Cerebral constraints on reading and arithmetic:

Education as a "neuronal recycling" process

Stanislas Dehaene

Inserm Unit 562 "Cognitive Neuroimaging", CEA/DRM/DSV, Orsay, France

dehaene@shfj.cea.fr

Why should brain research be relevant to education? Many parents and educators consider that it is not. No one denies, of course, that the brain is, in the final analysis, the biological organ that supports the child's learning and memory processes. However, this biological fact seems quite remote from the day-to-day events that are occurring in schools. Biology is usually not thought to place much constraint, if any, on education.

Beneath this judgment, I have often observed that educators hold onto an implicit model of brain as a *tabula rasa* or "blank slate" (Pinker, 2002), ready to be filled through education and classroom practice. In this view, the capacity of the human brain to be educated, unique in the animal kingdom, relies upon an extended range of cortical plasticity unique to humans. The human brain would be special in its capacity to accommodate an almost infinite range of new functions through learning. In this view, then, knowledge of the brain is of no help in designing educational policies.

Although admittedly presented here in somewhat caricatured form, this view is not so distant from some modern connectionist or neo-constructivist statements (e.g. Quartz & Sejnowski, 1997). It is also supported by an apparent infallible logical reasoning. Much of current classroom content, so the reasoning goes, consists in recent cultural inventions, such

as the symbols that we use in writing or mathematics. Those cultural tools are far too recent to have exerted any evolutionary pressure on brain evolution. Reading, for instance, was invented only 5400 years ago, and symbolic arithmetic is even more recent: the Arabic notation and most of its associated algorithms were not available even a thousand year ago. Thus, it is logically impossible that there exist dedicated brain mechanisms evolved for reading or symbolic arithmetic. They have to be learned, just like myriads of other facts and skills in geography, history, grammar, philosophy… The fact that our children can learn those materials implies that the brain is nothing but a powerful universal learning machine.

While such a learning-based theory might explain the vast range of human cultural abilities, it also implies that the brain implementation of those abilities should be highly variable across individuals. Depending on an individual's learning history, the same brain region might become involved in various functions. During learning, random symmetry breaking might ultimately lead to the assignment of dedicated territories to different competences, but this assignment should be randomly determined for different individuals. Thus, one would not expect to find reproducible cerebral substrates for recent cultural activities such as reading and arithmetic.

This prediction, however, is precisely where the paradox lies. As I will show in the remnant of this chapter, a wealth of recent neuroimaging and neuropsychological findings shed light on the ability of the human brain to acquire novel cultural objects such as reading and arithmetic. Those data go against the hypothesis of an unbiased *tabula rasa*. Converging psychological, neuropsychological and brain-imaging evidence demonstrates that the adult human brain houses dedicated mechanisms for reading and arithmetic. Small cortical regions, which occupy reproducible locations in different individuals, are recruited by these tasks. They accomplish their function automatically and often without awareness. Furthermore, the lesion of those regions can lead to specific reading or calculation impairments. In brief, the

evidence seems to support the existence of distinct, reproducible and rather specific brain bases for reading and arithmetic.

Close examination of the function of those brain areas in evolution suggests a possible resolution of this paradox. It is not the case that those areas acquire an entirely distinct, culturally arbitrary new function. Rather, they appear to possess, in other primates, a prior function closely related to the one that they will eventually have in humans. Furthermore, many of the functional features that make them highly efficient in processing human cultural tools are already present. Relatively small changes may suffice to adapt them to their new cultural domain. I am therefore lead, in the conclusion, to tentatively proposing a "neuronal recycling" hypothesis, according to which the human capacity for cultural learning relies on a process of pre-empting or recycling pre-existing brain circuitry. In my opinion, this view implies that an understanding of the child's brain organization is essential to education.

