Chapter H: Nervous System

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H.1. Introduction Nervous System

A. Introduction:

<table>
<tr>
<td>1.
And now we arrive at the most central and complicated system in the body; the nervous system!</td>
<td>2.
This is the system that controls everything in our body; from the blood pressure, the digestion in our guts to our thoughts, our memories and, yes, our intelligence!</td>
</tr>
<tr>
<td>3.
In fact, this system is so complicated that ‘they’ have divided this ‘organ’ system into three parts:
a) The Central nervous system
b) The Peripheral nervous system
c) The Autonomic nervous system</td>
<td>4.
The central nervous system consists of two major structures:
a) the brain
b) the spinal cord.

These organs are so delicate that they have to be protected by the skull and the vertebral column.</td>
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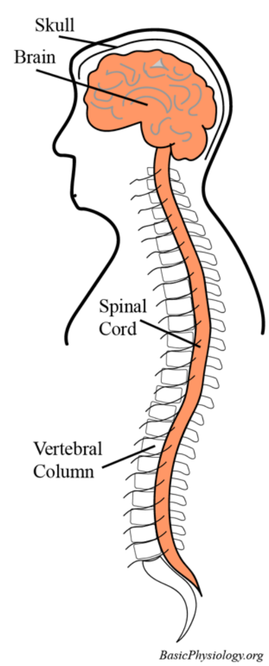
<tr>
<td>5.
The peripheral nervous system is the nervous system that connects the central nervous system to all the organs in the body (heart, blood vessels, muscles, glands, etc). It is called ‘peripheral’ because this system is located outside the central nervous system.</td>
<td rowspan="2">
</td>
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<tr>
<td>6.
The nerves in the peripheral nervous systems can be divided into two systems:
a) Afferent nerves: transport sensory signals from receptors in the body to the central nervous system.
b) Efferent nerves: transport signals from the central nervous system to peripheral effectors such as muscles, glands etc.</td>
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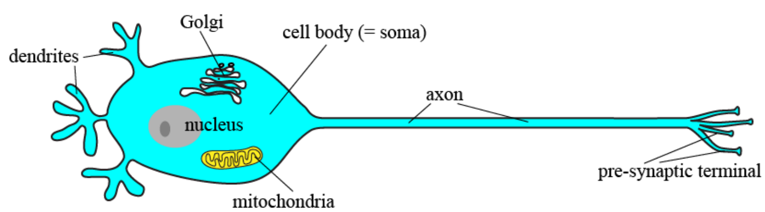
<tr>
<td>7.
The autonomic nervous system is a system that controls all kind of functions in our body such as blood pressure, respiration, digestion.</td>
<td>8.
This autonomic system can (also!) be divided into two parts:
a) The Sympathetic system
b) The Parasympathetic system</td>
</tr>
</table>

9. Although I will discuss this in more details later, one can say that the sympathetic system ‘stimulates’ local organs whereas the parasympathetic system has the opposite effect, makes them ‘quieter’.	

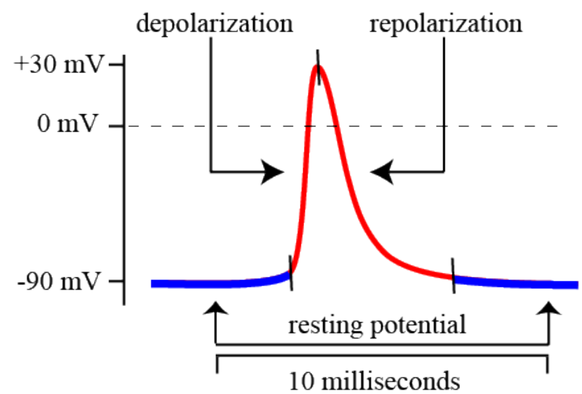
B. Nerve cells

1. What are the cells in the brain (and the spinal cord)? The most common cells are the nerve cells and the glia cells.	2. We already discussed the nerve cells, in some detail, in a previous chapter (<u>*The Nerve Cell A.3*</u>.) but I will summarize the major points here.
3. A typical nerve cell consists of the following **four** components: a. dendrites b. soma (= cell body) c. axon d. pre-synaptic terminals	4. The dendrites are structures that ‘receive’ signals from other nerve cells. The soma (=cell body) is where all the intracellular structures are located to keep the nerve cell alive (mitochondria, etc).
5. The axon (sometimes short, but in some nerve cells very long; > 1 meter!) is an elongated tube that transports the action potential to the other end of the nerve cell.	6. The pre-synaptic terminal is the ‘end’ of the nerve cell where the action potential can ‘jump’ to the next (nerve) cell.

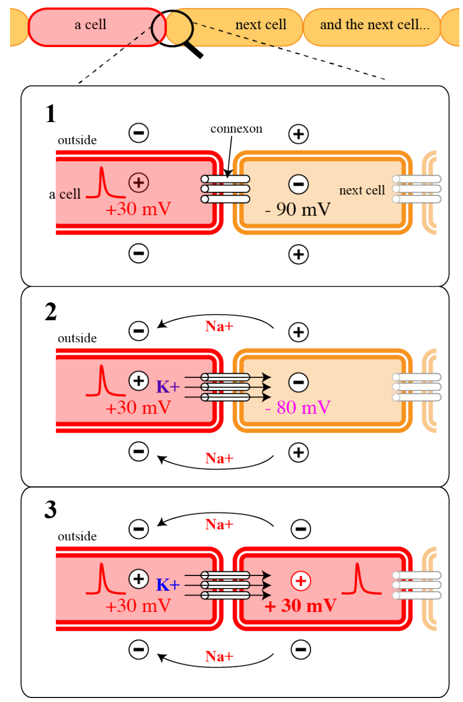
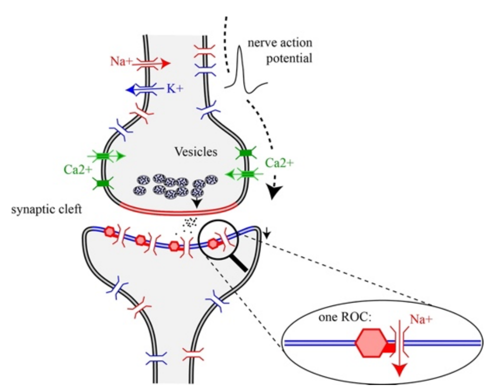


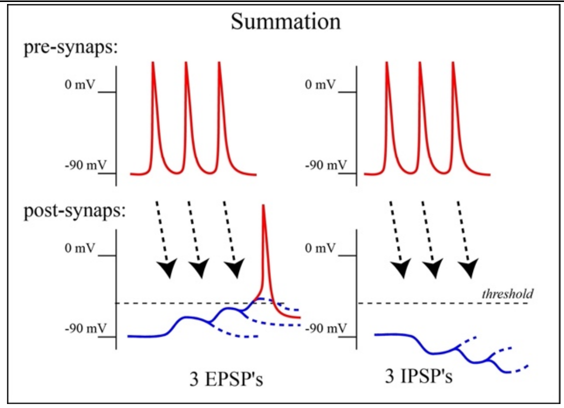
C. The Action Potential

1. The major function of a nerve cell is to produce and transport an action potential; which is an electrical signal. This is the signal that says “Hé, here I am!!”.	2. This action potential can be generated by electrical signals originating from neighbouring cells, that are connected to this cell by a synapse.

3. You may remember that at rest, a nerve cell displays a negative potential; typically, about -90 mV inside, compared to outside the cell (see *A.3.2. The Resting Potential*).	
4. When a nerve cell is stimulated, it produces an ‘action potential’. This is a sudden change in the potential, from -90mV to ±30 mV. This is called the ‘depolarization’.	5. But once the cell is depolarized, it quickly restores its negative potential, back to about -90 mV. This is called the ‘repolarization’.
6. In other words, the action potential is very short; only 5 to 10 milliseconds. A short but sharp signal!	7. Some of you may remember here that action potentials can last much longer, especially in (cardiac) muscles; up to 300 milliseconds! (*link*).
8. But what do we do with an action potential? Nothing, unless it is transported to another cell!	9. Once an action potential is generated, it can either be transmitted to another cell (a chain reaction) or initiate something else such as a muscle contraction, gland secretion, etc.

D. Action Potential Transmission

1. Transmission to another (nerve) cell can occur in two different ways: a) an electrical synapse b) a chemical synapse	
2. In this diagram of an electrical synapse, you can see that the two neighbouring cells are connected by small tubes, called ‘connexon’. These tubes allow the flow of intracellular ions such as potassium, to influence the potential in the neighbouring cells and initiate a new action potential.	
3. A chemical synapse is much more complicated, as you can see in this diagram. It consists of an interplay between the electrical signal, the function of a transmitter that has to diffuse through the synaptic cleft to the next cell, and the opening of new channels in that second cell. This all takes much more time than in the electrical synapse (about 1-4 milliseconds compared to 0,2 msec in an electrical synapse!).	

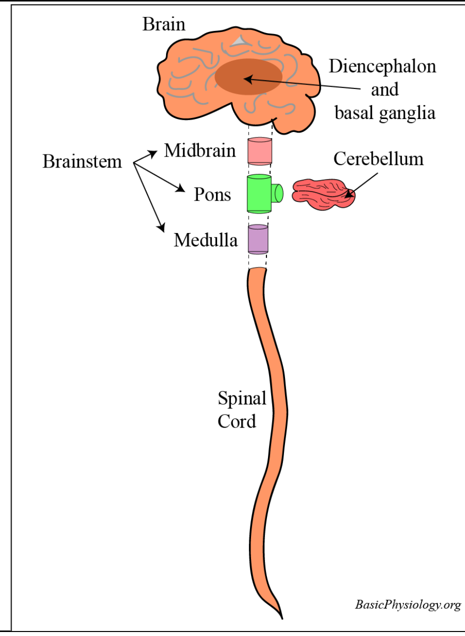
4. Furthermore, in contrast to the electrical synapse, the new signal is NOT an action potential but a small change in the post-synaptic potential.	
5. There are actually two different types of chemical synapses; an excitatory and an inhibitory chemical synapse, called an EPSP or IPSP.	
6. An EPSP (Excitatory Post Synaptic Potential) is a small depolarization in the past synaptic membrane. If several depolarizations are quickly initiated by incoming action potentials, then the threshold in the postsynaptic membrane can be reached and a new action potential is generated.	7. In an IPSP (Inhibitory Post Synaptic Potential) synaps however, incoming action potentials will shift the post-synaptic potential further away from threshold making this nerve cell less excitatory. In a certain sense, these chemical synapses function like positive (or negative) calculators! We shall discuss later why such ‘calculations’ are crucial to our mind and body.

E. Glia cells

1. Glia cells (also called neuroglia) are very different cells and their purpose is to support neighbouring nerve cells and their environment. They are (also) located in the central and peripheral nervous system.	2. There are several types of glia cells with different functions, all of which will be discussed later (*coming …!*)
3. Breaking news! Recently, a new system was discovered which describe and analyse the function of these glia cells; the **Glymphatic System**.	

H.2.1. Anatomy of the Central Nervous System

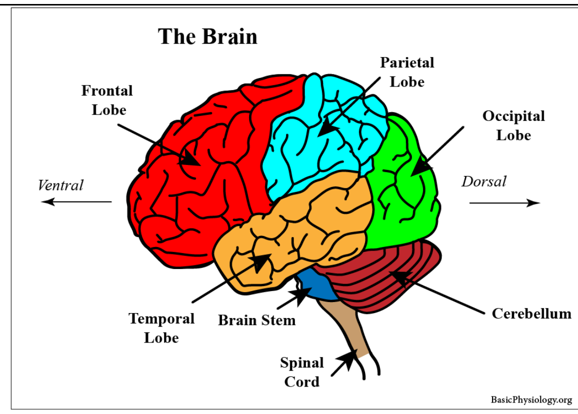
A. Introduction

1. The Central Nervous System consists of the brain and the spinal cord. The brain is contained (and protected) in the skull while the spinal cord is located in and protected by the vertebral column.	
2. The brain itself consists of the following components: a) The cerebrum (large brain) b) The cerebellum (small brain) c) The truncus cerebri (brain stem)	

B. The Brain (Cerebrum)

1. We will first discuss the various parts of the cerebrum. This is not an easy matter as the brain consists of several regions, each with a special function.	2. Because of all these functions, these regions have special names (which you will have to remember!).
3. Let's start with the major regions. As you can see in the picture, the front (anterior) part of the brain consists of the **frontal** region (also called frontal lobe). This is our cognitive region (memory, emotions, social interaction, motor control, etc).	

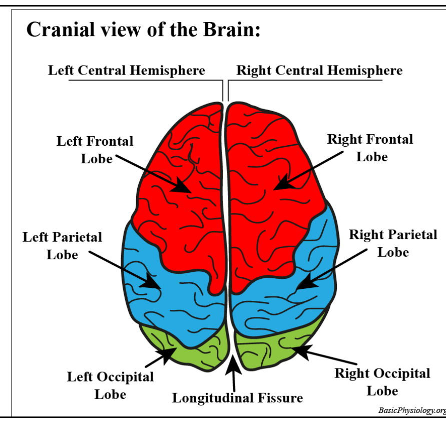
4.
Behind the frontal lobe is the **parietal** lobe. This centre collects information from several sensors such as touch and the position and movements of our body such as our arms, legs etc.



5.
Below the frontal and the parietal lobe is the **temporal** lobe. This lobe processes information from our sensors (ears, processing emotions, storing and retrieving memories).

6.
The **occipital** lobe, at the back of the brain, is the area where our visual information (obtained from the eyes) is processed, such as depth, colour, object and face determination and memory (again!).

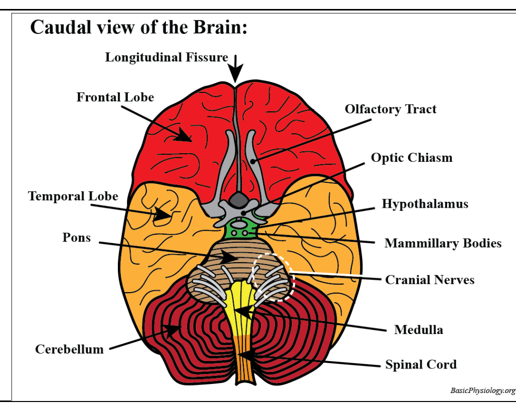
7.
In the adjoining diagram, you can now see the brain from above (= cranial). This shows that we have actually **two brains**; one right and one left! So, we actually have two frontal lobes, two temporal lobes etc!



C. Brain stem, cerebellum, spinal cord

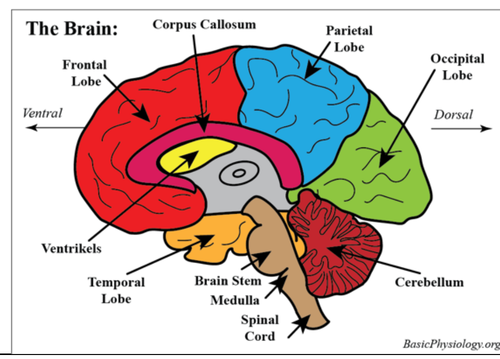
1.
Below the brain (cerebrum) there are three additional structures:

a. the brain stem
b. the cerebellum
c. the spinal cord

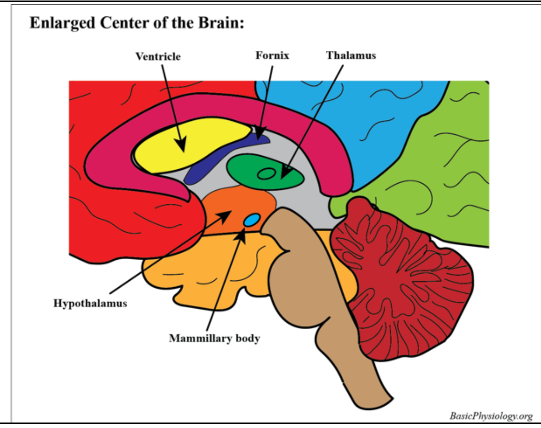


2. The **brain stem** is the structure that connects the brain (cerebrum) with the cerebellum and the spinal cord.	3. The **cerebellum** plays a major role in the regulation of our movements (= motor control) together with balance control (you don't want to lose your balance!).
4. The **spinal cord** is a huge relay station connecting our body, through the peripheral nervous system, to our brain (cerebrum, cerebellum and brainstem) (*see panel F*)	5. In addition, we also have the entry or exit points of quite a number of **cranial nerves**. On the diagram are shown: a) the olfactory (nose) tract b) the optical chiasm (the start of the optical nerve)

D. Middle Brain

1. After having seen the brain from the side, from above and from below, now is the time to cut the brain in half and see how it looks inside!	
2. Most of the structures seen from above or outside are also visible in this cross-section.	3. But at the 'bottom' of most lobes, there is a structure called 'corpus callosum', which, in turn, surrounds an internal area, in the middle of the brain.
4. The corpus callosum is an area where the nerve fibres connect the right and the left hemispheres (brains). Through these nerves the brain comminate info about our senses (vision, hearing, touch, taste and smell), about our movements and about our cognitive function (memory etc).	5. There are also additional centres located in the 'middle' of the brain such as: 1) the thalamus (relay centre of our senses) 2) the hypothalamus (keeps our body stable in temperature etc) 3) the fornix (part of the limbic system) 4) the mamillary body (part of the memory system

6.
And, finally, there is also space! These are the **ventricles**, which are filled with fluid. Adjacent to the ventricles are areas such as the thalamus, the hypothalamus, the mammillary body and the fornix. All these will be discussed at length in the Autonomous Nervous System (*coming…*).



E. Ventricular System

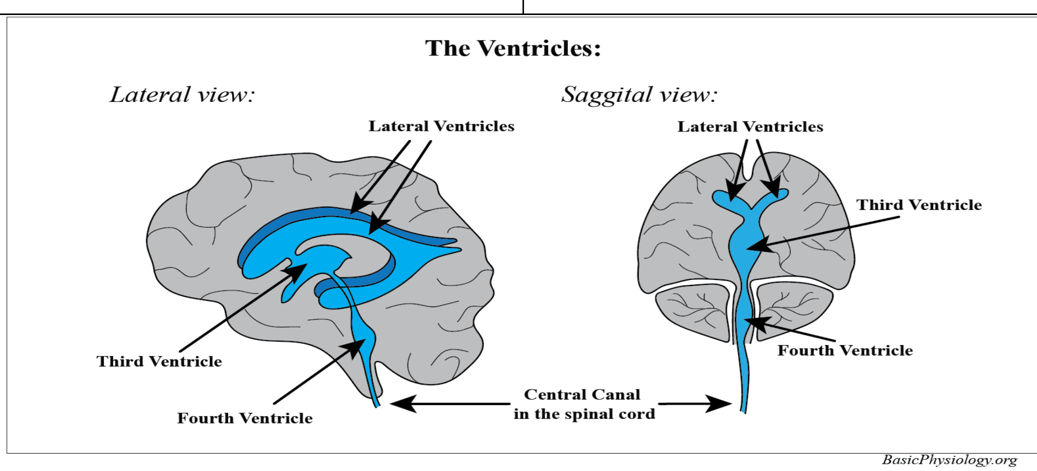
1.
The brain must be kept alive at all costs! There are several systems that provide the brain and the brain cells with oxygen, nutrients etc. The most important one is of course the blood circulation (which will be discussed *later*).

2.
But there are additional systems and one of them is the **liquor cerebrospinal system**. But for this system, several cavities and channels mut be present in the central nervous system.

3.
This system is termed the ventricular system (not be confused with the *ventricles* in the heart!).

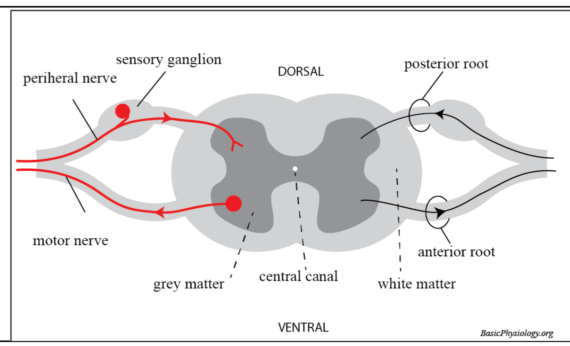
4.
The ventricular system consists of four ventricles (cavities) that are connected to each other:

a) Two lateral ventricles in the cerebrum (left and right)
b) A third ventricle located in the upper brainstem
c) A fourth ventricle located in the lower brainstem



5. These ventricles are connected through several canals. Below the fourth ventricle, starts the central canal that runs all the way down the spinal cord.	6. The liquor itself is produced by special cells located mostly in the wall of the fourth ventricle. From there it flows through the other cavities and through the arachnoidal space into the sinus sagittal, located in the dura matter which surrounds the brain.
7. The main function of the cerebrospinal liquor is to provide a fluid 'shell' around the cerebrum in which the brain can 'float'. This is important as it protects the brain tissue from internal damage when the skull is being hit by an object.	8. The second purpose of the liquor is to drain metabolic products from the brain tissue to the lymph circulation. Approximately 0,5 l liquor is being produced every day.

F. The Spinal Cord

1. Finally, we also need, in this introduction, to discuss the basics of the spinal cord.	2. As you may know, the spinal cord is where all the nerves run from the brain to the rest of the body or from the body back to the brain.
3. But it is not just a bundle of wires as in a telephone cable! It is much more organized which we will discuss, in some detail, here.	
4. In this cross-section of the spinal cord, you may notice two different shades of 'grey' on its surface; the 'white matter' and the 'grey matter'.	5. The grey matter, in the centre of the cord, consists mainly of the soma of the nerves; the cell bodies. Surrounding this grey matter, is the white matter, which is mainly caused by the myelin-sheath surrounding the nerve cables.

6. Remember the myelin-sheath? This is a sheath or a sleeve that surrounds and isolated an axon from its neighbours and thereby also increases the propagation of the action potentials in the axons (*see A.3.5. Saltatory Propagation*)	7. Since there are a lot of these ‘cables’ (= axons) running up or down the spinal cord, this are mostly located surrounding the central zone which makes this area more ‘whitish’.
8. Also note that from this white matter, some of these nerves may leave the spinal cord through the anterior roots to the body. These are usually motor nerves that will stimulate a neighbouring muscle.	9. On the other side of the roots are the posterior roots, which is the entry point for the sensory nerves, that conduct sensory information from various parts of the body to the brain.

