Neurocognitive mechanisms of number processing and developmental dyscalculia

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"All science requires mathematics. The knowledge of mathematical things is almost innate in us... This is the easiest of sciences, a fact which is obvious in that no one's brain rejects it; for laymen and people who are utterly illiterate know how to count and reckon."

Roger Bacon (1214-1294)

Roger Bacon's statement was perhaps a valid judgment of the importance of mathematics and its innate nature, but certainly a poor prediction of what happens in education.

Math is hard to learn for quite a few children and adults. Deficiencies in math are not rare.

Plan of the talk

Mental processes and effects.

The neurocognitive basis of these mental processes.

Developmental Dyscalculia – DD,

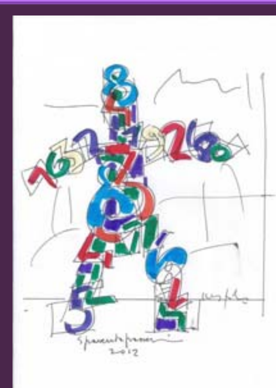
Heterogeneity in DD.

Size and amount.

Summary and conclusions.

Mental processes

Mental processes and effects:



Subitizing and counting

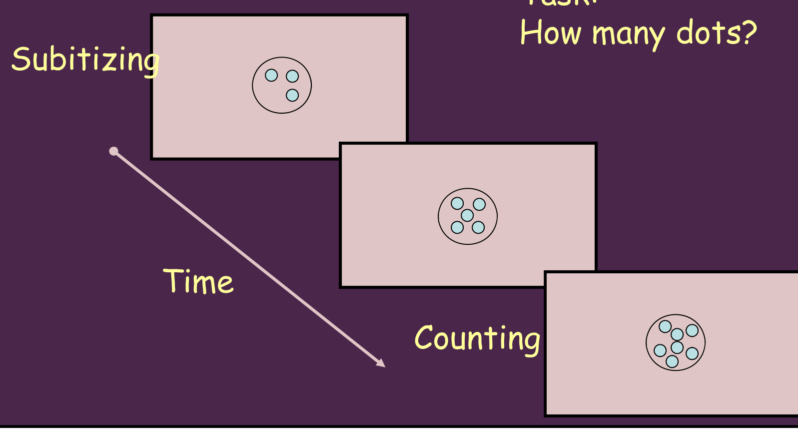
The distance effect

Automaticity of numerical processing – the size congruity effect

Mental processes

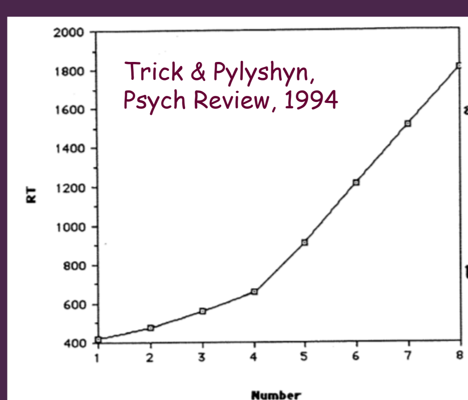
Subitizing & counting

Task:
How many dots?

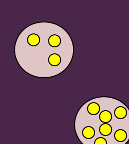


Mental processes

Task:
How many dots?