1. Cerebral bases of arithmetic

Many neuroimaging studies, throughout the world, have examined brain activity while adults engage in simple arithmetic tasks. The technology of functional magnetic resonance imaging (fMRI) currently allows us to capture a series of whole-brain images of blood oxygenation, tightly coupled to neuronal activity, with a time resolution of a few seconds. This methodology is sufficient to examine what brain areas are activated when subjects compute a simple subtraction (e.g. 7-2), compared to a control situation in which subjects simply name the digits without calculating (for instance). A remarkable outcome of such studies has been the discovery of a highly reproducible substrate for mental arithmetic (as reviewed in Dehaene, Piazza, Pinel, & Cohen, 2003). A reproducible set of areas is systematically activated during arithmetic, amongst which the left and right intraparietal sulci and the left and right precentral sulci figure prominently (figure 1). Only a few minutes of

testing are now needed to isolate this network in every individual tested, with a variability of only about a centimeter in standardized brain coordinates.

The parieto-precentral network for arithmetic has been observed in many different laboratories, with adults from many different countries and with strikingly different languages and educational systems (e.g. China, Japan, France, United States). The parietal component of this network also appears to be common to essentially all arithmetic tasks. Its activation is strongest during calculation (e.g. subtraction, addition, multiplication) or approximation of a calculation (e.g. is 21+15 closer to 40 or to 90?) (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). However, parietal number-related activity can also be elicited in a completely automatic manner when subjects merely have to detect a digit in a visual or auditory stream (Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003). Indeed, the mere subliminal presentation of an Arabic digit for a very brief duration is sufficient to elicit it (Naccache & Dehaene, 2001). Those results present a deep paradox: why is the same brain area systematically assigned to processing Arabic digits, in a highly automated way, while letters, which are an equally arbitrary cultural construction, lead to no activation in this area?

A simple but fruitful hypothesis has been proposed which might begin to resolve this paradox (Dehaene, 1992, 1997; Gallistel & Gelman, 1992). It postulates that, although Arabic digits and verbal numerals are culturally arbitrary and specific to humans, the sense of numerical quantity is not. This "number sense" is present in very young infants and in animals. We learn to give meaning to our symbols and calculation by connecting them to this pre-existing quantity representation.

In support of this view, many experiments have shown that animal and human infants possess a rudimentary and non-verbal sense of number. Pigeons, rats, dolphins, monkeys and apes can perceive the "numerosity" of a set of visual or auditory objects, even up to 40 or 50. Similarly, six month-old human infants can perceive the difference, say, between 8 and 16

dots on a computer screen (Lipton & Spelke, 2003). Naturally, this ability is not as precise as ours, and thus cannot support complex digital calculations. Animals and infants cannot discriminate two neighboring numbers such as 36 and 37, but only have an approximate feeling of numerosity which gets progressively coarser as the numbers get larger (Weber's law).

The same approximate representation continues to be evidenced in human adults, not only when we perceive sets of objects, but even when we process symbolic digits. A telling sign of our reliance on this "number sense" is the distance effect in number comparison. When deciding which of two Arabic numerals is the larger, we are considerably faster when the numbers are distant (e.g. 1 and 9, or 31 and 65) than when they are close (e.g. 8 and 9, or 51 and 65). Such a variable performance would not be expected from a digital comparison algorithm, as present for instance in modern computer. It suggests that, even when confronted symbolic inputs, our brain quickly converts the numerals into an internal approximate quantity code – an internal "number line" in which similar quantities are coded by similar distributions of activations.

In the last few years, we have learned a lot about how this quantity code is implemented at the neural level. Andreas Nieder and Earl Miller (Nieder, Freedman, & Miller, 2002; Nieder & Miller, 2003, 2004) recorded from single neurons in awake monkeys trained to perform a visual number match-to-sample task. Many neurons were tuned to a preferred numerosity: some neurons responded preferentially to sets of one object, others to two objects, and so on up to five objects. The tuning was coarse, and became increasingly imprecise as numerosity increased. The characteristics of this neural code were exactly as expected from a neural network model which had been proposed to account for the distance effect and other characteristics of numerical processing in adults and infants (Dehaene & Changeux, 1993). Most important is the location where the number neurons were recorded.

Initially, a large proportion were observed in dorsolateral prefrontal cortex, but more recently another population of neurons with a shorter latency has been observed in the parietal lobe (Nieder & Miller, 2004; see also Sawamura, Shima, & Tanji, 2002). These neurons are located in area VIP, in the depth of the intraparietal sulcus, a location which is a plausible homolog of the human area active during many number tasks.

