COGNITIVE NEUROSCIENCE
Core Knowledge

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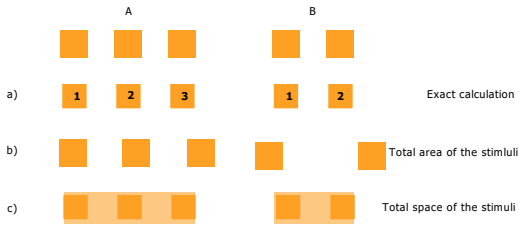
Core knowledge

Numbers

- The discrimination of relative numerosity
  - is the ability to establish that 2 sets of elements are not equal and to approximately discriminate their relative numerosity
  - is a protonumerical capability (Davis & Perusse, 1988)



Numbers

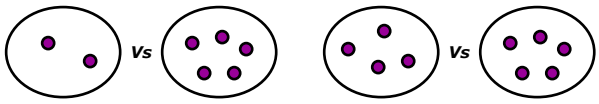
- How to control for extra-numerical variables?
  1. matching the area
  2. modifying the spatial position
  3. changing the nature of the stimuli (transfer)
  4. with a sequential presentation

Numbers

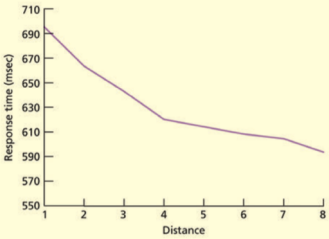
- Two effects rule the relative numerosity judgements

PRINCIPLE of the **NUMERICAL DISTANCE**

the larger the distance, the better the discrimination between the two magnitudes



Subject sees	3	6	9	8	2	7
Distance	3		1		5	

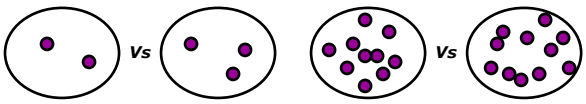


Numbers

- Two effects rule the relative numerosity judgements

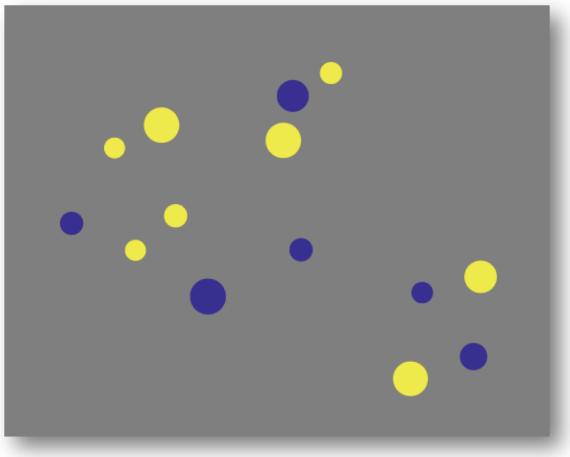
PRINCIPLE of the **NUMERICAL MAGNITUDE**

When the distance between two sets is kept the same, the discrimination get worse when the two sets have a larger number of elements that need to be compared to give an answer



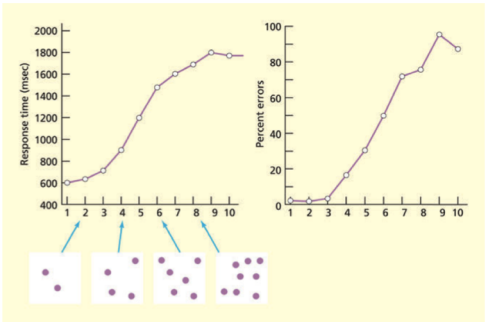
Numbers

- How many yellow dots?
  - There are 8 yellow dots
- Decide whether there are more blue or yellow circles
  - There are more yellow circles

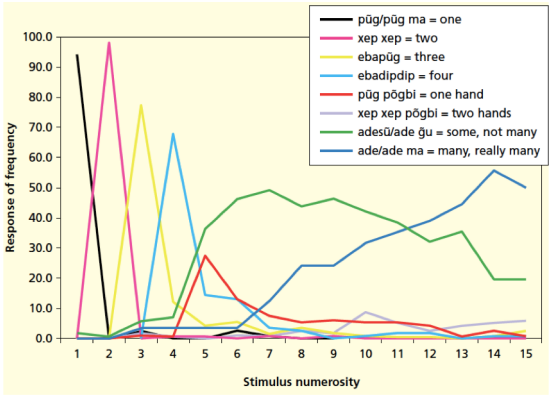


Numbers

- If you present a cloud of dots and you ask to count exactly how many
  - There is the need of some pairing with an internal standard (linguistic or not)
  - Usually we are fast with a few stimuli and we get slower when the elements increase (Mandler and Shebo, 1982)