H.2.2. Cranial Nerves

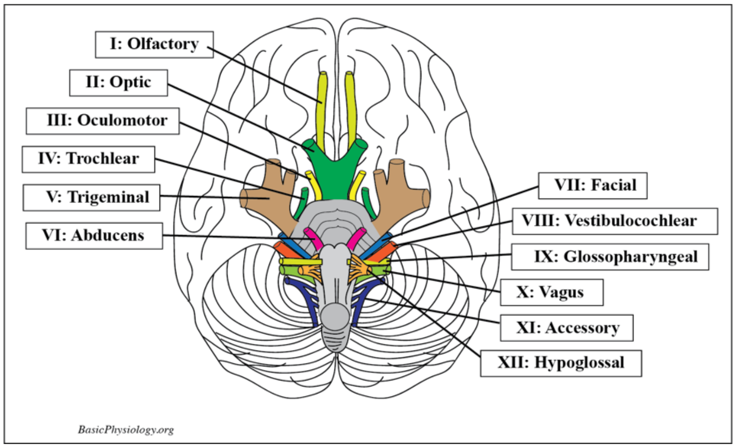
A. Cranial Nerves:

1. There are numerous connections between the (central) brain and the body but one of the most important ones are the **cranial nerves**.	2. As the name implies, these are nerves that come from the cranium (= skull), hence the name ‘cranial’.
3. There are **12** pairs of cranial nerves!	4. Pairs? Yes, every cranial nerve comes as a pair; left and right. So, in fact, we have a total of 24 cranial nerves.

5. These are the 12 cranial nerve pairs:

I – Olfactory nerve	V – Trigeminus nerve	IX – Glossopharyngeal nerve
II – Optic nerve	VI – Abducens nerve	X – Vagal nerve
III – Oculomotor nerve	VII – Facial nerve	XI – Accessory nerve
IV – Trochlear nerve	VIII – Vestibulocochlear nerve	XII – Hypoglossal nerve

6. Whew! That’s a lot! And, of course, we have to discuss them …	7. I drew a picture of all these nerves where they emerge from the bottom of the brain.



8. You don't have to remember all these structures (unless you want to become a cranial nerve doctor!).	9. The idea is just to show you how all these nerves come out of the bottom of the brain.

B. The function of all 12 cranial nerves; one by one!

I: Olfactory nerve:	This is a sensory nerve bundle that connects the sensory cells in your nose to the olfactory bulb in the brain.
II: Optic nerve:	This is a sensory nerve bundle that connects the light receptors in your eye (retina) to the visual cortex, located in the back of the brain.
III: Oculomotor nerve:	This is a motor nerve bundle, from the midbrain, to the eye (=oculo) that controls a) eye movements and b) pupil diameter
IV: Trochlear nerve:	This is also a motor nerve bundle, also from the midbrain, that controls the oblique movements (downward, out- and inward view) of the eye.
V: Trigeminal nerve:	As you can guess (=tri!); this cranial nerve consists of **three** separate bundles: a. Ophthalmic: sensory signals from the upper part of your face, around the eyes b. Maxillary: sensory signals from the middle part of your face, cheek and upper lip c. Mandibular: sensory signals from the lower part of your face, chin, lower lip and ears but also has a motor function of your jaw muscles and ear.

VI: Abducens nerve:	This is a motor nerve bundle that controls the outward movements of the eye (abduct= move away from the axis of the body).
VII: Facial nerve:	This nerve provides both sensory and motor functions such as: a. Contracting several muscles in the face and jaw b. Innervating glands such as the salivary glands and tears c. Innervating taste sensors in the tongue d. Sensory information from the skin of the ear
VIII: Vestibulocochlear nerve:	This nerve consists of two sensory parts: a. the cochlear part; sensory information about the sound from your ear b. the vestibular part; transmits information about your movements of your head
IX: Glossopharyngeal nerve:	This nerve consists of both sensory and motor functions: a. sensory information from the throat, from the sinuses in the skull and part of the tongue b. stimulating the stylopharyngeus muscles in your throat
X: Vagus nerve:	Contains also both sensory and motor nerves: a) sensory information from the ear canals b) sensory information from heart and intestines c) motor control of the throat muscles d) motor control of the intestines e) sensory information from the tongue
XI: Accessory nerve:	Motor nerve that controls the muscles in the neck
XII: Hypoglossal nerve:	Motor nerve that controls the movements of the tongue

C. What are the most important cranial nerves?

1. Whowww! That's a lot of nerves! Do we have to know all of them? **NO**.	2. Unless you want to become a cranial nerve specialist, most 'medical persons' only know/remember a few cranial nerves.
3. It depends very much on your speciality which nerves are really important, just like anything else in medical sciences.	4. For the basic physiologist, I have listed those nerves that are most prominent in our field.
content5. These are (in my mind) the most important cranial nerves: X: Vagus nerve II: Optical nerve I: Olfactory nerve	6. The vagus nerve (X) is so crucial to our body function that I have dedicated a special page for this nerve (*coming* ….).
7. The optical nerve (II) is also very important and quite complicated which necessitated another page! (*H.4.1. Vision*).	8. The olfactory nerve (I) is much simpler and easier but important too; therefore, another dedicated page (*H.4.4. Taste and Smell*)

H.3.1. Sensory Receptors

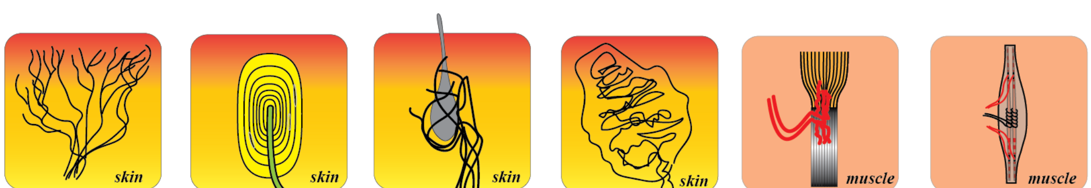
A. Introduction:

1. The sensory system starts with the detection of sensory stimuli such as temperature, touch, pain, taste, etc.	2. For this we need sensory receptors which are specialized in detecting a specific stimulus.
3. These receptors will then 'translate' the strength of the stimuli into nerve signals that are transmitted through nerves to the central nervous system.	4. There is a HUGE number of sensory receptors in our body (*millions* …). These can be classified into the following categories: 1) mechanoreceptors 2) thermoreceptors 3) nociceptors (noci = pain) 4) electromagnetic receptors (eye vision) 5) chemoreceptors (taste, oxygen level)

5. Interestingly, a receptor will only detect a specific type of stimuli, for example touch, but no other stimuli such as temperature, taste, vision, etc.	6. In this chapter we will discuss the first three types of receptors while the electromagnetic (in the eye – vision) and the chemoreceptors (taste, oxygen level, etc) will be discussed in other chapters (*H.3.3. Special Senses*)
7. All these stimuli are ‘translated’ by their receptors into a string of action potentials which are then conducted to the brain.	8. But if all these sensory feelings are transmitted into the same type of action potentials, how does the brain know which feeling is which “feeling” (pain, cold, or a brush of air)?
9. That is because the nerve of every receptor goes to a **specific site** in the brain. Each site is dedicated to that particular “feeling”.	10. If for some reason this specific site is stimulated in another way, by an external stimulus for example, then we would still feel that particular “feeling”.

B. Types of receptors:

1. Because there are so many types of receptors, we will only discuss a few, hopefully the most important ones!	2. Many of these receptors are located in the skin, or in (skeletal) muscles but there are also sensors in other parts of the body such as pressure receptors in the blood circulation, oxygen receptors in the lungs, etc.



free nerve endings — Pacinian corpuscle — tactile hair ending — Meissner’s corpuscle — Golgi tendon apparatus — Muscle spindle

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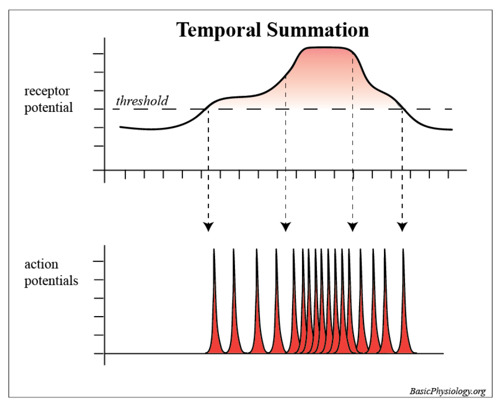
3. We will start with the “**free nerve ending**” which is the most common receptor in the skin. These nerve endings detect “dangerous” signals which are most often perceived as pain (“ouch!”).	4. Another ‘famous’ receptor is the **Pacinian corpuscle** (discovered by Pacini in 1835 and by other scientists) which detects pressure and vibrations. These receptors are located in the skin but also in internal organs such as the breast, genitalia, joints etc.

5. Then we also have the **hair follicles** (= tactile hair ending) that can detect small movements along the skin such as soft touch, or a breath of air.	6. The **Meissner corpuscle** (discovered by Meissner; very good!) detects pressure and vibrations when applied to the skin. There are especially many of them in the skin of our fingers.
7. I have also added in this list two types of receptors located in skeletal muscles; the **muscle spindle** and the **Golgi tendon apparatus**.	8. The functions of these receptors are discussed in *H.4. Motor System*.

C. Temporal and Spatial Summation:

1. As you have seen in panel A, sensory information is transmitted to the brain tissue by means of action potentials. That's all, there is no other way.	2. Interestingly, there are several ways in which these action potentials are transmitted to convey extra information to the brain about what the receptors are sensing.
3. One way is to relate the strength of the stimulus to the number of action potentials transmitted; **temporal summation**.	
4. In this mechanism, the strength of the stimulus is translated into a potential in that sensory organ. That receptor potential in turn can then, if it is higher than the threshold, initiate action potentials in the efferent nerve.	
5. What is clever about this mechanism is that if the stimulus strength is increased, then the receptor potential also increases which, in turn, increases, the number of transmitted action potentials.	6. In this manner, the brain does not only know that a stimulus has been detected but also how strong it is!

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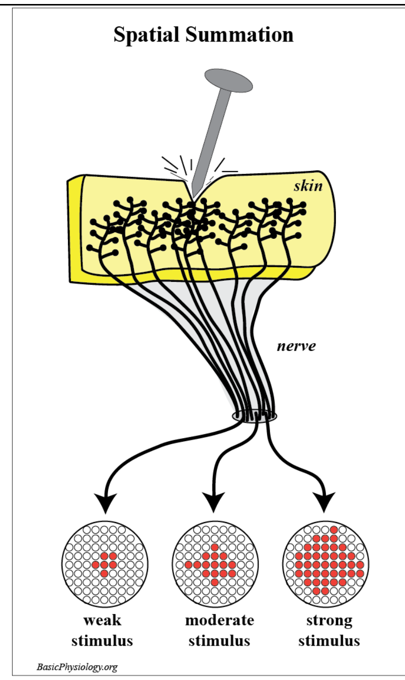
<tr><td>7.
Another way to transmit ‘more’ info to the brain is by spatial summation.</td><td rowspan="3">
</td></tr>
<tr><td>8.
As shown in this diagram, a pin induces a ‘painful’ pressure in the skin which is perceived by the free nerve endings that serve as pain receptors.
As there are many free nerve endings in the skin, each with their own axon, then a stronger stimulus, which induces a larger depression, will induce action potentials in more neighbouring axons.</td></tr>
<tr><td>9.
And so, again, the brain gets more information with this spatial summation of active efferent nerves.</td></tr>
</table>

D. Neuronal Pools:

1. But there are even more clever ways to relate more information to the brain. In a way, it seems we have micro-chips implanted in our nervous system!	2. In many parts in the brain, nerves connect together to form several kinds of “loops”. This may for example increase the number of action potentials.
3. Diagram A shows the simplest example, a kind of a feed-back loop in which the axon of a nerve sends a loop back to its own cell body though a second synapse.	4. In the diagram, the synapse is labelled excitatory which means that the cell has become more excitable for future excitations.
5. But the synapse could also have been “inhibitory’ which would make this cell temporarily less excitable.	

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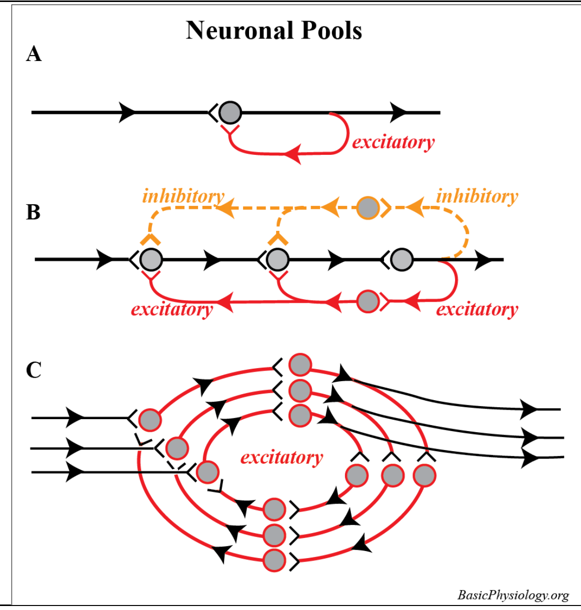
<tr><td>6.
Diagram B shows a more complex set of neurons containing both excitatory loops and inhibitory loops.</td><td rowspan="3">
</td></tr>
<tr><td>7.
Diagram C shows an even more complex system in which a simple action potential may trigger a series of new action potentials.</td></tr>
<tr><td>8.
In other words, neuronal loops can be very complicated!</td></tr>
</table>

E. Types of Senses:

<table>
<tr><td>1.
Unfortunately, medical/physiological literature is sometimes confusing by using different terms to describe our sensory system.</td><td>2.
In this chapter, we have used the following classification:
a. mechanoreceptors
b. thermoreceptors
c. nociceptors
d. electromagnetic receptors
e. chemoreceptors</td></tr>
<tr><td>3.
But here is another classification system:

1. exteroreceptive sensations – from the surface of the body
2. proprioceptive sensations – position sensations (from muscle and tendons), pressure sensations, equilibrium
3. visceral sensations; from the viscera of the body (internal organs)
4. deep sensation – deep tissues such as fasciae, muscles, bones</td><td>4.
You may choose your own system!</td></tr>
</table>

H.3.2. Sensory Pathways

A. Introduction:

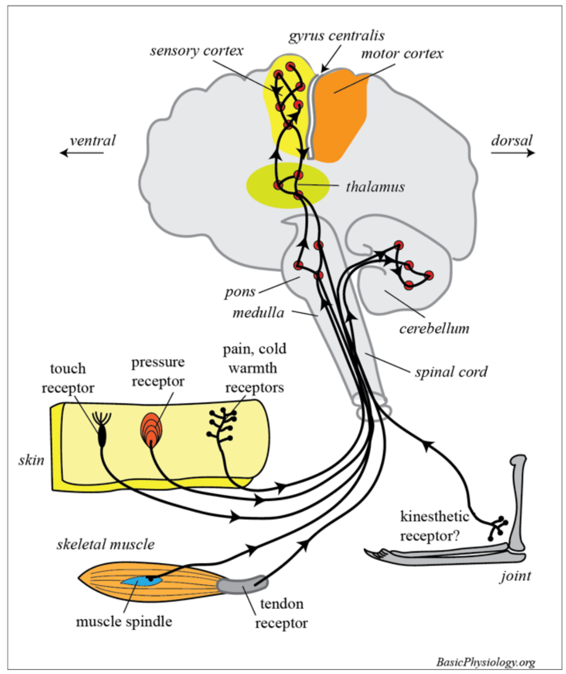
1.
As you can imagine, the sensory part of the brain is the system that ‘senses’ all kind of sensory experience from the outside world and transmits that info to several regions in the brain.

2.
In the previous chapters, we already discussed several types of receptors involved in the detection of several senses.

3.
This sensory information can cause many different reactions; from immediate action to long term storage in our memories.

4.
Also be aware that all this info does not need to go all the way to our ‘upper’ brain. Much of this info will also excite other levels of our brain, even in our spinal cord (as we shall see later).

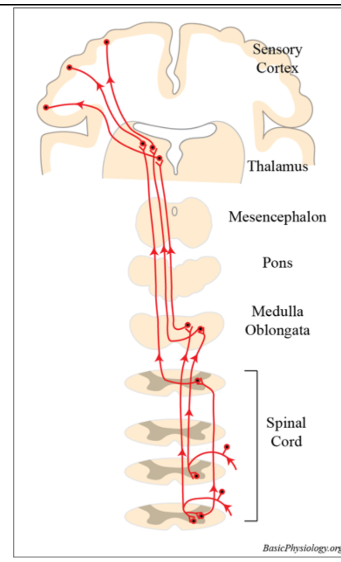
5.
The diagram shows the major pathways of our sensory system. As you can see, the sensory nerves first go to and trough the spinal cord before reaching the brain. There it becomes very complicated as it travels through various parts of the brain such as the cerebellum, the pons, medulla to finally end in the sensory cortex.



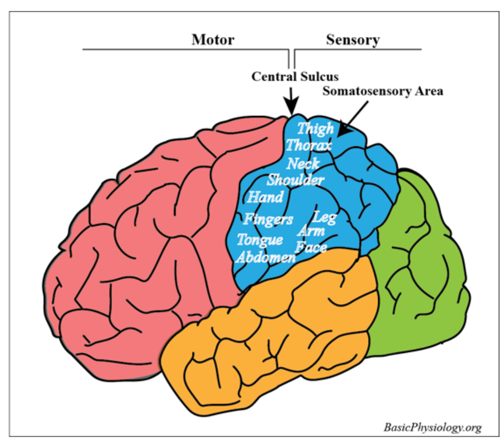
B. Spinal Cord:

1.
When the sensory nerves enter the spinal cord through the dorsal root, it immediately splits into several branches.

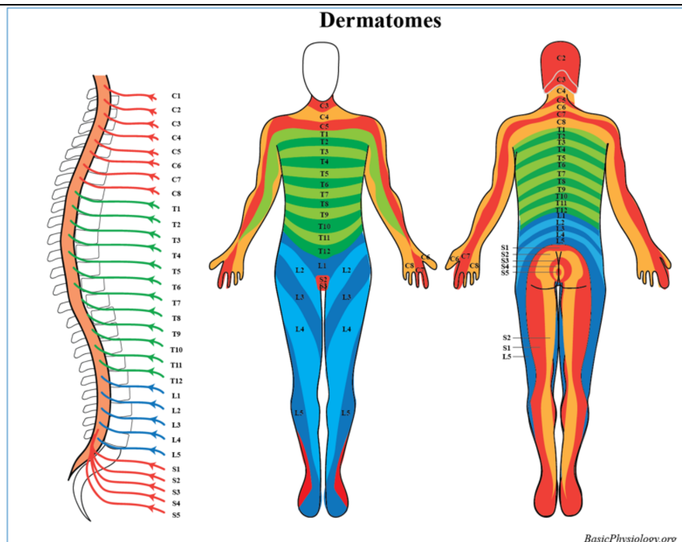
2.
Some of these branches move to the dorsal side of the spinal column and then upward in a dorsal column all the way to the brain.

<table>
<tr><td>3.
Another branch enters the dorsal horn and there divides into several (many!) branches that connect to local neurons. Hey thereby form all kinds of local neuronal circuits.</td><td rowspan="2">
</td></tr>
<tr><td>4.
Some of these fibres induce local spinal cord reflexes. Other fibres move up the spinal cord to end in the cerebellum.</td></tr>
</table>

C. Cerebral Cortex:

<table>
<tr><td>1.
But the most “important” fibres go straight to the cortex of the large brain; the cerebral cortex.</td><td rowspan="3">
</td></tr>
<tr><td>2.
And, they end up in a special ordained region, depending upon from which area of the body they came from.</td></tr>
<tr><td>3.
As shown in the diagram, specific regions, show which areas receive impulses from the thigh region, or from the thorax, of, more specifically, from the fingers, the tongue or the face, etc.</td></tr>
<tr><td>4.
In other words, although all these action potentials are similar on the way to the brain, they, depending where they came from, all go to specific areas.</td><td></td></tr>
</table>

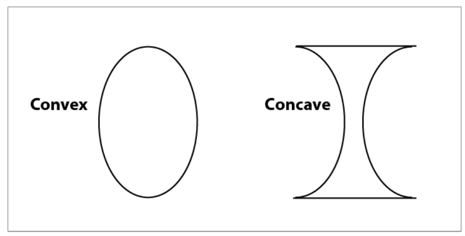
D. Dermatomes:



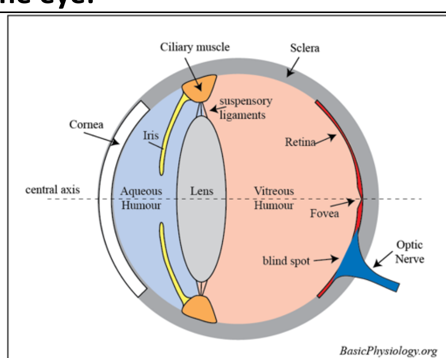
1. There is another interesting concept which is very popular in physiology and medicine in general; the **dermatomes**; see diagram. (*dermis = skin*)	2. It is actually not that important but probably popular because of this beautiful picture of a human with all these coloured stripes, as seen from the front and the back.
3. This actually refers to the fact that the sensory endings in the skin, especially the taste sensors, are connected, through a long list of afferent nerves, to the spinal cord and finally to the brain cortex.	4. Depending on the location of the skin sensors, the efferent nerves will enter the spinal cord through the space between adjacent spinal vertebrae.
5. If something happens in a particular region (cancer, trauma, whatever) or in the nerve bundle that runs to the spinal cord, then this could disrupt the transport of signals from that particular area of the skin to the brain.	6. This disruption can cause local pain, rash, or other sensory problems.
7. You may notice that some areas, such as the face, are not coloured in this diagram. That’s because their innervation is quite complicated.	8. In reality, the boundaries of the dermatomes are not as ‘sharp’ as suggested by the diagram but nevertheless, nice to know and to visualize.

