Developmental trajectories of symbolic and non-symbolic number processing:

behavioral and brain-imaging studies

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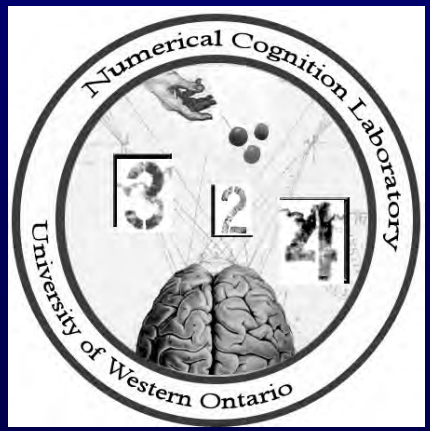
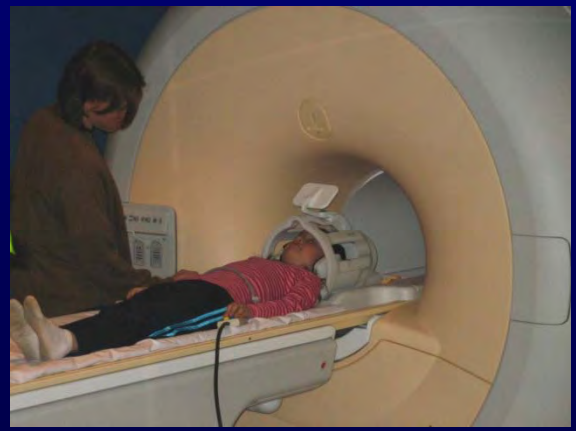




Western

College de France, Paris, March 11th 2008

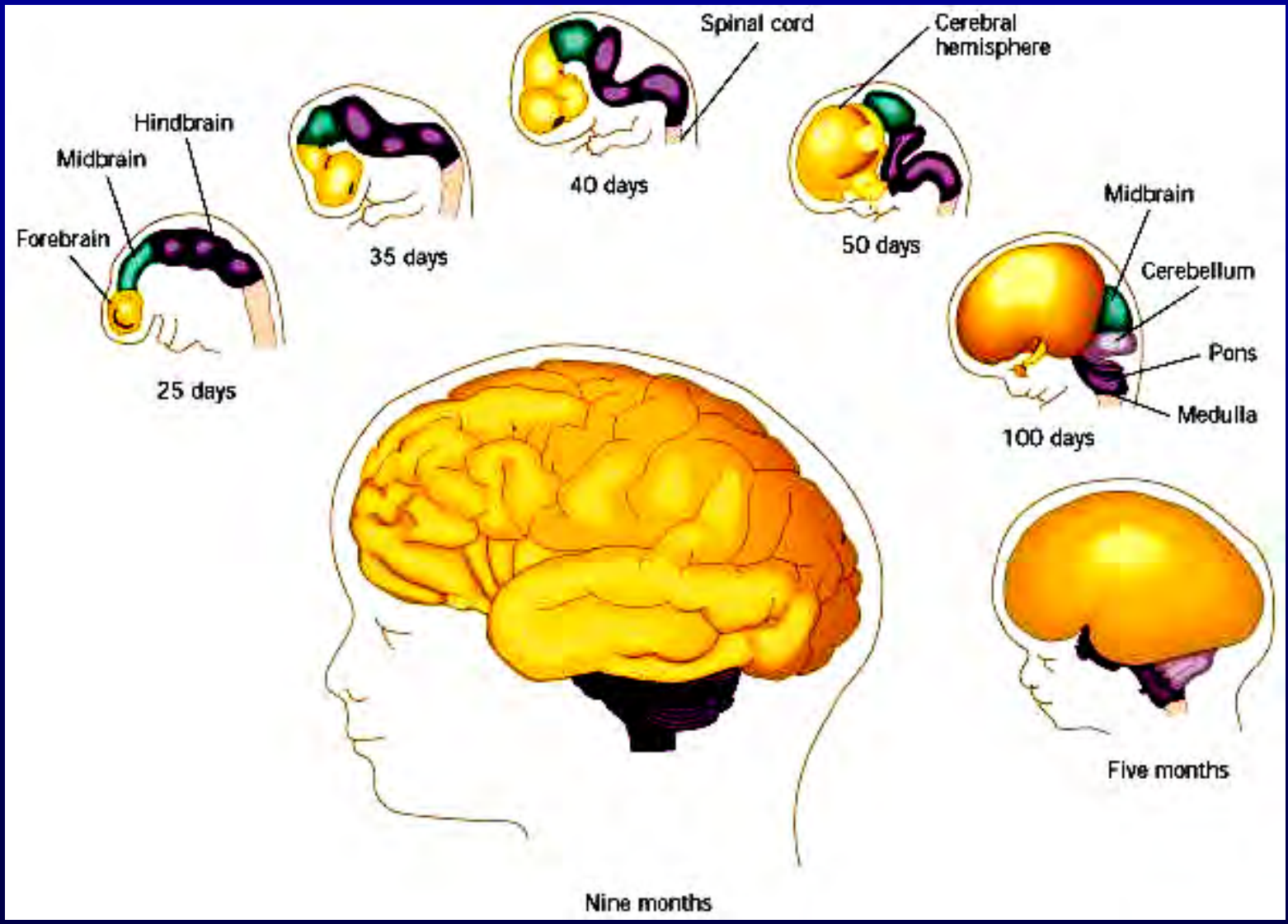
Outline

- Developmental Cognitive Neuroscience
  - Why study brain development?
    - Structural Development
    - Functional Development
- The case of number
  - What can the study of functional brain development add?
    - Study of basic magnitude representation
    - Symbolic vs. non-symbolic
    - Mental arithmetic
    - Neural correlates of Developmental Dyscalculia
- Conclusions & Future Challenges

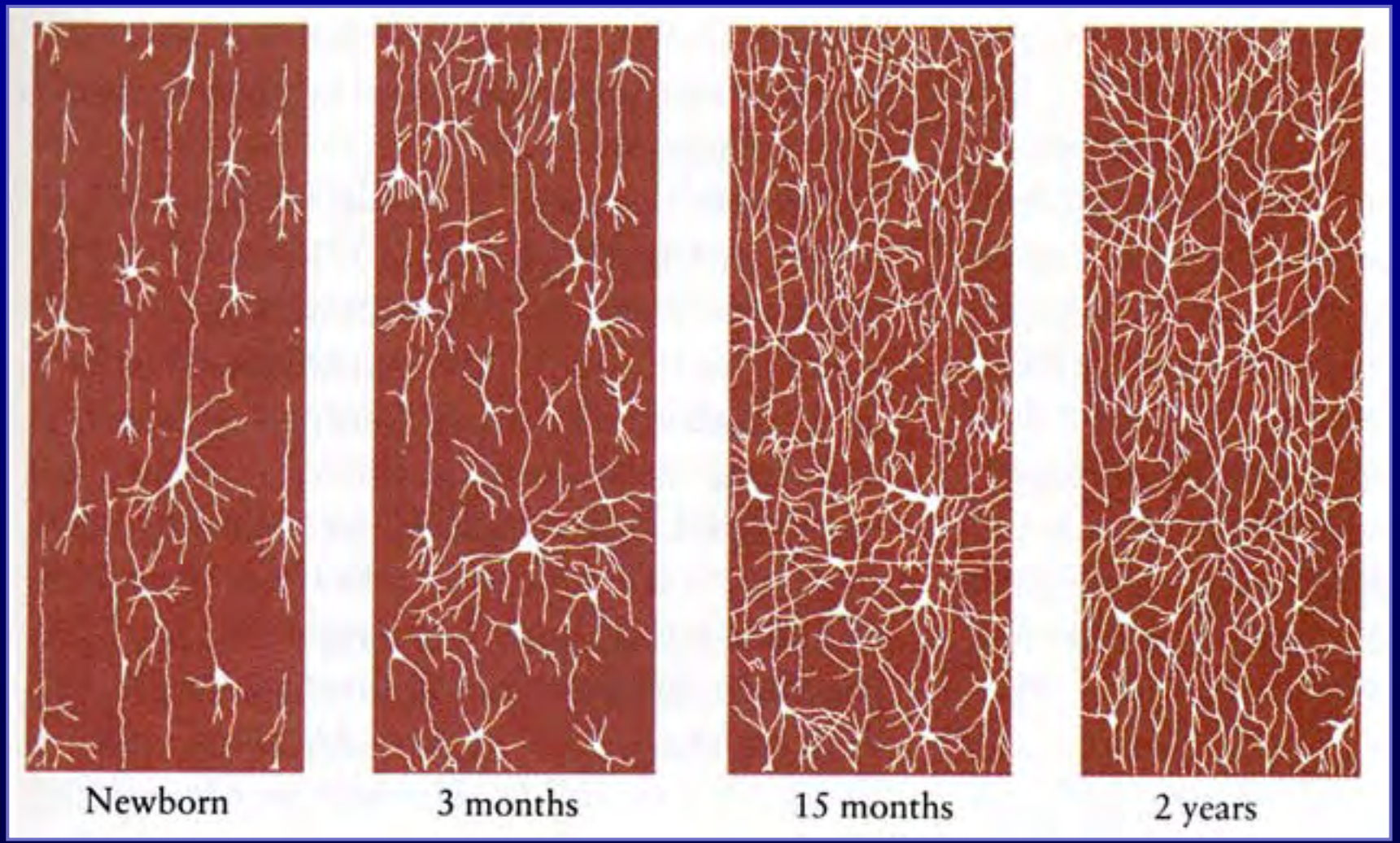
Developmental Cognitive Neuroscience

Structural Development

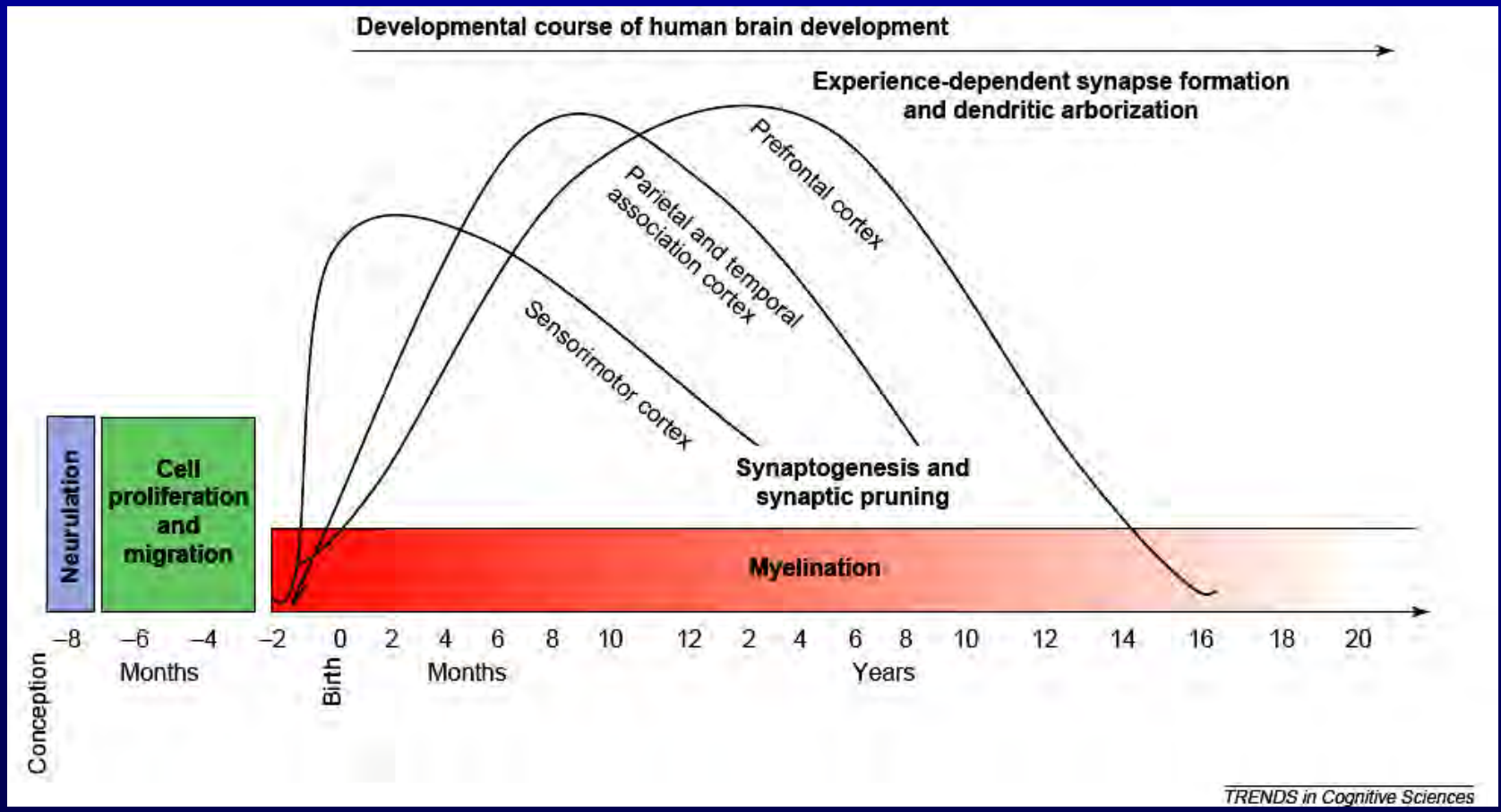
Prenatal Brain Development



Postnatal Brain Development

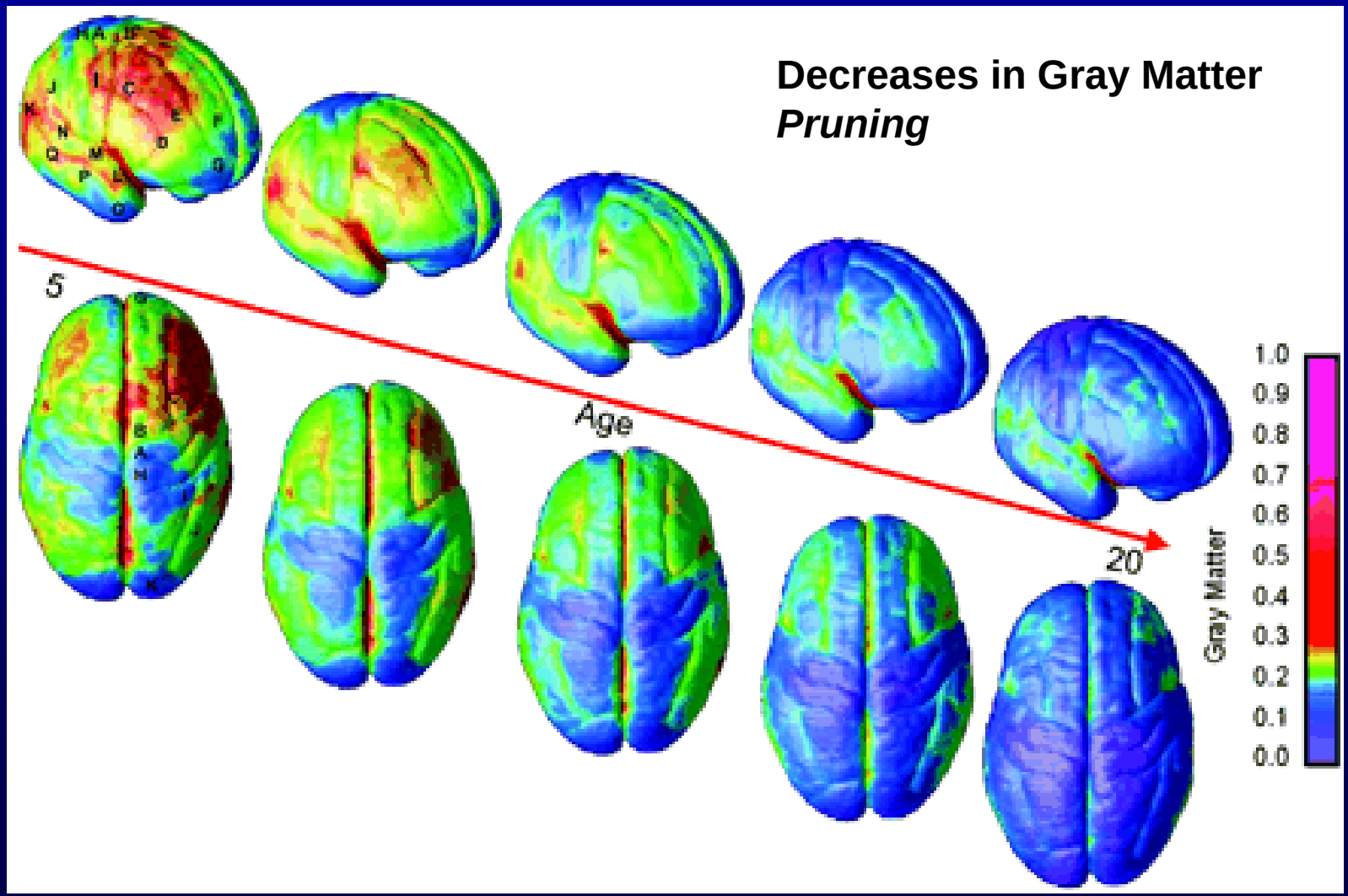


Postnatal Brain Development



from Casey et al. (2006)

Postnatal Brain Development

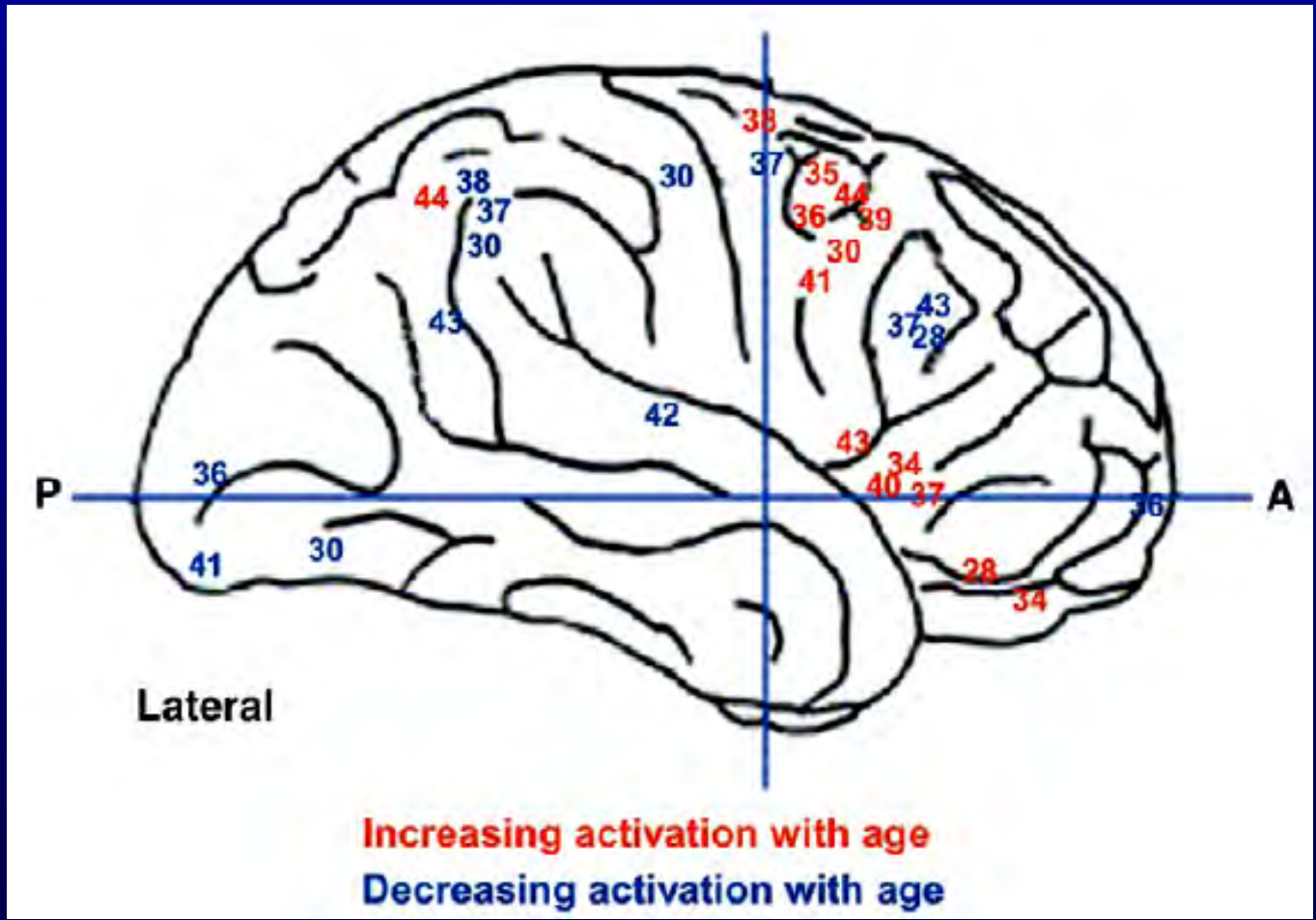


Gogtay et al. (2004)