Numbers

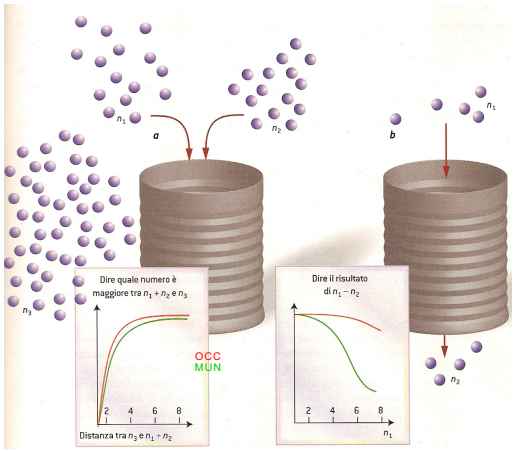


- Tribal populations with a limited lexicon for numbers and no formal mathematical training
  - Asked to name numbers of sets from 1 to 15 dots (in order to study how they use numbers and what names they have in their vocabulary)

Numbers

- **Estimation of magnitude (comparison)**: subjects were shown two clouds of dots and had to judge which of the two sets was larger
- **Approximate computation**: they were shown short video clips illustrating simple operations (20 seeds + 30) and the subject must say whether the total was more or less than another set (for example, of 40 seeds)
- **Computing with exact numbers:** they were asked to give the result of a precise mathematical operation (for example, 6 seeds minus 4 seeds)

Numbers



Pica et al., 2004

Numbers

- If they have to add 5 to 7 seeds, they choose an answer like "approx. a dozen" (meaning 11, 12 or 13) ➜ correct
- If they have to answer about distant numbers (i.e., to sum 8 to 20) they cannot answer in no way

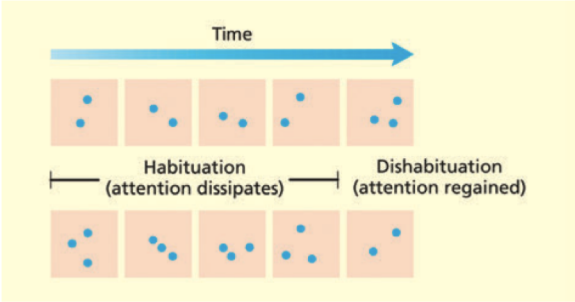
- There is a distinction between symbolic and non-symbolic representations:
  - The symbolic representations allow both the exact and approximate quantification
  - The non-symbolic representations allow an approximate quantification only

Numbers

- Macaques *vs.* Students
  - **Students provide the 94%** of correct answers
    average time for an answer: **1 sec**
  - **Macaques provide the 76%** correct answers
    average time for an answer: **1 sec**
  - Both groups suffered from too close alternatives (e.g. correct summation = 11; choice between 11 *and* 12)

