

Characterizing the Neurocognitive Mechanisms of Arithmetic

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CHARACTERIZING THE NEUROCOGNITIVE MECHANISMS OF ARITHMETIC

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Dissertation submitted for the degree of
Doctor of Philosophy

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Introduction

- Mathematics is among the most remarkable human inventions.
- The fundamental language of science.
- Arithmetic is the most elementary branch of mathematics.

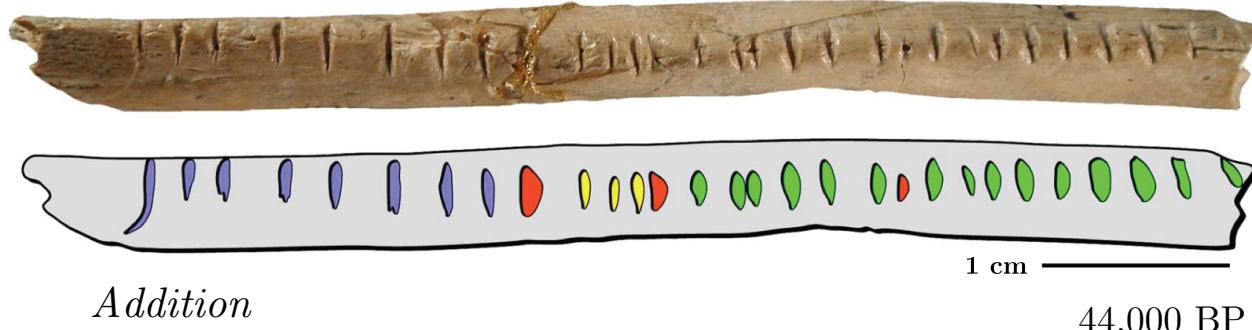


- How are two numbers combined into a third? i.e. $3+5=8$.
- Sophisticated abstract concepts and complex network of brain regions.

Paleolithic Arithmetic

Artificial Memory Systems

Lebombo Bone (baboon fibula)



44,000 BP

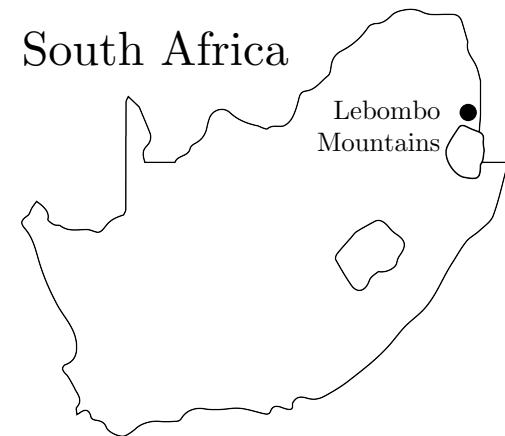
Spatula (rib)



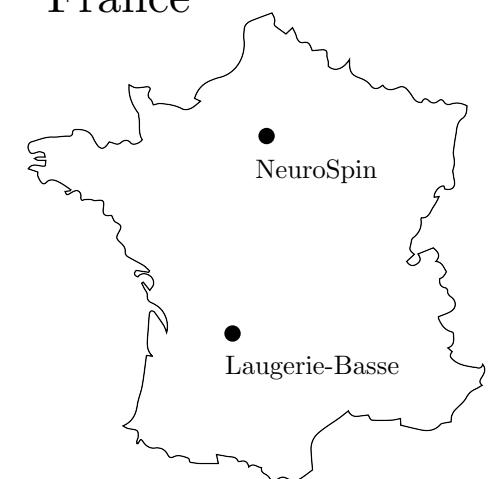
Subtraction

17,000 - 12,000 BP

South Africa



France

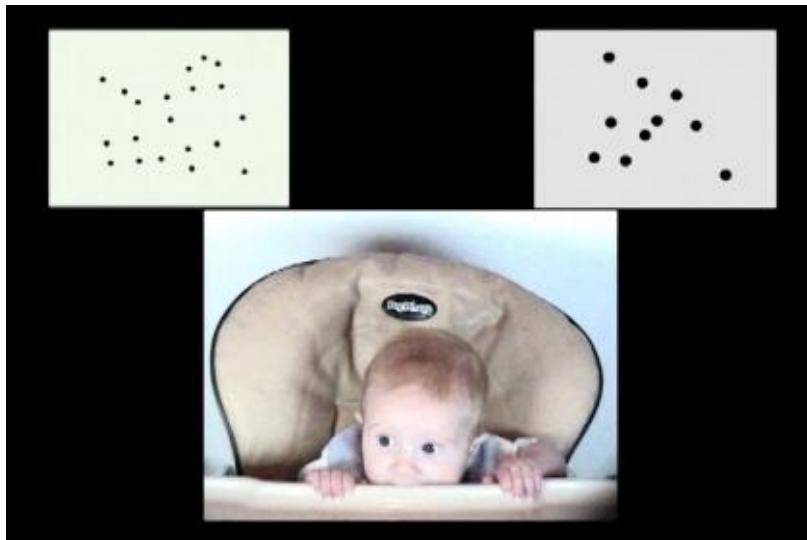


The origins of arithmetic thinking

- **The Number Sense** (*Dantzig, 1967; Dehaene, 1999*)
 - Approximate Number System - obeys Weber's law.
 - Object-tracking system – *subitizing* 1-4 items.
- Evolutionary origin: protect cubs, select preys, mating, etc.

Number discrimination in babies

(*Starr et al., 2013; Izard et al., 2009*)



Democratic decisions in baboons

(*Piantadosi & Cantlon, 2017*)

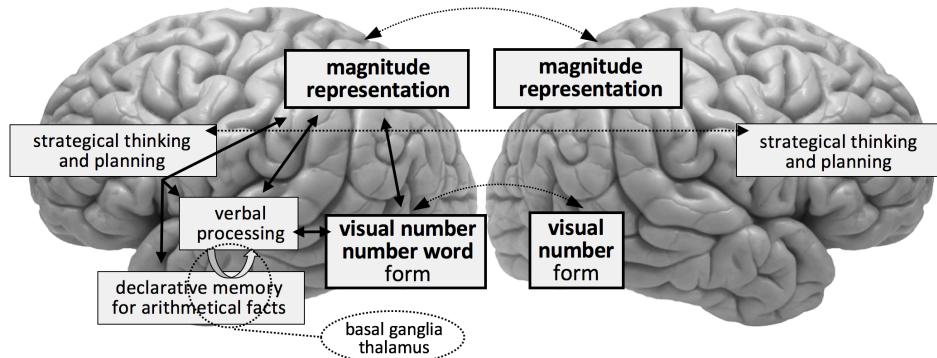


- ANS allows for approximate calculation (babies, children & monkeys). (*McCrink & Wynn, 2004; Gilmore & Spelke, 2007; Livingstone et al. 2014*)

Brain networks for arithmetic processing

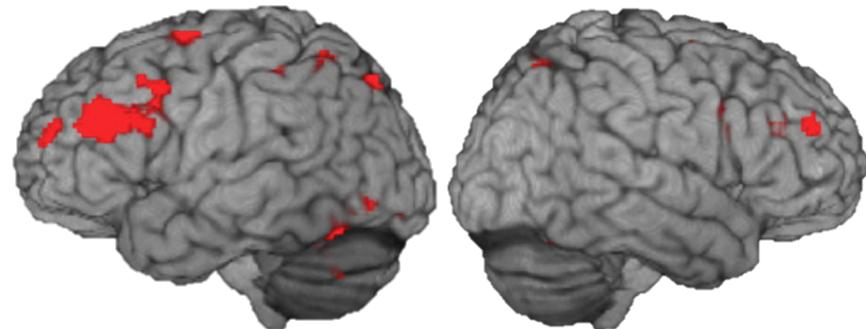
Putative network - neuropsychology

(Dehaene & Cohen, 1995)



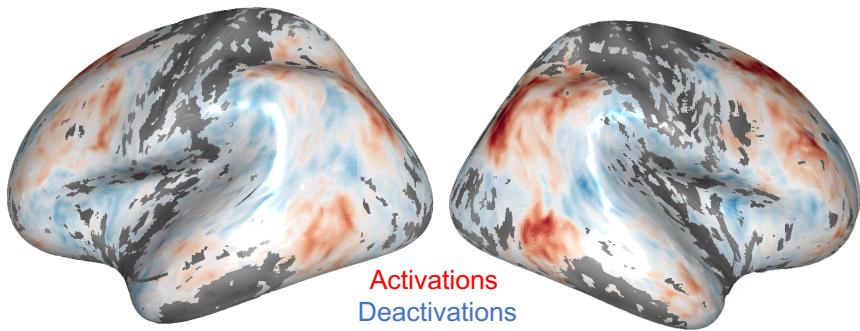
fMRI meta-analysis

(Arsalidou & Taylor, 2011)



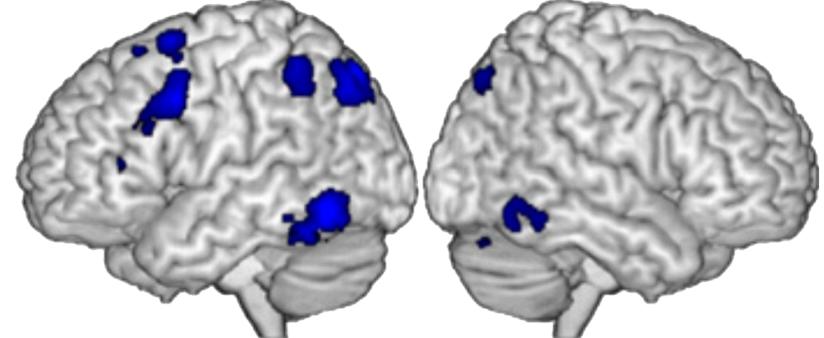
fMRI activations for number words in natural speech

boldpredictions.gallantlab.org



Similar network engaged in high-level mathematics

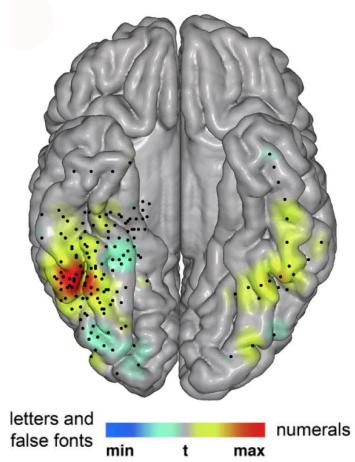
(Amalric & Dehaene, 2016)



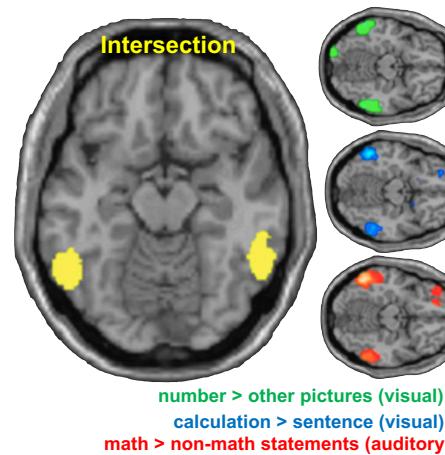
- **Lateral parietal cortex**: main hubs for magnitude processing and calculation. BOLD activity in the IPS and SPL increase as a function of **problem-size**.
(Dehaene et al., 1999; Kanjlia et al., 2016, etc.)
- **Ventral temporal cortex**: visual recognition of numerals.

Arithmetic processing in the *ventral stream*

'Number Form Area' in the pITG
(Shum et al. 2013)



Activation during high-level math
(Amalric & Dehaene, 2016)

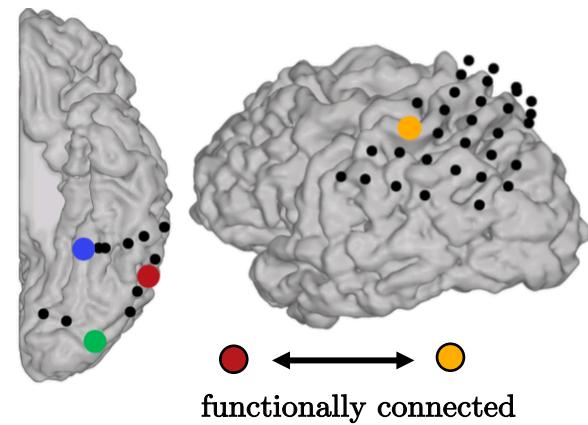
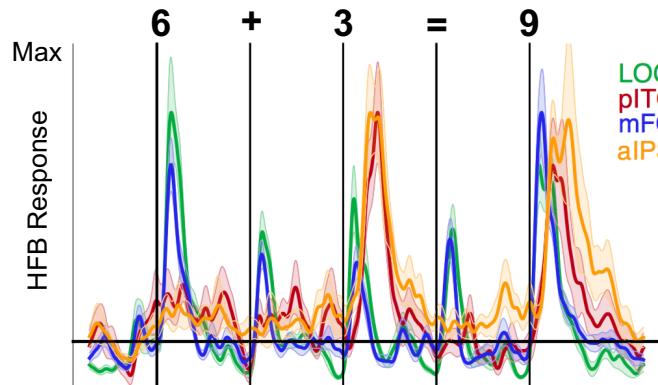
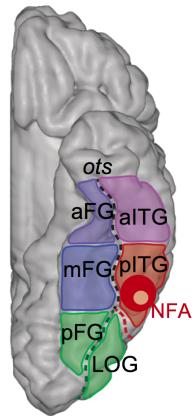


Possible role of the pITG in arithmetic

(Daitch et al., 2016)

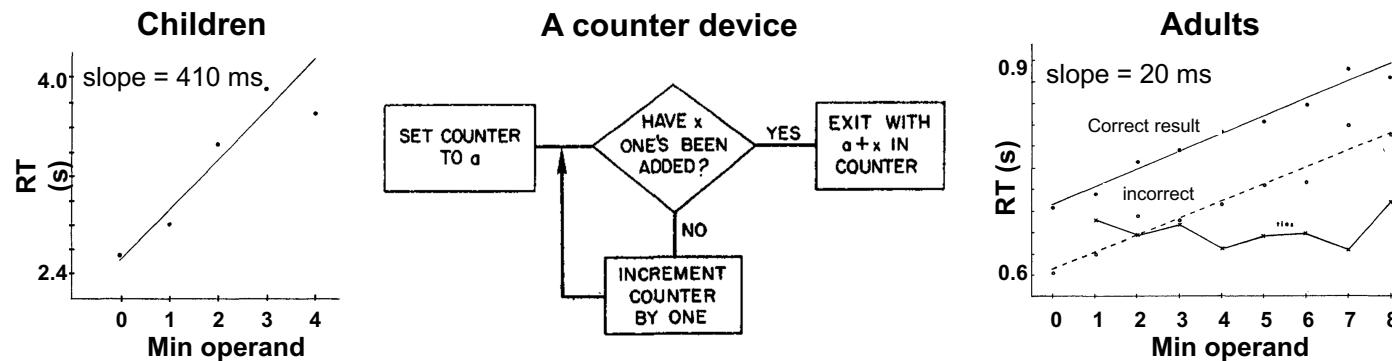
NFA: response to numerals
is *context independent*

Adjacent population – pITG_{math}:
response to numerals depends on *calculation*



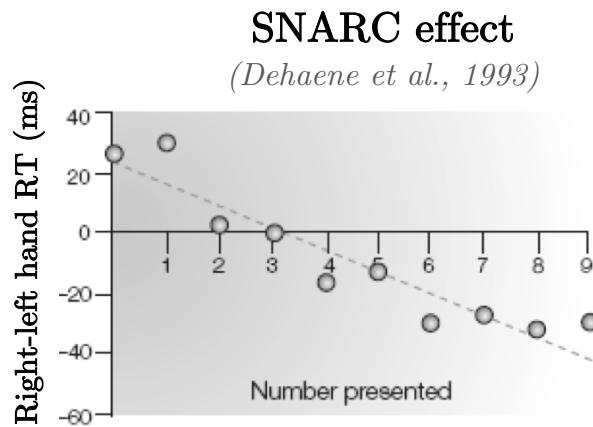
Cognitive models of symbolic arithmetic

- Problem-size effect: RTs increase as a function the size of the operands.
- The '*min*' counting model (*Groen & Parkman, 1972*).

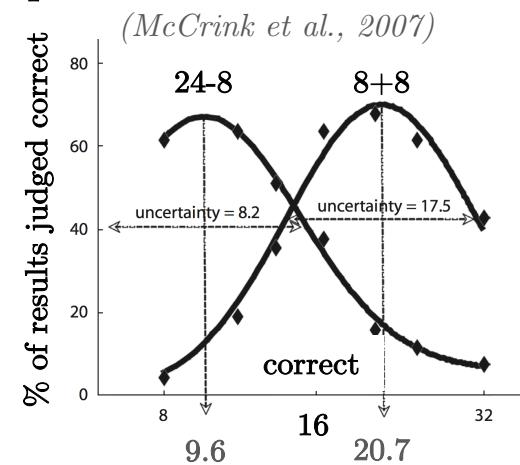


- Fact retrieval models
 - Acquisition history determines strategy (*Siegler & Shrager, 1984*).
 - Tabular representation of the addition facts (*Ashcraft, 1992*).
 - Only half of the table is memorized (larger+smaller) (*Butterworth et al., 2001*).
- Compact counting procedures
 - Linear increase in RT even in very small additions (*Barrouillet & Thevenot, 2013*).
 - Operator-priming effect in additions & subtractions (*Fayol & Thevenot, 2012*). Procedures can be pre-activated by the operation sign.

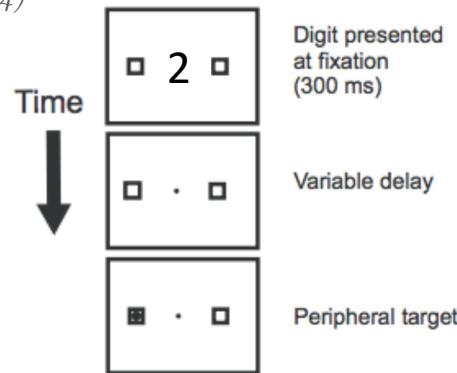
Calculation as '*movement*' along the mental number line



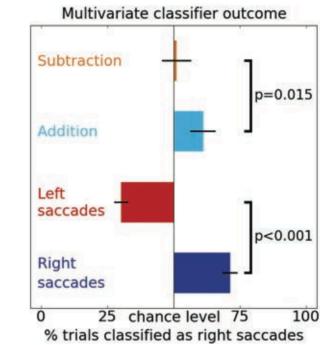
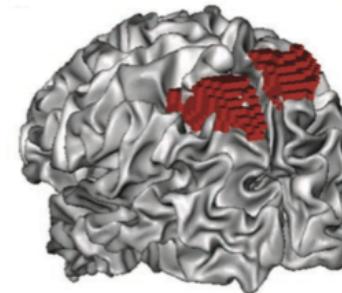
Operational Momentum effect



Perceiving numbers shift spatial attention
(Fischer et al, 2004)



Decoding right vs. left saccades generalizes to add vs. sub in pSPL
(Knops et al, 2009)



VIP-LIP vector addition for eye movement control
(Pouget, et al., 2002)

- Compatible with *min* and tabular fact retrieval models.
Precise mechanism still unknown.

Introduction

- Simple additions and subtractions: direct retrieval from long-term memory.
Recent challenges: Operational momentum & operator priming effects.
 - Compact counting procedures: 'movement' along the mental number line.
- LPC: magnitude processing and calculation; VTC: visual recognition of numerals.
Recent challenges: 2 distinct neuronal populations in VTC.
 - NFA: selective response to numerals irrespectively of the context.
 - Adjacent pITG_{math}: response to numerals only during calculation.
- Methodological barrier – summary measures of the entire processing chain.
 - Mental chronometry: blind to the absolute timing and order of the stages.
 - fMRI: low temporal resolution & relatively coarse functional specificity.
- Approach to parse and characterize the processing stages of calculation:
 - Trajectory-tracking, iEEG and time-resolved MVPA applied to MEG.

Index of the presentation

- Chapter 2. Pinheiro-Chagas, P., Dotan, D., Piazza, M., Dehaene, S. (2017). Finger tracking reveals the covert stages of mental arithmetic. *Open Mind: Discoveries in Cognitive Science*, 1(1), 30-41.
- Chapter 3. Pinheiro-Chagas, P.*, Daitch, A.* , Parvizi, J., Dehaene, S. (*under review*). Brain mechanisms of arithmetic: a crucial role for ventral temporal cortex.
- Chapter 4. Pinheiro-Chagas, P., Piazza, M., Dehaene, S. (*under review*). Decoding the processing stages of mental arithmetic with magnetoencephalography.
- General discussion and perspectives.

