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High-level expertise for mathematical concepts recycles lateral occipito-temporal and parietal regions for number processing

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INTRODUCTION: WHY SCAN MATHEMATICIANS ?

- Experiments in infants, preschoolers, and adults without access to education have demonstrated the existence of innate **"core knowledge" for numbers and space**[1,2], endowing humans with spontaneous intuitions of arithmetic and geometry.

- Here, we address the debated issue of how those intuitions lead to the **emergence of higher-level mathematics** :

- Does the human brain represent advanced mathematical concepts through **language**? For instance, learning to count with number words is thought to lead to an understanding of exact quantities.[3]

- Or does the acquisition of advanced mathematics rely mainly on a "neuronal recycling"[4] of brain regions involved in **number sense, spatial coding, and number recognition**?

In the latter case, we would expect that

- the **intraparietal sulcus**[5,6], which plays a key role in basic number sense and in school-based arithmetic, would be recruited by expert mathematicians during abstract mathematical thinking, even in domains that do not involve any numbers.
- Math should also recruit the recently discovered "**visual number form area**" in the ventral visual cortex.[7]

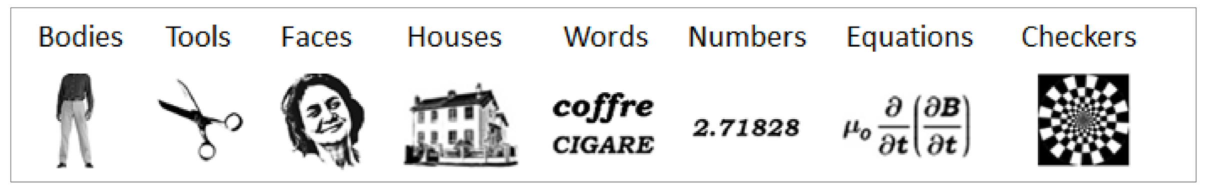
METHOD

We scanned 15 professional mathematicians and 15 controls subjects devoid of any mathematical training.

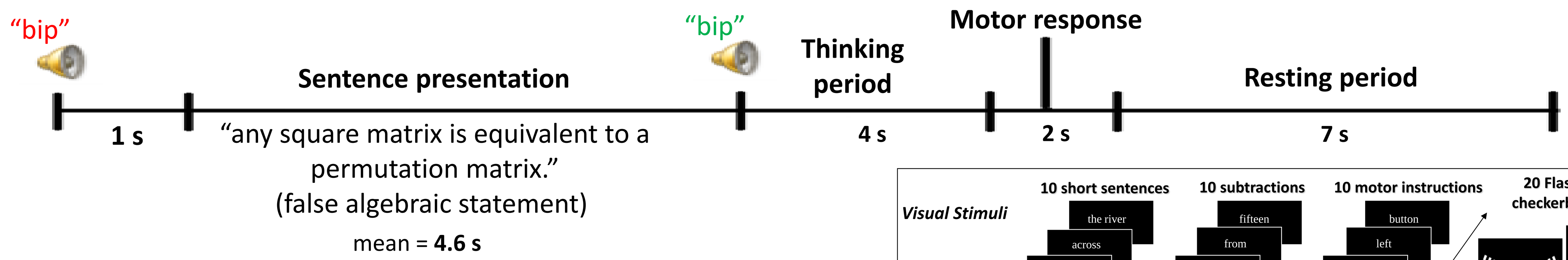
Paradigm:

- **2 Visual runs** evaluating cortical responses to various categories of visual stimuli, while the participants performed a one-back task.

