Chapter H: Central Nervous System

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H.3. Sensory System

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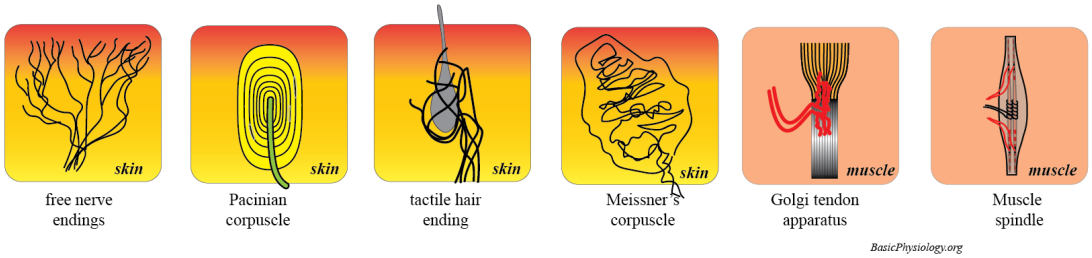
H.3.1. Sensory Receptors

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".

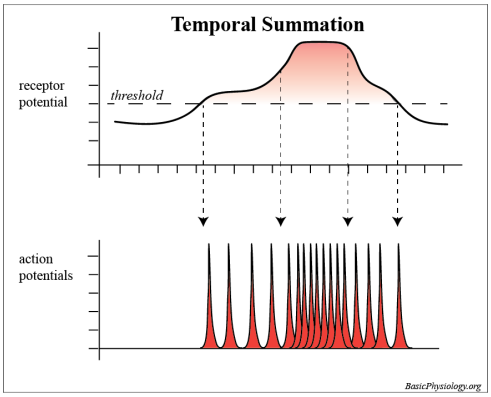
B. Types of receptors:

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.
	
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**.

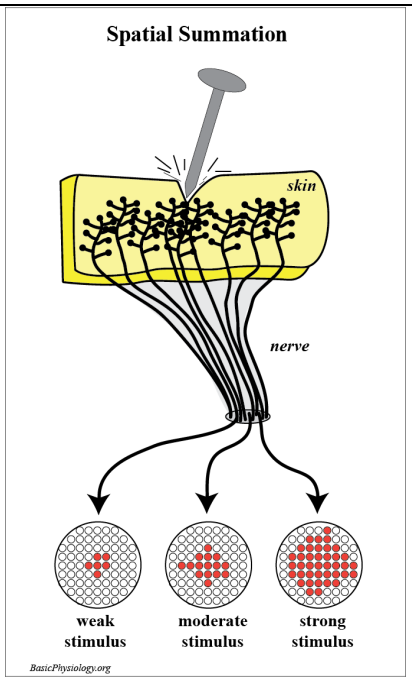


4.
In this mechanism, the strength of the stimulus is translated into a potential in that sensory organ. That receptor potential in turn can then, if it is higher than the threshold, initiate action potentials in the efferent nerve.

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!

7.
Another way to transmit 'more' info to the brain is by **spatial summation**.

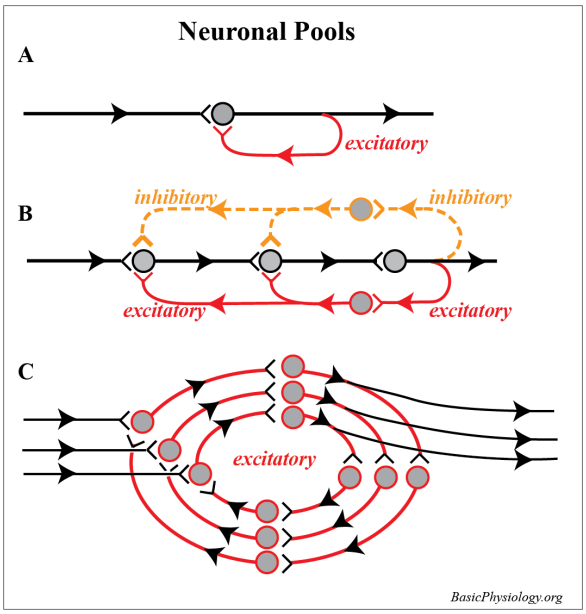


8.
As shown in this diagram, a pin induces a 'painful' pressure in the skin which is perceived by the free nerve endings that serve as pain receptors.
As there are many free nerve endings in the skin, each with their own axon, then a stronger stimulus, which induces a larger depression, will induce action potentials in more neighbouring axons.

