Numerical cognition: Spotting typical and atypical neurocognitive profiles in the classroom

Numerical processing is multifaceted. Recent studies on numerical cognition have provided evidence that some very basic nonverbal capacities influence the subsequent acquisition of arithmetic and continue to modulate more advanced stages of mathematical cognition.

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Theme/s:

Learning mathematics

This report arises from Science of Learning Fellowships funded by the International Brain Research Organization (IBRO) in partnership with the International Bureau of Education (IBE) of the United Nations Educational, Scientific and Cultural Organization (UNESCO). The IBRO/IBE-UNESCO Science of Learning Fellowship aims to support and translate key neuroscience research on learning and the brain to educators, policy makers, and governments.

Executive summary

- Mathematical achievement is multifaceted. Evolutionarily ancient numerical abilities including the fast and exact enumeration of the number of items in sets of objects and numerical magnitude comparison, together with complex nonnumerical cognitive processes including language and executive functions, contribute to mathematical achievement.
- Studies in animals, adults, and children support the existence of a neural architecture dedicated to numerical processing in the human brain.
- Atypical numerical processing profiles have been consistently reported in children exhibiting significantly low mathematical achievement or developmental dyscalculia (DD), a specific learning disability for math.
- It is important to differentiate between low numerical or arithmetic performance associated with deficits in basic numerical abilities and those explained by deficits in nonnumerical processes.
- The early characterization of children's specific processing profiles and the detection of children at risk of low mathematical achievement could allow the design of more individualized and inclusive pedagogical and neurocognitive stimulation, remediation, and intervention strategies.

Introduction

Numerical processing is multifaceted. Recent studies on numerical cognition have provided evidence that some very basic nonverbal capacities influence the subsequent acquisition of arithmetic and continue to modulate more advanced stages of mathematical cognition[2-6]. These abilities include the rapid and precise apprehension of the exact number of items (numerosity) of a small set of objects (a capacity known as *subitizing*[1]) and numerical magnitude comparison. Also, research has determined complex nonnumerical cognitive processes contribute to the representation of numerical information.

Defining "numerical cognition"

It has been suggested that humans are endowed with a "number sense," an "intuition" that allows us to represent and compare the number of objects in sets[7]. Research shows that, from the first day after birth, infants are able to associate visually presented arrays of objects with auditory sequences of syllables matched in number[8]. This ability seems to be accounted for by two core systems for representing numerical information: (1) a system able to estimate accurately and precisely ("subitise"), the number of items in small sets of up to three or four objects "at a glance"; and (2) an *analog magnitude system*, dedicated to the representation of large approximate numerical quantities as language-independent mental magnitudes and the ordering of sets (otherwise known as *approximate number sense*, ANS)[9].

These core systems seem to underlie the understanding of the relationship between sets and their numerosities, as well as the types of manipulations that may affect the numerosity of sets. However, they are not able to represent the exact cardinality of larger sets. Only after children acquire language, a new cognitive process, verbal counting allows the exact enumeration of sets of objects beyond five items. "True counting" requires the mastery of a set of principles regarding the semantics of numbers[10]. These principles include:

- *stable order:* number words (numerals) always appear in the same order in the counting sequence ("one," "two," etc.)
- *one-to-one correspondence:* each numeral in the counting sequence is associated with only one object in the set
- *cardinality principle:* the numeral employed to "label" the last object in the set represents the cardinality (numerosity) of the set
- *order irrelevance:* objects can be enumerated in any order
- *abstractness:* anything can be counted