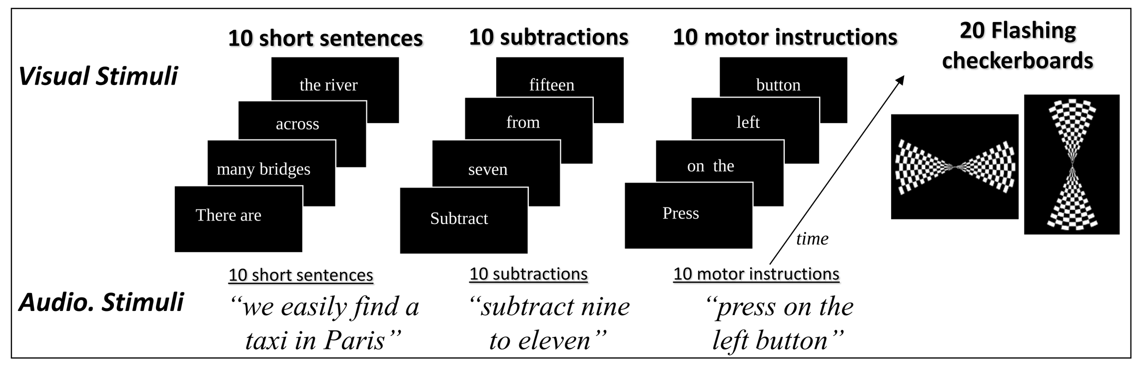
The stimuli included **numbers and mathematical formulas**.



- **6 Auditory runs** in which participants were asked to perform fast intuitive semantic judgments on spoken mathematical and non mathematical statements (classify them as true, false, or meaningless). Four domains were studied: **analysis, algebra, topology and geometry**.



- **A "localizer" run** with horizontal and vertical checkerboards, written and spoken sentences, motor commands, and calculation problems.



fMRI acquisition and analysis :

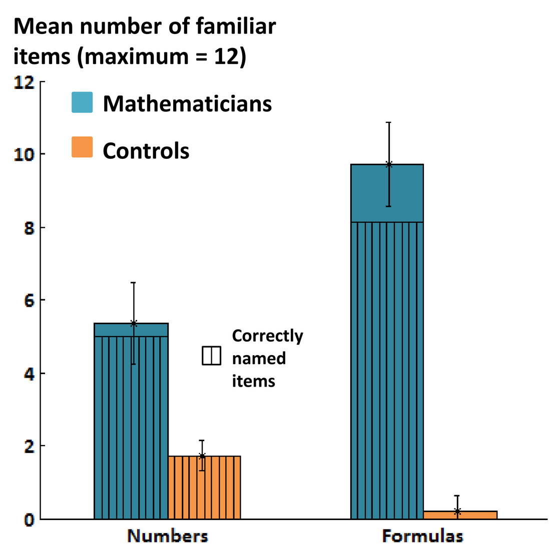
- High resolution multiband fMRI sequence: TR = 1.5 s, voxel size = 1.5*1.5*1.5 mm^3
- Standard pre-processing and 2 mm smoothing
- General linear model computed in SPM8 at single and group levels.

BEHAVIORAL RESULTS

Visual runs:

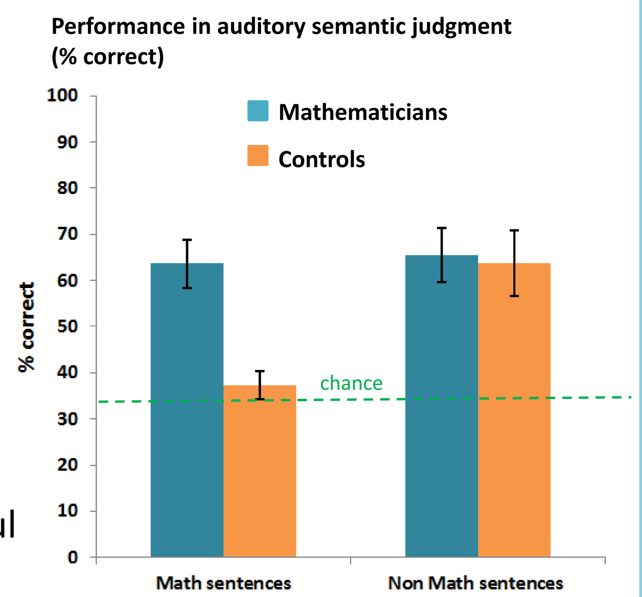
- Mathematicians were better than controls in recognizing and naming mathematical formulas and numbers ($p<0.001$).

