Neuronale Informationsverarbeitung für Gehirn-Computer Schnittstellen

TECHNISCHE UNIVERSITÄT DARMSTADT

Neural Information Processing for Brain-Computer Interfaces

MAX-PLANCK-GESELLSCHAFT

Outline of the lecture

1. A history of research on brain-computer interfaces (BCIs)
2. Cognitive neuroscience
3. Recording neural activity
4. Signal Processing
5. Machine Learning
6. Spatial filtering of EEG/MEG signals
7. Paradigms for non/semi-invasive brain-computer interfacing
8. Practical day: Building a first BCI

Outline of the current lecture

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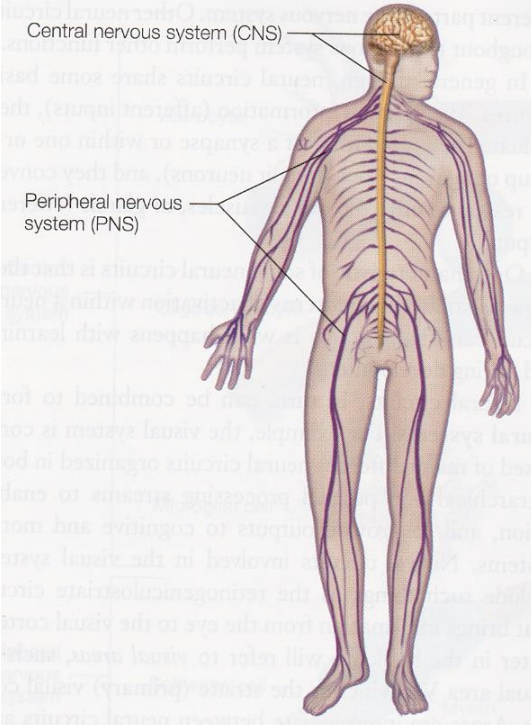
2. Cognitive neuroscience
    - The central nervous system (CNS)
    - The cerebral cortex
    - Brodmann areas
    - The visual system
    - The sensorimotor system
    - The auditory system
    - Cortical columns
    - The neuron
    - Cortical connectivity
    - The default mode network
    - Large scale resting-state networks & behaviour
    - The Neurosynth database
    - Whole brain activation in simple tasks

The central nervous system (CNS)

- The central nervous system is composed of **the brain** and **the spinal cord**

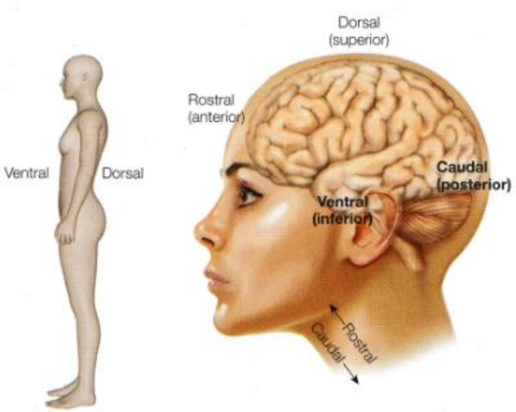
- The brain and the spinal cord are …
  - … pending in cerebrospinal fluid which can be found between the arachnoid layer and pia layer and …
  - … are covered by the three protective layers each called meninges

- The three protective layers from the outside to the inside are …
  - ... the thick dura matter
  - … the arachnoid matter
  - … the sensitive pia matter which adheres on the brain surface

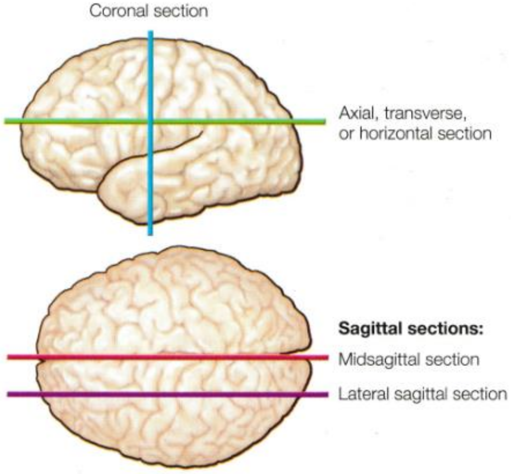


The central nervous system (CNS)

- We will use the following terminology to navigate the human brain (as we does for the body)
  - **Ventral** and **dorsal** describe the front and the back respectively
  - **Rostral** and **caudal** describe the top and bottom respectively



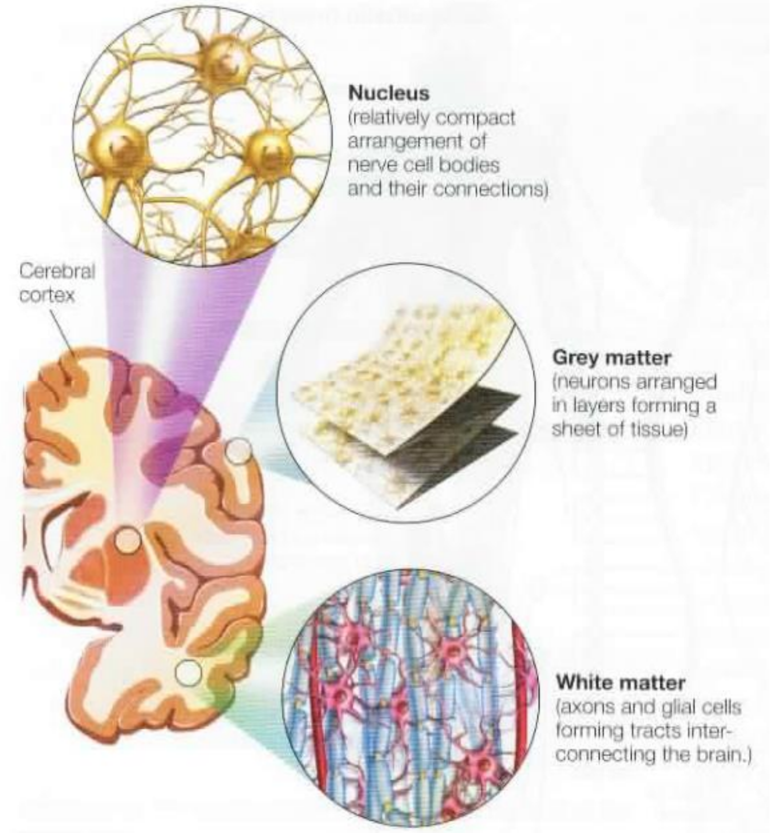
- When looking at slices of the brain, we refer to the following terminology as can be seen in the picture to the right



The central nervous system (CNS)

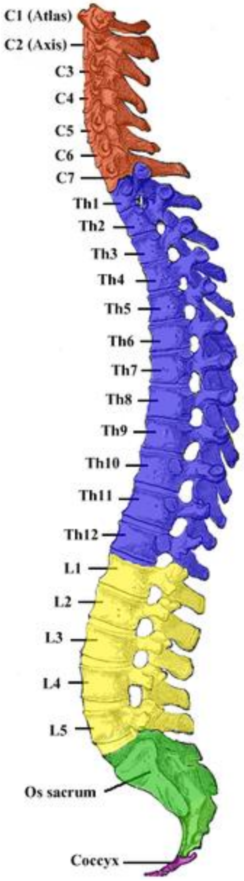
- The central nervous system contains a bundle of neurons as depicted in the following

- The two most common organizational clusters are embodied either in a nucleus or in a layer
  - Grey matter is composed of neuronal cell bodies
  - White matter is composed of axons and glial cells



The central nervous system (CNS)

- The spinal cord is connected to the brainstem, i.e. the Medulla
  - Receives sensory information, transmits it to the brain and conducts the final motor commands from the brain to the muscles
  - Additionally, the spinal cord also has reflex pathways
- The spinal cord is enclosed in a stack of separate bones, i.e. the vertebrae
  - The vertebrae column is divided into different sections, cf. image (from top to bottom): cervical, thoracic, lumbar, sacral, coccygeal



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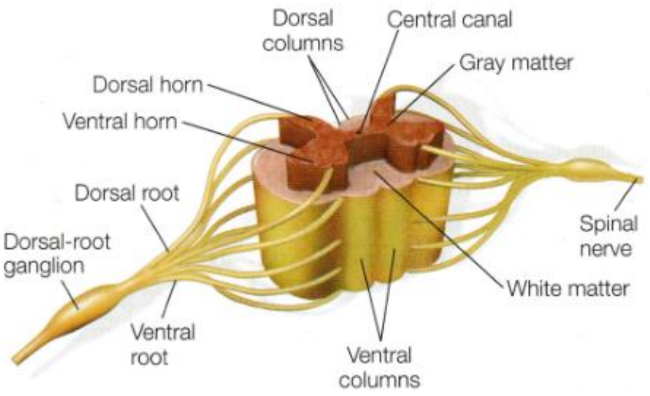
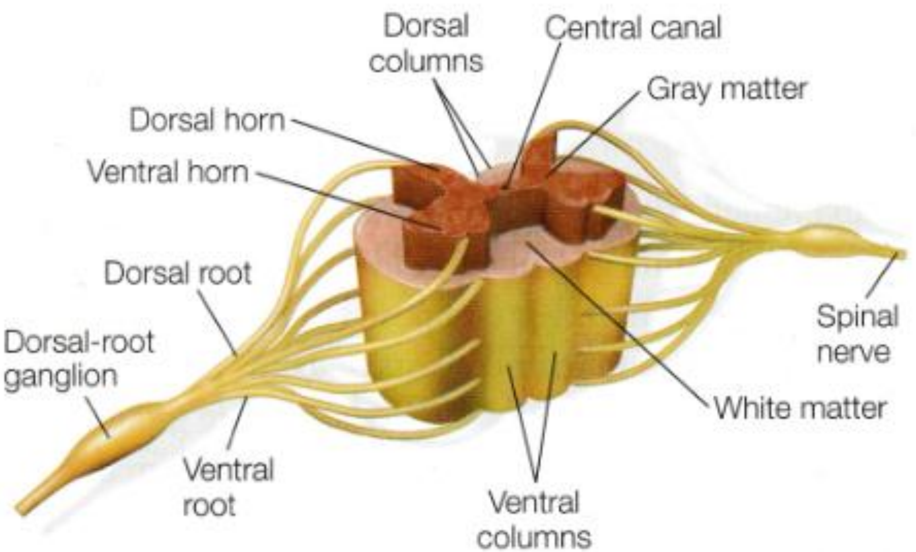
The central nervous system (CNS)

