STEM Education, Learning Disabilities, and the Science of Dyslexia

Brain Imaging Studies of Reading and Arithmetic in Dyslexia

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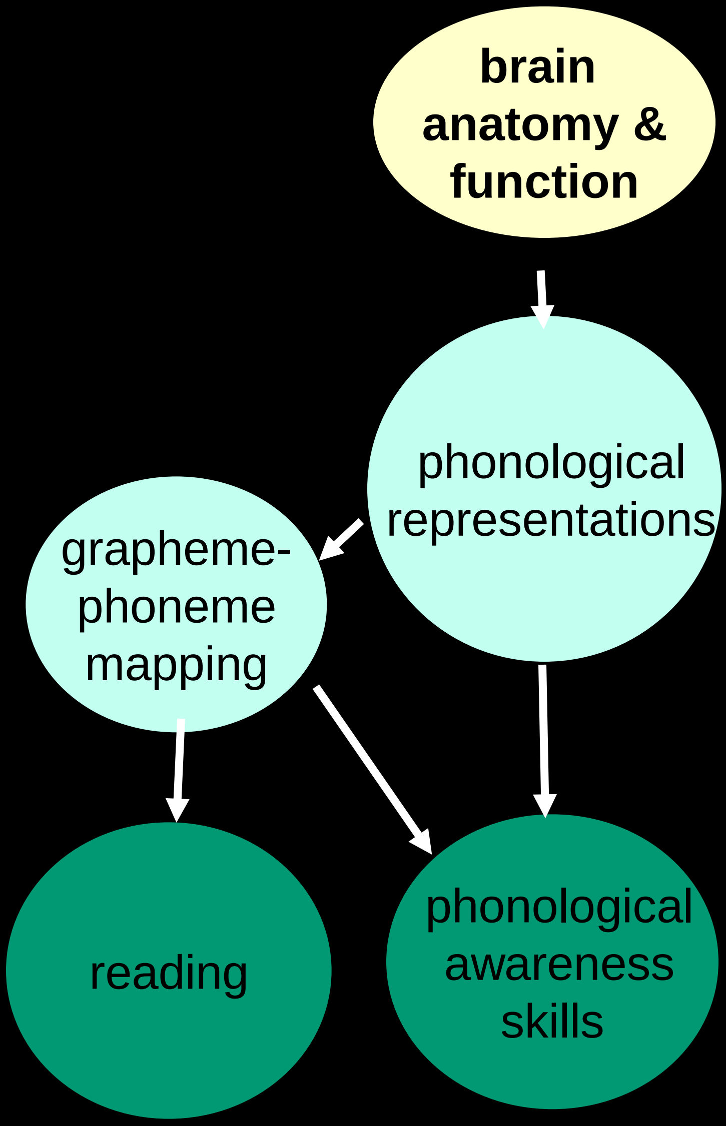
Motivation

- Developmental dyslexia (Reading Disability) and dyscalculia (Math Disability) are prevalent learning disabilities that interfere with academic success.
- This is especially true for STEM-related subjects which rely on written and numerical materials.

Developmental Dyslexia

- International Dyslexia Association and NICHD Research Definition of Dyslexia (Lyon et al. 2003)
  - Specific learning disability neurological in origin
  - Characterized by
    - Difficulty with accurate/fluent word recognition
    - Poor spelling/decoding abilities
  - Due to
    - Deficit in phonological component of language unexpected in relation to cognitive abilities/classroom instruction
  - Secondary consequences
    - Reduced reading experience, vocabulary growth, and reading comprehension

Developmental Dyslexia



Magnetic Resonance Imaging (MRI)

The Neural Basis of Reading

- Left inferior frontal gyrus
- Left temporo-parietal cortex
- Left infero-temporal cortex

- From Pugh et al., 2000

Research Questions

- What is the neural bases of dyslexia?
- What is the neural correlate of successful reading intervention in dyslexia?
- Is there shared brain function for reading and arithmetic?
- Is the functional anatomy of arithmetic altered in dyslexia?

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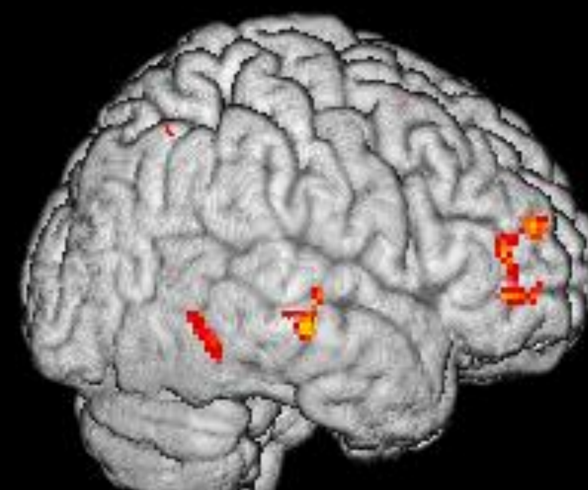
Phoneme Deletion

Task	fixate	repeat	delete
Stimulus	+	rat	rat
Response		rat	at
Processes	fixation	vocalization	vocalization + phonological manipulation

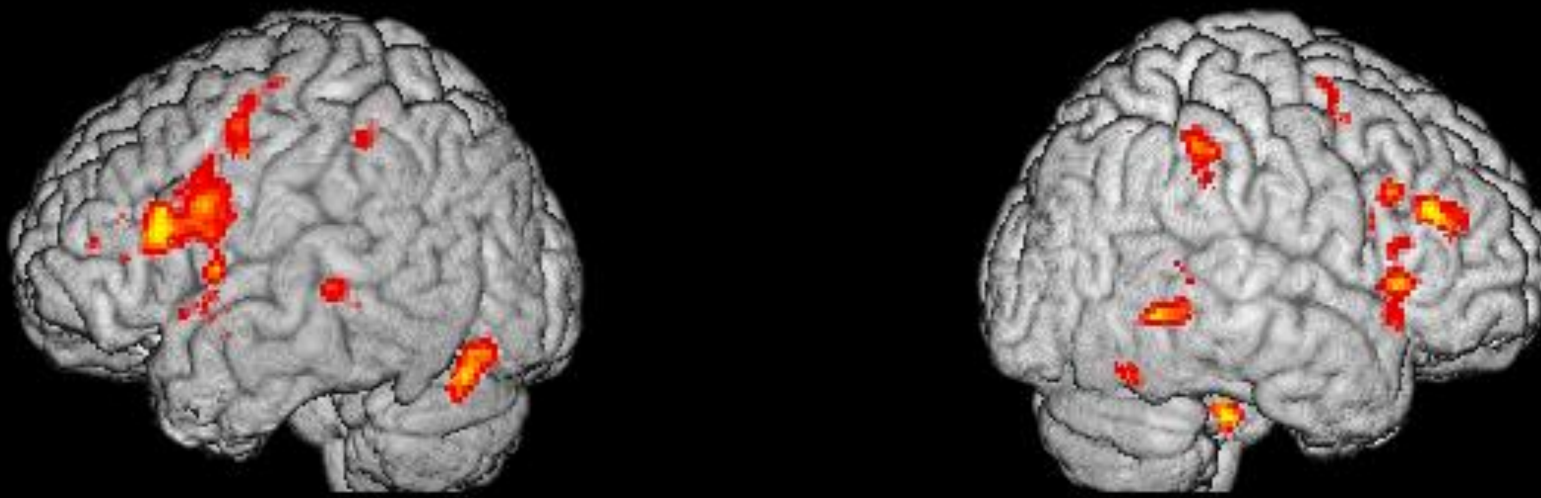
Typical Readers: Deletion versus Repetition

left



right

Dyslexic Readers: Deletion versus Repetition



left

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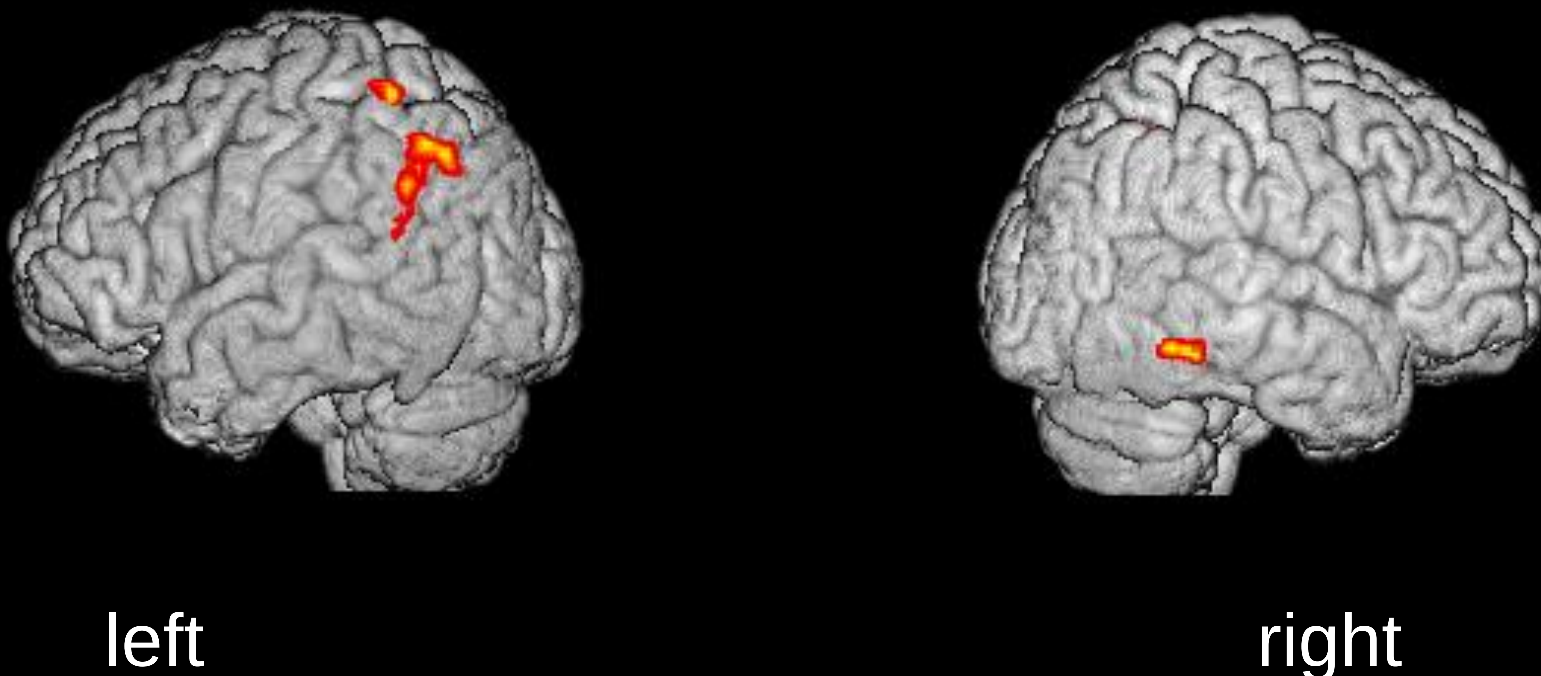
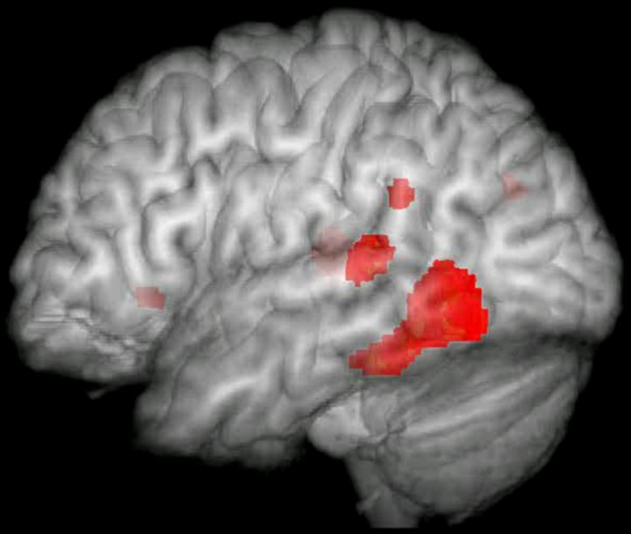
Group Comparison: Controls > Dyslexics