Several behavioural effects indicate a typical development of core numerical cognition. For instance, when the exact numerosity of sets of objects in the "subitizing range" (up to four items) is estimated with very high accuracy and speed, with no significant increase in the time to respond added per object in the set, showing a flat slope. This is considered a behavioural signature of this exact numerosity estimation process that has been coined as the "subitizing effect"[1]. In contrast, during verbal counting, response times and error rates typically rise linearly with increasing numerosity, showing a steep slope. In the case of numerical comparison of sets of objects, shorter response times have been consistently reported when adults, children, and animals compare small numerosities (within the subitizing range: 1 vs. 2) in contrast to larger numerosities (beyond 5 objects: 8 vs. 9). This has been coined as the "numerical size effect." In addition, shorter response times have been consistently reported when distant numerosities (1 vs. 8) are compared, as opposed to sets with small numerical distance between them (1 vs. 2; 9 vs. 8). This has been coined the "numerical distance effect." Also, numerical magnitude comparisons of sets of objects follow the "Weber's law," whereby response time and error rates decrease as the ratio or distance between the numerosities to be compared increases. For example, comparing 4 vs. 3 (ratio 1.3) is harder than comparing 9 vs. 3 (ratio 3)[11.]Hence, the "Weber's fraction" (w) can be used as a behavioural proxy for the resolution of approximate numerical representations.

Interestingly, after children learn the Arabic digits, similar numerical size and distance effects emerge in relation to Arabic representations of quantities and these have been explored in behavioural and neuroimaging studies. In addition to the acquisition of verbal counting, the acquisition of the Arabic number system seems to profit from the core systems for number representation and has a tremendous impact on the refinement of the numerical core representations. The verbal auditory symbols for numbers ("one," "five") and the visual Arabic codes ("1," "5") are mapped to the ANS ("●", "●●●●●")[7]. This process is putatively mediated by the subitizing ability for small numerosities and then supported by verbal counting for larger numbers. Finally, the new symbolic representations refine and increase the accuracy of the preexisting analogue representations[12].

Studies in animals, adults, and children

Several behavioural and neurophysiological studies conducted in animals have supported the numerical processing architecture outlined above. These studies show that monkeys, dolphins, rats, birds, chicks, and bees share the "number sense" with humans, even when controlling for nonnumerical cues that co-vary with the total number of objects in the sets, such as the total area occupied by the objects, their luminosity, density, or the sum of their contour[13-14].

Experiments conducted in awake, behaving animals, and especially in nonhuman primates such as monkeys, are essential for understanding the relations between cognitive processes and the brain, including numerical cognition. The animal can be trained to perform numerical tasks (such as discriminating and memorizing numerosities and Arabic digits). Then, while the animal is performing the task, the electrical activity of individual neurons can be measured using fine-tipped conductors (microelectrodes) inserted in specific areas within the brain. The electrical activity of single neurons connected in neural networks acts as a "physical carrier of information in the brain"[15], and its analysis, together with the behavioural information collected while the animal is performing the task, presents an exceptional opportunity to understand the neural foundations of the corresponding cognitive processes*[1].

Using this approach, it has been reported that there are "number-neurons" that selectively respond to a "preferred" numerosity in the brains of rhesus monkeys. While actively discriminating if sequentially presented arrays of dots were matched in numerosity, single neurons in the lateral prefrontal cortex, and the posterior parietal cortex of rhesus monkeys (see Figure 1A) consistently showed maximum electrical activity when the animal was presented with a specific numerosity; proving that these individual neurons were encoding those particular numerosities[16-17]. Also, after long-term training to associate Arabic digits with numerically matched sets, neurons in the prefrontal cortex of these monkeys showed comparable activity irrespective of whether the animal was presented with sets of dots or Arabic digits[18-19]. These results suggest a parietal-prefrontal brain network is specialized in the representation of cardinality and the association of semantic cardinality to arbitrary shapes, including Arabic digits, in primates.

Populations of neurons showing preference for specific numerosities have also been identified in the brain of human adults, using functional magnetic resonance images (fMRI)—a technique that measures the variations in oxygenated blood flowing to active brain regions. These populations were located in the human parietal cortex and responded preferentially to small numerosities. The neural populations showed an interesting organization, similar to a "numerosity map," where larger cortical areas responded to smaller numerosities and smaller cortical areas responded to larger numerosities. Also, larger numerosities produced a "noisier" signal in the brain[19].

Likewise, studies show that 6- to 7-year-old typically developing children, when presented with both sets and numerical symbols, recruit parietal areas just like adults. However, children also recruit the inferior frontal cortex to a much greater degree than adults[20]. Additionally, 8- to 9-year-old children show greater activation in the left prefrontal cortex during arithmetic calculations compared to adults, who exhibit greater activity in bilateral parietal and occipital-temporal brain cortices. Altogether, the studies suggest multiple anatomical and functional brain networks support numerical cognition, including parietal, temporal, and prefrontal areas. Also, the role of prefrontal brain structures involved in complex cognitive processes in the initial developmental stages of numerical competence is evidenced.

