Typical and Atypical Development of Number Concept and Mathematical Skills

H-126 Typical and Atypical Neurodevelopment
October 30th, 2017

'The knowledge of mathematical things is almost innate in us…This is the easiest of sciences, a fact which is obvious in that noone's brain rejects it; for laymen and people who are utterly illiterate know how to count and reckon.'
Roger Bacon (c. 1219–1294)

Overview

- What is ‘Number sense” ?
- The ‘distance/ratio effect’
- What do infants know about numbers/systems of number representations?
- The typical mathematical brain
- What is Developmental Dyscalculia?
- The atypical mathematical brain

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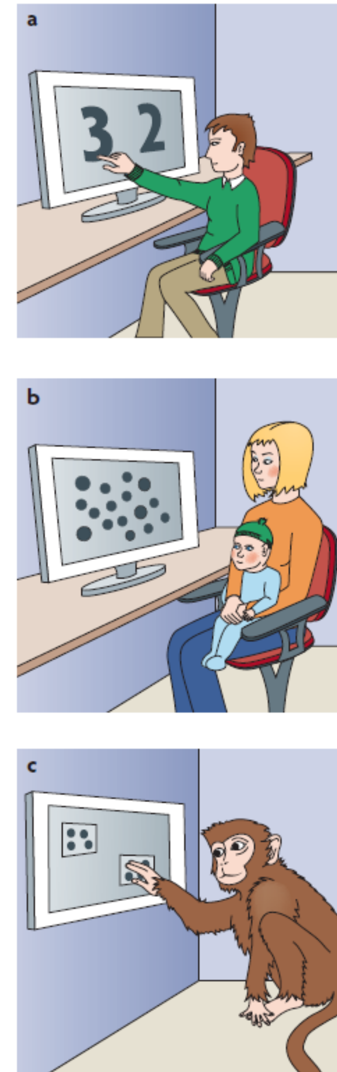
Definition of ‘number sense’

- ‘Number sense’ (or approximate number system, ANS) is not the ability to count, but the ability to (nonverbally) represent and manipulate numerical quantities nonsymbolically (e.g. perceive changes in the number of things in a set).
- However, other fields (e.g. education) often uses the terminology ‘number sense’ as an ‘intuitive understanding of numbers, their magnitude, relationships, and how these numbers are affected by various arithmetic operations’.

Number sense

- Humans share with non-human primates, birds, and amphibians the ability to discriminate numerical magnitudes.
- The so called 'number sense' therefore probably has a long evolutionary history.
- Comparative psychologists have shown that animals can discriminate numerosities (i.e., the cardinality of a set or set size) (Brannon & Terrace 1998, Davis &Perusse 1988).
- Field studies have convincingly demonstrated that animals use numerical information on a regular basis to make informed decisions (e.g., in foraging or in social interactions such as fights) McCombet al. 1994,Wilson et al. 2001).
- The basic ability to discriminate numerical quantities can therefore not fully explain the entire extent of human numerical and mathematical skills.



Nieder & Dahaene, 2009; Ansari, 2008

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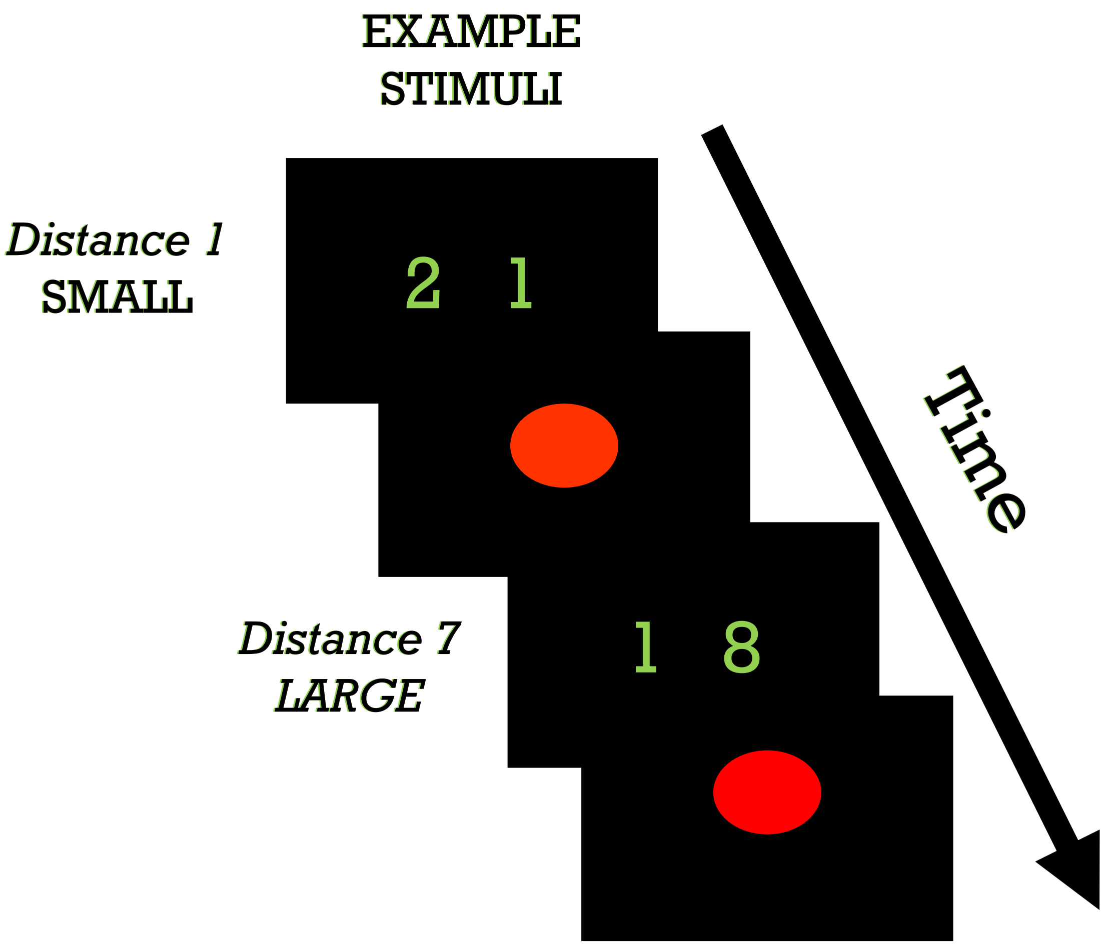
Number Comparison



Which is larger?

(Slide: D. Ansari)

Distance Effect

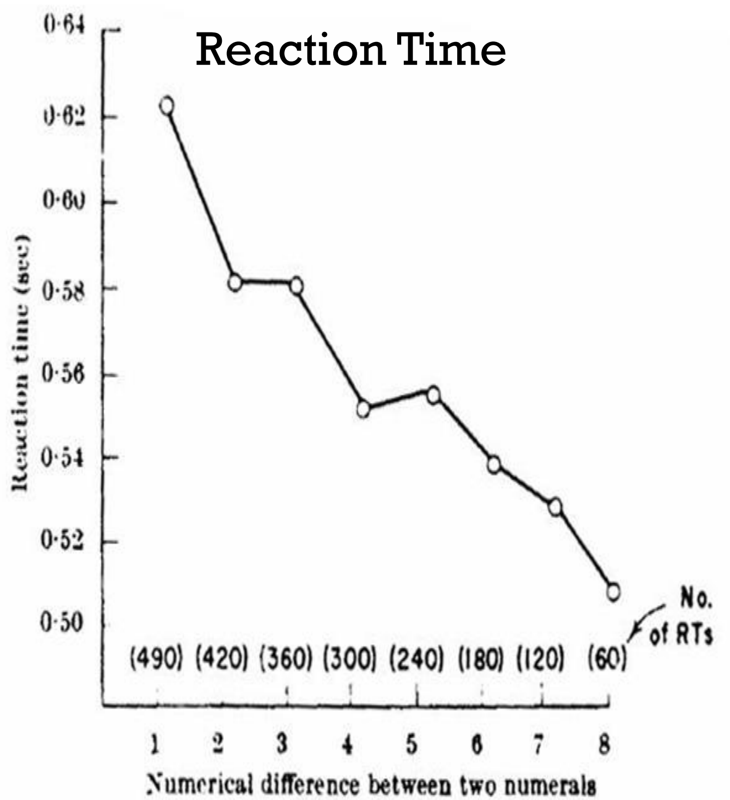


Fig. 1. Reaction time as a function of numerical difference between the two stimulus digits.

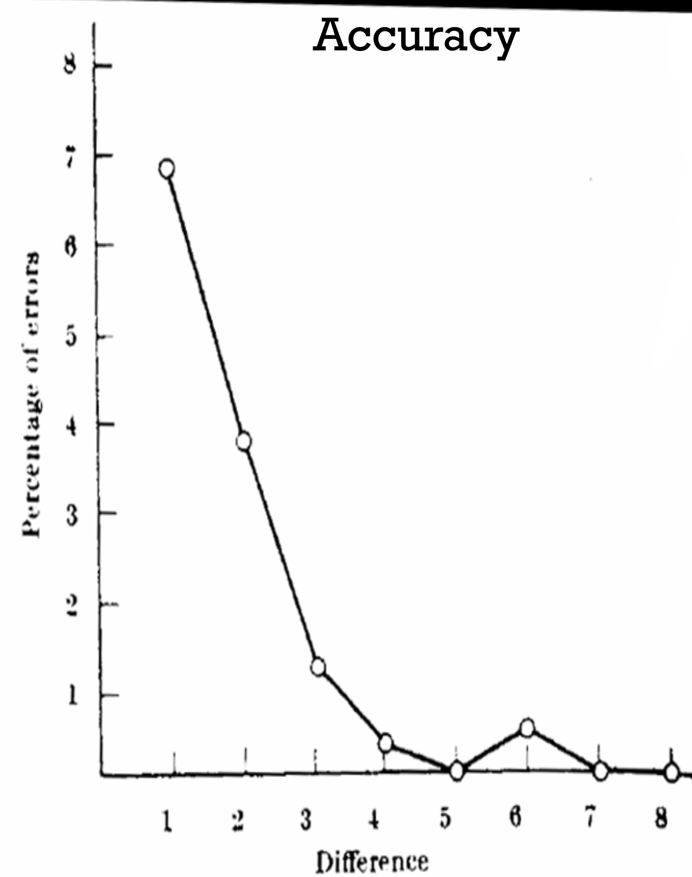


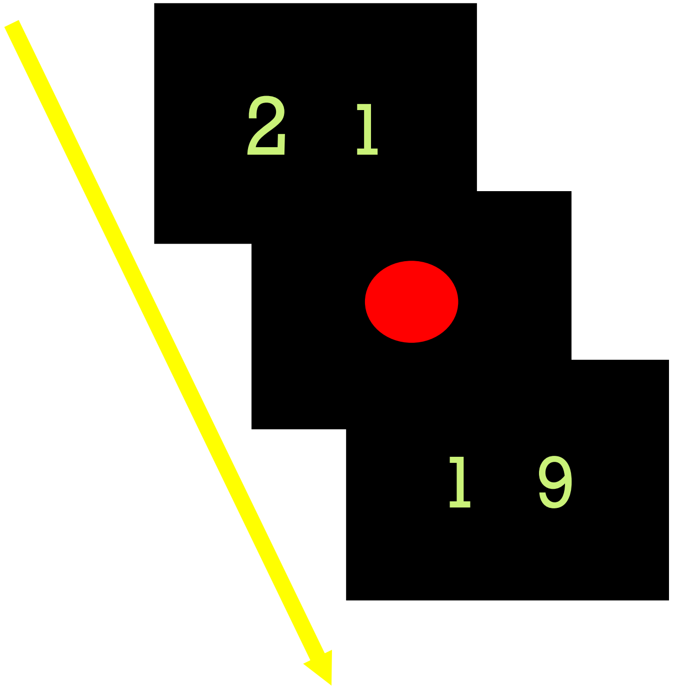
Fig. 2. Distribution of errors as a function of numerical difference between the two stimulus digits.

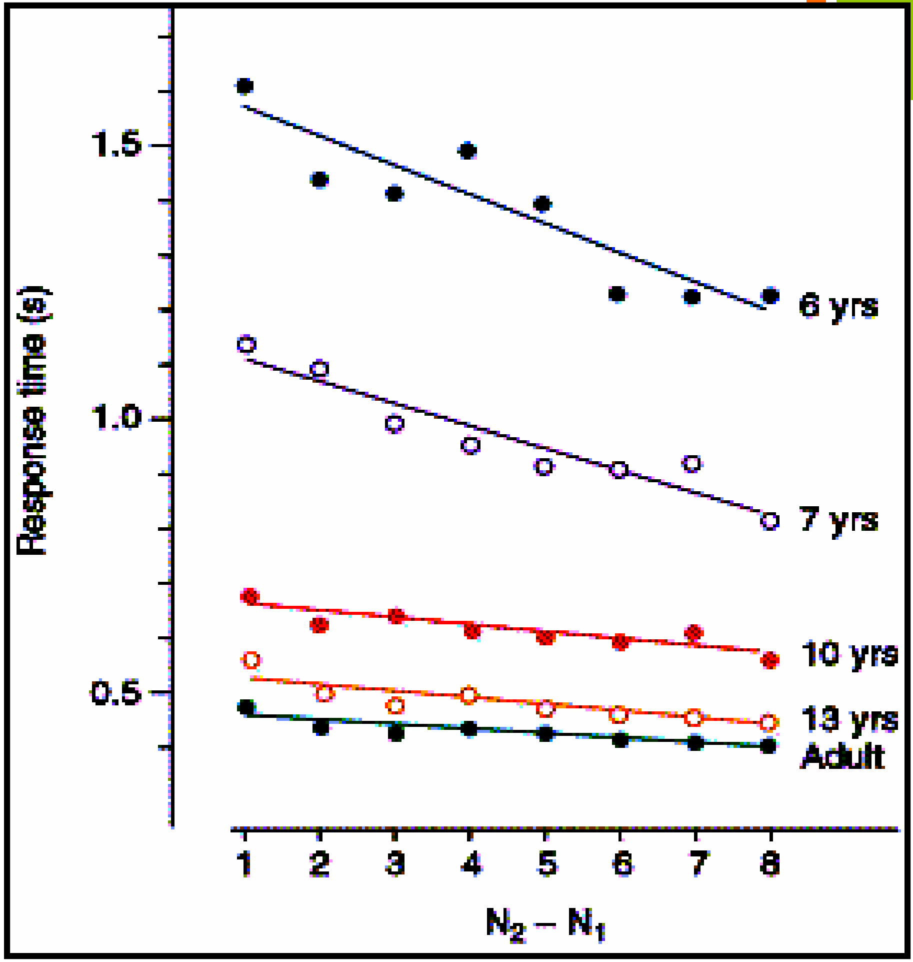
Moyer & Landauer(1967)

(Slide: D. Ansari)