Developmental Cognitive Neuroscience

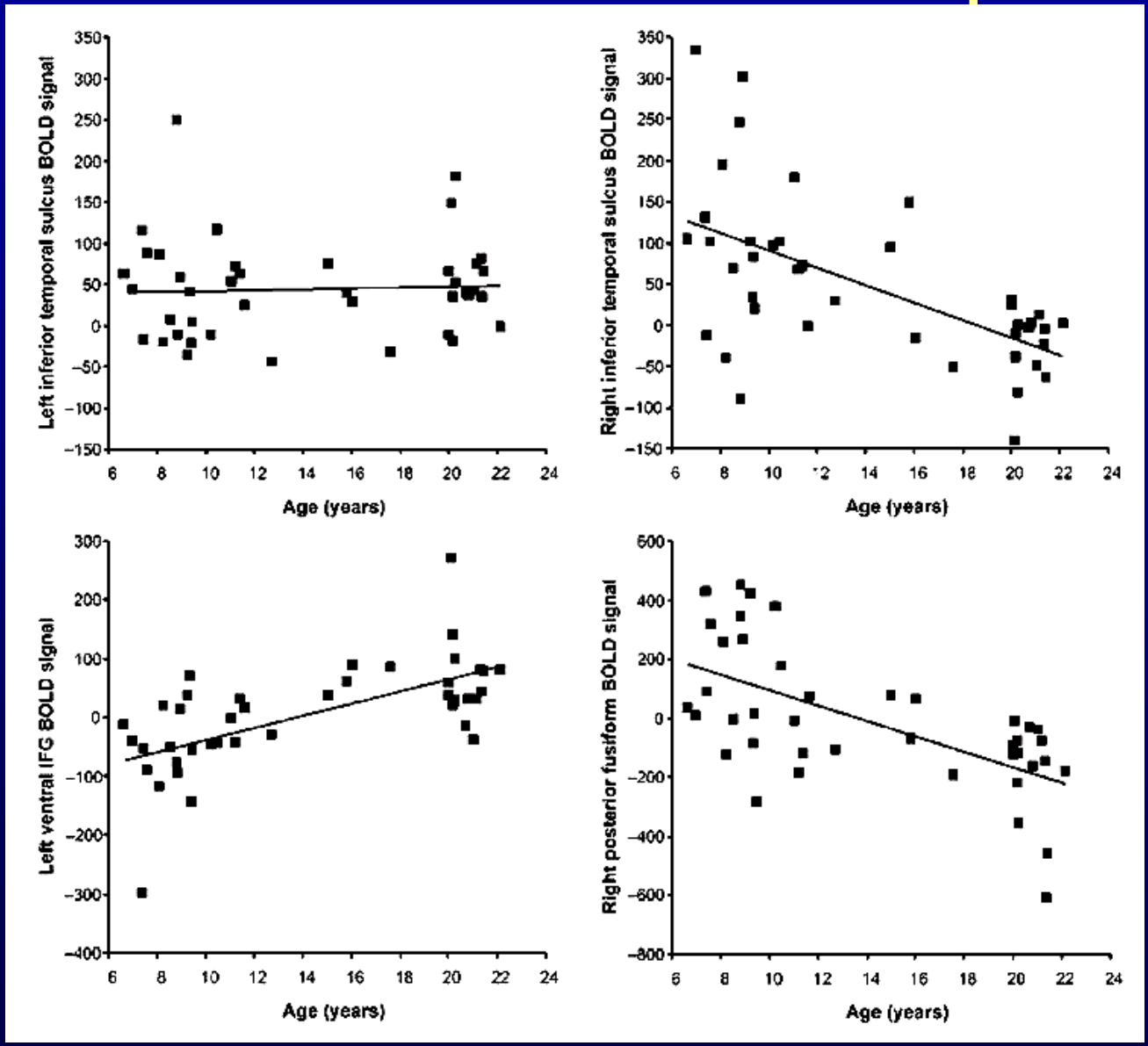
Functional Development

Functional Brain Development



Casey et al. (2005)

Functional Brain Development



Turkeltaub et al. (2003)

Developmental Cognitive Neuroscience

- Dynamic, age-related changes in *structure and function*
- Decreases and increases in activation underlying cognitive processes
- ***The study of these changes informs understanding of:***
  - How regions become specialized for particular cognitive operations
  - May help to better understand origins of dev. difficulties
  - Elucidate how the brain comes to represent cultural stimuli (i.e letters, Arabic numerals)

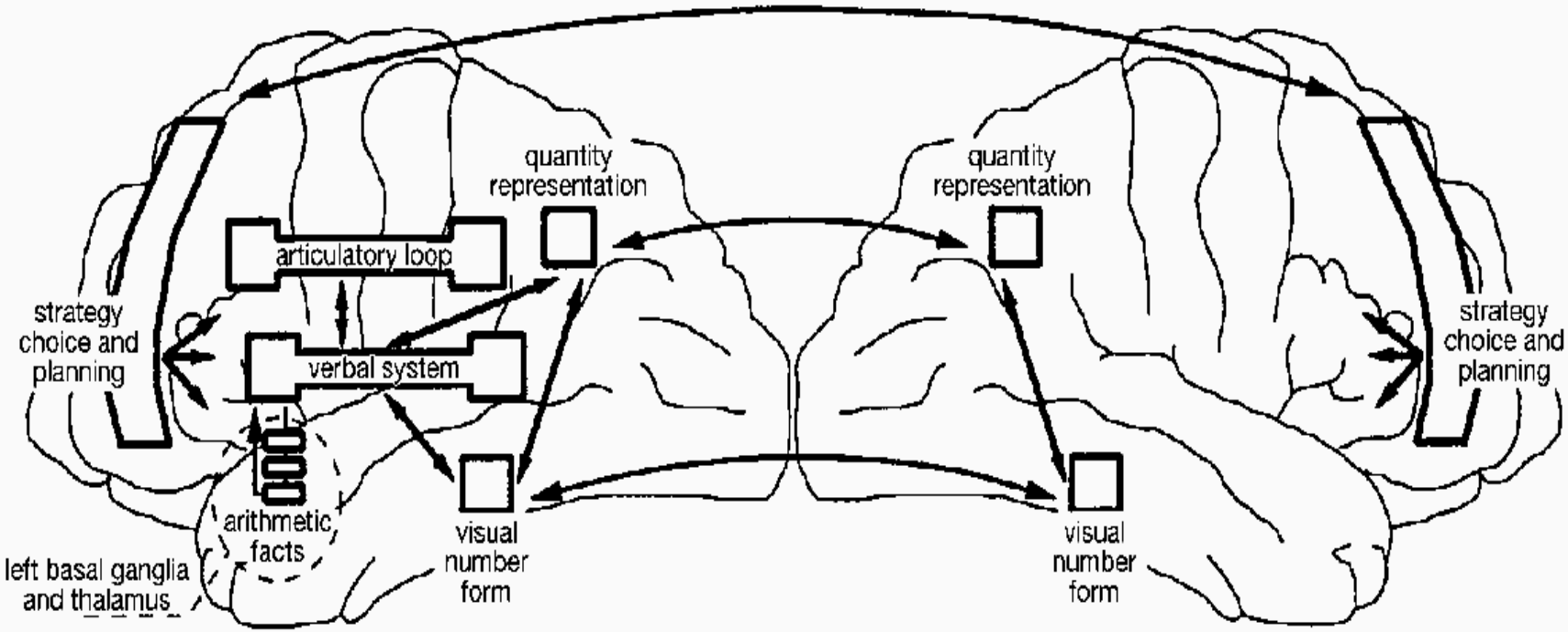
Developmental Cognitive Neuroscience

The case of number

Evidence from the Adult Brain

Evidence from Adults

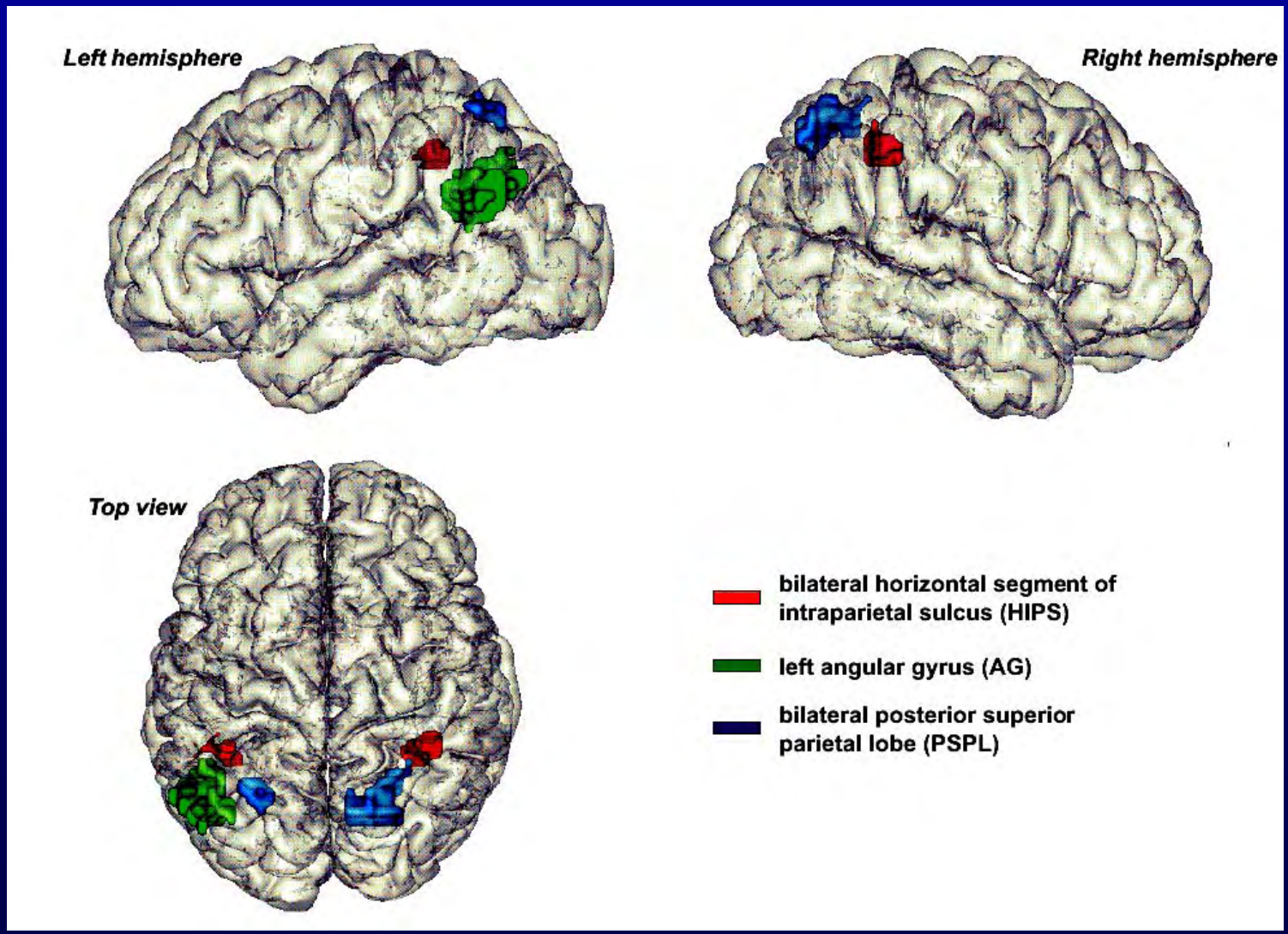
Neuropsychology



Dehaene & Cohen (1995)

Evidence from Adults

Functional Brain Imaging



Dehaene et al. (2003)

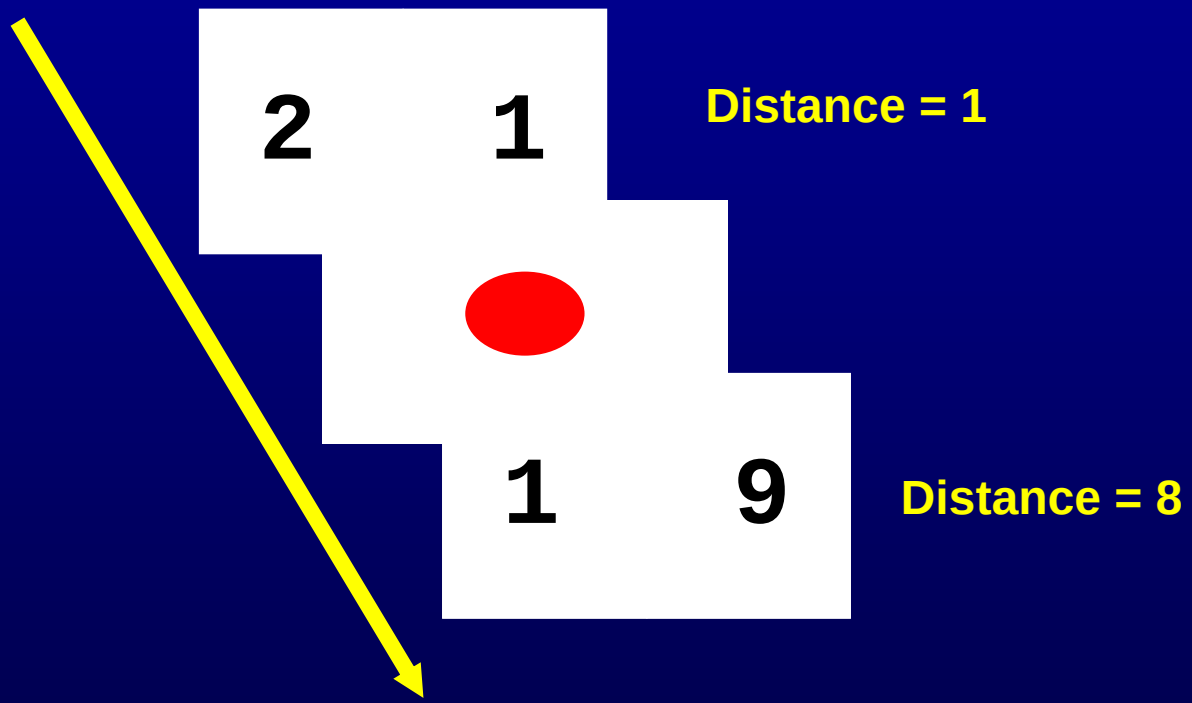
Evidence from Adults

- The study of neuropsychological patients & functional brain imaging has:
  - Delineated brain regions involved in mature number processing
  - Anatomically distinct regions subserve different functions
  - Dissociation between regions - independence of processing

Development of brain representation of number

- Very few neuromaging studies of number development
- Where to start?
  - Start with basics:
    - Representation and processing of numerical quantity
  - Start with a well-replicated effect
  - Start with an effect that captures an important aspect of number development

The Task: Number Comparison



“Choose the larger number”

The effect:
Distance Effect
Adults

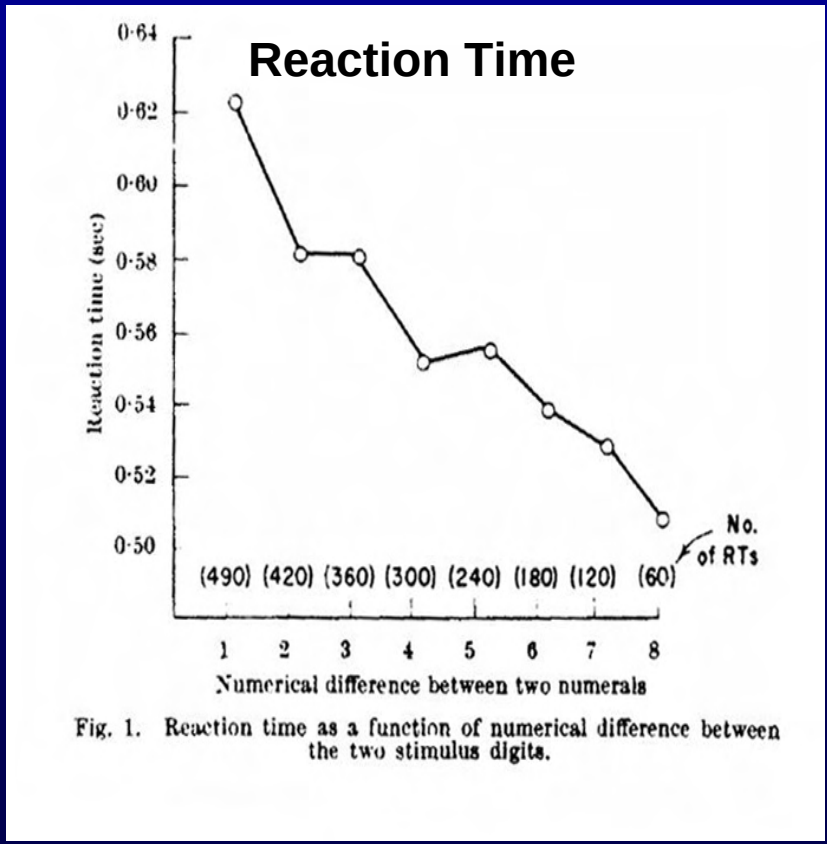


Fig. 1. Reaction time as a function of numerical difference between the two stimulus digits.

