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Hippocampal-neocortical functional reorganization underlies children's cognitive development:

Insights from maturation of arithmetic problem solving skills

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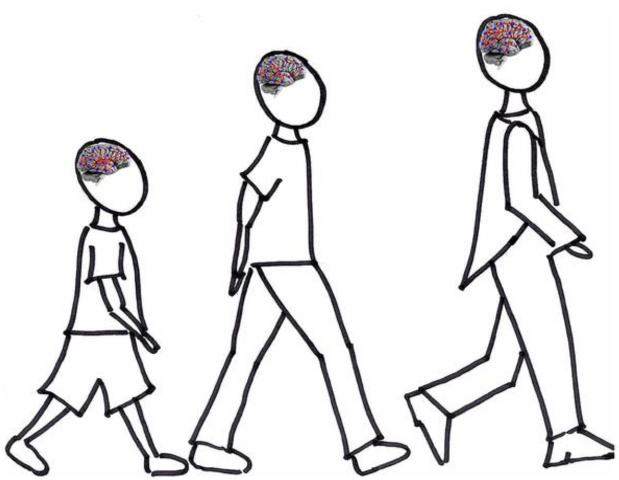
Introduction

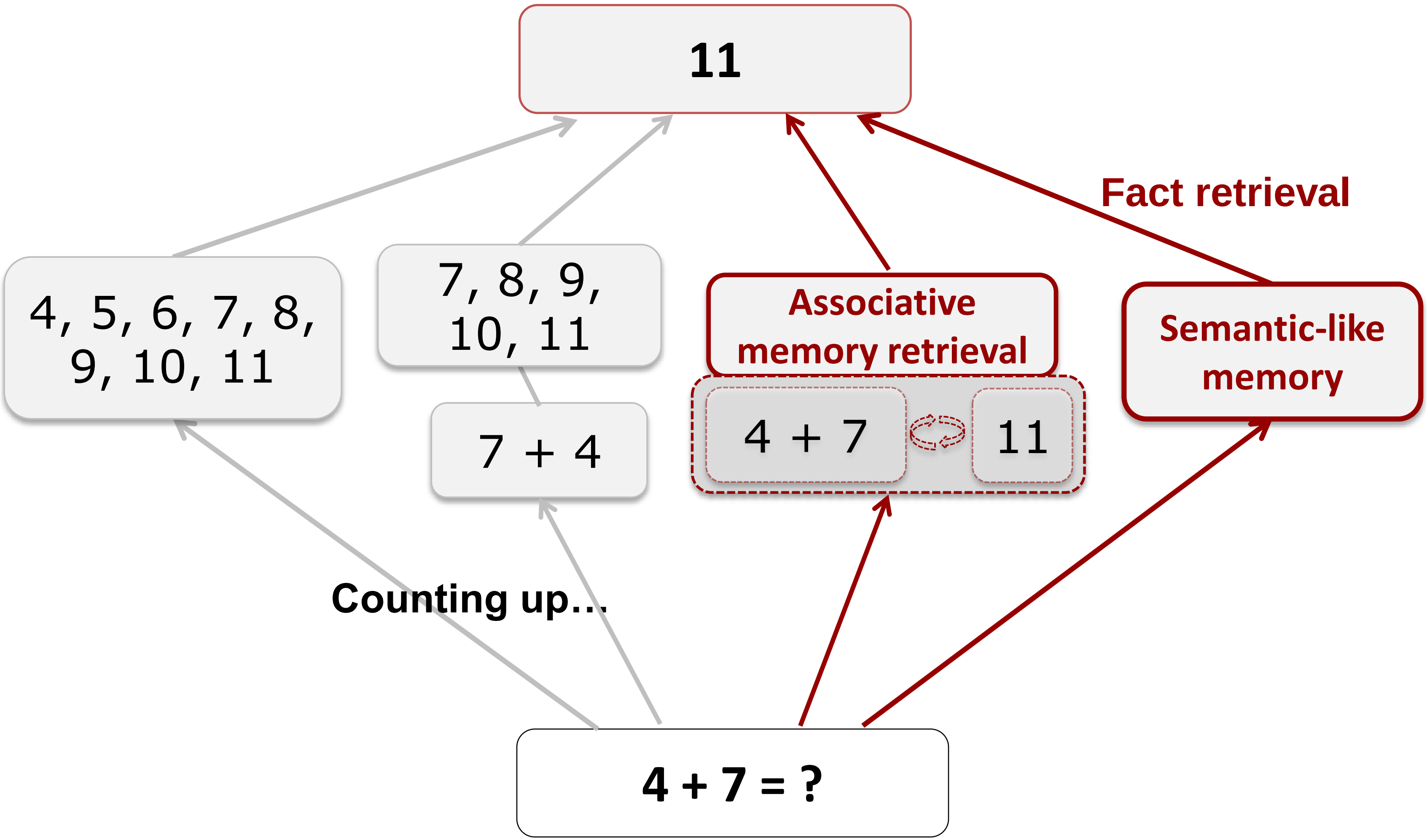
- **The ability to efficiently retrieve basic facts from memory and bring them to bear into ever-changing situations is a cardinal feature of children's cognitive development.**
  (Siegler, 1996; Geary, 2006)



- **Little is known about how this ability develops as the brain matures from childhood through adolescence into adulthood?**

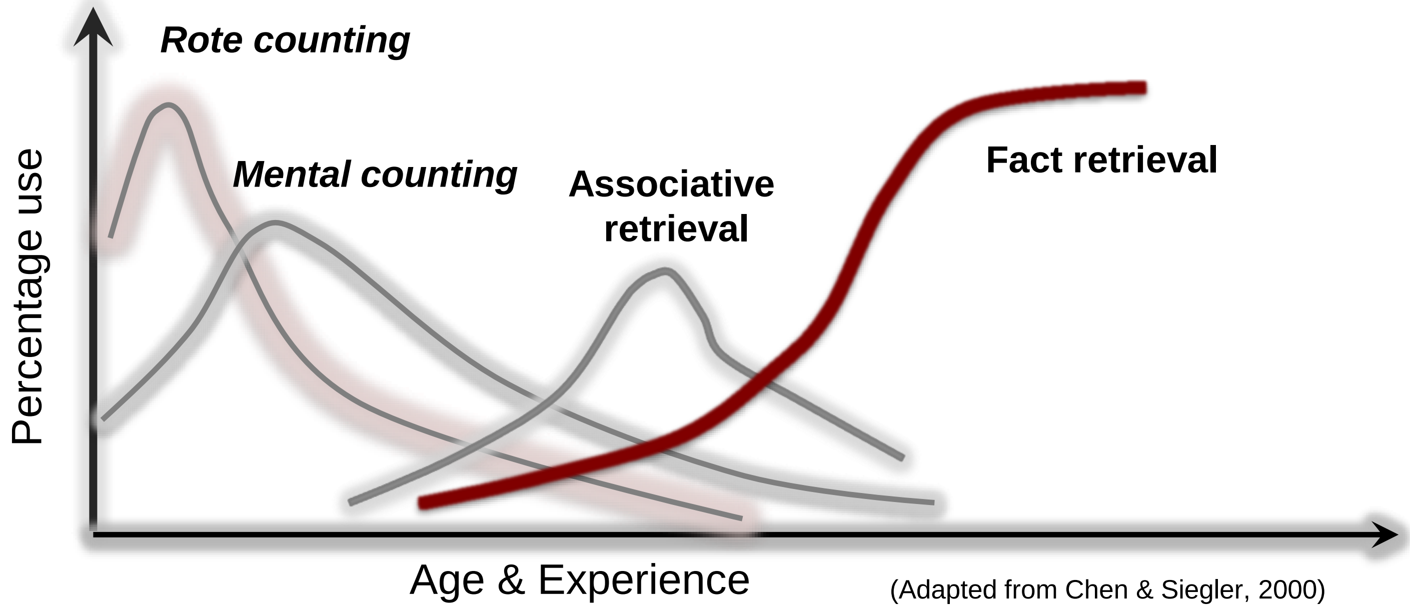
Introduction

Children’s mix of multiple strategies in arithmetic problem solving



Introduction

Overlapping waves theory in children's arithmetic problem solving

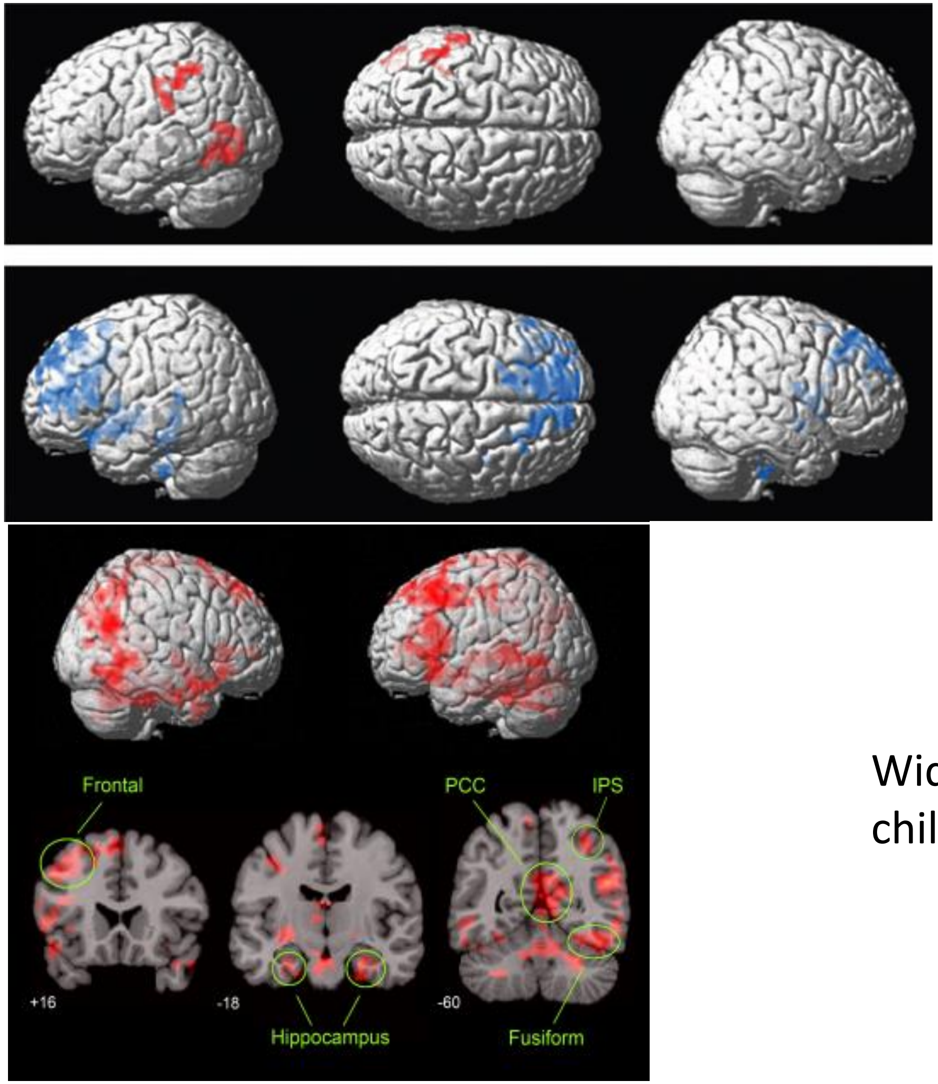


(Adapted from Chen & Siegler, 2000)

- Over development, children become more dependent on **memory-based retrieval** of math facts and less dependent on effortful counting strategies.
- These transitions are associated with **high inter-trial variability in RTs** during childhood, become refined and more stable through adolescence into adulthood.

Introduction

Neural correlates of arithmetic problem solving in children and adults



Increase with age
(ages 8 - 20 yrs)

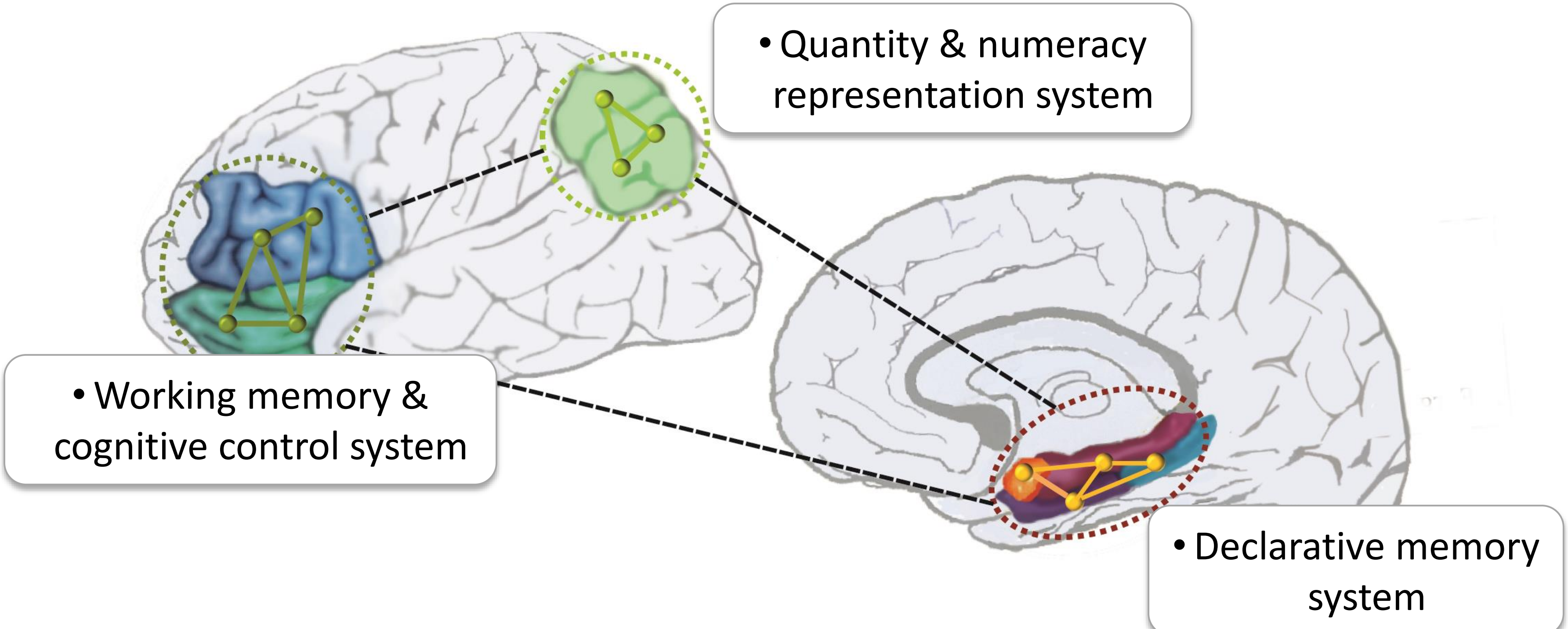
Decrease with age
(ages 8 - 20 yrs)