One may thus propose a simple scenario for the acquisition of arithmetic in humans. Evolution had endowed the primate parietal lobe with a coarse representation of numerosity, which was presumably useful in many situations in which a set of objects or congeners had to be tracked through time. This primitive number representation is also present in humans. It is present early on in human infancy, although its precision is initially quite mediocre and develops continuously during the first year of life (Lipton & Spelke, 2003). It provides children with a minimal foundation on which to build arithmetic: the ability to track small sets of objects, and to monitor increases or decreases in numerosity. In the first year, this knowledge is entirely non-verbal, but around 3 years of life, it becomes connected with symbols, first with the counting words of spoken language (and their surrogate the fingers), then with the written symbols of the Arabic notation.

It is thus not surprising that Arabic digits and their computations become ultimately tied to a restricted brain area located reproducibly in all individuals. Indeed, this area does not emerge through "training" in arithmetic. Rather, it is present from the start and is progressively modified as it gets connected to symbol systems in other brain areas, thus giving numbers their meaning

While this scenario describes normal number development, it also predicts the existence of specific impairments in arithmetic. In adults, some brain lesions are known to cause acalculia, a selective impairment in arithmetic (Dehaene, Dehaene-Lambertz, & Cohen, 1998). Lesions of the intraparietal sulcus, in particular, may cause severe impairments in

addition and subtraction, but also in basic number understanding such as approximation, numerosity estimation and comparison (Lemer, Dehaene, Spelke, & Cohen, 2003). Crucially, a similar syndrome exists in children, where it is called developmental dyscalculia (Shalev, Auerbach, Manor, & Gross-Tsur, 2000). Some children, from birth on, experience severe difficulties in learning arithmetic. Nevertheless, they may be of normal intelligence and from a normal social background, and need not suffer from associated deficits in reading or attention. In some of them, the deficit may even impact on very basic tasks. Even the ability to decide whether a set comprise two or three objects, or which of 5 or 6 is the larger number, may be compromised (Butterworth, 1999). A natural hypothesis, thus, is that the quantity representation may be affected, either by a genetic disease or by an early brain insult.

This hypothesis was recently vindicated by two cognitive neuroscience studies of dyscalculia. In one (Isaacs, Edmonds, Lucas, & Gadian, 2001), young adolescents born premature were sorted in two groups, those that suffered from dyscalculia during their childhood and those who did not. Magnetic resonance imaging was used to estimate the density of gray matter throughout the cortex. Dyscalculics suffered from a selective reduction in gray matter density in the left intraparietal sulcus, at the precise coordinates where activations are observed in normal adults during mental arithmetic. In the second study (Molko et al., 2003), young adult women with a genetic disease, Turner's syndrome, were compared to controls on an anatomical and functional magnetic resonance test. Cortical anomalies were observed in the right intraparietal sulcus, which was also abnormally activated during the computation of additions with large numbers.

It is currently not known why dyscalculia sometimes affects the left or the right parietal lobe – nor which proportion of children with dyscalculia actually have identifiable brain insults. Nevertheless, the very existence of a category of children with normal intelligence and schooling, and yet with a disproportionate deficit in arithmetic, invalidates

the view that arithmetic education rests on domain-general learning mechanisms. Rather, a narrow, dedicated pre-representation of numerosity, with a specific brain substrate, acts a pre-requisite to learning in arithmetic. All humans have the capability of growing mathematics – but only if they start from the right seed.

2. Cerebral bases of reading

Numbers are a basic parameter of our environment, so it should perhaps not be so surprising that our brains come prepared by evolution to represent it. More paradoxically, similar discoveries have been made in the domain of reading. Reading was invented at most 5400 years ago, and until very recently it concerned only a very small proportion of humanity. Thus, there has been no time or pressure to evolve brain circuits for reading. Indeed, the principles of reading are a mixed bag of tricks, highly variable from culture to culture, combining the rebus principle with the possibility of depicting sound elements ranging from whole words to syllables, rhymes or phonemes using various visual shapes. While it is likely that *homo Sapiens* has evolved dedicated cortical mechanisms for speech processing, which is a defining feature of our species, on the visual side it seems impossible that the brain comes prepared for the arbitrary features of the reading system.