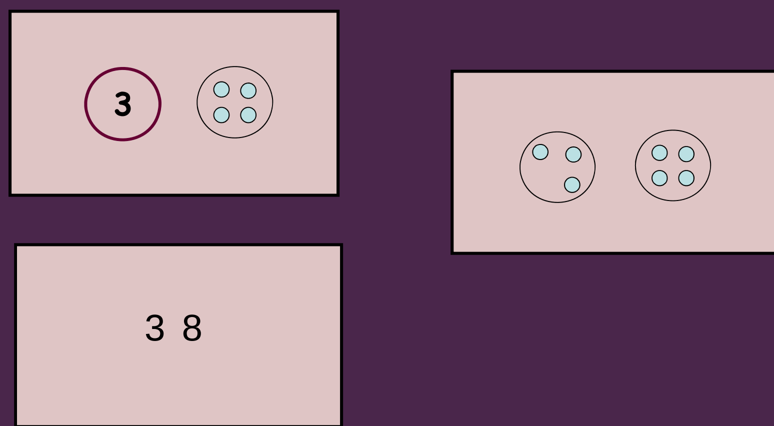


When there are 4 or fewer items, the slope of the function is shallow; each additional item may add 40-100 ms. When there are more than 4 items, the slope jumps by 250-350 ms/item.



Mental processes

Comparative judgment

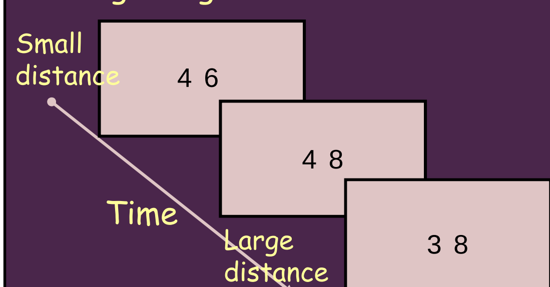


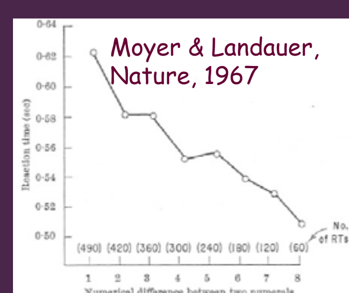
Mental processes

The distance effect

Increase in distance produces faster responding

Task:
Which is the larger digit?





Mental processes

Automaticity: The size congruity effect

Task:
Which is the larger digit?

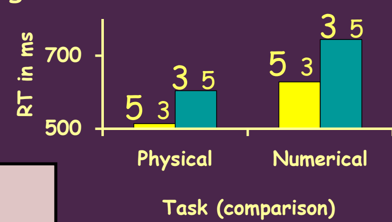
Results:
Incongruent trials produce slower responding

Congruent 4 6

Neutral 4 4

Incongruent 3 8

Time



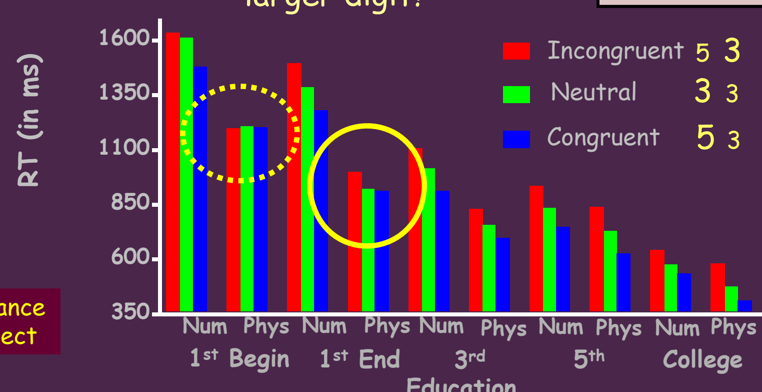
Henik & Tzelgov, Memory & Cognition, 1982 (Exp. 2)

Mental processes

Development of facilitation and interference

3 8

Which is the larger digit?

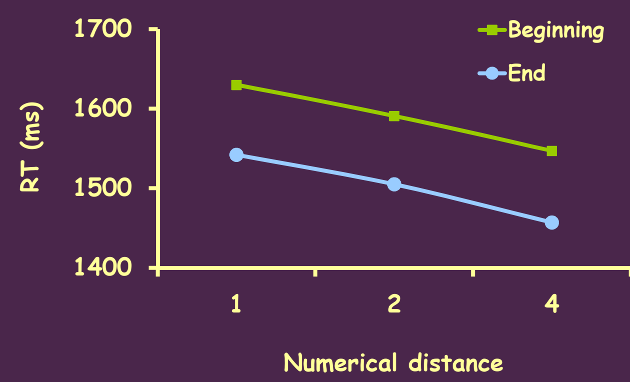


Distance effect

Rubinsten et al., JECP, 2002

Mental processes

Distance effect first grade



Rubinsten et al., JECP, 2002

Neurocognitive basis

What was found regarding these mental processes?

