fMRI在數學認知研究的應用

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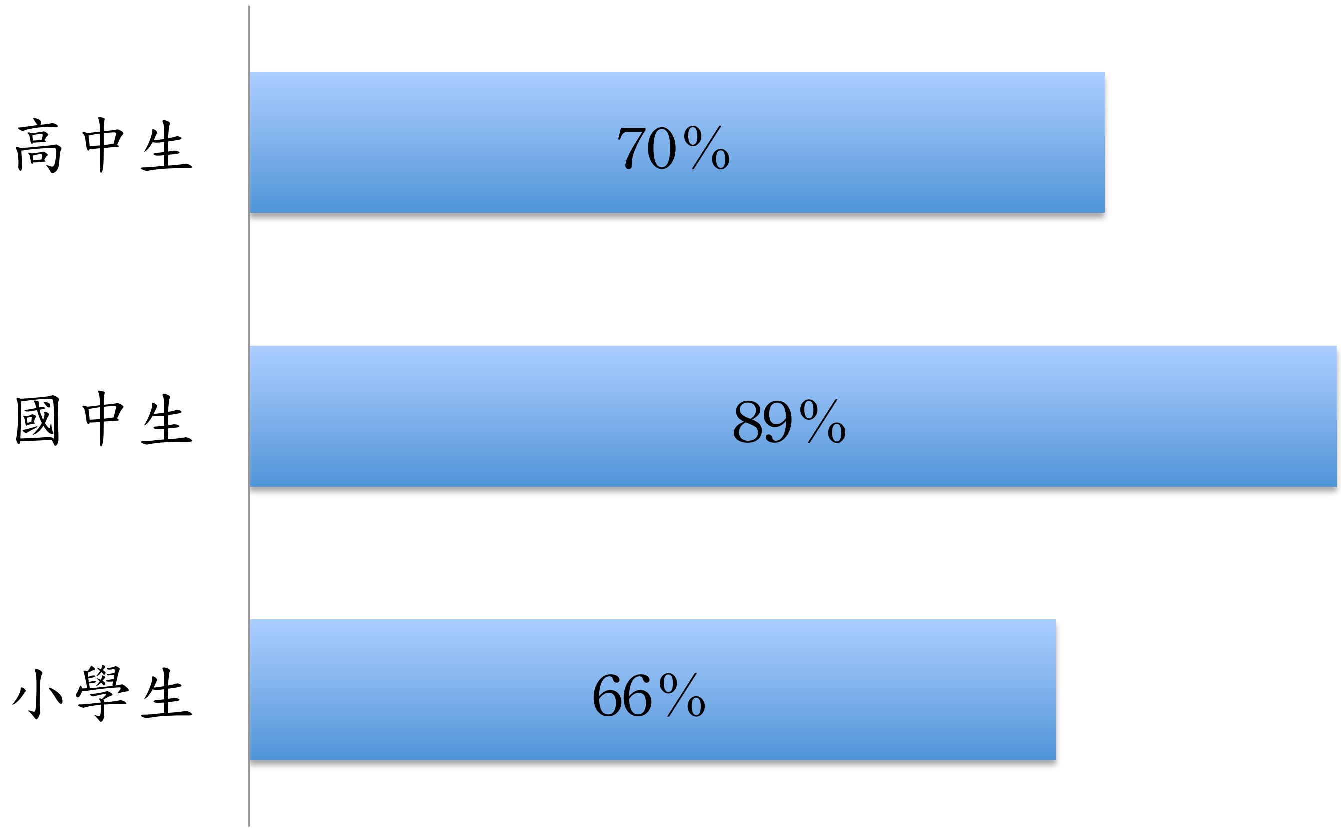
Why study mathematical cognition?

- Quantitative reasoning in everyday life
- Early math skills strong predictor of educational achievement (Duncan et al., 2007)
- Some children & adults present with 'Developmental Dyscalculia'

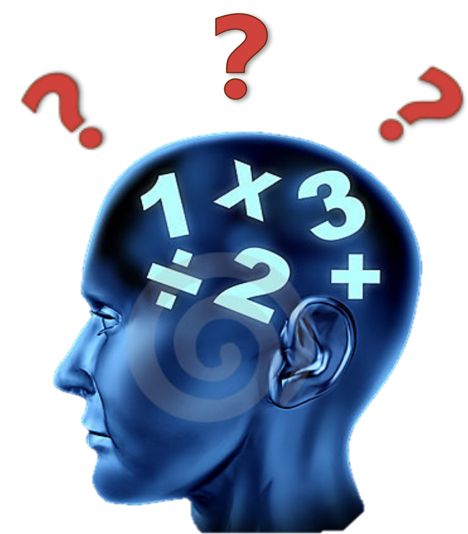
中小學生補習數學者佔補習人口比例



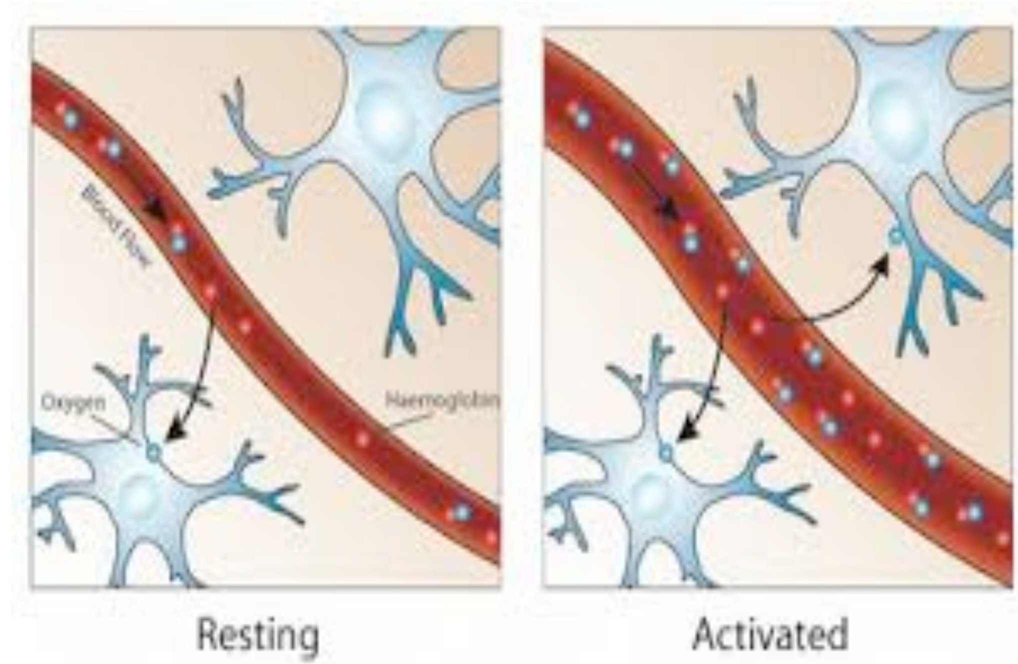
(張雅俐, 2011; 林宜慧, 2007;
許綺婷, 2001; 徐政業, 2008）

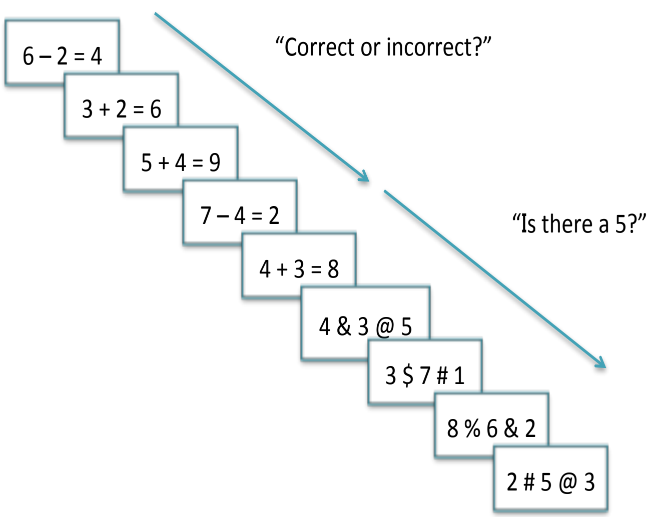
Three interrelated questions

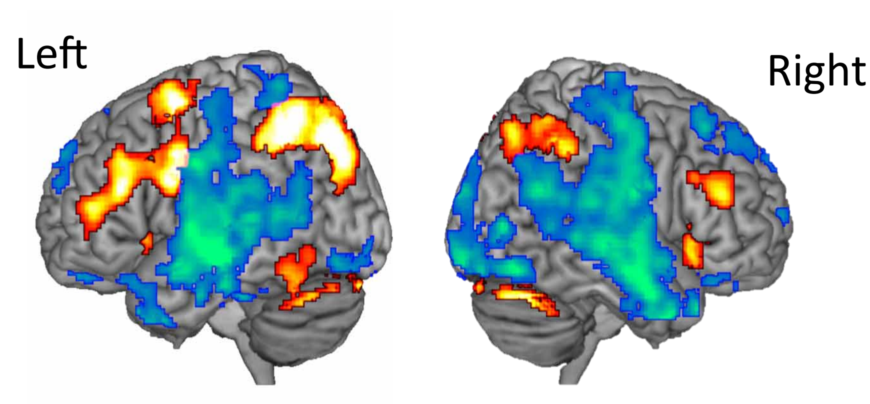
- How is mental arithmetic stored and processed in the brain?
- How does the neural network of mental arithmetic processing develop with learning and experience?
- How does atypical developing arithmetic skills represented in the brain?

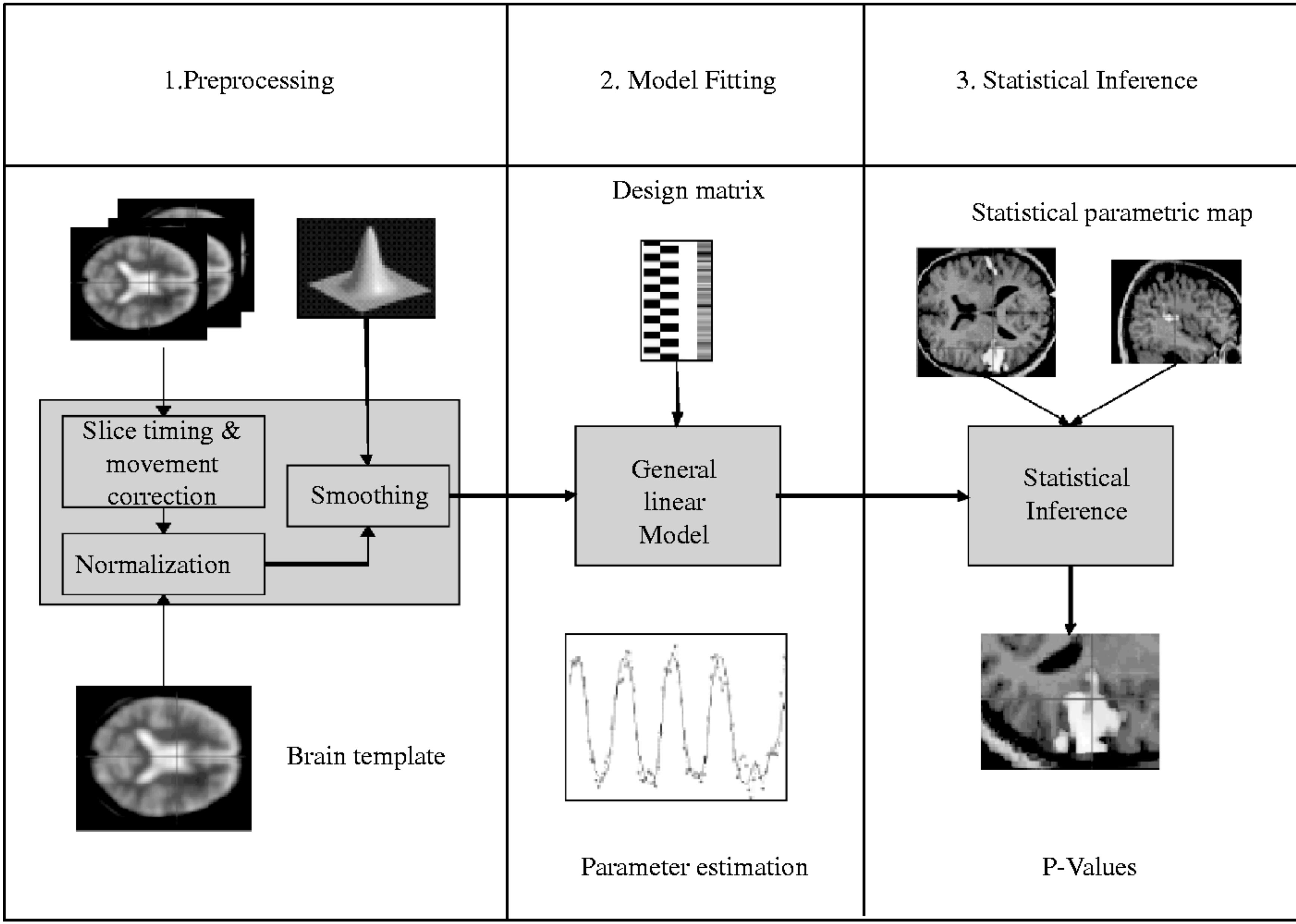


functional Magnetic Resonance Imaging (fMRI)





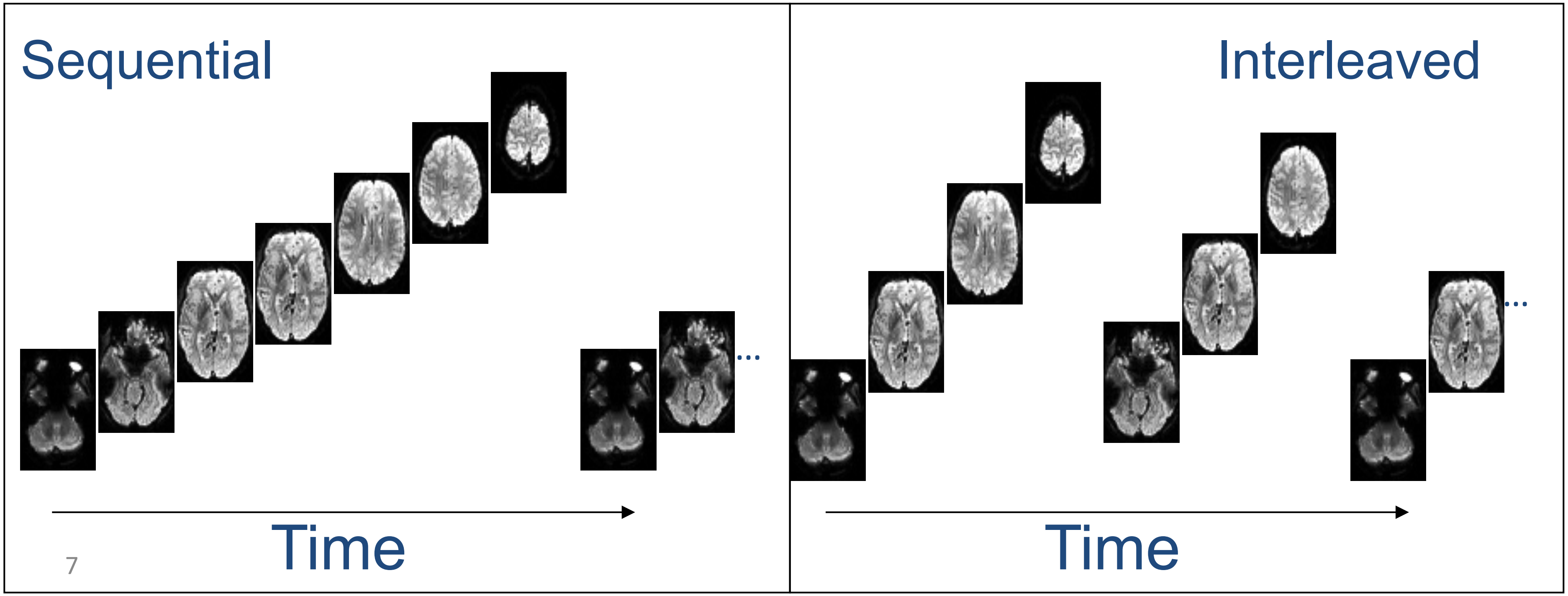




Source: Frackowiak *et al.* (2004)

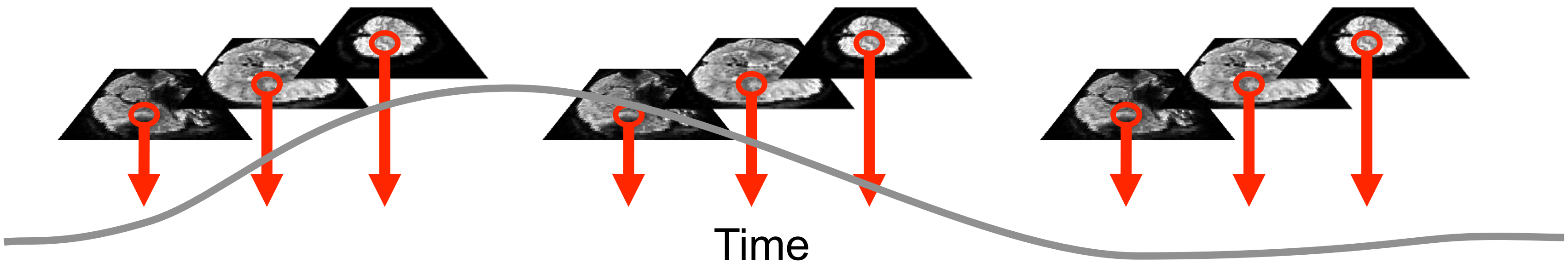
Creating 3D volumes from 2D EPI

- Slices can be either collected sequentially or interleaved order.

