Arithmetic and the brain

Stanislas Dehaene*, Nicolas Molko, Laurent Cohen and Anna J Wilson

Recent studies in human neuroimaging, primate neurophysiology, and developmental neuropsychology indicate that the human ability for arithmetic has a tangible cerebral substrate. The human intraparietal sulcus is systematically activated in all number tasks and could host a central amodal representation of quantity. Areas of the precentral and inferior prefrontal cortex also activate when subjects engage in mental calculation. A monkey analogue of these parieto-frontal regions has recently been identified, and a neuronal population code for number has been characterized. Finally, pathologies of this system, leading to acalculia in adults or to developmental dyscalculia in children, are beginning to be understood, thus paving the way for brain-oriented intervention studies.

Addresses
Institut National de la Santé et de la Recherche Médicale unit 562 'Cognitive neuroimaging', Service Hospitalier Frederic Joliot, Commissariat à l'énergie atomique/DRM/DSV, 4 Place du general Leclerc, 91401 Orsay cedex, France
*e-mail: dehaene@shfj.cea.fr

Current Opinion in Neurobiology 2004, **14**:1–7

This review comes from a themed issue on Cognitive neuroscience
Edited by John Gabrieli and Elisabeth A Murray

0959-4388/$ – see front matter

DOI 10.1016/j.conb.2004.03.008

Abbreviations
fMRI functional magnetic resonance imaging
HIPS horizontal segment of IPS
IPS intraparietal sulcus

Introduction

Number theory is a complex achievement of the human mind. However, the core concept of arithmetic number is simple, and all human cultures have at least a few words for numbers. Seven years ago, I proposed the hypothesis that 'number sense' is a basic capacity of the human brain [1]: dedicated brain circuits, inherited from our evolutionary history, are engaged in recognizing numerosity (the number of objects in a set), and provide us with a basic intuition that guides the acquisition of formal arithmetic.

The purpose of the present review is to re-evaluate this hypothesis in the light of recent findings in cognitive neuroscience. Progress has been fast in several domains, which are each reviewed in turn: neuroimaging of number processing in humans, animal models of the cerebral bases of number sense and developmental psychology of basic numerical abilities and their disorders.

The intraparietal sulcus and number sense

Which brain areas are engaged when we compute $7 - 4$ or 3×7? Modern neuroimaging confirms that a reproducible set of parietal, prefrontal and cingulate areas is systematically activated (over and above the activations related to stimulus identification and response output) whenever subjects are asked to perform a calculation [2,3••,4–8]. A recent meta-analysis indicates that the horizontal segment of the bilateral intraparietal sulcus (HIPS), in particular, is implicated in most neuroimaging studies of number processing, with a reproducibility of 5–7 mm in standardized coordinates [9•]. The precentral sulcus and inferior frontal gyrus are also frequently co-activated [10]. Yet some studies have observed dissociations between these areas; for instance, the inferior frontal activation varies with the time pressure imposed, whereas the HIPS activation varies with the number of operands involved [11]. In the simplest experiments, which involve number detection or comparison rather than more complex calculation, the HIPS is sometimes the only region specifically engaged [12••,13,14]. This suggests that the HIPS region plays a central role in basic quantity representation and manipulation, whereas other prefrontal areas might serve a more supportive role in the management of successive operations in working memory.

Simon *et al.* [3••] used functional magnetic resonance imaging (fMRI) to characterize the anatomical organization of calculation-related activations in the intraparietal sulcus (IPS). When comparing multiple tasks of pointing, grasping, saccades, attention movements, phoneme detection, and subtraction, the depth of the HIPS was found active solely during calculation. Importantly, this study indicates that the HIPS activation during calculation cannot be explained away by spatial, attentional, eye or finger movement artifacts, as these tasks activated a distinct set of regions.

Other studies have found that neither calculation nor working memory is needed to obtain parietal number-related activations. For instance, Eger *et al.* [12••] merely asked subjects to detect a specific target letter, digit and color during fMRI. They then investigated whether the presentation of non-target digits led to specific activations over and above those evoked by non-target letters or colors. Only the left and right HIPS regions were activated. Similarly, Naccache *et al.* [13] studied which brain areas would show subliminal repetition priming for numbers. The left and right HIPS were the only regions where fMRI activation to a visible target digit was reduced when the digit was preceded by a flashed presentation of the same number (the 'prime'). This was true even though the prime was masked and could not be perceived or reported. This neuroimaging paradigm thus adds to the recent behavioral evidence for subliminal semantic priming of numbers [15–18].

In addition to demonstrating the automaticity of HIPS activation, both the Eger and the Naccache studies indicate that this region is amodal and not specialized for a particular number notation: it reacts identically whether numerals are spoken or written, and whether they appear in Arabic notation or in spelled-out form [12••,13]. Pinel *et al.* [14] studied the effects of number notation in a number comparison task. In addition to notation, they also manipulated the numerical distance between the numbers to be compared, which is known to affect the difficulty of the comparison operation. Behaviorally, notation and distance had additive effects on response times. In fMRI, this additivity was reflected in the presence of activity in two almost entirely distinct sets of regions. In particular, the HIPS activation was affected solely by the semantic distance between numbers, not by their notation. The size of the numbers also modulates the amount of activation in the HIPS region during a simple addition task [10].

