MSc in Artificial Intelligence and Robotics
MSc in Control Engineering
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Neuroengineering

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we start talking about the single computational unit of the brain which is the neuron. We have introduced its main function that are the same of the brain or of the entire neurosystem. All neurons work together to produce more complex computations and making decision, but also planning and executing actions.

3- PRINCIPLES OF NEUROANATOMY AND BRAIN ORGANIZATION

Learning objectives of the lesson

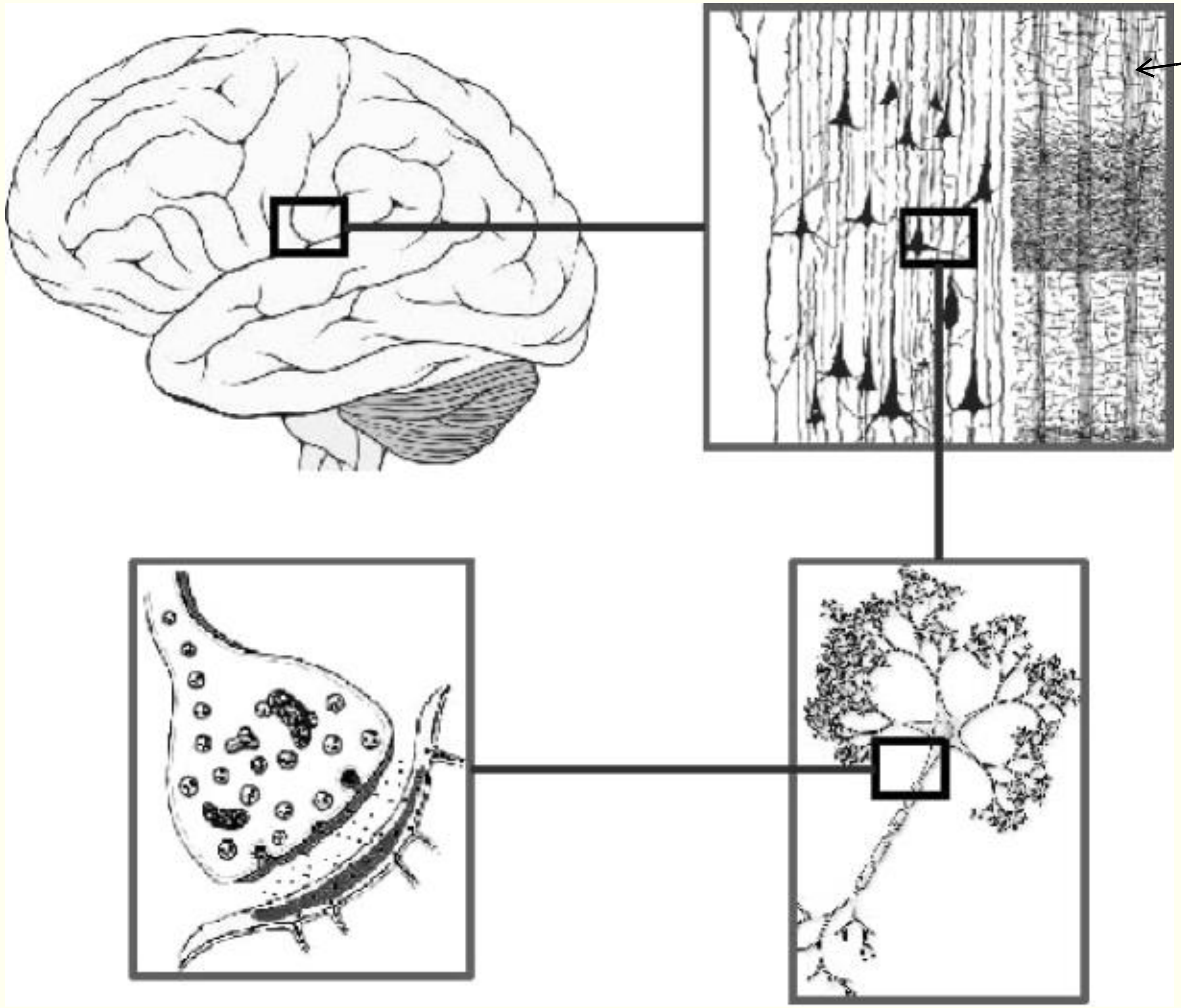
how brain works in temporal and spatial scales

1. Illustrate the temporal and spatial scales of brain activity → it's very important for engineers
2. Describe how cortical neurons organize in layers, columns, regions (Brodmann areas), lobes, systems
3. List the main functions of the four cortical lobes
4. Compare the location and structure of cortical and subcortical areas
5. Provide examples of two brain regions organized in feature maps
6. Illustrate the concept of brain plasticity (no static) and its role in the human lifespan
   capability of neurons, brain or synapses to modify their shape and their functioning dynamically througout lifespan
7. Explain the four main neuronal mechanisms behind brain plasticity

we start from the single neuron(but in particular networks) and then we focus on the synapses.

Neural organization

organization of multiple neurons(network)



zoom of brain cortex. This is the outer layer of the brain in which we find 6 layers of neurons which are organized to work together to complish specific functions.

Bernardet & Verschure, Neuroinformatics 2010

Studying the human brain

summary of the history of brain studing

we can lose parts of the brain from neurosurgical operation or we can lose the ability to use this part by cause of an accident

The brain predicts the future on the basis of the past, helping the individual to survive and perpetuate the species

- Studied at first by lesion and animal studies
- Then by neuroimaging and neuromodulation
- Link to behavioural and clinical data

with this we are able to directly interfere with brain activities in non invasive and reversible way. We can do this in 2 directions: out->in and in->out

one of the most important case of study in the history of the brain study was the epilepsy. We learn that removing a part of the brain we can cure this. In epilepsy the brain shows an anormal electrical behavior, electrical activity increases in specific regions

The brain in time and space

It's the temporal scale of the neurons and synapses. Neurons work at the time scale of milliseconds and even fractions of them.

- Temporal scale of milliseconds caffeine and drugs can change it, but we don't move for ex. from ms to more ms but not from ms to s
- Spatial scale of μm (soma; membrane thickness: nm) spessore

what is the smallest portion of the cell that we can associate to a specific elechtrical signal? It's the membrane(nanometers). It's not easy to access at this small part

Brain evolution: in time

- Collective our brain modifies its shape and functioning across thousand of years to adapt to environment and purposes

our brain at individual level, continuously adapt itself

- Individual: the brain is plastic during the entire lifespan (learning, memorization, spontaneous recovery, neurorehabilitation)

Grey and white matter

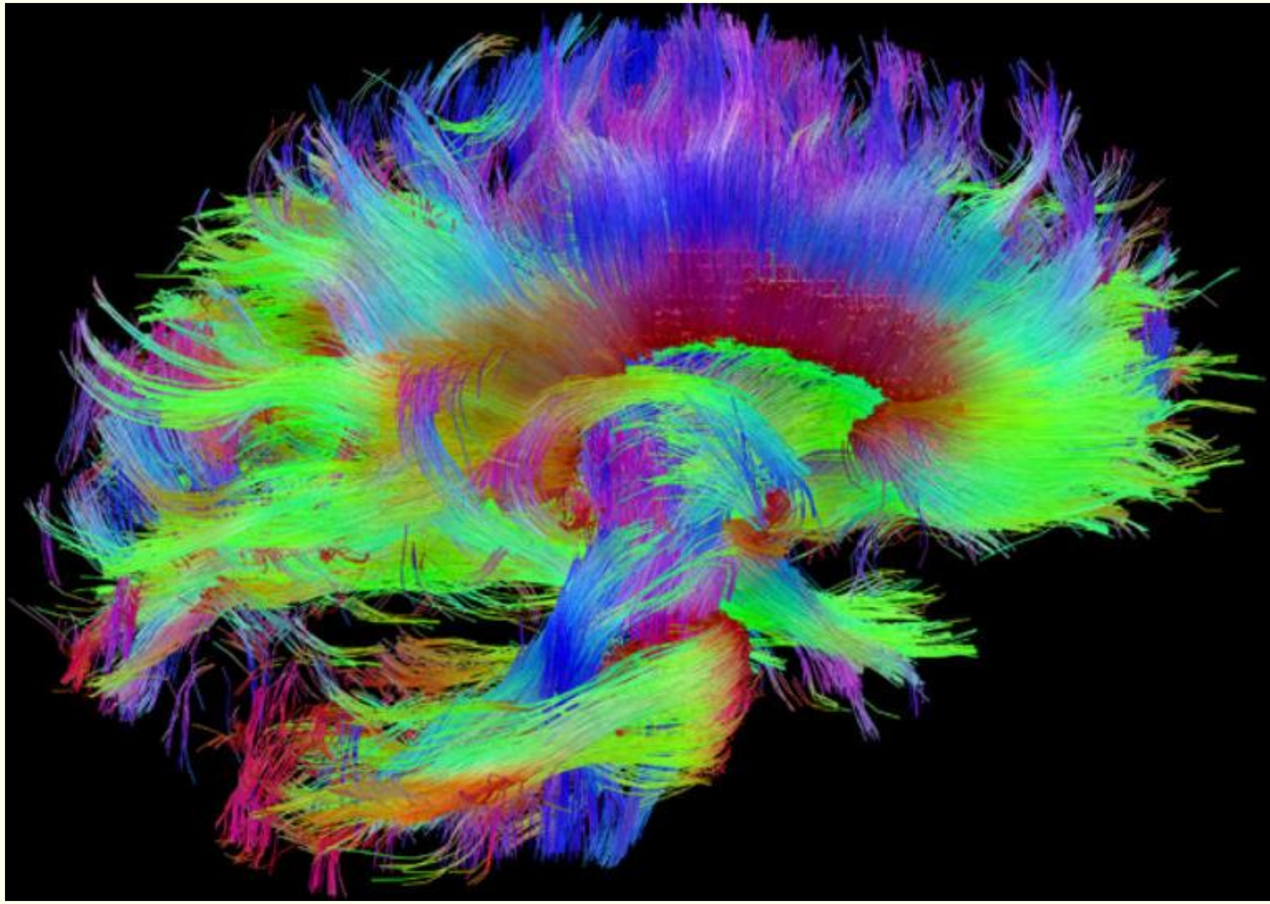
- Grey matter: cell bodies and dendrites of the neurons
- White matter: (fibers) myelinated axons
- White matter tractography: in vivo procedure based on diffusion tensor imaging (DTI)