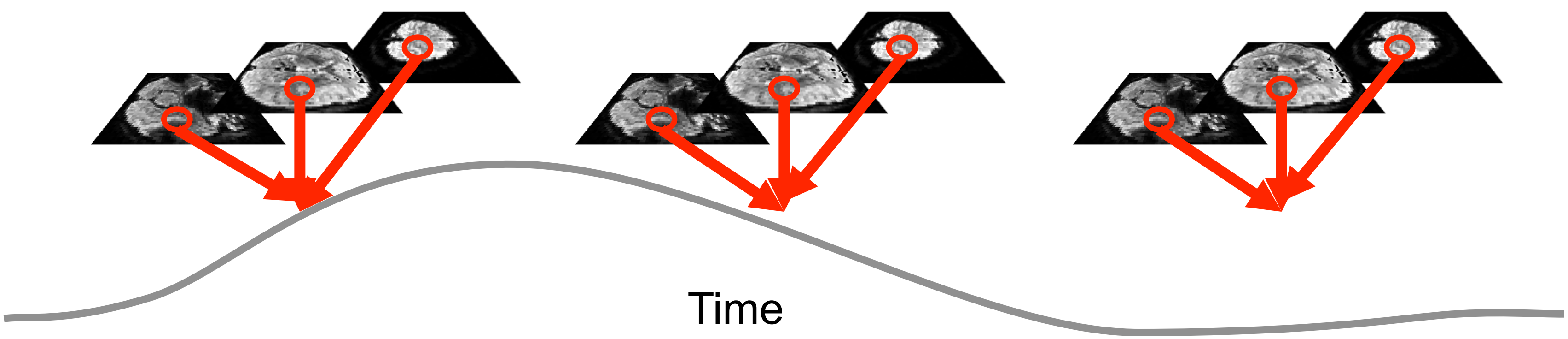


Slice timing

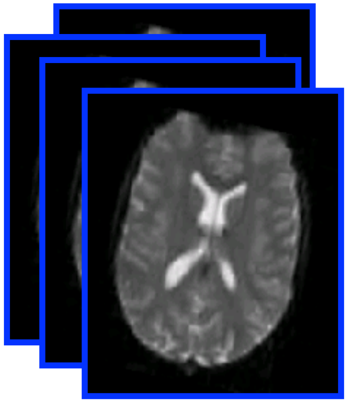
- Consider 3D volumes collected as ascending axial slices
  - For each volume, we see inferior slices before superior slices



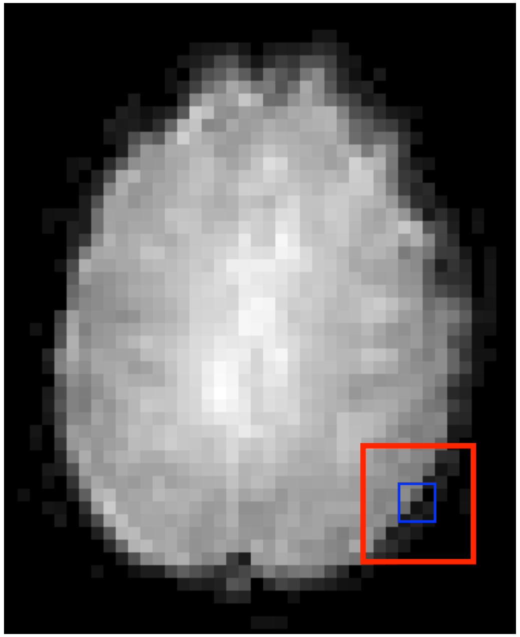
Statistics assume all slices are seen simultaneously…



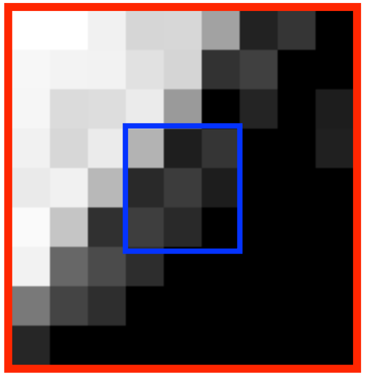
Head movement



A

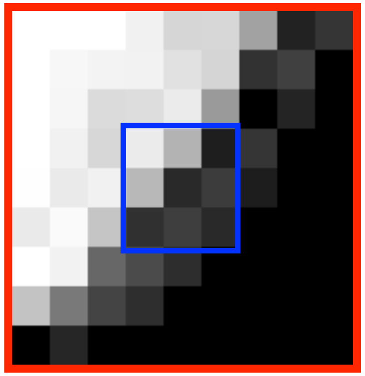


B



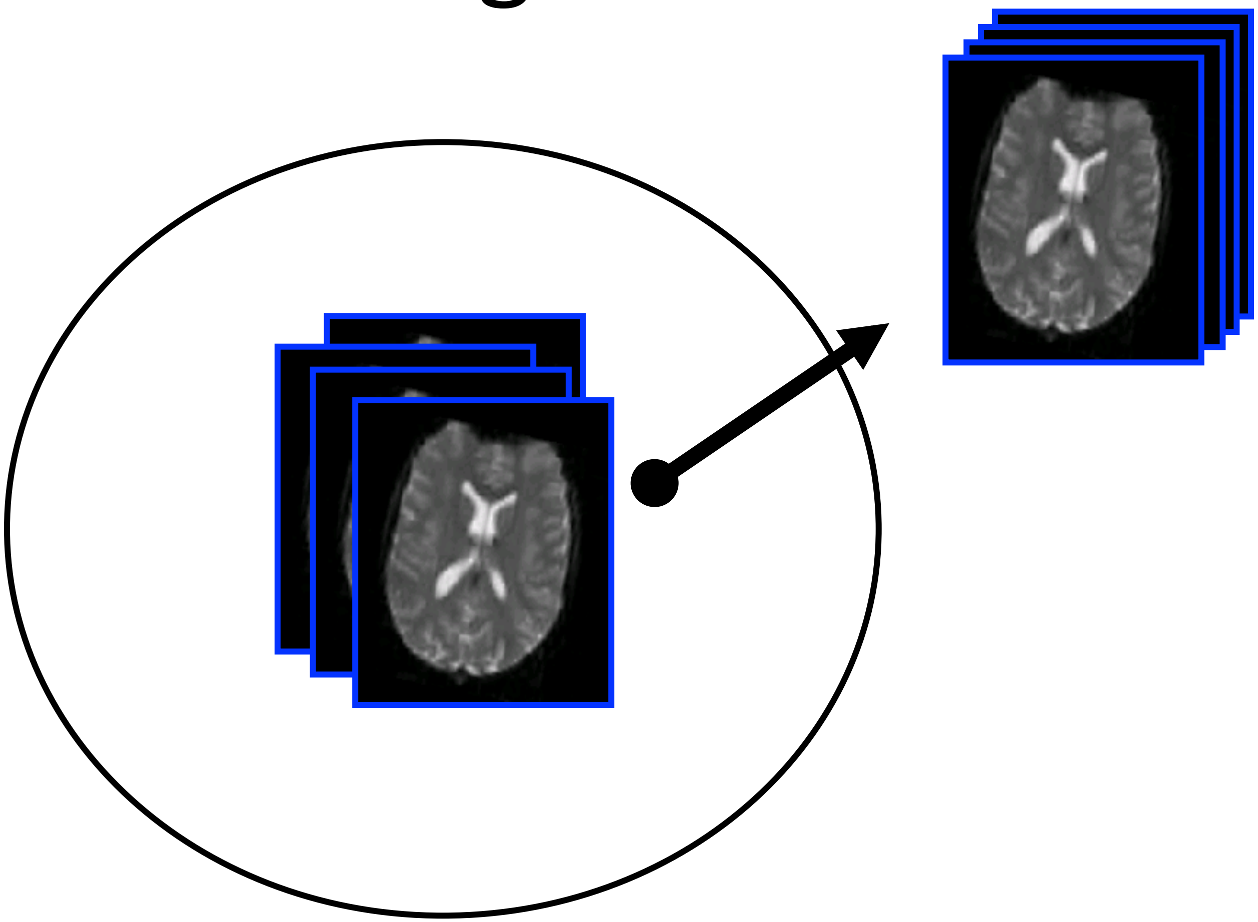
507	89	154
119	171	83
179	117	53

C

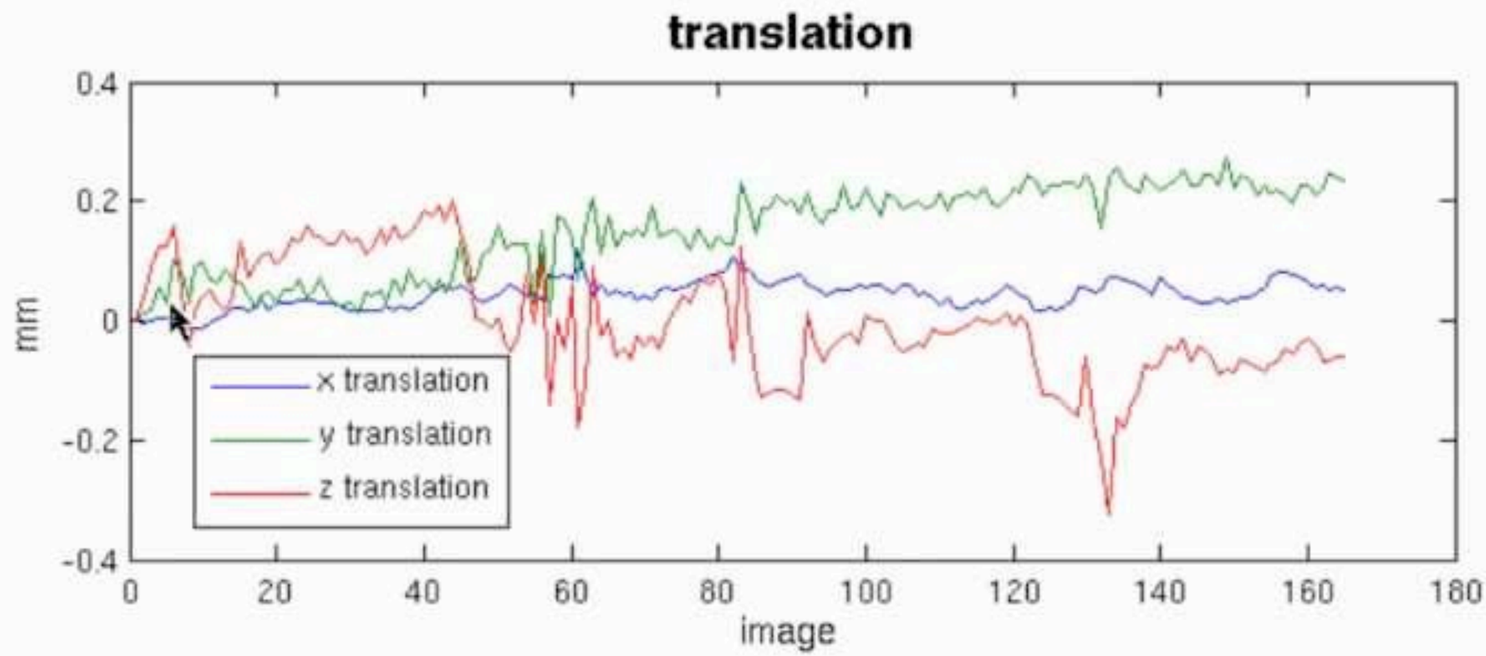


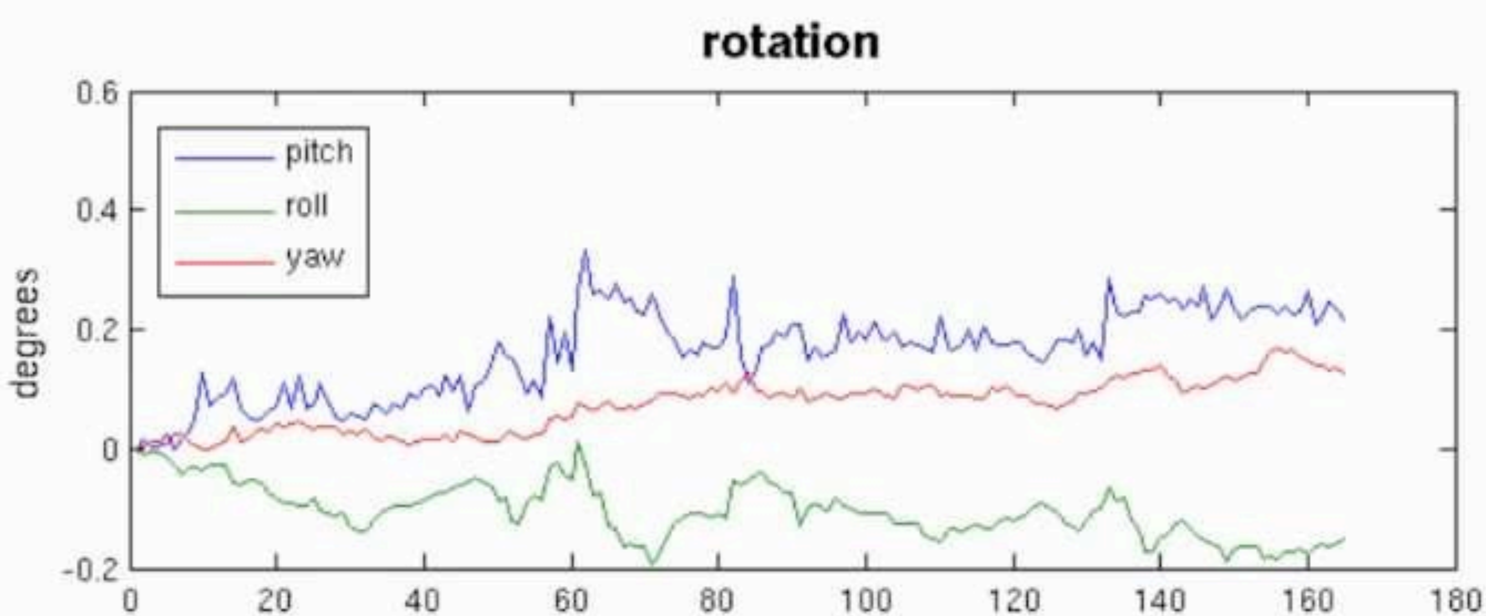
663	507	89
520	119	171
137	179	117

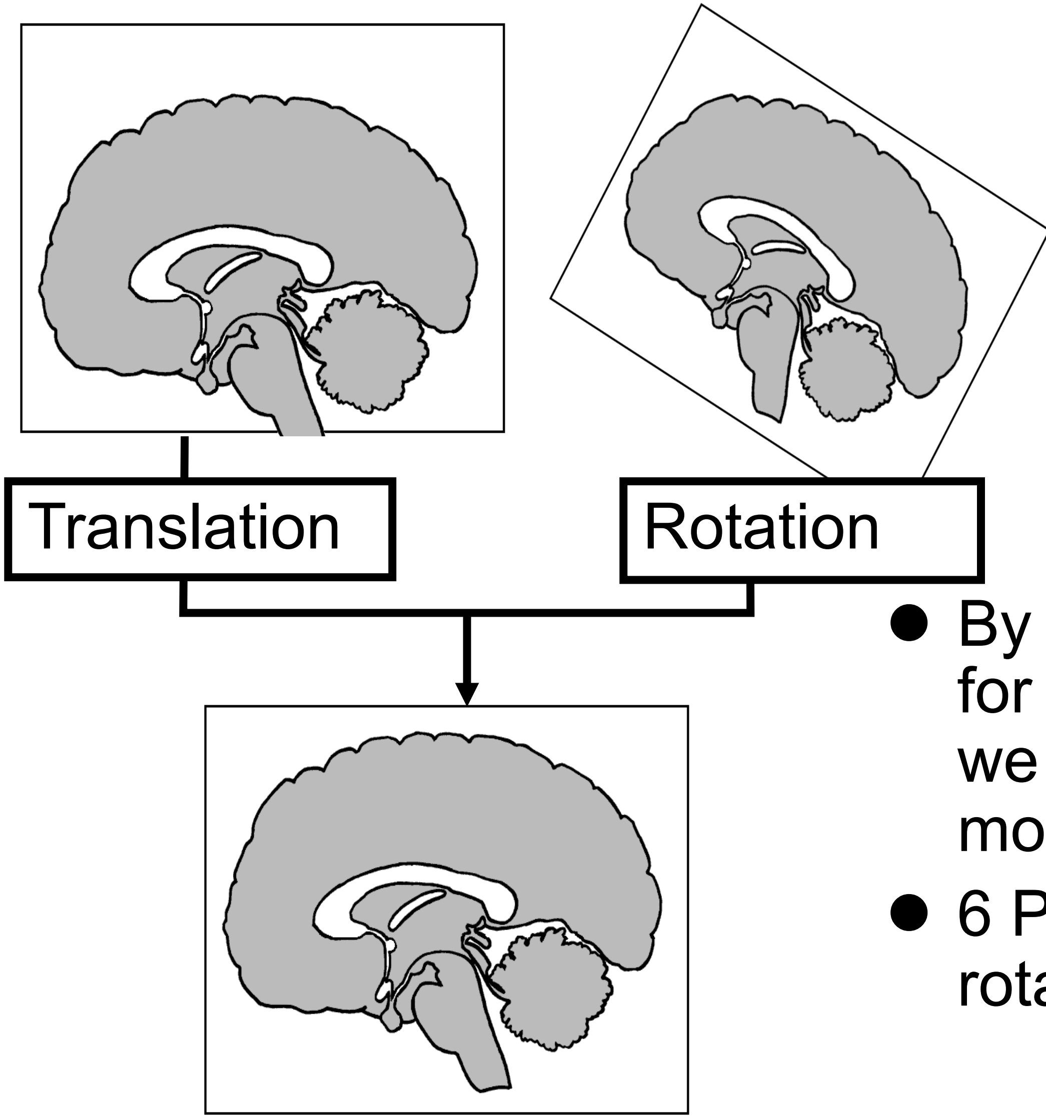
realignment



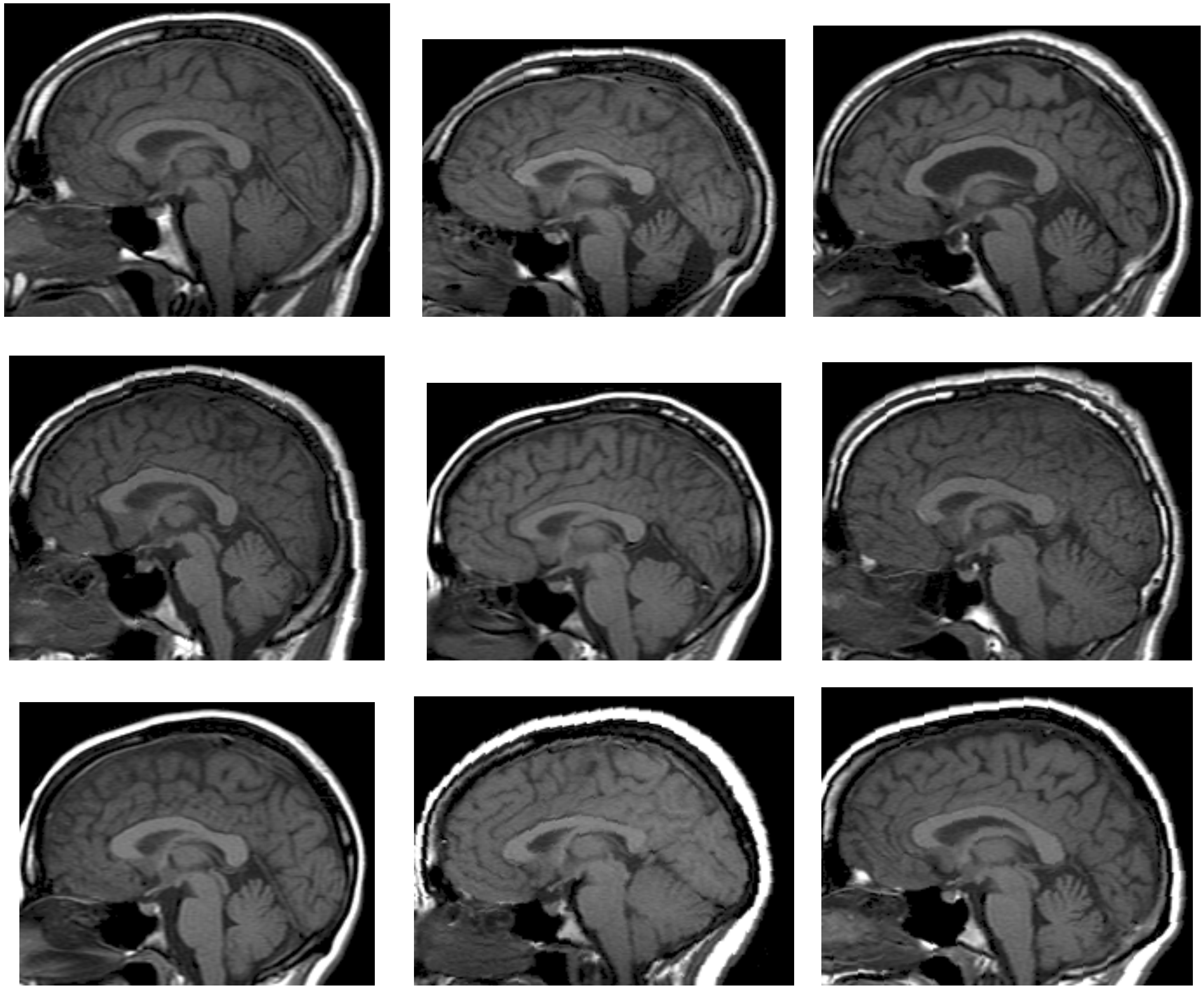
Registration of the fMRI
scans (across time)


translation
0.4
0.2
0
-0.2
-0.4
mm
x translation
y translation
z translation
0
20
40
60
80
100
120
140
160
180
image


rotation
0.6
0.4
0.2
0
-0.2
degrees
pitch
roll
yaw
0
20
40
60
80
100
120
140
160
180