Although the bulk of neuroimaging work concerns calculation with Arabic numerals, HIPS activation, especially in the right hemisphere, can be seen when subjects estimate the numerosity of a set of concrete visual or auditory objects [19]. Note that this deep intraparietal activation related to numerical quantity must be carefully distinguished from the more posterior dorsal parietal activation observed whenever subjects count, which relates to movements of spatial attention [9•]. Single-trial analyses of fMRI activation during numerosity naming [20•] indicate that the activation of this attentional system is not needed to 'subitize' (perceive number of items at a glance) at least for very small displays of up to three objects. Subitizing and estimation could directly activate approximate numerosity information in parallel across the display, without requiring serial counting [21].

The HIPS region, which is thought to relate to quantity processing, must also be distinguished from the angular gyrus, which is also activated during some arithmetic tasks such as multiplication, but might relate more to linguistic than to quantity processing [9•]. Several studies have now found increased activation of the HIPS region for tasks that emphasize quantity, including approximate addition relative to retrieval of addition facts [5] or subtraction compared to retrieval of multiplication facts [4], whereas the converse contrasts show increased angular gyrus activation [22•]. This dissociation has also been replicated in a single case study of disruption of calculation by electrical stimulation of cortex during surgery of the left parietal lobe. Stimulation of an anterior left IPS site disrupted subtraction and stimulation of a more posterior left angular site disrupted multiplication [23]. The angular gyrus is jointly activated by other language tasks including digit naming [8] or phoneme detection [3••]. These results are thus compatible with a simple dichotomy according to which some arithmetic operations are more dependent on language-based fact retrieval, and others on quantity processing on a mental 'number line' (Figure 1; [24,25]). Nevertheless, it is currently questioned whether or not this dichotomy suffices to account for the range of acalculia patients that have been reported: some cases strongly support the notion of an internal number-line [26••] and of quantity- versus language-dependent operations [27–29], whereas others present challenges to this view [9•,30,31,32•,33].

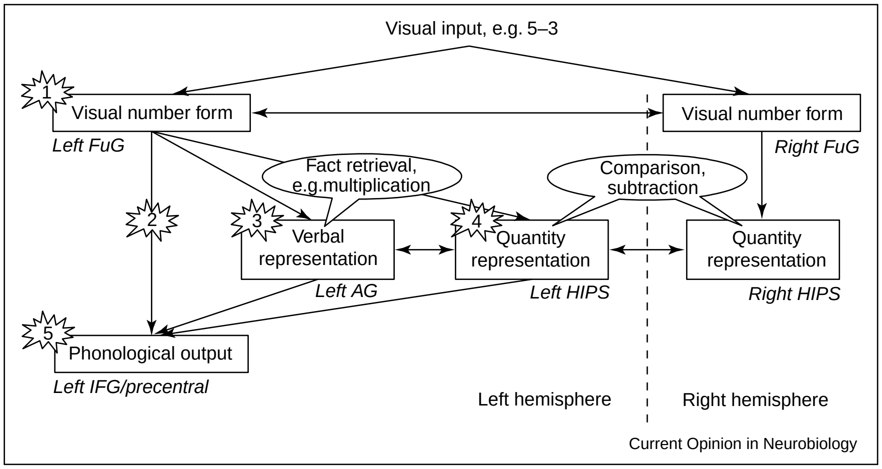
Taken together, neuroimaging studies converge to suggest that the HIPS region holds an amodal and language-independent semantic representation of numerical quantity, which can be accessed through various symbolic or non-symbolic codes. The location of this semantic region outside the classical temporal areas for semantic processing might explain recent reports of selective sparing of numbers in patients with severe semantic dementia [34,35]. Yet, is this region specific for numbers? Or would it also be engaged by quantitative processing of other non-numerical dimensions such as physical size or brightness? This issue is currently open to discussion and an active focus for further research [36].

Number sense in the animal brain

The human number sense has roots in evolution. It has long been known that many animal species can discriminate stimuli that differ only in numerosity. Considering only recent work, dolphins [37] and salamanders [38] have joined macaques [39,40], tamarin monkeys [41•,42], and lions [43] in the list of number-competent species, which suggests that number sense is widespread. Importantly, several of these studies observed untrained behavior, for instance showing that animals spontaneously select the more numerous of two sets [38,40,41•,42,43]. Many studies also incorporated controls over non-numerical variables [37,39,41•,42]. Finally, several studies that used trained animals tested them for generalization to new displays or to a new range of numbers [37,39], thus demonstrating that animals possess more knowledge of numbers than could have been inculcated by training alone.

