Putting neurons in culture:
The cerebral foundations of reading and mathematics

I. Recycling the visual brain for reading

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Early art forms

Chauvet Cave, Ardèche, France
~32,000 years ago

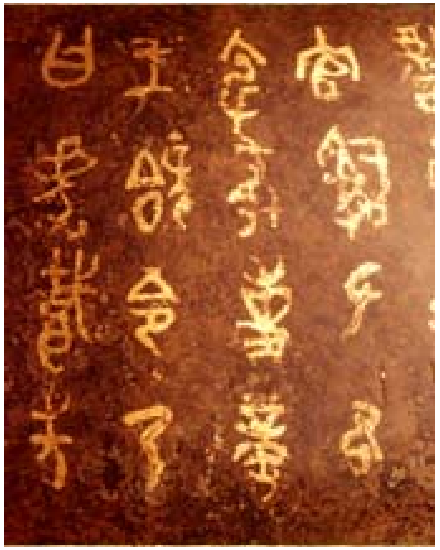
Lascaux cave
~18,000 years ago

Emergence of symbolic writing

Egyptian hieroglyphs

Cuneiform

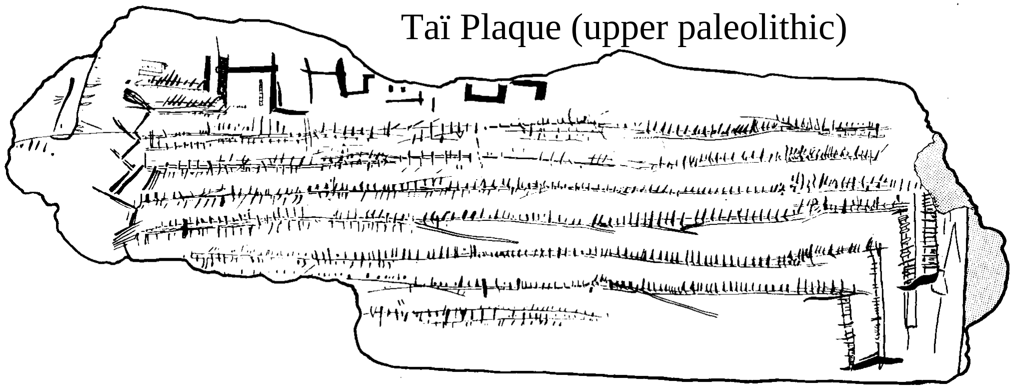
Chinese



Maya

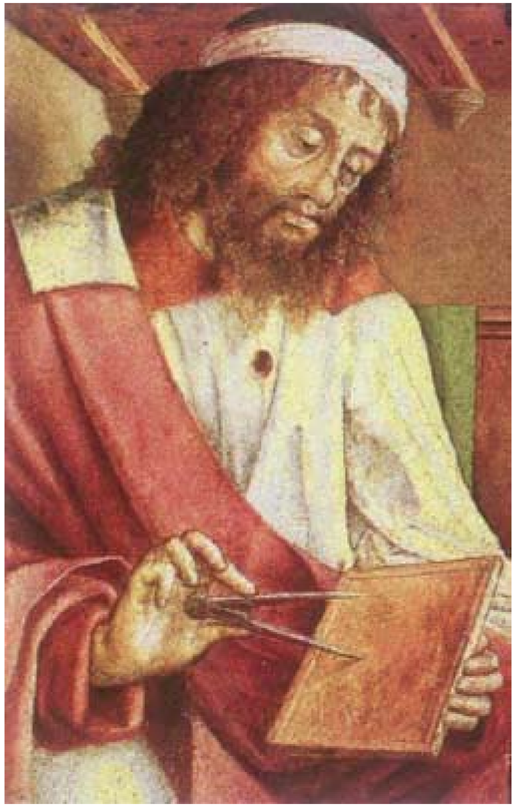
Emergence of symbolic mathematics

Taï Plaque (upper paleolithic)

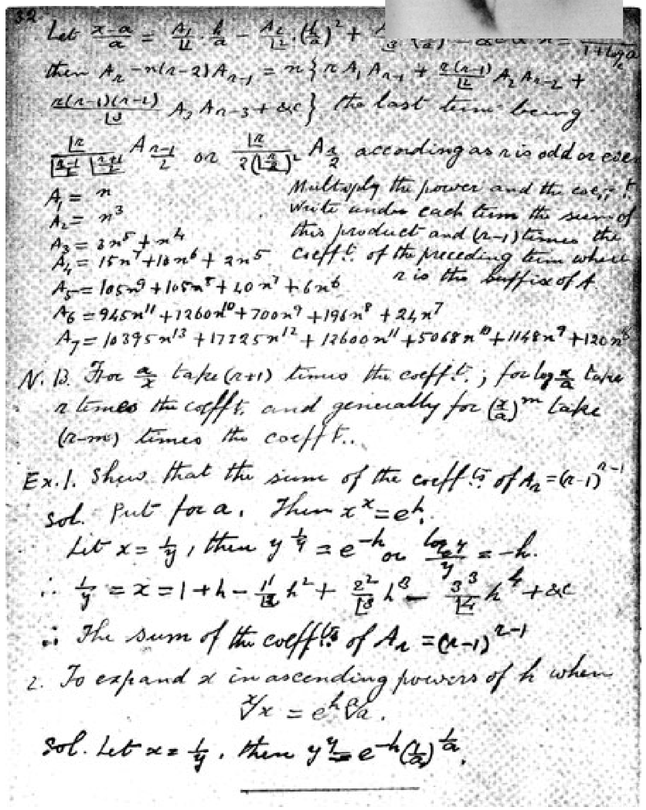


Rhind papyrus

Euclid’s Elements



Ramanujan notebooks



Let $\frac{x-a}{a} = \frac{A_1}{1!}\cdot\frac{h}{a} - \frac{A_2}{2!}\left(\frac{h}{a}\right)^2 + \ldots$

then $A_n - n(n-2)A_{n-1} = n\{n A_1 A_{n-1} + \frac{n(n-1)}{2!} A_2 A_{n-2} + \frac{n(n-1)(n-2)}{3!} A_3 A_{n-3} + \&c\}$ the last term being $\frac{n!}{\frac{n-1}{2}!\,\frac{n+1}{2}!} A_{\frac{n-1}{2}}$ or $\frac{n!}{2(\frac{n}{2}!)^2} A_{\frac{n}{2}}^2$ according as n is odd or even.

$A_1 = n$
$A_2 = n^3$
$A_3 = 3n^5 + n^4$
$A_4 = 15n^7 + 10n^6 + 2n^5$
$A_5 = 105n^9 + 105n^8 + 40n^7 + 6n^6$
$A_6 = 945n^{11} + 1260n^{10} + 700n^9 + 196n^8 + 24n^7$
$A_7 = 10395n^{13} + 17325n^{12} + 12600n^{11} + 5068n^{10} + 1148n^9 + 120n^8$

Multiply the power and the coeff. Write under each term the sum of this product and (n−1) times the coeff. of the preceding term where n is the suffix of A.

N.B. For $\frac{a}{x}$ take (n+1) times the coeff.; for $\log\frac{x}{a}$ take n times the coeff. and generally for $\left(\frac{x}{a}\right)^m$ take (n−m) times the coeff.

Ex. 1. Shew that the sum of the coeff. of $A_n = (n-1)^{n-1}$

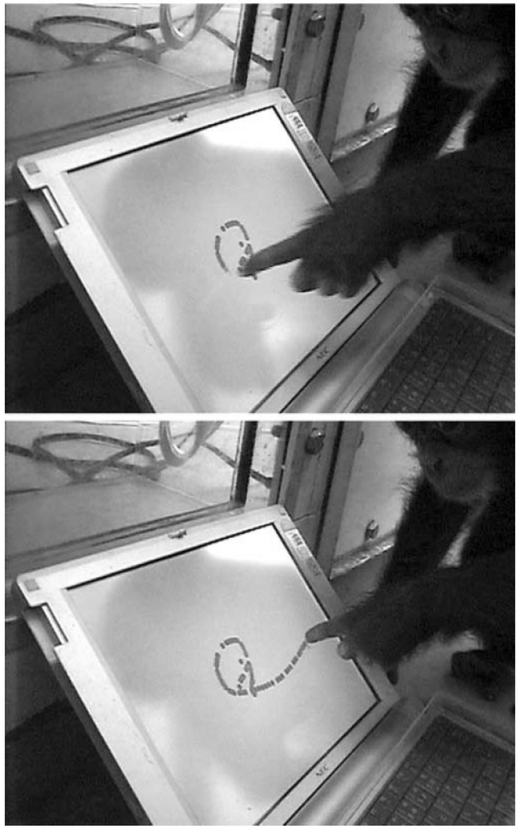
Sol. Put h for a. Then $x^x = e^h$.
Let $x = \frac{1}{y}$, then $y^{\frac{1}{y}} = e^{-h}$ or $\frac{\log y}{y} = -h$.
$\therefore \frac{1}{y} = x = 1 + h - \frac{1}{2!}h^2 + \frac{2^2}{3!}h^3 - \frac{3^3}{4!}h^4 + \&c$
$\therefore$ The sum of the coeff. of $A_n = (n-1)^{n-1}$

2. To expand x in ascending powers of h when $\sqrt[x]{x} = e^h \sqrt[a]{a}$.

Sol. Let $x = \frac{1}{y}$, then $y^y = e^{-h}\left(\frac{1}{a}\right)^{\frac{1}{a}}$.

The cultural singularity of the human primate

A thirteen-month-old chimpanzee traces curves on a graphic tablet (Tanaka et al., 2003)



Composition produced by an adult chimpanzee living semi-independently in the Mefou Forest Reserve in Cameroon (© Canadian Ape Alliance)

- Other primates have a clear ability to learn new skills, tools (Iriki, 2005) and even symbols such as Arabic digits (Matsuzawa, 1985)
- They possess rudiments of cultures (Whiten et al., 1999) which are locally transmitted.
- But they exhibit virtually no **cultural creativity**

What are the biological foundations of human culture?

- What brain architectures support cultural inventions such as reading and arithmetic?
- What novel features of brain organization, if any, make us « the cultural species » by excellence, the only species capable of cultural invention?

According to the « standard social science model », brain architecture is largely **irrelevant** when it comes to understanding high-level cultural acquisitions.
Most social scientists implicitly or explicitly adhere to a view that I call « **generalized brain plasticity and cultural relativism** », reminiscent of the « blank slate ».

> *John Locke: « **Let us then suppose the mind to be white paper void of all characters, without any ideas. How comes it to be furnished?** »*

Freed from the constraints of biology, the human brain, unlike that of any other animal species, would be capable of absorbing any form of culture.

*Noam Chomsky (Knowledge of Language, 1986): "[According to a commonly held view,] it is the richness and specificity of **instinct of animals** that accounts for their remarkable achievements in some domains and lack of ability in others, so the argument runs, whereas **humans, lacking such articulated instinctual structure**, are free to think, speak, discover and understand without such limits. Both the logic of the problem, and what we are now coming to understand, suggest that **this is not the correct way to identify the position of humans in the animal world**."*

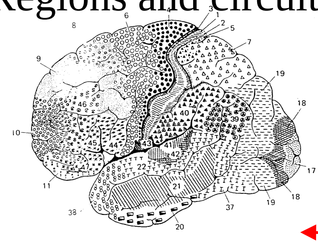
Does brain organization constrain cultural acquisitions?

~~Is the brain even relevant?~~
~~• Constructivist neurobiology~~
~~e.g. Quartz & Sejnowski (1997): «developing cortex is largely equipotential and free of domain-specific structure»~~
~~• Functionalist psychology~~
~~e.g. Johnson-Laird: « the physical nature [of the brain] places no constraints on the pattern of thought »~~

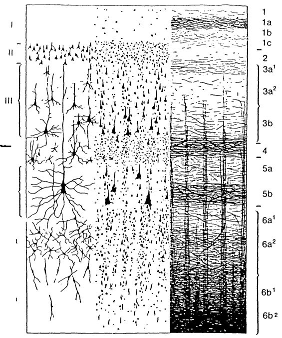
Culture and education

Behavior

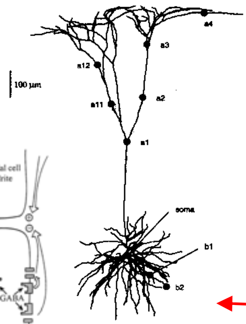
Regions and circuits



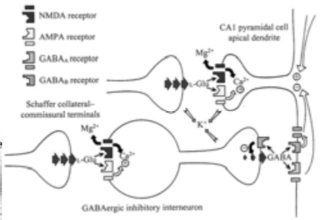
Cortical columns



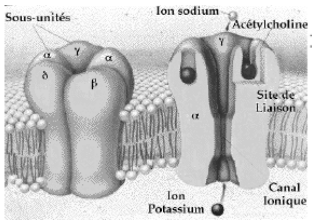
Neurons



Synapses

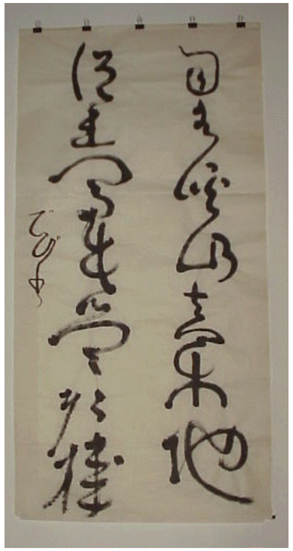


Receptors



Search for **bridging laws** between nested levels



Putting neurons in culture

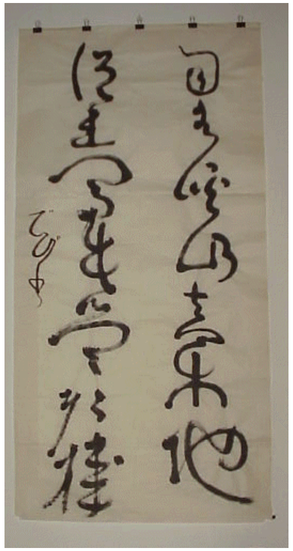
- **Non-invasive neuro-imaging techniques** now allow us to study the brain mechanisms underlying cultural tools.
- For both reading and arithmetic, in spite of cultural variability, we find **reproducible** and partially **specialized** brain regions.
- These findings raise an obvious **paradox**, as evolution did not have enough time to adapt brain architecture to these recent cultural objects.

The “neuronal recycling” model:

- The architecture of our primate brain is tightly limited.
- It is laid down under genetic control, though with **a fringe of variability and plasticity** (itself evolved and under genetic control).
- New cultural acquisitions are only possibly inasmuch as they fit within this fringe. Each **cultural object** must find its **neuronal niche**.
- Far from being a blank slate, our brain adapts to a given cultural environment by **minimally reconverting or “recycling”** its existing cerebral predispositions to a different use.

Consequences:

- Numerous **cultural invariants** should be identified and ultimately related to neuronal constraints
- The strengths and weaknesses of our brain architecture should determine the speed and ease of **cultural learning.**



Plan of the three talks

- **Today: « Recycling the visual brain for reading »**
- Cerebral and neuronal organization of the visual word recognition system
- Cross-cultural regularities in writing systems and in reading acquisition

- **Wednesday: « Space, time and number: cerebral foundations of mathematical intuitions »**
- Cognitive and neuronal foundations of elementary mathematical objects
- How are these elementary representations changed by the acquisition of symbols?

