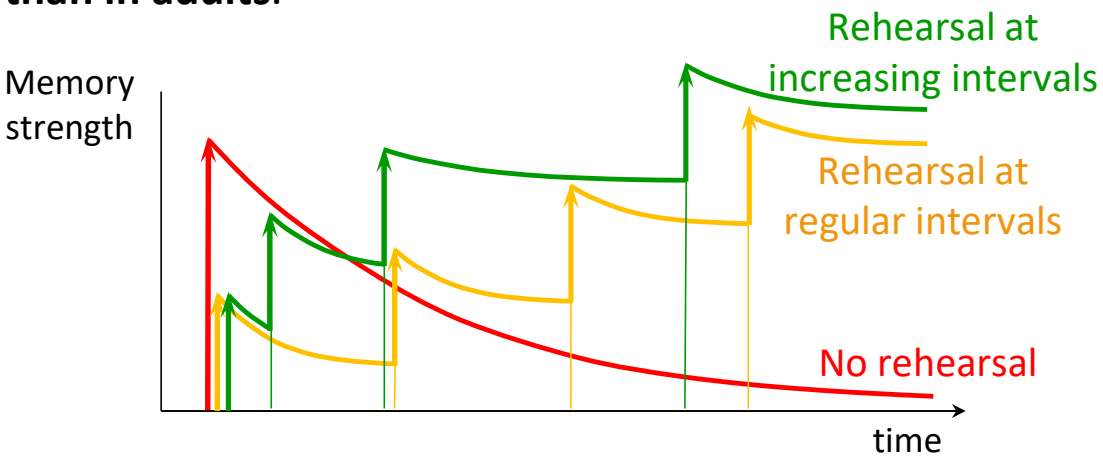
fMRI: Dehaene-Lambertz et al. 2018
Behavior: Zoccolotti et al. 2005

The crucial role of sleep in learning, consolidation and insight

- Sleep is an integral part of our learning algorithm
- During sleep, the brain **replays** significant events of the previous day.
- Sleep plays a key role in the **consolidation of learning.**
- Even a short period of sleep can improve
  - memory
  - generalization
  - insight
- Those effects are **three times larger in children than in adults**.
- Consequences:

(1) **The improvement of sleep** can be a very efficient intervention, particularly for children with attention deficits

(2) Learning must be **distributed over time**: a little progress every day !



Summary of main messages

The infant brain is a **highly structured organ**, right from birth, yet with a **huge potential of plasticity and learning**

This “super-computer” needs to be fed with structured inputs – **a well-designed curriculum**, for explicit teaching rather than discovery learning.

Education must be based on scientific principles

- Knowledge of the brain’s learning algorithms
- Experiments to test what pedagogies work best

Let’s all make optimal use of the “4 pillars of learning”

- Attention
- Active engagement and curiosity
- Feedback
- Consolidation, particularly during sleep