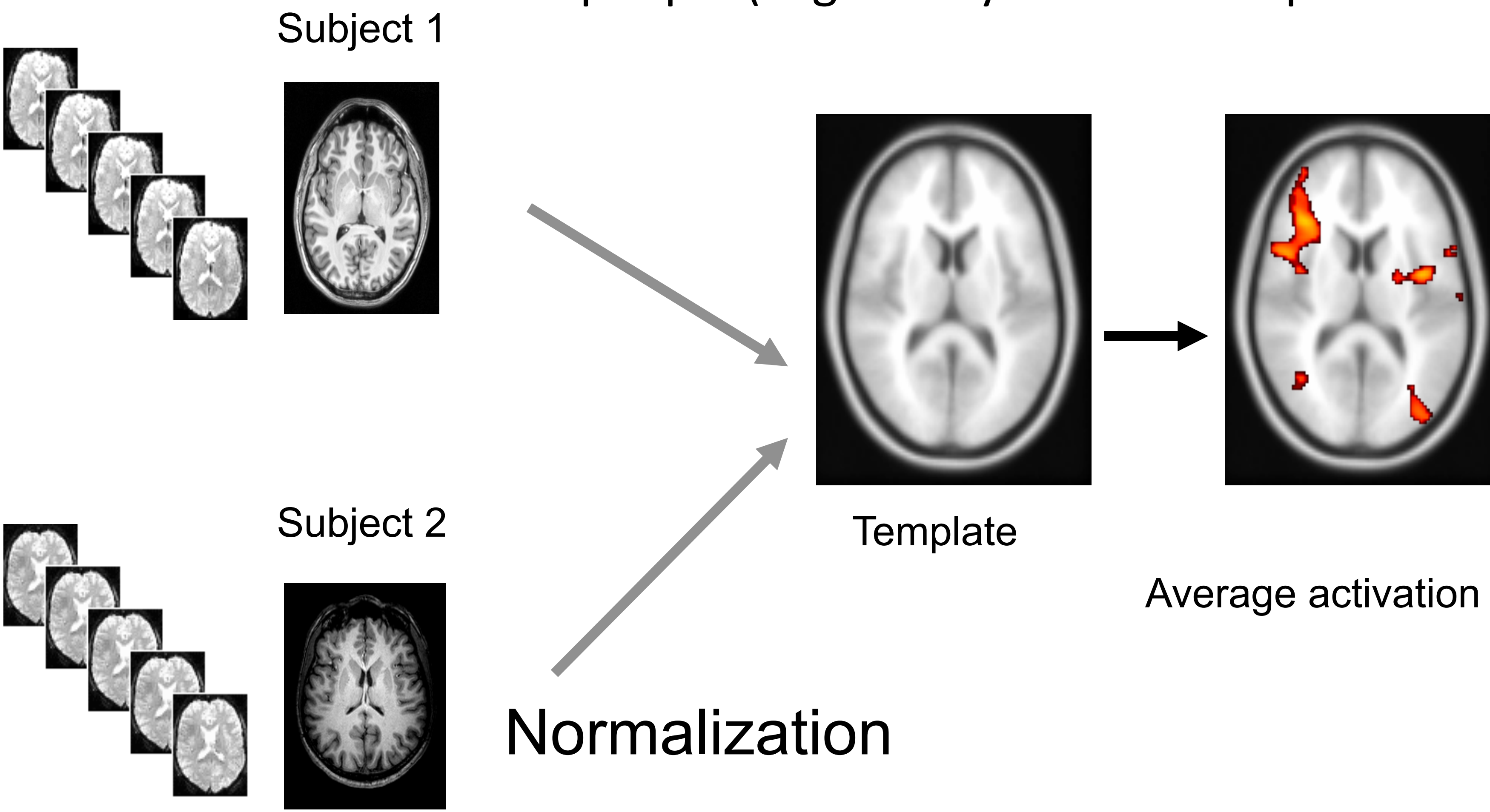


- By measuring and correcting for translations and rotations, we can adjust for an object's movement in an image.
- 6 Parameters: translation and rotation each in 3 dimensions.

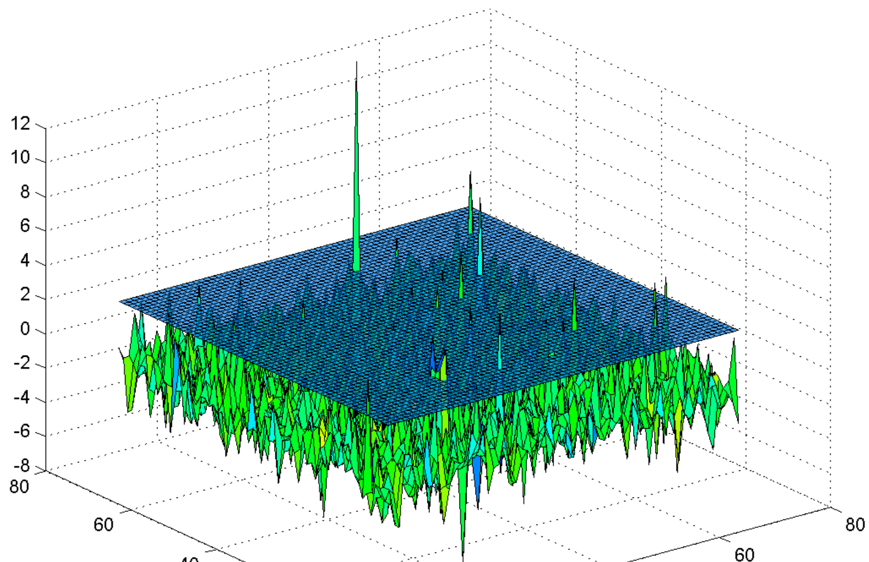


Normalization

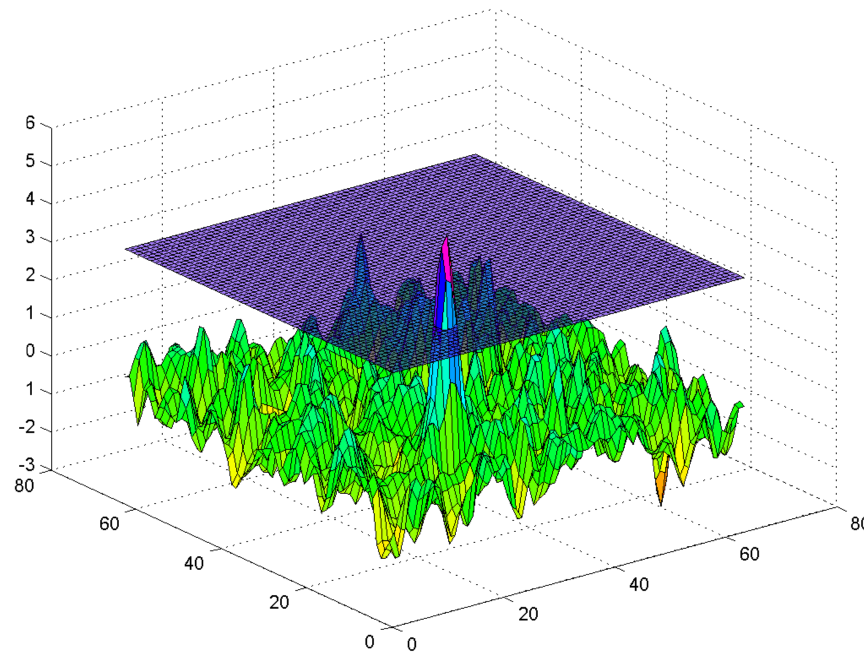
- Normalization: align images from different people (align everyone to a template image)



Spatial Smoothing

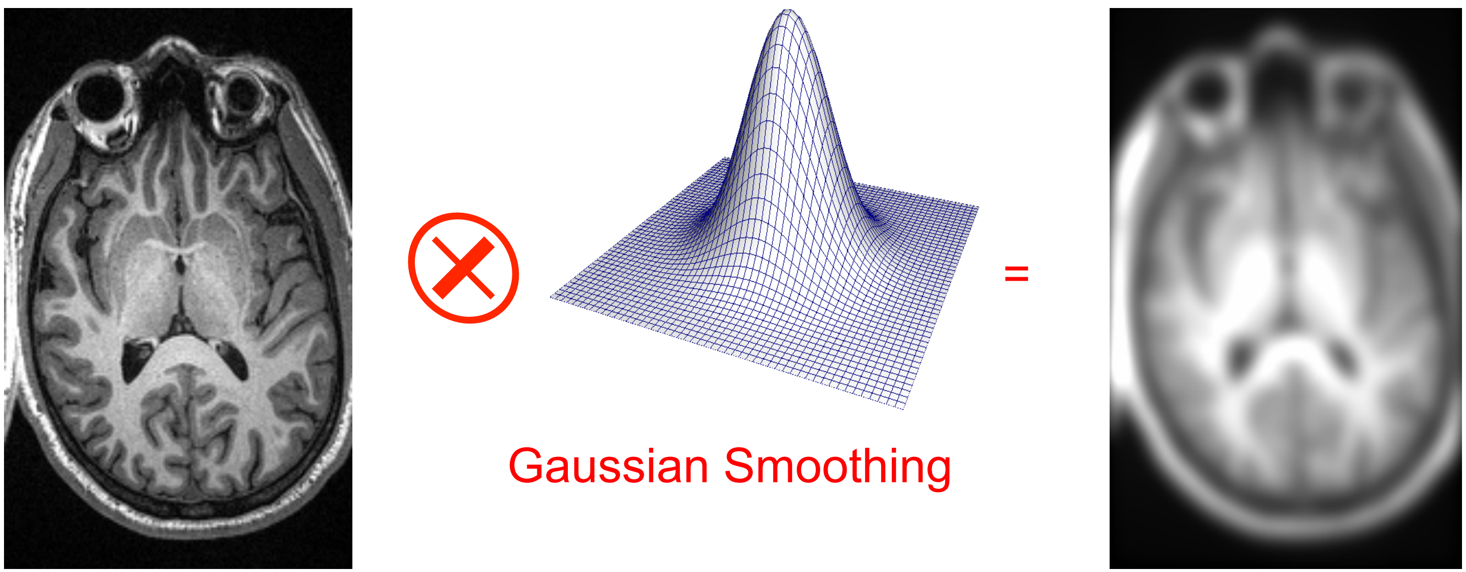


Before smoothing



After smoothing

Spatial Smoothing



$$5 + 3 = ?$$

$$14 + 25 = ?$$

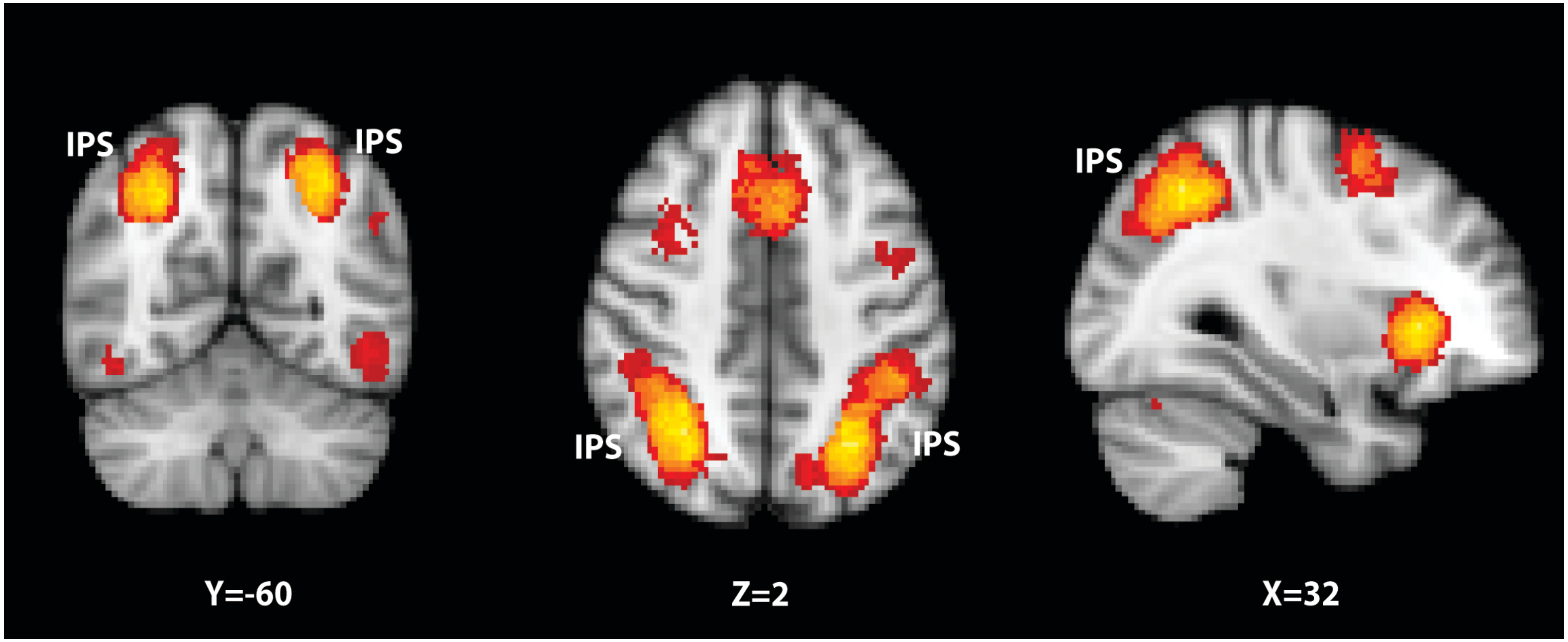
$$45 + 78 = ?$$

$$2874 + 3527 = ?$$

Arithmetic strategy

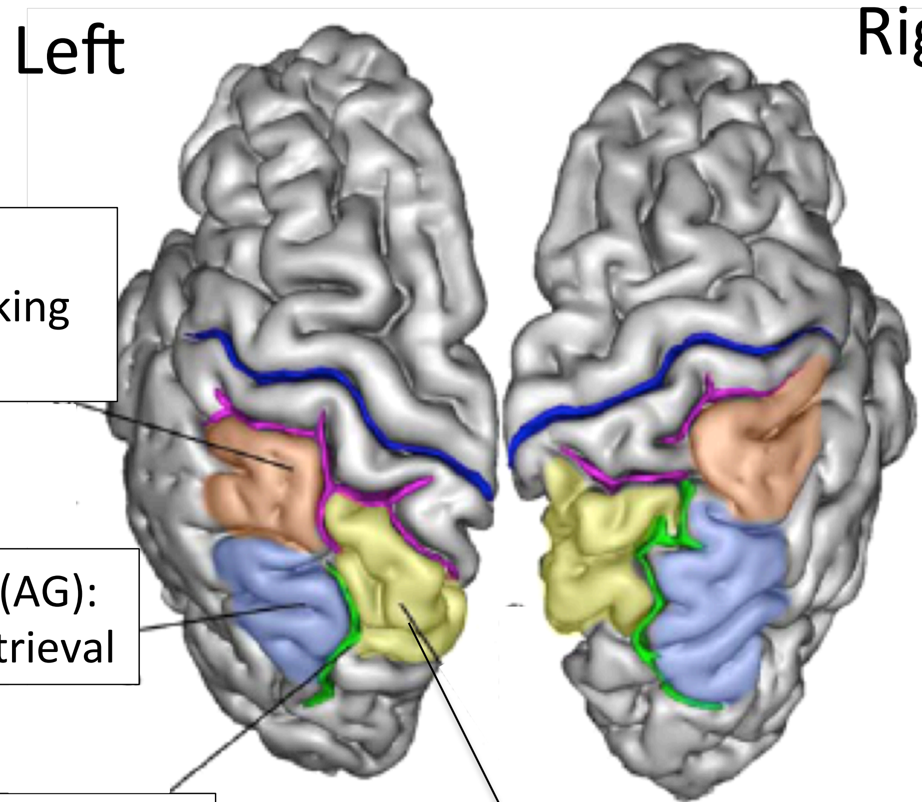
- Retrieval
  - Directly recollect answer in one step
- Procedural calculation
  - Calculate answer using explicit algorithm

Canonical Brain Areas Involved in Arithmetic Problem Solving



Maps are based on meta-analysis of 44 studies of arithmetic in neurosynth (Yarkoni et al. 2011).

Posterior Parietal Cortex (PPC)



Supramarginal Gyrus (SMG):
Visual and Phonological Working Memory

Angular Gyrus (AG):
Verbal Fact Retrieval

Intraparietal Sulcus (IPS):
Domain Specific Abstract Quantity Representation

Superior Parietal Lobule (SPL):
Attentional Orientation

Menon (2010), Dehaene et al., (2003)

Distinct PPC profile

Arabic Numeral :

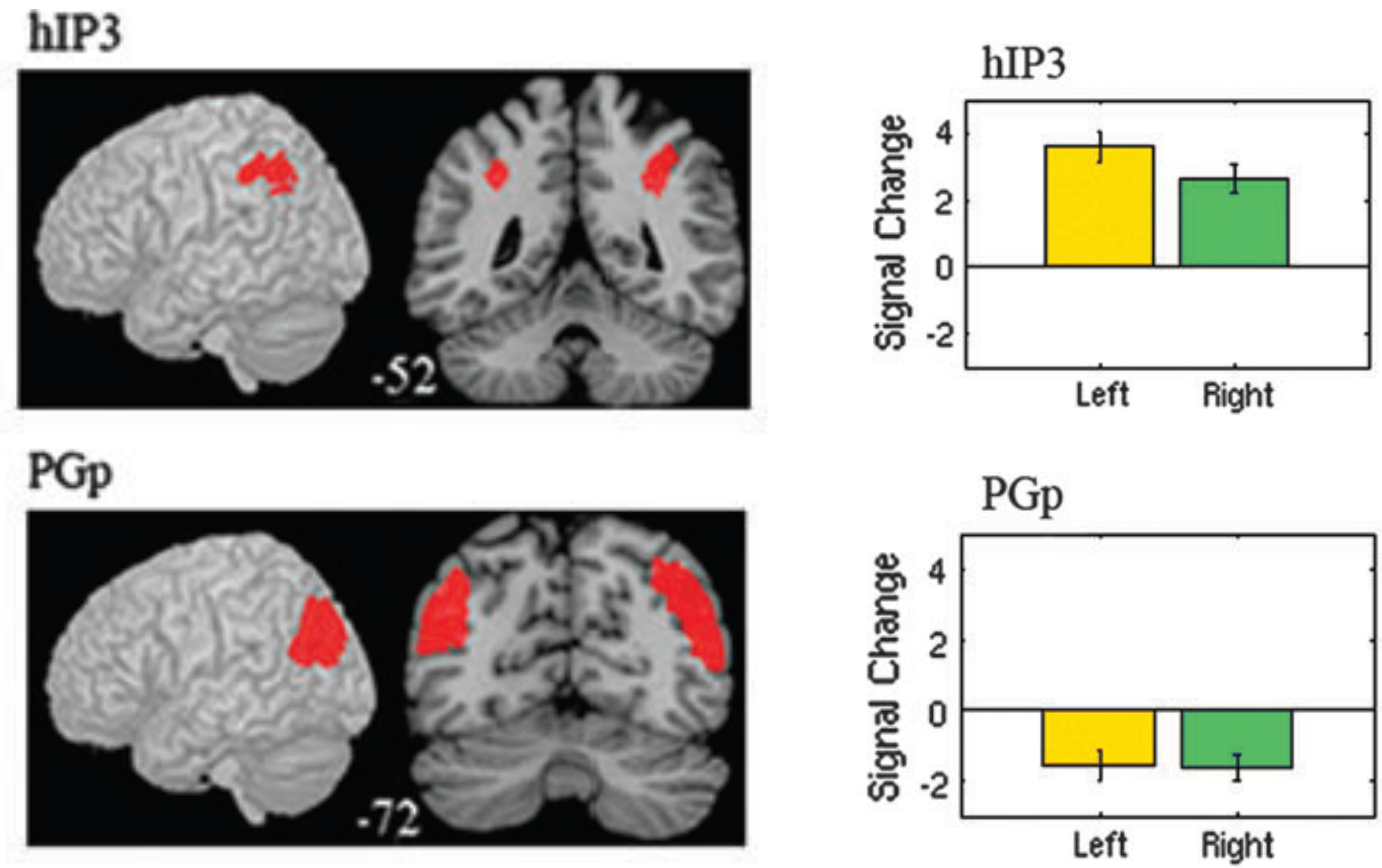
"Is this correct?"