Widely-distributed brain activation in children (ages 7 – 9 yrs)

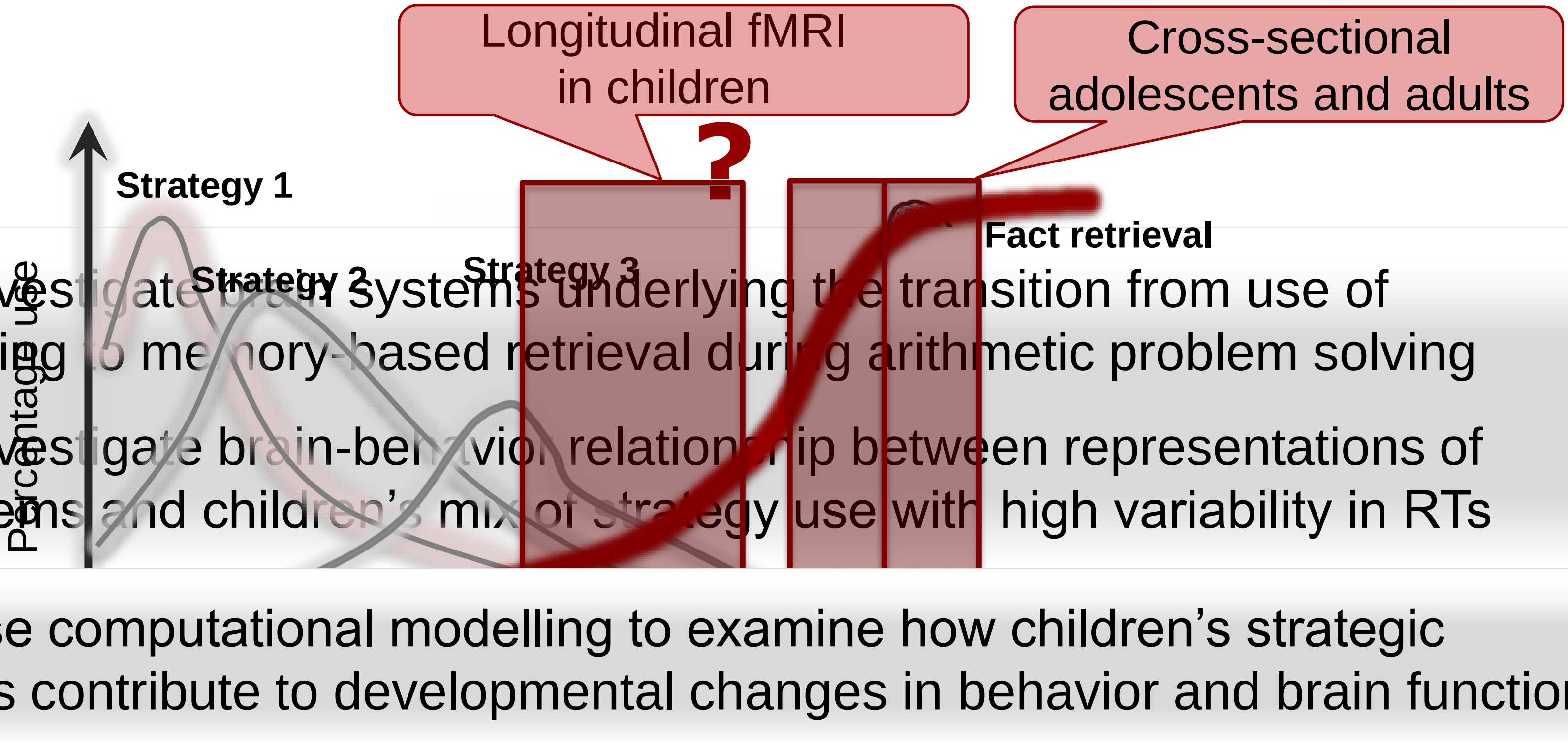
Rivera et al., 2005; Cho et al., 2010;
Rosenberg-Lee et al., 2011; Menon, 2014

Experimental Questions

Neural correlates of arithmetic problem solving in children and adults



Aims



Aim 1: Investigate brain systems underlying the transition from use of counting to memory-based retrieval during arithmetic problem solving

Aim 2: Investigate brain-behavior relationship between representations of problems and children's mix of strategy use with high variability in RTs

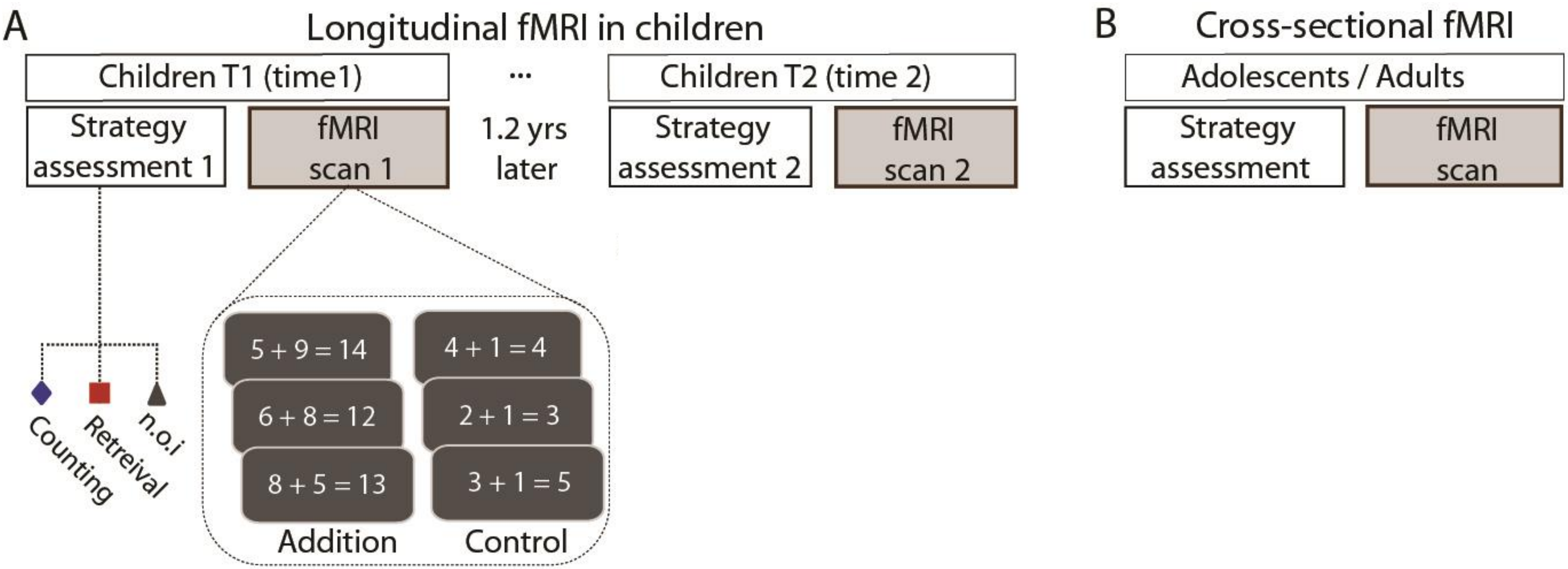
Aim 3: Use computational modelling to examine how children's strategic transitions contribute to developmental changes in behavior and brain function

Aim 1: Experimental Design

- Participants

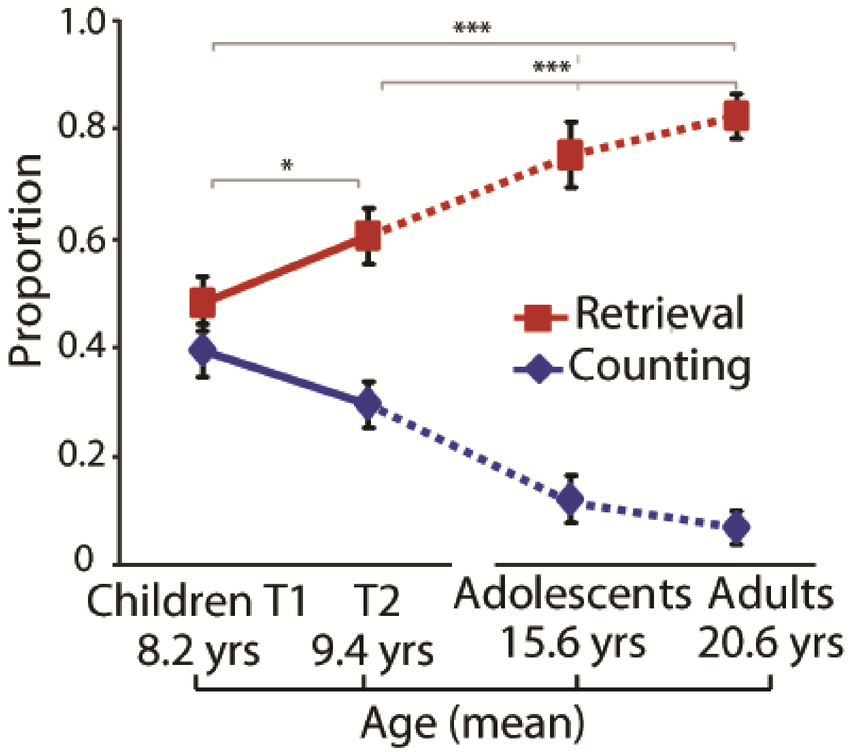
  28 young children (aged 7–9 year-old at Time 1; aged 9–11 at Time 2)

  20 adolescents (aged 15–17) ; 20 adults (aged 19–22)



Aim 1: Behavioral Results

Developmental changes in strategy use during problem solving

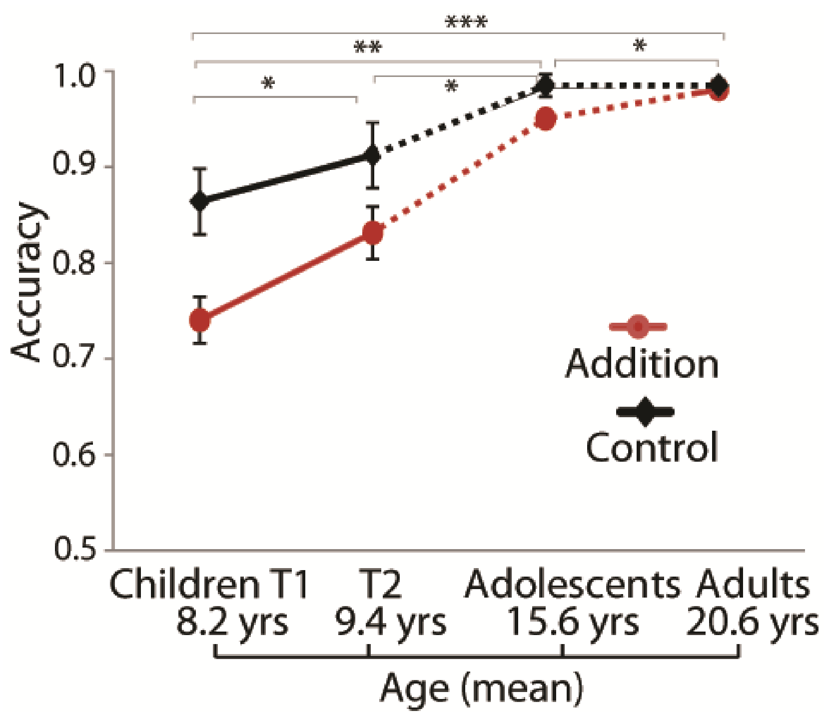


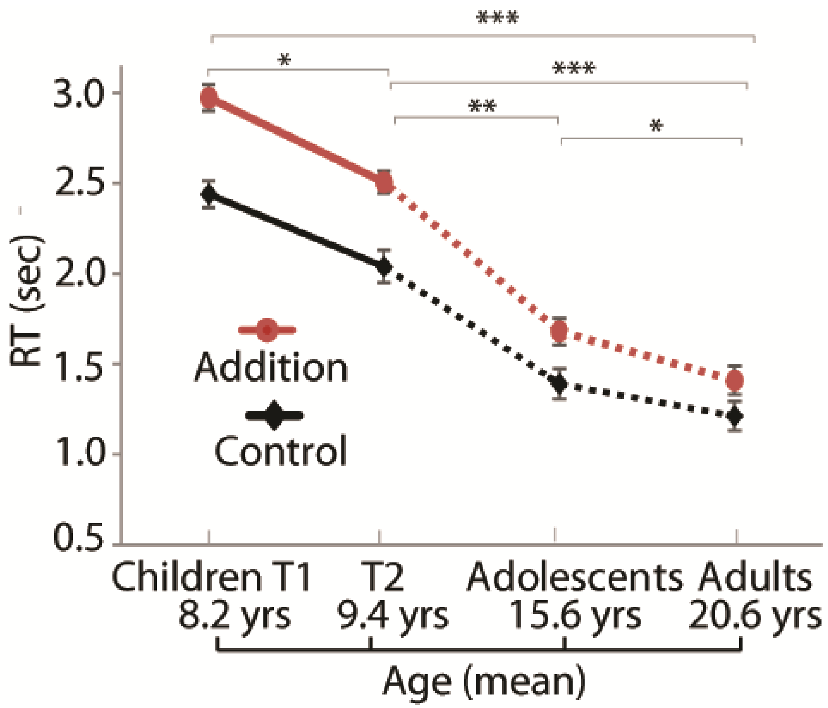
- Over a 1.2-year period children became more dependent on memory-based strategy use and less dependent on effortful counting strategies.
- This pattern continues to improve during adolescence and adulthood.

@Qin et al., 2014 Nat Neurosci.