- Moreover, the spinal cord is usually anatomically dissected into 31 segments
  - These segments have a left and a right **spinal nerve** each; entering and exiting through openings that are called *foramen*
  - Each spinal nerve has sensory and motor axons where one **afferent neuron** carries sensory input (through the dorsal root into the spinal cord) and one **efferent neuron** carries motor output (through the ventral root away from the spinal cord)



The central nervous system (CNS)

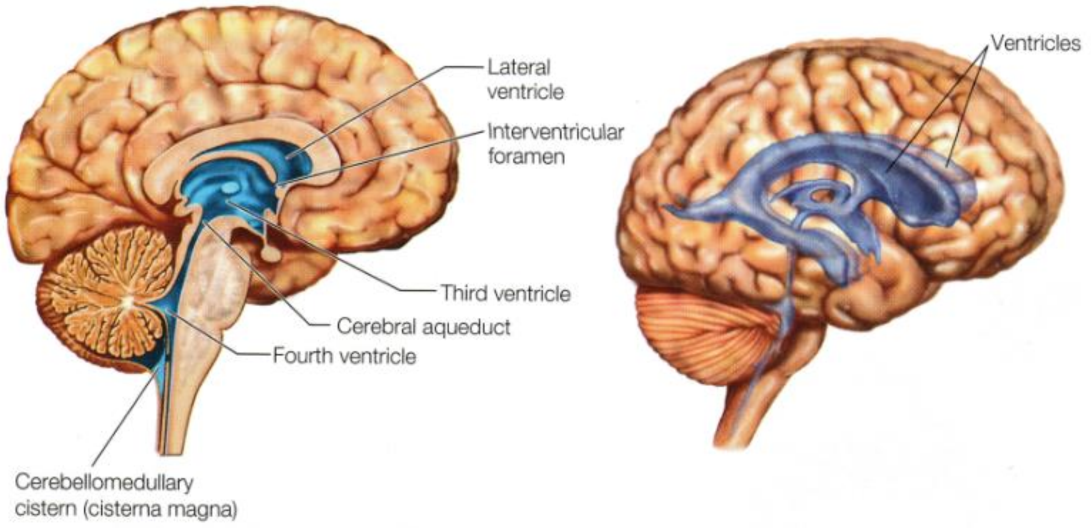


- The **ventral horn** contains large motor neurons that projects to muscle
- The **dorsal horn** contains sensory neurons and interneurons
  - Interneurons project to motor neurons on the same side (ipsilateral) and on the opposite site (contralateral) to help with coordination of limb movements

The central nervous system (CNS)

- Within the brain are empty chambers, the so called **ventricles**
  - These empty chambers are filled with fluid called *cerebrospinal fluid* (CSF)
  - CSF is a clear fluid containing proteins, glucose and ions (especially potassium, sodium and chloride)

- The function of the CSF is to stabilize the brain, so that it floats to help offset the pressure

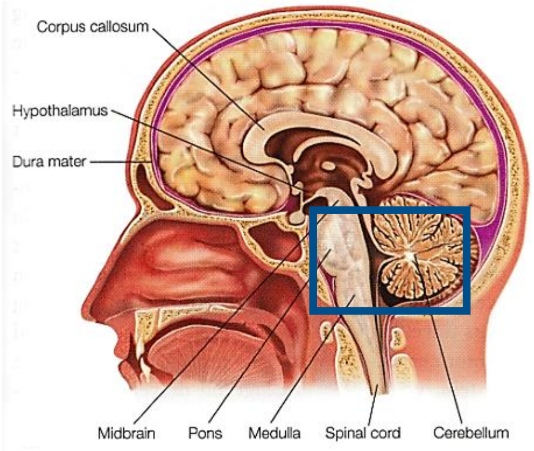


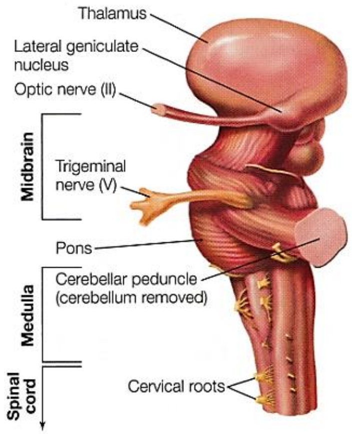
The central nervous system (CNS)

- The brainstem assembles out of the **medulla**, the **pons**, the **cerebellum**, and the **midbrain** and connects the spinal cord with the diencephalon

  - The brainstem plays an important (**!**) role within the brain because it contains groups of …
    … motor and sensory nuclei, …
    … nuclei of widespread modulatory neurotransmitter systems, …
    … and white matter tracts of ascending sensory information and descending motor signals

  - Brainstem nuclei control respiration and the global state of consciousness (e.g. sleep and wakefulness)



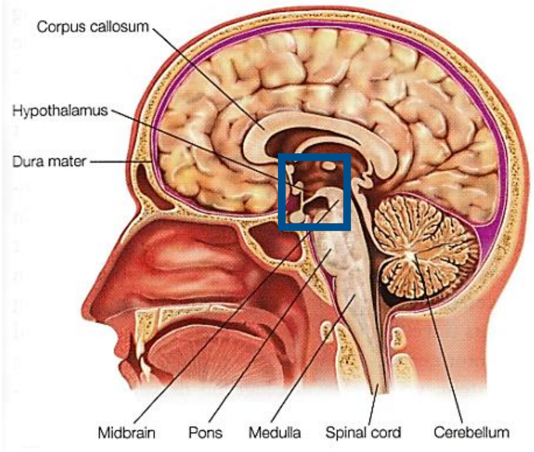


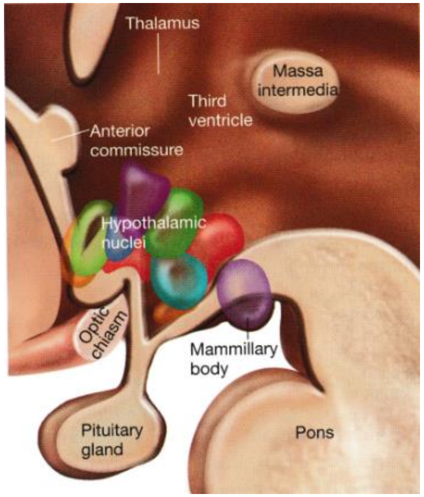
The central nervous system (CNS)

- The diencephalon assembles out of the **thalamus** and the **hypothalamus**

- The thalamus is right in the center of the brain (and right on top of the brainstem, cf. previous slide)
  - Also called “the gateway to the cortex” because it is the relay station for almost all sensory information

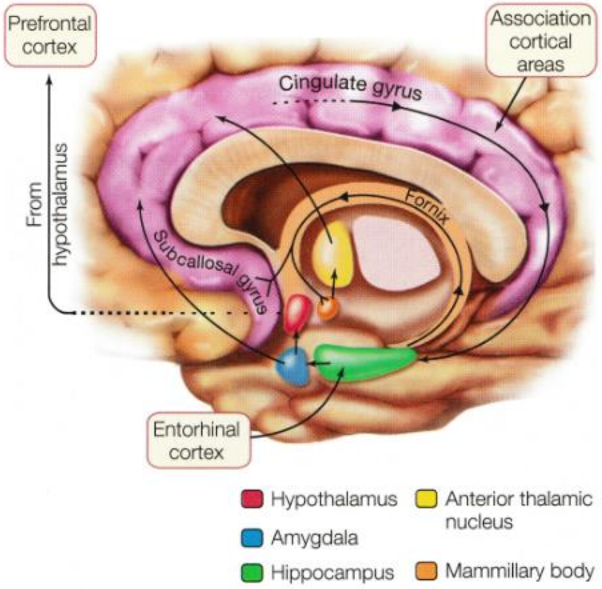
- The hypothalamus plays an important role for the autonomic nervous system and endocrine system
  - Controls functions necessary for the maintenance of homeostasis
  - Involved in control of releasing hormones into the bloodstream

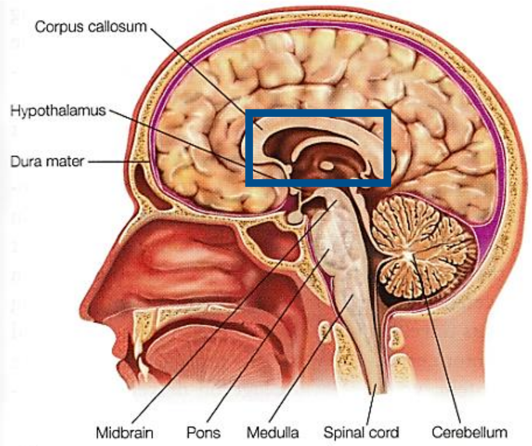




The central nervous system (CNS)