Vision H.3.3.1.a: The Eye

A. **Optical terms and concepts:**

1. Before we start ‘learning’ about the eye and vision, we need to ‘remember’ some basic terms and concepts:	**2.** Here are some of these terms: A: Reflection <-> Refraction B: Convex <> Concave C: focal line, focal point, focal length
3. and … D: Convergence, Divergence E: refractive power = Dioptre (=D) (1 Dioptre = 1-meter focal length) F: positive “+” lens -> convex negative “- “lens -> concave	4.  If you don’t know or remember these terms, you will have to study some basic physics! Sorry!

B. Functional Anatomy of the eye:



Sclera: the outer 'skeleton' of the eye.	**Cornea**: the transparent window into the eye.
Lens: provides for a variable refraction.	**Ciliary muscle**: provides for changes in lens curvature.
Aqueous Humour: fluid in front of the lens that provides for the intra-ocular pressure.	**Vitreous Humour** (or body): provides for a transparent gel mass between lens and retina.

Retina: contains the photoreceptors that are sensitive to the light and the nerve cells that communicate to the optic nerve and the brain.	**Optic Nerve**: nerve bundle (= cranial nerve II) that connects the retina to the occipital cortex in the brain.

C. Accommodation of the eye 1:

Accommodation occurs when the eye changes the shape (curvature) of the eye to focus on objects close to or distant from the eye

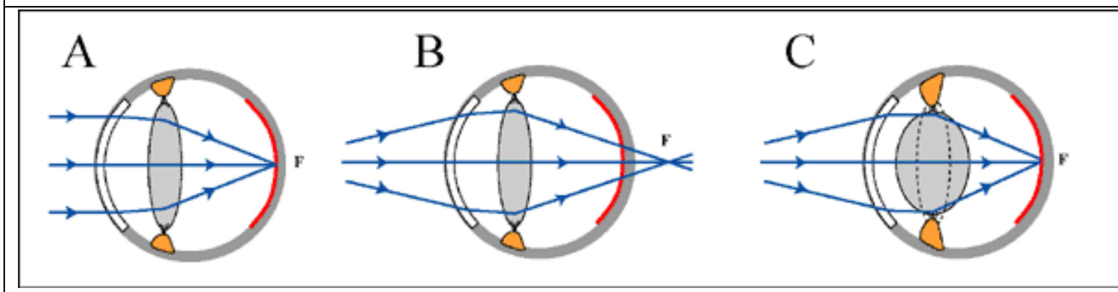


Fig A. The eye is not accommodated. In this situation, when the light travels in parallel rays, from far away, then the focus will fall on the fovea.	**Fig B. When the light rays diverge,** because the image is close to the eye (for example when one is reading), then, if nothing changes, the focus will fall behind the fovea, and the picture will be unclear.	**Fig C. Accommodation.** To move the focus towards the fovea, the curvature of the lens must become more convex. This will increase the refraction of the lens and the light rays will converge on the fovea.

D. Accommodation of the eye 2:

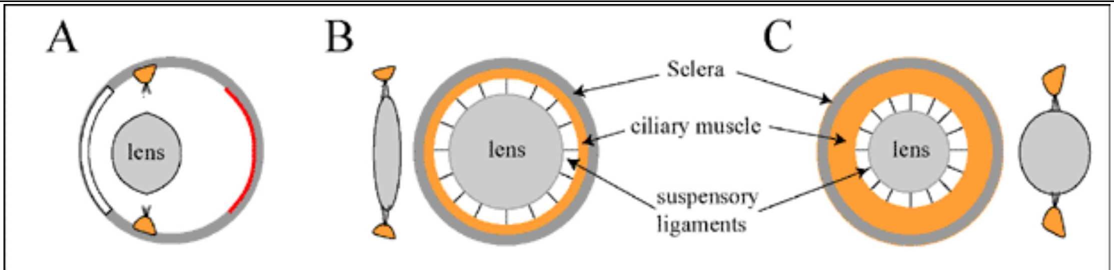
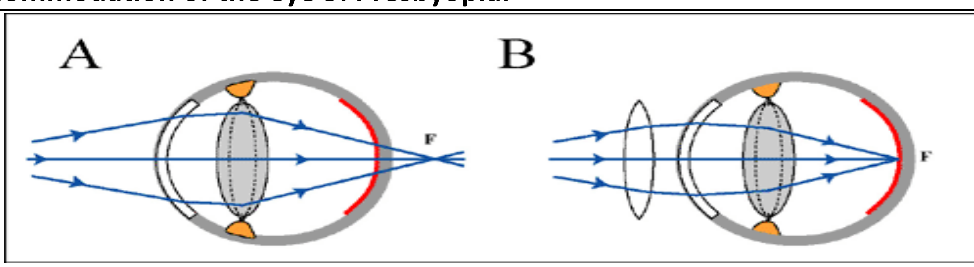


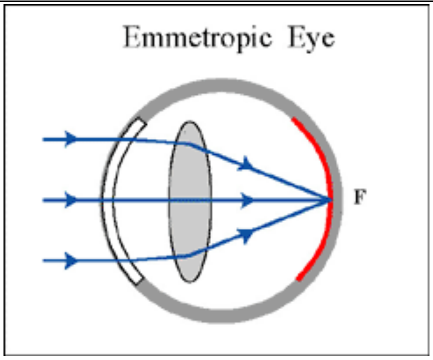
Fig A. The natural recoil of the lens.	Fig B. Non-accommodated.	Fig C. Accommodation.
The lens, by itself, when cut of from the suspensory ligaments, is very convex (close to a sphere). It is, in the eye, stretched by the suspensory ligaments and the ciliary muscle into a thinner and lesser convex lens.	In this situation, the ciliary muscle is resting and stretches the ligaments, thereby also stretching the lens into a less-convex shape. This is the situation when looking far away.	When the lens has to accommodate (=reading), then the ciliary muscle contracts, the 'hole' in the muscle becomes smaller, the suspensory ligaments move towards the centre, and this allows the lens to become more convex.

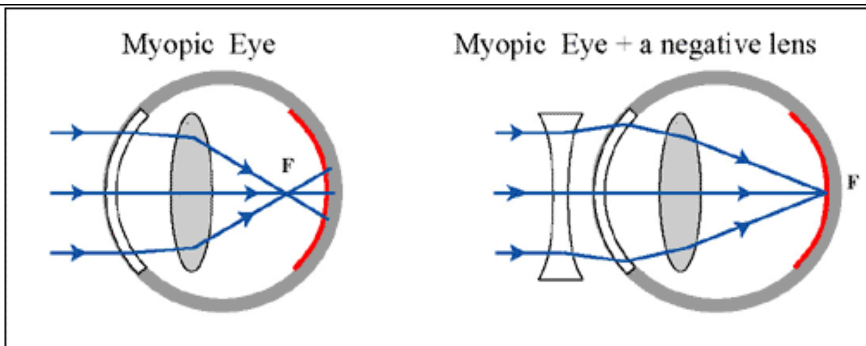
E. Accommodation of the eye 3: Presbyopia.

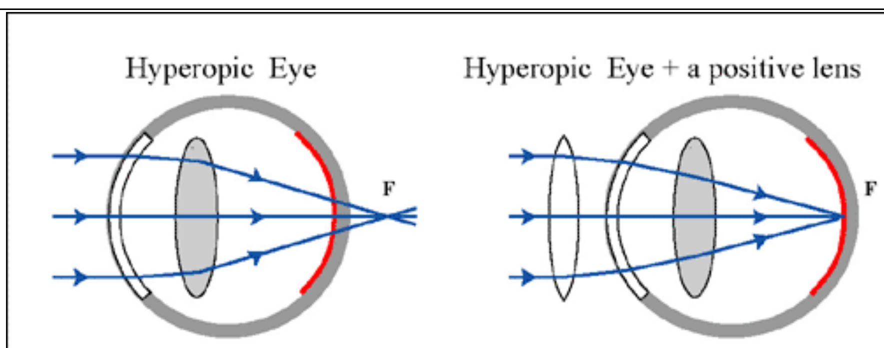


Presbyopia.	Fig A. Maximum accommodation.	Fig B. Reading lenses.
In some eyes, especially in older people, the elasticity of the eye has decreased and the lens is no longer as convex as before.	In that situation, a maximum accommodation (= contraction of the ciliary muscle) will still not be able to move the focus to the fovea and the image remains blurry. This situation is called **presbyopia**.	This situation can be helped by using reading lenses, which are convex lenses (positive "+" lenses). They help in breaking more the diverging light rays to focus the light rays on the fovea.

F. Major Refraction Anomalies: Myopia and Hyperopia.

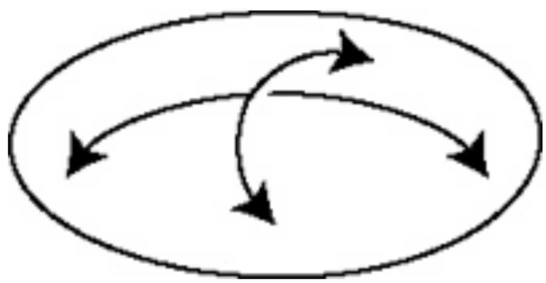
	In an **emmetropic** eye, light rays from far away (thereby creating parallel light rays) fall on the fovea. These patients do not need glasses to look far away.

	
In a **myopic** eye (=myopia), light rays from far away fall in front of the fovea. To the patient, the image looks blurred. The solution is to provide the patient with a concave ("-") lens.	**Note** that such a person can look sharp at images close to the eye (like reading) as this will move the focus towards the fovea. That is why these people are called "near-sighted"

	
In a **hyperopic** eye (=hyperopia), parallel light rays will fall "behind" the retina. To	**Note** that these patients can (and do) help themselves by accommodating their

help these patients, a convex ("+") lens is required which will help 'break' the light rays more.	lens. This will also move the focus onto the fovea. They do this automatically and therefore often they don't know that they have a refraction anomaly. They are therefore called "farsighted". They will often complain of headaches or tiredness as their ciliary muscle contracts all the time.

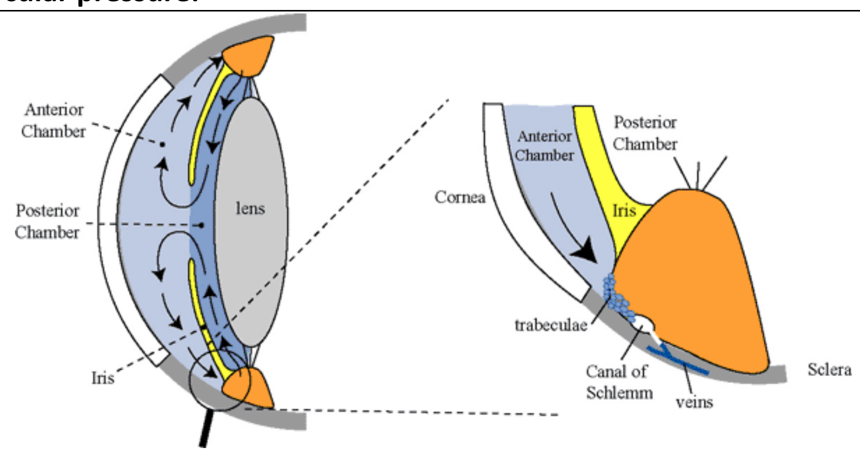
G. Astigmatism:

1. In the previous refraction anomalies (myopia and hyperopia) the curvature or the bending of the lens was the same at all angles. In some patients however, the degree of curvature is different between two (or more) different angles. In the diagram, this is illustrated by a flat convex lens that is more curved from top to bottom then from left to right. An exaggerated example of such a curvature is the surface of an egg; more curved in one direction then in another.	
2. The consequence of astigmatism is that there is not one focal point but several, located between one extreme and the other. Such patients require specially designed lenses in which the curvature of the lens is adapted to their astigmatism. This can be seen in some lens prescription as follows: +1.5 D at 100 degrees and +0.5 D at 45 degrees.	

H. Cataract

 A normal eye; the pupil is black.	**Cataract**: In some patients, the lens becomes, gradually, less-transparent. There are many reasons for this to happen including metabolic diseases, congenital or old age. Because the lens becomes gradually less transparent, the patients will see the images more and more blurred. The therapy is to remove the lens and to replace it with a new artificial intra-ocular lens.	 **Cataract**; the pupil is cloudy or 'milky'

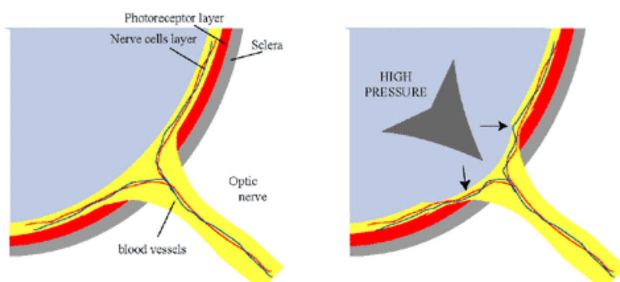
I. Intra-ocular pressure:



Anterior and Posterior Chamber:	**Intra-ocular circulation 1:**	**Intra-ocular circulation 2:**
The space between the cornea and the lens is filled with a fluid (= the aqueous humour). The iris divides this fluid in two spaces; a **posterior** and an **anterior** chamber (chamber = room).	The ocular fluid is secreted by the ciliary body into the posterior chamber. From there, it flows through the pupil (= the opening between the iris), into the anterior chamber. There, it flows back into the corner between the sclera, the base of the iris and the ciliary body.	In this (narrow) angle there are trabeculae that filter the fluid into a canal (= canal of Schlemm) which, in turn, drains into a local vein.

Intra-ocular circulation 3:	**Intra-ocular pressure:**
In this manner, fresh fluid (with nutrients etc) is constantly flowing through the anterior part of the eye and, by diffusion, through the lens and the vitreous body towards the retina.	This also provides for a small pressure in the eye of about 5-10 mmHg. This keeps the eye in the shape of a ball and all its internal structures (lens etc) in place. If the pressure were too low, then the eyeball would collapse and vision becomes blurred.

J: Glaucoma:

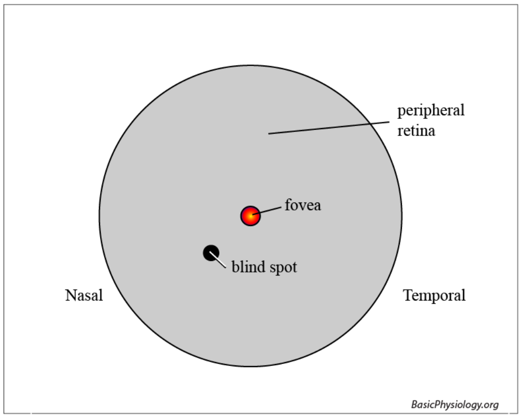


Glaucoma 1:	**Glaucoma 2:**
If the pressure gets too high (=glaucoma), then another danger arises. A too high pressure (> 20 mmHg) will impede or block blood flow through the optic nerve. These vessels are crucial as they perfuse the retina.	If the perfusion is stopped, the photoreceptor cells will become ischemic (= no blood) and die. The person will become blind.

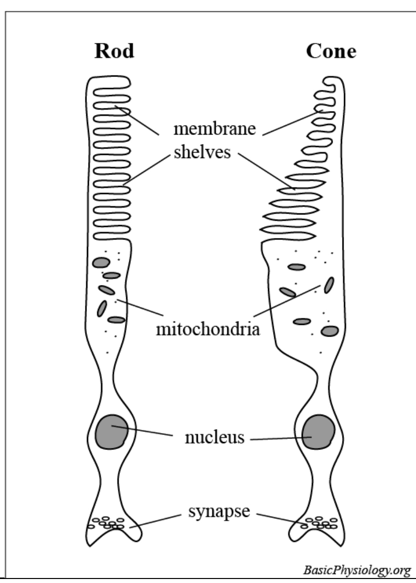
Glaucoma 3:
An acute glaucoma (pressures 70-80 mmHg) can occur if there is an obstruction of the flow to the canal of Schlemm. A chronic glaucoma (pressures 20-30 mmHg) occurs when the obstruction is limited.

Vision H.3.3.1.b. The Retina

A. The Retina:

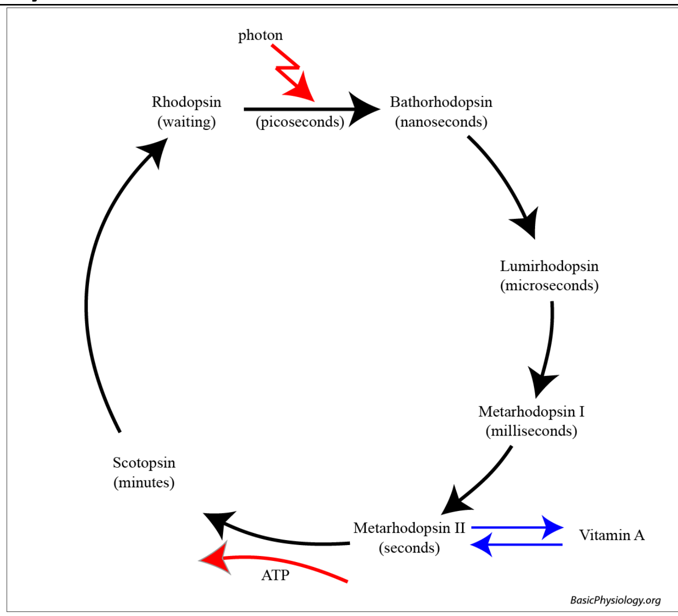
	The **retina** consists of: the **fovea**: located in the centre. This is a very small area (< 1 mm^2) that contains three types of **cone photoreceptors** (for red, green and blue). This small area provides for sharp and colour vision. (*memory trick; cone = colour*) the **peripheral** retina which contains only rod photoreceptors. These rods only sense black and white but are more sensitive than the cones. There is also a **blind spot**, located in the inferior and nasal quadrant of the eye where the optical nerves exit the eye on their way to the brain.

B. The Photoreceptors:

	**Photoreceptors**: Both types of photoreceptors (rods and cones) share the same plan: 1. At one end is a stack of "shelves" which are really infoldings of the plasma membrane. These shelves contain millions of photo pigment molecules (such as rhodopsin). 2. The second part (or segment) contains the molecular machinery for the cell (mitochondria etc). 3. The third part contains the nucleus 4. At the other end is the synapse that connects the receptor cell to other nervous cells in the retina.

	The **difference** between the two cells is that in the **rods**, the shelves are of the same size whereas in the **cones**, the shelves diminish in size further away from the cell body, hence its shape and its name.

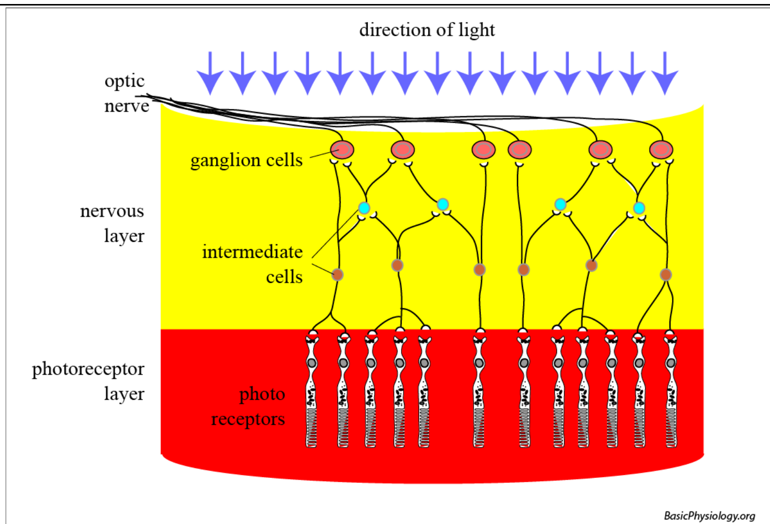
C. The Rhodopsin cycle:



1. Rhodopsin:	**2. Excitation**:	**3. Unstable**:
this is the molecule that is waiting on the shelves to be excited by a passing photon. In a normal situation, there will be millions of rhodopsin waiting.	Once excited by a light ray, the collision with the photon will cause one chemical bond in rhodopsin to change from a -trans to a -cis configuration. This is very fast. This molecule is now called bathorhodopsin (*the names are not really important here*).	This new molecule is very unstable and changes spontaneously into the next molecule, lumirhodopsin, which is still unstable and changes into the next (metarhodopsin I) which finally stabilizes as metarhodopsin II.

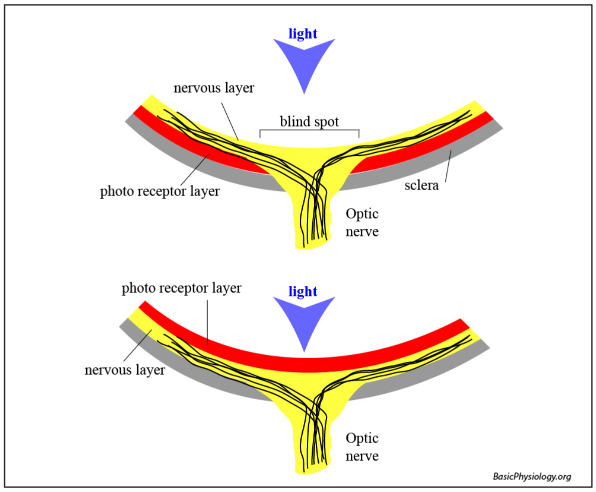
4. Delay:	5. Restoration of Rhodopsin:	6. Vitamin A:
All these spontaneous transformations also take sequentially more time (from pico- to micro- to milliseconds). This is necessary for the metabolic processes in the cell (which takes milliseconds) to react to this excitation.	The final stable meta-rhodopsin II is converted through scotopsin back to rhodopsin. This takes time (minutes) and energy (ATP).	The rhodopsin molecules are derived from vitamin A. If there is not enough vitamin A (deficient diet) then the person becomes gradually less sensitive to light (night blindness).