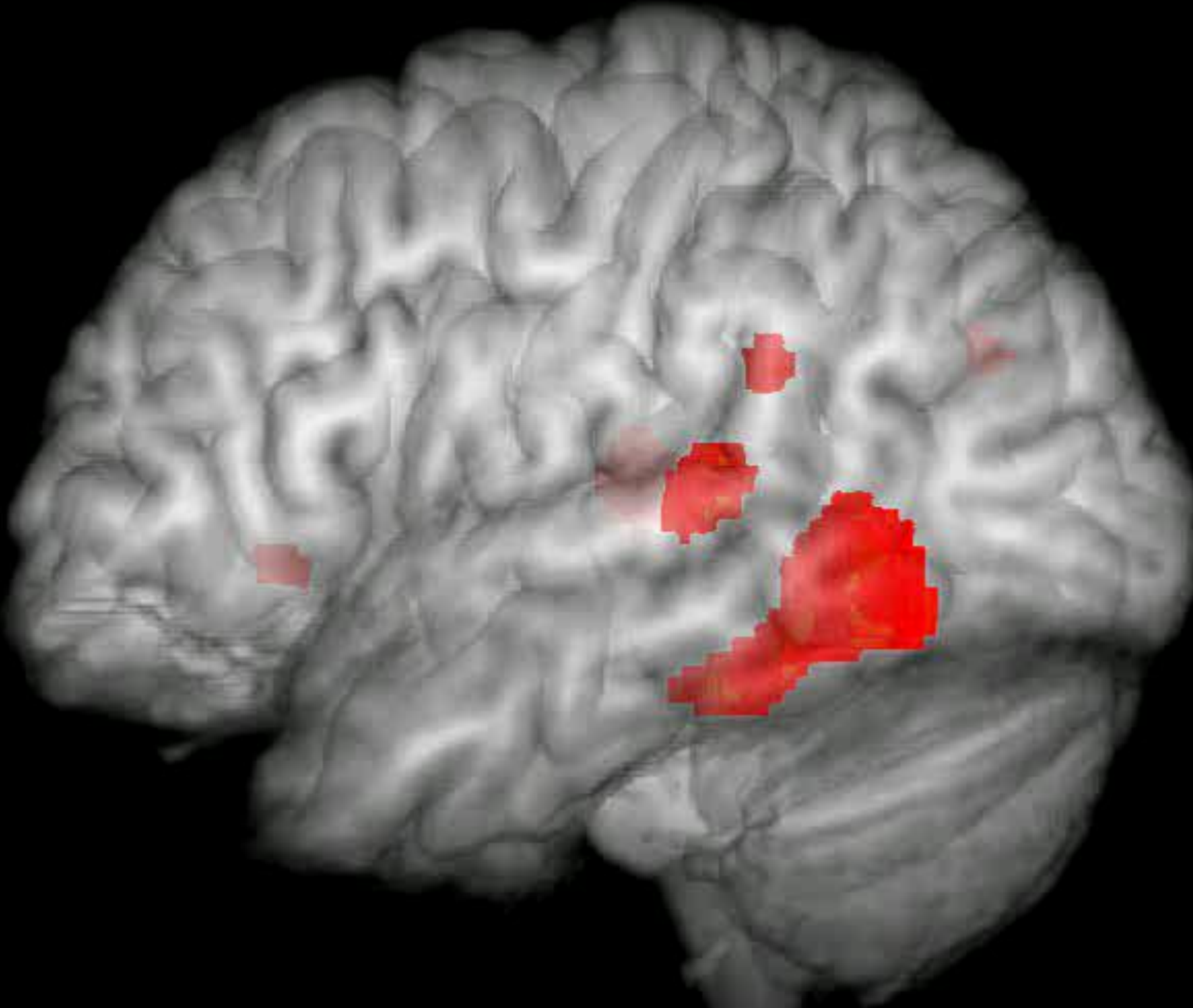
Eden et al., *Neuron* 2004

Meta-analysis of the Neurobiological Bases of Dyslexia



Typical Readers **>** **Dyslexic Readers**

Maisog et al. PNYAS, 2008;
see also Richlan et al , 2012; Linkersdorfer et al., 2012



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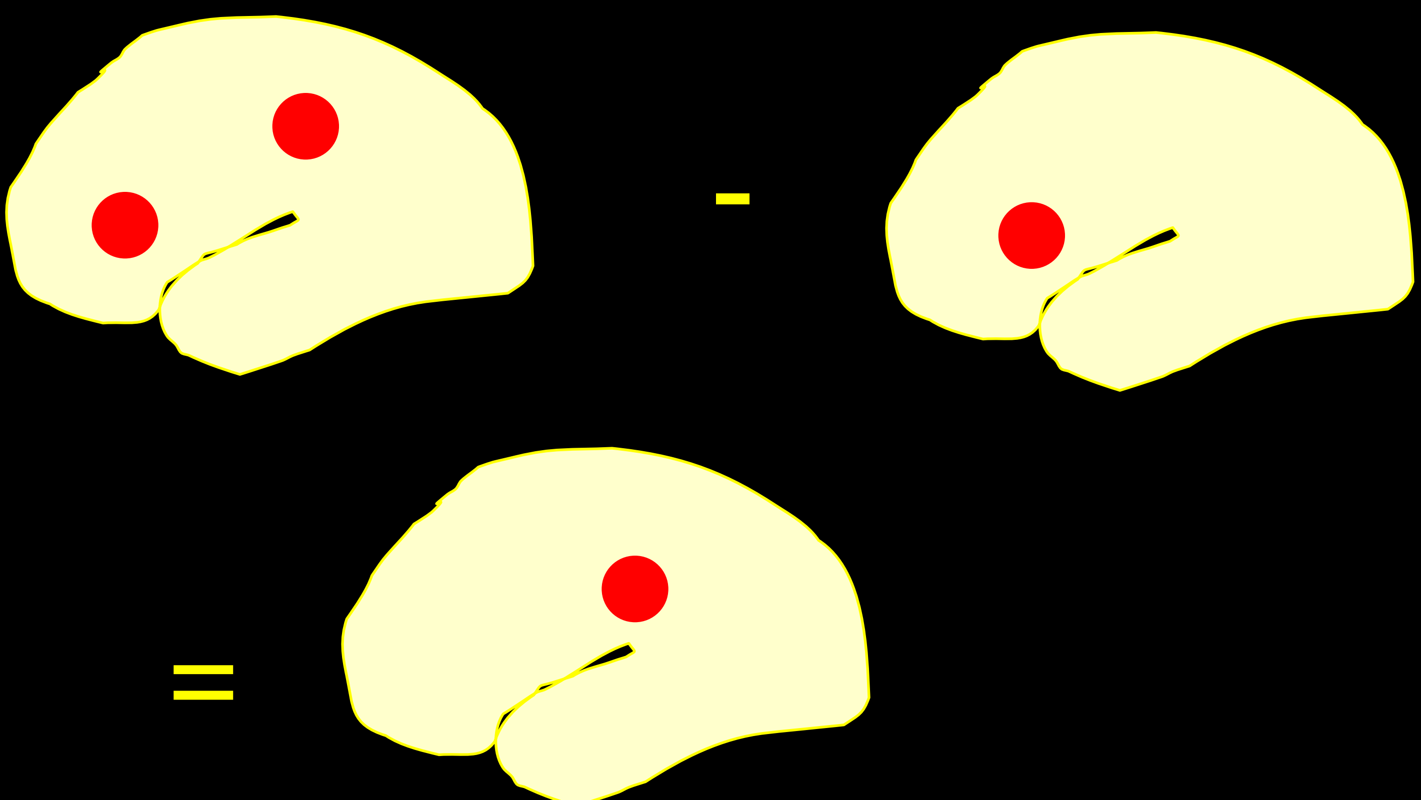
After Intervention

Before Intervention



Adult Reading Intervention Study

Subjects:

• 20 Adults with life-long history of dyslexia from Orton Center

June L. Orton

Intervention:

• 3 hours/day, over 8 weeks

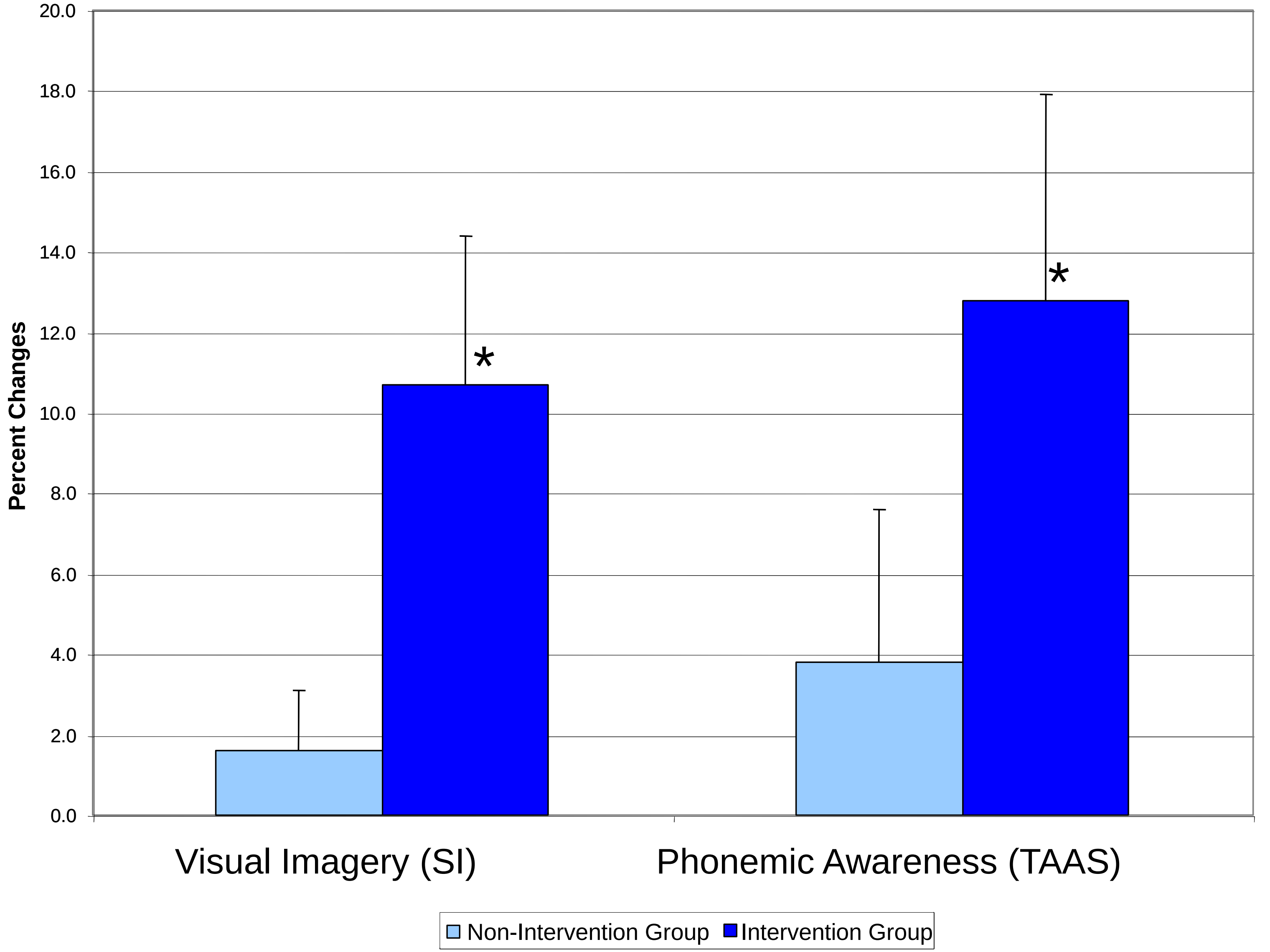
• "Seeing Stars" and "Visualizing Verbalizing"

Intervention Trial: Study Design

- Randomized assignment into two groups
- Groups equal in reading prior to intervention