- During fMRI, mathematicians and controls performed identically in the one-back task, regardless of the stimulus category (ANOVA on d', no group X category interaction).



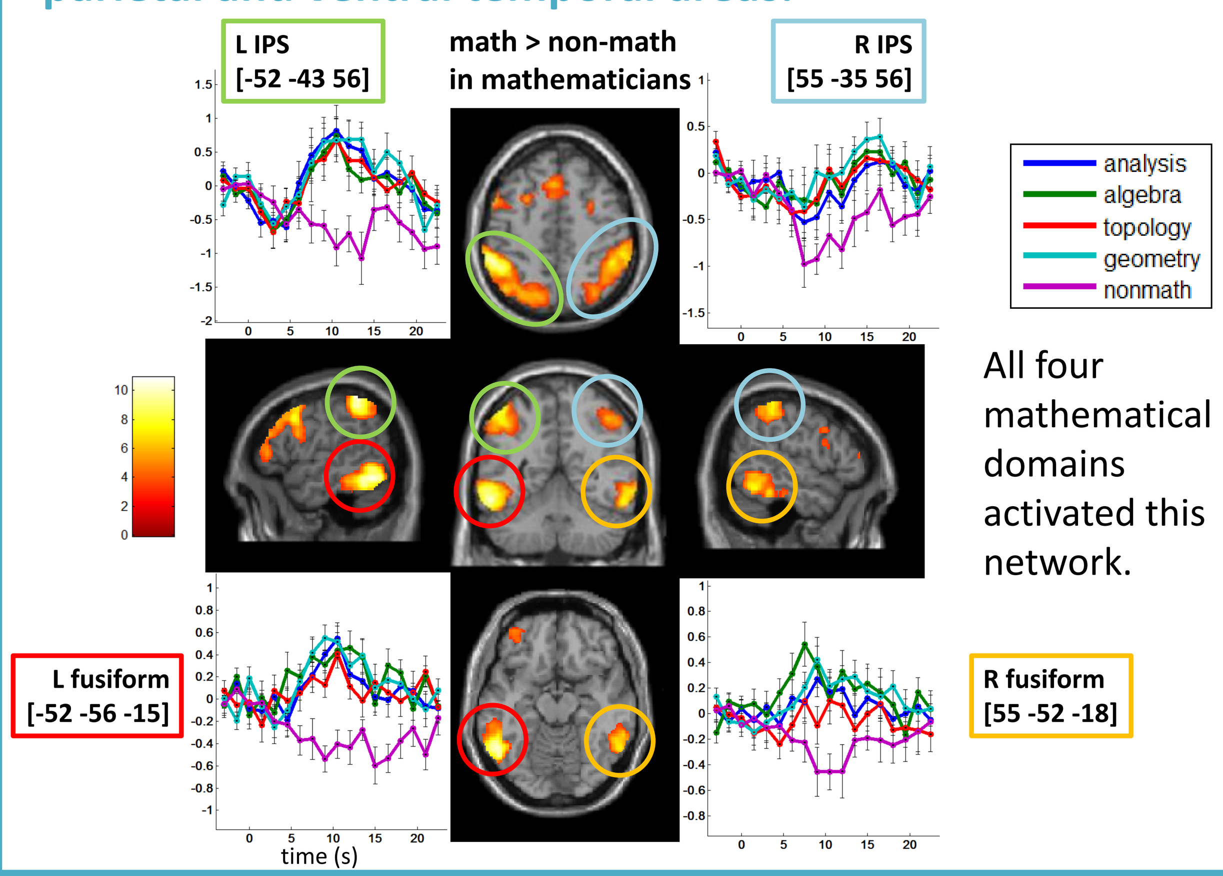
Auditory runs:

- Mathematicians performed better than chance with math and non-math sentences.
- Controls performed better than chance only with non-mathematical statements.
- Mathematicians easily rejected meaningless math statements, but found it harder to judge the truth value of meaningful statements (55 % correct).