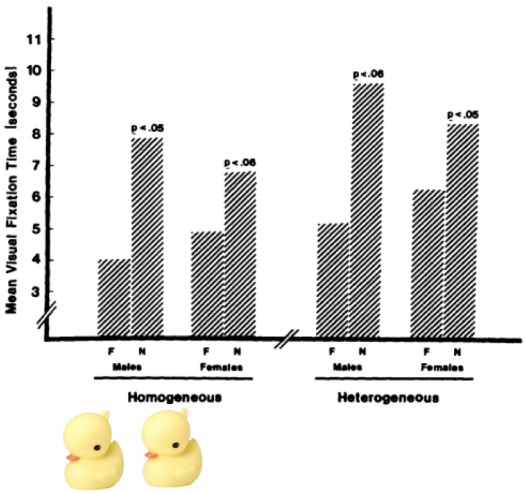
Numbers

- Antell and Keating (1983) tested 1 day old newborns



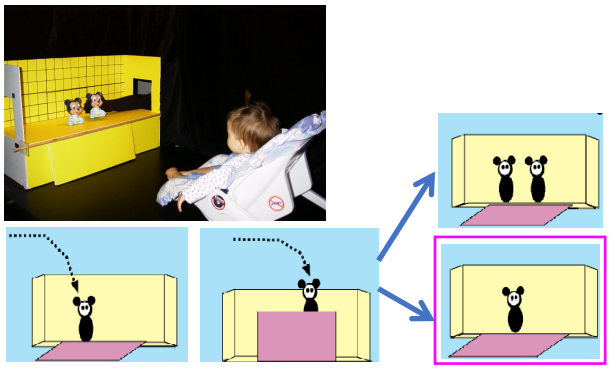
Numbers

- One alternative explanation for the results observed by Antell and Keating is the possibility that attention was regained by any new stimulus instead that the novel numerosity
- Strauss e Curtis (1981)

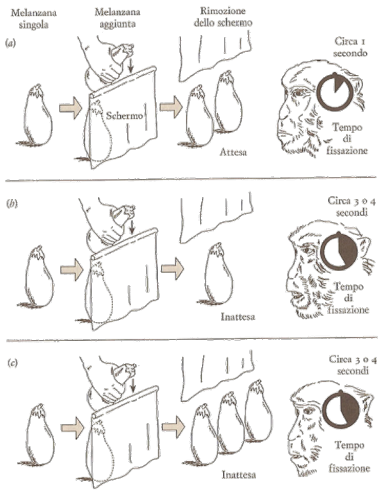


Numbers

- Wynn, 1992



Numbers



Numbers

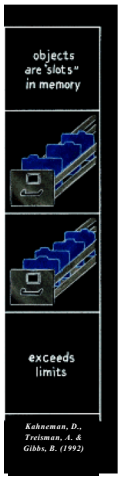
- In conclusion: The names of numbers are
  - neither essential to manage gross arithmetical concepts (quantities, more/less)
  - not important to run approximate estimations
- The names of numbers are important
  - to compute exact calculations with more than 4-5 elements
  - to number the elements in an automatic way

Numbers

- A sub-set of our core numerical abilities is shared with different species
  - human and non-human animals share a "core set" of abilities to compare non-verbally approximate numerosities
  - and to compute raw, non-verbal, arithmetic
- Indeed, when you prevent human participants to count explicitly, they can resort to use only an approximate system of magnitudes:
  - our non-verbal representation of numerosities is comparable to that of other species

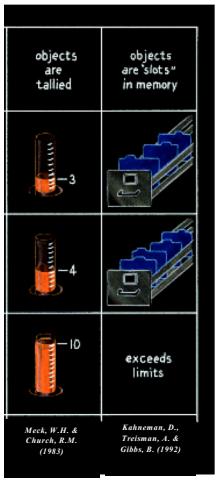
Numbers

- Two systems describe the core numerical cognition:
  - For SMALL NUMEROSTIES there is the OBJECT-FILE SYSTEM: each element is a symbol, there is a one-to-one equivalence for object-number (there is a mental image of each object)
  - Calculations are computed in parallel and are stored in a temporary storage system
  - It has limits:
    - It allows precise computatinos but has a limit of 3-4 units especially when groups differ of 1 unit only



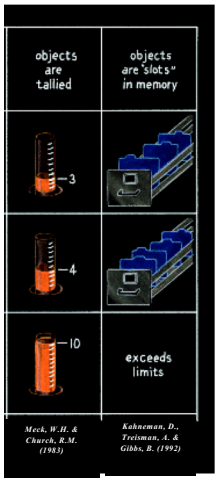
Numbers

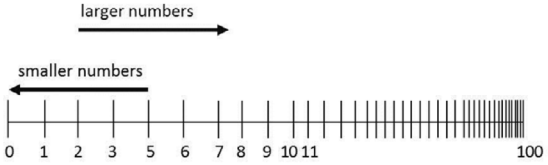
- For LARGE NUMEROSITIES there is the ACCUMULATOR MODEL:
  - It allows a "*fuzzy*" mathematics: two sets are discernable whenever the distance between the two increases
  - An organism can rapidly estimate relevant quantities for survival
  - Inputs are accumulated and only at the end are quantified
  - It means that different numerosities correspond to different levels within the accumulator and if the difference is small, two sets can be named with the same label



