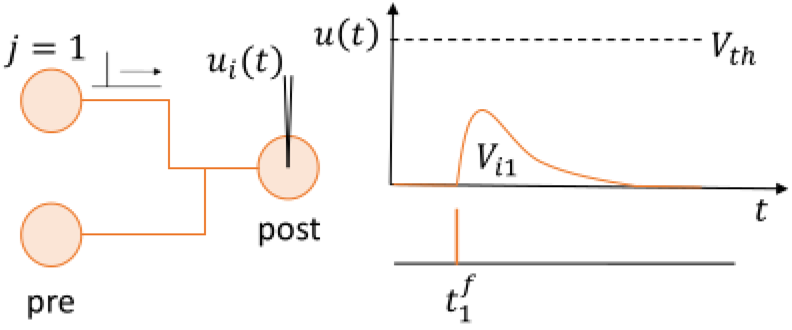
2.1 Basic Building Blocks of Neural Networks

- Now let's systematize our previous discussion and consider the following arrangement:
  - ➢ In this arrangement two pre-neurons connect to one post-neuron.
  - ➢ Each presynaptic spike t_j^f evokes an excitatory postsynaptic potential (EPSP) $u_i(t)$ that can be measured with an electrode as a potential difference:

$$u_i(t) - u_{rest} = V_{ij}(t)$$

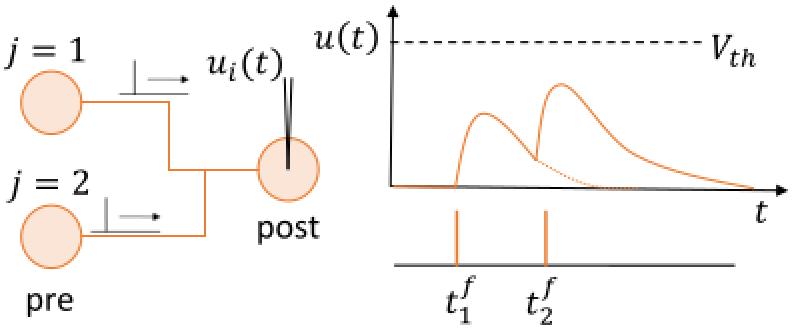


  - ➢ The time course of the EPSP caused by the spike of neuron is:

for j = 1 : $V_{i1}(t - t_1^f)$

  - ➢ An input spike from a second presynaptic neuron j = 2 that arrives shortly after the spike from neuron j = 1 causes a second postsynaptic potential that adds to the first one:

$$u_i(t) = \sum_j \sum_f V_{ij}(t - t_j^f) + u_{rest}$$

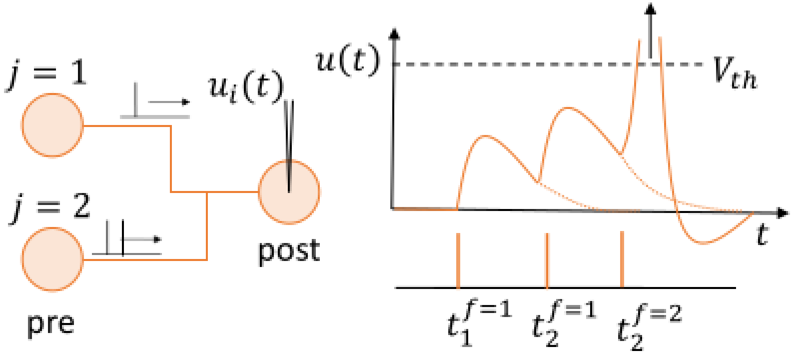


2.1 Basic Building Blocks of Neural Networks

- If $u_i(t)$ reaches the threshold V_{th}, an action potential is triggered.

$$u_i(t) = V_{th} \quad \text{and} \quad \frac{du_i(t)}{dt} > 0 \Rightarrow t = t_j^f$$

- As a consequence, the membrane potential starts a large positive pulse-like excursion (arrow). On the voltage scale of the graph, the peak of the pulse is out of bounds.
- After the pulse the voltage returns to a value below the resting potential.