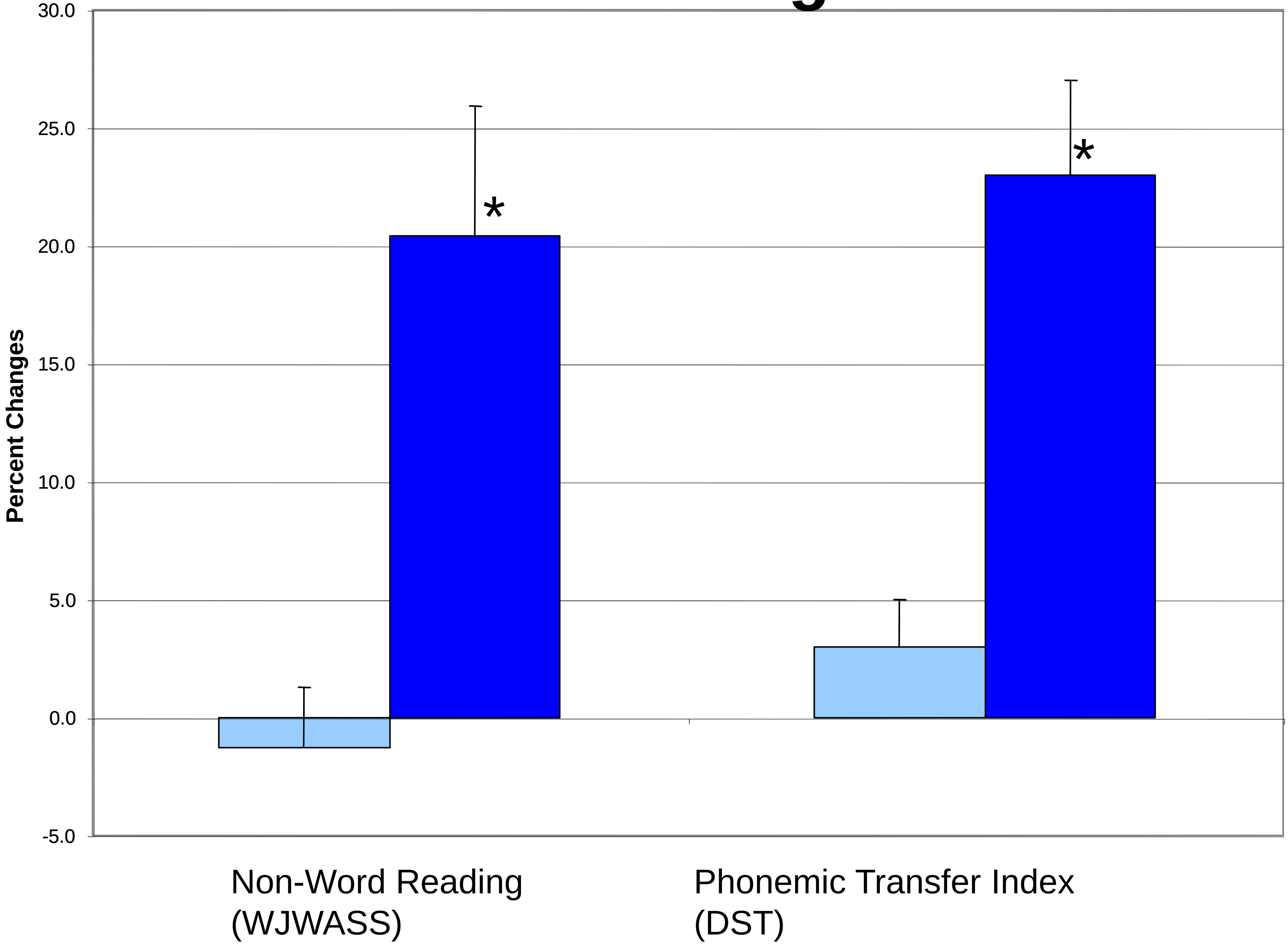
	Group1	Group 2
Pre intervention	↓ Intervention	↓ No Intervention
Post intervention		

Skills Targeted by Intervention



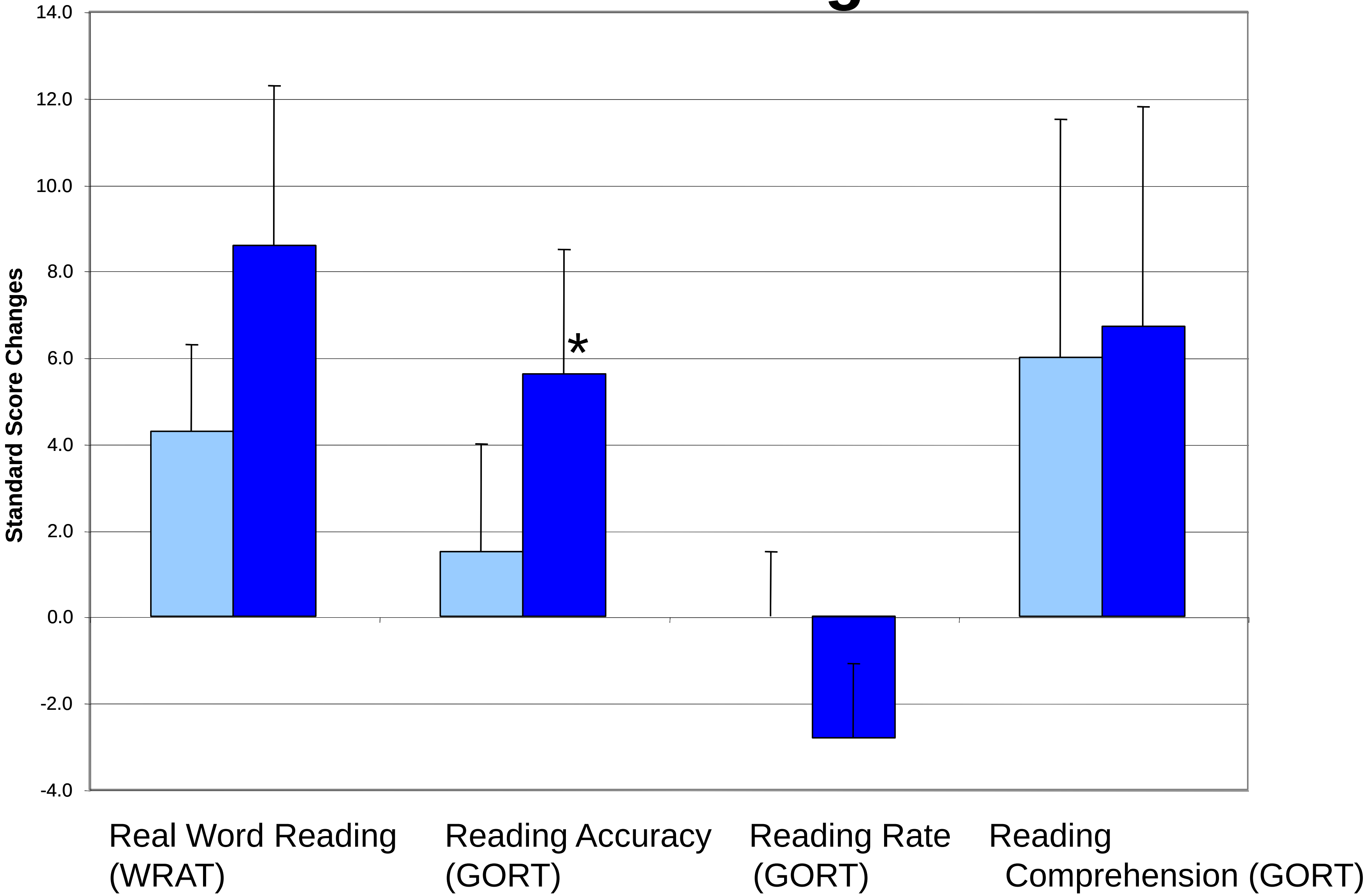
*p < .05

Decoding

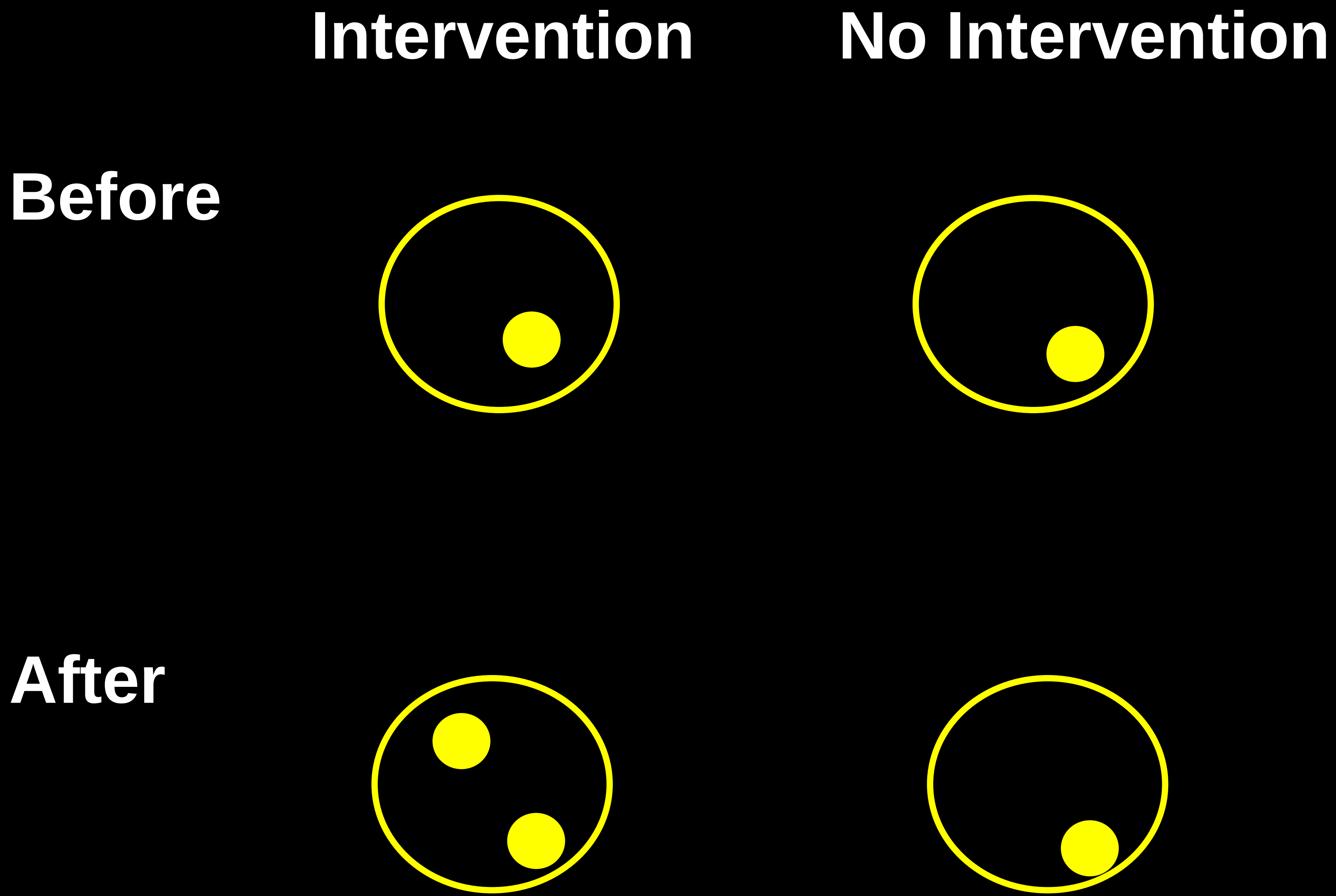


*p < .005

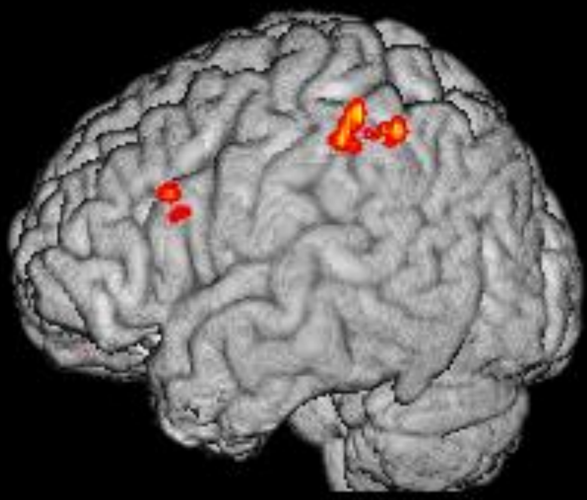
Oral Reading



*p < .05


Intervention
No Intervention
Before
After

ANOVA Group x Day: Increases in Activity Following Intervention



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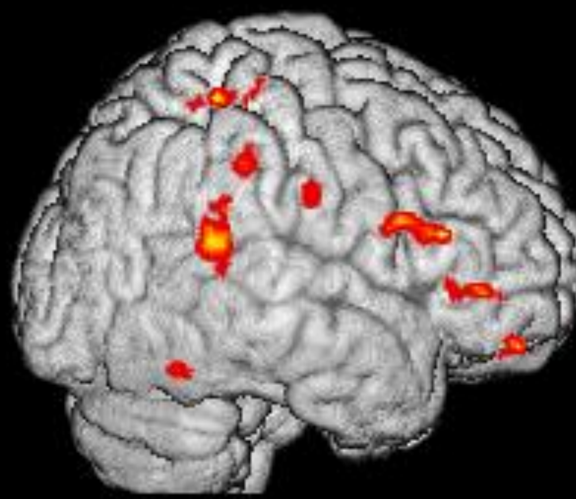
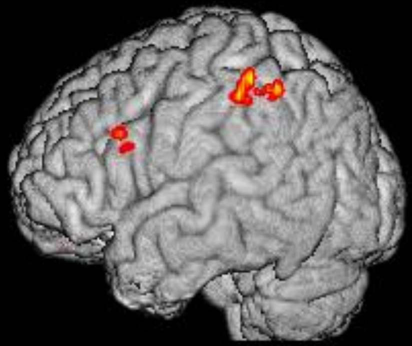


right

Eden et al., Neuron 2004

Conclusions



- Following intervention adults with dyslexia show increased activation in the left and right hemispheres.

