UNIVERSITÀ DEGLI STUDI DI TRENTO
CIMeC - CENTER FOR MIND/BRAIN SCIENCES

Inserm
Institut national
de la santé et de la recherche médicale

Neurocognitive start-up-tools in numerical cognition

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NEUROCOGNITIVE *"START-UP-TOOL"*
=
a system that GUIDES and CONSTRAINS
knowledge acquisition

- From cognitive science: ***Core systems*** (domain-specific representational priors) (e.g., Spelke "Core knowledge", 2004, 2007)

- From neuroscience: ***Neural coding bias*** (cortical region-specific coding biases)

Numerical cognition

- **Dissociable from other cognitive domains**
  - » Double dissociations (ex. dyscalculia vs. aphasia, ex. Deahene & Cohen, *Cortex* 1997; semantic dementia, ex. Butterworth et al., *Nature Neuroscience* 2001)
- **With a reproducible neural substrate: parietal cortex**
- **Rooted on an ancestral « sense » of approximate numerical quantity**

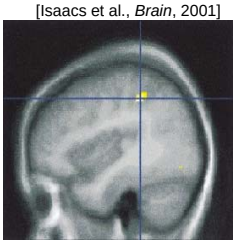
The role of parietal cortex in numerical cognition

PARIETAL DYSFUNCTIONS CAUSE ACALCULIA

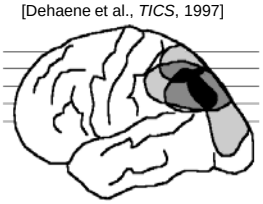
developmental

acquired

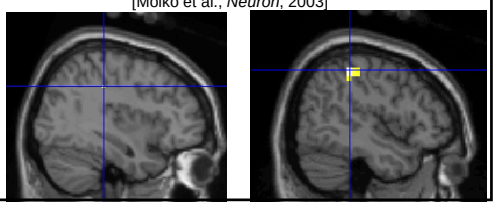
Missing gray matter in premature children with dyscalculia
[Isaacs et al., *Brain*, 2001]



Classical lesion site for acalculia
[Dehaene et al., *TICS*, 1997]



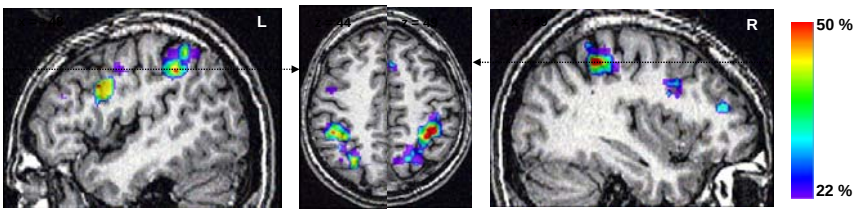
Missing gray matter and abnormal activation in Turner's syndrome with dyscalculia
[Molko et al., *Neuron*, 2003]



The role of parietal cortex in numerical cognition

PARIETAL ACTIVATION IS SYSTEMATICALLY OBSERVED DURING NUMBER PROCESSING

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 ***quantity-related metric*** (number size, numerical distance)

→ Crucial parameter coded: **numerical quantity**

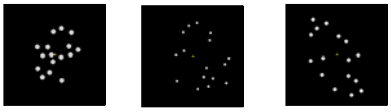
[Dehaene, Piazza, Pinel, & Cohen, *Cognitive Neuropsychology* 2003]

Numerical judgments across ages and species respond to a simple psychophysical law: Weber law (ratio-dependent)

Human adult

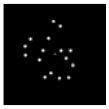
Three samples of a given numerosity (16 or 32)

N1



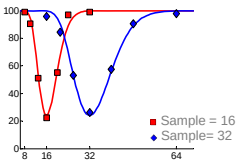
Followed by a single test (8,10,13,16,20,24,32)

N2

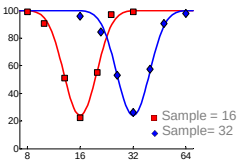


Same or different numerosity?