- Toward the front of the diencephalon is the telencephalon that includes the **limbic system**, the **basal ganglia** and the **cerebral cortex**

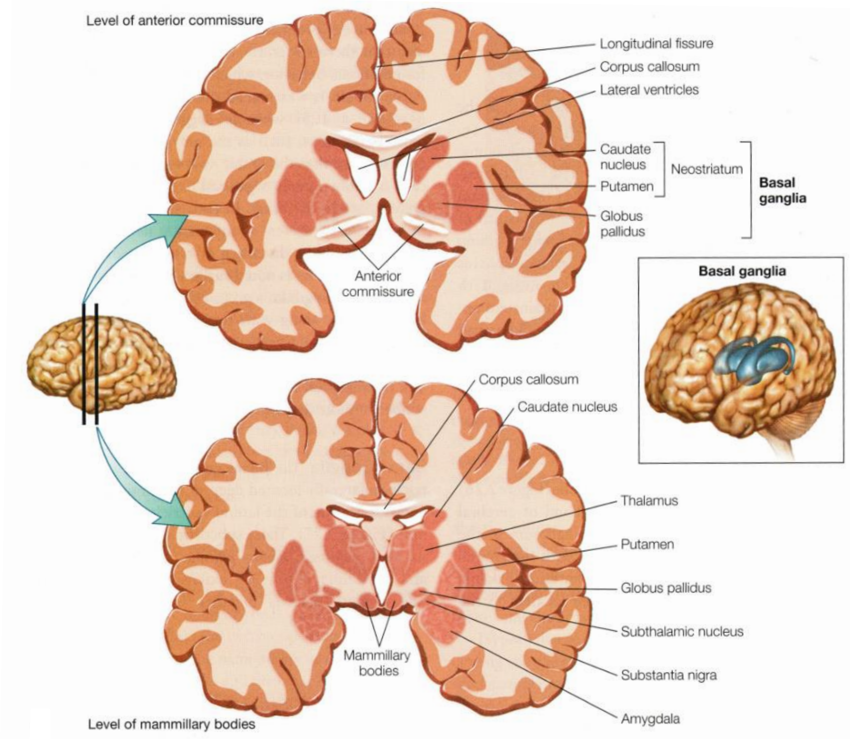


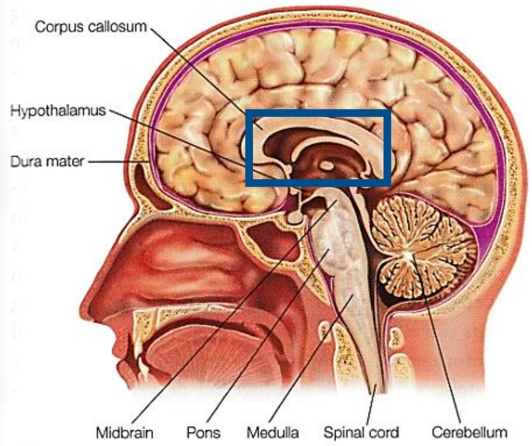


- The limbic system contains interconnected subcortical and cortical structures and plays a role in emotions

The central nervous system (CNS)

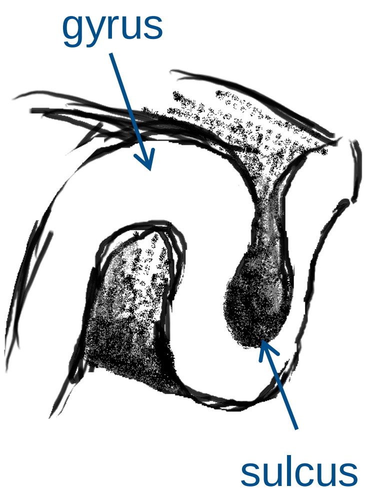
- The basal ganglia are involved in a variety of crucial brain functions such as action selection, action gating, reward-based learning, motor preparation, timing, task switching, etc.





The cerebral cortex

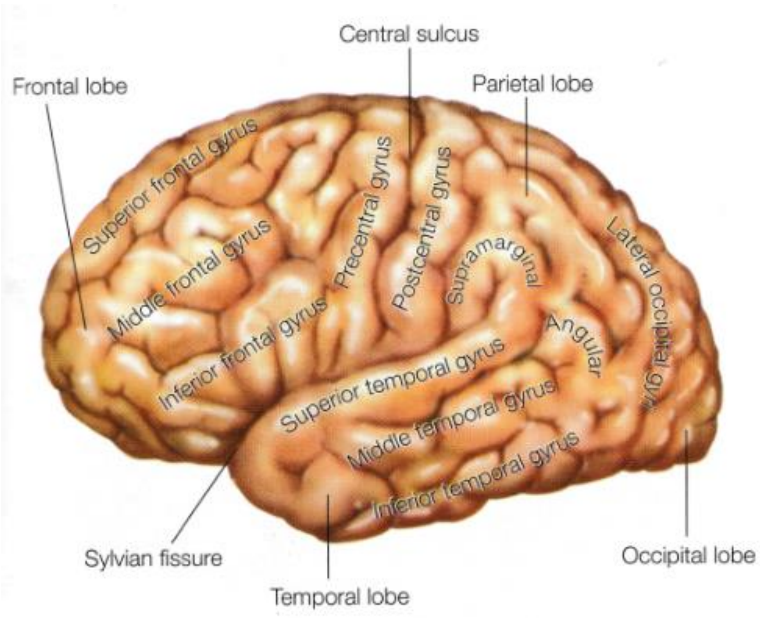
- The cerebral cortex (roughly *"brain bark"* because of its infolding) is the outermost tissue surrounding the structures of the diencephalon
  - The infoldings of the cortical sheet are called **sulci** and **gyri**

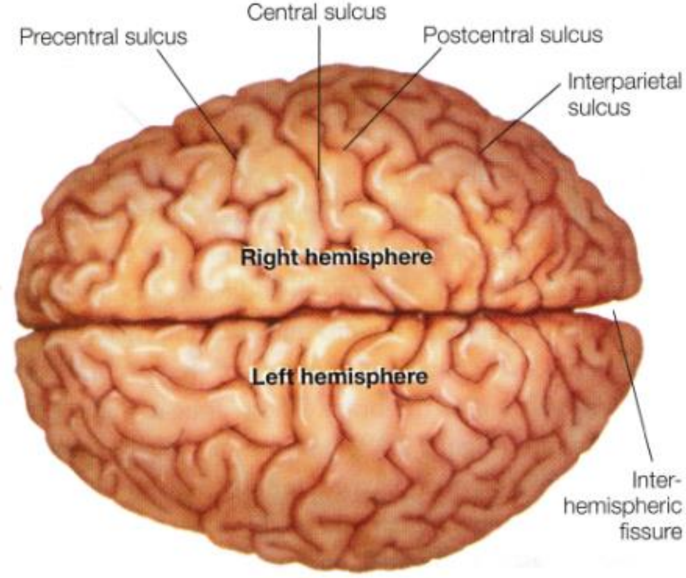


- The folds within the cerebral cortex possess different functions
  - Enable to fit more cortical surface into the skull (the surface spans about 2200 to 2400 cm^2 if flattened out)
  - Neurons get into a closer three dimensional relationship to each other yielding reduced neuronal conduction time between different areas
  - Bring nearby regions closer together

The cerebral cortex

- The cerebral cortex is divided into two symmetric hemispheres
  - Lateral view of the left hemisphere in the left image and dorsal view of the brain in the right image

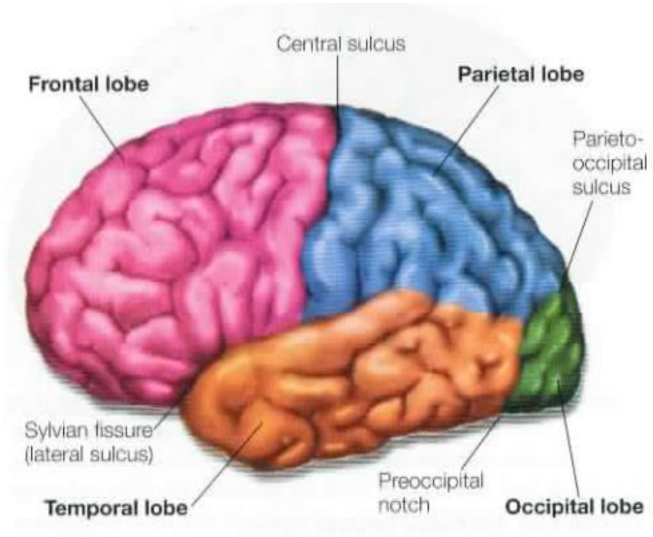




The cerebral cortex

- For now, let us look at the anatomically dissection of the human brain to get a better grasp of it

- There are four main segments (shown in a lateral view here)
  - **Frontal**, **parietal**, **temporal** and **occipital lobe**
  - The names of these lobes are derived from their overlying skull bones
  - The lobes are usually distinguished by different sulci