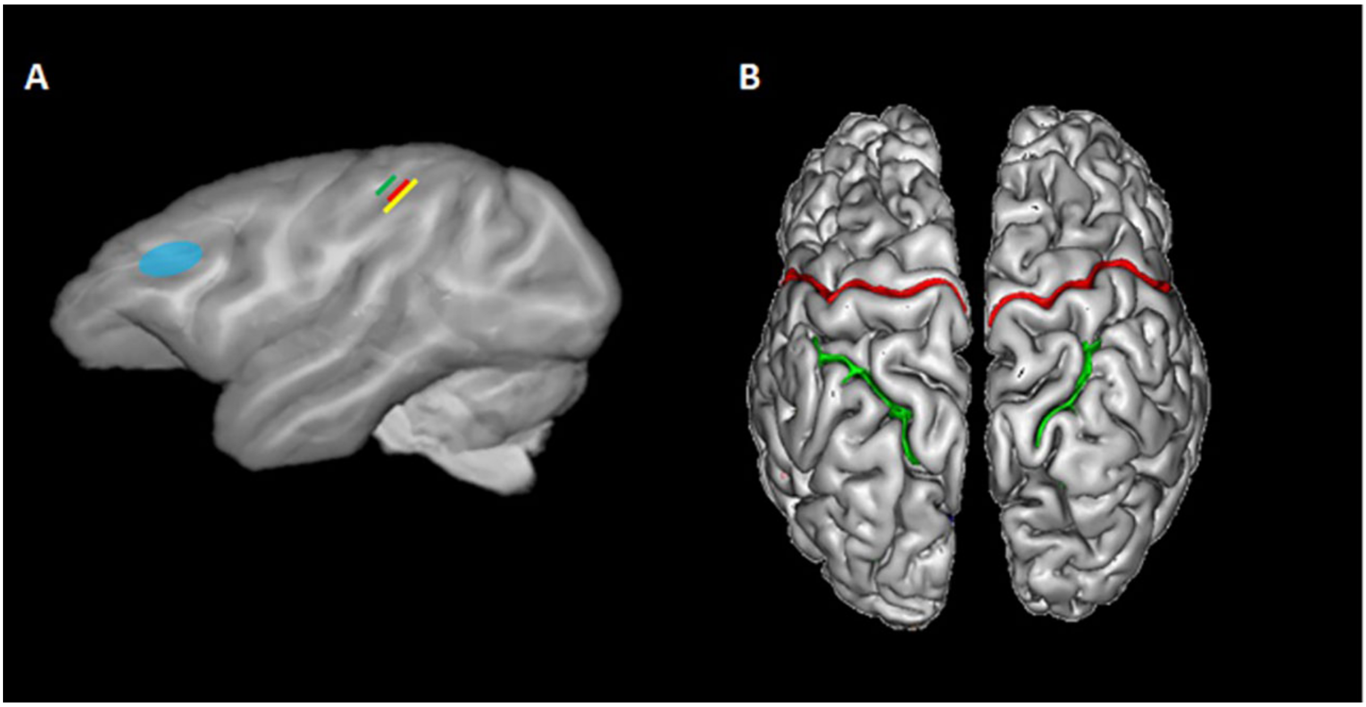

Figure 1. Brain areas involved in numerical information processing. (A) Dorsolateral view of the average rhesus macaque brain (available at https://afni.nimh.nih.gov/pub/dist/atlases/macaque/). The colored areas represent the approximate location of the regions in which "number neurons" (i.e., neurons attuned to specific numerosities) were identified. Areas include the lateral prefrontal cortex (LPFC) in blue, the SPL, in green, the ventral intraparietal area (VIP) in red, located at the fundus of the intraparietal sulcus, and the lateral intraparietal area (LIP), in yellow. (B) The image shows the 3D reconstruction of the brain of a typically developing children. In it, the intraparietal sulcus (an area reported to respond selectively to the numerosity of sets of objects) is shown in green, the central sulcus, in red, is presented as a reference anatomical landmark. The image was reconstructed using the BrainVisa software (available at http://brainvisa.info/web/download.html).