- The right hemisphere areas are similar to those in the left hemisphere involved in phonological processing in good readers.

Research Questions

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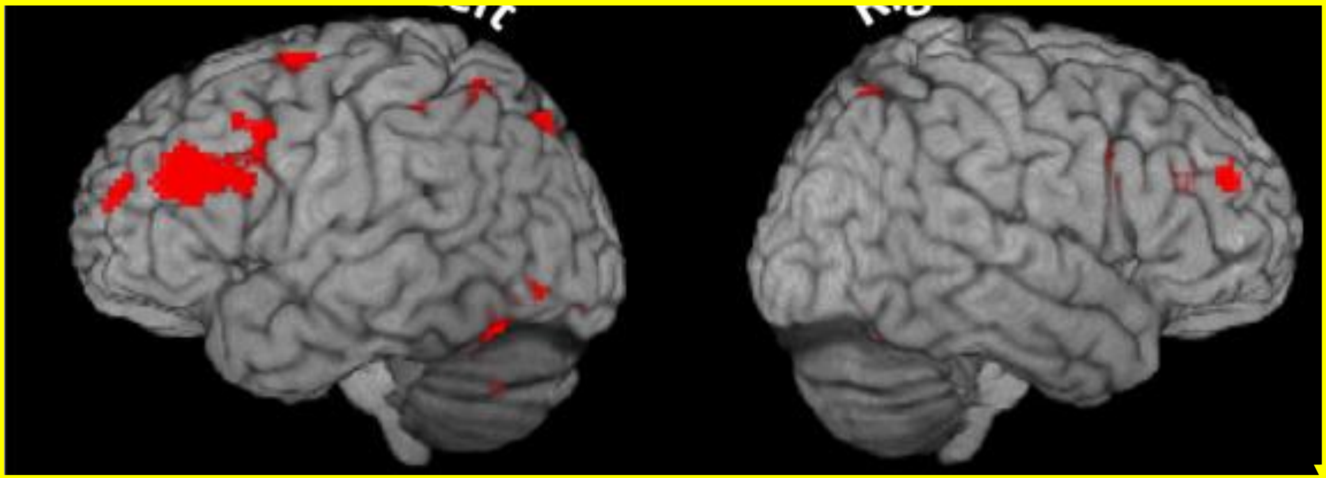
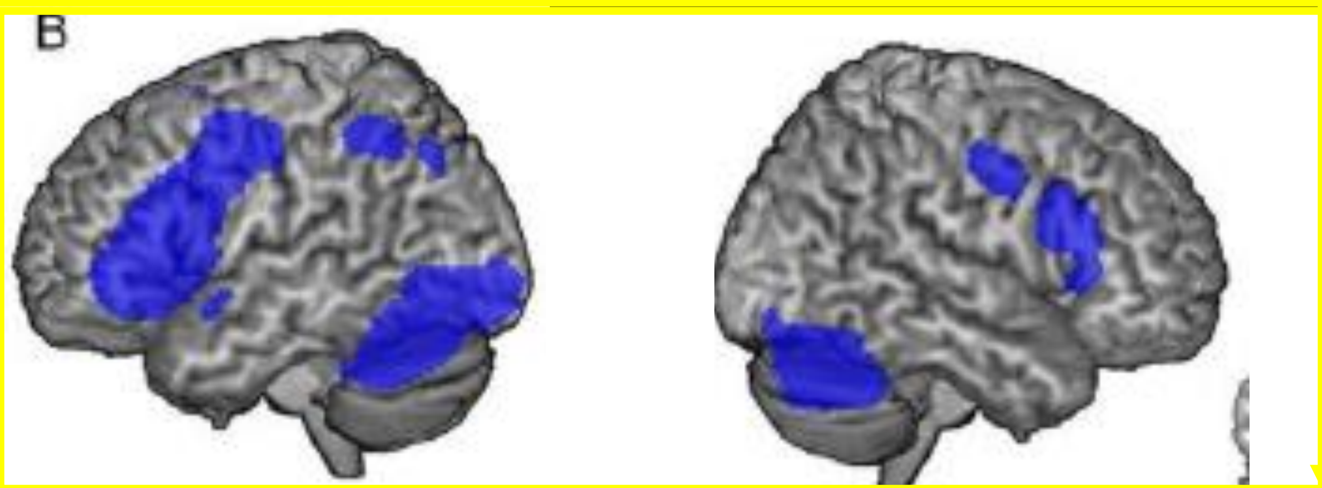
Meta-analyses of the Brain Bases for Arithmetic and Reading



Arithmetic:
Arsalidou & Taylor, *Neuroimage*, 2011



Reading:
Martin et al. *HBM* 2015

Arithmetic

3 + 4

Arithmetic

3 + 4

5 + 2

Arithmetic

3 + 4

5 + 2

3 + 6

Arithmetic

3 + 4

5 + 2

3 + 6

7 + 1

Arithmetic

3 + 4

9 – 3

5 + 2

3 + 6

7 + 1

Arithmetic

3 + 4

5 + 2

3 + 6

7 + 1

9 – 3

6 – 2

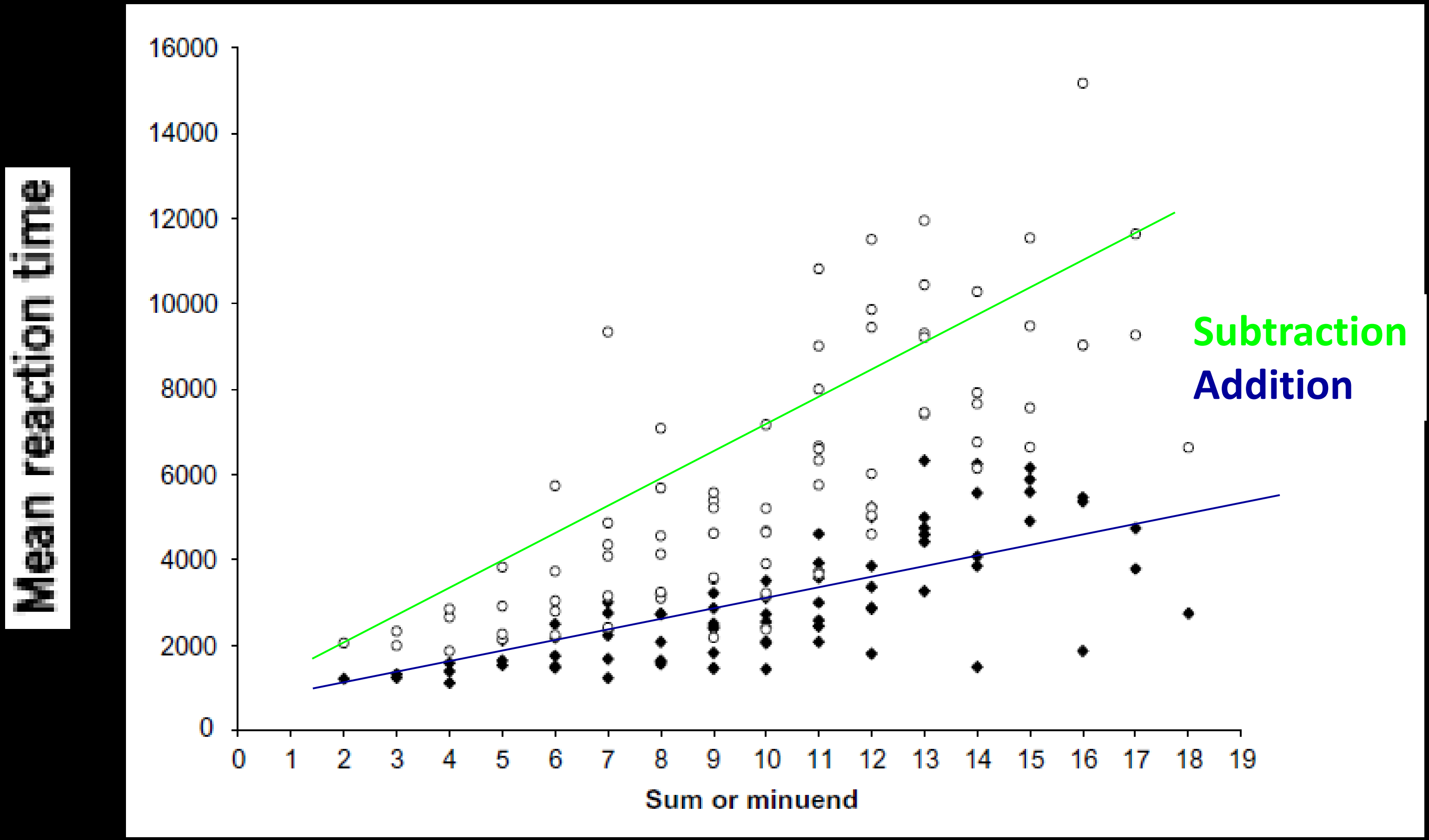
Arithmetic

3 + 4	9 – 3
5 + 2	6 – 2
3 + 6	7 – 4
7 + 1	

Arithmetic

3 + 4	9 – 3
5 + 2	6 – 2
3 + 6	7 – 4
7 + 1	8 – 5

Subtraction and Addition Reaction Times



Barrouillet *J Exp Child Psych* 2008

Children's Strategy Use in Addition & Subtraction

Strategy	Problem type		
	Small		
	Use (%)	Mean latencies	Accuracy (%)
Subtraction			
Algorithmic	37	5399	85
Retrieval	31	2274	97
Additive fact	33	3109	98
Addition[a]			[b]
Algorithmic	16	3589	—
Retrieval	84	1820	—

Small problem sets (solutions < 18)