Numbers

- ANS: Aproximate Number System
- It suffers from general imprecision, which is due to its logarithmic nature. That is, larger numbers are represented closer together than smaller numbers
- quantity discriminations are more prone to error as a function of the magnitude and decreased ratio between sets





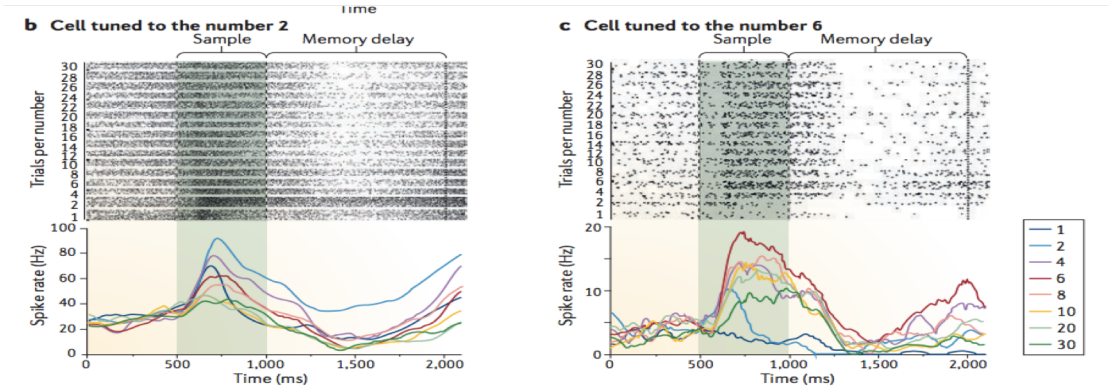
Numbers

- At the neurophysiological level, how are represented different numerosities?
- We can use single-cell recording in nonhuman primates to answer this question
  - With the assumption that
    - in different species these neurons support raw basic numerical abilities
    - In humans they can be linked (maybe modified) by symbolic representations (Nieder and Dehaene, 2009)
- Different populations of neurons have been found

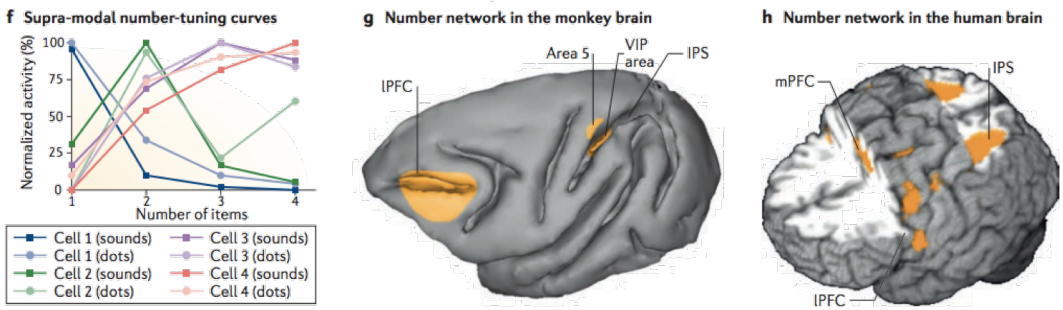
Numbers

- The most interesting class of cells is tuned to a specific quantity
  - These cells have the highest activity in response to a stimulus of a certain number (e.g., 5 dots)
  - Some are activated by different modalities (e.g., 5 visual stimuli, 5 bursts of noise)
  - They respond with the optimum to '5' and to a lesser extent to '4' and '6' and even lesser to '7' and '3' and so forth
  - It is not unusual to record from cells whose activity is tuned to '10' but respond still vigorously to '9' or '11' element showing the magnitude effect

Numbers

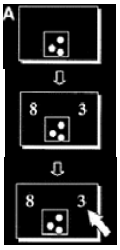


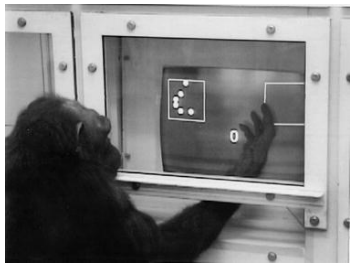
Numbers



Numbers

- It is possible to train animals to associate a certain number of dots with an arbitrary symbol of the same quantity
  - Frontal neurons are selectively activated by both symbolic and nonsymbolic aspect
  - Meaning that they show a discharge frequency when the animal sees 3 dots or sees symbol '3'