D. Cross-section of the Retina:



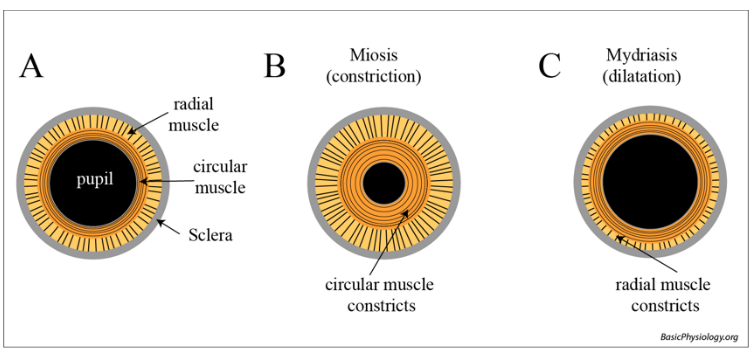
The retina has **two** layers: **a.** the **photoreceptor** layer: which consists of rods (shown in this diagram) or cones. **b.** the **nervous** layer: the receptor cells do not connect immediately to the brain cells. Instead, they interconnect with other nerve cells. These **intermediate** cells already process the signals before communicating with the ganglion cells. The axon of the ganglion cells then combines to form the **optic nerve**.	Note that the direction of light is **opposite** to what you would expect. The light rays have to go through the (thin) nervous layer before reaching the photoreceptors.

E. The Blind Spot:

<table>
<tr>
<td rowspan="2">


</td>
<td>1.
The blind spot is located where the axons from the ganglion cells leave the eye ball. Because the nervous layer is on top of the photo-receptor layer, the nerve has to go through this photo receptor layer to reach the sclera and leave the eye. Therefore, at that site, the photoreceptor cell layer is interrupted, hence the '"blind" spot.</td>
</tr>
<tr>
<td>2.
Note that if the photo receptor layer had been at the other side of the nervous layer, and in front of the light rays, that then, there would have been no blind spot!</td>
</tr>
</table>

F. The Iris and the Pupil:

<table>
<tr>
<td colspan="3">


</td>
</tr>
<tr>
<td>The ciliary muscle

also controls the iris and therefore the size of the pupil. It actually consists of two muscles; one outer muscle which is oriented in the radial direction and a second inner muscle that is oriented in the circular direction.</td>
<td>Miosis:

When the circular muscle contracts, the hole (= pupil) within the muscle becomes smaller. This works like a sphincter that you can see in other parts of the body (in the gut or the blood vessels for example).</td>
<td>Mydriasis:

is the opposite action (dilatation of the pupil) which is caused by contraction of the radial muscle. This happens in dim light allowing more light into the eye.

This contraction is controlled by the</td>
</tr>
</table>

	This is actually a famous reflex (**pupillary light reflex**) that doctors often use when shining a bright light into the eye to check whether the patient is still alive. This reflex is controlled by the **parasympathetic** nervous system.	**sympathetic** nervous system.

G. Adaptation of the eye to light or dark:

Chemical Adaptation:

Dark adaptation: When you step from a bright room into a dark one, then initially, sensitivity to vision is much reduced. But with time, the eyes become more sensitive and one sees better in the dark.	**Light adaptation:** is the opposite of dark adaptation. When you step from a dark to a bright room, then all the rhodopsin molecules will be activated.
This is because, when you stepped from the bright room, a lot of the rhodopsin had been activated and were being used in the cycle. These molecules were therefore not available to pick up the few photons in the dark room.	In fact, one may be even very insensitive to light (=blind) as all the rhodopsin have suddenly become unavailable (= refractory) but in time, one can see again, but at a reduced sensitivity.
But with time (up to minutes), the molecules revert back to the rhodopsin shape and the amount of rhodopsin molecules increases. This makes the eye more sensitive.	

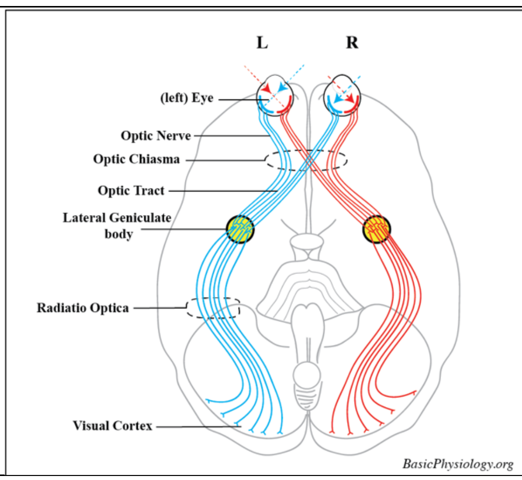
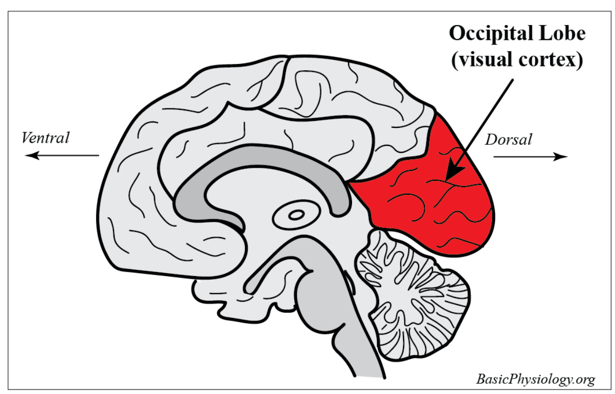
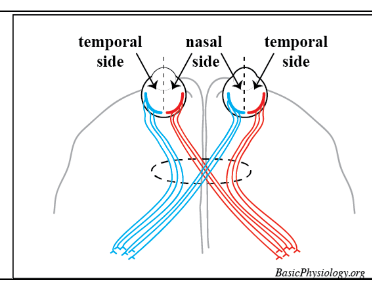
Pupillary Adaption:	
Dark adaptation: The pupil dilates (with the radial fibres) to allow more light into the eye (sympathetic reflex).	**Light adaptation:** The pupil constricts (with the circular fibres) to reduce the amount of light into the eye (parasympathetic reflex).

H. Central and Peripheral Vision:

Central vision:	**Peripheral Vision:**
This is the vision as captured by the **fovea**. Most of the photoreceptors in the fovea are **cones** and practically every cone has its own nerve to the brain. Therefore, the image is sharp and in colour. The whole eye is built to project the image sharp (in focus) onto the fovea.	The remainder but largest part of the retina is covered by the rods, which are light sensitive but not colour sensitive. In fact, the rods are more light-sensitive than the cones. For example, at night when you are outside, and you look at a faint star, you may see it better when you don't look at it straight but at a slight distance from the star.
Warning System: The rods in the peripheral retina, and the nervous system attached to them, are especially sensitive to **movements**. Therefore, when something moves, in the "corner" of the eye, it attracts our attention; we turn our eye towards the source of the movement and see it sharp and in colour.	**Tunnel Vision**: In some patients, who have their peripheral vision destroyed, the lack of a peripheral vision is striking. They can still see clearly and in colour with their fovea but they are often involved in road accidents, as they have not seen other cars moving into their path from other directions. They lack an early warning system. (Chronic glaucoma for example).

H.3.3.1.c. The Optic Nerve

A. Anatomy of the Optic Nerve.

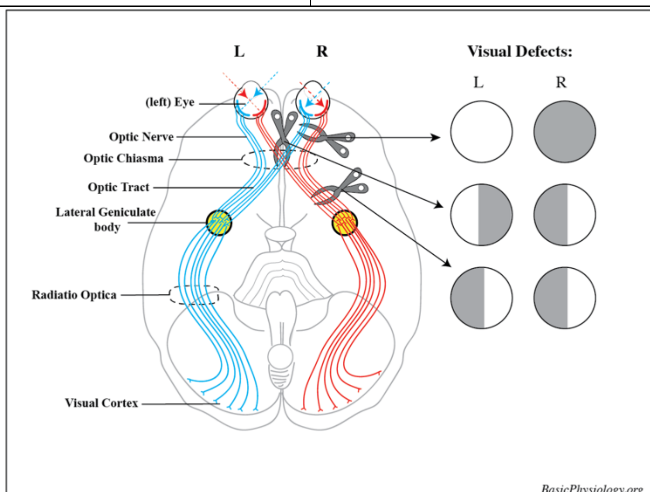
1. As you can guess, the optic nerve connects the retina of the eye to the brain.	2. As light excites the retina cells in the eye, action potentials are then transported through the optic nerves to the brain so that you become aware of what you see!
3. But this connection between the eye and the brain is not as straightforward as you would expect.	4. As you can see in the diagram, the connection depends upon whether the nerve originates from the right side or the left side of the retina…
5. At first, all the nerves from the retina propagates as bundles, called the optic nerve, underneath the brain towards a central location, called the **Optic Chiasma**.	6. In this chiasma (= intersection or cross-over) something strange happens! All the nerves from the inner side of the retina cross-over to the other side while the nerves from the outer side of the retina do not cross but stay at the same side of the brain!
	
7. The inner side is called the 'nasal' side of the retina (closer to the nose) while the outer side is called the 'temporal' side of the retina.	

8. Why do these nerves cross-over like this? Nobody knows! But is, unfortunately for students, a fact.	9. Therefore, from this chiasma, the optic tract (as it is now called), contains, at the left side, information collected from the ‘right’ side of both eyes, and the opposite happens in the right optic tract.

10.
After this tract, the nerves connect to a second set of nerves, one by one, in the lateral geniculate bodies, and form the nerves that travel to the optic (also called visual) cortex.

B. Visual defects

1. Why is all this important? When something happens in this region of the brain, it depends on the location of the event (cancer, trauma etc) what happens to our visual perception!	2. Therefore, I plotted, in the diagram above, a scissor at three different locations along the optic nerve and tract.

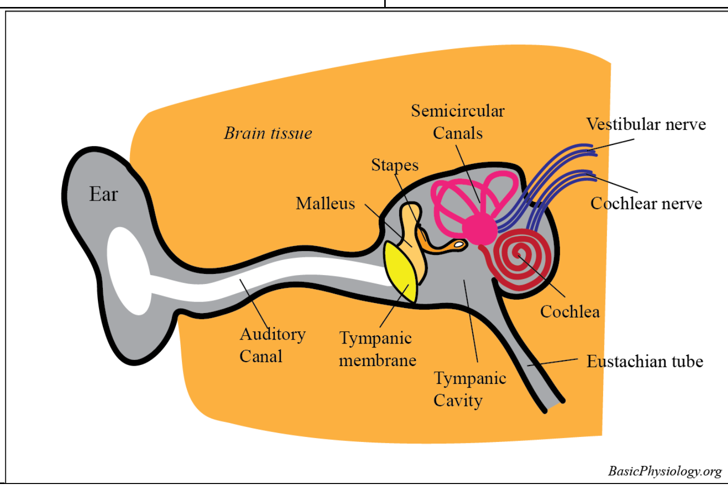


3. If the optic nerve is damaged (a), then the result is quite simple. That eye becomes blind; in the diagram, the right eye.	4. If there is a damage to the optic chiasma, then only the two bundles that crossover to the other side are damaged. That makes that half the retina, both located at the nasal side, become blind, in both eyes!
5. And, even more complex, is when a trauma occurs in the optic tract. Then again two halves of the retina become blind, but now either to the left or the right side of the retina.	6. In other words, by studying which part of both eyes are not responding to light stimuli, one can determine which part of the optic nerve or tract is damaged.

H.3.3.2.a. Hearing

A. Major Structures in Hearing:

1. The ear is (like all special senses) quite complicated! It consists of three different parts: a. the outer ear b. the middle ear c. the inner ear	**2.** The outer ear is what we all can see; a beautiful shape that collects the sound signals from the outside world and which we sometime adorn with jewelry and/or piercings. And, it also contains the auditory canal that conduct the sound waves towards the tympanic membrane.
3. The middle ear consists the three ossicles that collect the sound vibrations from the tympanic membrane, amplifies them and transmit to the inner ear	4. The inner ear is actually the cochlea, a spiral shaped structure with a base, close to the middle ear, and an apex, at the distal end. This is where the sound signal is transformed into neural signals, to be transported towards the brain.
5. What is confusing to many students is that adjacent to the cochlea, there is another structure, the semicircular canals.	6. This is however a totally different system, part of the vestibular system, another special sensor, that detect and controls our body balance (*see H.3.3.3. Balance*).



B. Middle Ear:

<table>
<tr><td>1.
In the air-filled space between outer ear and inner ear is the middle ear. Inside, there are three ossicles; the malleus, the incus and the stapes:</td><td>1. the malleus is connected to the Tympanic Membrane
2. the incus connects the malleus to the stapes
3. the stapes is connected the oval window.</td></tr>
<tr><td colspan="2">These ossicles work as levers; thereby magnifying the amplitude of the sound waves (approximately 20x).</td></tr>
<tr><td>2. The Eustachian Tube:

Connects the middle ear to the pharynx (inside your throat!) and therefore to the outside world. This communication is necessary to keep the pressure inside the middle ear equal to that outside the Tympanic membrane.</td><td>3.

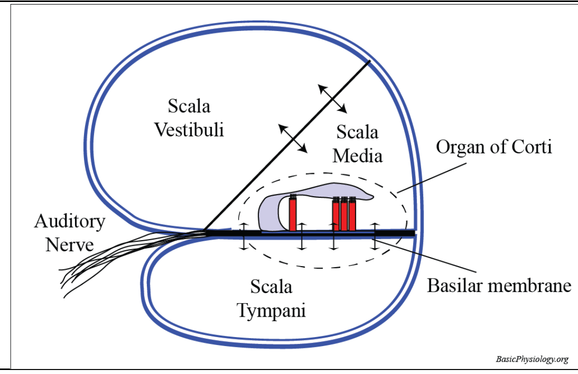
Otherwise (if there is a pressure difference), this will cause the tympanic membrane to be pushed either in or out of the middle ear. This imbalance will make a person deaf and can be very painful.</td></tr>
<tr><td>4. The Attenuation Reflex:

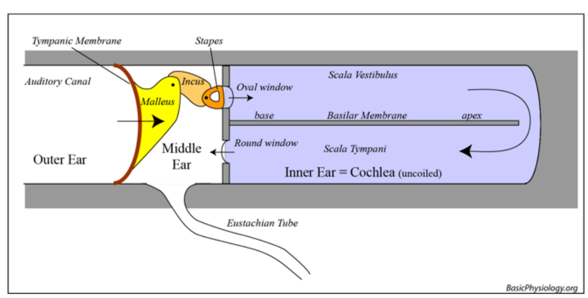
The ossicles are very delicate and, when there is a loud noise, they need protection. Two muscles are attached to the ossicles:

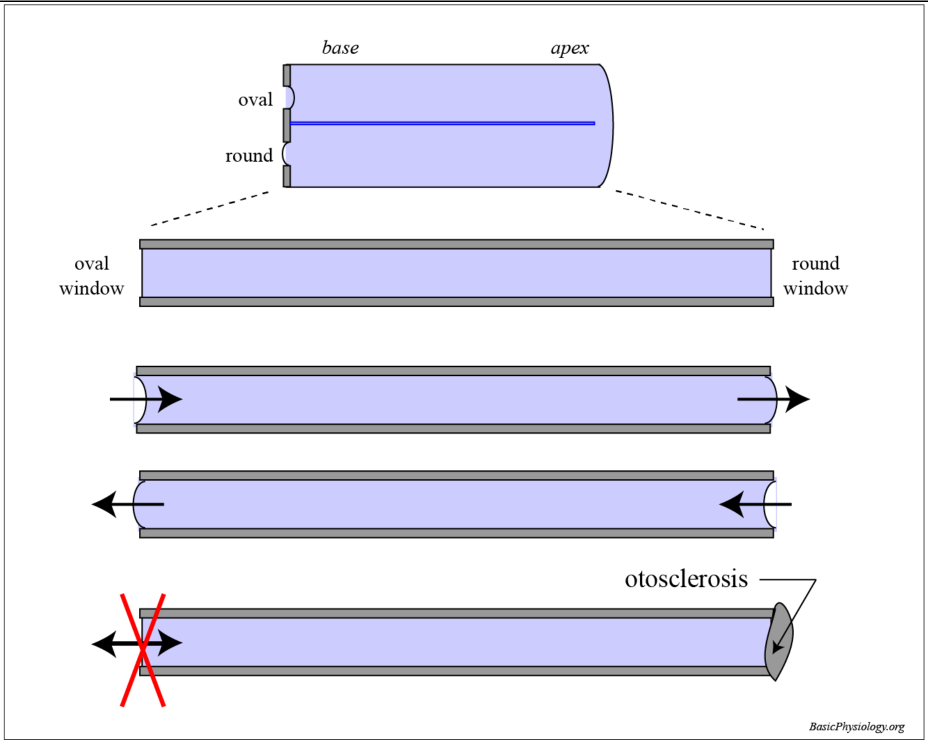
1. the stapedius muscle

2. the tensor tympani.</td><td>5.
These muscles contract by reflex, when there is a loud noise, to pull at the ossicles and to prevent them of getting dislodged.</td></tr>
</table>

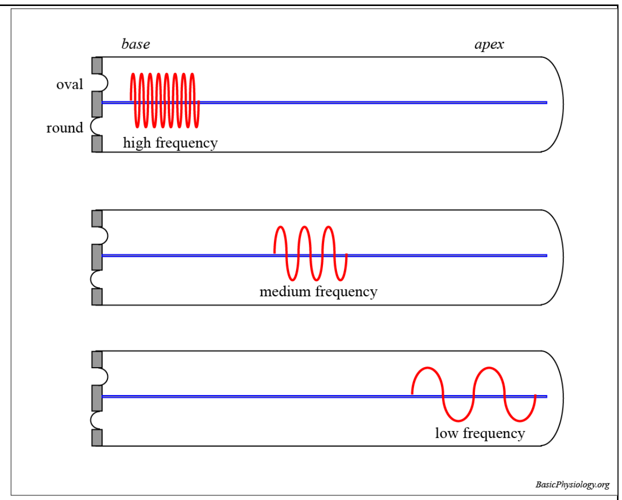
C. Inner Ear (= cochlea):

1. The cochlea is a spiral shaped structure with a base, close to the middle ear, and an apex, at the distal end.	

2. The inside of the cochlea is subdivided into three scala's: the **scala vestibuli** the **scala media** the **scala tympani**.	3. The **scala media** and **scala vestibuli** work together. Between these two and the **scala tympani**, there is the **basilar membrane**.
4. On this basilar membrane, the sensor of the ear, the **organ of Corti** is located. *(Scala = Italian for staircase)*	5. The **inner ear** can be described as a single tube which starts at the oval window and ends at the round window. This tube is filled with fluid. If the membrane of the oval window is pushed inwards, by a sound vibration, then the round window membrane, at the other end of the tube, is pushed outward. This is because fluid is not compressible.
6. The opposite happens when the oval membrane is pulled outwards, then the round membrane will be pulled inwards. During normal hearing, this push and pull will occur very quickly and the fluid will oscillate left and right (thereby creating vibrations in the basilar membrane; not shown in this diagram).	



7.
The **basilar membrane** will vibrate when the fluid in the upper and in the lower scala's vibrate. But the basilar membrane is not the same (homogeneous) along its length. Rather, it contains fibers that are short and stiff in the base and long and slender in the apex.
Therefore, the basilar membrane will vibrate more at the base when the sound has a high frequency. Lower frequencies are better detected in the basilar membrane in the apex.



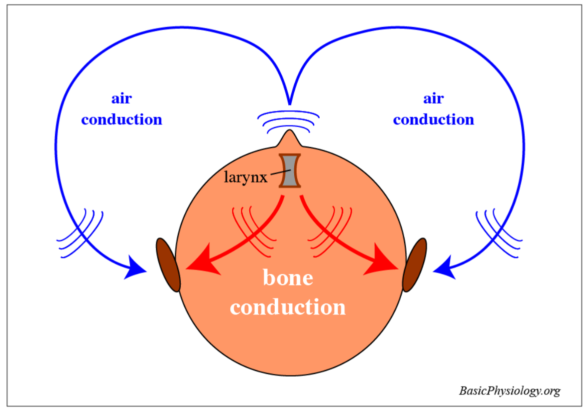
D. Air and Bone conduction:

1. **Air Conduction**:

The usual way of hearing is by conduction of sound waves through the **air** to our ears. That is how we listen to music, to talks, to my lectures, etc.

2.

But, when we**, ourselves,** talk, then we also listen to ourselves in a different way, namely through **bone conduction**.



3. **Bone Conduction:**

As shown in the diagram, sound waves are generated in the **larynx** and propagate from the mouth through the air to the ears. But they also propagate through the **skull** to the ears. This is called **bone conduction**. Therefore, we hear ourselves talking both through the air and the skull.

4.

The propagation and the frequency of the sound through the skull is **influenced** by the bone. Therefore, we hear ourselves talk in a different way from anybody else. The only time you really hear your own voice is when you hear it back from a recording on your mobile, an iPad, or something like that. And then; **nobody** likes their own voice!

H.3.3.2.b. Hearing Abnormalities

A. Deafness (Hearing Abnormalities):

1. Deafness can be caused by an abnormality in the outer ear, the middle ear or the inner hear.	
2. If there is a problem in the outer ear, or in the middle ear, then there is a problem in the **conduction** of the sound waves. Therefore, these problems are called Conduction abnormalities which result in **Conduction Deafness**.	3. Abnormalities in the cochlea (the inner ear) or in the nerves are called **Nerve deafness** or **Sensorineural deafness**.
4. Audiogram: An audiogram is a measurement of how well we can hear. This is tested by producing sound at different frequencies and at different amplitudes and plotted in a graph (= audiogram). Furthermore, we can test, separately, air and bone conduction.	5. In **air conduction**, sound is perceived through the outer ear, the middle ear and the inner ear. In **bone conduction**, sound is perceived by creating sound waves through the skull, thereby bypassing the outer and the middle ear and only stimulating the inner ear.
6. This distinction makes it possible to differentiate between **conduction deafness** and **nerve deafness** (see below).	