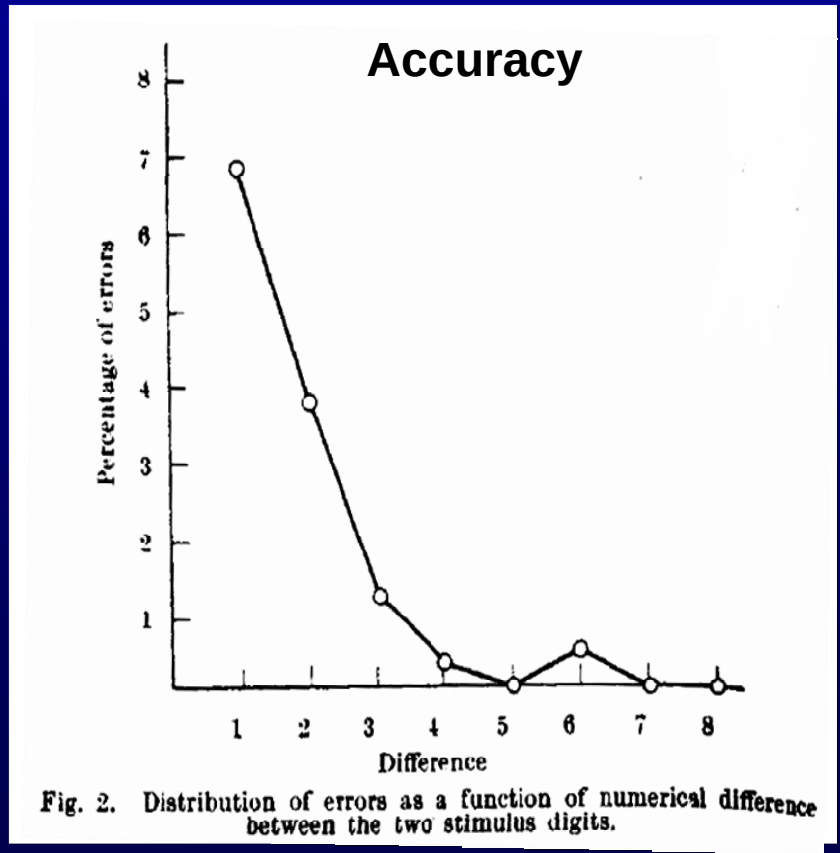


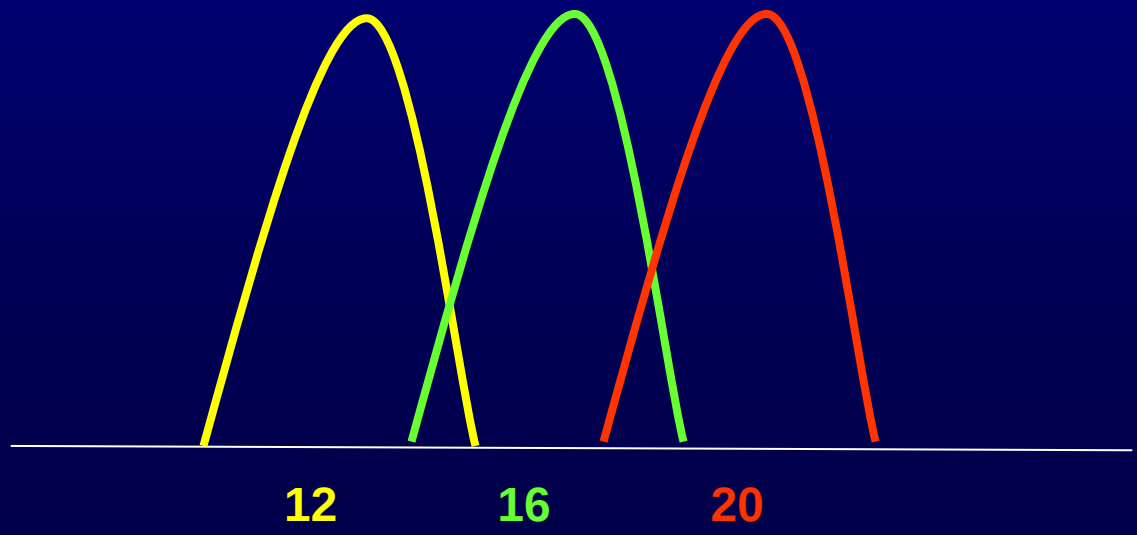
Fig. 2. Distribution of errors as a function of numerical difference between the two stimulus digits.

Moyer & Landauer(1967)

Distance Effect

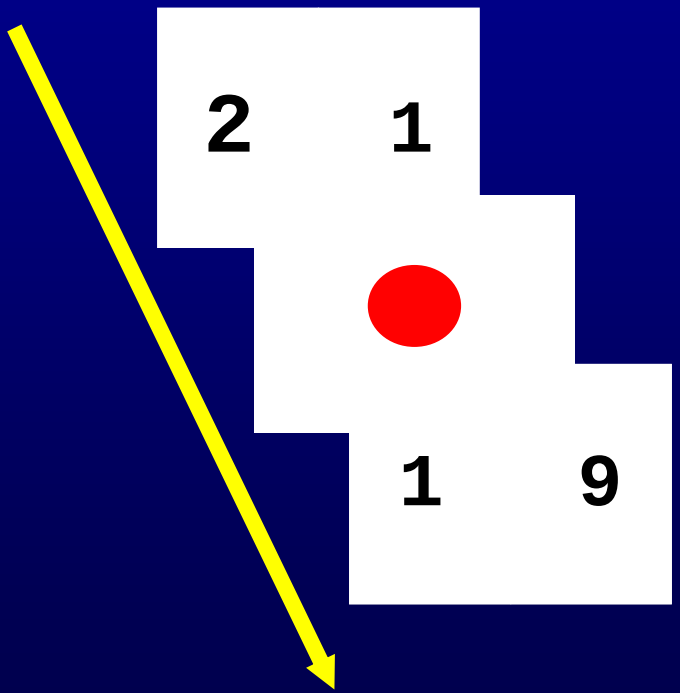
Adults

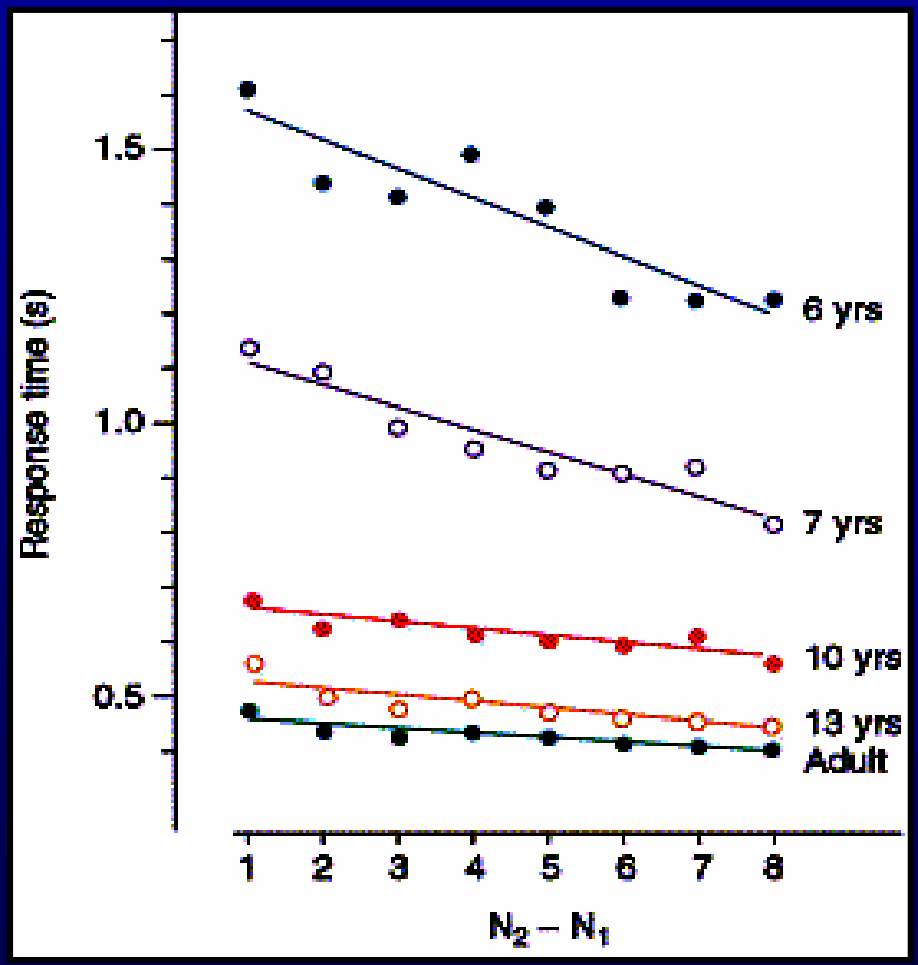
- Distance effect reveals features of underlying ***quantity*** system
- Noisy mental “Number Line” (Dehaene, 1997)



Distance Effect

Development



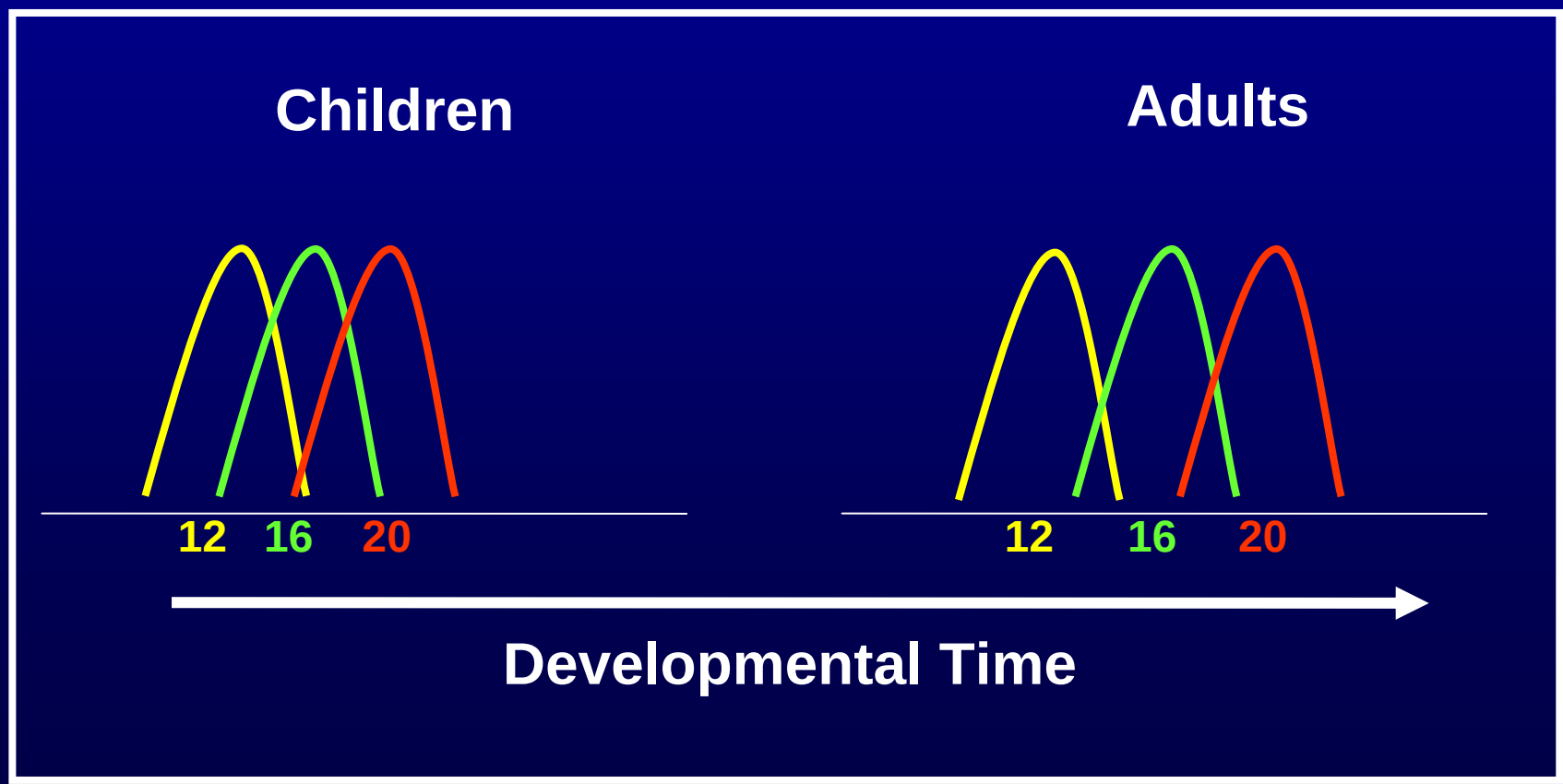


Sekuler & Mierkiewz (1977)

Distance Effect

Development

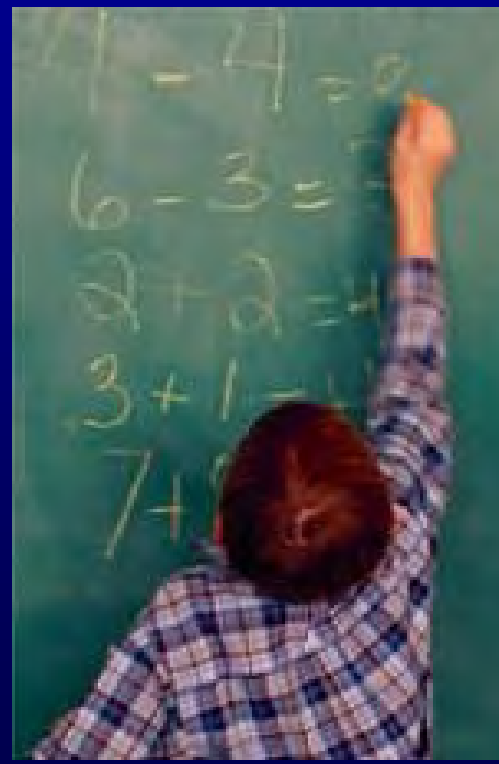
- Decrease of distance effect over dev. time
- Decrease in noise → increase in precision



What is the functional significance of these changes?

Functional significance of dev. changes in Distance Effect?

- Does the distance effect predict individual differences in mathematics achievement?
- 78, 6-8 year olds
- Symbolic distance effect
- WJ Math and Reading tests



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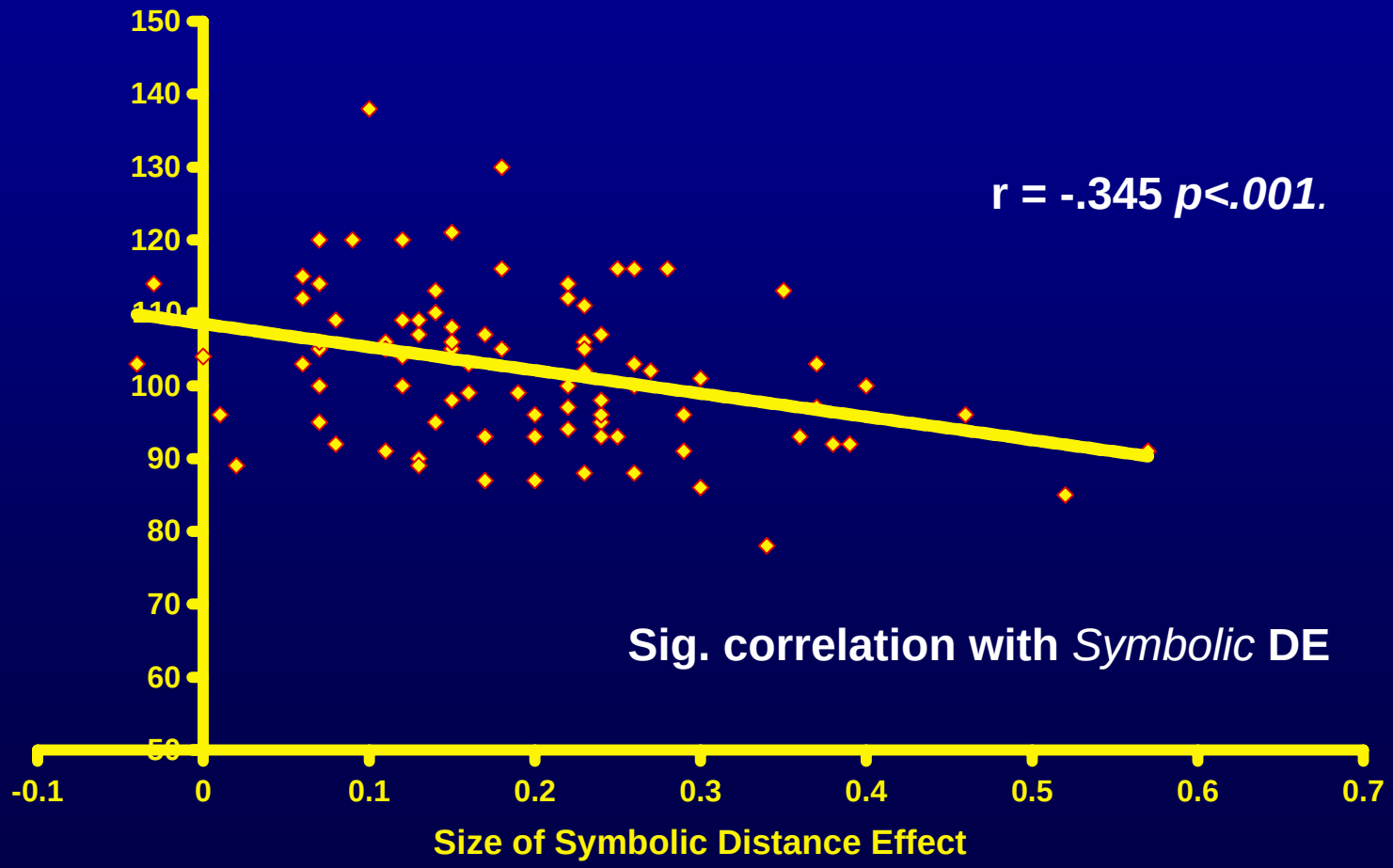
Distance Effect

Development - Functional Significance?

Size of Distance Effect = (larger RT – Small RT/ Large RT)



Holloway & Ansari (under review)

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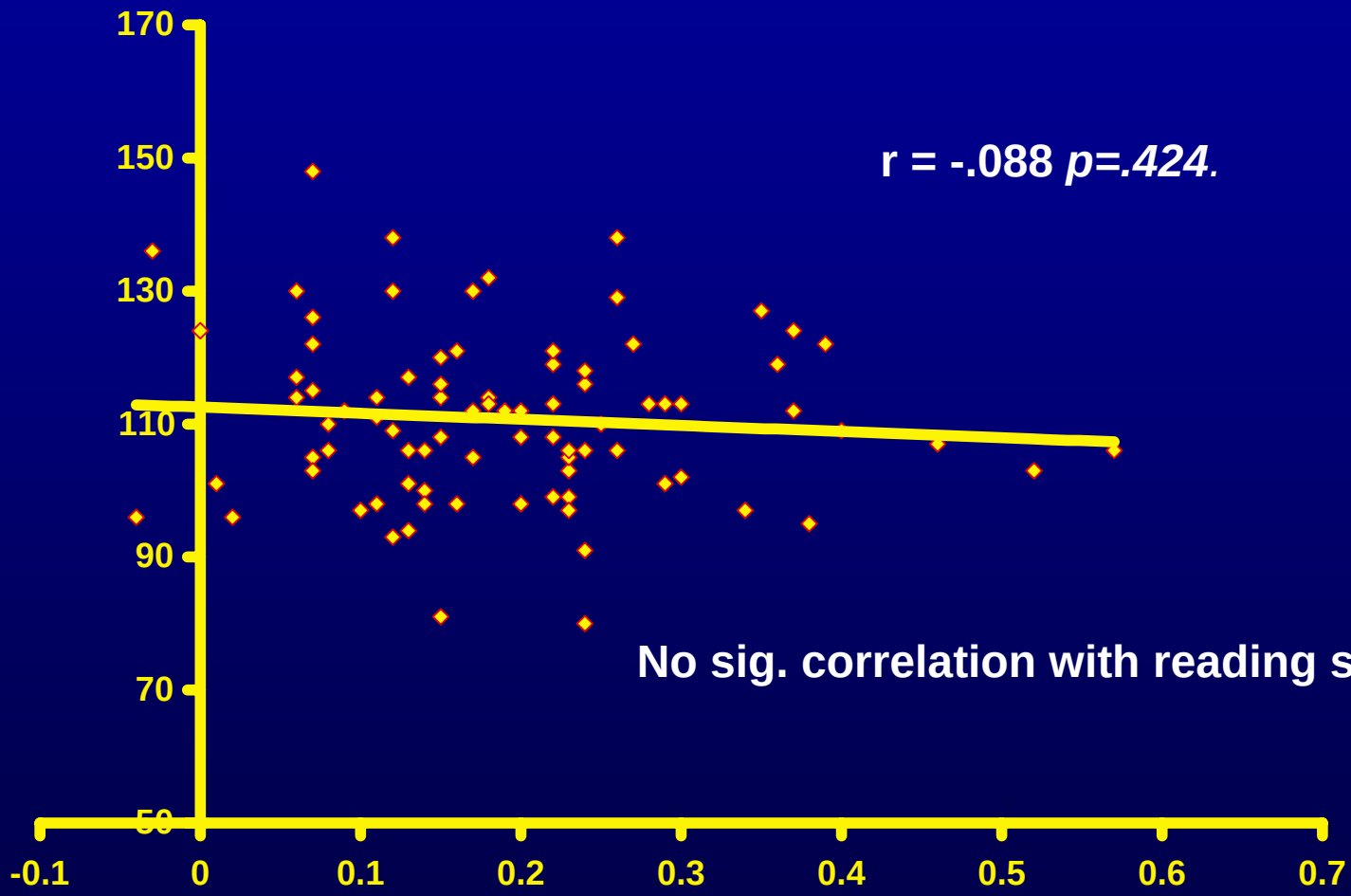
Distance Effect

Development - Functional Significance?