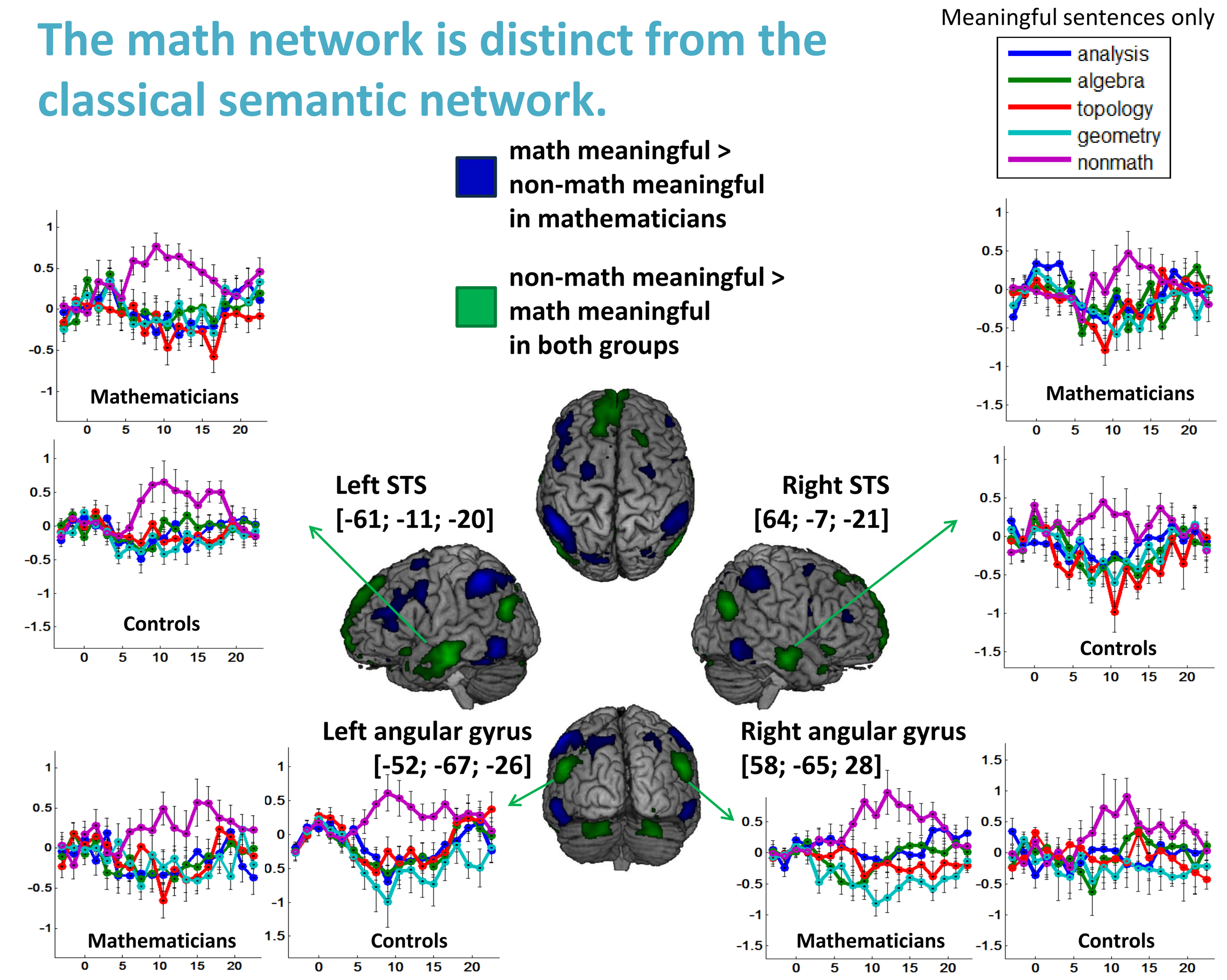
fMRI RESULTS

High-level mathematical reflection activates parietal and ventral temporal areas.