Distance Effect

Development



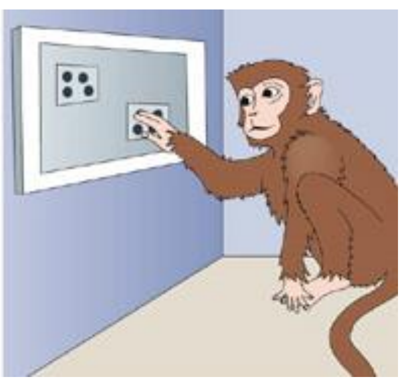


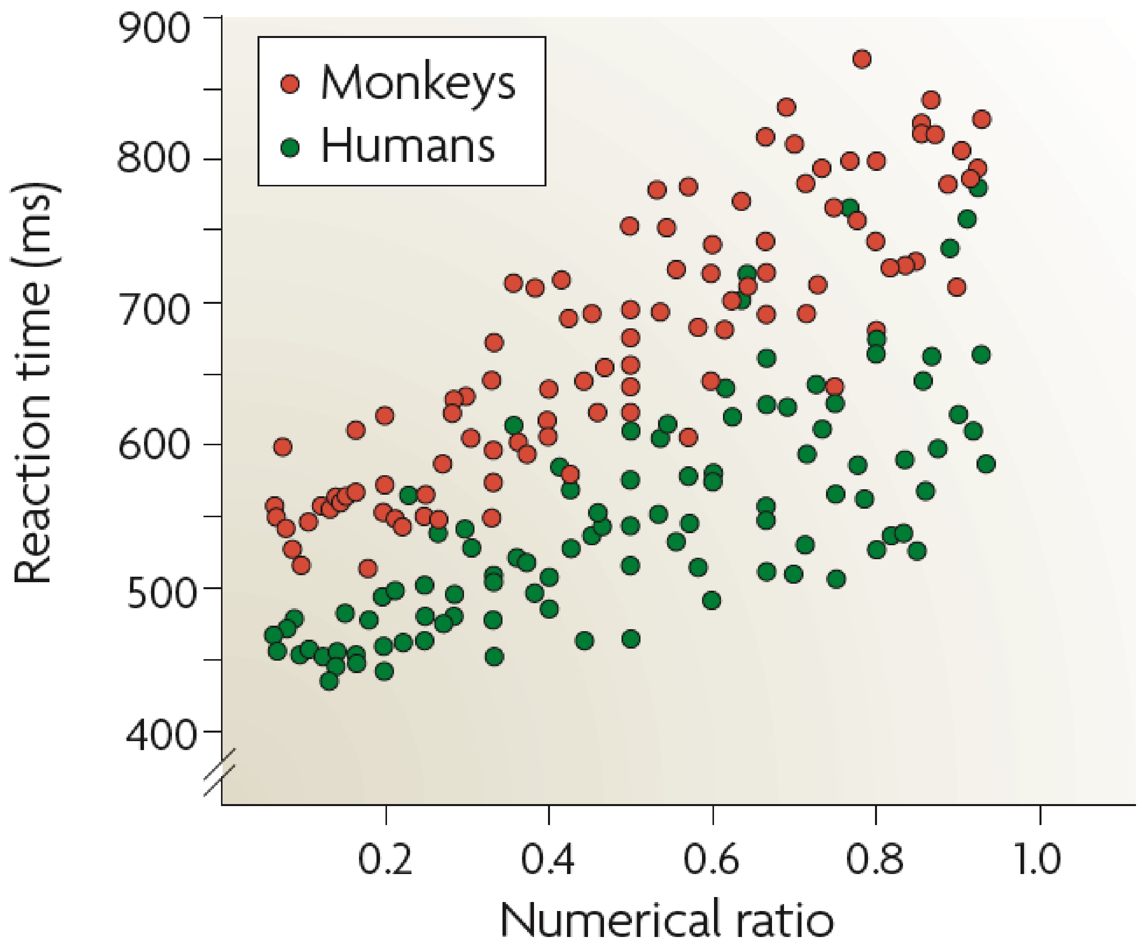
Sekuler & Mierkiewz (1977)

(Slide: D. Ansari)

Size (ratio) effect

	Distance	Ratio
1 - 2	1	0.5
9 - 8	1	0.88





Cantlon et al. (2006)

(Slide: D. Ansari)

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Can infants represent number?

- 'Number sense' has been demonstrated in human infants (Starkey & Cooper 1980, Feigenson et al. 2004). Infants of only a few months of age have the capacity to represent cardinality (the number of elements in a set).

- It has been suggested that infants can also engage in rudimentary arithmetic (Wynn 1992) but others have significantly challenged these results (Feigenson et al., 2002).

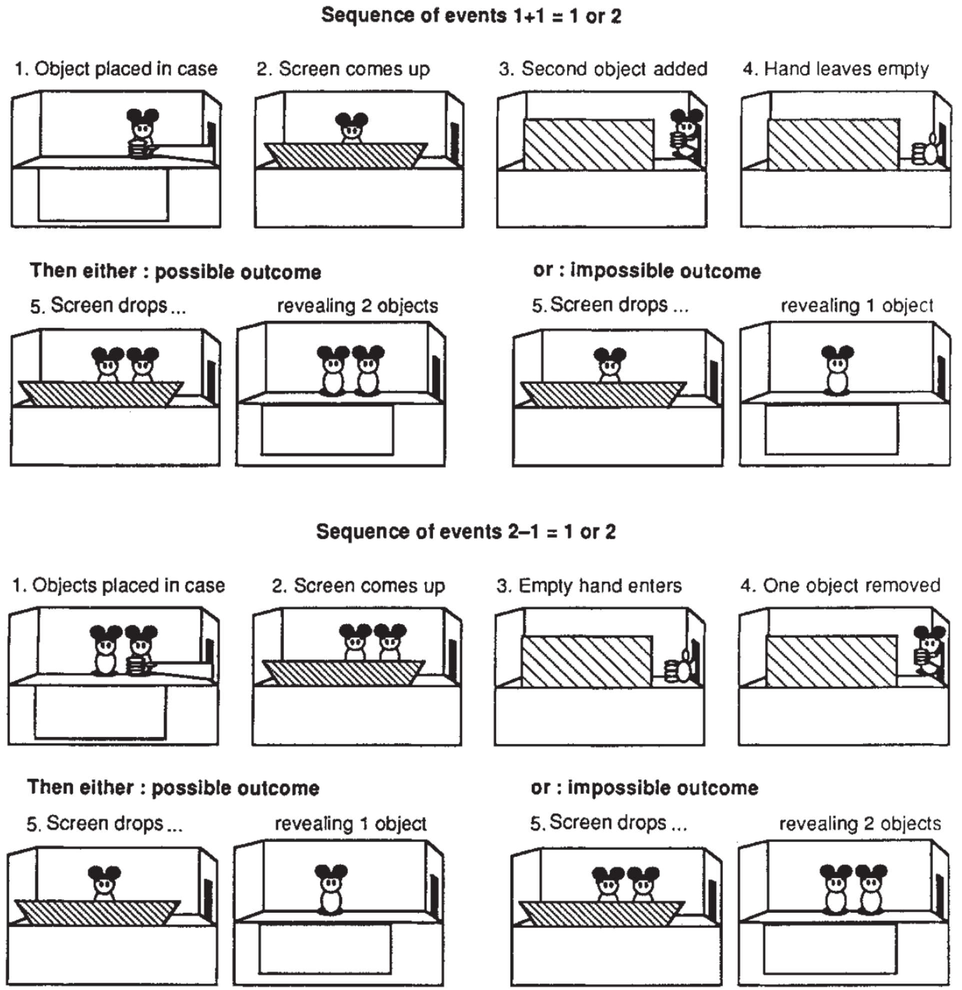
- Anthropological studies showed that even human adults who have been deprived of cultural transmission of number symbols, and whose societies don't have much need for exact quantification, are still able to quantify objects (Gordon 2004) and perform arithmetic operations in an approximate fashion (Pica et al.2004)

Nieder & Dehaene, 2009

Addition and subtraction by human infants

Karen Wynn

Department of Psychology, University of Arizona, Tucson, Arizona 85721, USA



Infants' Discrimination of Number vs. Continuous Extent

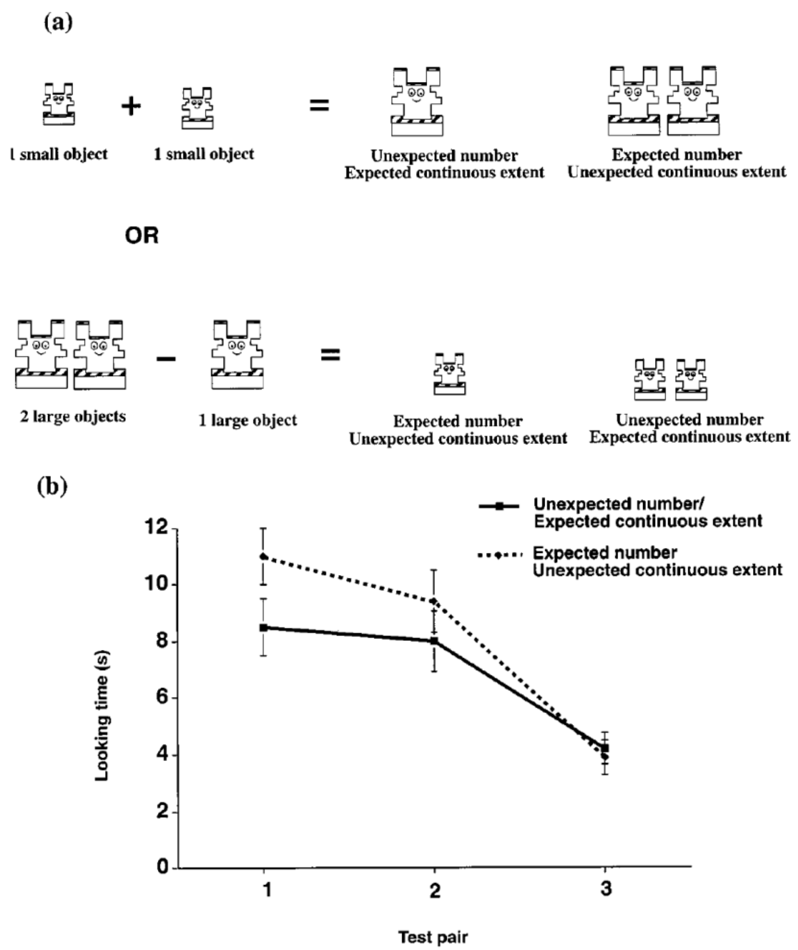
Lisa Feigenson and Susan Carey

New York University

and

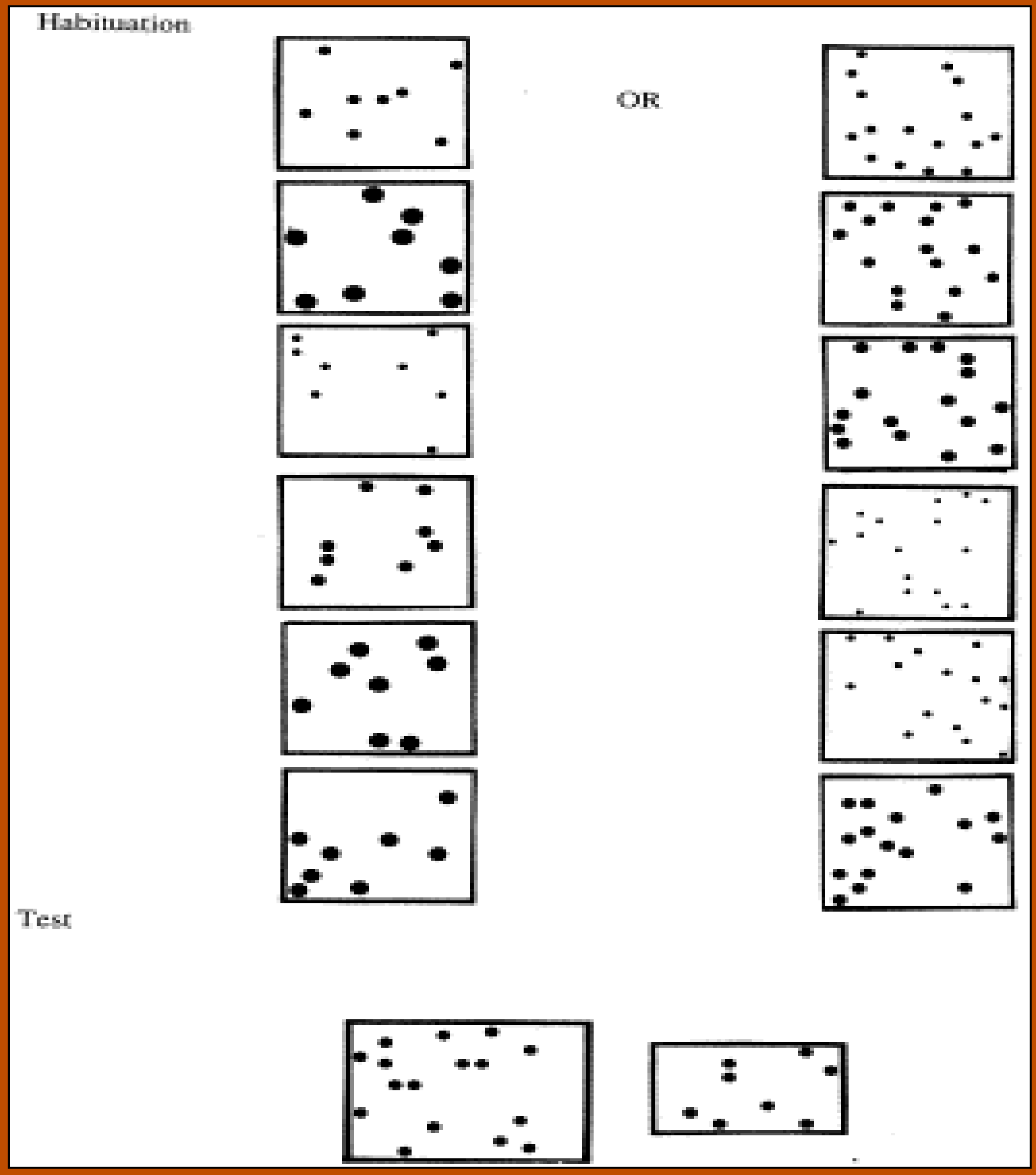
Elizabeth Spelke

Department of Brain and Cognitive Sciences,
Massachusetts Institute of Technology



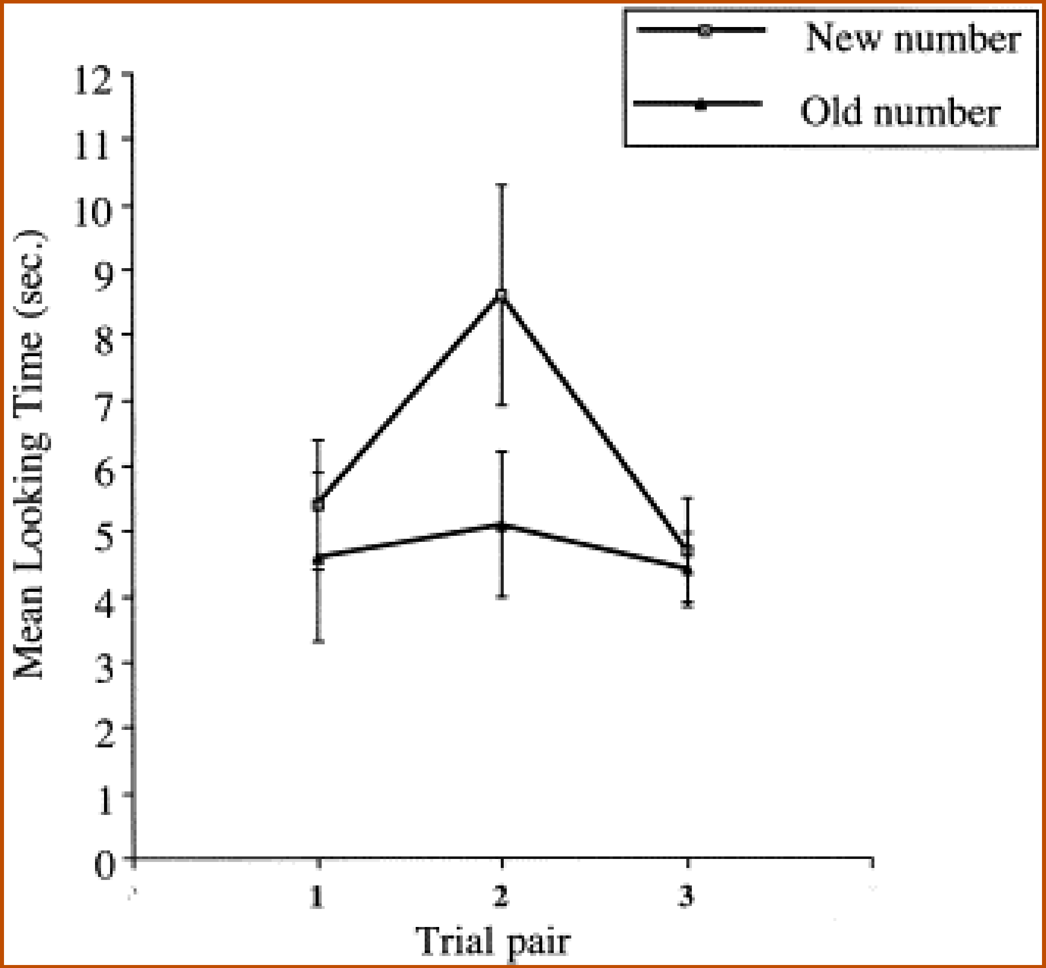
- The novelty of the test outcome may have been based on a change in one or more dimensions of continuous extent rather than on the change in number…