Size of Distance Effect = (larger RT – Small RT/ Large RT)



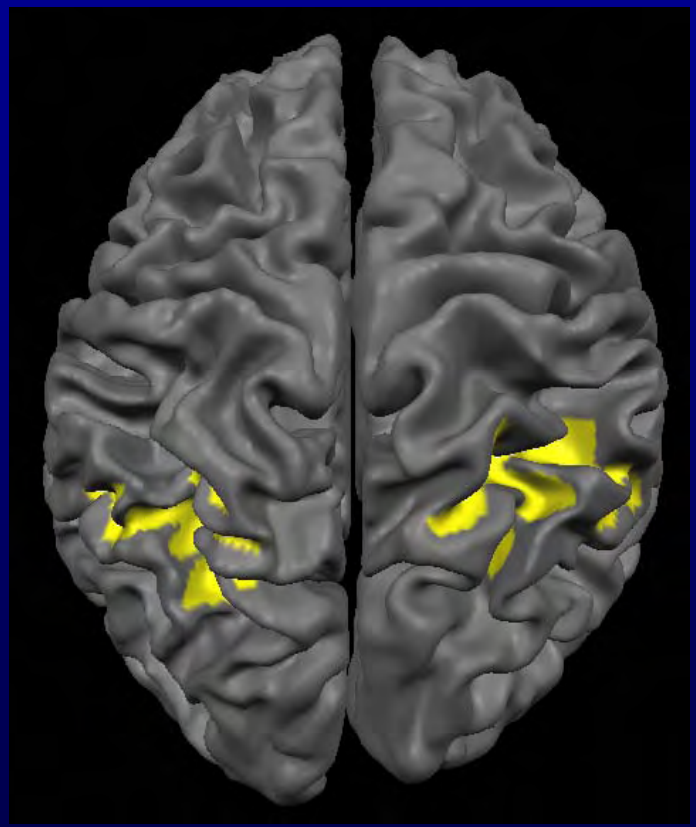
Holloway & Ansari (under review)

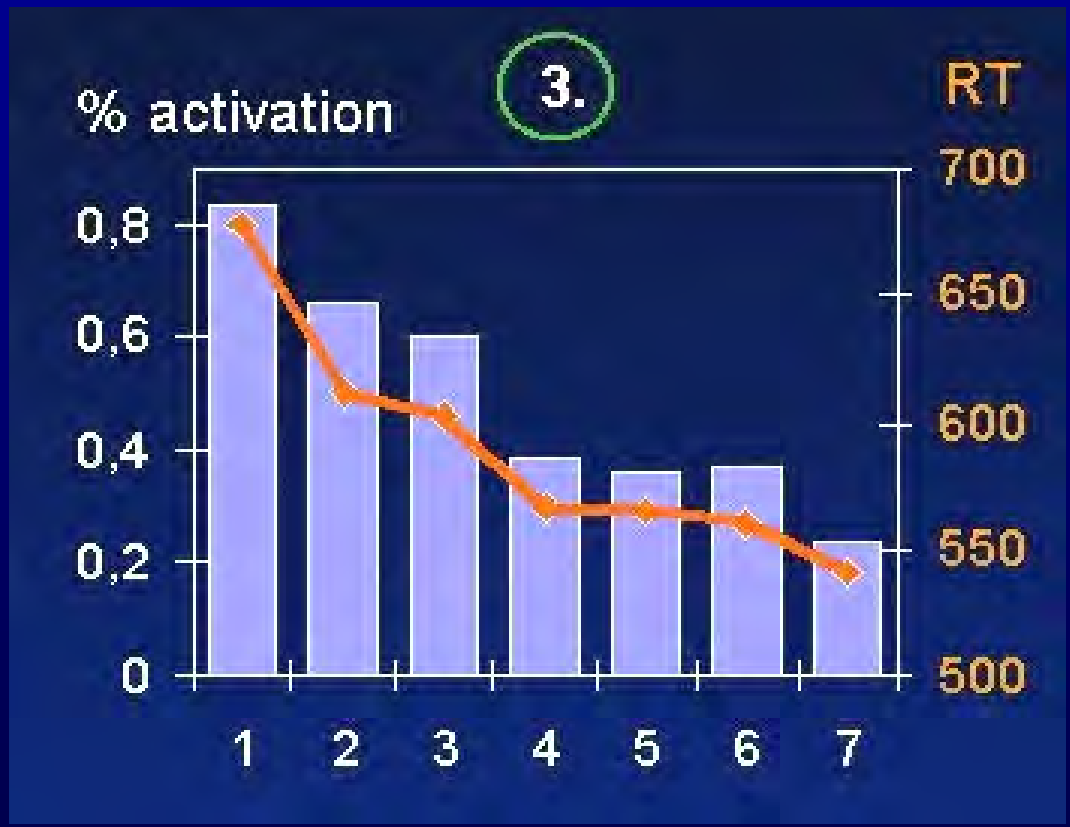
Neural correlates of the distance effect?

Distance effect

Neural correlates

Distance modulates a network of parietal areas

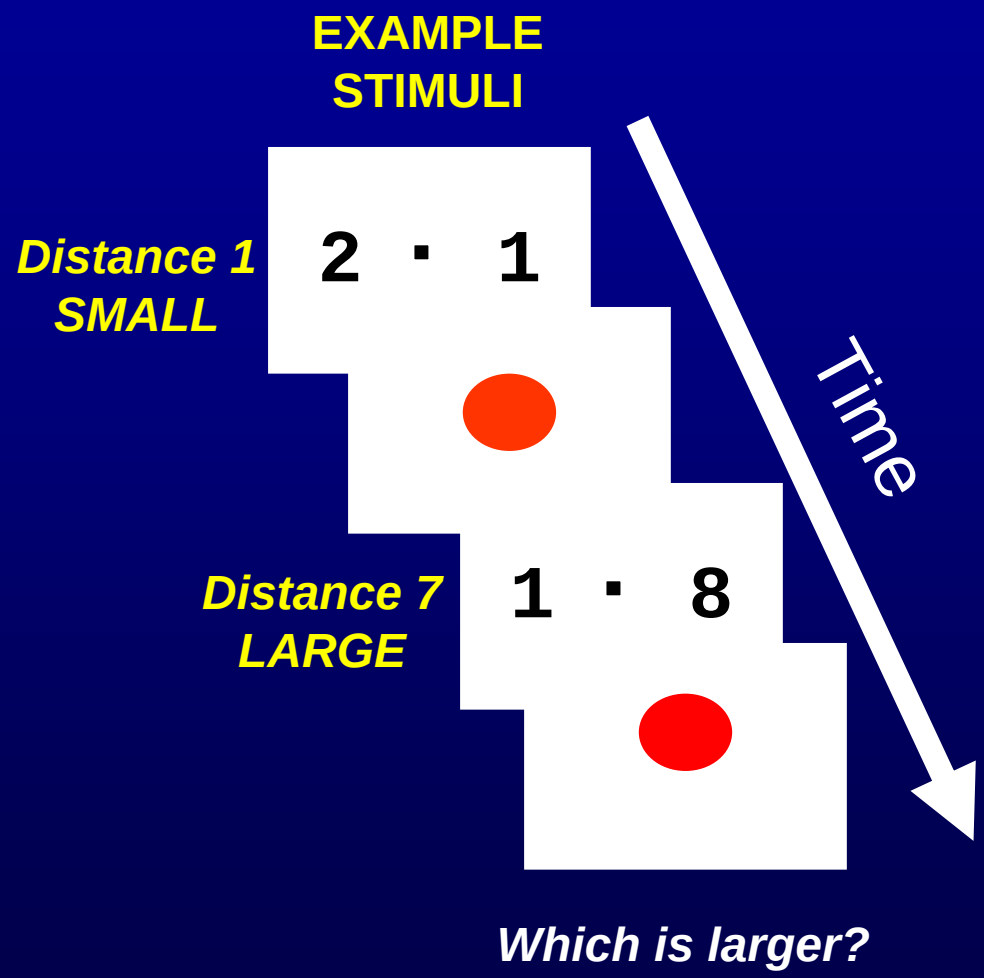




Pinel et al. (2001)

Developmental changes in the neural correlates of the distance effect?

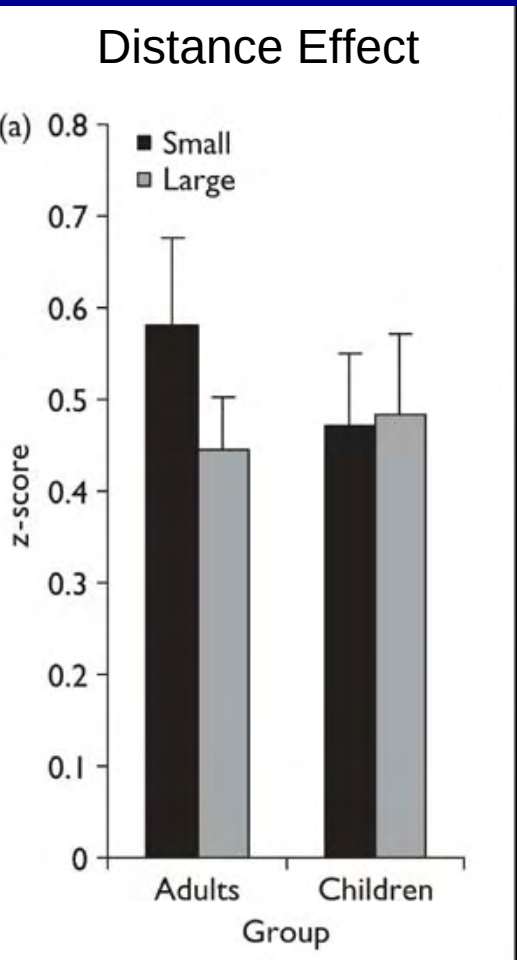
Symbolic Distance Effect

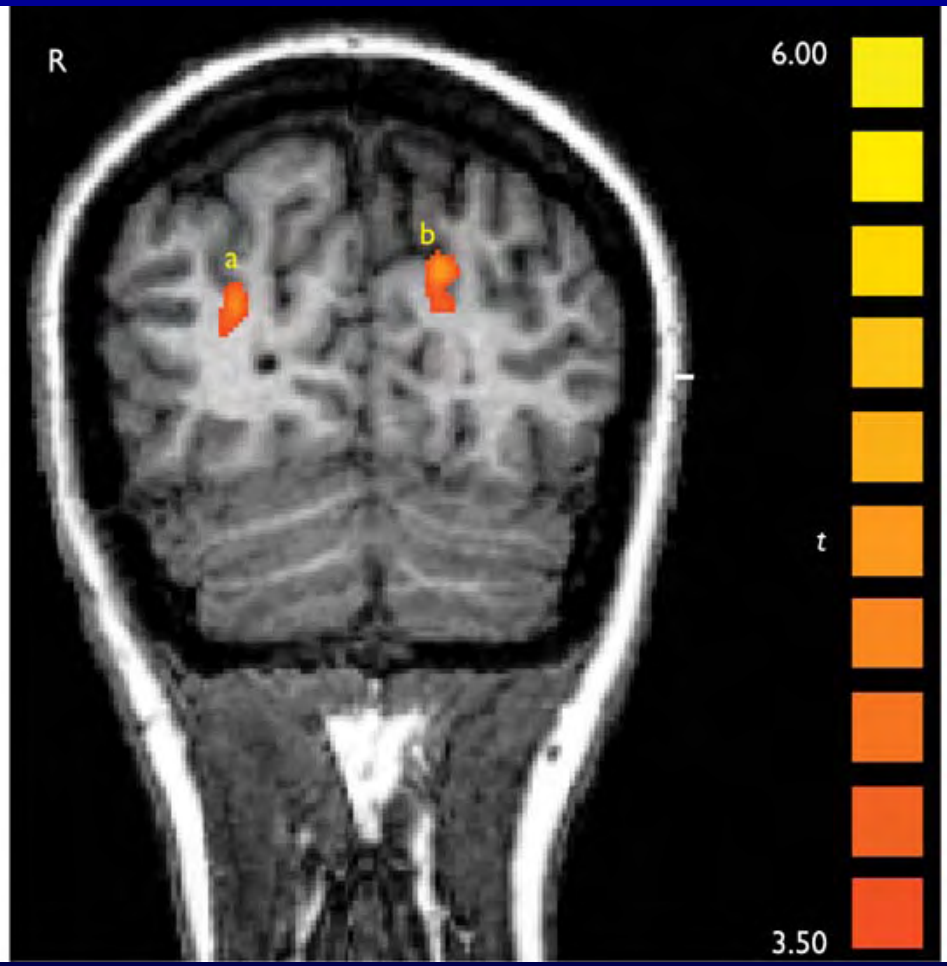


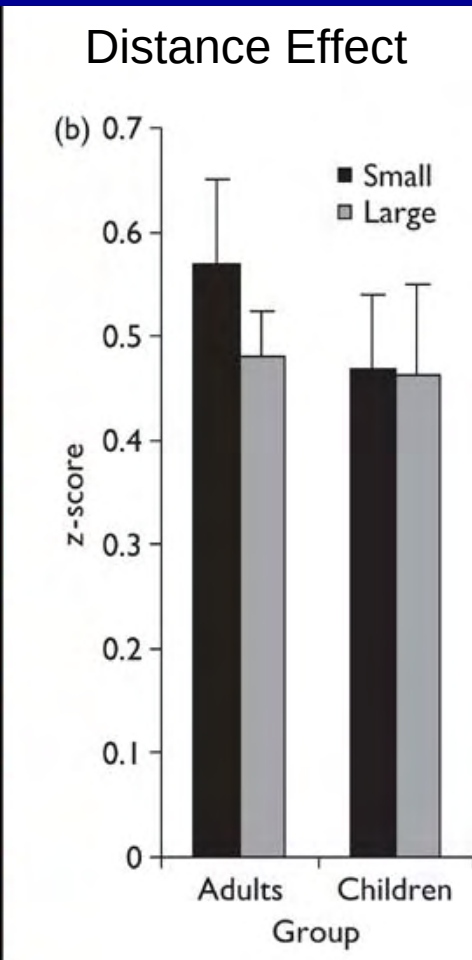
- 8-12 year olds (N=12)
- Adult college students (N=12)
- Event-related fMRI design
- 1.5 GE Scanner

Symbolic Distance Effect

Adults



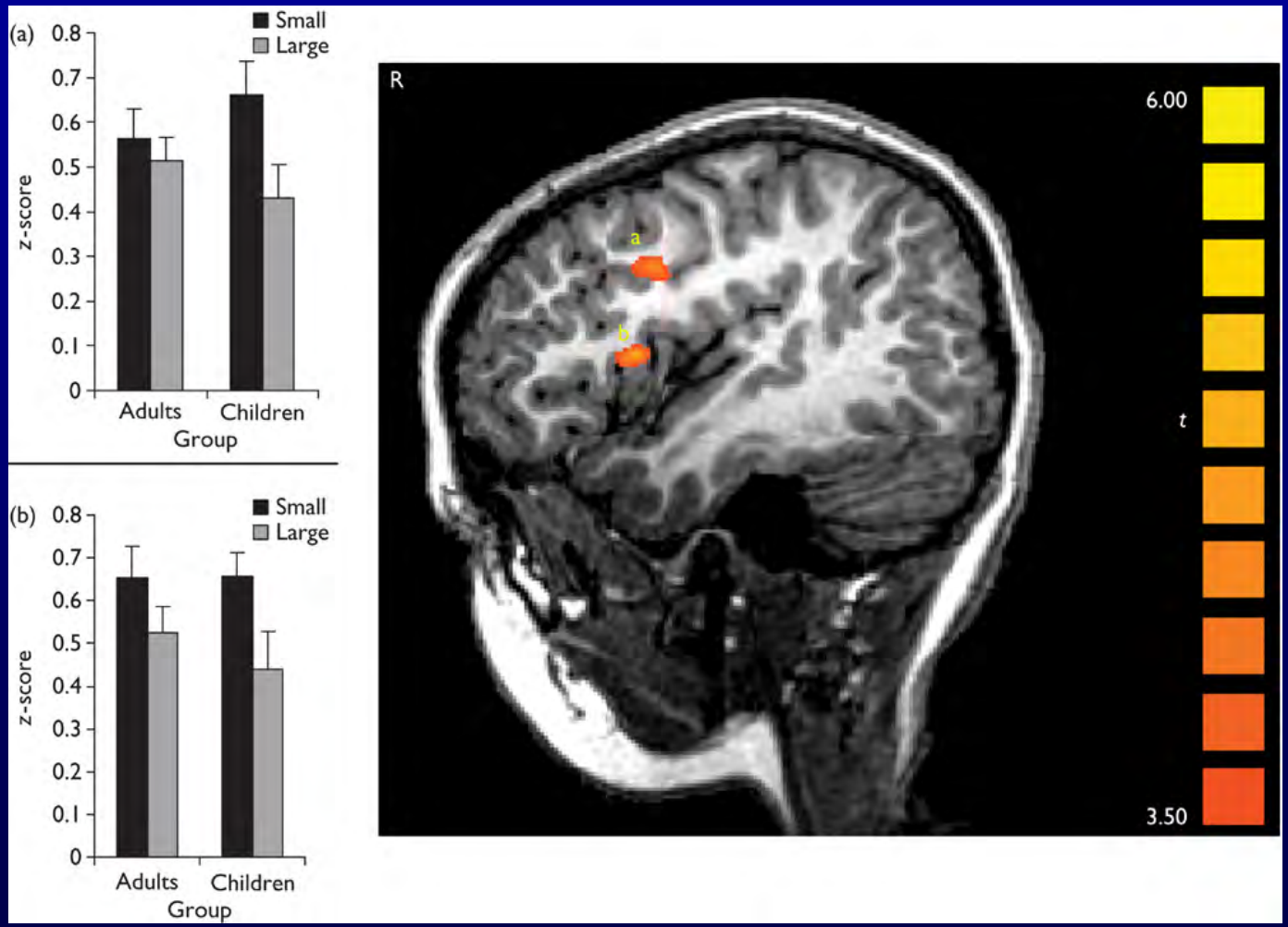




Ansari, Garcia, Lucas, Hamon & Dhital (2005)

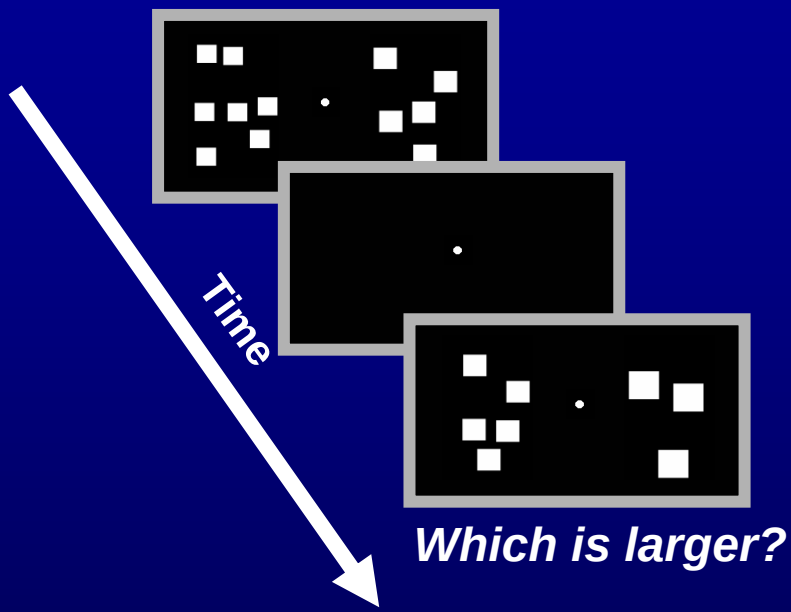
Symbolic Distance Effect

Children



Ansari, Garcia, Lucas, Hamon & Dhital (2005)