non invasive way

- Corpus callosum: white matter, highway of information between hemispheres

most important group of fibers which is like high speed highway that connect the 2 hemispheres

modifications of the corpus callosum are related to pathologies or ages



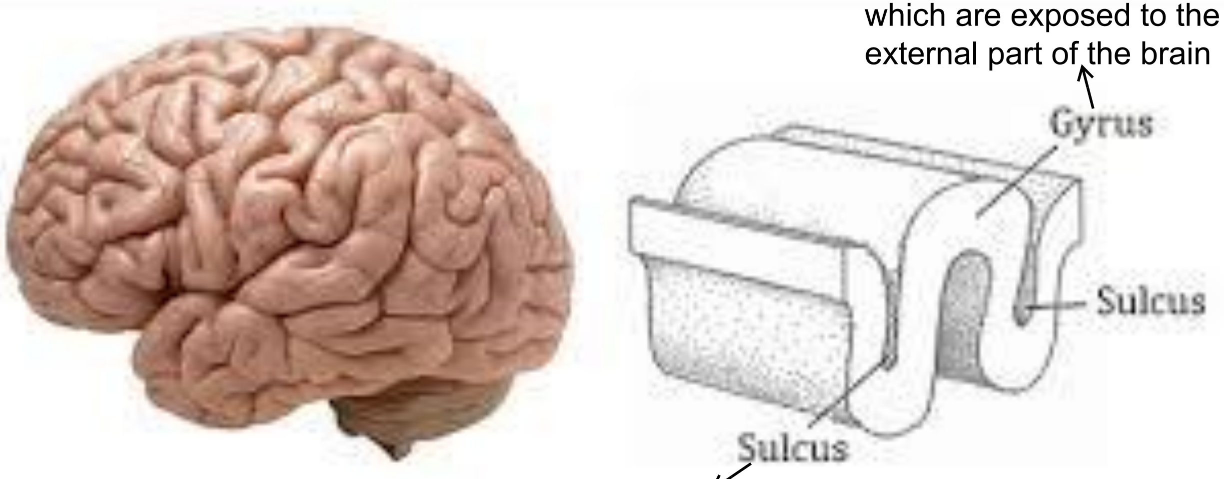
DTI image, Laboratory of Neuro Imaging at UCLA and Martinos Center for Biomedical Imaging at MGH, Consortium of the Human Connectome Project the position of the gray matter is also important. The brain has the out layer that is the brain cortex and some subcortical regions(areas).

Brain cortex

intelligence is not only related to the surface of the brain but to the number of neurons connections

- 1,5% of the body weight, 15% of the total blood flow (the whole brain uses 20%)
- Folded to increase the cortical surface in a limited volume
- Gyri and sulci (sulci=2/3 of the surface)

which are exposed to the external part of the brain



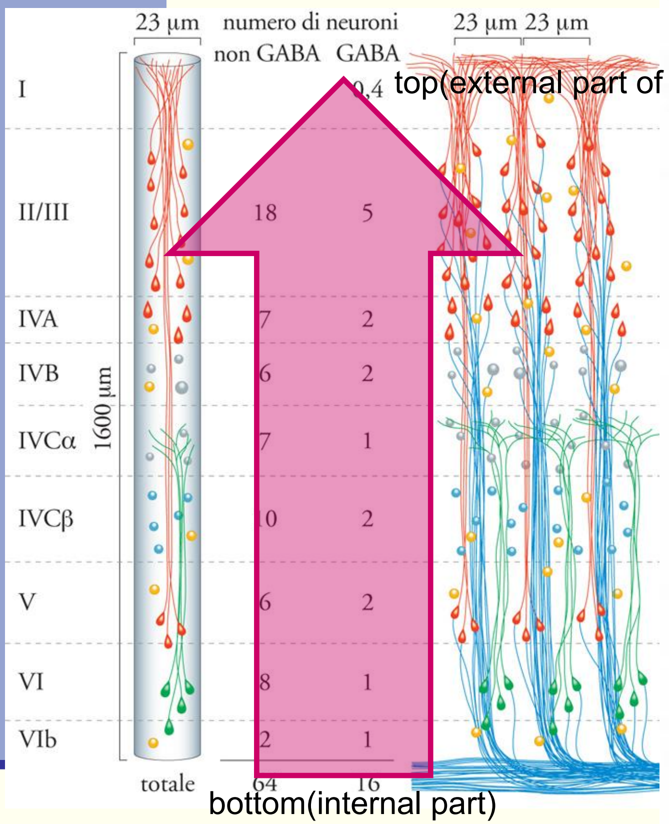
inner foldes

Cerebral folds: Gyri and Sulci

how is the cortex organized? First of all the so called neurocortex which is the exterior, and for us the most important part of the cortex, is organized in 6 vertical layers(like layers in a cake), in each layer there are different neurons with slightly different structure and functions. All these layers are interconnected, they comunicate continuously, and so we have an interlayer comunication in each cortical part of the cortex.

Cortical organization

We have also an orizontal organization of the neurons(columns), in each column we have 6 layers that are connected and work together to perform a function. So all neurons in a column work together and give the same response to the same stimulation and can be seen as a unit of info processing. This is very useful when we model neural encoding and decoding

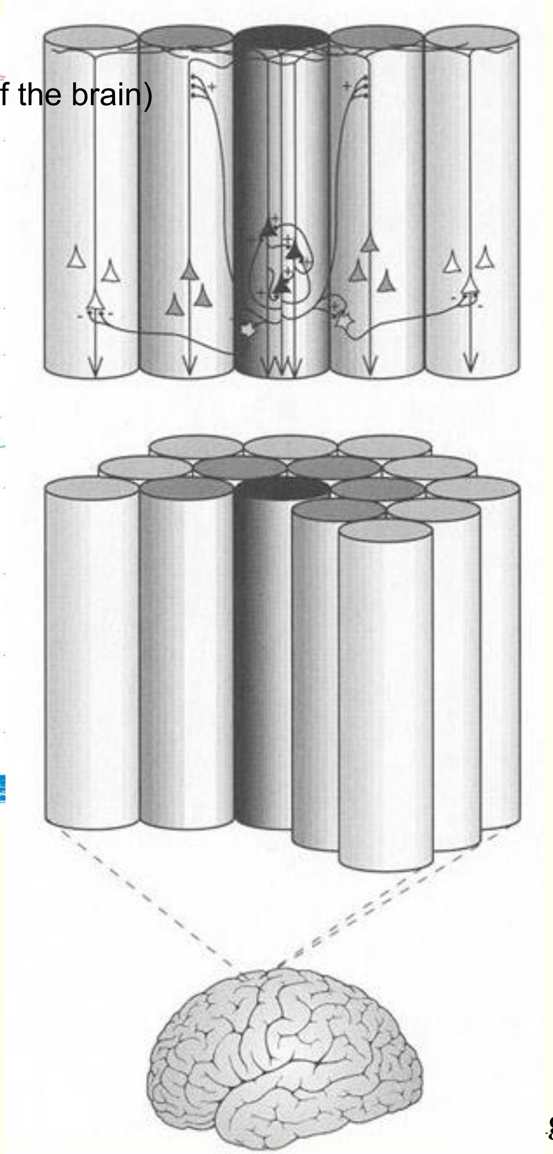


top(external part of the brain)

bottom(internal part)

Information processing

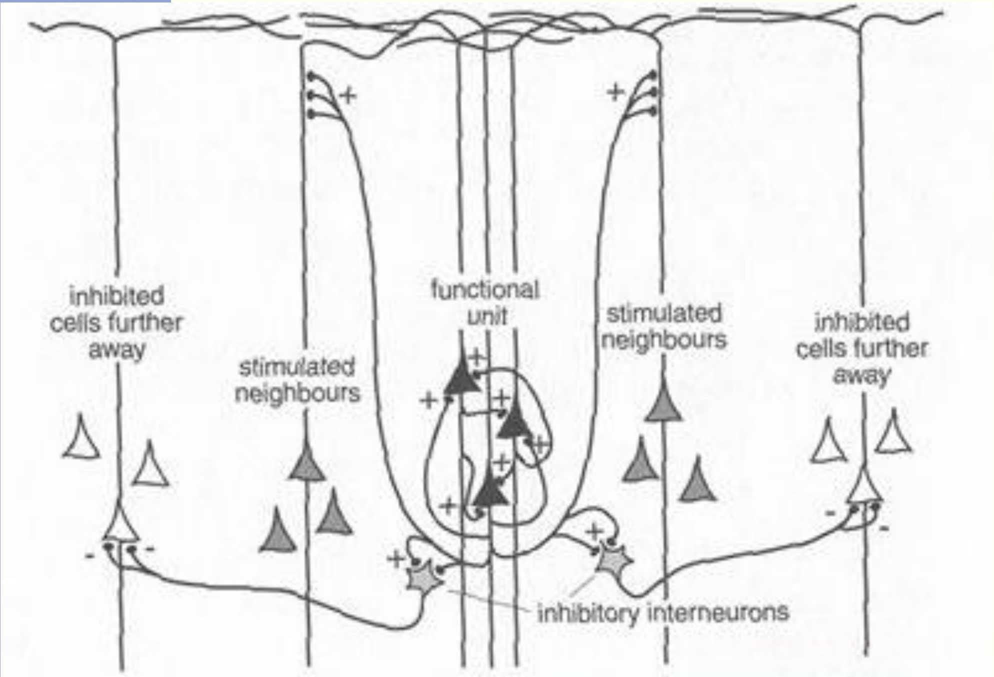
this has a direction(pink arrow)



- Six vertical layers, strictly interconnected
- Neurons are organized in columns (0.5 mm in diameter)
- Perpendicular to the cortical surface
- Same behavior in response to the same stimulus

Since we have a direction of the info processing, we can define 3 types of interneurons connections.