In spite of this seemingly logical arguments, brain imaging studies have identified a strikingly reproducible brain system for the visual stage of reading, which is termed the "visual word form" system. Whenever a good reader is presented with a written word, activation can be observed in an area of the left ventral visual region, located in the occipito-temporal sulcus (for review, see Cohen & Dehaene, 2004). The variability in this activation from person to person is only a few millimeters (figure 2). Furthermore, it is present at the same location in readers of all cultures, including the Hebrew right-to-left script as well as non-alphabetic Chinese and Japanese reading systems (see Paulesu et al., 2001).

The region also presents specificity for reading. For instance, it is distinct from a more mesial activation observed when viewing faces. It also responds more to strings of real letters than to pseudo-letters with a similar shape; or to real words than to strings of consonants that could not possibly form a pronounceable word (Cohen et al., 2002); see figure 2). Rare cases in whom intracranial recordings are available support the existence of micro-territories of visual cortex that respond preferentially or sometimes exclusively to words (Allison, Puce, Spencer, & McCarthy, 1999).

There is also evidence for functional specificity. Several of the computational problems posed by reading appear to be solved by exquisitely adapted mechanisms in occipito-temporal cortex. One such problem is location invariance: words must be recognized regardless of their location on the retina. The visual word form area achieves location invariance by collecting activation from the left and right hemispheres, in a few tens of milliseconds, throughout appropriate intracortical and callosal fibers (Molko et al., 2002); see figure 2). Another problem is posed by variations in font and case. The same word can have a strikingly different visual form in upper and lower case, for instance RAGE and rage. The mapping between upper and lower case is a matter of cultural convention and must be learned. Nevertheless, brain imaging has revealed that a case-invariant representation is achieved early on in the reading process (Dehaene et al., 2004), through a bank of dedicated letter-detector neurons, each assigned to a different location of the fovea and working in parallel. Visual word recognition is so efficient that the visual word form area can be activated in a subliminal manner by words presented for only 29 milliseconds (Dehaene et al., 2001).

Finally, just like for arithmetic, there is evidence that brain lesions can selectively disrupt the visual stage of reading. Déjerine (1892) reported the first case of "pure alexia", a selective disruption of reading with no concurrent impairment in speech production, speech

comprehension, or even of writing. Many cases have been observed since then. Pure alexia arises from left ventral occipito-temporal lesions that affect the region of visual cortex where activations are observed in normal subjects during reading (Cohen et al., 2003). Outside of reading, vision may be highly preserved, including face and object recognition. Although the patients may remain able to identify single letters, one at a time, they have lost the ability to recognize a whole word at once, by processing the letters in parallel. Furthermore, they are often unable to regain fluent reading, even years after the lesion. The contrast between preserved visual object recognition and impaired reading indicates that a specialized system has been lost – a fast, dedicated and reproducible "mental organ" for visual word recognition, even though the existence of such a system seems impossible on logical grounds.

As in the case of numeracy, resolution of this paradox requires consideration of what could be the prior function of the visual word form system in non-human primates. Many of the properties of the invariant word recognition system are already present in primates -- only they are used to recognize objects and faces, not words. The primate occipito-temporal pathway as a whole is concerned with visual recognition. It has evolved as a "what" system capable of invariant identification of faces and objects, and opposed to a dorsal "where" system responsible for the localization of objects and their use in motor acts. Much is known about the neuronal organization of the ventral visual pathway in the macaque monkey, where a hierarchy of neurons with increasingly abstract and invariant properties has been observed. Some neurons respond only to parts of objects, with a relatively narrow receptive field – they might for instance be sensitive to the shape of an eye at a specific place on the retina. Others respond to a larger configuration, for instance the profile of a face or the shape of a fire extinguisher. Finally, some respond to a given person, whether it is presented as a face or as a profile. These computations unfold in an effortless and non-conscious manner, and can be observed even in the anesthetized monkey.

