Modeling the human brain

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Introduction

The brain, or the central nervous system (CNS), is extremely complex – there is no limit on what can be read or said about it.

Therefore, I must constrain my objective:

"Understand" the brain in an information processing context

So, I seek a model of the central nervous system which is reasonable and comprehensive. We need to understand how information is ***transported***, ***processed*** and ***stored***. In "information" I include algorithms, knowledge and skills.

This is closely related to **how the brain is developed** (designed).

Introduction

VLSI ↔ CAD

Silicon chip evolution is characterized by utilizing computers to develop next generation chips and computers

Similarly, brain developes itself

Staffan Gustafsson 1983, ”Rita på kisel”

Introduction

A *reasonable* model of CNS must be fully compatible with

Physics (including information theory)

Chemistry

Biology (including evolution)

CNS context (body, physical and social context)

Biology, two forms of evolution:

Evolution of the species (through natural selection; Phylogenesis)

Evolution of the individual (from conception to death; Ontogenesis)

Introduction

Classically, CNS have been considered *static* with *minor changes* occurring over time.

Compare the cellular neural network (CNN) models, based on highly interconnected cells with variable interconnect strength.

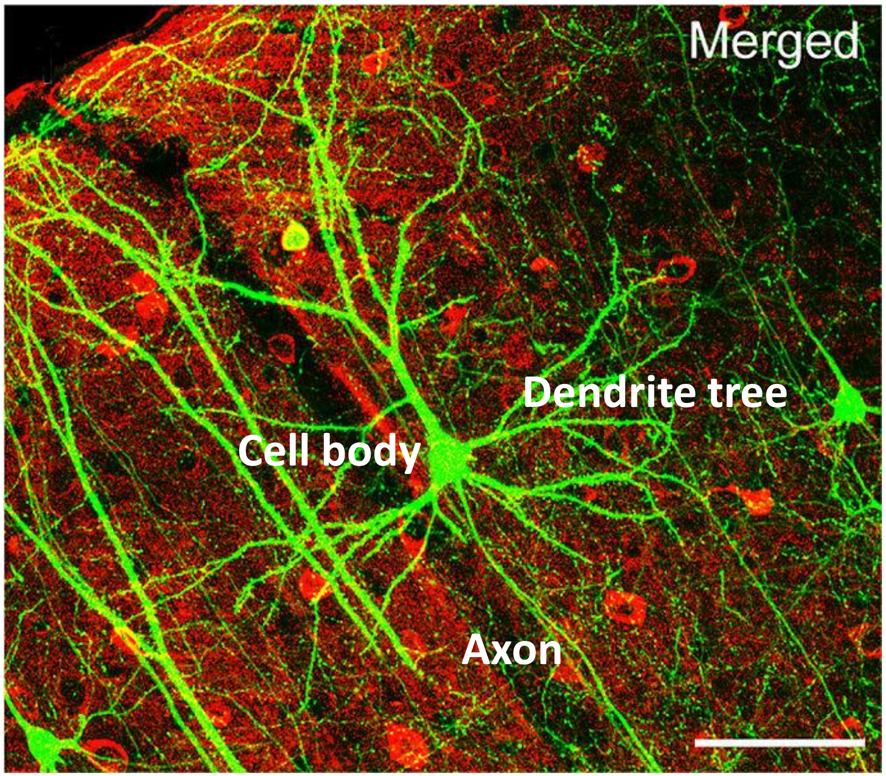
Recent research rather indicates that CNS is **highly dynamic** referred to as **neural plasticity**

Introduction

I will discuss this topic by formulating a series of hypotheses of the development and function of the CNS.

BUT, let me start by introducing some well established facts about the CNS.