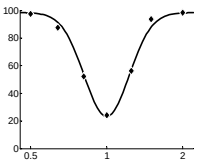
Same-Different Task
% "different" responses



Test number (linear scale)



Test number (log scale)

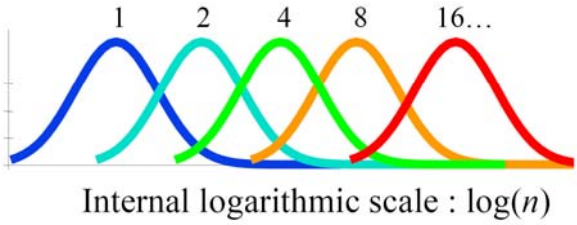


Deviation ratio (log scale)

[Piazza et al. *Neuron* 2004]

A SIMPLE MODEL of the internal representation of numerical quantity

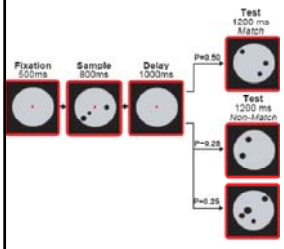
Hp: number is represented approximately on a compressed continuum, by the firing of a population of numerosity detectors, whose tuning curve is a Gaussian on a logarithmic number line



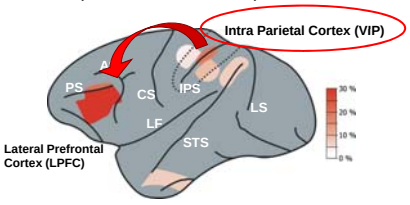
[Dehaene & Changeaux, *JOCN* 1993]

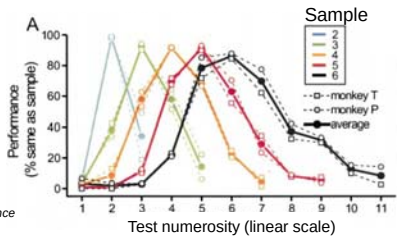
Neurons coding for numerical quantity in the macaque monkey

Task: same-different judgment

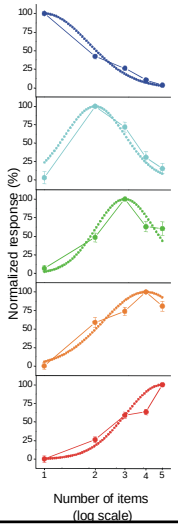


Recording sites
(% "number neurons")





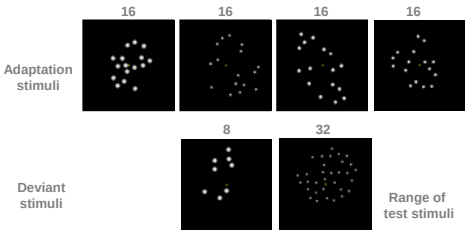
Neural tuning curves



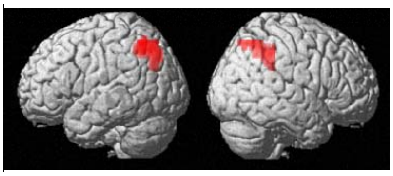
Nieder, A., Freedman, D. J., & Miller, E. K. (2002). *Science*
Nieder, A., & Miller, E. K. (2003). *Neuron*
Nieder, A. & Miller, E.K. (2004). *PNAS*

Parietal cortex codes numerical quantities in human adults

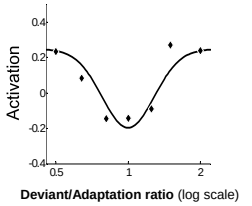
Number adaptation protocol



Brain response to change in number

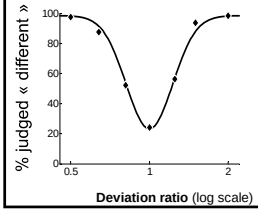


PARIETAL ACTIVATION



Behavioral responses

Same-Different Task



[Piazza et al., *Neuron* 2004]

- An evolutionary ancient cortical system for approximate numerical quantity (the Approximate Number System)
- This system ***guides*** and ***constrains*** the cultural acquisition of symbolic number skills:

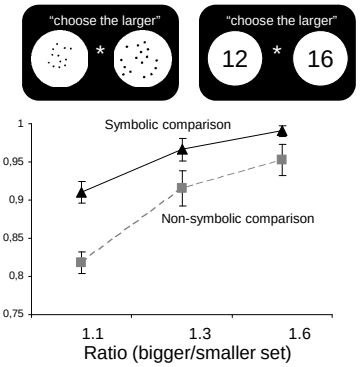
  -> some *traces* of the ANS are present even when we manipulate symbolic numbers.

