

Cognitive Neuroscience for AI Developers

The Brain's Structure and Functional Systems

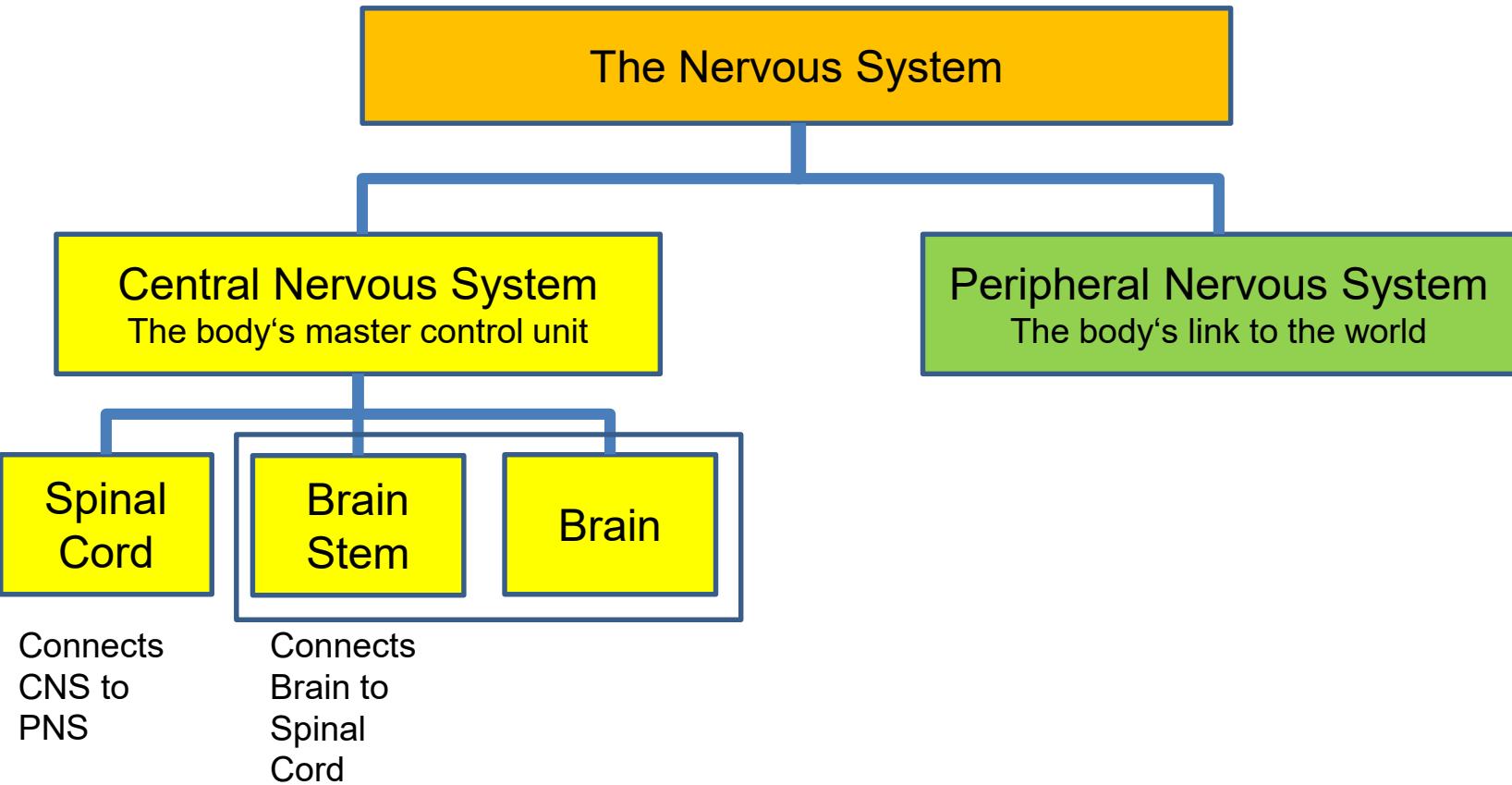


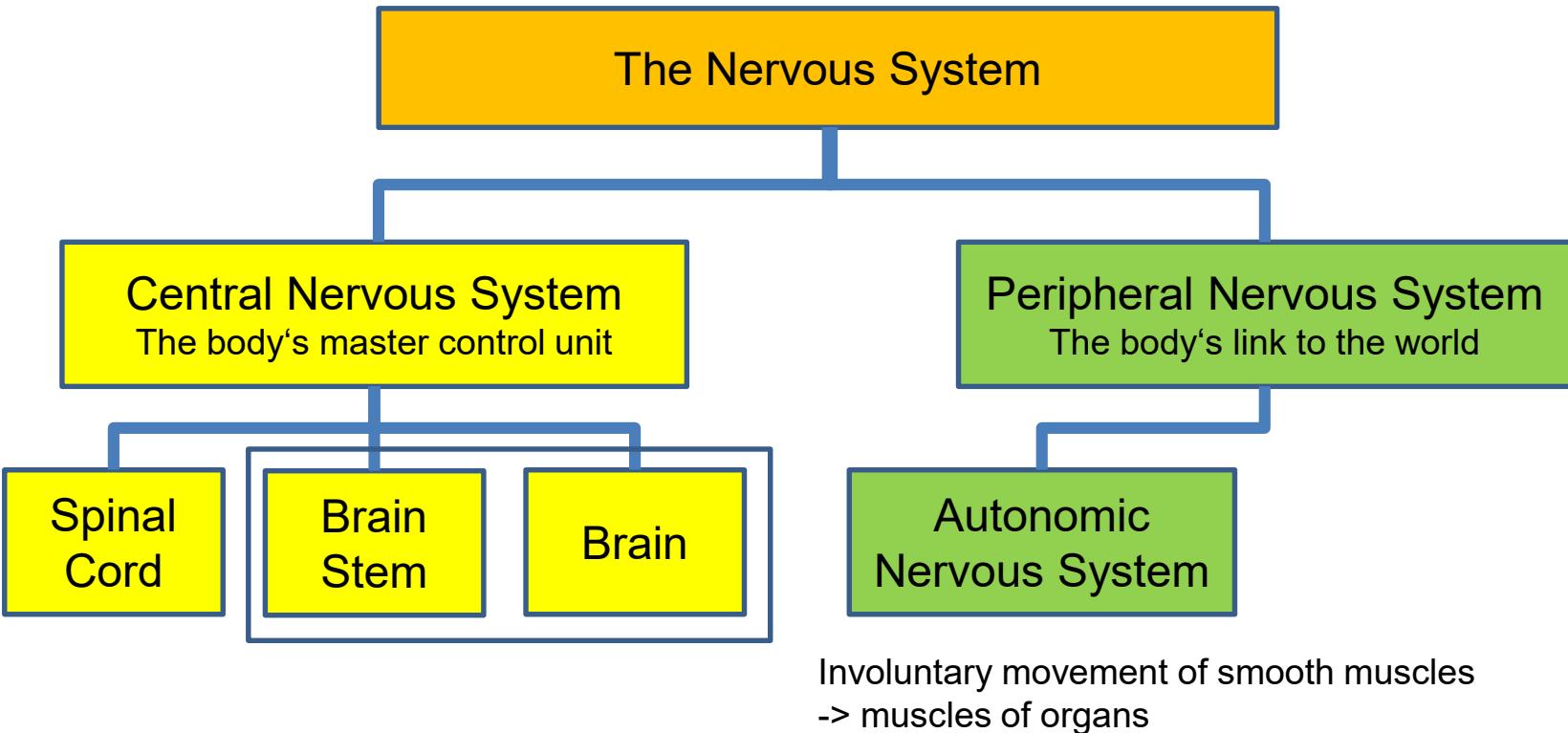
The human nervous system (coarse grained)

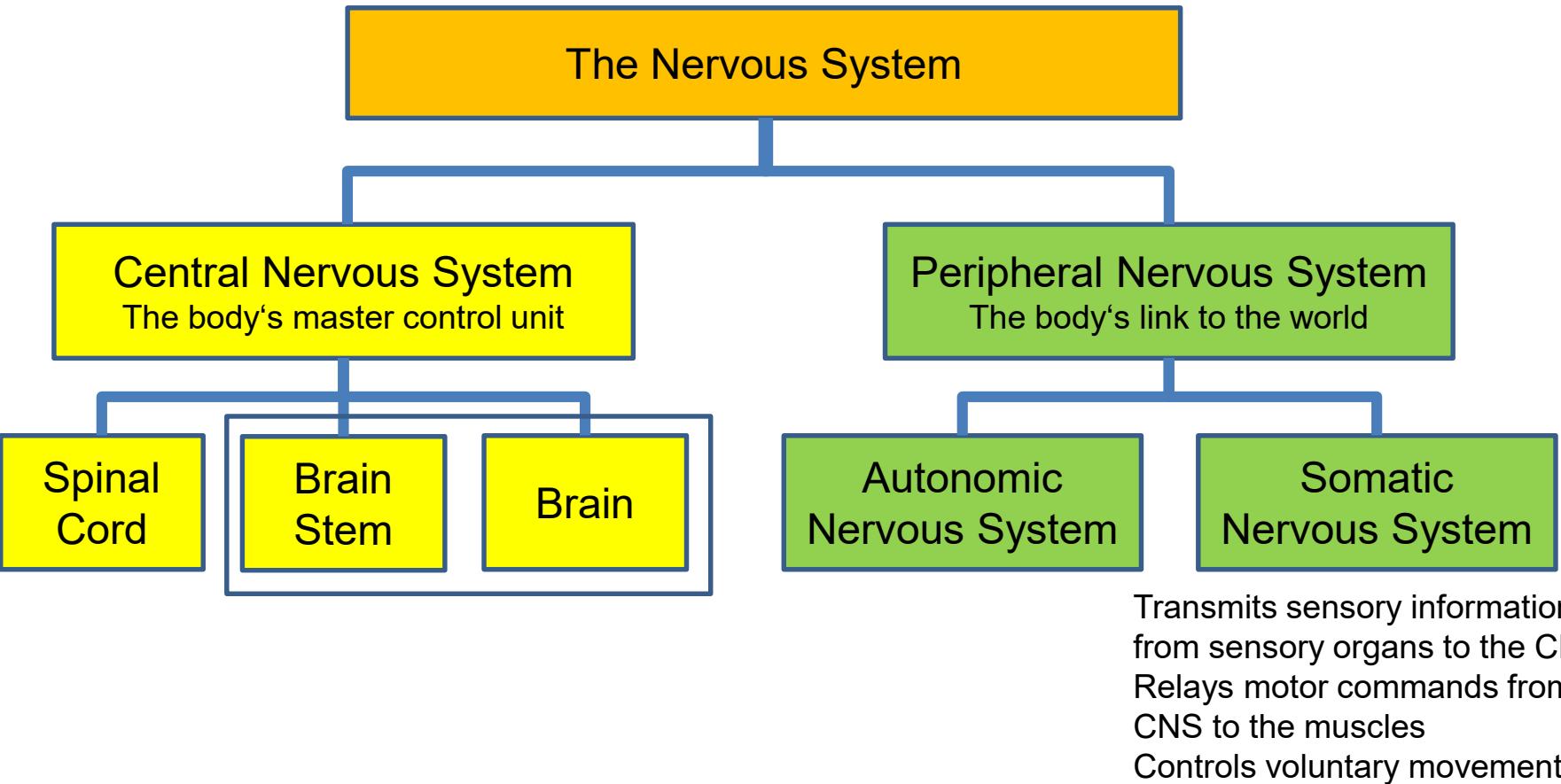
The Nervous System

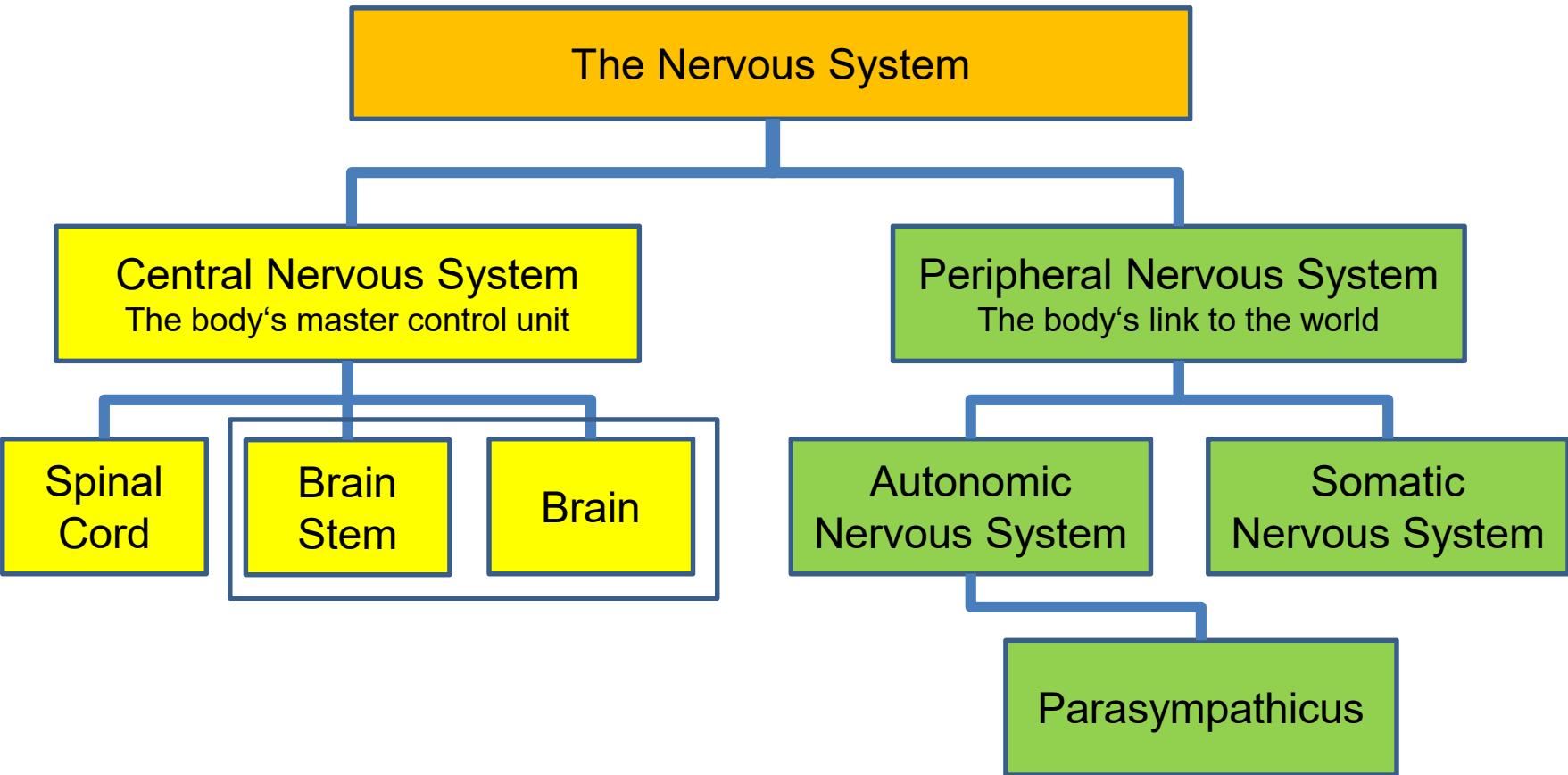
Central Nervous System
The body's master control unit