Introduction, some basics



Wikipedia

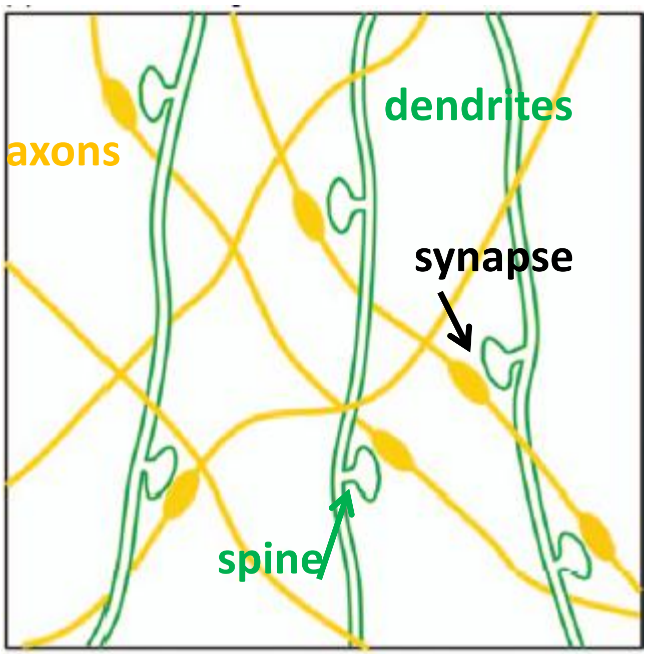
CNS is built from **neurons**.

A neuron comprises a **cell body**, an **axon** and a **dendrite trees.**

Information flow is **unidirectional** from the **dendrite tree**, via the **body** to the **axon**.

Information transport within the neuron is **electrochemical**

Introduction, some basics



(Fu 2011)

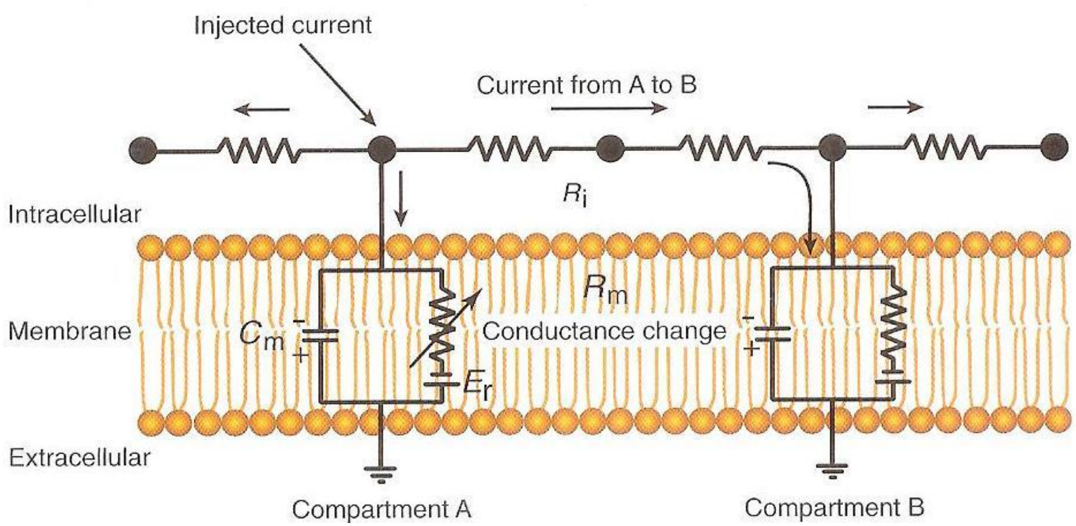
Neurons are interconnected via **synapses,** connecting **axons** with **dendrites.**

Information transport inside the synapse is **chemical.**

Synapses have different **strengths.**

Synapses may be excitatory or inhibitory

Introduction, some basics



Model of the cell membrane (for example along the axon)