  -> the *integrity* of the ANS is a *necessary* condition for normal development of symbolic number skills.

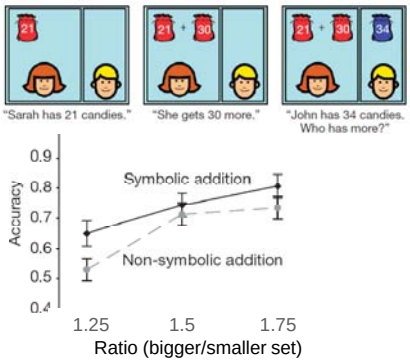
"Traces" of the ANS in symbolic number processing

Both non-symbolic and symbolic number comparison are governed by ratio-dependent laws in children AND adult human subjects

ADULTS



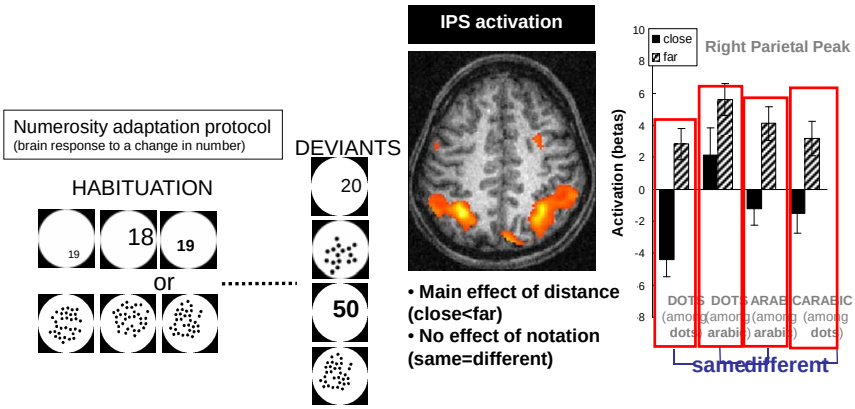
KINDERGARTENERS



[Chinello et al., *under revision*]

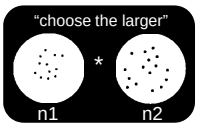
[Gilmore et al., *Nature* 2007]

Convergence towards a quantity code in the IPS in adults



[Piazza et al., *Neuron* 2007]

The necessity of ANS for numeracy development: dyscalculia

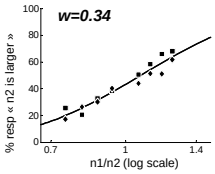


4 groups of subjects

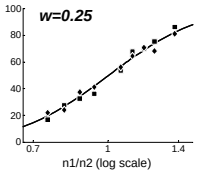
(1) 4-6 years old
(2) 8-11 years old
(3) Adults
(4) 8-11 years old dyscalculic (diagnosis: Italian standardized test) matched for IQ and cronological age, no neurological problems

RESULTS (non dyscalculic subjects)

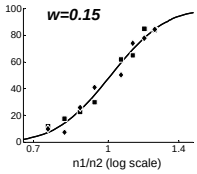
4-6 years



8-11 years

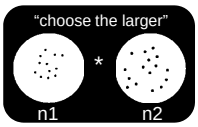


Adults

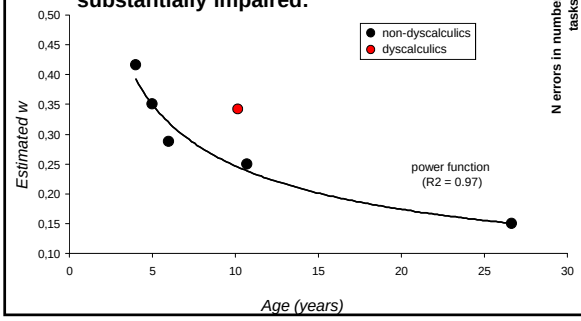


[Piazza et al., *Cognition* 2010]