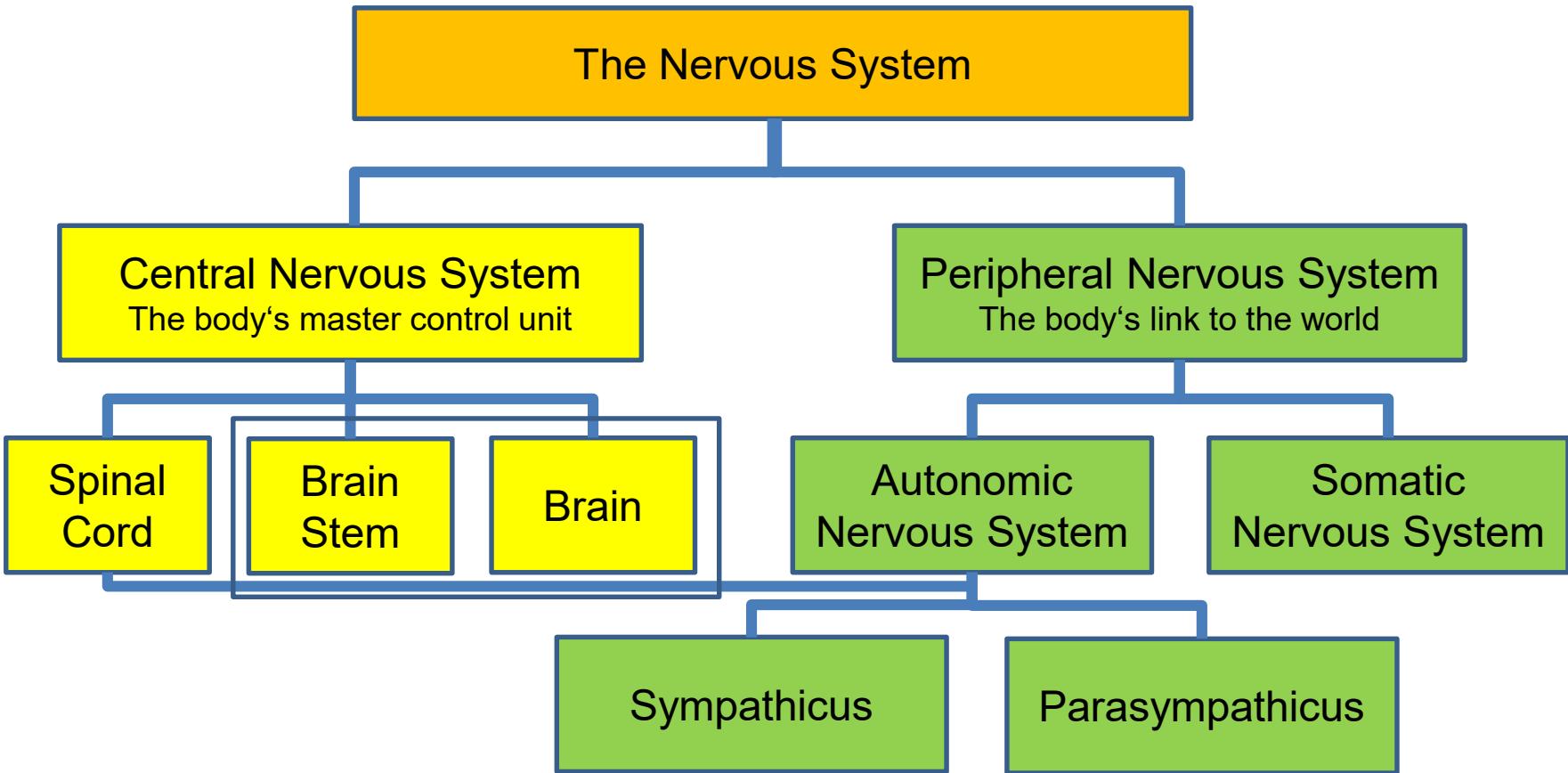
Peripheral Nervous System
The body's link to the world







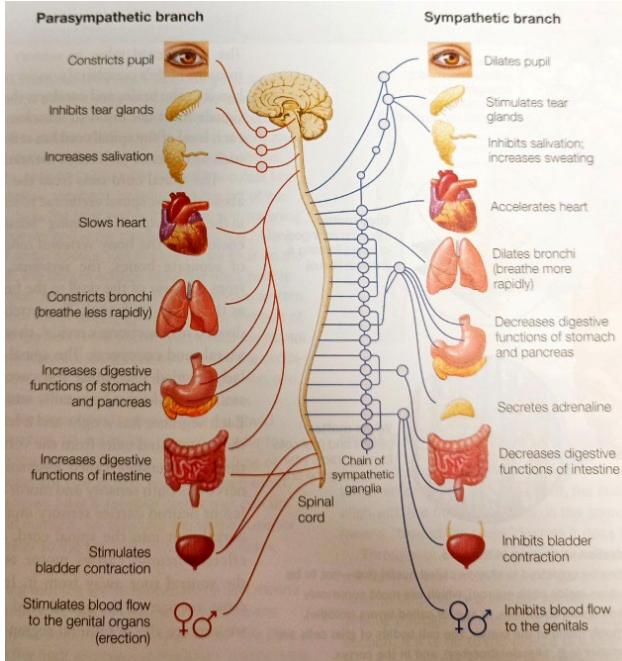




The autonomic nervous system

A quick description of the autonomic nervous system (also called visceral)

- Autonomic system controls involuntary action of smooth muscles, heart and glands
- Autonomic system has two subdivisions: Sympathicus and parasympathicus
- **Sympathicus:**
 - increases heart rate, prepares body for action (fight or flight)
- **Parasympathicus:**
 - slows heart rate stimulates digestion



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

A quick description of the autonomic nervous system (also called visceral)

Not very interesting for cognitive neuroscience!

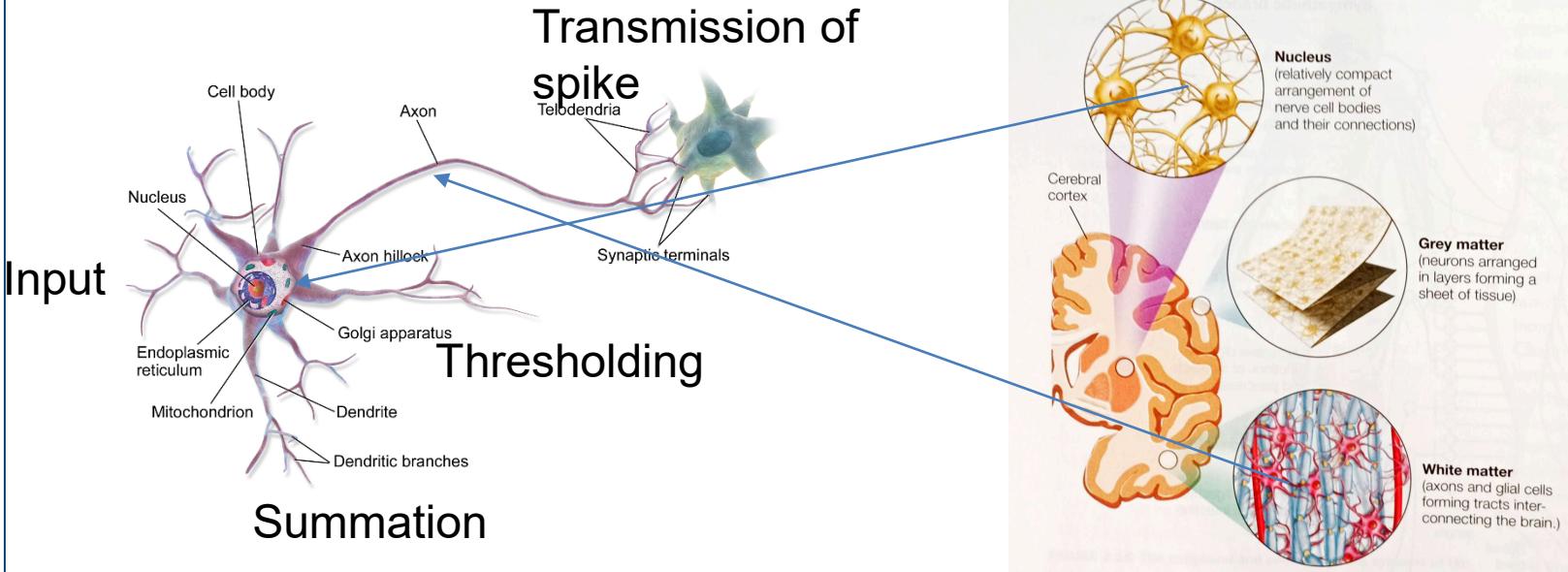
- For cognitive neuroscience the somatic nervous system and CNS is more important

The central nervous system (CNS)

Basic Terms (CNS)

Organization of neurons in the CNS

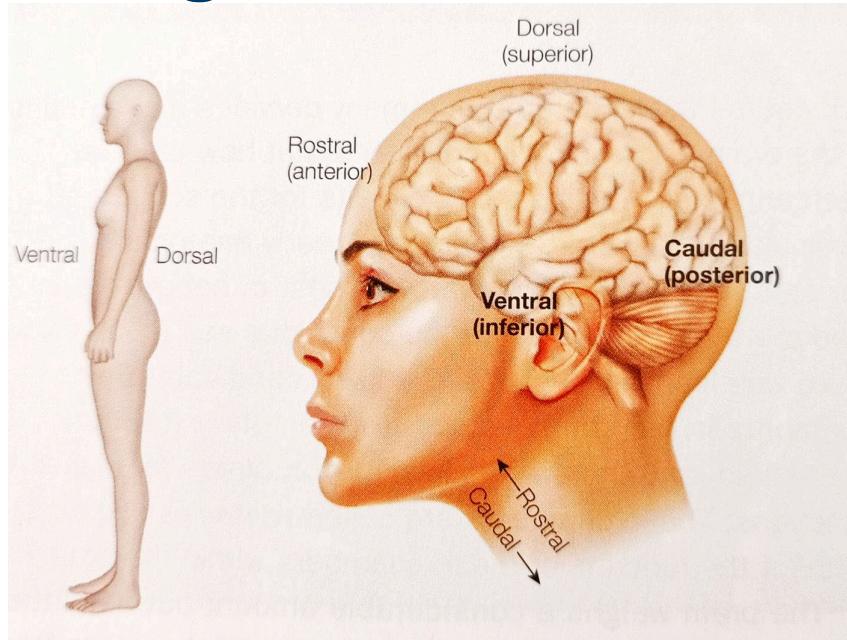
Neuron: processing unit of the brain (analog to transistor)



<https://en.wikipedia.org/wiki/Neuron>

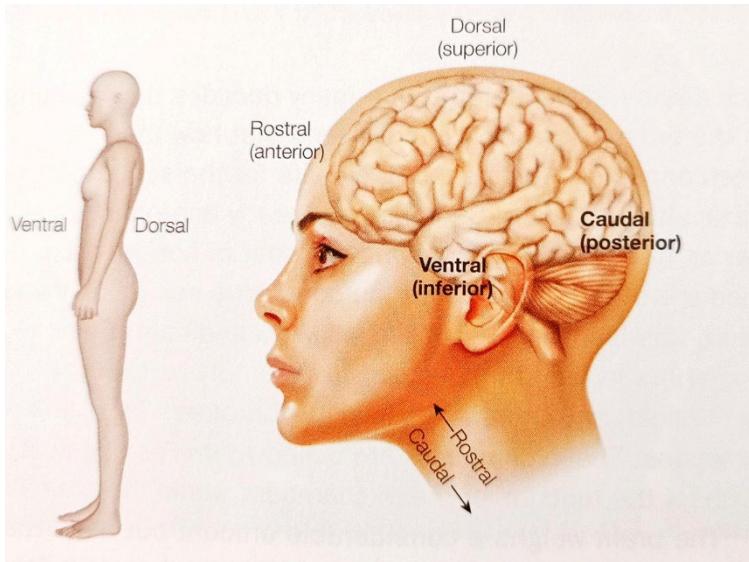
Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Navigate through the CNS