Although these studies indicate the presence of a representation of numbers in animals, with behavioral characteristics comparable to those of humans, they do not reveal anything about the underlying neural substrate. However,

Figure 1



Schematic diagram of information-processing pathways involved in processing Arabic digits during various arithmetic tasks. This diagram, which adapts to the number domain the classical multiple-route model of word reading, represents a simplified synthesis of similar diagrams in references [24,25,28,69,70]. Although still insufficiently specified at both anatomical and functional levels, such diagrams might begin to explain the various neuropsychological dissociations that are observed in human adult lesion cases (functional lesion sites are indicated with stars). Lesion 1, associated with pure alexia, would create an inability to read numbers and to multiply, but not to compare or subtract [27,28]. Lesion 2, associated with phonological dyslexia, would create an inability to read numbers, but not to multiply, subtract or compare [32•]. Lesions 3 and 4 might explain the frequent double dissociation between multiplication and subtraction in patients who can still read numbers [30,31,33], and the presence or absence of associated deficits in comparison and non-symbolic numerosity processing [29]. Lesion 5 might explain residual calculation abilities in patients who fail to produce the solution of arithmetic problems orally, but can still solve them in writing [33]. Abbreviations: left AG, left angular gyrus; FuG, fusiform gyrus; HIPS, horizontal segment of intraparietal sulcus; IFG, inferior frontal gyrus.

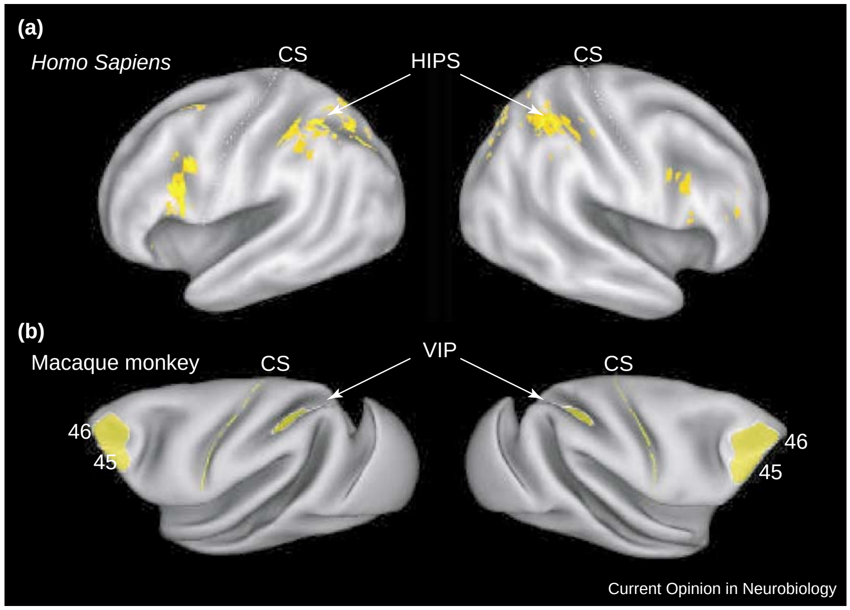
the application of electrophysiological techniques has recently led to groundbreaking progress in this area.

Sawamura and co-workers [44•] recorded from the superior parietal lobule, in the anterior bank of the IPS. Two macaque monkeys were trained to alternatively pull a lever a fixed number of times (e.g. five), then turn it the same number of times. In the time interval before making the next movement, neuronal firing was tuned to ordinal number. Each neuron fired preferentially after a certain number of actions had been performed, with the preference of different neurons being broadly distributed over the range of numerosities 1–5. Unfortunately, this motor paradigm does not easily lend itself to a systematic variation of non-numerical parameters. Furthermore, the cells did not appear to encode a purely abstract representation of number, because many showed numerical tuning only for one action, not for the other.

Nieder and Miller [45••,46••,47] recorded from both lateral prefrontal cortex (PFC) and IPS. Two monkeys were trained to perform a visual numerosity match-to-sample task: they were shown a sequence of two successive visual displays, each comprising between 1 and 5 objects, and decided whether or not the numerosity of the first set matched the numerosity of the second set. During this task about a third of prefrontal neurons and up to 15% of neurons in the depth of the IPS were found to be tuned to numerosity, firing selectively after a certain numerosity was presented. Stringent stimulus controls showed that non-numerical variables could account neither for this tuning nor for the monkey's performance.

Although these studies represent only a first stab at identifying the neural code for number, their findings are highly informative and are entirely compatible with an earlier neuronal network model of number processing [48]. First, the latency of selective firing is significantly shorter for parietal neurons (median 99 ms) than for prefrontal neurons (median 116 ms). Furthermore, their tuning strength is identical during stimulus presentation, but stronger in PFC during the delay period. This suggests that numerosity is first computed in the parietal cortex, then transmitted and held on-line by prefrontal delay activity. Second, the latency is identical for the numerosities 1–5, incompatible with serial counting, but in agreement with a parallel extraction of numerosity across all retinal locations (see Dehaene and Changeux [48]). Third, the tuning curves get broader as numerosity increases (Weber's law), and their shape is best modelled as Gaussian over a logarithmic numerical scale. Those properties can explain the distance and magnitude effects that are found in many human and animal behavioral paradigms, with both symbolic and non-symbolic stimuli [49]. Future work should explore whether or not the monkey areas where such neurons are found are true