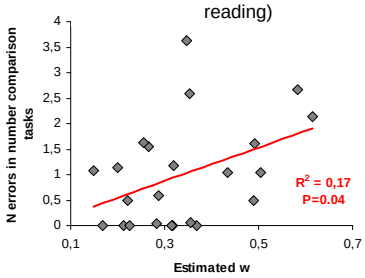
The necessity of ANS for numeracy development: dyscalculia



In dyscalculic children the ANS is substantially impaired:



Impairment in the ANS predicts symbolic number impairement but not performance in other domains (word reading)



[Piazza et al., *Cognition* 2010]

- Interim Conclusions:

(1) Children come to life with ***IMPORTANT INTUITIONS*** ON ***APPROXIMATE NUMERICAL QUANTITY***.

(2) Behavioral and neuroimaing data indicate that the culturally-mediated acquisition of symbolic numbers is ***built upon*** these pre-existing intuitions.

→ This should be taken into serious account in educational programs especially in the initial years of schooling.

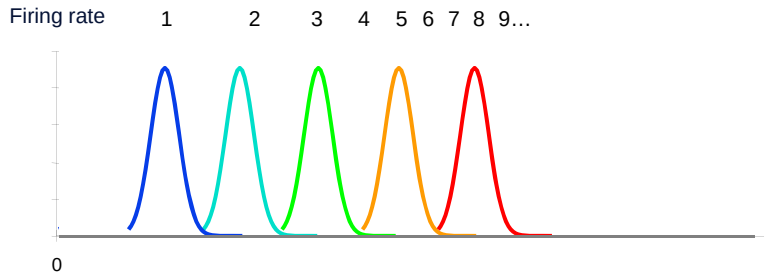
→ Children should be made aware that they can **count on** their **numerical intuition**:

- improve self-confidence
- might decrease math anxiety
- no gender differences in the ANS in young children!

From approximate quantity to exact number: **a major conceptual step**

→ lexical acquisition in the number domain: from a ***continuous*** (analogue) to a ***categorical*** (digital) representation of number

→ How does the brain ***BRIDGES this GAP*** ?



Lexical acquisition entails ***creating a new representation***:

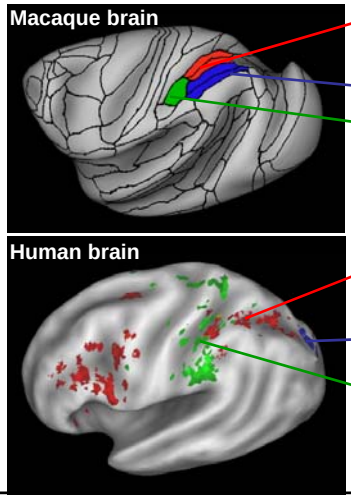
(1) Based on pre-existing approximate number representation (a sub-set of neurons undergo a process of "tuning sharpening")

(2) Connected to a set of symbols and a syntax establishing relations among them
→ numbers and the successor function (counting)

(3) Thanks to a set of tools to ***instantiate*** the notion of a **EXACT** number
→ individuation -object tracking - spatial attention - finger counting - pointing

Parietal cortex

"Associative cortex", a crossroads between the senses and action:
A mosaic of sub-regions coding ***objects*** and the ***self*** and performing ***complex spatial co-ordinate transformations (***for ***action)***



VIP (multisensory -Approximate number)

LIP (spatial attention -ocular movements)

AIP (visual/tactile/proprioceptive- grasping)

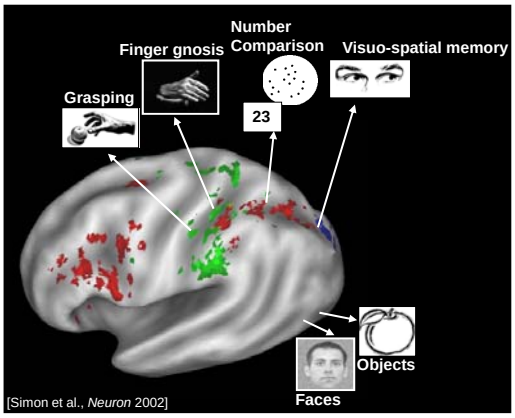
Medial parietal (multisensory -Approximate number -CALCULATION)