9.
And so, again, the brain gets more information with this spatial summation of active efferent nerves.

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

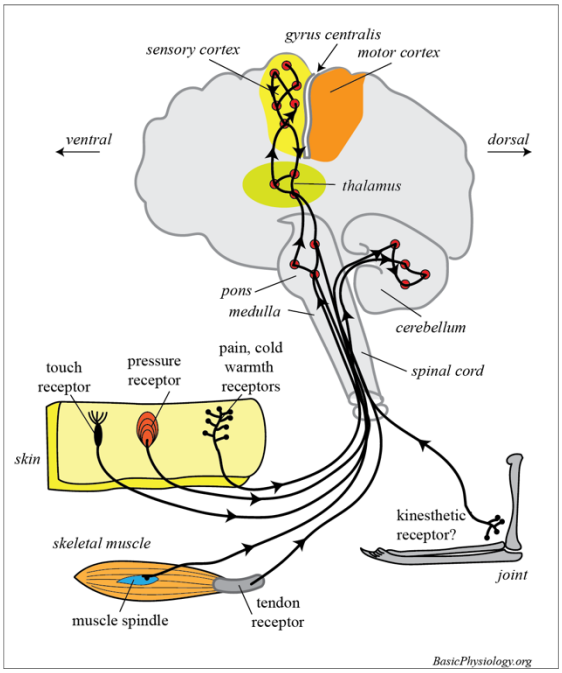
E. Types of Senses:

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

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	4. You may choose your own system!

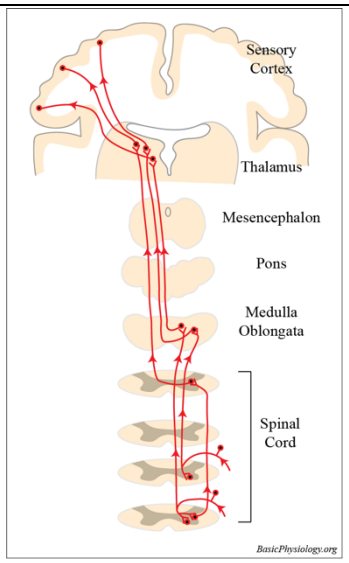
H.3.2. Sensory Pathways

A. Introduction:

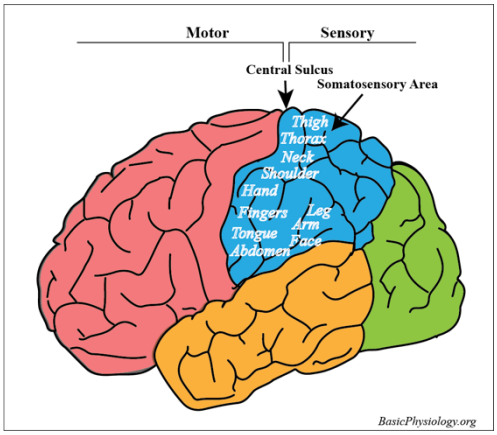
1. As you can imagine, the sensory part of the brain is the system that 'senses' all kind of sensory experience from the outside world and transmits that info to several regions in the brain.	2. In the previous chapters, we already discussed several types of receptors involved in the detection of several 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:

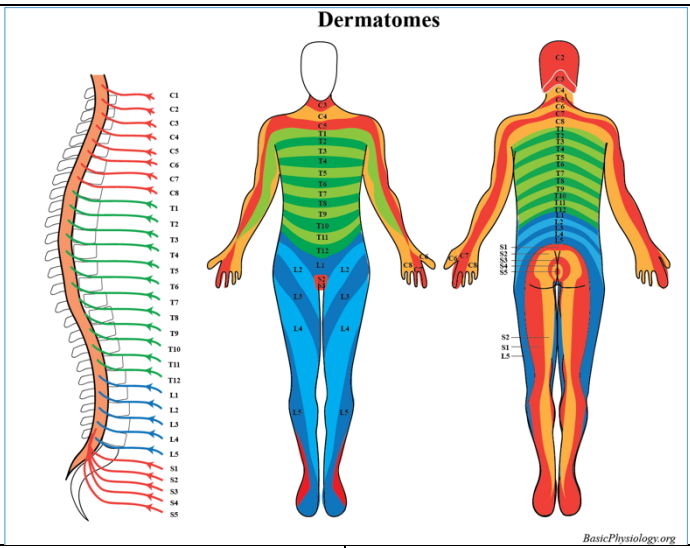
1. When the sensory nerves enter the spinal cord through the dorsal root, it immediately splits into several branches.	
2. Some of these branches move to the dorsal side of the spinal column and then upward in a dorsal column all the way to the brain.	
3.	