Xu and Spelke (2000)



Xu and Spelke (2000)

8 vs. 16 dots (1:2 ratio)

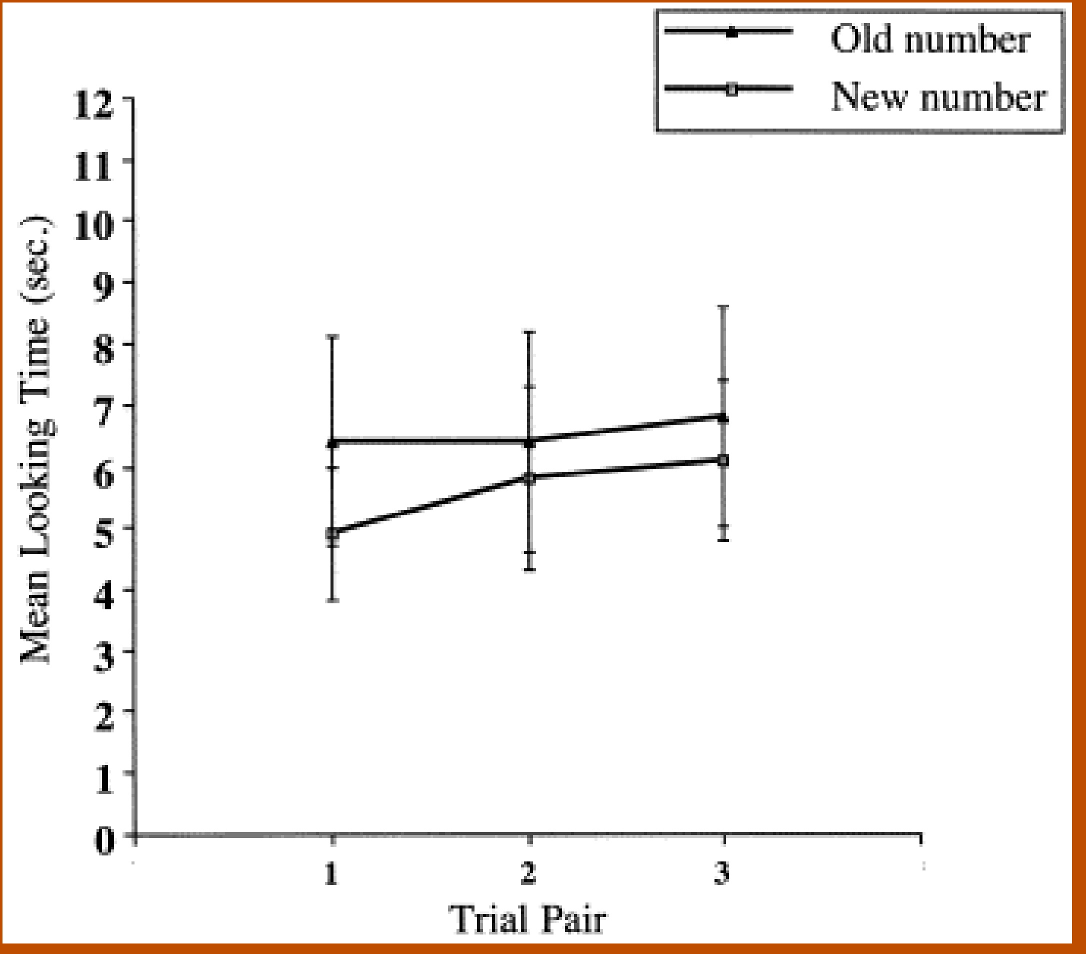


Xu and Spelke (2000)

8 vs. 12 dots (2:3 ratio)

Abstract

Six-month-old infants discriminate between large sets of objects on the basis of numerosity when other extraneous variables are controlled, provided that the sets to be discriminated differ by a large ratio (8 vs. 16 but not 8 vs. 12). The capacities to represent approximate numerosity found in adult animals and humans evidently develop in human infants prior to language and symbolic counting.



Weber's law: The ratio between quantities determines their discriminability (e.g.; Libertus & Brannon, 2009)

An integrative theory of numerical development (Siegler & Lortie-Forgues, 2014)

Four major acquisitions during time course of development:

Representing magnitudes of nonsymbolic numbers increasingly precisely

↓

Linking nonsymbolic to symbolic representations of numerical magnitudes

↓

Extending understanding to increasingly large whole numbers whose magnitudes can be represented accurately

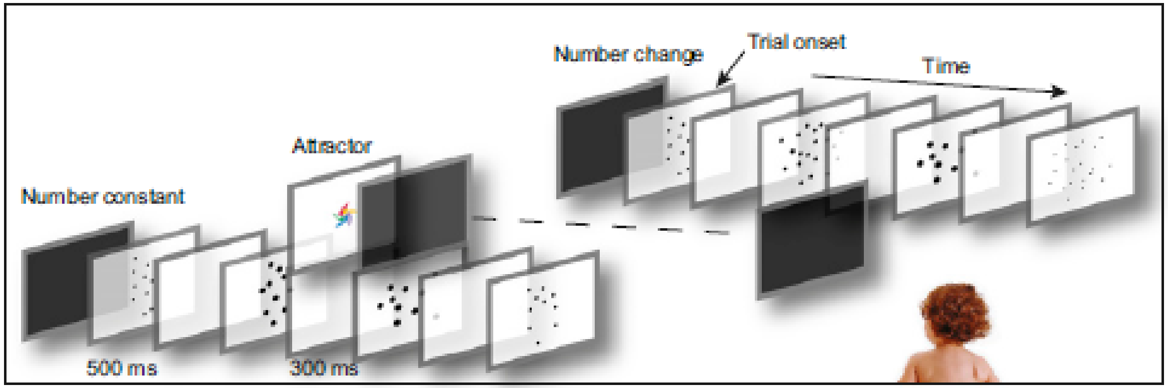
↓

Representing accurately the magnitudes of numbers other than whole Numbers (fractions, decimals, negatives)

Can 'number sense' predict mathematics performance ?

https://www.youtube.com/watch?v=7uh8FkR_4OU

A

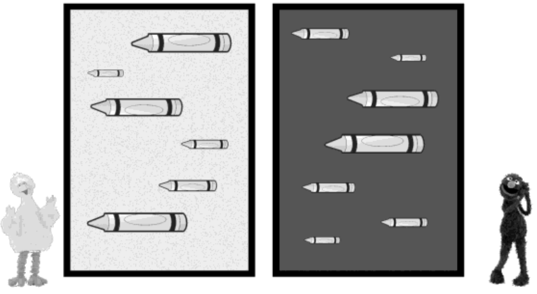


B

6 months			3.5 years		
Construct	**Test**	**Measure**	**Construct**	**Test**	**Measure**
ANS acuity	Numerical change detection task	Numerical preference score	ANS acuity	Non-symbolic number comparison task	Weber fraction (w)
Perceptual discrimination ability	Non-numerical change detection task (color or size)	Non-numerical preference score	Math ability	Test of Early Mathematics Ability (TEMA-3)	Standardized math score
			Counting knowledge	Give-A-Number task	Number knowledge (dichotomous)
			General intelligence (IQ)	Reynolds Intellectual Assessment Scales (RIAS)	IQ score

Starr et al., 2013)

Can 'number sense' predict mathematics performance ?



“Who has more crayons?”

- Preschoolers' Precision of the Approximate Number System Predicts Later School Mathematics Performance (Mazzocco et al., 2011)

- However, in six year olds, number knowledge and not 'number sense' is the best longitudinal predictor of subsequent mathematics performance 1 year later (Gobel et al., 2014)

- A recent meta-analysis reported consistent predictive value for symbolic numbers but the findings for non-symbolic formats were very inconsistent (De Smedt et al. 2013, see also Lyons et al., 2014).

- This suggests that the predictive value of the 'number sense' changes over the developmental time course.

Individual differences in Spontaneous Focus on Numerosity (SFON)

- SFON: the tendency to focus on numerical features in the environment without prompting)
- SFON emerges as early as kindergarten and the amount of SFON children generate has been shown to predict their later mathematical but not reading skills (Hannula & Lehtinen, 2005; Hannula, Lepola & Lehtinen, 2010).
- It is not yet known why some children randomly focus on number more than others: it could be due to better innate number sense, more number knowledge, or math-promoting home environments.

What basic number processing measures in kindergarten explain unique variability in first-grade arithmetic proficiency?

Dimona Bartelet [a,*], Anniek Vaessen [b], Leo Blomert [b,1], Daniel Ansari [c]

- Children's efficiency to compare digits
- Children's ability to count
- Children's ability to estimate numerosities

→ Predict arithmetric difference above and beyond non-numerical factors

→ Children's efficiency to process symbols is important for the development of their arithmetic fluency in Grade 1 above and beyond the influence of non-numerical factors.

Math at home adds up to achievement in school

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sciencemag.org SCIENCE

Talia Berkowitz,* Marjorie W. Schaeffer,* Erin A. Maloney, Lori Peterson, Courtney Gregor, Susan C. Levine,† Sian L. Beilock†

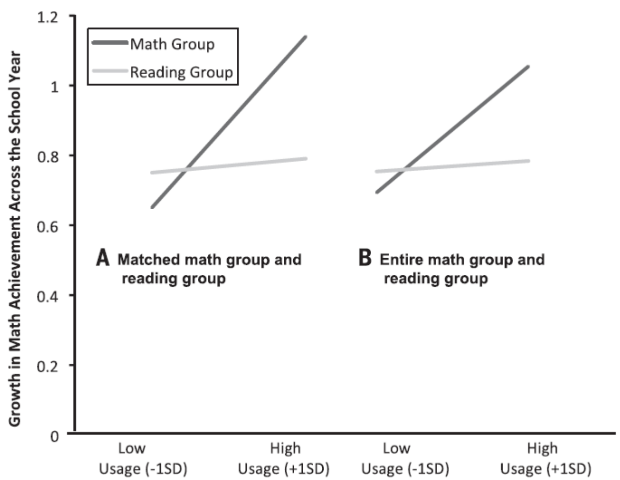
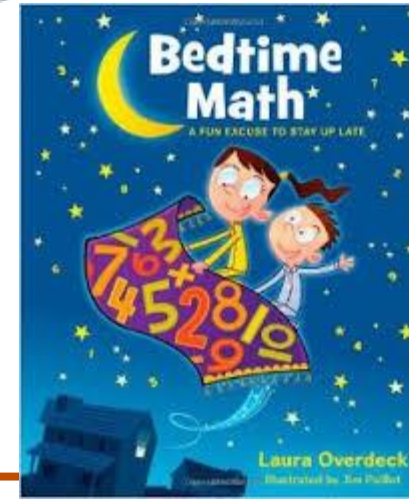


Fig. 1. Estimated number of months of math knowledge children gained across the school year (1 equals 9 months or one school year) as a function of average weekly app use.



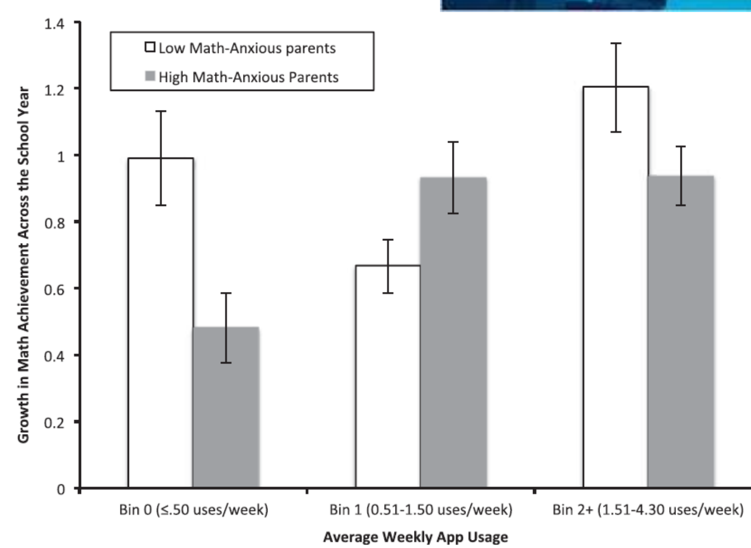
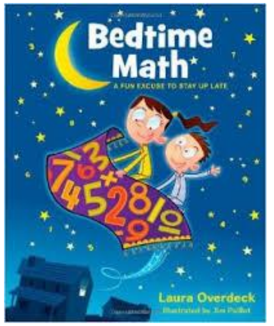


Fig. 2. Number of months of math knowledge children gained across the school year (1 equals 9 months or one school year) as a function of average weekly app use and parents' math anxiety.

Using 'Bedtime Math, an ipad App can lead to significant growth in Math achievement over a school year

Example: Bedtime Math



Our moon is bigger than you think. It may look small, but it is about 2,000 miles across, the same width as the US from Florida to California! The moon looks teeny only because it is a quarter million miles away. So our fan Quinn F, asked, how many stairs would you need to walk to the Moon? Well, you are climbing 240,000 miles, which is more than 1 billion feet (1,267,200,000 feet), or about 15 billion inches. House stairs are supposed to be 7 ¾ inches tall at most. So you need 1,962,116,129 steps – almost 2 billion stairs to climb that high! The problem is, stairs are also 10 inches from front to back. So, those stairs would start 310,000 miles way over to the side. You'd have to fly into outer space just to start climbing.

- **Wee ones:** Look out the window. Do you see any space objects right now, like the Moon, Sun, or starts? What shapes do you see?
- **Little kids:** If you climb steps 2 at a time, after the 2^{nd}, 4^{th} and 6^{th} which step do you touch next?
- **Big kids:** Can you "spell" 2 billion as a number, without looking at the numbers above?
- **The Sky's the Limit:** While the Moon is ¼ million miles away, the Sun is 93 million miles away. If you need 2 billion steps to reach the Moon, how many do you need to reach the Sun? (Hint if needed: How many do you need to climb 1 million miles?)

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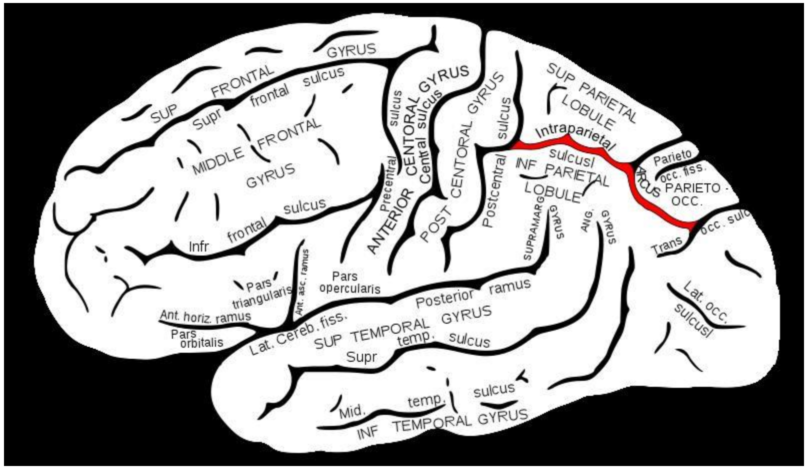
The typical mathematical brain

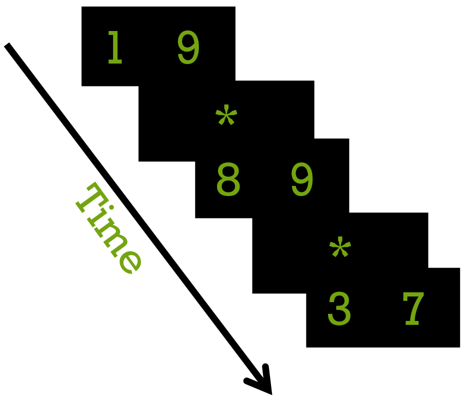
- Converging evidence from studies in preschool children (Cantlon et al., 2006), and adults (Ansari, 2008; Rosenberg-Lee et al., 2011), as well as nonhuman primates (Cantlon & Brannon, 2006) and brain-damaged patients, have implicated the (bilateral) intraparietal sulcus (IPS) as one crucial area for the processing of numerical magnitude.
- However, multiple distributed brain structures are known to be important for mathematical cognition.