Different neural connections

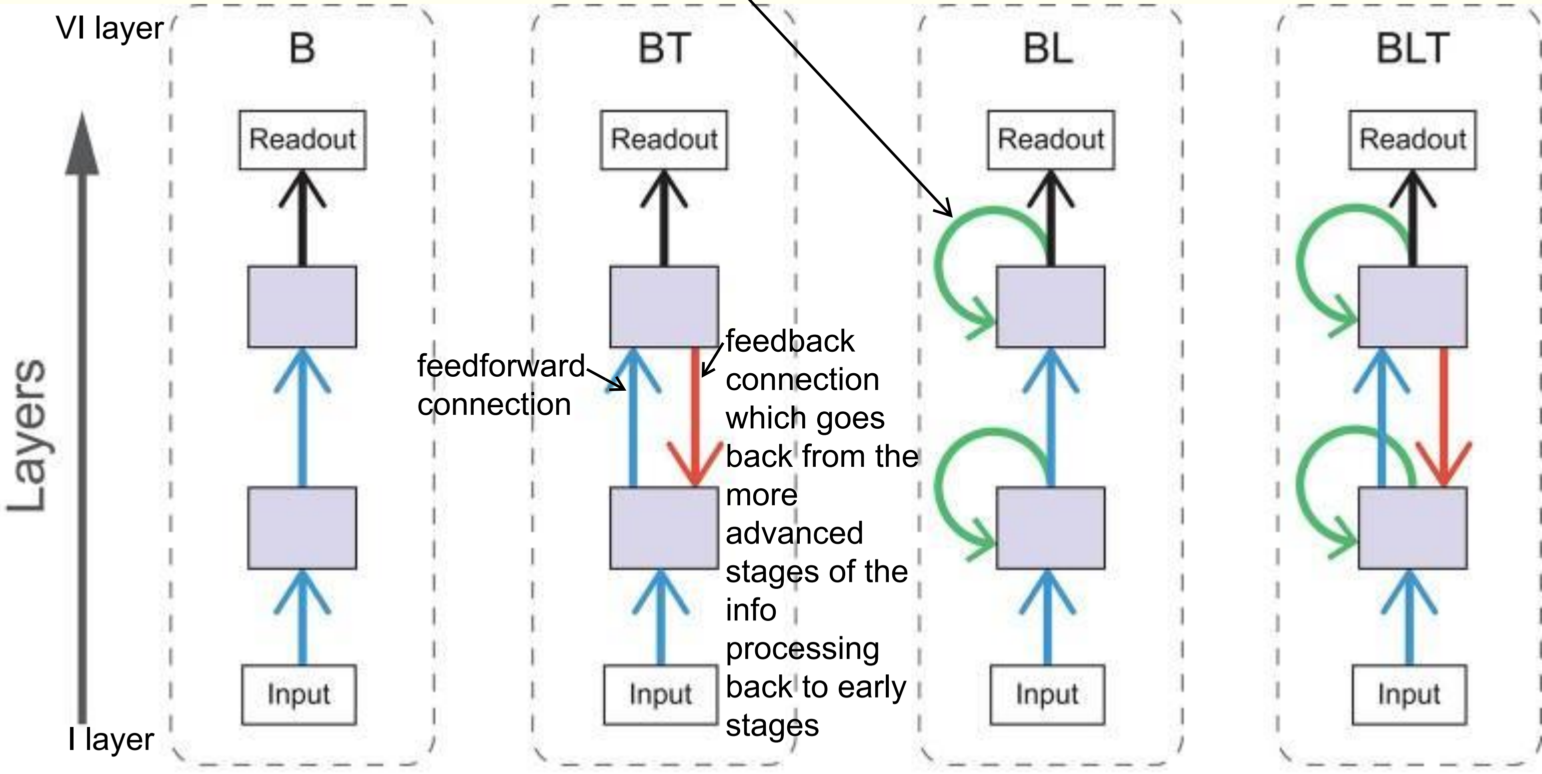


Feedforward, or bottom-up: directed from regions at the first processing stages to the following ones

Lateral: connections linking same stage regions

Feedback or top-down: from advanced stages back to previous ones

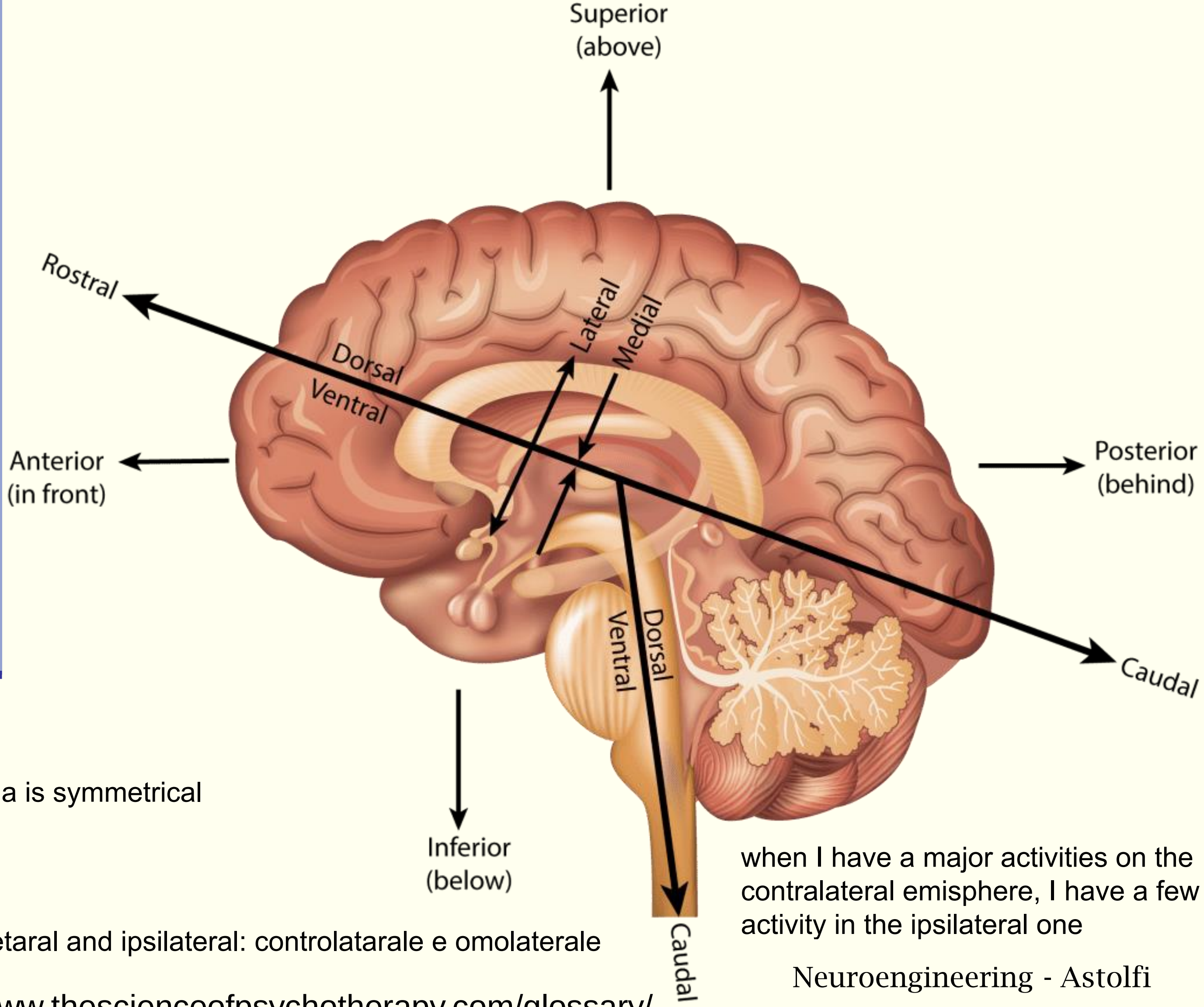
lateral connection. neurons in the same layer do interact and these connection are the most popular in neurons activities