Chapter 2. Finger-tracking reveals the covert stages of mental arithmetic

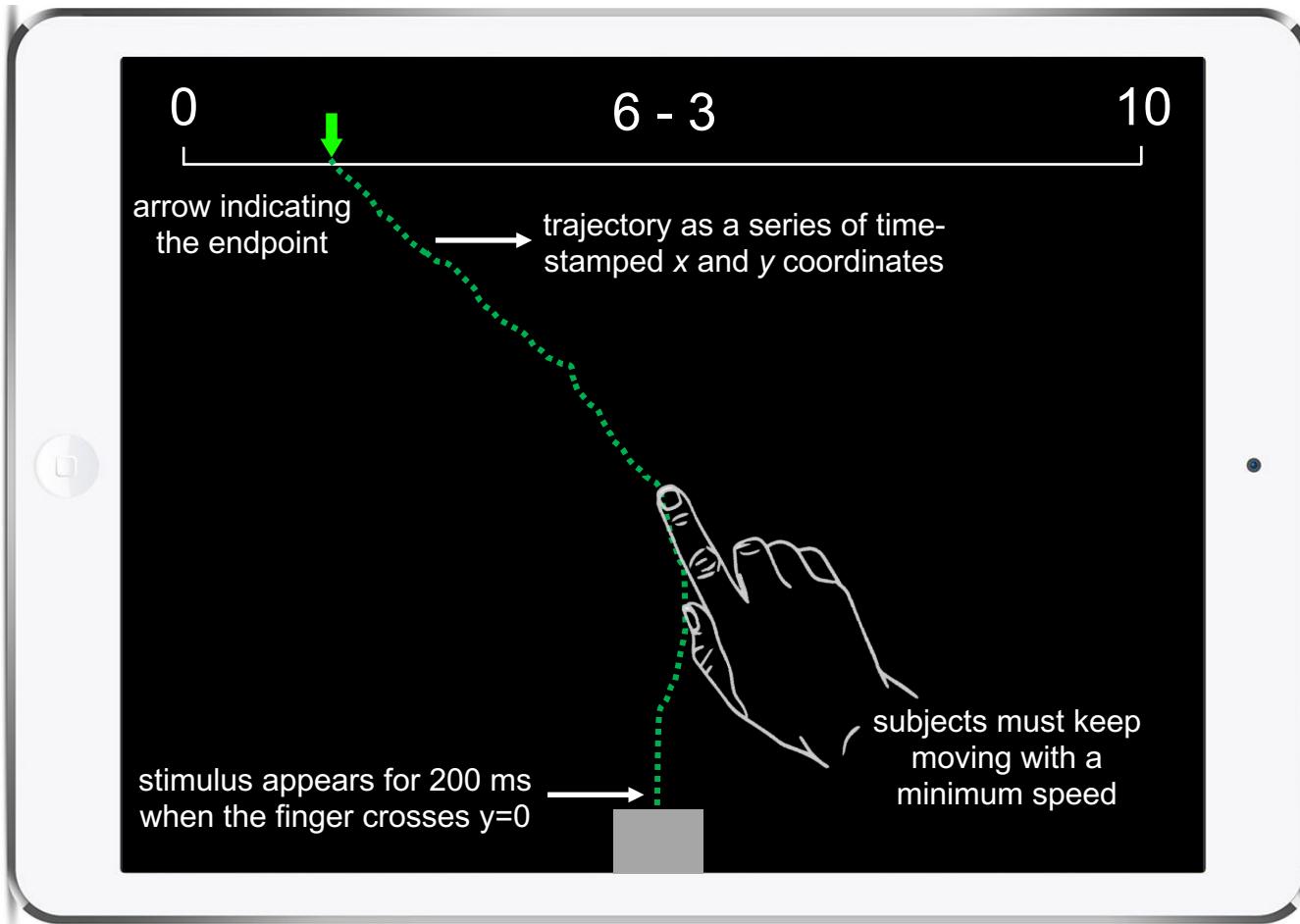
- Decompose the covert stages of mental arithmetic.
- Are the two operands processed serially or in parallel?
- Is there a stage whose duration increases linearly with the size of the numerical quantities, as implied by counting models?
- Can we visualize a reordering of the two operands when solving additions, as predicted by the COMP model?
- Can we determine the moment when the visuospatial biases underlying addition and subtraction occur?



Dror Dotan
Lecturer & finger-tracker
Tel Aviv University

Experimental Setup

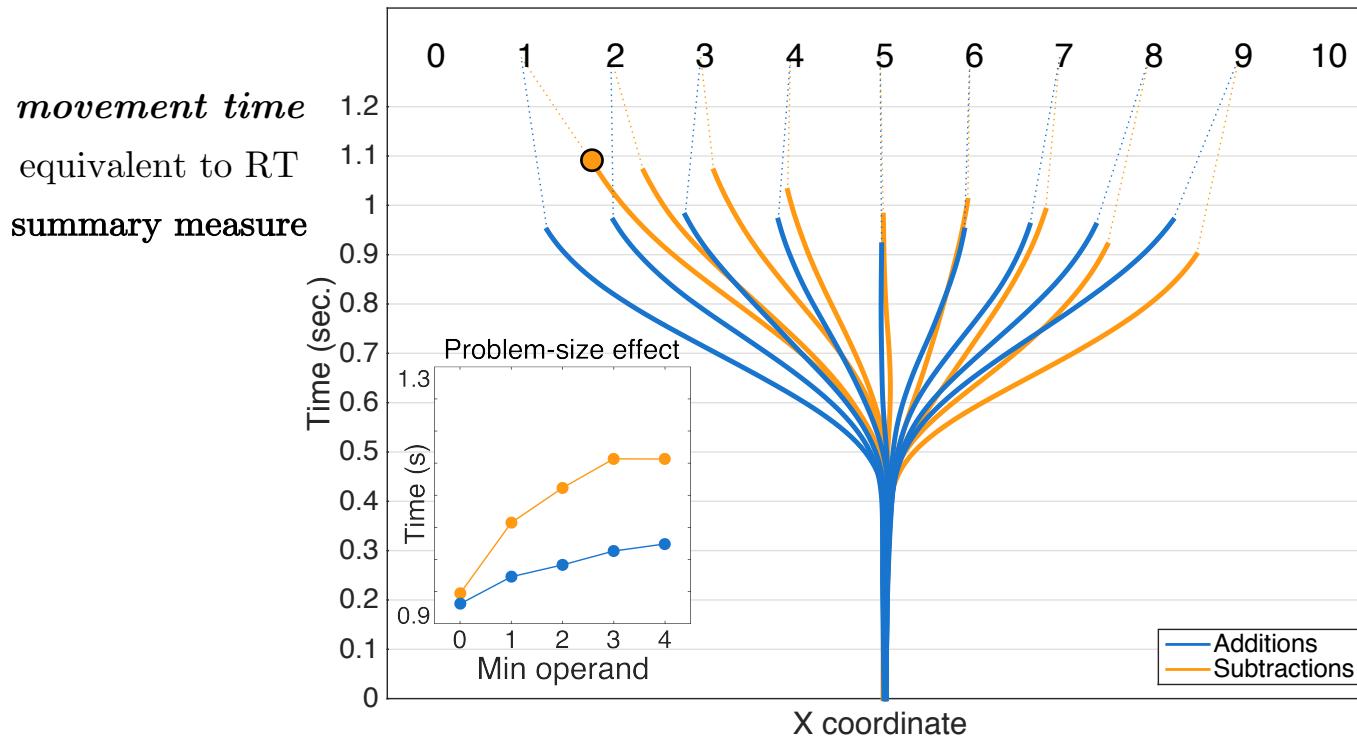
30 adults, students, right-handed



Assumption

*finger trajectories track the ongoing decision process
underlying a cognitive task*

Averaged trajectories by result

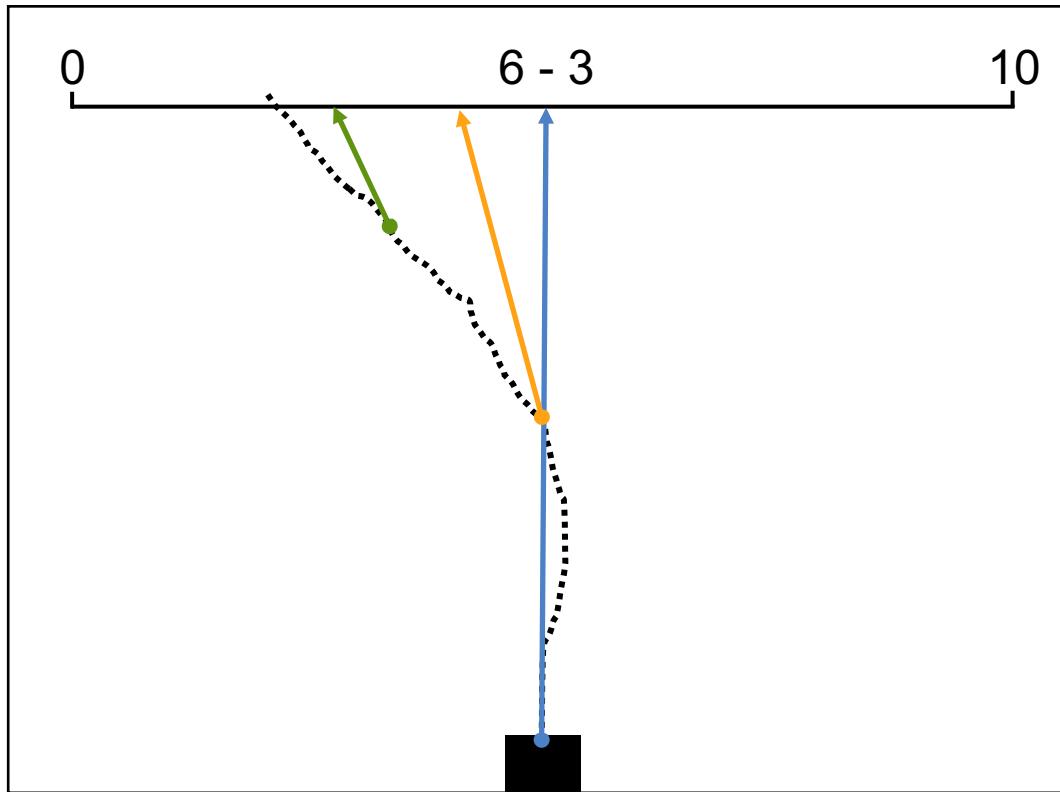


- The *min* operand is the best predictor of MT in additions & subtractions
slope: 55 ms *sub*; 25 ms *add*; *Replicates Groen & Parkman (1972)*, etc.

*Research in the past 40 years would stop at this stage
to formulate cognitive models of arithmetic*

Decomposing the calculation task

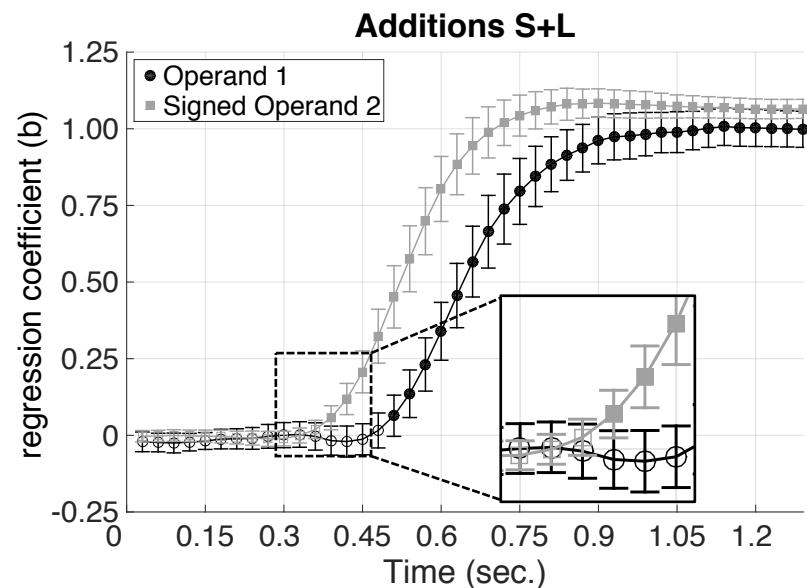
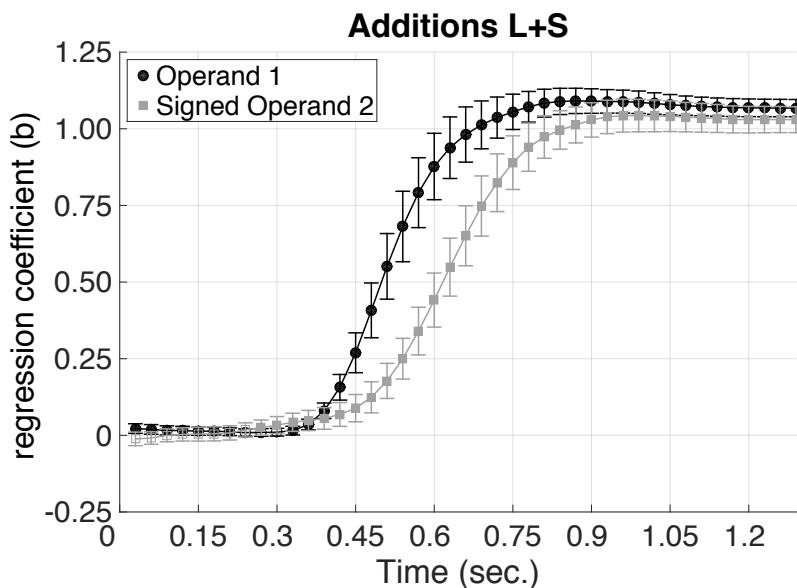
Time-resolved multiple regression



Implied endpoints: where the subject is aiming at each time t

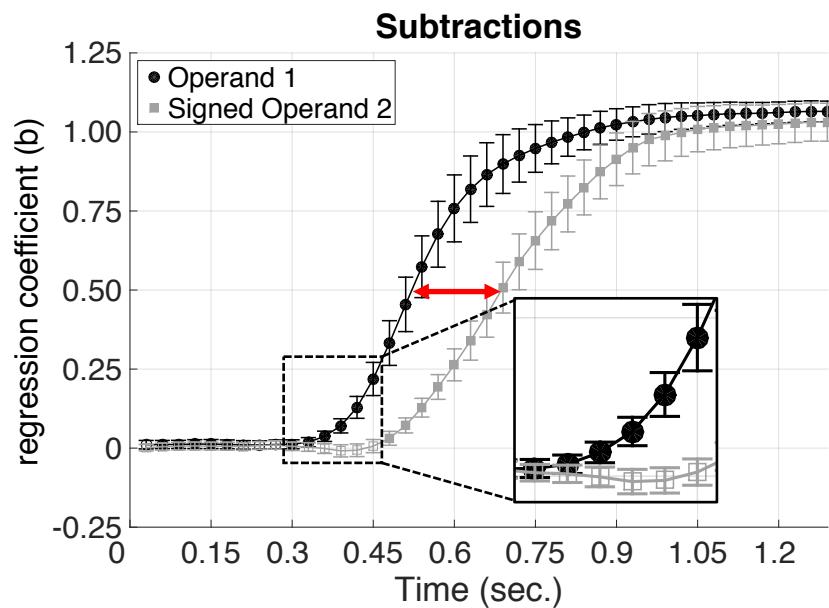
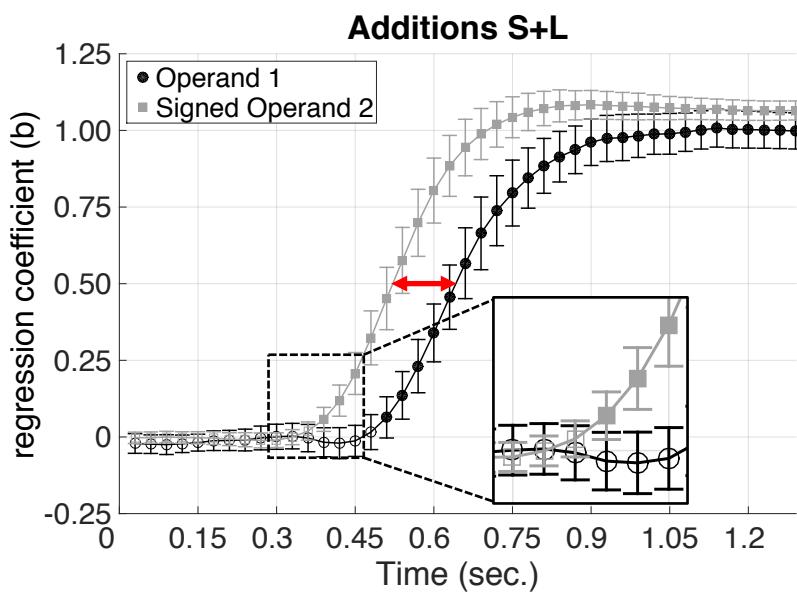
- Multiple Regression at each time sample (30 ms), per subject
 - *Dependent variable:* implied endpoint
 - *Predictors:* operand 1, operand 2, etc.

Serial processing of the operands in additions

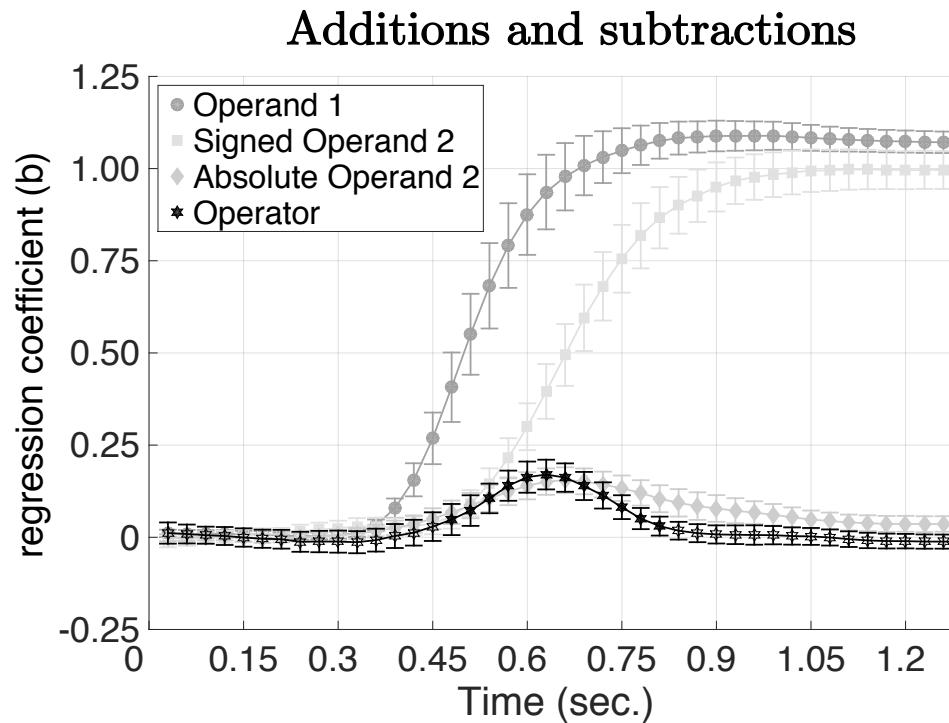


- **Reordering of the operands:** subjects first point to the larger operand irrespectively of the its location.
- Cost in MT of 14 ms.

Higher serial processing of the operands in subtractions

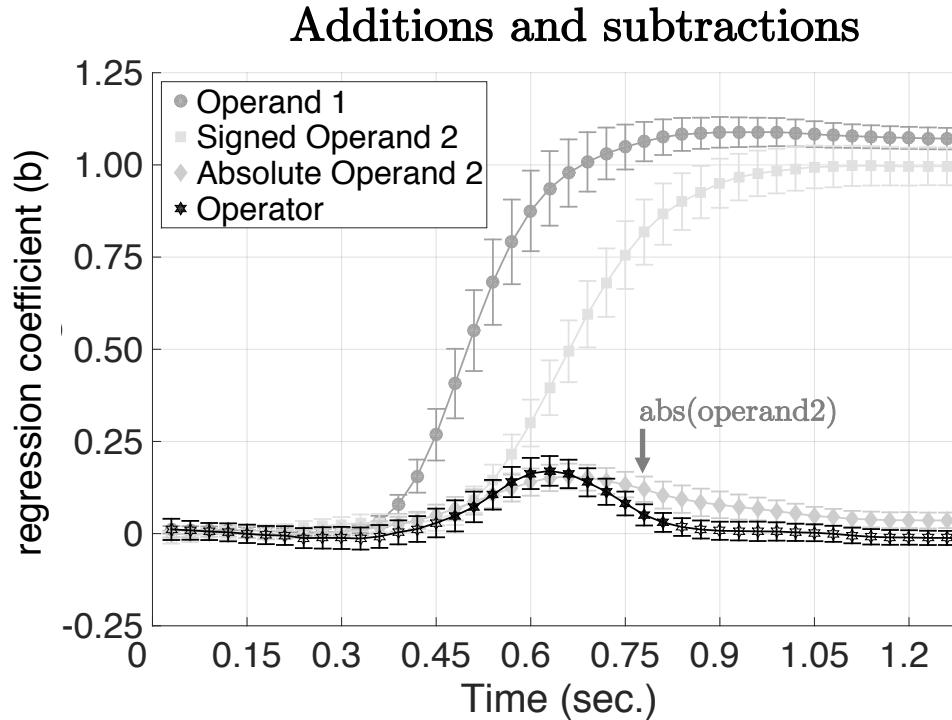


Transient OM effect at the time of processing the *min* operand



- OM effect: + and – signs distorts the finger to the right & left sides

Transient activation of the absolute value of the subtrahend



- Additional stage in subtraction: discard the absolute value of the subtrahend

Chapter 2. Discussion and conclusions

- The **operands** are processed **serially**: larger operand first independent of its location: **direct visualization** of the **reordering effect** for additions S+L
- The deviation from the larger operand to the correct result unfolds serially and **proportionally** to the **size** of the **min operand** (intermediate stages?)
- **Transient OM effect** at the time of the **integration of the min**: visuospatial attention system actively engaged during the calculation.
- **Transient activation** of the **absolute value** of the **subtrahend**. Potentially explain why subtractions are generally slower.
- Support for a model in which single-digit additions and subtractions are computed by a stepwise displacement on the mental number line
Compatible with compact counting procedures & retrieval by tabular search

Chapter 3. Brain mechanisms of arithmetic: a crucial role for ventral temporal cortex

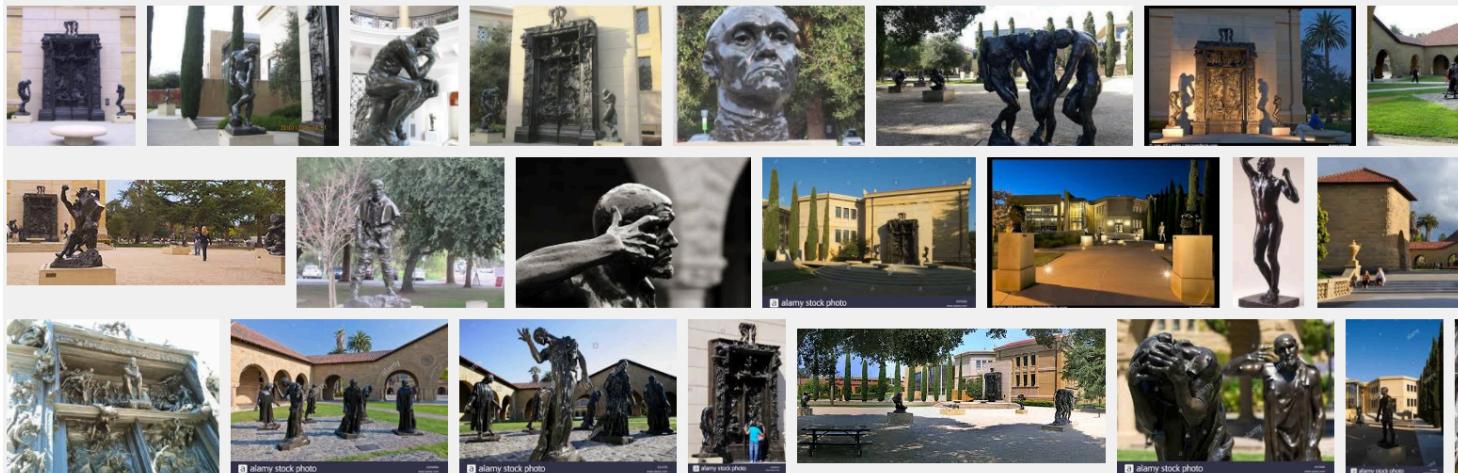
- Traditional view:
 - **LPC**: main hubs for magnitude processing and calculation.
 - **VTC**: visual recognition of numerals.
- Recent findings suggest that the **VTC engagement is more complex**.
- Fine-grained re-evaluation of the **LPC and VTC roles in arithmetic**. processing, by recording electrophysiological activity directly from the brain.
- Test if, how and when numerical features (*problem-size*) modulate the activity in calculation-selective neuronal populations in the **LPC and VTC**.