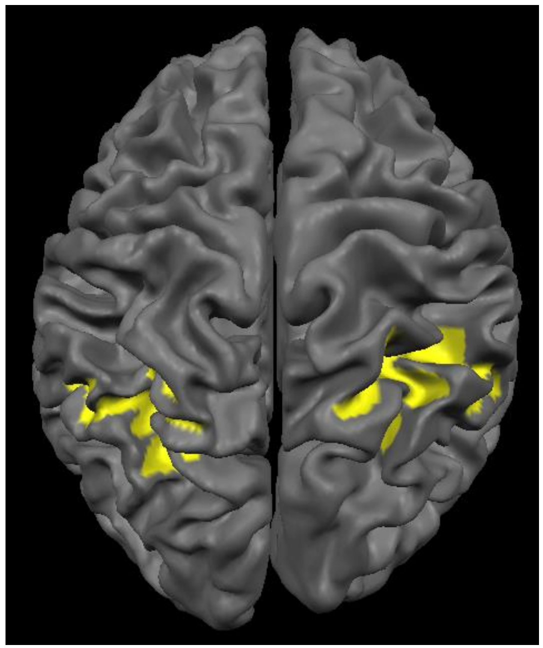
Picture: commons.wikimedia.org

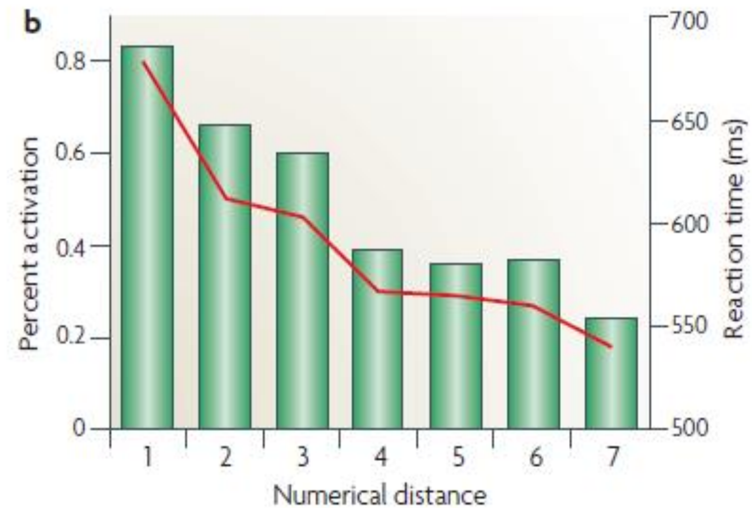
‘Distance Effect’ in the Brain

Distance modulates a network of parietal areas



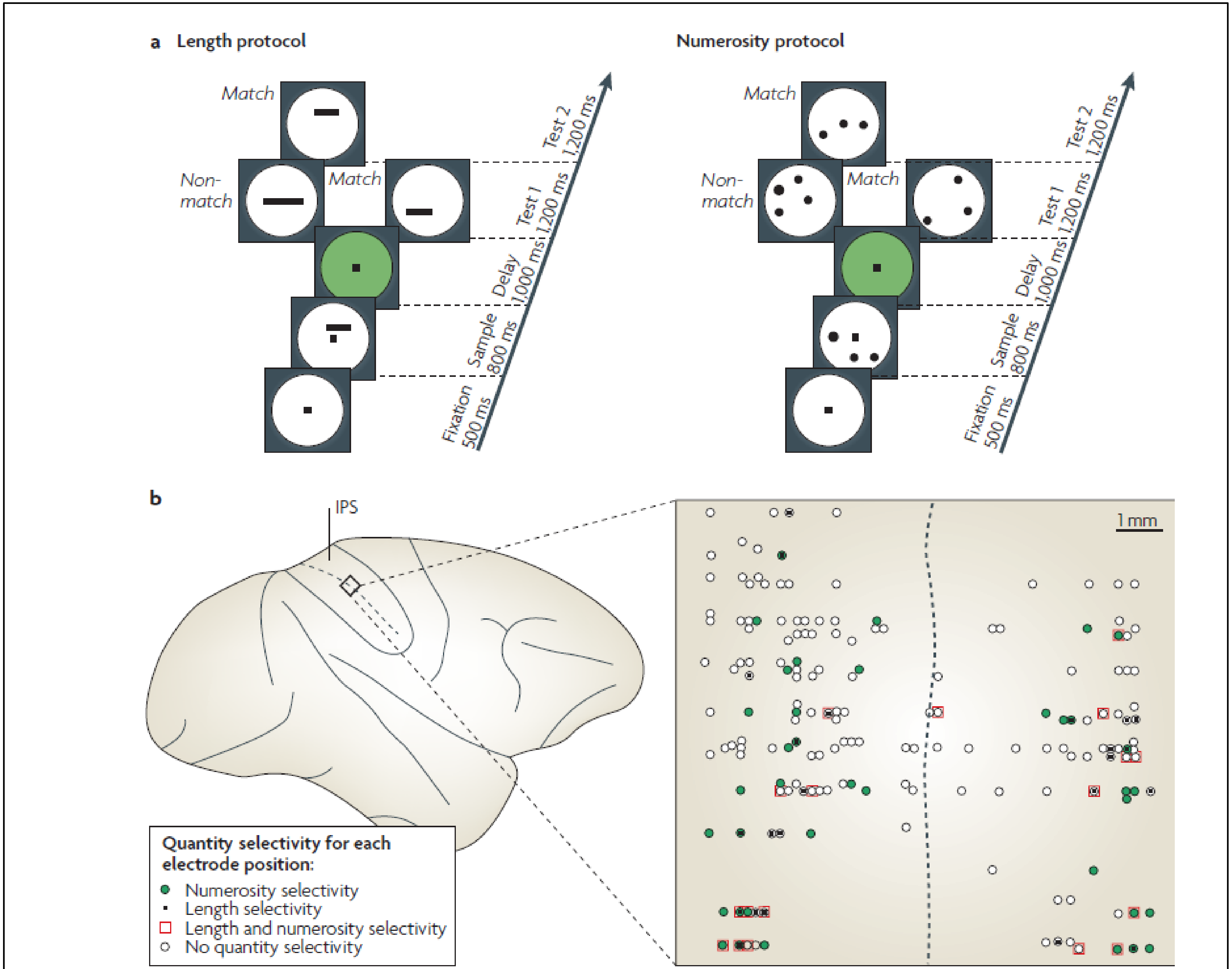
Which is larger ?





(Pinel et al., 1999, 2001, 2004; Kaufmann et al., 2006; Ansari et al;, 2006)

Length versus numerosity in the monkey brain



Tudusciuc & Nieder, 2007; picture: Ansari, 2008)

Numerical versus non-numerical processing

- Non-symbolic stimuli, like symbolic stimuli, are external representations of numerical magnitude that need to be mapped onto internal representations.

- Some data already suggest that symbolic representations of numerical magnitude might be different from non-symbolic representations. For example, Polk et al. 2001 reported that a patient with damage to the left supramarginal gyrus (SMG) was severely impaired on symbolic but not non-symbolic magnitude processing.

- In monkeys, neurons that code for non-symbolic magnitudes have slightly different response properties to those that code for symbolic magnitude.

(Ansari, 2008)

Development of the mathematical brain

- Although there are similarities in brain areas engaged by numerical tasks in adults and children, there are key differences as well.

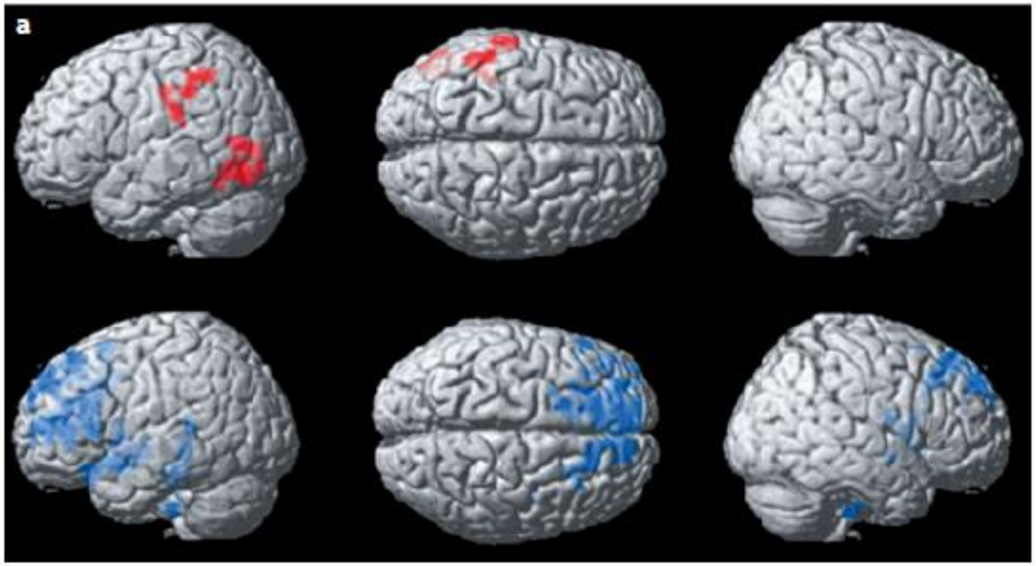
- With experience, decreased dependence on the PFC and greater reliance on multiple regions of the parietal cortex, including the left IPS (Ansari & Dhital, 2006; Cantlon et al., 2006; Rivera et al., 2005).

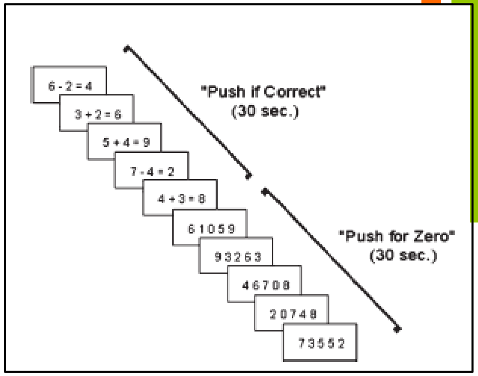
- Furthermore, even the seemingly brief one-year interval spanning Grades 2 and 3 is characterized by significant task-related changes in brain response, a finding that suggests that pooling data across wide age ranges and grades can miss important neurodevelopmental changes (Rosenberg-Lee et al., 2011).

- Specifically, over the long term, there is a shift from more controlled and effortful to more automatic processing of both numerical magnitude and arithmetic problem solving (Ansari & Dhital, 2006; Cantlon et al., 2009; Rivera et al., 2005);

(Ashkenazi et al., 2013)

Development of mental arithmetic



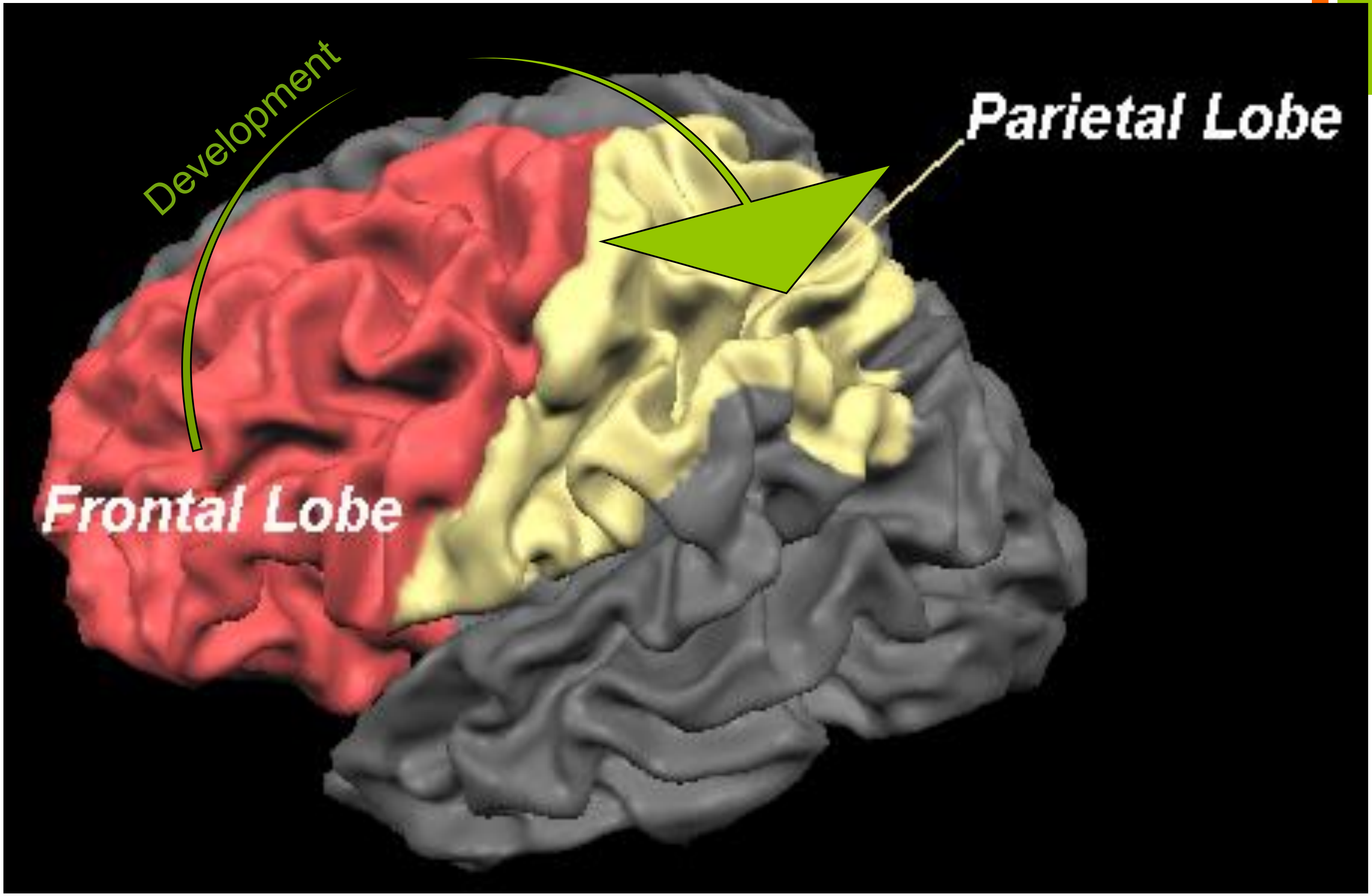


- A frontoparietal shift in activity seems to underlie the development of arithmetic skills.
- The decrease in the reliance on frontal regions might relate to reduced reliance on processes of cognitive control, attention and working memory with age.
- Findings indicate that learning/development result in the recruitment of distinct parietal circuits for numerical-magnitude processing and calculation, with specialization of the left temporoparietal cortex for calculation and the bilateral IPS for numerical-magnitude processing.