Figure 2



Anatomical areas involved in quantity processing in humans and macaques. **(a)** Partially unfolded view of left and right human hemispheres, with intraparietal and prefrontal activations identified in a recent meta-analysis of many fMRI studies of arithmetic [9•]. **(b)** Partially unfolded view of left and right hemispheres of a macaque monkey; areas colored in yellow are those where Nieder and Miller [45••,46••,47] identified neurons tuned to numerosity. Whereas the posterior parietal area in both species occupies a plausibly homologous location, much more distortion would be needed to align the prefrontal areas. This figure was prepared with Caret software (http://brainmap.wustl.edu/resources/caretnew.html). Abbreviations: CS, central sulcus; HIPS, horizontal intraparietal sulcus; VIP, ventral intraparietal area; 45,46, Brodmann areas 45 and 46.

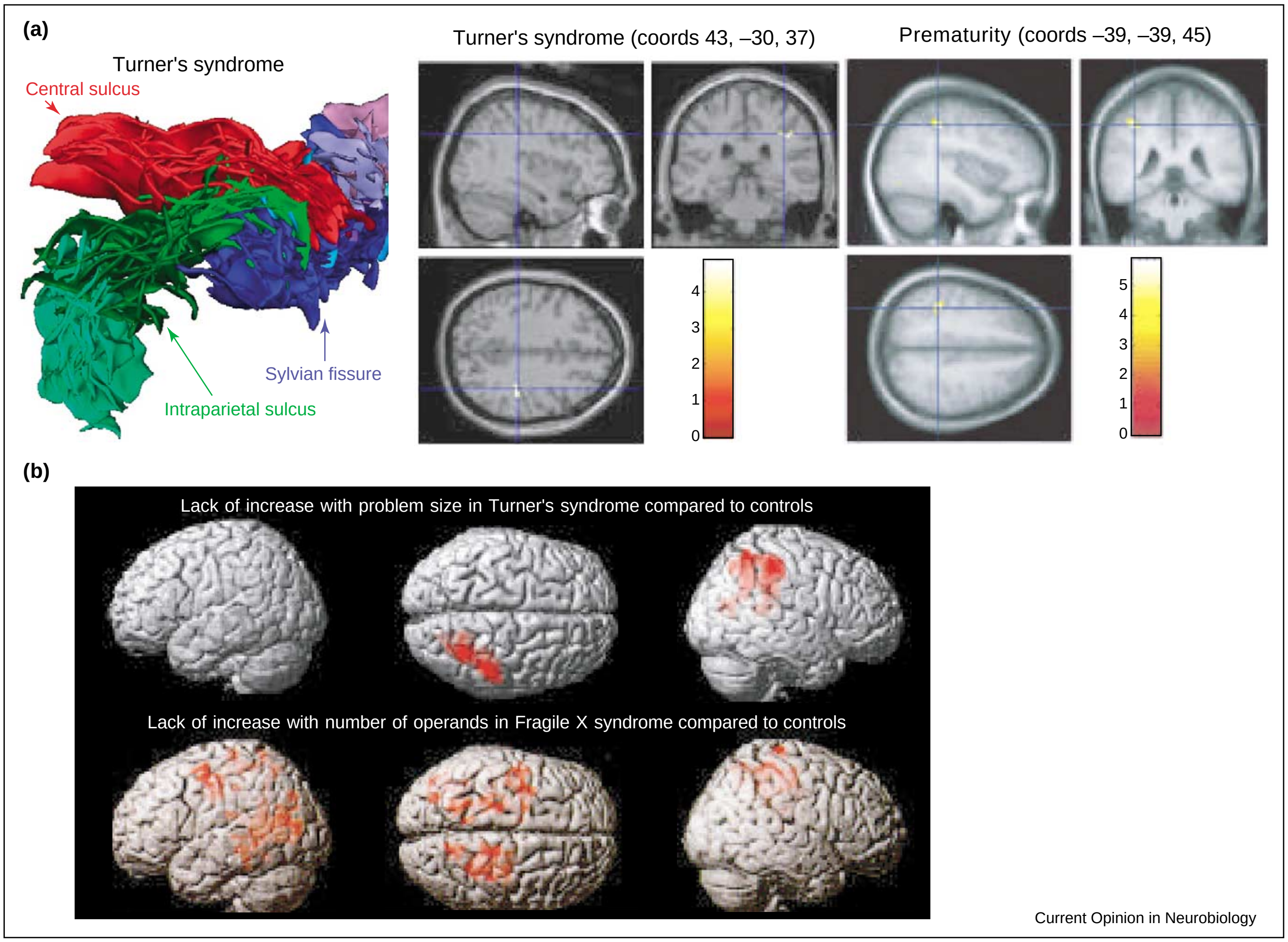
homologs of the human areas activated during mental arithmetic (Figure 2), and whether or not numerosity tuning can also be observed in humans.