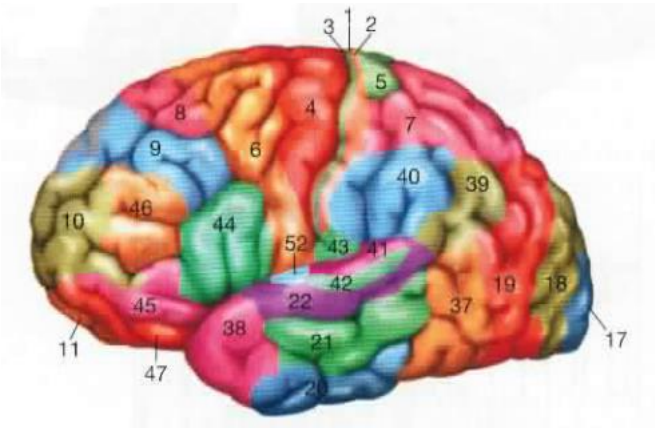


- Not visible here; the **insula** is located between the frontal and temporal lobe
  - The insula is an island of folded cortex hidden deep in the lateral sulcus, i.e. there is one per hemisphere
  - The insula divides into the anterior and posterior insula and is related to emotional intelligence

Brodmann areas

- We have seen the anatomically dissection of the cerebral cortex which is pretty coarse
  - The refinement of the anatomically dissection is called “Cytoarchitectonically” (roughly *“cell architecture”*) dissection of the human brain
  - We also look at functional homogeneous areas of the brain

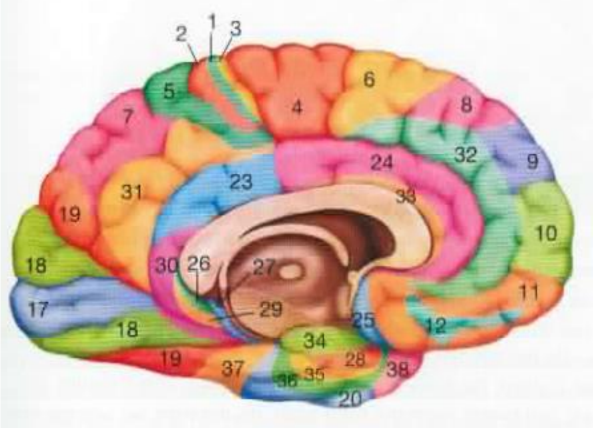
- Korbinian Brodmann identified approximately 52 regions of the cerebral cortex
  - The numbered color code categorizes differences in cellular morphology and organization
  - Depicted here is the lateral view of the right hemisphere of the Brodmann areas



Brodmann areas

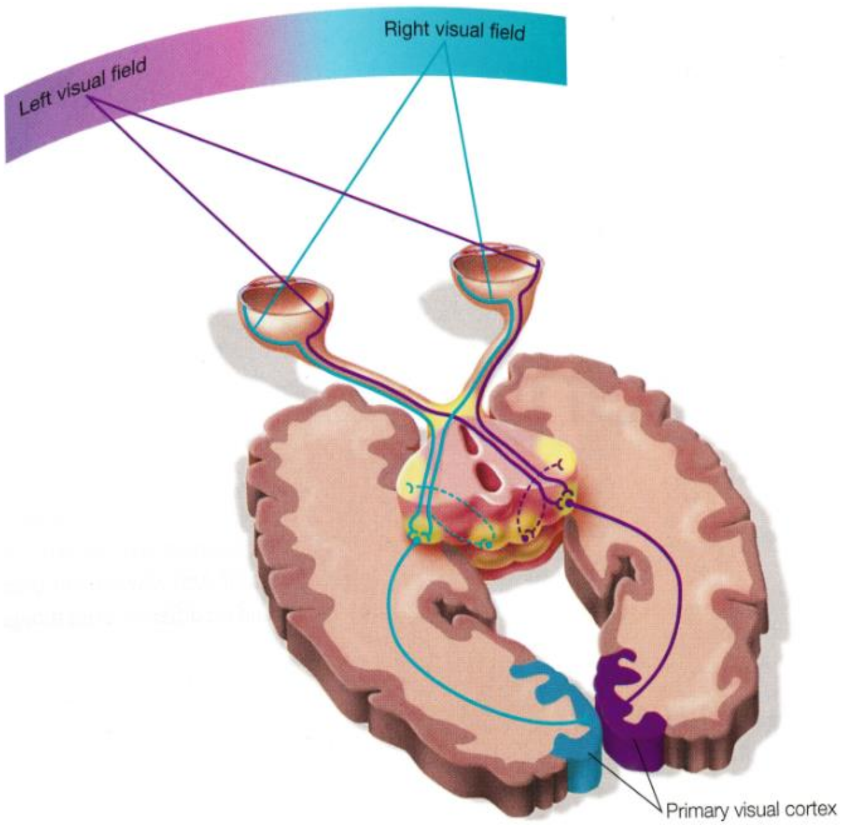
- There are other more finely dissections of functional clusters (up to 200) of the cerebral cortex
  - The nomenclature of the cortex is not fully standardized
  - We restrict ourselves to the numbering of Brodmann in the following
    - We refer to different regions with BA#, e.g. BA17 for the visual area (V1)

- The numbering follows no direct system and seems to be chaotic
  - The numbering corresponds to the order in which Brodmann sampled a region
  - Depicted here is the medial view of the left hemisphere showing the Brodmann areas



The visual system

- The occipital lobe is responsible for the visual system, i.e. vision
- Cerebral cortex begins to process visual information in the primary visual cortex (BA17)
  - The optical nerve ends in the BA17 on the medial surface (in humans)

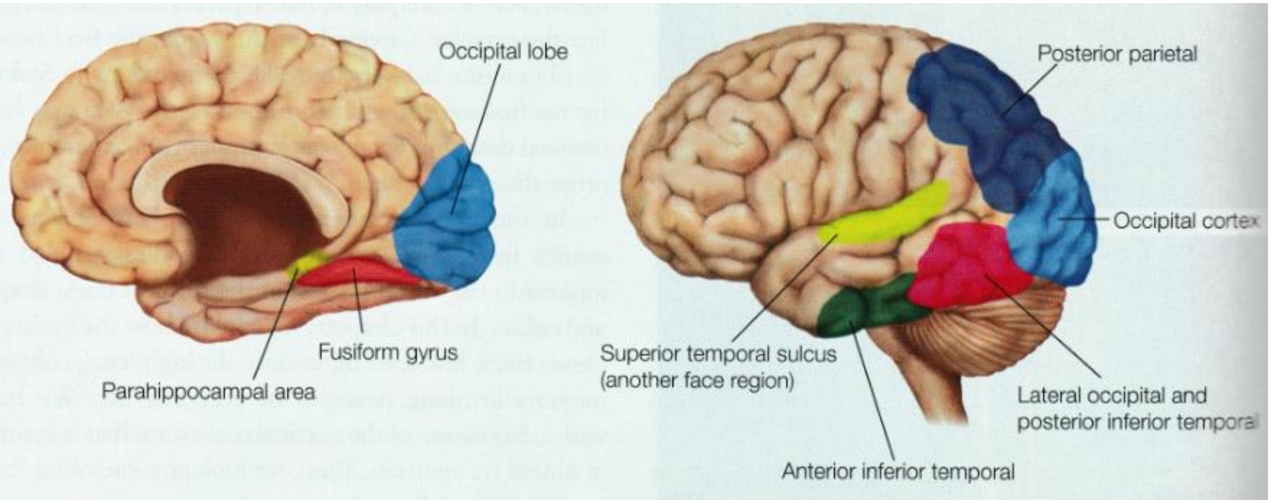


The visual system

- We start with object recognition for the visual system
  - The distinction of the phenomena sensation, perception, and recognition is an important principle
- Humans generally perceive an object as unified whole
  - Our perception of objects is robust although our perspective changes
  - Perception is tightly linked with the memory
- The above principle of object recognition derives from a disorder called **agnosias** (greek for “without knowledge”)
  - Humans with a visual agnosias are unable to recognize common objects which are presented to them visually
  - However, they will recognize it when touching, hearing, smelling, or tasting it

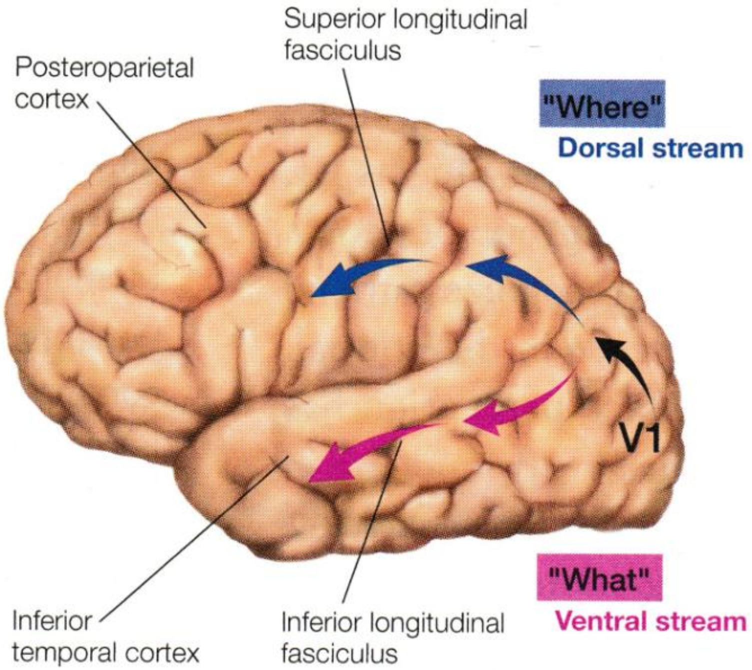
The visual system

- We learned about object recognition and its principles – where to go from here?
  - We will have a look at the anatomy of object recognition to see how it works
- There are specific regions in the brain to do distinct object recognition