(Rivera et al., 2005; Ansari, 2008)

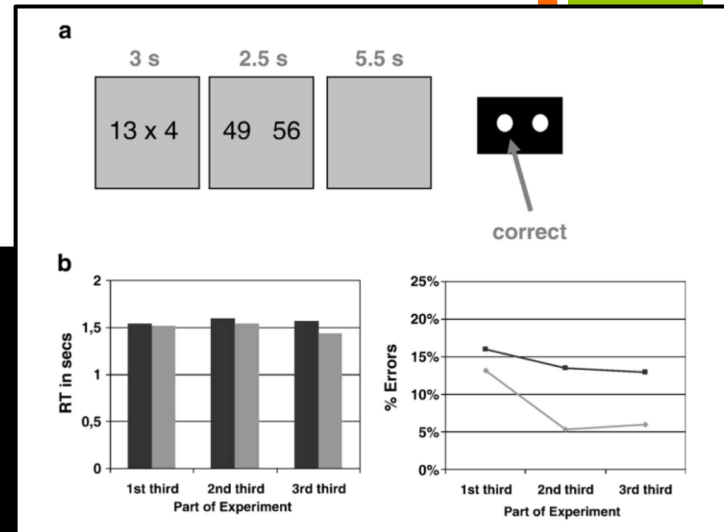
Age-related shift

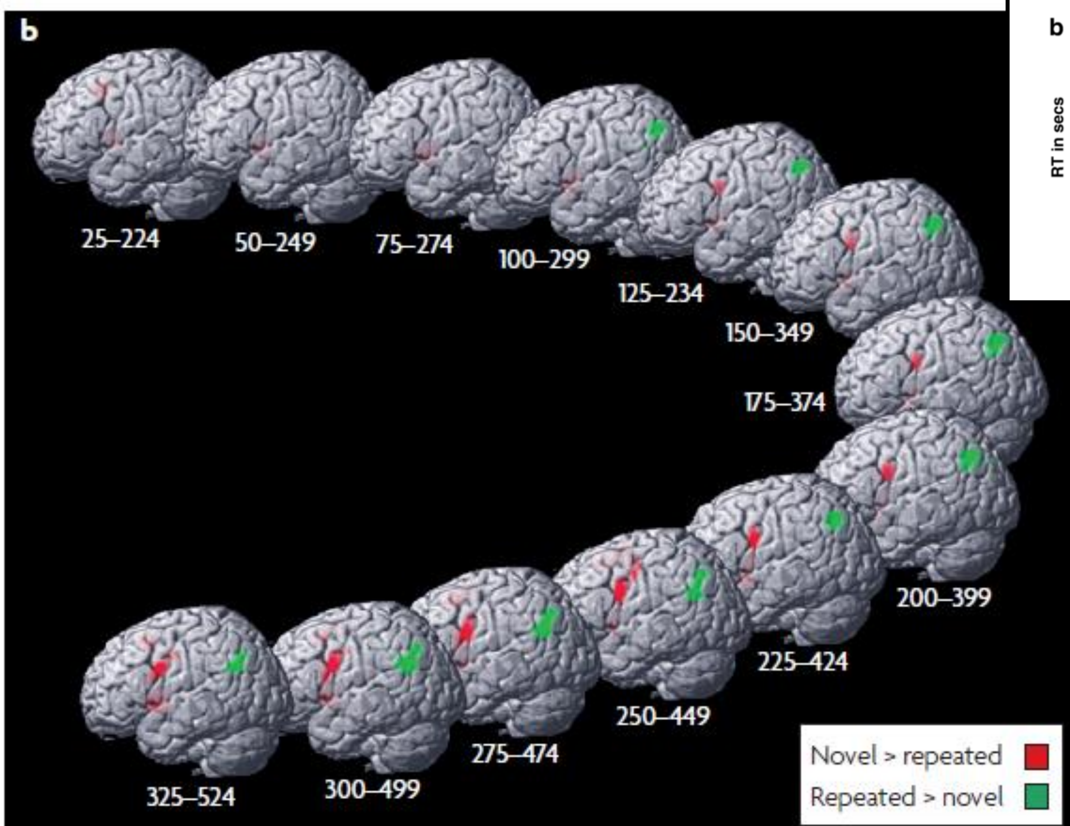
(Slide: D. Ansari)



Ansari et al. (2005); Ansari & Dhital (2006); Kaufmann et al. (2006)

The calculating brain changes dynamically as a function of learning



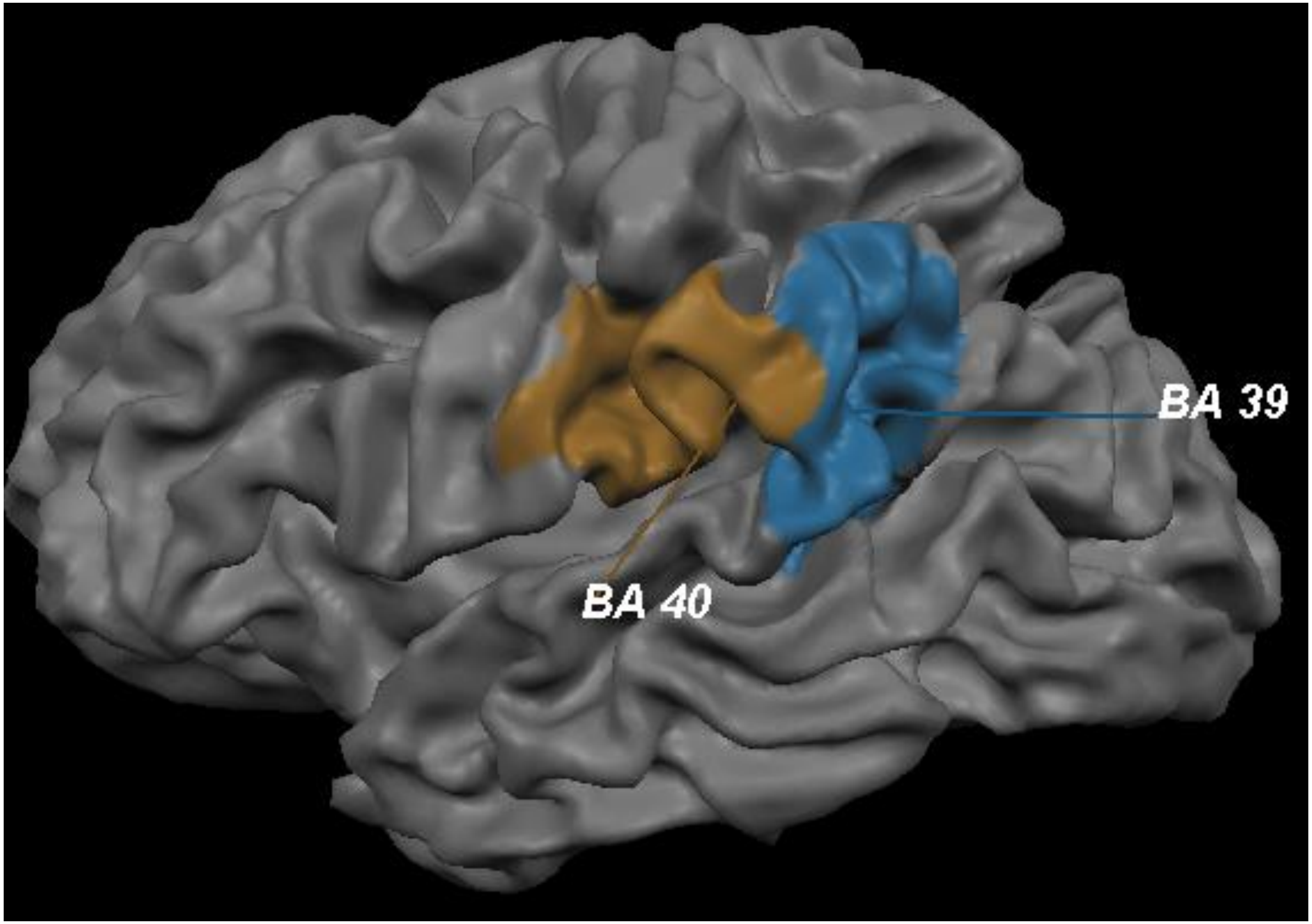


(Ischebeck et al., 2007)

Mental Arithmetic

(Slide: D. Ansari)

LEFT TEMPORO-PARIETAL CORTEX



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

See also ‘Gerstman Syndrome’ (acalculia, agraphia)

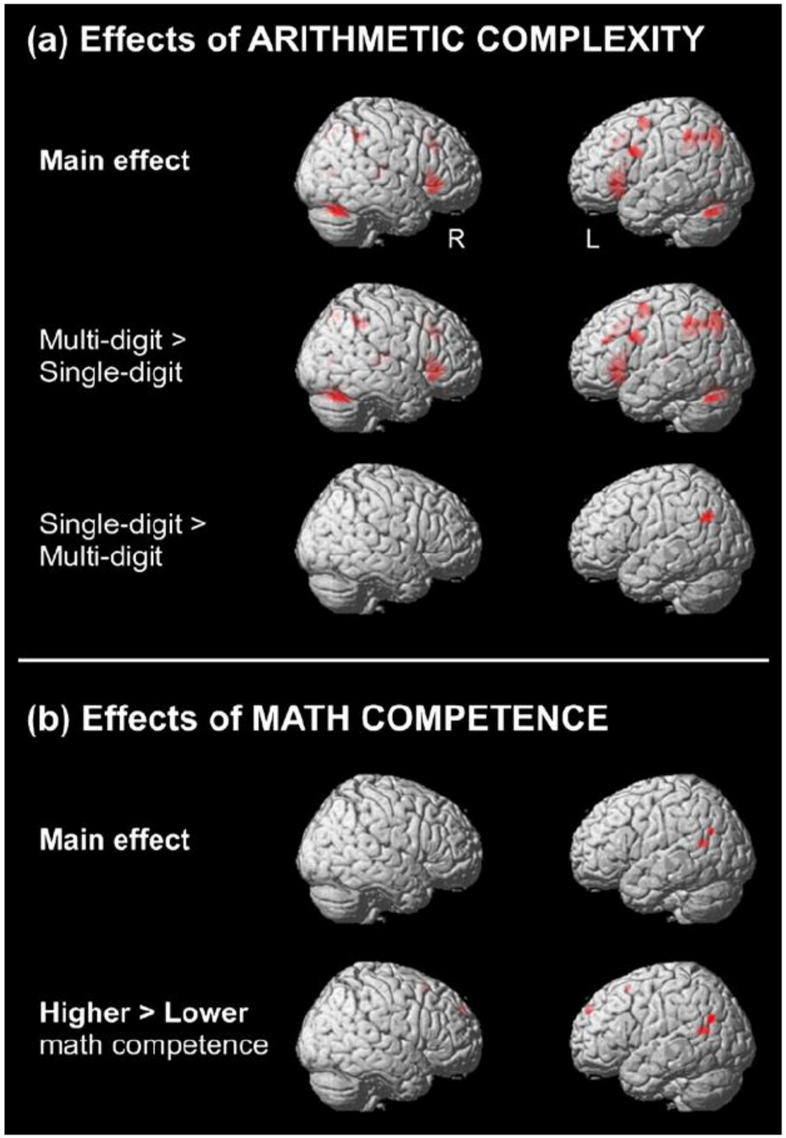
Gerstmann’s syndrome

- Gerstmann's syndrome is a cognitive impairment that results from damage to a specific area of the brain -- the left parietal lobe in the region of the angular gyrus. It may occur after a stroke or in association with damage to the parietal lobe. It is characterized by four primary symptoms: a writing disability (agraphia or dysgraphia), a lack of understanding of the rules for calculation or arithmetic (acalculia or dyscalculia), an inability to distinguish right from left, and an inability to identify fingers (finger agnosia)

ninds.gov

Individual differences in mathematical competence predict parietal brain activation during mental calculation

Roland H. Grabner,[a,b,c,*,1] Daniel Ansari,[d,*,1] Gernot Reishofer,[e] Elsbeth Stern,[c]
Franz Ebner,[a] and Christa Neuper[b]



Mental Arithmetic

4 x 6 = 24

13 x 7 = 91

Arithmetic Verification

Grabner, Ansari et al. (2007)

Basic neurocognitive processes involved in arithmetic

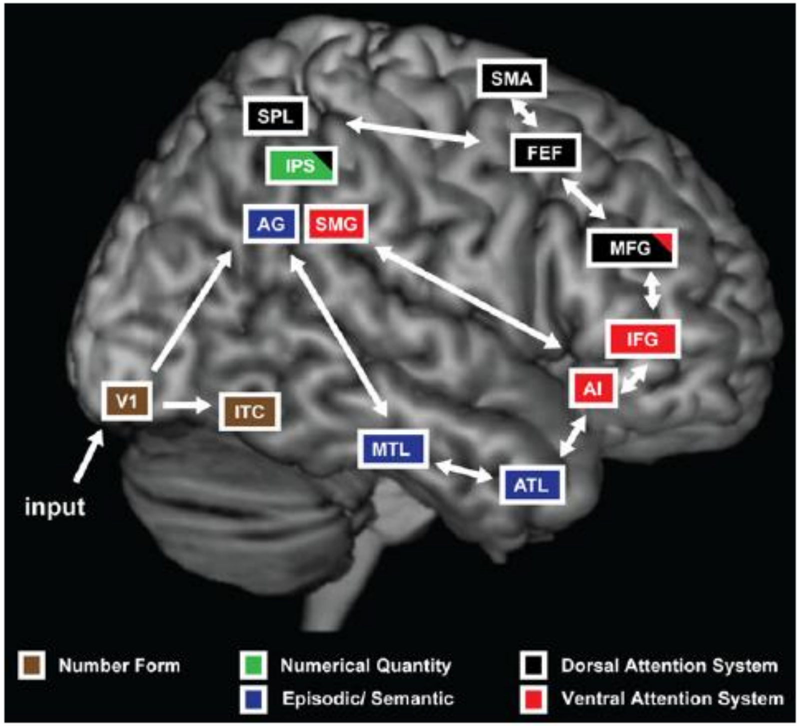


Figure 1 *Schematic diagram of math-related brain circuits. It is increasingly recognized that mathematical processing requires interaction within and between multiple interacting brain systems, including systems involved in processing lower-order visual information and number form (brown), numerical quantity (green), episodic and semantic memory (blue), and attentional control (red and black). Adapted from Fias* et al. *(2014). AG = angular gyrus, AI = anterior insula, ATL = anterior temporal lobe, FEF = frontal eye fields, IFG = inferior frontal gyrus, IPS = intraparietal sulcus, ITC = inferior temporal cortex, MFG = middle frontal gyrus, MTL = medial temporal lobe, SMA = supplementary motor area, SMG = supramarginal gyrus, SPL = superior parietal lobe.*