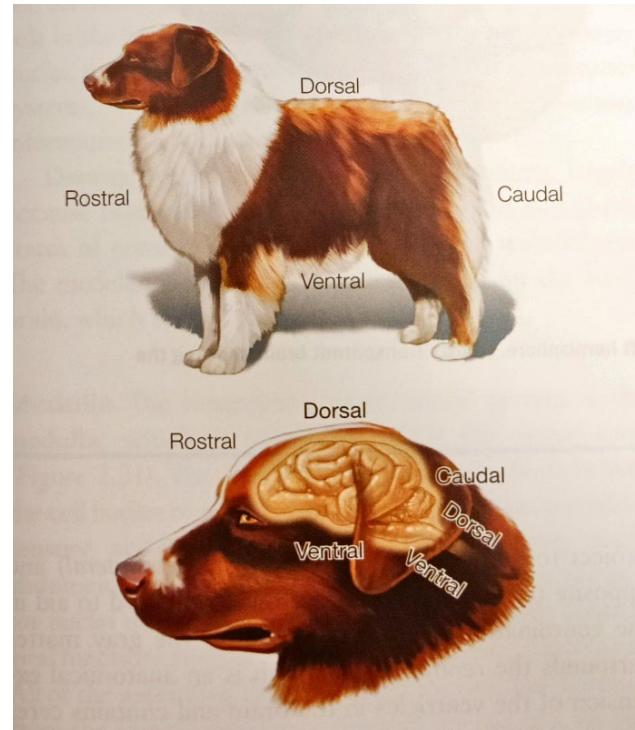


Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Navigate through the CNS



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

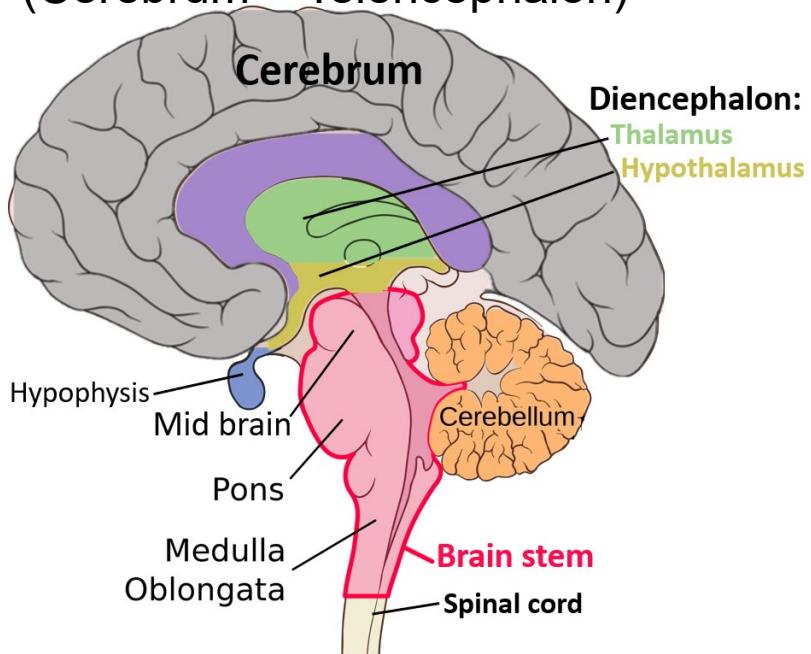


Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

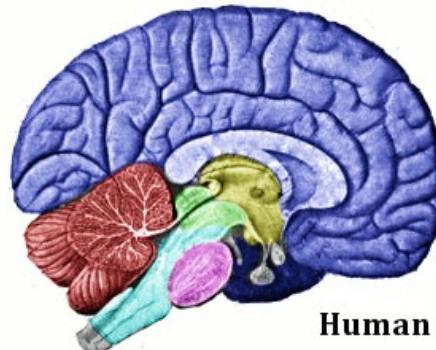
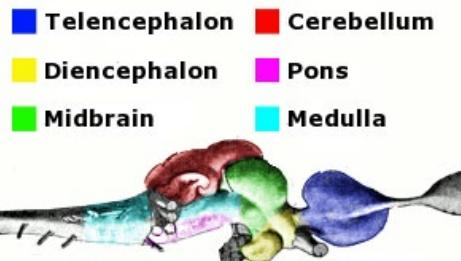
The parts of the central nervous system (CNS)

The gross organization of the brain

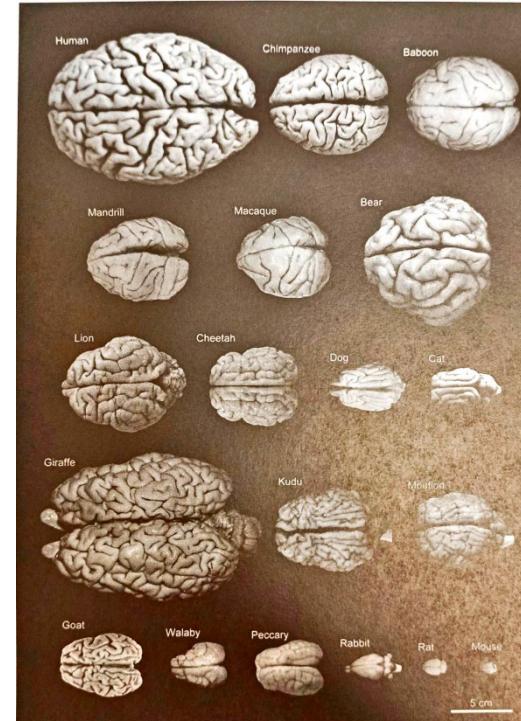
(Cerebrum = Telencephalon)



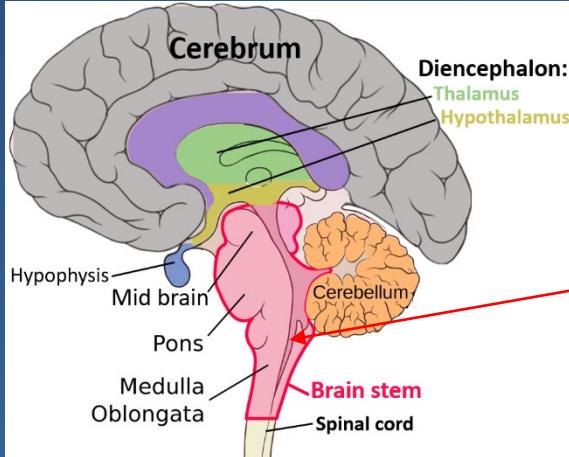
https://en.wikipedia.org/wiki/List_of_regions_in_the_human_brain#/media/File:Basic_structures_of_the_brain_highlighted.png



<https://en.wikipedia.org/wiki/Brain>



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

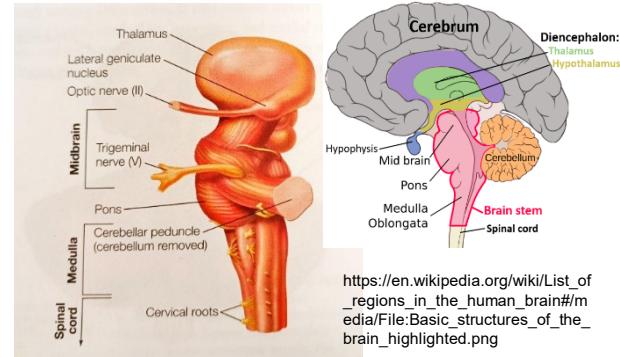


The brainstem

https://en.wikipedia.org/wiki/List_of_regions_in_the_human_brain#/media/File:Basic_structures_of_the_brain_highlighted.png

The brainstem (Medulla, Pons, and Midbrain)

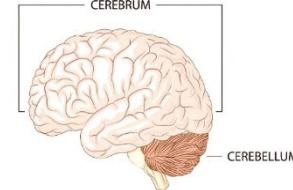
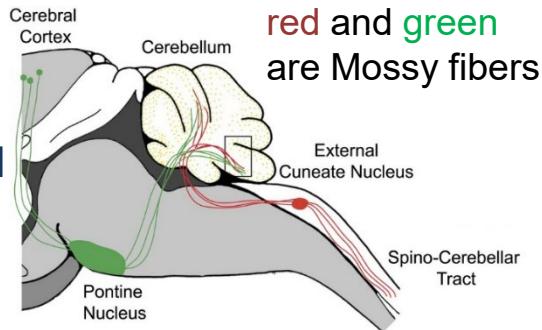
- Contains basic function: Damage is life threatening
- **Medulla (oblongata)**: motor nuclei that innervate the heart, controls respiration, heart rate etc, relay station for sensory and motor information
- **Pons**: connection between brain and cerebellum, important for eye movement (saccades), responsible for generating rapid eye movement (REM) sleep
- **Midbrain (mesencephalon)**: large fiber tracts from the telencephalon run through the midbrain to spinal cord or cerebellum, midbrain contains:
 - **inferior colliculus**: important to locate auditory stimuli
 - **superior colliculus**: important to locate visual stimuli
 - **red nucleus**: motor coordination (arm swing while walking)



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

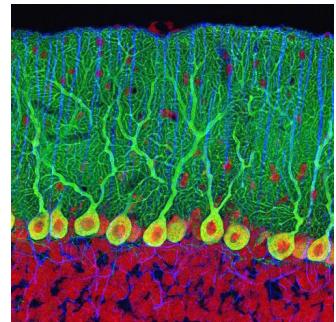
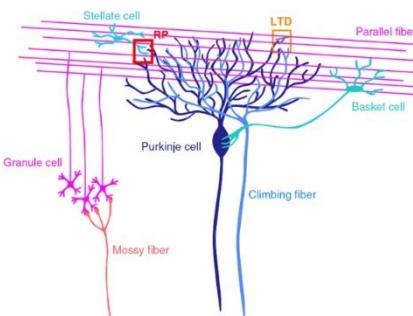
Cerebellum

- Contains most neurons of the brain!
69 billion neurons from 86 billion neurons in total
- Temporal coordination of movements (and cognition) and error correction of movements -> smooth execution of movements and learning new motor skills
- Extremely regular structure
- Climbing fibers: error signal (from sensory and motor cortices), Mossy fibers: motor and sensory signals
- Purkinje cells only output from cerebellum (inhibition) -> to vestibular nuclei in medulla (balance)



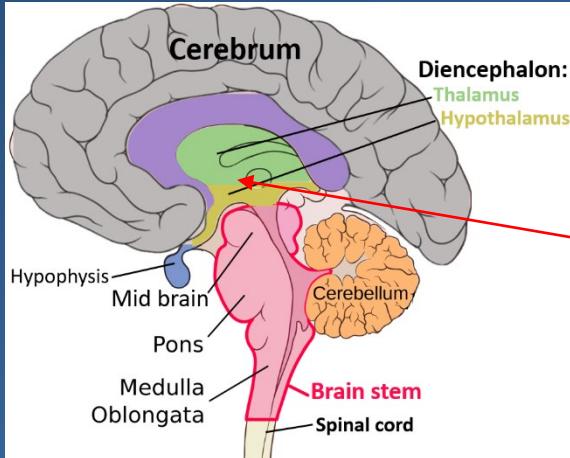
Source:
www.psychologytoday.com

<https://elifesciences.org/articles/00641>



<https://www.frontiersin.org/articles/10.3389/fncel.2014.00042/full>

<https://www.psychologytoday.com/intl/blog/the-athletes-way/201411/autism-purkinje-cells-and-the-cerebellum-are-intertwined>

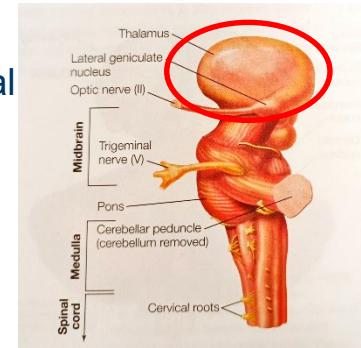


The diencephalon

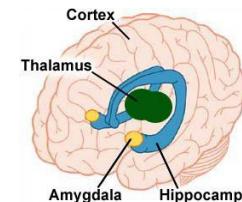
https://en.wikipedia.org/wiki/List_of_regions_in_the_human_brain#/media/File:Basic_structures_of_the_brain_highlighted.png

The diencephalon (thalamus and hypothalamus)

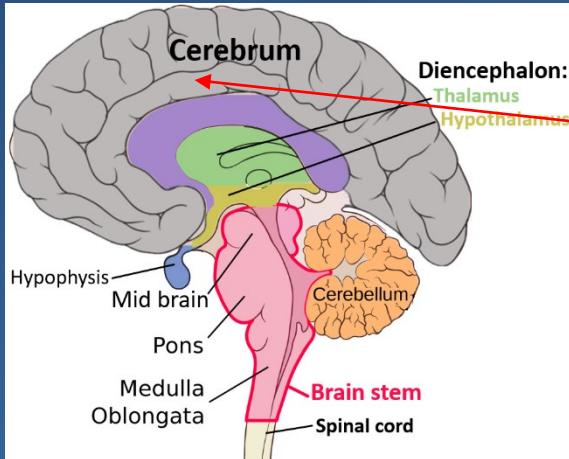
- Thalamus:** „gateway to cortex“ („gateway to consciousness“)
 - All sensory input has to pass the thalamus (except olfactory input)
 - Builds neuronal circuits with basal ganglia, cerebellum, neocortex, and medial temporal lobe
“Grand Central Station of the Brain”
 - Several nuclei: lateral geniculate nucleus, medial geniculate nucleus, ventral posterior nuclei, pulvinar nucleus (attention)
- Hypothalamus:** Connection of the brain and the endocrine system
 - Mammillary bodies: circadian rhythm (light dark cycles)
 - Hypothalamus controls functions of maintaining normal state of body
 - Sends signals out that drive behavior to alleviate hunger and thirst
 - Controls body temperature
 - Controls pituitary gland which releases hormones into the blood stream



Cognitive neuroscience,
Gazzaniga, Ivry, Mangun,
2014



Source: <https://www.pinterest.de/pin/384494886932859162/>



The telencephalon

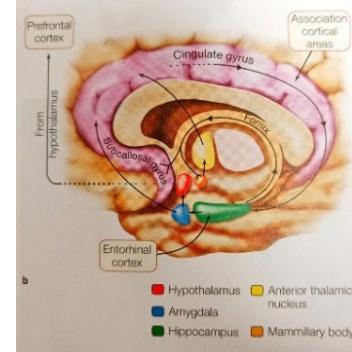
https://en.wikipedia.org/wiki/List_of_regions_in_the_human_brain#/media/File:Basic_structures_of_the_brain_highlighted.png

The telencephalon (limbic system, hippocampus, amygdala, basal ganglia, cerebral cortex)