3 + 4 – 2 = 5

Roman Numeral :

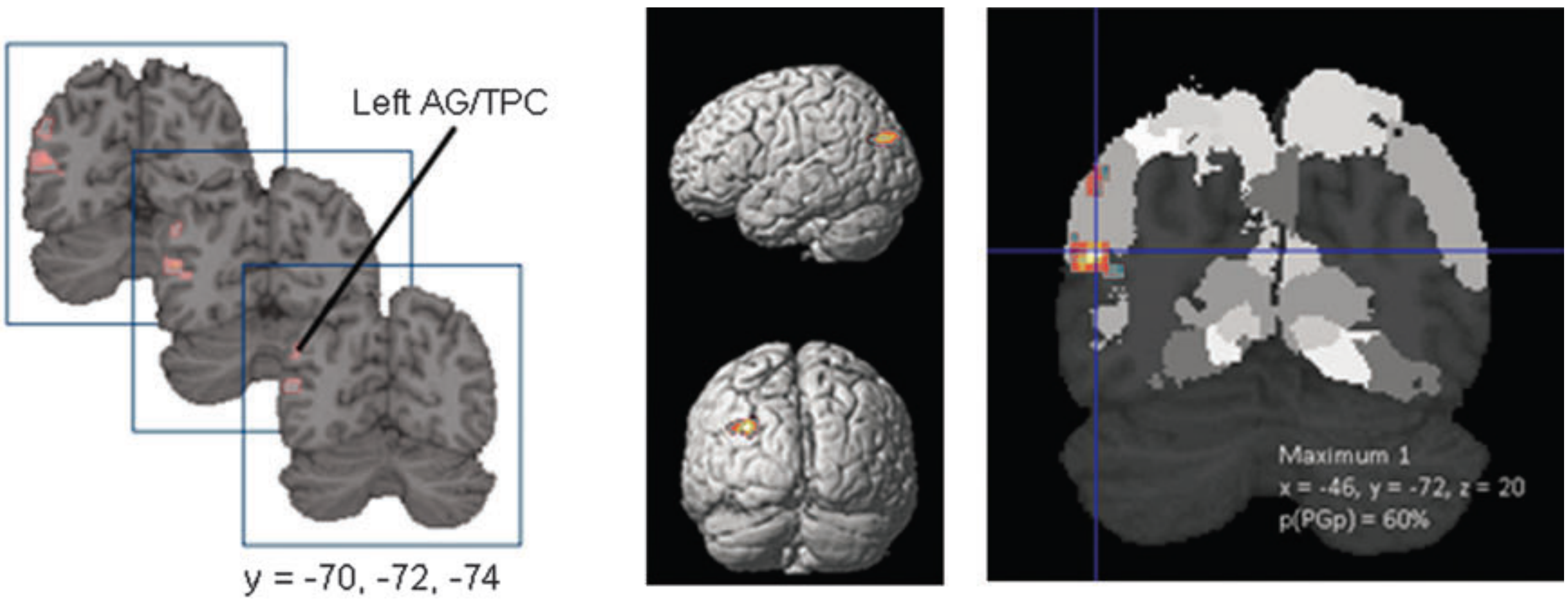
"Is this correct?"

III + IV – II = V



Wu, Chang et al. (2009)

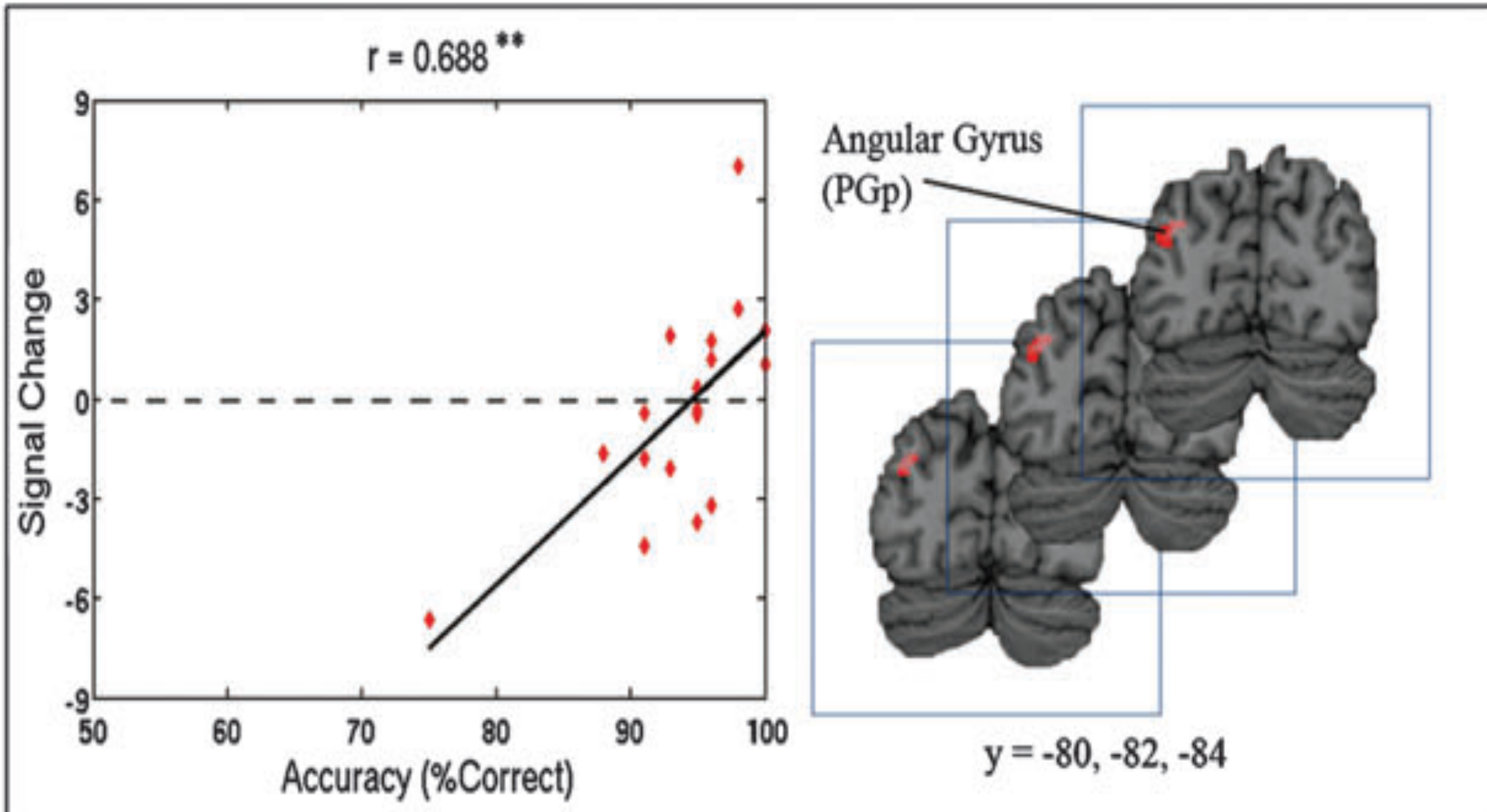
Activation Difference Between Arabic and Roman Numerals



Wu, Chang et al. (2009)

Are the neural correlates of mental arithmetic modulated by mathematical competence?

AG activation Correlates with Accuracy



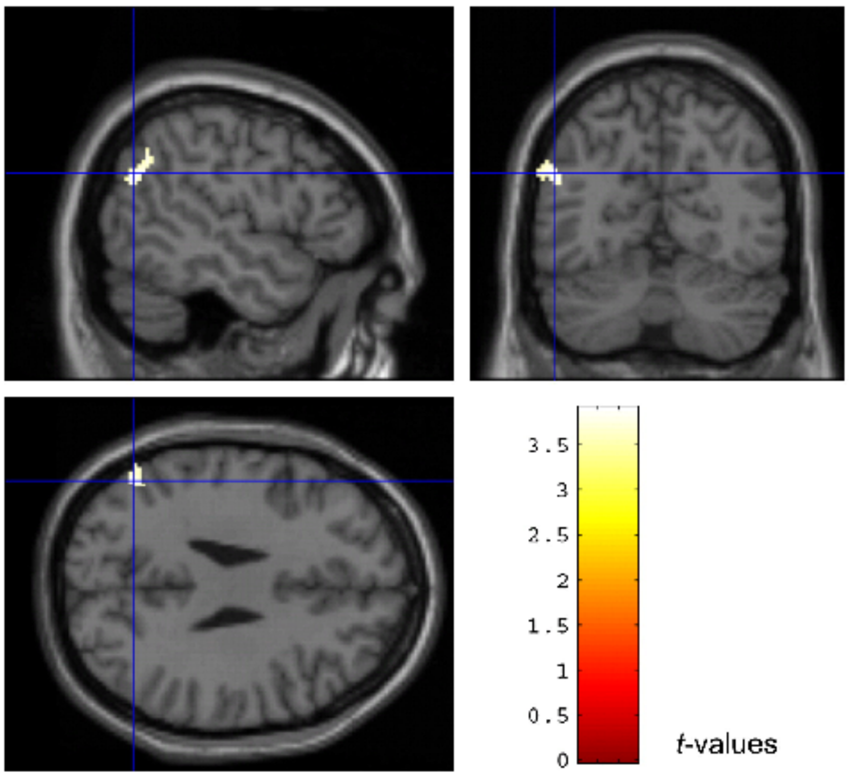
Wu, Chang et al. (2009)

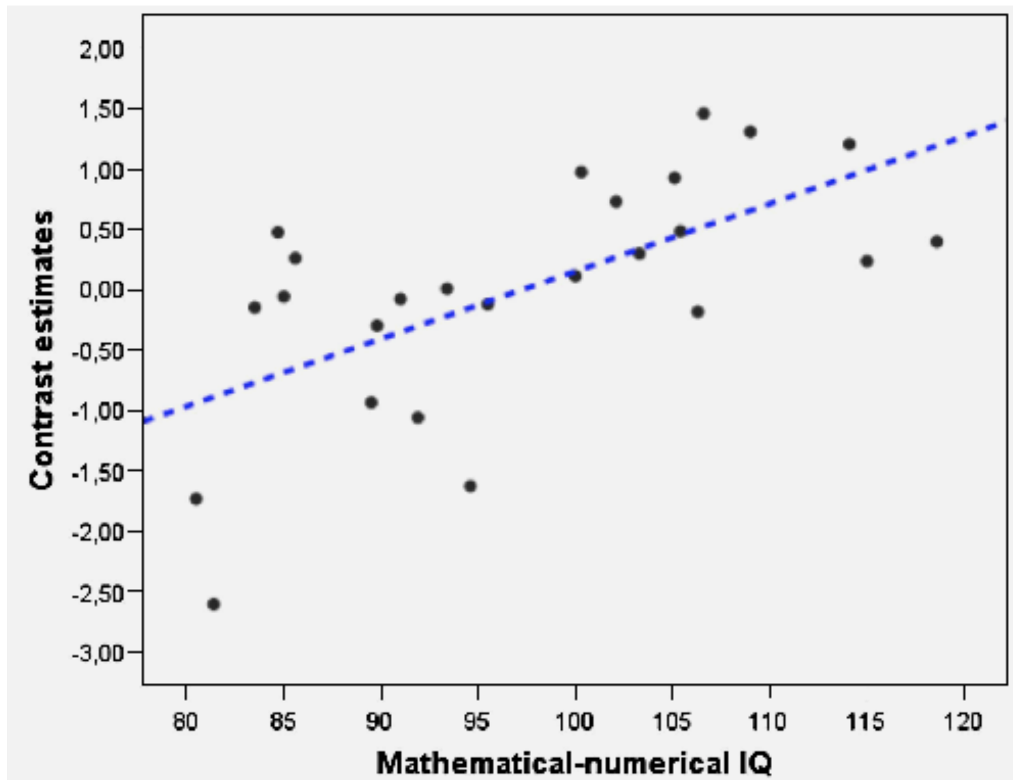
- Screened a large sample of adults (138)
- Selected *individuals who did not differ in IQ but varied in their mathematical competence*
- fMRI study
  - Multiplication verification **4 x 6 = 24**
  - Control Task **3 = 3 = 3**

Which brain regions activated during multiplication correlated with mathematical competence?

Grabner, Ansari et al. (2007)

Relationship between AG activation and individual difference in math skill

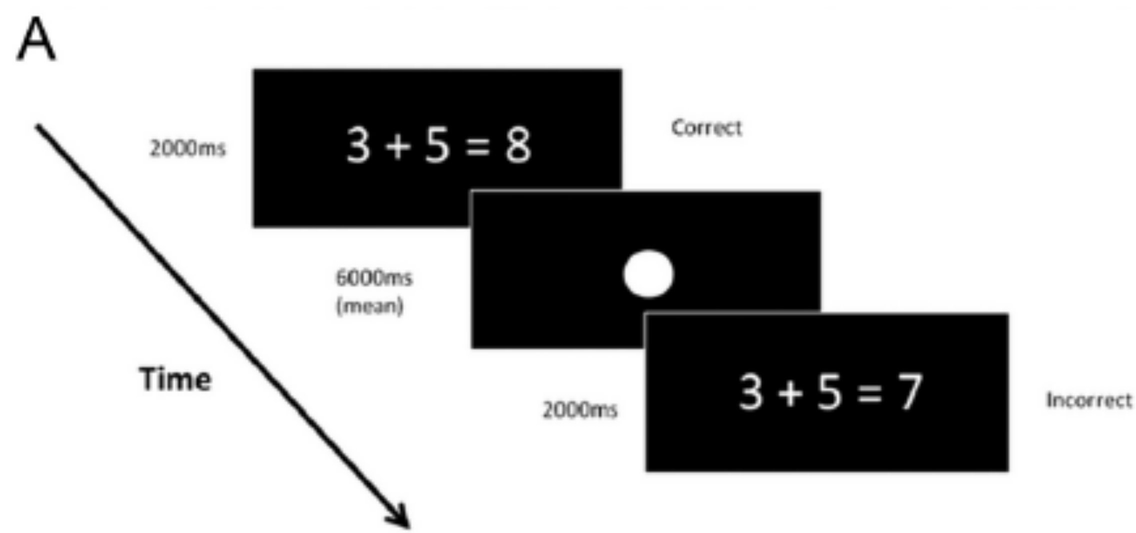




Grabner, Ansari et al. (2007)

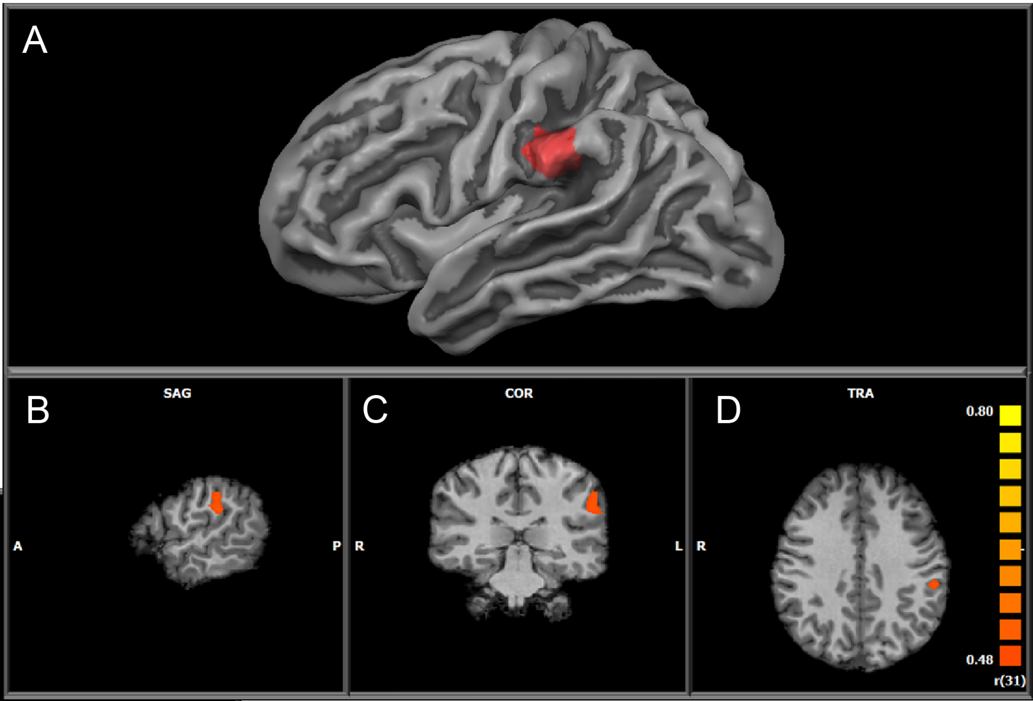
Mental arithmetics predicts high school math

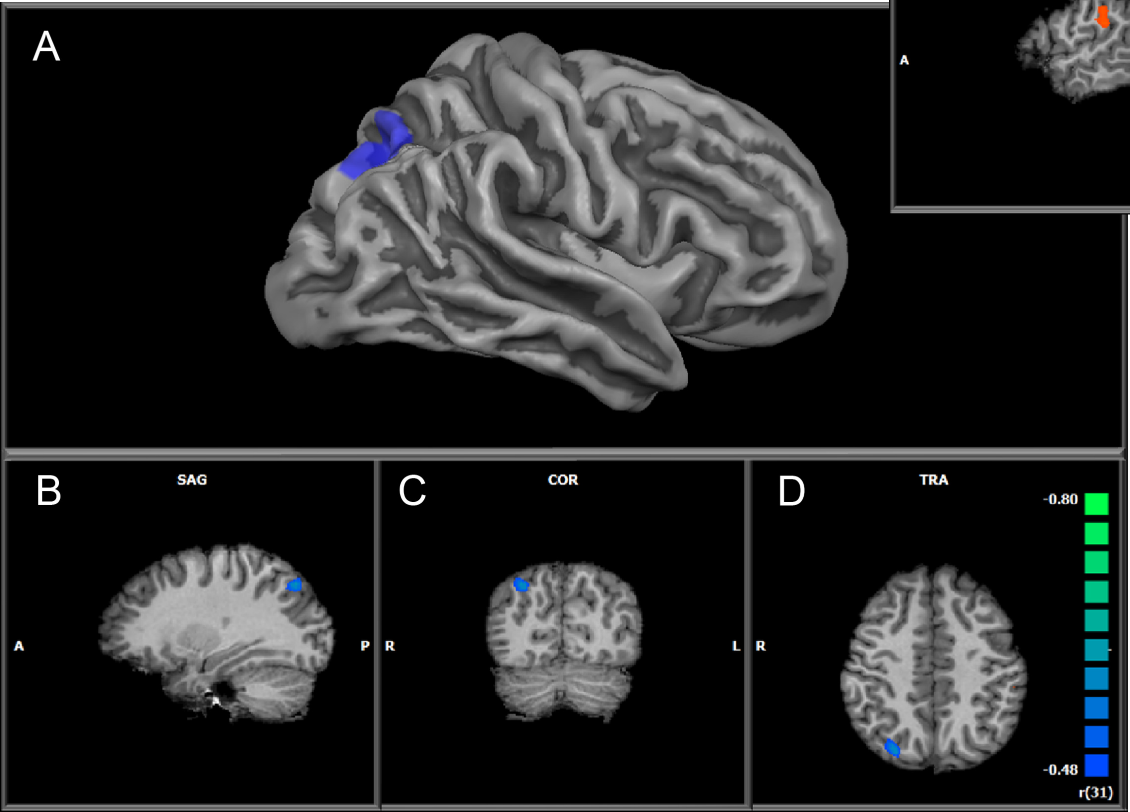
- Participants
  - 33 high school students (mean age :17 yrs)
- Math skill assessment
  - PSAT