- We have already converted the essential process at the synapse into a (technical) mathematical model.
  - Although this is quite simple and only describes the biology in a rudimentary manner, it already includes the neuronal dynamics.

- Next, we want to leave the cellular level and go to the network level….

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Neuromorphic Engineering I

Information Processing in Neural Networks

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Slides adapted from M. Ziegler, U Kiel

2.2 Information Processing in Neural Networks

Learning objectives:

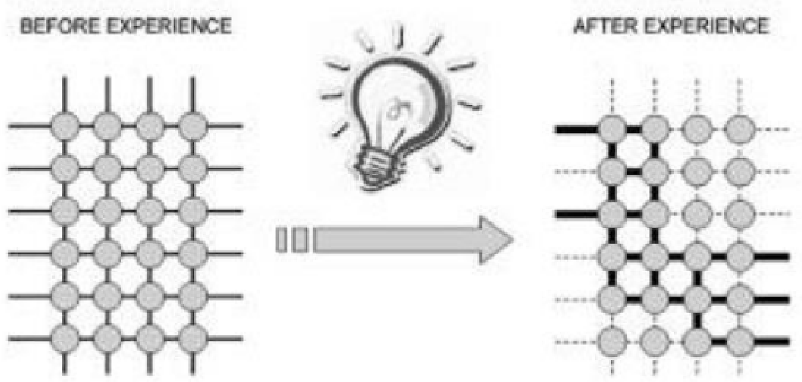
In this chapter I would like to give you an overview of how information is processed in the brain. For this, the chapter deals with our brain - its anatomy, functioning and conceptual approaches to neurobiology.

In this chapter I would like to answer the following questions:

- How is information processed in neural networks?
- What is the central nervous system?
- How is our brain structured?
- How is learning and memory formed?
- How does perception, awareness, experience, language and emotions arise?

2.2 Information Processing in Neural Networks

- In the chapter we want to follow up on the last one and answer the question how is information processed?
  - As we already know, this happens between the neurons at synapses by changing the coupling strength between neurons in a network of them, but what does it do?
  - for this we consider the following model:
    - In the illustration, the circles are supposed to be neurons and the lines between them are their couplings via synapses.
    - On the left is the network before the learning process: signals would spread uniformly in the network. One thinks of a circuit in which the synapses are represented by resistors.
    - The same network is shown on the right after a learning process: now some connections are strengthened and the signal is directed through the network. Again similar to the resistance network: electricity flows where the resistance is the lowest.



  - Thus, changing the efficiency of transmission in selective synaptic connections within a neural network modifies the flow of information.

- If we look at biology and our brain in particular - extraordinarily complex networks are formed through synapses.
  - Our brain consists of 10^{11} neurons, which corresponds to the order of stars in the milky way- a whole galaxy.
  - Actually, it is these complex networks that enable all of our intellectual achievements.

2.2 Information Processing in Neural Networks

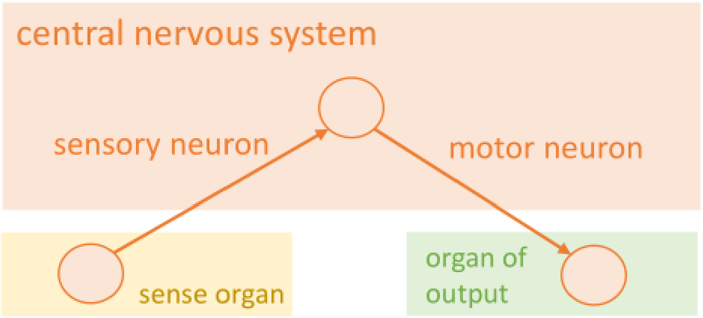
- Thus the synapses connect complex networks, the nervous system. In vertebrates this is the central nervous system which is divided into the brain, spinal cord and peripheral nervous system.
- This network is very complex to understand in detail. Therefore, I would like to reduce myself to a rather technical description about information processing:
  - ➢ Sensory cells absorb stimuli from the environment and pass this information on to sensory nerves in the form of action potentials into the nervous system. In terms of technology, this would correspond to the input of information.
  - ➢ In the central nervous system, this information is recognized, evaluated, possibly saved and compared, so the information processing took place here.
  - ➢ As a result of processing, there is often a reaction, the disclosure of information. E.g. a movement carried out by motor nerves controlled by the central nervous system.