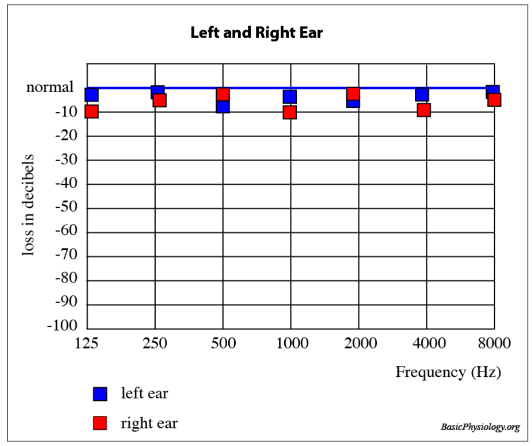
B. Normal Audiograms:

1. **Audiogram:** An audiogram is a **graph** that plots the **threshold** levels for hearing sounds at different frequencies, usually from 125 to 8000 Hz. These levels are expressed in **decibels** (dB) on a logarithmic scale. Zero dB represents threshold for normal healthy people.	2. The audiogram is measured for **both ears** separately (with earphones) and by comparing air conduction and **bone conduction**. Bone conduction is induced with a vibrator placed against the **mastoid** (the bone behind the ear).

3. **Decibel:**

is the unit of sound on a logarithmic scale. It is actually the ratio between the actual sound and the threshold for sound which is set at 0 dB. A whisper produces a sound of 20-30 dB, a conversation 40-50 dB, a vacuum cleaner produces 80 dB noise, a truck rumbles at 90 dB, and a civil defense siren blasts at 130 dB which is close to the threshold of pain.

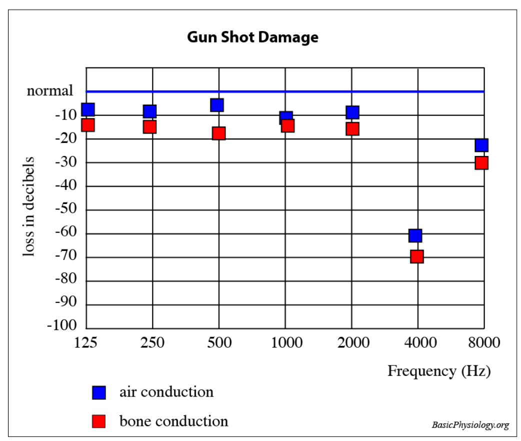
Hz (= Hertz; a former German scientist**):**



C. Abnormal audiograms:

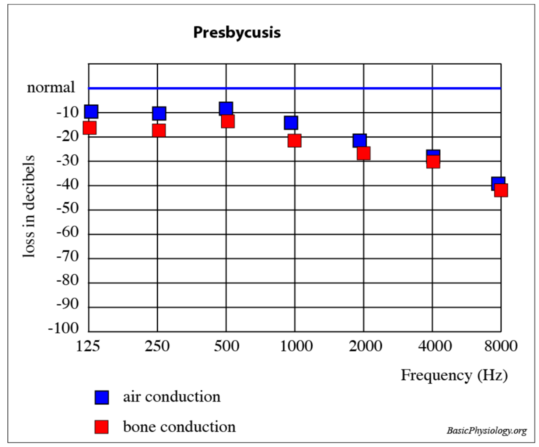
1. Gun-shot damage:

In this patient, air and bone conduction is impaired at a specific frequency; in this case at about 4000 Hz. Since bone and air conduction are **both equally** affected, it is a sensorineural deafness. A damage at one frequency means that a small portion of the **basilar membrane** is damaged; usually by being exposed repeatedly to a high-volume noise of a specific frequency; for example, the cocking of the head and the ear close to the barrel of a **rifle** (hence the name!). Nowadays, such damages often occur when people work in environments where there is a lot of (industrial) noise such as airports but also disco's etc.



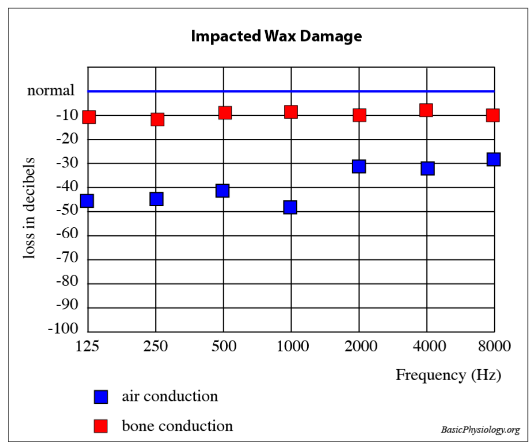
2. Presbycusis:

In this patient, the hearing for **higher** frequencies is impaired, whereas it is ok at the middle and lower frequencies. Both the air and the bone conduction have declined at the high frequencies. This implies that the problem is located in the inner ear; the cochlea or the nerve. Usually, this is due to the wear and tear in the organ of Corti (= old age!).



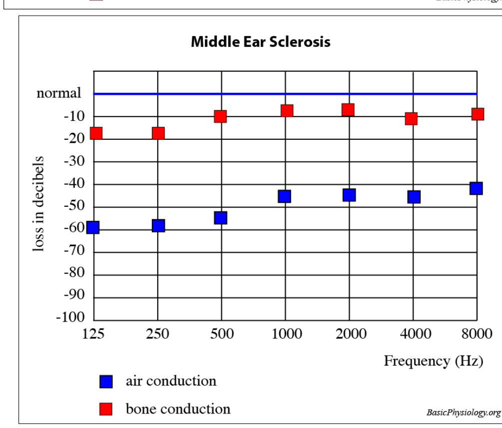
3. Impacted Wax:

In this case, the external auditory canal is blocked by old and hardened wax. This is a typical **conduction problem**. The bone conduction is therefore normal. A ruptured tympanic membrane would produce a similar audiogram.



4. Otosclerosis:

In this patient, bone has accumulated in the middle ear thereby impeding the movements of the ossicles. This is a conduction problem as there is no problem with the cochlea. So, the measured **bone conduction is normal** but his **conduction** is impaired. The same type of pattern could be obtained in the case of an **otitis media** (= middle ear inflammation).

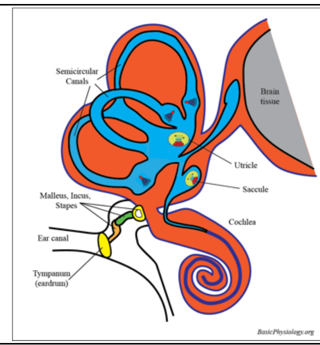


H.3.3.3. Equilibrium

A. Introduction:

<table>
<tr><td colspan="2">The vestibular system can be divided into two parts:

a. the parts that detect linear acceleration (utricle and saccule); also called static movements
b. the parts that detect rotational acceleration (the three semi-circular canals); also called dynamic movements.</td></tr>
<tr><td>2.
Just a reminder of the most important structures in the vestibuli, adjacent to the outer ear, the middle ear and the cochlea. Not the location of two structures at the base of the semi-circular canals; the utricle and the saccule, and that of the crista-ampullaris in the three semi-circular canals</td><td>

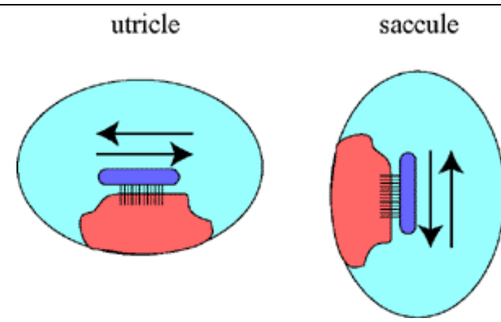


</td></tr>
</table>

B. The Utricle and the Saccule:

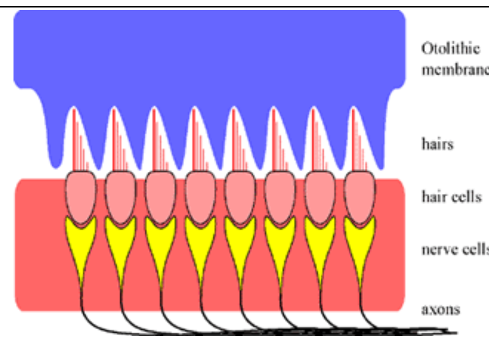
<table>
<tr><td>1. The Utricle and the Saccule:

The utricle and the saccule are fluid-filled spaces. They contain a macula which is oriented in the horizontal direction (= utricle) or in the vertical direction (= saccule). These two organs therefore detect movements in the horizontal and in the vertical direction.</td><td>



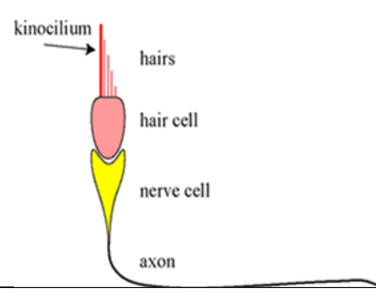
</td></tr>
<tr><td>2. The Macula:

The macula is the sensor in these two organs. It essentially consists of a row of hair cells. The hairs are connected to a gelatinous mass called the otholithic membrane. The other side of the hair cell is connected to a nerve. This is the beginning of the vestibular nerve.</td><td>

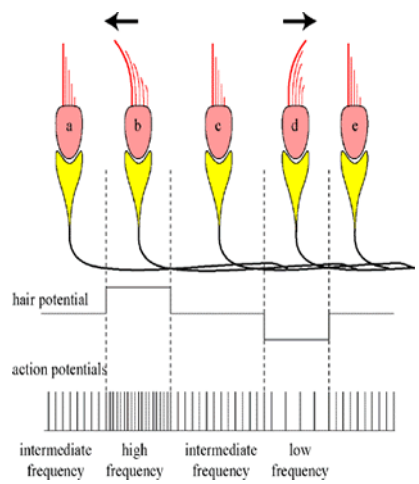


</td></tr>
<tr><td>3. The Hair Cell:

In contrast to the hair cells in the cochlea, there is also an orientation in the configuration of the hairs in the macula. One of the hairs is longer and thicker than the others. This special hair is called</td><td>

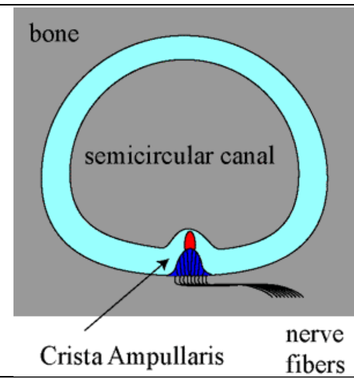
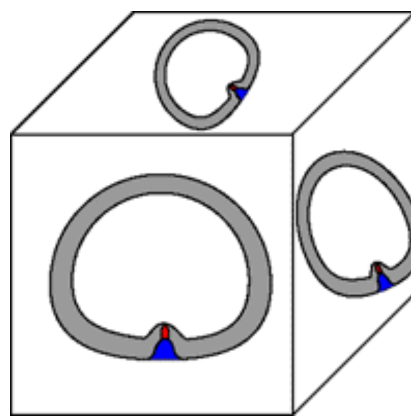
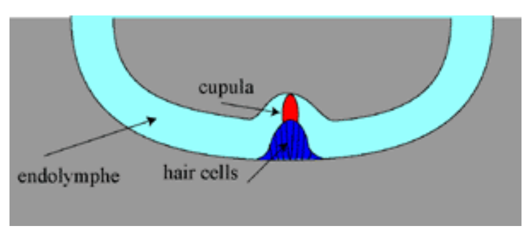


</td></tr>
</table>

a **kinocilium** (plural kinocilia) and is, as it were, a point of reference for these hairs.	
4. How does it work? When the head starts to move in one direction, the otolithic membrane will move in the opposite direction. This is due to the **inertia** of the **otolith**. Because the hair cells move in one direction and the otolithic membrane in the other, all the hairs will **bend**. As we have seen before in the organ of Corti, this will influence stretch channels in the neighbourhood to open, thereby depolarizing the membrane and generating action potentials.	
5. Forward and backward or up-and-down? But in the saccule and the utricle, there is an additional problem. These two organs must also detect whether the horizontal movement is forward or backward (or in the case of a saccule; vertical movement, up or down). As shown in the diagram, this is solved in the following manner. If the hairs bend towards the kinocilium, then there will be a **depolarization** in the hair cell. If the hairs bend the other way, away from the kinocilium, then the hair cell will **hyperpolarize**.	6. Frequency modulation: The final step is to **transduce** (=translate) the depolarization into action potentials. As in the organ of Corti, depolarization causes more action potentials and the frequency becomes higher. This is because the polarity moves closer to the threshold. The opposite happens when the polarity moves away from the threshold. Then, during hyperpolarization, there will be less action potentials; the frequency is lower. This transduction from amplitude to frequency is (technically) called "**frequency modulation**" (like in the radio! *FM vs. AM*).
7. Acceleration versus velocity. It is important to realize that it is the **acceleration** that stimulates the otolithic membrane to shift, thereby bending the hairs, not the **velocity** itself. If it had been the velocity that shifted the otoliths, then we would never be able to drive in a **car** or fly in a **plane**. No, it is the **change in**	8. Frequency modulation. Note that when the utricle or the saccule are in rest, that then the hair cells **still** generate action potentials. In other words, it is actually telling the brain that it is working and that there is at the moment no acceleration or deceleration. But if the frequency increases or

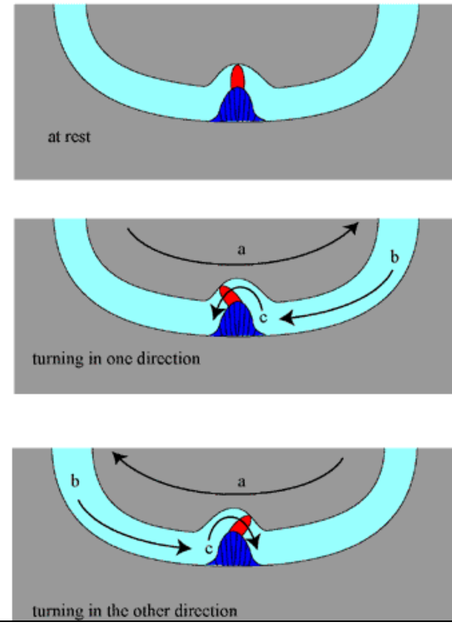
velocity (=acceleration or deceleration) that shifts the otoliths and that is what we feel.	decreases, then it can report how **much** (the change in frequency) and in which **direction** (accelerating or decelerating).

C. The Semi-Circular Canals:

1. The semi-circular canal: This is a canal that is filled with **endolymph**. The canal is circular which means that the fluid can move in a circle. At one end of the canal, there is the **crista ampullaris** that detects the movements of the fluid and pass on that information to the vestibular nerve.	
2. The orientation of the three semi circular canals. The three canals are oriented in three different directions and at right angles to each other. Like the three faces of a cube: one is at the front plane, one at the side plane and the third at the top plane. In this way, rotation at any angle can be picked up by one or two canals.	
3. The Crista Ampullaris As in the macula, there are hair cells in the bottom of the canal. The hairs are fixed to a "cupula" (= sort of a hat) which is a gelatinous mass. This **cupula** can turn left or right, depending on the flow of the endolymph.	

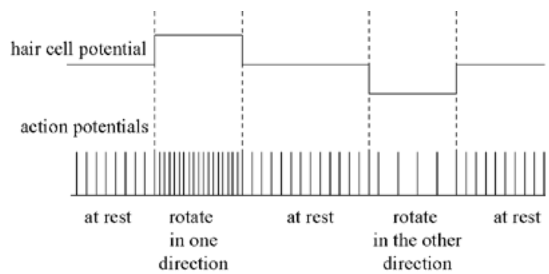
4. How does it work?

When the head starts to **rotate**, the bone (=skull), and therefore the canal will also start rotating. But the endolymphe, due to its **inertia**, will not move immediately. So, if the head rotates in direction **a**, then the fluid, which lags behind, will flow in the opposite direction (**b**). This fluid flow will push the cupula to bend to the left (**c**). If the head rotates in the opposite direction, then of course, the fluid will also flow in the opposite direction and the cupula will bend to the right.

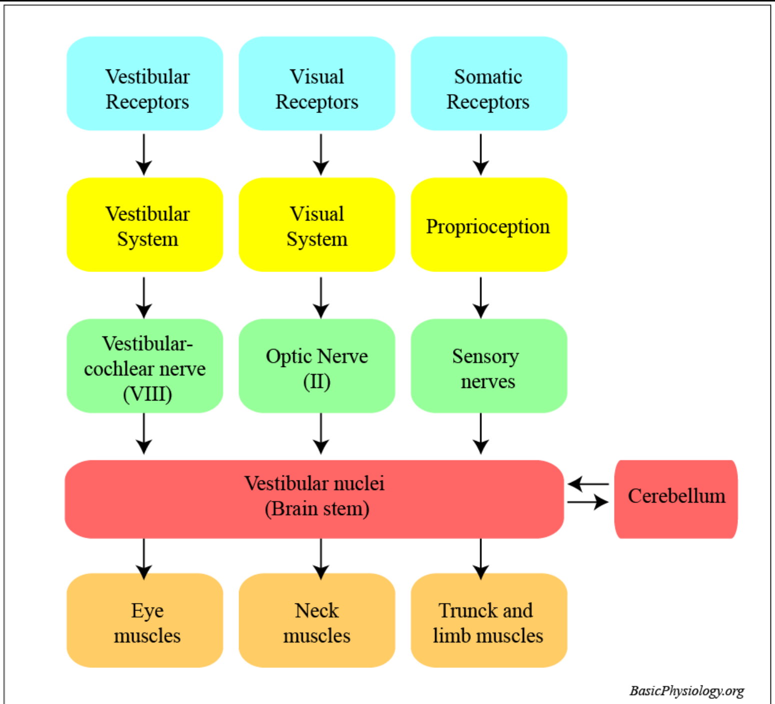


5. Frequency Modulation

As in the saccule and utricle, it is crucial to know whether the head its rotating to the right or to the left. Therefore, in a similar way, there is a system of **modulating** the intracellular potential to action potential frequency. Thus, rotation in one direction will **increase** the (resting) frequency whereas rotation in the opposite direction will cause a **decrease** in the resting frequency.



D. Integration of the Vestibular system with other systems in the body:



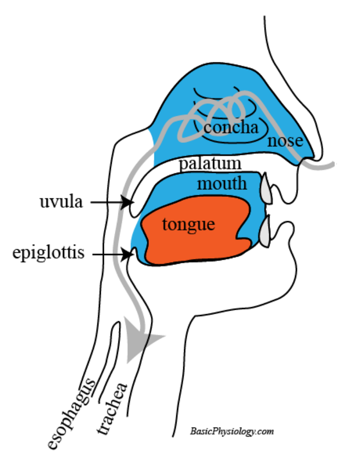
1. Three systems are involved in our balance: a. the vestibular system b. the visual system c. the musculo-skeletal system	2. **Proprioception**: This is the system that informs the brain of our "position" in space. Sensors are located in the joints (to measure the angle), in the skeletal muscles (to measure their length) and especially in the neck (to determine the relation of the head to the rest of the body).
3. **Vestibular nuclei**: All this information is fed into the **vestibular nuclei** for processing. In addition, there is a close relation between these nuclei and the **cerebellum** (=auto pilot).	4. **Effectors**: From the vestibular nuclei, commands are given to the eye muscles, the trunc, the limb and the neck muscles to either keep the shape of the body or to change it according to demand. The role of the **neck** is very visible in animals with long necks such as horses and camels. The animal can rotate its neck to look, for example, behind itself. When the animal then wants to move in that direction, then the body, as it where, "follows" the neck.

5. Vestibular nuclei: All this information is fed into the **vestibular nuclei** for processing. In addition, there is a close relation between these nuclei and the **cerebellum** (=auto pilot).	**6. Effectors:** From the vestibular nuclei, commands are given to the eye muscles, the trunc, the limb and the neck muscles to either keep the shape of the body or to change it according to demand. The role of the **neck** is very visible in animals with long necks such as horses and camels. The animal can rotate its neck to look, for example, behind itself. When the animal then wants to move in that direction, then the body, as it where, "follows" the neck.
7. When are we in balance? We are in balance when the information from the three systems agree with each other. For example, suppose that you are in an elevator which looks outside (as in some expensive hotels) and you go up in that elevator. Then your **eyes** tell you that you are going up, your **sacule** feels that you are going up and the **pressure** sensors in your musculo-skeletal system informs the brain that the body is moving upwards.	**8. Motion sickness** But if there is a conflict between the information received from one (or two) of the three systems, then we become violently sick: **motion sickness**. This is well known when one is on a boat in a choppy sea. Another current example is trying to read a book while riding in a car. Your eyes concentrate on the reading (stable) while your vestibular system and your proprioception inform you that you are constantly accelerating and decelerating. Good reason to become very *very* **sick**.
9. Symptoms: The symptoms of motion sickness are quite **severe**: 1. nausea 2. vomiting 3. pallor 4. rapid breathing	**10. Why so severe?** Body position is **crucial** fo survival. The brain needs to know **all the time** the **EXACT** position of the head, the limbs etc. It must be able to act **immediately** in the case of danger. If there is a conflict in the information it is receiving, it can then no longer react

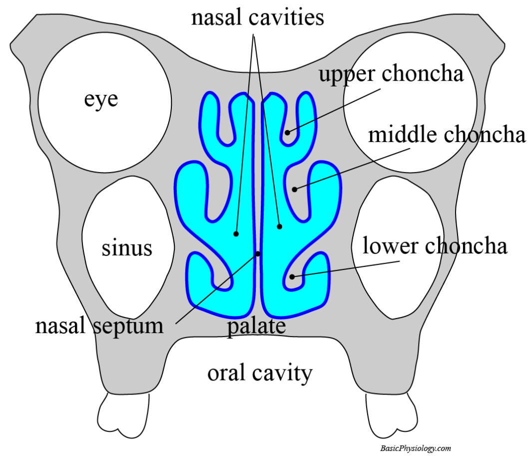
5. sweating	adequately to danger. Whatever causes this mis-information must **STOP** immediately. Hence, **motion sicknessis** really incapacitating.