Aim 2: Behavioral Results

Developmental changes in accuracy and RTs during problem solving



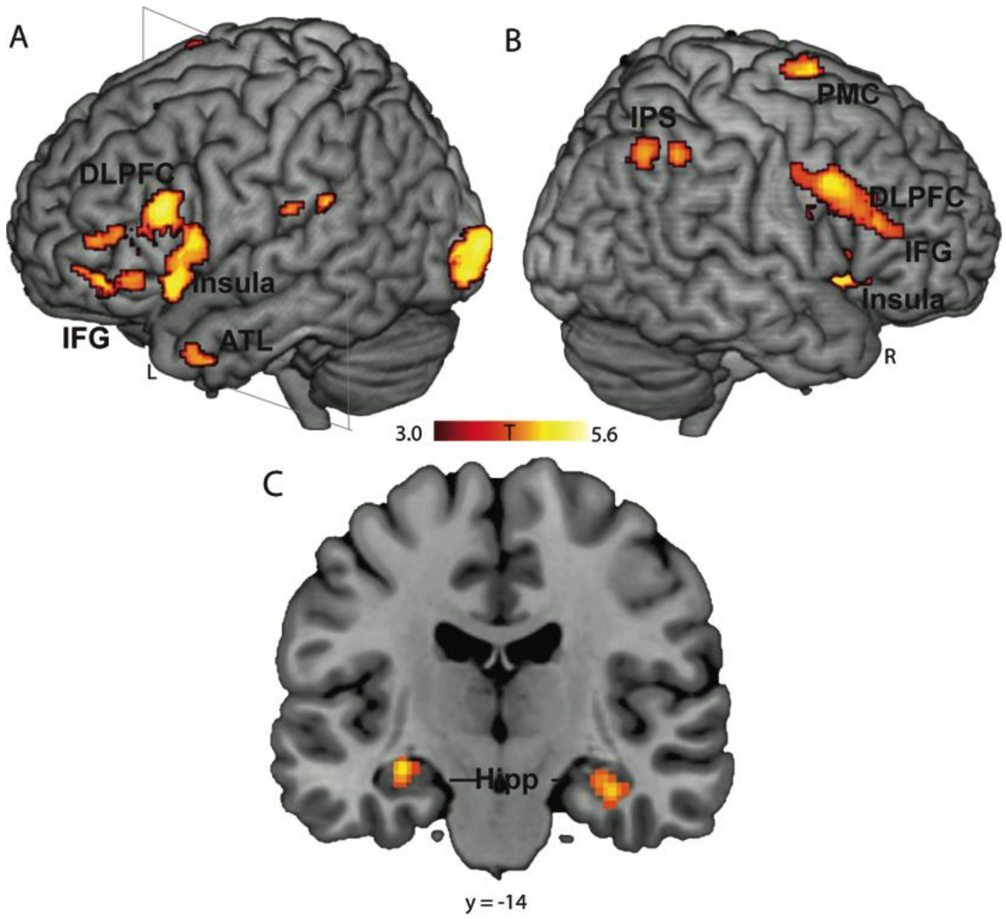


- Over a 1.2-year period children's accuracy and RTs in problem solving significantly improved.
- This pattern continues to improve in adolescence and adulthood.

@Qin et al., Nat. Neurosci.

Aim 1: Neuroimaging Results

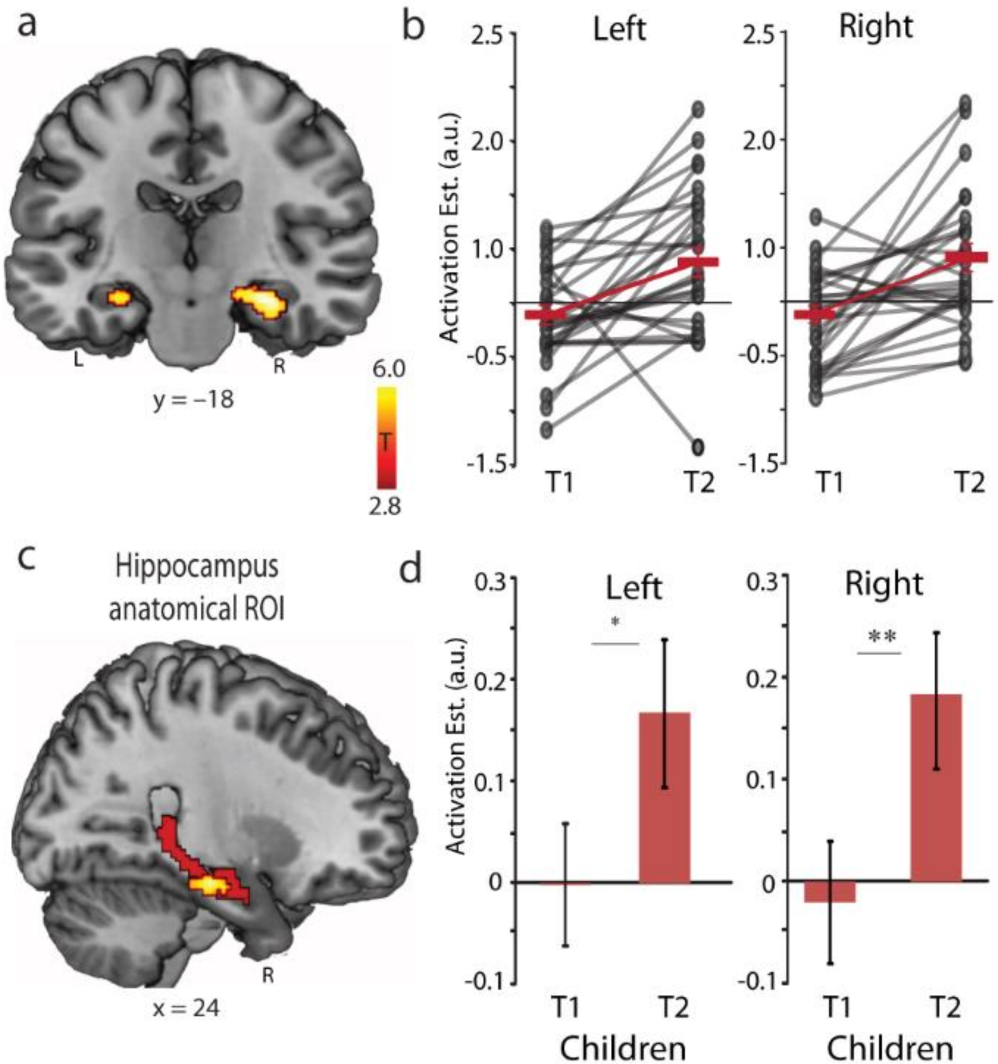
Brain systems involved in solving addition problems during childhood



@Qin et al., 2014 Nat Neurosci.