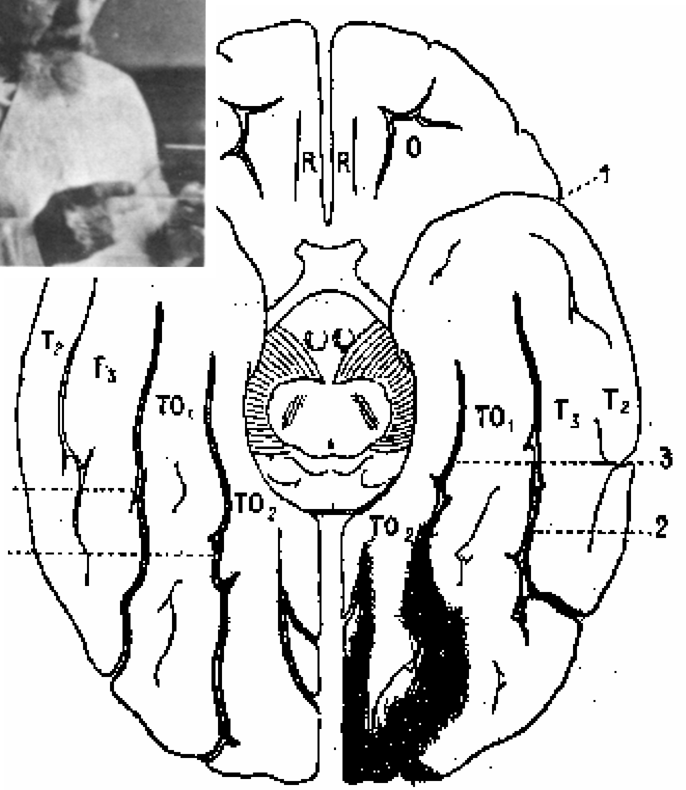
- **Thursday: « The human Turing machine »**
- Why are we the only primates capable of cultural invention?
- Existence of a flexible « global workspace system », capable of top-down recruitment of other brain processors, and implementing a rudimentary « Turing machine ».

The brain architecture for reading

We are absurdly accustomed to the miracle of a few written signs being able to contain immortal imagery, involutions of thought, new worlds with live people, speaking, weeping, laughing. (…) What if we awake one day, all of us, and find ourselves utterly unable to read?

Vladimir Nabokov, *Pale Fire*

Déjerine, 1892



In October 1888, Mister C., a retired salesman, suddenly realises that he can no longer read a single word

Pure alexia

-Word reading is severely impaired

-Object naming and face recognition are preserved

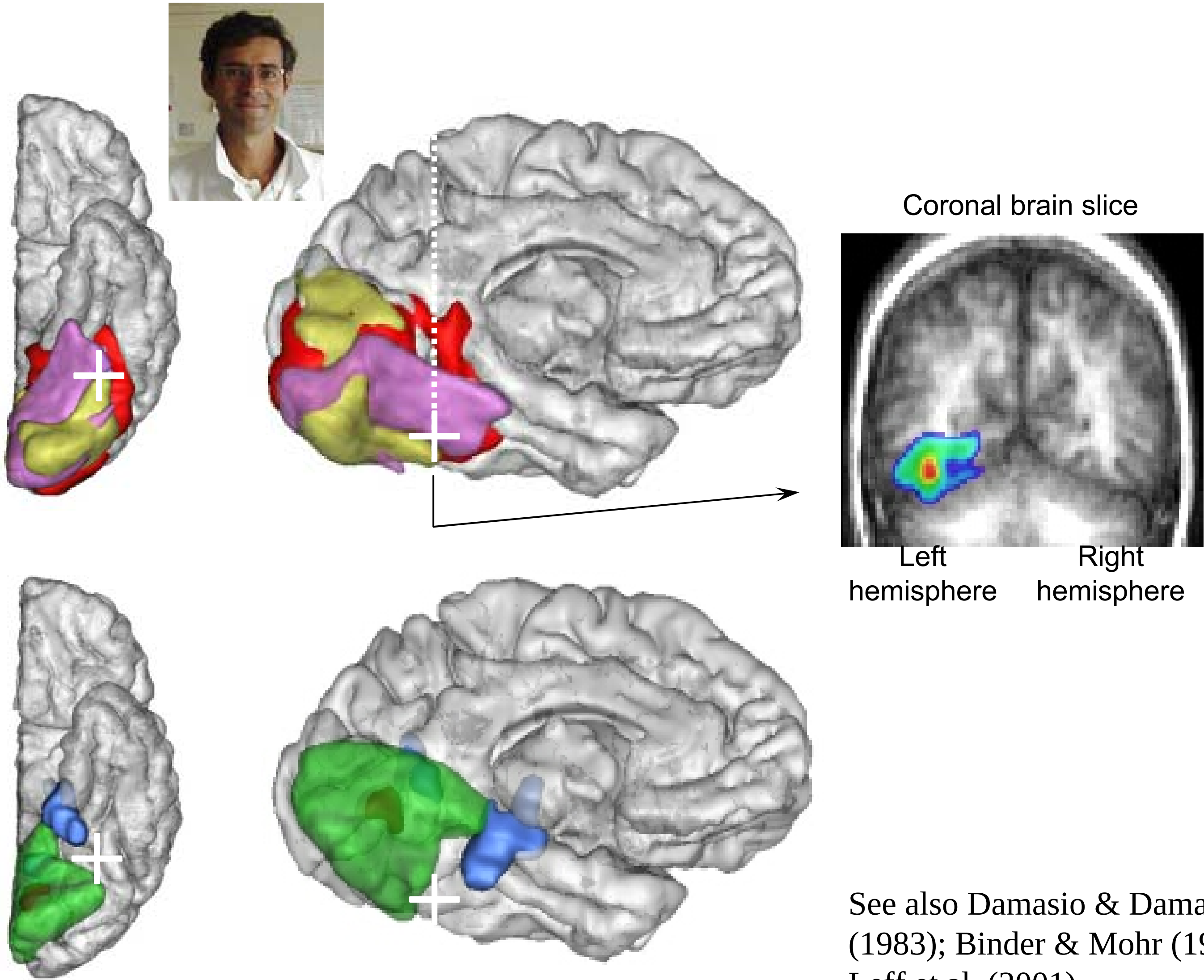
-Speech perception, production, and even writing are preserved

Pinpointing the lesion site associated with pure alexia

Laurent Cohen and collaborators, 2003

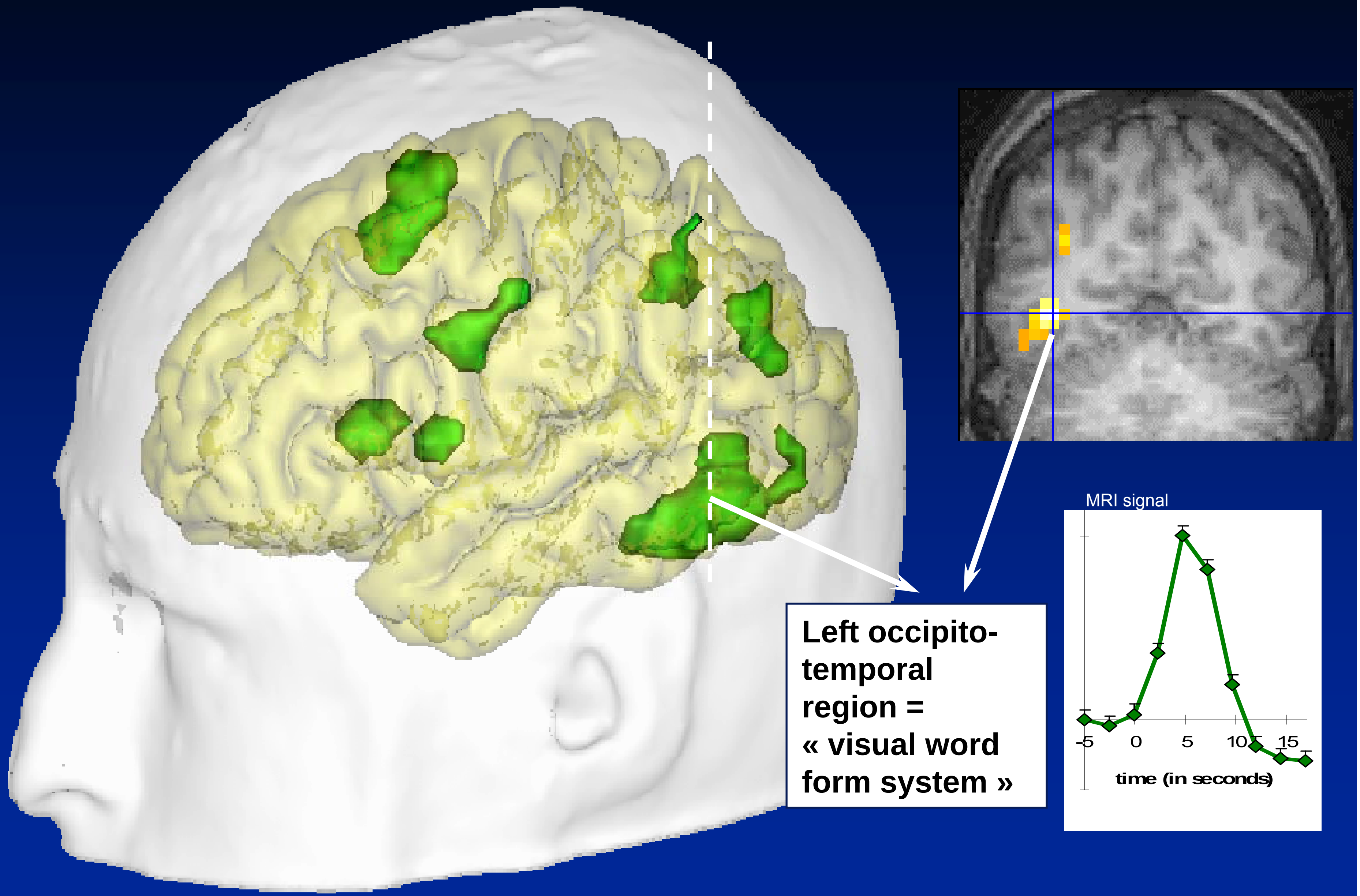
3 patients
***with* alexia**

2 patients
without
alexia



See also Damasio & Damasio (1983); Binder & Mohr (1992); Leff et al. (2001)

fMRI studies of reading point to a similar site

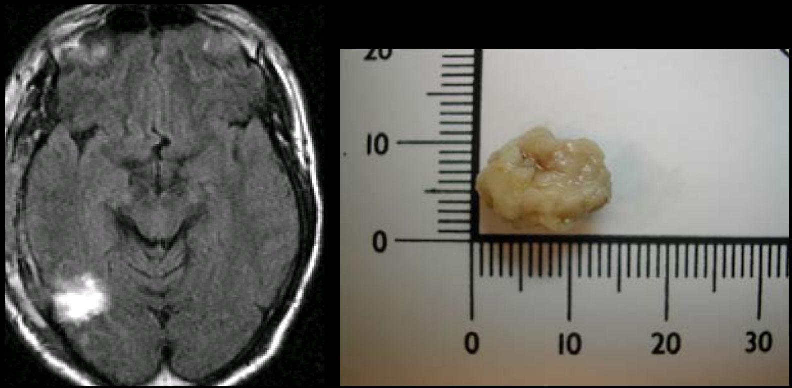


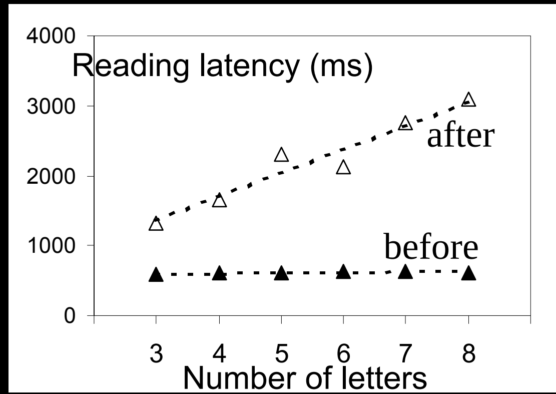
Left occipito-temporal region = « visual word form system »

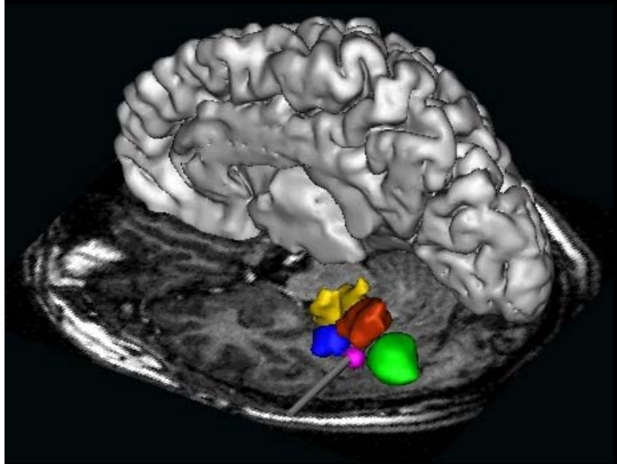
Specialization for reading in left infero-temporal cortex: A single-case study

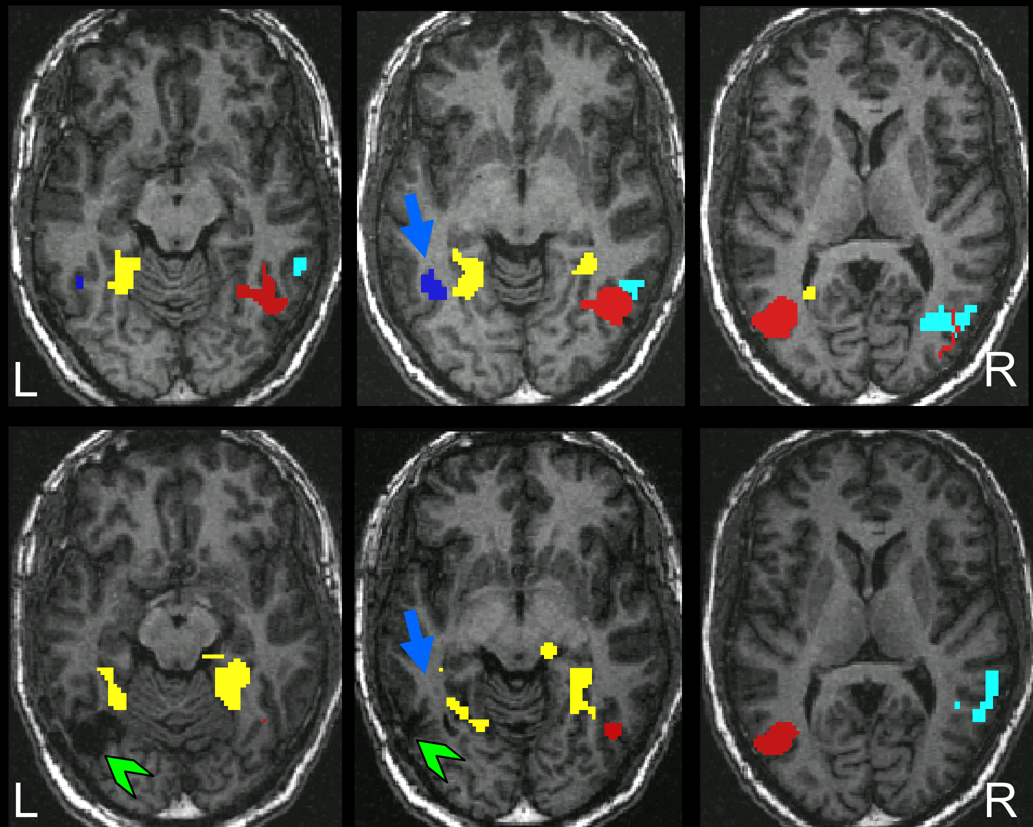
with R. Gaillard, L. Cohen, L. Naccache, C. Adam, M. Baulac (*Neuron*, 2006)