Jolles et al., 2016

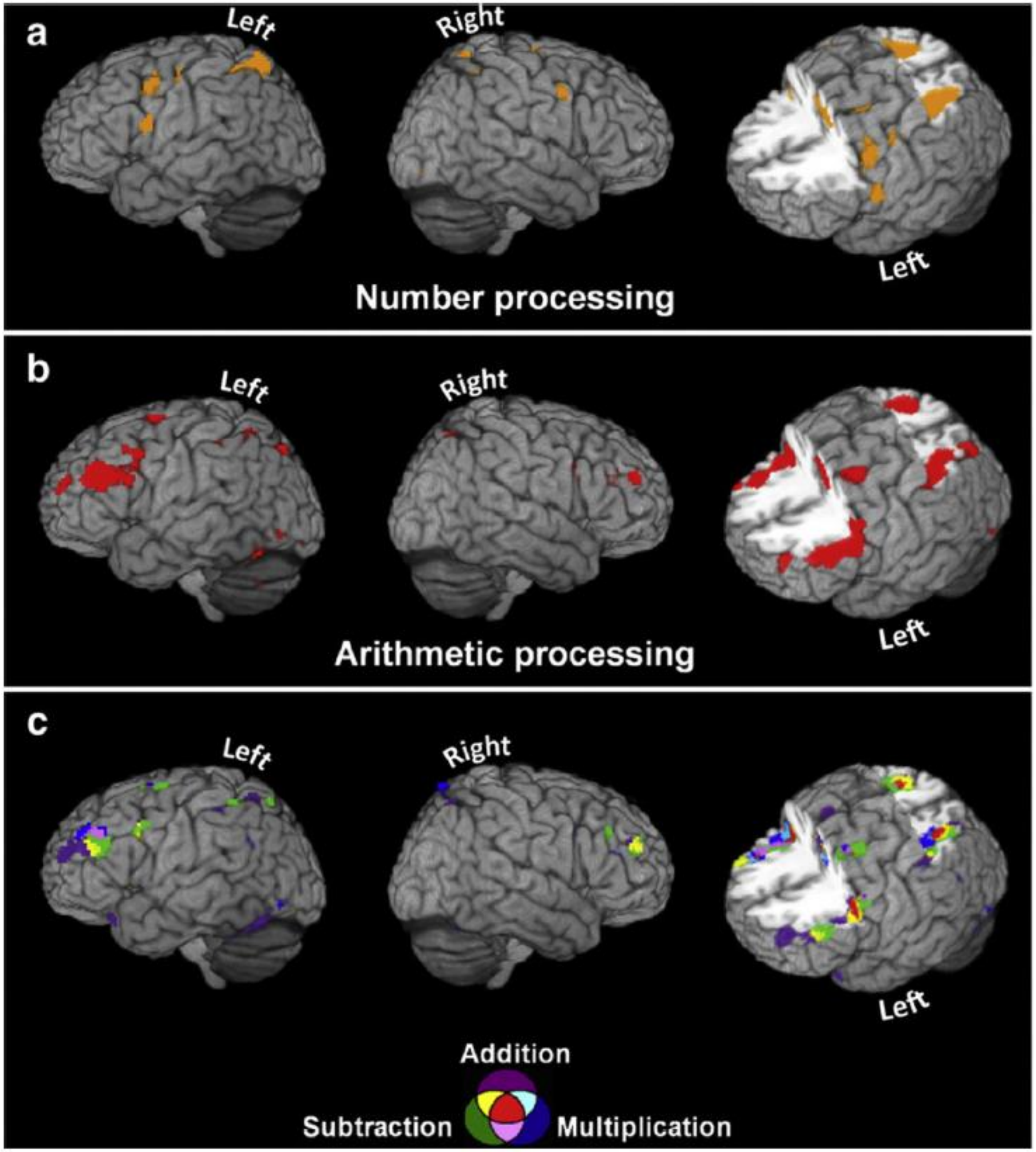
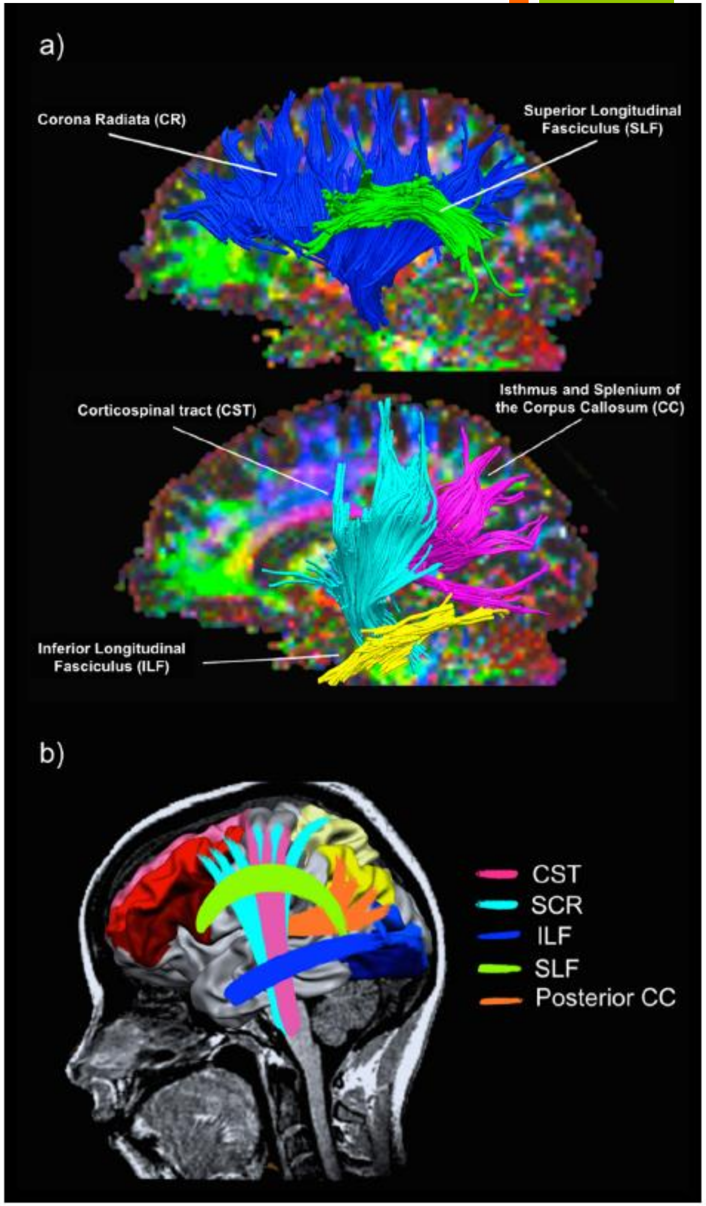


Fig. 1. Brain areas activated during numerical and mathematical tasks. Figure is adapted from Arsalidou and Taylor (2011).

(Matejko & Ansari, 2015)

White matter tracts associated with numerical and mathematical processing

- Superior longitudinal fasciculus (SLF)
- Posterior segment of the corpus callosum (CC)
- Inferior longitudinal fasciculus (ILF)
- Corona radiate(SCR)
- Corticospinal tract (CST)

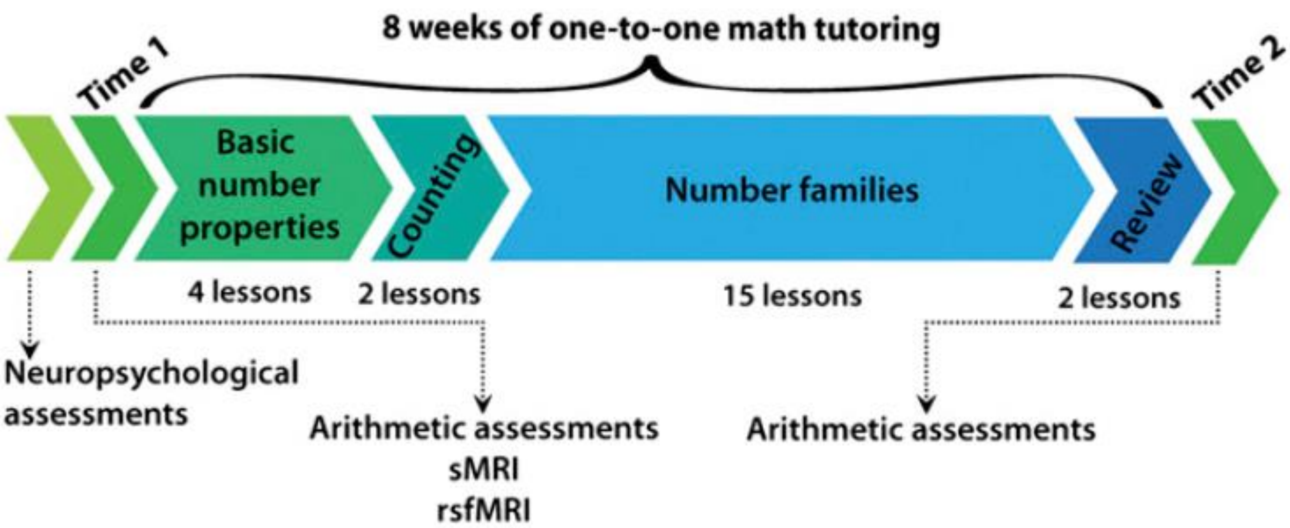


Matejko & Ansari, 2015)

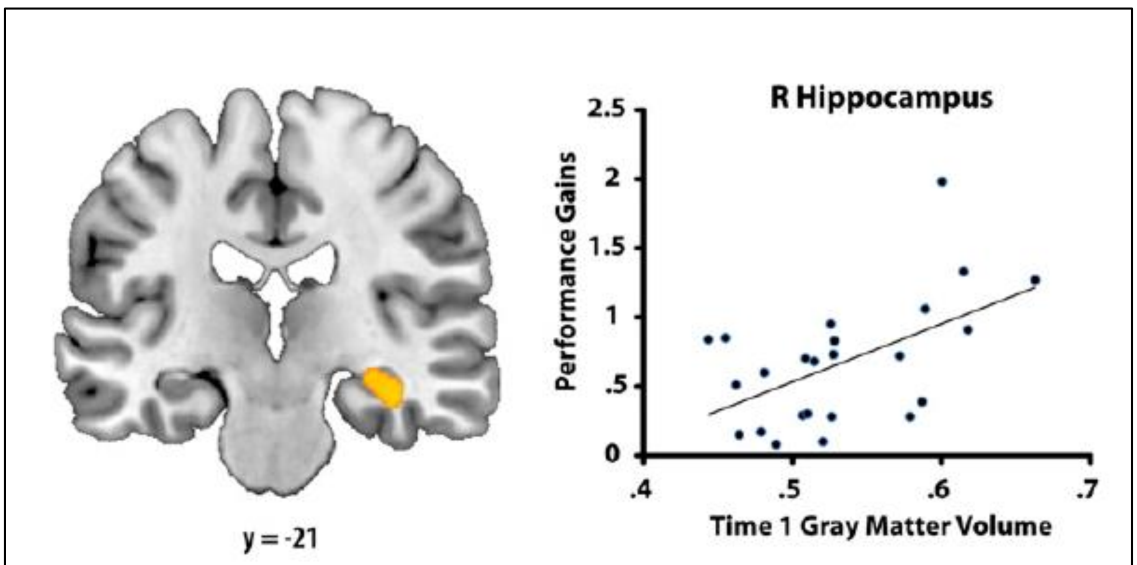
Neural predictors of individual differences in response to math tutoring in primary-grade school children

Kaustubh Supekar[a,1,2], Anna G. Swigart[a,1], Caitlin Tenison[a], Dietsje D. Jolles[a], Miriam Rosenberg-Lee[a], Lynn Fuchs[b], and Vinod Menon[a,c,d,e,2]

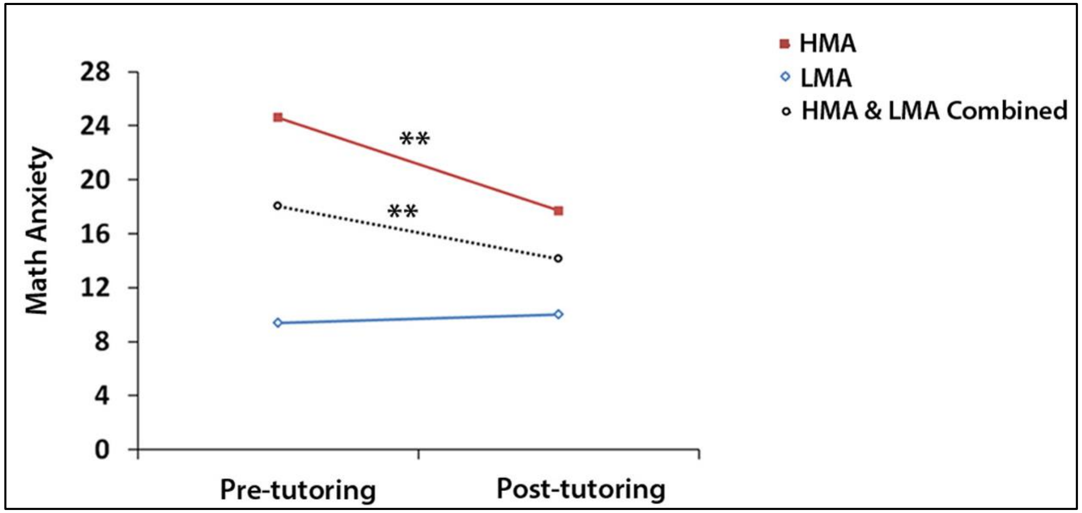
- Can behavioral or brain measures predict individual differences in arithmetic performance improvements with tutoring?

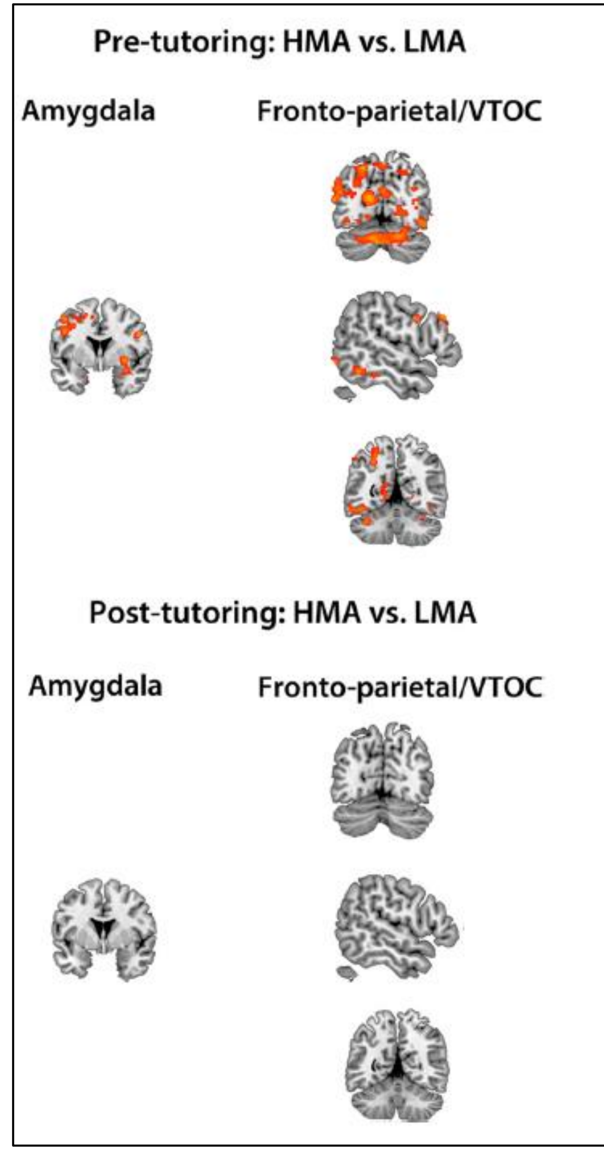


- A significant shift in arithmetic problem-solving strategies from counting to fact retrieval was observed with tutoring.
- Speed and accuracy of arithmetic problem solving increased with tutoring, with some children improving significantly more than others.
- No behavioral measures, including intelligence quotient, working memory, or mathematical abilities, predicted performance improvements.
- In contrast, pre-tutoring hippocampal volume (associated with learning and memory) predicted performance improvements.



(Supekar et al., 2013)





- Math anxiety during early childhood has adverse long-term consequences for academic and professional success
- Intensive 8 week one-to-one cognitive tutoring not only reduces math anxiety but also remarkably remediates aberrant functional responses and connectivity in emotion-related circuits anchored in the amygdala.

(Supekar et al., 2015)

A THREATENING INTELLECTUAL ENVIRONMENT:
Why Females Are Susceptible to Experiencing Problem-Solving Deficits in the Presence of Males

Michael Inzlicht[1] and Talia Ben-Zeev[2]
[1]Brown University and [2]Williams College

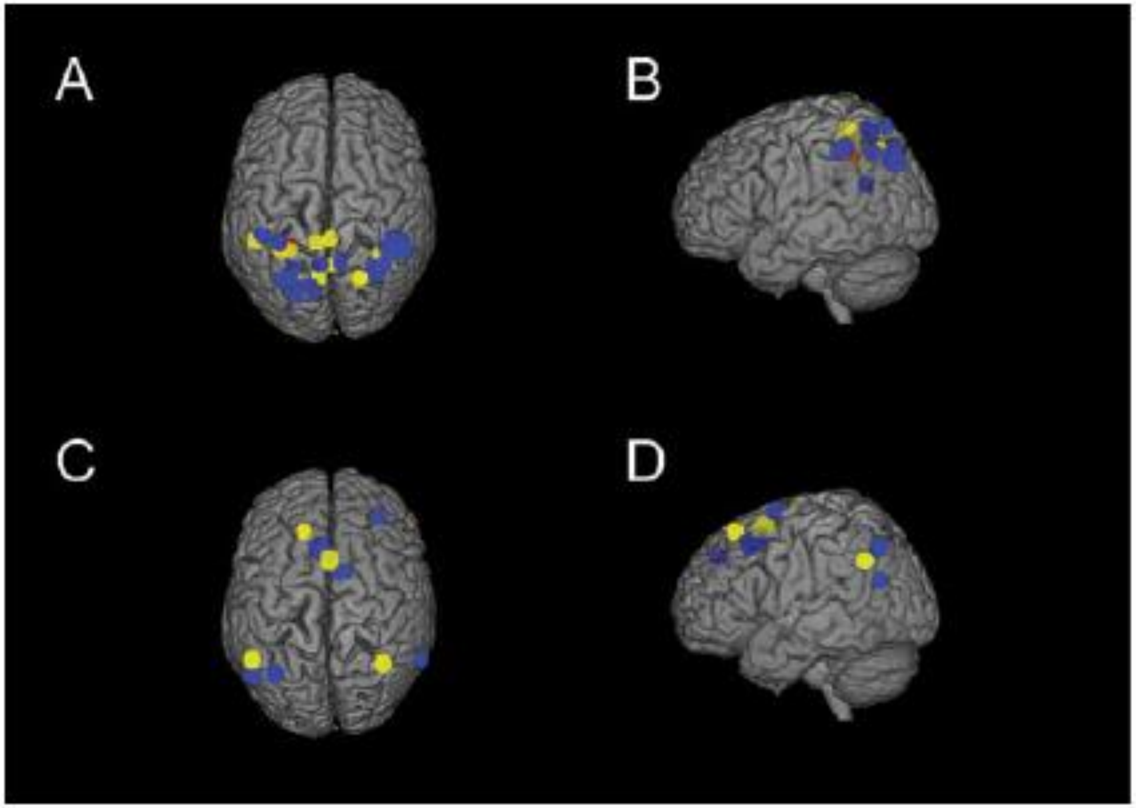
- Is a situational cue, such as gender composition, sufficient for creating a threatening intellectual environment for females—an environment that elicits performance-impinging stereotypes?
- Participants completed a difficult math or verbal test in 3-person groups, each of which included 2 additional people of the same sex as the participant (same-sex condition) or of the opposite sex (minority condition).
- Female participants in the minority condition experienced performance deficits in the math test only, whereas males performed equally well on the math test in the two conditions.
- Further investigation showed that females' deficits were proportional to the number of males in their group. Even females who were placed in a mixed-sex majority condition (2 females and 1 male) experienced moderate but significant deficits.