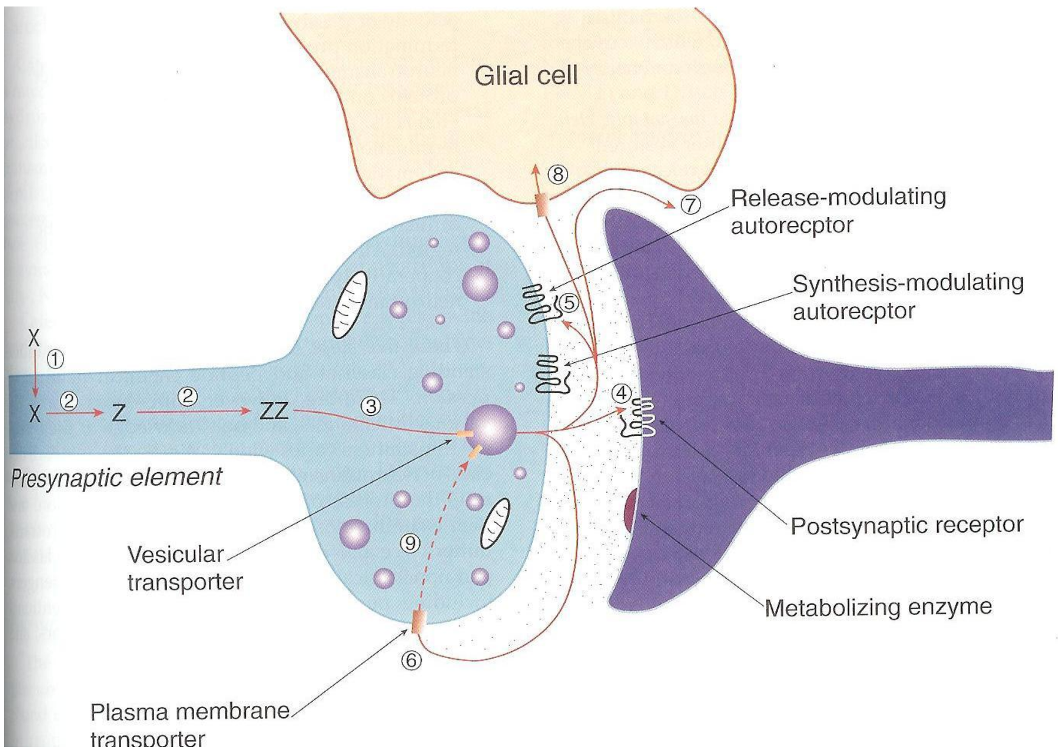
The R, C and the voltage dependent conductance leads to an active wave transport of waveforms along the axon

By surrounding the axon by fatty cells (myelin layer)
the velocity increases

Introduction, some basics

Model of the synapse

Presynaptic element, synaptic cleft, postsynaptic element



Neurotransmitters are released from vesicles, transported through cleft and absorbed by receptor

Absorbtion make receptor change membrane voltage

Introduction, some basics

CNS **structure** (circuits) constitutes both **function** and **memory** (algorithms, knowledge, and skills) .

Synapse **strength** is increased by **high activity.**

Increase of synapse strength through activity is the simplest form of **learning** and **memory** (Hebbian learning, Hebb 1949)

More advanced experiments: Kandel, Nobel prize 2000

Introduction, some basics

Kandel, 1970

Experiments on giant neurons in Aplysia (a sea snail)

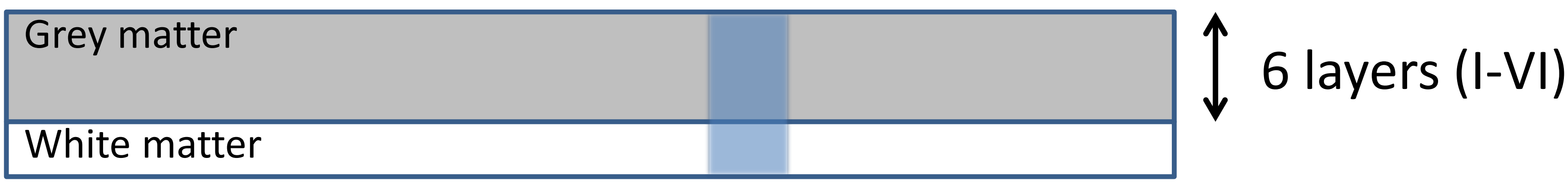
Short term memory via strengthening of synapses via interneurons (process includes enhancement of neurotransmitter release via Kinase A)

Long term memory via growth of new synaptic connections. This requires protein synthesis via the cell nucleus and its mechanisms for gene expression (process initiated by migration of Kinase A to cell nucleus)