Infant research

Animal studies

Brain tissue - neurologically intact individuals

Acquired acalculia

Neurocognitive basis

Infants

ALU2

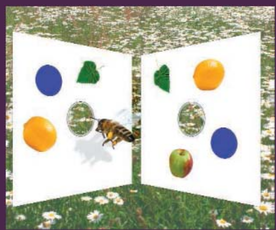
Infants can discriminate between sets of objects. This ability obeys Weber's Law.

For example, at 6 months of age infants successfully discriminate values that differ by a 1:2 ratio (e.g., 4 vs. 8; 8 vs. 16) but fail to discriminate when the ratio is 2:3 (e.g., 4 vs. 6; 8 vs. 12).

Neurocognitive basis

Numerical processing in animals

Animals use a nonverbal ability to approximate numbers (numerosity), to guide decisions on where to forage, when to flee from predators, and whether to fight intruders.



Gross et al., PlosOne, 2009

Responding of female lions to a perceived threat.
McComb et al., Animal Behaviour, 1994

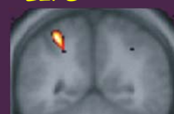
Female mosquito fish.
Agrillo et al., Animal Cognition, 2008

Neurocognitive basis

Neurologically intact participants

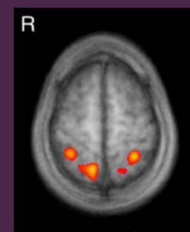
Comparative judgment

LIPS



Fias et al., JoCN, 2003

Bilateral IPS



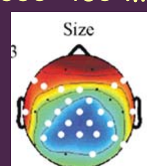
Ansari et al., Brain Res., 2006

Size congruity

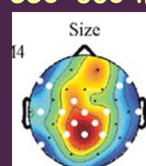
Cohen Kadosh et al., JoCN, 2007

Interference

330-460 ms

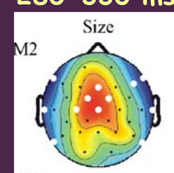


550-660 ms



Facilitation

280-330 ms



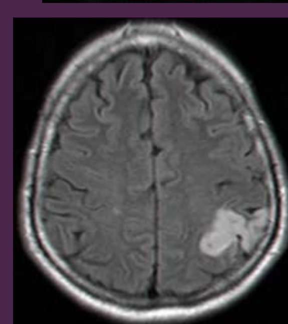
Szucs & Soltesz, Neuropsychologia, 2007

Neurocognitive basis

Acquired acalculia

AD, Engineer, 67 years old.
On a Friday evening while watching TV he felt numbness in his right arm. An MRI scan revealed a lesion in the left IPS.
He suffered from dysgraphia and acalculia. Most signs of the dysgraphia disappeared after several days.
He was released from the hospital after two days and went back to work after a week.
The current work was conducted six months following the incident.