Tanaka and his colleagues (Tanaka, 1996) have studied the minimal features of objects that make monkey occipito-temporal neurons discharge. To this end, they have used a procedure of progressive simplification. First, a large set of objects is presented until one is found that reliable causes a given neuron to discharge. Then, the shape of the object is simplified while trying to maintain an optimal neuronal response. When the shape cannot be simplified further without losing the neuronal discharge, it is thought that one has discovered the simplest feature to which the neuron responds. Remarkably, many of those shapes resemble our letters: some neurons respond to two bars shaped in a T, others to a circle or to two superimposed circles forming a figure 8, etc. Obviously, those shapes have not been learned as letters. Rather, they have emerged, in the course of ontogeny and/or phylogeny, as a simple repertoire of shapes which can collectively be used to represent a great variety of natural forms and objects.

Another essential property of inferotemporal neurons is their plasticity. Training studies with arbitrary shapes such as fractals (Miyashita, 1988) or randomly folded paper clips (Logothetis, Pauls, & Poggio, 1995) have indicated that entire populations of cells eventually become highly responsive to these shapes, and then transfer to these shapes their properties of location, size and viewpoint invariance. In some cases, cells can become responsive to two arbitrary views that are paired during training. This pairing capacity provides a potential substrate for learning to recognize A and a as the same letter, or the sound /house/ and the word HOUSE as referring to the same word.

Finally, why is there a reproducible localization for the visual word form area amongst the vast cortical territory dedicated to visual recognition? Recent neuroimaging studies by Hasson, Malach and collaborators (Hasson, Levy, Behrmann, Hendler, & Malach, 2002; Malach, Levy, & Hasson, 2002) may begin to explain this surprising finding. This group has described large-scale gradients of biases that cut across the entire set of visual areas. Because

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these gradients are so extensive, it seems likely that they are laid down very early on in development. One possibility is that they reflect the diffusion, during embryogenesis, of a chemical substance that would achieve a differential concentration across the cortical surface. According to a model first proposed by Alan Turing, (Turing, 1952), spatial diffusion of biochemical agents is a key mechanism through which biological organisms acquire spatial structures (a simple example is the zebra's stripes). Malach et al.'s results point to the possibility that similar diffusion-reaction mechanisms are at work in the human brain, and explain both the formation of brain areas and their bias towards certain domains such as words, faces or houses.

One broad bias identified by Malach's team is for retinal eccentricity: some cortical territories respond preferentially to the fovea, others to the periphery of the retina. Remarkably, the visual word form area, like the face area, systematically occupies the fovea-sensitive peak of this biased gradient. This makes sense inasmuch as both word and face recognition capitalize on fine-grained details of foveal stimuli. The recognition of places and houses, on the other hand, requires integration of information across a larger extent of the visual field and activates the peripheral peak of the gradient. It thus seems that each category of objects is preferentially acquired by whichever neurons have the relevant pre-learning biases – and that such biases can explain the tight and reproducible localization of the visual word form system without having to assume an innate "mental organ" for reading.

In summary, reading, just like arithmetic, does not rely only on domain-general mechanisms of learning. Rather, learning to read is possible because our visual system already possesses exquisite mechanisms for invariant shape recognition, as well as the appropriate connections to link those recognized shapes to other areas involved in auditory and abstract semantic representations of objects. Learning is also possible because evolution has endowed this system with a high degree of plasticity. Although we are not born with letter detectors,

letters are sufficiently close to the normal repertoire of shapes in the inferotemporal regions to be easily acquired and mapped onto sounds. We pre-empt part of this system when learning to read, rather than creating a "reading area" *de novo*.

Indeed, it can be argued that, although the human brain did not evolve for reading, the converse might have occurred: the cultural evolution of writing systems has been shaped, at least in part, by the facility and speed with which the systems could be learned by the brain. This seems to have resulted, over the course of centuries, in the selection of a small repertoire of letter shapes that nicely matches the set of shapes that are spontaneously used in our visual system to encode objects.