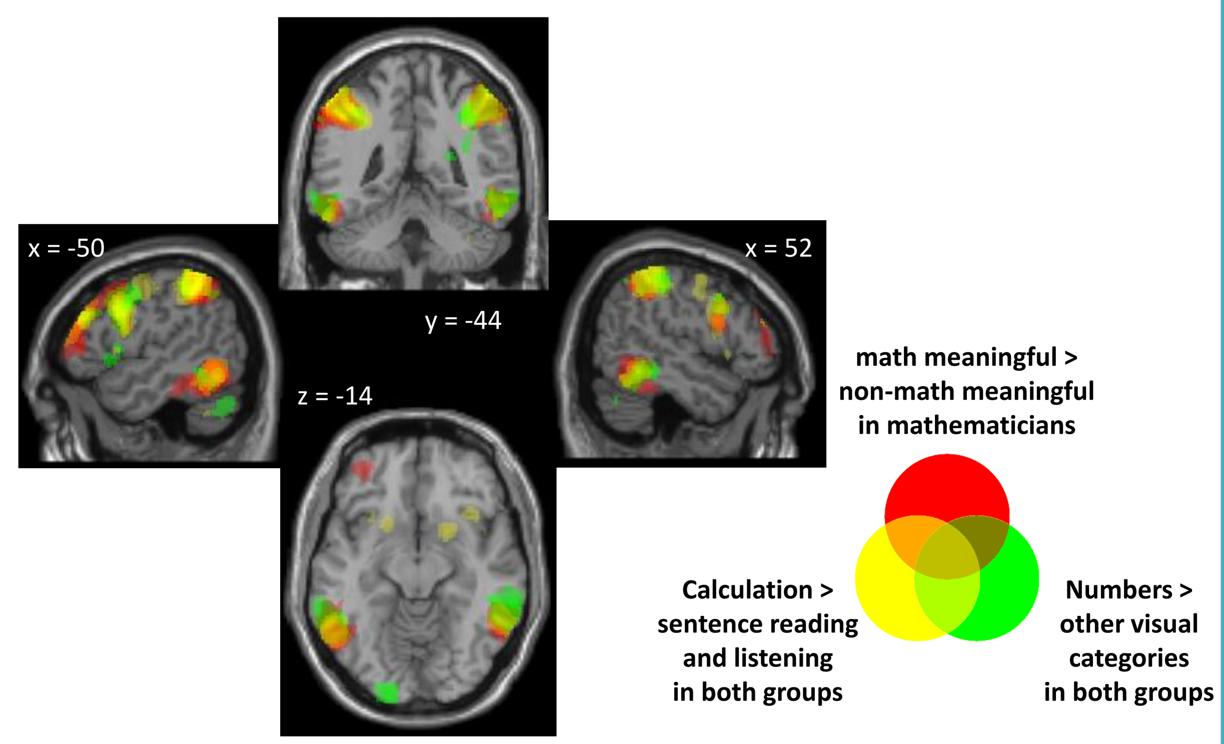


All four mathematical domains activated this network.