Left occipito-temporal resection









Z=-12 Z=-6 Z=+6

Houses

Faces

Words

Tools

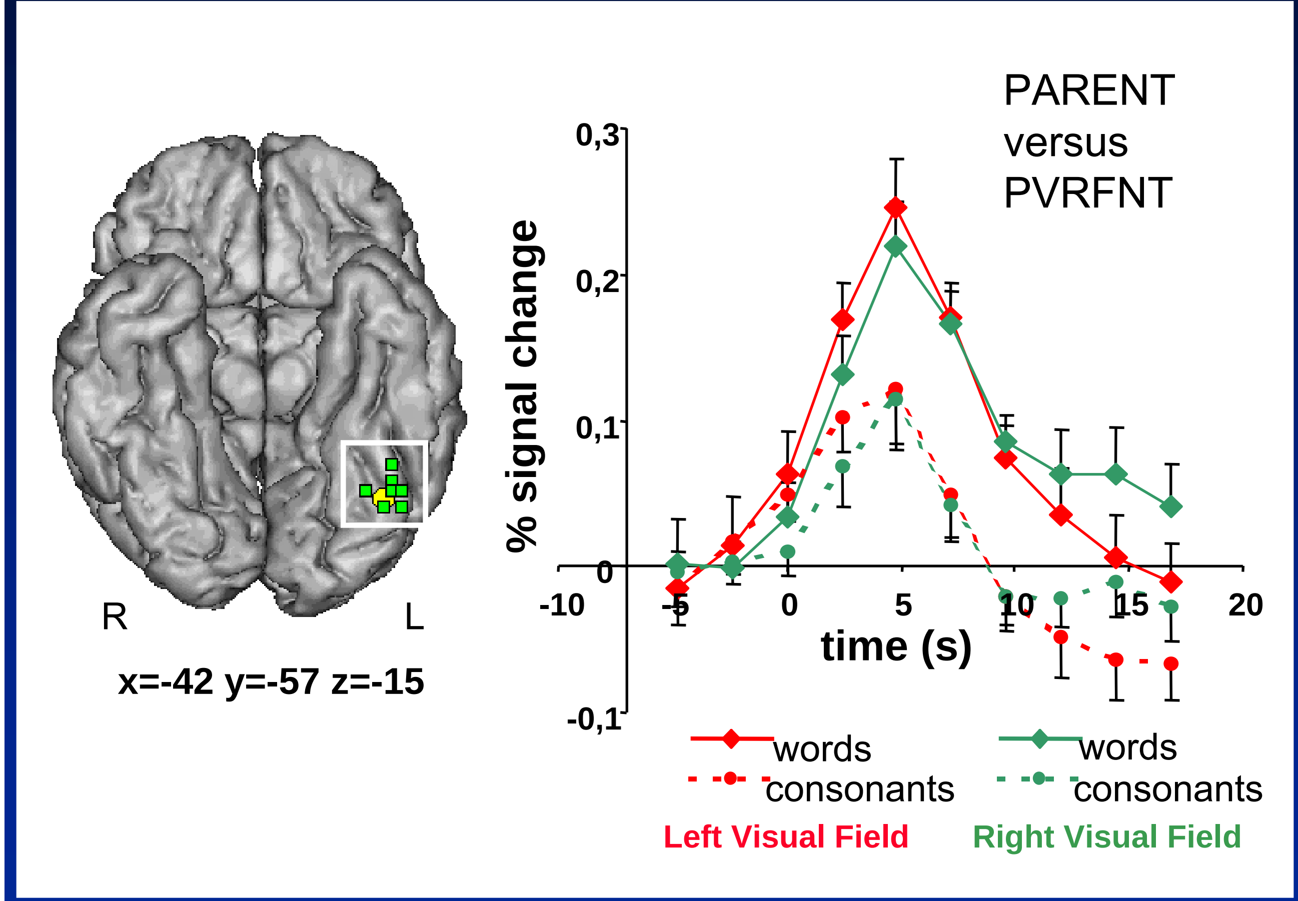
Control = Scrambled

After surgery

lesion

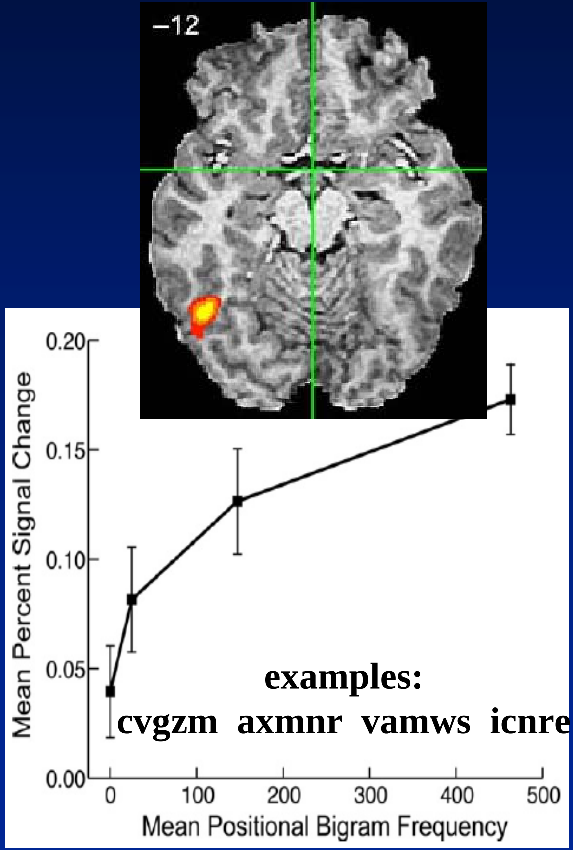
The visual word form area adapts to recurrent writing patterns in a given culture

It responds more to words than to consonant strings



Cohen, L., Lehericy, S., Chochon, F., Lemer, C., Rivaud, S., & Dehaene, S. (2002). *Brain, 125*, 1054-1069.

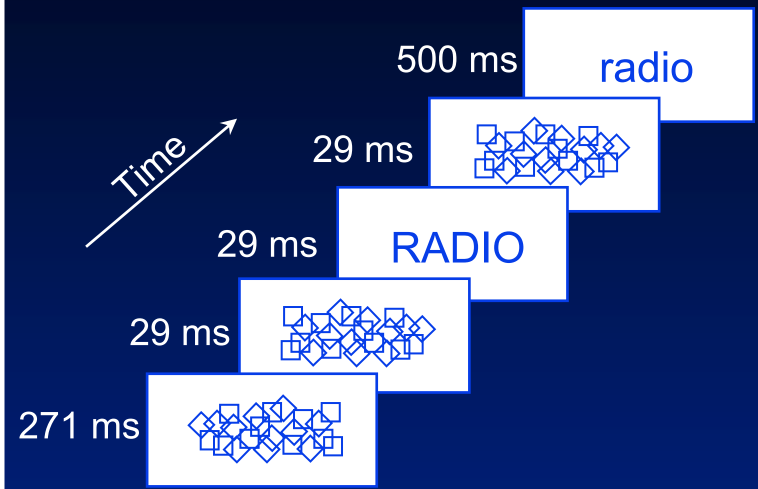
It prefers non-words made of frequent bigrams



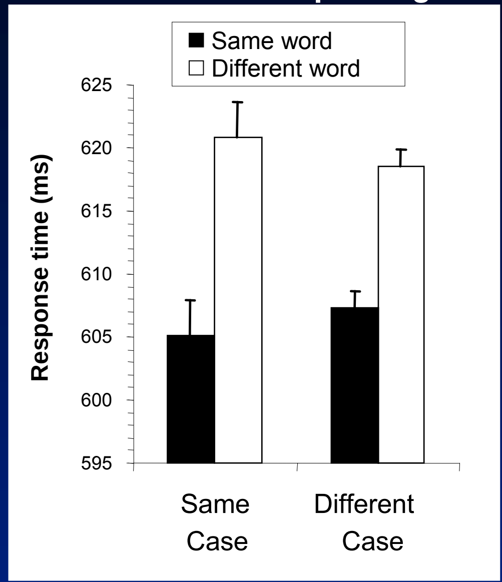
Binder et al. (2006)
Neuroimage

Invariance for case in the visual word form area

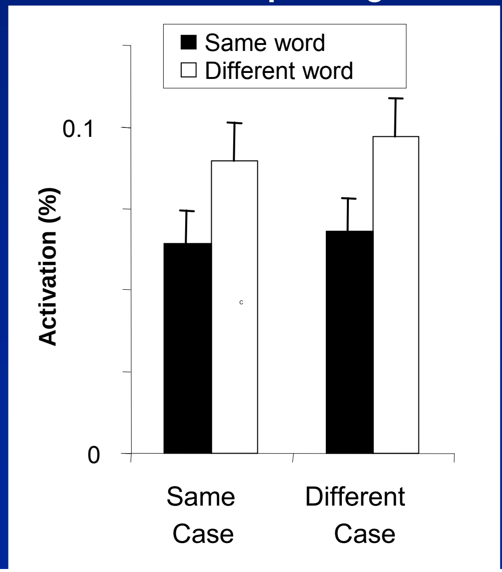
Dehaene et al, *Nature Neuroscience*, 2001; *Psychological Science*, 2004

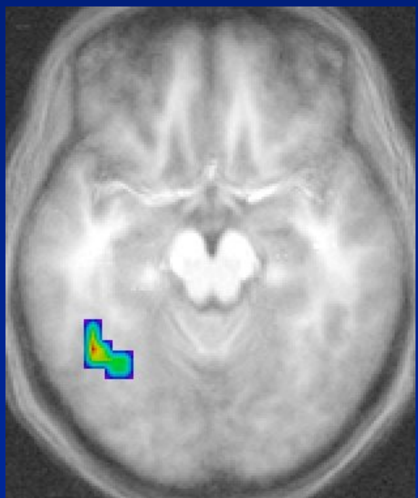


Behavioral priming



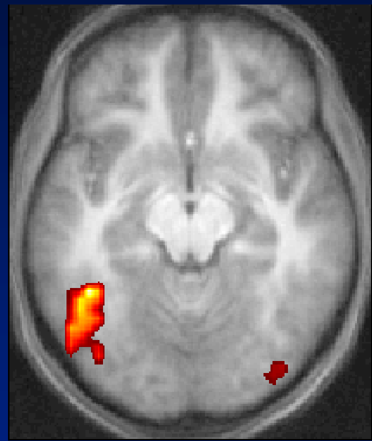
fMRI priming



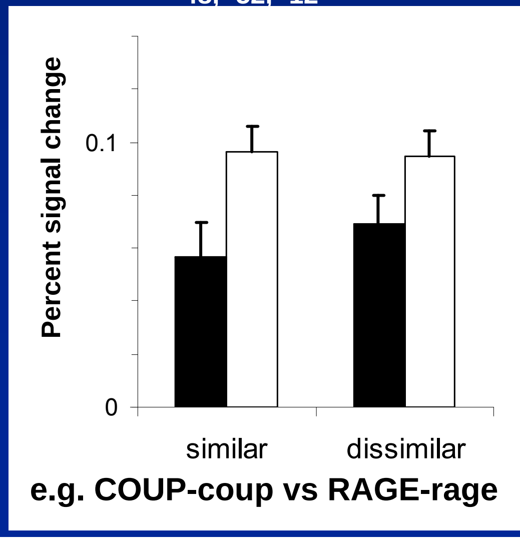


Left fusiform
(-44, -52, -20)

Case-invariant priming independent of letter similarity



Left fusiform
-48, -52, -12



The visual word form area activates at a similar location in all writing systems (English, French, Hebrew, Japanese, Chinese)

e.g. in Japanese

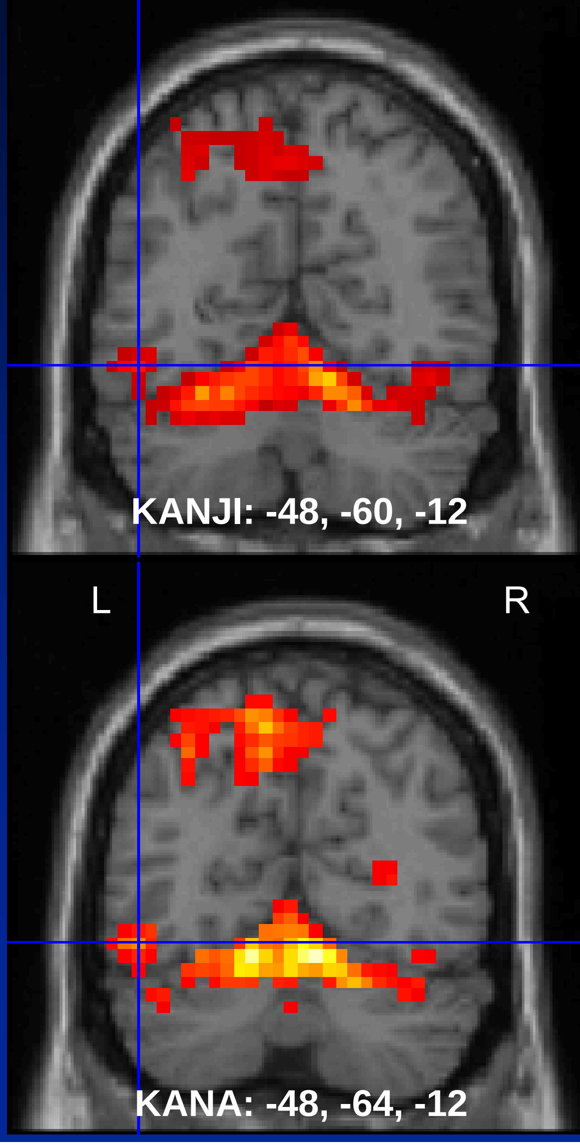
Kanji

神	/kami/
神社	/jiN-ja/
神経	/shiN-kei/
精神	/sei-shiN/
神主	/kaN-nushi/
神戸	/kou-be/

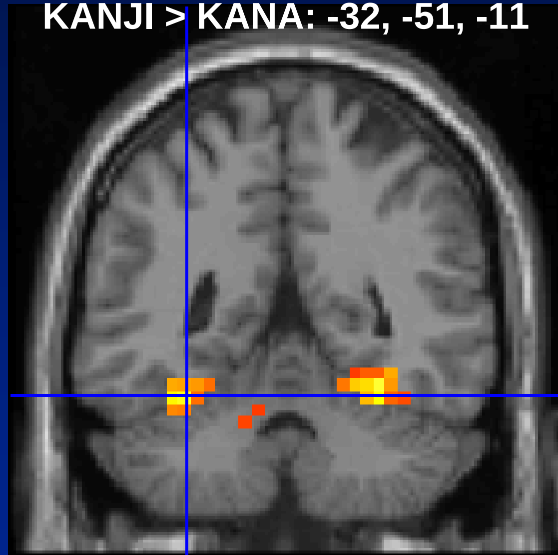
Kana

か	/ka/
かみ	/ka-mi/
かさ	/ka-sa/
あか	/a-ka/
たから	/ta-ka-ra/

Joint activation of the left visual word form area



Slight mesial displacement and greater right-hemisphere contribution in Kanji

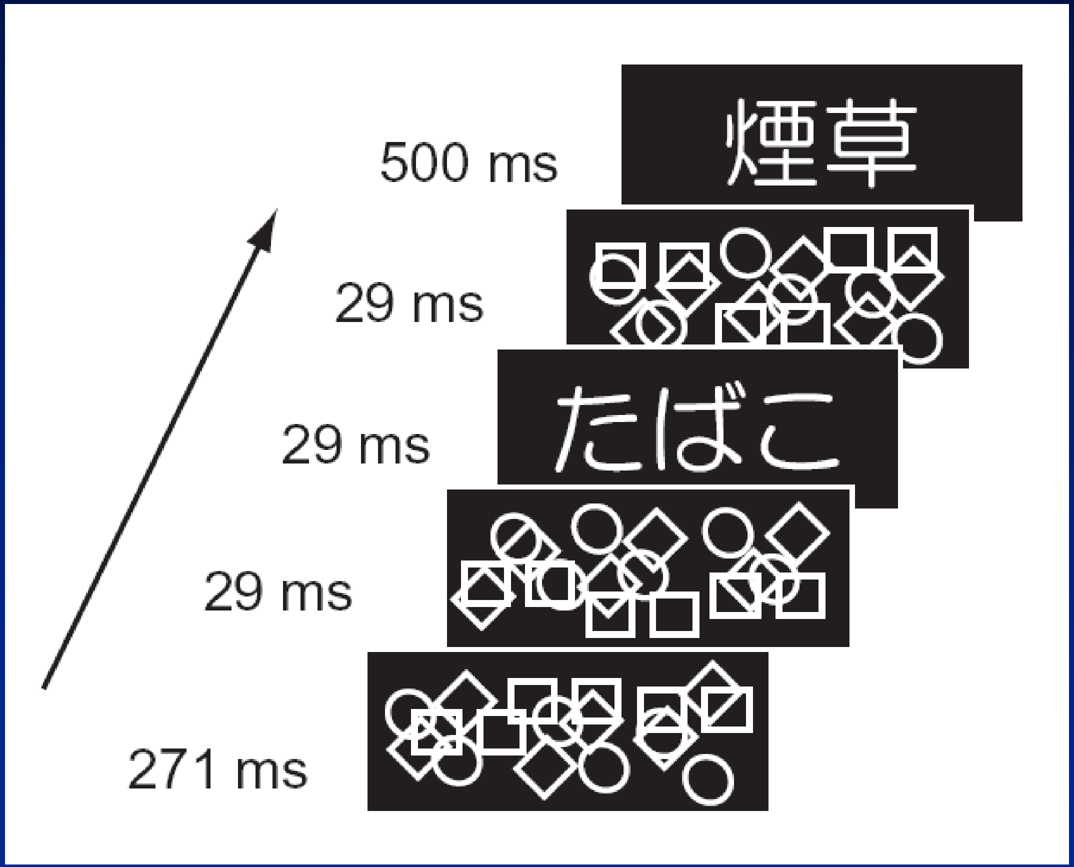


Nakamura, Dehaene et al., JOCN, 2005

Priming within and across scripts in Japanese subjects

Design:

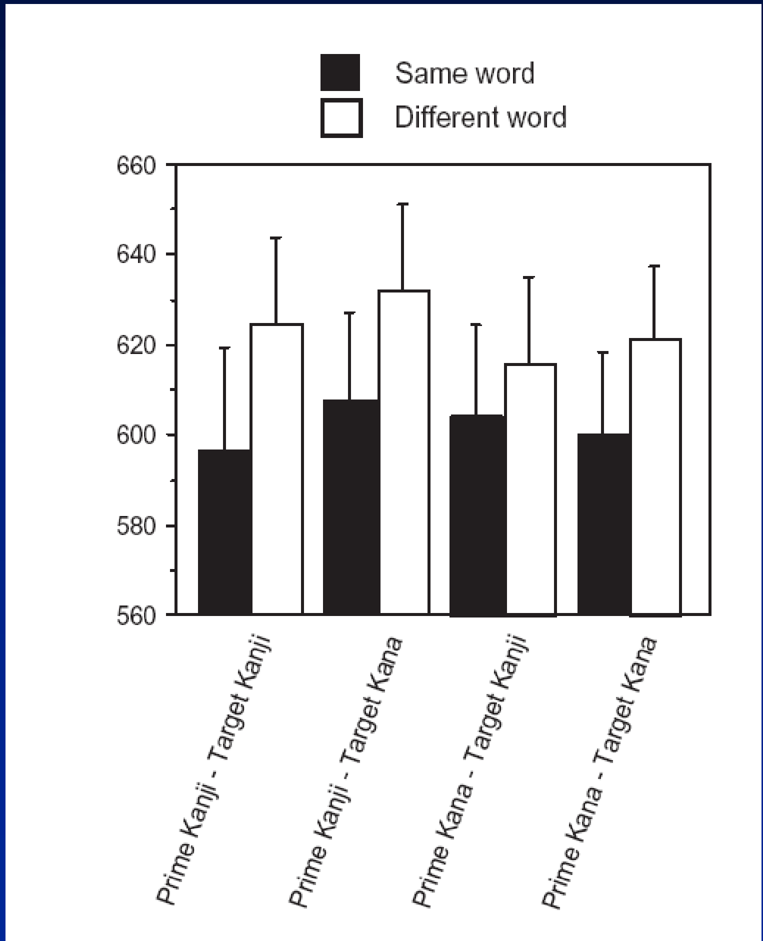
- Targets and primes can appear in Kanji or in Kana
- Task = semantic classification (natural/man-made)



Nakamura, Dehaene et al., JOCN, 2005

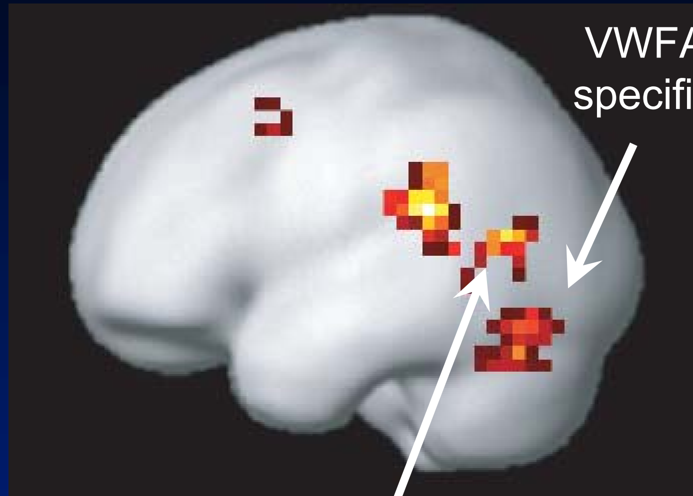
Repetition priming in Japanese

Within and cross-script priming in response times



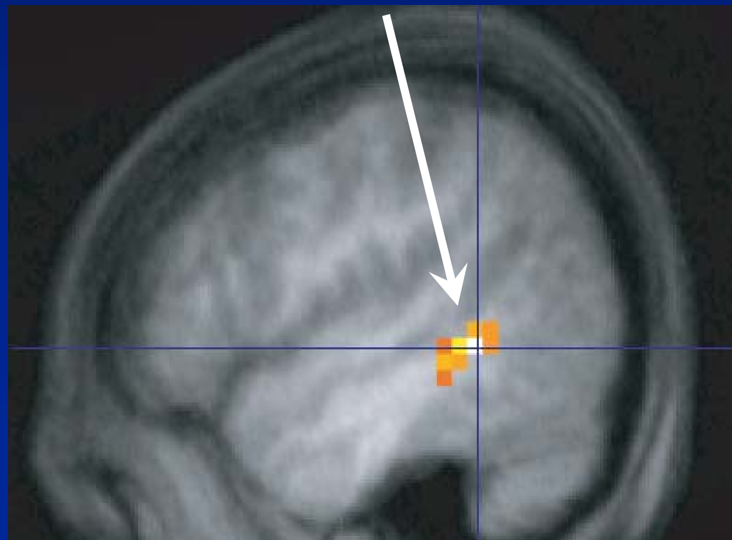
Nakamura, Dehaene et al., JOCN, 2005

Repetition priming with Kanji primes and Kanji targets



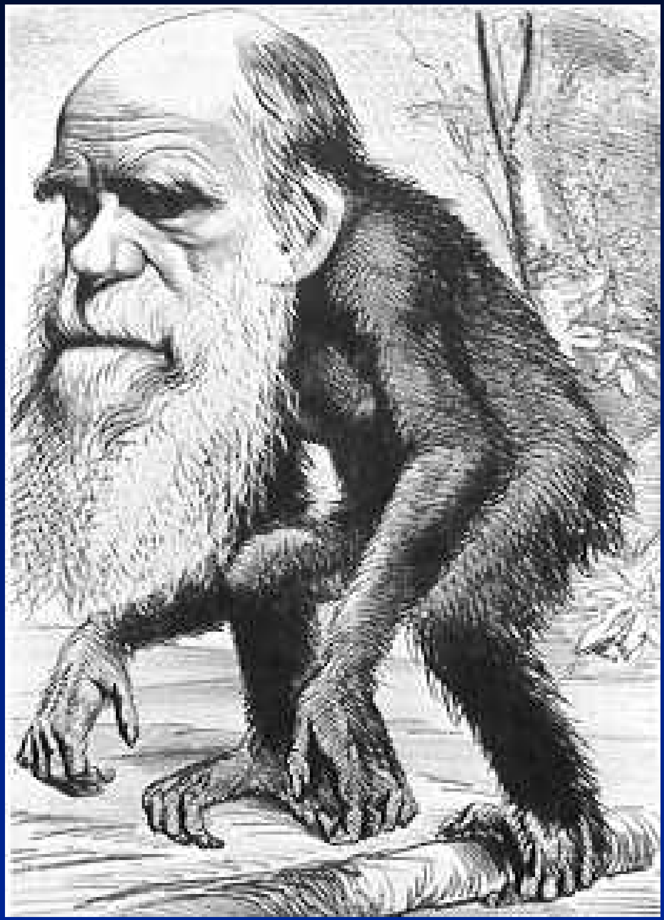
VWFA: Script-specific priming

Left middle temporal region: Cross-script priming (semantic?)

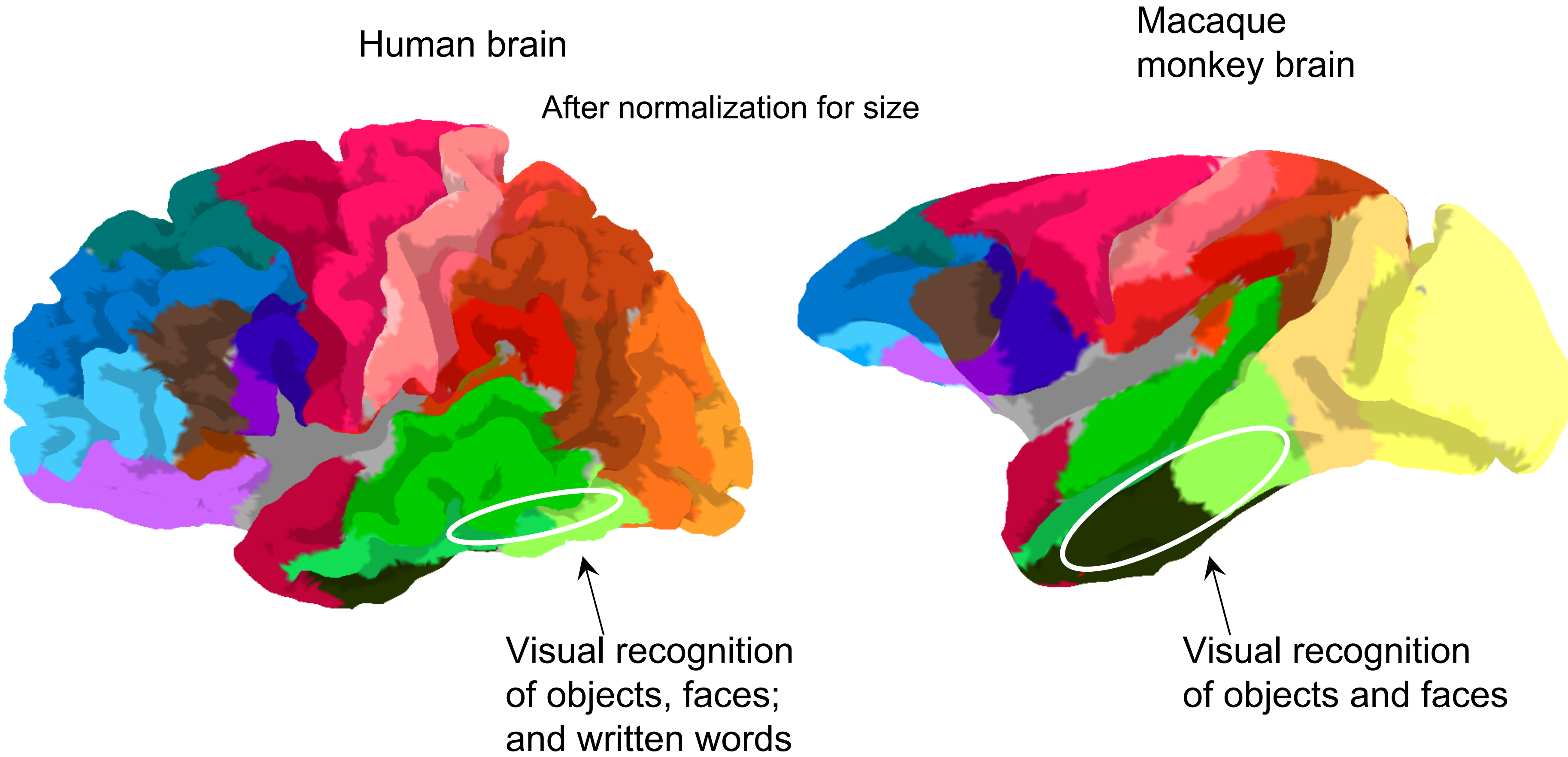


The « paradox of reading »

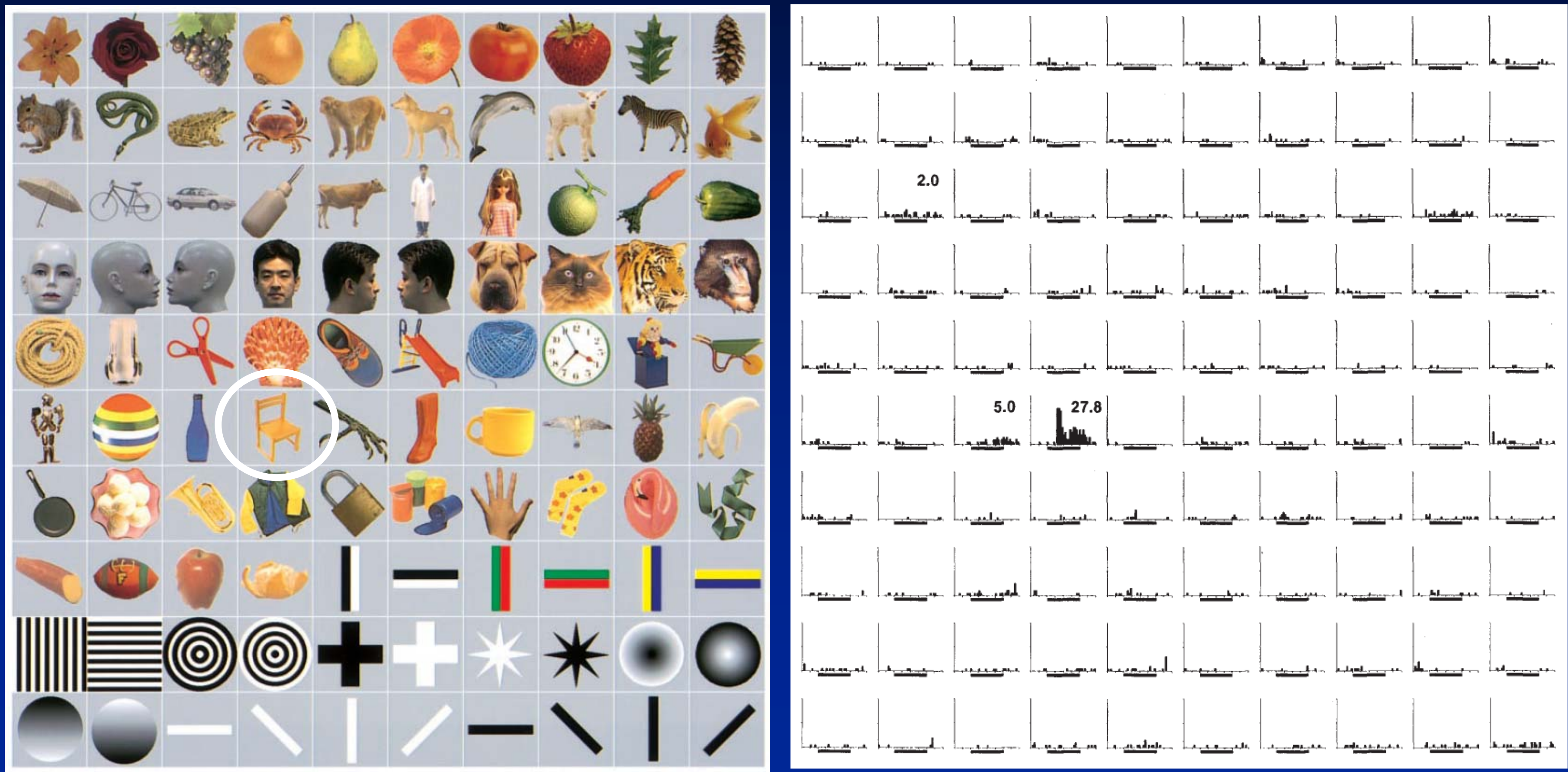
- All good readers activate a reproducible and restricted brain area, part of which is highly attuned to invariant visual word recognition.
- The localization of this area is reproducible across individuals and cultures (within 1 cm)
- How is this possible?
- This part of the visual system has an evolutionarily older role in object recognition. We « recycle » it for reading
- Elementary shape recognition, position- and size-invariance are already present in this area in macaque monkeys
- Case invariance can be understood as a kind of « viewpoint » invariance



What is the prior function of the visual word form area in the monkey brain?