Conclusion: Education as a "neuronal recycling" process

The domains of arithmetic and reading, on which this chapter is focused, exhibit significant commonalities but also important differences. In both cases, humans learn to attribute meaning to conventional shapes (Arabic digits or the alphabet), and they eventually do so in a highly efficient manner, even subliminally. Furthermore, the brain activations associated with these cultural activities are highly reproducible. Finally, the brain areas involved turn out to have a significantly related function in primate evolution. There is however an important difference between arithmetic and reading. On the one hand, there is a genuine precursor of arithmetic in primate evolution. Intraparietal cortex already seems to be involved in number representation in primates, and the cultural mapping of number symbols onto this representation significantly enhances, but does not radically modify its computational capacity. On the other hand, the evolutionary precursor of the visual word form area is initially unrelated to reading. It evolved for object recognition, a function significantly different from the mapping of written language onto sound and meaning.

As a generalization of those two examples, I tentatively propose that the human ability to acquire new cultural objects relies on a neuronal "reconversion" or "recycling" process

whereby those novel objects invade cortical territories initially devoted to similar or sufficiently close functions. According to this view, our evolutionary history, and therefore our genetic organization, specifies a cerebral architecture that is both constrained and partially plastic, and that delimits a space of learnable objects. New cultural acquisitions are possible only inasmuch as they are able to fit within the pre-existing constraints of our brain architecture.

It is useful to contrast this "neuronal recycling" model with the opposite, if somewhat caricatural "blank slate" model of the brain. According to the latter, education can be compared to the filling-in of an empty brain space, capable of absorbing any type of instruction. Yet educators know that this is not what is occurring in the classroom. The real child is both much more gifted and, occasionally, much more resistant to change than the blank slate model would predict. Under the "neuronal recycling" model, both children's intuitions and their occasional stubbornness can be understood as effects of prior brain structure. In many cases, the cerebral representations that we inherit from our primate evolution facilitate school-based learning. Mathematical education, in particular, should capitalize on such early intuitions, which probably extend beyond the numerosity dimension to many other domains of science and mathematics including space, time, movement, force, etc…

In a few cases, however, education must go beyond the child's intuitive understanding of a domain, or even fight actively against an existing bias. For instance, in arithmetic, it seems that the brain's spontaneous approximate representation of numerosity is initially unable to represent zero, negative numbers, or fractions. Children's intuition must therefore be extended to those cases, a difficult enterprise which was also a major hurdle in the history of mathematics -- but one which can probably be helped by teaching appropriate metaphors

such as the notion that negative numbers correspond to an extension of the number line towards the left side.

Similarly in reading, a possible source of difficulty for the child lies in having to unlearn one type of invariance which is spontaneously provided by our visual system: invariance for left-right symmetry. There is evidence that the primate visual system, once it has learned to recognize a shape, spontaneously generalizes to the corresponding symmetrical shape (Baylis & Driver, 2001; Noble, 1968; Rollenhagen & Olson, 2000). However, this capacity is actually counterproductive when having to learn that p and q, or b and d, are unrelated letters. In agreement with the neuronal recycling model, many if not all children appear to pass through a stage where they spontaneously make left-right reversal errors, and only slowly learn that this generalization is inappropriate in reading (McMonnies, 1992).

Another, perhaps more central limitation in reading is that alphabetic systems map letter shapes onto elements of sound, the phonemes, that are not initially made explicit by our auditory processing system. Understanding what a phoneme is, and connecting phonemic representations to abstract letter shapes, appears as a major hurdle for many children (see Usha Goswami's chapter in this volume). Indeed, it may be the single most important source of reading difficulties in children with developmental dyslexia.

As shown by these examples, understanding the child's initial representations, and how these representations are modified in the course of learning, is likely to be essential in order to improve basic education in language and mathematics. I have chosen to deal specifically with two domains, arithmetic and reading, but a very similar argument could be developed for second-language learning or for many other aspects of mathematics. In each case, educators will gain much by understanding the initial state, the developmental trajectory, and the end state of the brain changes that they are trying to teach. Finally, teachers must also be aware that a small category of children may have genuine brain impairments that do not

affect general intelligence, but have a restricted impact on learning in domain-specific areas of knowledge. In this field too, understanding the cerebral basis of these pathologies is likely to improve our ability to rehabilitate or bypass them.