Non-symbolic Distance Effect

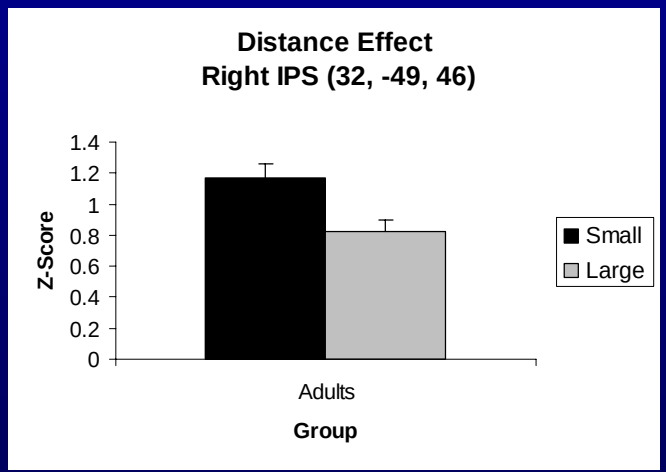


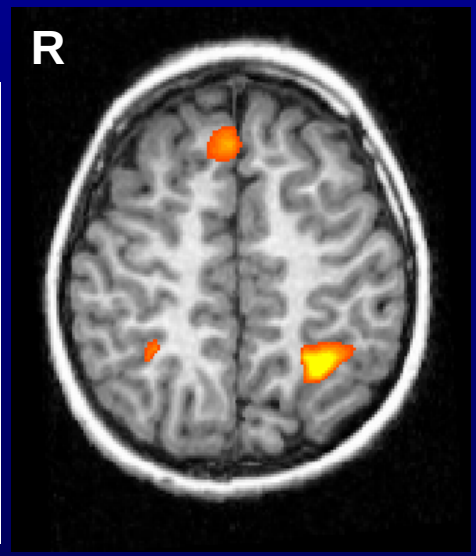
8-12 year old children (N = 9)
Adult college students (N = 9)
Event-related fMRI study

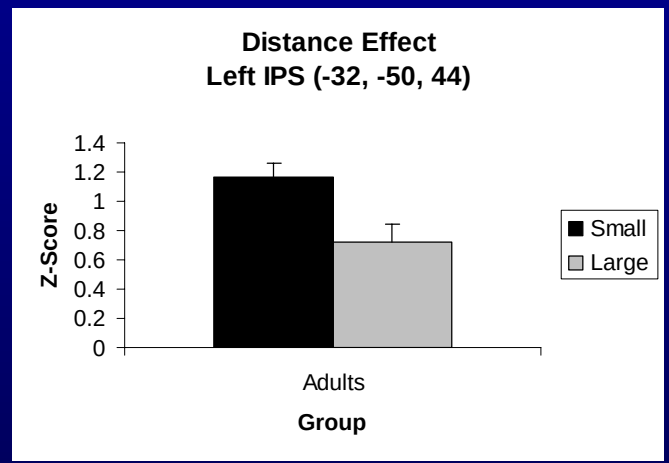
Ansari & Dhital (2006)

Non-symbolic Distance Effect

Adults



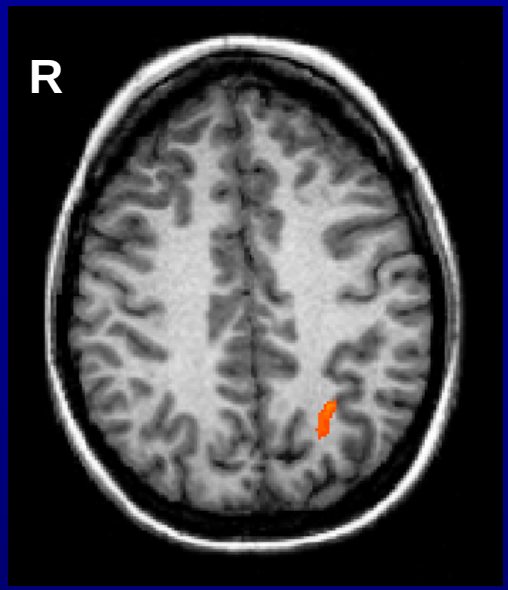


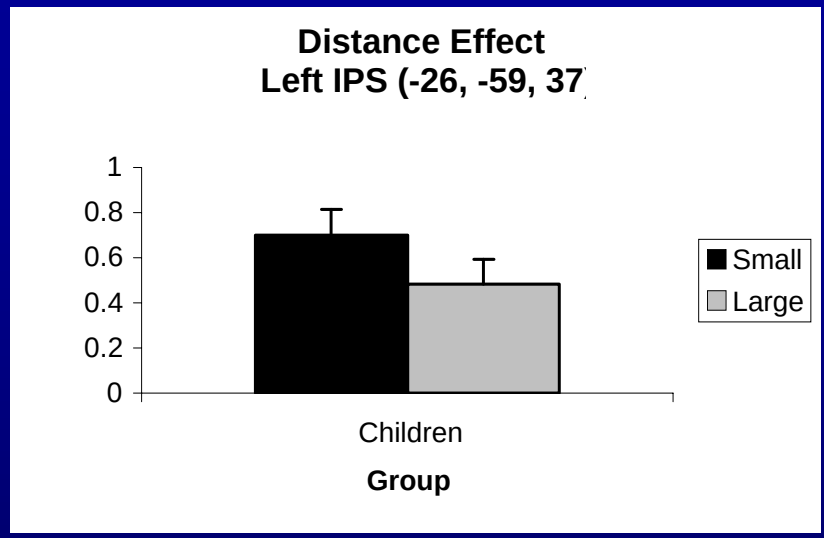


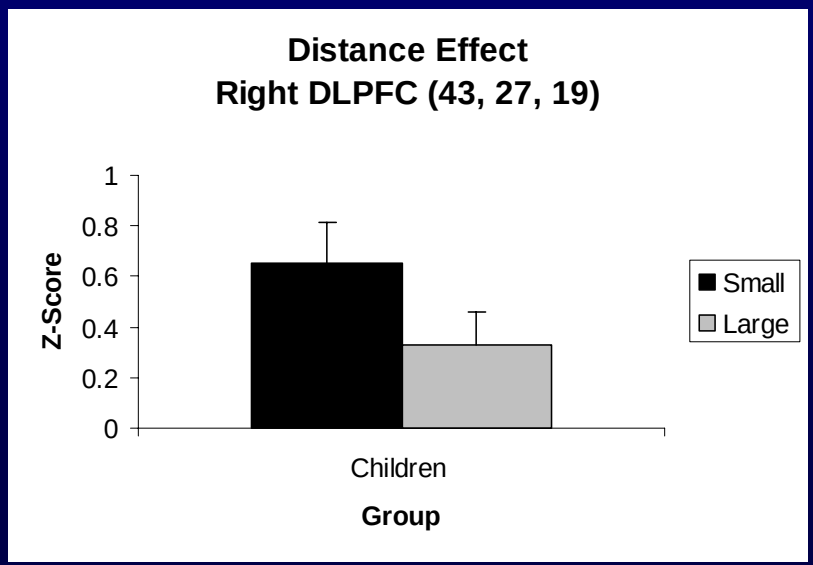
Ansari & Dhital (2006)

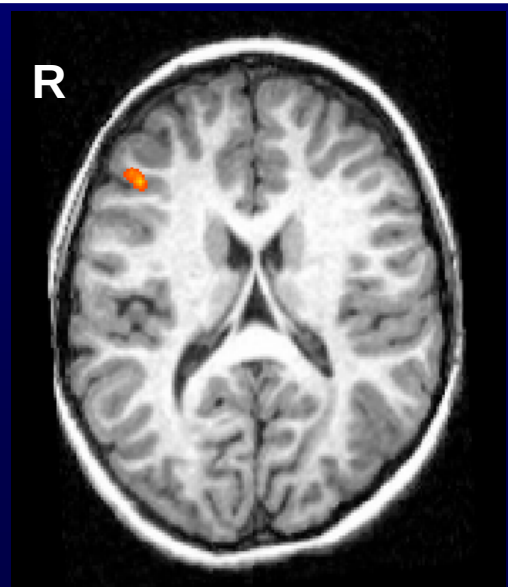
Non-symbolic Distance Effect

Children



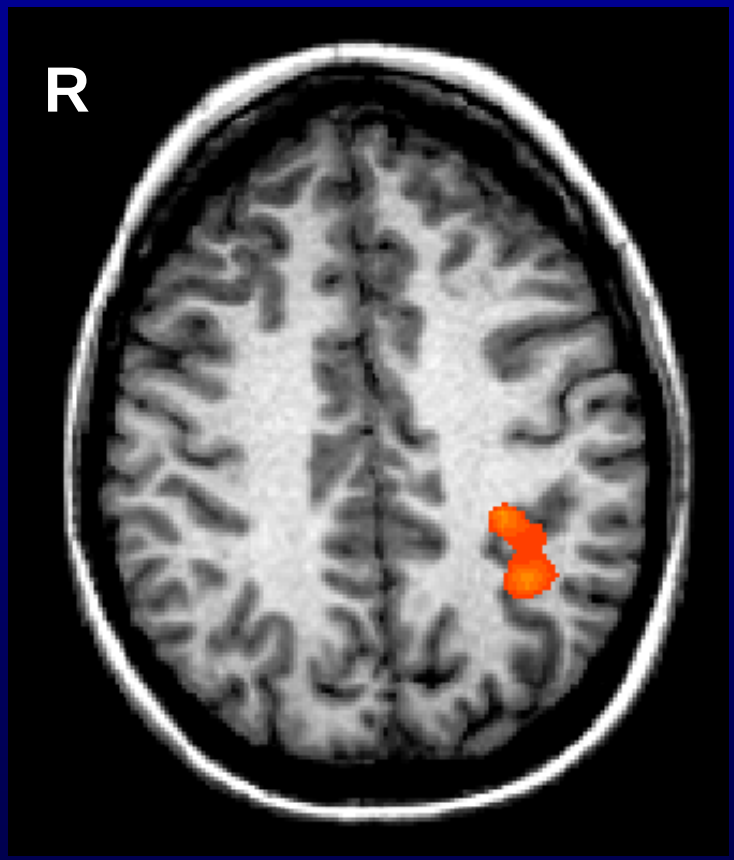






Non-symbolic distance effect

Distance (small vs. large) X Age (Children vs. Adults)



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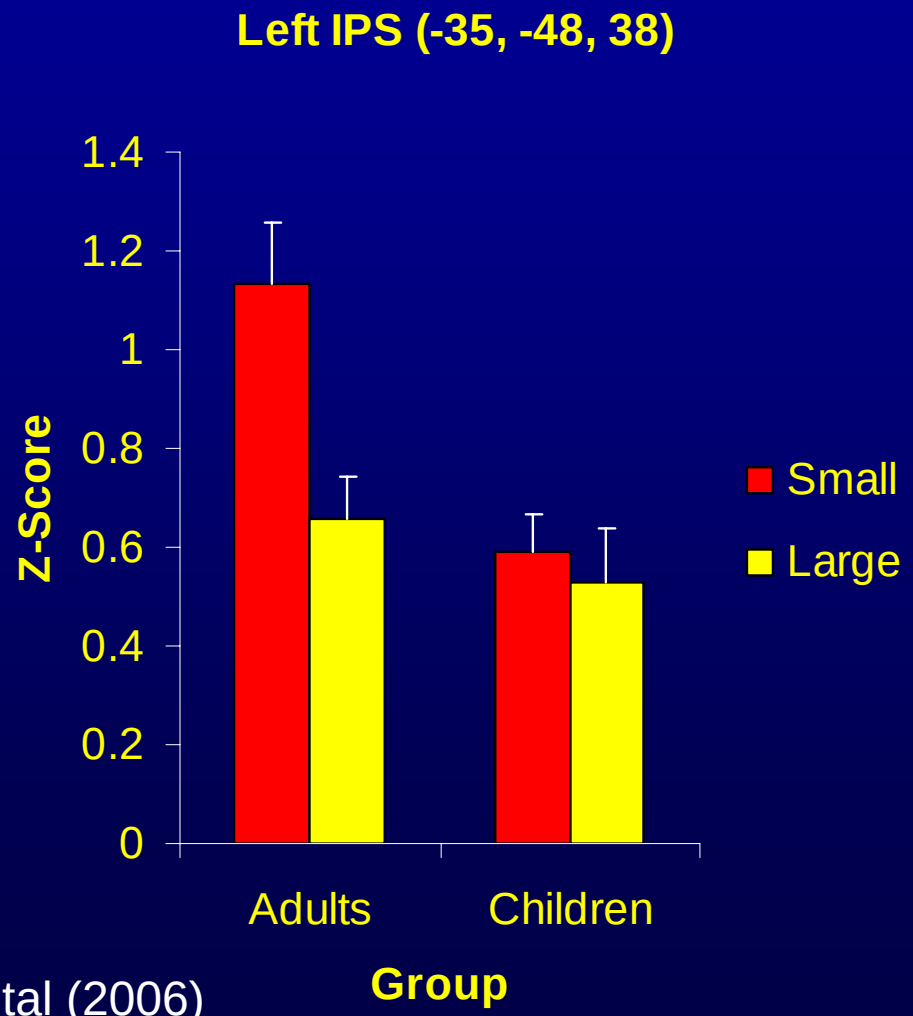
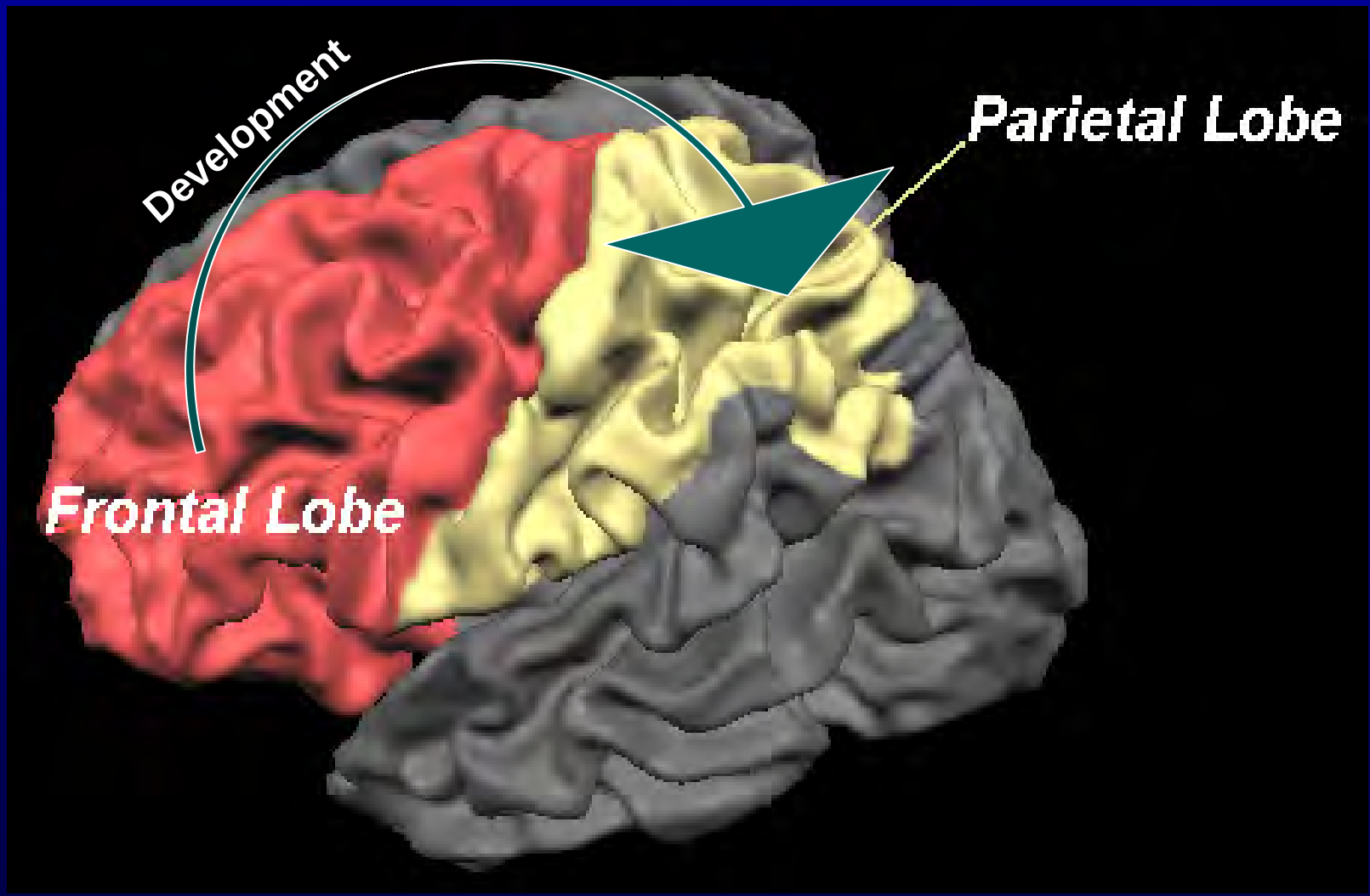


Ansari & Dhital (2006)

Age-related shift



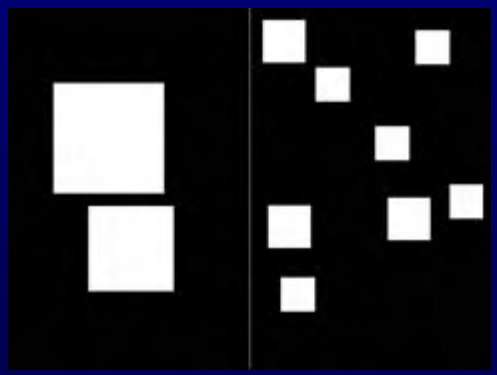
Also see: **Rivera et al., 2005; Kaufmann et al., 2006**

How specific are age-related changes in functional neuroanatomy?

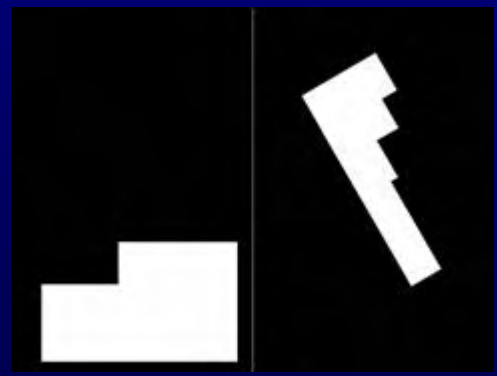
Specificity of dev. changes

Symbolic Comparison
"Which is larger"

Symbolic Control
"Which is more like a line?"



Non-symbolic Comparison
"Which is larger"

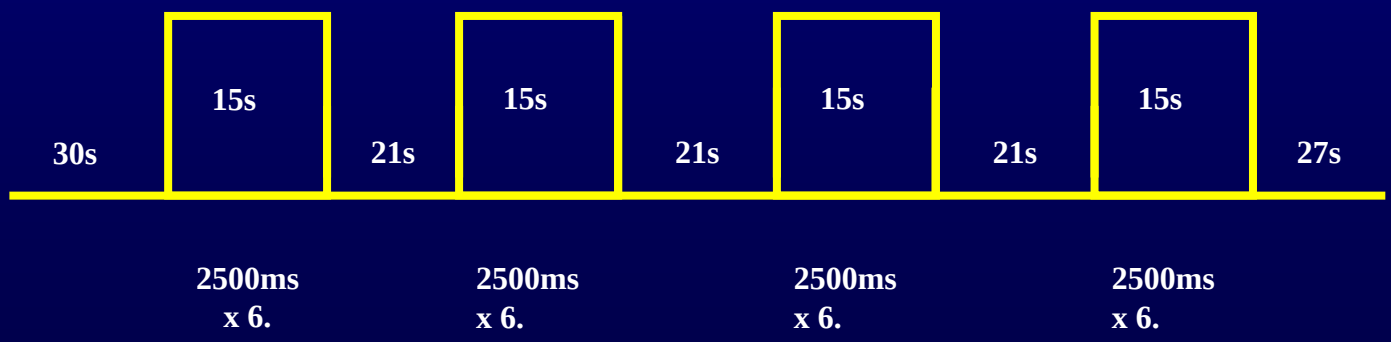


Non-symbolic Control
"Which is more like a line?"