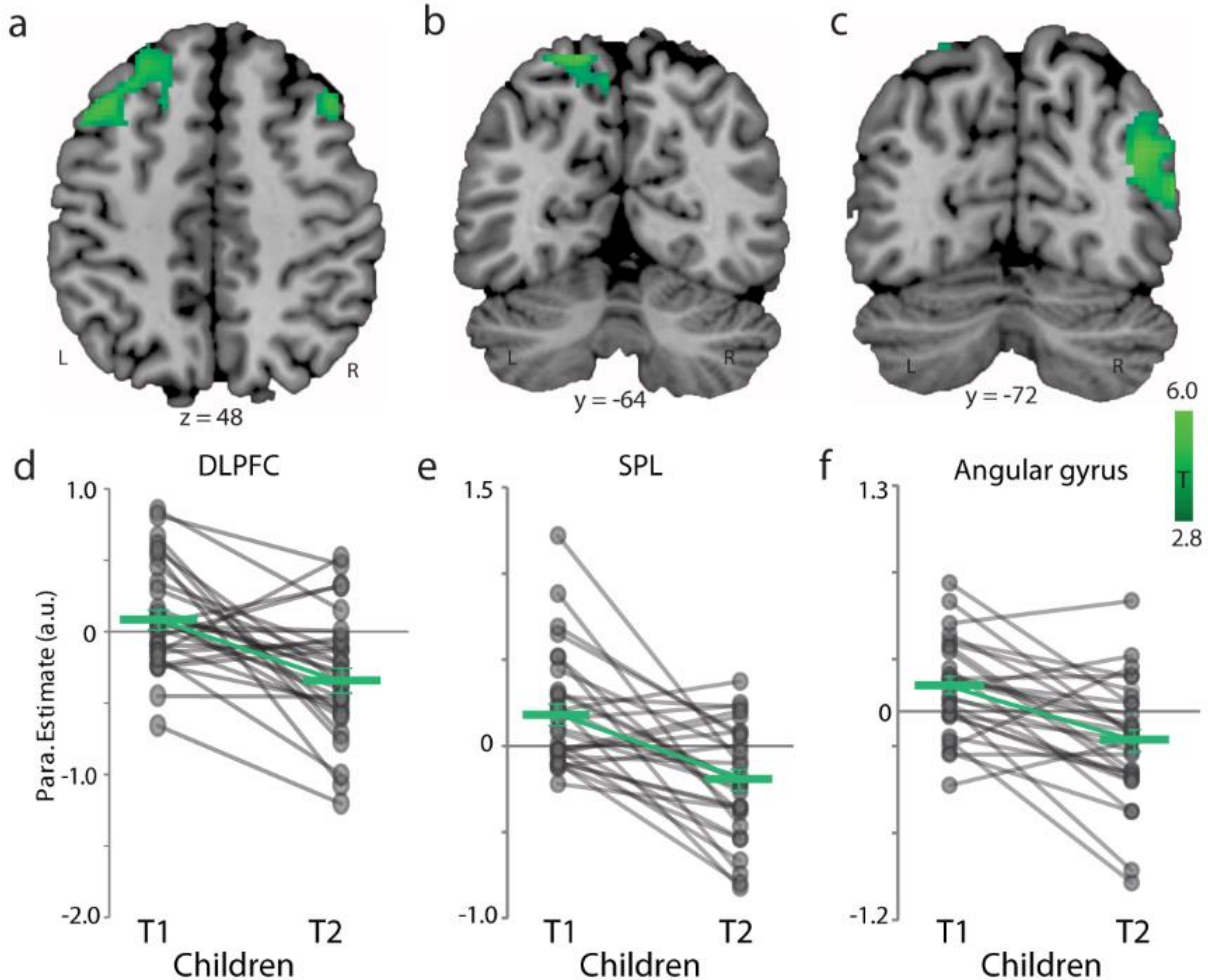
Aim 1: Neuroimaging Results

Longitudinal increase in hippocampal engagement during problem solving



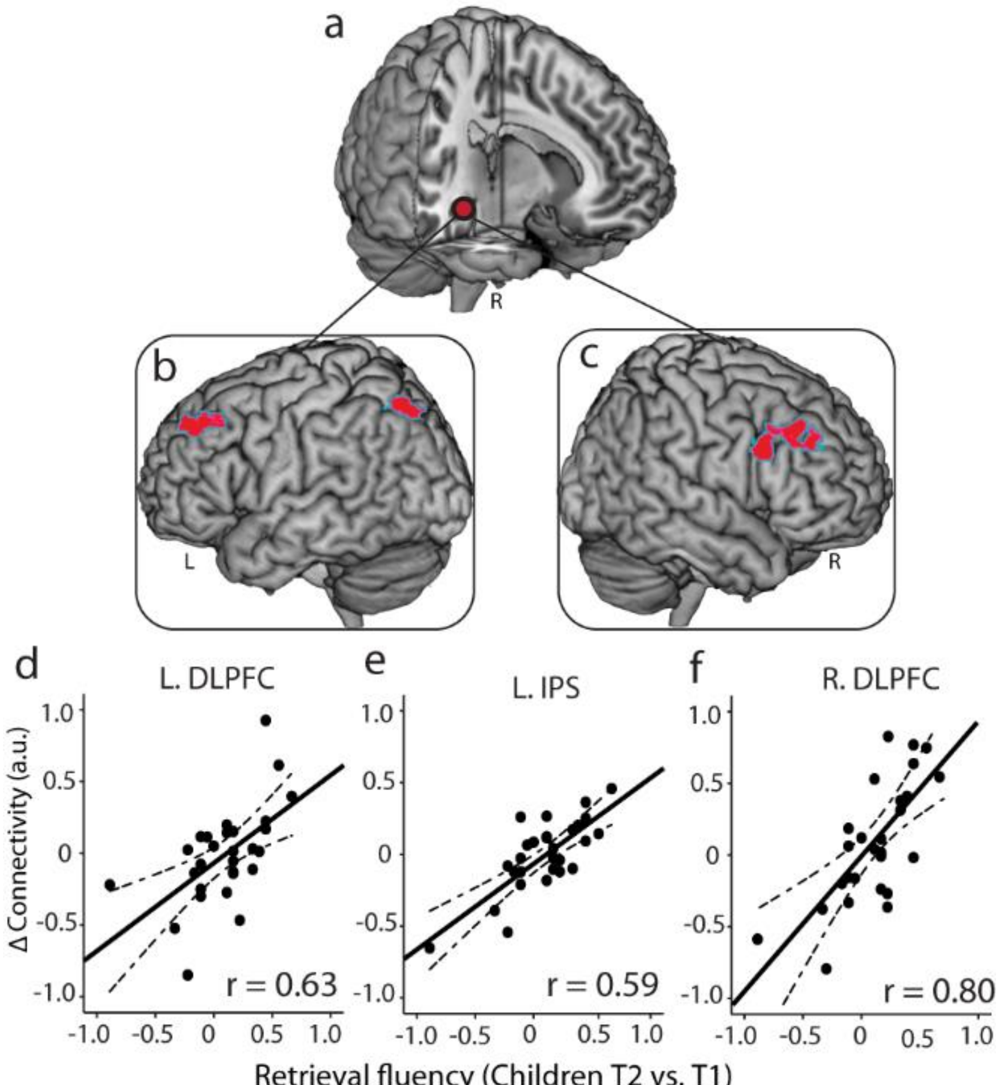
Aim 1: Neuroimaging Results

Longitudinal decrease in prefrontal-parietal engagement during problem solving



Aim 1: Neuroimaging Results

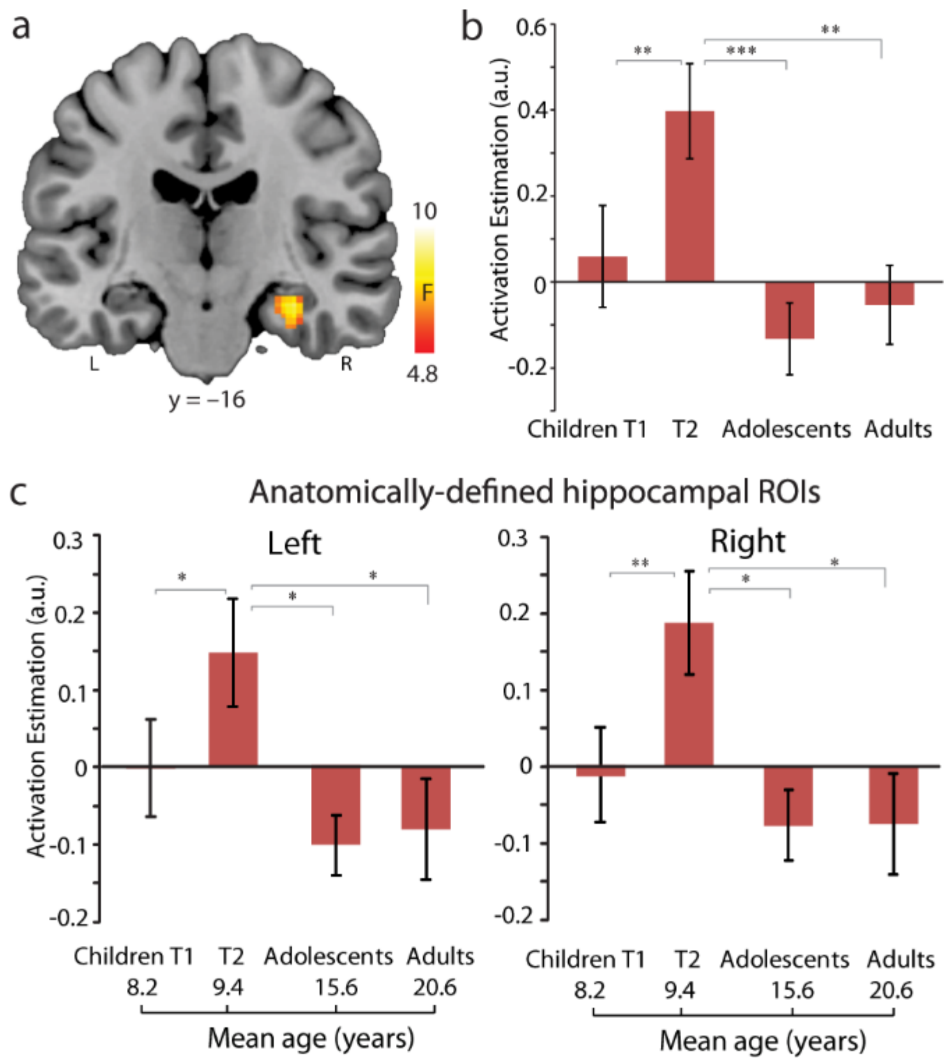
Longitudinal changes in hippocampal-neocortical connectivity predict improvement in retrieval-strategy use



@Qin et al., 2014 Nat Neurosci.

Aim 1: Neuroimaging Results

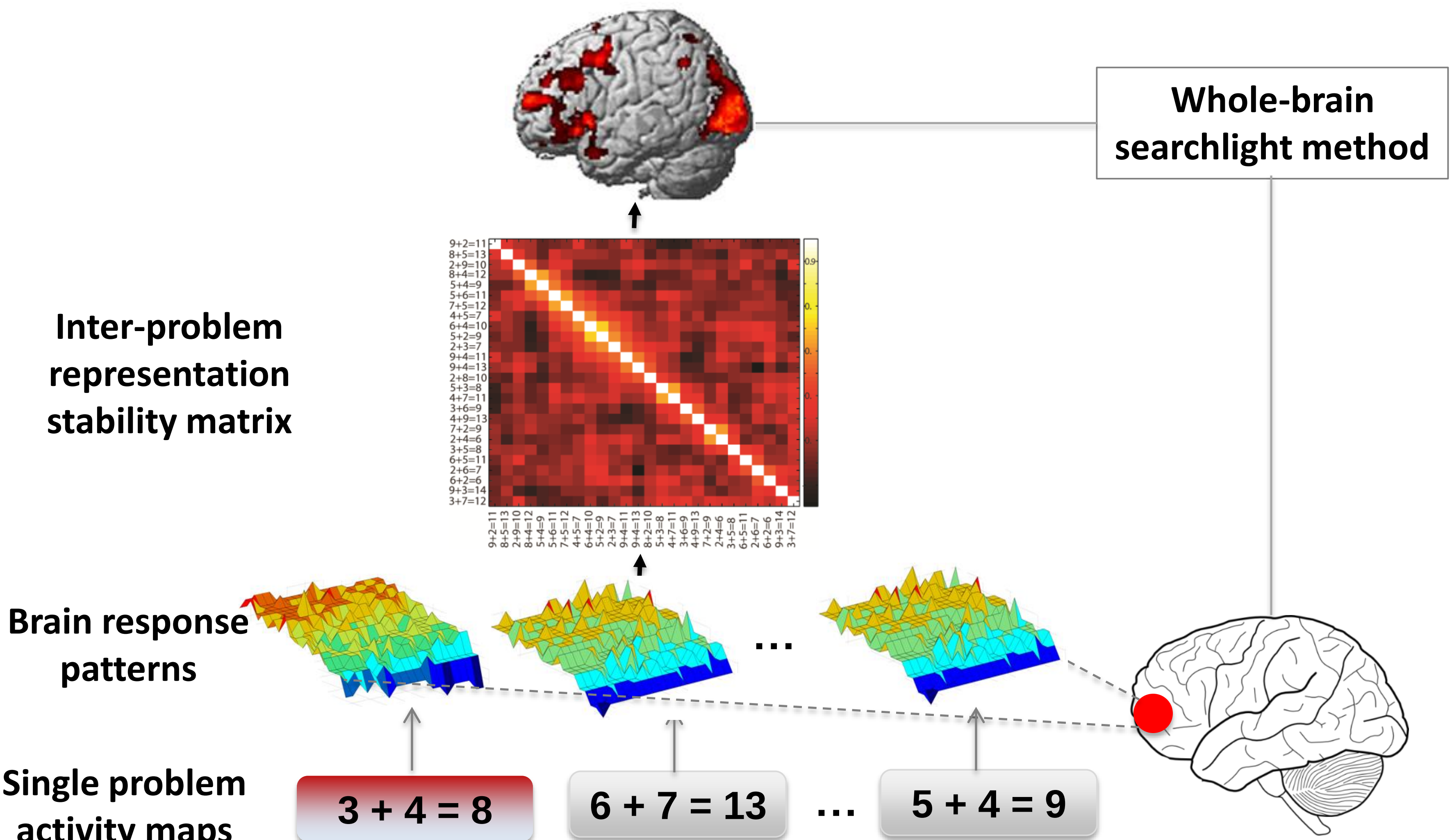
Non-linear developmental changes in hippocampal engagement from childhood through adolescence into adulthood



@Qin et al., 2014 Nat Neurosci.

Aim 1: Neuroimaging results

- **Trial-wise analysis of inter-problem multivoxel representation stability**

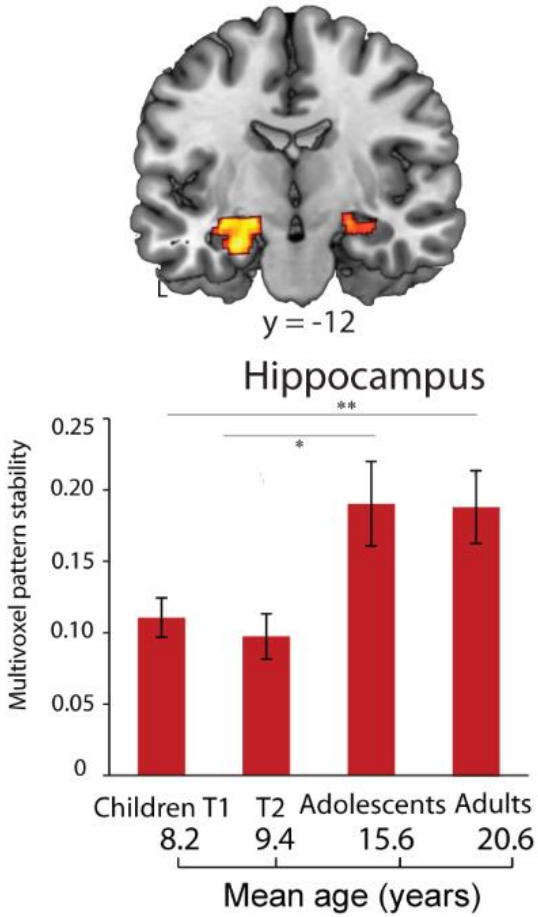


Aim 1: Neuroimaging Results

No significant longitudinal changes in inter-problem multivoxel representation stability between T1 and T2 during childhood

Aim 1: Neuroimaging Results

Developmental changes in representation stability from childhood to adulthood



- Over a 1.2-year period children's inter-problem representation stability remains no significant changes, but become more stable in adolescence and adulthood.

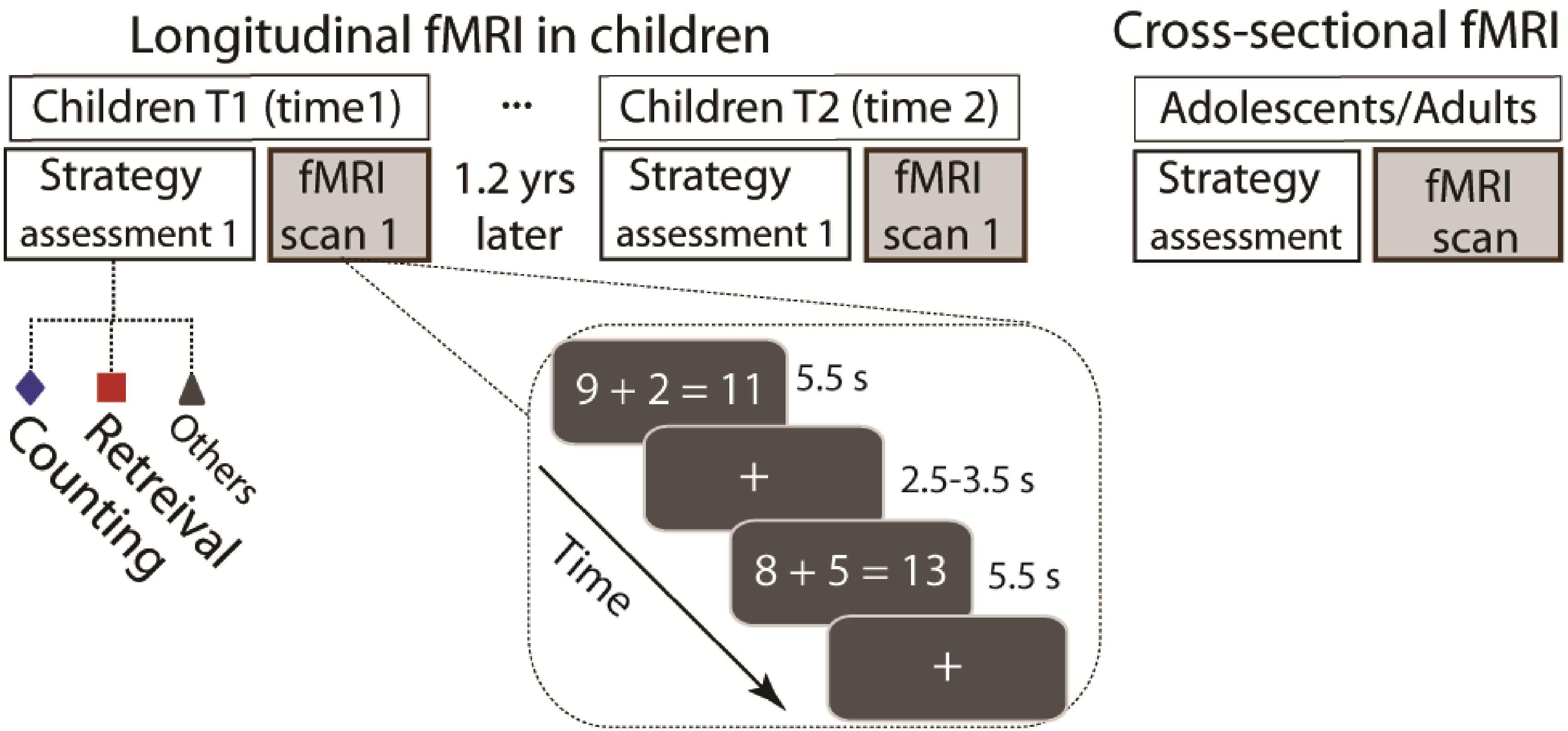
Aim 1: Investigate brain systems underlying the transition from use of counting to memory-based retrieval during addition problem solving

Aim 2: Experimental Design

- **Participants**

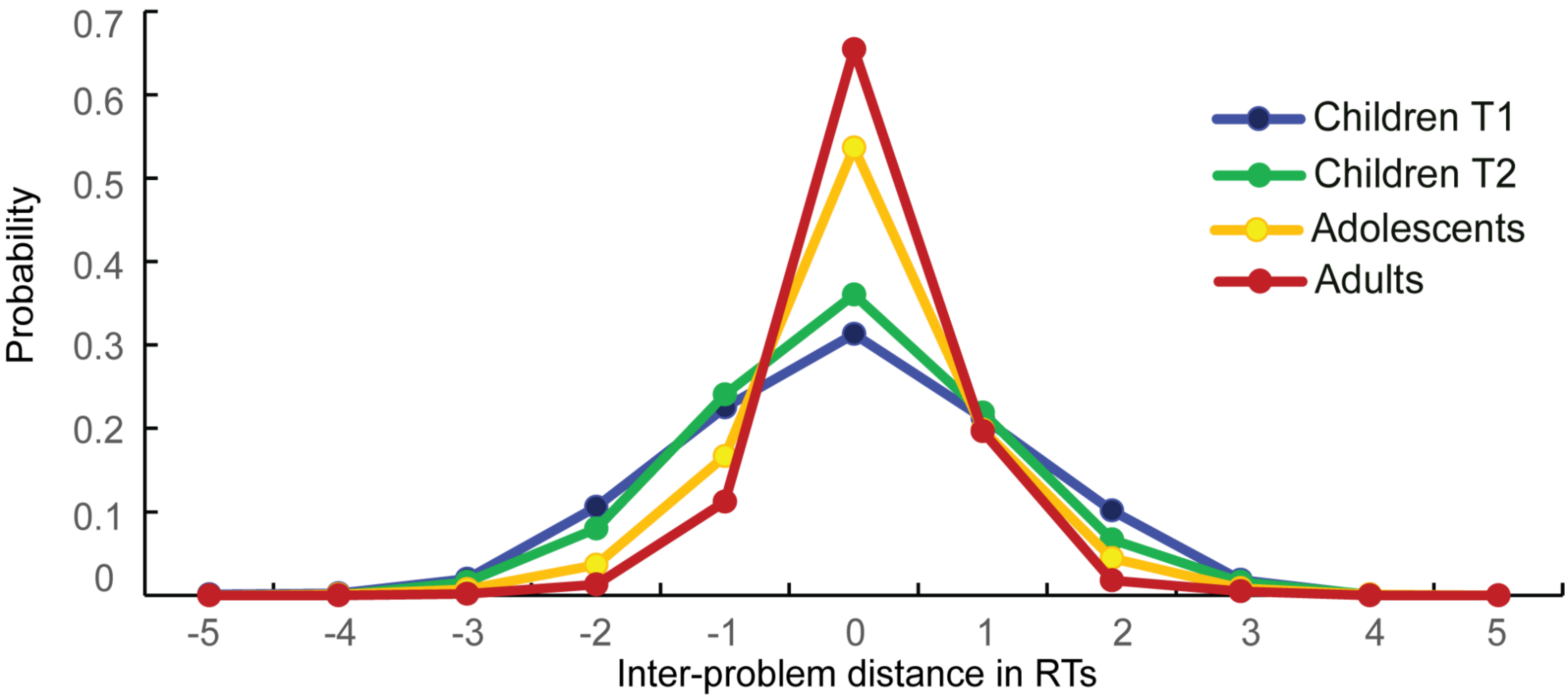
  20 young children (aged 7–9 year-old at time1, 9-11 year-old at time2)