H.3.3.4. Smell

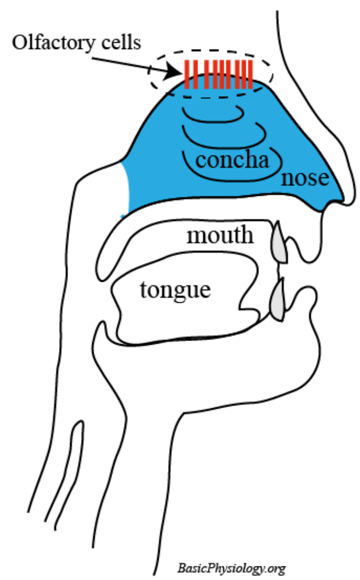
A. Nose (*copied from C.2. Upper Respiratory Airways***):**

1. *As air flows into the body, during inspiration, it flows through the following structures:* *1. nasal cavity* *2. oral cavity* *3. pharynx* *4. larynx* *5. trachea* *6. bronchial tree*	*2.* *During the inspiration, the inspired air is modified as follows:* *a. The airways* ***clean*** *the air from large particles (larger than 4 micron).* *b. The air is* ***humidified*** *(makes it 'wet')* c. *The* ***temperature*** *of the air is increased to body temperature.*
3. *During inspiration, the airflow becomes very* ***turbulent****. This is due to structures in the nasal cavity such as the* ***concha****, which obstructs and diverts the air flow.*	
4. *This is good because this turbulence causes close contact between the air and the* ***mucosa*** *that lines the wall of the nose, mouth etc. thereby trapping large particles.*	

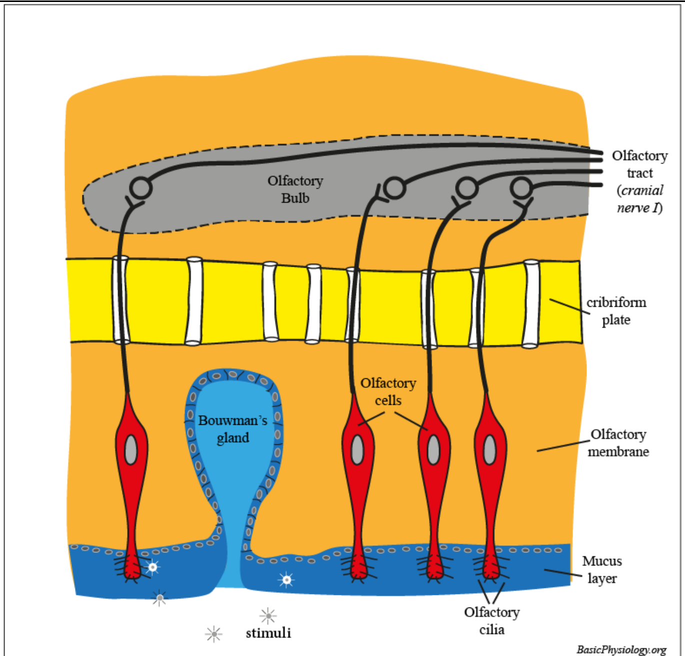
B. The Nasal cavity:

1. *The **nasal cavity**, from the nostrils to the nasopharynx, consists of two cavities (in blue), left and right, divided by a nasal **septum**. It is separated from the mouth by the **palate** (= palatum).*	
2. *The nose has three **conchae's** (upper, middle and lower) in each cavity. These structures help in increasing the mucosal surface and in creating air turbulence, which also increases the chances of detecting a smell.*	

A. Definitions and Structural components required:

1. The olfactory (= smell) membrane or epithelium is located in the superior part of the nose.	
2. The area covered is about 2-3 cm^2 in each nose and contains millions of sensors.	
3. The sensors are actually nerve cells! They have a bipolar shape.	
4. At one end, there are numerous olfactory hairs = cilia) sticking out into the mucus of the nose.	

5.
At the other end of the olfactory cells, non-myelinated axons, that run through openings of the **cribriform plate,** into the overlying olfactory bulb.



6.
Essentially, these axons run through the base of the skull into the brain!

7.
And, as in the taste buds, there are also **basal cells**, which are really stem cells that make new olfactory cells.

8.
This is probably the only known situation in which nerve cells (as the olfactory cells really are) are **renewed**. All other nerve cells cannot do so.

9.
Olfactory cells live about **60 days; ONLY!**

10.
We should also mention that in the olfactory epithelium there are also **olfactory glands (=** Bowman's gland**)**, which makes the mucus.

11.
This **mucus** is very important because it 'catches' and contains the chemicals from the air that will stimulate the cilia of the olfactory cells.

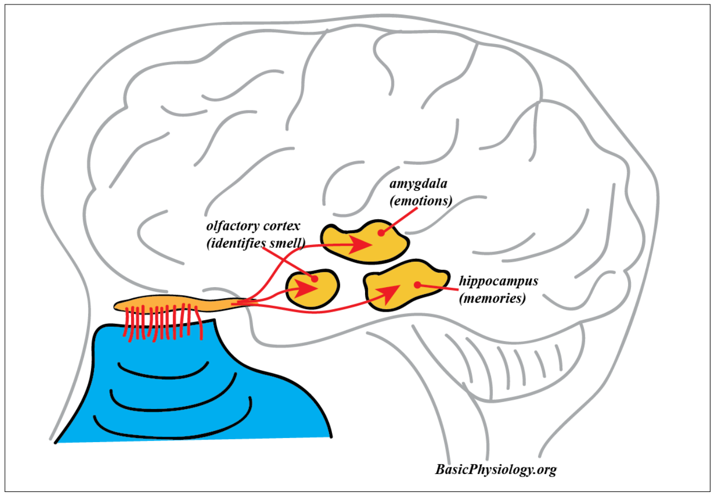
B. Stimulation of the olfactory cells:

1. The odours that we smell are actually chemicals floating in the air that stick to the mucus and dissolves in it.	2. Therefore, we can only smell chemicals that are **volatile**. It also helps if the chemical is also water-soluble.	3. These chemicals bind to a receptor, which is actually part of a G-protein complex.
4. The G-protein activates a compound (=adenylyl cyclase) which opens sodium-channels.	5. The influx of sodium ions will depolarize the olfactory cell and if that reaches threshold, will induce one or more action potentials. If the smell is strong, there will be more action potentials.	6. As the olfactory cell is actually a nerve cell, the action potential will propagate along the un-myelinated axon towards the olfactory bulb.

C. Primary sensations of smell:

1. As with taste, scientists have and are searching for the basic components of smell.	2. One attempt, based on psychological studies, came up with the following list of smells:	3. a. Camphoraceous b. Musky c. Floral d. Pepper minty e. Ethereal f. Pungent g. Putrid
4. Biochemical and gene studies are starting to show that there are hundreds if not thousands of primary smells.	5. Also important is the fact that the threshold for smell is VERY low. Some compounds can be detected at extreme low concentrations (just a few molecules in 1 mml air!).	6. Finally, the olfactory cells will also adapt to a stimulus. This occurs already in the first few seconds. There is a second adaptation but that occurs in the brain.

D. Olfactory Bulb and Tract:

<table>
<tr><td colspan="2">1.
The olfactory bulb contains glomeruli, in which thousands of axons from the olfactory cells synapse to.</td><td colspan="2" rowspan="3">
</td></tr>
<tr><td colspan="2">2.
In addition, there are other nerve cells, such as the mitral cells that receive the axons from the olfactory cells.</td></tr>
<tr><td colspan="2">3.
The nerve cells in the glomeruli send their axon, though the olfactory tract towards several centres in the brain.</td></tr>
<tr><td colspan="2">4.
The olfactory bulb and the olfactory tract together form cranial nerve I (= the first nerve). Further on in the brain, the tract divides into several parts.</td><td colspan="2">5.
One part of the tract radiates to the olfactory cortex, (which identifies the recoded smell).</td></tr>
<tr><td colspan="2">6.
Another tract connects to the hippocampus area (which stores the smell memories!)</td><td colspan="2">7.
Other fibres go to the amygdala region. This area is important because there the smell stimuli are associated with emotions!</td></tr>
</table>

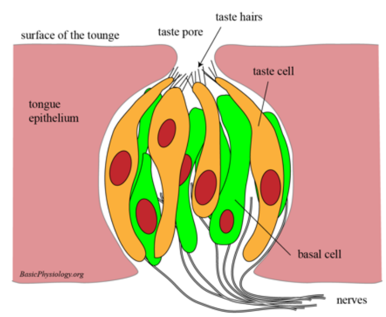
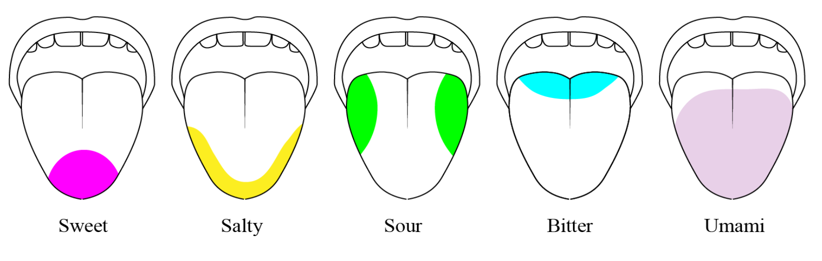
E. Pathologies of Smell:

1. **Anosmia** is when you cannot smell. Other names are **hyposmia** (= less sensitive), **dysosmia** (= distorted smell) and **hyperosmia** (= increased sensitivity).	2. Anosmia (= no smell at all!) may happen following a **trauma** to the head.	3. In that case, the axons from the olfactory cells that run through the cribriform plate to the olfactory bulbs, have been broken. This is (unfortunately) **irreversible**!

4. Other, less traumatic, events may also reduce our sense of smell such as a cold, an allergy, smoking, etc.	5. It is also interesting that **taste** is so much dependent on **smell**. If there is no smell, then food becomes much less tasty.	6. Brain disorders may also affect smell. Following brain surgery or trauma, some patients have **olfactory hallucinations**!

H.3.3.5. Taste

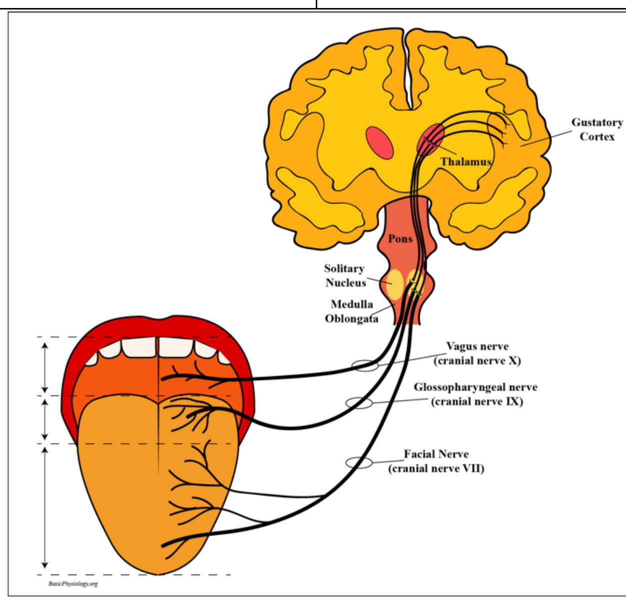
A. The tongue (*copied from E.2. The Mouth and the Nose)*

<table>
<tr><td>1.
The tongue is a skeletal muscle, attached at one end to the bones of the skull.</td><td>2.
Its major function is to move the food (= bolus) around the mouth, by the teeth and the inner membranes of the mouth cavity and to mix it with saliva to help the digestive process.</td></tr>
<tr><td>3.
The upper surface of the tongue also has several sensors to detect five types of tastes. They do this by having taste buds imbedded into the surface of the tongue.</td><td>
</td></tr>
<tr><td>4.
These taste buds have sensory cells that pick up a particular taste with their taste hairs and then deliver action potentials to the nerves that go to the brain.</td><td>5.
Because these taste cells don’t live very long, 5-10 days max, they are constantly being replaced by the accompanying base cells.</td></tr>
<tr><td colspan="2">
</td></tr>
</table>

6. *These are the five tastes that the tongue can detect. Please note that the tip of the tongue detects the nicest thing in our food: sweet!*	*7.* *Also note that that the back of the tongue detects what could be most dangerous for us, before swallowing something that is very bitter!*
8. *Although you may be familiar with the tastes sweet, salty, sour and bitter, you may not be familiar with the taste 'Umami" (I wasn't!).*	*9.* *Umami as a taste was 'discovered' only last century by a Japanese scientist. Umami in Japanese means 'delicious'. It tastes essentially as yummy, nice flavour in many types of food, in sushi's, in tomato sauce etc.*
10. *A recent article informed me of two new/important facts about these taste bugs:* *a) the taste areas depicted in the above figure shows where a particular taste (sweet, or salty, etc) is most sensitive. But other areas in the tongue can also detect sweet, salty or other tastes, only less sensitive. In other words, the taste bugs are located all over the tongue.*	*11.* *b) we also have taste bugs elsewhere in the body! Apparently, taste bugs are also located in the gastrointestinal tract, muscles, brain etc. and ongoing research will discover more locations and what they are doing there!* *(for more see: The Textbooks Were Wrong About How Your Tongue Works in BasicPhysiology.org/literature)*

B. Further info about Taste

1. Also, interesting to know that the thresholds for perceiving the different types of taste are not the same.	2. In fact, the threshold for bitter is the lowest! This is of course to detect as soon as possible something that might be 'toxic' in the food!
3. At the other end of the sensitivity scale are "sweet' and 'salty'.	4. On the other hand, there is also the possibility of 'taste blindness'; some people cannot taste certain substances.
5. And, as you may have experiences, some people have more sensitive tastes than others!	6. Taste senses are not only located on the tongue but are also found in the palate, in the epithelium of the roof of the mouth, the soft palate, the throat lining and the epiglottis!

7. Moreover, the tongue contains not only taste receptors, but also temperature sensors, pressure sensors, and touch sensors. A very sensitive organ indeed!	8. And oh yes, what you taste is also influenced by what you smell, in your nose! How complex can it be, all for the protection of humans?
9. Finally, the action potentials generated in the afferent nerves must also travel to the brain. The anterior two-thirds of the receptors in the tongue travel via the facial nerve, and the posterior one-third travel via the glossopharyngeal nerve to the brainstem. The back of the mouth is innervated by the vagus nerve.	10. From the brainstem, the nerve fibres travel to the solitary nucleus in the thalamus, and from there, they ultimately reach the gustatory cortex. Interestingly, the taste nerves, in contrast to the optical nerves do not (partially) cross-over to the other side of the brain! No one knows why or why not ;-)
	

C. Further info about the tongue!

1. While researching about 'taste', I discovered also more interesting info about the tongue, especially as it has multiple functions.	2. It is basically a striated muscle that is attached on one end (to a bone; *os hyoideum*) and mobile at the other end.

3. In addition, at the back there is also the lingual tonsil, a lymphatic organ, part of the immune system.	4. The tongue mucosa is a thick layer of squamous epithelium with a rough, sometimes bumpy, surface.
5. And of course, you have the taste buds which contain the taste sensors (see above).	6. But the tongue has several functions in the mouth.
7. It examines the food using touch, taste and temperature sensors.	8. It is also important in chewing and mixing the food with saliva.
9. The tongue also plays an important role in swallowing food, but also in speaking and it even helps in cleaning the teeth.	10. And… oh yes… the tongue also plays an important role in human eroticism; French kissing and licking!!!

H.4.1. Motor System

A. Introduction:

1. As you can imagine, the large brains consist of several systems located in different parts of the large brains.	2. We can not consider ALL systems (there are so many) but will concentrate on the most important ones: a) The motor system b) The sensory system c) The autonomic system????
3. Of course, nothing is simple, certainly not in the brain. The motor system, for example, also consists of two different systems, fortunately collaborating with each other (!). These are: a) The pyramidal motor system b) The extrapyramidal motor system	

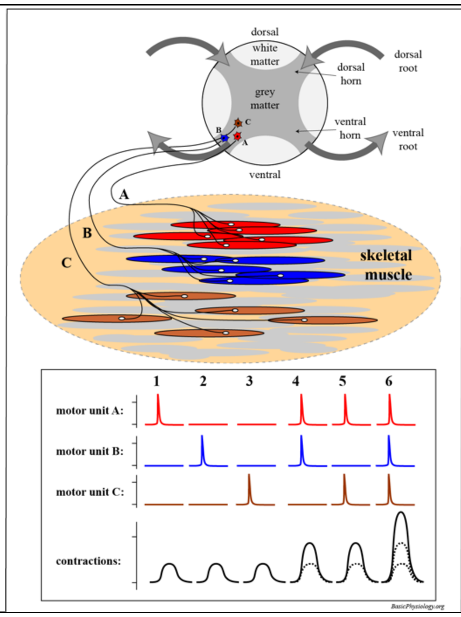
B. Remember the Motor Units in the spinal cord?

1.
The function of the motor system, as you can imagine, is to determine our motility, for which we have the skeletal muscles, the muscles that are connected to our skeleton.

2.
The skeletal muscle will contract when it is stimulated by an impulse (= an action potential) that comes from a nerve cell located in the spinal cord. This is what we called a motor unit (link: *A.4.6. Motor Units*).

3.
This is in contrast to other types of muscle cells such as the smooth muscle cell or the cardiac cell which are innervated (excited) in their own organs (see *chapter A*).

4.
Maybe it is good at this stage to repeat the picture from Chapter A:

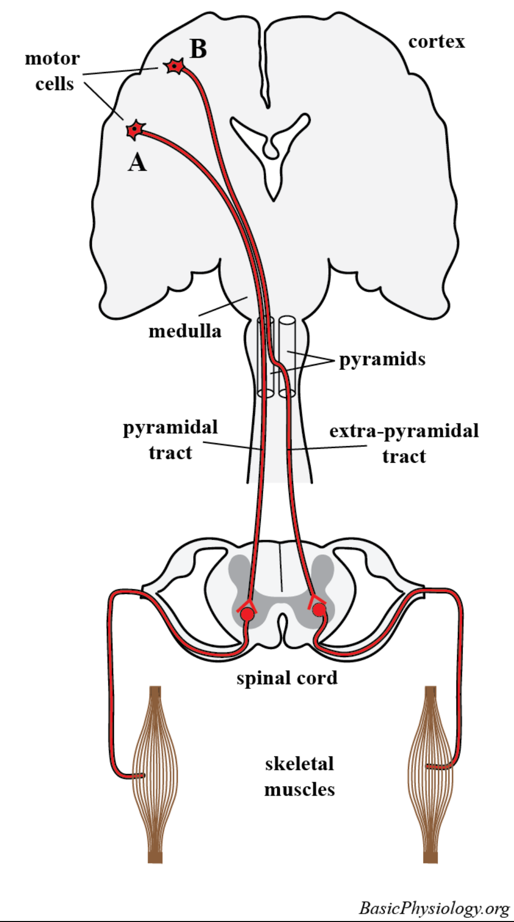


5.
As you can see in this diagram, the action potential that will stimulate a group of cells in a skeletal muscle originate from nerve cells located in the ventral horn of the spinal cord; 'a', 'b' and/or 'c' nerve cell (and many more …)

6.
The major question in this chapter; how does this nerve cell know when to stimulate these skeletal muscle cells?

C. The pyramidal and the extra-pyramidal motor system:

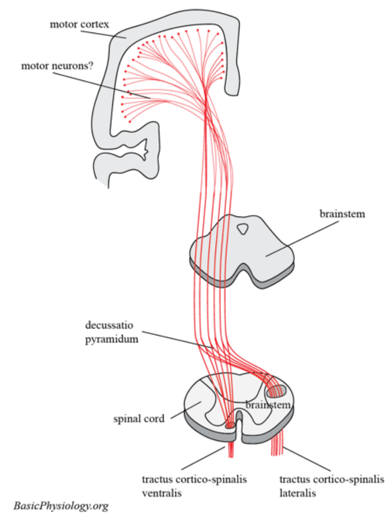
1.
As you can see in the diagram, the principle is quite simple; there is a nerve cell, located in the cortex (= superficial layer) of the large brain. The axon from this cell then conducts the nervous impulses all the way through the brain, through the medulla into the spinal cord until it reaches the appropriate level in the spinal cord.

<table>
<tr><td>2.
At this level, the axon synapses to a second nerve cell which is the cell that innervates the appropriate skeletal muscle fibber. That’s all! Really?? Yes and no 😜!!!</td><td rowspan="3">
</td></tr>
<tr><td>3.
Yes; there is one specific neuron in the large brain cortex that sends signals, through a second nerve cell in the spinal cord, to stimulate a group of fibres in a specific skeletal muscle.</td></tr>
<tr><td>4.
And since we have a lot of skeletal muscles in our body, there must be a lot of nerve cells in the cortex that are all coupled to specific muscles.</td></tr>
<tr><td>5.
But the diagram also shows something even more strange. Look at the second axon (axon B). It also starts from the same area and runs through the large brain, but, just below the medulla, it suddenly ‘jumps’ to the other side and innervates a spinal cord cell in the right side of the body!</td><td>6.
Why? No one knows. Evolution? In fact most of these motor axons cross-over, at this level, to the other side of the body; about 95%! In other words, our left cortex controls 95% of the skeletal muscles in the right body and the right cortex controls 95% of the left body!</td></tr>
<tr><td>7.
This crossing-over occurs in a specific region of the medulla called the pyramids (one left and one right).</td><td>8.
That is why the axons that run through the pyramid and remain on the same side (±5%) are called the pyramidal tract while those crossing over (±95%) are called the extra-pyramidal tract.</td></tr>
</table>

D. Cortical Homunculus:

1.
This diagram is essentially a repitition of the previous diagram but with large number of axons plotted to show the extend of the motor nerve cells in the cortex and their axons running throuhg the brain and of course the large number (95%) of axons that cross-over to the other side. This crossing over is called ‘**decussatio pyramidum’** which is latin for “crossing at the pyramid”.

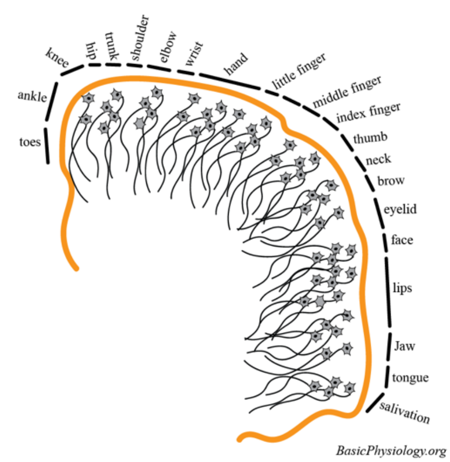
2.
In the spinal cord, the two tracts are called tractus cortico-spinalis ventralis (same side) and tractus cortico-spinalis lateralis (opposite side). You don’t need a lot of latin to understand this!