Culture and Math

- Math is a universal cognitive construct
- Relatively duration required to utter numerical digits in Chinese allowing larger numerals to be held in short-term memory, and facilitating calculations with larger numbers.
- Differences in teaching methods across cultures AND within the developmental trajectory

→ 'Western'

→ 'Eastern'



(Tcheang, 2014)

Overview

- What is ‘Number sense” ?
- What do infants know about numbers/systems of number representations?
- The typical mathematical brain
- What is Developmental Dyscalculia?
- The atypical mathematical brain

What is Developmental Dyscalculia?
(Math Learning Disability MLD)

- Affects 1-10% of children (most estimates around 3-5%).
- learning disorder affecting the acquisition of school level arithmetic skills, and is characterized by poor arithmetic achievement in the context of typical IQ, schooling, and socio-economic background.
- The following symptoms have been described:
  - Difficulties with retrieval of mathematical facts from memory
  - Perseverance of immature calculations, problem-solving and counting strategies
  - Difficulties understanding concepts of place values, and quantity, number lines, positive and negative values
  - Difficulty using steps involved in math operations
  - Difficulty understanding fractions
  - Difficulty with making change and handling money
  - Difficulty recognizing patterns when adding, subtracting, multiplying, or dividing
  - Difficulty putting language to math processes
  - Difficulty understanding concepts related to time such as days ,weeks, moths, seasons, quarters, etc.
  - Difficulty organizing problems on the page, keeping numbers lined up, following through on long division problems
- Cognitive difficulties may further include visual-spatial deficits or deficits in working memory or attention.
- High comorbidity with ADHD and Dyslexia
- No medications available.
- Rate of publications on Dyslexia versus Dyscalculia 14:1

Diagnosing dyscalculia

- Common diagnostic criteria include:
  - Divergence between IQ and standardized mathematics tests
  - Assignment to special educational programs
  - Percentile rank below 25th percentile

Diagnosing dyscalculia

- Diagnostic criteria not as clear as for other developmental disabilities (?)
- Most likely various subtypes of dyscalculia
- For example, a person who has trouble processing language will face different challenges in math than a person who has trouble with visual-spatial relationships. Another person may have trouble remembering facts and keeping a sequence of steps in order. This person will have yet a different set of math-related challenges to overcome.
- For individuals with visual-spatial troubles, it may be hard to visualize patterns or different parts of a math problem. Language processing problems can make it hard for a person to get a grasp of the vocabulary of math.

National Center for Learning Disabilities

Warning signs of dyscalculia

Young Children	School-Age Children	Teenage and Adults
• Difficulty learning to count • Trouble recognizing printed numbers • Poor memory for numbers • Difficulty organizing shapes	• Learning math facts (addition, subtraction, multiplication, division) • Difficulty developing math problem-solving skills • Difficulty with math vocabulary • Difficulty measuring things	• Difficulty estimating costs like groceries bills • Difficulty learning math concepts beyond the basic math facts • Poor ability to budget or balance checkbooks • Difficulty with concepts of time

NUMERACY SCREENER

HOME | ABOUT THE TEST | GET YOUR SCORE | USERS | ABOUT US

Background

A wealth of evidence shows that children's ability to understand numerical magnitude (quantity) is a critical building block of early math skills. Numerous studies have shown that children who are faster and more accurate at comparing which of two numbers is larger are also those that perform better on standardized measures of math achievement, such as tests of arithmetic achievement. For a review see De Smedt et. al 2013. There is evidence showing that both the ability to compare numbers that are presented as symbols (e.g. the Arabic Numerals; 1,2,3...) and non-symbolically (e.g. clouds of dots or collections of objects) is related to individual differences in children's present and future math skills. *For example:*

It should be noted, however, that there is more consistent evidence for an association between symbolic numerical magnitude comparison performance and arithmetic skills than there is for a relationship between non-symbolic processing abilities and calculation abilities.

Most of the current evidence showing the importance of early numerical magnitude processing skills has come from tests that are run on a computer. The motivation behind designing the numeracy screener was to build a simple paper-and-pencil tool that could be

http://www.numeracyscreener.org

Central theories of Dyscalculia

- Four hypotheses grounded in cognitive theory have been proposed to characterize core deficits of dyscalculia.
- Domain-specific processes: non-symbolic and symbolic representations of quantity.
- Domain-general processes: working-memory or attention.

1. Core deficit in processing quantity (core deficit perspective)?

- Dyscalculia as a core deficit in processing quantity and number sense, the inability to make judgments about quantity and to reason with symbolic representations of quantity.
- Compared to typically developing children, children with dyscalculia have lower than expected abilities in quantity estimation and abnormal magnitude representations.
- Preschoolers with a strong intuitive sense of quantity, score higher on mathematics achievement tests than other children, controlling for intelligence, effortful control, and preliteracy knowledge.
- Preschoolers at high risk for a learning disability in mathematics have a poor intuitive sense of quantity, and their poor understanding of more and less, and slow learning of Arabic numerals, number words, and their meanings may constitute a stronger long-term risk.

(summarized in Ashkenazi et al., 2013)

Developmental Dyscalculia

Lack of understanding numerical magnitude

→

Difficulties to learn the meaning of numerical expressions and their maintenance in memory

DEVELOPMENT

(Slide: D. Ansari)

An integrative theory of numerical development (Siegler & Lortie-Forgues, 2014)

Four major acquisitions during time course of development:

Representing magnitudes of nonsymbolic numbers increasingly precisely

↓

Linking nonsymbolic to symbolic representations of numerical magnitudes

↓

Extending understanding to increasingly large whole numbers whose magnitudes can be represented accurately

↓

Representing accurately the magnitudes of numbers other than whole Numbers (fractions, decimals, negatives)

2. Specific impairment in symbolic processing?

- Weakness in automatically mapping symbols to their internal magnitude representations, reflecting a specific impairment in symbolic processing that does not affect nonsymbolic processing (Rousselle & Noël, 2007; Rubinsten & Henik, 2005).
- Individuals with dyscalculia have difficulties in the comparison of numbers but not the length of sticks (Rousselle & Noël, 2007) and have weakness in the automatic association between number and quantities but intact automatic association between size and quantities (Rubinsten & Henik, 2005).

(Ashkenazi et al., 2013)

An integrative theory of numerical development (Siegler & Lortie-Forgues, 2014)

Four major acquisitions during time course of development:

Representing magnitudes of nonsymbolic numbers increasingly precisely

↓

Linking nonsymbolic to symbolic representations of numerical magnitudes

↓

Extending understanding to increasingly large whole numbers whose magnitudes can be represented accurately

↓

Representing accurately the magnitudes of numbers other than whole Numbers (fractions, decimals, negatives)

3. Domain-general deficit in working memory and attention?

- Domain-general phenomenon involving working memory, rather than as a specific deficit in number processing.
- Individuals with dyscalculia often have deficits in the use of developmentally appropriate arithmetic procedures, impairments that have been attributed to weaknesses in working memory rather than to specific deficits in number sense.
- In further support of a domain-general hypothesis, a meta-analysis examining 28 studies of children with dyscalculia indicated that the MD groups consistently demonstrated visuospatial and verbal working memory deficits.

(summarized in Ashkenazi et al., 2013)

4. A "hybrid hypothesis"

- Impairment both in representing and manipulating numerical magnitude on an internal number line <u>and</u> in working memory and attention, cognitive processes that are not specific to number processing.
- Deficits in any of these nonmathematical processes should be reflected not only in impaired math skills but also in poor reading and learning abilities.
- Hypothesis predicts subgroups of dyscalculia that present isolated difficulties in number sense as well as difficulties with word problems. Consistent with this model, it has been suggested that two thirds of children with dyscalculia have comorbid DD, whereas one third have "pure" dyscalculia.
- Number processing and mathematical problem solving is built on multiple neurocognitive components that are implemented by distinct and overlapping brain systems. Impairments in any of these components can compromise efficiency of numerical problem solving skills.
- Heterogeneity and comorbidities observed in dyscalculia are a natural consequence of such a multicomponent system.

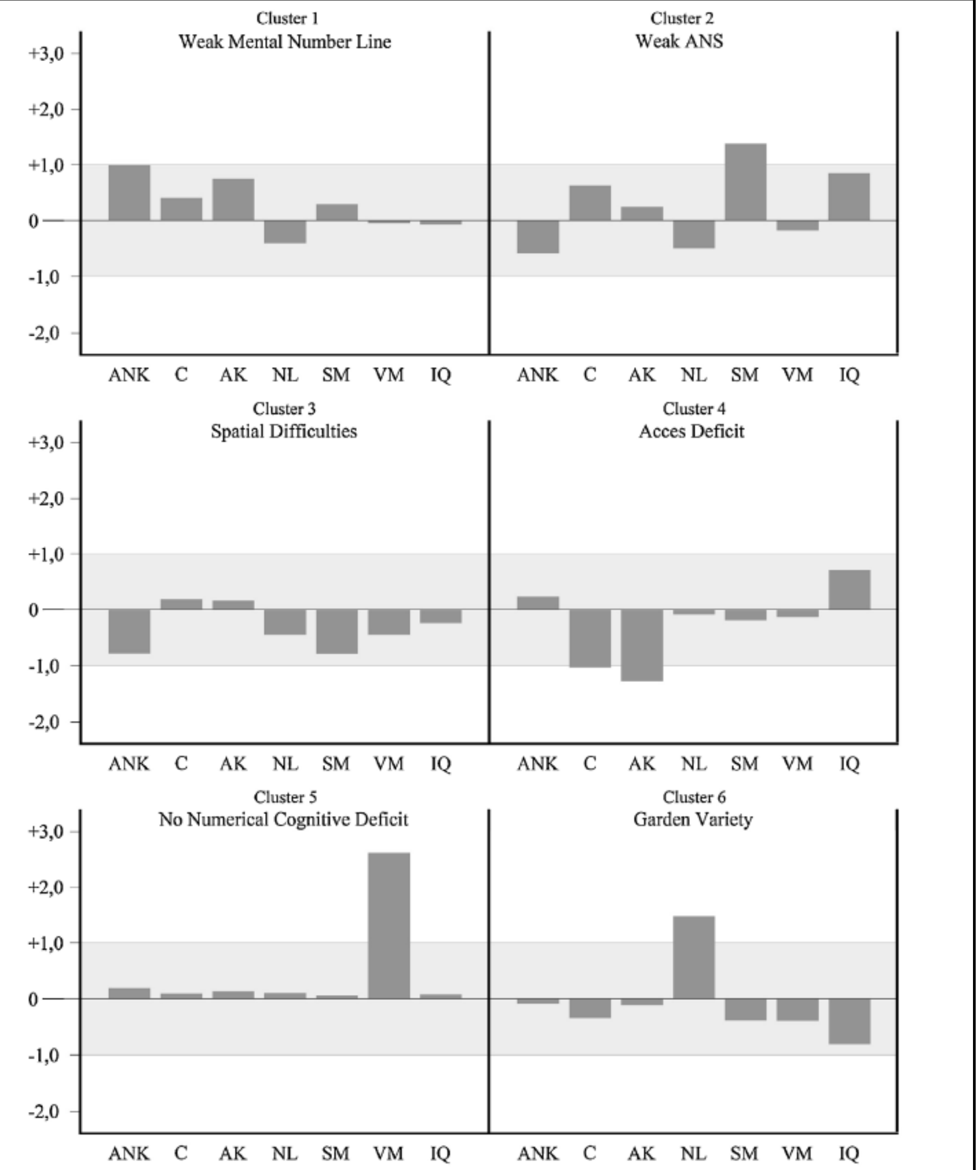
(summarized in Ashkenazi et al., 2013)

Cognitive subtypes of mathematics learning difficulties in primary education

Dimona Bartelet [a,*], Daniel Ansari [b], Anniek Vaessen [c], Leo Blomert

Six Cogntive Subtypes:

- Weak Mental Number Line
- Weak ANK (ANS)
- Spatial difficulties
- Access deficit
- No numerical cognitive deficit
- Garden-variety



Note. ANK = approximate numerical knowledge, C = counting, AK = Arabic numeral knowledge, NL = number line, SM = spatial short-term working memory, VM = verbal short-term working memory, IQ = nonverbal IQ.

Visuo-spatial working memory or deficit in quantity estimation?

- Visuo-spatial working memory strongly predicts ANS accuracy in incongruent trials.
- Highlights role of visuo-spatial working memory and perceptual processes during ANS task

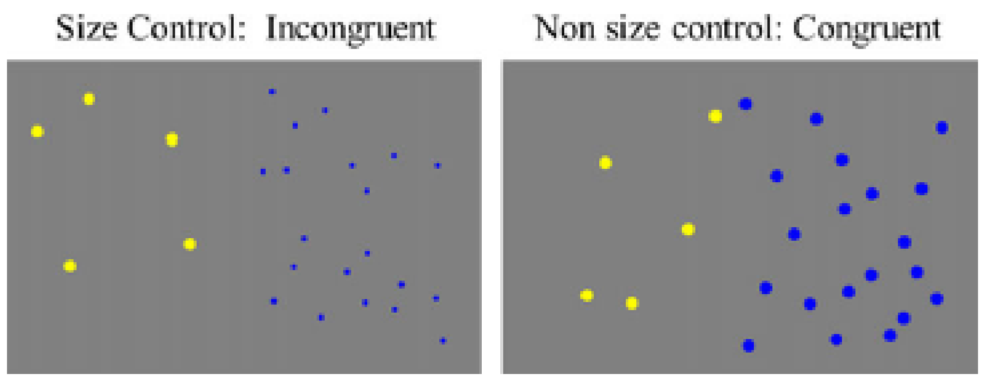
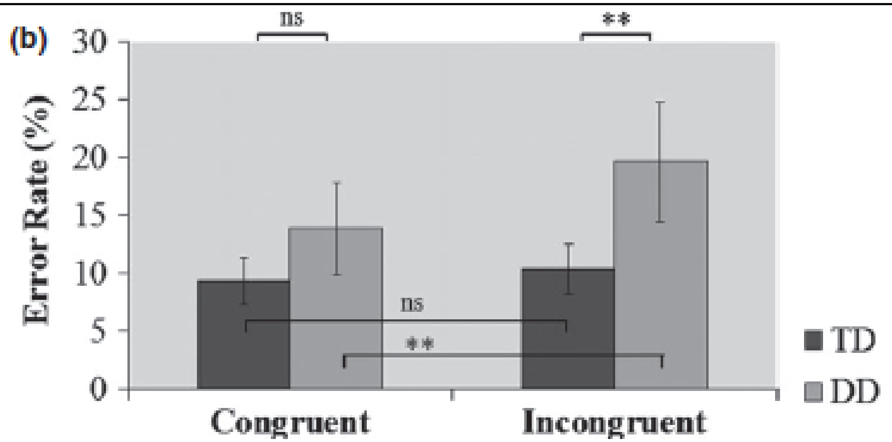


Figure 3 *An example of incongruent and congruent stimuli administered in the Panamath task.*



(Bugden & Ansari, 2015)

Overview

- What is ‘Number sense” ?
- The ‘distance/ratio effect’
- What do infants know about numbers/systems of number representations?
- The typical mathematical brain
- What is Developmental Dyscalculia?
- The atypical mathematical brain

Atypical mathematical brain

- Inferior Parietal Sulcus as a major locus of deficits in children and adults with dyscalulia (Cohen Kadosh et al., 2007; Kaufmann, Vogel, Starke, Kremser, & Schocke, 2009; Mussolin, DeVolder, et al., 2010; Price et al., 2007).
- Children with dyscalculia show atypical functional activation in the IPS during basic numerical processing whether the task requires the use of symbolic(Arabic digits) or nonsymbolic (sets of objects) stimuli (Price et al., 2007; Mussolin et al.,).
- This suggests that the behavioral deficits in dyscalculia may stem not just from an impairment in accessing numerical magnitude representation through Arabic digits, but that the representation itself may be compromised.