  20 adolescents (aged 15–17); 20 adults (aged 19–22)

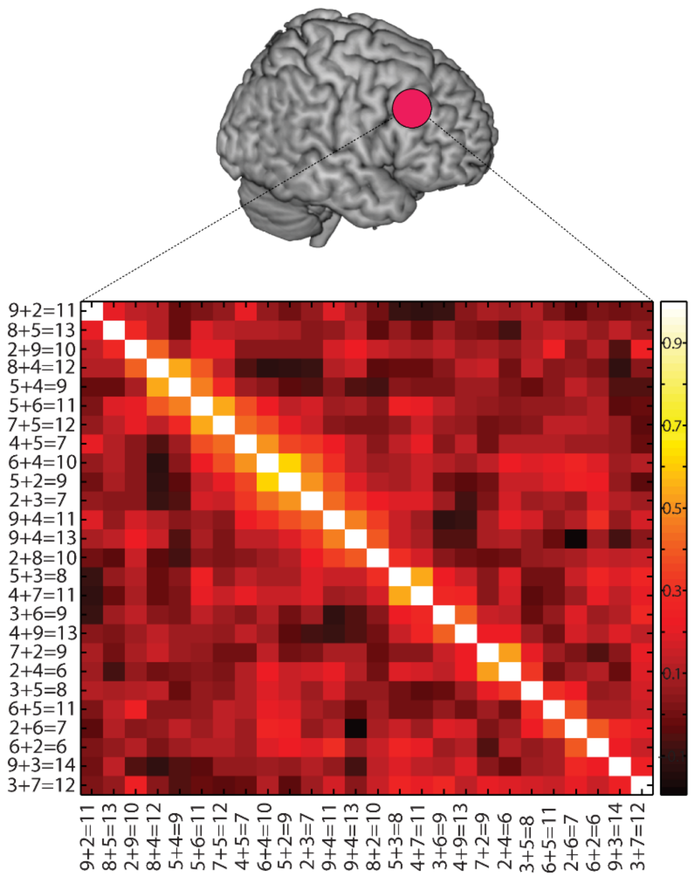


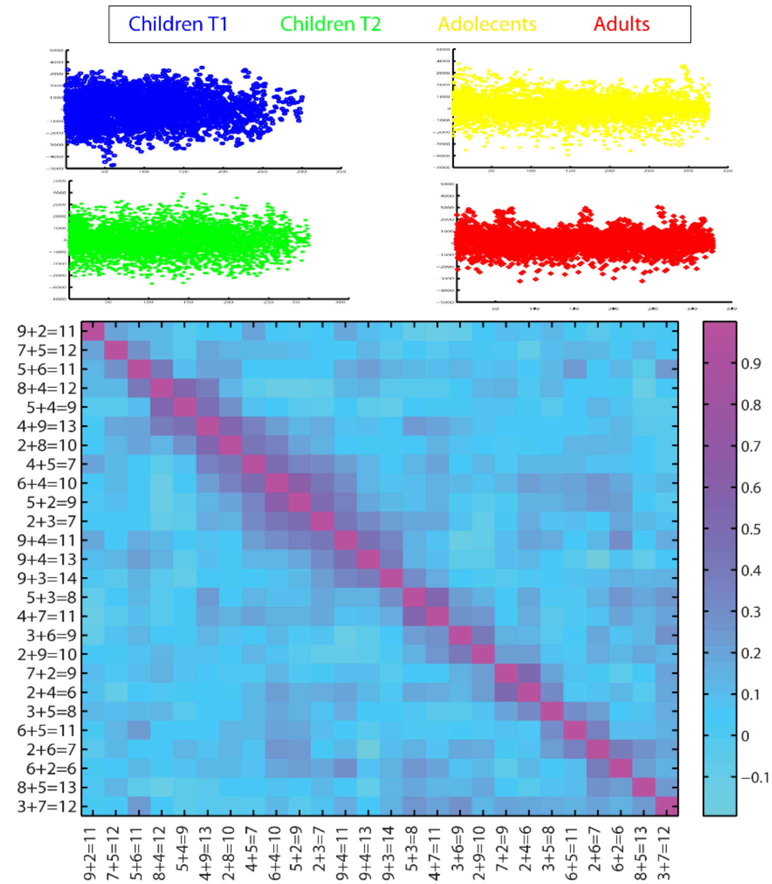
Aim 2: Behavioral Results

Developmental changes in inter-problem variability in RTs



Aim 2: Brain-Behavior Correlation Analysis





X = Inter-problem representation stability

Y = Inter-problem variability in RTs

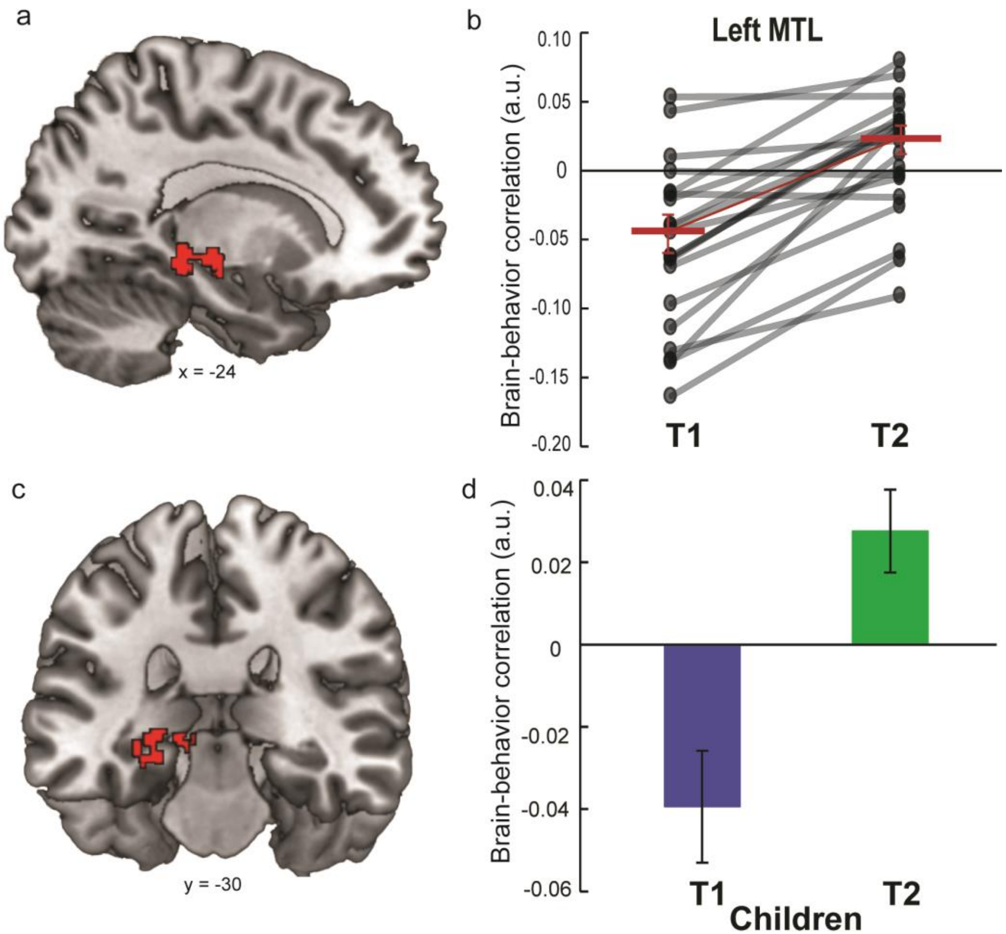
corr(X, Y)

Whole brain-behavior relationship analysis

@Qin et al., In Preparation

Aim 2: Neuroimaging Results

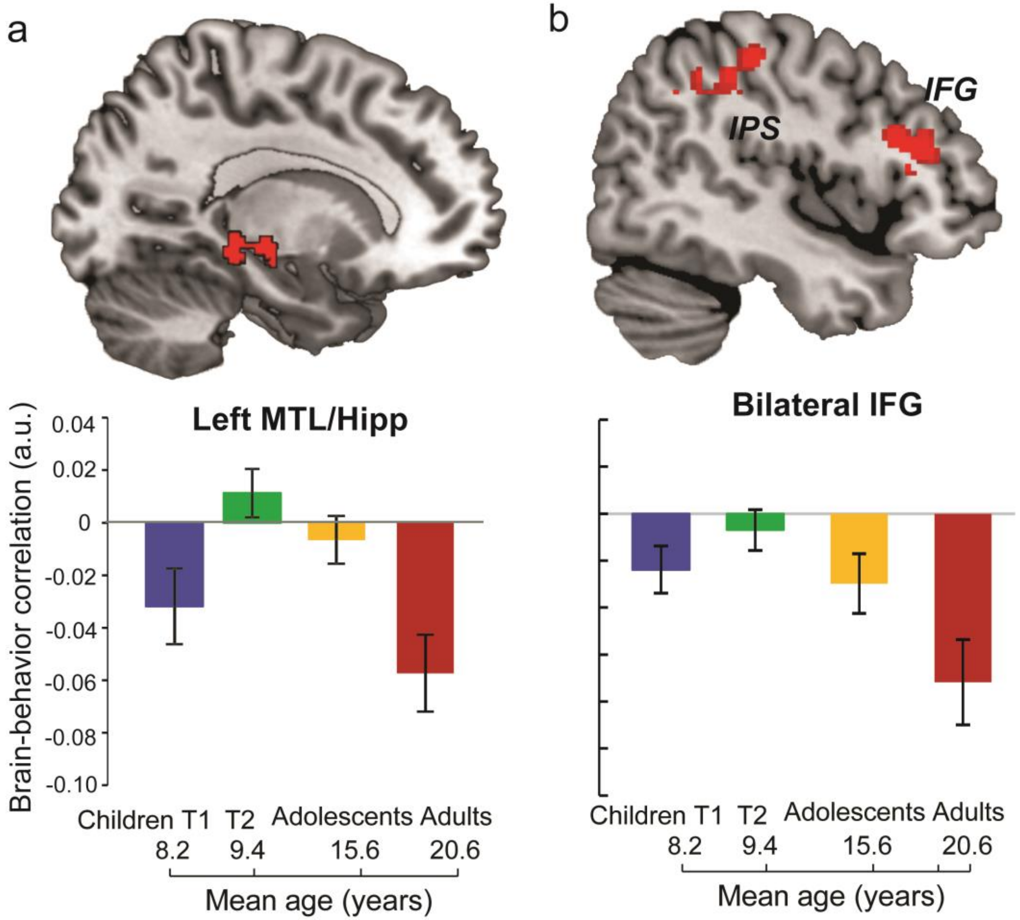
Longitudinal increases in brain-behavior correlation in MTL during childhood



- Over a 1.2-year period children showed greater brain-behavior correlation between inter-problem representation stability and inter-problem variability in RTs.

Aim 2: Neuroimaging Results

Developmental changes in inter-problem brain-behavior correlations

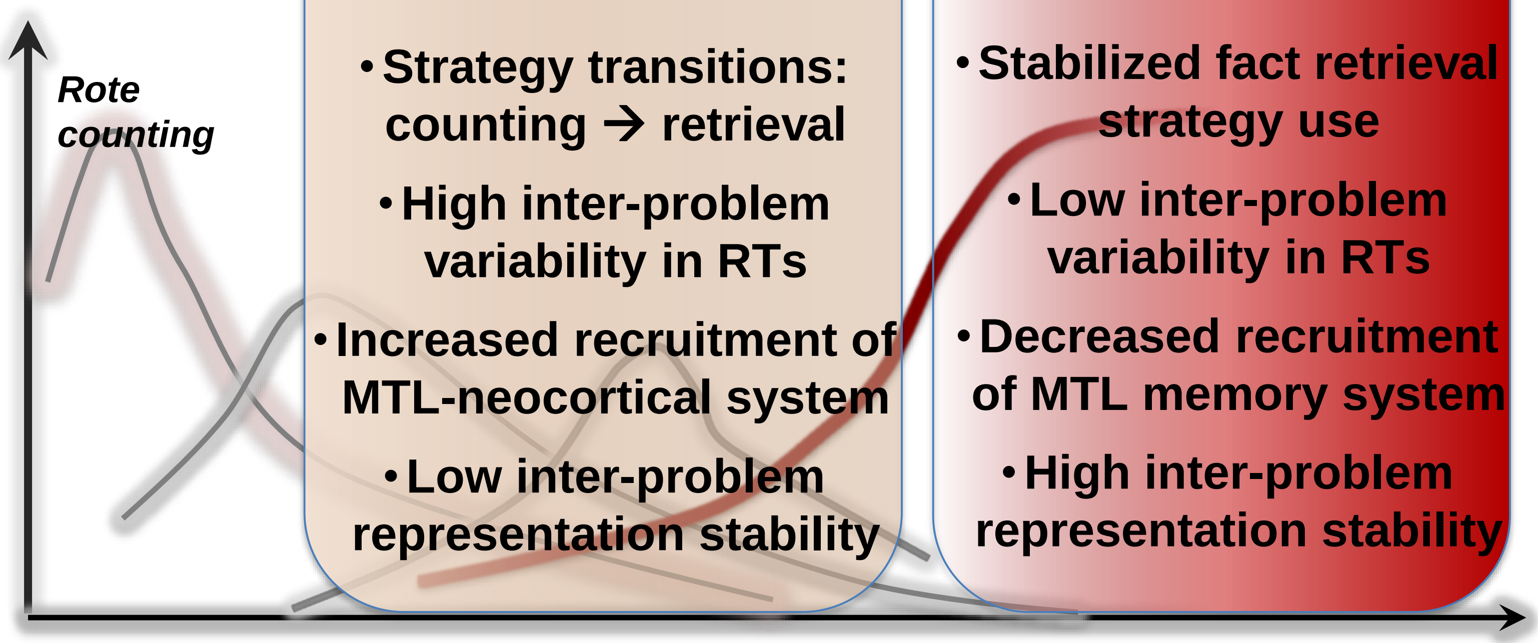


- Higher inter-problem representation stability in MTL, prefrontal and parietal systems predicts lower inter-problem variability in RTs during adolescence and adulthood.
- No significant changes in brain-behavior correlation for control problems