Holloway, Price & Ansari (in preparation)

Specificity of dev. changes

- Participants
  - 19 children (6-9 year olds)
  - 19 adults (18 – 24 year olds)
- Methods
  - Continuous variables systematically controlled for
  - fMRI Block Design
  - 3T Phillips Intera Magnet

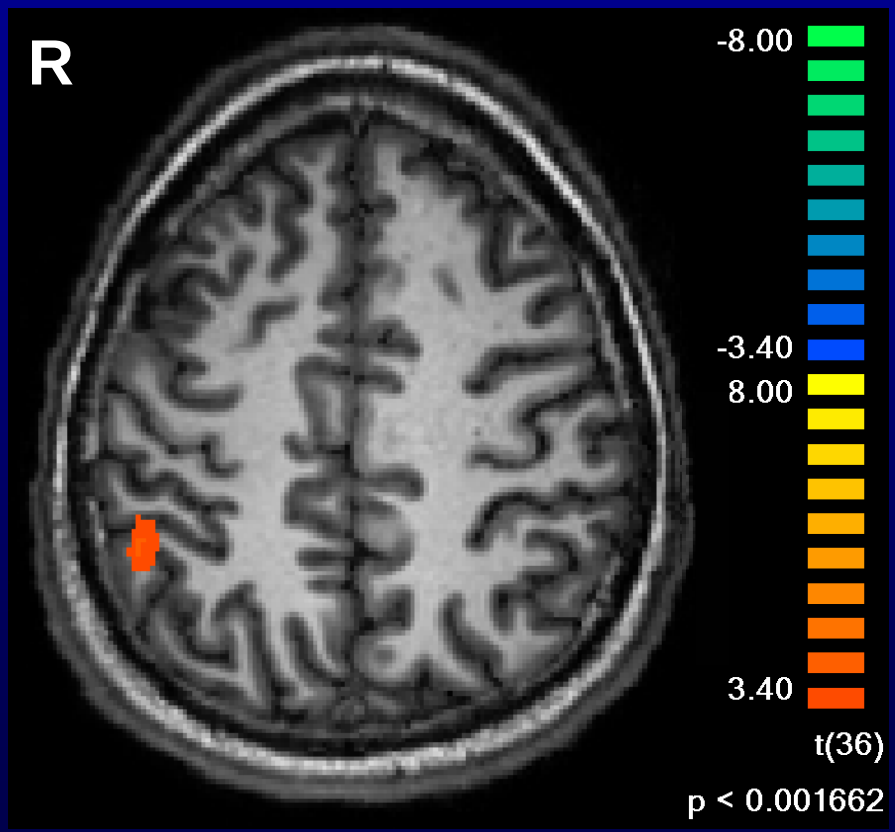


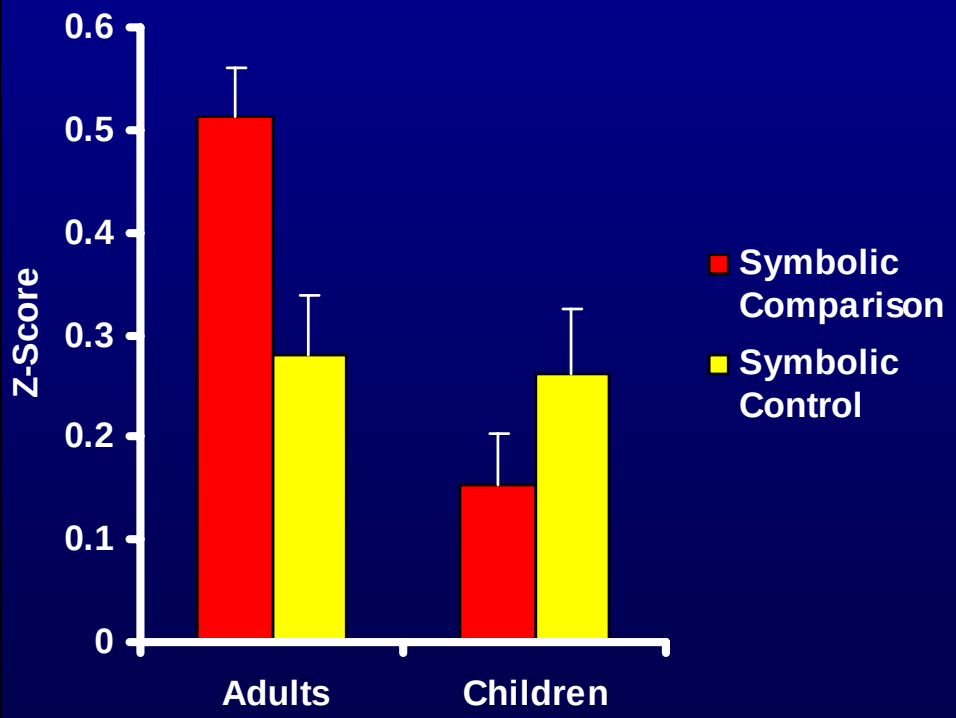
Holloway, Price & Ansari (in preparation)

Which brain regions show greater developmental changes in numerical vs. non-numerical tasks?

Results - *Symbolic*

Task (Symbolic vs. Control) X Age (Children vs. Adults)

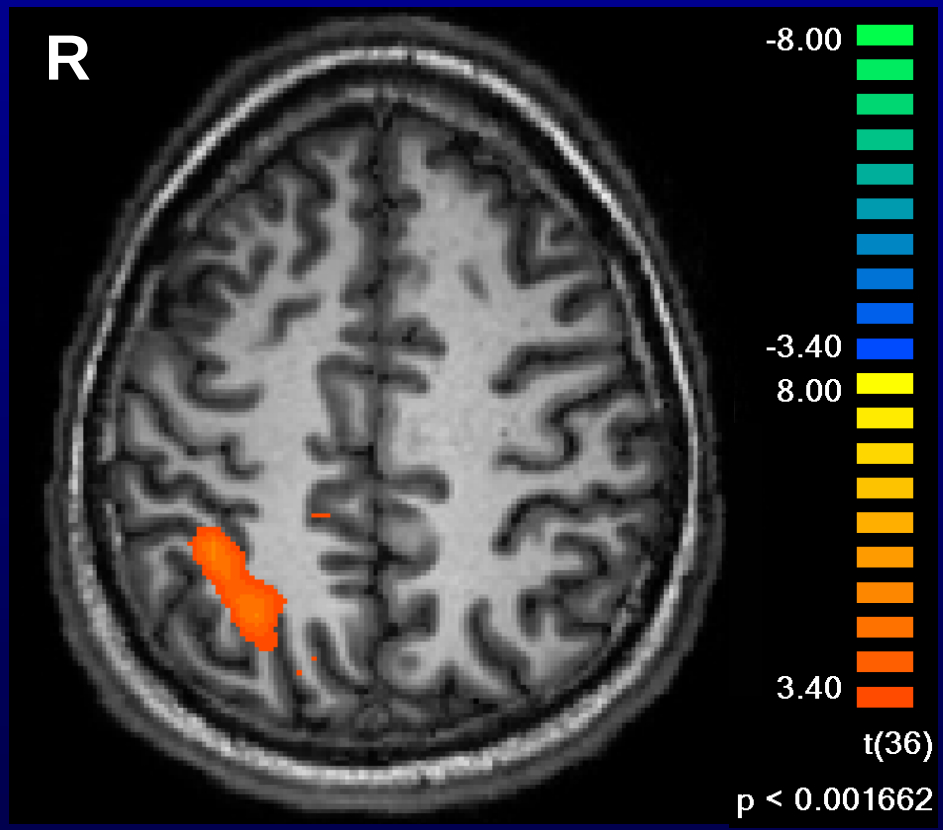


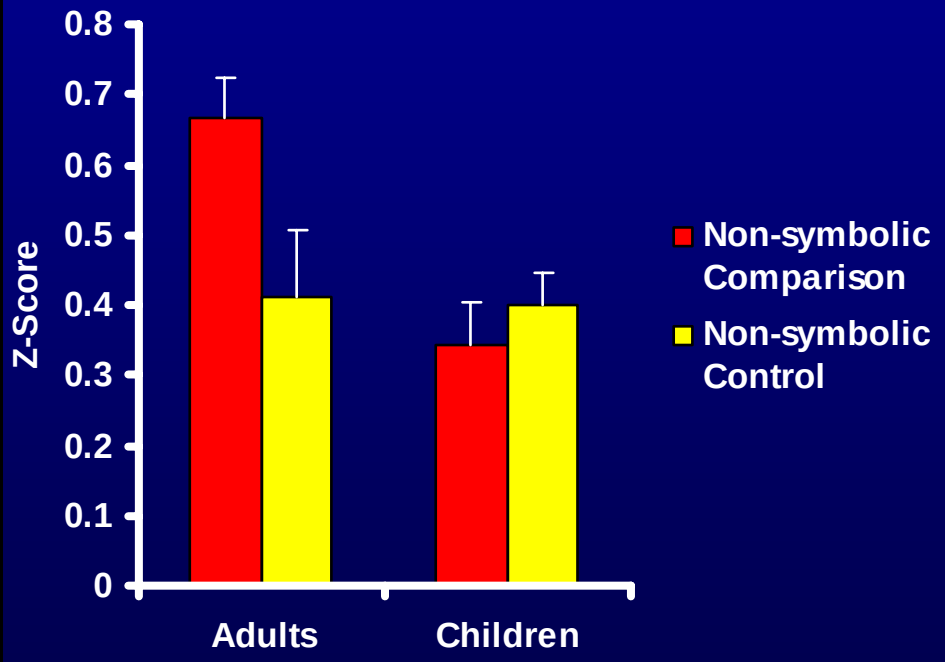


Holloway, Price & Ansari (in preparation)

Results – *Nonsymbolic*

Task (Non-symbolic vs. Control) X Age (Children vs. Adults)





Holloway, Price & Ansari (in preparation)

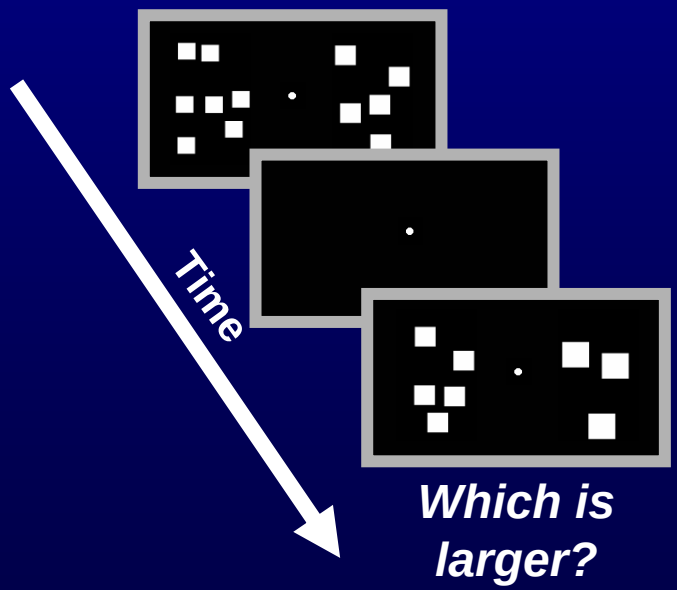
Implications

- Age-related increases in parietal cortex activation during numerical magnitude processing:
  - Greater than changes associated with non-numerical comparison in right IPS
    - Note: left IPS greater in adults than children at lower thresholds
  - Dev. increases in parietal cortex are specific to representation of magnitude

Disruption of ontogenetic changes in Developmental Dyscalculia?

Evidence from Developmental Dyscalculia

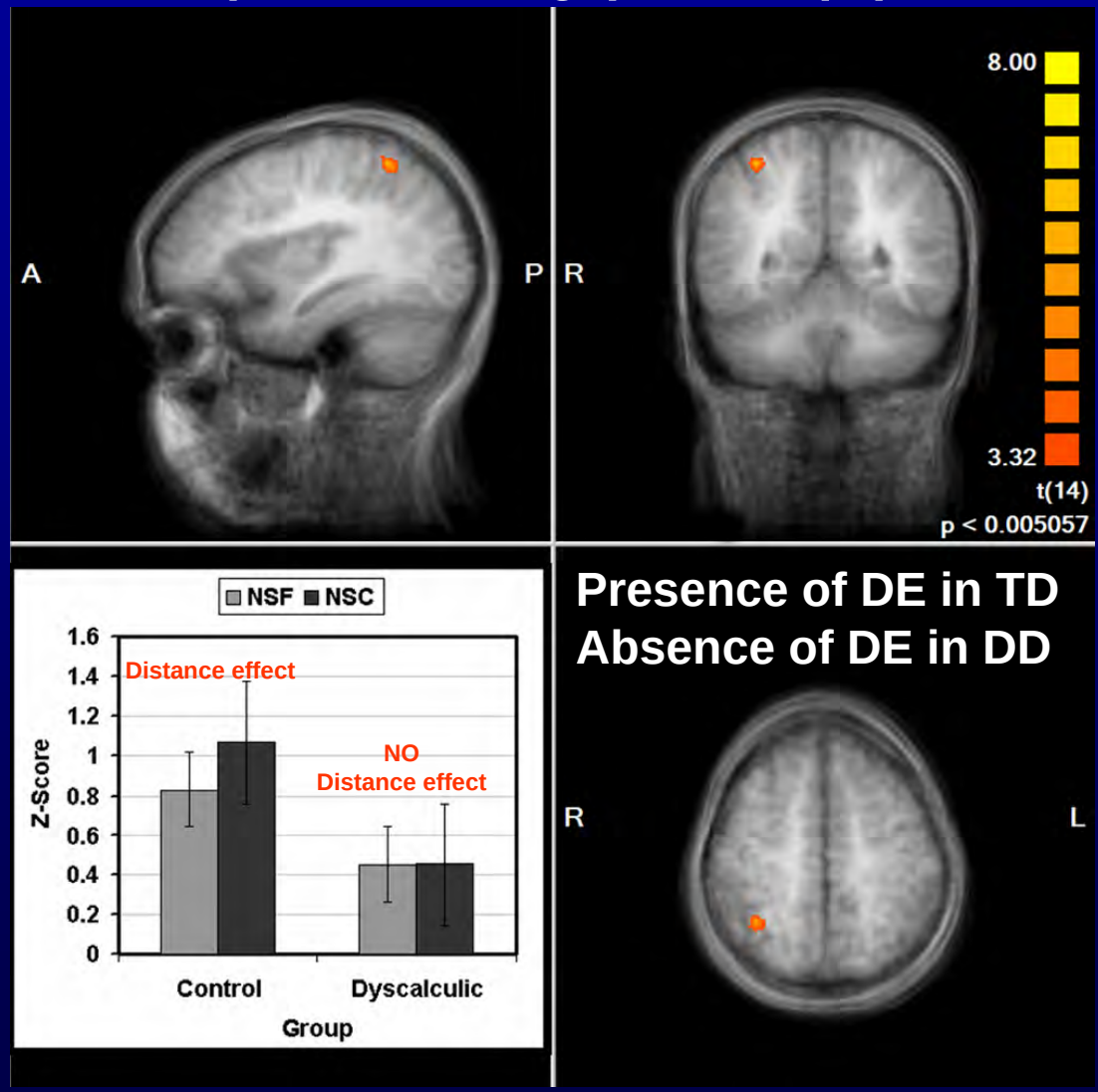
- Eight, 12-year olds with Developmental Dyscalulia (DD)
  - Specifically impaired on tests of calculation (< 1.5 Std)
- Eight, typically developing 12-year olds
- Non-symbolic number comparison



Price et al. (2007)

Evidence from Dev. Dyscalculia

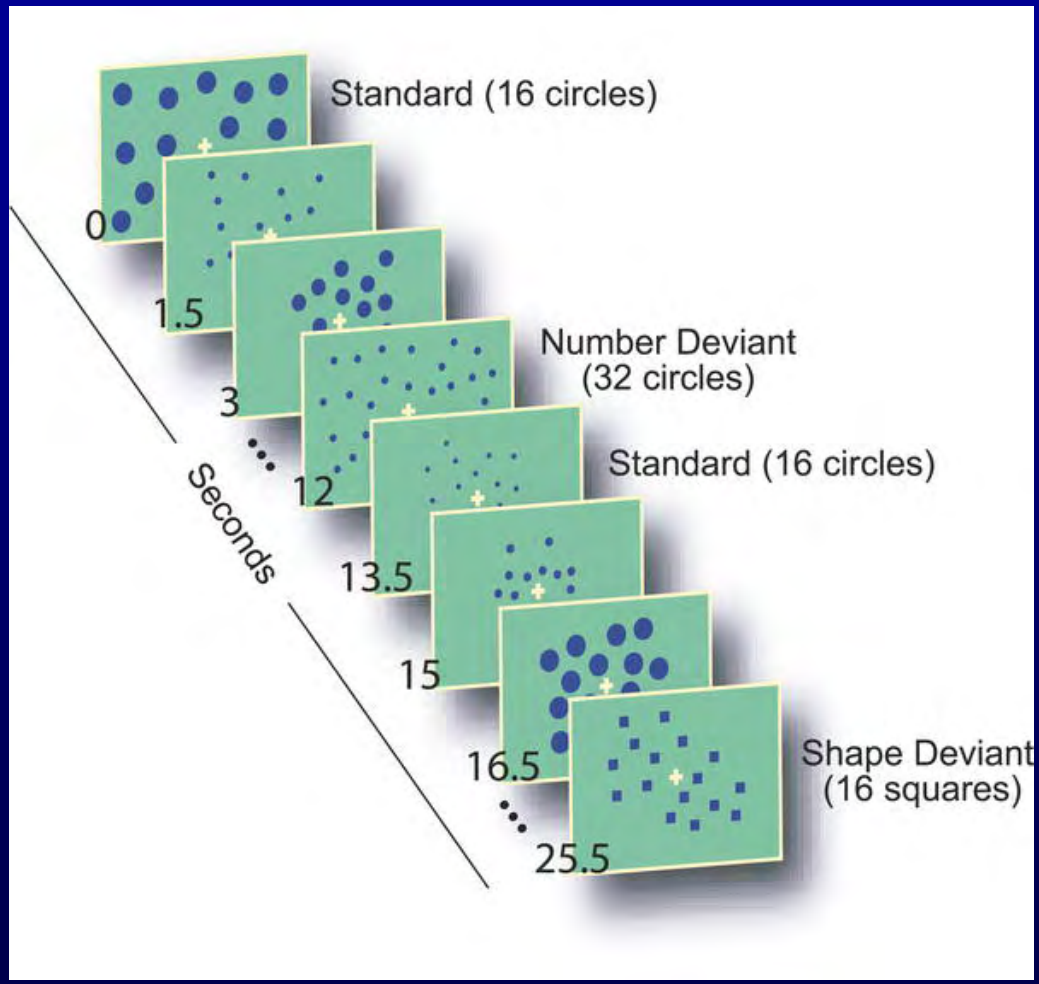
Distance (Small vs. large) X Group (TD vs. DD)



Price et al. (2007)

Evidence for Developmental Similarities

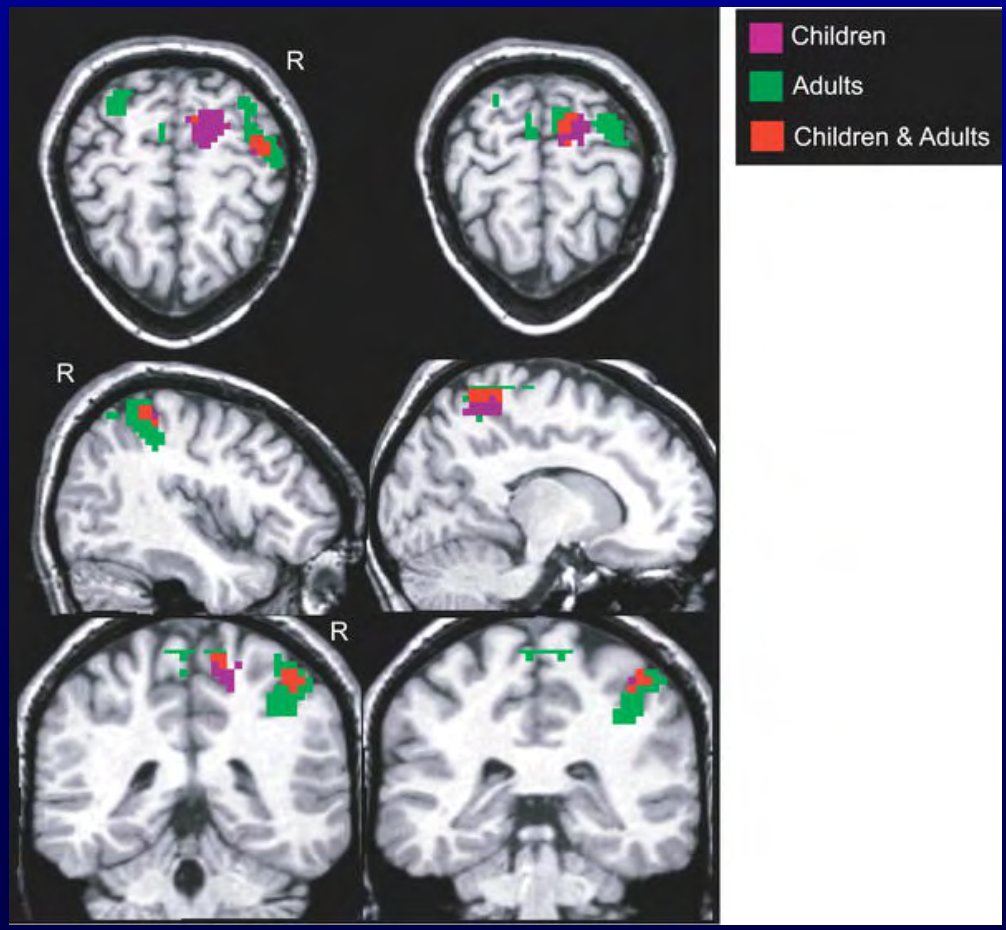
Evidence for developmental similarities



Cantlon et al. (2006)

Evidence for developmental similarities

Responses to number deviants in IPS



Cantlon et al. (2006)

Implications

- Dev. Differences ***and*** similarities
- Graded representations? (Munukata, 2003)
  - ***Dependent on the degree of explicit manipulation required?***
- Comparison of passive vs. active studies
  - Will help to better understand "*what develops?*"

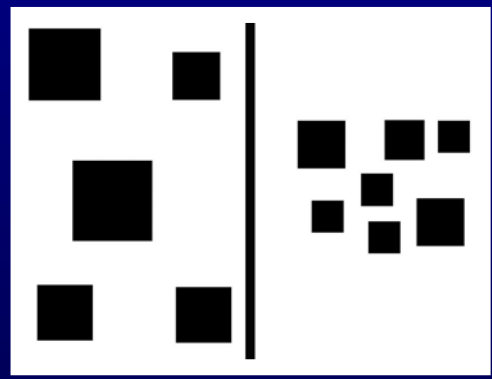
Developmental specialization for symbolic number processing in the brain?