- Evolutionary newer
- Limbic system (functional structure):
 - Consists of cingulate cortex (band of cerebral cortex), parts of hypothalamus, hippocampus
 - Limbic system as system of emotional behavior,
-> Criticism: Limbic system is nebulous -> **could be discarded**

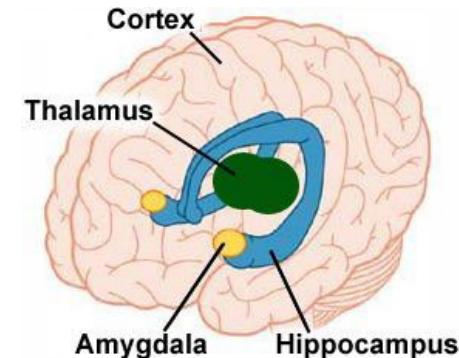
• Hippocampus:

- Spatial Navigation
- Episodic Memory
- Memory formation
- Organization of thoughts



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- Amygdala: Emotional responses, Control of fear, anxiety, aggression



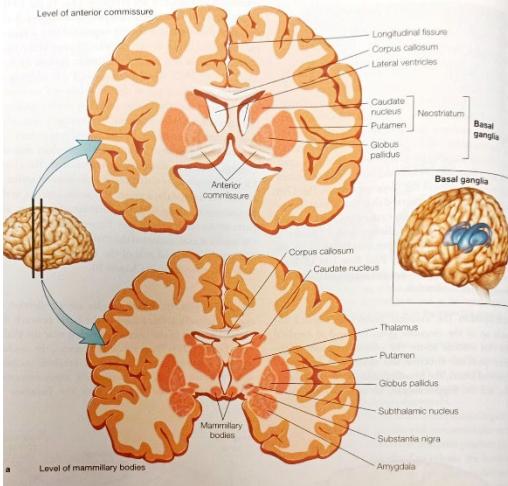
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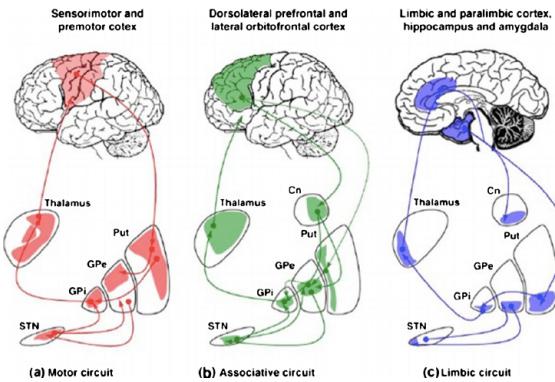
Source: [wikipedia.org](https://en.wikipedia.org)

Basal ganglia

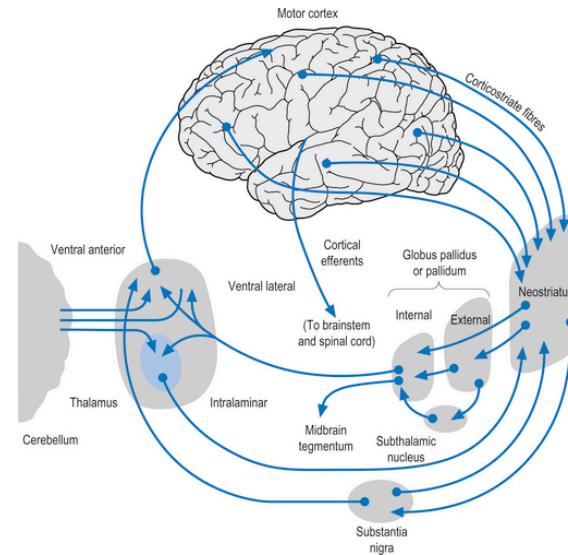
- Collection of nuclei near the thalamus
- Caudate nucleus, globus pallidus, subthalamic nucleus, substantia nigra
- Tasks: action selection, motor preparation, motor learning, reward-based learning
- Feedback loops with cortex areas and Thalamus etc.



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014



Source: www.researchgate.net/publication/263584956_Neuromodulation_for_Obsessive-Compulsive_Disorder/figures?lo=1



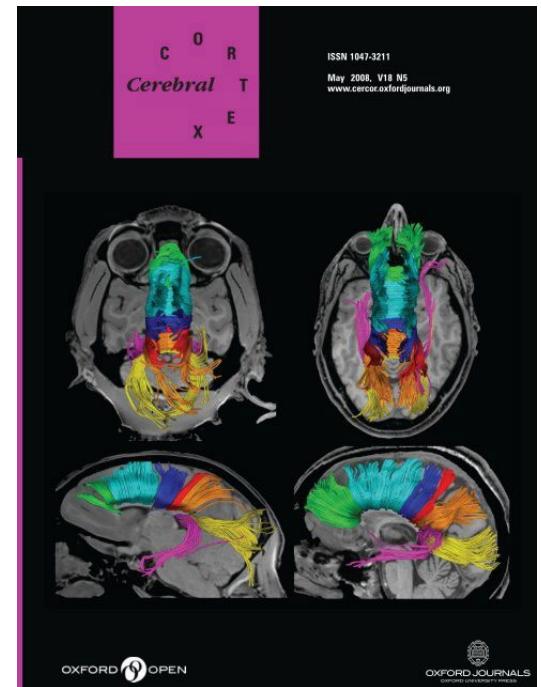
Source: <https://clinicalgate.com/the-basal-ganglia/>

The cerebral cortex (part of telencephalon)

The Cerebral Cortex

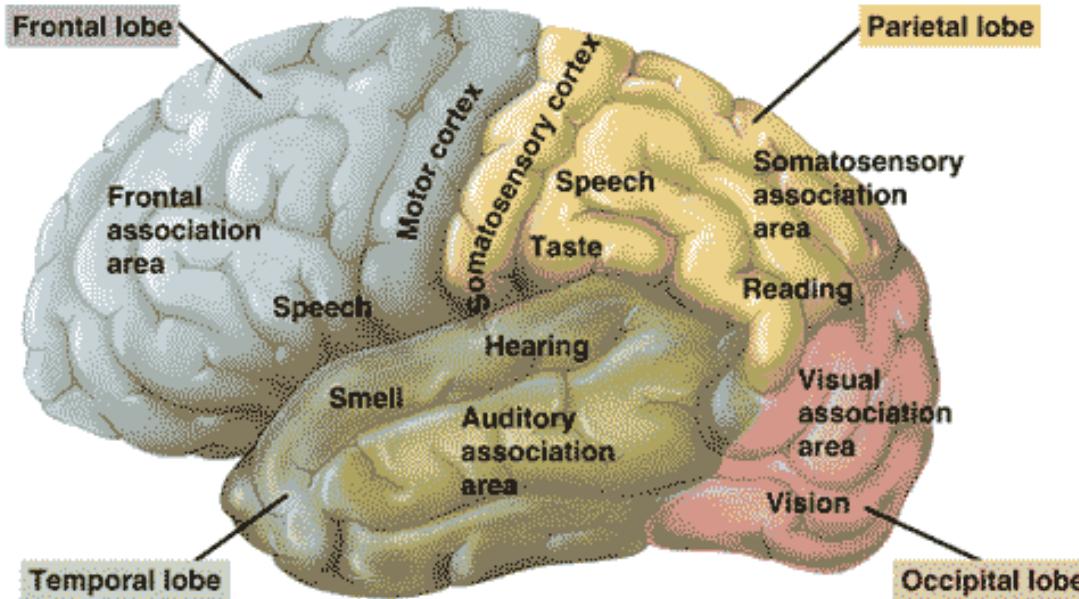


Source: Brainline.org



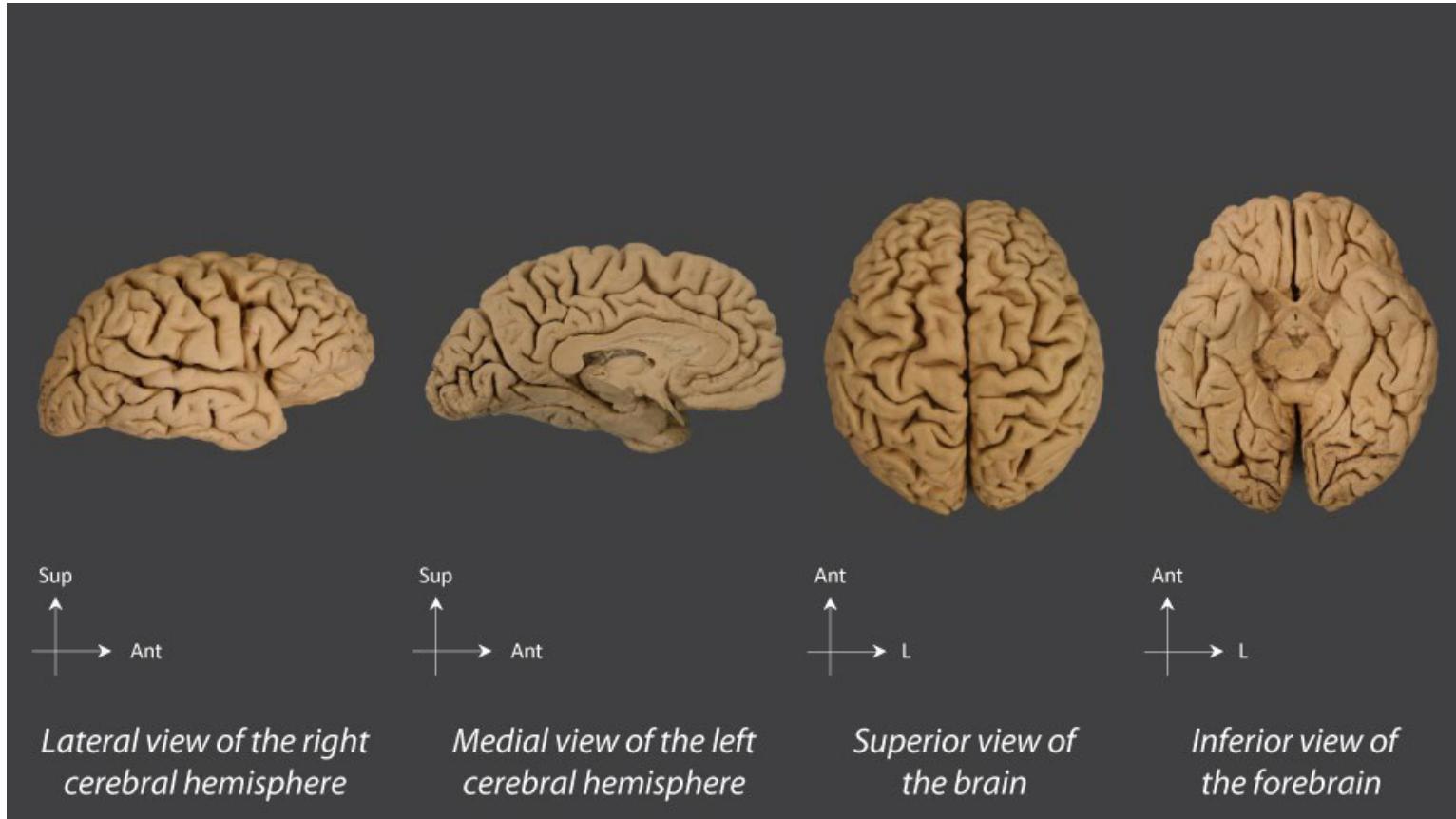
Source: <https://academic.oup.com/cercor>

Cerebral Cortex



- Approx. **16 billion neurons**
- Highest level of control
- Voluntary movements
- Conscious perception
- Highest cognitive functions
 - Language
 - Math
 - Reading
- Semantic memory
- Auto-biographic memory

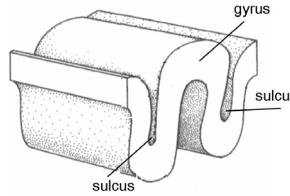
→ Lecture 11 (Memory)



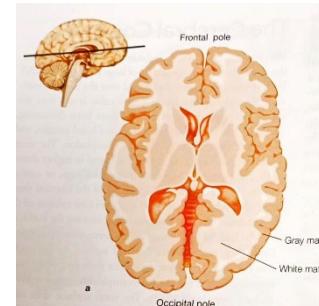
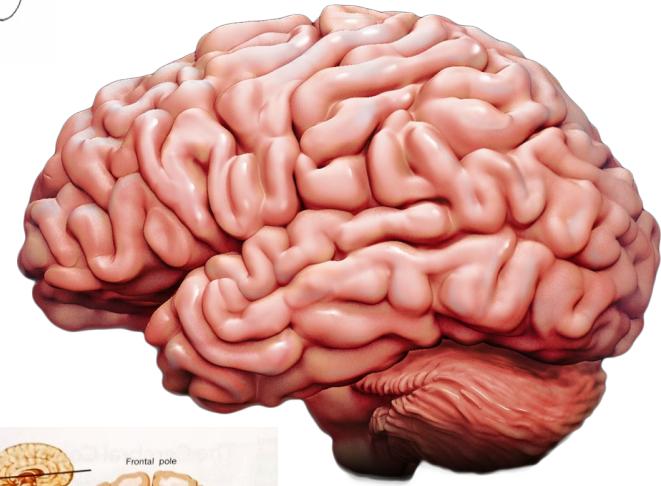
Source: sites.uclouvain.be

The Cerebral Cortex

- Made of large sheets of layered neurons (contains cell bodies and dendrites, input axons)
- Draped and folded over two **nearly symmetrical** hemispheres
 - Folding for larger surface
 - Shorter axonal connections (3D structure)
- Cortex can divided anatomically, cytoarchitectonic, and functional