@Qin et al., In Preparation

Interim Summary

Neurobehavioral features of children's cognitive development



Childhood
(immature, unstable)

- **Strategy transitions: counting → retrieval**
- **High inter-problem variability in RTs**
- **Increased recruitment of MTL-neocortical system**
- **Low inter-problem representation stability**

Adulthood
(mature, stable)

- **Stabilized fact retrieval strategy use**
- **Low inter-problem variability in RTs**
- **Decreased recruitment of MTL memory system**
- **High inter-problem representation stability**

(Adapted from Chen & Siegler, 2000)

Follow-up Questions

Open questions raised from Aim 1 and Aim 2:

- How **children's strategy transitions** truly contribute to our observed developmental changes in **inter-problem variability in behavior** (RTs)?
- How this actually leads to our observed developmental changes in the brain, especially characterized by **an initial increase in hippocampal** engagement during childhood and **a subsequent decrease** through adolescence and adulthood, along with **more stable inter-problem representations?**

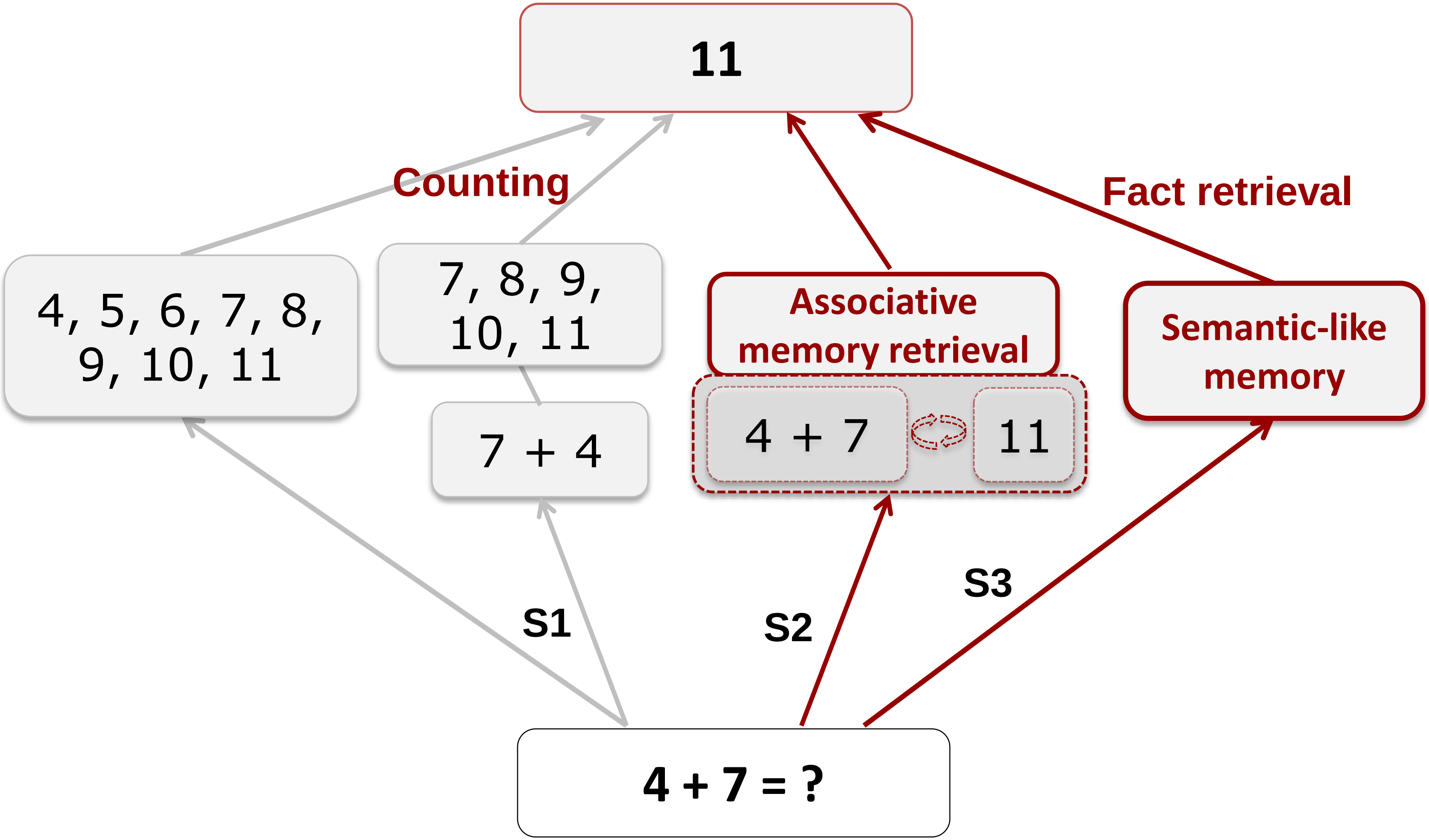
Aim 1: Investigate brain systems underlying the transition from use of counting toward memory-based retrieval to solve addition problems

Aim 2: Investigate brain-behavior relationship between representations of problems and children’s mix of strategy use as reflected by inter-problem variability in RTs)

Aim 3: Use computational modelling to examine how children’s strategic transitions contribute to developmental changes in behavior and brain function

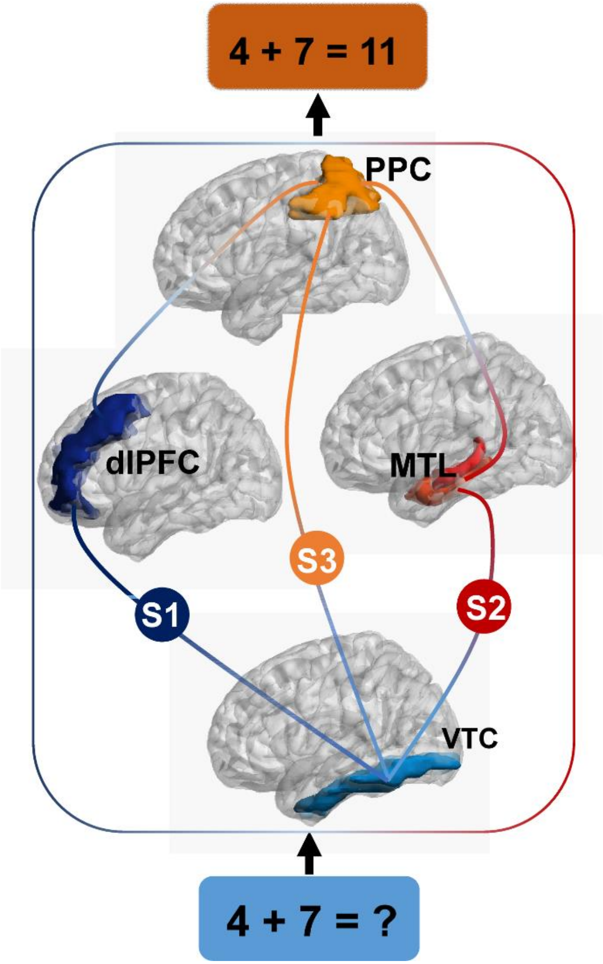
Revisit: Children's strategy transitions

Children's mix of multiple strategies in arithmetic problem solving



Aim 3: Model Specification

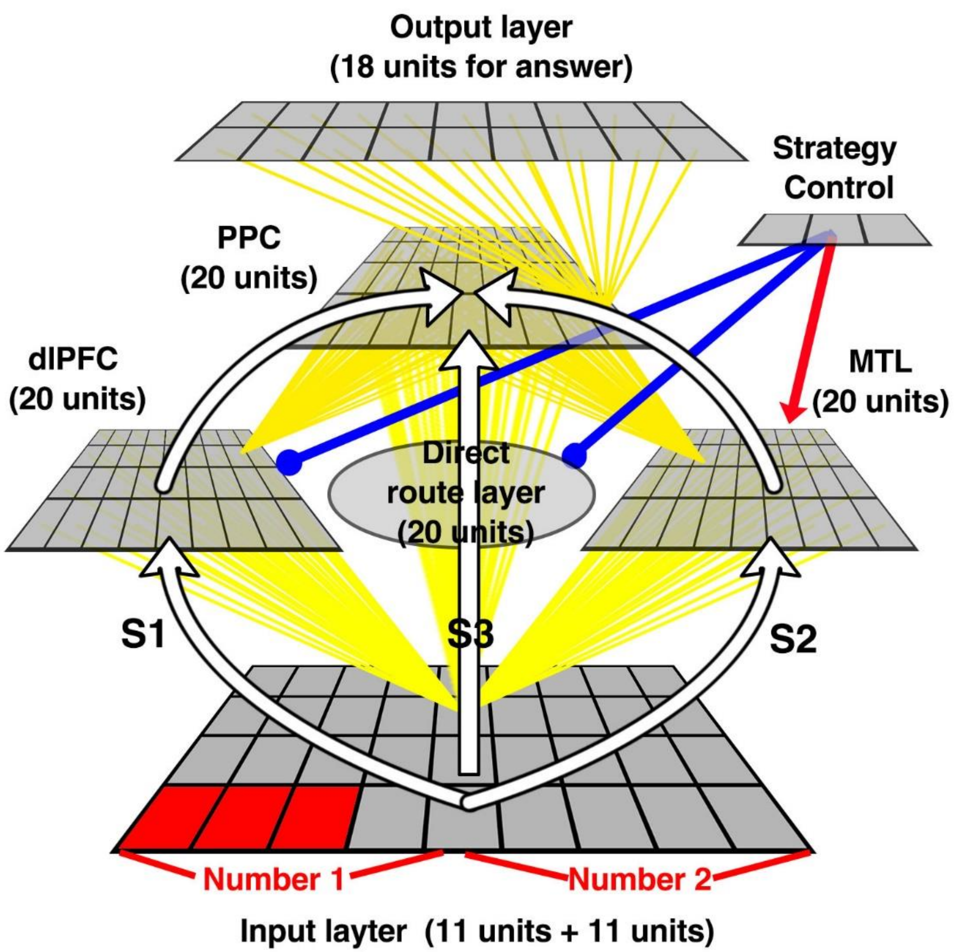
Functional pathways underlying strategy transitions in problem solving



S1: Counting strategies mediated by dlPFC; **S2**: hippocampal-dependent associative retrieval; **S3**: hippocampal-independent semantic-like fact retrieval.

Aim 3: Model Parameters (Lang)

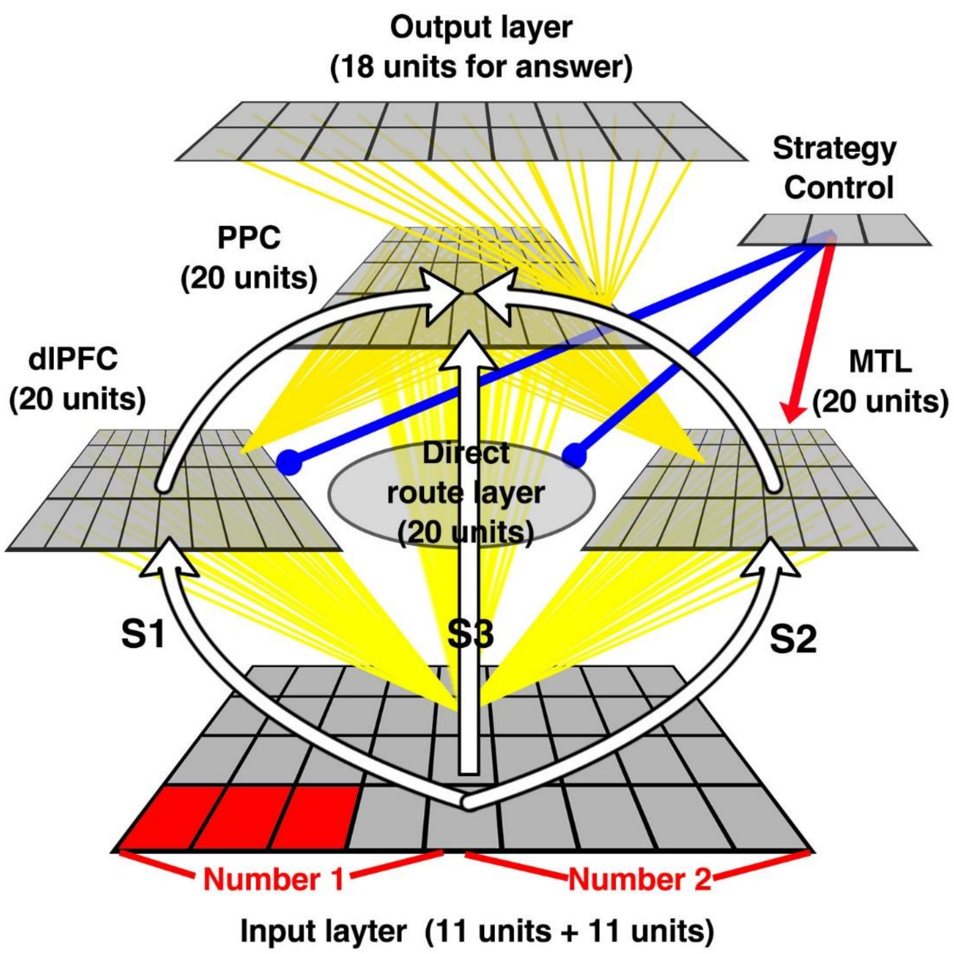
Model architecture



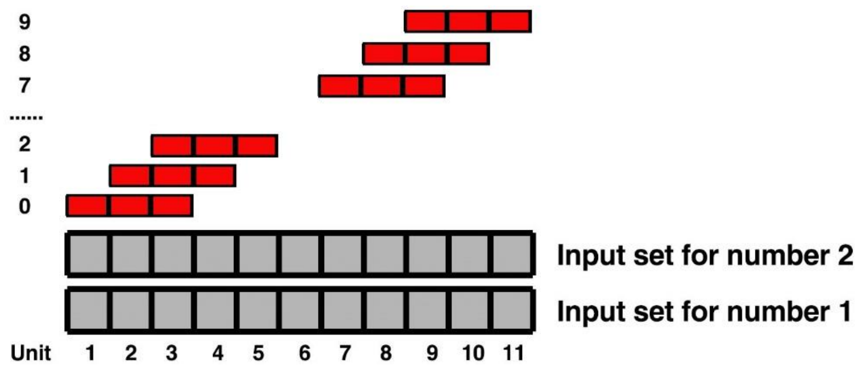
- Full recurrent network with backpropagation
- Only forward connections from input → hidden layers → output
- All hidden layers (dlPFC, Direct, MTL, PPC) were self-connected
- Strategy control units for directing pathways for three strategies by potentiating target pathway and inhibiting irrelevant pathways.
- Negative bias (-5) for hidden units for 0 initial activation