Ashkenazi et al., Cortex, 2008



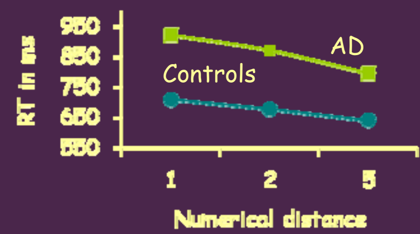
Neurocognitive basis

AD comparative judgment

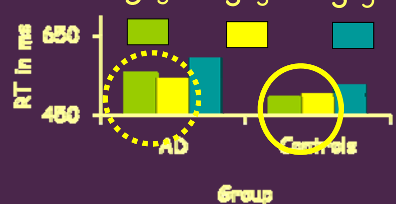
ALU3

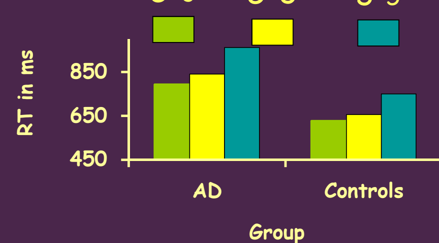
3 8

Numerical comparisons



Physical comparisons





Ashkenazi et al., Cortex, 2008

DD

Developmental dyscalculia - DD

Developmental dyscalculia (DD) is an isolated problem due to number-specific underlying deficits.

Prevalence rates of developmental dyscalculia are 3.5% to 6.0%.

Compared with controls, DD participants show:

- Problems in execution of arithmetical procedures
- Difficulties in retrieval of arithmetic facts
- Immature problem-solving strategies (finger counting)

Deficits in DD

For many years studies have been directed at higher level, school-like concepts. For example:

poor working memory (Geary, 1993)

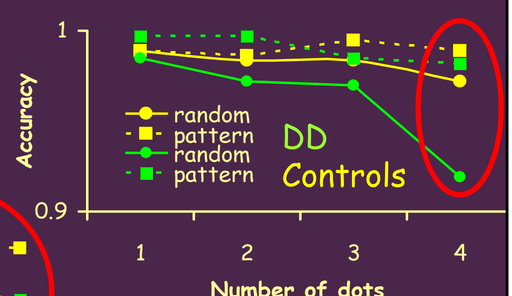
deficits in attention systems (Shalev et al., 1995)

disorder of visuo-spatial functioning (Bull et al., 1999)

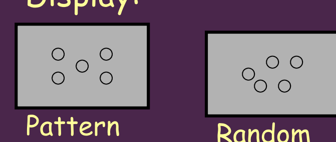
In recent years there has been a change toward identifying low-level deficits in DD, similar to successful work in developmental dyslexia.

Subitizing and counting in 3rd and 4th graders

Task:
How many dots did you see?

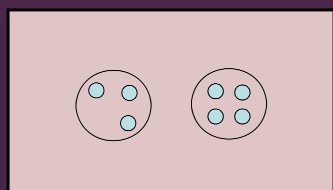


Display:

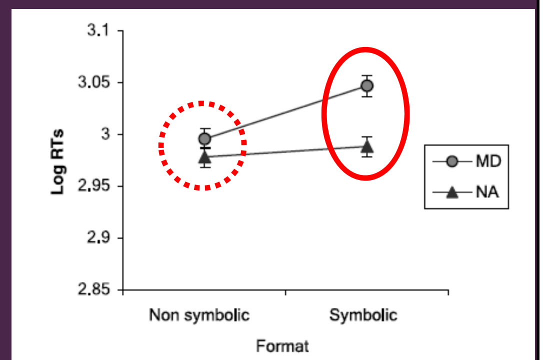


Ashkenazi et al., Dev Sci, 2013

Comparative judgment



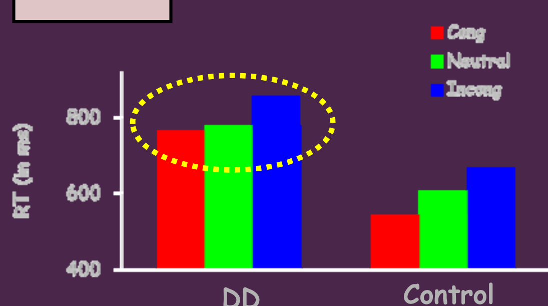
3 8



Rousselle & Noel, Cognition, 2007

Facilitation and interference in DD participants and controls

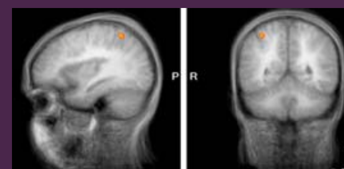
3 8



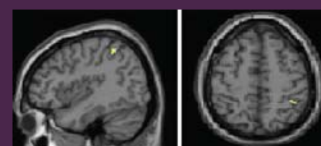
Rubinsten & Henik, Neuropsychology, 2005