Ontogenetic specialization for symbolic number processing

How does the brain come to process cultural representations of numerical magnitude?

5 · 7

VS.

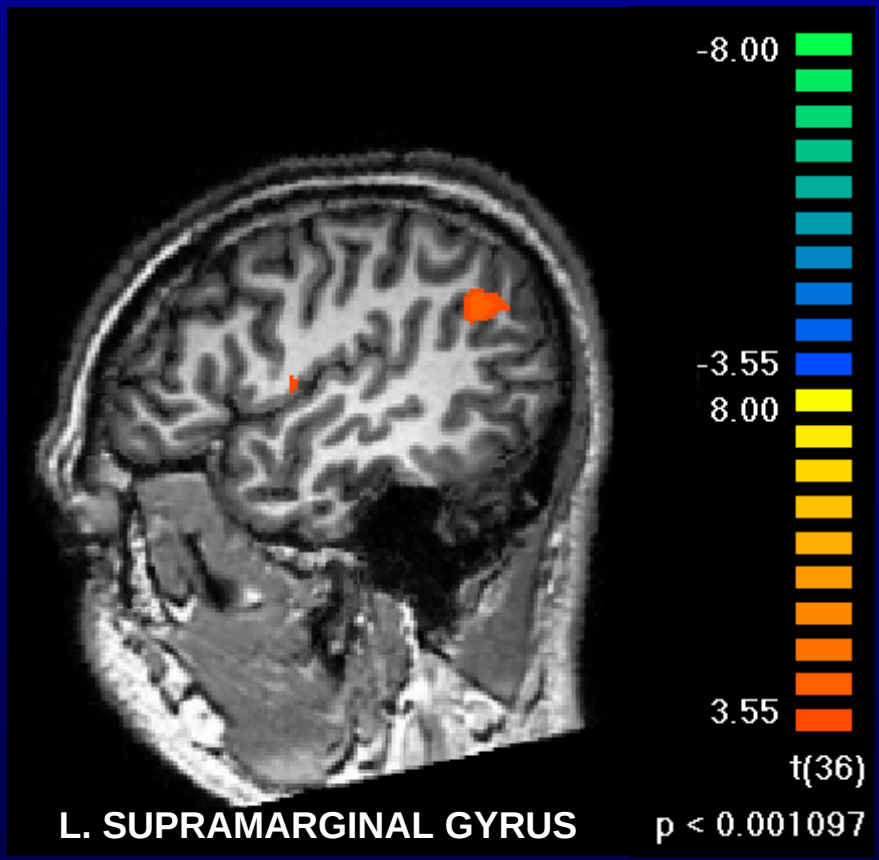


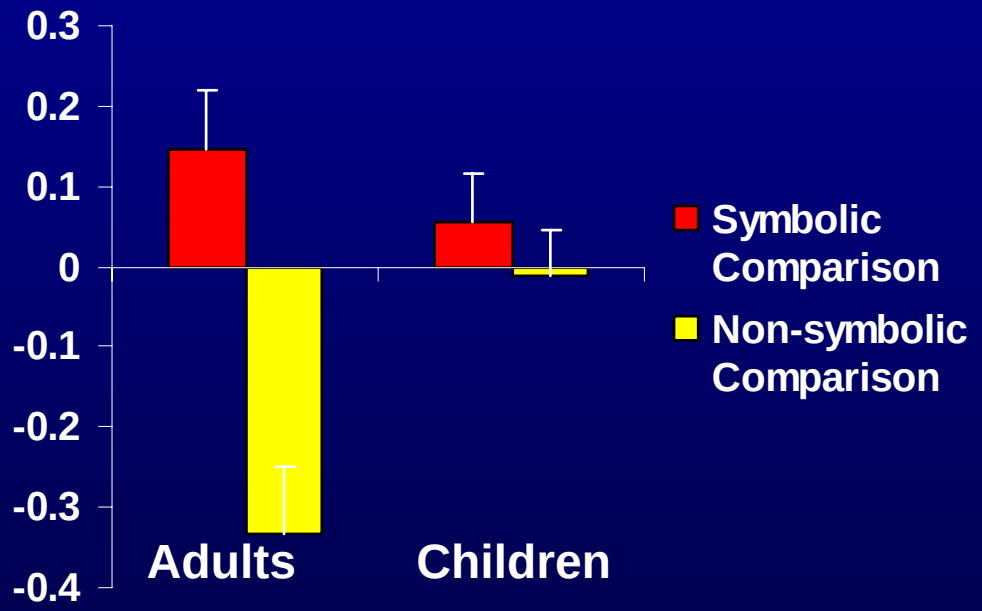
?

Holloway, Price & Ansari (under review)

Ontogenetic specialization for symbolic number processing

Format (Symbolic vs. non-symbolic) X Age (Children vs. Adults)

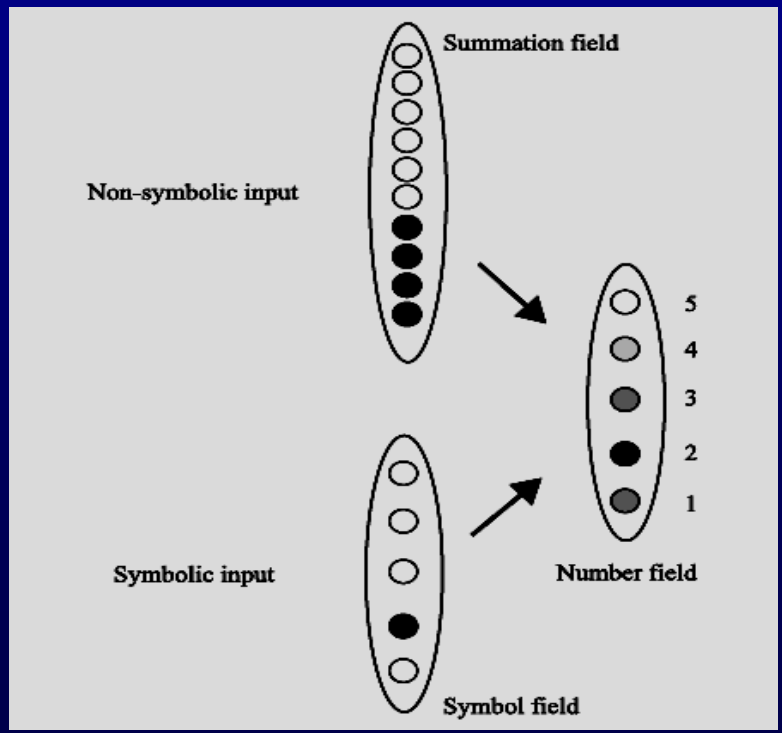




Holloway, Price & Ansari (under review)

Implications

- Specialization of the SMG for symbolic processing of numerical magnitude
  - Pathway for mapping numerals onto magnitude
  - Suppression of *inappropriate* format?
  - SMG involved in reading
  - Symbol-referent links?

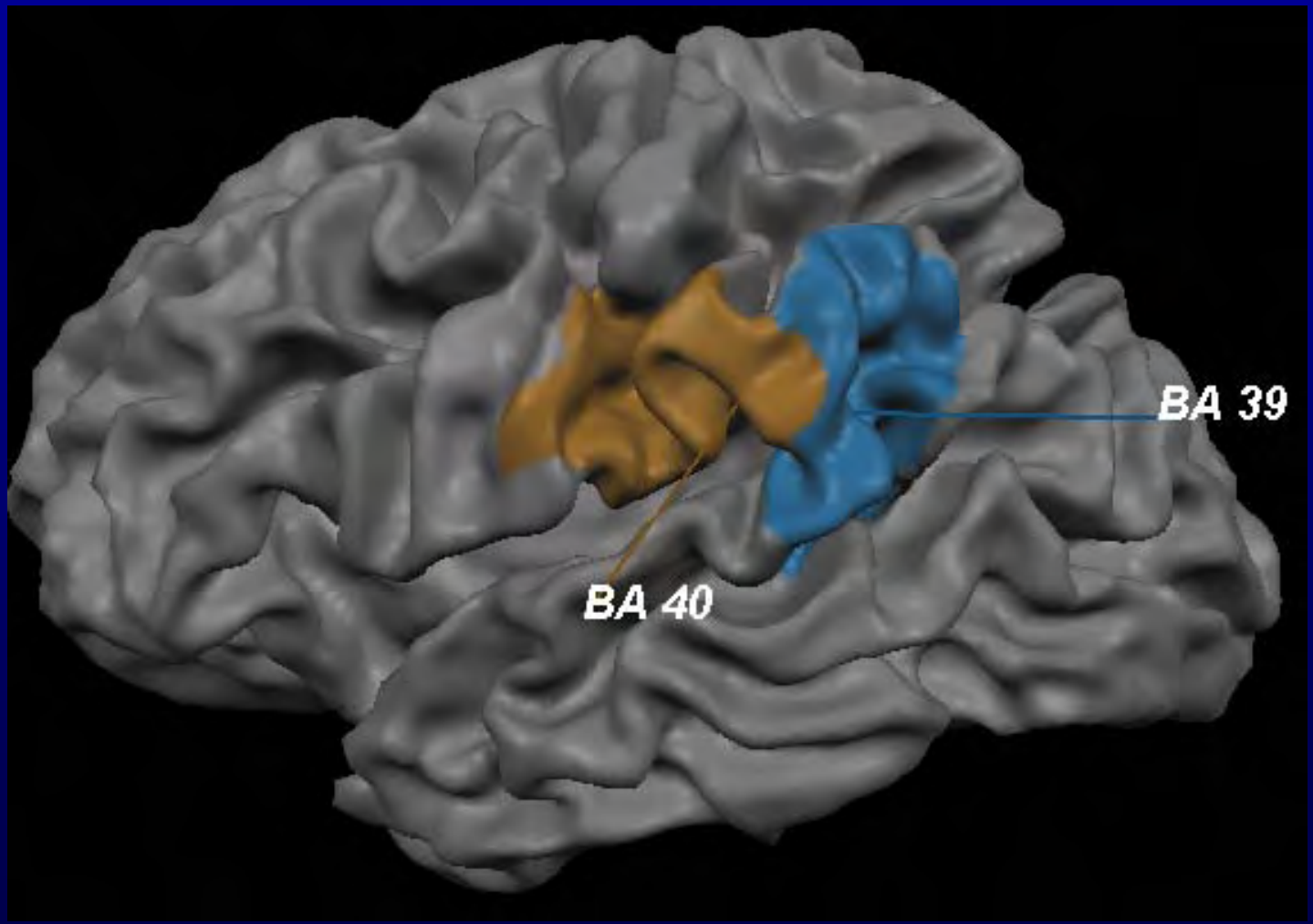


Verguts & Fias (2004)

Neural correlates of mental arithmetic

Mental Arithmetic

LEFT TEMPORO-PARIETAL CORTEX



(i.e Gerstman, 1940; Roland & Friberg, 1985; Dehaene et al., 1996, 1999)

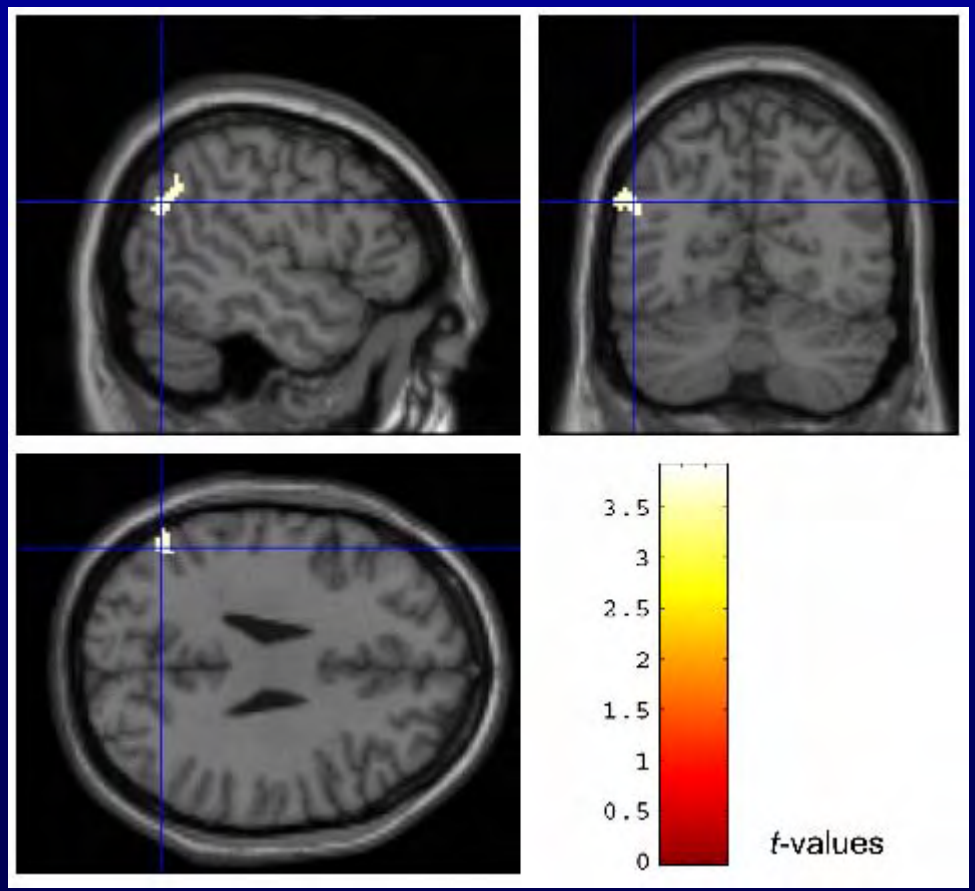
Mental Arithmetic

Arithmetic Verification

4 x 6 = 24

13x7 = 91

Single-digit > Multi-digit

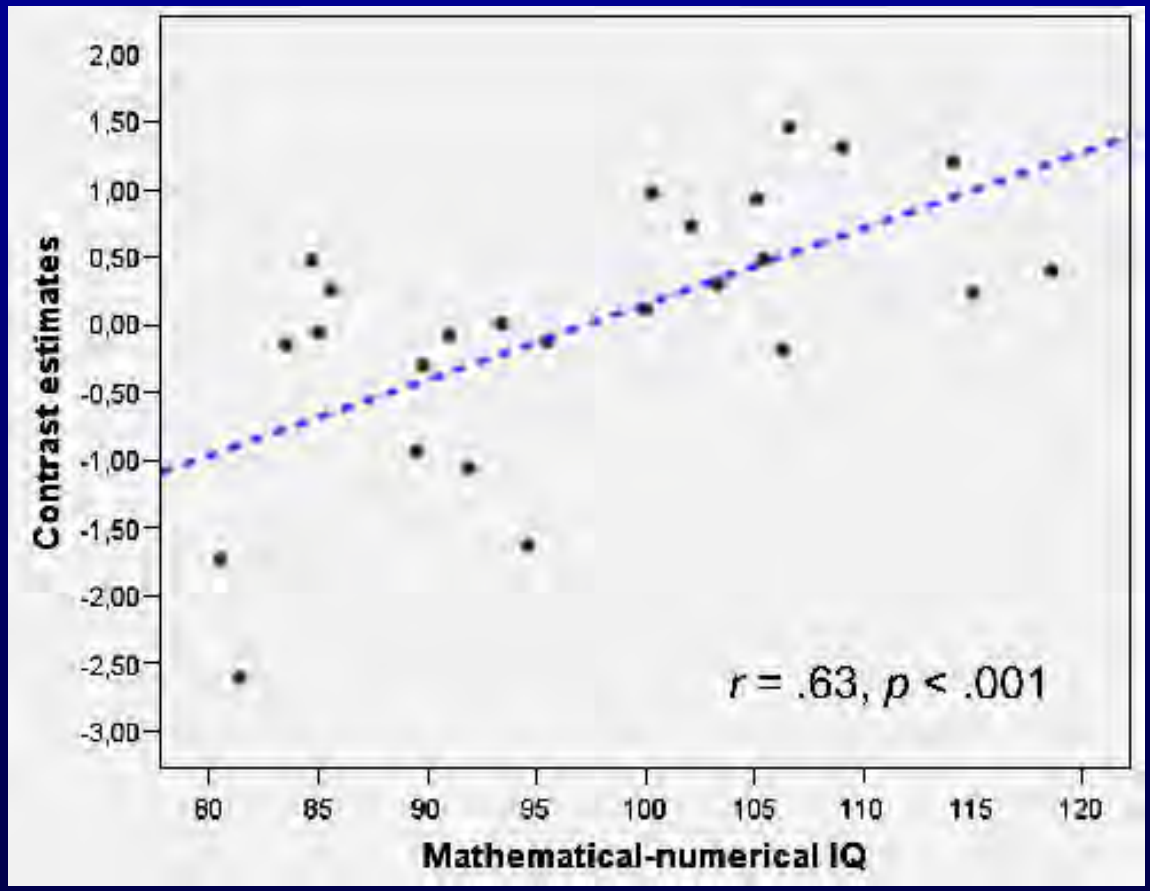


FACT RETRIEVAL

Grabner, Ansari et al. (2007)