The majority of connections are lateral ones

All these connections can be excitatory or inhibitory

How to get oriented



Anterior	In front of
Posterior	Behind
Superior	Above
Inferior	Below
Rostral	Towards the front of the brain
Caudal	Towards the back of the brain
Ventral	Towards the belly
Dorsal	Towards the back
Proximal	Closer to a set point
Distal	Farther from a set point
Medial	Towards midline of body
Lateral	Towards appendages
Contralateral	On the opposite side
Ipsilateral	On the same side

the soma is symmetrical

contraletaral and ipsilateral: controlatarale e omolaterale

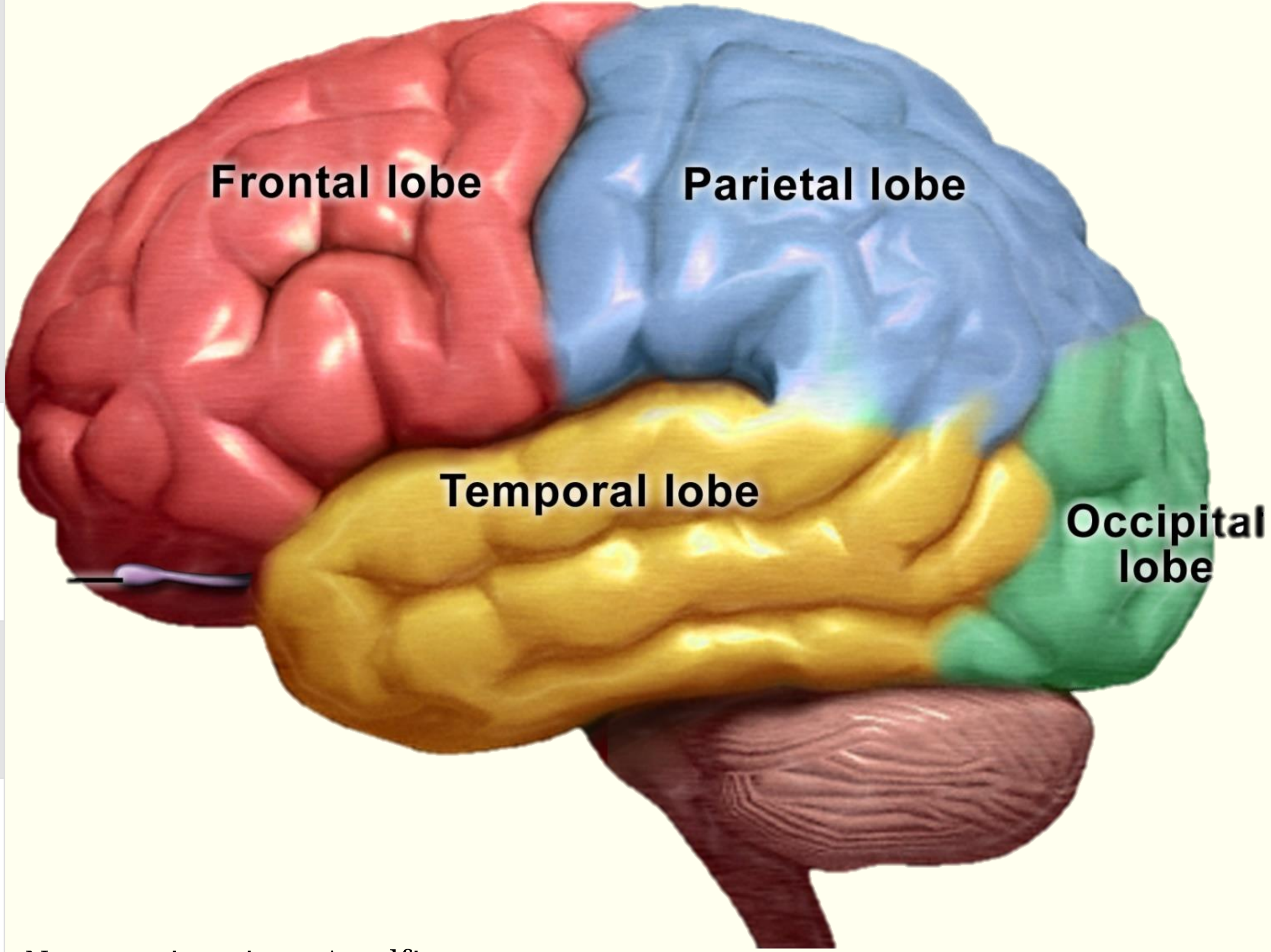
when I have a major activities on the contralateral emisphere, I have a few activity in the ipsilateral one

https://www.thescienceofpsychotherapy.com/glossary/

Brain lobes

lobes are associate to different functions

Lobe	Role
Frontal	Control center for executive functions: • reasoning • decision-making • expressive language • higher level cognitive processes • orientation (person, place, time, and situation integration of sensory information) also face recognition • planning and execution of movement
Parietal	• Primary and secondary somatosensory cortex • spatial navigation • touch, pressure, temperature, and pain
Occipital	• primary visual cortex • processing and interpretation of visual information
Temporal	• auditory cortex • center for receptive language • hippocampus (memory formation and emotion)



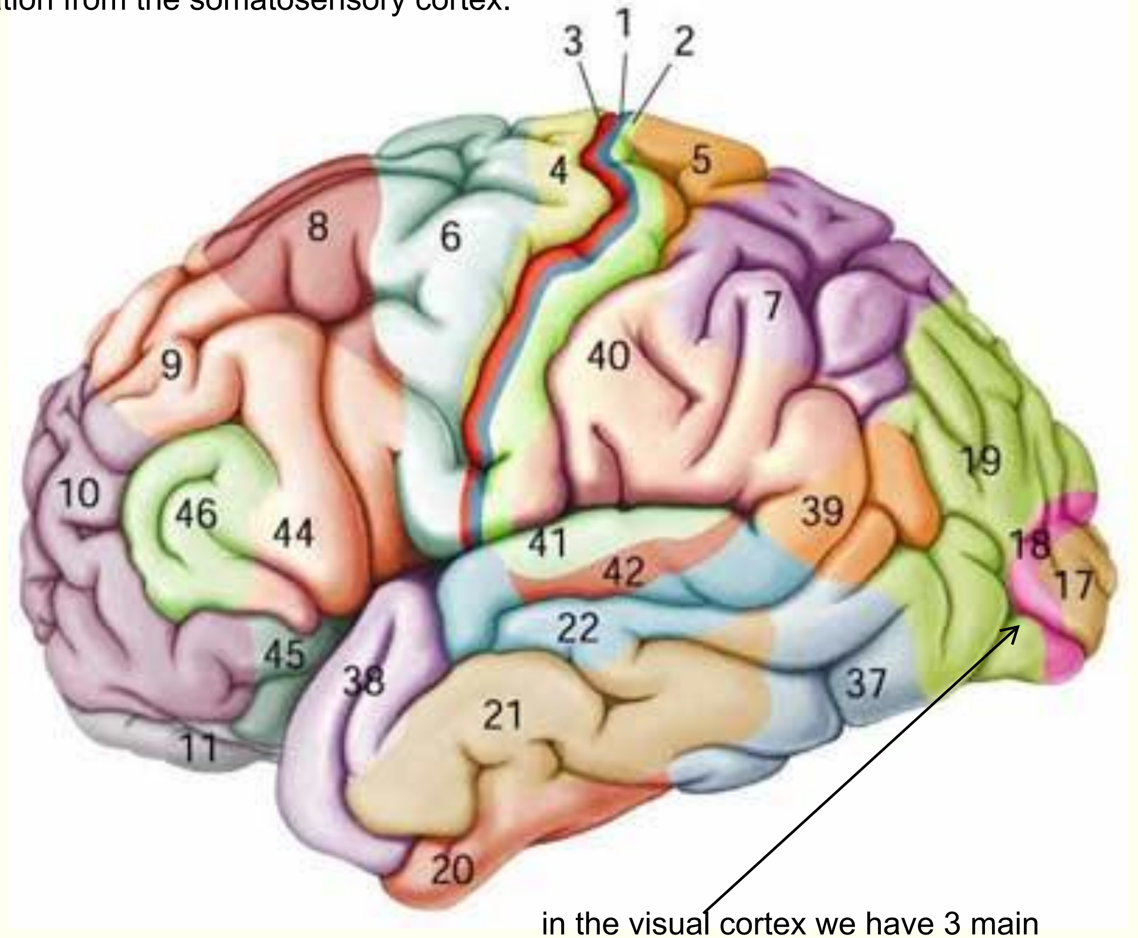
Medical gallery of Blausen Medical 2014

this is the name of the anathomist that began to study the brain cytoarchitectonic structure. CYTO is related to the cells, in this case to brain cells, ARCHITECTURE means the spatial organization. After death, if we dissect the brain, we can see that different regions are different type of cells with different organization and dimension...

Brodmann areas

since in nature the structure goes with the function, if we have different regions so different functions. This is a functional mapping of the brain. In the brain, the same function can be performed by more than one region. For ex. for the somatosensory function we have 3 broadmann regions (1-2-3) that together produce the behavior of the elaboration of the sensory information from the somatosensory cortex.

- First described in detail by Korbinian Brodmann in 1909
- Based on cytoarchitecture (neural cells type and organization), later associated with function
- Multiple areas/tissue types may participate in the same function: e.g., areas 3, 1, and 2 all comprise the sensory cortex



in the visual cortex we have 3 main broadmann regions with different aspects.