Price et al. (2013)

PSAT positive correlates with AG/SMG and negatively correlates with IPS

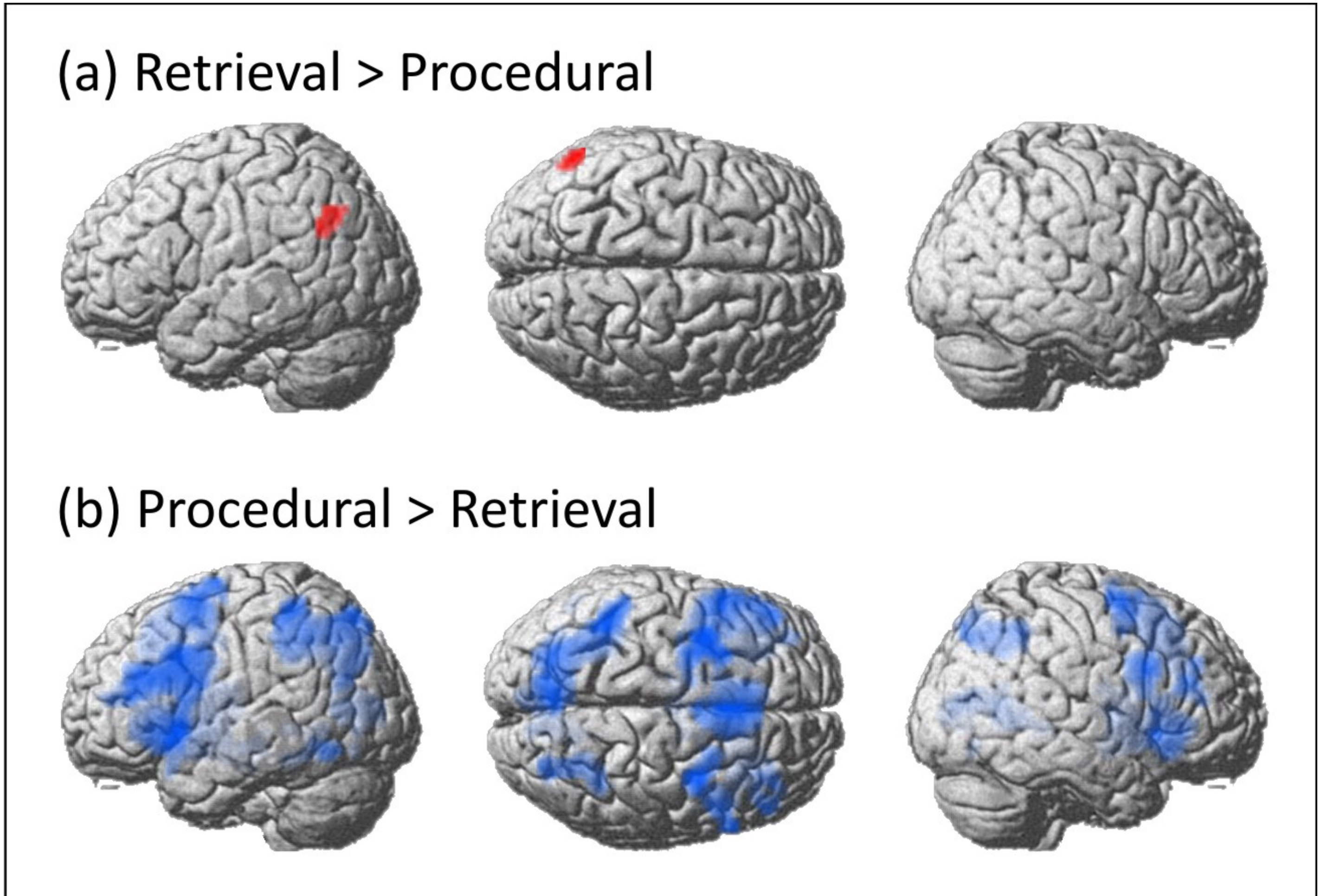




Price et al. (2013)

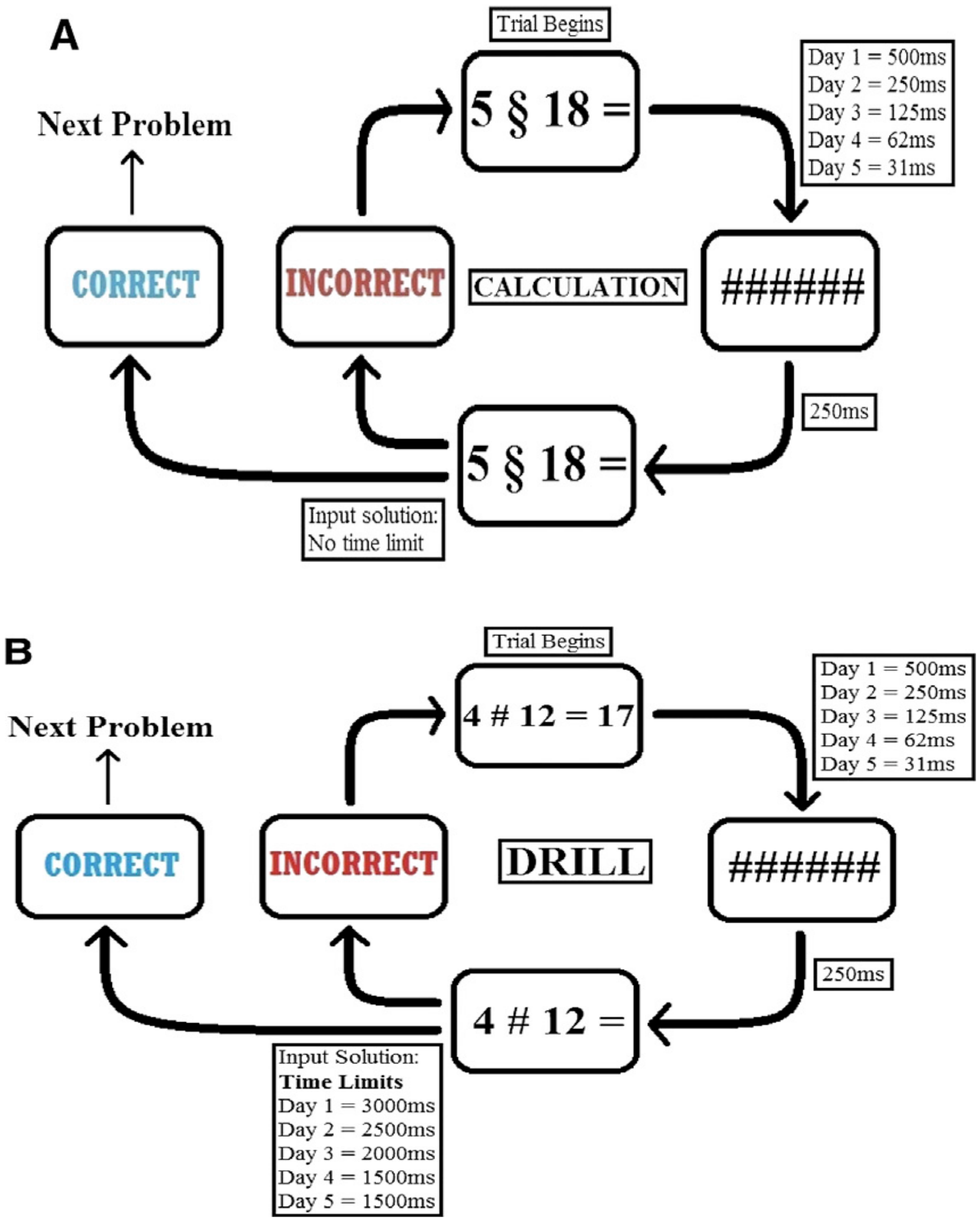
Are the neural correlates of mental arithmetic modulated by strategy choice?

Strategy Variability
Evidence from Brain Imaging



Grabner, Ansari et al. (2009)

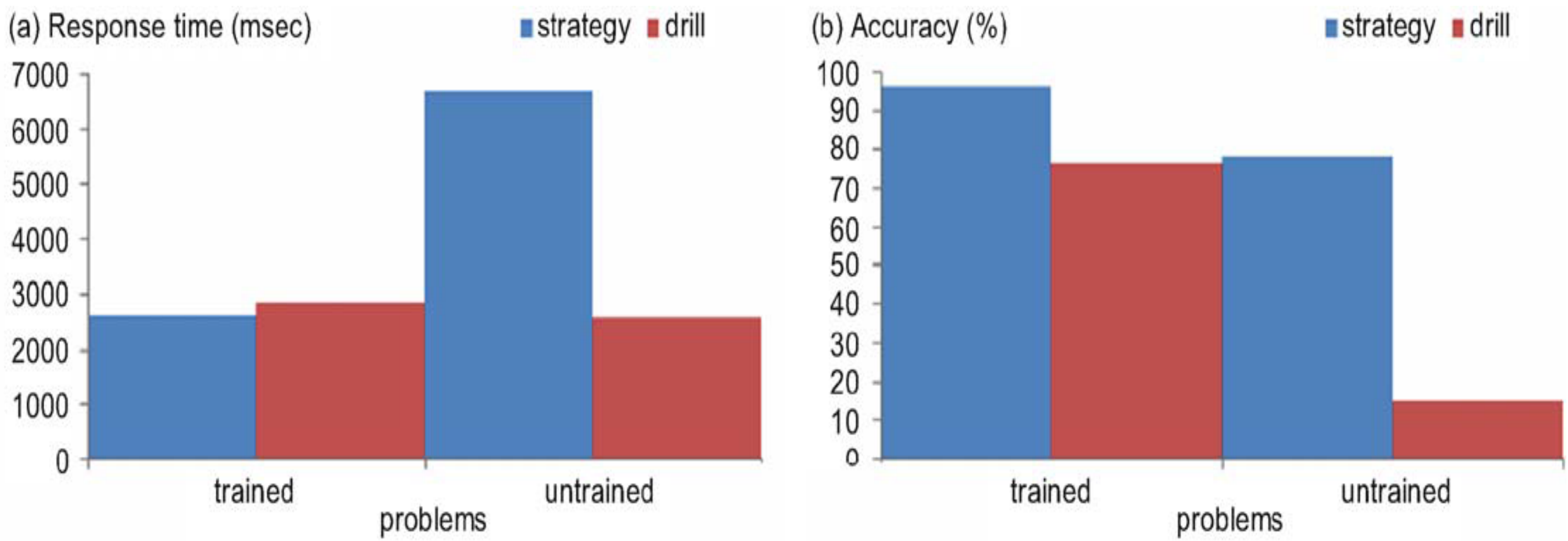
Learning by algorithm or learning by drill?



Procedure:

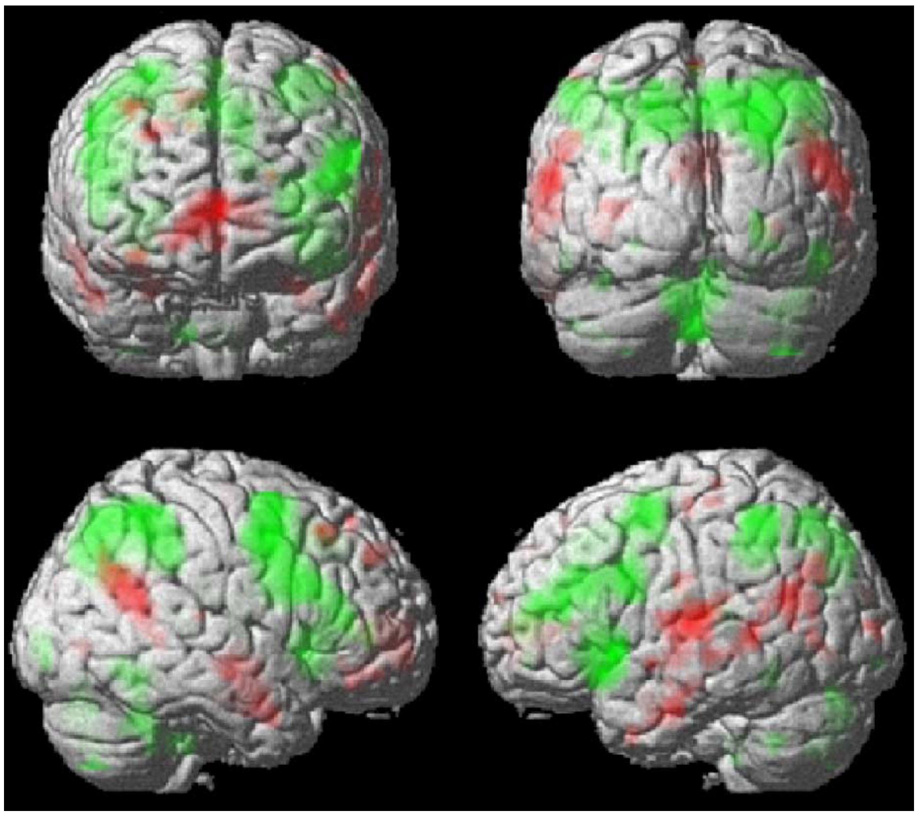
1. [(right number – left number) + 1] + right number
2. [(right number + left number) − 10] + right number

Delazer et al. (2005)

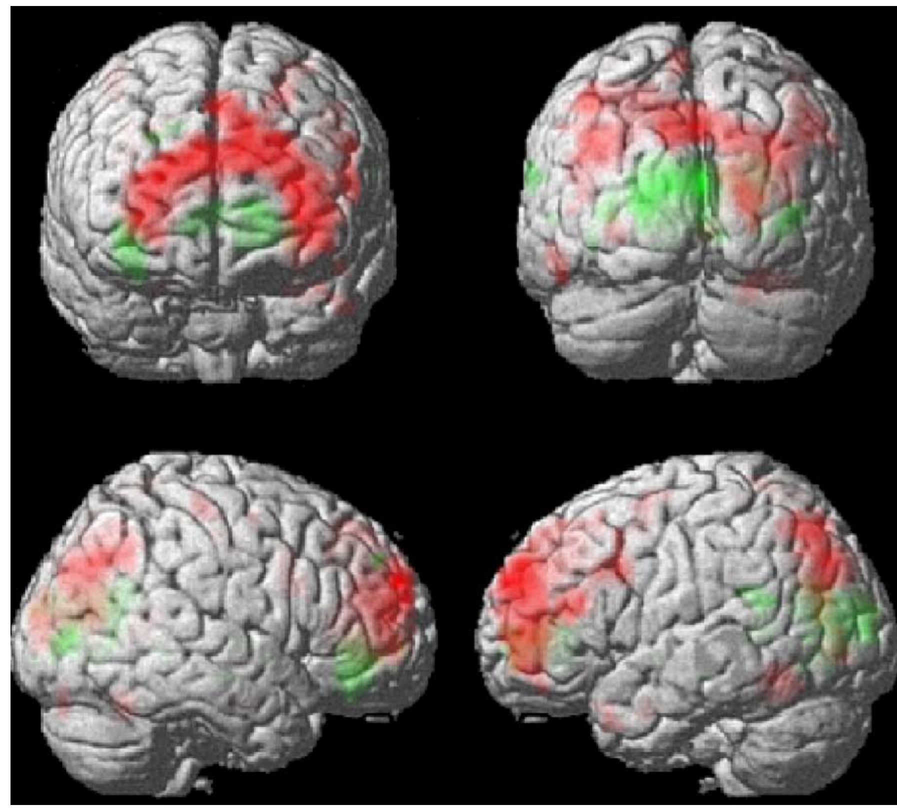


Delazer et al. (2005)

Training effect:
trained vs. untrained
untrained vs. trained

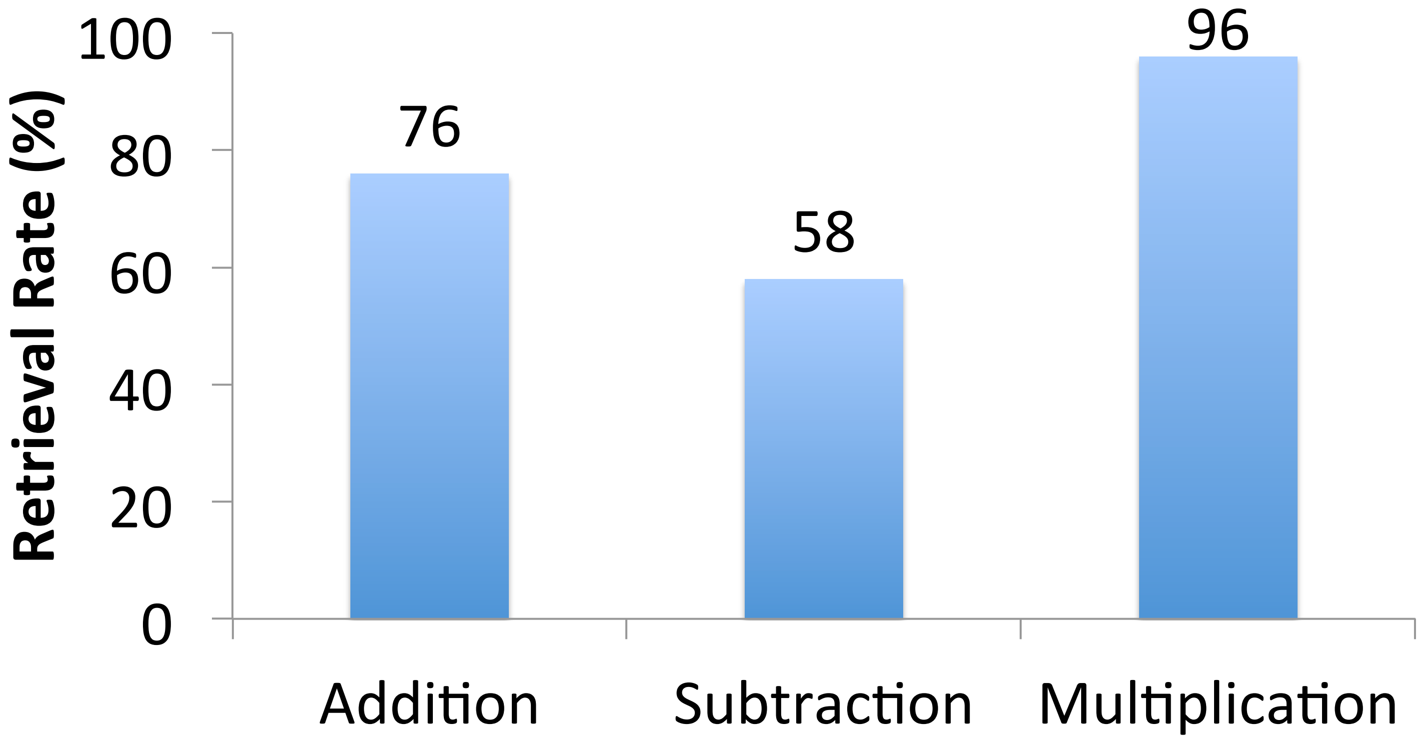


Strategy effect:
drill vs. algorithm
algorithm vs. drill



Does the brain activate differently across basic arithmetic operations?