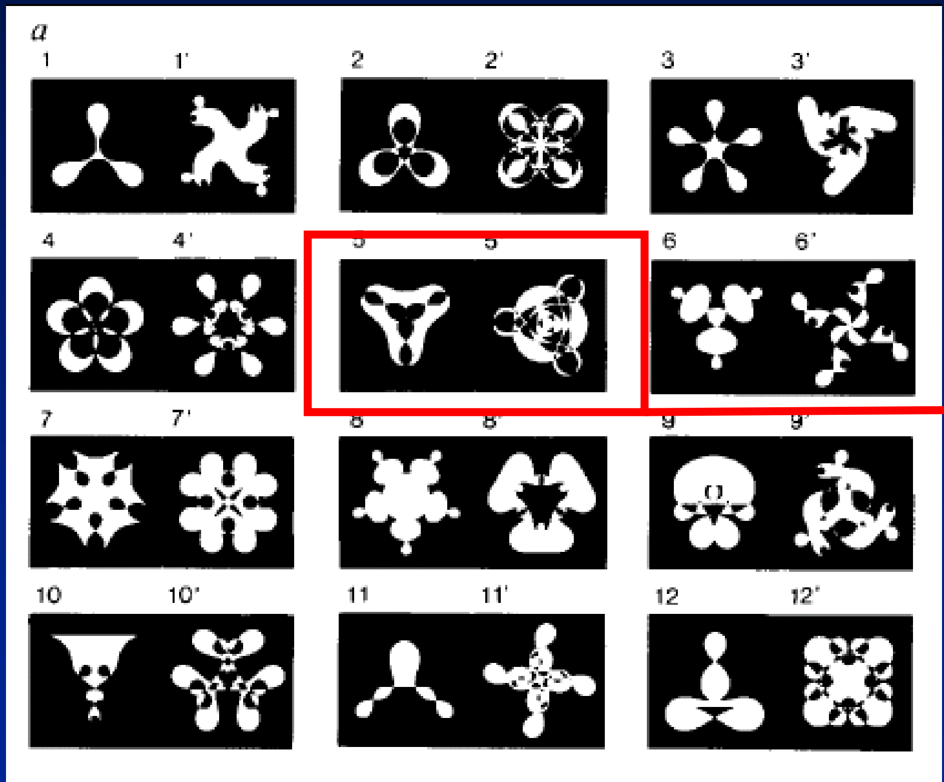


Infero-temporal neurons are selective for objects or their parts



Tamura et Tanaka, 2001

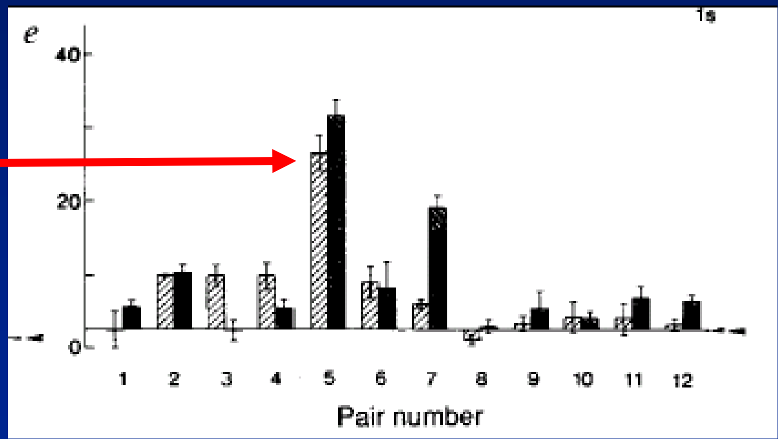
Evidence for plasticity and arbitrary learning in infero-temporal cortex



Infero-temporal neurons learn

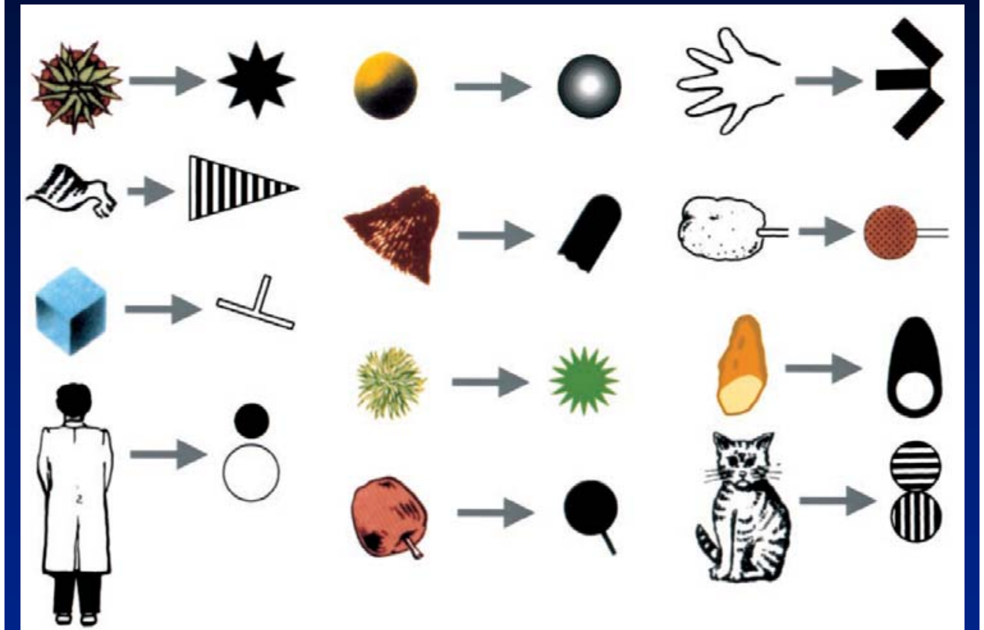
- to respond to arbitrary shapes of fractals

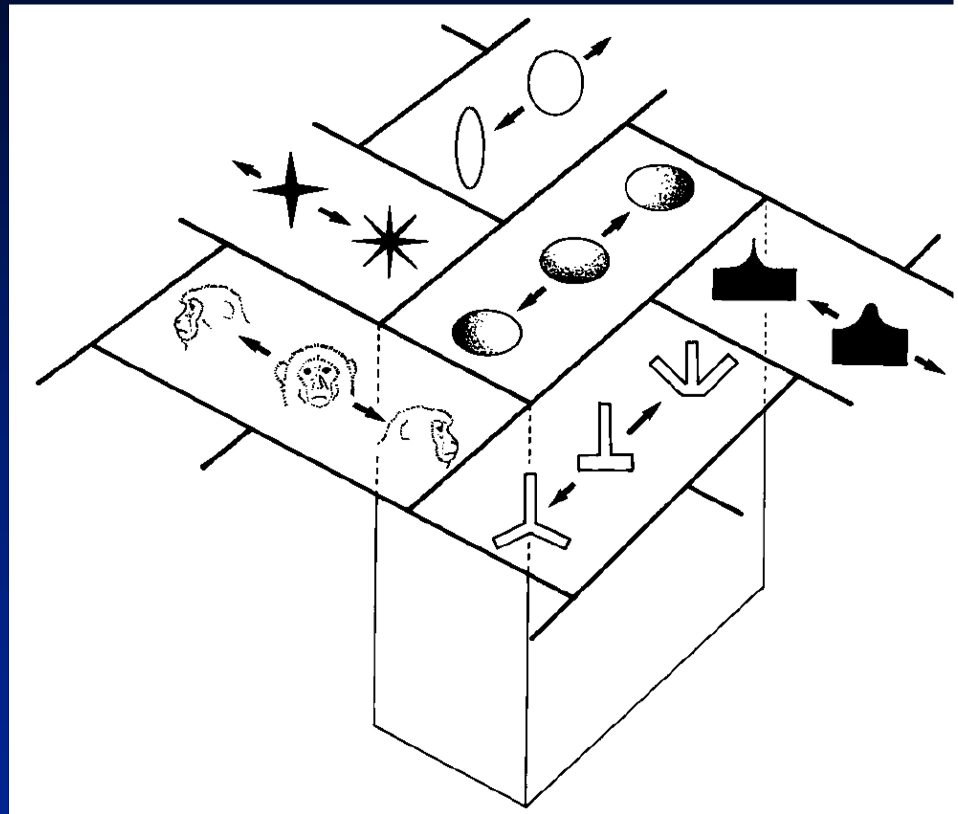
- to pair frequently associated arbitrary shapes



Sakai & Miyashita, *Nature*, 1991

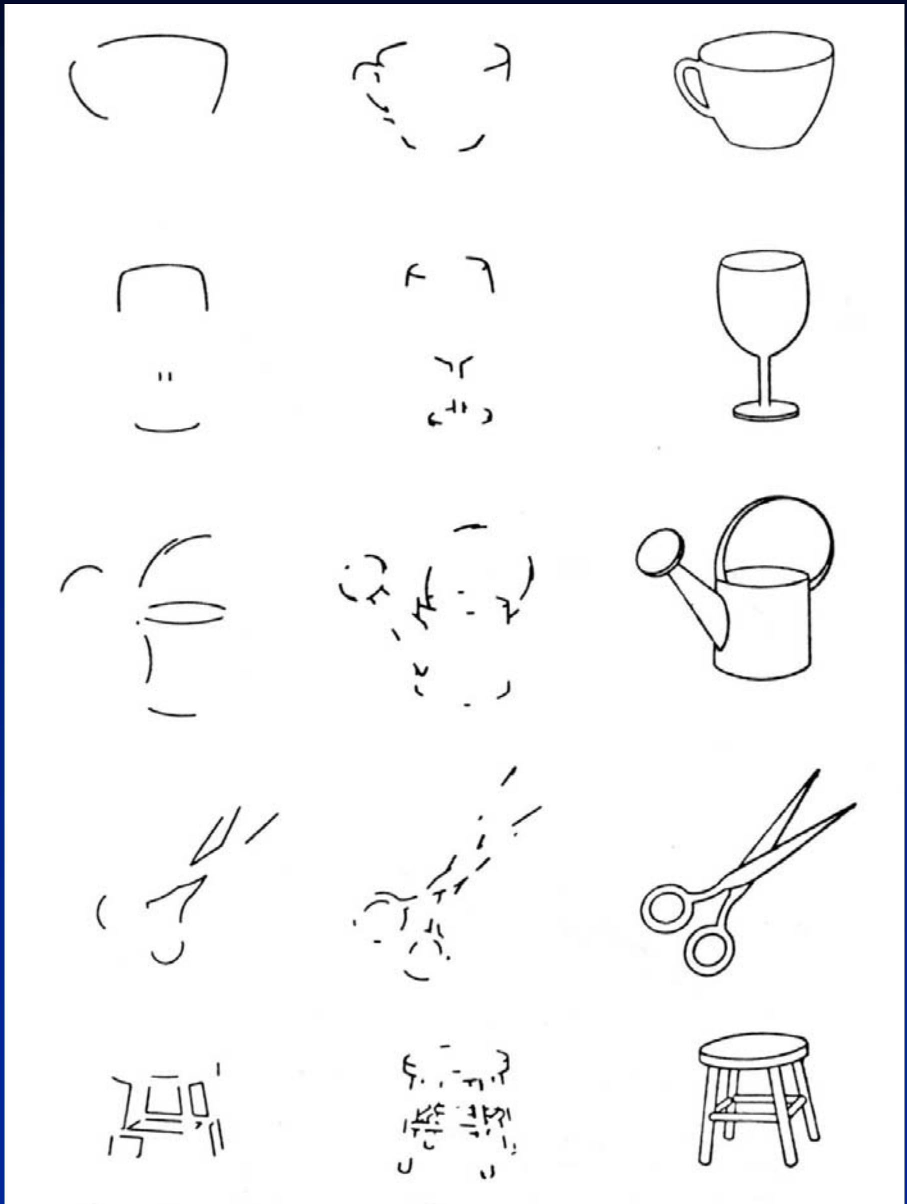
An « alphabet » of object features in macaque infero-temporal cortex

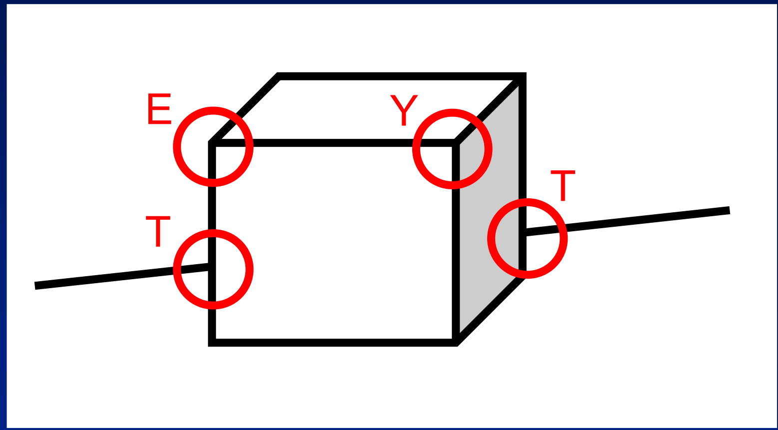




K. Tanaka, 1996

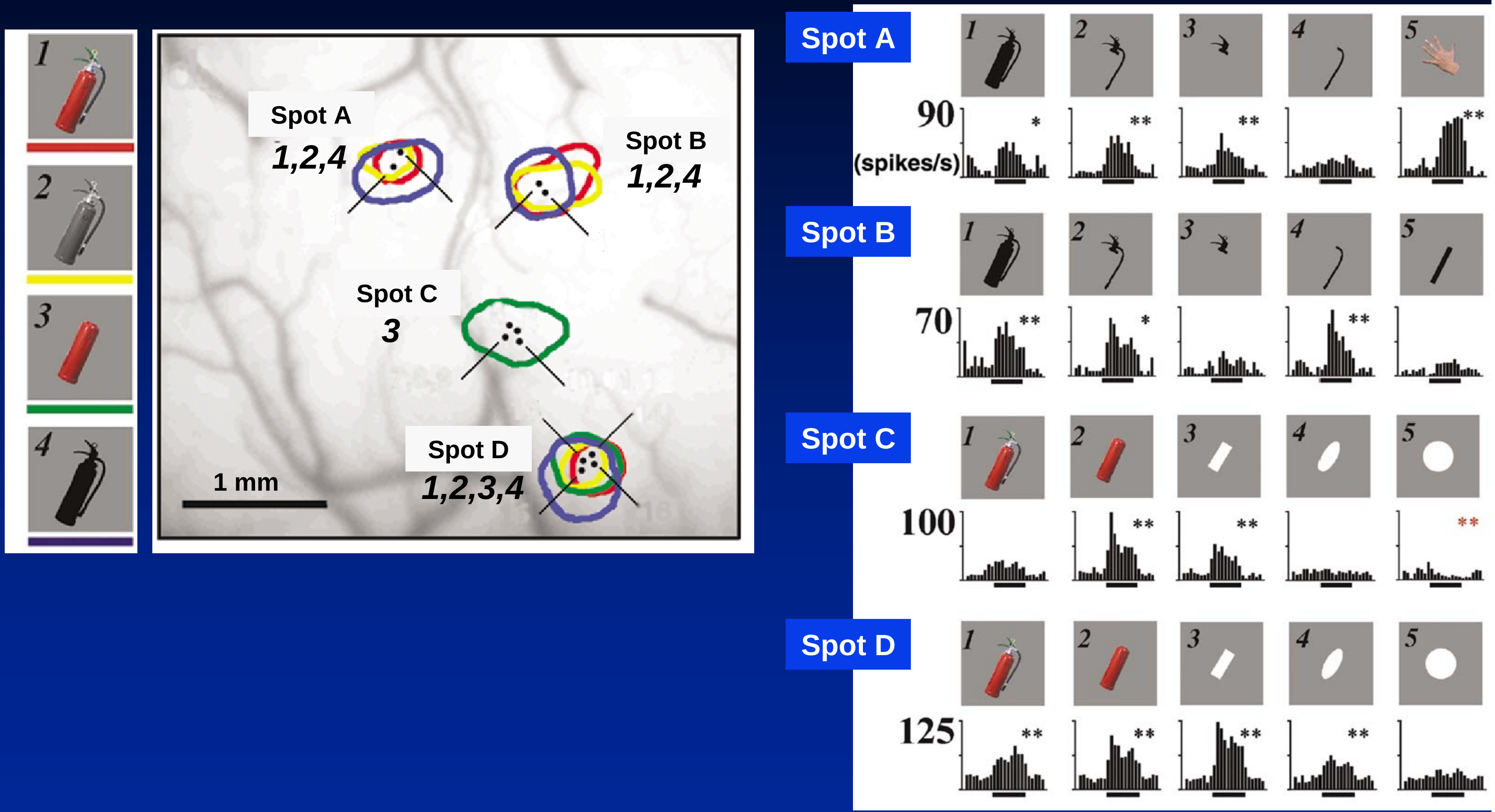
Origins of the monkey infero-temporal « alphabet » : Some neurons may encode non-accidental properties