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.	
4. Some of these fibres induce local spinal cord reflexes. Other fibres move up the spinal cord to end in the cerebellum.	

C. Cerebral Cortex:

1. But the most "important" fibres go straight to the cortex of the large brain; the cerebral cortex.	
2. And, they end up in a special ordained region, depending upon from which area of the body they came from.	
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.	
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.	

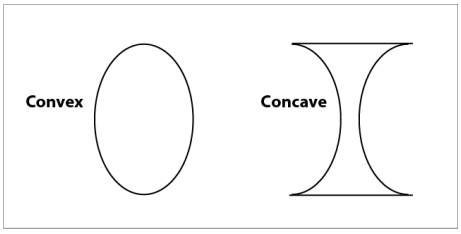
D. Dermatomes:



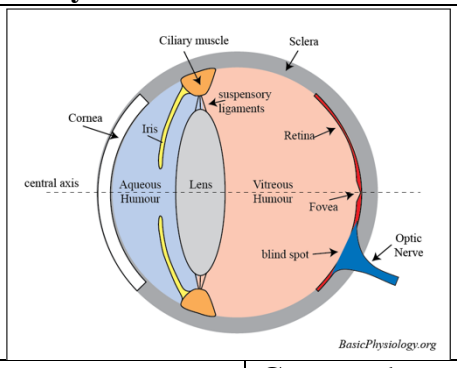
1. There is another interesting concept which is very popular in physiology and medicine in general; the **dermatomes**; see diagram. (*dermis = skin*)	2. It is actually not that important but probably popular because of this beautiful picture of a human with all these coloured stripes, as seen from 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

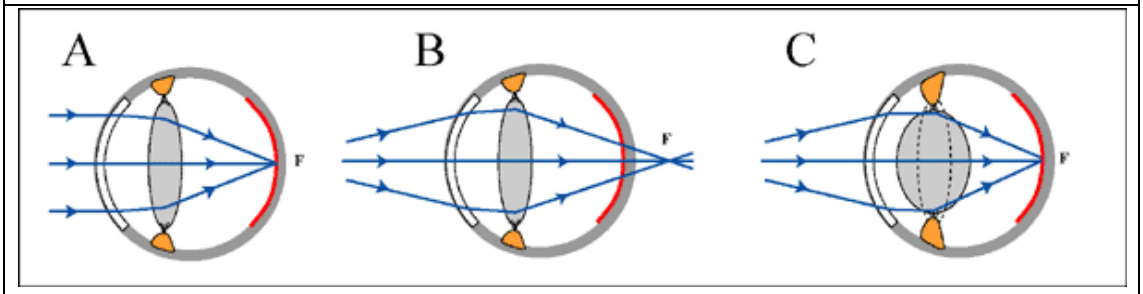


Fig A. The eye is not accommodated. In this situation, when the light travels in parallel rays, from far away, then the focus will fall on the fovea.	**Fig B. When the light rays diverge,** because the image is close to the eye (for example when one is reading), then, if nothing changes, the focus will 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:

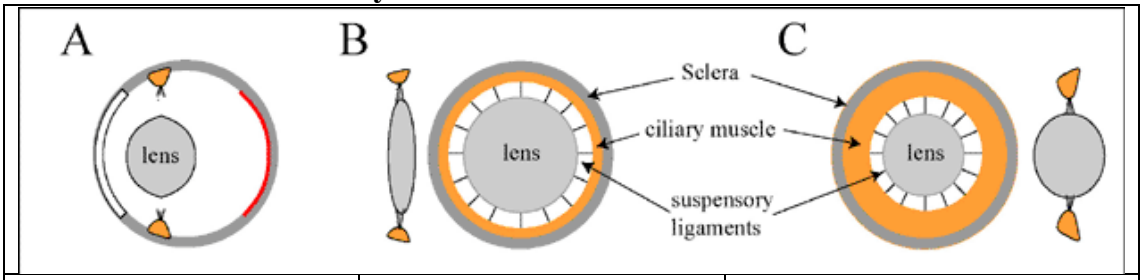
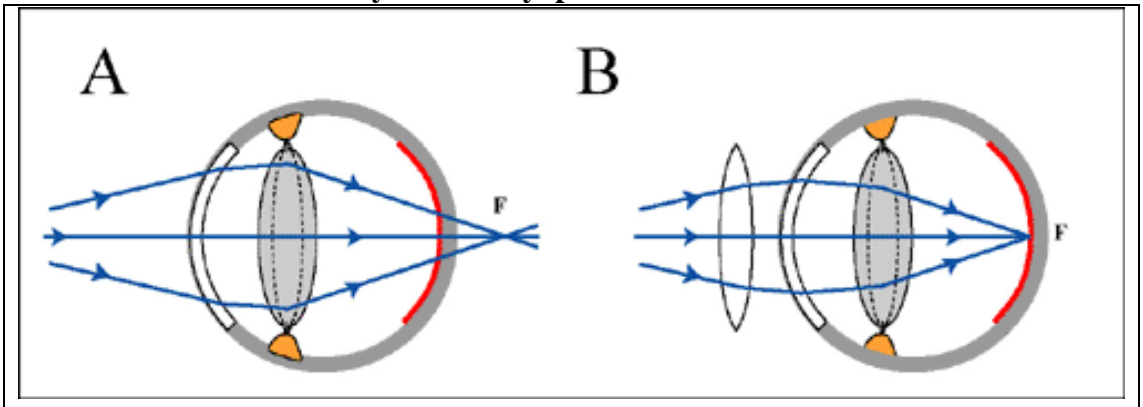


Fig A. The natural recoil of the lens. The lens, by itself, when cut of from the suspensory ligaments, is	**Fig B. Non-accommodated.** In this situation, the ciliary muscle is resting and stretches the	**Fig C. Accommodation.** When the lens has to accommodate (=reading), then the ciliary muscle contracts, the 'hole' in the

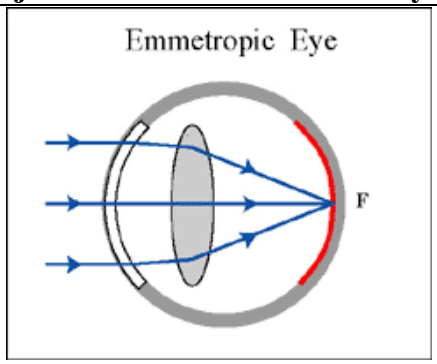
very convex (close to a sphere). It is, in the eye, stretched by the suspensory ligaments and the ciliary muscle into a thinner and lesser convex lens.	ligaments, thereby also stretching the lens into a less-convex shape. This is the situation when looking far away.	muscle becomes smaller, the suspensory ligaments move towards the centre, and this allows the lens to become more convex.

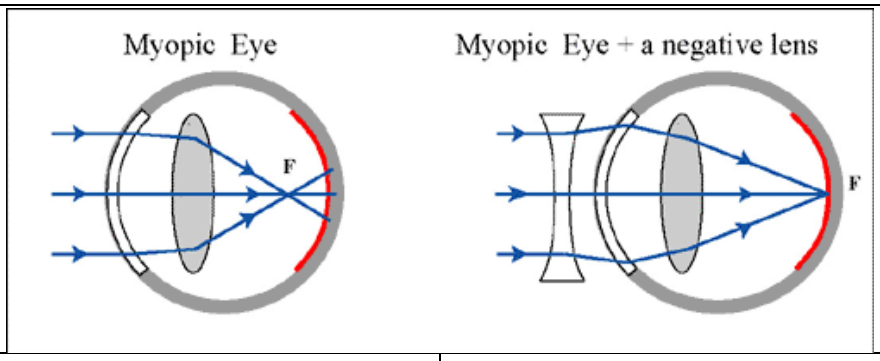
E. Accommodation of the eye 3: Presbyopia.