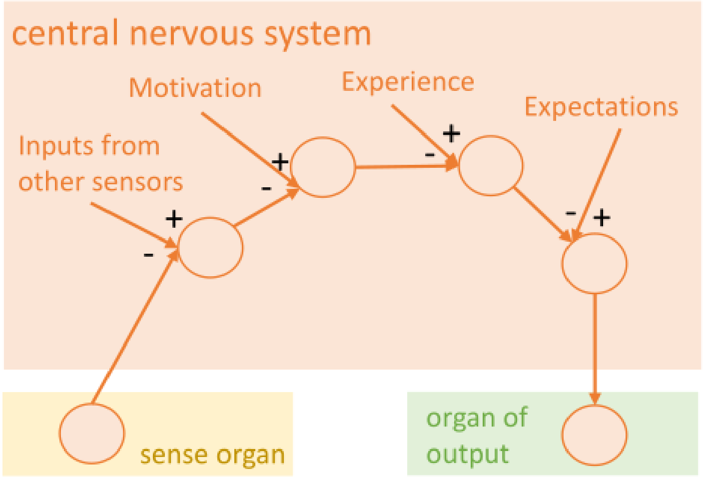
➢ we want to take a closer look at these mechanisms on the next slide…

2.2 Information Processing in Neural Networks

- These central aspects are schematically represented in the figures with regard to different levels of complexity:

  - In the simplest case, a sensory neuron is directly coupled to a motor neuron. Such simple structures are subject to our reflexes, in which the central nervous system is not involved.
  - A somewhat more complex representation is shown below, which includes the central nerve system. Exciting or inhibiting from other areas can be included at each synapse.
  - This already includes the complexity of decision making. Do you think e.g. a visit to the Mensa, so many factors are relevant, ranging from hunger to maintaining social contacts. But experience can also influence the decision here.
  - Thus, it can be many processing steps between the input of information and the output. Generally speaking, the more complex and flexible a process controlled by the central nervous system, the more complex the network.
  - That is the great difficulty: the human brain can process more complex processes than a jellyfish, but the network structures required for this are also much more complex. But let's take a closer look at these structures….

