PERSPECTIVES: NEUROSCIENCE

A Head for Figures

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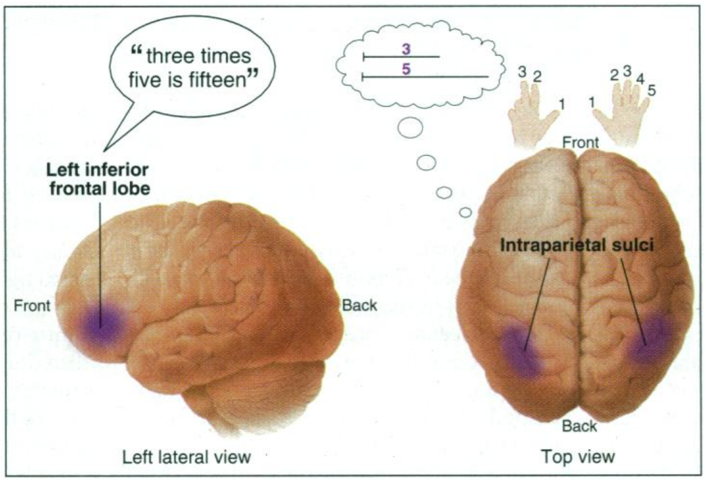
What is the source of our ability to think about the world in numerical terms, to have a sense of the twoness of our eyes and fiveness of our fingers? The Swiss psychologist Jean Piaget argued that this ability emerges around 5 years of age and require the prior development of logic skills such as transitive reasoning and putting two sets of objects into one-to-one correspondence (*1*). More recently, it has been established that infants as young as 6 months are able to detect changes in the number of objects in a visual array (*2*). These infants have arithmetical expectations about the results of adding and subtracting one object to a display (*3*). From these findings, it has been inferred that we are born with a specialized neural apparatus for categorizing the world according to the numerosities of (small) sets of objects (*4*, *5*), rather as we are born with the ability to categorize the world by color. On page 970 of this issue, Dehaene and his colleagues propose a more sophisticated explanation based on a series of behavioral and brain-imaging experiments in bilingual individuals (*6*). Mathematical ability, they claim, results from the integration of two nonnumerical neural circuits in the brain: the left frontal lobe, which controls linguistic representations of exact numerical values, and the parietal lobes, which control visuo-spatial representations of approximate quantities (see the figure).

According to their view, arithmetical tasks that require exact numerical answers depend on verbal representations of numbers, whereas tasks requiring estimation or approximation depend on nonlinguistic representations of approximate quantities. The authors tested this idea by teaching new two-digit addition facts to Russian-English bilinguals. Subjects were then tested either in the teaching language or in the other language. If the test required language skills to find the exact solution to an addition problem—in this experiment, selecting between the correct answer and one where the second digit was one unit off—then there should be a cost to switching from the language in which the fact was taught to the other language. It turns out that there is, and the cost is considerable—for response times of 2.5 to 4.5 s, exact solutions in the other language took 1 s longer. In contrast, for approximate addition (where the subject was required to estimate the result and pick the closest number) there was no cost to switching languages. Several other tasks requiring either exact calculations or approximations yielded similar findings. The investigators conclude that solving exact numerical tasks is language-dependent, requiring verbal representations of numbers, whereas solving estimation tasks does not require language but instead involves representations of approximate quantities.



Figuring out arithmetic. The principal brain regions involved in calculating exact and approximate mathematical problems. The left inferior frontal lobe is involved in verbally coded number facts that can be used in exact calculations. The intraparietal sulci of the left and right parietal lobes are implicated in estimations and approximate calculation, which are dependent on visuo-spatial representations of numbers. The intraparietal sulci are part of the circuit controlling finger movement and are likely to be crucial to finger counting, a near universal stage in learning arithmetic.

To establish whether these two types of numerical representations are controlled by different brain regions, brain activity was recorded in subjects as they carried out the exact and approximate numerical tasks. In the first study, brain activity was measured by functional magnetic resonance imaging, which has good spatial resolution compared with other methods. For judgments requiring exact calculations, there was an increase in activation of speech-related areas in the left frontal lobe. In contrast, approximate arithmetical tasks increased activation in the intraparietal sulci of both hemispheres and the inferior parietal lobule (regions that are known to be involved in visuo-spatial processing).

Converging evidence from a second technique with high temporal resolution—which measures electrical activity (event-related potentials) in the brain using scalp electrodes—demonstrated that brain activity in response to the exact and estimate tasks began to differ soon after presentation of identical sets of numbers. After 216 to 248 ms of exact calculation, the electrodes over the left frontal lobe showed the greater change in electrical potential indicating increased brain activity in this region. In contrast, after 256 to 280 ms of the approximate calculation task, the electrodes over the parietal lobes showed the greater change in electrical potential.