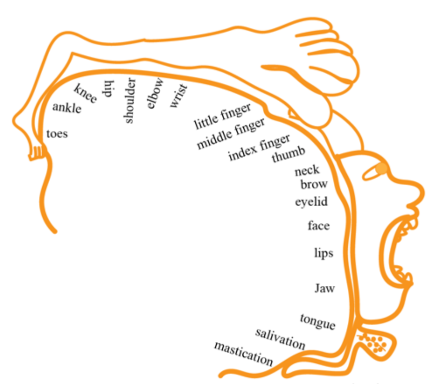


3.
Ok, let’s go back to the cortex because there is something there which is even more interesting!
This diagram shows the relationship between the location of the motor neurons in the cortex and the body parts that are mobilized by these skeletal muscles.

4.
Now you can see which neurons innervate the muscles in the legs (toe, ankle, knee), innervate the muscles in the face (lips, jaw etc.), and more. As you can see, some areas, indicated by the black bars, are larger than others. For example, the number of neurons innervating the muscles in the lip is much higher than those innervating the muscles in the neck, for example.

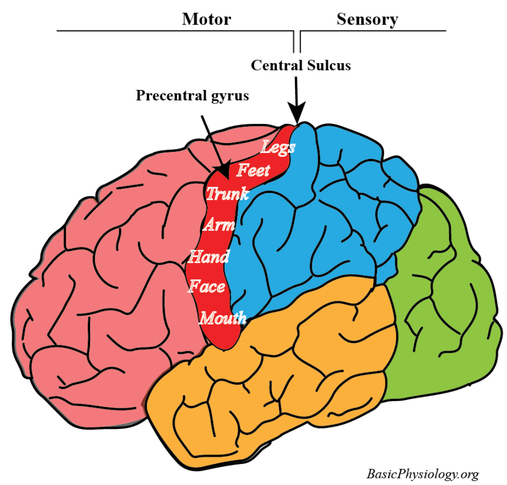
5.
In fact, in many neurology books, you will see a diagram depicting a human being drawn along the motor cortex with their size related to the number of neurons that innervate those areas.





6.
Sometimes, this is called the cortical “homunculus”. This is Latin (again!) for a small human being, but distorted to reflect the degree of motor neuron innervation of the body parts.

7.
Another way to look at this cortex, is shown in this diagram.
Here you can see the location of the **precentral gyrus** with, in white, the location of the motor neurons innervating several major body parts, from the legs (top) all the way to the mouth (bottom).



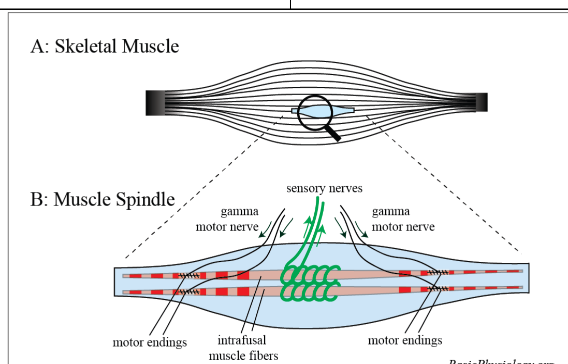
8.
Btw, this is an important name to remember; precentral gyrus. **Gyrus** means a ridge-like elevation of the brain tissue. “Precentral” means “before the central sulcus”. The central sulcus is a groove that separates the precentral gyrus from the postcentral gyrus.

9.
Sorry for all these terms but these are quite common in this field; sorry!!

H.4.2. Muscle Spindle and Tendon Organ

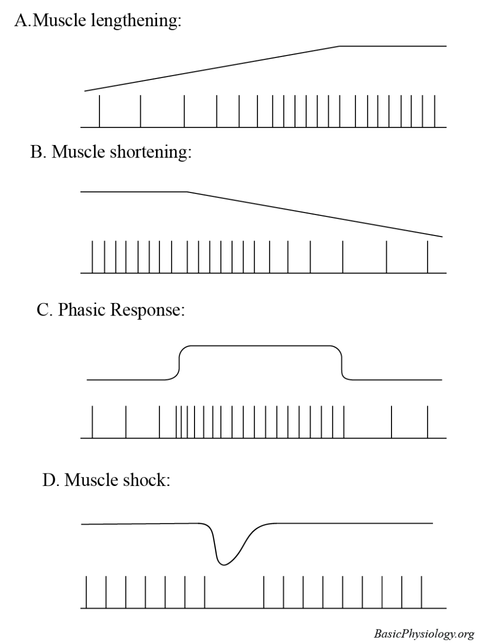
A. The Muscle Spindle:

<table>
<tr><td>1.
Muscle spindles are stretch receptors that are located/distributed in the belly of skeletal muscles.</td><td>2.
They primarily detect changes in the length of the muscles which is (of course) very useful to know, for the brain!</td></tr>
<tr><td>3.
For this function, special muscle fibres are located inside the spindle. These are called intrafusal fibres (and the ‘normal fibres outside the muscle spindles are now called extrafusal fibres).</td><td>4.
Around these intrafusal muscle fibres, there are loops of sensory nerve endings wrapped around the fibres. These detect the length/tension in these intrafusal fibres and send that information to the brain.</td></tr>
<tr><td>5.
In addition, the muscle fibres in the muscle spindles can also be stimulated, just like the extrafusal fibres, with efferent nerves, called gamma motor neurons.</td><td>6.
As we will see later, these innervations may influence the sensitivity and the function of the muscle spindles.</td></tr>
<tr><td colspan="2">

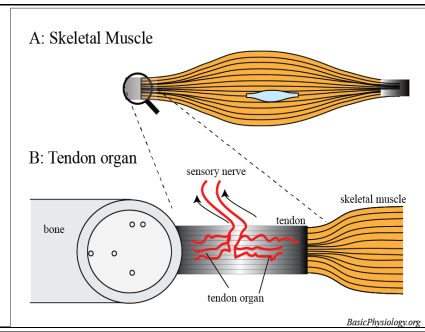
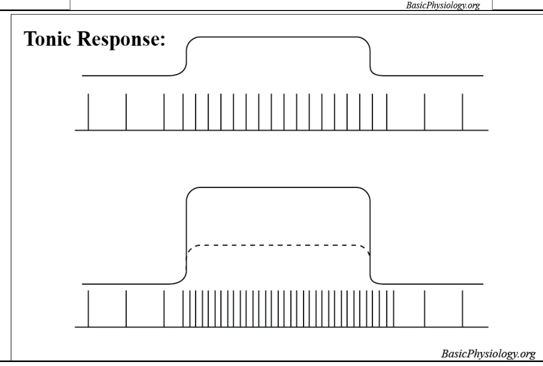


</td></tr>
<tr><td>7.
How many muscle spindles are there in a typical skeletal muscle? Not many, about 25 to 100, on average, in a single muscle.</td><td>8.
But there is a large variation in muscles. Some muscles, such as muscles in the legs or the arms have quite a lot of muscle spindles whereas other muscles such as the facial muscles have little or even no muscle spindles at all.</td></tr>
<tr><td colspan="2">9.
We don’t really know yet what determines this variation. Amount of cerebral control is of course important. But why facial muscles don’t have muscle spindles at all, no idea!</td></tr>
</table>

B. Function of the muscle spindles:

<table>
<tr><td>1.
The function of the muscle spindle is to constantly measure the length of the skeletal muscle, which it does with the sensory endings wrapped around the intrafusal fibres.</td><td>2.
At rest, the muscle spindles discharge a constant rhythm of action potentials that propagate to the brain.</td></tr>
<tr><td>3.
When the muscle is gradually stretched, the action potential frequency gradually increases (panel A) whereas, when the muscle is shortened, the opposite occurs (B).</td><td rowspan="3">
</td></tr>
<tr><td>4.
If there is a sudden increase in the length of the muscle (a jerk) then the firing of the action potentials will suddenly increase and then gradually settle back to that particular length (C).</td></tr>
<tr><td>5.
And, when the muscle is suddenly shortened, the opposite occurs (D).</td></tr>
<tr><td>6.
Btw, why are the gamma motor nerves innervating the intrafusal fibres?</td><td>7.
These gamma motor nerves are constantly sending action potentials to the intrafusal fibres which makes these fibres always (slightly) contracted.</td></tr>
<tr><td>8.
That is important because it means that the fibres are constantly alert to changes in the skeletal muscle length.</td><td>9.
Suppose, that the intrafusal fibres were not constantly contracted but just hang loose in the spindle, then they would not detect any change in the skeletal muscle. In other words, constant contraction keeps these fibres alert all the time!</td></tr>
</table>

C. The Tendon organ:

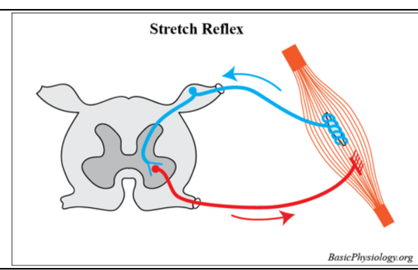
<table>
<tr><td>1.
And then, we have another sensor in the skeletal muscles or, rather, in the tendons that fix the muscles to the skeleton.</td><td>2.
The tendon organ records the tension in the attached muscle; irrespective whether this is induced by active contraction or otherwise.</td></tr>
<tr><td>3.
The amount of tension is ‘translated’ into the frequency of action potentials that are then send to the brain. The higher the tension, the higher the number of action potentials.</td><td>
</td></tr>
<tr><td>4.
Btw, the tendon organ is sometimes also called the Golgi tendon, since Golgi was the first person to describe this structure (born in 1843!).</td><td>
</td></tr>
<tr><td colspan="2">5.
Remember Golgi? Yes! He discovered and described the function of the Golgi body; a group of vesicles located in many cells that collect small molecules into vesicles for further transportation (see A.2.1.F.).</td></tr>
</table>

H.4.3. Motor Reflexes

A. Introduction:

1. What are reflexes? These are 'automatic' responses in the body. These can be motor or sensory responses, usually induced by a stimulus.	2. For example, if you are in a dark room and see suddenly a bright light, then your pupils will react, automatically. Likewise, if your finger suddenly feels something sharp, the muscles in your arm will automatically jerk your hand away from this stimulus. This is called the withdrawal reflex.
3. Reflexes are always very fast, and, you cannot control them.	4. On this page, we will discuss the neuronal reflexes, that occur in the central nervous system. We will start with the most simplex reflex; the muscle stretch reflex.

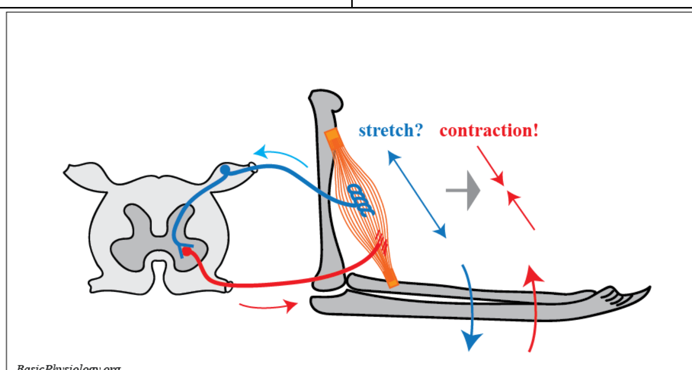
B. Muscle Stretch Reflex:

1. Probably the most 'basic' type of reflex is the stretch reflex, also called the myotatic reflex.	2. As you can see in the diagram, it consists of a muscle spindle and a motor endplate, both located in the same muscle. From the muscle spindle, a sensory nerve propagates to the spinal cord where it enters into the dorsal root.
3. There the nerve connects, in the anterior horn, with a synaps to an alpha-motor neuron. The axon of this neuron leaves the spinal cord, through the dorsal root, to the motor endplate of the same muscle.	
4. Its function is simple. When the muscle is (suddenly) stretched, this stretch is detected by the intrafusal fibers in the muscle spindles.	5. This stretch induces action potentials in the muscle spindle that propagate, through the sensory nerve to the spinal cord. The nerve ends as a synapse onto the body of the motor neuron, in the anterior horn.

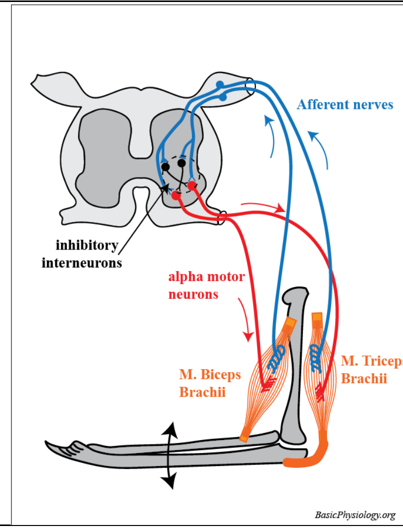
6. There it stimulates the neuron to produce action potentials that propagate, through the motor nerve, to the motor-endplates of the same muscle.	7. This will lead to muscle contractions that will reduce the length of the muscle to its original length. It is like a feed-back loop!
8. This reflex works very fast! From stretch to contraction, about 25 msec!	

C. Body Position and Posture:

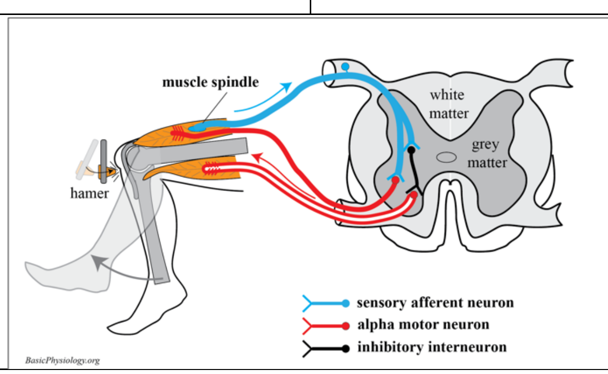
1. Why do we need this stretch reflex?	2. To keep our posture! Without this reflex, our body would collapse.
3. Look at this simple diagram. The biceps muscle holds the lower arm at an angle to the upper arm, in this case about 90 degrees.	4. If for some reason, the lower arm moves downwards, then the intrafusal fibers in the muscle spindle will also be stretched which will evoke action potentials.



5. These action potentials will propagate to the spinal cord where it will excite the alpha-motor neurons of the biceps.	6. These action potentials will propagate back to the biceps to increase its contraction force which will move the lower arm back to its original position. All this automatically and very fast (25 msec!).
7. But what about the other muscles that are also attached to the arms around the elbow joint? After all, they also play an important role in keeping up this position.	

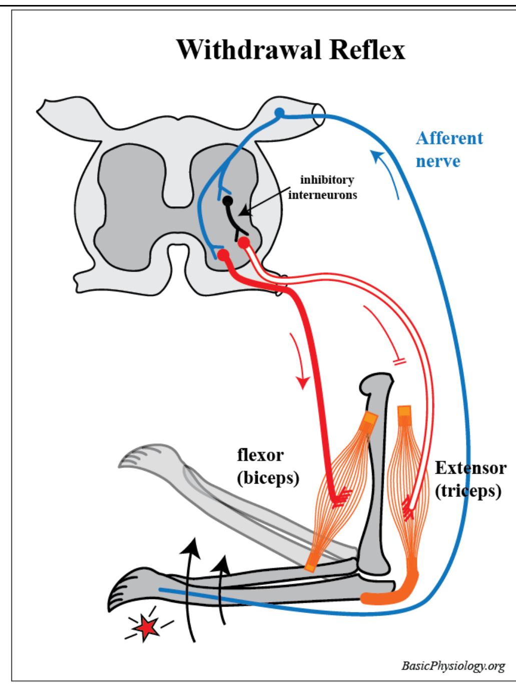
<table>
<tr><td>8.
But, as you can see in this second diagram, it now becomes a bit more complicated in the spinal cord.</td><td rowspan="2">
</td></tr>
<tr><td>9.
As one muscle, for example the biceps, is contracting, then the ‘opposite’ muscle, the triceps, must do the opposite; relax!</td></tr>
<tr><td>10.
And if the triceps contracts, then the biceps must relax. And all this very very fast!</td><td>11.
Fortunately, this is taken care of by negative intermediary neurons (in black in the diagram). So, when one alpha motor neuron is activated, the ‘opposite’ motor neuron is inhibited.</td></tr>
<tr><td colspan="2">12.
And, as you have to realize, this is the case for all our skeletal muscles in our body, adjacent to all our joints, from elbow to knee joint etc.</td></tr>
</table>

D. Knee jerk reflex:

<table>
<tr><td>1.
A nice way to test this system, which is often used by doctors, is the knee jerk reflex.</td><td>2.
In this test, a hammer is used to strike the tendon of the knee patella.</td></tr>
<tr><td colspan="2">
</td></tr>
</table>

3. This tendon is attached to the upper leg muscle. The sudden ‘jerk’ of the tendon will suddenly stretch the muscle fibers including the muscle spindles inside that muscle.	4. As the intrafusal fibers are also suddenly stretched, they will send action potentials along their afferent nerves to the spinal cord.
5. This will excite the corresponding alpha motor neuron which will contract this muscle and move the lower leg, suddenly, upwards, like a ‘kick’.	6. At the same time however, the opposite muscle must be inhibited (relaxed) to allow this jerk movement to take place.
7. Therefore, that muscle must be inhibited. This is performed by an interneuron, located in the spinal cord and activated by action potentials from the same excited muscle spindle.	8. However, the action potentials in that interneuron will inhibit action potentials of the opposite muscles, allowing that muscle to relax.

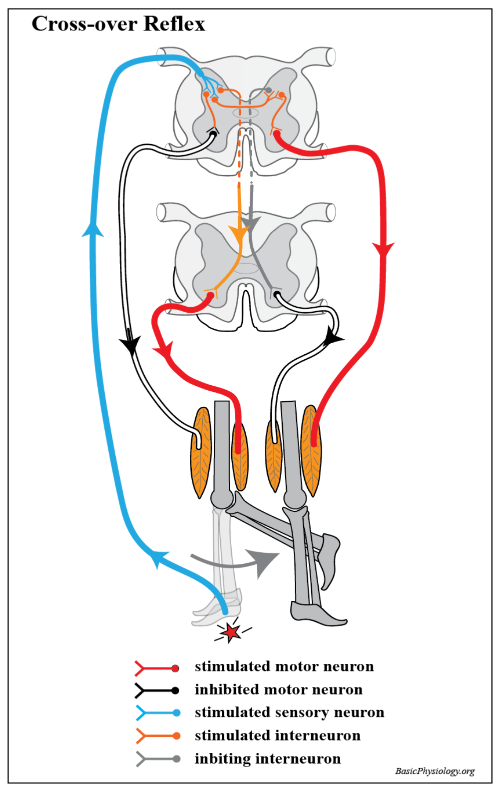
E. Withdrawal reflex:

1. The withdrawal reflex occurs when your hand (or foot) encounters a sharp (or hot) object inducing a sudden withdrawal of your limb.	
2. The purpose of this reflex is to jerk your hand away from this dangerous stimulus.	
3. And again, this must happen very fast, to avoid further damage to your hand.	
4. The diagram shows the most important pathways of this withdrawal reflex. Starting with the hand where a sharp object has stimulated a painful stimulus.	
5. This induces action potentials in the sensory nerves that travel to the spinal cord. Once in the spinal cord, the nerve synapses to a motor neuron and to an interneuron.	6. The motor neuron is connected and excites the corresponding flexor (in this case the biceps) to contract strongly.

7. The interneuron is connected, as an inhibitory neuron, to the motor neuron of the opposite muscle; the extensor.	8. This is important because you want the arm to move rapidly away from the painful stimulus and therefore, the extensor muscle must not contract, but relax.

F. Cross-over reflex:

<table>
<tr><td>1.
In the arms, the withdrawal reflex works fine; jerk your hand and arm away from the painful stimulus. That’s all!</td><td>2.
But in the legs, jerking your foot suddenly away from a painful stimulus is more complicated.</td></tr>
<tr><td>3.
If your right foot/leg is suddenly jerked away, then you would suddenly fall over! And, remember, all this happens very quickly.</td><td>4.
To avoid your falling over, your other leg must take over your posture. Fortunately, we have neuronal connections for this!</td></tr>
<tr><td>5.
But since several muscles in the upper and lower legs are involved in this reflex, the neuronal connections must also cross-over to the other side of the spinal cord and to other segments in the spinal cord.</td><td rowspan="5">



</td></tr>
<tr><td>6.
So, the flexor in the right leg must be stimulated to withdraw the foot from the painful stimuli. This is a simple withdrawal reflex.</td></tr>
<tr><td>7.
At the same time, the opposite extensor muscle in the right leg must be inhibited. Like in the withdrawal reflex</td></tr>
<tr><td>8.
But, the muscles in the left leg must also be excited. But this time it is the extensor that must be stimulated while the flexor must be inhibited. The opposite action!</td></tr>
<tr><td>9.
Fortunately, as you can see in the diagram, there are several interneurons that connect the motor neurons in the right way.</td></tr>
</table>

10. Btw, the withdrawal effect is only functioning in the legs. Not in the arms! We don't need that in the upper limbs.	11. That's because you will not 'fall over' when you suddenly 'withdraw' an arm. The legs are keeping us stable, thanks to all the stretch reflexes in our legs.