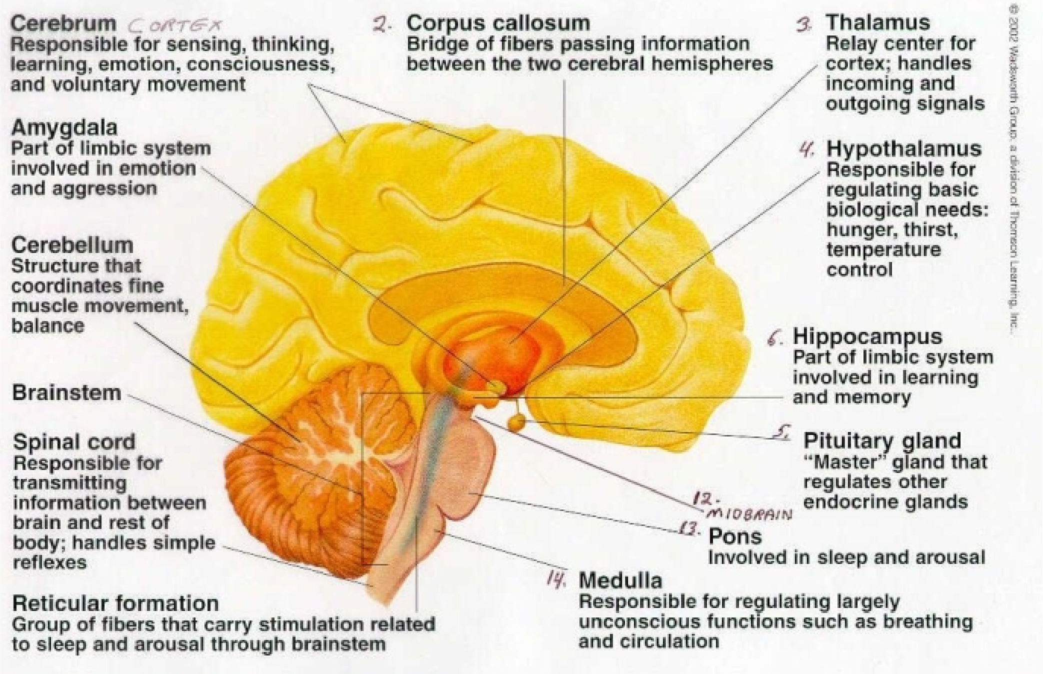




2.2 Information Processing in Neural Networks

- The brains of all vertebrates have a very similar structure and are homologous in terms of the number and arrangement of brain sections. There are differences in the relative size and function of individual brain sections:

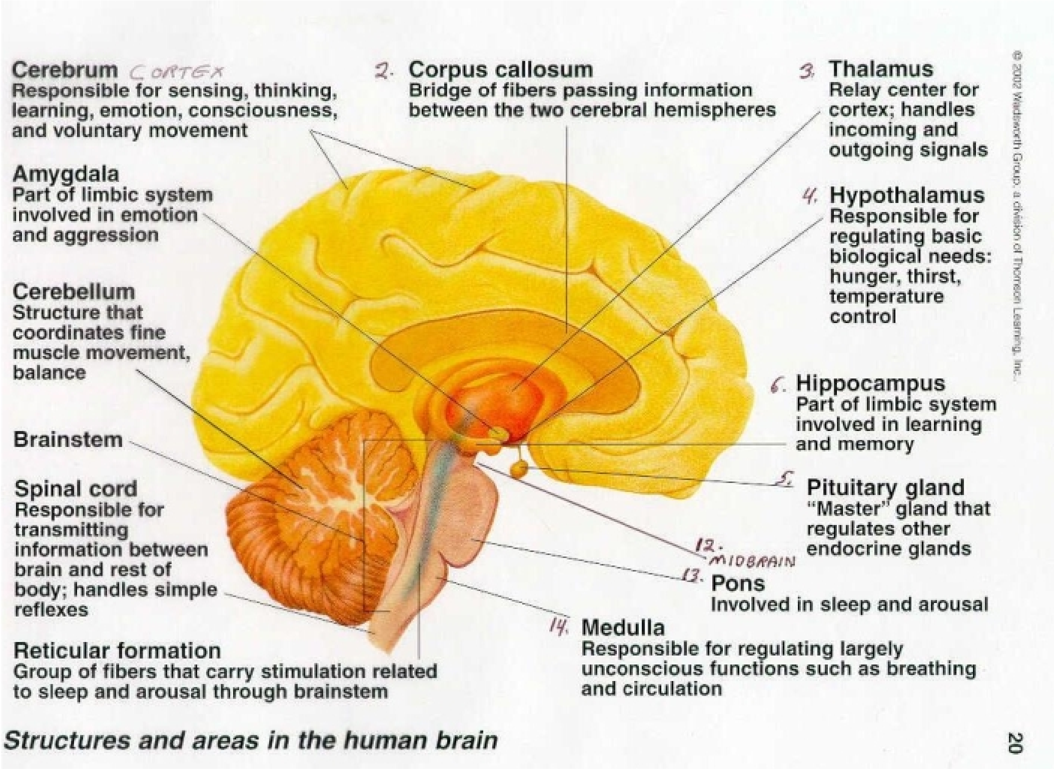
  - The transition from the spinal cord to the brain includes the hindbrain, which together with the midbrain is called the brain stem. As a passage of nerve pathways from the body into the brain and vice versa, it is the origin and target area of all brain nerves (except for the olfactory and optic nerves).
  - The midbrain connects to the midbrain and consists essentially of the thalamus and hypothalamus.
  - The thalamus is the switch between the senor nerves and the cerebrum and thus a gathering point for sensory information.
  - The hypothalamus is the control centre for numerous body functions such as body temperature and is closely linked to the hormone system. You can understand it as the control centre of our brain and it controls our sleep-waking rhythm and also your sexual behaviour.