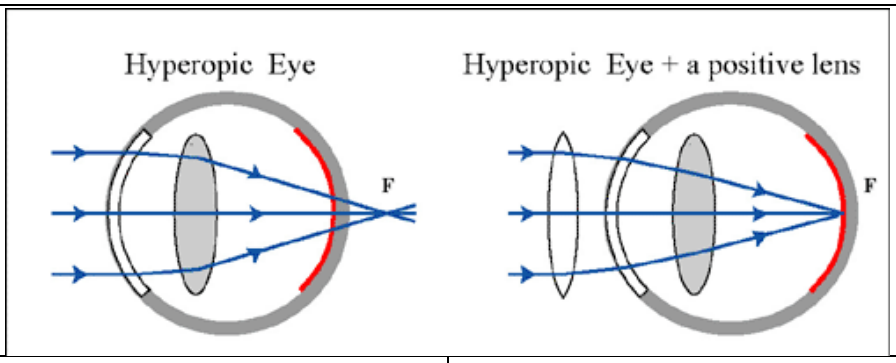
Presbyopia. In some eyes, especially in older people, the elasticity of the eye has decreased and the lens is no longer as convex as before.	**Fig A. Maximum accommodation.** In that situation, a maximum accommodation (= contraction of the ciliary muscle) will still not be able to move the focus to the fovea and the image remains blurry. This situation is called **presbyopia**.	**Fig B. Reading lenses.** 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.

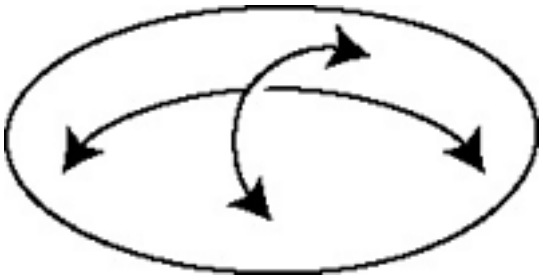


In a **myopic** eye (=myopia), light rays from far away fall in front of the fovea. To the patient, the image looks blurred. The solution is to provide the patient with a concave ("-") lens.	**Note** that such a person can look sharp at images close to the eye (like reading) as this will move the focus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

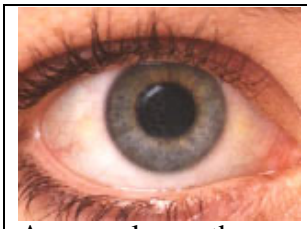
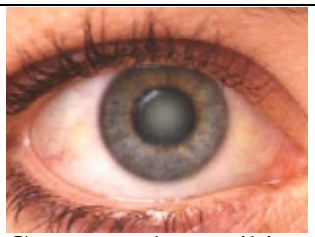


In a **hyperopic** eye (=hyperopia), parallel light rays will fall "behind" the retina. To help these patients, a convex ("+") lens is required which will help 'break' the light rays more.	**Note** that these patients can (and do) help themselves by accommodating their lens. This will also move the focus 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:

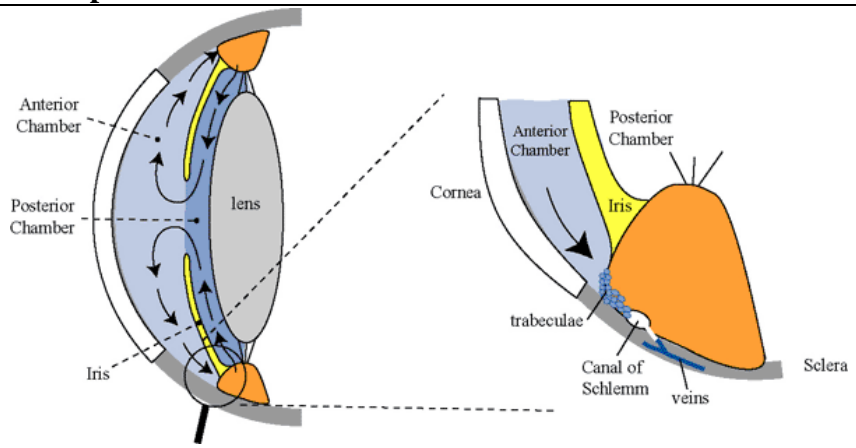
1. In the previous refraction anomalies (myopia and hyperopia) the curvature or the bending of the lens was the same at all angles. In some patients however, the degree of curvature is different between two (or more) different angles. In the diagram, this is illustrated by a flat convex lens that is 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	 **Cataract**; the pupil is cloudy or 'milky'

	blurred. The therapy is to remove the lens and to replace it with a new artificial intra-ocular lens.	