Josef Parvizi



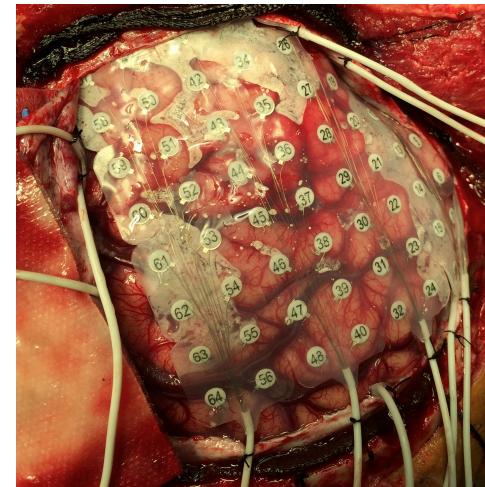
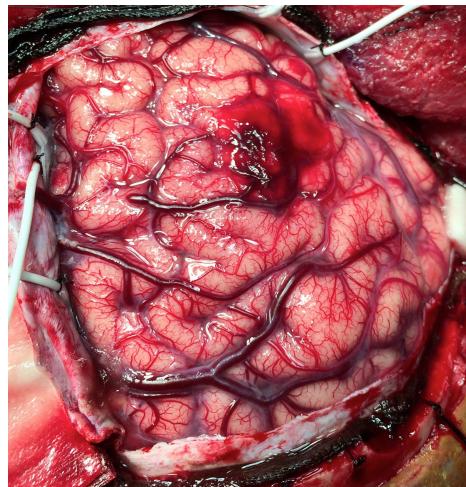
Amy Daitch



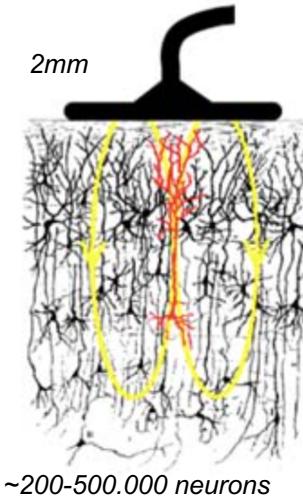
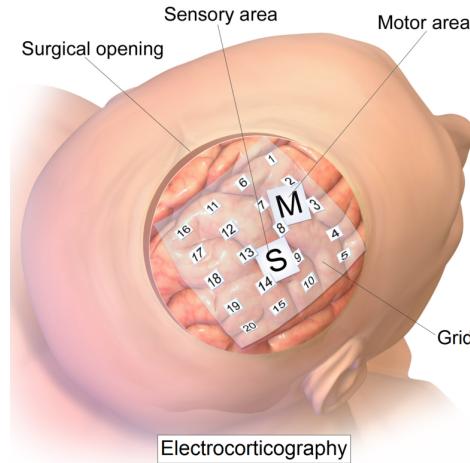
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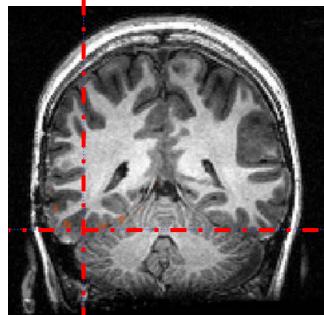
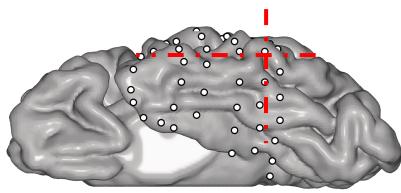
Electrocorticography (ECoG)



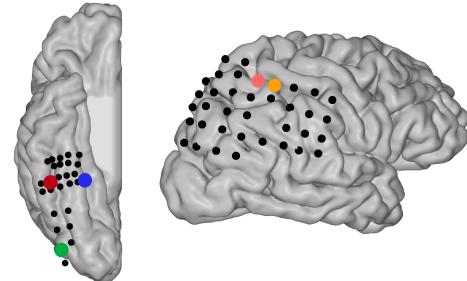
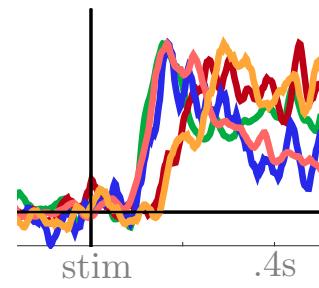
EEG (Electrocorticography)



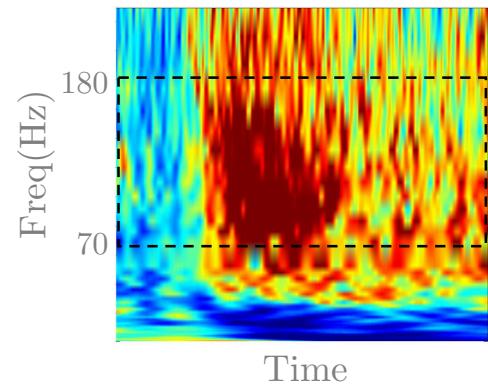
High spatial precision



High temporal resolution

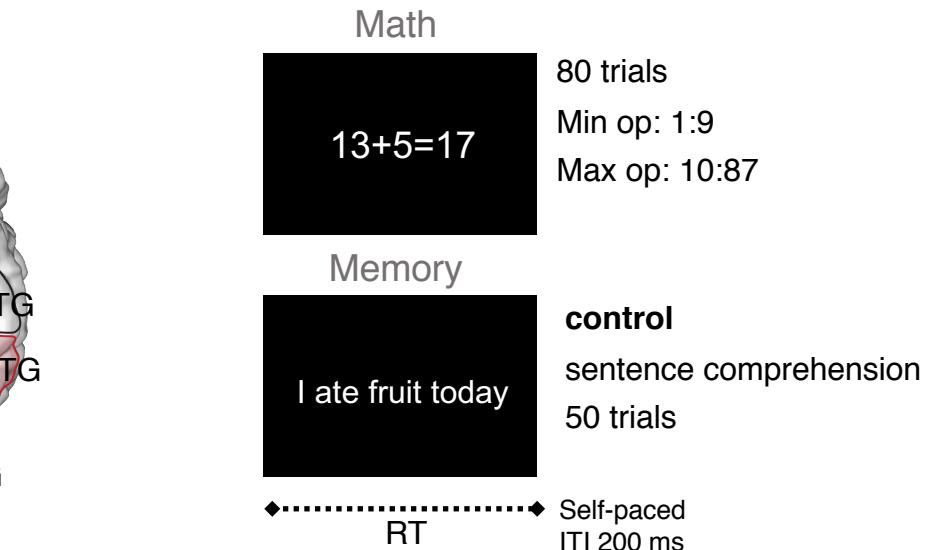
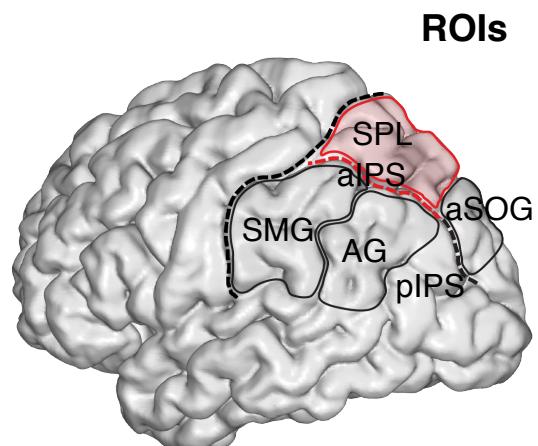


Rich frequency content

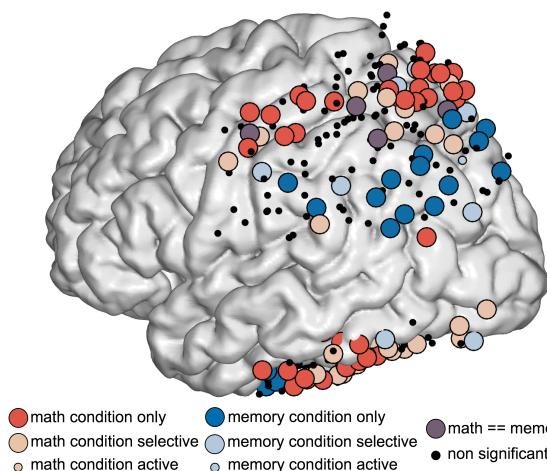


Task, ROIs, selectivity and problem-size effect

10 subjects with coverage in VTC and LPC

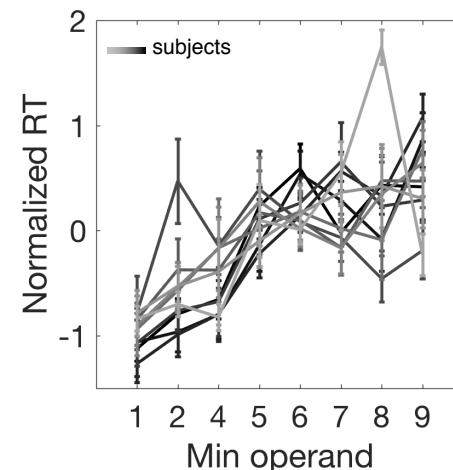


Channel selectivity



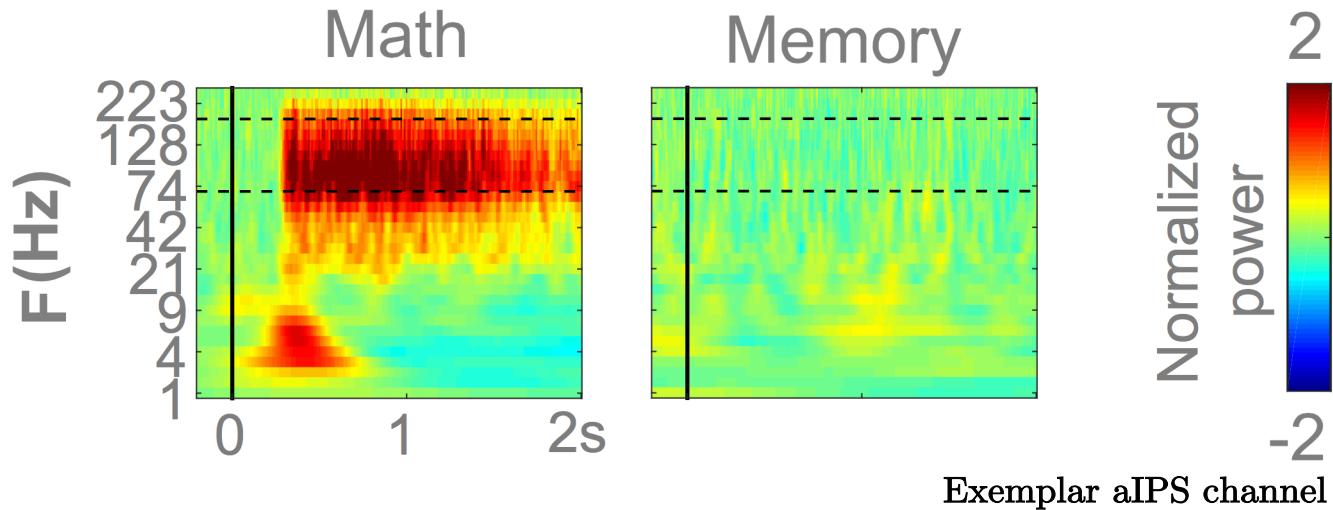
All sites from all subjects projected into a single left hemisphere

Problem-size effect



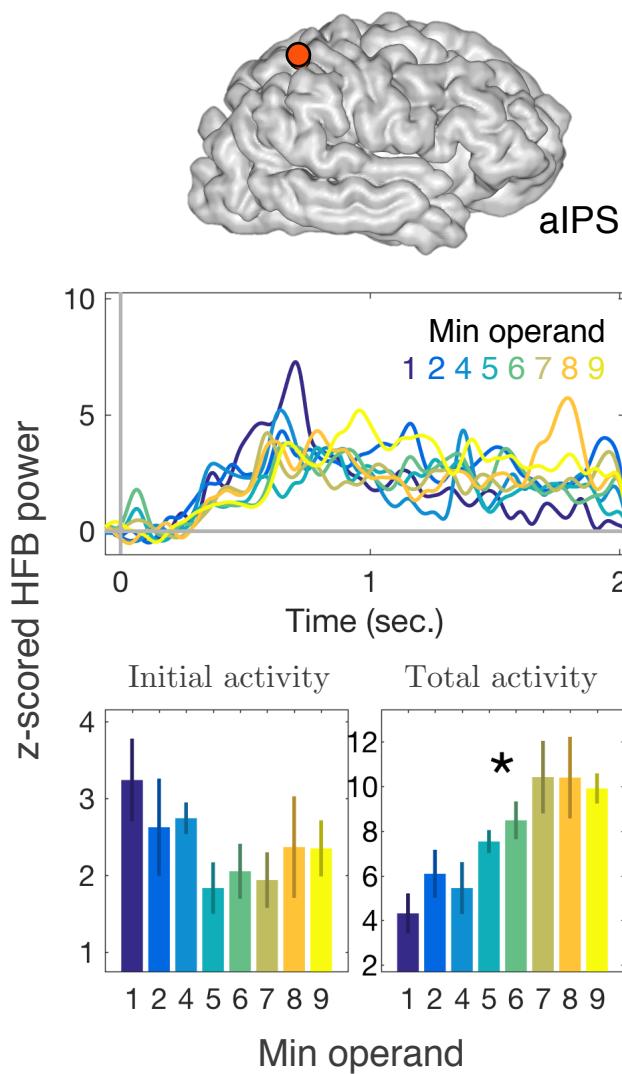
Best predictor of RT in 9/10 subjects

High frequency broadband (HFB): 70–180 Hz

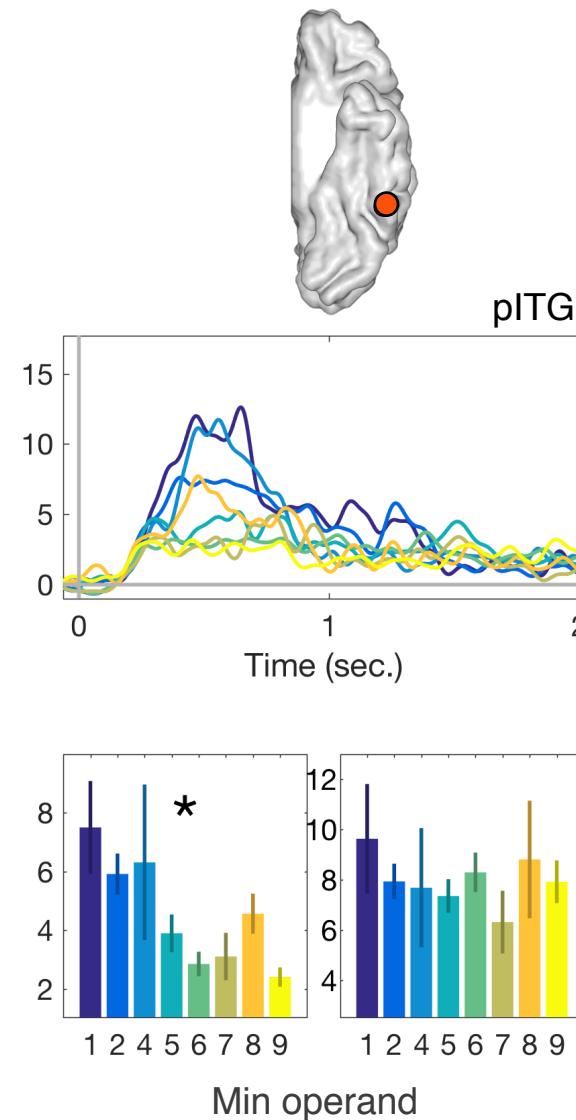


- **initial activity : 1st second**
averaged over the 1st second, when greatest increase in activity occurs
- **total activity: integral**
integral of the activity from trial onset to response: equivalent to BOLD

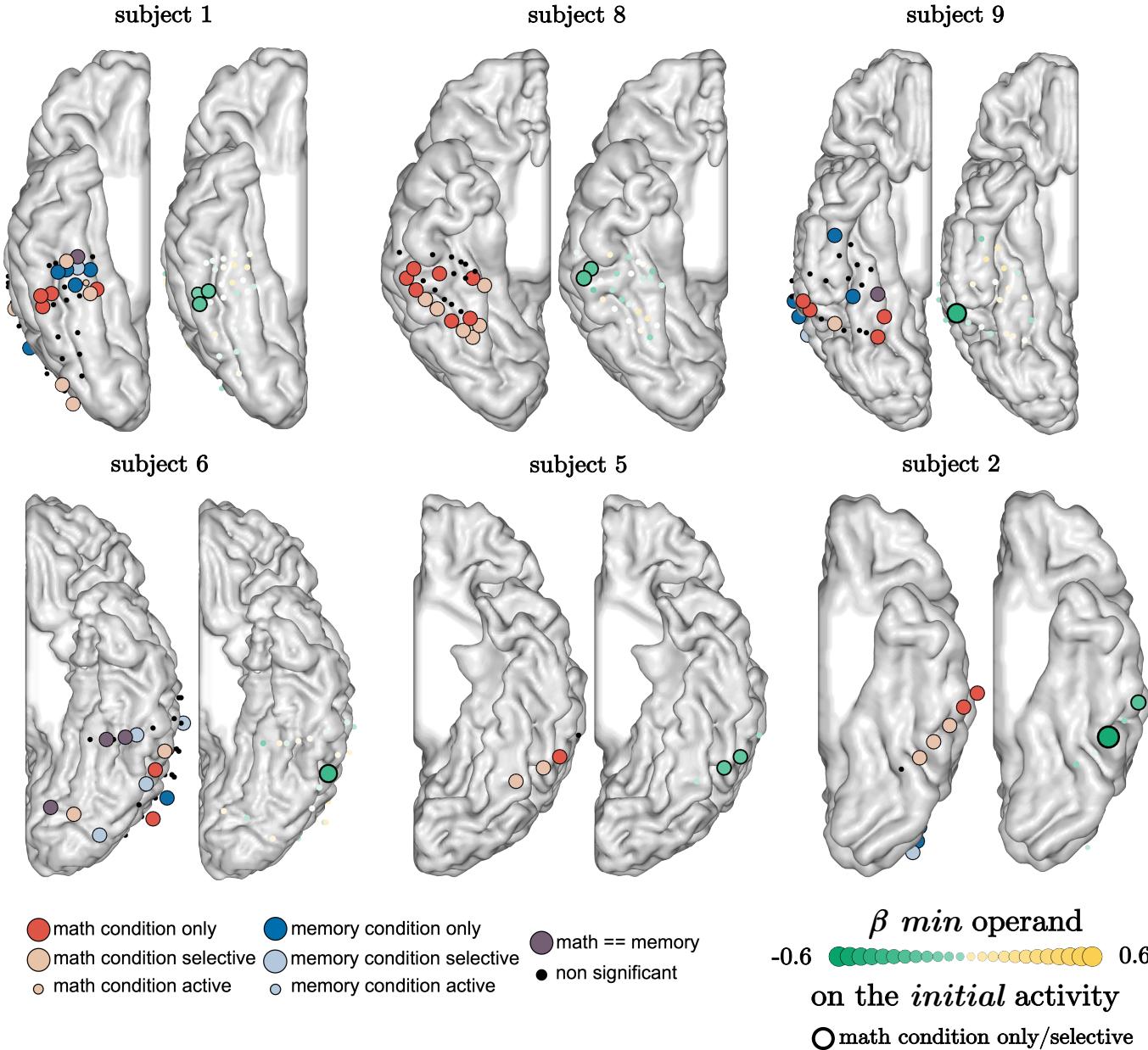
**Increased *total* activity by
min operand in aIPS and SPL**