Posterior parietal (spatial attention -ocular movements)

Anterior pairetal (visual/tactile/proprioceptive - grasping)

Hubbard, Piazza, Pinel, Dehaene *Nature Reviews Neuroscience* 2005
Simon, Mangin, Cohen, LeBihan, and Dehaene, *Neuron* 2002

PARIETAL CORTEX FUNCTIONS DURING DEVELOPMENT



A large group of kindergarteners (3 to 6 yoa, N= 94) and of adults (N = 36)

5 "dorsal" tasks:

- visuo-spatial memory (Corsi)
- numerosity comparison
- verbal number comparison
- finger gnosis
- grasping

2 "ventral" tasks (Golara et al., 2007):

- face recognition
- object recognition

[Chinello et al., *under revision*]

Parietal Tasks

FINGER GNOSIS

Visually guided ***recognition*** of touched ***finger***
→ N errors

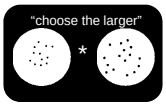
GRASPING

Visually guided ***grasping*** objects
→ Modulation from object size of grip aperture during grasping trajectory

VISUO-SPATIAL MEMORY

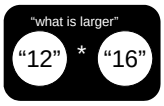
Memory of ***spatial positions***
→ N objects tracked (SPAN)

ANALOGIC NUMBER COMPARISON



Comparison of ***numerosity***
→ Weber fraction/ N errors

SYMBOLIC NUMBER COMPARISON



Symbolic number comparison
→ N errors

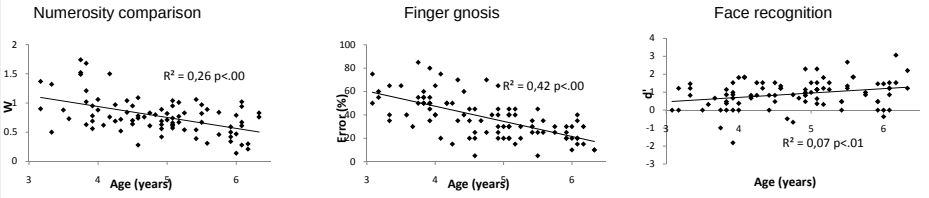
Ventral Tasks

FACE RECOGNITION

Recognition memory
→ D'

OBJECT RECOGNITION

Recognition memory
→ D'



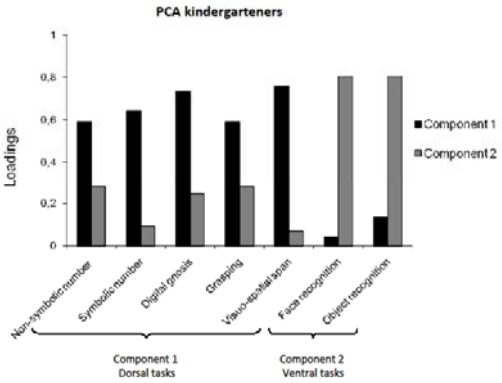


Figure 2

RESULTS

(1) Dorsal and ventral functions undergo separate developmental trajectories and are not correlated across children.

(2) The inter-individual variability in all tested parietal functions correlate across children.

[Chinello et al., *under revision*]

Numbers, fingers and space

- In young children, the ANS naturally correlates with all other parietal functions which are necessary for the transition from the ANS to exact number knowledge.

- In older children math achievement is predicted by not only the ANS, but also by finger gnosis and spatial tasks

- Dyscalculic children often report quantity deficits as well as finger agnosia and visuo-spatial deficits. Our hypothesis is that dyscalculia can also emerge by impaired single systems.

"Core quantity deficit"

"*Supporting* systems deficit"
1. - finger gnosis deficits
2. - spatial deficits (dyspraxia?)

"General parietal syndrome"

Broader implications for math education

- Children come to school with strong intuitions on quantities and their relations.
- Moreover, they also possess a set of functions functionally-correlated with the ANS to track individual objects in space.

- These intuitions should be ***all*** used as a support for learning of more advanced material.

- More time should be spent on intuition than on rote and procedural learning

25 +
38 =