Numbers

- The first neurophysiological evidence in a bird brain of spontaneous number-related activity
- Despite macroscopic difference in brain architecture between monkeys and birds, there is comparable neuronal activity for numbers
  - Evolution found a different strategy to organize brains so that they can respond to the specific number of items in a particular set
  - However, these were adult individuals (should be tested in the young)
- What is this representation for, is still debated:
  - Maybe it evolved for social reasons -> are less evident in solitary species?

Numbers

OPEN ACCESS Freely available online PLOS BIOLOGY

Monotonic Coding of Numerosity in Macaque Lateral Intraparietal Area

Jamie D. Roitman[1¤*], Elizabeth M. Brannon[2,3], Michael L. Platt[1,3]

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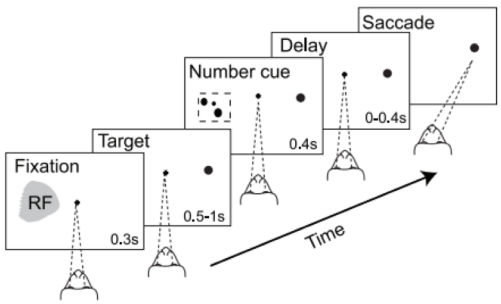
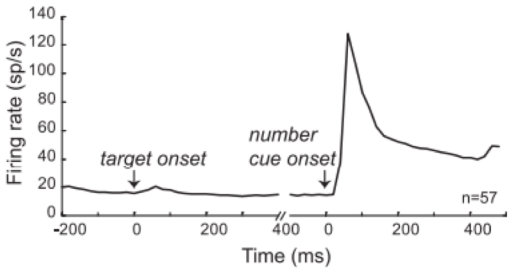
- One class responds to higher quantities (Roitman et al., 2007)
  - […] *a population of neurons in the lateral intraparietal area of monkeys encodes the total number of elements within their classical receptive fields in a graded fashion*
  - *the modulation of neuronal activity by visual quantity developed rapidly, within 100 ms of stimulus onset, and was independent of attention, reward expectations, or stimulus attributes such as size, density, or color.*
  - *The responses of these neurons resemble the outputs of ''accumulator neurons'' postulated in computational models of number processing.*
  - *Numerical accumulator neurons may provide inputs to neurons encoding specific cardinal values, such as ''4,'' that have been described in previous work* […]

Numbers

implicit numerical discrimination task





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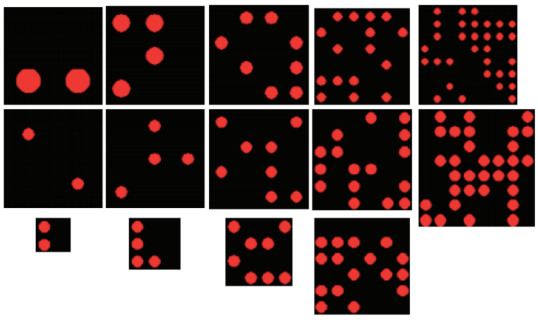

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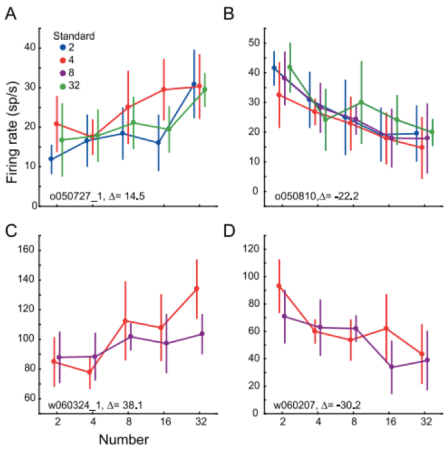
Numbers



Numbers

- You have in front of you the list with 10 numbers from 0 to 9
- In a separate room, your friend is presented with the same list
- You know you can choose one number only
- If the number –you and your friend– choose is the same, you will win 100,00EUR
- If you go for two different numbers, the game is over
- Almost all participants go for ZERO!