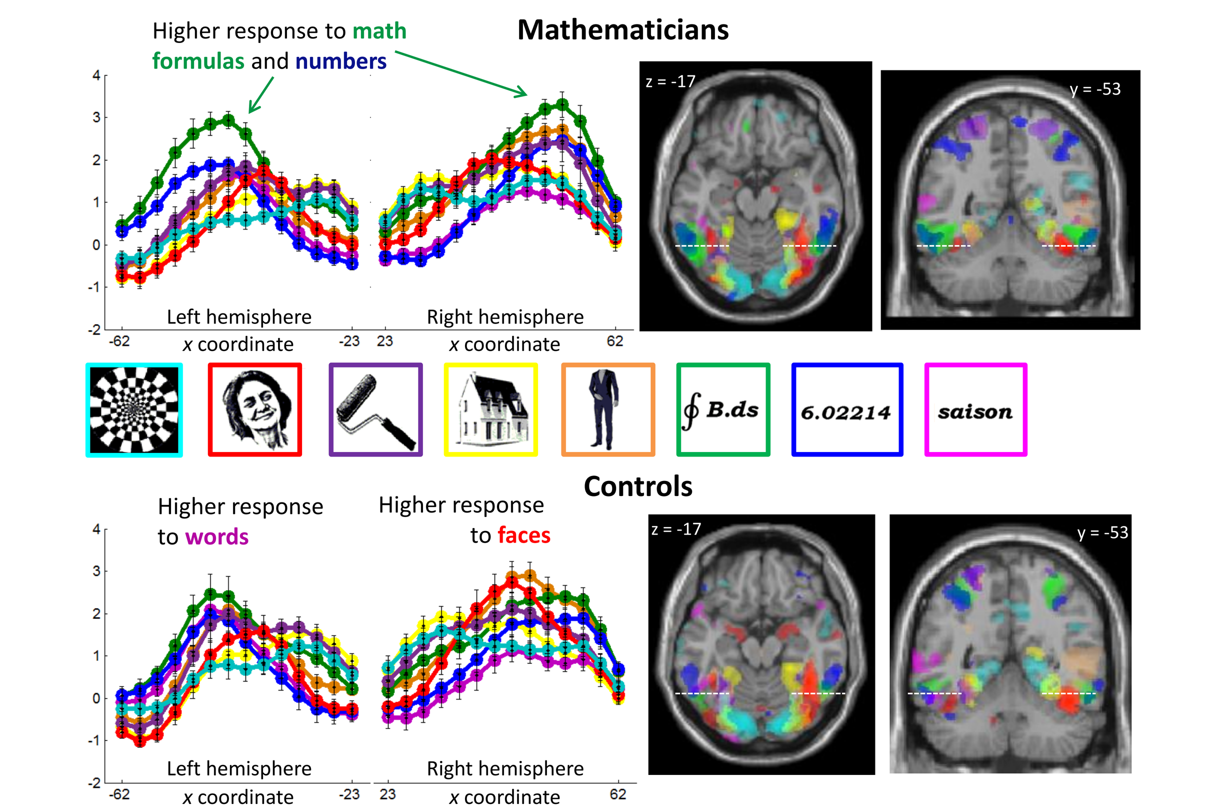
The math network is distinct from the classical semantic network.



Math recycles the cortical networks for number recognition and calculation.



The ventral visual stream seems to be partially reorganized with mathematical expertise.



CONCLUSIONS

- High-level mathematics does not recruit the classical language semantic network.
- On the contrary, higher-level math activates cortical networks previously associated with number recognition and calculation :
- the intraparietal sulcus
- the visual number form area[2]
- These findings are consistent with previously reported dissociations between the neural substrates of linguistic competence and the brain regions activated during the processing of syntax-like operations in the domain of algebra[8]. They also fit with evidence that severe aphasics may still understand and perform algebraic operations.

- Expertise for mathematical formulas also recruits the "number form area" and the neighboring occipito-temporal cortex.
- Mathematical expertise seems to induce a partial reorganization of the ventral visual stream.

- Although this study suggests that advanced mathematical concepts are not encoded through language *in expert adult mathematicians*, this finding does not mean that language plays no role in the *acquisition* of mathematical concepts.

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