Barrouillet *J Exp Child Psych* 2008

Arithmetic Strategy

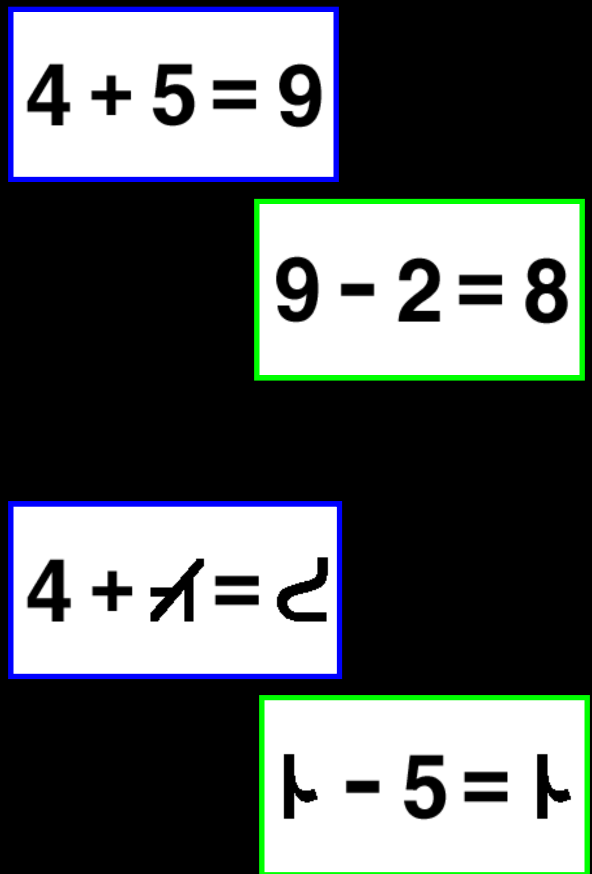
$4 + 5 = 9$

$7 - 2 = 5$

Fact Retrieval

Quantitative Strategy: Procedural-based

Arithmetic Task



- **Experimental Condition**
  - single digit addition & subtraction verification task
  - correct or incorrect (50% each)

- **Control Condition**
  - pseudofont symbol matching
  - same or different (50% each)

Reading Task

- **Experimental Condition**

  Indicate presence of ascender in real word

- **Control Condition**

  Indicate presence of ascender in pseudofont strings

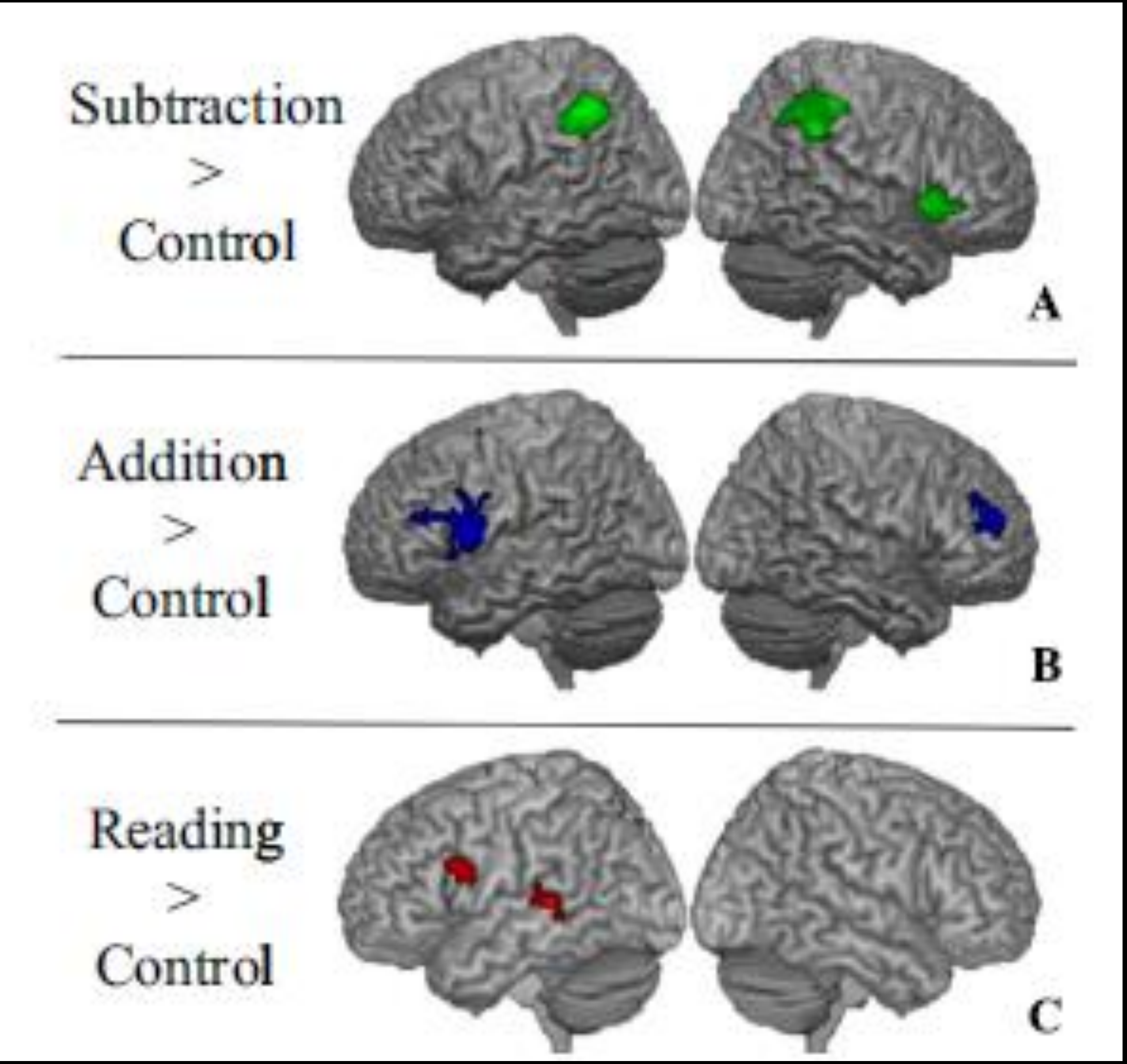
(Price et al., 1996)

Implicit Reading Activity

6- 9.4 y	9.4- 18 y	20- 23 y
n=13	n=13	n=15

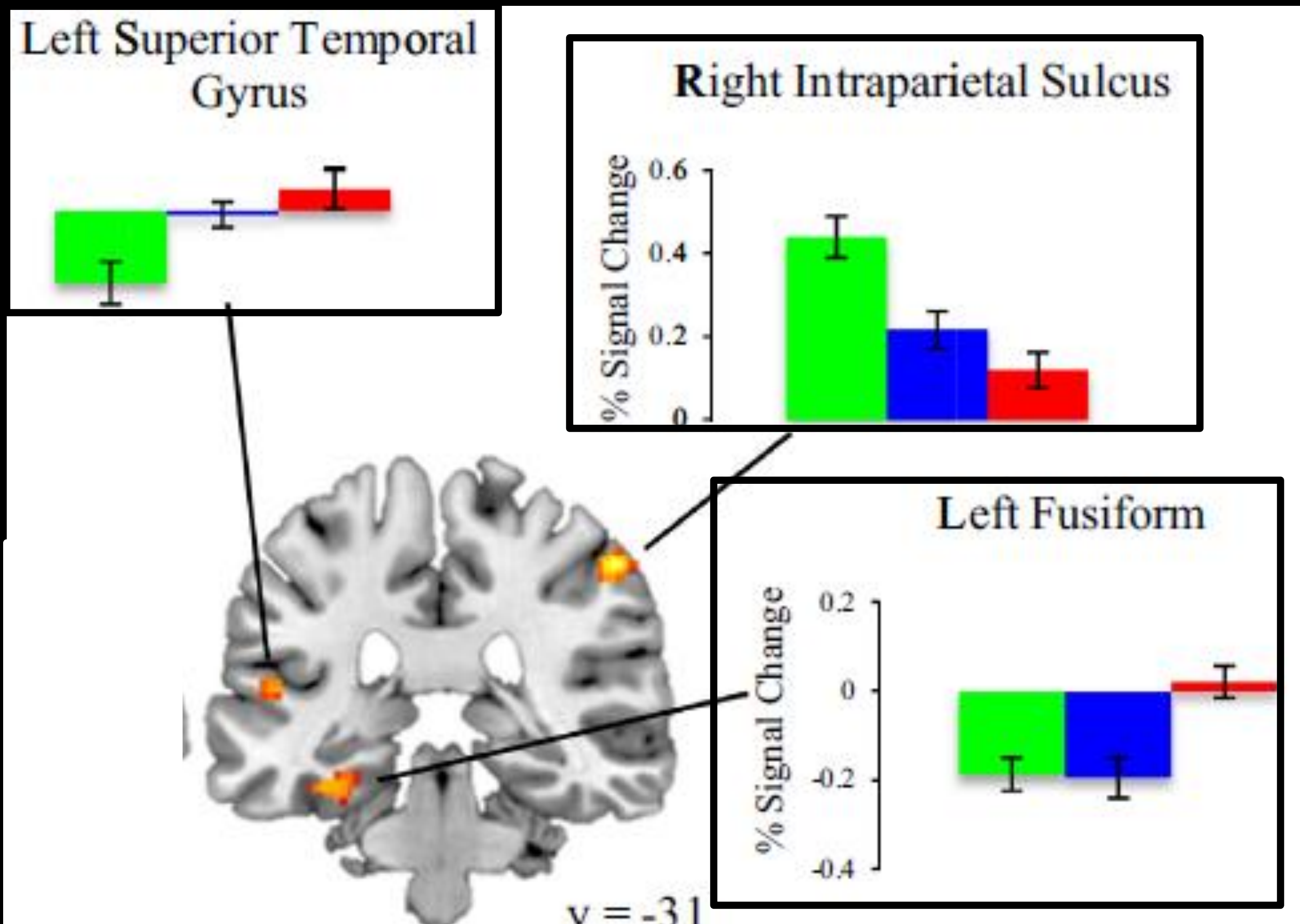
Turkeltaub et al. *Nature Neuroscience*, 2003

Brain Bases for Arithmetic and Reading



Evans et al., *Neuroimage* 2016

Brain Bases for Arithmetic and Reading



Subtraction

Addition

Reading

Evans et al., *Neuroimage* 2016

Conclusion

- Small number addition (fact retrieval) and reading activate left superior temporal gyrus.
- Small number subtraction (procedural based) activates bilateral intraparietal sulcus, supramarginal gyrus and inferior frontal gyrus.
- Reading activates left fusiform gyrus

Research Questions

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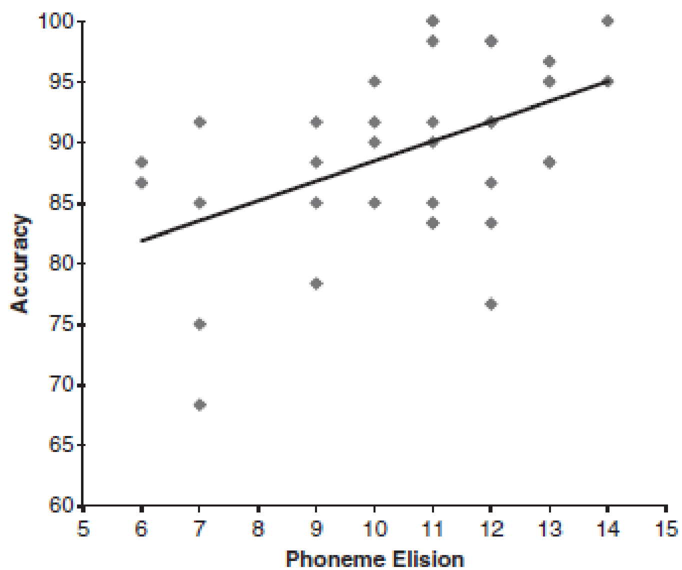
Arithmetic and Dyslexia

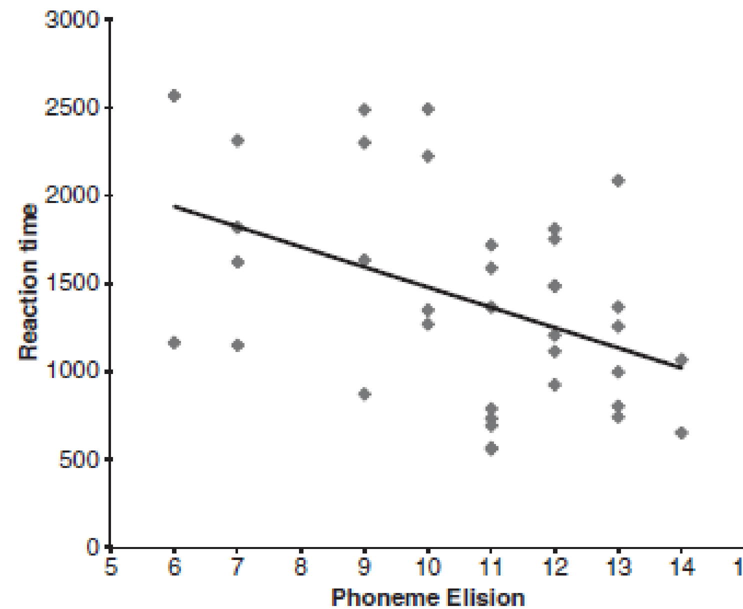
Comorbidity of dyslexia and dyscalculia (Lewis *et al*., 1994)