DD

Parietal involvement in DD



Right IPS showed a stronger distance effect in the control than the DD group.
(used squares - non symbolic)
Price et al., Current Biology, 2007



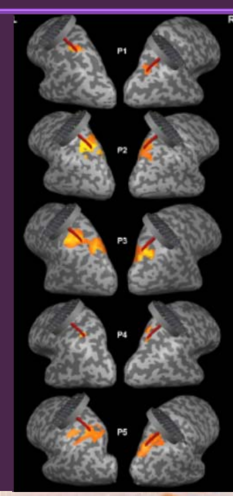
Right IPS

Right IPS and left superior parietal lobule (SPL) showed greater activation in control than in DD children.
(used digits – symbolic)
Mussolin et al., JoCN, 2009

Left SPL

DD

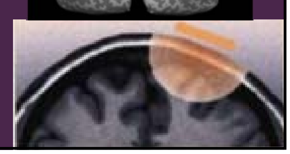
fMRI-TMS study of size congruity



fMRI – Size congruity ALU4

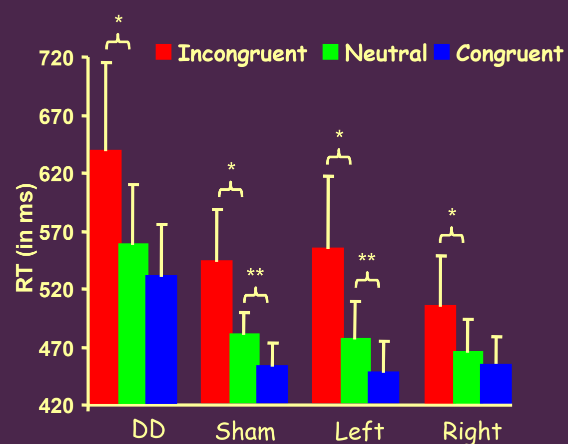
In the four TMS sessions (left IPS, right IPS, and left & right sham), participants underwent event-related triple-pulse TMS while performing the size congruity task.

Pulses were applied 220, 320, and 420 ms after stimulus presentation.



DD

TMS



* 0.05

** 0.005

Cohen Kadosh et al., Current Biology, 2007

DD

Interim conclusions

- People suffering from DD show deficiency in basic numerical abilities (e.g., subitizing, distance effect, the association of numerical symbols and quantities).
- The numerical deficiency in DD could be due to IPS abnormality. ALU5

Hetero-geneity

The presentation so far could lead to the view of:

An innate, domain-specific foundation of arithmetic.

Arithmetic disability involves a domain-specific deficit.

However

Several findings suggest that this view needs to be examined carefully.

Hetero-geneity

Arithmetic seems to rely on both domain-specific and domain-general abilities.

Examples for domain-general abilities are:

Attention

ALU6

Working memory

Executive functions

Hetero-geneity

DD could be characterized by deficits in other areas:

Associating symbolic and non-symbolic events (e.g., Rubinsten & Henik, 2005; Rousselle & Noël, 2007; Noël & Rousselle, 2011).

Attention (e.g., Ashkenazi & Henik, 2010a, 2010b).

Working memory (e.g., Rotzer et al., 2009; Geary, 2004; Geary et al., 1992; Gross-Tsur et al., 1996).

Hetero-geneity

Brain structures other than the IPS are involved in DD:

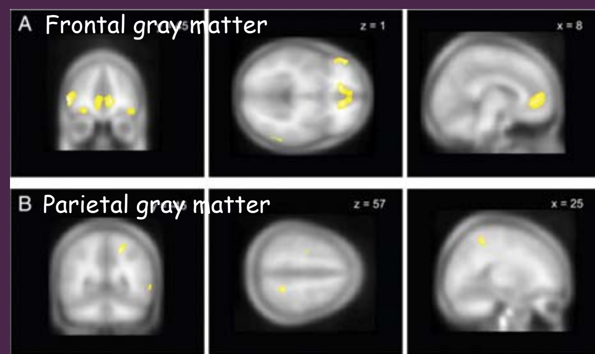
Frontal lobes (e.g., Rotzer et al., 2008; Ashkenazi et al., 2012).