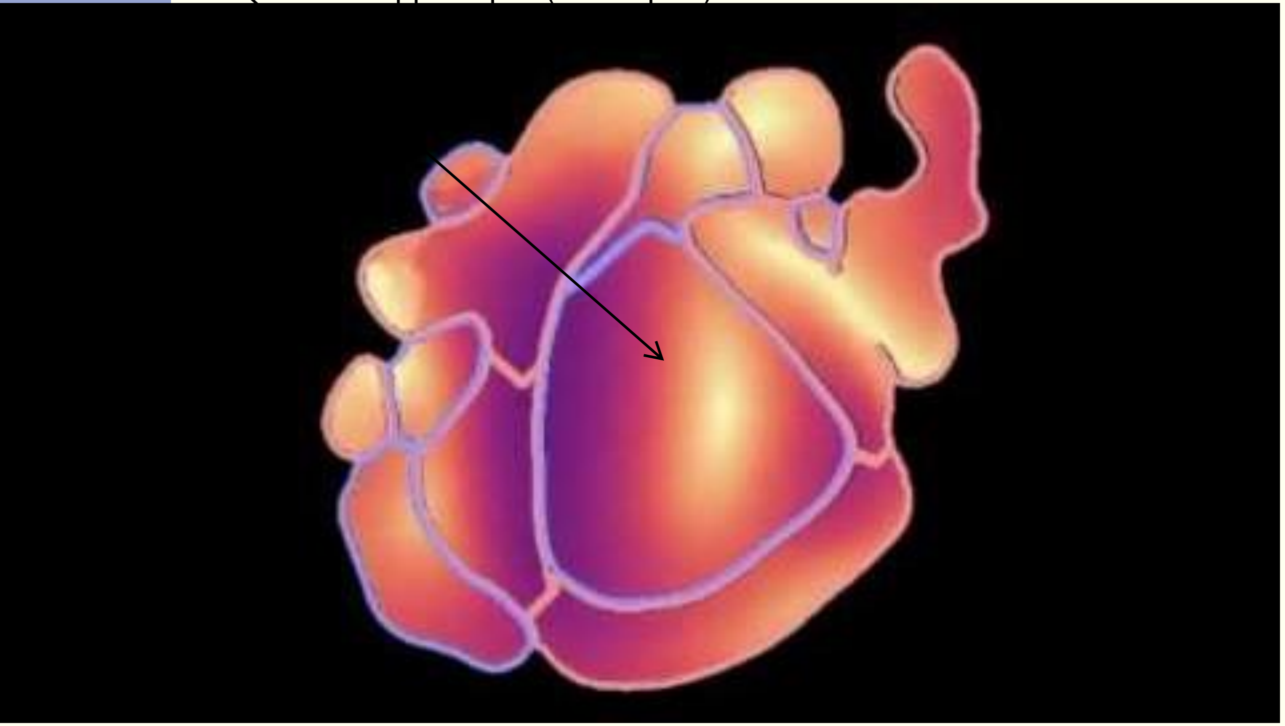
Cortical feature maps – visual cortex

located in the occipital part of the brain

Visual cortex: Retinotopic

It means that the position of the neurons in the cortex is related to what we have in our retina(back part of the eye which collect info from the outside and send it to the cortex)

when the eye look up, the part of the visual cortex that is activated is the opposit part(below part) and viceversa



- Highly specialized for processing information about static and moving objects and is excellent in pattern recognition
- this retinotopic mapping is a transformation of the visual image from retina to V1.
- Specialized neuronal families for shape, movement, contrast,…

visual and auditory apparatus are the most useful to interact we can note also that the part that is related to the leg is as larger as the part related to the hand(but the hand is smaller than the leg). It means that the amount of the portion is not proportional with the phisical extension of the muscle. This is because the priority of the hand movement, because we have more info to process and we need more accuracy

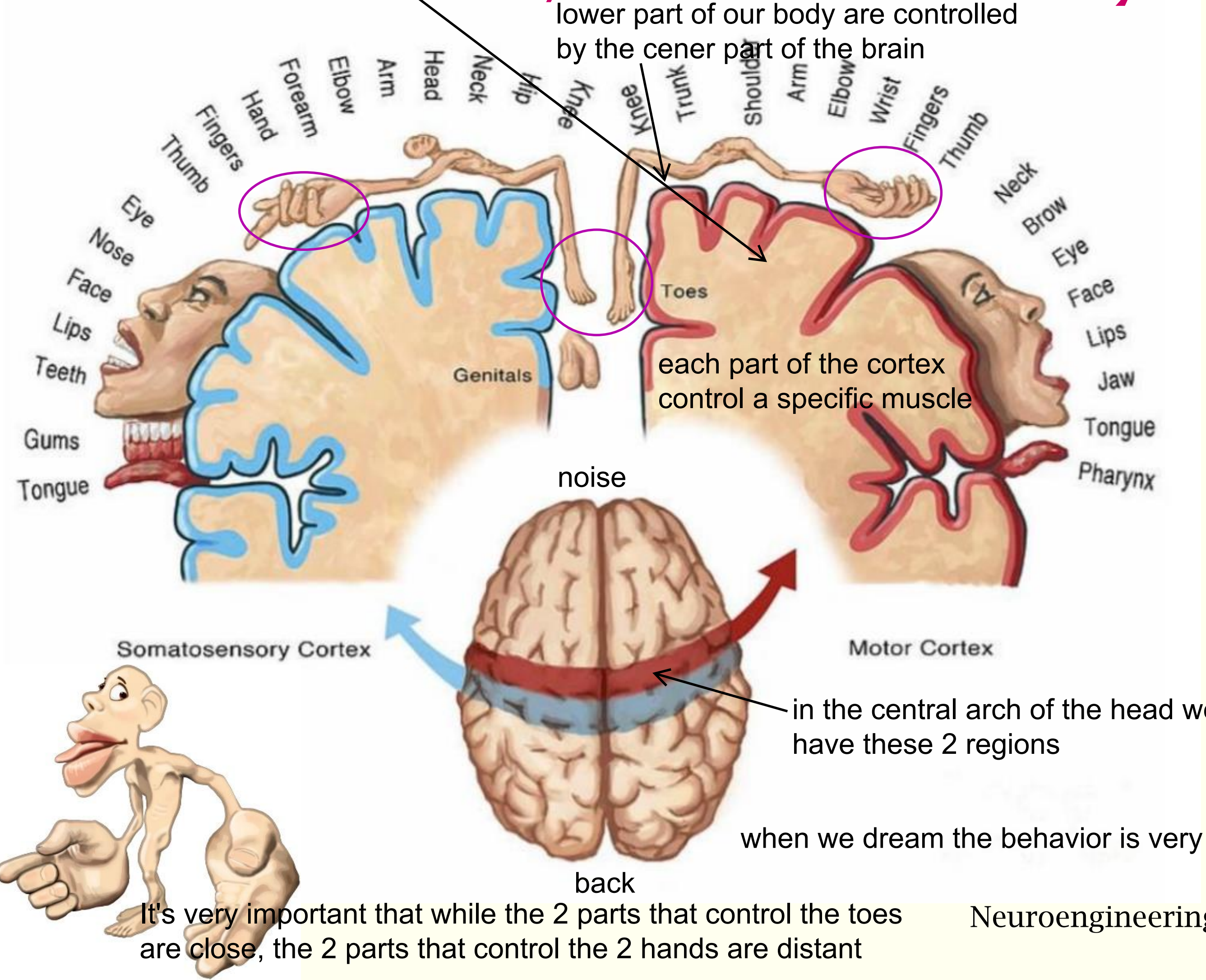
Cortical feature maps – motor and somatosensory

the left part of the brain control the right side of the body and viceversa(CONTROLATERAL SOMA)

SOMA: is the body. SOMATOTOPIC means that a specific part of the body is mapped on a specific part of the brain

Motor/somatosensory cortex: somatotopic

lower part of our body are controlled by the cener part of the brain



each part of the cortex control a specific muscle

noise

in the central arch of the head we have these 2 regions

when we dream the behavior is very different

back

It's very important that while the 2 parts that control the toes are close, the 2 parts that control the 2 hands are distant

motor primary cortex is responsable for the xecution of movements and to the control of muscles

- Motor control area: pre-central gyrus of the frontal lobe (Brodmann area 4, in red)
- Somatosensory areas: post-central gyrus of the parietal lobe (Brodmann areas 3,1,2, in blue)

the part of the brain are related not to muscles but to the receptors on our brain

name of the scientist

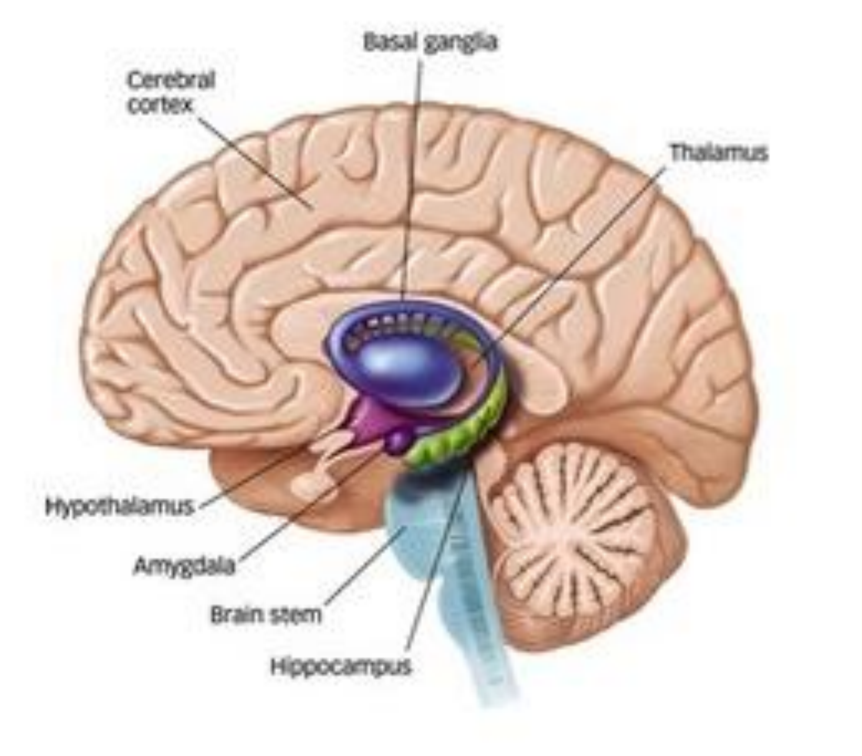
small human

- Penfield Homunculus: derived from stimulating awake patients during epilepsy surgery

there are 2 homunculus(red and blue)

for ex. if you play the piano, the part that control fingers increases and if you stop play it decreases to the original dimension(plasticity). It change in days, month, years, depends on how many time you spend on these activities the cotex is more accessible and also easier to influence the cortical activitiy by neuralmodulation.

16 Subcortical areas



main areas

It's important also for the cortical activity because it's like a pacemaker for the brain cortex.