Aim 3: Model Parameters (Lang)

Input and output representations

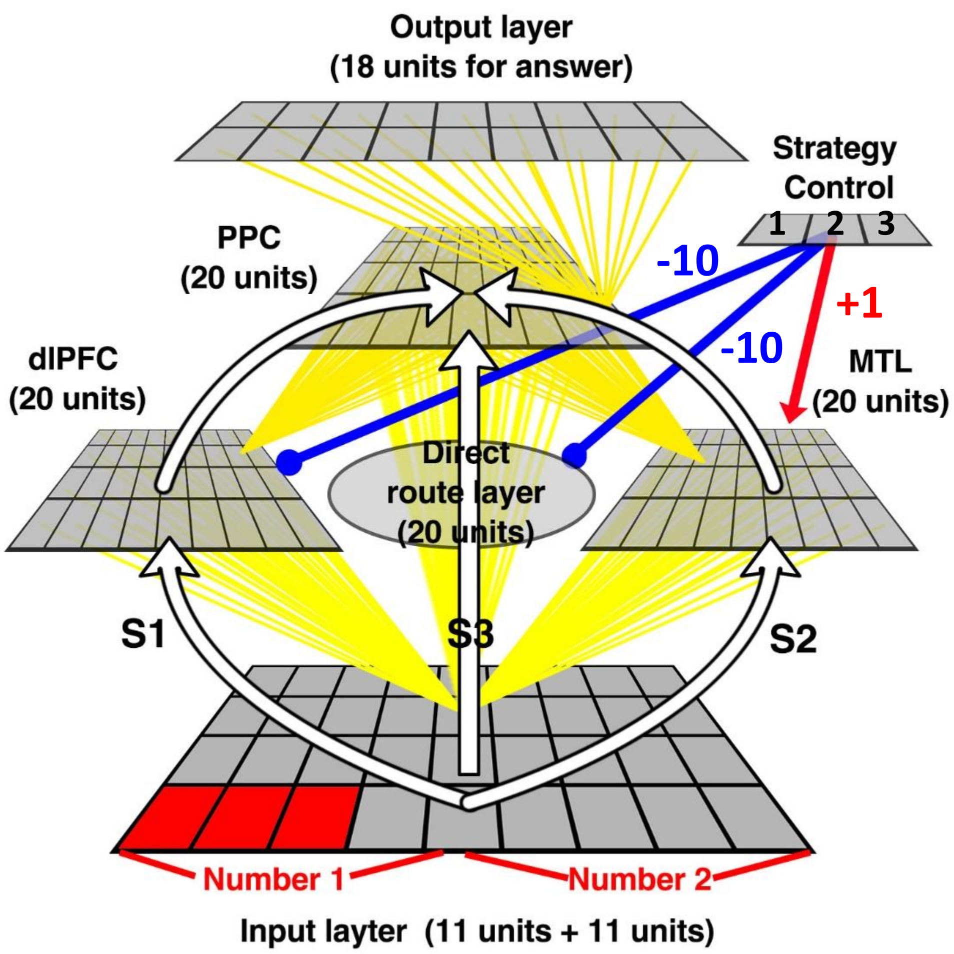


- Distributed input representations for numbers from 0 to 9
- Localist output representations for answers from 1 to 18



Aim 3: Model Parameters (Lang)

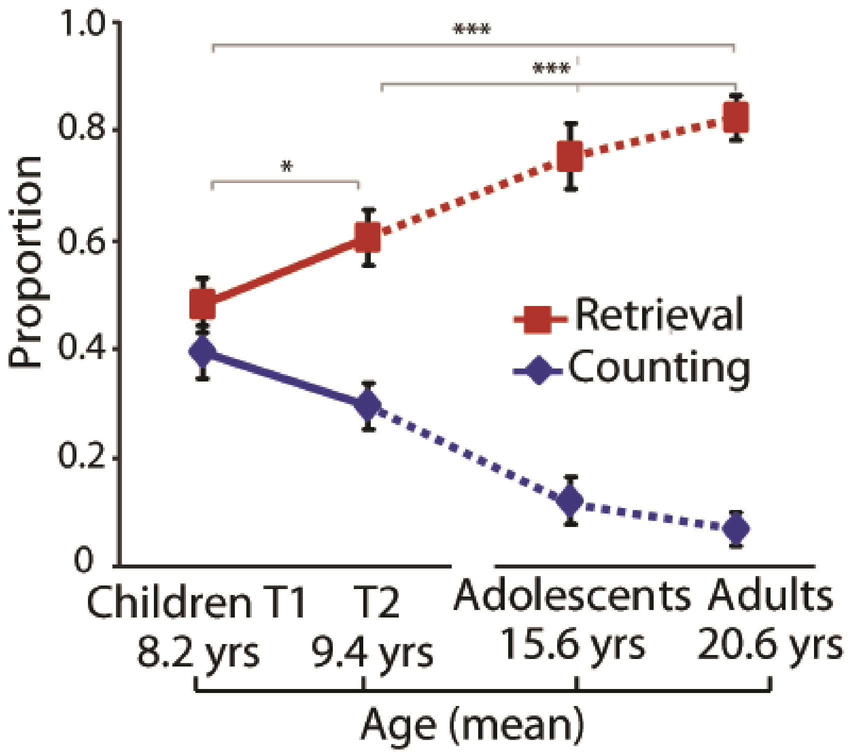
Manipulating strategy differences in pathways

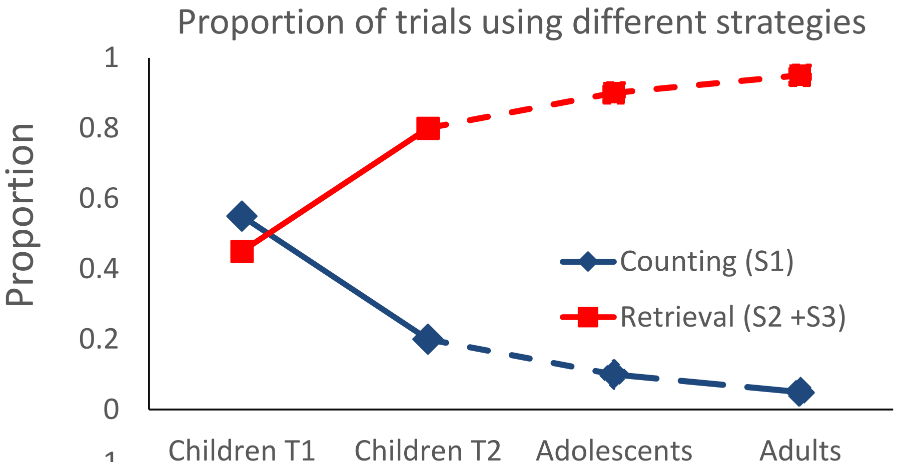


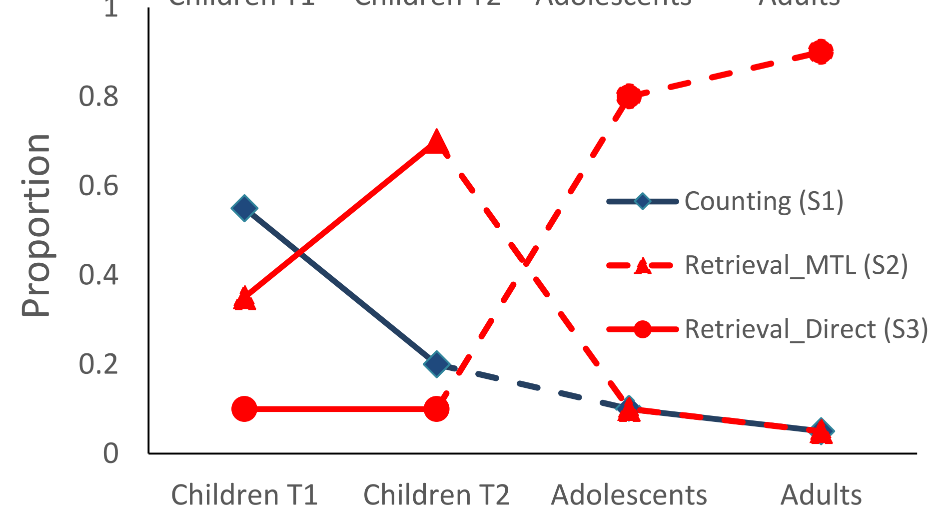
Control	S 1	S 2	S 3
dlPFC	0	-10	-10
MTL	-10	+1	-10
Direct	-10	-10	+2

Aim 3: Model Parameters (Lang)

Manipulating strategy differences in testing environment





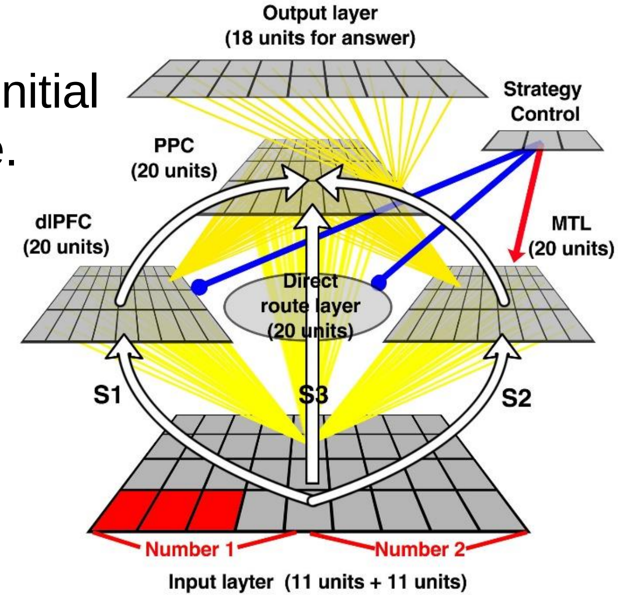


We created four sets of testing environment to reflect ratio of differences in strategy use

Aim 3: Model Parameters (Lang)

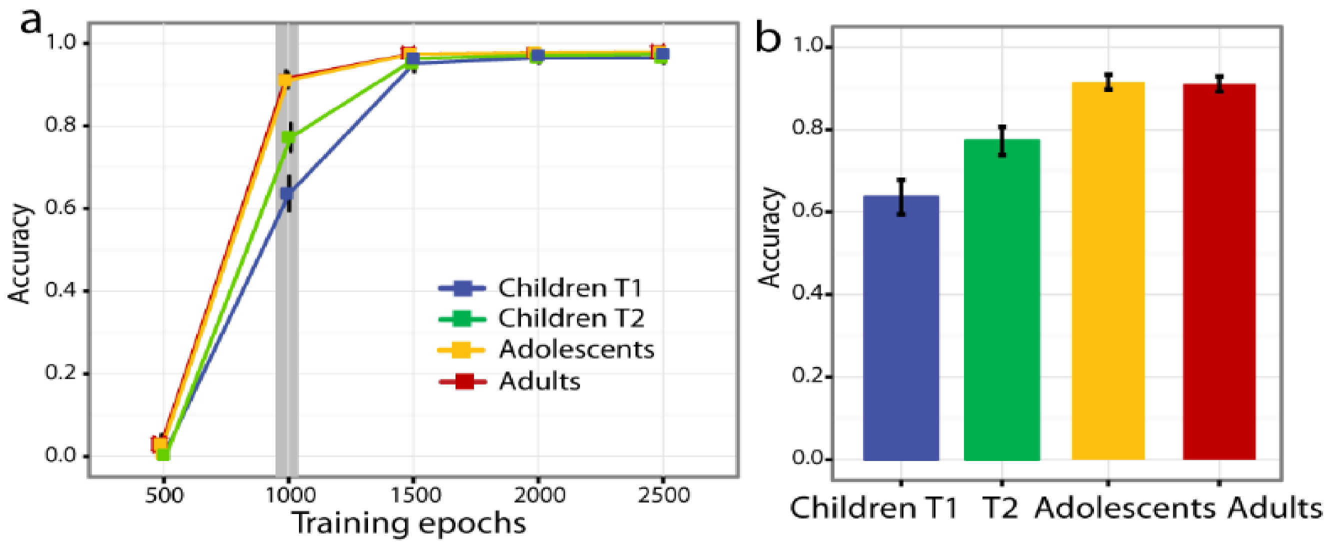
Model training and testing

- The model is trained to learn 1-digit addition equations by using three strategies, excluding 0s, 1s, and repeating numbers on the left side of equation (e.g., 0+9, 1+3, 5+5).
- We do not assume developmental differences in experience (could be done).
- The recruitment of difference strategies across age groups is employed in testing sets.
- Within each age group, 15 different runs with random initial weights were implement to reflect individual difference.
- The same set of addition equations were used for for testing, but the exact strategy used for the same equation was randomized across individual runs.
- Absolute unit activation was taken as analogy of brain signal.