**Decreased *initial* activity by
min operand in pITG**

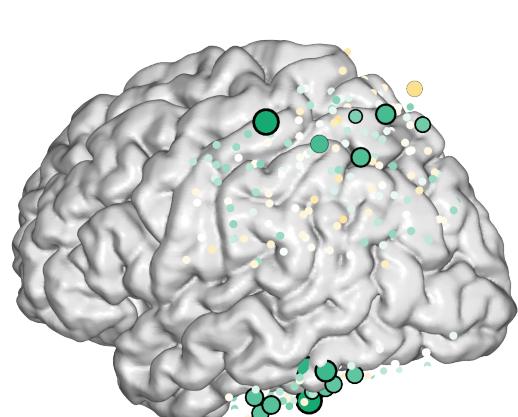


Anatomical and functional precision of the pITG modulation

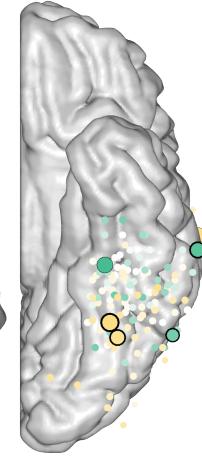
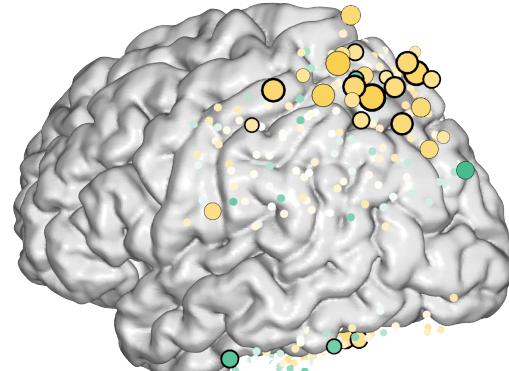
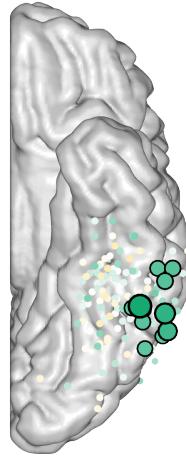


Effect of the *min* operand on the:

initial activity



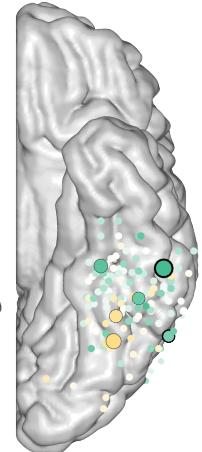
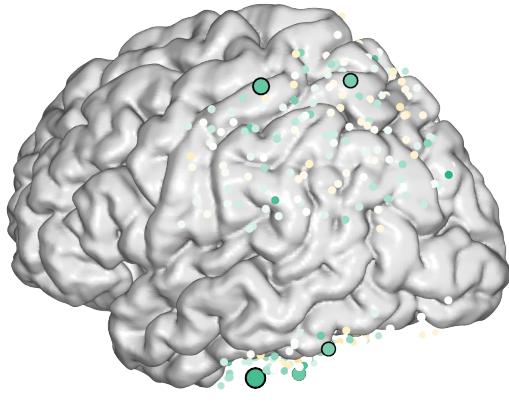
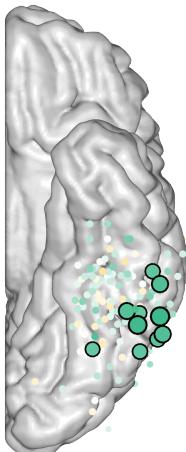
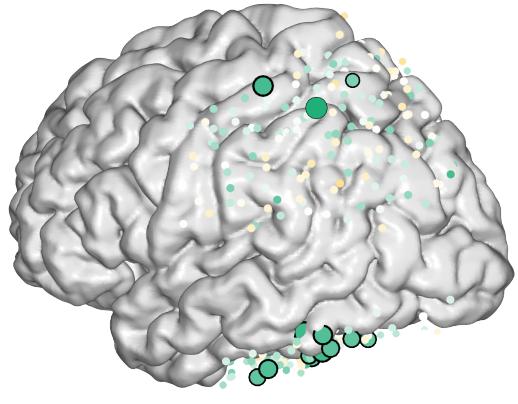
total activity



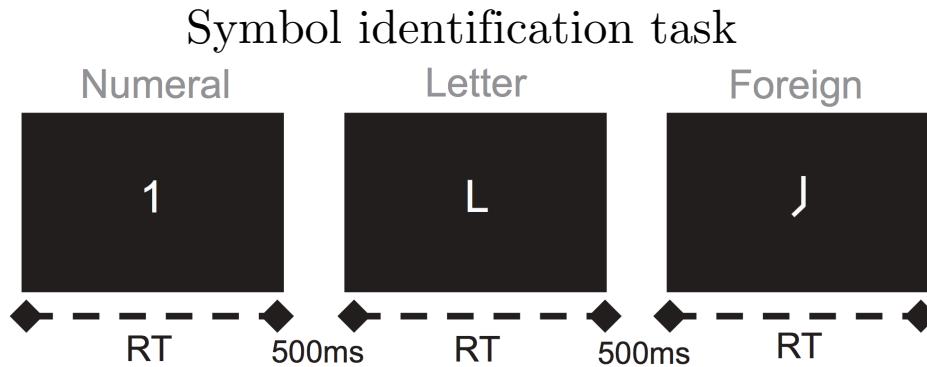
○ math selective

0.6
β
-0.6

Effect of min operand controlled by RT



Modulation of pITG does not reflect tuning to digits



Subject	Hemi	Region	Numeral active	Numeral selective	Modulation by numeral
S1	R	pITG	✓	-	-
S1	R	pITG	✓	-	-
S1	R	pITG	-	-	-
S2	L	pITG	✓	-	-
S2	L	aITG	-	-	-
S5	L	pITG	✓	-	-
S5	L	pITG	✓	-	-
S6	L	pITG	-	-	-
S8	R	pITG	✓	✓	-
S8	R	pITG	✓	-	-
S9	R	pITG	-	-	-

Hemi, hemisphere; Numeral active (relative to baseline); Numeral selective (relative to baseline, Latin letters, and foreign letters). (✓) Statistically significant at $P < 0.05$, FDR corrected.

- 9/10 pITG sites are **not NFA**.
- pITG modulation is exclusive to the **calculation task**.

Chapter 3. Discussion and conclusions

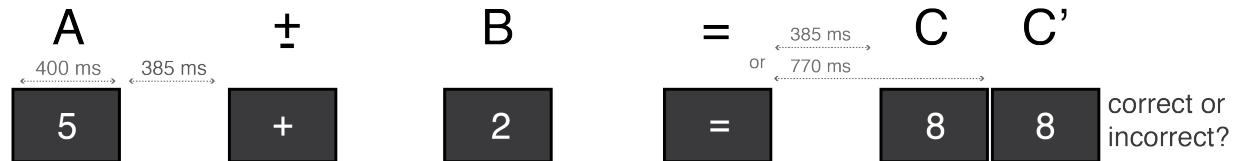
- Modulation of aIPS and SPL corroborates previous fMRI findings.
 - Increased total activity as a function of problem-size.
 - Slow and sustained – highly correlated with RT.
 - Index the accumulation of evidence to achieve a decision.
- Surprising role of pITG in mental arithmetic beyond digit recognition.
 - Decreased initial activity as a function of problem-size: blind to fMRI.
 - Fast - not correlated with RT.
 - Early identification of problem difficulty (amount of evidence?).
- Re-evaluation of neurocognitive models of arithmetic and dyscalculia.
 - pITG as an **important hub** for **calculation**.
- **Expands the classical view of the VTC:** contains regions specifically involved in sophisticated symbolic forms of reasoning, such as mental arithmetic.

Chapter 4. Decoding the processing stages of mental arithmetic with MEG

- New insights on the neurocognitive mechanisms of mental calculations discovered in the previous studies.
- Still lacking a comprehensive picture of the organization of brain processes.
- Time-resolved multivariate pattern analysis applied to MEG.
- Can we decode the identity of the operands?
- Can we track in time the emergence of the internally computed result?
- Are the brain processes completely serial or do they partially overlap in a form of a cascade of computations that can be simultaneously decoded?

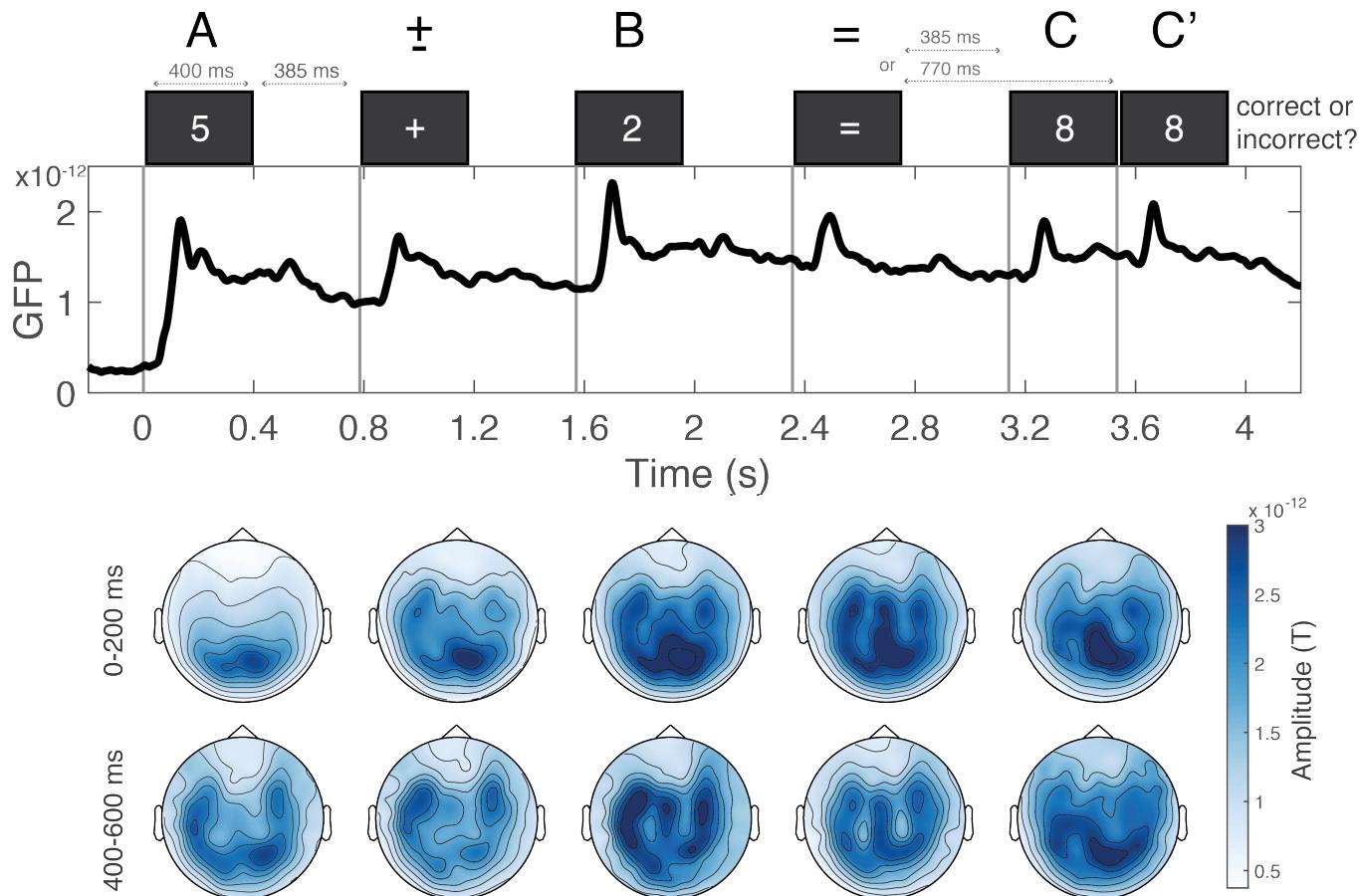
Experimental Design

20 adults, students, right-handed

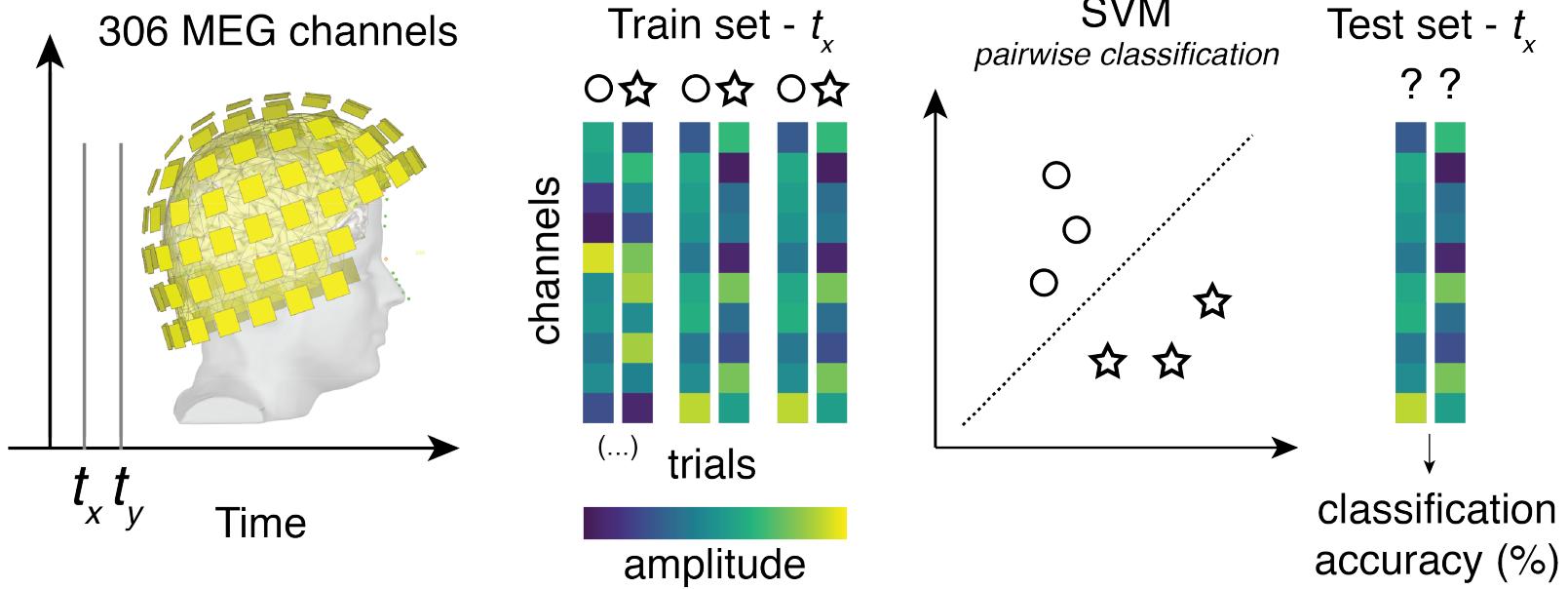


- A - max operand = 3, 4, 5, 6
- B - min operand = 0, 1, 2, 3
- Result = 0 – 9 (3, 4, 5, 6 - 50 trials each)
- C – proposed result = 0 – 9
50% incorrect (absolute distance: 1, 2, 3, 4)

Sustained activation from posterior to anterior sensors

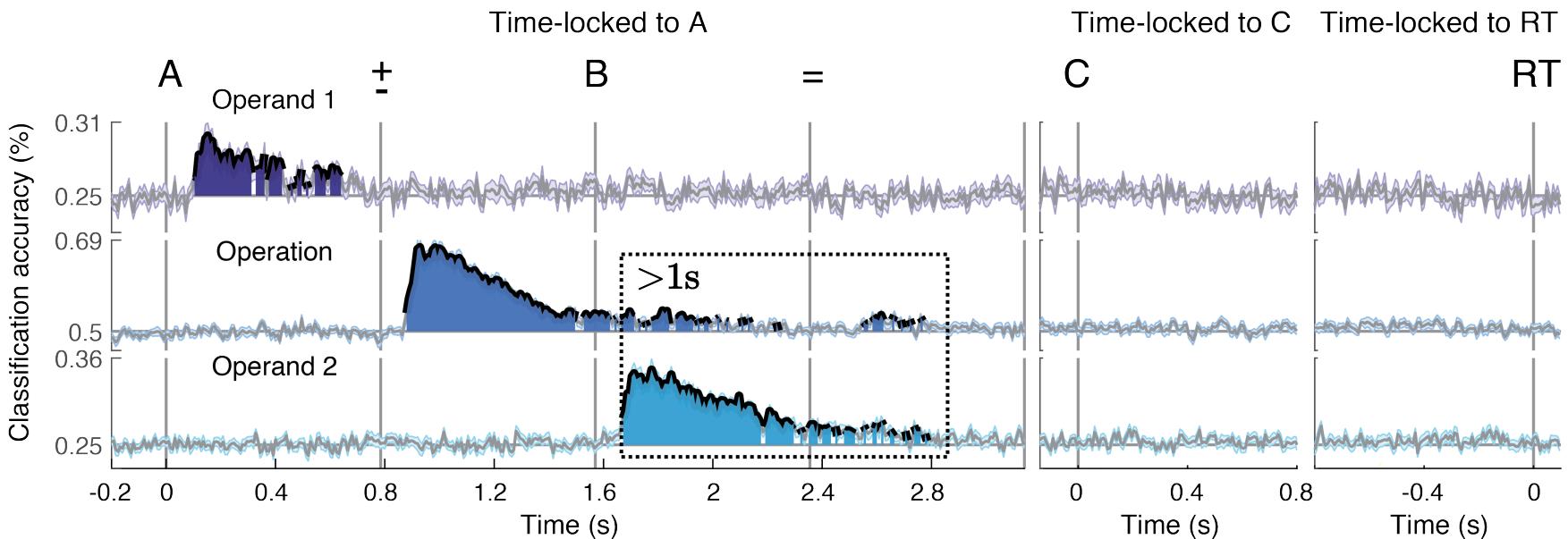


Time-resolved decoding



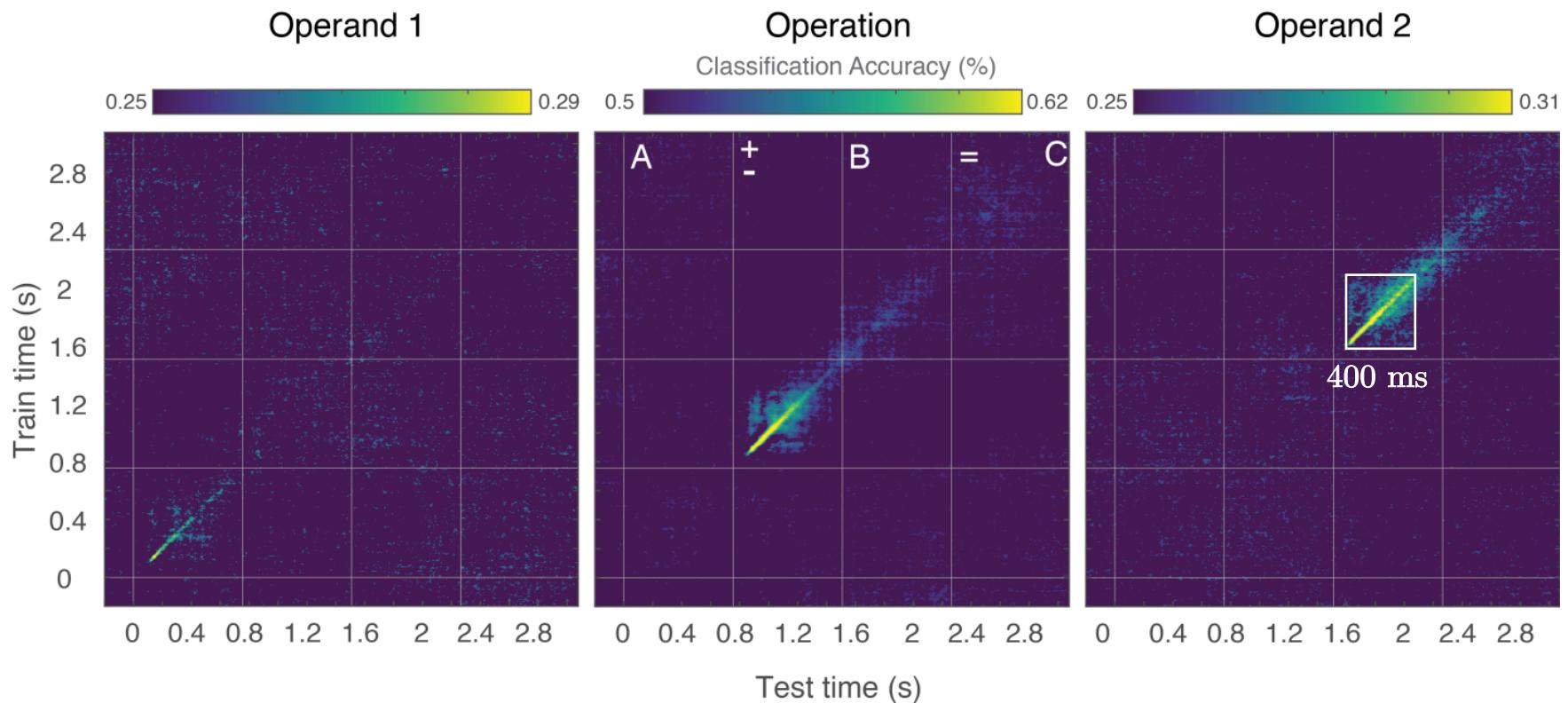
- The classifier is applied at each time sample t_x , t_y ... , per subject.
- Generalization across time: can the classifier trained at t_x generalize to t_y ?
- Generalization across conditions: test the existence of possible common codes.