Activation differences between children with and without DD were observed not only in parietal regions but also in the frontal and occipital cortex (meta-analysis by Kaufmann et al., 2011).

Hetero-
geneity

Involvement of frontal structures

Twelve children with DD and 12 typically developing age-matched controls.

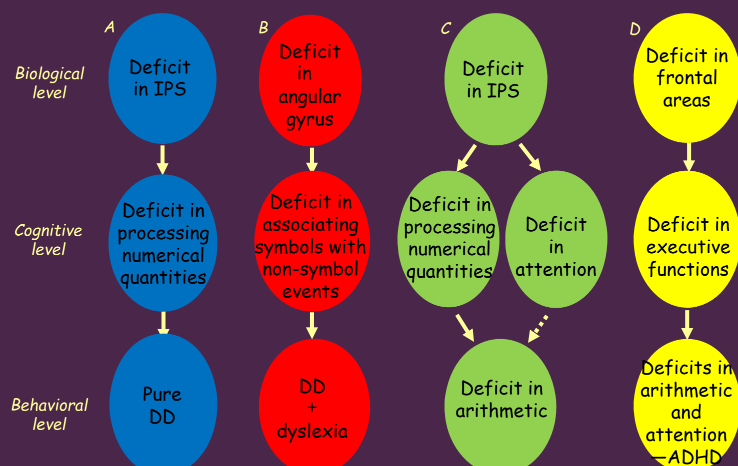


Rotzer et al., NeuroImage, 2008

Voxel-based morphometry showed reduced gray and white matter in DD participants in right IPS and bilateral frontal areas.

Hetero-
geneity

Possible manifestations of DD



Rubinsten & Henik, TICS, 2009; Henik et al., The Oxford Handbook of Mathematical Cognition, 2014

A numerical core system: domain-specific foundations of arithmetic

As reviewed earlier, quite a few researchers have suggested that enumeration is the foundation of arithmetic and its proper development.

(e.g., Butterworth, TICS, 2010)

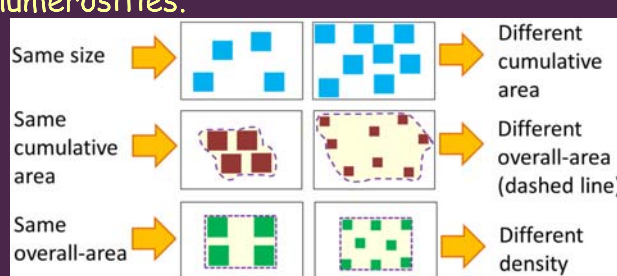
Ansari, Nat Rev Neuro, 2008

However

ALU7

Numbers are intimately associated with sizes and other non-countable dimensions (e.g., area, brightness).

Moreover, arrays of items (used to study numerosity) always carry continuous properties that highly correlate with numerosities.



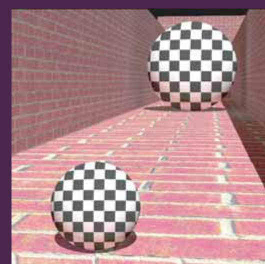
Leibovich & Henik, Frontiers Psych, 2013

Size & amount

Size is a basic feature of objects.

Perceived size (not only retinal size) modulates activity in V1.

A distant object that appears to occupy a larger portion of the visual field activates a larger area in V1 than an object of equal angular size that is perceived to be closer and smaller.



Murray et al., Nature Neuroscience, 2006

Size & amount

The possible contribution of size perception

ALU8

We have recently suggested that a system designed to perceive size and evaluate continuous dimensions may contribute to the development of numerical cognition.