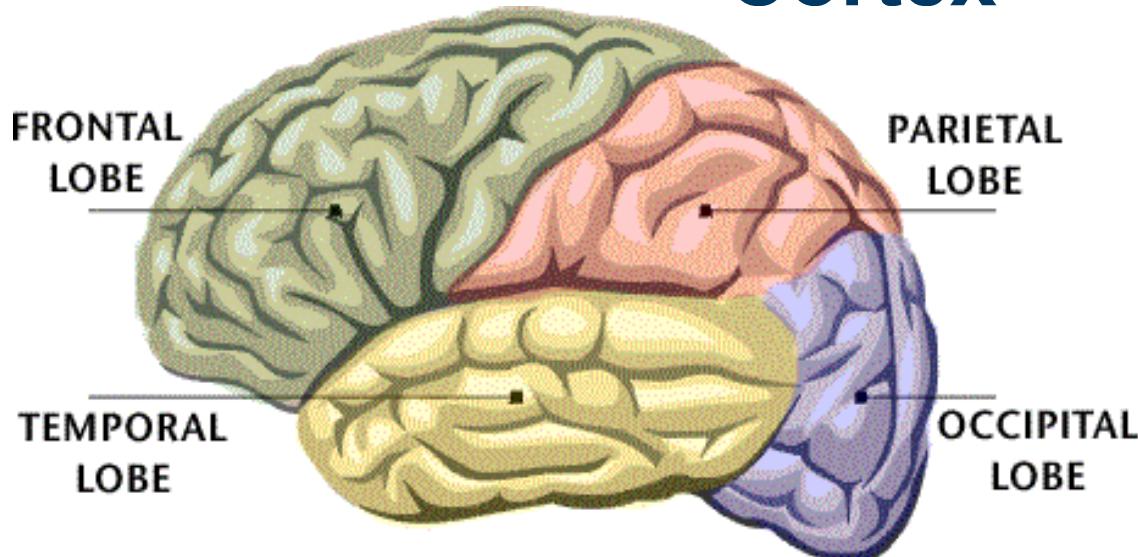
Source: wikipedia.org



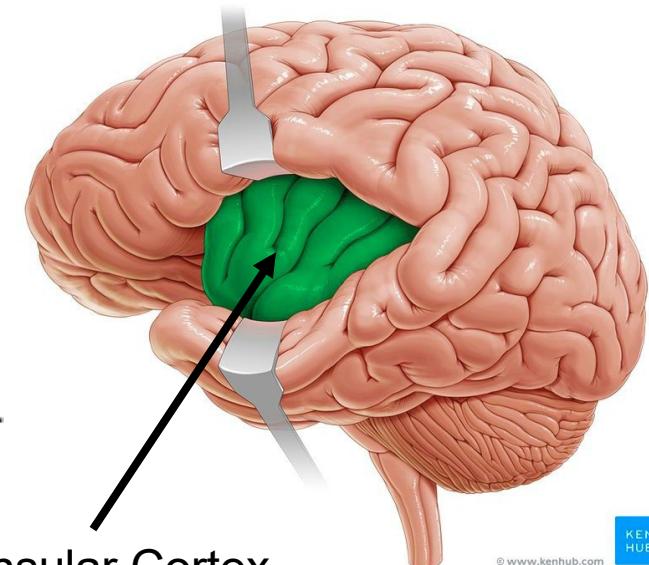
Source: Brainline.org

Anatomical organization of the cerebral cortex

Anatomical Organization of the Cerebral Cortex



Source: http://michellejl.github.io/education_digest/brain.html



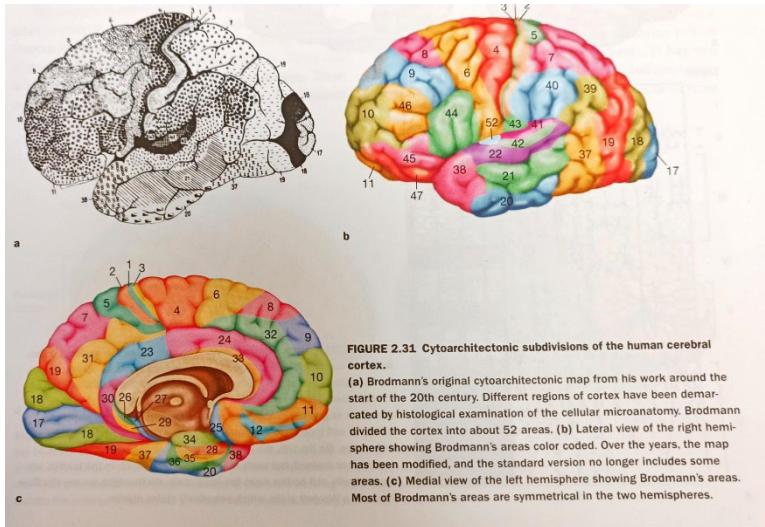
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Source: kenhub.com

Cytoarchitectonic organization of the cerebral cortex

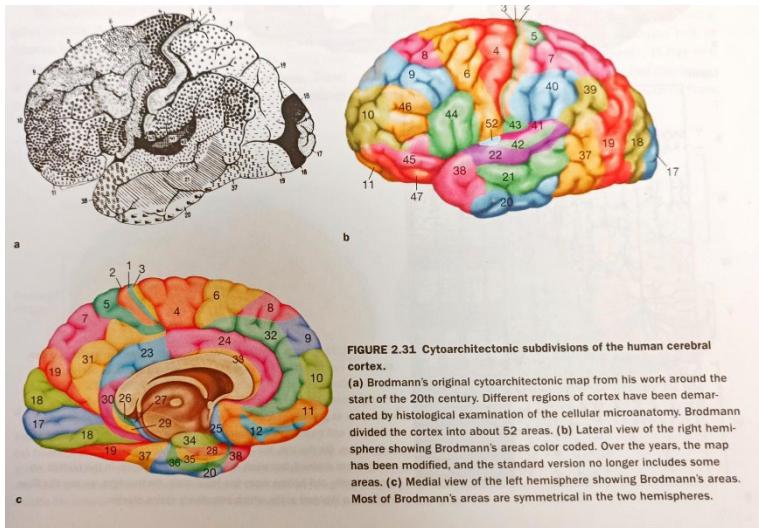
Cytoarchitectonical Organization of the Cerebral Cortex



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

- Cytoarchitectonics uses microanatomy of cells
- started with Korbinian Brodmann at beginning of 20th century
- Brodmann found 52 regions
- Later more than 200 regions were defined based on cytoarchitectonics
- However: Brodmanns numbering scheme is still used
- **Problem:** nomenclature not fully standardized!

Cytoarchitectonic Organization of the Cerebral Cortex



- Example for bad nomenclature:
 - First cortex are to perceive visual input
 - Brodmann area 17 (cytoarchitectonic)
 - Striate cortex (highly visible stripe of myelin, cytoarchitectonic)
 - Calcarine cortex (surrounding calcarine fissure, anatomical)
 - Primary visual cortex (functional)

Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Cortical Layers

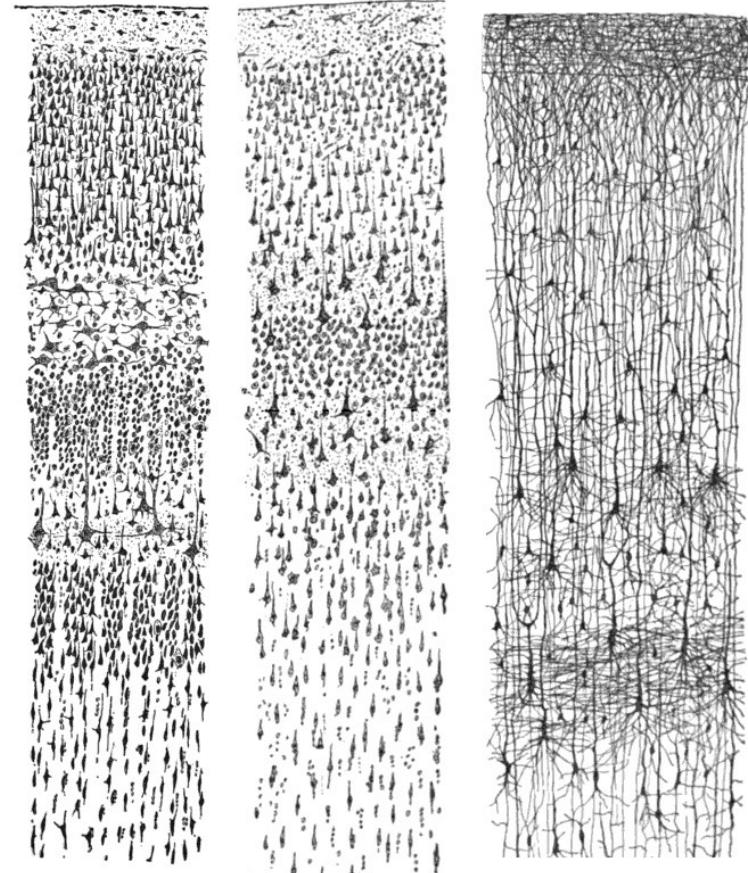
1. **Nissl stain:** cell bodies of neurons

2. **Golgi stain:** dendrites and axons of a random subset of neurons

Left: Nissl-stained visual cortex, adult

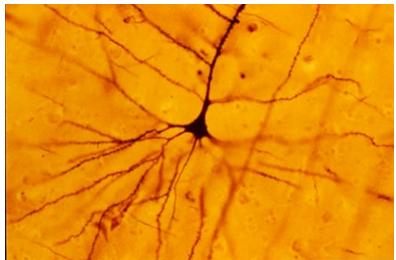
Middle: Nissl-stained motor cortex, adult

Right: Golgi-stained cortex of an infant

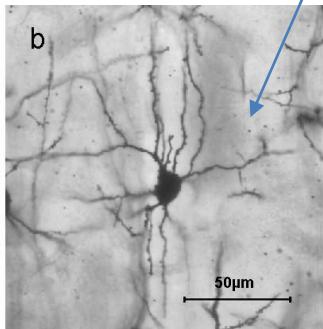


Cortical Layers

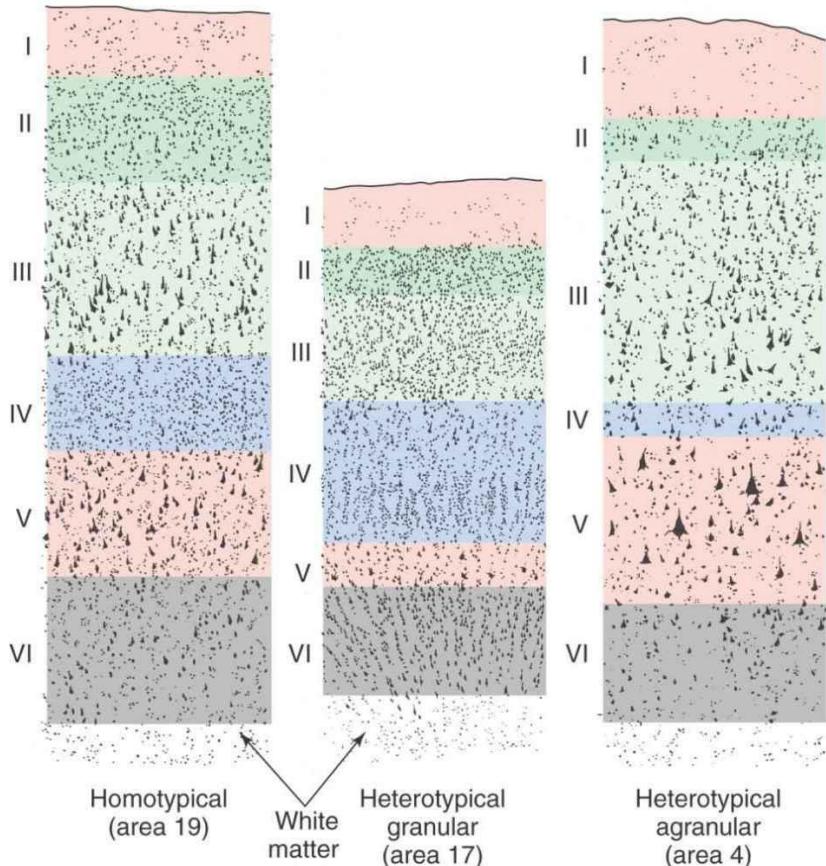
- Six layers with characteristic cell types in each layer
 - Layer 4: input layer (stellate neurons)
 - Layer 5: sends signal from cortex back to thalamus (pyramidal neurons)
- > Later more