Decoding operands and operation

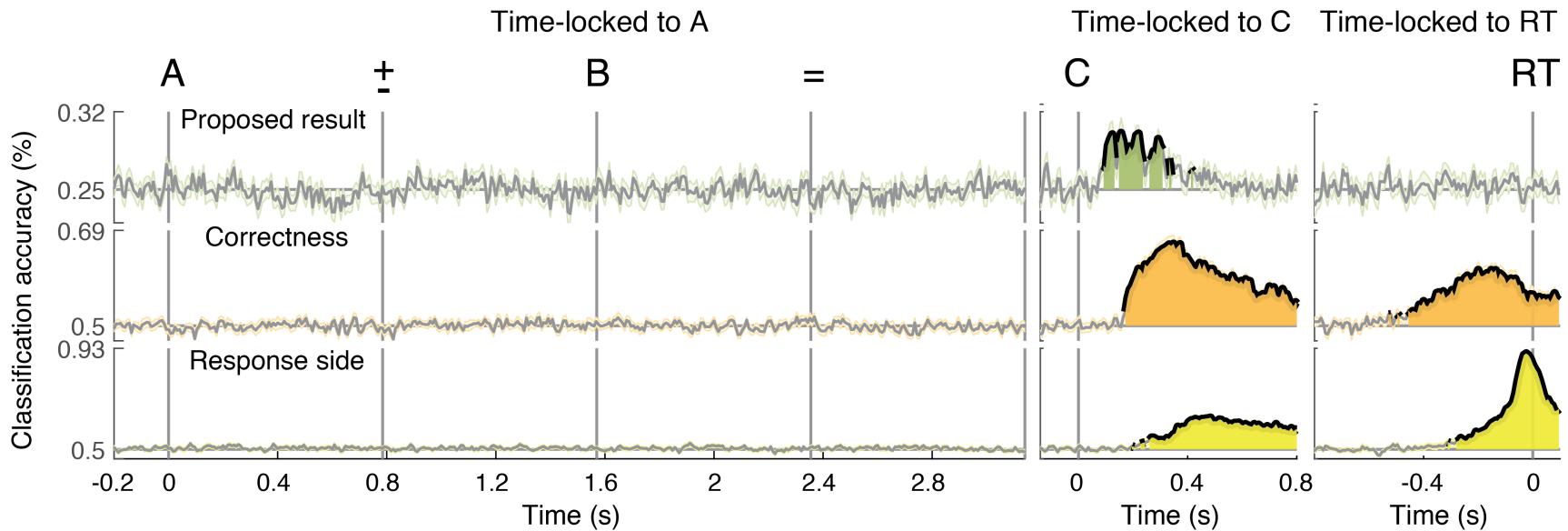


- **Operand 1:** transient, rapidly decreases after stim offset.
 - **Operand 2:** higher accuracy and for a **longer** period – 1s.
 - **Operation (sub vs. add):** **sustained** for 2s, rebound after equal sign.
 - Long **overlap** between **operation** and **operand 2** – 1s.
-
- Classifier trained on **sub** vs. **add** generalized to **operand 2 (0-1 vs. 2-3)**, not to operand 1.

Short time generalization: highly dynamic coding scheme

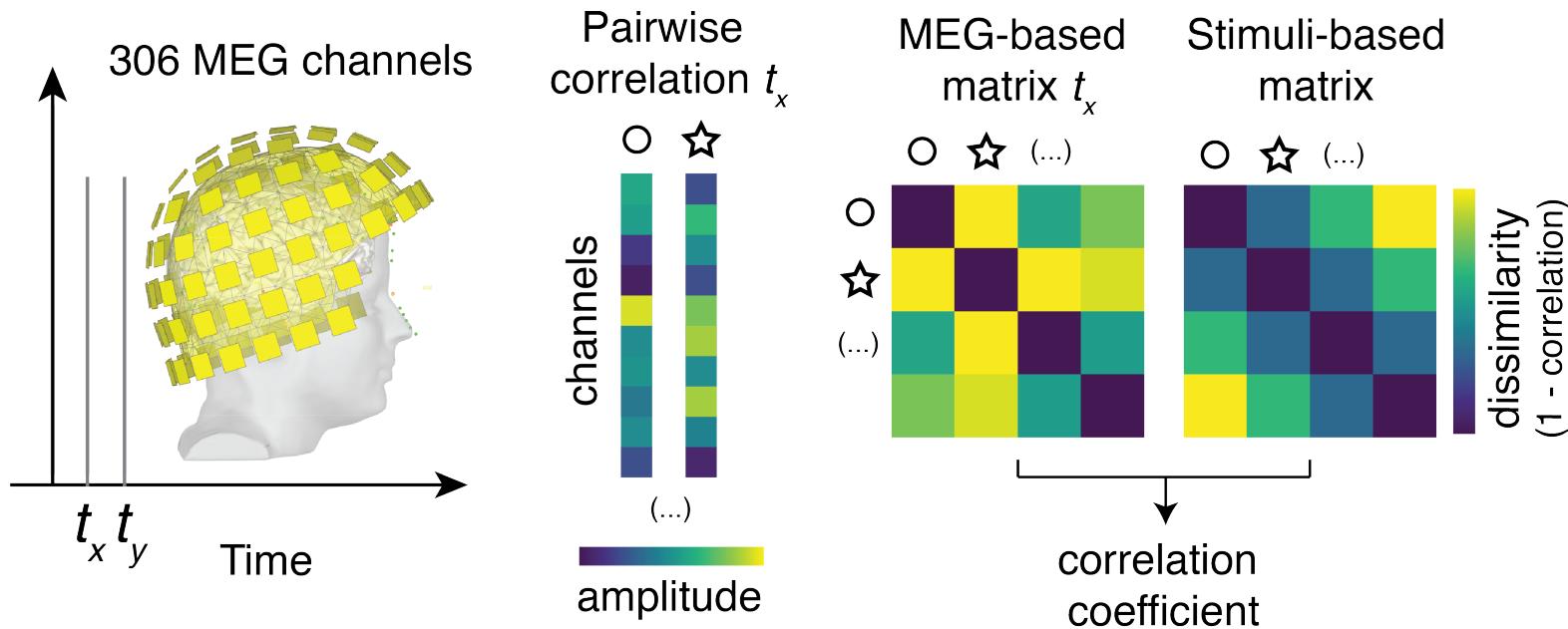


Highly overlapping dynamics at the decision stage



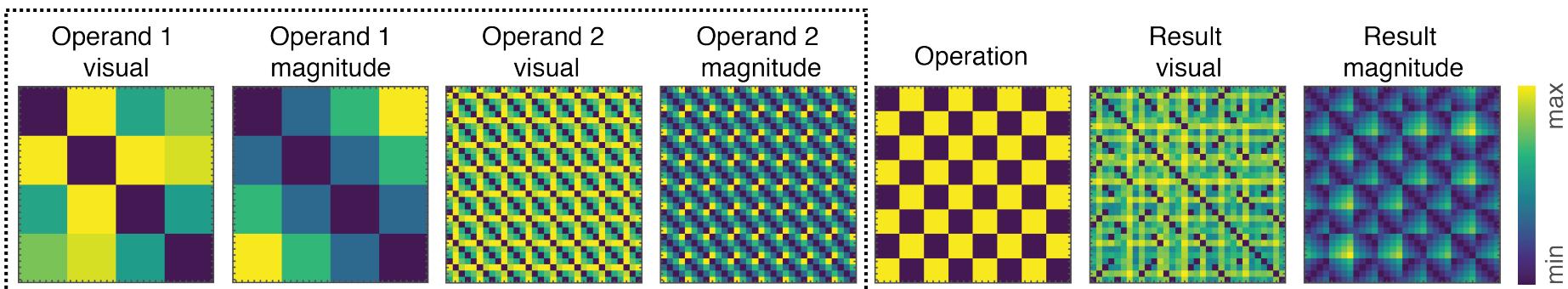
1. Identify the proposed result.
2. Judge whether it is correct or incorrect.
3. Press the response button.

Time-resolved Representational Similarity Analysis

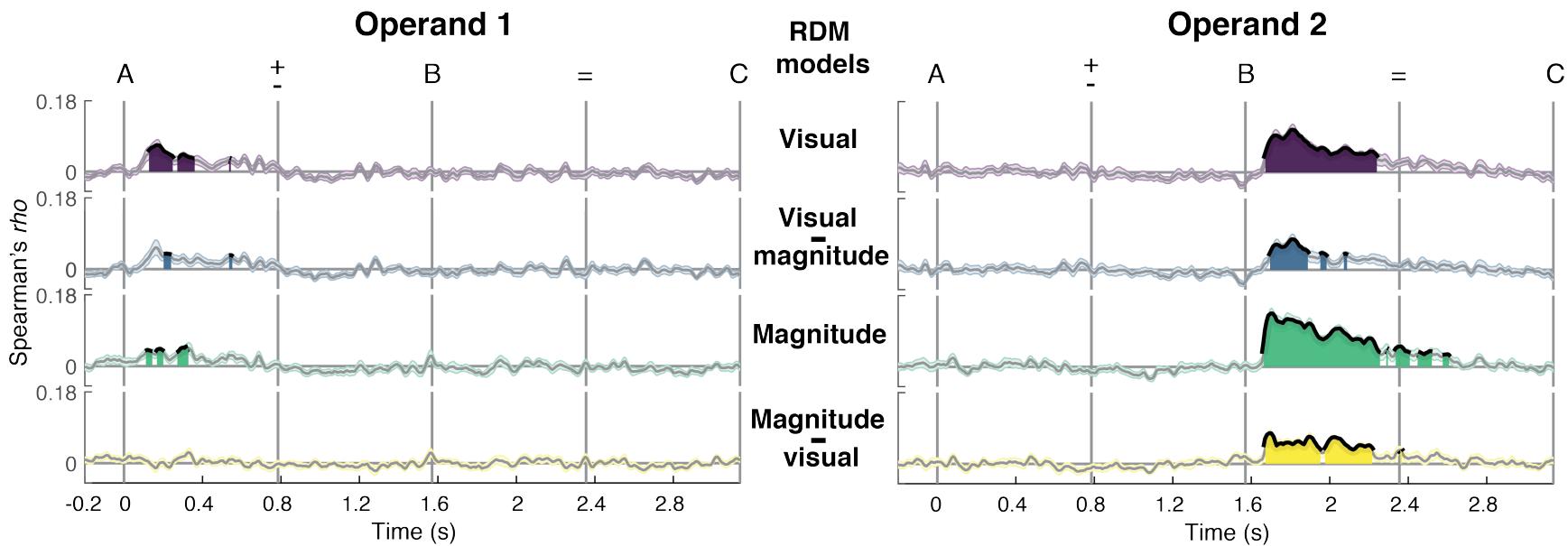


- The RSA is computed at each time sample t_x , t_y ... , per subject.
- Explicitly partial-out the effect of other stimuli-based models.

RDM models:



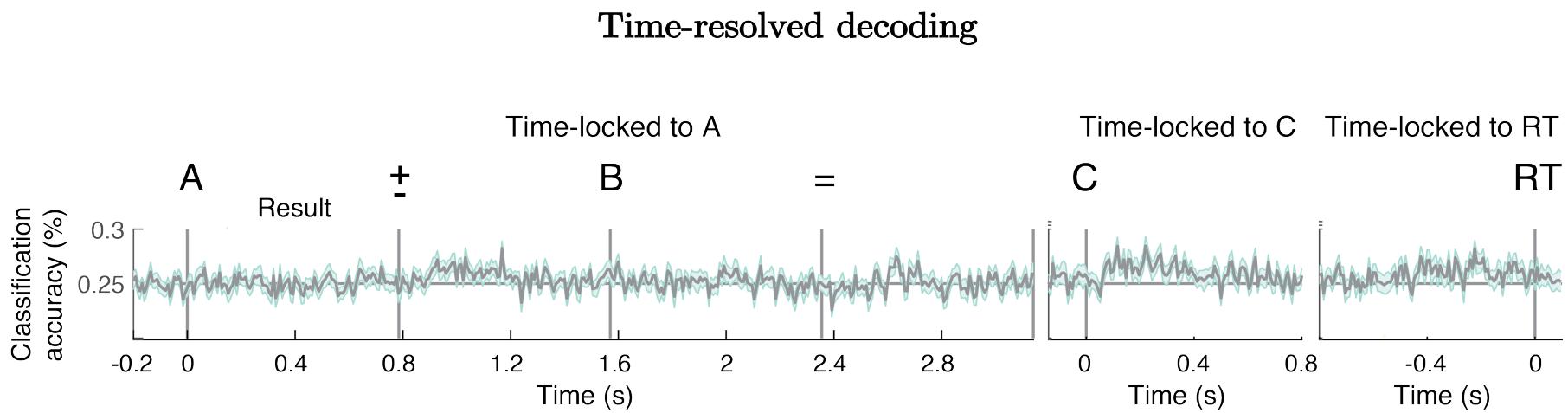
Representational geometries of the operands



- **Operand 1:** visual dimension is dominant.
- **Operand 2:** both visual and magnitude dimensions, **magnitude** dominant.
No precedence of the visual dimension.

Searching for a neural signature of the internally computed result

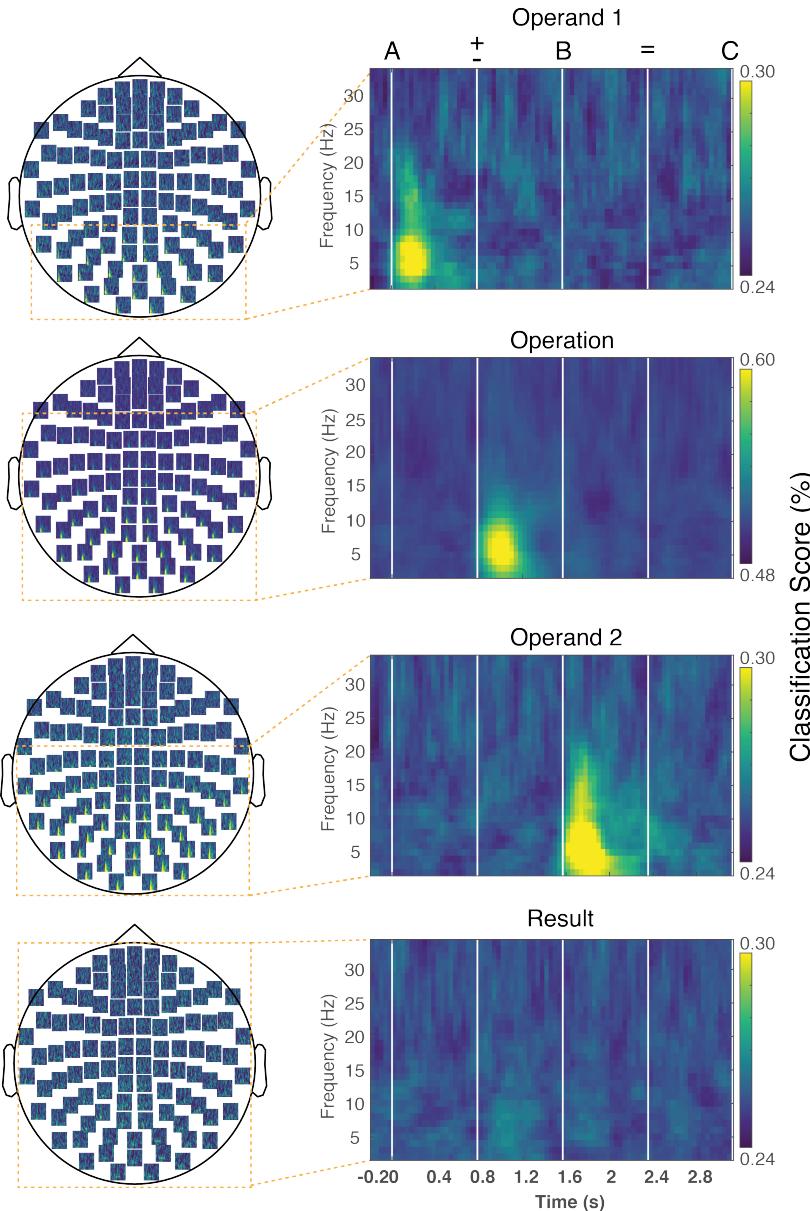
Several attempts, no success



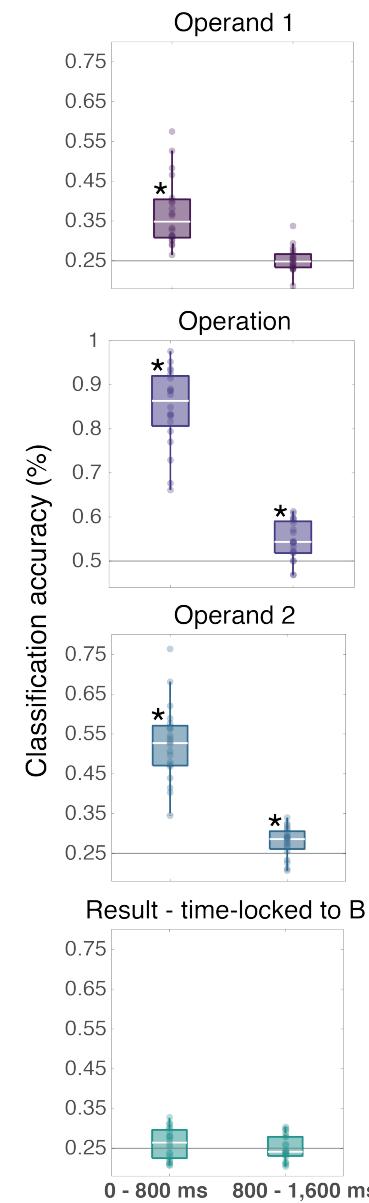
Searching for a neural signature of the internally computed result

Several attempts, no success

Searchlight LDA (sensor, time and frequency)



Riemannian Geometry (integrated over time)



Chapter 4. Discussion and conclusions

- First comprehensive picture of the unfolding processing stages underlying arithmetic calculations at a single-trial level.
- Decoding of **operand 1**: visual dimension.
- Decoding **operand 2**: visual and **magnitude** dimensions; possibly sharing a common code with operation type: link between SNARC and OM effects?
- **Fast and highly overlapping dynamics** at the **decision stage**:
 1. Identify the proposed result.
 2. Judge whether it is correct or incorrect.
 3. Press the response button.
- **Inability to decode the internally computed result**
 - Externally and internally generated codes have different neural substrates.
 - Internally generated: '*silent states*', rare gamma bursts, sparse code?
Hard to capture with MEG.
 - Limitations of the design (n_{trials} , no time-stamping, etc.).

General conclusions and future directions

- Single-digit addition and subtraction rely on quantity manipulation:
 - Stepwise displacement on the mental number line.
 - Possible common code between *min* operand and operation type.
 - *How does it actually work? Computational modelling.*
- Arithmetic is implemented in the dorsal and ventral pathways:
 - IPS and SPL: arithmetic computations and decision-making.
 - pITG: digit recognition and early identification of problem difficulty.
 - *How they communicate? iEEG – postdoc.*
- Decoding the processing stages of mental calculation:
 - Cascade of highly dynamic and partially overlapping brain states.
 - Operand 1: visual; Operand 2: visual and magnitude codes.
- Searching for neural signatures of the internally computed result.
 - Inability to decode with MEG.
 - *When and where is it generated? iEEG – postoc.*
- Beyond numbers: the syntactic structure of arithmetic expressions.

Stay tuned for the next articles

Pinheiro-Chagas, P., Dotan, D., Piazza, M., Dehaene, S. (*in preparation*).
Decomposing the syntactic structure of arithmetic expressions.

Dotan, D., Pinheiro-Chagas, P., Dehaene, S. (*in preparation*) Track it to crack it:
revealing the succession of processing stages with pointing trajectories.

Baek, S., Daitch, A., Pinheiro-Chagas, P., Parvizi, J. (*under revision*). Neuronal
population responses in the human ventral temporal and lateral parietal cortex during
arithmetic processing with digits and number words.

Other articles produced during the dissertation

Dresler, T., Bugden, S., Gouet, C., Lallier, M., Oliveira, D., **Pinheiro-Chagas, P.**, Pires, A., Wang, Y., Zugarramurdi, C., Weissheimer, J. (*under review*). Translational research in learning disabilities: the place of neuroimaging.

Borghesani*, V., de Hevia*, L., Viarouge*, A., **Pinheiro-Chagas, P.**, Eger, E., Piazza, M. (*under review*). Processing number and length in the parietal cortex: sharing resources, not a common code.

Pinheiro-Chagas, P.*, Dinino, D.*., Haase, V. G., Wood, G., Knops, A. (*in preparation*) The developmental trajectory of the operational momentum effect.

Borghesani*, V., de Hevia*, L., Viarouge*, A., **Pinheiro-Chagas, P.**, Eger, E., Piazza, M. (2016). Comparing magnitudes across dimensions: a univariate and multivariate approach. International Workshop on Pattern Recognition in Neuroimaging, 1-4.

Pinheiro-Chagas, P. Wood, G., Knops, A., Krinzinger, H., Lonnemann, J., Starling-Alves, I., Willmes, K., Haase, V. G. (2014). In how many ways is the approximate number system associated with exact calculation? *PLoS One*, 19, 9(11), e111155.

Carvalho, M. R., Vianna, G., Oliveira, L., Costa, A. J., **Pinheiro-Chagas, P.**, Sturzenecker, R., Zen, P. R., Rosa, R. F., de Aguiar, M. J., Haase, V. G. (2014). Are 22q11.2 distal deletions associated with math difficulties? *American Journal of Medical Genetics Part A*, 164A(9), 2256-62.

Haase, V. G., Júlio-Costa, A., Lopes-Silva, J. B., Starling-Alves, I., Antunes, A. M., **Pinheiro-Chagas, P.**, Wood, G. (2014). Contributions from specific and general factors to unique deficits: two cases of mathematics learning difficulties. *Frontiers in Psychology*, 13, 5-102.

Moura, R., Wood, G., **Pinheiro-Chagas, P.**, Lonnemann, J., Krinzinger, H., Willmes, K., Haase, V. G. (2013). Transcoding abilities in typical and atypical mathematics achievers: the role of working memory and procedural and lexical competencies. *Journal of Experimental Child Psychology*, 116(3), 707-27

* The authors equally contributed to the work

TrajTracker: track it to crack it

Platform for trajectory tracking experiments & data analysis

Home

Experiment

Paradigms

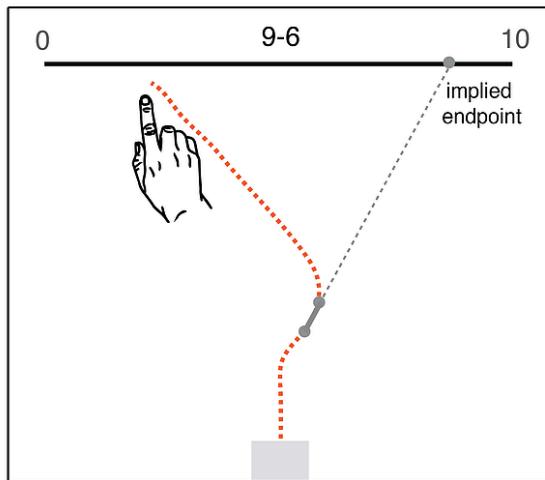
Analyze

About

TrajTracker Experiment 1.0 (beta version) is now released!