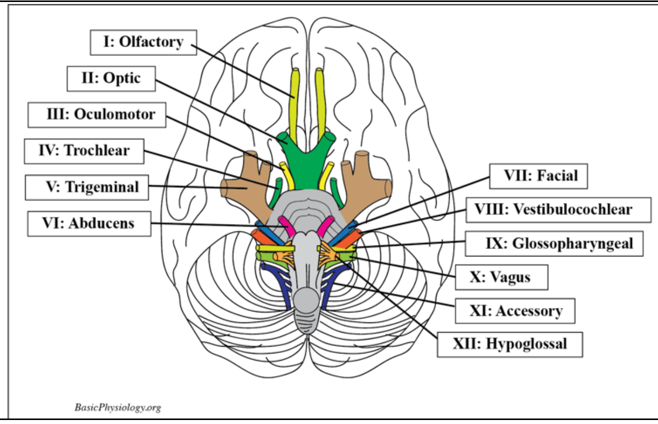
H.5. Somatic Nervous System

A. Introduction:

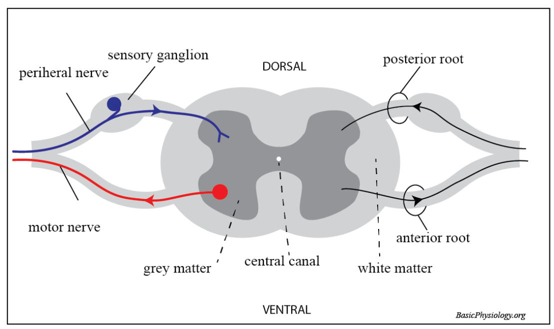
1. In the previous sections/chapters, we discussed at length the major parts of the Central Nervous System (CNS).	2. It is now time to start discussing the other part of the nervus system; the Peripheral Nervous System.
3. What is the major difference between the Central and the Peripheral nervous system? The peripheral system is located **outside** the skull and the vertebrae; is therefore not protected by the bony structures.	3. The Peripheral Nervous System consists of two major parts: a. the Somatic Nervous System b. the Autonomic Nervous System
4. In this section (H.5.), we will discuss the Somatic Nervous System and in H.6. the Autonomic Nervous System (ANS).	

B. Somatic Nerves:

1. The somatic nervous system consists (again!) of two parts; afferent motor nerves that run to effectors (muscles, glands etc.) and efferent sensory nerves (such as taste and touch) to the CNS.	2. All these nerves can be grouped into nerve bundles. In the upper part of the body, these nerves run though the 12 cranial nerves (I-XII). *See H.2.2. Cranial Nerves*
3. The first two cranial nerves (olfactory and optic nerve) are actually part of the CNS as they are located inside the skull but that is a minor issue.	4. The other 10 cranial nerves (III-XII) originate from the brainstem and are mostly involved in the function of organs (muscles etc.) located in the head.

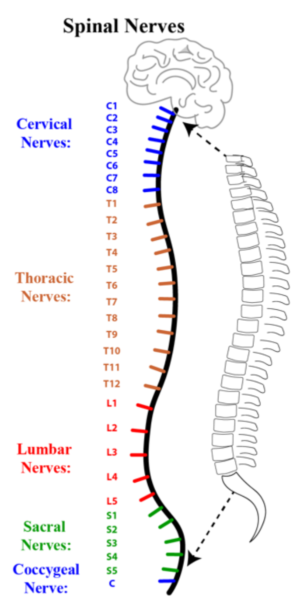


5.
For the rest of the body, the spinal nerves are responsible for the somatosensory network.
These spinal nerves come out of the spinal cord in the space between two adjoining vertebrae, towards and from the left and the right side of the body.



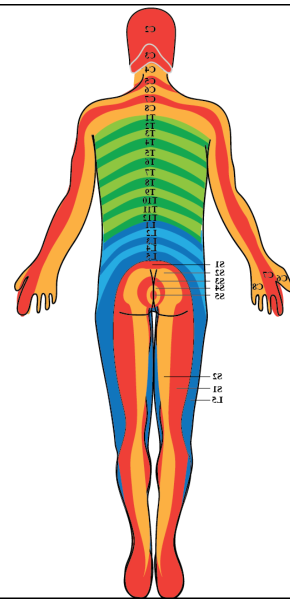
6.
In humans, there are 31 pairs of spinal nerves:

a. 8 cervical
b. 12 thoracic
c. 5 lumbar
d. 5 sacral
e. 1 coccygeal



7.
The last one, the coccygeal (= tailbone; remnant of ‘our’ tail) nerve is often forgotten! Even I forgot it (*see H.3.2 Sensory pathways*).

C. Remember the dermatomes?

1. As we said before, the sensory nerves come for a large part from sensors located in the skin (touch, temperature and pain). These afferent nerves run to the nearest nerve bundle to enter the spinal cord and the brain.	
2. The origin of these nerves and their sensors can therefore be grouped together into 'dermatomes', as discussed in *H.3.2. Sensory Pathways.*	
3. More or less the same also applies to the efferent nerves; the nerves that run from the spinal cord to their effectors (muscles, glands etc.). However, these effectors are located inside the body, coupled to the skeleton and other organs and therefore not 'visible' on the surface of the body as are the sensors.	4. In fact, the efferent nerves can be better described in anatomical then in physiological terms.

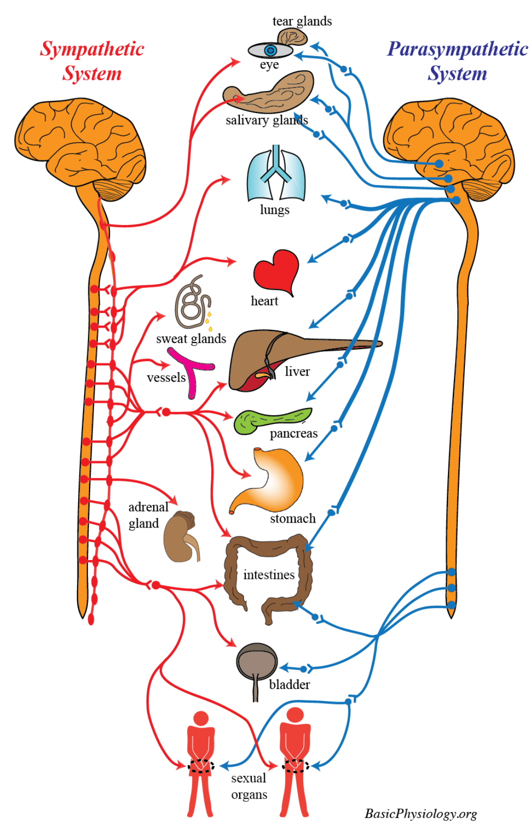
D. Nerves and Muscle groups in the Human Body:

Neck area: The Phrenic nerve: from C3 and C4 and runs straight through the thorax to the diaphragm. It is a major nerve for our respiration! -	
Shoulder: The muscles on and around the shoulder and the upper part of the thorax are innervated by:	N. Thoracicus longus -> M. Serratus anterior N. Thoracodorsalis -> M. latissimus dorsi N. Pectoralis medialis and lateralis -> the major and minor pectoralis muscles N. Axillaris -> M. deltoideus N. Dorsalis scapulae etc. -> shoulder muscles

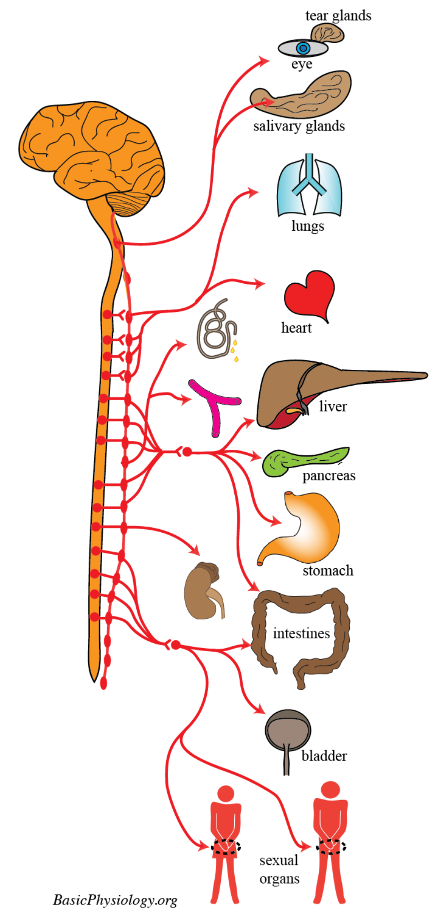
Arm: All the nerves for the arm originate in the brachial plexus (C1 – C8):	N. Musculocutaneus -> M. biceps, M. brachialis etc.) N. Medianus -> many muscles in the lower arm and hand N. Ulnaris -> many muscles in the hand N. Radialis -> many muscles in upper and lower arm
Thorax and Abdominal wall: these nerves originate from Th1 up to Th12.	N. Intercostales -> innervate the muscles of the ribcage (Breathing!) and also the muscles in the abdominal wall (M. rectus abdominis etc.)
Hip and Pelvis: these nerves originate from the plexus lumbosacralis (from L1-L5 and S1 to S4)	M. psoas major, minor N. ilioinguinalis and N. genitofemoralis innervate the skin (sensory) and muscles (motor) of the external genitalia of both males and females N. Gluteus superior and Inferior innervate the gluteus muscles in the hip (M. gluteus maximus etc.)
Leg: these nerves also originate from the plexus lumbosacralis	N. Obturatorius innervate several adductor muscles in the legs N. Femoralis innervate the muscles that stretch our legs (M. quadriceps femoris and M. sartorius) N. Ischiadicus innervate the dorsal muscles and also divides int two other nerves: a. N. Peroneus and N. Tibialis who also innervate many muscles in different parts of the legs.

H.6. Autonomic Nervous System

A. Introduction:

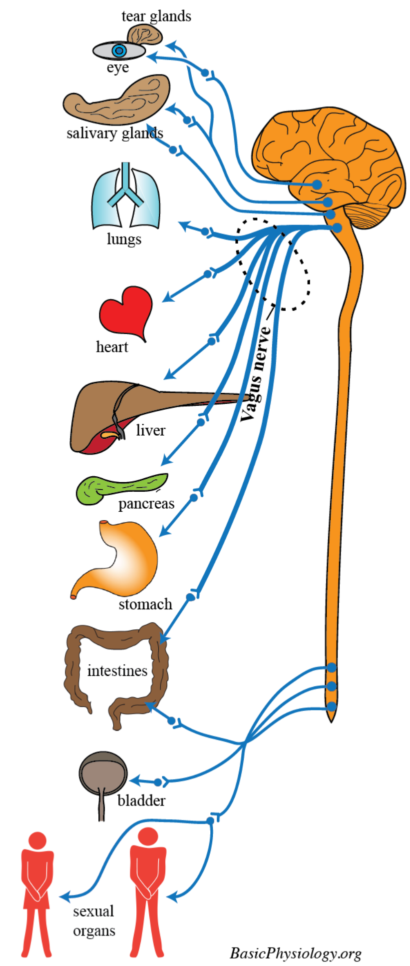
<table>
<tr><td>1.
Autonomic Nervous System!! This is a nervous system that is autonomic; that is; independent (to a certain degree) of the CNS.</td><td>2.
It is like having a robot inside your body that controls things that you have no idea about!</td></tr>
<tr><td>3.
I am not exaggerating. This part of the nervous system is very busy controlling many things in our body.</td><td>4.
As you can see in the diagram, the autonomic nerves are projecting into an immense number of internal organs, from the heart and the lungs, to the intestines, all kind of glands, etc.</td></tr>
<tr><td>5.
The autonomic nervous system, is also called the vegetative system or the involuntary system.</td><td rowspan="4">
</td></tr>
<tr><td>6.
It involves 'controlling' five different intestinal systems:
1. the Circulatory system
2. the Respiratory system
3. the Digestive system
4. the Urinary and Genital system
5. the Skin</td></tr>
<tr><td>7.
Not only must all these systems be 'regulated', but they must also be coordinated and work together.</td></tr>
<tr><td>8.
For example, it is pointless to force the heart to pump harder and the lungs to decrease breathing at the same time; that would contradict each other. Of course, that shouldn't happen!</td></tr>
<tr><td>9.
The autonomic nervous system consists of two systems that are each other's opposite:
a) The Sympathetic System
b) The Parasympathetic System</td><td>10.
All the internal organs are controlled by both systems whereby the sympathetic usually ‘excites’ the organ while the parasympathetic system ‘inhibits’ these organs.</td></tr>
</table>

B. The Sympathetic System:

<table>
<tr><td>1.
The sympathetic system starts with several nuclei, located in the hypothalamus, the medulla oblongata, and the spinal cord.</td><td rowspan="4">
</td></tr>
<tr><td>2.
As you can see in the diagram, the nerves from these centers leave the Central Nervous system into a string of nuclei, many of them located as a ‘string’ running parallel to the spinal cord.</td></tr>
<tr><td>3.
In these nuclei, the nerves connect through a synapse to a second nerve that connects to the intestinal organs.</td></tr>
<tr><td>4.
It is actually quite a complicated network of nuclei and synapses, that must be very interesting for neurophysiologist. But for us, basic students, the important thing to remember is that the sympathetic nerves runs from the central nervous system, to all the internal organs in the body; that’s enough!</td></tr>
<tr><td>5.
What is much more interesting and relevant is what does the sympathetic system do? In one word: WORK!</td><td>6.
The sympathetic system excites (= stimulates) the internal organs. This is necessary when the body is going to exercise, strong emotions, harder working, fear, or anger!</td></tr>
<tr><td>7.
In those situations, more energy is required for muscles to work harder, so the lungs and the heart must work harder and/or stronger to pump more oxygen to these muscles, and more sugar and adrenaline is also required for this to happen.</td><td>8.
But, at the same time, the work of some other internal organs simultaneously be decreased. For example, the stomach and the intestine must work less or else they would interfere with the harder work that the heart and the lungs have to perform.</td></tr>
<tr><td>9.
So, there is a delicate balance between those internal organs that are working harder while other organs work less.</td><td>10.
You can also see that in the behavior of the blood vessels. During the sympathetic drive, the blood vessels to the skeletal muscles will</td></tr>
</table>

<table>
<tr><td></td><td>dilate (to transport more oxygen and nutrients to the muscles), while the blood vessels to the intestines will constrict. Perfect balance!</td></tr>
</table>

C. The Parasympathetic System:

<table>
<tr><td>1.
As you can now understand, the parasympathetic system is the opposite of the sympathetic system!</td><td rowspan="4">
</td></tr>
<tr><td>2.
Instead of activating or simulating our body, the parasympathetic system calms it down!</td></tr>
<tr><td>3.
The parasympathetic system decreases the heart rate and contraction, lowers the breathing of our lungs, narrows the blood circulation to the skeletal muscles, etc.</td></tr>
<tr><td>4.
And, again, as the opposite of the sympathetic system, it also activates some internal organs that are useful in restoring and keeping our body healthy, by stimulating the intestines, dilating the relevant blood vessels, storing energy in our cells, so that we are again prepared for another sympathetic ‘attack’!</td></tr>
<tr><td>5.
There is one more important thing to remember in the parasympathetic system, and that is the presence of the most important nerve in our body; the vagus nerve.</td><td>6.
As you can see in the diagram, in contrast to the innervation of the sympathetic system, most of the parasympathetic nerves run though one ‘huge’ nerve, the vagus nerve.</td></tr>
<tr><td>7.
Only high in the brain and the upper part of the spinal cord, and in the most distal part of the spinal cord, do other parasympathetic nerves connect to their respective organs.</td><td>8.
But the vast majority of the internal organs are parasympathetically connected through the vagus nerve. Remember!</td></tr>
</table>

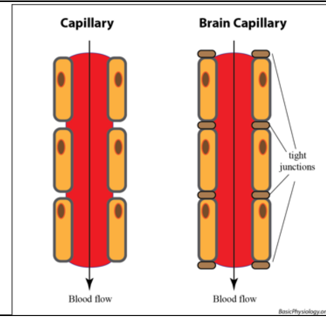
H.7. Blood Circulation and Glymphatic System

D. Introduction:

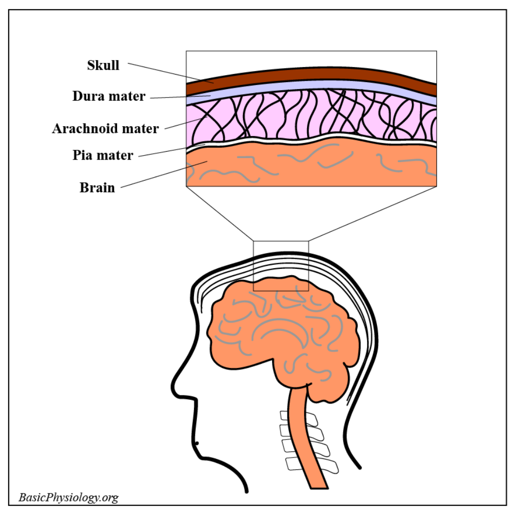
1. There are many special things about the CNS (as you have seen in previous pages) but there is one more to go! The blood circulation and the lymph circulation.	2. The blood circulation is of course crucial to our well-being and because our brains are so 'delicate', they need extra protection, even from the circulating blood!
3. And, then, there is another surprise; there are NO lymphatic vessels in the CNS!	4. That is weird! Isn't the lymphatic system designed to remove waste products from the external fluid?
5. Yes, that is true, but this is so crucial that another system has developed in the CNS; the **glymphatic** system; which we will (also) describe in this page.	

E. Blood circulation:

1. As in other organs, the capillaries in the CNS are responsible for the transport of fluid and many molecules from the blood to the interstitial fluid and back.	2. This is case for the transport of water, carbon dioxide, oxygen, and other lipid-soluble substances such as anesthetics and … alcohol (How NICE!),.
3. In fact, there is a huge amount of blood vessels, especially capillaries, in the brain tissue. The length of all the capillaries together is estimated to cover more than 500 miles!	4. However, the delicate brain tissue must also be protected against noxious material that may be present in the circulating blood.
5. Therefore, the capillaries are NOT permeable to plasma proteins and other large molecules, such as therapeutic drugs. This non-permeability is called **Blood Brain Barrier**!	6. As you can see in the diagram, the boundary of the capillaries between the blood and the interstitium, which is readily accessible in normal tissue, is firmly closed by **tight junctions** in the brain; hence the name Blood-Brain-Barrier!

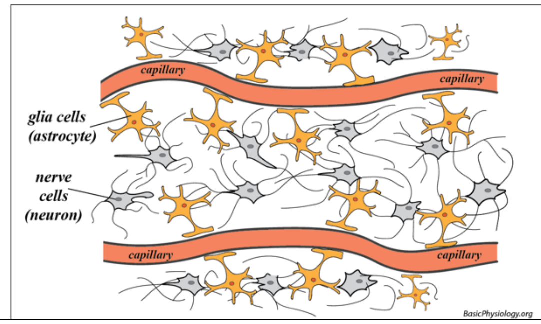
7. Because of this barrier, only the most essential nutrients are allowed to leave the blood capillaries. These essentials are of course the gasses (oxygen and carbon dioxide), and fat-soluble molecules.	
8. In addition, there are also several transport systems available, for example to transport glucose into the brain.	9. Unfortunately, this barrier also makes it difficult or impossible to provide medical treatment such as anti-microbrial drugs to the brain.

C. Breaking News: The Glymphatic System.

1. But we are still facing the problem of the lack of lymph vessels in the brain. How does the brain get rid of waste products etc?	2. Breaking news! There is after all, a lymphatic system in the brain but, in several aspects, quite different from that in other organs.
3. There are lymph vessels that are located, together with the arteries, the veins and nerves, in the arachnoid space. This arachnoid space is located between the dura mater and the pia mater, just below the skull:	
4. Together, these layers form the meninges: a) Dura mater (outer layer) b) Arachnoid mater (middle layer) c) Pia Mater (inner layer) *Btw, 'mater' is Latin for 'mother'!*	
5. But below the meninges, in the brain, there are arteries, veins and plenty of nerves, but no lymph vessels!	6. In the interstitial space, between the neurons, there is still fluid streaming from the capillaries into the interstitial space, to provide oxygen etc. and streaming back to the capillaries to remove CO2 etc.
7. But what about those waste products that do not make it back to the capillaries and that, in	8.

other tissues, are removed by the lymph vessels?	This is where a new system comes in, new because this was recently discovered but, of course, has been there for millions of years! This is the **glymphatic system**.

D. The Glia Cells:

1. This diagram displays the architecture of the tissue located in the brain between the capillaries. As you can see, there are capillaries and many nerve cells. But interestingly, there is also another cell type prominently present; the glia cells (also called astrocytes).	
2. And, as "promised", there are no lymph vessels.	3. The current concept of the glymphatic system is that instead of the lymph vessels, there are glia cells that take care of the removal of waste products from the interstitial space.
4. It is not yet fully clear how that is done but one hint can already be seen in this picture; the fact that many glia cells seem to have a 'foot' that is located close to a capillary membrane.	5. Recently, an ion channel was found in these "feet" which, when these channels were blocked, led to local interstitial swelling. In other words, the glia cells together with these channels in some ways are responsible for the removal of extra fluid and waste products from the brain tissue.
6. Interestingly, this glymphatic system has only been discovered/described in recent years. When I started studying physiology (some ±40 years ago; ☺) no one knew anything about this system!	7. However, it must be clear that this is a developing 'story' and that many laboratories around the world are now working hard to solve this interesting problem!
8. And, oh yes, why has this new system been called "glymphatic"? Because this word is a junction of "glia" and "lymph"!	

E. Who discovered the Glymphatic System?

1. In 2013, Danish neuroscientist Maiken Nedergaard and her team discovered (and described) the glymphatic system.	2. She gave this system the term 'glymphatic' as it is similar to the lymphatic system but also required glial cells for its function.
3. But, as always, in science, she was not the first one (or the last one) to study this system.	4. Previous scientist, such as Rudbeck (18^{th} century!), Csanda (1966) and many others have also 'worked' on the problem of lymph circulation in the CNS. And, as you can now imagine, we will learn much more in coming years!

Basic Physiology Info:

This book collects the text and figures from my website: *BasicPhysiology.org*. This may be useful for anyone who either wants all that info in the same document, a pdf in this case, away from the internet or for any other reason.

What is this book about?

1. This is a **simple** book, dedicated to teaching the **basics** of physiology.	2. I have used a similar site for many years, teaching human medical physiology in several medical and para-medical schools.
5. While I am (**still**) expanding and upgrading this and future chapters, I most certainly welcome your comments, suggestions and/or questions. Feel free to contact me: wlammers@smoothmap.org	*Thank you for your interest!*  *Wim Lammers*

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