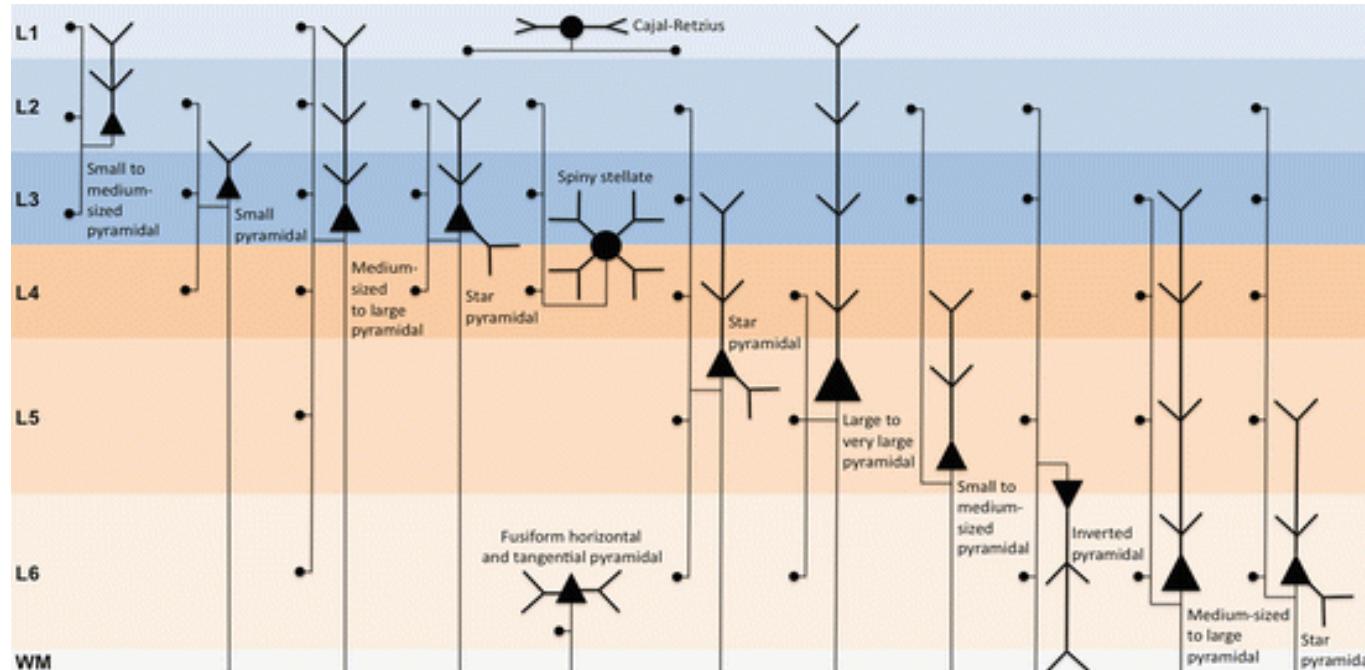
https://en.wikipedia.org/wiki/Pyramidal_cell



https://en.wikipedia.org/wiki/Stellate_cell

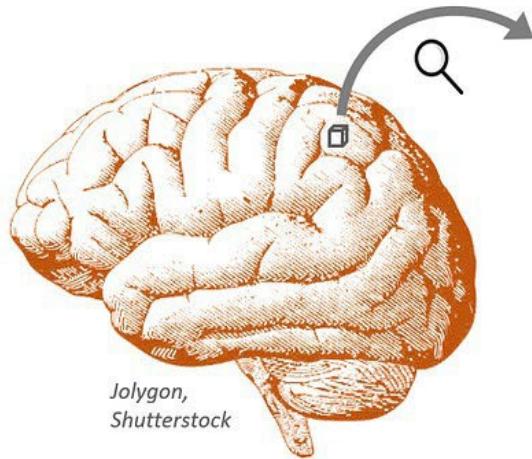


Cortical cell types



Source: SpringerLink

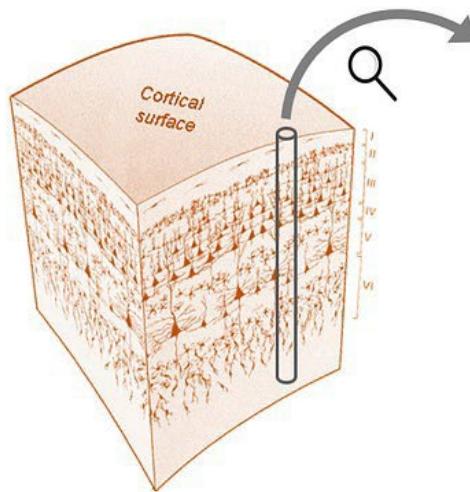
Cortical Columns



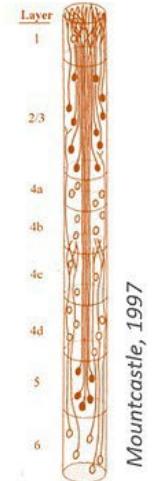
Jolygon,
Shutterstock

1 cortical sheet

2 million macrocolumns
200 million minicolumns
20 billion neurons



1 macrocolumn
100 minicolumns
10.000 neurons

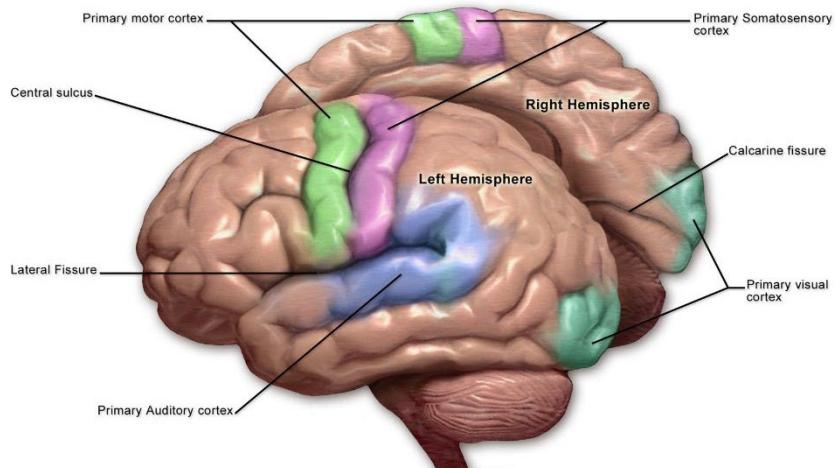


1 minicolumn
100 neurons

- Minicolumns fundamental processing unit in the cortex

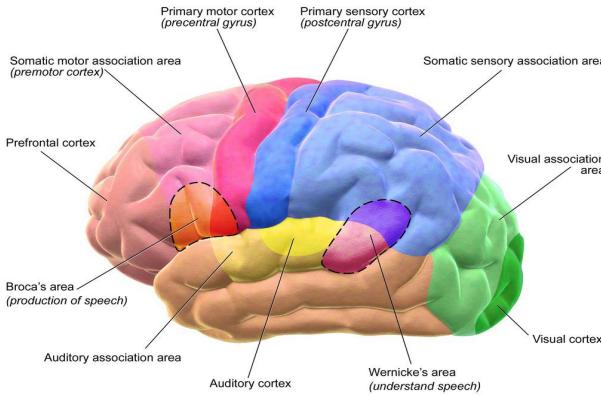
Functional organization of the cerebral cortex

Functional Organization of the Cerebral Cortex



Source: Blausen.com staff (2014)

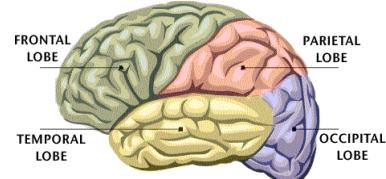
Motor and Sensory Regions of the Cerebral Cortex



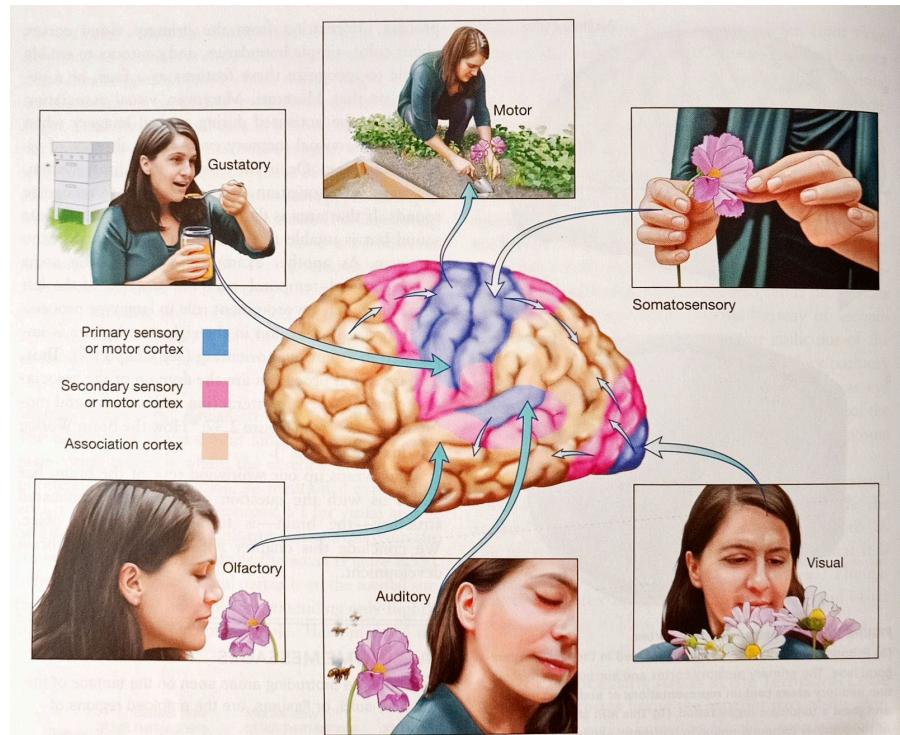
Source: Blausen.com staff (2014)

Source:
http://michellej.github.io/education_digest/brain.html

- Motor areas at frontal lobe: planning and execution of motions
- Somatosensory areas of the parietal lobe
- Visual processing in the occipital lobes
- Auditory processing at temporal lobe
- Association cortex: not sensory not motor cortex (integrate information)