Phonological awareness skills correlate with arithmetic problem solving (Hecht et al., 2001; DeSmedt *et al*., 2010)

Distinct representations of subtraction and multiplication in the neural systems for language (Prado *et al*., 2011)

Arithmetic Processing & Phonological Awareness in Children





Correlations Specific to Retrieval Problems **4 + 5 = 9**

Relationship NOT found for Procedural Problems **7 - 2 = 5**

DeSmedt *et al*., 2010

Arithmetic Abilities in Dyslexia without Dyscalculia

Children with dyslexia, who score within normal range on standardized math tests, show difficulties specific to speed of number fact retrieval (Simmons & Singleton 2007)

No operation effect (faster multiplication vs. subtraction) in children with dyslexia (Boets & DeSmedt 2010) and slower in exact addition and multiplication in adults, while same as controls in subtraction (Gobel & Snowling 2012)

Brain Bases of Arithmetic in Dyslexia

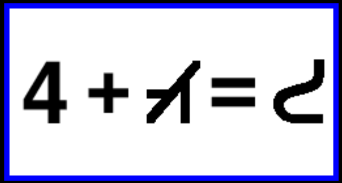
	Dyslexics n = 14(7 M)		Controls n = 14(9 M)		
	Mean	SD	Mean	SD	Sig
Age	10.37	1.32	10.21	2.76	ns
Verbal IQ	111.3	10.78	118.79	14.52	ns
Performance IQ	98.93	8.70	113.36	11.43	*
Real word reading	81.93	6.81	117.86	11.00	*
Pseudoword reading	95.86	5.42	112.93	10.64	*
Phonemic awareness	99.36	8.50	113.79	11.25	*
Calculation	107.07	13.41	114.46	7.03	ns