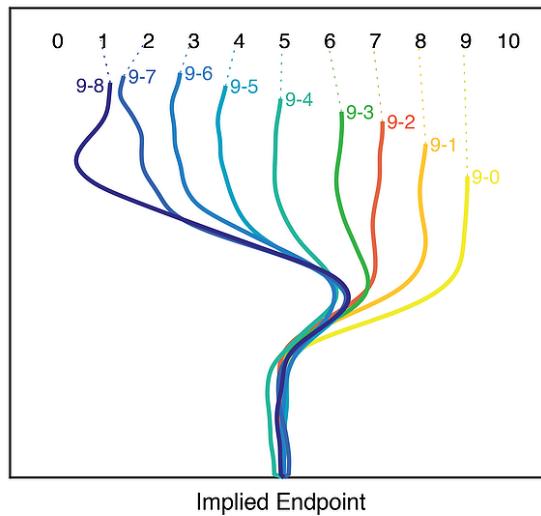
Android support will be available with the next release of [Expyriment](#) for Android.

Number-to-position mapping



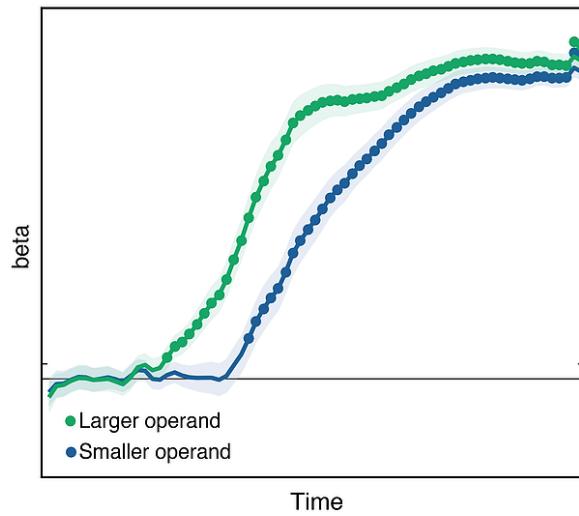
Point to the correct result on the number line

Averaged trajectories



Implied Endpoint

Time-resolved multiple regression



Time

tracking mental calculation online



TrajTracker is a software package for running and analyzing psychology experiments, focused on mouse/finger tracking experiments. New to trajectory tracking? Read about it [here](#).



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BETTENCOURT
SCHUELLER
FOUNDATION



Stan Dehaene
Collège de France; NeuroSpin



Manuela Piazza
University of Trento



Dror Dotan
Tel Aviv University



Amy Daitch
Stanford University



Josef Parvizi
Stanford University

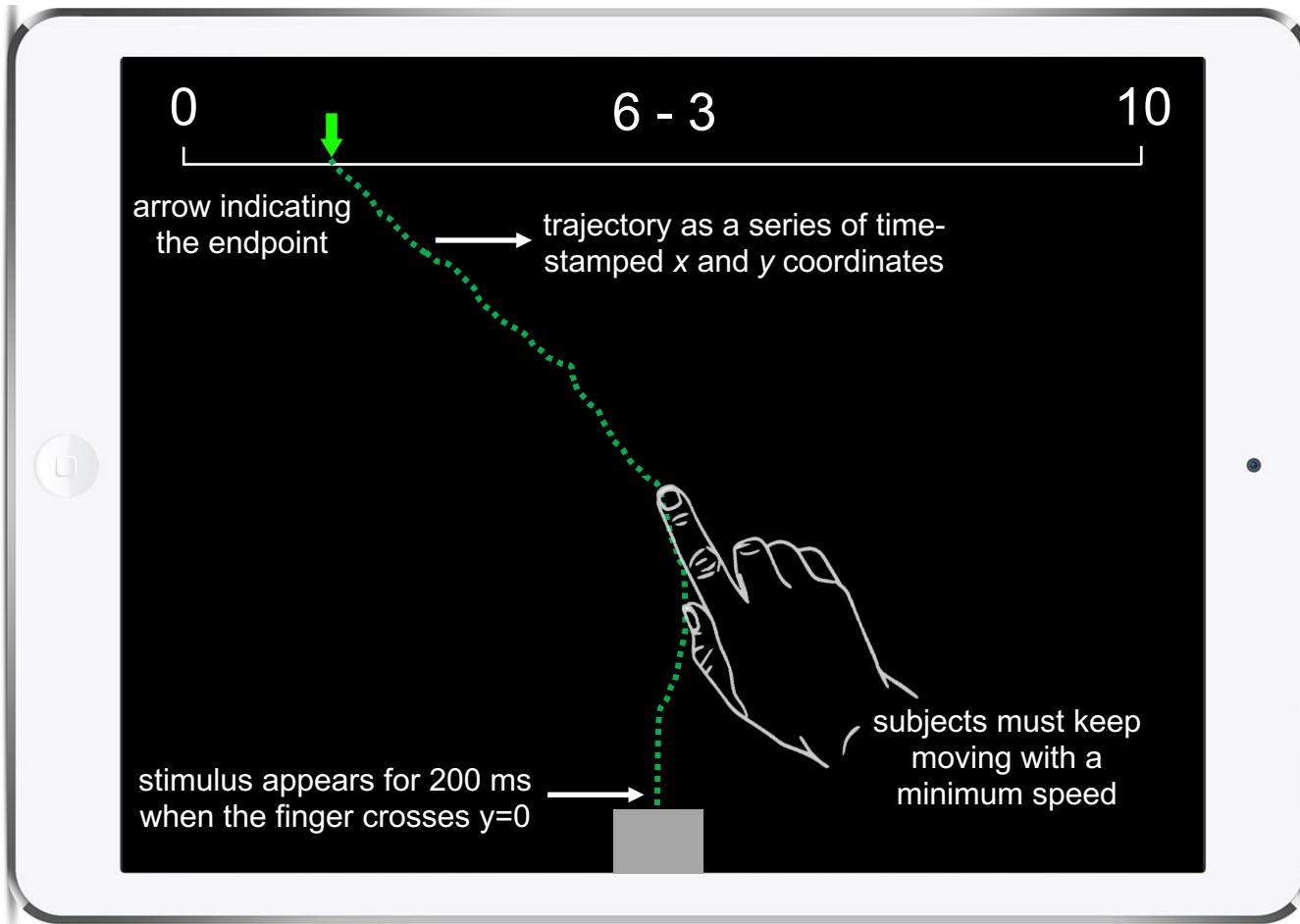


Supplementary Slides

Distribution of calculations iPad

Experimental Setup

30 adults, students, right-handed

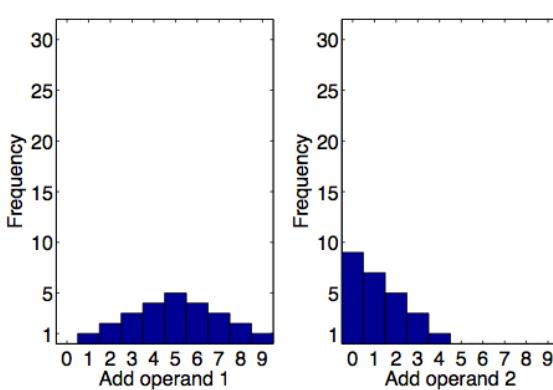


Block1 – Matched Operands
All problems $x+y$ and $x-y$
with results between 1:9

Block2 – Matched Results
All results 1:9 are equally likely
for both addition and subtraction

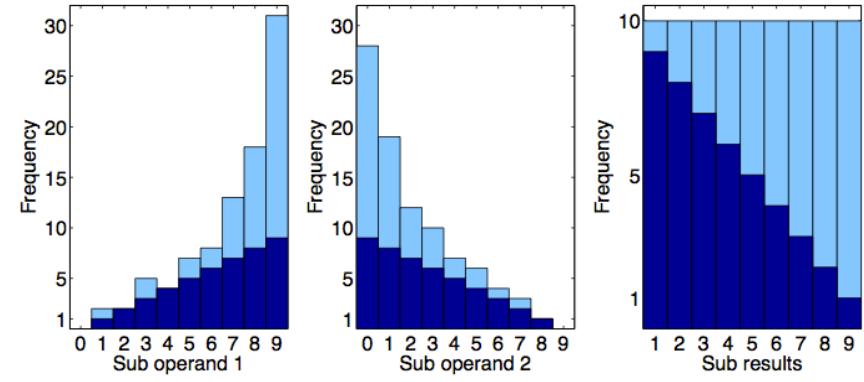
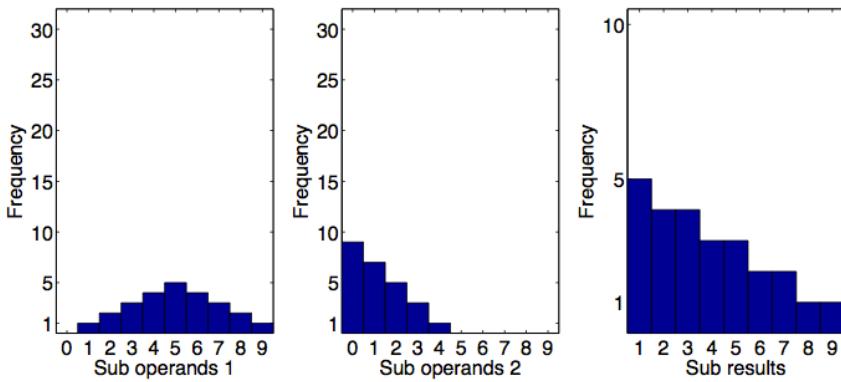
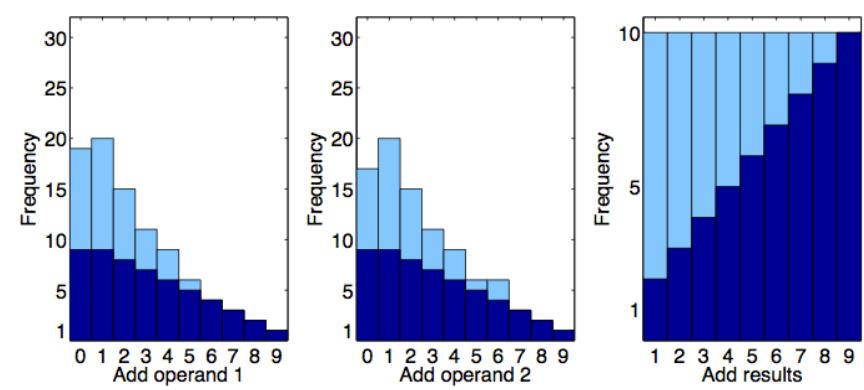
List of stimuli for the experiment

Block1 – Matched Operands



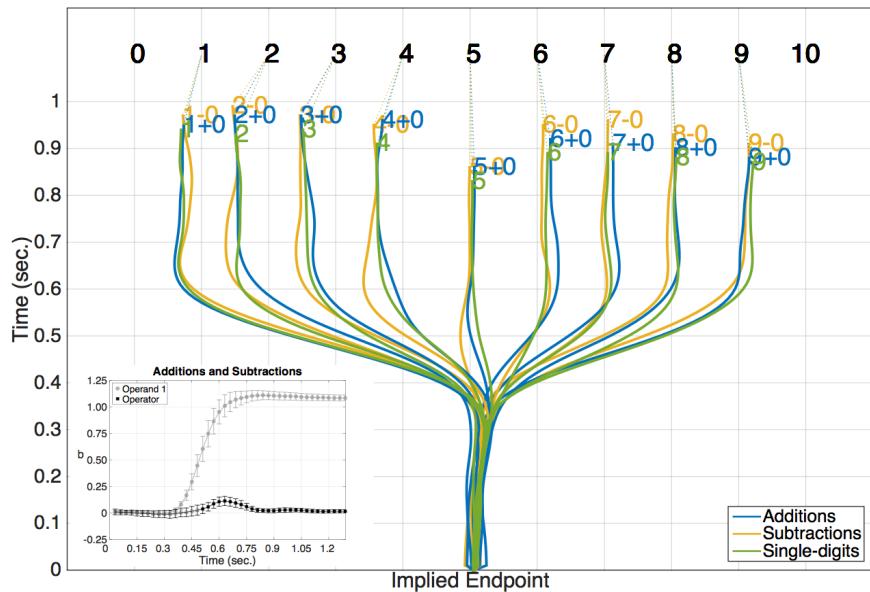
Block2 – Matched Results

Distributions of operands and results

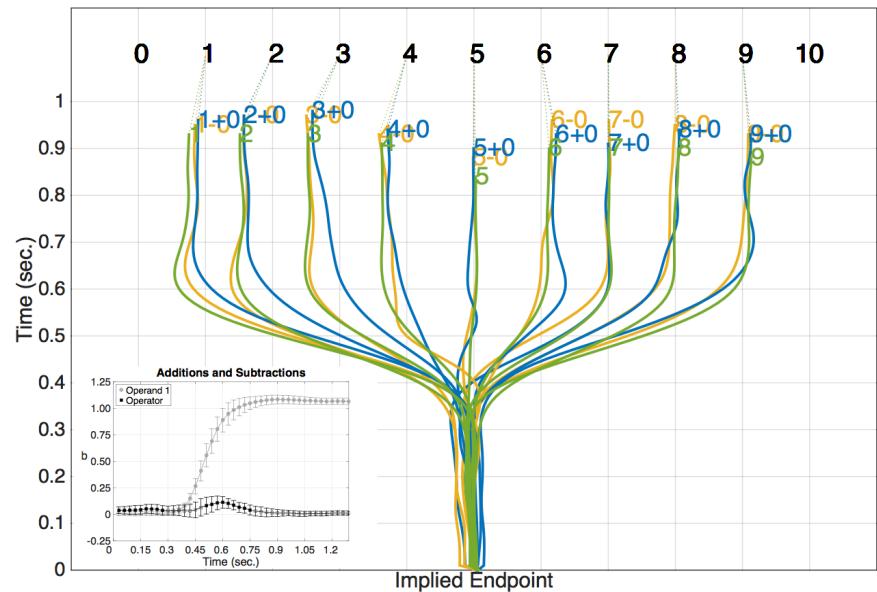


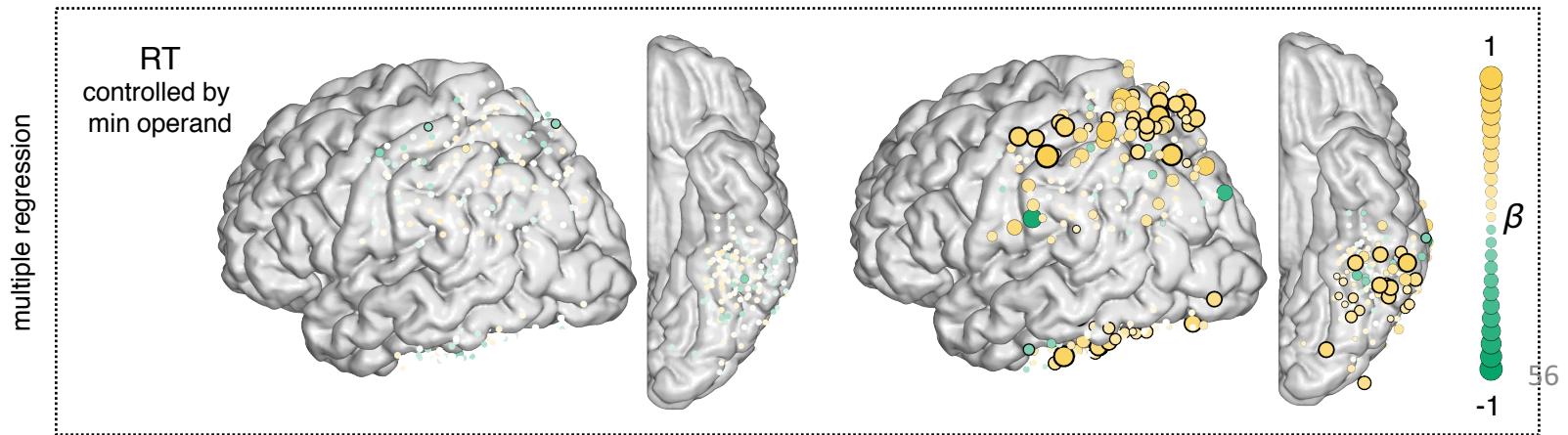
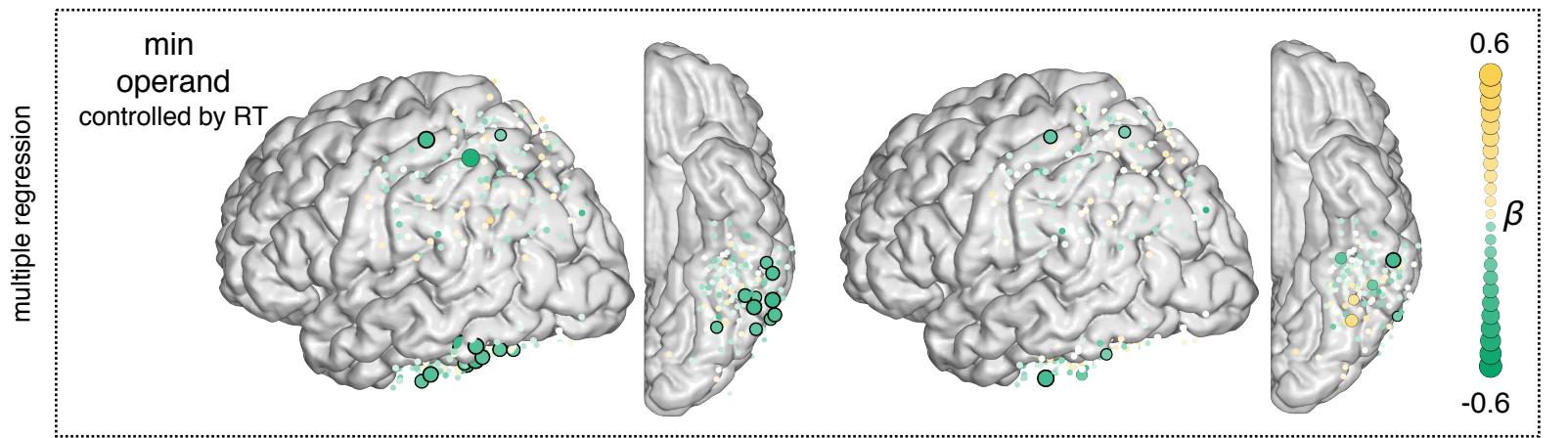
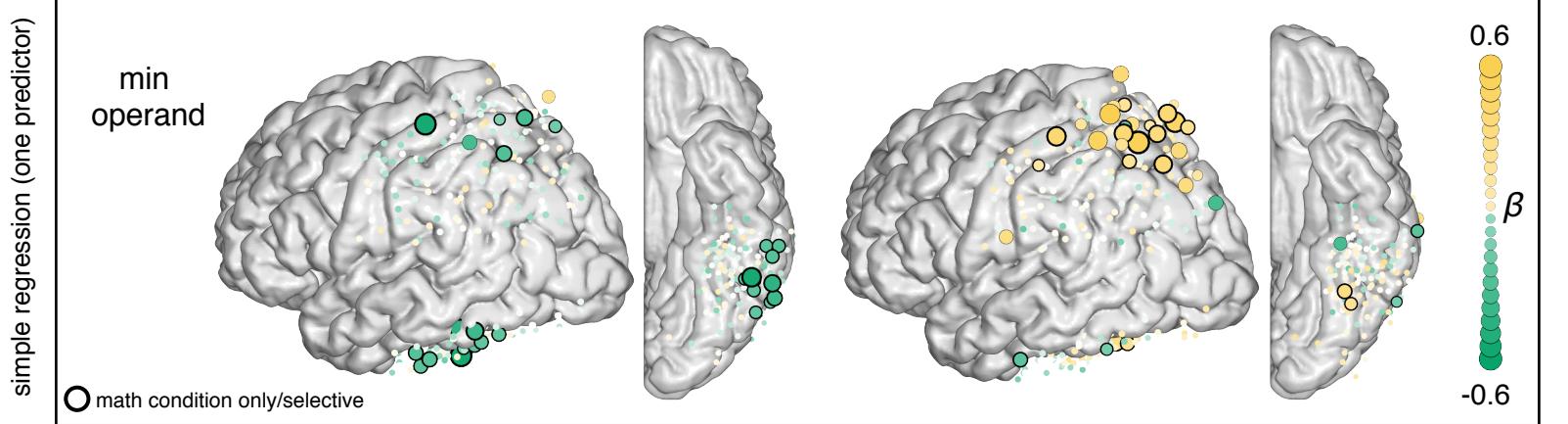
OM in zero problems