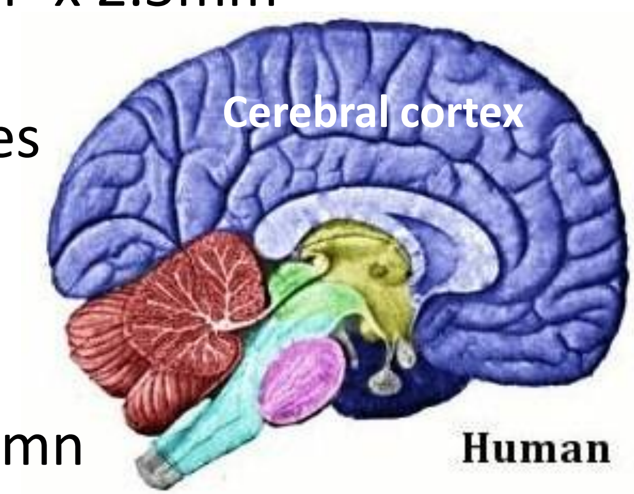
Introduction, some basics

Example of neural architecture, cerebral cortex

Basic unit: Cortical column; 5000 neurons



Flattened cerebral cortex, totally 2000cm^2 x 2.5mm



Totally about $2 \cdot 10^{10}$ neurons, 10^{14} synapses

White matter: axons (10^7 axons/cm^2)

I estimate 20,000 axons passing each column

Introduction, some basics

From what has been said so far:

Information **transport** – seems quite clear
Electrochemical in axons and dendrites; chemical in synapses

Information **processing** – seems relatively clear
Nonlinearly weighted sums of incoming data

Information **storage** – still enigmatic
Short term maybe clear, chemical changes in synapses
Long term requires changes in CSN structure

Selective Stabilization Hypothesis

First hypothesis: *selective stabilization hypothesis*, formulated by Changeux and Danchin 1973:

The genetic program **directs** the proper interaction between neurons. Several contacts form at the same site.

The early activity of the circuits, spontaneous (in embryo) and evoked (after birth), **increases the specificity** of the system by reducing redundancy.

Alternative terms: synaptic elimination, synaptic epigenesis, neuron plasticity, neuronal Darwinism (Edelmann 1987)

Selective Stabilization Hypothesis

During ontogenesis (CNS development from conception) various parts of the CNS grows as any other organ .

Types of neurons, approximate number of neurons, size and form of the part are **genetically controlled** (self-organization under a genetic rule set).

BUT, interconnections between neurons are controlled by the actual environment. For CNS this means under **control of internal and external neuronal signals**

Selective Stabilization Hypothesis

During ontogenesis **and** adulthood each neuron is *plastic*

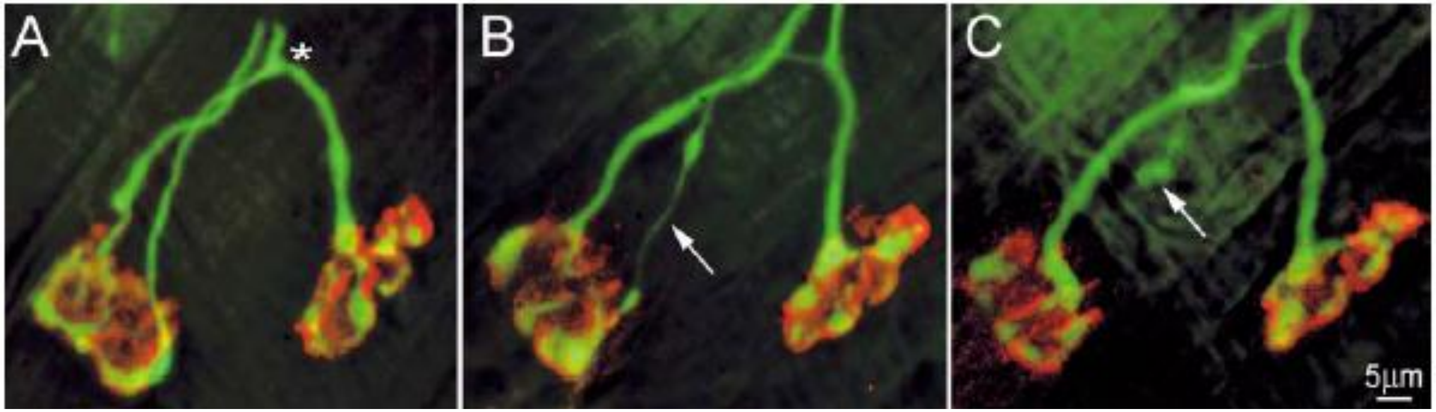
The dendrite tree is continuously growing and retracting, forming and retracting synapses with passing axons. This process is **controlled by synapse activity** through **selective stabilization** and destabilization.