I. Intra-ocular pressure:

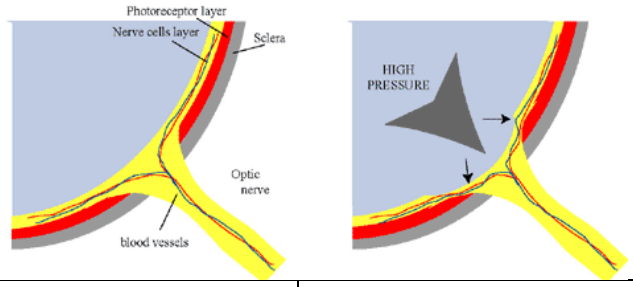


Anterior and Posterior Chamber:	**Intra-ocular circulation 1:**	**Intra-ocular circulation 2:**
The space between the cornea and the lens is filled with a fluid (= the aqueous humour). The iris divides this fluid in two spaces; a **posterior** and an **anterior** chamber (chamber = room).	The ocular 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:

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.

Glaucoma 2:

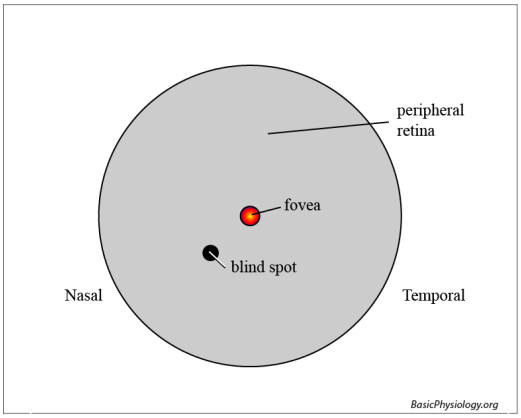
If the perfusion is stopped, the photoreceptor cells will become ischemic (= no blood) and die. The person will become blind.

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:



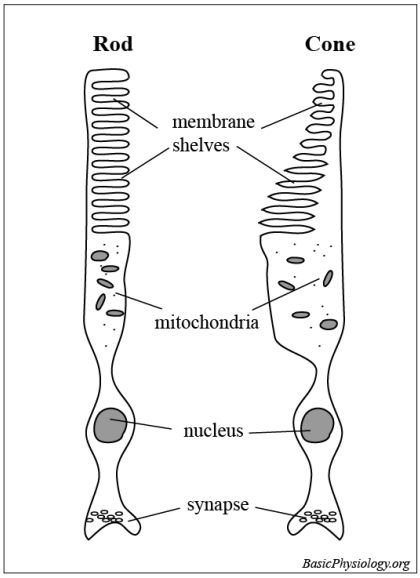
The **retina** consists of:

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:



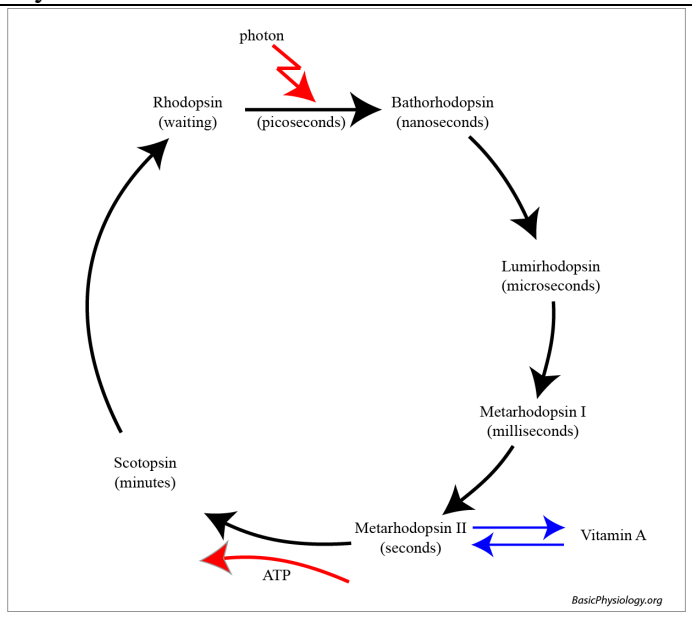
Photoreceptors:

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.