Block 1 – Matched Operands

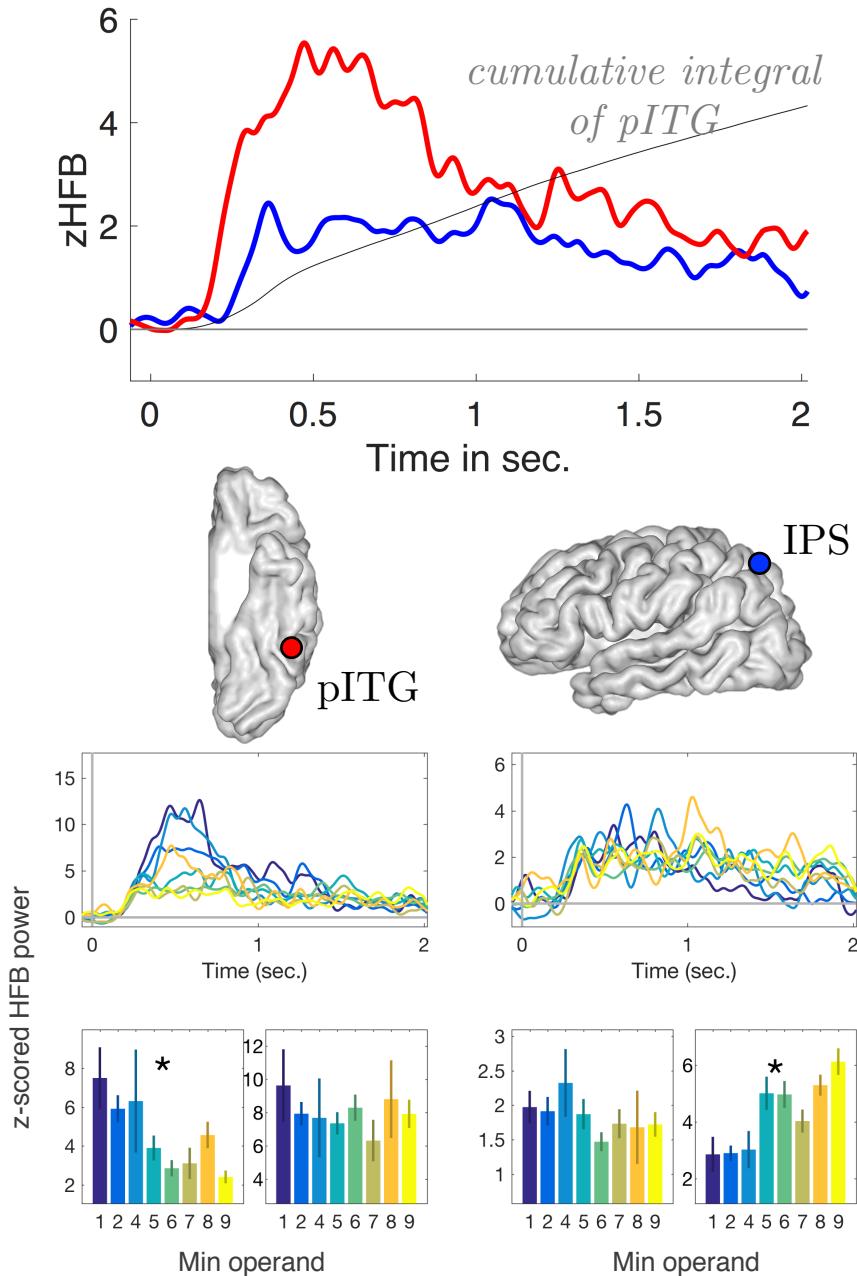


Block 2 – Matched Results

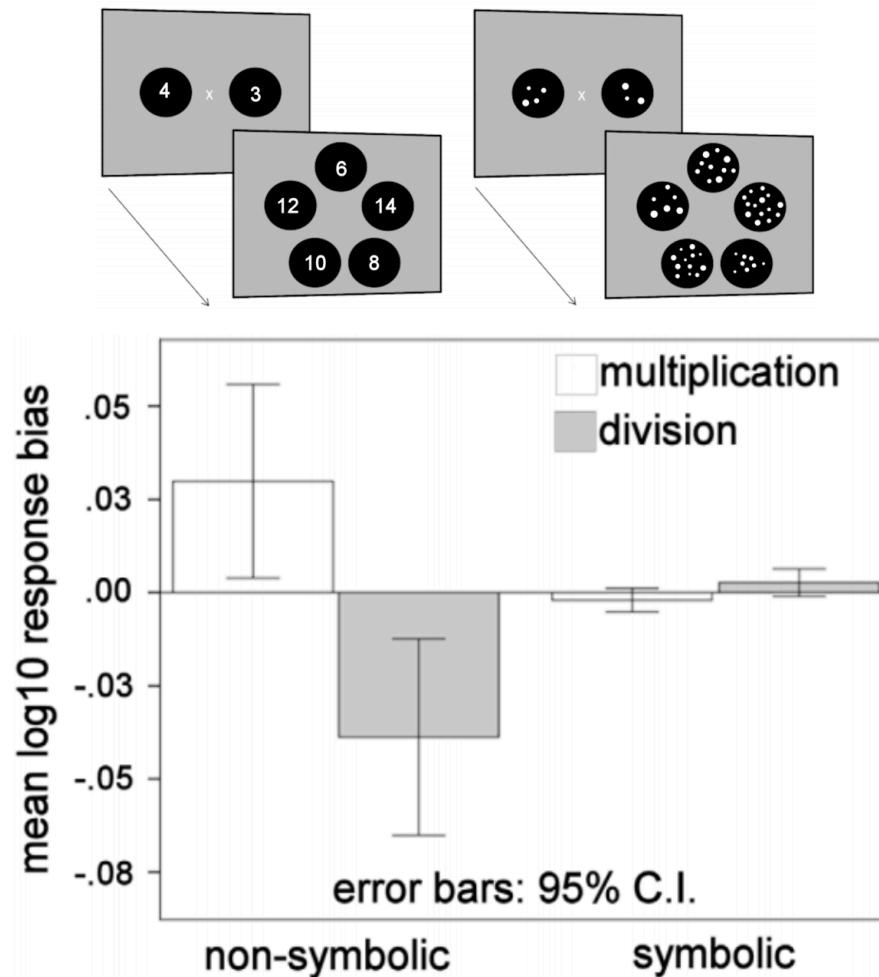




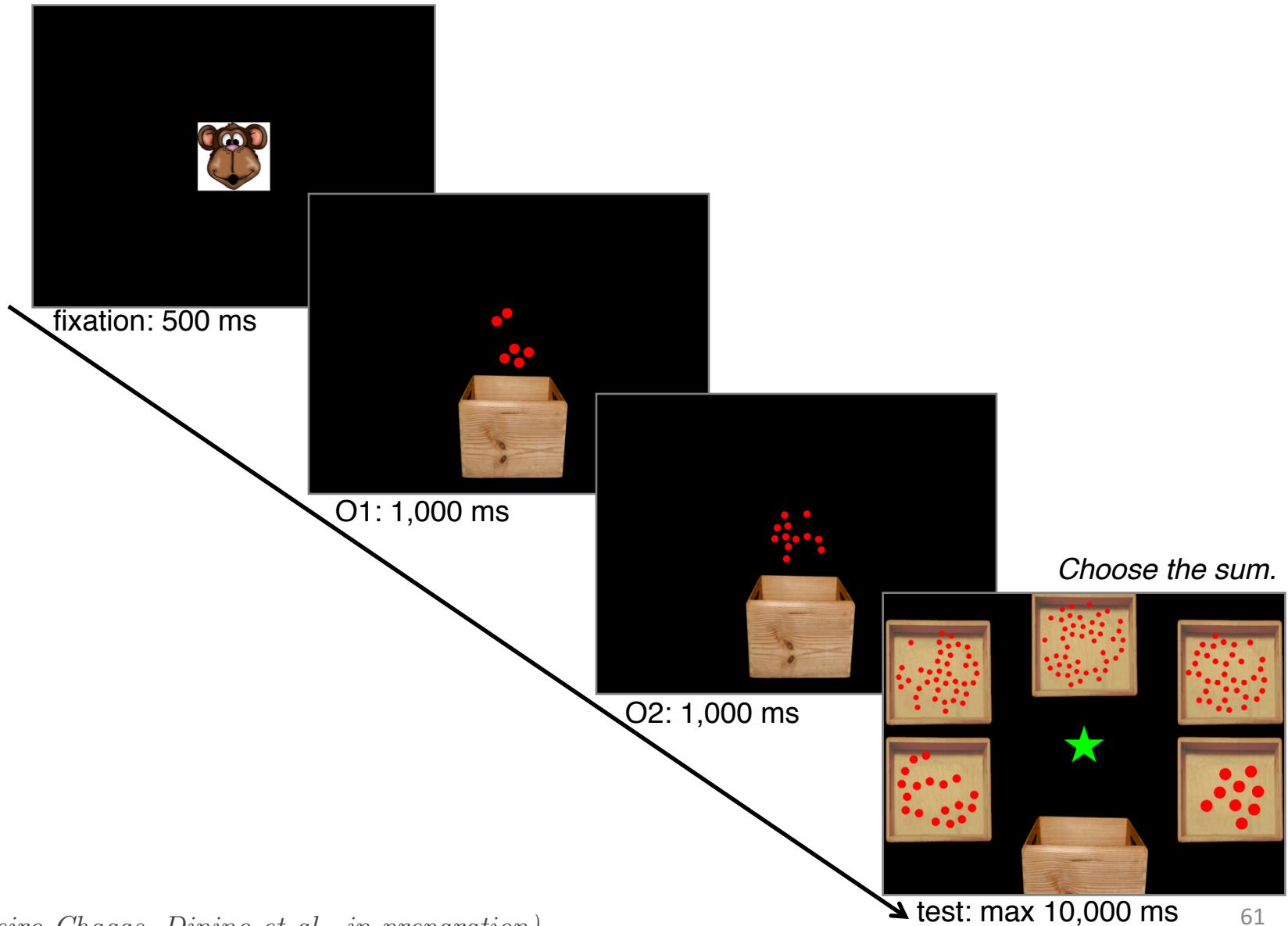
Relationship between decrease initial in pITG and increased total in IPS



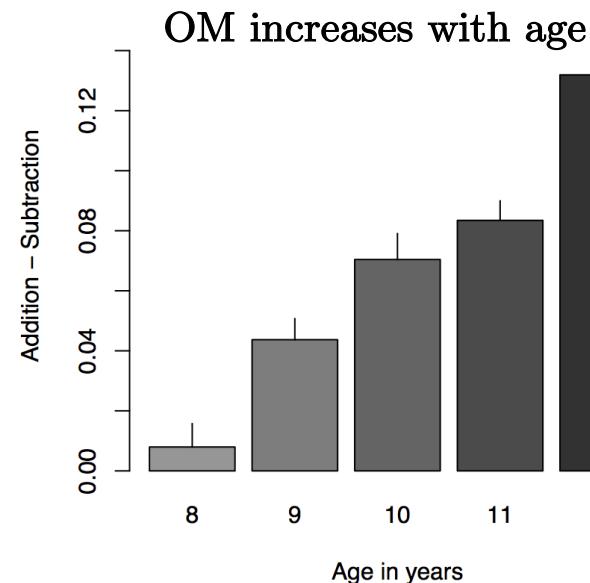
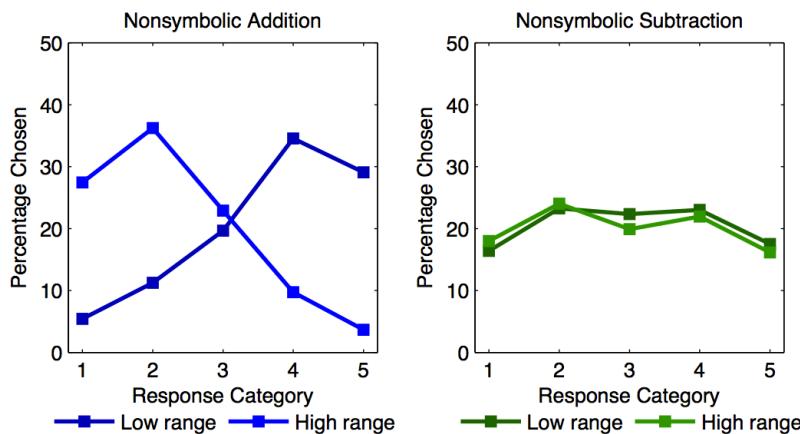
OM multiplication and division: only in non-symbolic notation



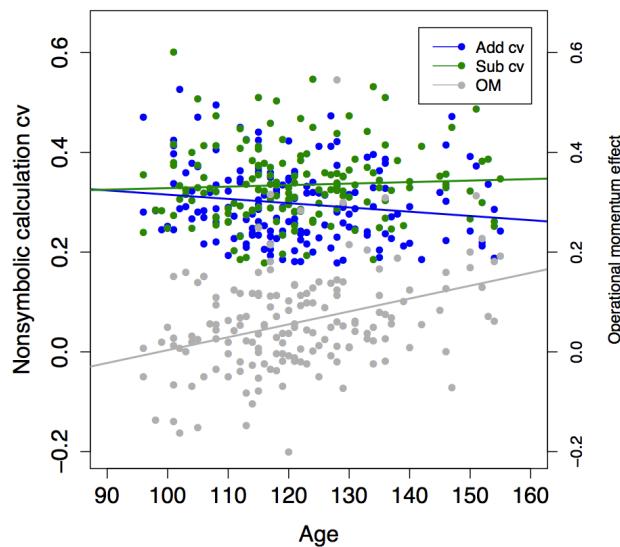
Development of the OM effect – Experimental Design



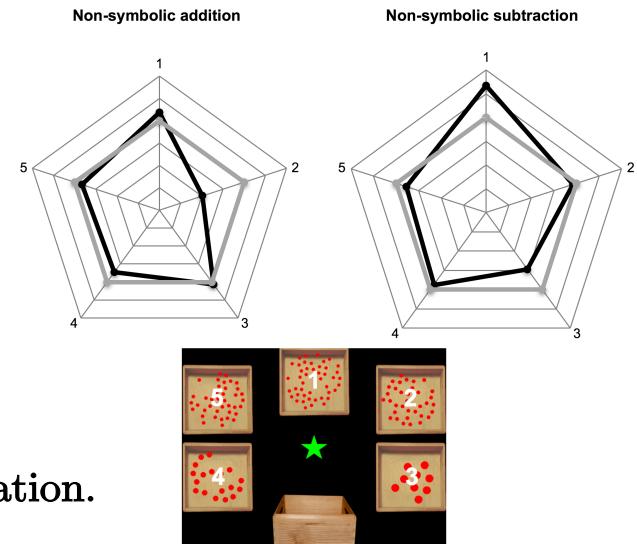
Development of the OM effect



Not a by-product of decrease in accuracy



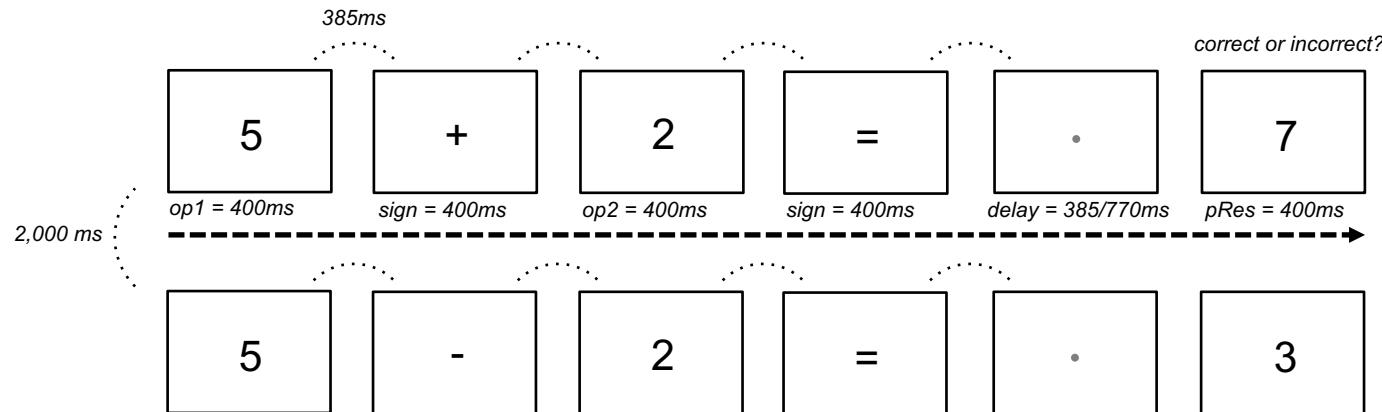
Dissociates from SOAR in children



- Does not correlate with non-symbolic comparison and estimation.

Calculation verification task - Experimental Design

20 adults, students, right-handed



Factors

OP1 = 3, 4, 5, 6

OP2 = 0, 1, 2, 3

Result correct = correct 0:9

pRes incorrect = distance from correct 1, 2, 3, 4

(no results that could be correct if the other operation)

Operation = addition, subtraction

Delay from last '=' sign = 385 or 770 ms

Event duration = 400 ms

ISI: 385 ms

ITI = 2,000 ms

Trials

160 additions

160 subtractions

10 blocks of 32 trials each

Experiment duration = ~40 min

Stimuli list

$3 + 0 = 3$

$3 + 1 = 4$

$3 + 2 = 5$

$3 + 3 = 6$

$4 + 0 = 4$

$4 + 1 = 5$

$4 + 2 = 6$

$4 + 3 = 7$

$5 + 0 = 5$

$5 + 1 = 6$

$5 + 2 = 7$

$5 + 3 = 8$

$6 + 0 = 6$

$6 + 1 = 7$

$6 + 2 = 8$

$6 + 3 = 9$

$3 - 0 = 3$

$3 - 1 = 2$

$3 - 2 = 1$

$3 - 3 = 0$

$4 - 0 = 4$

$4 - 1 = 3$

$4 - 2 = 2$

$4 - 3 = 1$

$5 - 0 = 5$

$5 - 1 = 4$

$5 - 2 = 3$

$5 - 3 = 2$

$6 - 0 = 6$

$6 - 1 = 5$

$6 - 2 = 4$

$6 - 3 = 3$

Frequency of operand 1

Value	Count	Percent
3	80	25.00%
4	80	25.00%
5	80	25.00%
6	80	25.00%

Frequency of operand 2

Value	Count	Percent
0	80	25.00%
1	80	25.00%
2	80	25.00%
3	80	25.00%

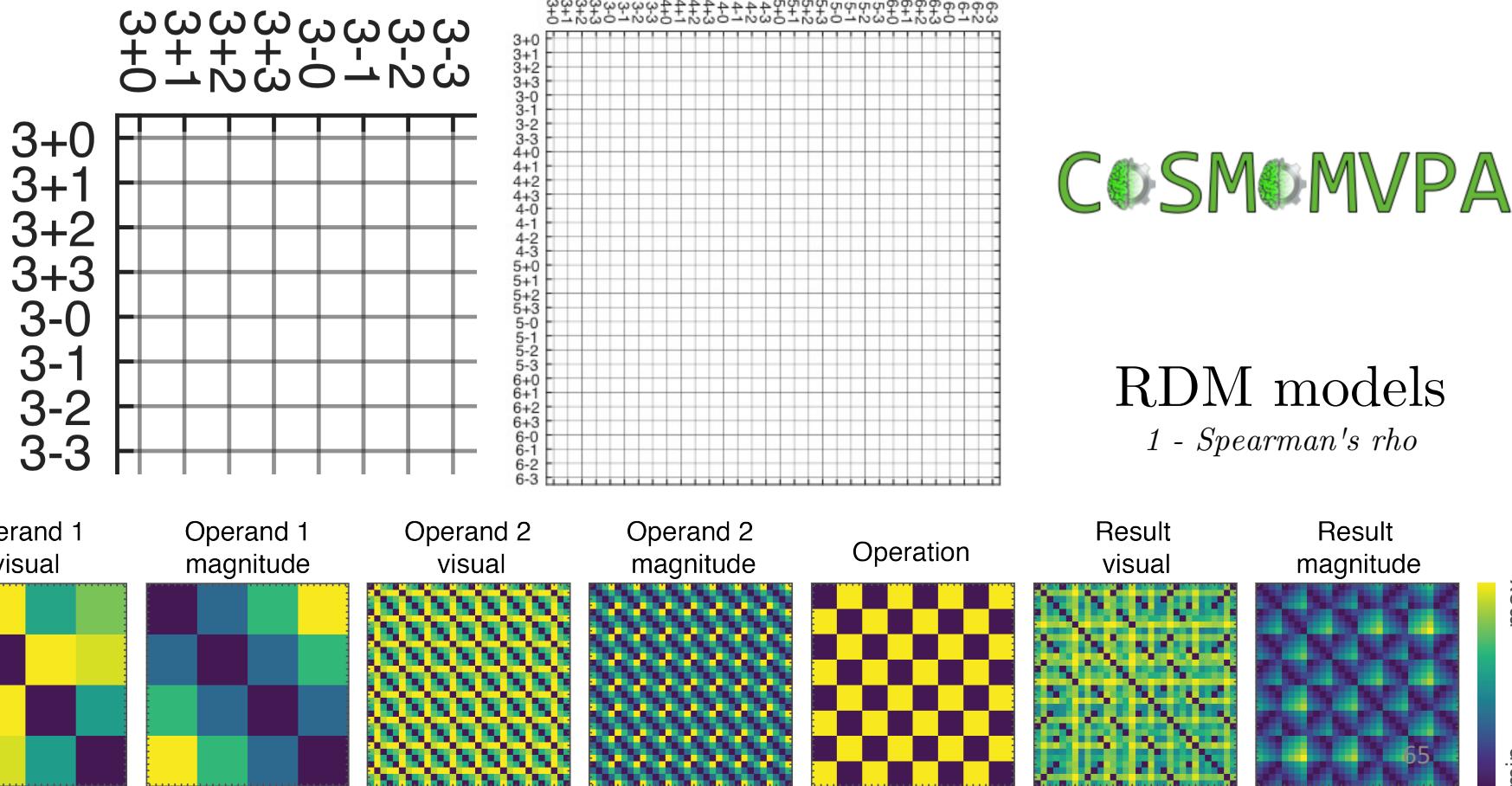
Frequency of results add and sub together

Value	Count	Percent
0	10	3.12%
1	20	6.25%
2	30	9.38%
3	50	15.62%
4	50	15.62%
5	50	15.62%
6	50	15.62%
7	30	9.38%
8	20	6.25%
9	10	3.12%

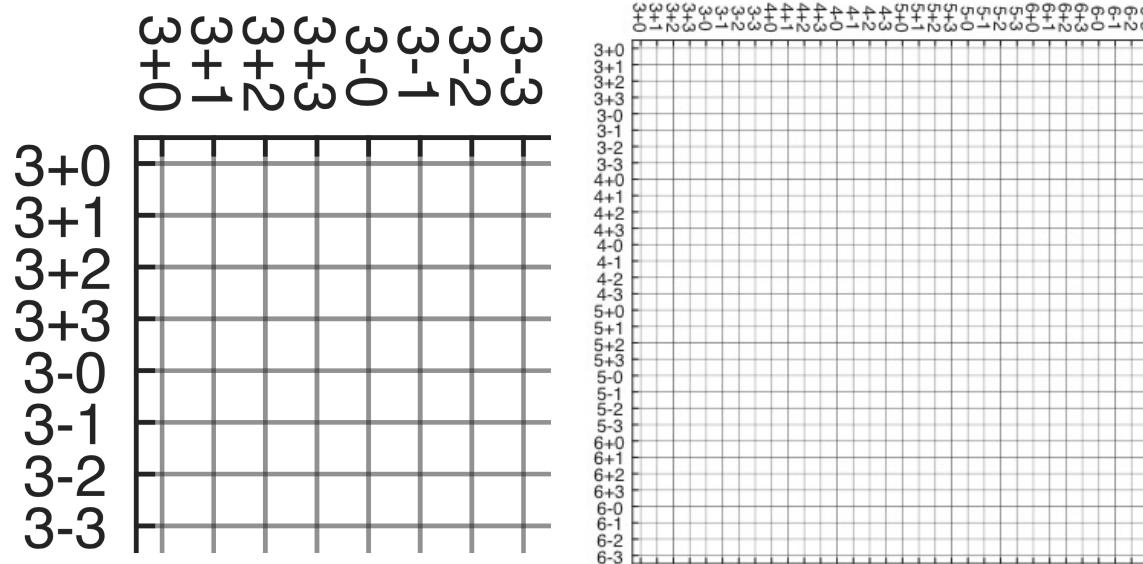
Representational Similarity Analysis (RSA)

1. Calculate a dissimilarity matrix based on the pairwise correlation between experimental conditions across the 306 MEG sensors, per each time sample.
2. Correlate the observed matrix with theoretical dissimilarity matrices derived from the stimuli features. Repeated for each time sample separately.