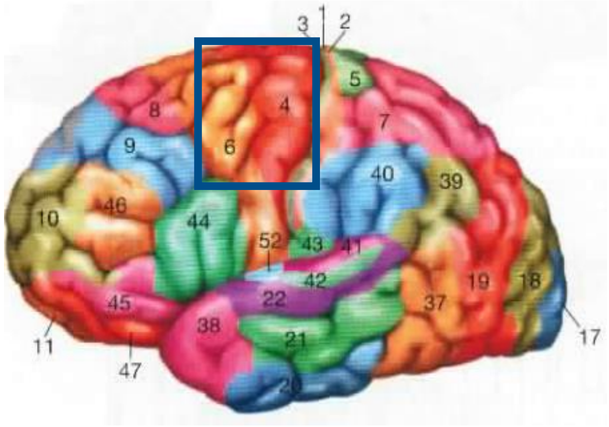
The visual system

- There are two pathways in the visual system
  - The occipitotemporal pathway (**ventral stream**) is specialized for perception and recognition of objects
    - Focus on *vision for recognition* and thus is called “what” stream
  - The occipitoparietal pathway (**dorsal stream**) is specialized for spatial perception, i.e. perception of positions
    - Focus on *vision for action* and thus is called “where” (or “how”) stream



The sensorimotor system

- The sensorimotor system consists of the pre- and postcentral gyri of the cerebral cortex
  - We start from the depths of the central sulcus and explain our way anteriorly, i.e. we focus on the frontal lobe
  - The primary motor cortex (M1) corresponds to BA4
  - Anterior to BA4 lies BA6 that is composed of two main motor areas of the cortex:
    - The premotor cortex on the lateral surface of the hemisphere
    - The supplementary cortex dorsal to the premotor area



- These motor cortical areas contain motor neurons (which we will see shortly)
  - Their axons extend to the spinal cord (also to synapse at the spinal cord) and the brain stem

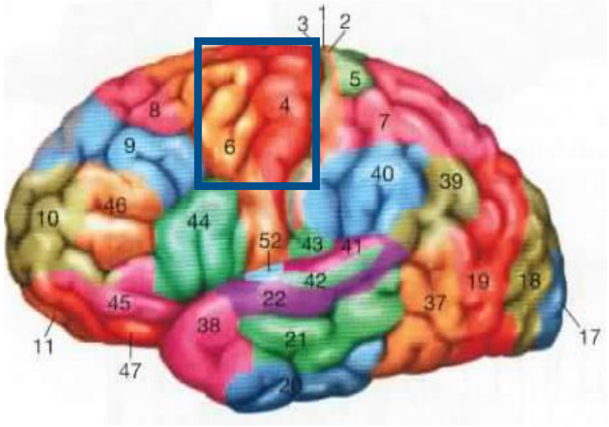
The sensorimotor system

- More anteriorly is the prefrontal cortex located

- The prefrontal cortex takes part in more complex aspects of planning, organizing, and executing behavior
  - Hence, the frontal lobe is often called “the center of executive function”

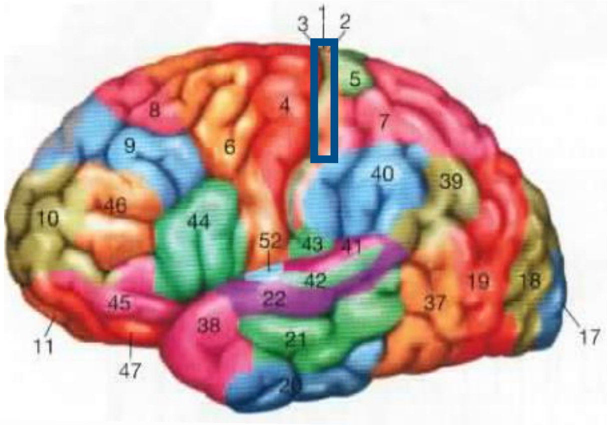
  - The frontal lobe needs to integrate information for an above given task over time which is quite essential

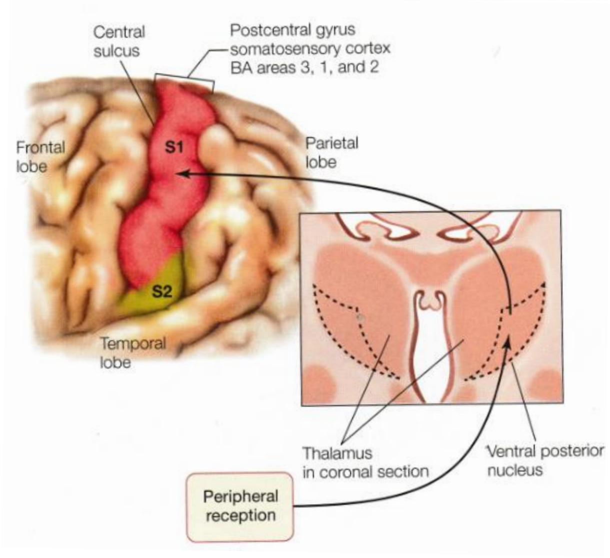
    - Humans with frontal lobe lesions often cannot establish information integration over time and thus are unable to perform an action sequence even though they are aware of each step that is to be done



The sensorimotor system

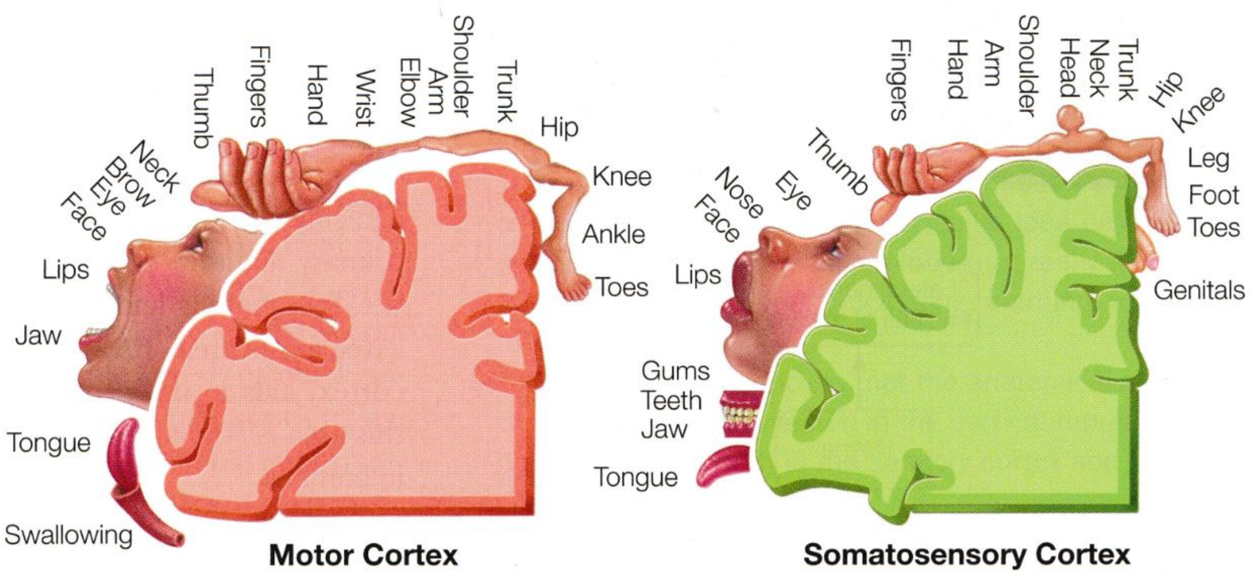
- We now move from the depths of the central sulcus posteriorly to learn about the somatosensory areas
- The primary somatosensory cortex (S1), here BA1-3, contains a somatotopic representation of the body (which we will see in a short)
  - The somatotopic representation is often called the sensory homunculus





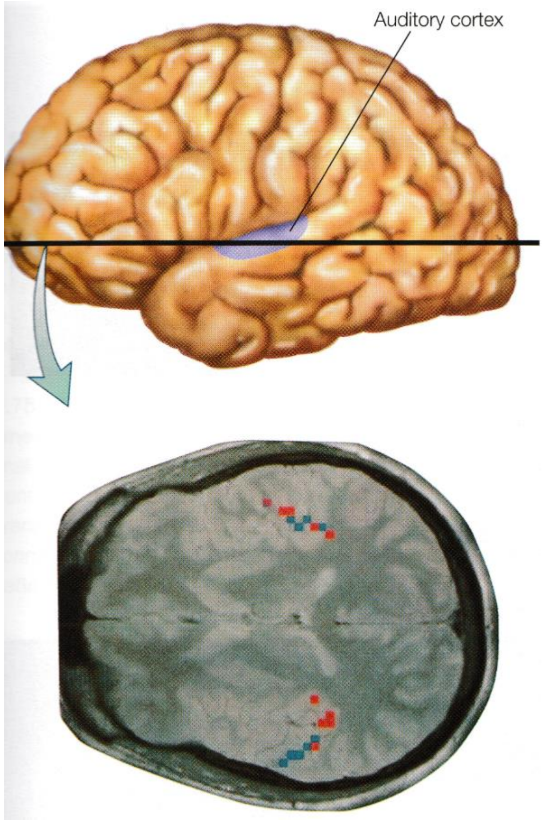
The sensorimotor system

- Finally, we will look at the cortical topography of the sensorimotor system
  - Principle that there is a (bijective) mapping from the cortical representation onto the anatomical organization of the body