It is possible that such a system became accessible to other systems that enabled development of numerical cognition.

From size evaluation to counting

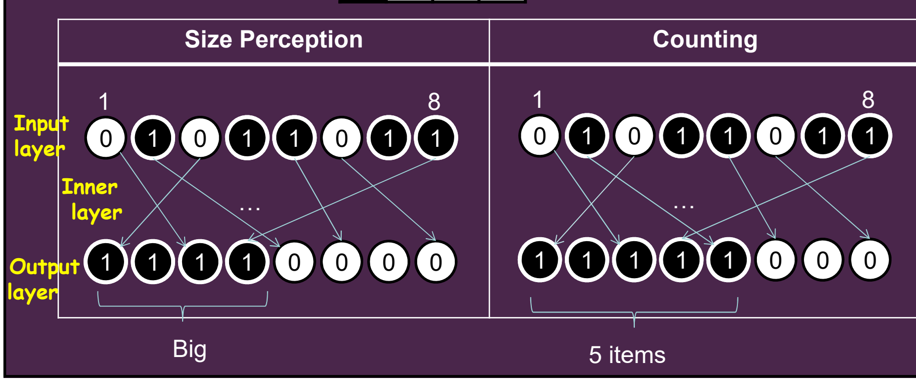
Would individuals who excel in size perception (classification) have an advantage in learning to count?

We use a branch of artificial intelligence termed *evolutionary computation* or *evolutionary algorithms* (EA). EA uses some mechanisms inspired by biological evolution (e.g., reproduction, mutation, recombination, and selection). Fitness function determines "survival" of individuals. Evolution of the population then takes place after the repeated application of the above operators.

We worked with artificial neural networks (ANNs), like the following, and evolved them to discriminate sizes ("Big/Small") and/or to enumerate (from 1 to 8).

Picture:
(image on retina)

BIG (5 pixels on and 3 off)



From size evaluation to counting

Our EA evolved the ANNs first to perceive size and then to count.

We compared those ANNs to a different group of ANNs that were evolved to count from scratch.

After the evolution simulation was done, both groups were tested in a counting test.

Preliminary results

It was much easier to learn size comparisons than to enumerate.

ANNs that started with size comparisons were better at learning to enumerate than ANNs that learned only to enumerate.

The different training methods created ANNs with different internal networks. Those that started with size comparisons were simpler (e.g., smaller number of inner nodes and connections).

Archer fish

We study Archer fish abilities to compare sizes and arrays of dots.

Fish have an optic tectum but lack fully developed cortical structures.

We selected this fish species because of its remarkable ability to shoot down insects found on foliage above the water level, and its ability to learn to distinguish between artificial targets presented on a computer monitor in an experimental setting.

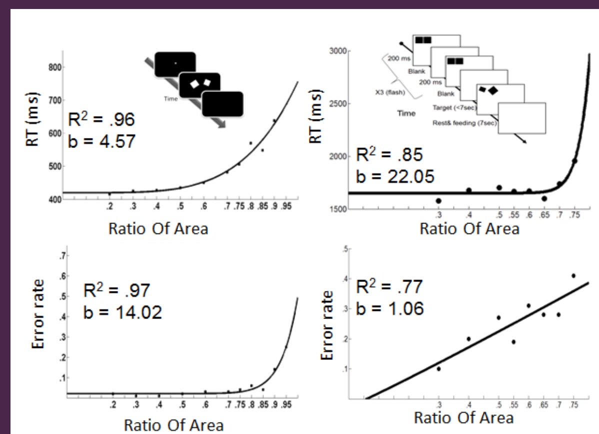
Who needs the parietal cortex?