Structures and areas in the human brain

2.2 Information Processing in Neural Networks

- The task of the cerebellum is to coordinate movements and orientation in space.
- The cerebrum is an evolutionary of the youngest parts of the brain and is particularly well-trained in humans.
- A lamb furrow divides this into two halves. A structure associated with 200 million axons. Furrows increase the surface area extremely (in humans to 1000 cm^2), which is particularly important since the structure called cortex is where essential parts of information processing and storage take place (see figure).
- About a third of all neurons are located in the cerebral cortex. In total there are 4 10^{14} synapses in the cortex. The networking is enormous. **Virtually every neuron is connected to every other neuron.**



Structures and areas in the human brain

- At this point, the comparison between the human brain and other mammals is also interesting. So you can see that humans have a much greater density and connection of neurons here. So as already mentioned - the more complex the network, the more powerful ;-)

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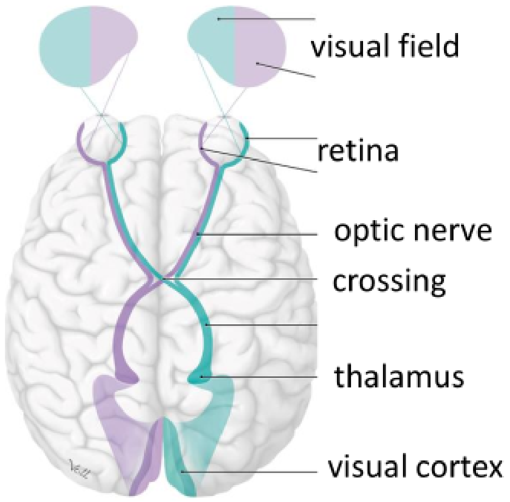
2.2 Information Processing in Neural Networks