Development and pathologies of number sense

Adult human arithmetic also has its roots in development. In recent years, claims of numerical competence in infants have received important qualifications. First, some tasks previously thought to tap numerical competence have been shown to engage a representation of physical amount rather than number [50,51]. Second, many tasks are now known to depend on a special object-file system limited to representing up to three objects [52,53]. Nevertheless, other studies have conclusively demonstrated a genuine system of approximate numerosity representation, capable of coding a broad range of numerosities, in the first year of life. For instance, six-month-old infants can discriminate visual numerosities as large as 8 versus 16 with the characteristic signature of Weber's law [54,55•]. Five-month-olds already have the capacity to attend to the number of sets in a display [56]. These abilities develop within the first year: 11- but not 9-month-olds exhibit knowledge of ordinality [57], and the distance effect and the Weber fraction decrease continuously throughout childhood [58,59].

Because of the difficulty of conducting imaging studies in infants, the neural substrates of infant numerical abilities remain unknown. Indirectly, however, studies of developmental dyscalculia can shed some light on this issue. Some children with otherwise normal IQ, environment, and education suffer severe deficits in arithmetic [60,61]. In specific subpopulations of dyscalculic children, recent neuroimaging studies have revealed anatomical and functional deficits of the IPS (Figure 3). Isaacs *et al.* [62] compared the density of gray matter between two groups of adolescents that were born at equally severe degrees of prematurity, but differed in the presence or absence of an arithmetic deficit. At the whole-brain level, only the left IPS showed reduced gray matter in dyscalculia, at the precise coordinates where activation is observed in normal subjects during arithmetic. Likewise, Molko *et al.* [63•] studied a genetic condition, Turner's syndrome (X monosomy), in which basic deficits of arithmetic are found [64,65]. They observed a disorganization of the right IPS, which was of abnormal depth. Furthermore, fMRI revealed reduced activation in the right IPS as a function of number size during exact calculation. A similar fMRI hypoactivation, extending to a broader parieto-prefrontal network, was observed in two other genetic conditions associated with dyscalculia, fragile X [66] and velocardiofacial syndrome [67]. However, the proportion of

Figure 3



Convergence of neuroimaging results in dyscalculia. **(a)** Anatomical findings include an abnormal shape and depth of the IPS in Turner's syndrome [63•] and missing gray matter in the left or right IPS in both Turner's syndrome [63•] and adolescents born premature and suffering from developmental dyscalculia [62]. **(b)** Functional activation findings indicate an abnormal inability to recruit the IPS as arithmetic difficulty increases, in both Turner's [63•] and fragile X [66] syndromes.

children with arithmetic deficits suffer from such a genetic or birth-related brain dysfunction remains unknown.

Conclusions

The present review suggests that quantity-related brain regions including the IPS are present early in evolution, are laid down under partial genetic control, and play a significant role in early numerical development, to the extent that their disorganization can create a lifelong impairment in arithmetic. The challenges for the future involve first, understanding the homologies, but also the differences, between the human and the macaque number-related areas; second, understanding the global coordination of these areas, not just their local coding schemes; and third, using this knowledge to guide rehabilitation attempts in dyscalculia [68] and monitor progress with neuroimaging [22•].

Acknowledgements

The authors are supported by Institut National de la Santé et de la Recherche Médicale, Commissariat à l'énergie atomique, a centennial fellowship of the McDonnell Foundation to S Dehaene and a Fyssen Foundation fellowship to A Wilson.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Dehaene S: *The Number Sense*. New York: Oxford University Press; 1997.

2. Chochon F, Cohen L, van de Moortele PF, Dehaene S: **Differential contributions of the left and right inferior parietal lobules to number processing**. *J Cogn Neurosci* 1999, **11**:617-630.

3. •• Simon O, Mangin JF, Cohen L, Le Bihan D, Dehaene S: **Topographical layout of hand, eye, calculation, and language-related areas in the human parietal lobe**. *Neuron* 2002, **33**:475-487.

The authors used fMRI in humans to localize number- and language-related activations in the parietal lobe relative to geometrically reproducible activations evoked by basic sensorimotor tasks such as pointing, grasping, saccades or attention. They also provide tentative homologies with corresponding areas of the macaque monkey.

4. Lee KM: **Cortical areas differentially involved in multiplication and subtraction: a functional magnetic resonance imaging study and correlation with a case of selective acalculia**. *Ann Neurol* 2000, **48**:657-661.

5. Dehaene S, Spelke E, Pinel P, Stanescu R, Tsivkin S: **Sources of mathematical thinking: behavioral and brain-imaging evidence**. *Science* 1999, **284**:970-974.

6. Gruber O, Indefrey P, Steinmetz H, Kleinschmidt A: **Dissociating neural correlates of cognitive components in mental calculation**. *Cereb Cortex* 2001, **11**:350-359.

7. Pesenti M, Thioux M, Seron X, De Volder A: **Neuroanatomical substrates of arabic number processing, numerical comparison, and simple addition: a PET study**. *J Cogn Neurosci* 2000, **12**:461-479.