Figure legends

Figure 1. Areas activated by various arithmetic tasks in humans ((left, redrawn after Dehaene et al., 2003), and areas where neurons coding for number have been recorded in the macaque monkey (right, redrawn from Nieder & Miller, 2004). There is a plausible homology between the parietal areas engaged in number processing in both species.

Figure 2. Localization and properties of the "visual word form area" in humans (adapted from Cohen et al., 2002). The top figure shows the location of activation to visual words in the left occipito-temporal sulcus (each dot represents a different person). The bottom graph shows the profile of fMRI activation in this region. There is a stronger response to words than to strings of consonants, indicating tuning of this area to the cultural constraints of the script that the participants could read. The identical response to words presented in the left and right visual fields suggests that spatial invariance is achieved in this region.

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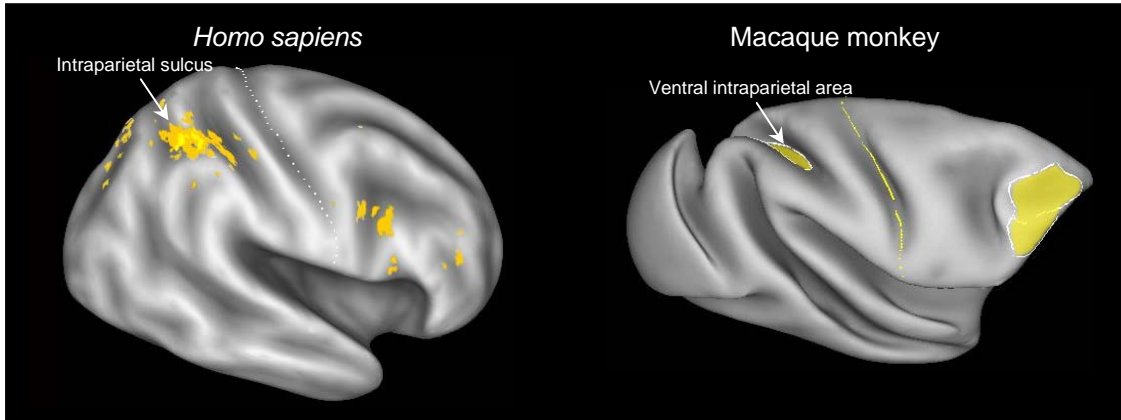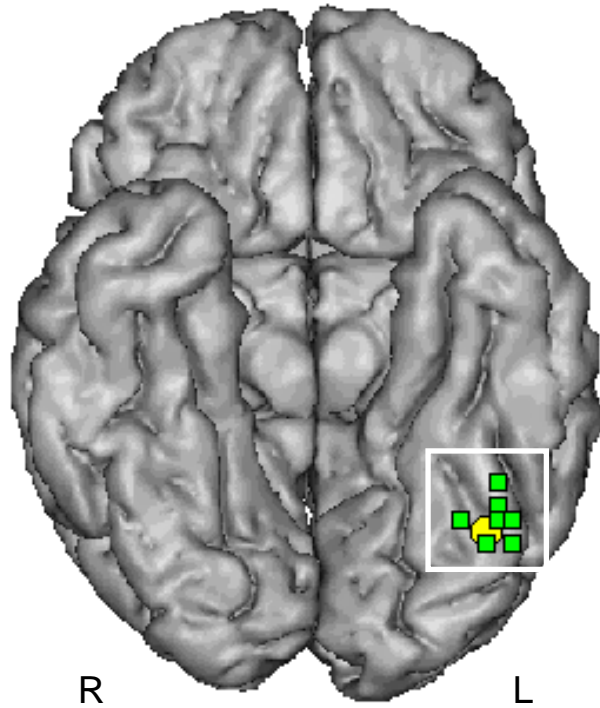Turing, A. M. (1952). The chemical basis of morphogenesis. *Philos Trans R Soc Lond B Biol Sci, 237*, 37-72.

Figure 1

x=-42 y=-57 z=-15

PARENT
versus
PVRFNT

% signal change

0,3

0,2

0,1

0

-0,1

-10   -5   0   5   10   15   20

time (s)

— ◆ — words   — ◆ — words
-- ● -- consonants   -- ● -- consonants

Left Visual Field   **Right Visual Field**