Problem solving strategies varies across arithmetic problems



Campbell & Xue, 2001

Functional Dissociation Between Basic Arithmetic Operations

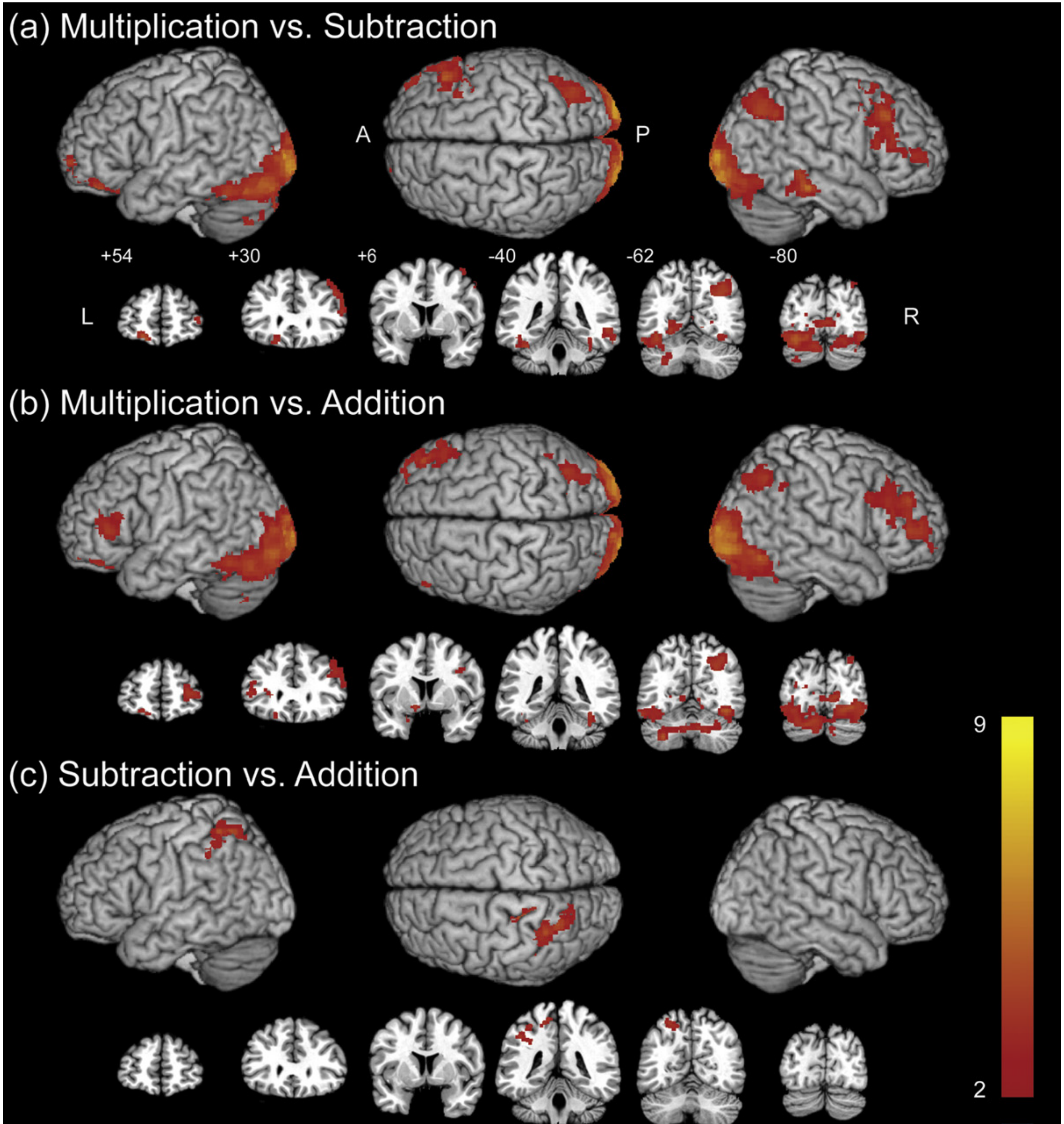
- **Participants**
  - 20 healthy adults (age 18-30)
- **Tasks**

Experimental Condition:

"Is this correct?"

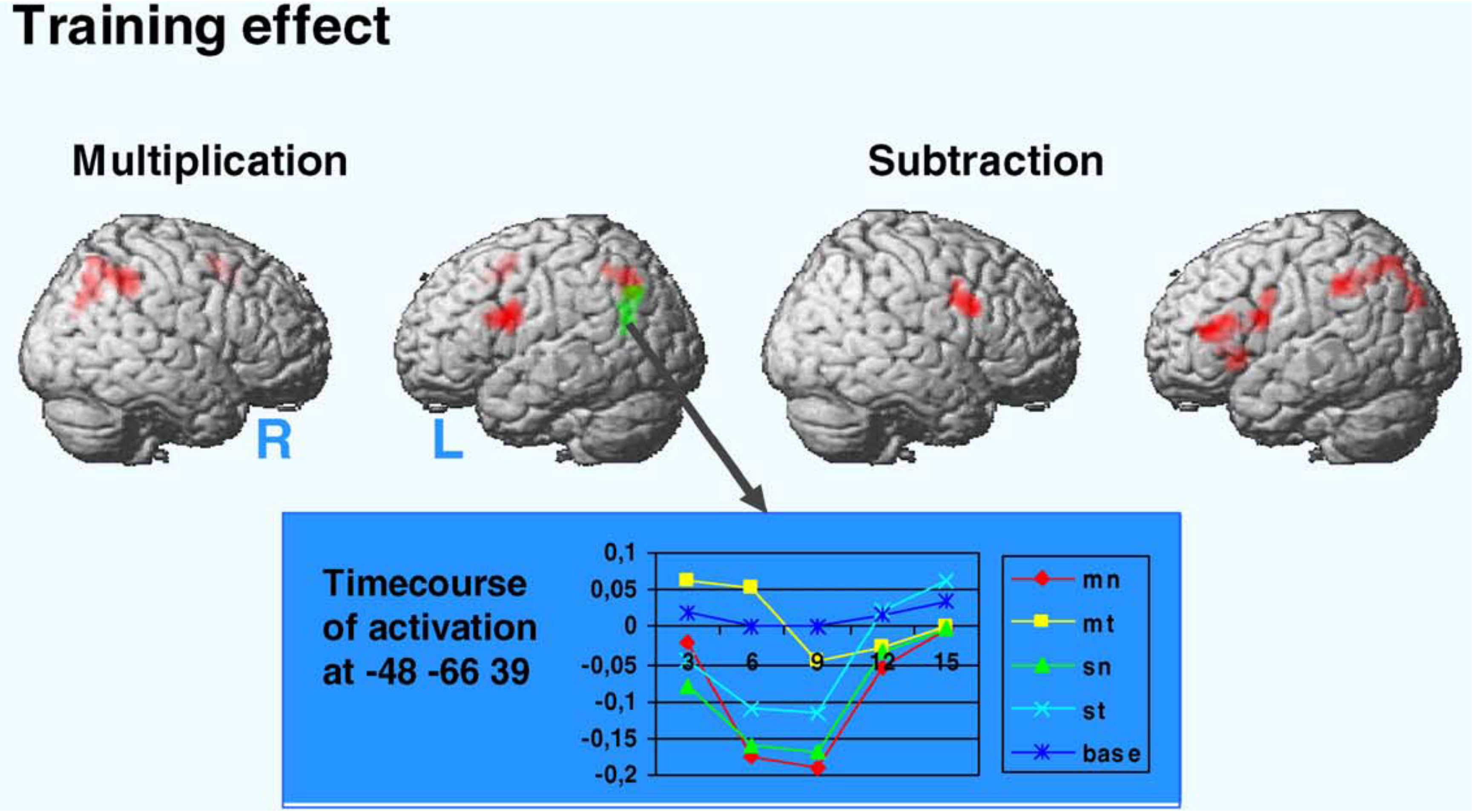
Addition	→	**5 + 4 = 8**
Subtraction	→	**8 - 4 = 5**
Multiplication	→	**3 X 2 = 6**

Rosenberg-Lee, Chang et al. (2011)



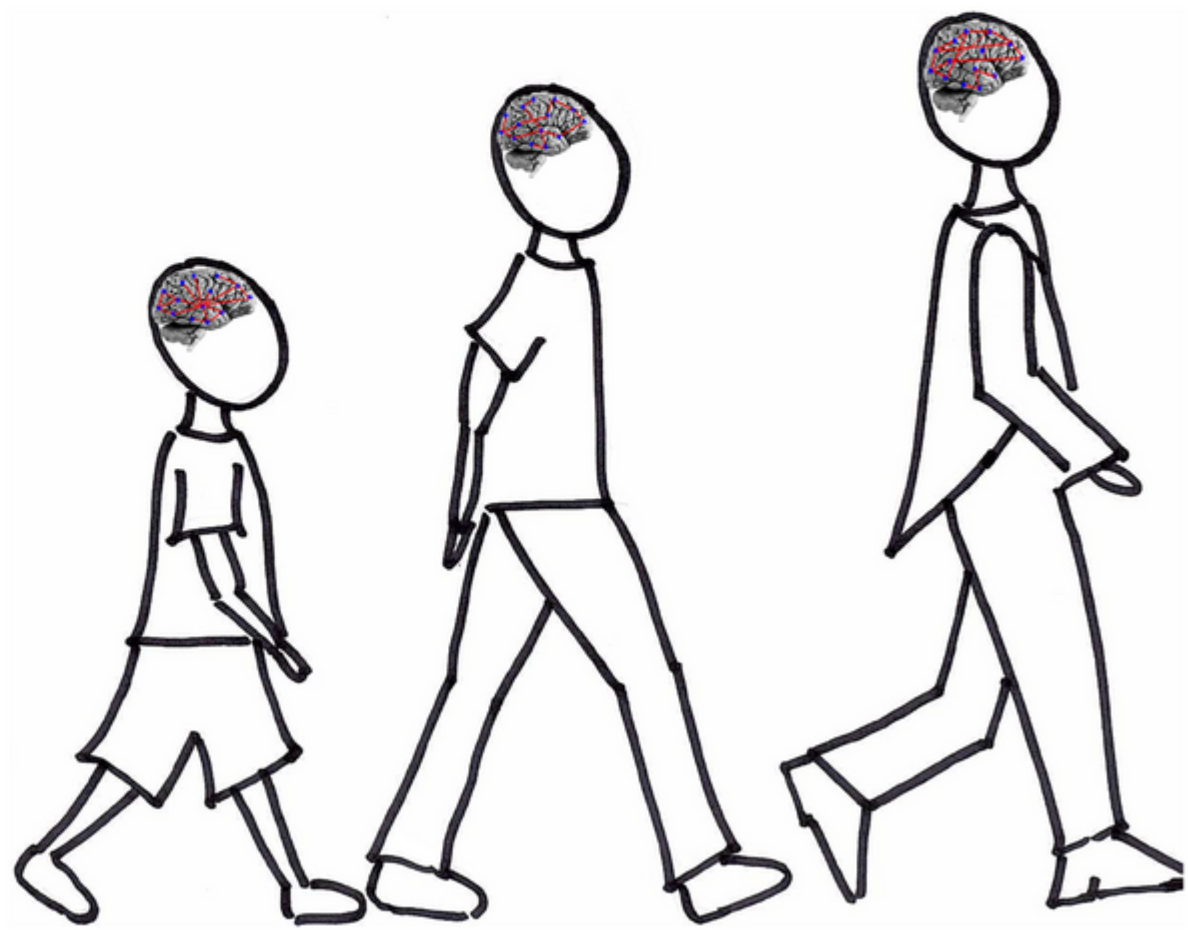
Rosenberg-Lee, Chang et al. (2011)

How specific do we learn?

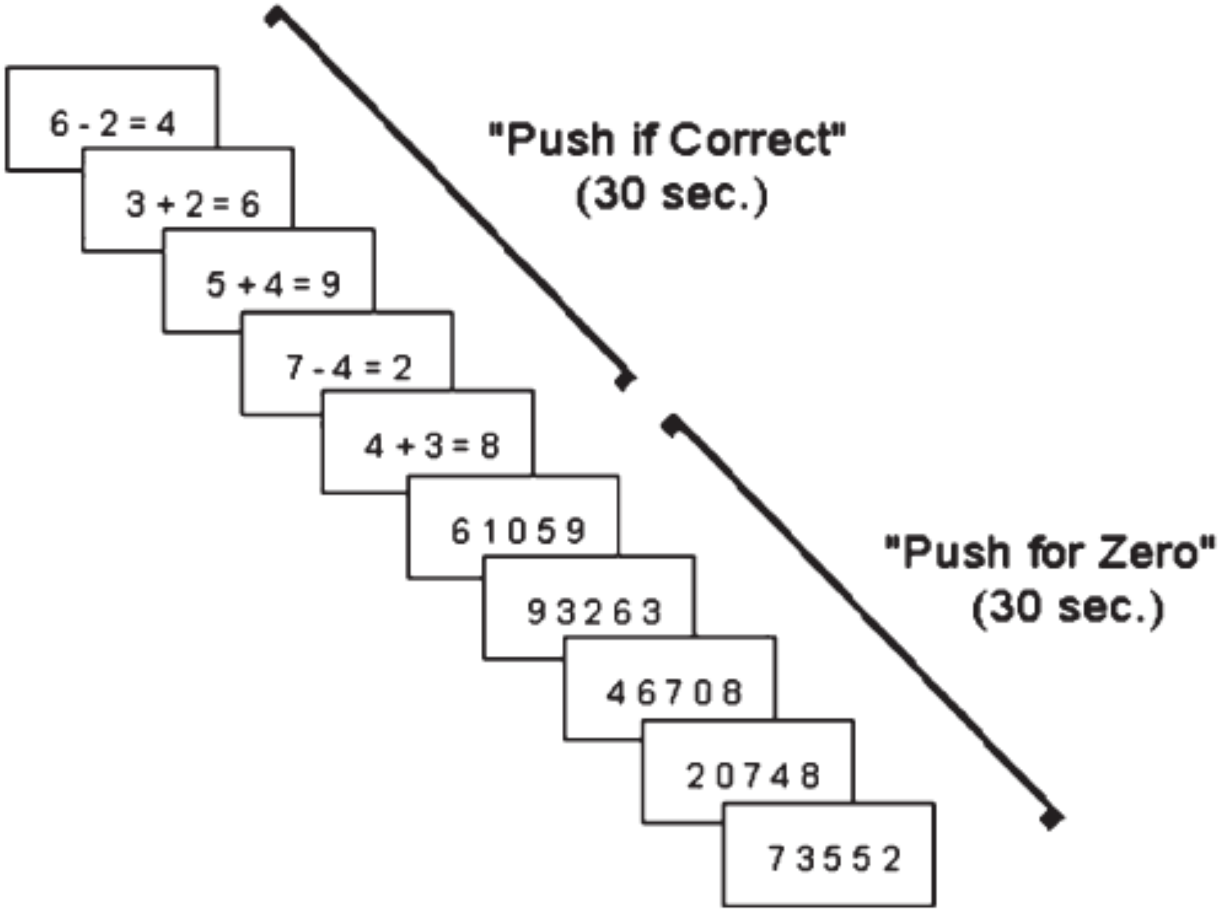


Ischebeck et al. (2006)

How does the neural network of mathematical information processing develop with learning and experience?

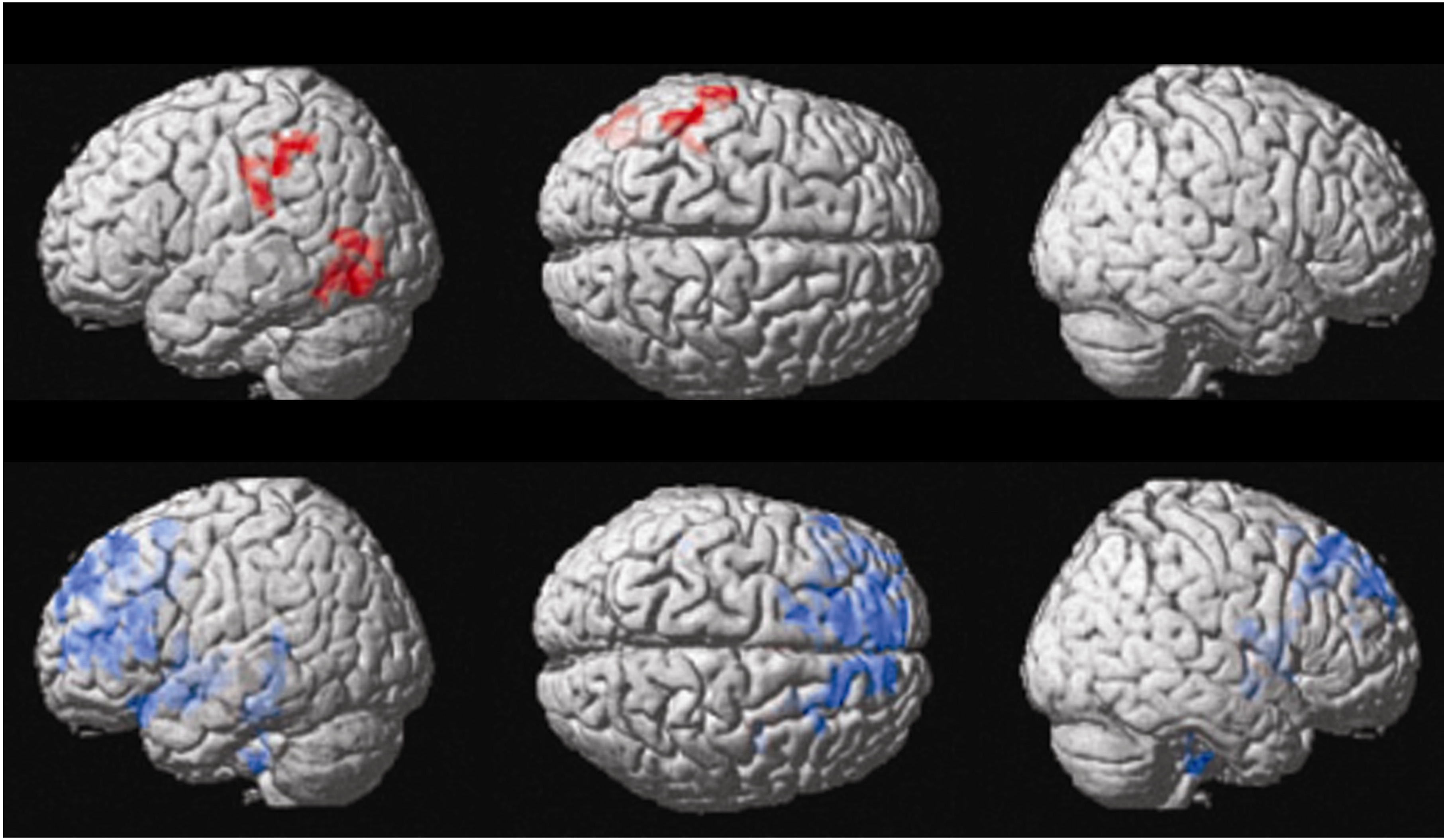


Development of mental arithmetic



Rivera et al. (2005)