FIGURE

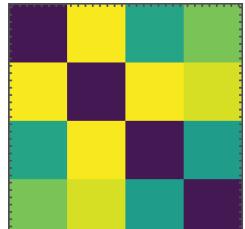


Representational Similarity Analysis (RSA)

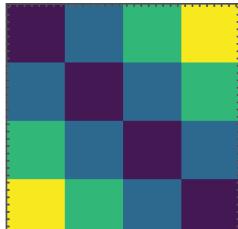


RDM models
1 - Spearman's rho

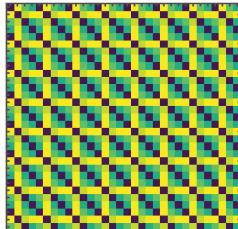
Operand 1
visual



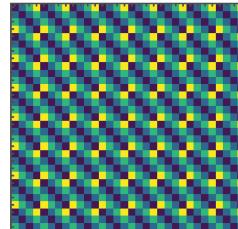
Operand 1
magnitude



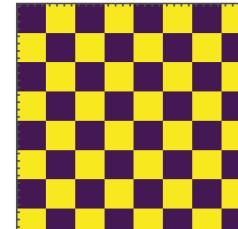
Operand 2
visual



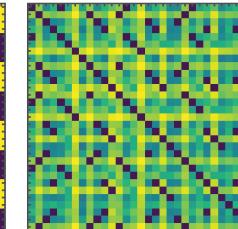
Operand 2
magnitude



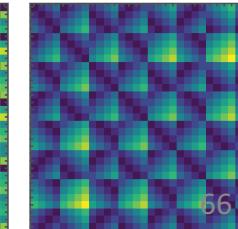
Operation



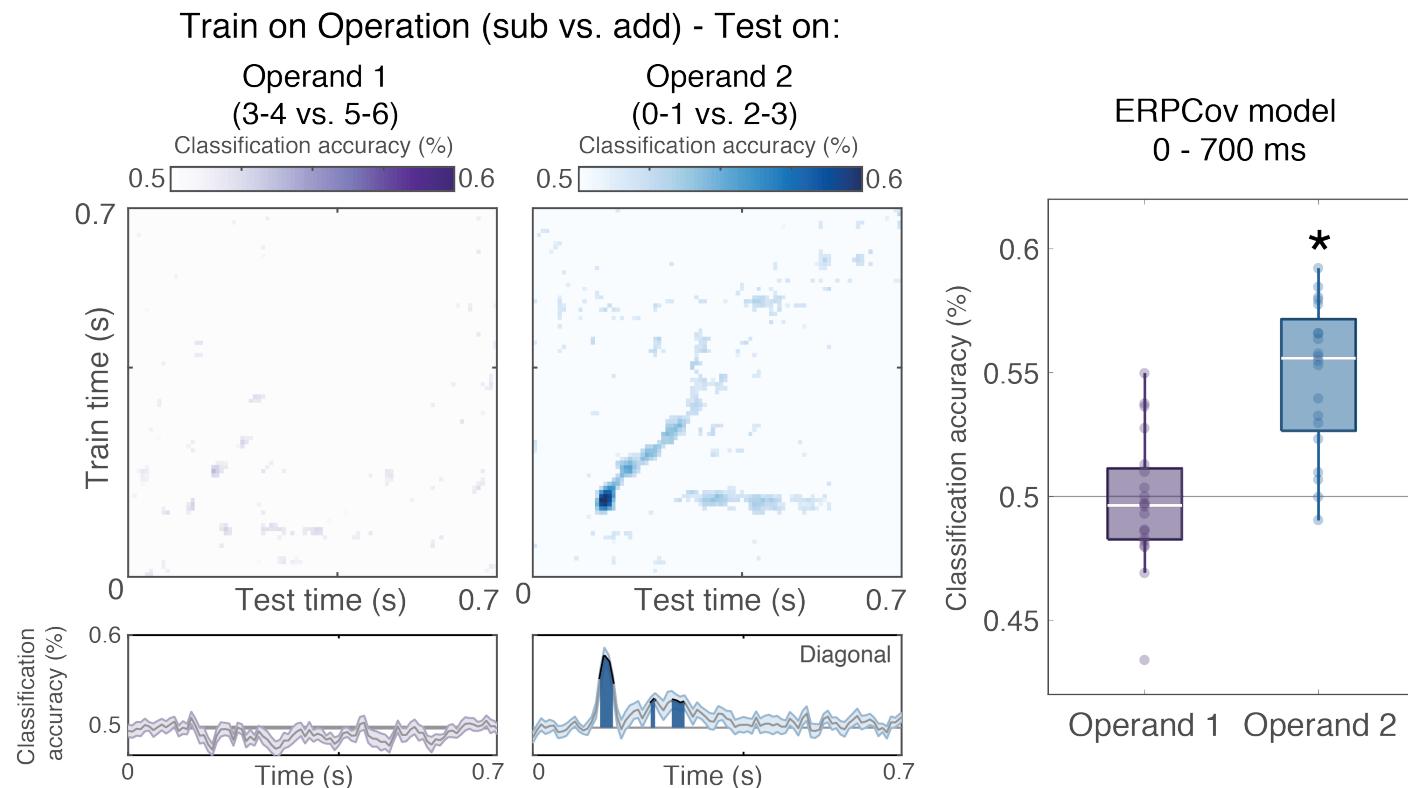
Result
visual



Result
magnitude



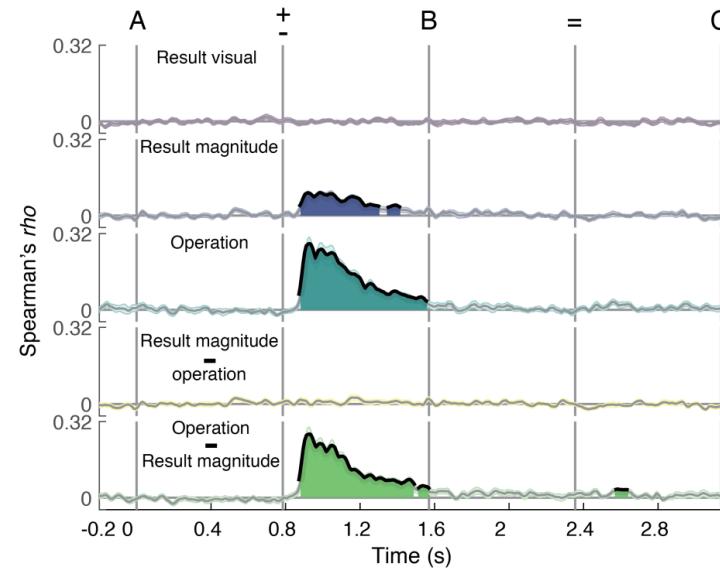
Common code: operation and magnitude of operand 2



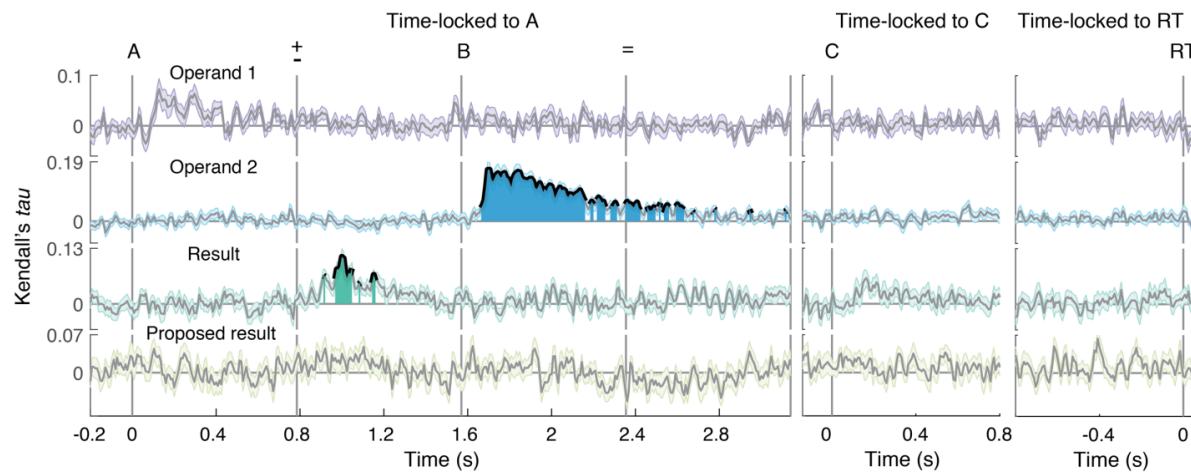
- Subtractions: smaller operand 2 (0-1); Additions: larger operand 2 (2-3)

Searching for a neural signature of the internal result

RSA



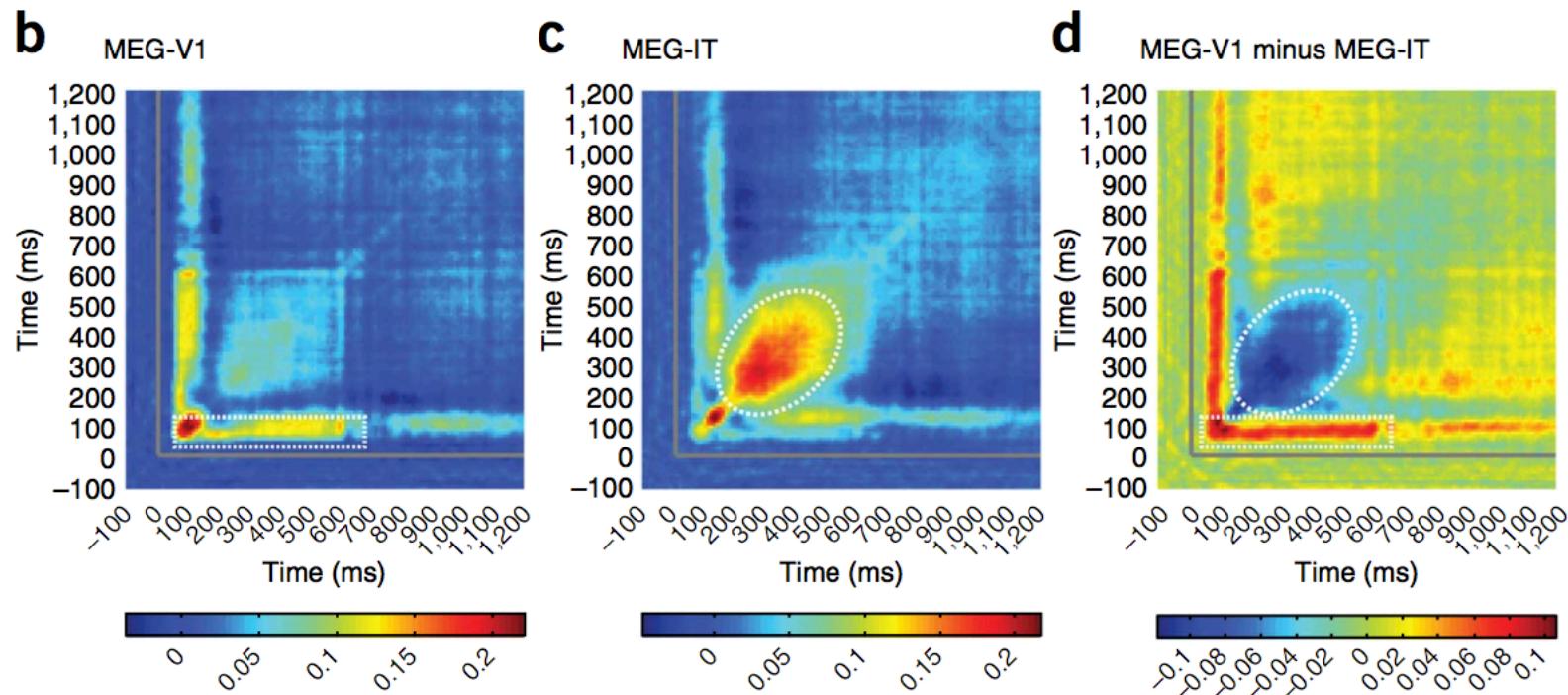
Decoding (regression)



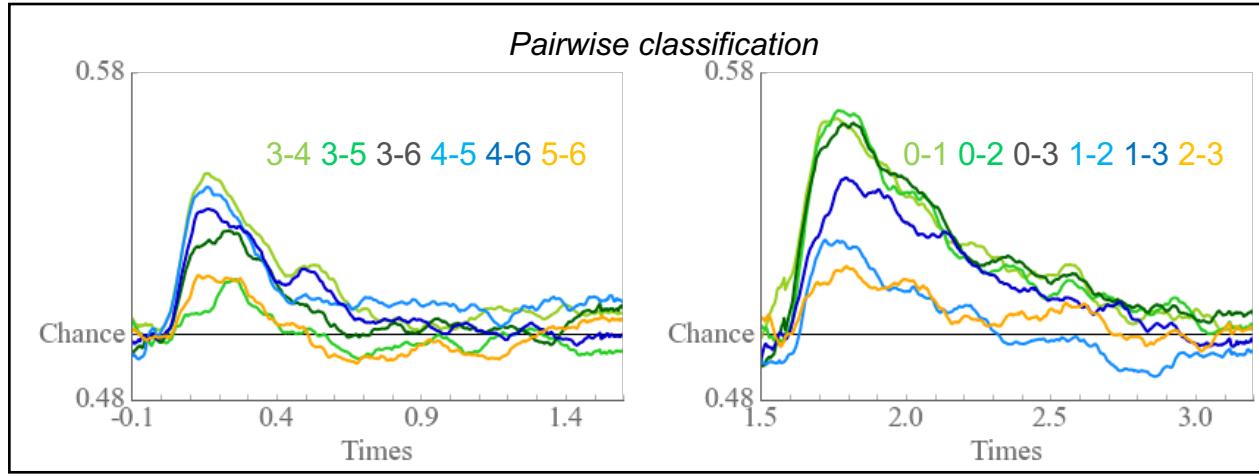
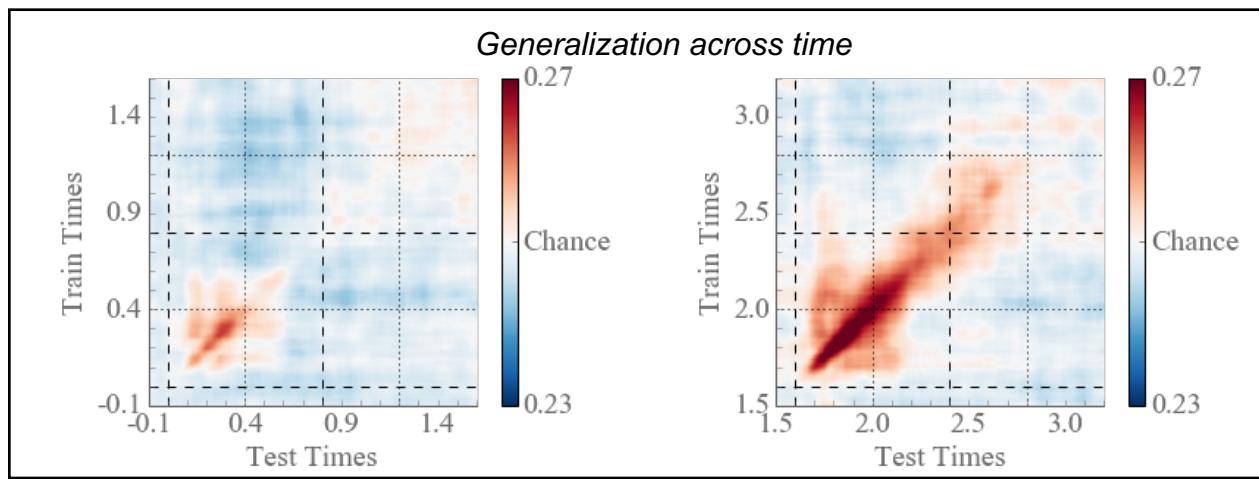
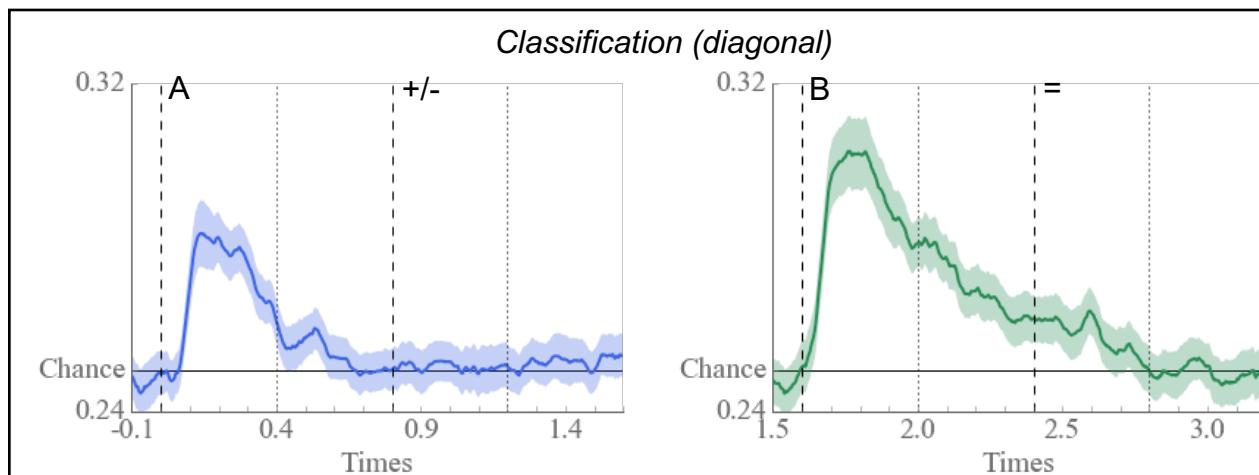
- Transient decoding after sign – overall results correlates with operation

Time-resolved decoding of object with MEG

(Cichy et al., 2014)



- Decoding in V1 is peaked and classifiers converge to the first 100 ms.
- Decoding in IT is much more persistent.



Chapter 5. General Discussion

- Trajectory tracking can dissect the calculation process, revealing the absolute timing of some of the **covert stages**
- Serial processing of the **operands**: larger operand **first** independent of its location. The deviation from the larger operand to the correct result unfolds **serially and proportionally** to the size of the **min operand**
- Transient **OM effect** during the **integration of min**: visuospatial attention system actively engaged during the calculation
- Supports a model whereby **additions** and **subtractions** are computed by a **stepwise displacement on the mental number line**
Compatible with automated procedures and fact retrieval based on a tabular search
- What is the **precise mechanism** of this **serial processing**? Children slower, adults faster. How does learning or procedure automatization happen?
Modelling work with Thomas Hannagan

Chapter 5. General Discussion

- IPS and SPL activity increase with arithmetic **problem-size**: engaged in the calculation mechanism *per se* and might index the accumulation of evidence to achieve a decision
- Surprising role of pITG in mental arithmetic beyond digit recognition: higher activity for smaller/easier problems
Early identification of problem difficulty (semantic evidence?)
- Re-evaluation of neurocognitive models of arithmetic and developmental dyscalculia: pITG as an **important hub for calculation**
- Expands the classical view of the VTC: contains regions specifically involved in **sophisticated symbolic forms of reasoning**, such as mental arithmetic
- Does pITG process magnitude? How do pITG and IPS interact? Does IPS integrates the activity of pITG? Is this process controlled by PFC? What is the role of subcortical structures? *Postdoc directions with Josef Parvizi*

Chapter 5. General Discussion

- Time resolved MPVA applied to MEG: first comprehensive picture of the unfolding processing stages underlying calculation at a single-trial level
- Decoding of **operand 1**: **visual dimension**; **operand 2**: visual and **magnitude** dimensions; Possibly sharing a common code with operation type? Ultimately grounded in a basic mechanism of the orienting of spatial attention?
- Fast and highly overlapping dynamics at the decision stage
- Where, how and when is the internal result computed?
 - Internally generated code: '*silent states*', rare gamma bursts, sparse code?
Hard to capture with MEG
- New experiments with iEEG - *Stanford-Unicog* collaboration
- Beyond numbers: the **syntactic structure** of **arithmetic** expressions (*with Dror*)

Questions

Can the + sign as fixation explain the transient processing of the absolute value of the smaller operand in subtractions?