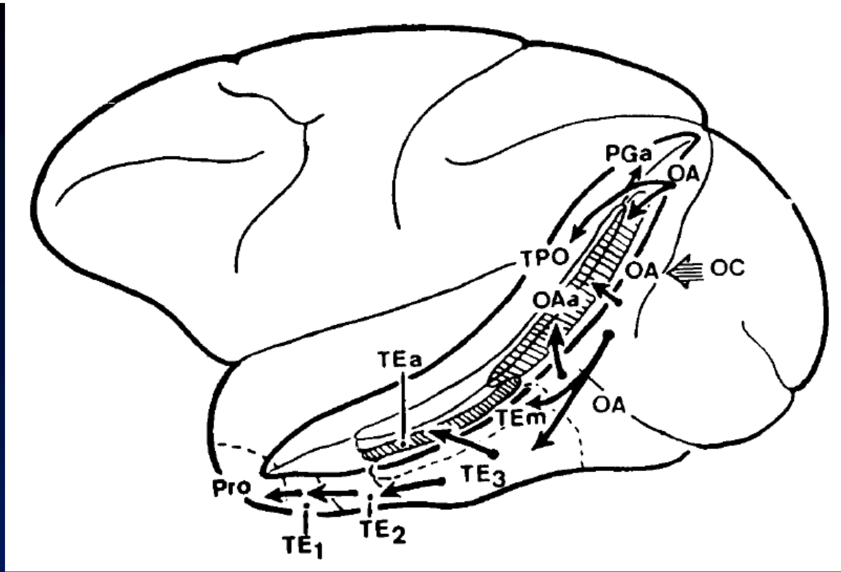


Biederman, *Psychological Review*, 1987

Each object is represented by IT neurons according to the arrangement of its parts

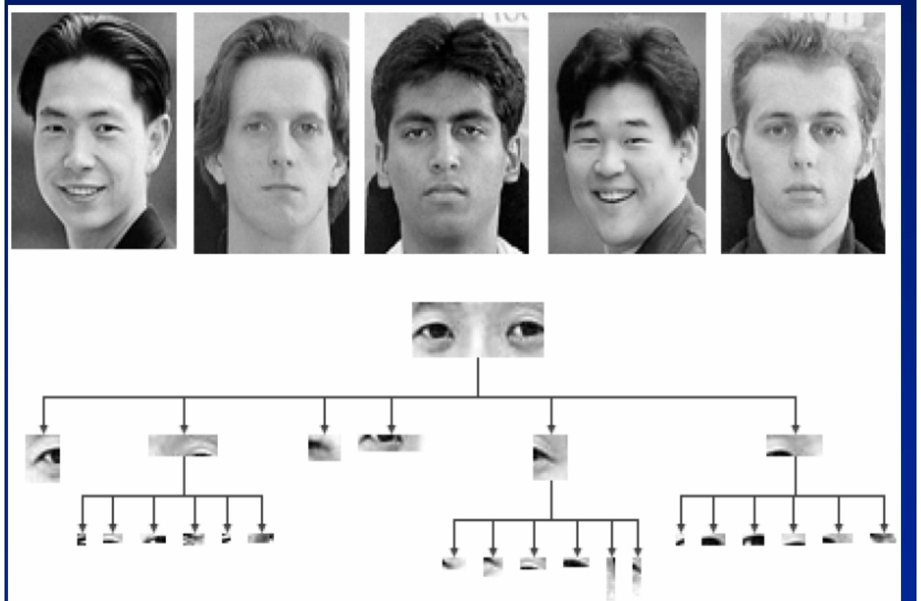


Tsunoda et al., with Tanifuji, *Nature Neuroscience* 2001

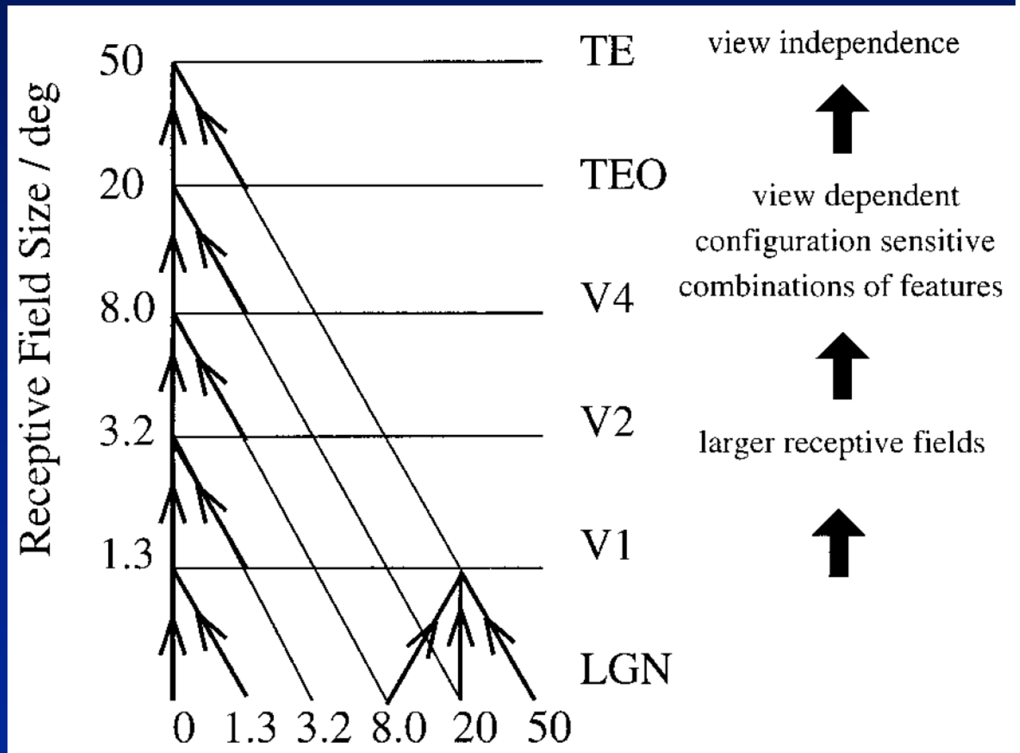


A visual hierarchy achieves invariant recognition in the primate visual system

- Rolls, *Neuron* 2000
- see also Tanaka, Logothetis, Poggio, Perrett, etc.

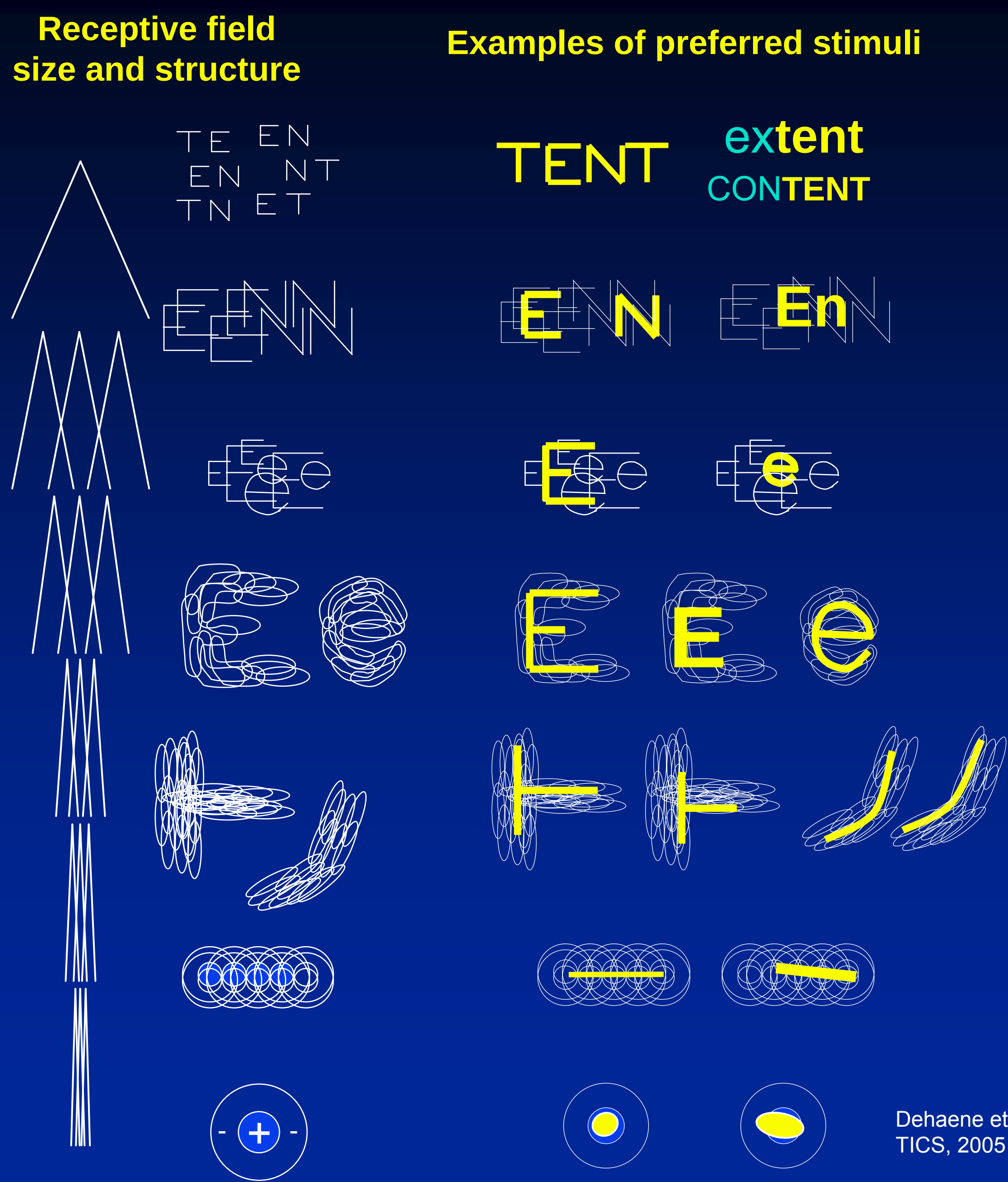


Shimon Ullman



Local Combination Detectors: A model of invariant visual word recognition

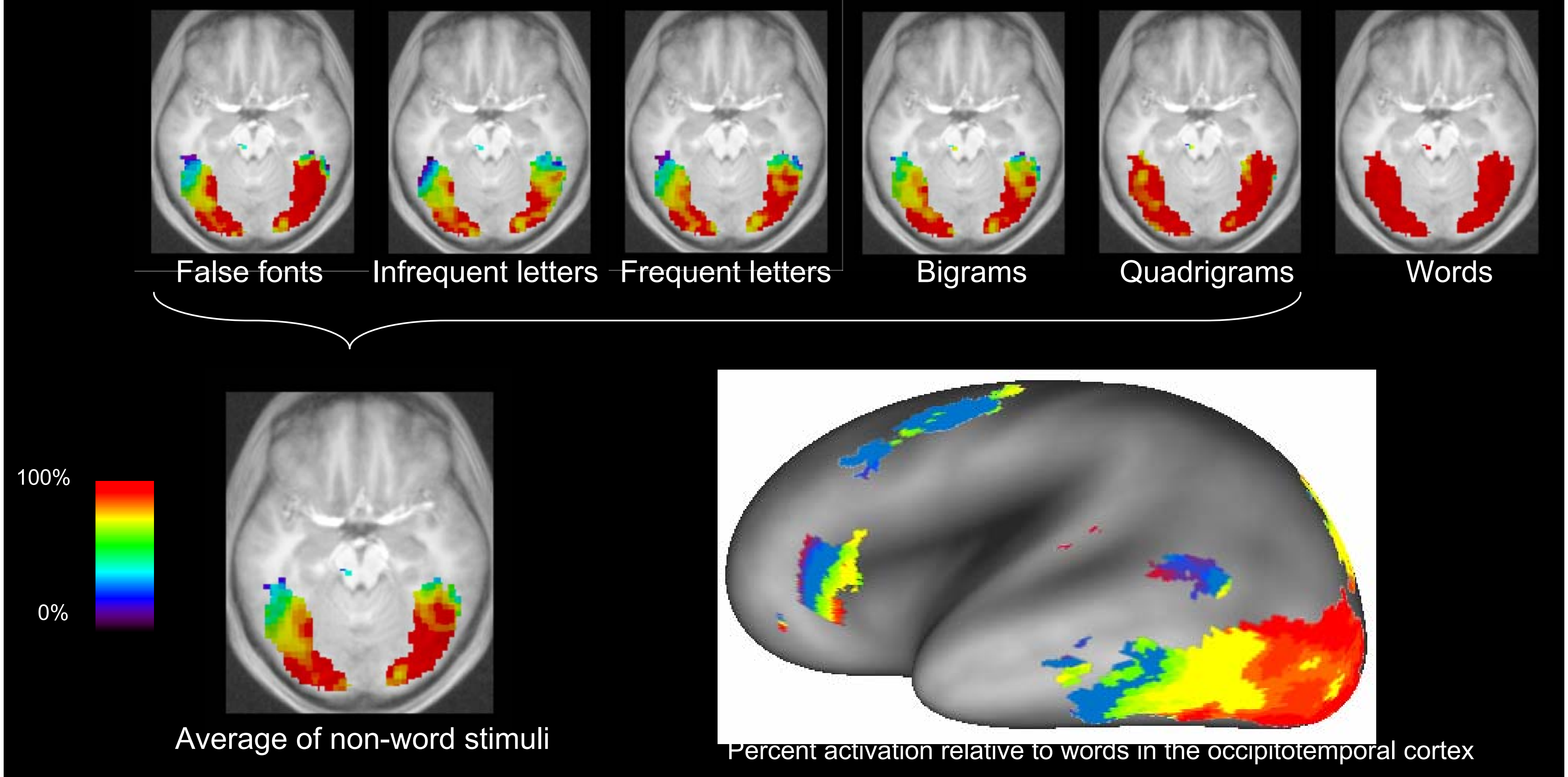
Putative area	Coded units
Left occipito-temporal sulcus? (y ≈ -48)	Small words and recurring substrings (e.g. morphemes)
Left occipito-temporal sulcus? (y ≈ -56)	Local bigrams
Bilateral V8? (y ≈ -64)	Bank of abstract letter detectors
Bilateral V4?	Letter shapes (case-specific)
Bilateral V2	Local contours (letter fragments)
Bilateral V1	Oriented bars
Bilateral LGN	Local contrasts