8. Zago L, Pesenti M, Mellet E, Crivello F, Mazoyer B, Tzourio-Mazoyer N: **Neural correlates of simple and complex mental calculation**. *Neuroimage* 2001, **13**:314-327.

9. • Dehaene S, Piazza M, Pinel P, Cohen L: **Three parietal circuits for number processing**. *Cogn Neuropsychol* 2003, **20**:487-506.

The authors present a review and meta-analysis of recent imaging and patient studies of calculation, guided by the theoretical proposal that intraparietal, angular, and posterior parietal regions play distinct functional roles in arithmetic.

10. Stanescu-Cosson R, Pinel P, van De Moortele PF, Le Bihan D, Cohen L, Dehaene S: **Understanding dissociations in dyscalculia: a brain imaging study of the impact of number size on the cerebral networks for exact and approximate calculation**. *Brain* 2000, **123**:2240-2255.

11. Menon V, Rivera SM, White CD, Glover GH, Reiss AL: **Dissociating prefrontal and parietal cortex activation during arithmetic processing**. *Neuroimage* 2000, **12**:357-365.

12. •• Eger E, Sterzer P, Russ MO, Giraud AL, Kleinschmidt A: **A supramodal number representation in human intraparietal cortex**. *Neuron* 2003, **37**:719-725.

The authors use fMRI to measure responses to numbers in a small subregion of the intraparietal sulcus. They demonstrate that this region can be activated by a mere number detection task, shows category-selectivity for numbers as opposed to letters or colors, and can be activated through both spoken and written input modalities.

13. Naccache L, Dehaene S: **The priming method: imaging unconscious repetition priming reveals an abstract representation of number in the parietal lobes**. *Cereb Cortex* 2001, **11**:966-974.

14. Pinel P, Dehaene S, Riviere D, LeBihan D: **Modulation of parietal activation by semantic distance in a number comparison task**. *Neuroimage* 2001, **14**:1013-1026.

15. Dehaene S, Naccache L, Le Clec'H G, Koechlin E, Mueller M, Dehaene-Lambertz G, van de Moortele PF, Le Bihan D: **Imaging unconscious semantic priming**. *Nature* 1998, **395**:597-600.

16. Naccache L, Dehaene S: **Unconscious semantic priming extends to novel unseen stimuli**. *Cognition* 2001, **80**:215-229.

17. Greenwald AG, Abrams RL, Naccache L, Dehaene S: **Long-term semantic memory versus contextual memory in unconscious number processing**. *J Exp Psychol Learn Mem Cogn* 2003, **29**:235-247.

18. Reynvoet B, Caessens B, Brysbaert M: **Automatic stimulus-response associations may be semantically mediated**. *Psychon Bull Rev* 2002, **9**:107-112.

19. Piazza M, Mechelli A, Butterworth B, Price CJ: **Are subitizing and counting implemented as separate or functionally overlapping processes?** *Neuroimage* 2002, **15**:435-446.

20. • Piazza M, Giacomini E, Le Bihan D, Dehaene S: **Single-trial classification of parallel pre-attentive and serial attentive processes using functional magnetic resonance imaging**. *Proc R Soc Lond B Biol Sci* 2003, **270**:1237-1245.

The authors used single trial fMRI and correlation of fMRI with vocal response times to study the cerebral bases of subitizing and counting. The results indicate that the deployment of posterior parietal attention networks can be detected on single trials, and is not needed to estimate numerosities smaller than three or four.

21. Cordes S, Gelman R, Gallistel CR, Whalen J: **Variability signatures distinguish verbal from nonverbal counting for both large and small numbers**. *Psychon Bull Rev* 2001, **8**:698-707.

22. • Delazer M, Domahs F, Bartha L, Brenneis C, Lochy A, Trieb T, Benke T: **Learning complex arithmetic-an fMRI study**. *Brain Res Cogn Brain Res* 2003, **18**:76-88.

This study demonstrates that fMRI can be used to monitor the changes in brain activation that occur during a short training period with novel multiplication facts. In the course of training, a shift was observed from the intraparietal sulcus to the left angular gyrus.

23. Duffau H, Denvil D, Lopes M, Gasparini F, Cohen L, Capelle L, Van Effenterre R: **Intraoperative mapping of the cortical areas involved in multiplication and subtraction: an electrostimulation study in a patient with a left parietal glioma**. *J Neurol Neurosurg Psychiatry* 2002, **73**:733-738.

24. Dehaene S, Cohen L: **Towards an anatomical and functional model of number processing**. *Math Cogn* 1995, **1**:83-120.

25. Dehaene S: **Varieties of numerical abilities**. *Cognition* 1992, **44**:1-42.

26. •• Zorzi M, Priftis K, Umilta C: **Brain damage: neglect disrupts the mental number line**. *Nature* 2002, **417**:138-139.

This remarkable article demonstrates that spatial attention mechanisms can operate on the mental number line. In a number bisection task neglect patients show a 'rightward' bias (towards larger numbers) although both stimulus and response are given in a non-spatial format (spoken number words).