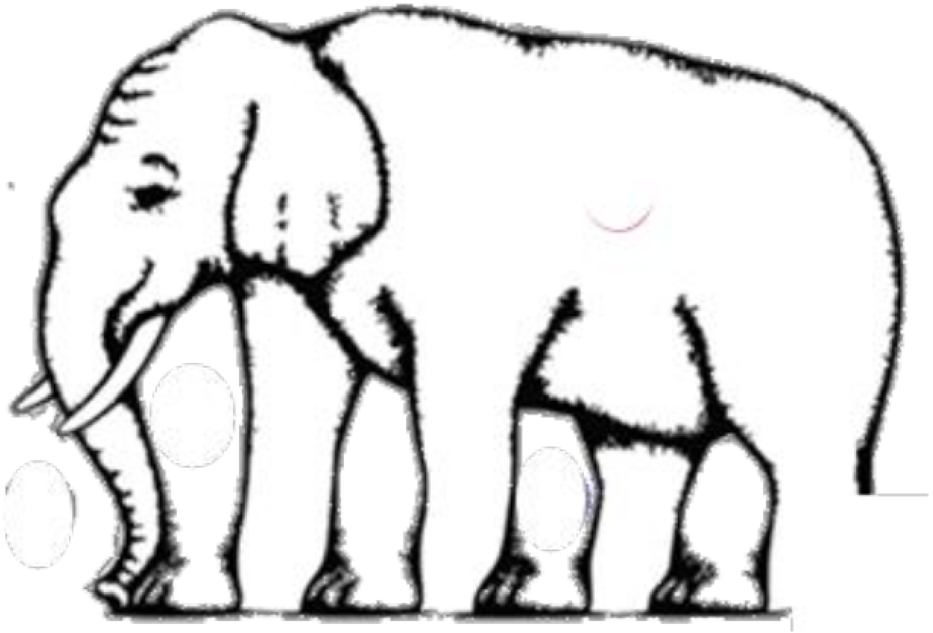
- But, how does all this work and do we now process the information within this complex network? Now, this is one of the greatest puzzles in the world and nobody can answer it. However, I would like to classify and describe a few functions. That's exactly what we would like to technically recreate ...
- We'll start with a bang: Perception using the example of seeing.
  - Seeing is much more than our eyes: if someone comes to us we have the impression that the person would grow, or why does the moon appear larger in the city than in the country (without reference point). If a person beckons us, the image on the retina changes and it is still perceived as a hand.
  - Apparently, information is not recorded passively, but always actively processed by the brain. This is called perception: the process of reconstructing a coherent image from sensory data.
  - The pathways of the optic nerves cross each other, so that the information of the left visual field reaches the right brain and that of the right visual field reaches the left brain. This enables spatial viewing. Each half of the brain receives information from both and can compare it.
  - The optic nerve leads into the thalamus, with a part already branching off in the brain stem into the centre of the reflex.
  - The main part ends in the cerebrum (visual cortex). The thalamus and the visual cortex are designed in such a way that a neural map - receptive field of the retina is created and the image on the retina undergoes a spatial reconstruction in the brain.



2.2 Information Processing in Neural Networks

- Images are interpreted before they are consciously perceived.
  - ➢ This already begins on the retina through contrast differences and ends in the visual cortex of the different areas, which are specialized in the processing of individual areas of the retina
  - ➢ For example, a field is responsible for the processing of the dynamic form, whereby we perceive a moving object as a form despite its movement.

- However, perception can also lead to mistakes, as can be seen from illusions.
  - ➢ An example of this is the picture of the elephant, which at first glance may look normal. It is only when you take a closer look that you realize that the drawing was not quite right.
  - ➢ the fact that we recognize the deception does not prevent it.



2.2 Information Processing in Neural Networks

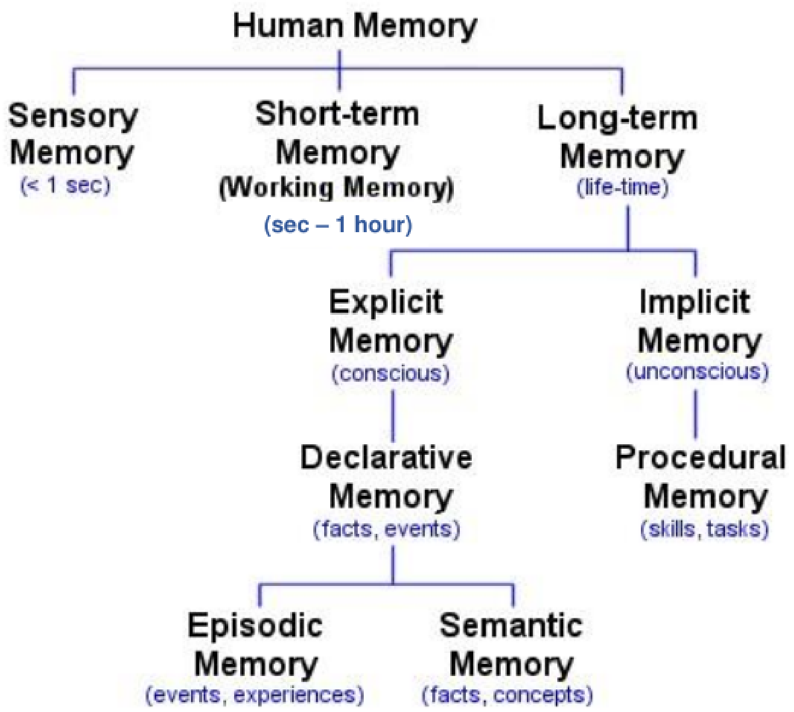
- We are only aware of a small amount of information that flows our senses every second. Thus, only a little part of the information will be available to us as new knowledge. This is what we call learning and memory, as was defined at the very beginning of the lecture.
- There is a whole range of different learning forms that differ in their complexity. We will talk about this in detail later in the lecture. But actually everyone is already familiar with it: Learning a poem by heart is something other than learning to cycle.
- In general, two learning forms can be distinguished from a neurobiological perspective:

  1. Cognitive, declarative or explicit learning is what we generally understand by learning. So learning that requires conscious participation, such as learning for an exam.
  2. Conscious participation is not required when learning is not cognitive, procedural or implicit. This is more about practicing. Like learning to ride a bike. This is difficult to explain to someone else how to keep balance and when explaining this it is often not very helpful.

- However, the processes at the cellular level are the same for all learning processes: The couplings between neurons at the synapses change. This is named synaptic plasticity and we will consider this in more detail later in the lecture.
- The different forms of change in synaptic transmission and their continued potentiation play an important role for learning and memory, as we will see later in the lecture.

2.2 Information Processing in Neural Networks

- The memory spans several levels. So we can usually only remember a sequence of numbers like a telephone number very briefly, although we can still remember some events from our childhood quite well. Apparently, certain events are stored differently for us depending on their significance.
- A distinction is therefore made between different levels of memory:
  - The sensory or ultra-short-term memory is based on a reverberation of neural excitation of the sensory organs (often not referred to as a memory).
  - The short-term memory is subdivided into the working memory and the primary memory. Information that is aware at the moment is stored in the primary memory (maximum of seven pieces of information). Information can be held in the working memory for up to an hour.
  - Information is permanently stored in long-term memory. This is due to a permanent change in the synapses. In the course of life it is assumed that 10^{10} to 10^{14} bits can be stored here, which comprises the content of 3000 to 30 million books.



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- In the hipppocampus, which is part of the limbic system, information is transferred into the long-term memory.
  - ➢ He has a special role in acquiring, processing, and evaluating new information. He make the decision which information has to be stored. Persons with hippocampus damage can not learn new things
  - ➢ Damage in the hippocampus can lead to memory loss. A well-known example is Alzheimer's disease.
- The hippocampus is not involved in learning implicitly. Here, the cerebellum is important, in which structural changes arise through learning.
  - ➢ In this way, special cortex areas for frequently used functions or body parts are enlarged.
- Memories can be understood as a kind of protocol of an activity pattern of neurons.
  - ➢ If we remember an apple as an example, the same nerve cells in the brain become active that also become active when you see, taste and smell an apple.
  - ➢ Here, neurons can be active on a wide variety of activity patterns and not the neuron itself stands for a concept, but rather an ensemble of neurons that are active at the same time.
  - ➢ This means that information can be stored in a very space-saving manner, which explains the high number of information that can be stored. Moreover, this is more fault-tolerant: if the neuron apple is damaged, you couldn't recognize an apple anymore. This makes a ensemble of neurons to represent an object much more robust.
  - ➢ But do not be afraid: this point will also keep us busy in the lecture…..