Evans et al., Neuroimage 2014

Brain Bases of Arithmetic in Dyslexia

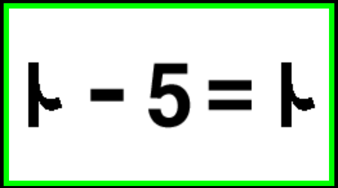
Retrieval-based

$4 + 5 = 9$

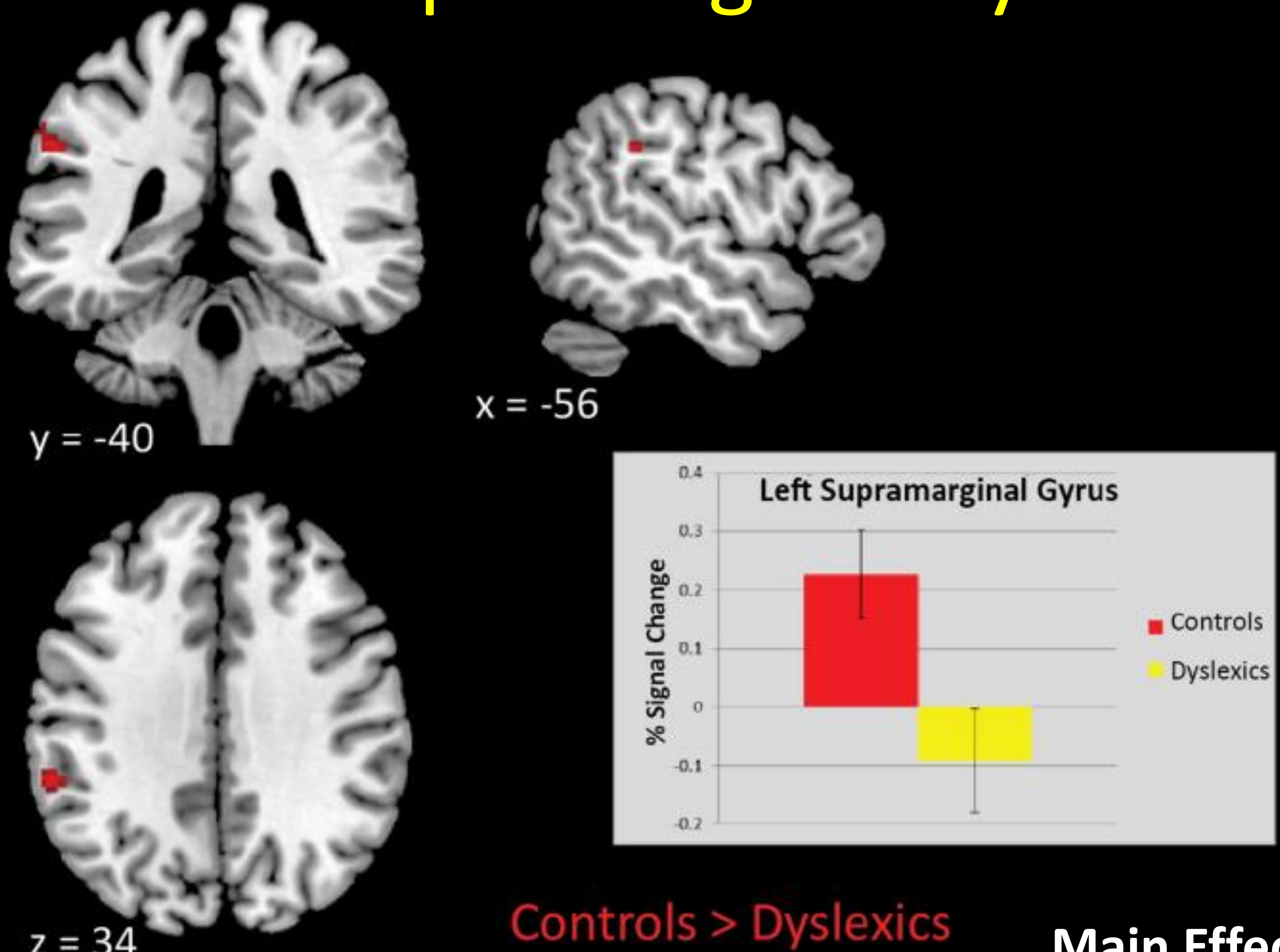


Procedural-based

$9 - 2 = 8$



Greater Activation in Controls in Left Supramarginal Gyrus

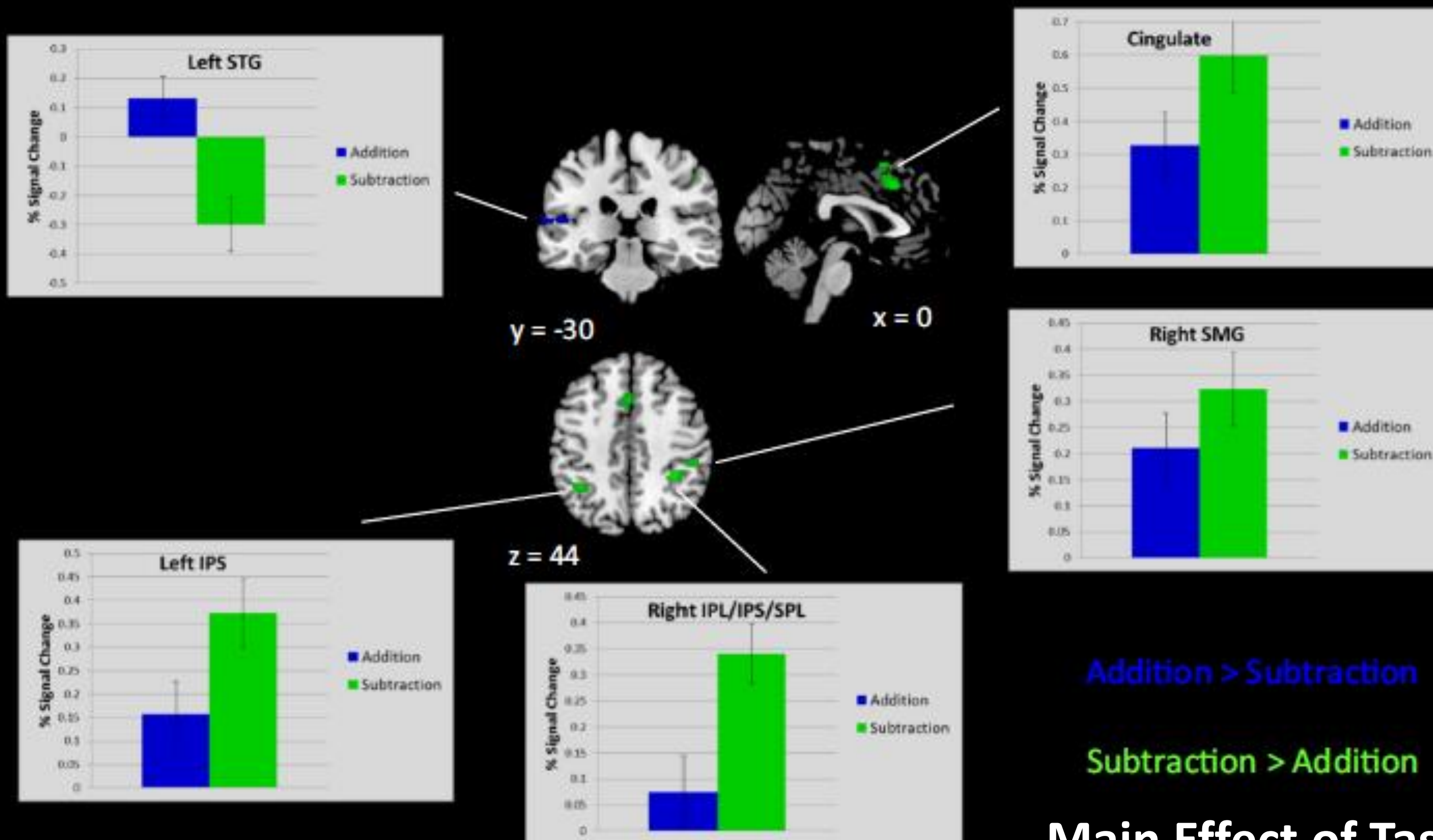


Main Effect of Group

Height threshold: $p < 0.001$
Extent threshold: $p < 0.05$

Evans et al., Neuroimage 2014

Greater Activation for Addition in Left STG, Subtraction in Bilateral Parietal

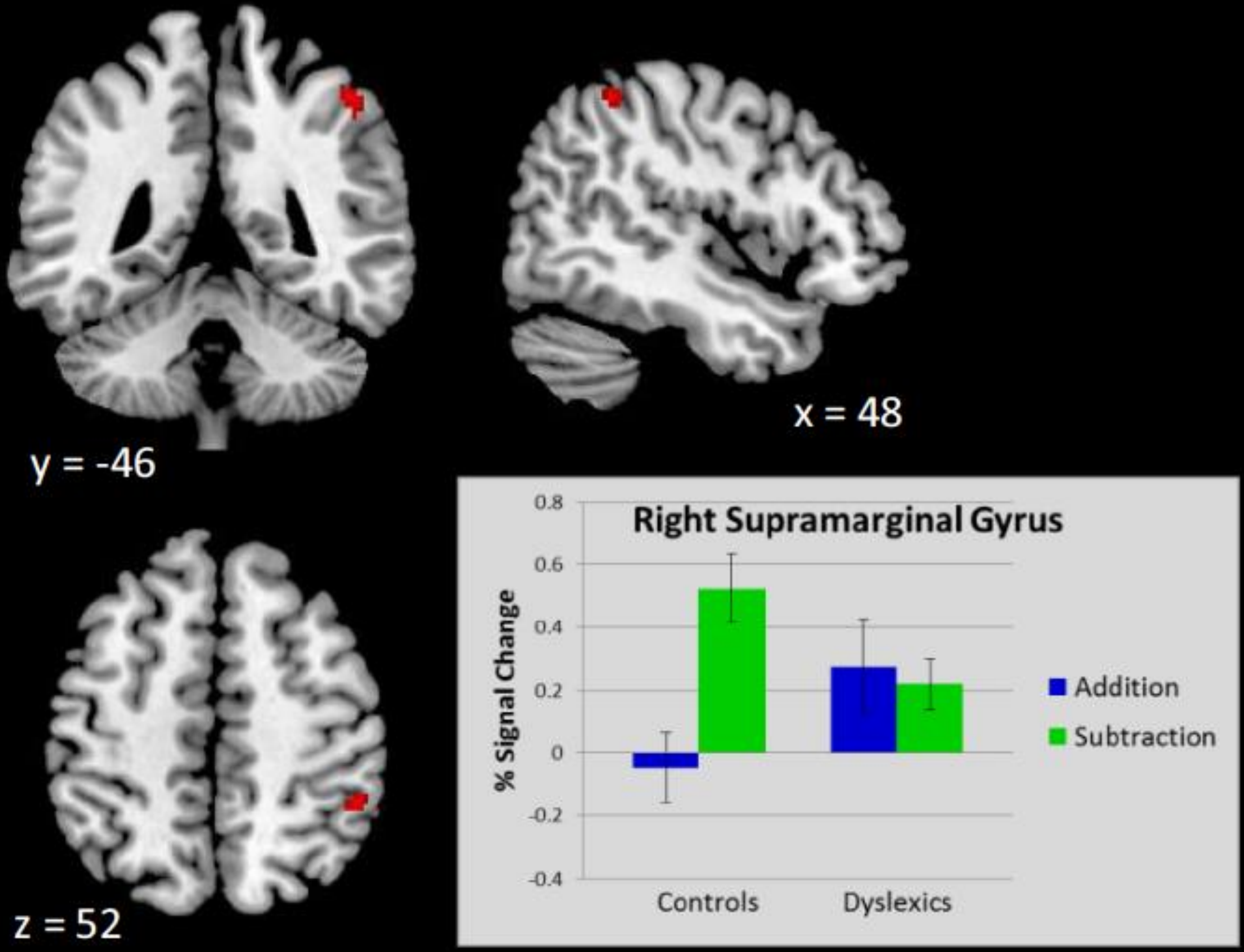


Main Effect of Task

Height threshold: $p < 0.001$
Extent threshold: $p < 0.05$

Evans *et al.*, 2014

Brain Bases of Arithmetic in Dyslexia



Group by Task Interaction

Height threshold: $p < 0.001$
Extent threshold: $p < 0.05$

Evans et al., Neuroimage 2014

Conclusions

- Children with dyslexia show less activity during arithmetic tasks in left supramarginal gyrus.
- They also lack modulation by operation in right supramarginal gyrus.
- This supports earlier behavioral work showing differences in math performance specific to retrieval-based problems (De Smedt and Boets, 2010).

Research Questions

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Overall Summary

- Dyslexia is characterized by underactivity in left parieto-temporal and occipito-temporal cortices during reading (and arithmetic).

- Successful reading intervention results in increased brain activity in parietal and frontal regions in both hemispheres.

Overall Summary

- Reading and (retrieval based) arithmetic rely on shared brain regions.

- Children with dyslexia use different brain regions to perform (retrieval-based) arithmetic.

Neuronal Recycling Hypothesis

– Reading and arithmetic did not emerge early enough to exert evolutionary pressure to shape organization of the human brain

– Force the brain to 'recycle' evolutionary older brain regions, thus subject to existing constraints of this circuitry

Dehaene and Cohen, 2007

Tanya Evans
Jose Maisog
Anna Matejko
Olumide Olulade
Peter Turkeltaub
John VanMeter

Wake Forest University
Lynn Flowers
Frank Wood

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Connections Between Calculation Fluency and Reading Fluency

Nancy C. Jordan
University of Delaware

Luke Rinne
University of Maryland

This work was supported by Award R324C100004 from IES

Background

- Children with math difficulties *and* reading difficulties (**MD-RD**) in primary school exhibit poorer arithmetic skills (involving addition & subtraction) than children with **MD** who are good readers (Jordan et al., 2003).
- But there's more to the story…
  - **MD** are more accurate than **MD-RD** on (untimed) exact calculations.
  - But not on rapid fact retrieval, where **MD** perform as poorly as **MD-RD**; also find a group of children with **RD** who perform as well as typically-achieving children.

- Nevertheless, arithmetic fluency is related to reading fluency.
  - Rapid automatized naming (RAN) and verbal counting uniquely predict both reading fluency and calculation fluency in second and third grade, when controlling for cognitive and demographic factors (Koponen et al., 2016).
  - Suggests reading and arithmetic may have partially shared cognitive underpinnings.

What about older kids (and multiplication)?

- Much of the prior research has focused on the primary grades and development of addition/subtraction fluency.
- Multiplication facts may not be learned in the same way as addition and subtraction combinations.
- For example:
  - Multiplication facts are primarily learned through effortful rote memorization instead of simply repeated exposure.
  - Backup strategies for multiplication (e.g., repeated addition) are much more difficult and inefficient than backup strategies for addition/ subtraction (e.g., counting on, finger counting, decomposition, etc.)
  - There are many more multiplication facts to learn.
  - Leads to increased reliance on *written* materials with symbolic representations (e.g., lists of facts, visual multiplication tables, and flash cards).

Example of common third-grade fact practice

1x	2x	3x	4x	5x	6x
1 x 1 = 1	2 x 1 = 2	3 x 1 = 3	4 x 1 = 4	5 x 1 = 5	6 x 1 = 6
1 x 2 = 2	2 x 2 = 4	3 x 2 = 6	4 x 2 = 8	5 x 2 = 10	6 x 2 = 12
1 x 3 = 3	2 x 3 = 6	3 x 3 = 9	4 x 3 = 12	5 x 3 = 15	6 x 3 = 18
1 x 4 = 4	2 x 4 = 8	3 x 4 = 12	4 x 4 = 16	5 x 4 = 20	6 x 4 = 24
1 x 5 = 5	2 x 5 = 10	3 x 5 = 15	4 x 5 = 20	5 x 5 = 25	6 x 5 = 30
1 x 6 = 6	2 x 6 = 12	3 x 6 = 18	4 x 6 = 24	5 x 6 = 30	6 x 6 = 36
1 x 7 = 7	2 x 7 = 14	3 x 7 = 21	4 x 7 = 28	5 x 7 = 35	6 x 7 = 42
1 x 8 = 8	2 x 8 = 16	3 x 8 = 24	4 x 8 = 32	5 x 8 = 40	6 x 8 = 48
1 x 9 = 9	2 x 9 = 18	3 x 9 = 27	4 x 9 = 36	5 x 9 = 45	6 x 9 = 54
1 x10 = 10	2 x10 = 20	3 x10 = 30	4 x10 = 40	5 x10 = 50	6 x10 = 60
1 x11 = 11	2 x11 = 22	3 x11 = 33	4 x11 = 44	5 x11 = 55	6 x11 = 66
1 x12 = 12	2 x12 = 24	3 x12 = 36	4 x12 = 48	5 x12 = 60	6 x12 = 72

7x	8x	9x	10x	11x	12x
7 x 1 = 7	8 x 1 = 8	9 x 1 = 9	10x 1 = 10	11x 1 = 11	12x 1 = 12
7 x 2 = 14	8 x 2 = 16	9 x 2 = 18	10x 2 = 20	11x 2 = 22	12x 2 = 24
7 x 3 = 21	8 x 3 = 24	9 x 3 = 27	10x 3 = 30	11x 3 = 33	12x 3 = 36
7 x 4 = 28	8 x 4 = 32	9 x 4 = 36	10x 4 = 40	11x 4 = 44	12x 4 = 48
7 x 5 = 35	8 x 5 = 40	9 x 5 = 45	10x 5 = 50	11x 5 = 55	12x 5 = 60
7 x 6 = 42	8 x 6 = 48	9 x 6 = 54	10x 6 = 60	11x 6 = 66	12x 6 = 72
7 x 7 = 49	8 x 7 = 56	9 x 7 = 63	10x 7 = 70	11x 7 = 77	12x 7 = 84
7 x 8 = 56	8 x 8 = 64	9 x 8 = 72	10x 8 = 80	11x 8 = 88	12x 8 = 96
7 x 9 = 63	8 x 9 = 72	9 x 9 = 81	10x 9 = 90	11x 9 = 99	12x 9 = 108
7 x10 = 70	8 x10 = 80	9 x10 = 90	10x10 = 100	11x10 = 110	12x10 = 120
7 x11 = 77	8 x11 = 88	9 x11 = 99	10x11 = 110	11x11 = 121	12x11 = 132
7 x12 = 84	8 x12 = 96	9 x12 = 108	10x12 = 120	11x12 = 132	12x12 = 144

Is multiplication fluency more dependent on reading fluency?

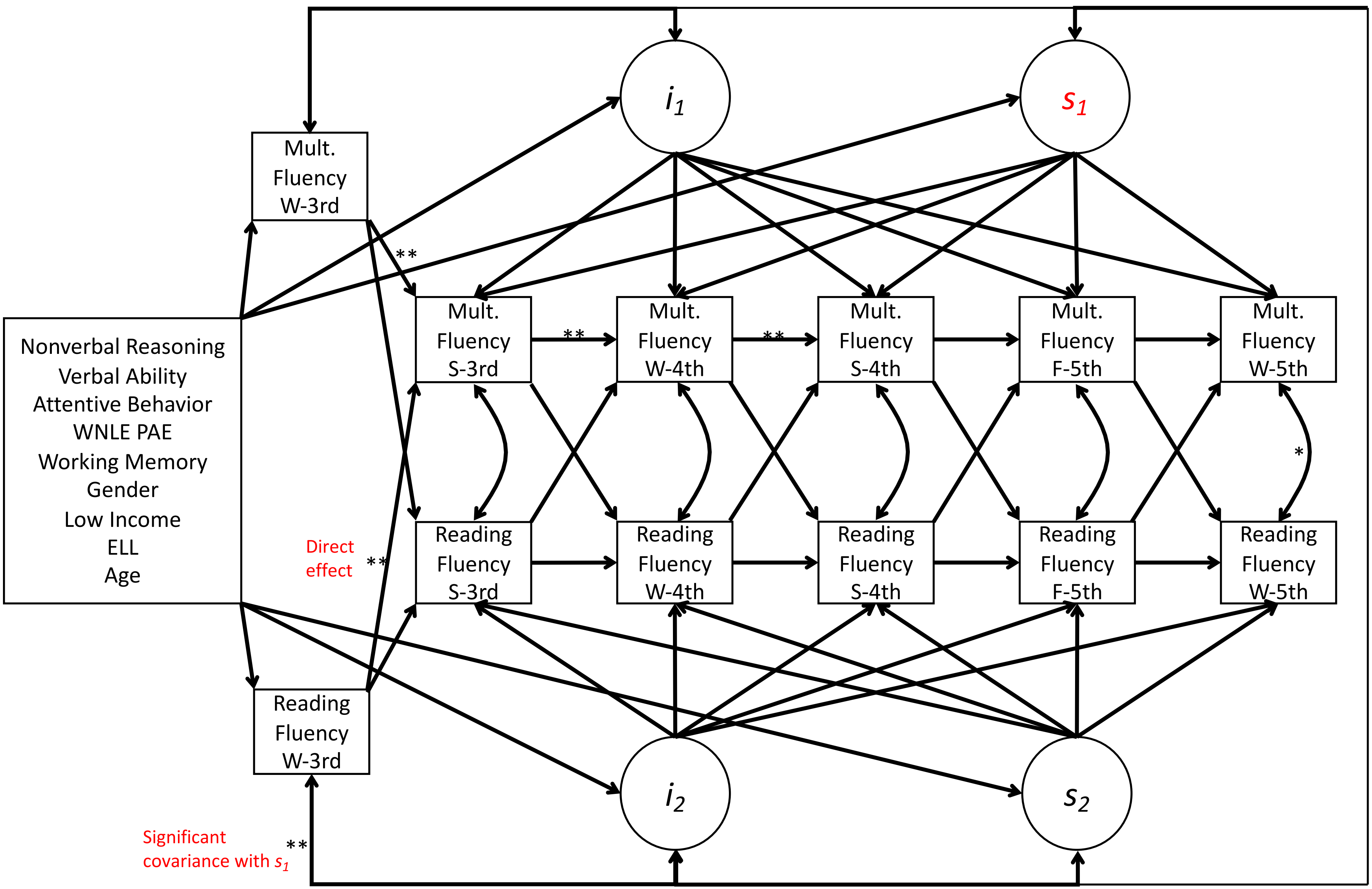
- Slow reading means more decay of just-read information in working memory (Baddeley & Hitch, 1974).
- Slow reading also means fewer rote repetitions of multiplication facts per unit time.
- We hypothesized that reading fluency would predict initial acquisition and growth of multiplication fluency over time (and to a greater extent than add/sub fluency).