Mental Arithmetic



Rivera et al. (2005)

Development of mental arithmetic across adolescence

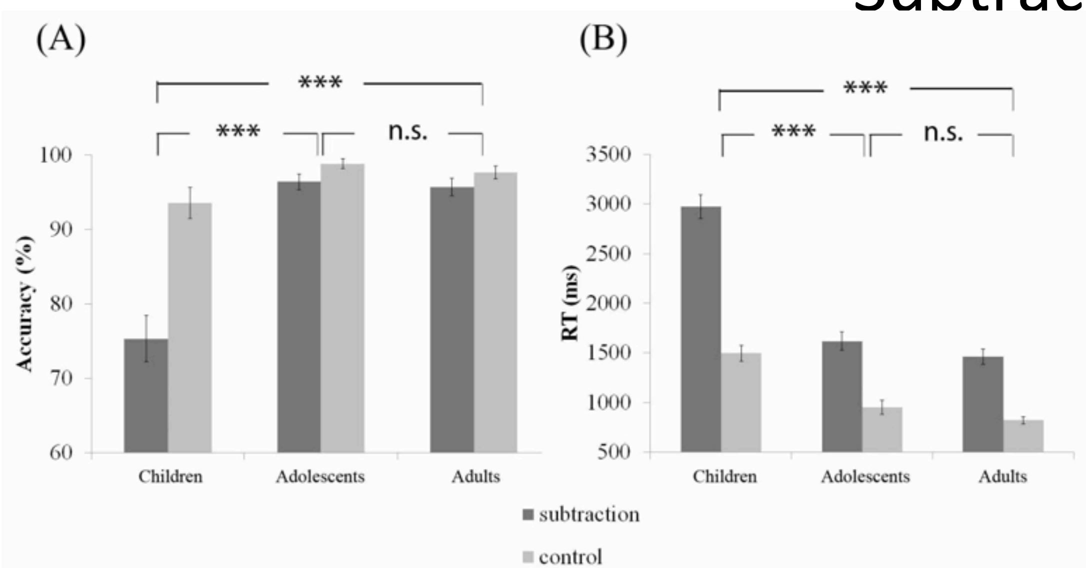
- Participants
  - 25 children (age 7-10)
  - 19 adolescents (age 13-17)
  - 26 adults (age 19-22)

13 – 5 = 9
12 – 3 = 7
9 – 5 = 4

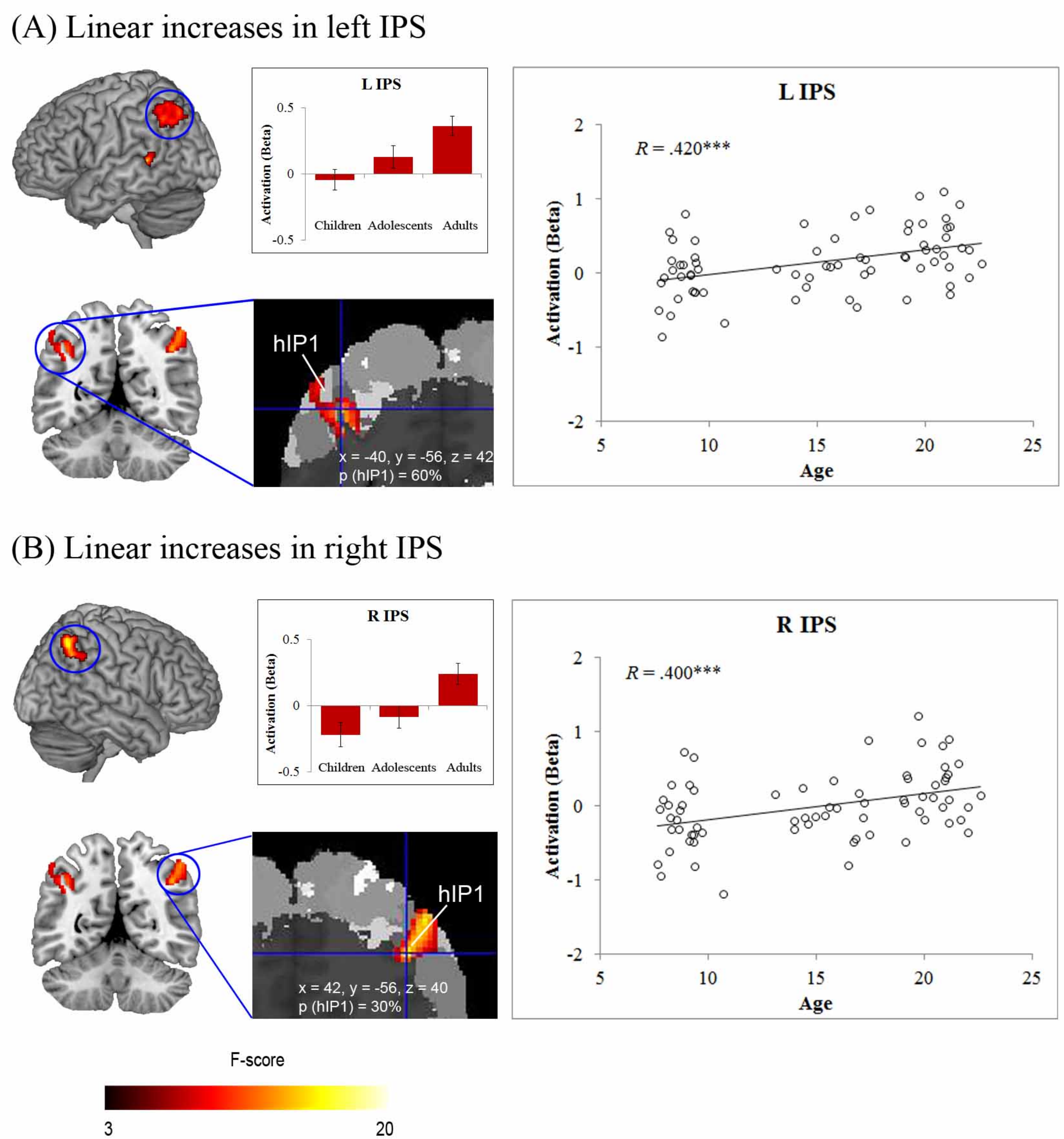
Subtraction

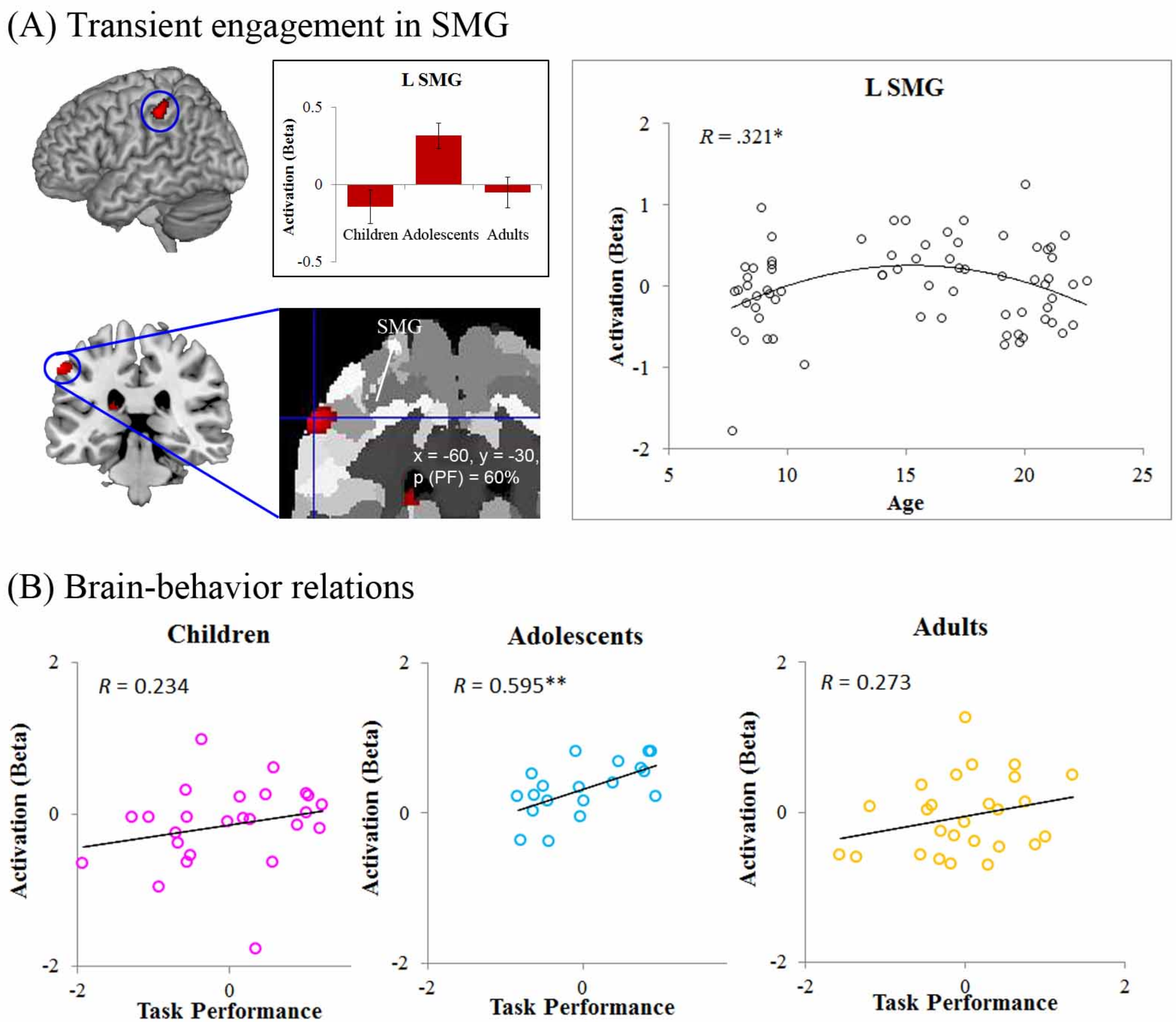
5 @ 1 $ 4
4 % 1 # 3
6 & 1 @ 7

Control



Chang et al. (in preparation)

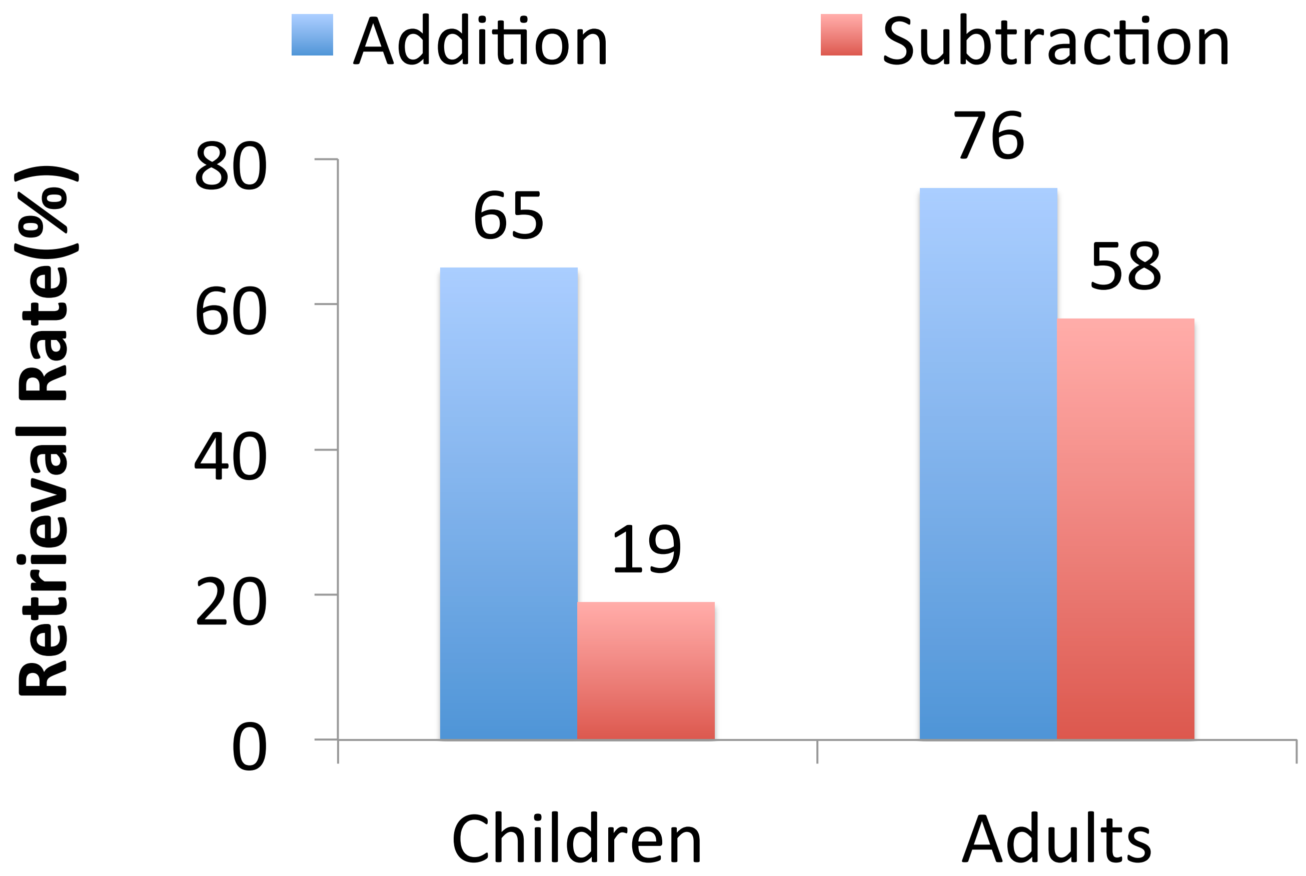

(A) Linear increases in left IPS
L IPS
0.5
0
-0.5
Activation (Beta)
Children
Adolescents
Adults
hIP1
x = -40, y = -56, z = 42
p (hIP1) = 60%
L IPS
R = .420***
2
1
0
-1
-2
Activation (Beta)
5
10
15
20
25
Age
(B) Linear increases in right IPS
R IPS
0.5
0
-0.5
Activation (Beta)
Children
Adolescents
Adults
hIP1
x = 42, y = -56, z = 40
p (hIP1) = 30%
R IPS
R = .400***
2
1
0
-1
-2
Activation (Beta)
5
10
15
20
25
Age
F-score
3
20



(A) Transient engagement in SMG
L SMG
Activation (Beta)
0.5
0
-0.5
Children Adolescents Adults
SMG
x = -60, y = -30,
p (PF) = 60%
L SMG
R = .321*
Activation (Beta)
2
1
0
-1
-2
5
10
15
20
25
Age
(B) Brain-behavior relations
Children
R = 0.234
Adolescents
R = 0.595**
Adults
R = 0.273
Activation (Beta)
Task Performance

How about the development of different basic arithmetic operation?

Arithmetic problem solving strategies converge across addition and subtraction



Campbell & Xue, 2001;Barrouillet, Mignon, & Thevenot, 2008

Experimental Design

- Cross-sectional fMRI
  - 28 Children (7-9 yrs)
  - 28 Adults (18-22 yrs)
- Block design