Numbers – zero: special status

- Since each collection of real elements has NO ELEMENTS it was thought that the zero was NOT PRESENT in the core set of representations
- Some facts supported this view:
  - hystorically, there is a late use of zero as a symbol
  - ontogenetically, the child learns very late to use the zero (ask a child who knows already the sequence of numbers: "zero, one, two, three, four..." which is the smallest number; he/she would say "one!"
  - The conclusion was that it has to be learned, it is not in the basic kit

Numbers

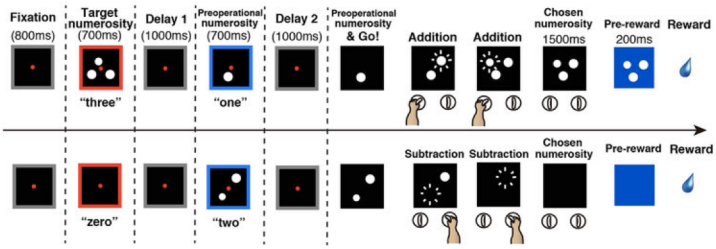
- Evidence against the previous interpretations:
  - The question for children is a ill-posed one
  - Sulkowski and Hauser showed that macaques solve these operations: 0+1 = 1 and 1-1 = 0
  - Biro and Matsusawa showed the same in chimps
  - Alex the parrot could use zero as a symbol
  - ...and think to its ecological meaning

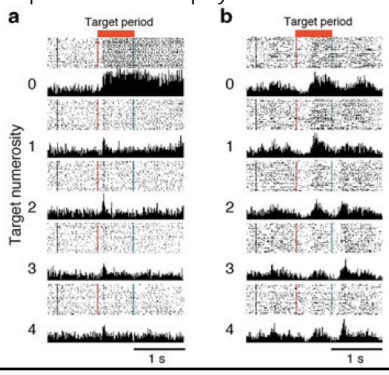
Numbers

- Thanks to the ANS, children and other species can reason about the empty collection: indeed, organisms are faster in saying that
  - 8 <18 than 8 < 12
  - 0 < 12 than 0 < 4
  - The conclusion is rather that there is nothing special in allocating the empty collection on the ladder of quantities in the first position...

Numbers

- However, Okuyama et al., showed that the zero has a special status; indeed, there are "two neurons for a zero":
  a) Neurons with exclusive response (increased freq for zero only)
  b) Neurons with continuous response (max freq for an empty collection)

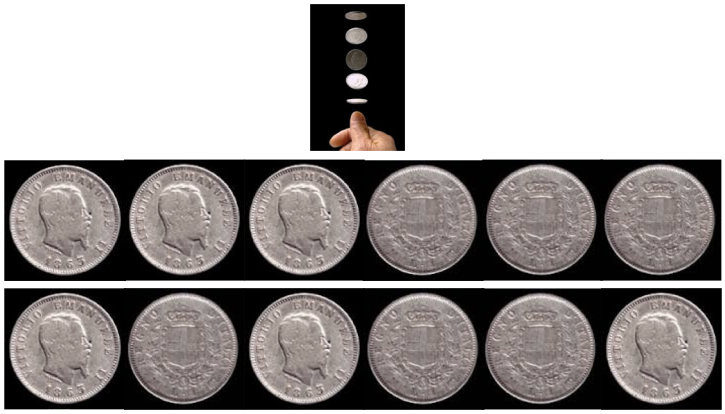




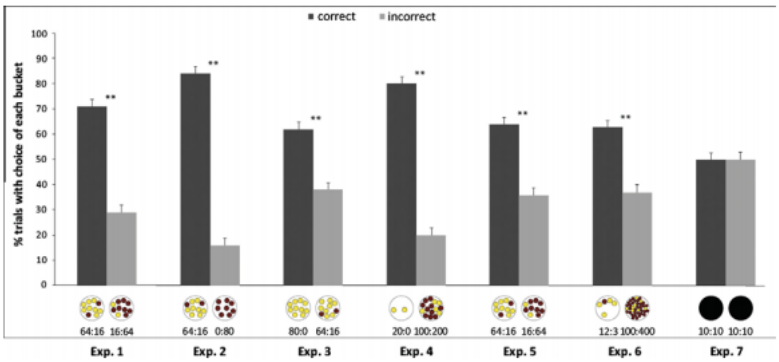
Numbers

- In a sense, between 'nothing' and 'something' there could be an asymmetric cognitive representation
  - Wynn showed that infants are surprised when an object that was placed behind an opaque screen has disappeared
  - Conversely, infants are not surprised if an object magically appears
    - Maybe it is a copy, a new object or the same...hard to disambiguate