27. Cohen L, Dehaene S: **Number processing in pure alexia: the effect of hemispheric asymmetries and task demands**. *Neurocase* 1995, **1**:121-137.

28. Cohen L, Dehaene S: **Calculating without reading: unsuspected residual abilities in pure alexia**. *Cogn Neuropsychol* 2000, **17**:563-583.

29. Lemer C, Dehaene S, Spelke E, Cohen L: **Approximate quantities and exact number words: dissociable systems**. *Neuropsychologia* 2003, **41**:1942-1958.

30. van Harskamp NJ, Rudge P, Cipolotti L: **Are multiplication facts implemented by the left supramarginal and angular gyri?** *Neuropsychologia* 2002, **40**:1786-1793.

31. van Harskamp NJ, Cipolotti L: **Selective impairments for addition, subtraction and multiplication. Implications for the organisation of arithmetical facts**. *Cortex* 2001, **37**:363-388.

32. • Garcia-Orza J, Leon-Carrion J, Vega O: **Dissociating arabic numeral reading and basic calculation: a case study**. *Neurocase* 2003, **9**:129-139.

The authors present an interesting single case study that challenges some models of the relations between language and arithmetic. The patient was able to provide the correct verbal answer to arithmetic problems that he failed to read. For instance, he read 7×3 as 'four times five', but produced the correct result 'twenty-one' (for related cases, see [27,28,33]). Note that in word reading the patient was classified as a phonological dyslexic, that is, unable to read through a direct grapheme-to-phoneme conversion route. Impairment of a shallow visual-to-phonological route for number reading might explain the pattern of errors (Figure 1).

33. Whalen J: **Representing arithmetic table facts in memory: evidence from acquired impairments**. *Cogn Neuropsychol* 2002, **19**:505-522.

34. Cappelletti M, Butterworth B, Kopelman M: **Spared numerical abilities in a case of semantic dementia**. *Neuropsychologia* 2001, **39**:1224-1239.

35. Crutch SJ, Warrington EK: **Preserved calculation skills in a case of semantic dementia**. *Cortex* 2002, **38**:389-399.

36. Fias W, Lammertyn J, Reynvoet B, Dupont P, Orban GA: **Parietal representation of symbolic and nonsymbolic magnitude**. *J Cogn Neurosci* 2003, **15**:47-56.

37. Kilian A, Yaman S, von Fersen L, Gunturkun O: **A bottlenose dolphin discriminates visual stimuli differing in numerosity**. *Learn Behav* 2003, **31**:133-142.

38. Uller C, Jaeger R, Guidry G, Martin C: **Salamanders (Plethodon cinereus) go for more: rudiments of number in an amphibian**. *Anim Cogn* 2003, **6**:105-112.

39. Brannon EM, Terrace HS: **Representation of the numerosities 1–9 by rhesus macaques (*Macaca mulatta*)**. *J Exp Psychol Anim Behav Process* 2000, **26**:31-49.

40. Hauser MD, Carey S, Hauser LB: **Spontaneous number representation in semi-free-ranging rhesus monkeys**. *Proc R Soc Lond B Biol Sci* 2000, **267**:829-833.

41. • Hauser MD, Tsao F, Garcia P, Spelke E: **Evolutionary foundations of number: spontaneous representation of numerical magnitudes by cotton-top tamarins**. *Proc R Soc Lond B Biol Sci* 2003, **270**:1441-1446.
Using untrained tamarin monkeys and a habituation–dishabituation paradigm, the authors demonstrate that large numerosities of sounds can be discriminated by naive animals, and that this large number system follows Weber's law.

42. Hauser MD, Dehaene S, Dehaene-Lambertz G, Patalano AL: **Spontaneous number discrimination of multi-format auditory stimuli in cotton-top tamarins (Saguinus oedipus)**. *Cognition* 2002, **86**:B23-B32.

43. McComb K, Packer C, Pusey A: **Roaring and numerical assessment in contests between groups of female lions, Panthera leo**. *Anim Behav* 1994, **47**:379-387.

44. • Sawamura H, Shima K, Tanji J: **Numerical representation for action in the parietal cortex of the monkey**. *Nature* 2002, **415**:918-922.
The authors present the first electrophysiological study of the neuronal bases of numerical competence in the macaque monkey. They demonstrate the presence of neurons tuned to number of actions in the superior parietal lobule.

45. •• Nieder A, Freedman DJ, Miller EK: **Representation of the quantity of visual items in the primate prefrontal cortex**. *Science* 2002, **297**:1708-1711.
The authors present the first detailed study of neuronal firing in the prefrontal cortex of two macaque monkeys trained to perform a number match-to-sample task. A simple population code is observed, in which single neurons are tuned to a preferred input numerosity. Elaborate controls rule out the contribution of non-numerical visual parameters to the cells' responses.

46. •• Nieder A, Miller EK: **Coding of cognitive magnitude. Compressed scaling of numerical information in the primate prefrontal cortex**. *Neuron* 2003, **37**:149-157.
The authors present further analyses of numerosity tuning in prefrontal neurons. They demonstrate that their firing properties can be given a precise mathematical formulation, in the form of a Gaussian tuning curve on a logarithmic internal number scale as predicted by the model presented by Dehaene and Changeux [48].