2.2 Information Processing in Neural Networks

- if we compare humans with animals, it's a strange thing: we can speak, have culture and puzzles about the origin of the world. Yes, even about how our own brains work and we question our own being. Without slipping from a lecture on technology into one on philosophy, I would like to briefly answer the question: Why we humans are so different to animals in that sense?
    - Now it is easy to assume that the answer should be found in our brain and especially in the cerebrum, where typical human abilities, such as language, can be determined in certain regions.
    - Thinking in objectives is essential for our ability to speak: this means that certain impressions captured by the senses are classified according to certain criteria.
    - Although some highly developed mammals and birds can form concepts, named nonverbal concepts, and can therewith relate to things and living beings that are grasped directly with the senses. In contrast, human thinking can completely break away from it. Abstract objectives, such as the study regulations or examination regulations, are abstract symbols that can only be explained with the help of language (sometimes with a lot of language by Ms. Scheibe).
    - The symbolic language enables people to communicate about something that is not present and cannot be grasped by the senses. Their development was the prerequisite for cultural evolution.
    - Thinking in objectives is an ability of associative fields of the entire cerebral cortex: Special areas represent sounds and specifications for connecting sounds to words and sentences. Additional fields mediate between these areas so that certain words can be assigned to certain objectives. However, there are many models and explanations for this and a detailed understanding is missing. What is known is that the language is localized in the left half of the brain.

2.2 Information Processing in Neural Networks

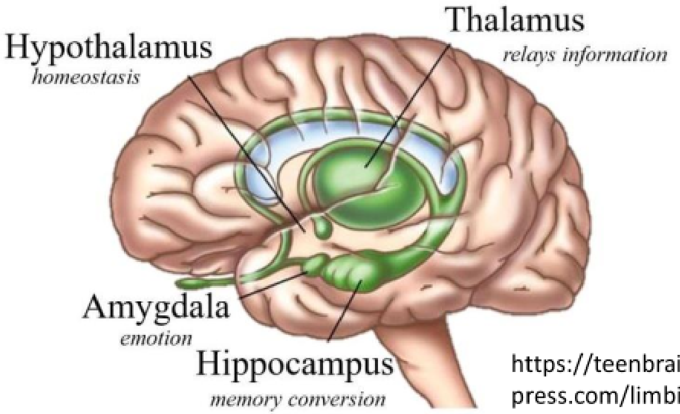
- In addition to language and the ability to think abstractly, consciousness is a typical human characteristic.
    - We experience our "self" in thinking and perceiving as a separate entity from the environment. We know what's inside and what's outside of us.
    - Very few animal species can do this. An example are Rhesus monkey where it could be shown that they recognize their own in a mirror.

Neng Gong et al., Current Biology

- However, this is one thing with consciousness and this poses a major challenge for science. There are essentially a few essential characteristics that can be described:
    1) There is no narrow brain area for consciousness: however, only those events can be consciously experienced that are accompanied by activities of receptive fields in the cerebral cortex. So what is not going on in the associative cerebral cortex is also not conscious.
    2) The capacity of awareness is very limited: only about seven information per second can be consciously experienced. It's just a tiny, almost vanishing part of the information that our brains process every second.
    3) The brain stem controls consciousness: states of consciousness such as sleep or awake are not controlled by the cerebral cortex but by the brain stem, among other things. Even the smallest injuries in the brain stem can lead to unconsciousness.

2.2 Information Processing in Neural Networks

- Our emotions are also related to certain brain structures.
  - Some emotions like fear cannot be imagined without a physical reaction such as heart races or sweats.
  - It is therefore not surprising that there are connections in the brain that connect both the receptive fields in the cerebral cortex and the hypothalamus, where our body reactions are controlled via neurotransmitter.
  - This system is called the limbic system (see figure on the right).



https://teenbraintalk.wordpress.com/limbic-system/

- Now it gets a bit philosophical at the end: for many philosophers such as Emanuel Kant considered emotions to be secondary and subordinate to reason.
  - Philosophy may have problems with this, but biology does not. Emotions are not second-class functions, but offer important stimuli to do certain things and leave others alone.
  - Those who make sensible decisions first go through various decisions and their effects.
  - Emotions are often used subconsciously to make decisions.
  - Associative fields in the frontal lobe and the limbic system play an important role here.