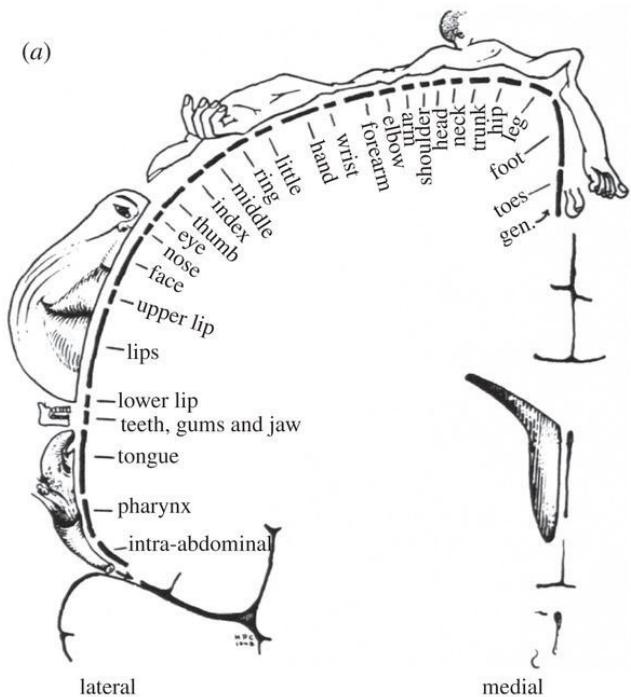


Functional Organization of the Cerebral Cortex



Cognitive neuroscience, Gazzaniga, Ivry, Mangun, 2014

Map-like organization (topographic) of cortical areas

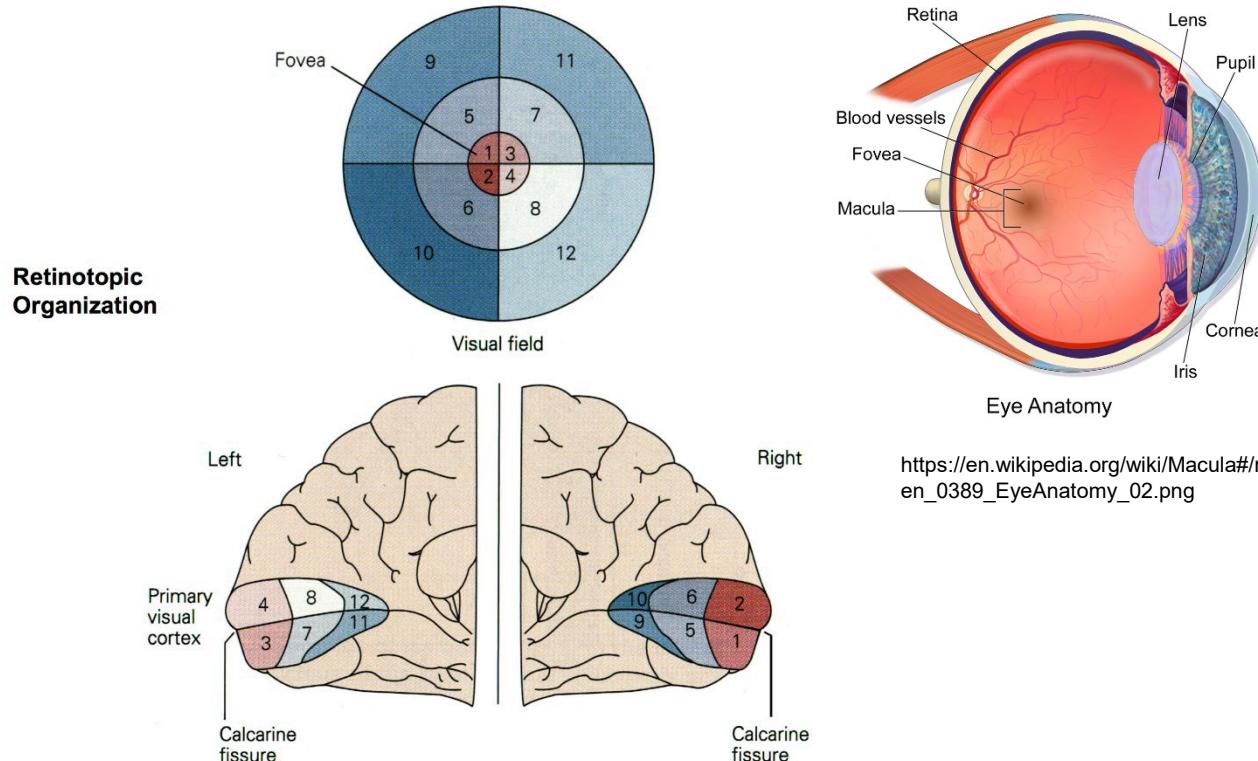


Somatotopy

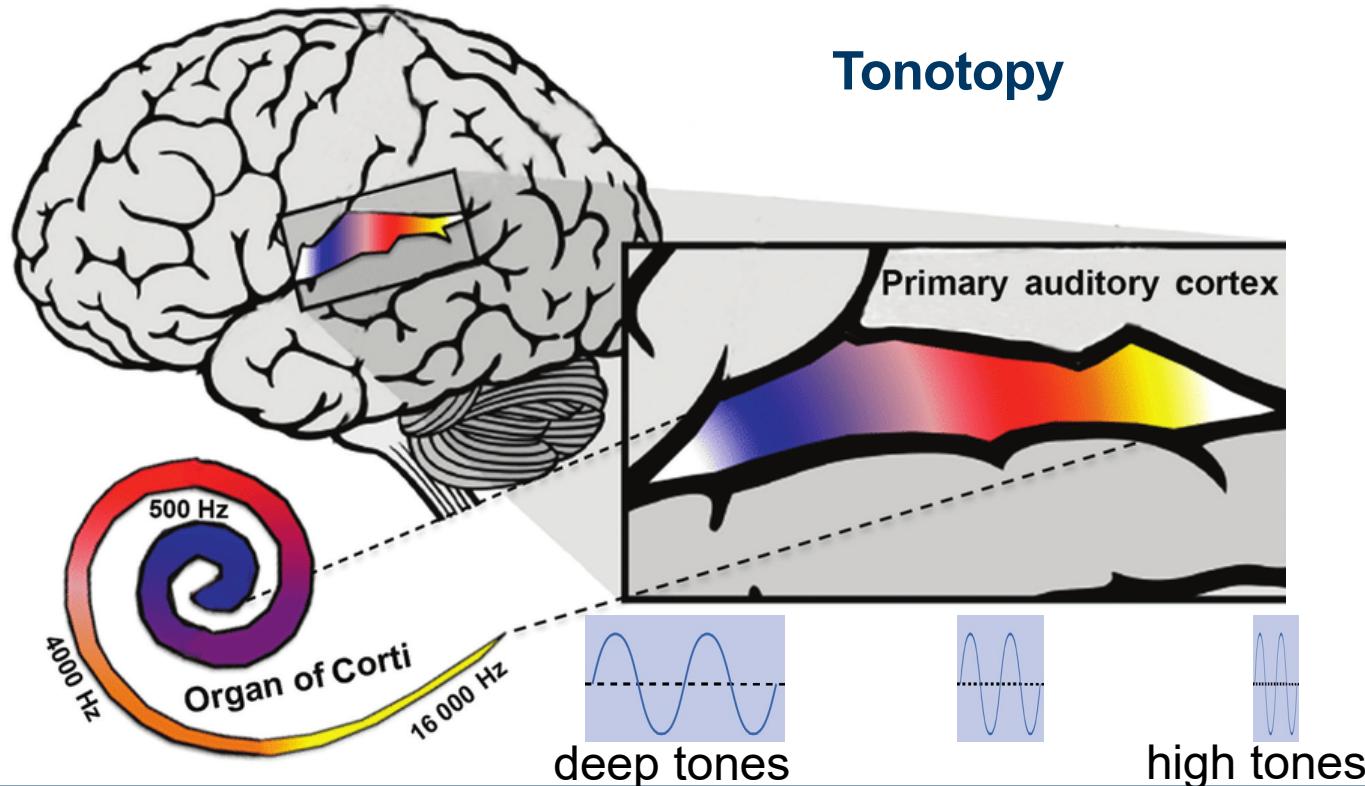
- Somatosensory Cortex
- Motor Cortex

Map-like organization (topographic) of cortical areas

Retinotopy



Map-like organization (topographic) of cortical areas



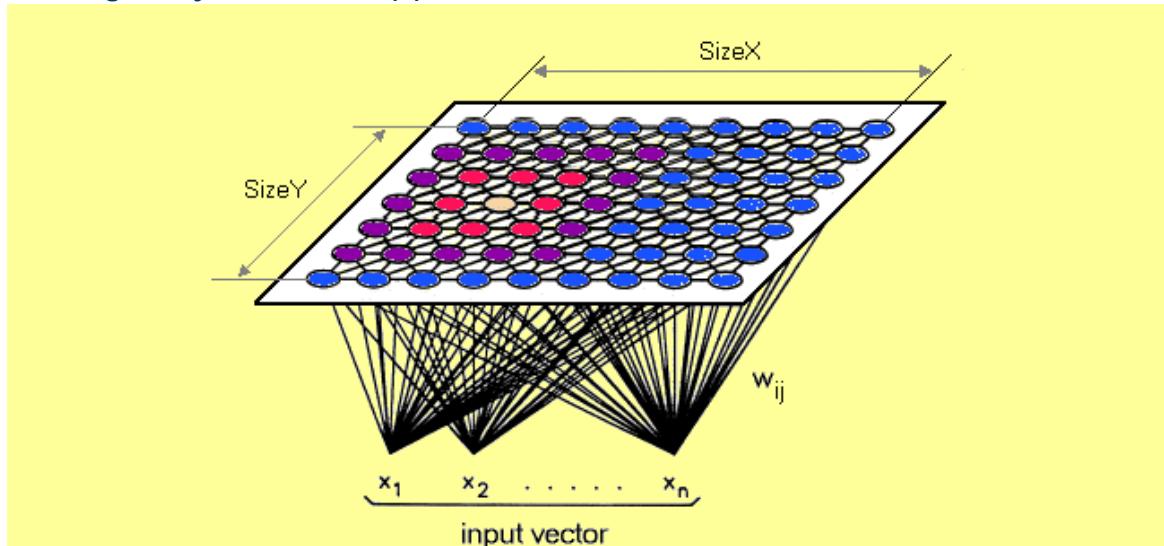
**Side note: Artificial creation of
topological correct feature maps
(as we have it in the cortex)**

Self-organizing feature maps

Introduced by Teuvo Kohonen, 1982

Kohonen, T. (1982). Self-organized formation of topologically correct feature maps. *Biological cybernetics*, 43(1), 59-69.

- Unsupervised learning
- Topological correct feature maps
- Not very often used to cluster in modern AI

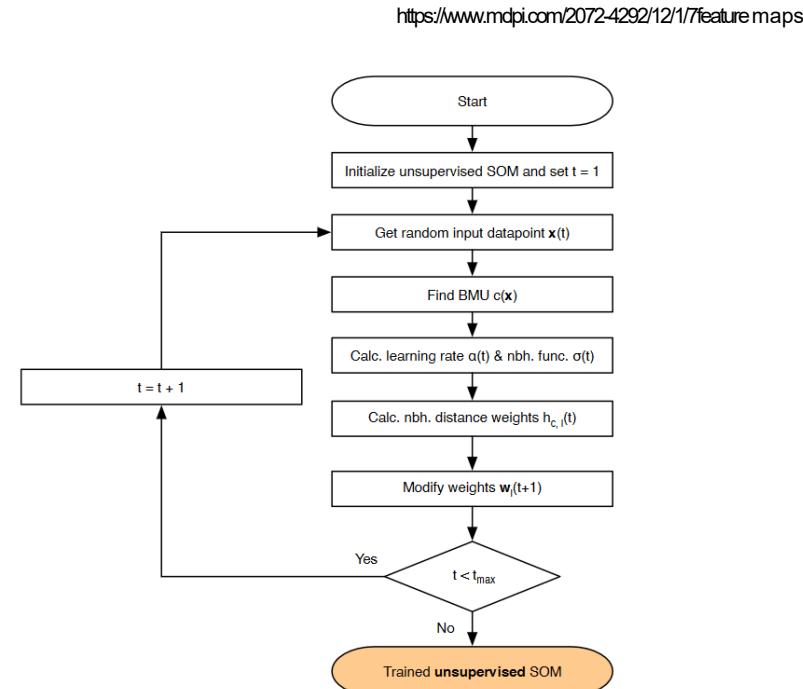


Source: <https://medium.com/@abhinavr8/self-organizing-maps-ff5853a118d4>

Self-organizing feature maps

Algorithm

- neurons are arranged in a grid -> **neurons have a physical position** (contrast to normal machine learning)
- Each neuron has a weight vector of the same size as the input data (n-dimensional)
- **Training:**
 - 1) Calculate Euclidean distance between input and weight vector
 - 2) Find neuron with the lowest distance of weight vector and input vector -> called BMU
 - 3) Update the weight vectors of all neurons however higher learning rates in neurons with lower distances to BMU
 - 4) Similar input is at similar position after training

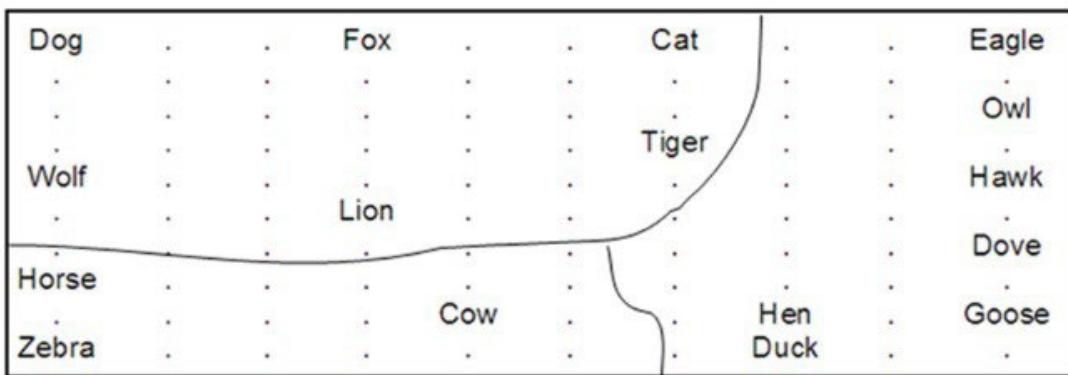


$$w_i(t+1) = w_i(t) + \alpha(t) \cdot h_{c,i}(t) \cdot (x(t) - w_i(t)), \quad (5)$$

with neighborhood function $h_{c,i}(t)$, learning rate $\alpha(t)$, and weight vector $w_i(t)$ of node i at iteration t .

Self-organizing maps

	dove	hen	duck	goose	owl	hawk	eagle	fox	dog	wolf	cat	tiger	lion	horse	zebra	cow
is small	1	1	1	1	1	1	0	0	0	0	1	0	0	0	0	0
is medium	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0
is big	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
has 2 legs	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
has 4 legs	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
has hair	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
has hooves	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
has mane	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0
has feathers	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
likes hunt	0	0	0	0	1	1	1	1	0	1	1	1	1	0	0	0
likes run	0	0	0	0	0	0	0	1	1	0	1	1	1	1	0	0
likes to fly	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
likes to swim	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0



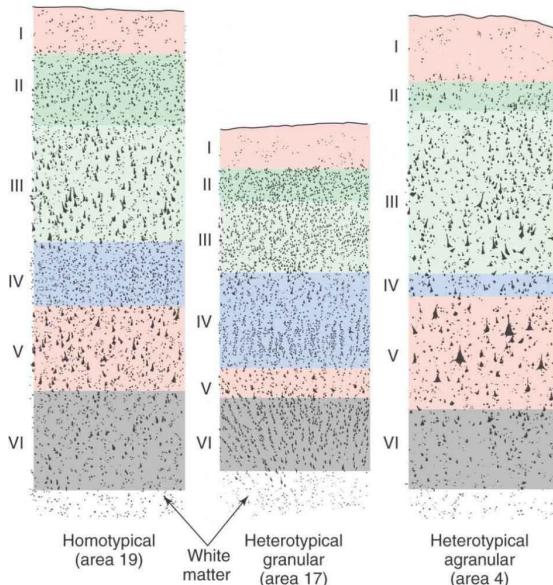
Source: <https://doi.org/10.3389/fpsyg.2013.00828>

Fig 1 Animal names and their attributes

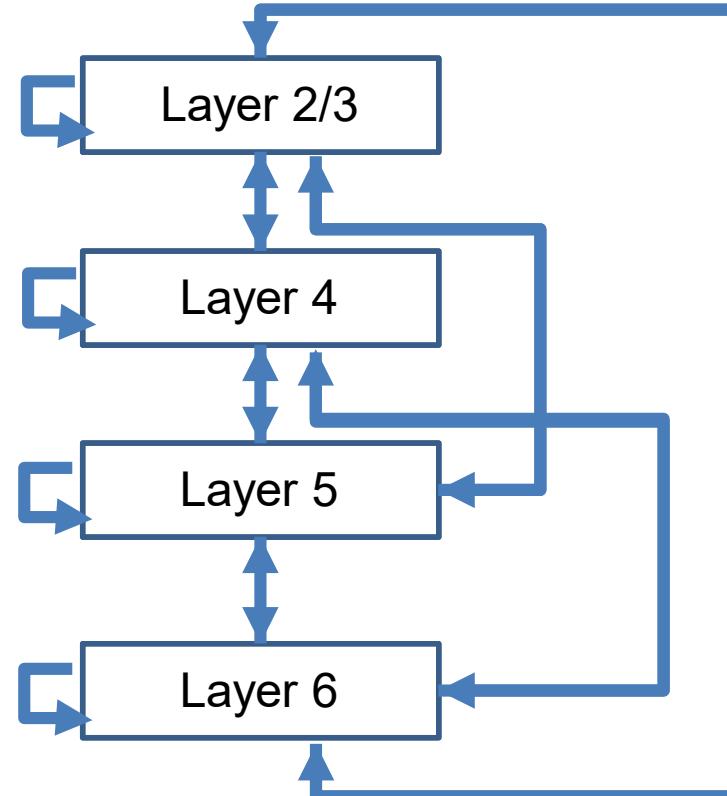
Source: semanticscholar.org

Canonical cortical connectivity (function of the 6 layers)