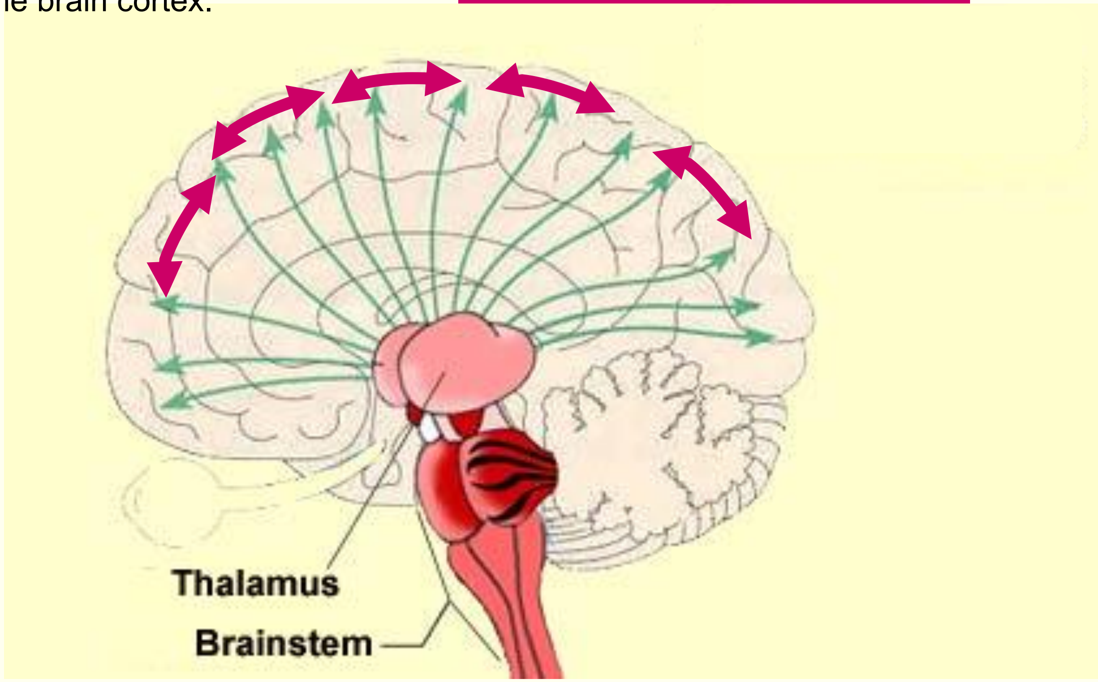
- Thalamus

(tronco encefalico)

- Brainstem

(gangli basali)

- Basal ganglia
- Cerebellum



- Difficult to reach, difficult to measure (especially noninvasively)

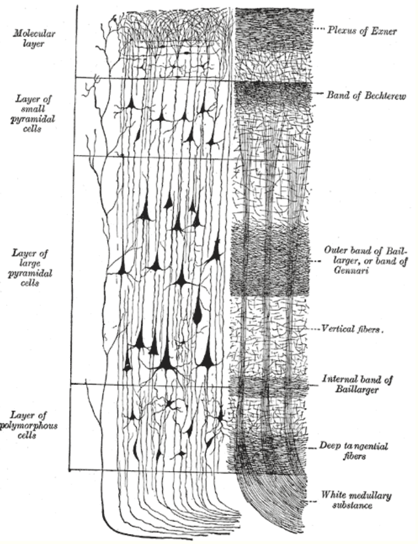
- Thalamus controls traffic from the periphery to the cortex (sensory afferents)

Brain organization at different levels

we need millimetric precision

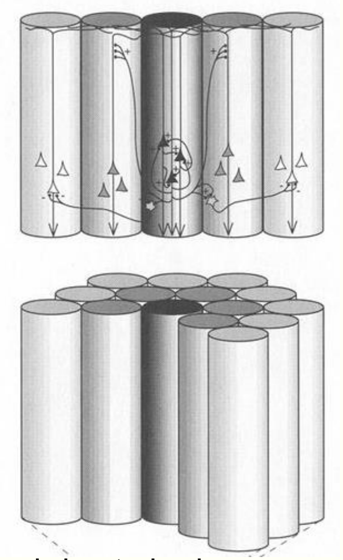
we need centimeters precision

Layers



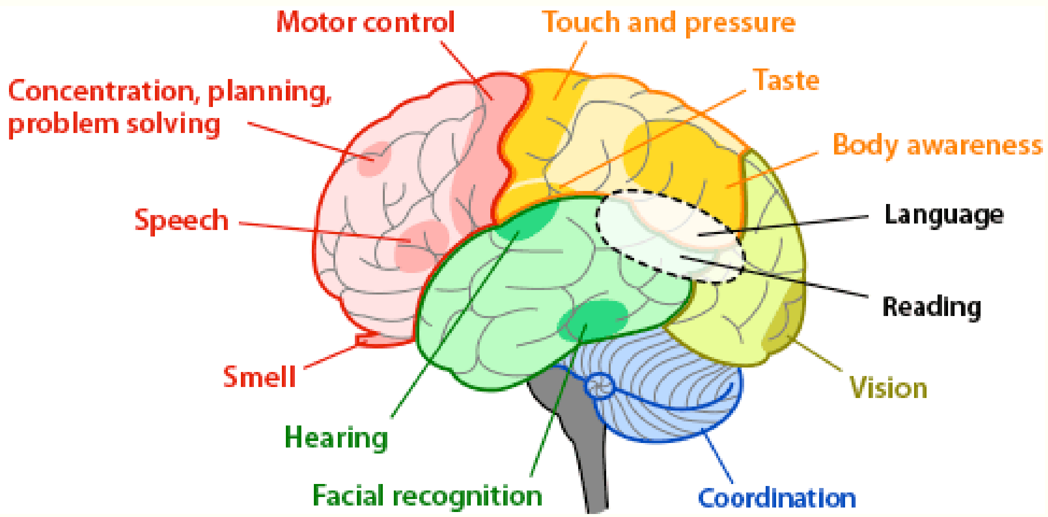
more detailed info

Columns

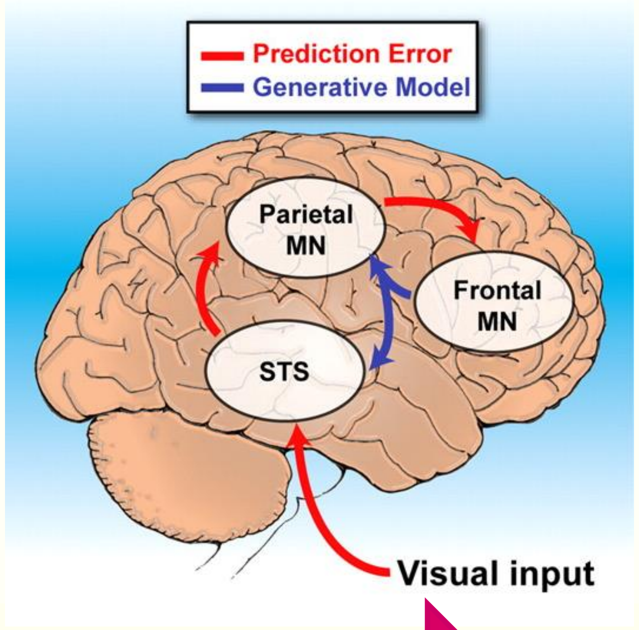


they bring to brain areas that can be the broadmann areas(more detailed) or brain lobes(more general)

Areas



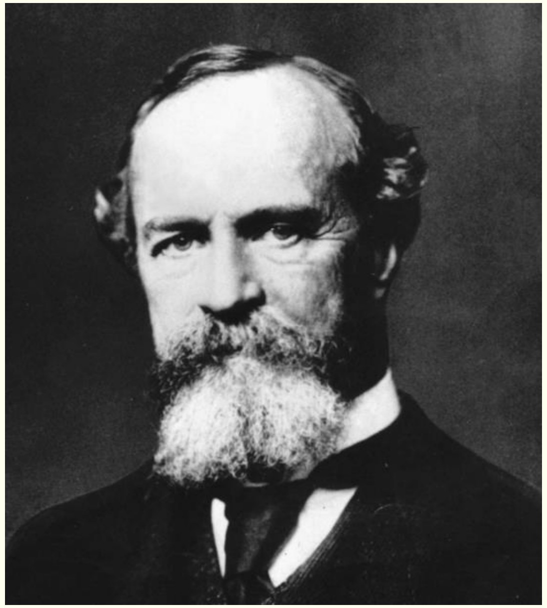
Circuits



to perform a movement we need to plan, prepare and execute this. To do this need cooperation between the parts

Different spatial scales (μm, mm, cm)

Brain plasticity



William James, *Principles of Psychology, 1890:*

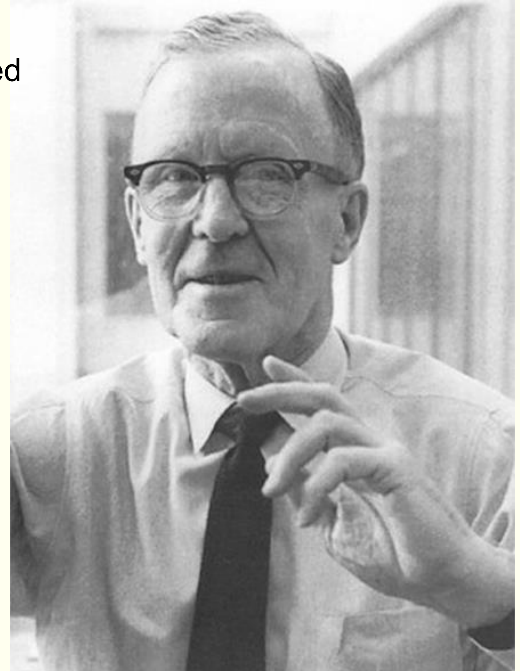
The phenomena of habit in living beings are due to the plasticity of the organic materials of which their bodies are composed.