Nonnumerical cognitive processes and math

Low-level cognitive processes such as processing speed (i.e., the speed to encode, transform, and retrieve information) and short-term memory (i.e., the temporary storage of information) are key for early mathematics skills. Complex cognitive processes have been implicated in many different types of mathematical tasks[21]. These processes include:

- *phonological processing:* the ability to manipulate phonological representations (i.e., sounds) and retrieve phonological representations from long-term memory
- *visuospatial skills:* abilities to represent, transform, generate, and recall symbolic, nonlinguistic information
- *working memory:* the ability to simultaneously store and process information
- *attention:* the appropriate allocation of cognitive resources to relevant stimuli
- *executive functions:* a set of cognitive skills required to direct a behaviour towards the attainment of a goal by deliberately inhibiting a dominant, automatic response in favour of a subdominant one (inhibition), encoding and evaluating incoming information for relevance to the current task and revision of information held in memory (updating), and the ability to shift

attention or to shift between strategies or response sets (switching)

Atypical numerical processing

Atypical numerical processing profiles can be understood as consistent associations and dissociations of deficits in basic numerical abilities. These have been reported in adults with brain lesions that produce severe deficits in arithmetic calculations[6-7], and in children with low arithmetical achievement and with developmental dyscalculia (DD)[3,22-29]. DD is a neurodevelopmental disorder caused by an impairment in the brain's ability to perceive and process numerical information efficiently and accurately (DSM-5, American Psychiatric Association, 2014)[30]. DD is characterized by significant and persistent difficulties mastering number sense, number facts, or calculation (e.g., poor understanding of numbers, their magnitude and relationships; counting on fingers to add single-digit numbers instead of recalling the math fact; lose track of arithmetic computation and switch procedures) or difficulties with mathematical reasoning (e.g., severe difficulties applying mathematical concepts, facts, or procedures to solve quantitative problems). However, DD children show spared-to-high intellectual capacity and usually cope well with the rest of their academic subjects. Neuroimaging studies conducted in DD children and children with neurodevelopmental disorders or risk factors exhibiting DD as part of their cognitive profile have shown less grey matter volume in the parietal cortex (specifically in the left[31] and right intraparietal sulcus[32]), frontal and temporal lobes[32], and abnormal brain connectivity between temporal-parietal brain areas[32].

Data from England[33], Israel[34], Germany[35], India[36], Greece[37], and Cuba[38] show the prevalence of DD ranges between 2.5% and 6.4% of the school-age population. DD significantly interferes with academic achievement, professional, and/or daily life activities involving numerical and arithmetic skills[30] and affects individuals' social success, access to employment opportunities, and their personal and professional fulfilment in general. Interestingly, a high co-occurrence of DD has been reported with developmental dyslexia, the specific learning disability for reading, and with attention deficit hyperactivity disorder (ADHD)[39-40]. Additionally, a recent meta-analysis including 75 cognitive profiling studies on children with math difficulties, representing 13,001 individuals (5,251 children with math difficulties and 7,750 typically developing children) showed that children with math difficulties, including DD, show deficits in processing speed, short-term memory, phonological processing, working memory, attention, visuospatial skills, and executive functions[41].

Following previously presented evidence, a teacher may suspect children are at risk of low arithmetic achievement or even DD, when they exhibit consistently some or all of the following behaviours:

- Effortful exact enumeration of small sets of objects or restricted subitizing range of up to 2 or 3 objects
- Have problems identifying the predecessor and successor of a number
- Have problems placing numbers in number lines
- Have difficulty in estimating the approximate result of arithmetic operations
- Are extremely slow when comparing small numbers or sets of objects and counting sets of objects
- Have difficulties when comparing large sets of objects
- Write numbers upside down or rotated
- Confuse similar digits (6 vs. 9)
- Have difficulties associating the cardinality of nonsymbolic quantities to numerical symbols
- Read or write the figures incorrectly
- Are extremely slow when performing single-digit calculations and/or fail to recall simple addition and subtraction facts and the multiplication tables
- Confuse operational signs when calculating
- Have problems naming the terms, operations, and/or mathematical concepts
- Find it challenging to learn the procedures to multiply, divide, and/or work with fractions