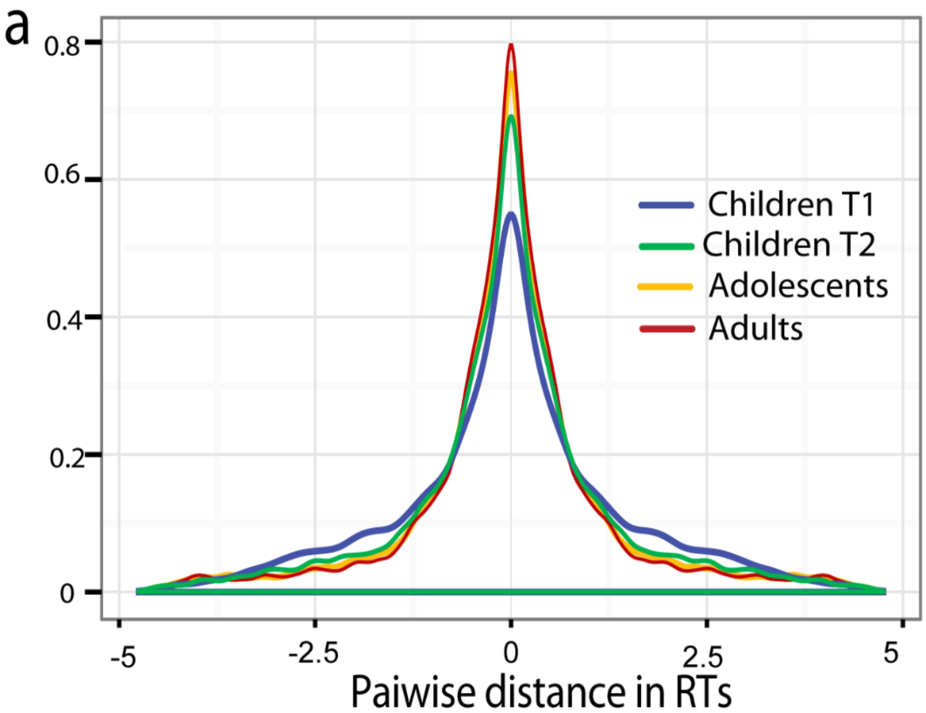
Aim 3: Stimulated Behavioral Outcomes

Developmental changes in accuracy for addition problem solving



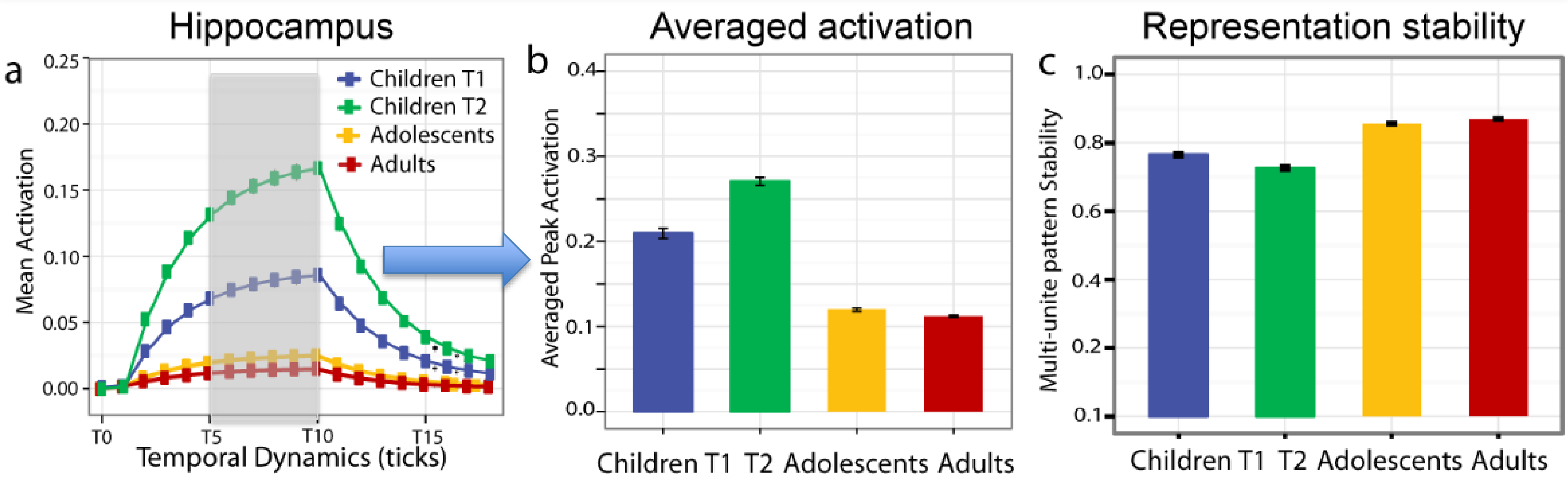
Aim 3: Stimulated Behavioral Outcomes

Developmental changes in inter-problem variability in RTs

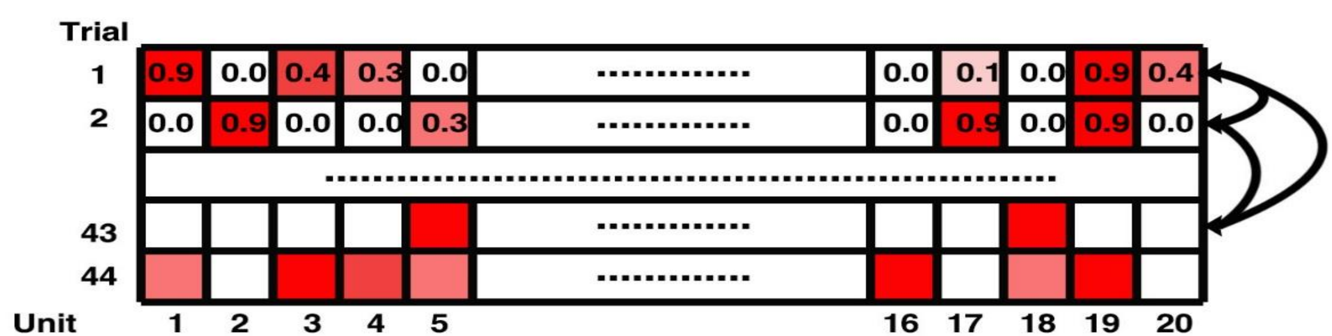


- Behavioral outcomes from computational modelling indicate that there is indeed a link between the development of children’s strategy transitions and developmental improvement in accuracy and reduced inter-problem variability in RTs.

Aim 3: Stimulated Neural Activation and Representations

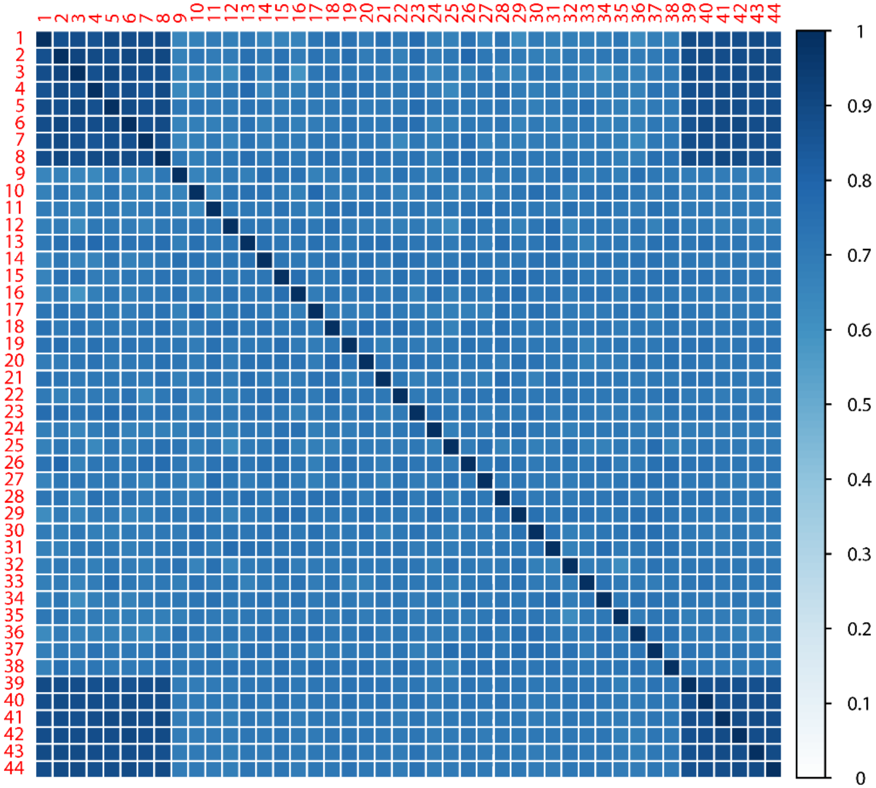


- Because there are trials with **0 activation patterns** in the **hippocampal/MTL** layer, we therefore calculated the pairwise inter-problem absolute difference of 20-unit activity patterns to measure multi-unit representation stability.

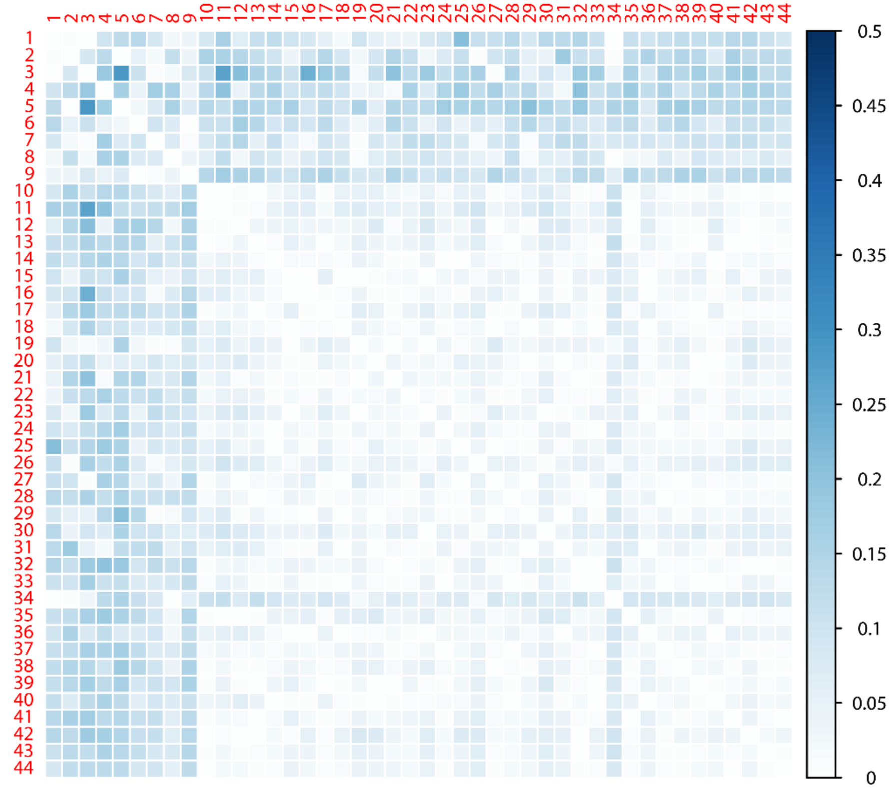


Aim 3: Stimulated Brain-Behavior Correlation

Children T2 (Neuronal)



Children T2 (RTs)



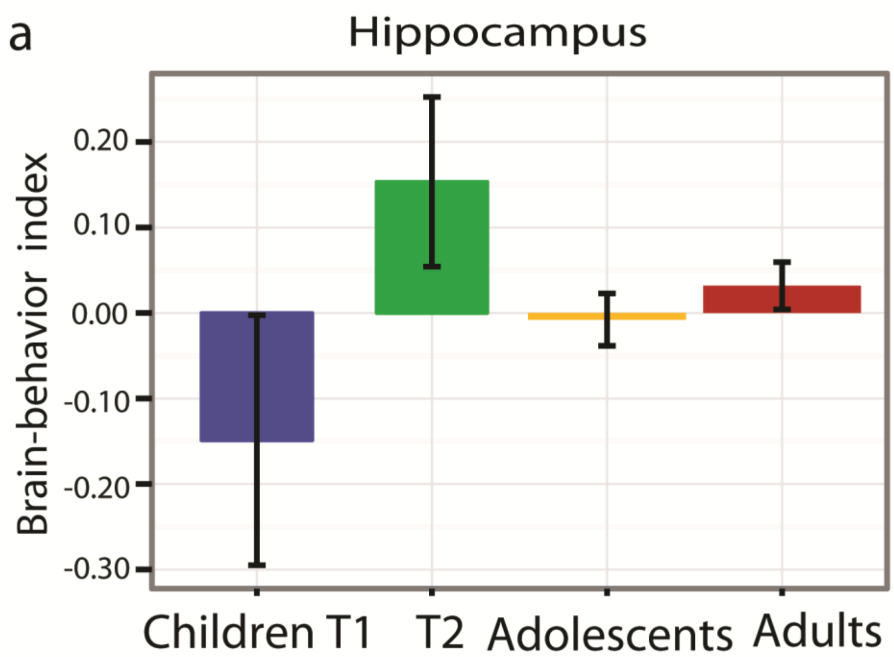
X = Inter-problem neural similarity

Y = Inter-problem variability in RTs

Corr(X, Y)

Aim 3: Stimulated brain-behavior relationship

Developmental changes in brain-behavior correlation



- Outcomes from computational modelling indicate similar non-linear developmental changes in neural activation, inter-problem representation stability and its relation with inter-problem variability in RTs.

General Summary

- Over development children became less dependent on counting but **more on memory-based retrieval** for arithmetic problem solving, along with increased accuracy and **reduced inter-problem variability** in RTs.
- Children's strategy transitions paralleled **increased hippocampal** and **decreased frontal-parietal engagement**, and **increased hippocampal-neocortical functional connectivity** during childhood.
- Beyond childhood, **memory-based** strategy use and **variability** in RTs continued to **improve** through adolescence into adulthood and with **decreased activation** but **more stable inter-problem representations** in the hippocampus and neocortex.
- **Inter-problem representation stability** in the hippocampus and frontal-parietal systems was predictive of **reduced inter-problem variability** in RTs from childhood through adolescence into adulthood.
- Preliminary results from **computational modelling** point to that the development of **children's strategy transitions** appears the key to understand maturational changes in our behavioral observations, hippocampal-neocortical engagement, inter-problem representation stability and its relation to inter-problem variability in RTs.

Discussion for future directions

- How to better assess **children's mix of multiple behavioral strategies**?
  - Dissociate associative (episodic-like) retrieval vs. semantic-like fact retrieval
  - Link strategy assessment with fMRI data in a better way
- How to **optimize** our current computational model to **better model children's mix of multiple strategy use** in arithmetic problem solving?
  - Implement distinct learning algorithms in hippocampal and prefrontal layers
  - Hippocampal sparse pattern separation and Hebbian learning in PFC
- How to better understand the **cognitive and neural processes** underlying the development of **children's strategy transitions** through **computational modelling** and **cognitive neuroimaging approaches**?
  - Embodied cognition: counting fingers/objects → fact retrieval
  - Associative learning and generalization
- **Other thoughts and comments?**

Acknowledgement

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Collaborator(s)

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