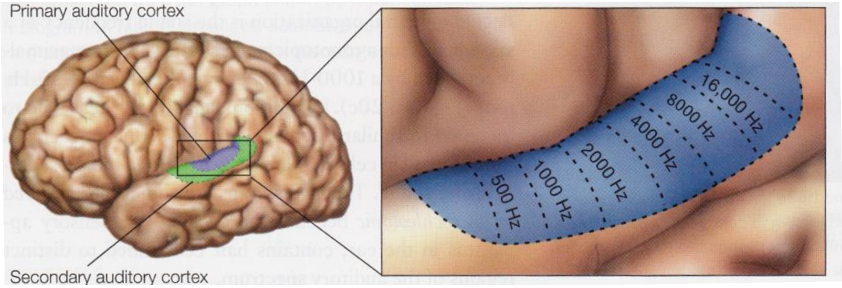


The auditory system

- The auditory cortex is seated in the superior part of the temporal lobe



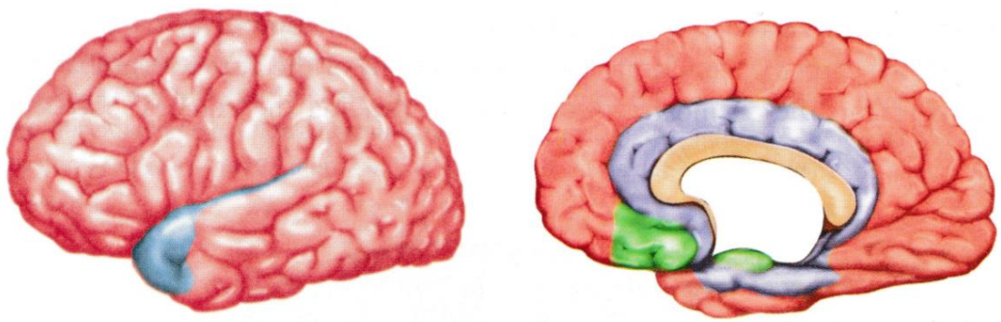
- This region is also known as *Heschl's gyrus* within the Sylvian fissure (roughly corresponds to BA41 and BA42)
- The physical layout of the neurons is based on the frequency of sound (tonotopic organization)
  - Neurons responding to a low frequency (red) are separated from neurons that respond well to an high frequency (blue)



Cortical columns

- We briefly explored the cerebral cortex – but what is it composed of?
  - We can subdivide the cerebral cortex into layers

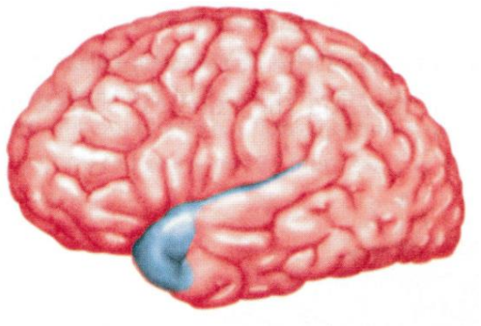
- We again use the a color code to separate between areas in the cerebral cortex with a different amount of layers
  - On the left side is the lateral surface of the left hemisphere and on the right side is the medial surface of the right hemisphere

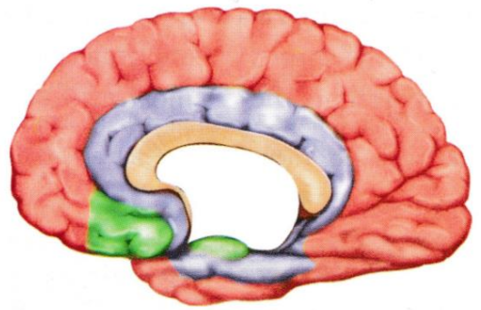


  - Both images show the neocortex (red), mesocortex (blue) and the allocortex (green)

Cortical columns

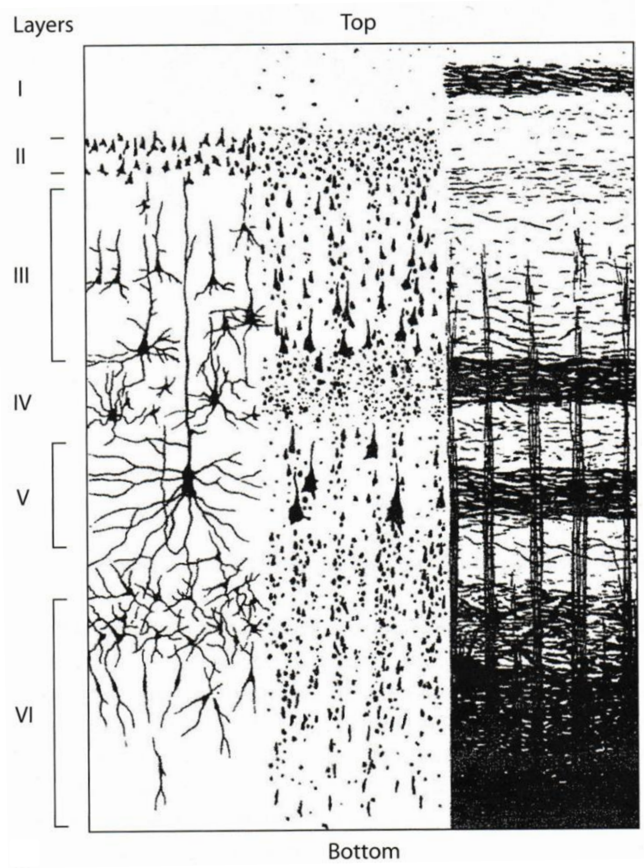
- **Neocortex** (red)
  - Makes up ninety percent of the cortex
  - Contains six cortical layers
- **Mesocortex** (blue)
  - Term for the so-called paralimbic region
  - Interposed between neocortex and allocortex
  - Usually has six cortical layers
- **Allocortex** (green)
  - Includes the hippocampal complex and the olfactory cortex
  - Typically has one to four cortical layers





Cortical columns

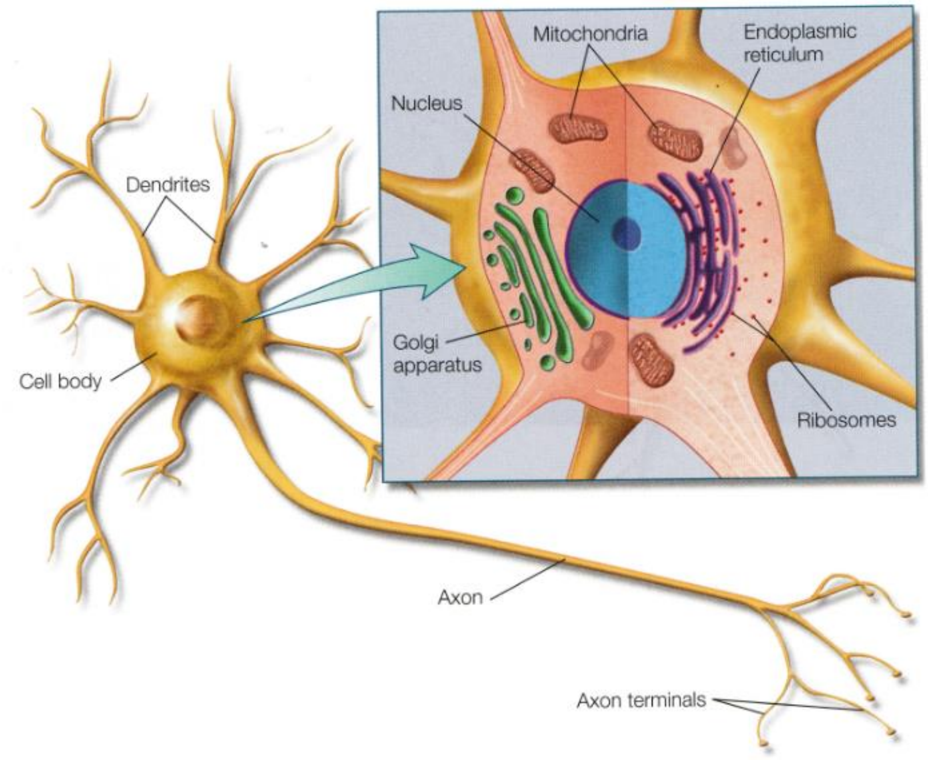
- What are layers made of? And what is the task of such layers?
  - A layer consists out of similar neurons typically
  - The neurons per layer are usually different
  - The layer 5 and 6 project primarily to targets outside the cortex and are considered as output layer
  - The layer 4 is typically the input layer which receives input from the thalamus and other more distant cortical areas
  - The superficial layers primarily project to targets within the cortex and it has also been suggested that they participate in higher cognitive functions



- **Cortical columns** are functional units within the cortex
  - They consist out of multiple connected neurons on layers where the layers again are connected