Cortical connectivity

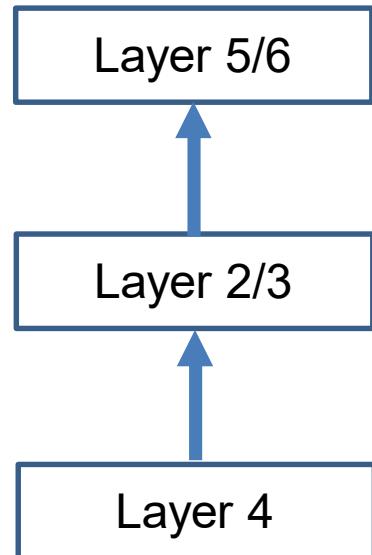


Source:
neopsykey.com



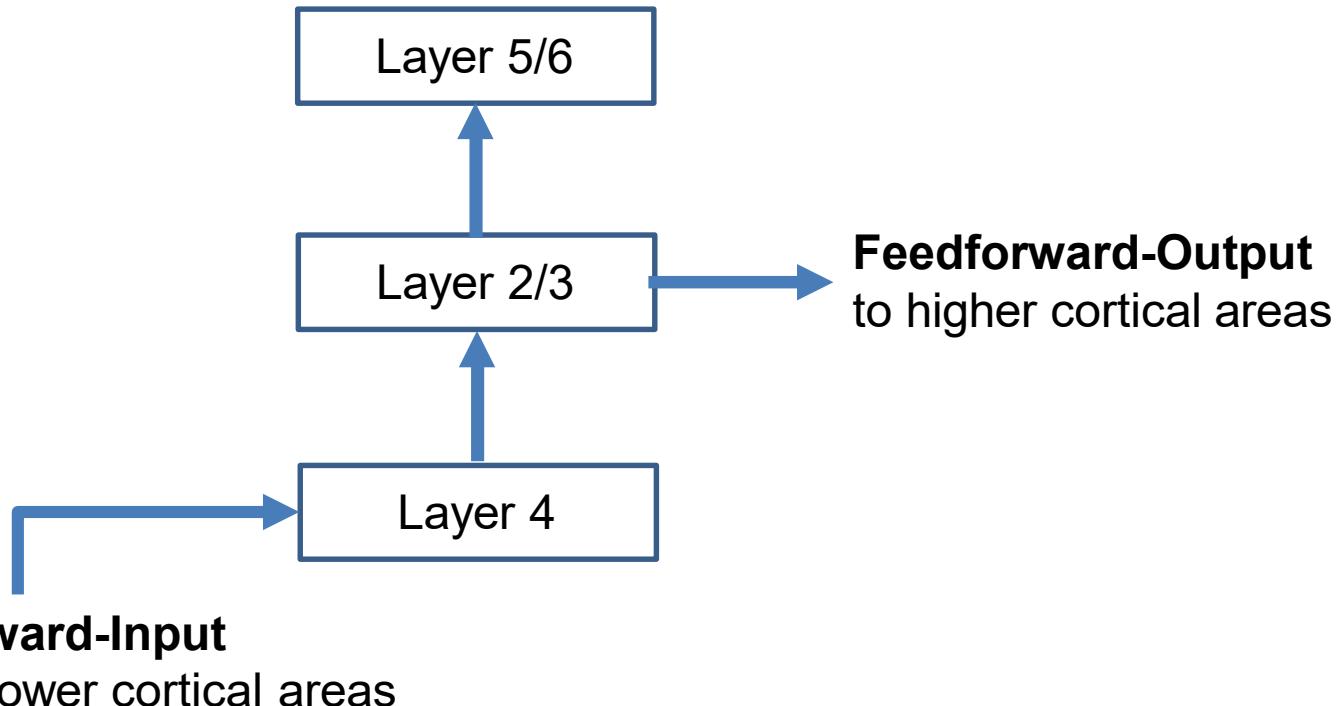
The Canonical Cortical Circuit

main information flow



The Canonical Cortical Circuit

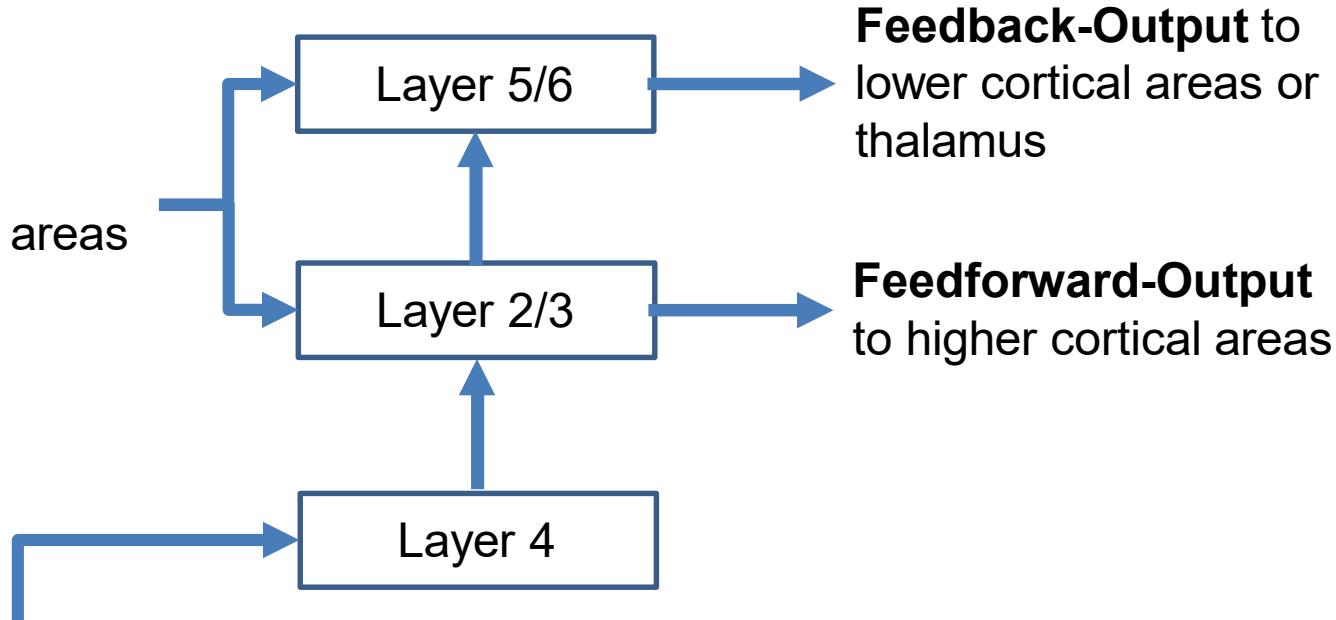
main information flow



The Canonical Cortical Circuit

main information flow

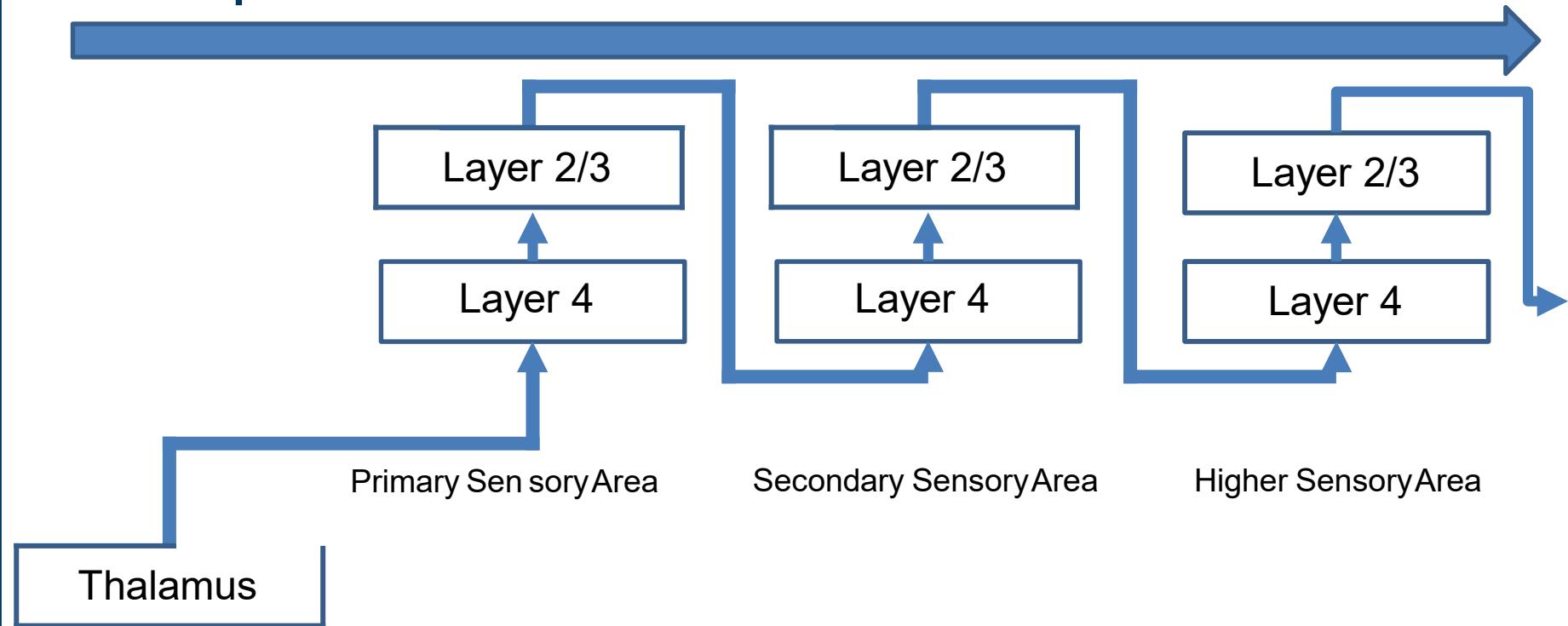
Feedback-Input
from higher cortical areas



Feedforward-Input
from thalamus or lower cortical areas

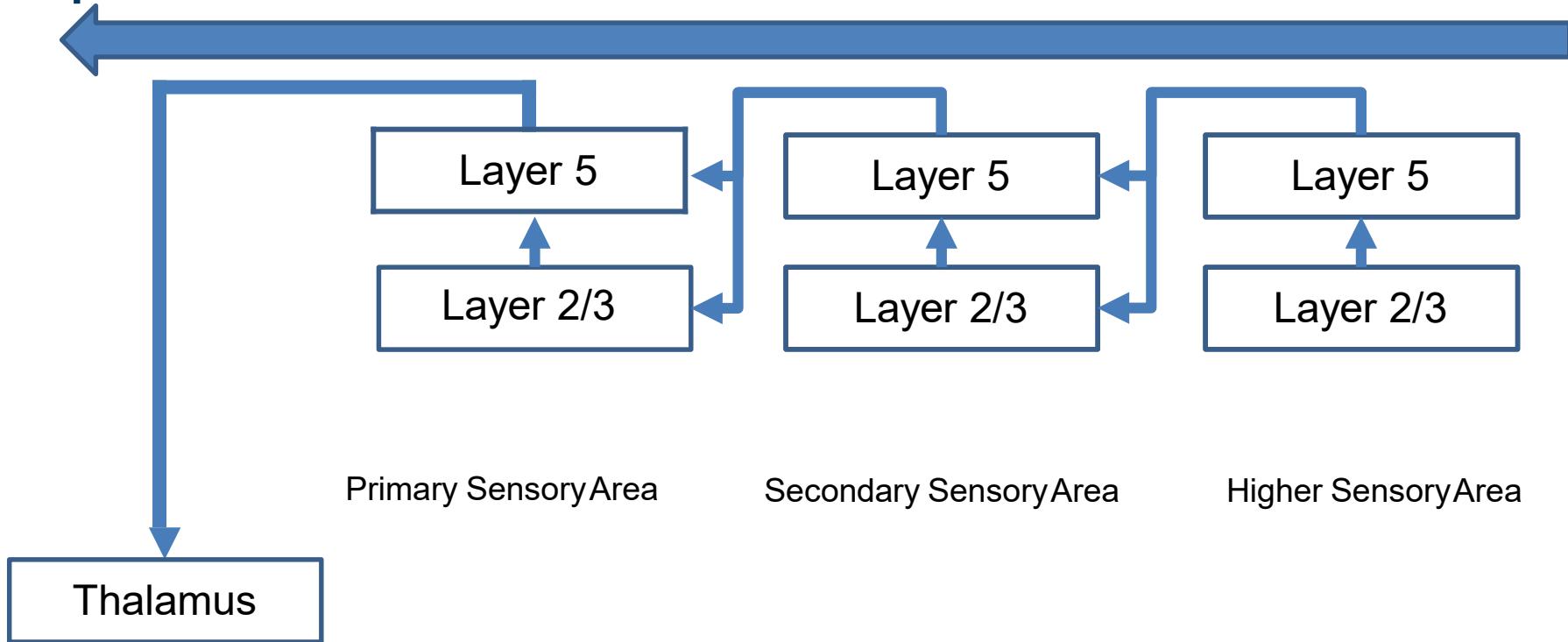
The Canonical Cortical Circuit

bottom up information flow / feedforward connections



The Canonical Cortical Circuit

top down information flow / feedback connections

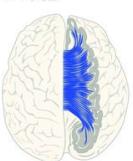


The Canonical Cortical Circuit

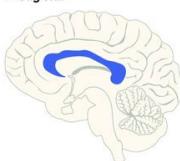
horizontal information flow / lateral connections, inter-hemispheric



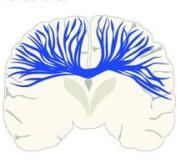
A Dorsal



B Sagittal



C Coronal



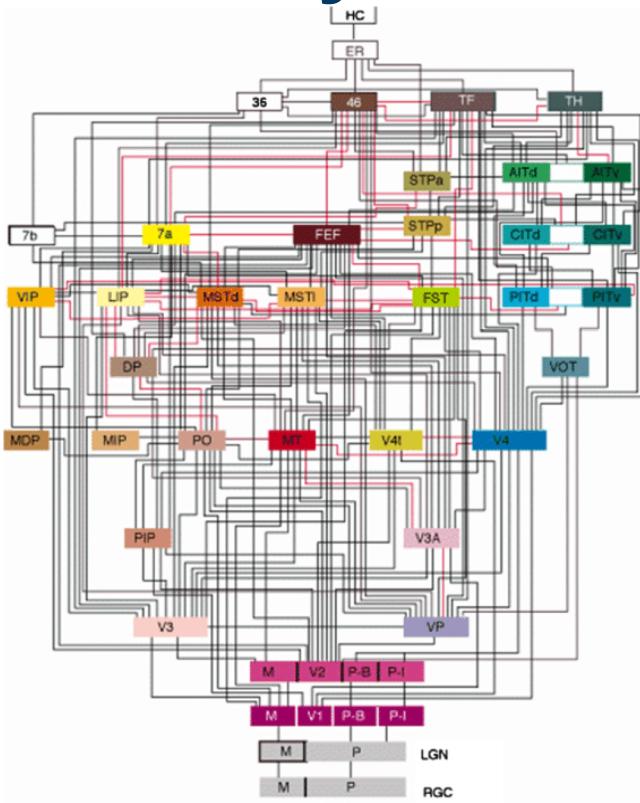
Area A

Area B

Area C

areas of same hierarchical level!

Hierarchy of cortical areas



- Visual System of monkeys
- Lowest level: **Thalamus and Primary Visual cortex**
- Highest level: **Hippocampus!**