47. Nieder A, Miller EK: **Neural correlates of numerical cognition in the neocortex of non-human primates**. In *From Monkey Brain to Human Brain*. Edited by Dehaene S, Duhamel JR, Hauser M, Rizzolatti G. MIT Press; in press.

48. Dehaene S, Changeux JP: **Development of elementary numerical abilities: a neuronal model**. *J Cogn Neurosci* 1993, **5**:390-407.

49. Dehaene S, Dehaene-Lambertz G, Cohen L: **Abstract representations of numbers in the animal and human brain**. *Trends Neurosci* 1998, **21**:355-361.

50. Feigenson L, Carey S, Spelke E: **Infants' discrimination of number vs. continuous extent**. *Cognit Psychol* 2002, **44**:33-66.

51. Wechsler-Clearfield M, Mix KS: **Number versus contour length in infants' discrimination of small visual sets**. *Psychol Sci* 1999, **10**:408-411.

52. Xu F: **Numerosity discrimination in infants: evidence for two systems of representations**. *Cognition* 2003, **89**:B15-B25.

53. Feigenson L, Carey S, Hauser M: **The representations underlying infants' choice of more: object files versus analog magnitudes**. *Psychol Sci* 2002, **13**:150-156.

54. Xu F, Spelke ES: **Large number discrimination in 6-month-old infants**. *Cognition* 2000, **74**:B1-B11.

55. • Lipton J, Spelke E: **Origins of number sense: large number discrimination in human infants**. *Psychol Sci* 2003, **14**:396-401.
Using auditory sequences controlled for non-numerical parameters, the authors demonstrate that infants discriminate large numerosities (>8) according to Weber's law, and that the Weber fraction becomes more accurate from six to nine months of age.

56. Wynn K, Bloom P, Chiang WC: **Enumeration of collective entities by 5-month-old infants**. *Cognition* 2002, **83**:B55-B62.

57. Brannon EM: **The development of ordinal numerical knowledge in infancy**. *Cognition* 2002, **83**:223-240.

58. Huntley-Fenner G: **Children's understanding of number is similar to adults' and rats': numerical estimation by 5–7-year-olds**. *Cognition* 2001, **78**:B27-B40.

59. Huntley-Fenner G, Cannon E: **Preschoolers' magnitude comparisons are mediated by a preverbal analog mechanism**. *Psychol Sci* 2000, **11**:147-152.

60. Shalev RS, Auerbach J, Manor O, Gross-Tsur V: **Developmental dyscalculia: prevalence and prognosis**. *Eur Child Adolesc Psychiatry* 2000, **9**:II58-II64.

61. Badian NA: **Persistent arithmetic, reading, or arithmetic and reading disability**. *Annals of Dyslexia* 1999, **49**:45-70.

62. Isaacs EB, Edmonds CJ, Lucas A, Gadian DG: **Calculation difficulties in children of very low birthweight: a neural correlate**. *Brain* 2001, **124**:1701-1707.

63. • Molko N, Cachia A, Riviere D, Mangin JF, Bruandet M, Le Bihan D, Cohen L, Dehaene S: **Functional and structural alterations of the intraparietal sulcus in a developmental dyscalculia of genetic origin**. *Neuron* 2003, **40**:847-858.
The authors present a detailed study of the functional neuroanatomy of the intraparietal sulcus in a small group of young adults with Turner's syndrome. This article also introduces a new method for automatized morphometric analysis of sulci.

64. Bruandet M, Molko N, Cohen L, Dehaene S: **A cognitive characterization of dyscalculia in Turner syndrome**. *Neuropsychologia* 2004, **42**:288-298.

65. Temple CM, Marriott AJ: **Arithmetic ability and disability in Turner's syndrome: a cognitive neuropsychological analysis**. *Dev Neuropsychol* 1998, **14**:47-67.

66. Rivera SM, Menon V, White CD, Glaser B, Reiss AL: **Functional brain activation during arithmetic processing in females with fragile X syndrome is related to FMR1 protein expression**. *Hum Brain Mapp* 2002, **16**:206-218.

67. Eliez S, Blasey CM, Menon V, White CD, Schmitt JE, Reiss AL: **Functional brain imaging study of mathematical reasoning abilities in velocardiofacial syndrome (del22q11.2)**. *Genet Med* 2001, **3**:49-55.

68. Girelli L, Seron X: **Rehabilitation of number processing and calculation skills**. *Aphasiology* 2001, **15**:695-712.

69. Cohen L, Dehaene S, Verstichel P: **Number words and number non-words: a case of deep dyslexia extending to arabic numerals**. *Brain* 1994, **117**:267-279.

70. Cipolotti L, Butterworth B: **Toward a multiroute model of number processing: impaired number transcoding with preserved calculation skills**. *J Exp Psychol Gen* 1995, **124**:375-390.