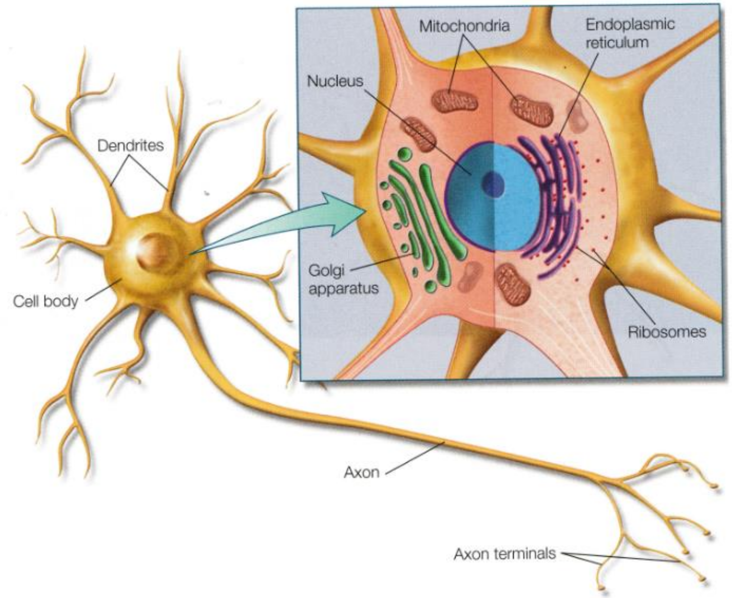
The neuron

- The neuron is an essential part of the nervous system
  - Transmit information throughout the nervous system (we will see how this works later)
  - Most neurons consist out of a **cell soma** (body), **axon**, and **dendrites**
    - A neuron is a eukaryotic cell, i.e. it has a nucleus
- An idealized mammalian neuron is depicted to the right



The neuron

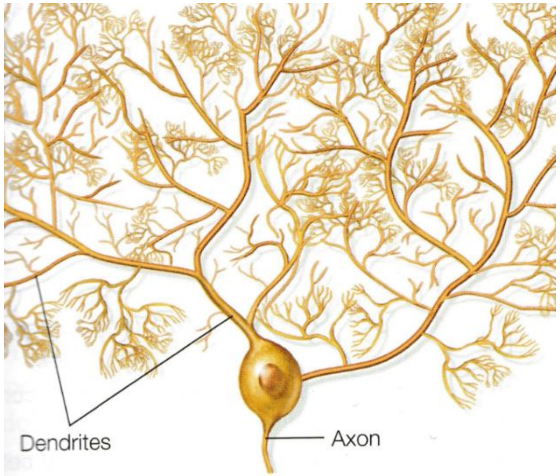
- Most neurons are like every other eukaryotic cell in our body
  - The components (Mitochondira, nucleus, ribosomes, endoplasmic reticulum, golgi apparatus) of the neuron are suspended in cytoplasm (salty intracellular fluid)
  - The intracellular fluid is made of a combinations of ions (mainly ions of potassium, sodium, chloride, and calcium)



- However, the neuron is unique as such that it can process information quickly
  - Unlike every other cell in our body, the neuron has dendrites and the axon

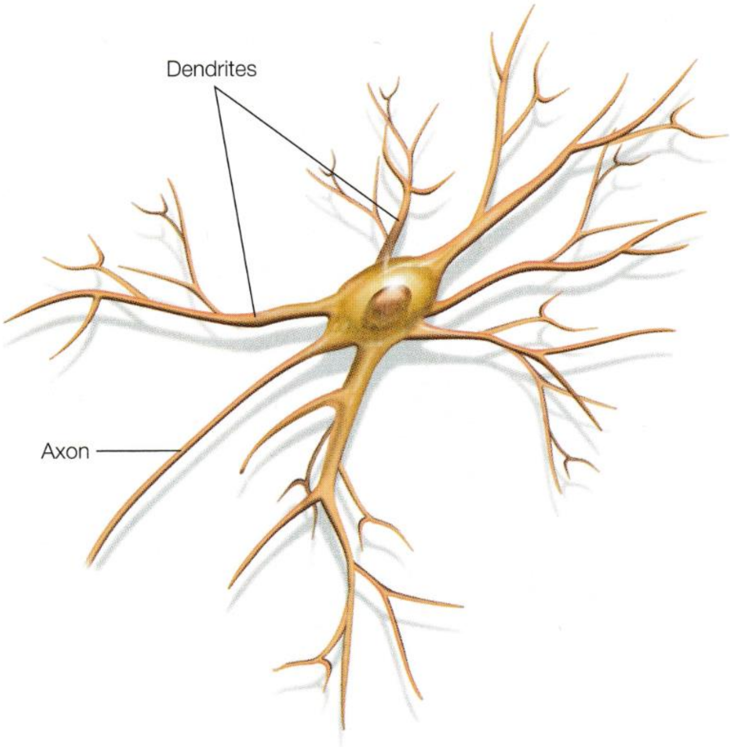
The neuron

- The dendrites branch from the neurons cell soma
  - The dendrites are responsible for receiving information from other neurons
  - The form of the dendrites and their complexity varies depending on their type and location within the brain
- To the right we see a purkinje neuron
  - Purkinje neurons are arrayed in rows in the cerebellum forming a sheet / layer of neurons
  - Purkinje neurons have distinctive dendrites compared to other neurons



The neuron

- The axon is a single process extending the neurons cell soma
  - The axon is responsible for transmitting information to other neurons
  - An electrical signal travels along the axon to its end where the communication with (an)other neuron(s) take place
  - The communication takes place at the **synapse**, a specialized construct where two neurons come close
    - There they exchange information in form of chemical or electrical signals
- To the right, a motor neuron can be seen



Cortical connectivity

- Cortical connectivity is very important for the intercommunication of neurons
  - There are a few steps you need to know about and you should also be able to interpolate and integrate your knowledge
  - We will black-box the topic on how neurons gather energy for signaling, i.e. building up membrane potentials
    - Be sure to know that the initial energy arise from splitting an adenosine triphosphate (ATP) into an adenosine diphosphat (ADP) and phosphate (P), i.e. $ATP + H_2O \rightarrow ADP + P$
  - So how does an action potential arise particularly?
    - Subsequently we will make our way from the dendrites of the neuron to its axon

Cortical connectivity

- **Excitatory postsynaptic potentials** (EPSPs) at the neurons synapses dendrites cause a flow of ionic currents into the cell soma
  - (If you are interested in details of this process, read about the membrane potential of neurons)

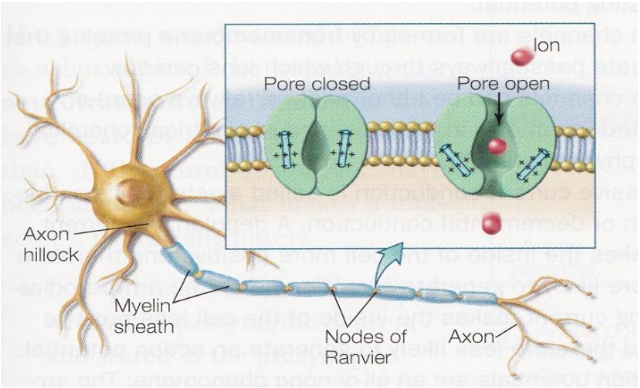
  - Neuronal signaling only takes place iff the currents are strong enough (**!**)
    - Electrical current is passively conducted through the cytoplasm of the neuron
    - However, electrical current produced by the EPSP diminishes by distance of its origin
    - The decremental process of the EPSP is called electronic conduction (or decremental conduction)

- So back to our question – how are neurons able to communicate anyway?
  - Here the **action potential** arises

Cortical connectivity

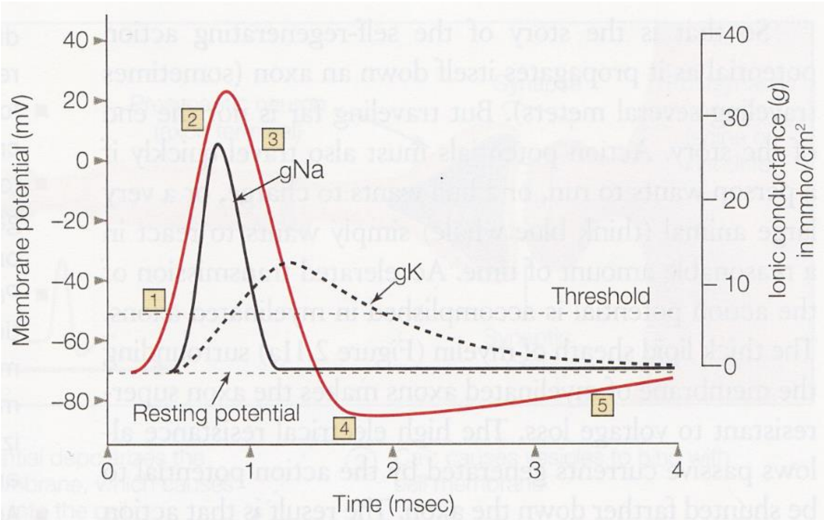
- The **action potential** (or spike) differs from the EPSP
  - Postsynaptic potentials decrement after a distance of ~1mm while the action potential regenerates itself
  - Regeneration functions with **voltage-gated ion channels** in the neuronal membrane
  - Voltage-gated ion channels are located at the axon hillock and along the axon
    - Myelinated (more conductive) axons have them located at the axon hillock and the nodes of Ravier

- How does the life of an action potential look like?
  - Action potentials basically consist of rapid depolarization and repolarization
  - Action potentials occur in a small area at a frequency of about 200 Hz, i.e. 200 times per second