(Changeux' original motivation: genetic information is far from sufficient to describe CNS complexity)

Selective Stabilization Hypothesis

Direct evidence of microscopic plasticity

Classical case: Muscle innervation. Number of motor axons contacting a muscle fiber is reduced from 4-6 to 1 in early development of mouse. Interpreted as a refinement of the system

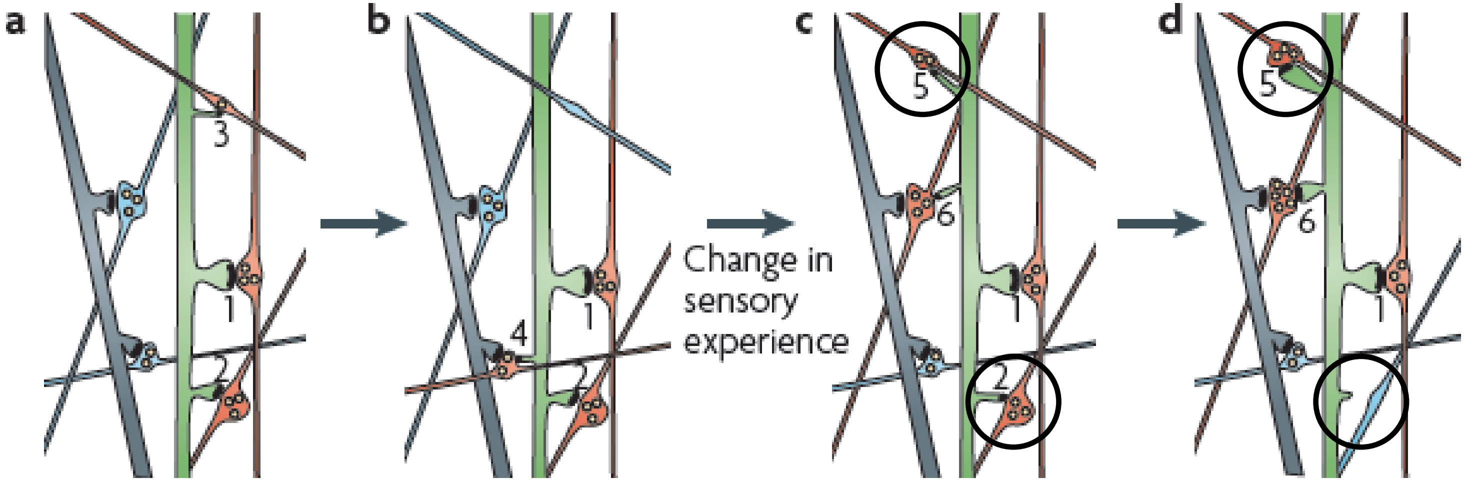


Postnatal day 7, 8 and 9 of a transgenic muse; neuromuscular junctions

Selective Stabilization Hypothesis

Direct evidence of microscopic plasticity

Experimental observation of spine and synapse formation and elimination in adult mouse neocortex *in vivo*. (Holtmaat et al 2008). Time scale: minutes – days. Whisker trimming as experience input.

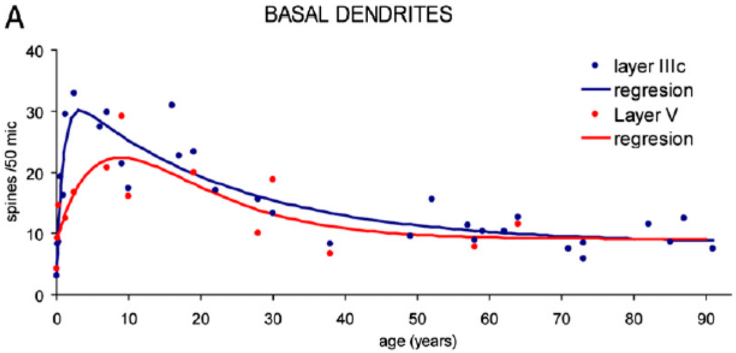


Green: dendrite, blue, red: axons. a,b) red contacts green, weak contacts retracts (3)
c,d) New spontaneous spines (2,5) retract or stabilize as a result of experience