From **BBC Weird Nature (3 of 6) Fantastic Feeding**

Size & amount

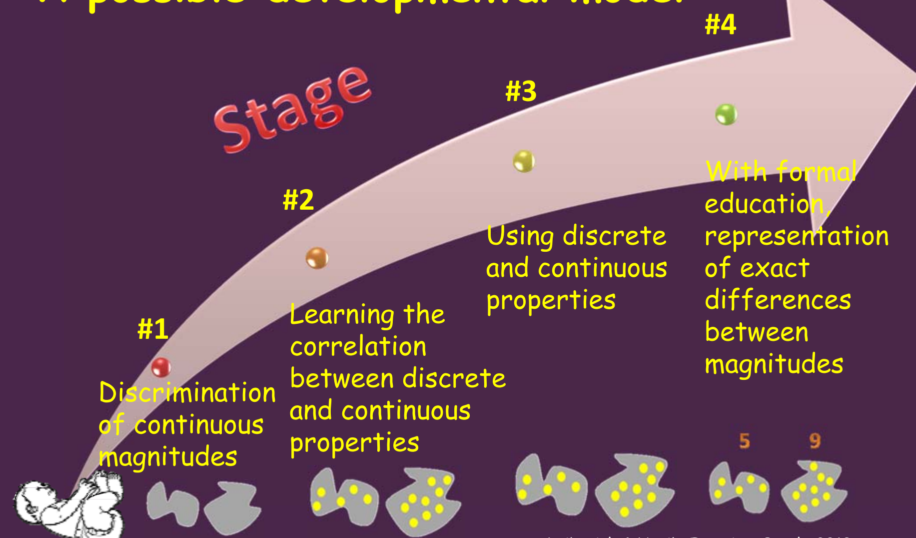
Lawful spitting

Humans | Fish



Size & amount

A possible developmental model



Leibovich & Henik, Frontiers Psych, 2013

Conclusions

We should be aware that homogeneity of symptoms is not as common as expected and heterogeneity of manifestations of a deficiency is not an exception.

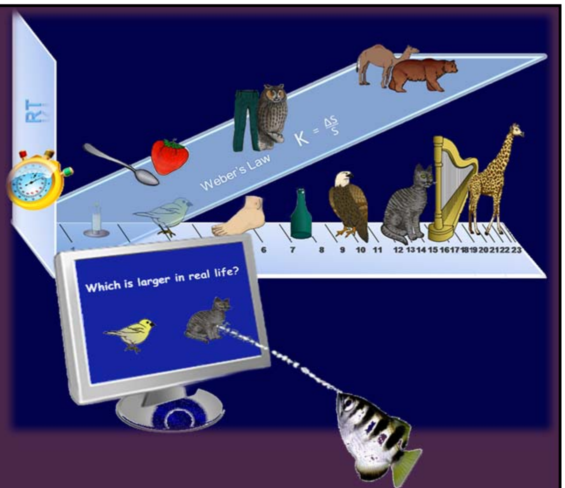
Core (common cause) deficits at the cognitive or brain level may show up as a network of symptoms even when there is a single deficit (e.g., a deficit in IPS).

A single deficit at the behavioral or cognitive level may produce, through development, a cascade of difficulties that may end up as a network of symptoms at the behavioral level.

Conclusions (continued)

Continuous (non-countable) dimensions play an important role in the development of numerical abilities.

Future research should reveal whether deficiency in evaluation and perception of sizes and amounts might be a core deficit in DD.

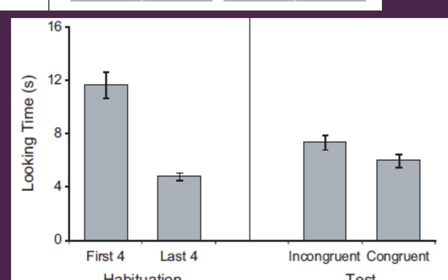


Thank you for your attention

Size congruity effect in 9-month-old infants

Arbitrary mapping between size and color-pattern (e.g., larger size: black with stripes; smaller size: white with dots).

Infants expected the same color-pattern mapping to hold for numerosity (i.e., greater numerosity: black with stripes; smaller numerosity: white with dots).



Lourenco & Longo, Psychological Science, 2010