the link between 2 neural cells can be established and reinforced when we use them together

Donald Hebb, *1949:*

"...two cells or systems of cells that are repeatedly active at the same time will tend to become 'associated', so that activity in one facilitates activity in the other." (Hebbian Learning)

if we use 2 things many time simultaneously became associated



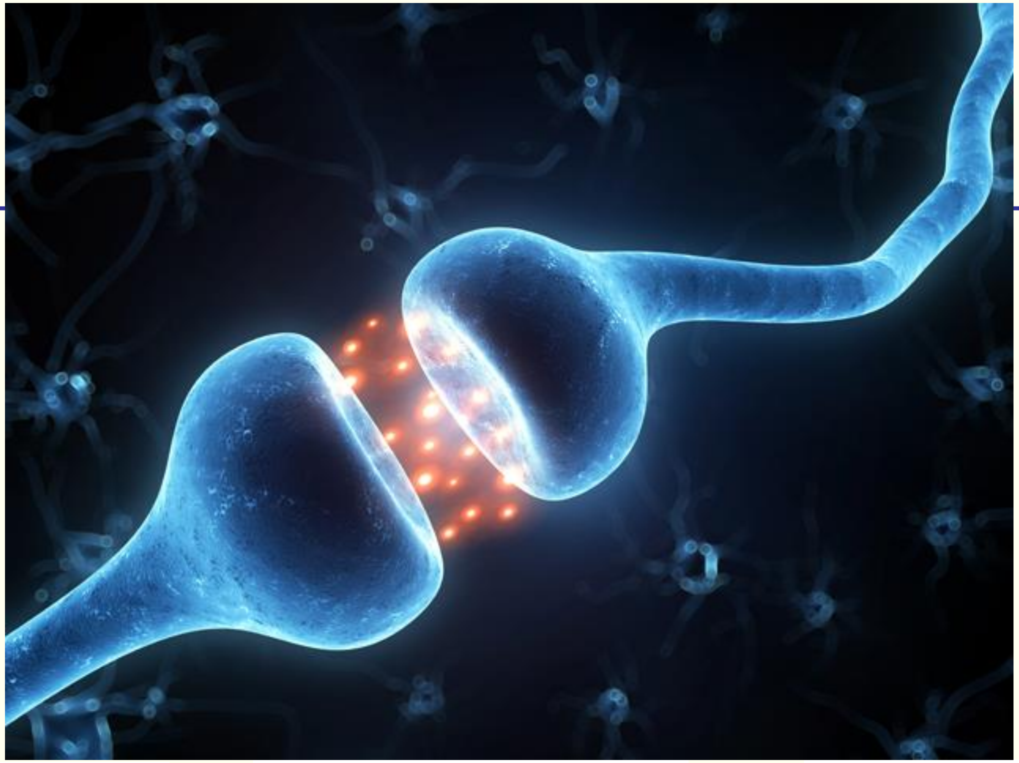
Brain plasticity during the lifespan

- Critical period (age 0-2): maximum brain reorganization, irreversible changes → very important
- However, we have evidences of plasticity in adults and even in the elderly people:
  - Learning
  - Memory
  - Consequences of sensory deprivation (amputees, acquired blindness, ...)
  - Reorganization after a brain lesion
  - Effectiveness of neurorehabilitation

1-Synaptic plasticity

most important mechanism at the base of plasticity

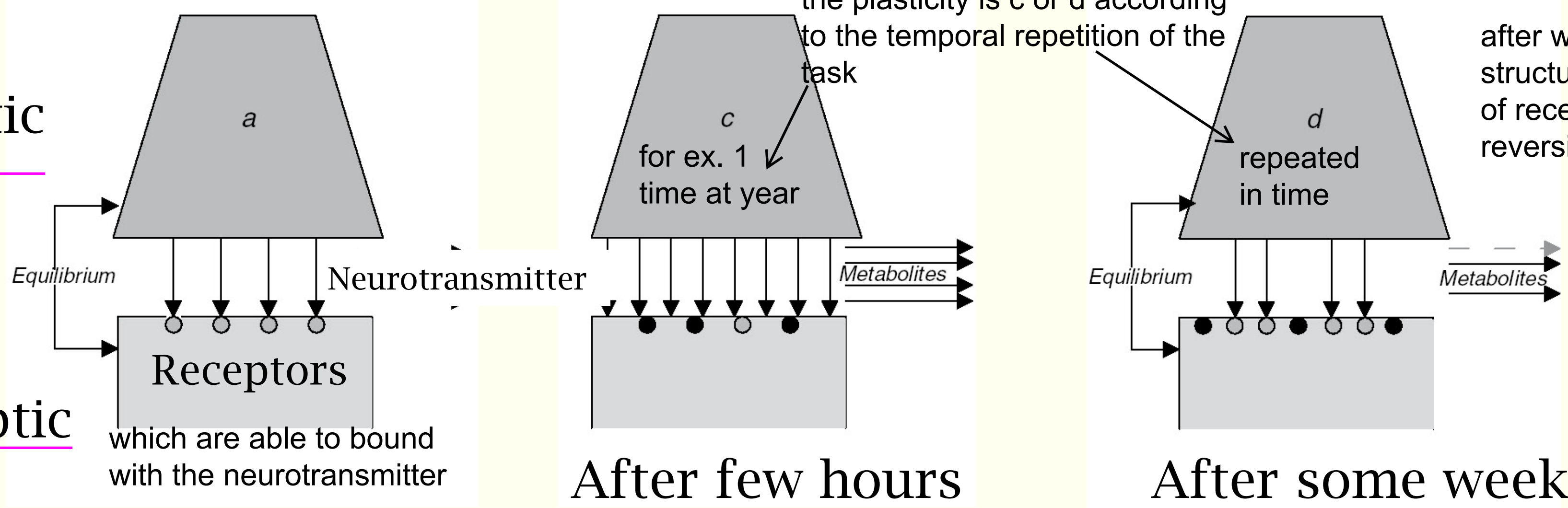
chemical and elechtric synapses. The second are less flexible than the first one. In chemical synapses the machanism by which the info is tranferred from the presynaptic to the postsynaptic cell is very complicated. It requires neurotransmitter and receptors.



for ex. if we are not able to play tennis table, in few hours we can learn. The amount of neurotransmitter which is released by the presynaptic cell to the postsynaptic cell increases. There is no change in the structure of the neurons or of the cell membranes, the cell is just using more neurotransmiters to improve the result of the info transfer. This process is reversible, if you don't play for time.

Presynaptic

Postsynaptic



the plasticity is c or d according to the temporal repetition of the task

for ex. 1 time at year

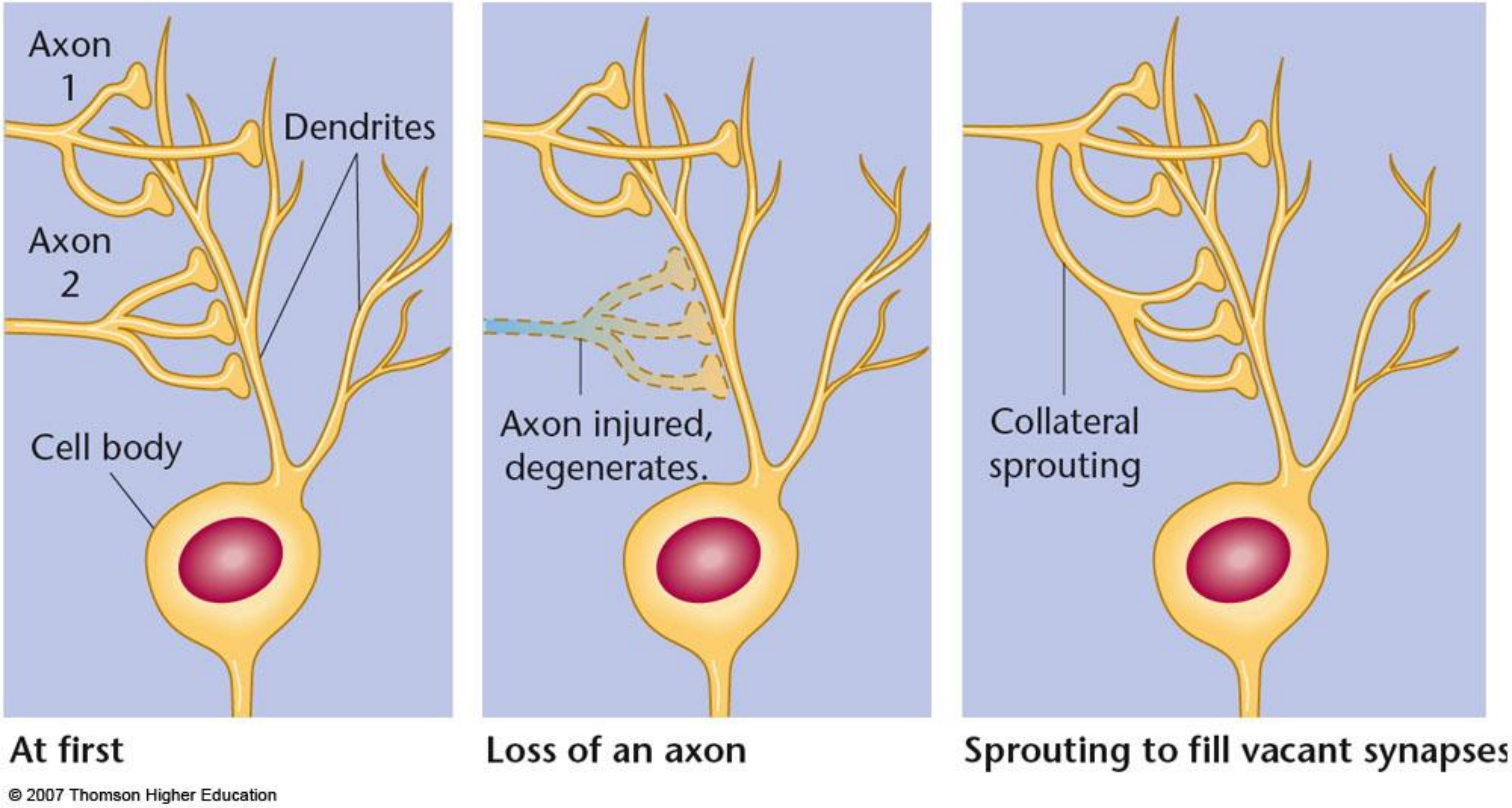
repeated in time

which are able to bound with the neurotransmitter

after weeks or months we have structural changes. Larger number of receptors. This is no longer reversible.