Dehaene et al.
TICS, 2005

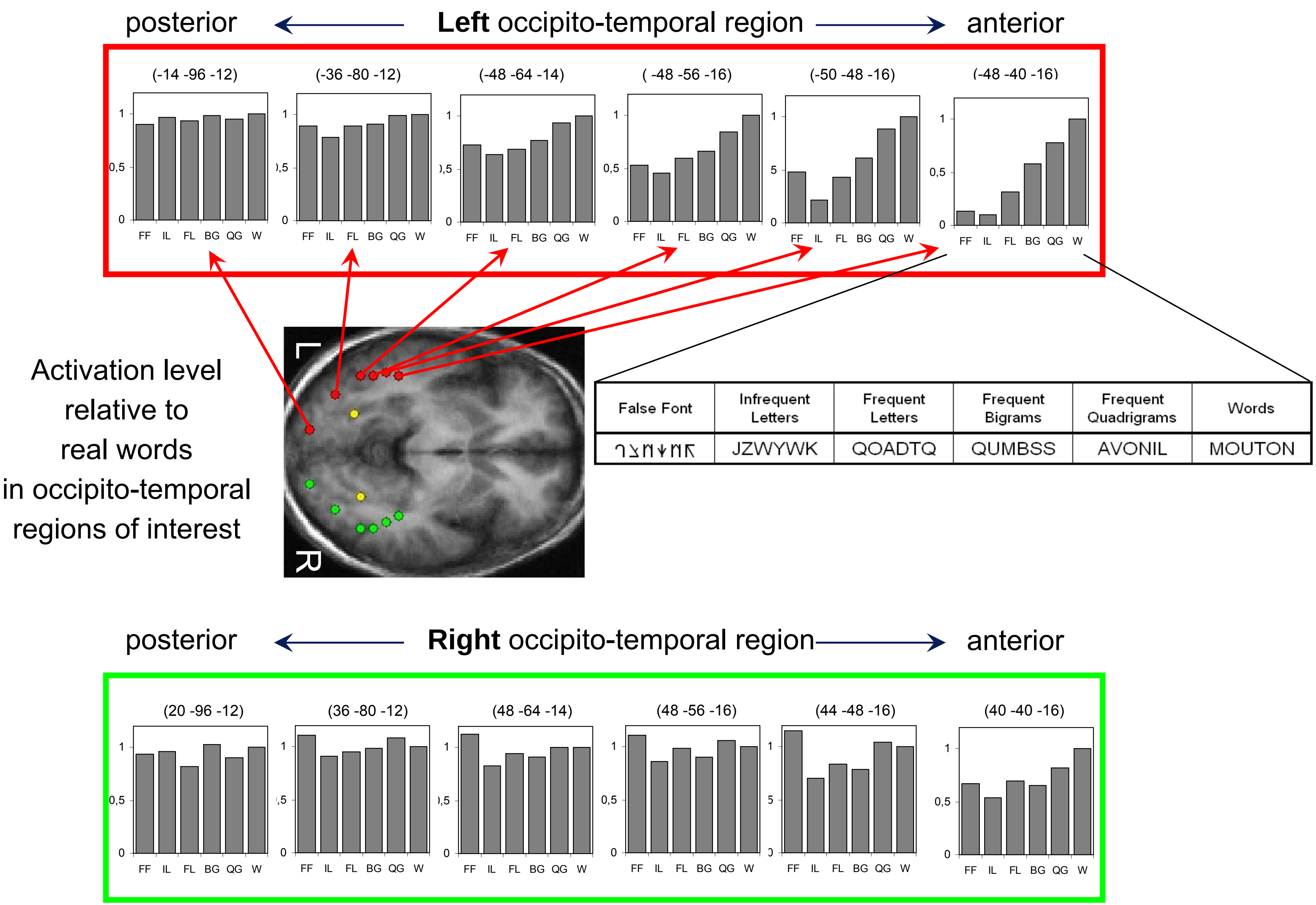
Testing the predicted hierarchical organization of the visual word form area

False Font	Infrequent Letters	Frequent Letters	Frequent Bigrams	Frequent Quadrigrams	Words
[illegible]	JZWYWK	QOADTQ	QUMBSS	AVONIL	MOUTON



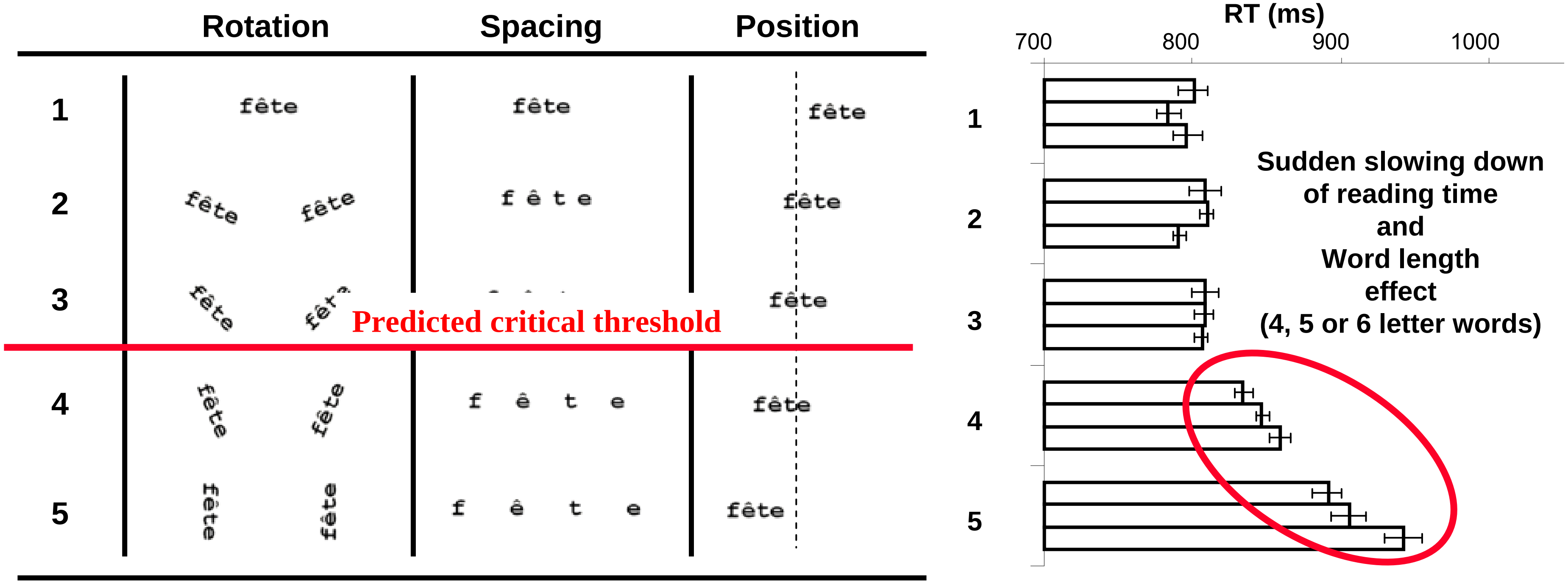
Cohen , Dehaene et al, submitted

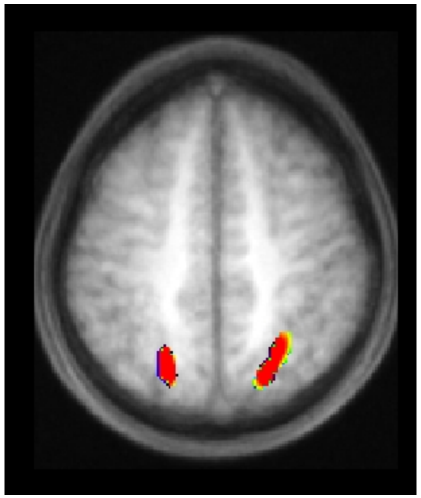
A hierarchical organization in left occipito-temporal cortex



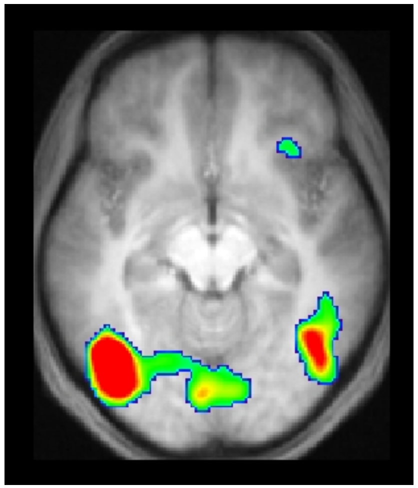
Testing the LCD model by word degradation

Three modes of word degradation





Sudden onset of parietal activation common to all three degradation modes



Amplification of activation in the posterior VWFA (peaking at the putative location of letter detectors)

Cohen, Dehaene, Vinckier et al (submitted)

Testing the LCD model in a parietal patient

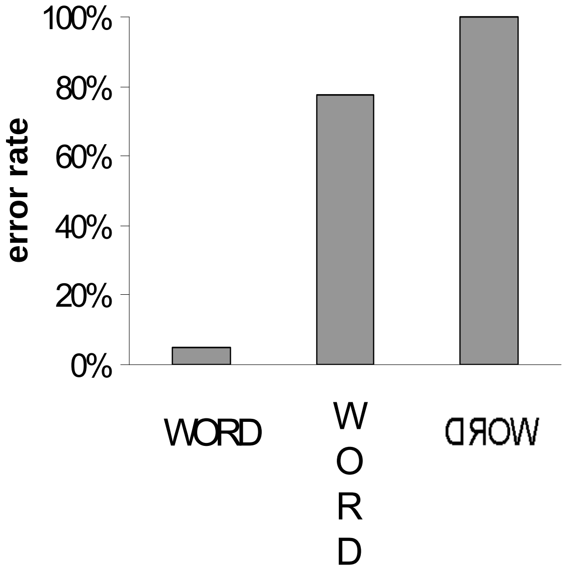
Vinckier, Cohen, Dehaene et al. JOCN, 2006

Normal ventral pathway

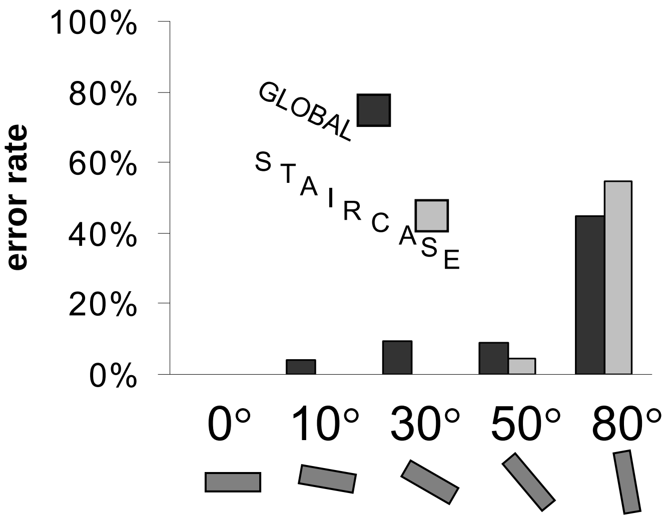
Impaired dorsal pathway

- Following a bilateral parietal degeneration, the patient became unable to deploy attention serially in space (simultanagnosia), and therefore to read letter-by-letter
- We used this case to exploit the limits of the isolated ventral visual word form system

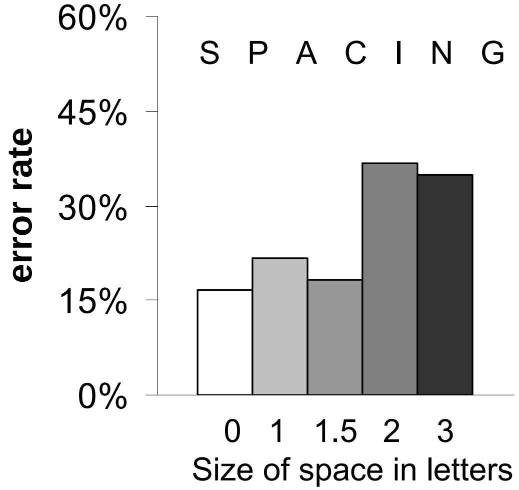
Orientation



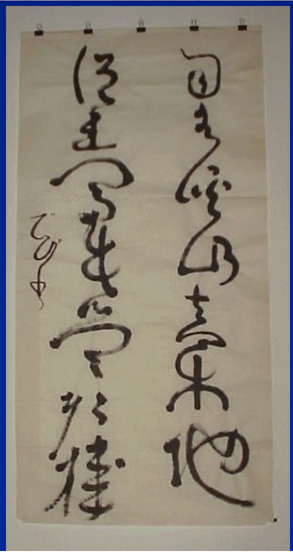
Rotation angle



Letter spacing



Two consequences of neuronal recycling



- Prediction 1:

The brain did not evolve for reading – Rather, writing systems evolved to be easily learnable by the brain.

Strong cross-cultural universals should be present in writing systems, and they ultimately be related to constraints of our brain circuitry.

Universal features of writing systems

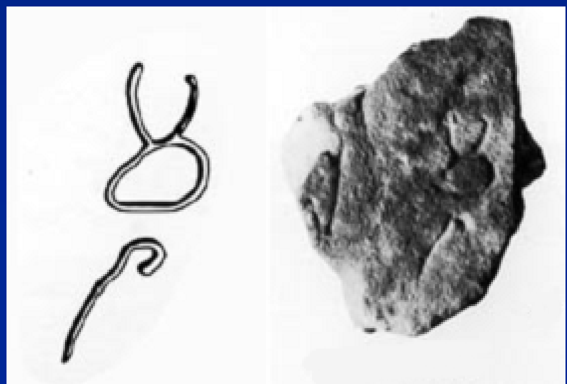
- All present, to the fovea of the retina, a high density of optimally contrasted black-on-white strokes
- All rely on a small repertoire of basic shapes whose hierarchical combinations generate sounds, syllables or entire words
- All take as granted that the location and absolute size of the characters is irrelevant
- All denote both speech sounds and semantic units (with variable granularity)

ri4	sun	日
qing1	green	青
qing2	sunshine	晴

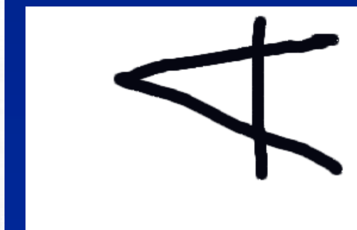
- Do symbol shapes obey universal principles, or are they just accidents of history?

Lascaux

Proto-sinaitic



Phoenician



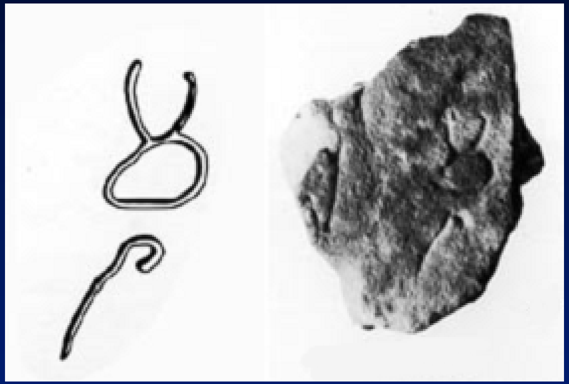
Greek / Latin

A

Are symbol shapes just accidents of history?