Present Study

- To test this hypothesis, we analyzed longitudinal data for students from 3rd to 5th grade (N = 449).
  - Students were drawn from two adjacent school districts with similar math curricula and standards.
  - Diverse ethnicity and SES, although we oversampled low SES.
- We measured arithmetic fluency and reading fluency longitudinally over 6 time points (2x per year in grades 3-5).
- Addition, subtraction, and multiplication fluency measured by separate Wechsler Individual Achievement Test (WIAT) scores.
- Reading fluency was measured by the Test of Word Reading Efficiency (TOWRE).

Data Analysis

- Cognitive and demographic control variables (3rd grade):
  - Nonverbal ability (WASI matrix reasoning)
  - Verbal ability (PPVT)
  - Working memory (WMTB-C)
  - Attentive behavior (SWAN teacher rating)
  - Number line (0-1000) estimation ability (PAE)
  - Age, gender, SES (school lunch program), and EL status
- We built autoregressive latent trajectory (ALT) models for addition, subtraction, and multiplication fluency.
  - ALT models include both cross-lagged and latent growth effects.
  - Models capture both long-term growth in arithmetic/reading fluency and short-term, cross-lagged effects from one time point to the next.



Note. * $p < .05$, ** $p < .01$. WNLE = Whole number line estimation. ELL = English language learner. W = Winter. S = Spring. F = Fall. *i* = growth function intercept. *s* = growth function slope.

Results

- We found significant effects of reading fluency on multiplication fluency (but **not** on addition or subtraction fluency).
    - There was a ***direct*** effect of early 3rd grade reading fluency on late 3rd grade multiplication fluency, the period when children are first learning multiplication facts.
    - Initial reading fluency also predicted the slope of growth in multiplication fluency between 3rd and 5th grade.
- Number line estimation acuity predicted both initial multiplication fluency and growth over time.
    - A good sense of numerical magnitudes makes it easier to learn multiplication facts.
    - Effects of reading fluency after controlling for number line estimation point to processes associated with rote memorization.

Table 1

Covariate Effects on Multiplication Fluency Intercept, and Growth

	Mult. Fluency Intercept (i_1)		Mult. Fluency Slope (s_1)	
	Est.	*SE*	Est.	*SE*
Nonverbal Reasoning	0.03	0.08	-0.03	0.06
Verbal Ability	0.00	0.02	0.00	0.02
Attentive Behavior	0.03	0.02	0.10**	0.02
Working Memory	0.01	0.01	0.01	0.02
WNLE (PAE)	-0.10**	0.04	-0.07*	0.03
Gender	0.56	0.41	0.25	0.43
Low Income	-0.77	0.78	-0.13	0.36
ELL	0.93	0.67	-0.04	0.62
Age	0.01	0.05	-0.07*	0.04

Note. * $p < .05$, ** $p < .01$. WNLE = Whole number line estimation. PAE = Percent Absolute Error. ELL = English language learner.

Conclusions

- Results suggest a different, unique mechanism through which RD may impede attainment of multiplication fluency, contributing to co-occurrence with MD in third grade and beyond.
- Some children known to have poor reading fluency may be helped by non-written representations and rehearsal to support verbal encoding. That is, when first learning facts they might do best on practice that emphasizes verbal (oral) rather than written contexts.
- Mathematics becomes more dependent on written representations as school progresses.
- Multiplicative reasoning and fluency are critical for learning fractions in the intermediate grades.
- It is important to note that we did not study a population of children already diagnosed with either MD or RD.
- We need more research on older children to better understand RD, MD and arithmetic fluency.

THANKS!!!!

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Can Arithmetic Fluency Training Improve Word-Reading Outcomes?

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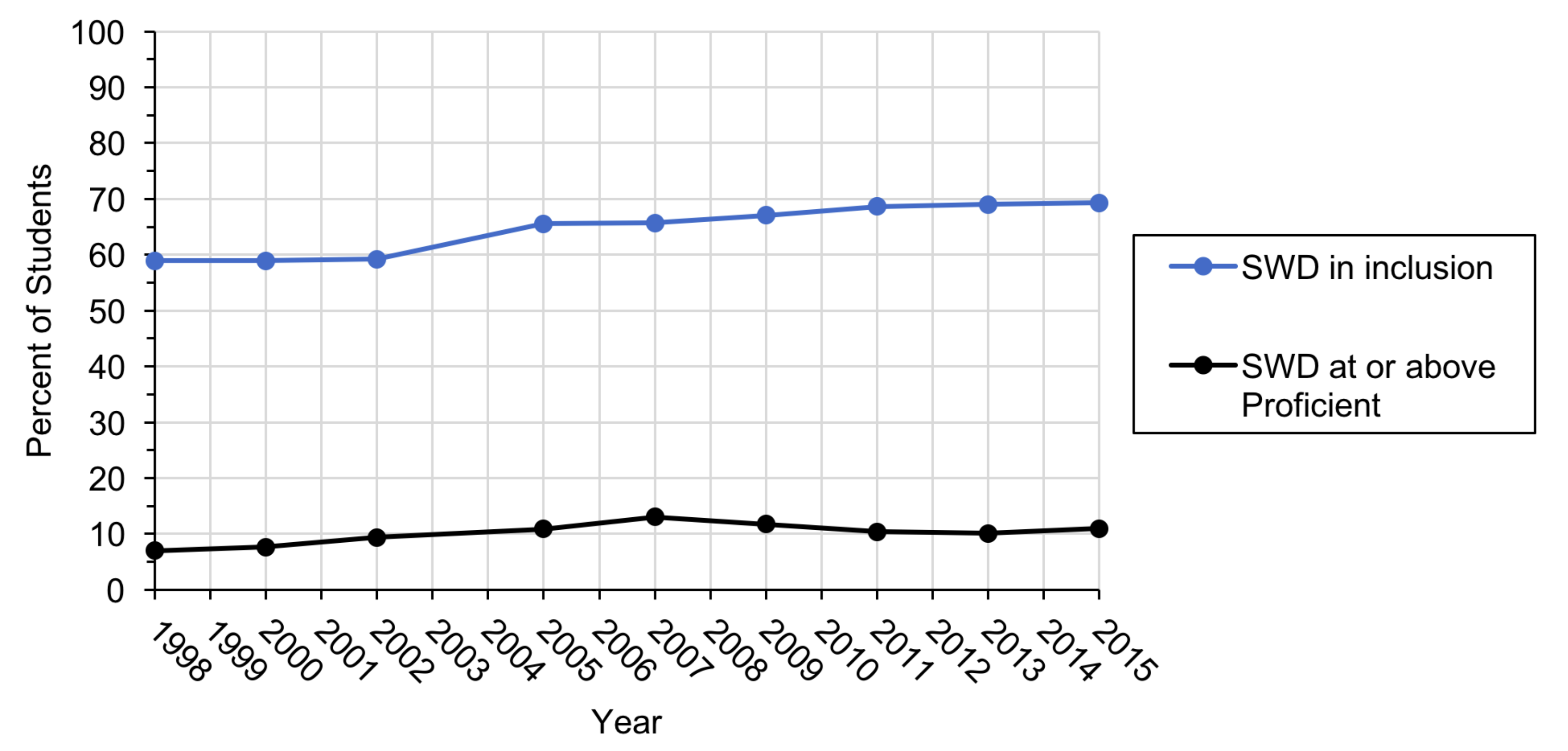
Poor School Achievement

- The academic achievement of most students w LD (and dyslexia) and other SWDs is abysmally poor. How come?
- (1) For decades, the severity of their learning problems has been greatly *underestimated*. (2) The effectiveness of inclusionary practices has been *overestimated*. (3) There has been an over-reliance on direct explicit instruction.
- More on #2 and #3.

Inclusion and Reading Achievement of SWD in the United States



Limits on Explicit Instruction

- For 30 years, the dominant and generally effective instructional approach for LD students has been explicit skills instruction. Yet, recent RTI research shows it fails to benefit 25-40% of study participants (Fuchs, Fuchs, & Compton, 2012)).

- We need new and validated instructional approaches targeting specific needs of LD subgroups, to supplement direct instruction.

- One subgroup likely to require such instruction is children with both severe R and M problems.

Comorbidity

- Koponen et al.'s unpublished longitudinal study: 40% of 1st-4th grade students below 16th percentile in R are also below 16th percentile on M (33% for 7th percentile).

- Distressingly, these comorbid students show especially poor instructional response. Moreover, many schools lack staff, expertise, and time to provide more than 1 intervention per student. R usually takes priority over M. Many with comorbid LD do not obtain M intervention.

Comorbidity

- On the brighter side, research suggests that word reading and math facts performance share similar cognitive processes (RAN, associative learning, visual-spatial memory, phonological processing, attentive behavior; Geary, 1993; deJong & Vriedlink, 2004; Waber et a., 2000), which interventionists might leverage in developing efficacious interventions.

- But there is little experimental work, and what exists is inconsistent about whether early R performance affects early M performance, vice versa, or both. Fuchs et al. (2016) obtained reciprocal effects, but early R was more strongly related to later M than vice versa. Duncan et al. (2007) found the reverse.

This RCT: Select Study Procedures

- 269 first graders were selected for R difficulty (M performance varied) in 2 cohorts, in 2 years.
- Randomly assigned to 3 conditions: word-reading intervention alone (DF), word-reading intervention with arithmetic fluency training (DF+M), and control.
- Intervention conducted 1:1; 21 wks; 63 sessions; 30 min per session for DF; 45 minutes for DF+M.
- Fidelity of implementing intervention tested twice per cohort; it was strong.

Reading and Math Interventions

- Reading (30 minutes)
  - Sight words, grapheme-phoneme correspondence, decoding, spelling, story word practice, story reading
  - Speeded practice to build direct retrieval of sight words

- Math (15 minutes)
  - Basic number knowledge information and efficient counting strategies for addition and subtraction
  - An important focus was on speeded practice to build direct retrieval of number combinations (“know it” or “count it”). Speed and accuracy.

Results

- DF+M and DF were superior to controls, and DF +M was superior to DF, on word- and non-word timed reading at posttest (spring of grade 1) and at follow-up (spring of grades 2 & 3).
- Mediation analysis showed the effect between DF+M and DF (from grade 1-3) was partially mediated via improvement in speeded but not non-speeded math performance.
- This suggests that arithmetic fluency training can improve word reading.

Connections between Word-Reading & Arithmetic Fluency?

- Across domains, procedural strategies (a) for linking arithmetic problem stems with answers and (b) for linking written and phonological representations of words produce repeated correct associations.

- Repeated, correct associations secure representations of arithmetic problems and words in long-term memory, maybe through the same underlying brain and cognitive mechanisms that reflect the ease with which students form arbitrary visual-verbal associations.

- This may explain the previously documented relation between word reading skill and arithmetic facts, both of which reflect the functional integrity of the relevant underlying domain-general brain and cognitive systems.

Connections between Word-Reading & Arithmetic Fluency?

- This may also explain our present finding that strengthening a domain-specific capacity for forming arbitrary visual-verbal associations – via math fact fluency practice – benefits children's capacity to secure representations of words in long-term memory.

- Alternatively or additionally, arithmetic fluency practice may strengthen one or more domain-general cognitive process that indirectly supports calculation as well as word-reading outcomes (attentive behavior, reasoning, visual-spatial memory, RAN, associative learning).

- Findings suggest the potential of thinking deeply about word-reading and arithmetic comorbidity (when defined in terms of fluency) for increasing understanding about LDs and expanding intervention efficacy and efficiency.

Caveats

- Differences in instructional time
  - DF intervention = 30 min per session
  - DF+M intervention 45 min per session (30+15).

- There is need of additional competing mediators for word and non-word reading, including domain-specific skills (e.g., counting knowledge) and domain-general processes (e.g., RAN, associative learning).