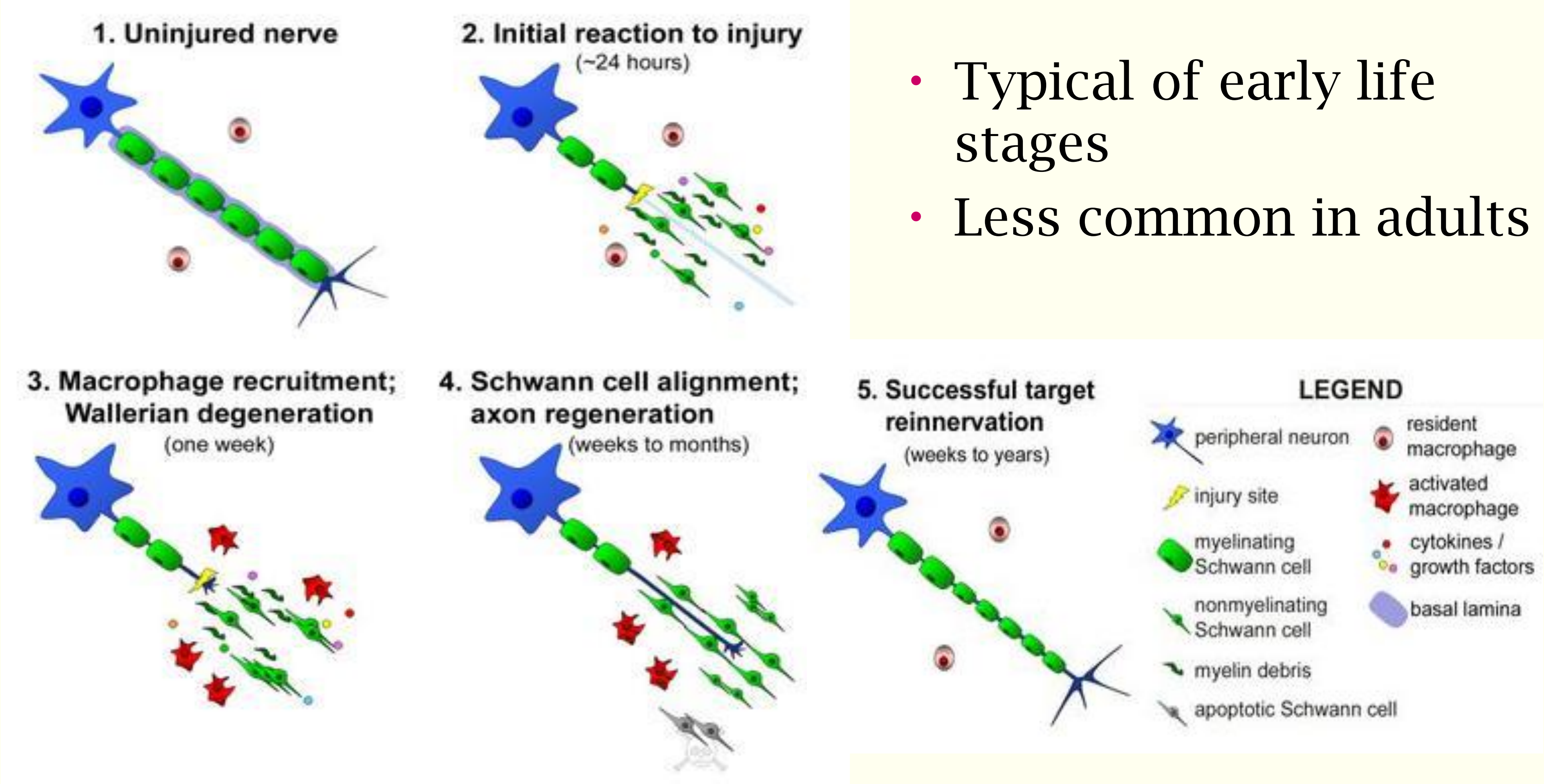
2- Axonal sprouting (or pruning)

production of new synapses



3- Axonal regeneration

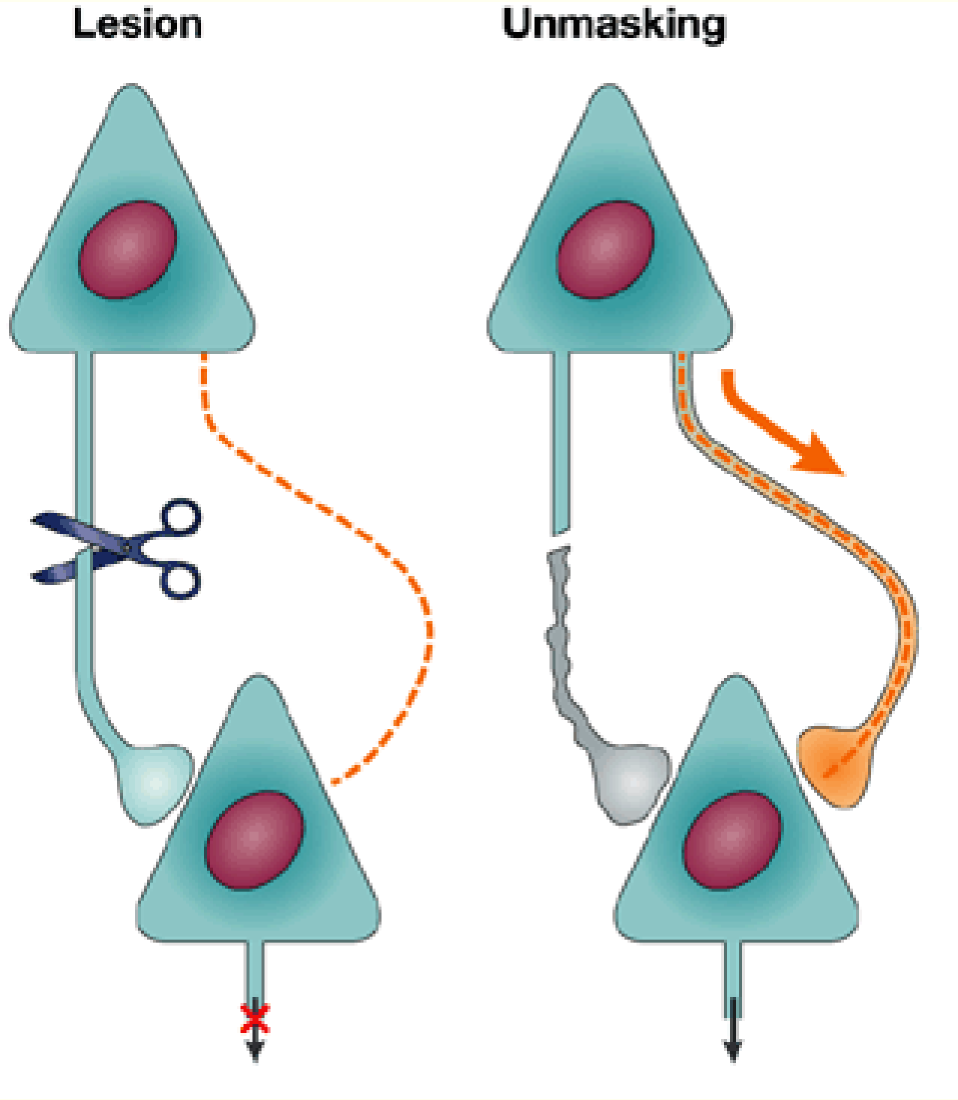
the complete regeneration of parts of neurons is more difficult in adults but typical in prenatal period and in critical situations



- Typical of early life stages
- Less common in adults

4- Unmasking of latent synaptic connections

Redundancy, synapses that are there but are not used until they are needed because of a lesion



References

- Hari & Puce:
  - Chapter 2, pagg.13-18 (Sections: Overview of the human brain; Functional structure of the human cerebral cortex; Communication between brain areas)
- Wolpaw&Wolpaw:
  - Chapter 2, pagg. 15-20
- http://learn.neurotechedu.com/neuroanatomy_and_brain_organization/

Self-evaluation test

1. At what temporal scale does the brain operate?
2. At which different spatial scales may we look at its functioning?
3. Put the following levels of cortical organization in a hierarchical order (from the smaller to the larger):
   A. Brodmann areas
   B. Cortical columns
   C. Brain lobes
   D. Cortical layers
   E. Brain circuits
4. Indicate which of the brain lobes houses the visual function:
   A. Frontal
   B. Temporal
   C. Parietal
   D. Occipital

Self-evaluation test

5. For each of the following brain areas, indicate if they are cortical or subcortical:
   A. Thalamus
   B. Primary motor area
   C. Cerebellum
   D. Broca (language) area
   E. Brainstem
6. Does the short-term synaptic plasticity involve:
   A. A structural change in the post-synaptic membrane
   B. An increased number of membrane receptors
   C. The amount of neurotransmitter released in the synaptic cleft
   D. An irreversible change in the synaptic structure
7. List the four main neuronal mechanisms behind brain plasticity