The challenge now is to integrate these new findings into our existing knowledge of the brain's number network. The idea that some numerical facts, such as multiplication tables, are verbally encoded is supported by studies of two patients with brain lesions who were able to recite multiplication facts accurately, but seemed to have lost the rest of their mathematical capabilities (*7*). One of these patients scored zero on a standard clinical test of arithmetic, and her understanding of multiplication was so poor that, when given $12 \times 4 = 48$, she was unable to solve $4 \times 12 = ?$ (*8*). Conversely, some patients who have lost their ability to retain multiplication facts can nevertheless use arithmetical procedures to solve multiplication problems, suggesting that distinct neural circuits in the brain control these different capabilities (*9*). An understanding of arithmetical principles is a prerequisite for using mathematical procedures to solve multiplication problems. One patient, who was unable to remember multiplication tables apart from 2 and 10 (which he probably solved without retrieving multiplication facts at all), would solve 8×7 by transforming it into $(10 \times 7) - (2 \times 7)$, thus bringing into play the law for distributing multiplication over subtraction. Transforming problems so that they can be solved more easily is a basic tenet of the normal arithmetical repertoire, even for single-digit addition (for example,

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turning 9 + 6 into 10 + 5) (*10*). The authors note that problems with larger numbers are more likely to be transformed in this way using, what they call, "quantity-based strategies" that "cause activation in the bilateral intraparietal circuits in regions identical to those active during approximation" (*6*).

Even the simplest arithmetic is more than just fact retrieval. Indeed, there is evidence that children learning multiplication tables are not simply passive recorders of the verbal form, but reorganize the facts to make them easier to retrieve—for example, by using a single preferred form for commuted pairs such as 6 × 2 and 2 × 6 (*11*).

Dehaene *et al.* identify the key role of the parietal lobes as representing approximate magnitude, but this region may serve other mathematical functions as well. It has long been known that brain lesions in the left parietal lobe severely impair many kinds of exact number tasks (*12*). However, the Dehaene results are unable to provide evidence for the involvement of the parietal lobes in exact calculations because this would require the comparison of both approximation and exact calculations with a common baseline condition.

The parietal lobes have been implicated in conceptualizing space, and hence make a plausible locus for a "mental number line" along which approximate magnitudes are arrayed. However, it is worth noting that the parietal lobes, and particularly the intraparietal sulci (*13*)—identified by Dehaene and colleagues as the crucial region for approximate calculations—are part of the neural circuit that controls handshapes and finger movements. This raises the possibility that these brain regions contribute to finger counting and finger calculation—an almost universal stage in the learning of exact arithmetic. This connection between fingers and arithmetic prompts the suspicion that the parietal lobes, in the course of development and learning, come to support the digital representation of numbers (*5*).

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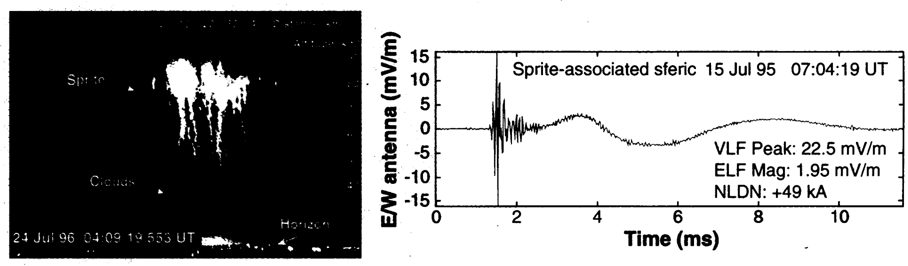
NOTA BENE: ATMOSPHERIC PHYSICS

Catching Sprites by Radio

Sprites are upper atmospheric optical phenomena associated with lightning (*1*, *2*). They have been implicated in electrochemical processes in the upper atmosphere (*3*) and transfer large amounts of charge between different atmospheric regions (*4*). Further interest comes from a growing body of evidence for perturbation of natural lightning by pollutants, with a recent study showing that smoke advected from southern Mexico into the United States led to large amounts of lightning with positive polarity, as well as an unusually high number of sprites (*5*).

The first images of sprites were serendipitously recorded only in 1990 (*2*), although anecdotal reports preceded this discovery. Sprites are barely detectable by the human eye because they are short-lived, faint compared with cloud-to-ground and intracloud lightning, and often obstructed by clouds. Associated with about one in every 100 lightning strikes—usually strong strikes with positive polarity—sprites occur at altitudes of about 40 to 90 kilometers above thunderstorms and reveal complex structures when viewed with an intensified television camera (see the figure).

Many aspects of sprite formation and their effect on the global atmospheric environment remain poorly understood. Purely visual observations of sprites are now complemented by other techniques, such as detailed optical spectra (*6*). A recent paper (*7*) shows that radio atmospherics or sferics, which are impulsive electromagnetic signals produced by lightning discharges, may enable determination of the global rate of sprite occurrence and the characteristics of sprite-producing storms by remote sensing. Sferics recorded for lightning associated with sprites have a long-lived tail (see the figure, right panel), whereas a normal lightning strike does not (*8*). Reising *et al.* (*7*) now demonstrate that a longer lasting current exists in lightning strikes that lead to sprites and that sprites themselves radiate low-frequency waves of similar strength to those emitted by the lightning. These features can be used over distances of up to 12,000 kilometers for sprite detection and characterization independently from optical measurements. The method potentially allows low-cost global detection and monitoring of sprites from just a few monitoring stations, and may help to quantify the amount of global ionization and heating in the middle and upper atmosphere due to sprites.



Now you see it.... Sprites above thunderstorms reach Earth's ionosphere. This false-color low–light-level television image was taken from a ground observatory near Fort Collins, CO, in the course of a Stanford University/Lockheed-Martin joint experiment aimed at studying sprites and related phenomena. **(Right)** A sprite-associated sferic shows a characteristic slow tail after the initial excitation.

CREDIT: S. REISING; SOURCE: STANFORD/LOCKHEED-MARTIN

References and Notes

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