5 + 9 = 14
6 + 8 = 12
8 + 5 = 13

Addition

4 + 1 = 4
2 + 1 = 3
3 + 1 = 5

Control

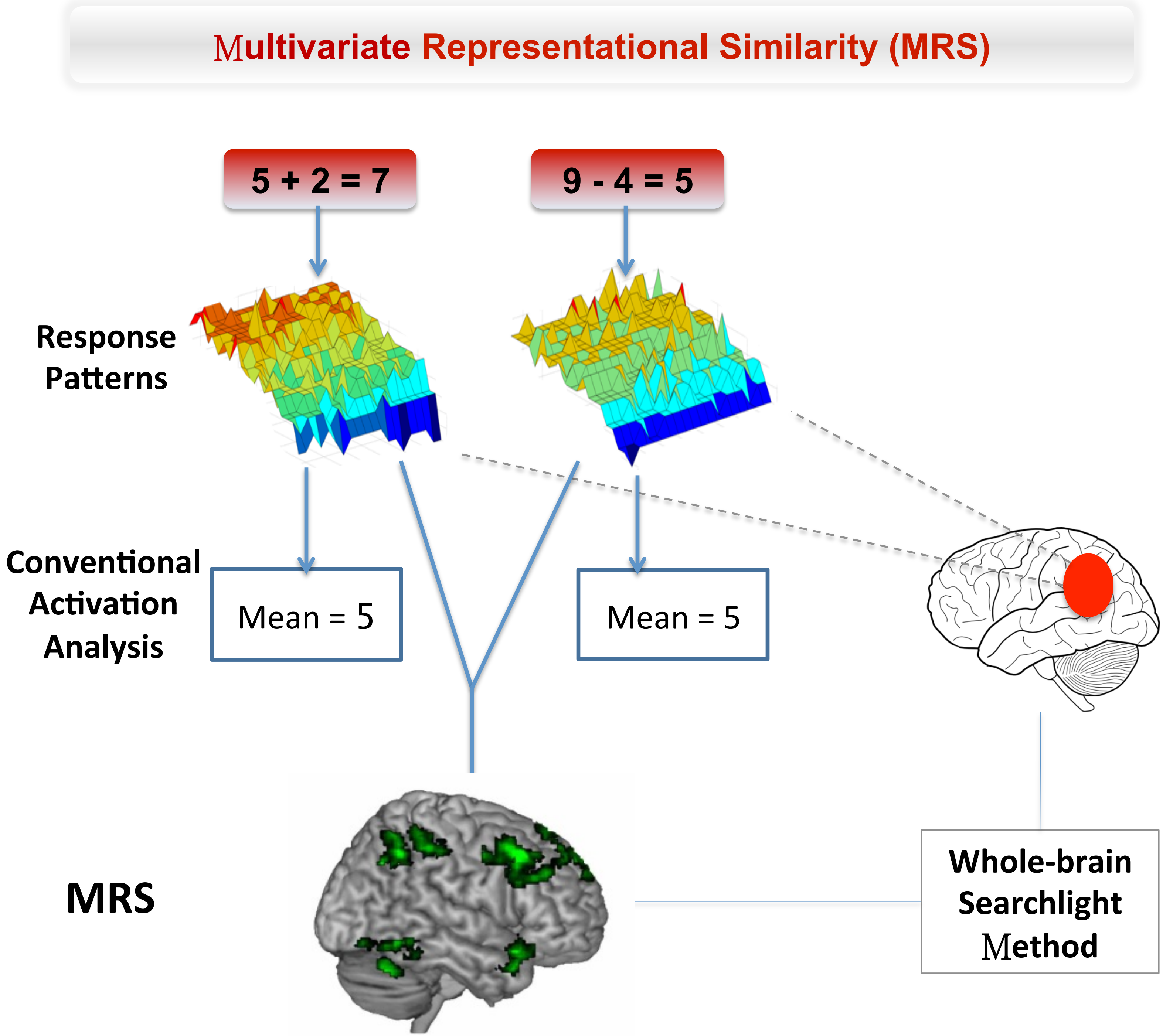
13 – 5 = 9
12 – 8 = 6
9 – 5 = 4

Subtraction

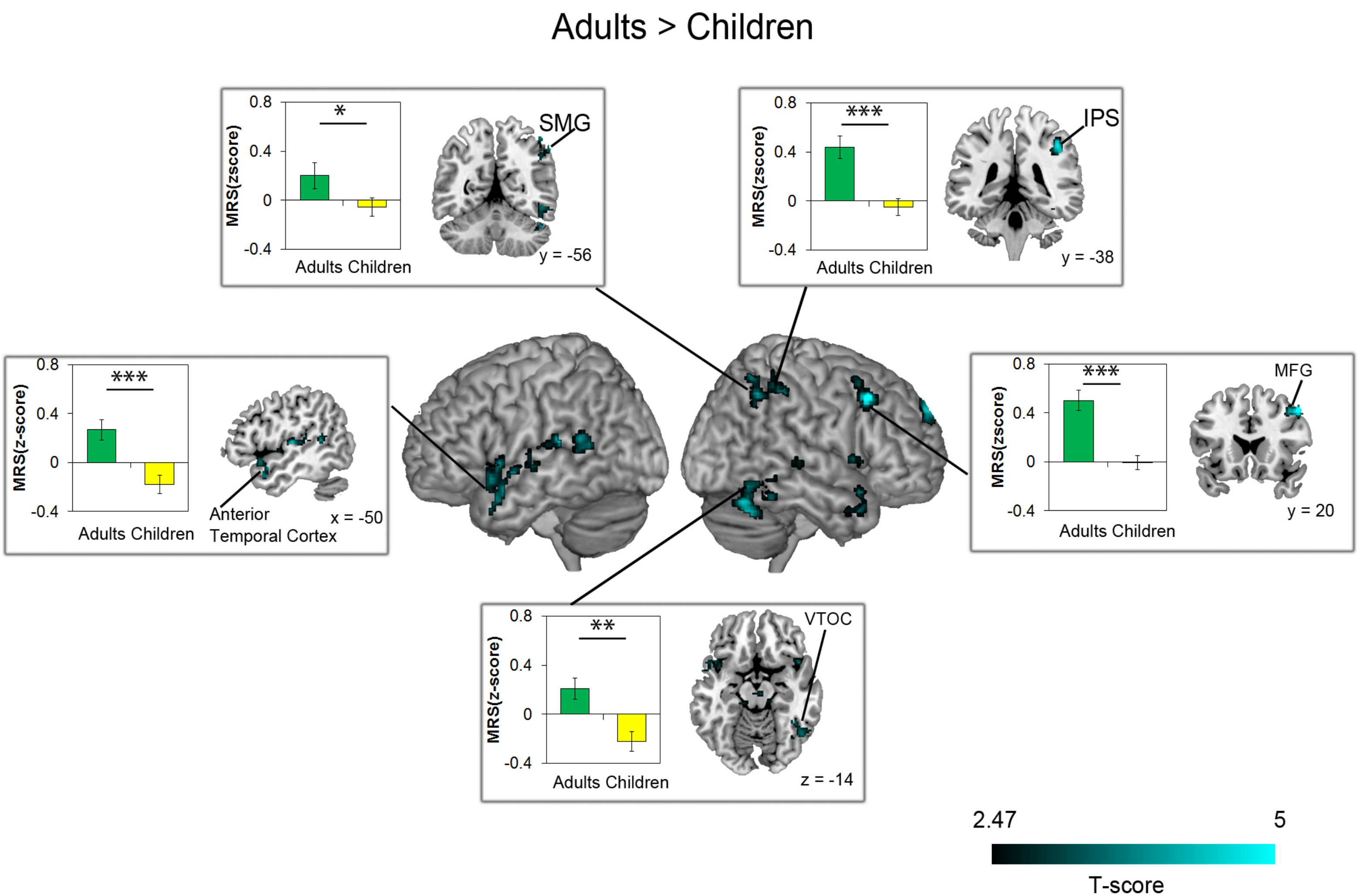
5 - 1 = 4
4 – 1 = 3
6 – 1 = 7

Control

Chang et al. (under review)

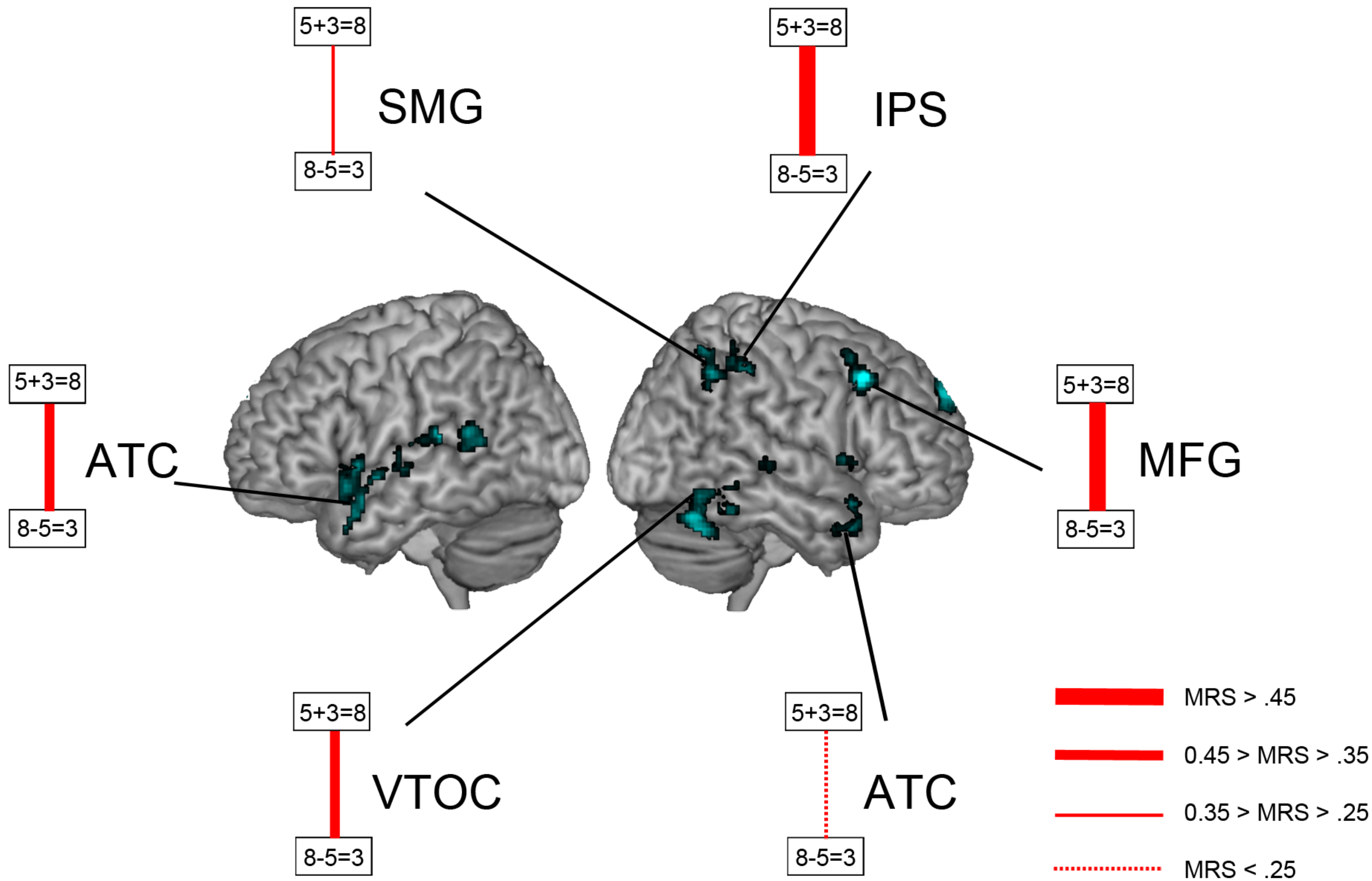

Multivariate Representational Similarity (MRS)
5 + 2 = 7
9 - 4 = 5
Response Patterns
Conventional Activation Analysis
Mean = 5
Mean = 5
MRS
Whole-brain Searchlight Method

MRS - whole brain

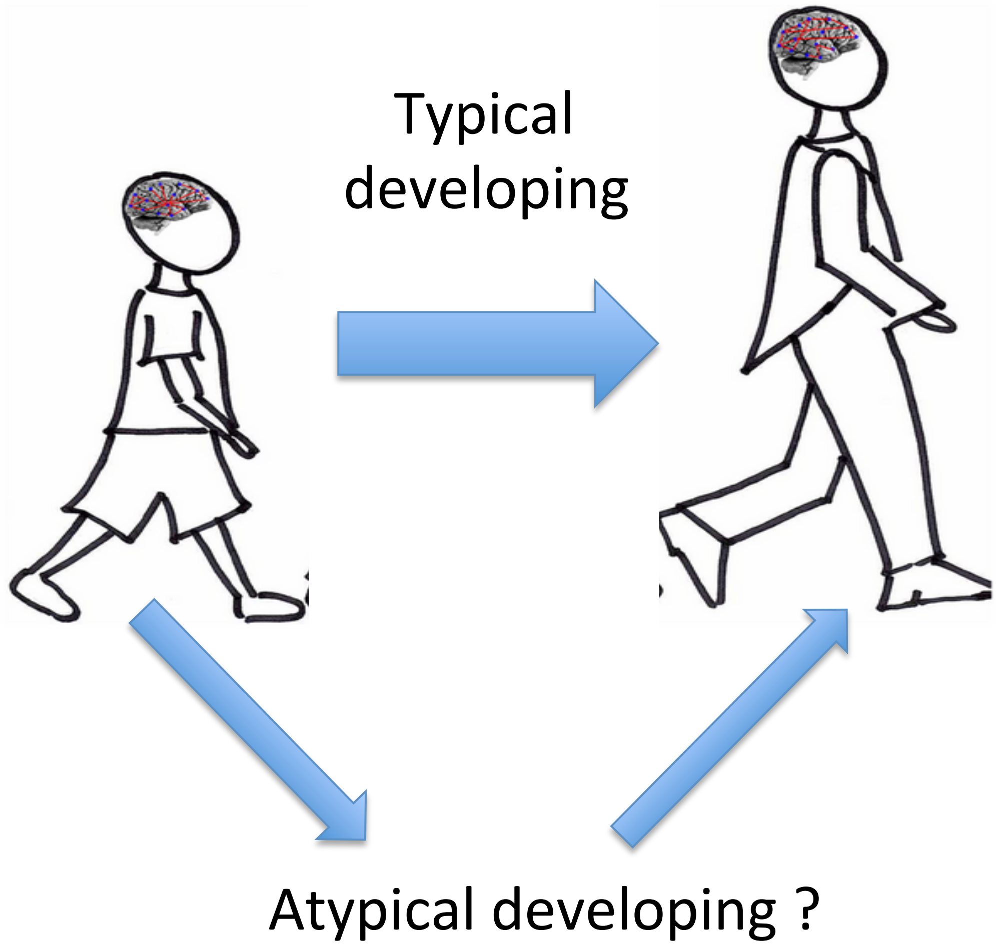


Chang et al. (under review)

Developmental effect in MRS

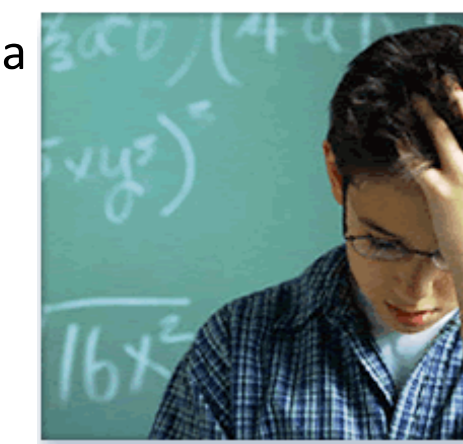


What about atypical developing?



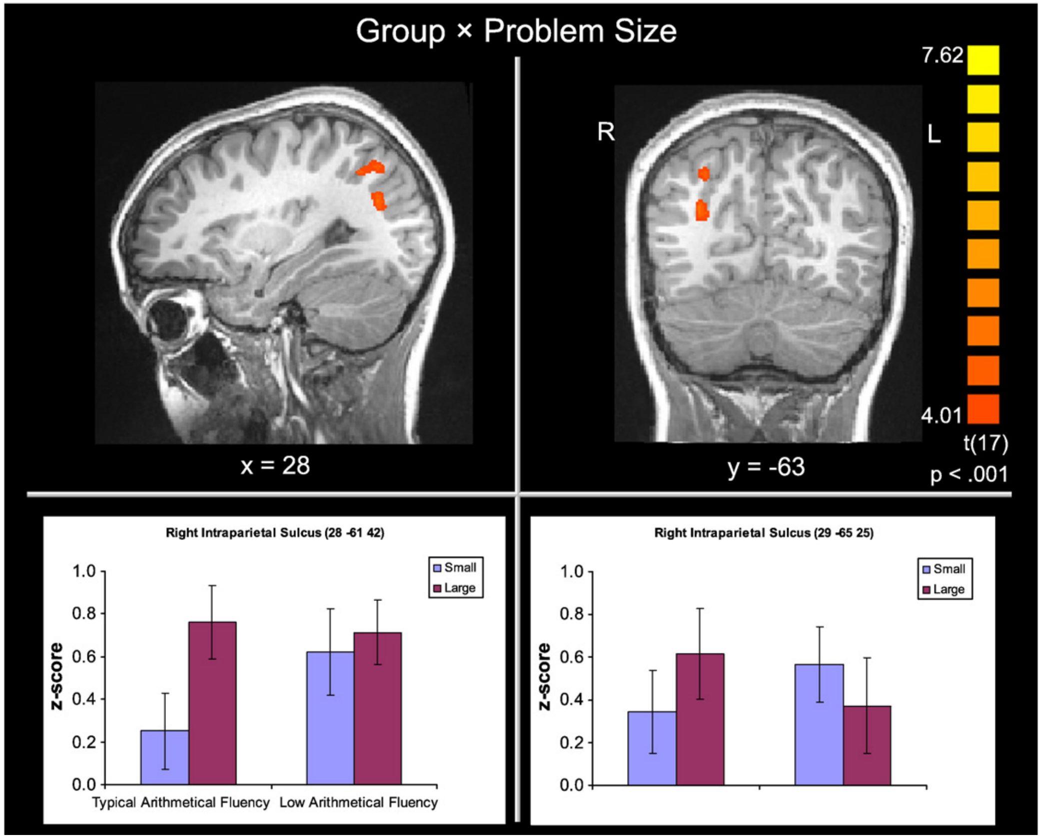
Developmental Dyscalculia (DD)

- DD is a specific learning disability affecting the acquisition of school-level mathematical abilities in the context of otherwise normal academic achievement, with prevalence rate of 3-6% (Price et al., 2007).
- DD children show persistent deficits in mathematical skill.
  - longitudinal study of 140 11-yr old children with DD (Shalev et al., 2005)
    - After 3 years, 95% of the group still meet DD criteria
    - After 6 years,
      - 51% could not solvle 7 X 8 (vs. 17% of controls)
      - 71% could not solve 37 X 24 (vs. 27%)
      - 49% could not solve 45 X 3 (vs. 15%)
      - 63% could not solve 5/9 + 2/9 (vs. 17%)

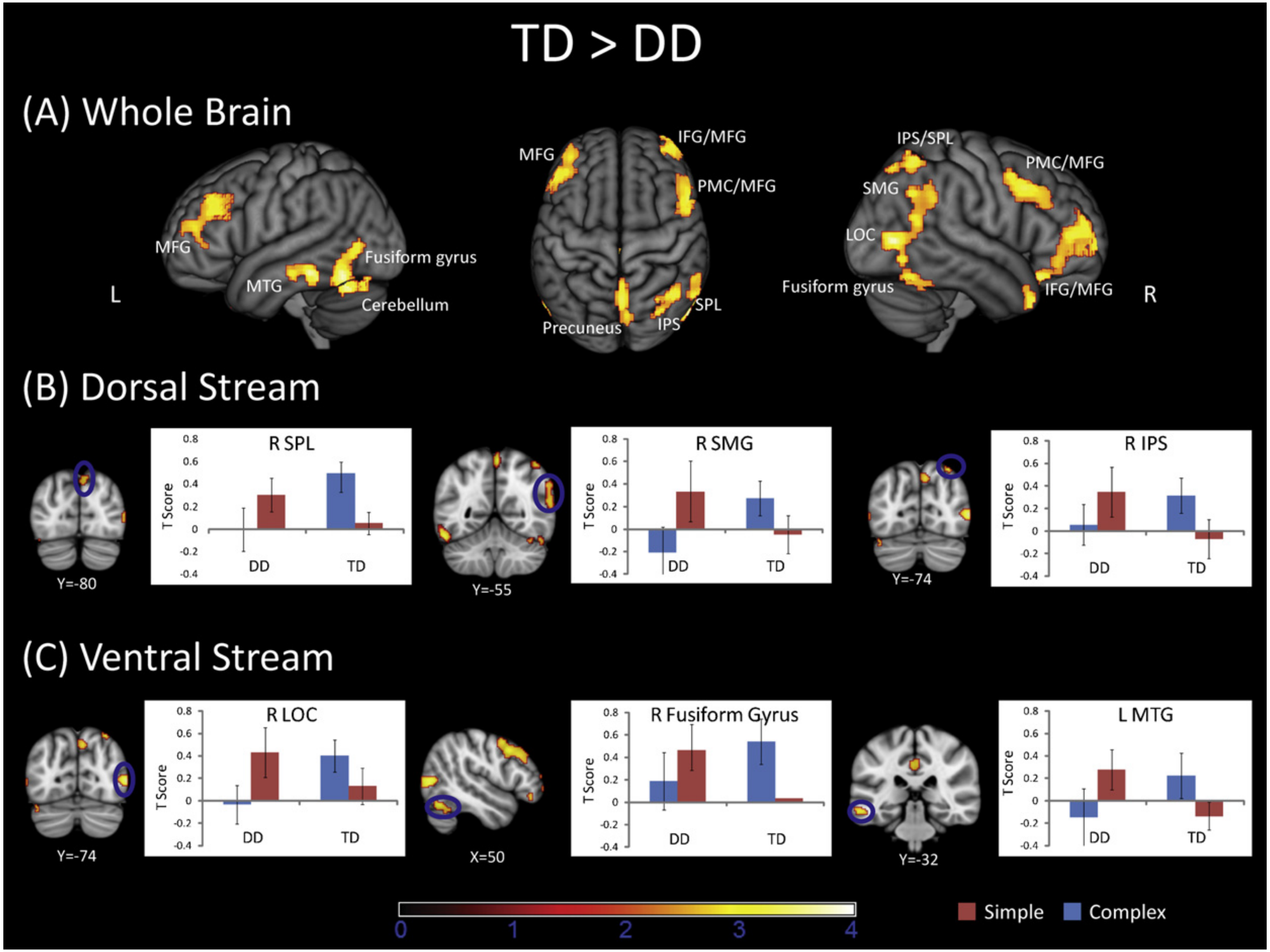


Children with low math skill

- fMRI study of complex and simple addition and subtraction problem
- 10-12 year old children



DeSmedt et al. (2011)



Ashkenazi et al. (2012)

Summary

- PPC is consistently implicated in mental arithmetics.
  - PPC has distinct function in mathematical cognition.
  - PPC is modulated by mathematical competence and strategy use.
- Development profile of PPC
  - developmental shift from PFC to PPC in mathematical cognition
  - Heterogeneous developmental trajectory of PPC
  - Neural representations of PPC converge between distinct problem types.
- Children with developmental dyscalculia
  - Show persistent deficit in mathematical skill
  - fail to generate distinct representation between different problem types.