Mental Arithmetic

Relationship between AG activation and indiv. difference in Math Competence

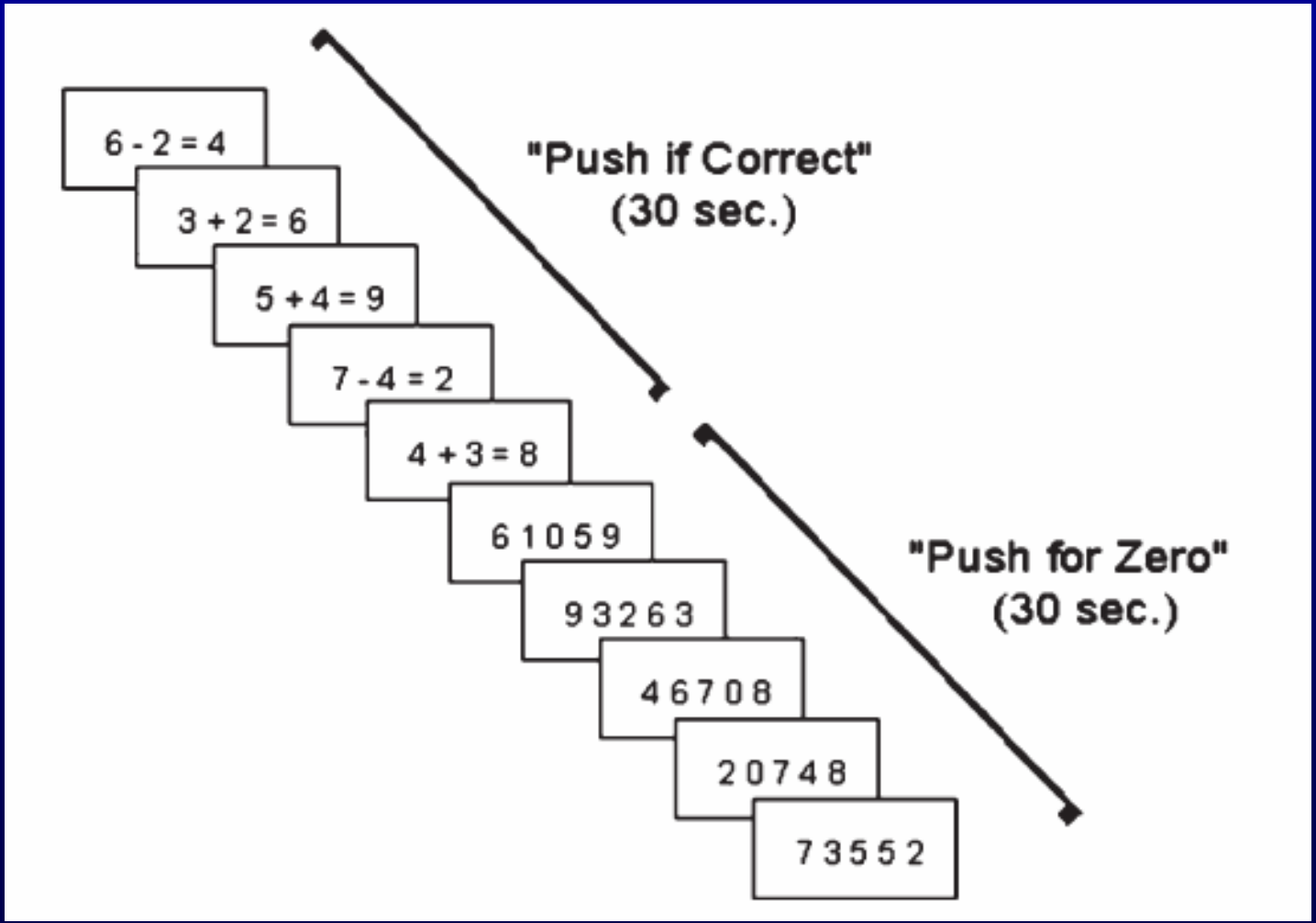


Grabner, Ansari et al. (2007)

Neural correlates of mental arithmetic

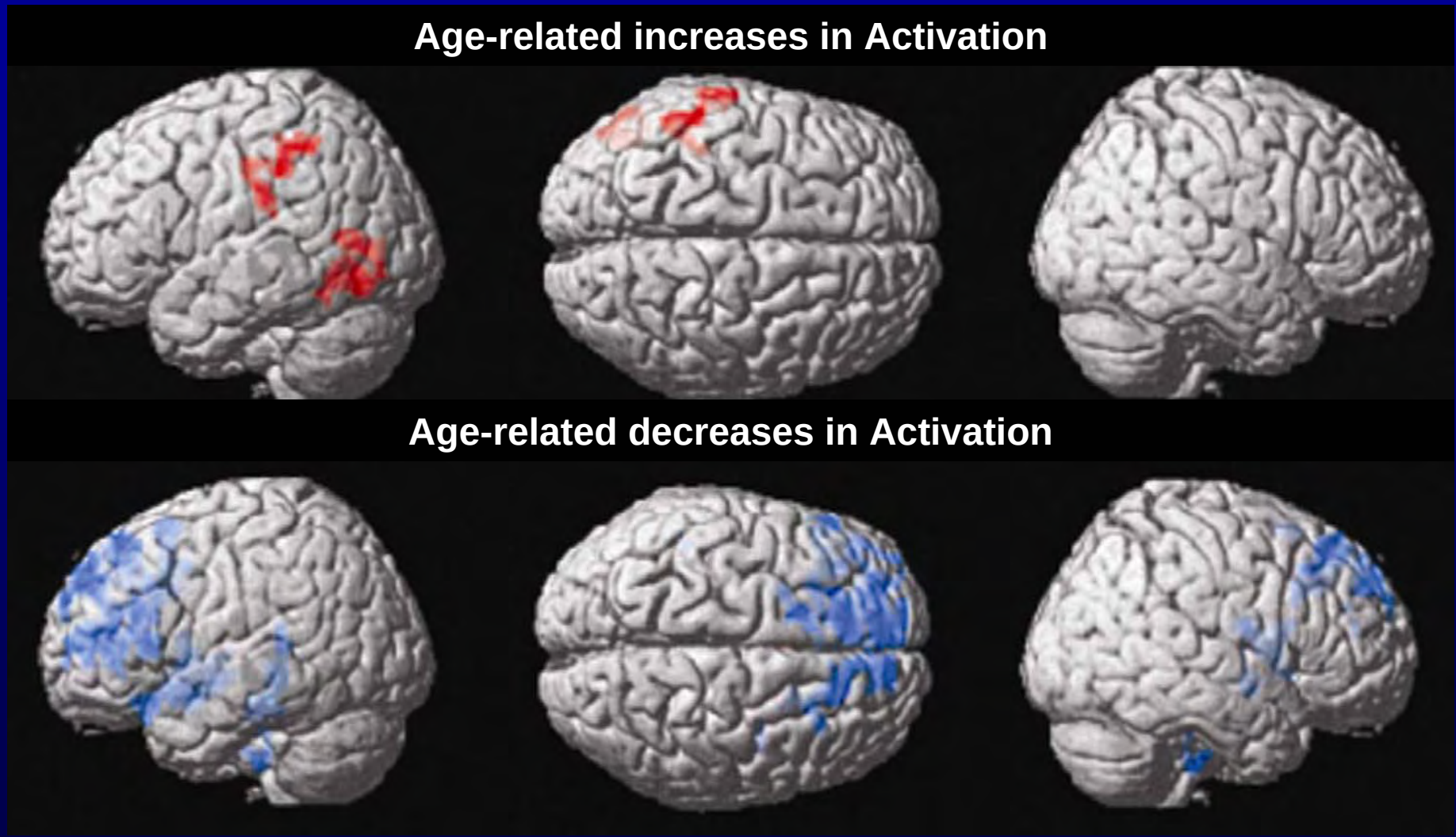
Developmental Changes?

Mental Arithmetic



Rivera et al. (2005)

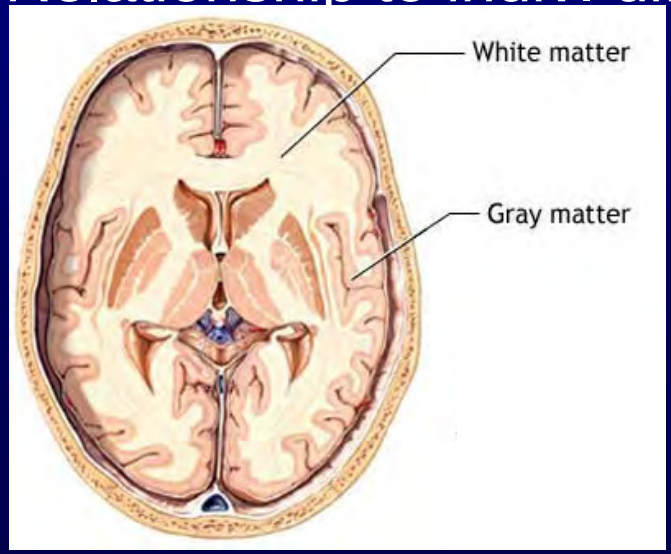
Mental Arithmetic

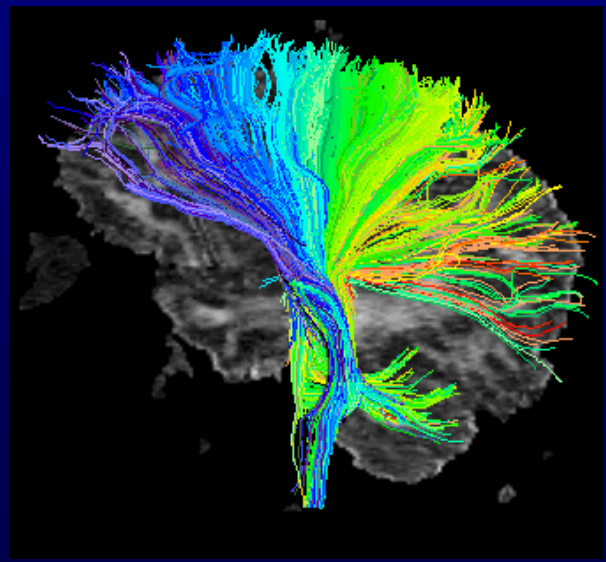


Rivera et al. (2005)

Mental Arithmetic

- What about structural development?
- White matter development
- Diffusion tensor imaging (DTI)
- Integrity of White Matter (*Fractional Anisotropy*)
- Relationship to indiv. diff in math?





Van Eimeren, Niogi, McCandliss & Ansari (in preparation)

Mental Arithmetic

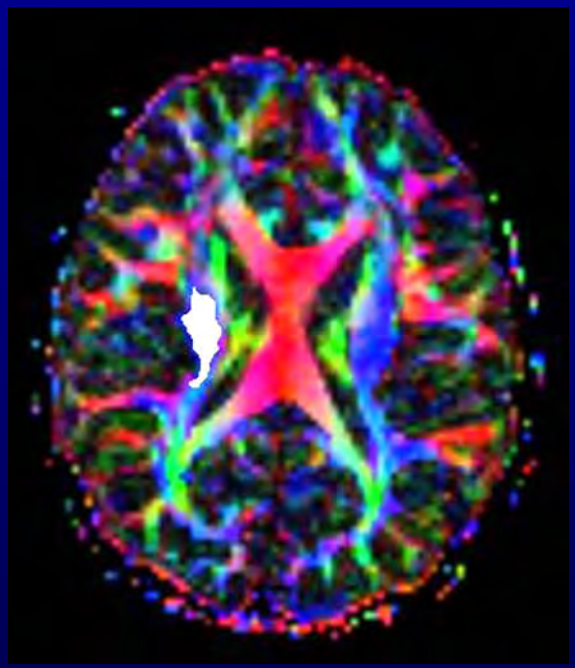
- 13 children (7-9 years)
- Diffusion Tensor Imaging at 3T
- Reproducible Objective Quantification Scheme (ROQS)
- Standardized tests of calculation
  - Wechsler Individual Achievement Tests
    - Calculation and math reasoning

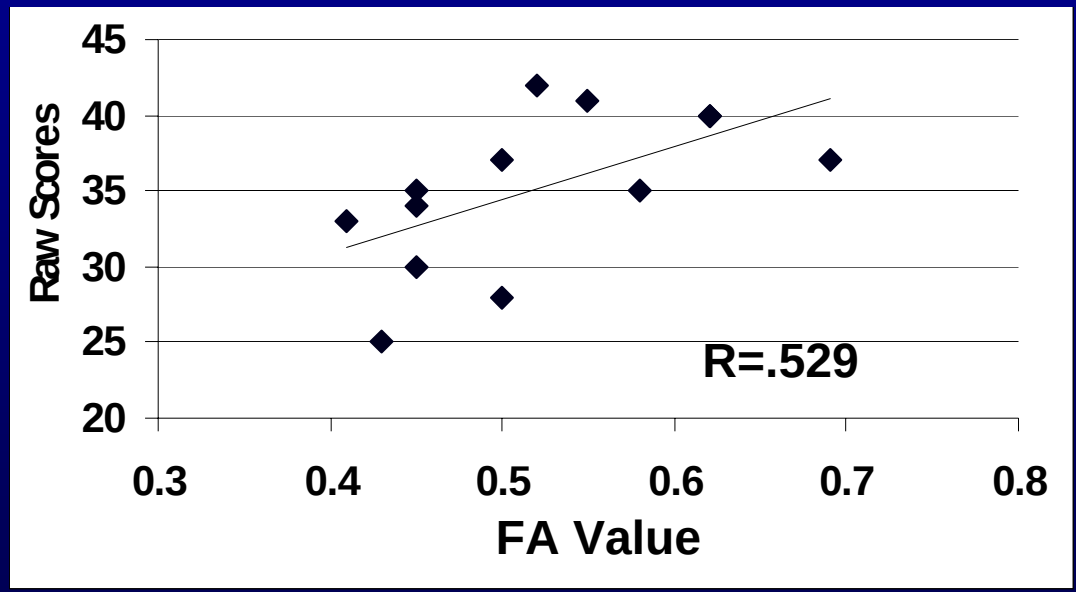
Is there a relationship between white matter microstructure and indiv. diff. in math competence?

Van Eimeren, Niogi, McCandliss & Ansari (in preparation)

Mental Arithmetic

Left Superior Corona Radiata



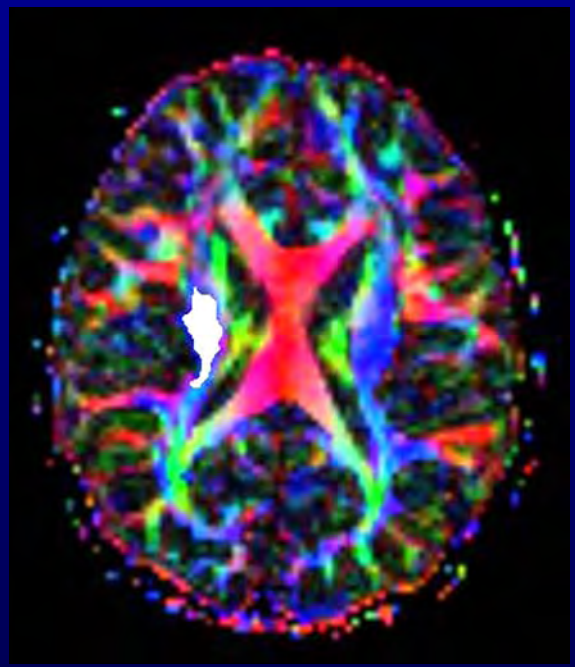


Indiv. diff in math reasoning and calculation correlate with FA values

Van Eimeren, Niogi, McCandliss & Ansari (in preparation)

Left SCR correlates with reading

Left Superior Corona Radiata



QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Indiv. diff in reading correlate with FA values

Niogi & McCandliss (2006)

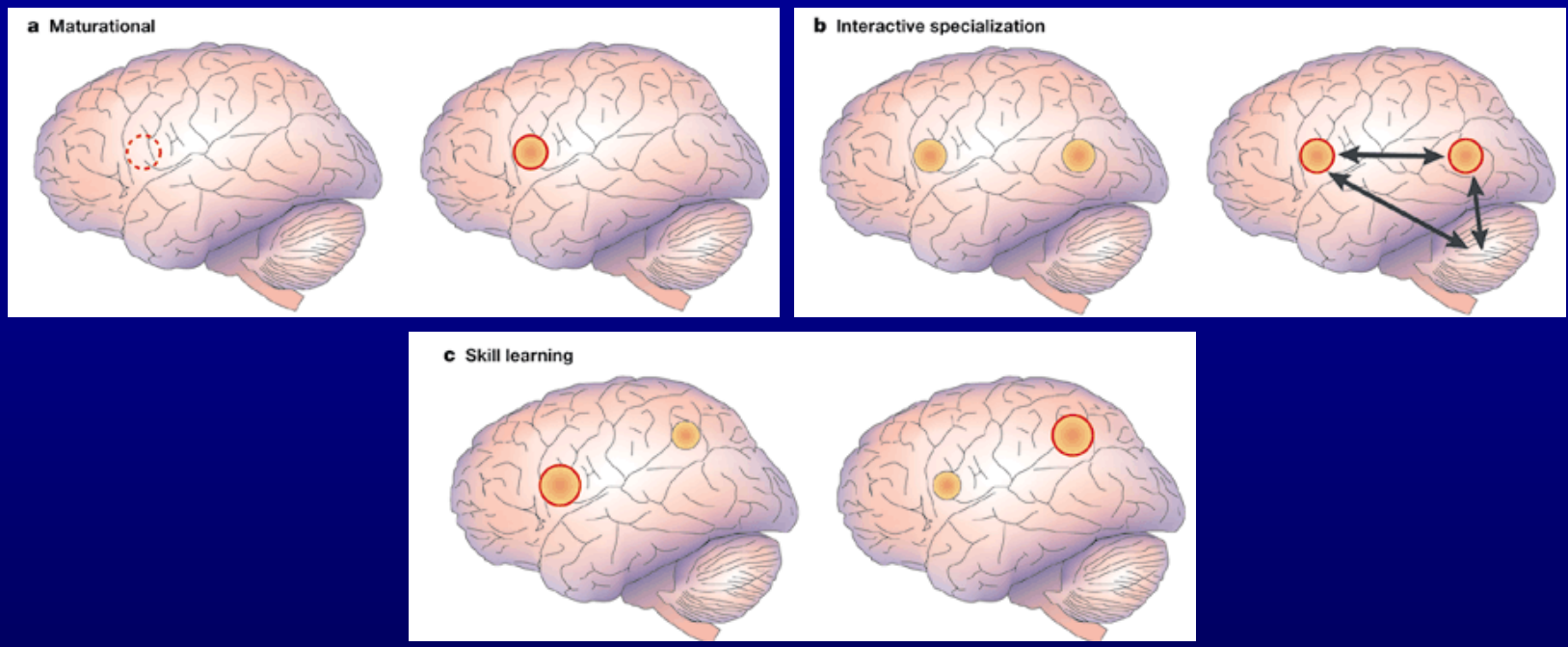
Summary & Conclusions

- **Evidence for developmental changes in:**
  - Functional neuroanatomy underlying symbolic and non-symbolic processing of numerical magnitude
    - Changes specific to numerical magnitude
    - Disruption of IPS activation in Dev. Dyscalculia
    - Specialization for symbolic processing in left SMG
    - LH temporo-parietal cortex increases for mental arithmetic
    - White matter related to math achievement

- **Study of development:**
  - Elucidates how adult brain system are constructed
  - Understand dev. breakdown of systems
  - How cultural symbols *become* represented

Future Challenges

- ***What is the specific nature/shape of change?***



Johnson (2005)

- What does and does not develop?
- Longitudinal studies
- Individual differences

Acknowledgements

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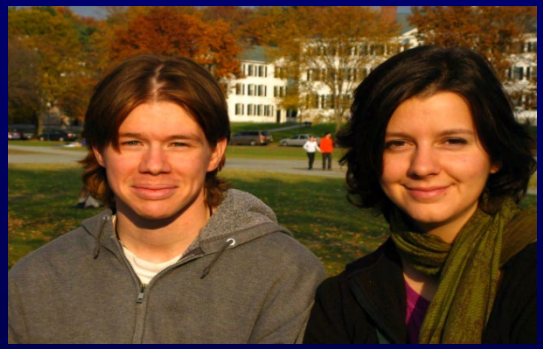
Those who did the work



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