(Price & Ansari, 2013)

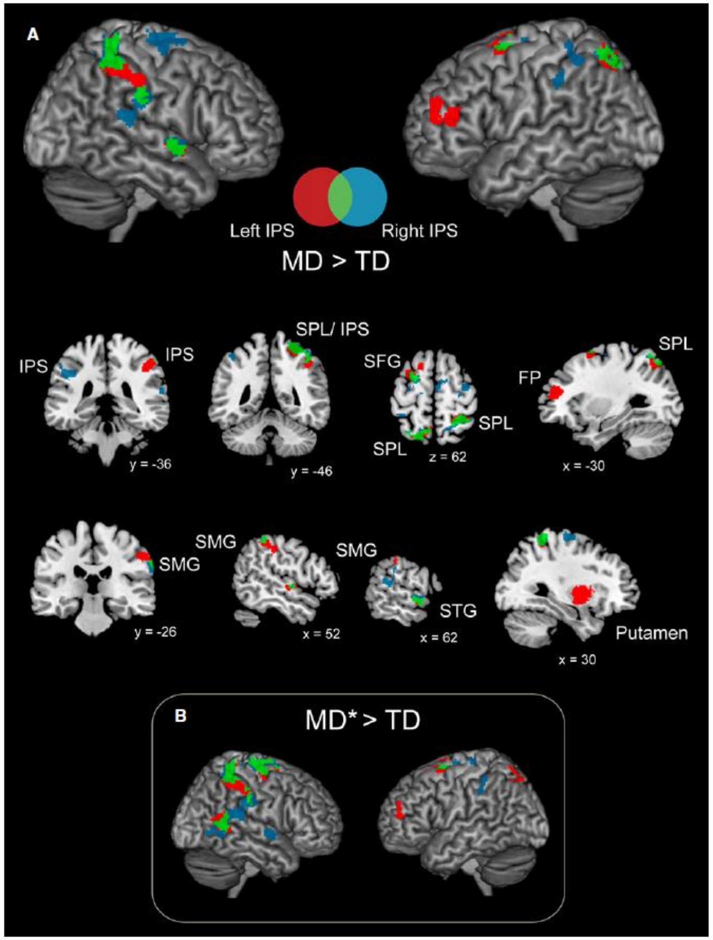
The model of IPS deficiency – a gross oversimplification?

- Individuals with dyscalculia show deficits in a distributed, but interconnected set of brain regions that includes the bilateral IPS and fusiform gyrus in posterior brain regions and the PFC.
- In typical developing children, the role of these areas varies according to the developmental stage and the nature of the numerical task performed, with more mature function characterized by decreased engagement of the PFC and increased engagement of posterior brain areas.
- The extent to which children with dyscalculia show systematic variation in patterns of brain responses and connectivity as a function of age, instruction, and intervention is at present unclear and is an important topic of ongoing research.

Fias et al., 2013

Parietal hyper-connectivity, aberrant brain organization, and circuit-based biomarkers in children with mathematical disabilities

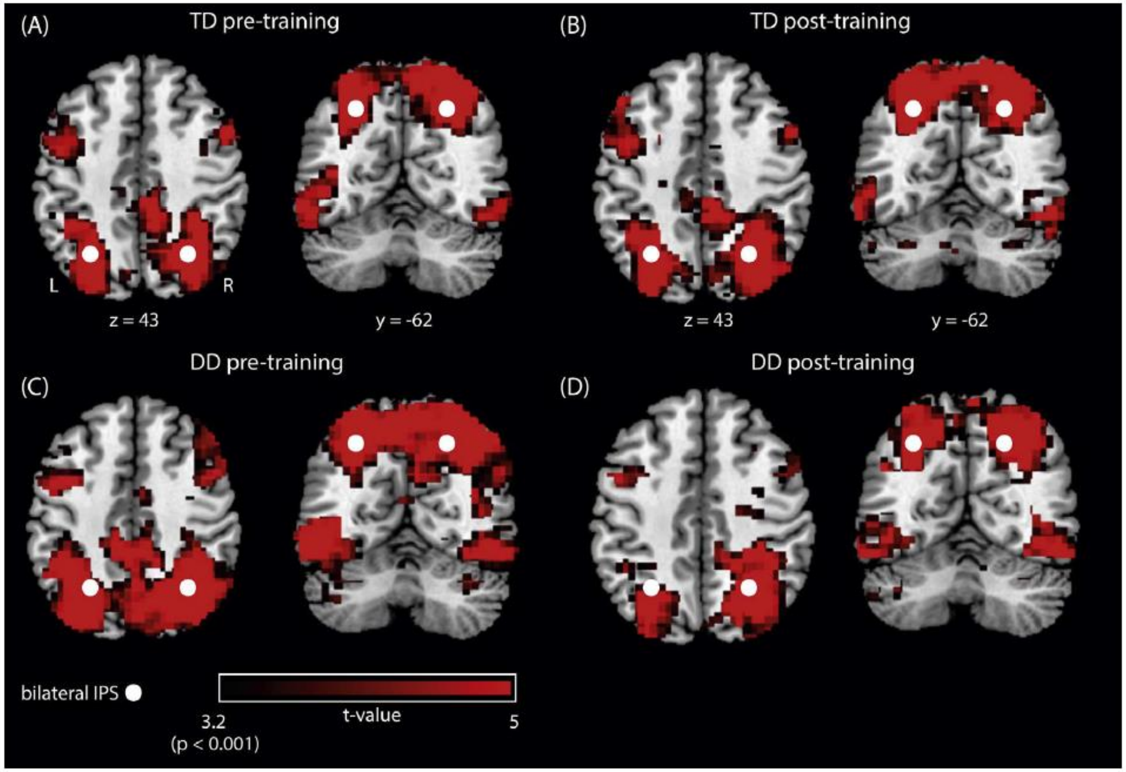
Dietsje Jolles,[1,3,*] Sarit Ashkenazi,[1,4,*] John Kochalka,[1] Tanya Evans,[1] Jennifer Richardson,[1] Miriam Rosenberg-Lee,[1] Hui Zhao,[1] Kaustubh Supekar,[1] Tianwen Chen[1] and Vinod Menon[1,2]



Functional hyperconnectivity vanishes in children with developmental dyscalculia after numerical intervention

Lars Michels[a,b,c,*], Ruth O'Gorman[b,c], Karin Kucian[b,c,d]

[a] *Clinic of Neuroradiology, University Hospital Zurich, Switzerland*
[b] *Center for MR-Research, University Children's Hospital Zurich, Zurich, Switzerland*
[c] *Children's Research Center, University Children's Hospital Zurich, Zurich, Switzerland*
[d] *Center for Neuroscience Zurich, University and ETH Zurich, Zurich, Switzerland*



Arithmetic processing deficits in dyscalculia

- Poor fluency in retrieval of arithmetic facts is one of the most prominent difficulties in children with dyscalculia (Geary, 2004).

- Typical developing children, typically during the second and third grades, show a rapid shift in the distribution of strategies toward greater use of direct retrieval in solving simple arithmetic problems (Ashcraft & Fierman, 1982; Carpenter & Moser, 1984; Geary, 1994; Siegler, 1996).

- In contrast, children with dyscalculia demonstrate poorer performance and continue to use less mature strategies, such as finger counting, to solve arithmetic problems (Geary, 1993; Shalev, Auerbach, Manor, & Gross-Tsur, 2000).

- Only a handful of brain imaging studies has examined the neural basis of arithmetic deficits in dyscalculia. Aberrant activity in IPS has also been implicated as the primary deficit underlying atypical development of arithmetic problem solving in individuals with dyscalculia (Butterworth et al., 2011).

(Ashkenazi et al., 2013)

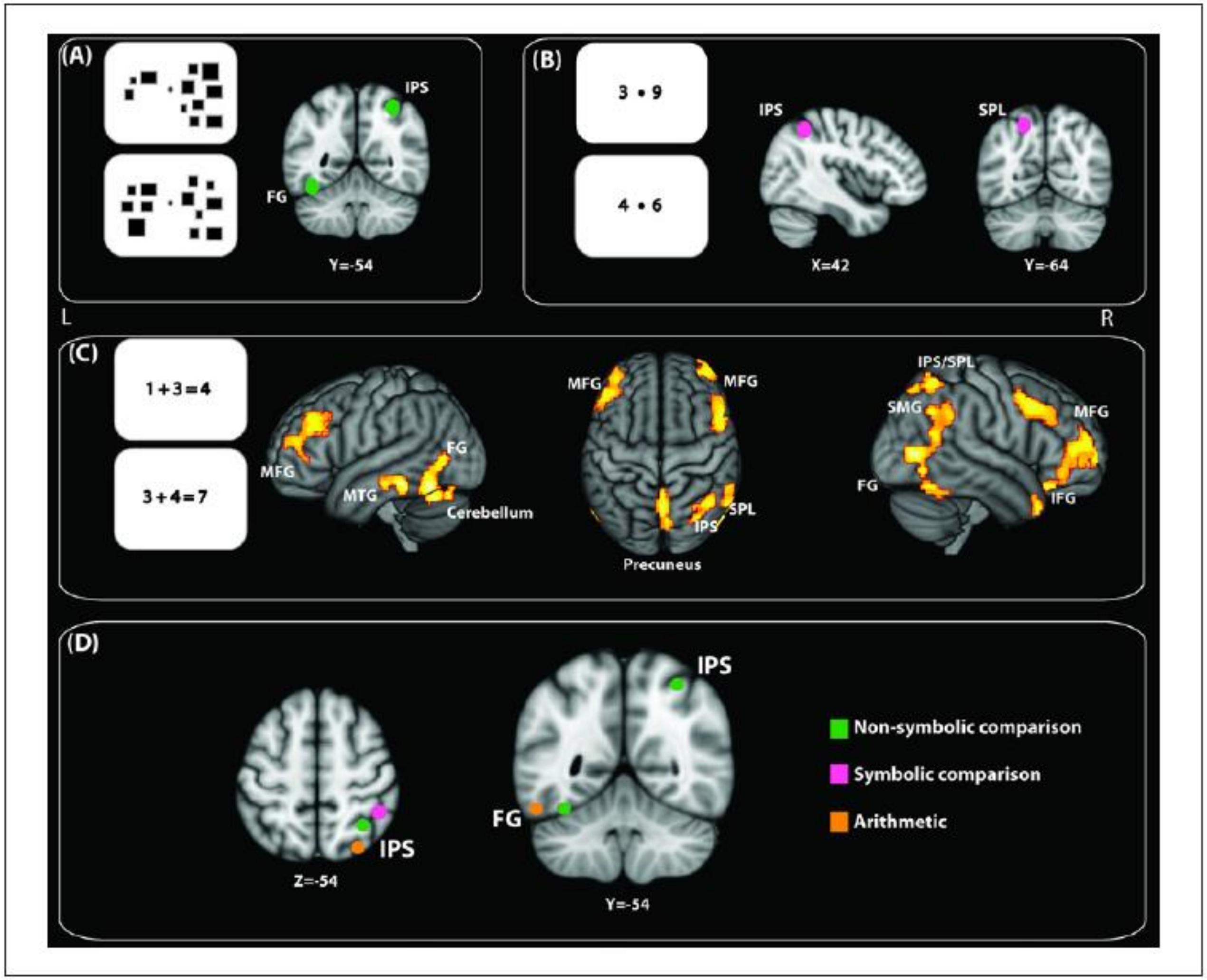
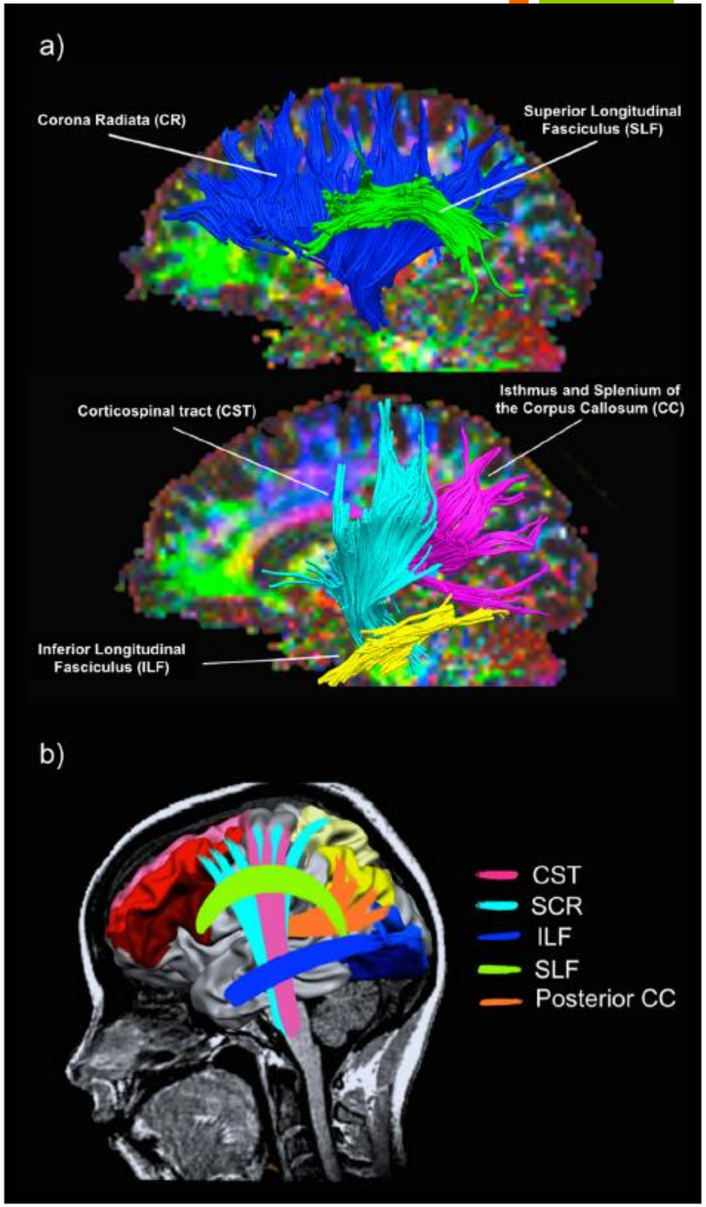


Figure 3. Aberrant functional brain responses during numercial tasks in MD. Brain regions that show decreased activation in MD relative to TD during (A) non-symbolic comparsion (Price et al. 2007), (B) symbolic comparison (Mussolin et al. 2010), and (C) an arithmetic problem solving task (Ashkenazi et al. 2012). Task paradigms are presented on the left in panels A, B, and C, with numerically "easy" tasks on top and numerically "difficult" tasks on the bottom. All studies in panels A through C found reduced activity in children with MD related to the difficulty of the tasks. (D) Summary of anatomical locations of brain regions highlighted in panels A through C. FG: Fusiform gyrus, IFG: Inferior frontal gyrus, IPS: Intraparietal sulcus, LOC: lateral occipital cortex; MFG: Middle frontal gyrus, MTG: Middle temporal gyrus , SPL: Superior parietal lobule.

(Ashkenazi et al., 2013)

White matter tracts associated with numerical and mathematical processing

- Impairments in mathematics tend to be associated with atypical white matter structures within similar regions, especially in inferior parietal and temporal tracts.



(Matejko & Ansari, 2007)

Typical and Atypical Development of Number Concept and Mathematical Skills

H-126 Typical and Atypical Neurodevelopment
October 30th, 2017

‘The knowledge of mathematical things is almost innate in us…This is the easiest of sciences, a fact which is obvious in that noone’s brain rejects it; for laymen and people who are utterly illiterate know how to count and reckon.’
Roger Bacon (c. 1219–1294)