Numbers



Numbers



Numbers

- Mayan populations (Kaqchikel and K'iche)
  - With no formal instruction in mathematics
- In a series of test of probabilistic reasoning, adults responded as good as Mayan children (who go to school) and Italian adults

Numbers

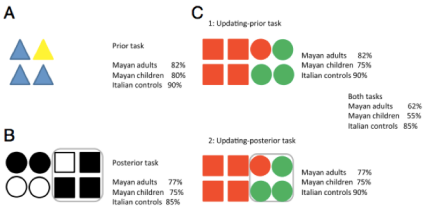
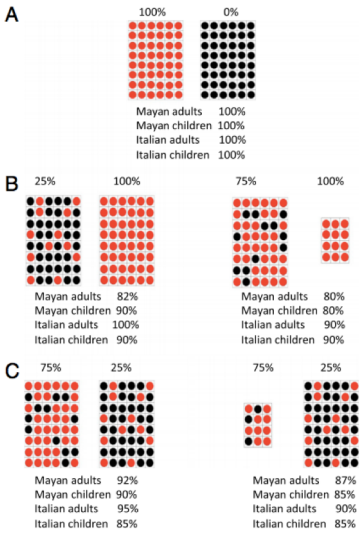


Fig. 2. Performance of Maya and Italian participants in tasks asking for a prior and/or posterior probability evaluation. In the prior task (*A*), participants had to bet on the color of a randomly drawn chip. In the posterior task (*B*), participants had to bet on the color of a randomly drawn chip whose shape was indicated by the experimenter. In the updating task (*C*), participants had to make both a prior and a posterior bet. The grey line indicates the possibilities compatible with the evidence, namely, the shape of the drawn chip: in *B*, the experimenter has drawn a square chip; in *C*, she has drawn a round chip. For each task, the figure reports the percentage of participants making the optimal bet.

Numbers



More red dots

Less red dots

Numbers

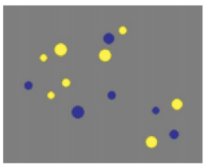
The preverbal ability to represent and manipulate quantities may constitute the foundation for the symbolic number system used for learning formal arithmetic

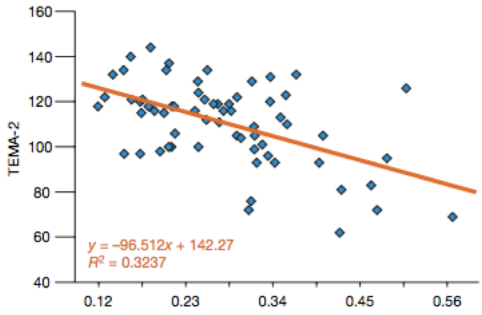
As young children develop language and a language-based symbolic number system (i.e., counting words and digits), it is believed there is a mapping of the counting words and visual symbols onto the innate number system

The foundational Approximate Number System (ANS) operates over multiple modalities, forming representations of the number of objects, sounds, or events in a scene

Numbers

- Individual differences in non-verbal number acuity correlate with math achievement (Halberda et al., 2008)