On the relevance of neurocognitive profiling

Given the multiple contributing neurocognitive factors underlying mathematical achievement, it is important to identify early the different cognitive profiles or subtypes of numerical processing in typically developing children, children with low mathematical achievement, and in children exhibiting a specific learning disability for math. In addition, it is important to distinguish between what has been defined as "primary" and "secondary" DD[42-43]. Primary DD is characterized by severe deficits in numerical or arithmetic processing associated with underlying biological factors. DD diagnosis may include further subtyping which considers the basic numerical capacities impaired, and interactions of the DD with nonnumerical cognitive processes.

In contrast to primary DD, secondary DD is characterized by impaired numerical processing that can be explained by deficits in nonnumerical cognitive processes. For instance, it was reported that very preterm children show significantly lower mathematical achievement, working memory, and visuospatial skills than term-born children. However, their difficulties in math were not due to imprecise numerical representations, but to deficits in visuospatial processing and working memory[44]. Likewise, children with neurofibromatosis type 1 (a genetic condition generally associated with intellectual deficiency and learning disorders), with DD as part of their cognitive profile, exhibited poor number facts retrieval but no deficits in basic numerical abilities accounting for the mathematical dysfluency[45]. The strategies to address the difficulties exhibited by these children are very likely to differ from the ones required to deal with "primary DD." Hence, neurocognitive profiling can provide the foundation for the design of more individualized cognitive intervention, instruction, and pedagogical adjustments to help make the math curricula accessible to all learners.

Implications for teachers and policy makers

The pertinence of early neurocognitive profiling emphasises the need for considering the implementation of early, evidence-based, universal screening of numerical competence. This would allow both characterization of individual learning profiles and the detection of children at risk of specific learning disorders, helping to expedite attention to the children. This goal has been pursued in Cuba, through the implementation of the OptimA Aprendizaje Package. This comprises a set of questionnaires and computerized tests for the neurocognitive characterization of children at risk of learning disorders. The package has been adopted by the Diagnosis and Orientation Centres of the Ministry of Education in the country. This whole system was also piloted in two provinces of the Republic of Ecuador[46]. However, given that the tools are only available for children older than 7 years, new studies are currently dedicated to lowering the screening age.

Also, in addition to the multifaceted cognitive nature of mathematical achievement, it is necessary to consider that some studies have shown different subtypes or cognitive profiles of mathematical difficulties may vary in time, depending on the developmental trajectories of the impaired processes[41]. Hence, teachers and policy makers should bear in mind that rather than looking for "the" strategy to address low mathematical achievement, the evidence points to a necessary shift towards the implementation of individualized teaching and neurocognitive interventions, as opposed to large-scale standardized solutions.

National-level implementations of these recommendations would require further defining and articulating the attention of low mathematical achievement and DD in the context of inclusive education. Concrete actions towards that end may include (and are not restricted to):

- introducing the neurocognitive foundations of numerical cognition in teacher training and professional development programs
- allowing flexibility in the accommodation or modification of math curriculum
- providing alternative forms for the assessment of learning outcomes in children with specific learning disorders and developing dedicated data-gathering systems

These systems would allow tracking of the impact of intervention strategies on the progress of children at risk of low academic achievement in math according to their cognitive profiles and so support improving them over time.

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[[1]] Experiments with animals are bound to strict ethical considerations, in order to prevent undue suffering. The studies are conducted under the proviso that they would allow to gather relevant data, otherwise unavailable, to contribute to deepen the understanding of disease in humans. Generally, these studies require the research protocol to be reviewed by an animal ethics committees, which take into consideration whether the animal experiments could be replaced by other methods (such as mathematical modelling), if the number of animals used is the minimum to obtain reliable data (avoiding duplicating experiments), and if the protocol minimizes the study's overall impact on the animals used.