Lascaux

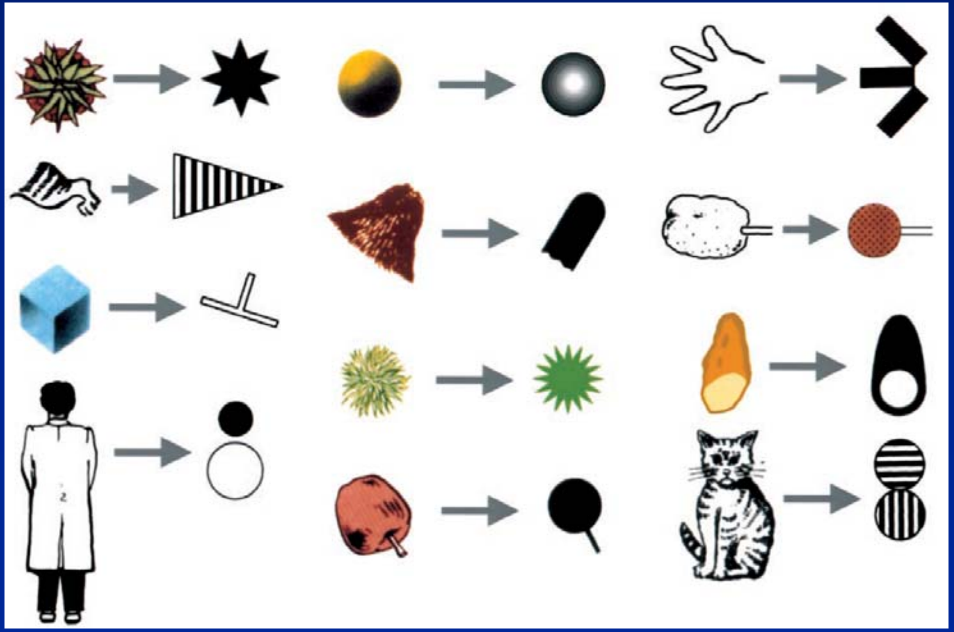
Proto-sinaitic



Phoenician

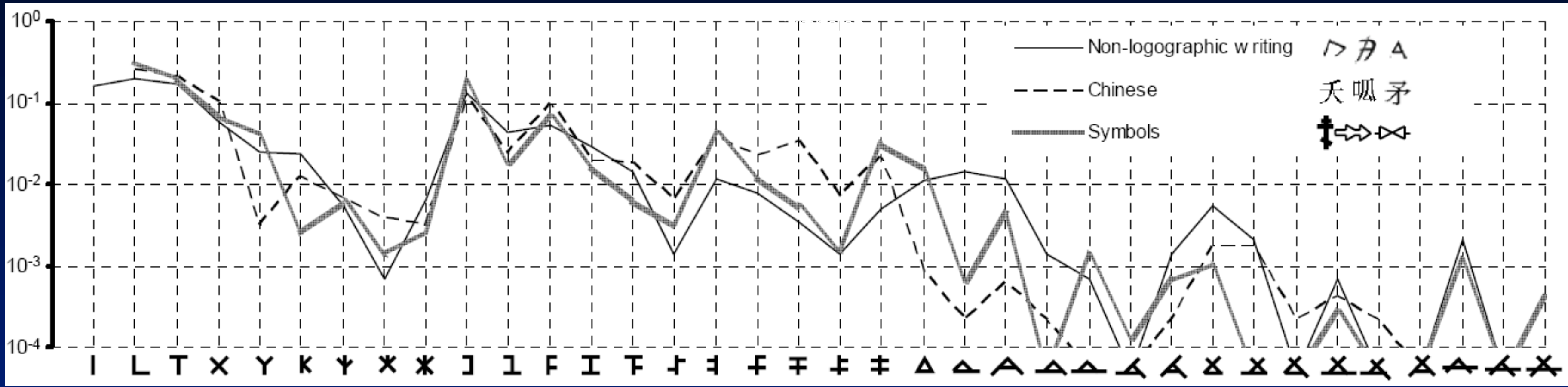
Greek / Latin

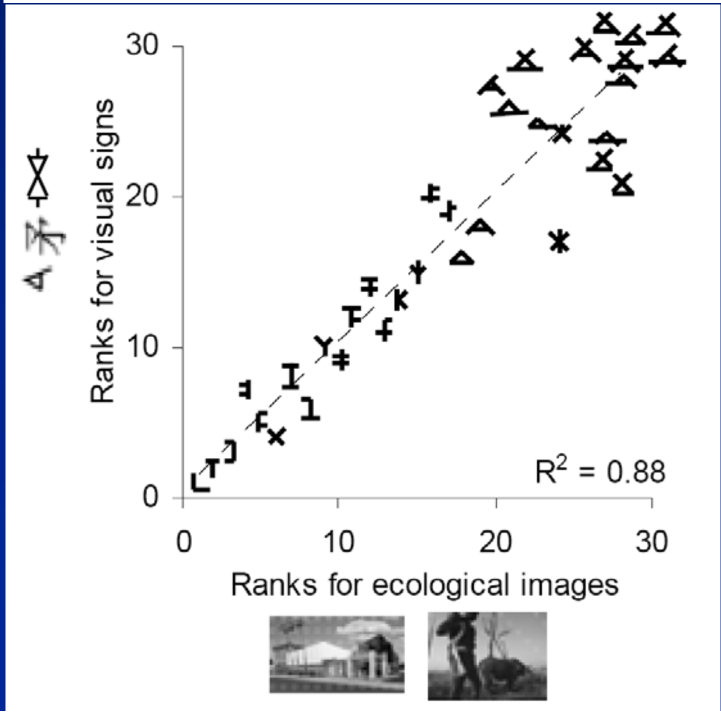
A



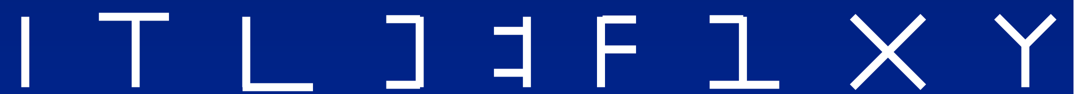
The topology of strokes in written symbols obeys a universal statistical distribution

Changizi's universal distribution





Changizi's 9 most frequent configurations



Changizi & Shimojo (2005)
Changizi et al (2006)

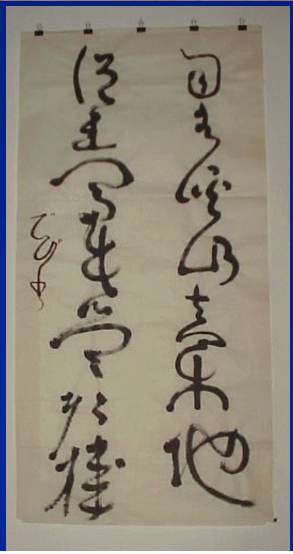
Two consequences of neuronal recycling

- Prediction 1:

The brain did not evolve for reading – Rather, writing systems evolved to be easily learnable by the brain.

Strong cross-cultural universals should be present in writing systems, and they ultimately be related to constraints of our brain circuitry.

- Prediction 2:



The difficulty of learning certain concepts or techniques should depend on the distance between the initial function and the new one.

- Plasticity, invariance are all advantageous to reading acquisition

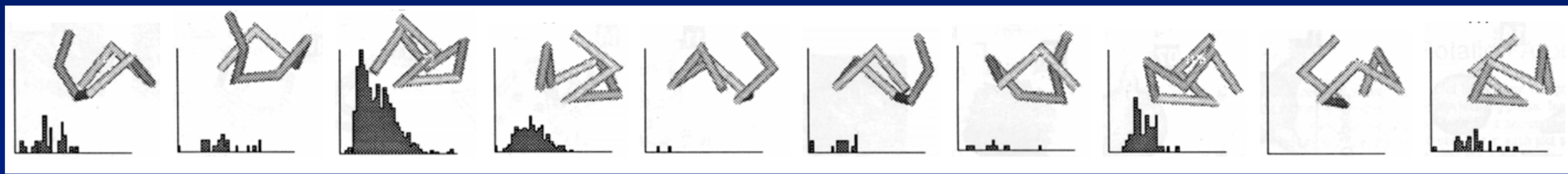
- Other features of brain organization may be detrimental to cultural learning

A neuronal « Panda's thumb » ?

Symmetry generalization:
The « Panda's thumb » of cultural recycling?

• We have evolved a symmetry mechanism that helps to recognize faces and objects regardless of their orientation

• Infero-temporal neurons spontaneously generalize to mirror images

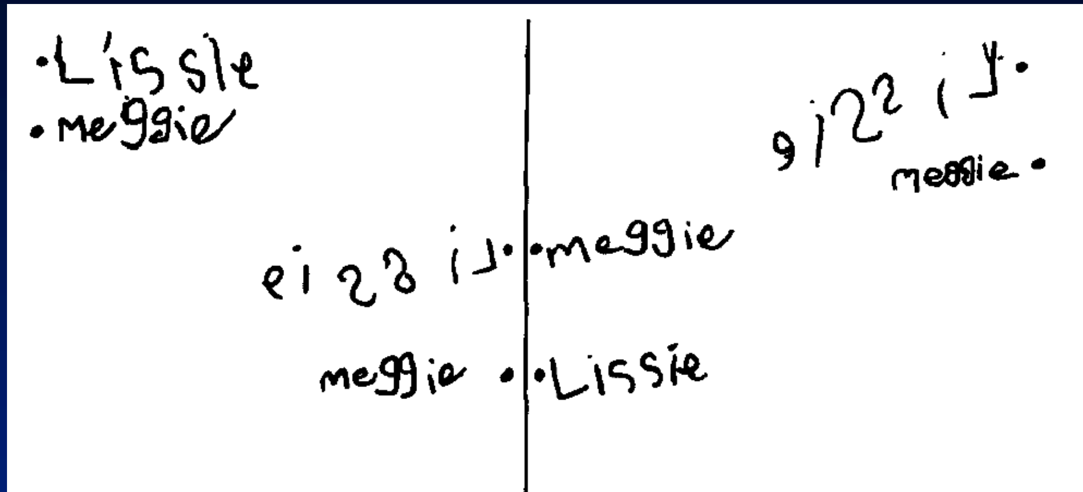


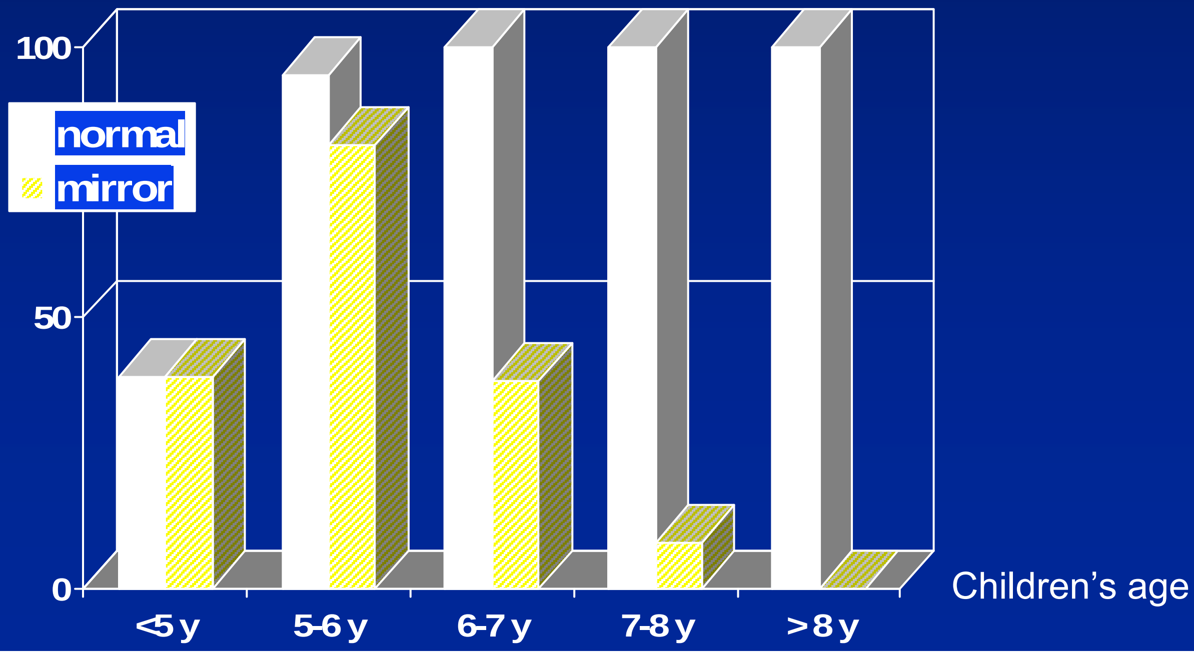
Logothetis, 1995

•This « symmetry generalization » may have to be **un-learned** when we learn to read

odil libo

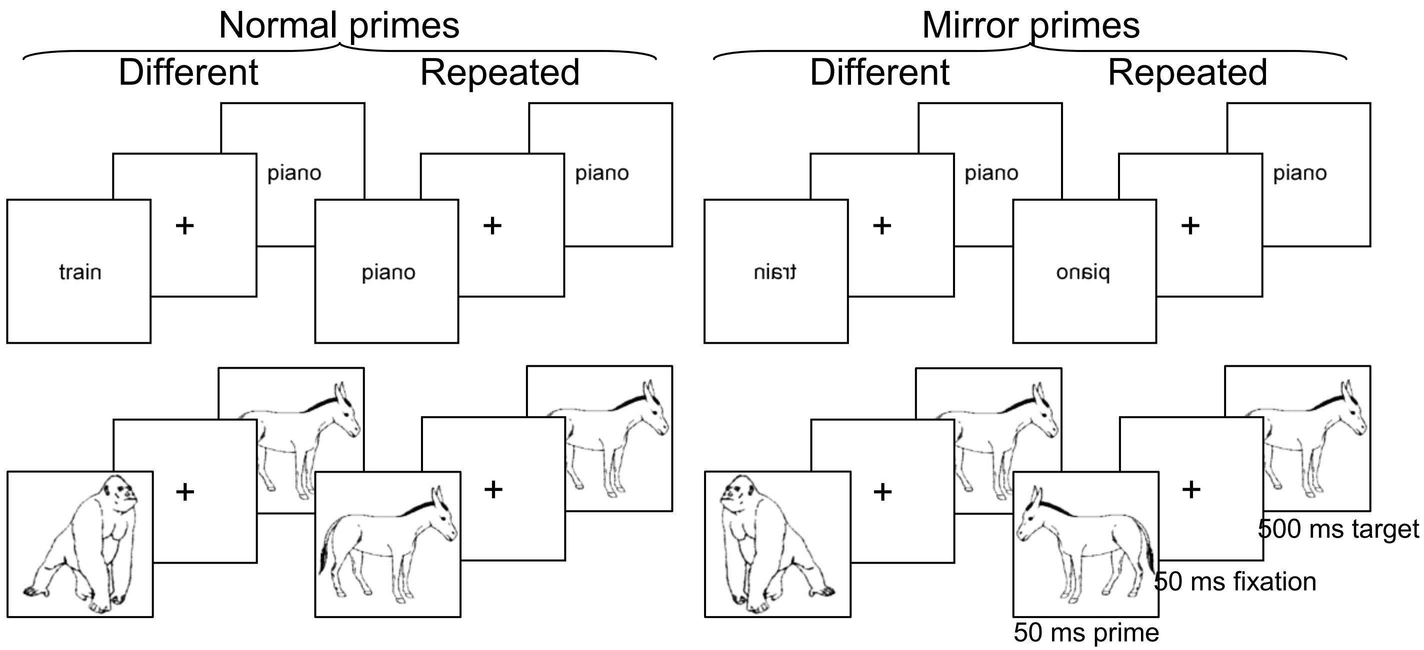
A trace of neuronal recycling?
A « mirror stage » in learning to read





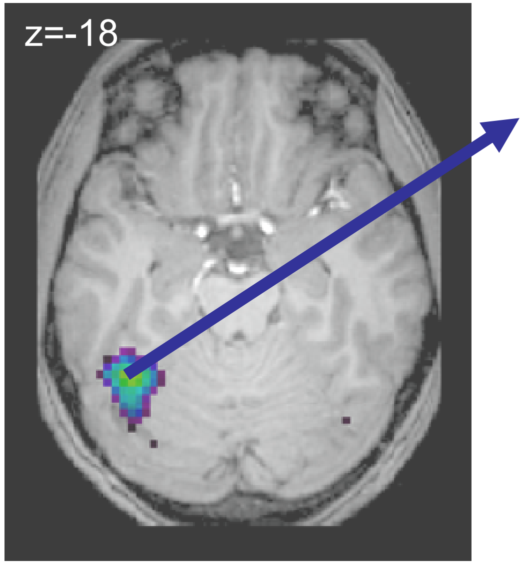
(Data from Cornell, 1985)

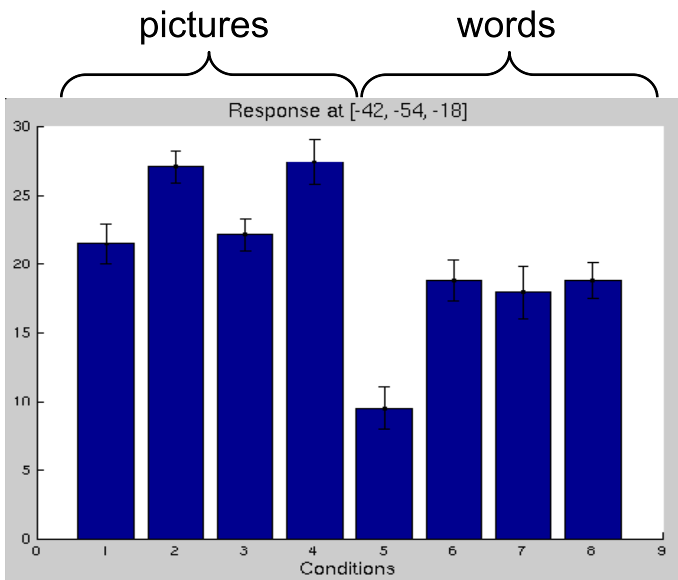
The adult visual word form area may have unlearned symmetrization



Picture repetition priming

Word repetition priming





Dehaene et al., in preparation

Conclusions

- Although writing is a recent cultural invention and show a large degree of cultural variation, reading acquisition is not « the furnishing of the mind's white paper »
- We are able to read because we inherit from evolution an efficient object recognition system with enough plasticity to learn new shapes and the relevant connections to link them to existing language areas.
- Cultural evolution can be viewed as a slow discovery of the optimal stimulus for our occipito-temporal system (yet the system remains sub-optimal, as attested by the example of mirror symmetry)
- We all learn to read with a similar brain system. Cognitive neuroscience data are relevant for the teaching of reading.