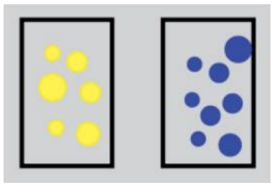


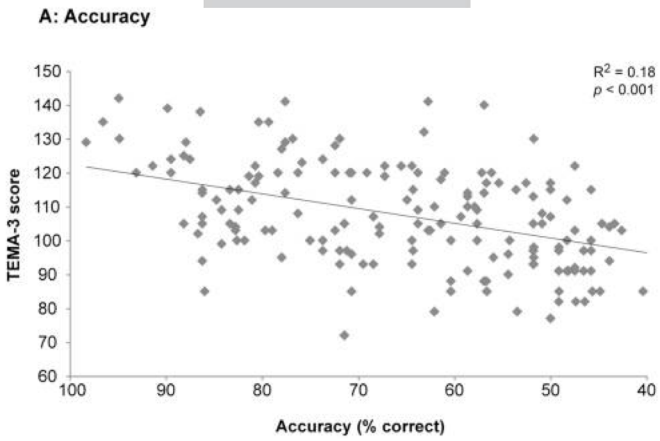


Numbers

- results obtained in a test that evaluates the number sense show a bi-directional relationship with formal arithmetic abilities:
  - children with higher acuity in the ANS tend to obtain higher scores in formal mathematic tests but not in other domains (logic, vocabulary, etc.) suggesting a specific relation
  - symmetrically, formal education in mathematics sharpens precision in the ANS

Numbers





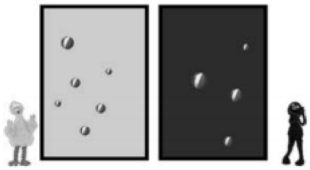
Libertus et al. 2011

Numbers

- The resolution of the ANS is specified by a Weber fraction:
  - it measures the smallest numerical change to a stimulus that can be reliably detected
  - it is equal to the difference between the two numbers divided by the smaller number; for example, 7:8 → (8 – 7)/7 .14
- When asked to indicate the more numerous of two simultaneously presented arrays containing 20 – 80 dots, French adults' Weber fraction is .12 and Amazonian adults' Weber fraction is .17; thus on average these adults could discriminate ratios differing by about 7:8 (Pica et al., 2004)

Numbers

- the resolution of the ANS, as specified by a Weber fraction, increases with age such that adults can discriminate numerosities that infants cannot.
- Studying the Weber fraction of the ANS in 3-, 4-, 5-, and 6-year-old children and in adults, it has been shown that the resolution of this system continues to increase throughout childhood, with adult-like levels of acuity attained surprisingly late in development.



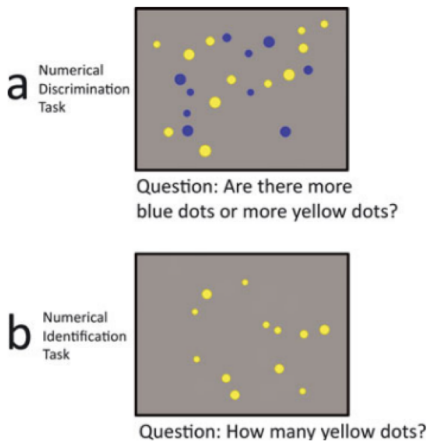
"Who has more balls?"

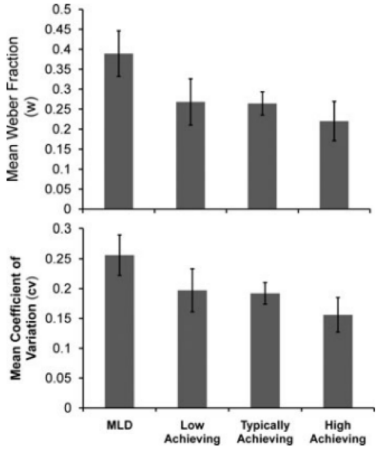
Numbers

- Many children have significant mathematical learning disabilities (MLD, or dyscalculia) despite adequate schooling

- **Developmental Dyscalculia** (DD) is a learning disorder affecting the normal acquisition of arithmetic skills in an otherwise-normal child and that affects roughly 3-6% of the population

Numbers





Mazzocco et al.,2011

Numbers

In numerical cognition, there is an association between pre-verbal abilities and formal arithmetical capabilities

- The verbal system for exact calculation can be added to pre-verbal abilities
- The set of core numerical knowledge is at the basis of the formal conceptual mathematical thinking

Numbers

- There is an extreme continuity in the processes that subtend the numerical reasoning in primates (human and nonhuman)
- In our species, two forms of representation are used jointly and allow a precise representation that is not restricted to specific quantities
- Other animals may have a precise representation for small quantities or a raw representation for large quantities

Core knowledge

The criteria hypothesized by Spelke (2000) seem to be satisfied as for the system of knowledge that support our approximate calculation on large quantities and exact computations on small numbers:

- Given at birth
- Independent from experience and formal culture/acculturation
- Largely shared between species
- At the basis of learning processes