Selective Stabilization Hypothesis

Direct evidence of microscopic plasticity

In humans the process of *significant* synaptic elimination proceeds to ≈30 years of age (Patanjek et al 2011)



A general conclusion

The detailed CNS structure ("circuit diagram") is formed during growth under influence of experience.

This process proceeds under adulthood with declining pace

CNS dynamics

During growth.

Neurons are created (under genetic control).

Neurons grow axons which are directed towards other neurons (sometimes very long distances; under genetic and experience control)

Dendrites and spines continuously grow and retract forming and eliminating synapses (under experience control)

During adulthood.

Neurons and axons are mainly stable

Dendrites and spines still grow and retract, forming and eliminating synapses

CNS dynamics

The change from growth to adulthood is **gradual** (all life).

The combined genetic and experience control leads to **critical periods.**

(Classical example: stereoscopic vision can only be learned before 6 months of age: neonatal cataract must be corrected before 6 months of age)

During growth, passive experience is sufficient to create neuronal imprint, during adulthood, experience must be accompanied by attention to create imprint.

CNS dynamics

Speculation:

Imprints during growth engage axonal structure, which leads to very stable (lifelong) memory (during dendrite growth and retraction a specific connection can be eliminated but also recreated)

Imprints during adulthood occur only via dendrite structure and is less stable. May stabilize through slow changes in axonal structure, possibly supported by slow neurogenesis in hippocampus

Neuronal reuse hypotheses

Second hypothesis: ***Neuronal recycling hypothesis***, Dehaene 2004
(Also termed neural reuse)

Innate structures can be reprogrammed to new skills
(Innate includes the effects of "natural" child experience)

New skills can be developed from old ones:

During development of the individual (ontogenesis, fast)
Carried over socially

Neuronal reuse hypotheses

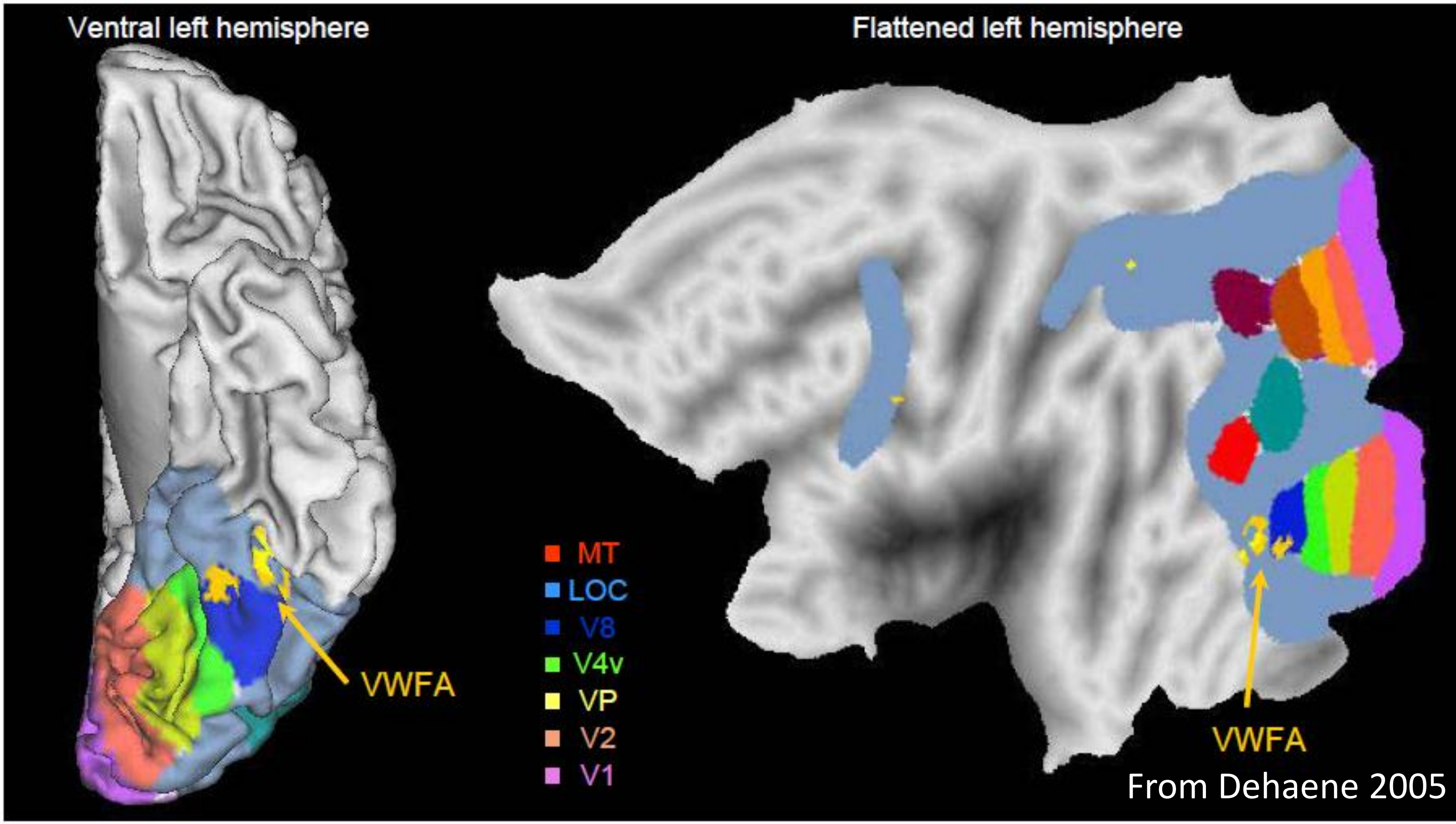
Example of neural reuse

Reading is obviously a skill that can not have be developed through evolution. So how can we acquire such a complicated skill?

Our vision system contains the skill to characterize primitive shapes as lines with specific tilts and the skill to combine primitive shapes into objects as for example faces.

These skills can be reused for the recognition of letters (primitive shapes) and words (objects) (Dehaene 2004)

Neuronal reuse hypotheses



From Dehaene 2005

Neuronal reuse hypotheses

Consequences

Neuronal reuse offers a reasonable explanation to the mechanism of the remarkable ability of the human to develop new and advanced skills over evolutionary very short periods of time.

The combined hypotheses of Neural plasticity and Neural reuse offers a reasonable explanation to social/cultural inheritance.

Example: Instead of considering language as a module in the brain, it is a social /cultural module outside brain, inherited by each individual from its social context.

Neuronal reuse hypotheses

Third hypothesis: *Massive redeployment hypothesis*, neural reuse hypothesis, M. L. Anderson 2007)

New skills can be developed from old ones:

During evolution of the species (phylogenesis, very slow)
Carried over via genes

I will not consider evolutionary aspects further in this talk

Special skills hypothesis

Fourth hypothesis: *Special skills hypothesis* (similar to *Pre-representations* (Changeux 1989), *Workings* (Bergeron 2008)

A particular part of CNS is characterized by special skills (genetically controlled envelope + interactive specialization)

This part is then used for basic purposes given by evolution AND reused for new purposes through neuronal reuse

Special skills hypothesis

Example of vision and pattern recognition

As mentioned before:

Our vision system contains the skill to characterize primitive shapes as lines with specific tilts and the skill to combine primitive shapes into objects as for example faces.