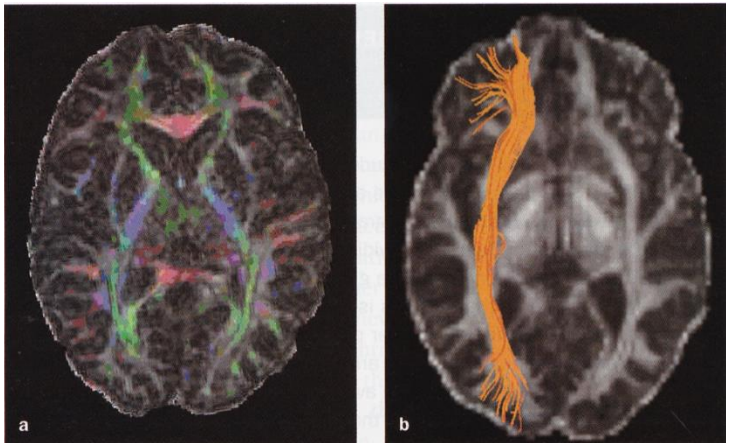
Cortical connectivity

1. Reaching membrane potential threshold
   - More voltage-gated Na^+ channels open
2. Stronger depolarization
   - Even more voltage-gated Na^+ channels open
3. Repolarization
   - The amount of Na^+ causes the voltage-gated K^+ channels to open
4. Hyperpolarization
   - All voltage-gated K^+ channels start to close
5. Hyperpolarization (**refractory period**)
   - The membrane potential returns to its equilibrium point (the resting potential)



Cortical connectivity

- The method **diffusion tensor imaging** (DTI) can be used to study the anatomical structure of the axon tracts that form the white matter
  - We get a first grasp of **cortical connectivity** between multiple neurons
  - DTI is performed with a magnetic resonance imaging (MRI) scanner that measures the density and the motion of the water contained in axons
  - DTI makes hereby use of diffusion characteristics of water



The default mode network

- A default mode is essential in understanding complex system
  - The brain is our most complex system and the default mode would be a “baseline” or “control state”
  - What is the brains baseline? Or does such a baseline even exist?

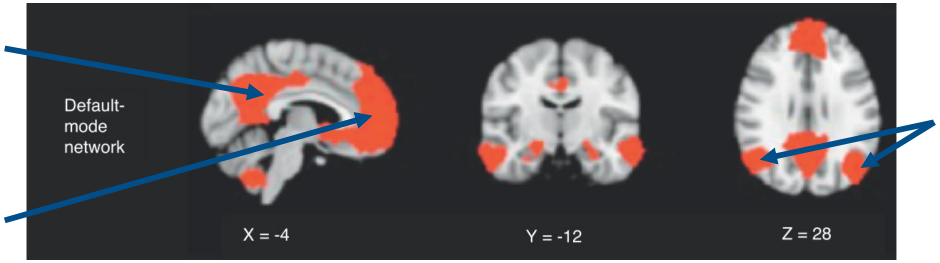
- Marcus E. Raichle et al. investigated the brain for baselines
  - They formulated a baseline of the *normal* adult human brain in terms of the brain **oxygen extraction fraction** (OEF)
  - The OEF is defined as the ratio of oxygen used by the brain to oxygen delivered by blood flow (uniform when awake but in a resting state)

- Locale deviations in the OEF represents the physiological basis of signals of change in neural activity
  - The result are obtained with functional MRI (fMRI, cf. DTI or lecture 3)

The default mode network

- Locale deviations in the OEF represents the physiological basis of signals of change in neural activity
  - OEF is obtained **regionally** throughout the brain by quantitative metabolic and circulatory measurements

- The aim is to find baseline default mode of brain function that is suspended during specific goal-directed behaviors, i.e. a default brain state of inactivity



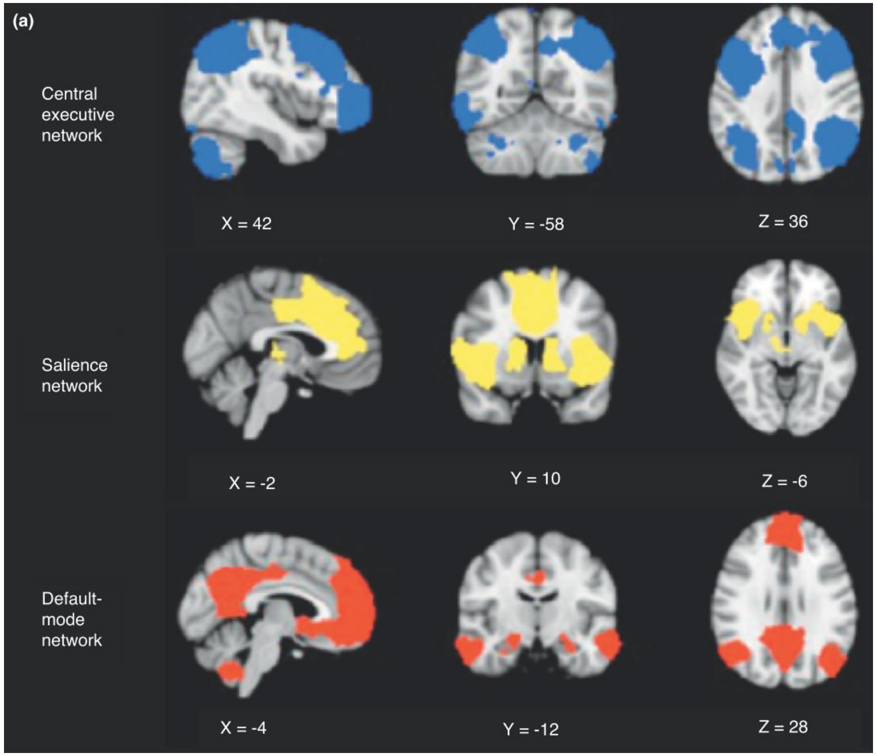
- Informative video to watch at home to the topic of default mode network: Web

Large scale resting-state networks & behaviour

- A large scale resting-state network is a powerful paradigm for the investigation on cognitive and affective dysfunctions in psychiatric and neurological disorders

- Understanding cognitive functions of the human brain depends on knowledge of its large-scale organization

- Network approaches (i.e. graphical networks) give insight on how functionally connected systems engender and constrain cognitive functions
  - New insights into aberrant brain organization in several psychiatric and neurological disorders



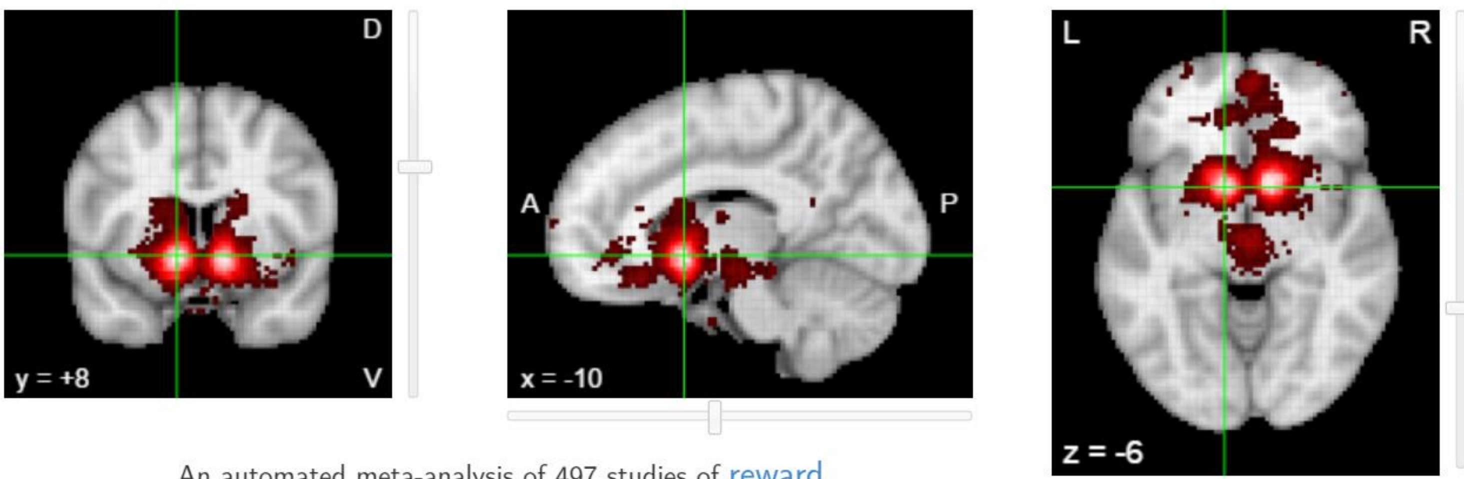
Large scale resting-state networks & behaviour

- Understanding how disturbances in distributed brain areas – operating in a large scale network – contribute to dysfunction in behaviour is (nowadays) crucial
  - The brain is assumed to be organized intrinsically into coherent functional networks
  - The default mode network (DMN) is one of the resting-state network which actually induced the idea of large scale networks (because of high amounts of metabolism)
  - Salience networks (SN) are important systems in attentional capture of biologically and cognitively relevant events
  - Finally, dynamic interactions within the large scale network regulates shifts in attention and access to domain-general and domain-specific cognitive resources

The Neurosynth database

- Web: Neurosynth

- Neurosynth is a platform for automatically synthesizing the results of many different neuroimaging studies



An automated meta-analysis of 497 studies of reward

Whole brain activation in simple tasks

TECHNISCHE UNIVERSITÄT DARMSTADT

- The brain is the largest energy consumer (~ 20 percent) and ist biological cause consciousness remains elusive until today

- The theory of large scale networks emphasizes a localizationist view of the brain

- Gonzalez et al. challenge this localizationist view of the brain; they averaged large amounts of time-series per subject to reduce the noise in the data
  - There is evidence that under optimal noise conditions, the brain does not only change in specific regions in simple tasks

  - They state that the localizationist view emerges from high noise and overly strict predictive response model of active brain regions

Literature

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