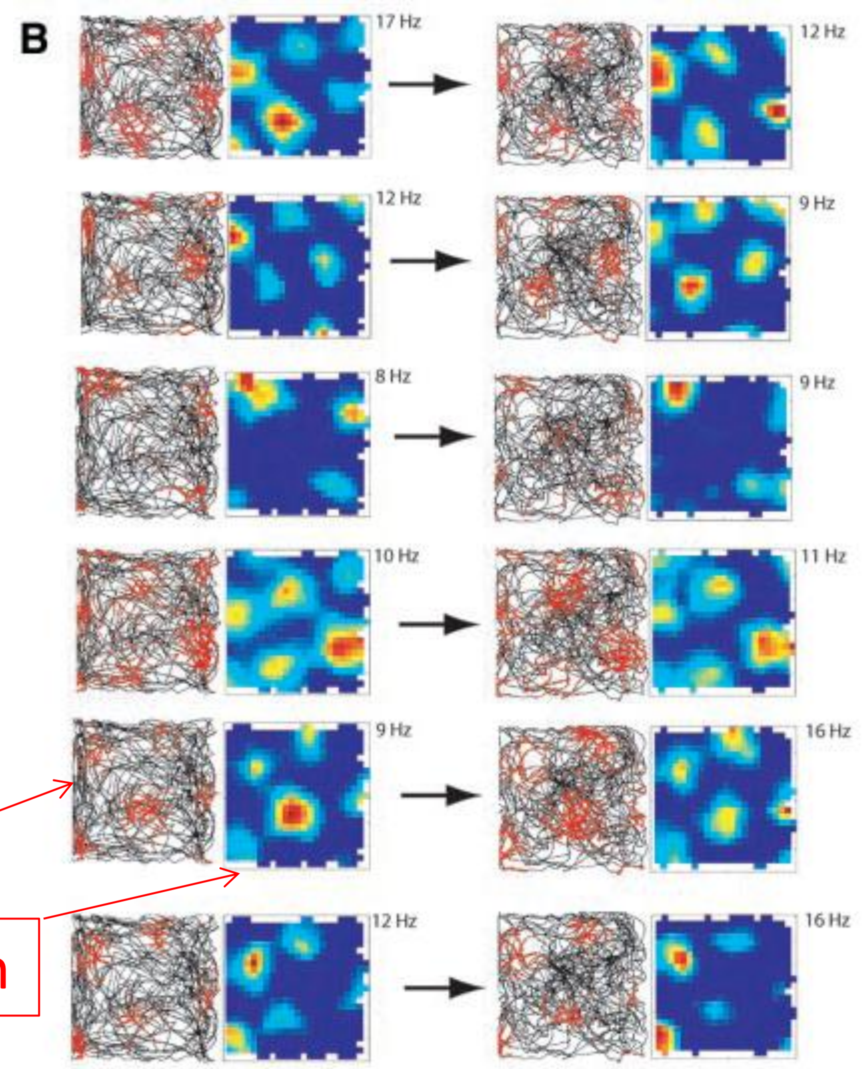
This system occupies quite a large part of the human brain.

Special skills hypothesis

Example of spacial maps

Spacial maps in Medial Entorhinal Cortex (MEC)

A mouse with electrodes moves in a square compartment (figure).
A single nerve cell fires at certain positions in the compartment.



Mouse path, cells firing at red

Neuron firing rate vs mouse position

Special skills hypothesis

Example of spacial maps

Grid cells constitutes a geometrical grid
Direction cells constitutes moving direction
Wall cells constitutes an adjacent wall
etc.

Together, we have an advanced skill for spacial mapping

Preliminary conclusions

The original question:

"Understand" the brain in an information processing context

So, I seek a model of the central nervous system which is reasonable and comprehensive. We need to understand how information is ***transported***, ***processed*** and ***stored***. In "information" I include algorithms, knowledge and skills.

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Preliminary conclusions

What we have learned

Basic principles for **information transport** and **processing** are reasonably understood

The mechanism of **storage** is most reasonably modeled as **part of the continues development of the CNS from conception to death**

The mechanism of **design** constitutes two parts, **phylogenesis** through **natural selection** and **ontogenesis** through **self learning**

Preliminary conclusions

Some consequences of the present picture

Algorithms, knowledge and skills are defined by the actual **structure (circuits)** of CNS

This structure results from a combination of **genetic information** and **individual experiences** from conception to death

As CNS structure is a result of each individuals social context, **the culture of a society is defined by the common CNS structure** of the individuals constituting that society

Preliminary conclusions

Some consequences of the present picture

Scientific models of the world are based on the basic skills of CNS.

Example : Both in mathematics and in physics we use geometric models (coordinate systems, vectors, n-dimensional spaces) because our brain has a special skill to manage spacial models.