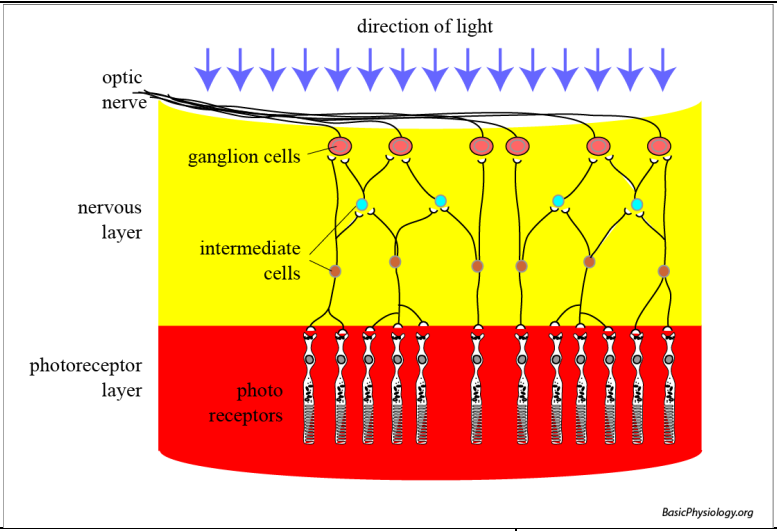
The **difference** between the two cells is that in the **rods**, the shelves are of the same size whereas in the **cones**, the shelves diminish in size further away from the cell body, hence its shape and its name.

C. The Rhodopsin cycle:



1. Rhodopsin: 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.	**2. Excitation**: 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*).	**3. Unstable**: 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: 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.	**5. Restoration of Rhodopsin:** The final stable meta-rhodopsin II is converted through scotopsin back to rhodopsin. This takes time (minutes) and energy (ATP).	**6. Vitamin A:** 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:



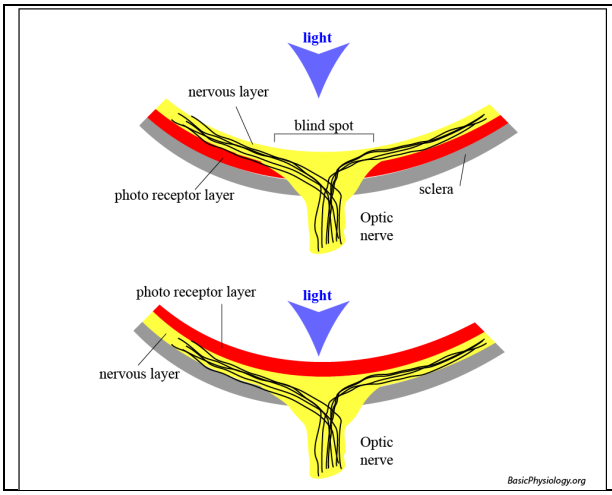
The retina has **two** layers:

- **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.

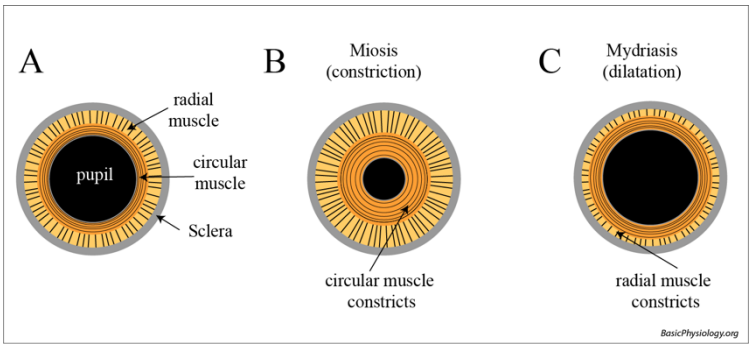
E. The Blind Spot:

	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.



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!

F. The Iris and the Pupil:



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.	**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). 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	**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 **sympathetic** nervous system.

	parasympathetic 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).

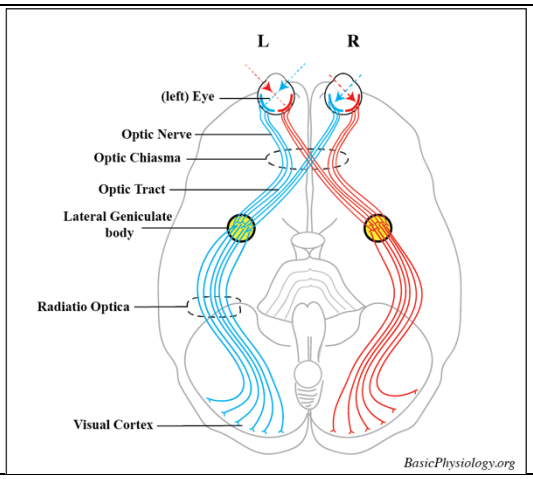
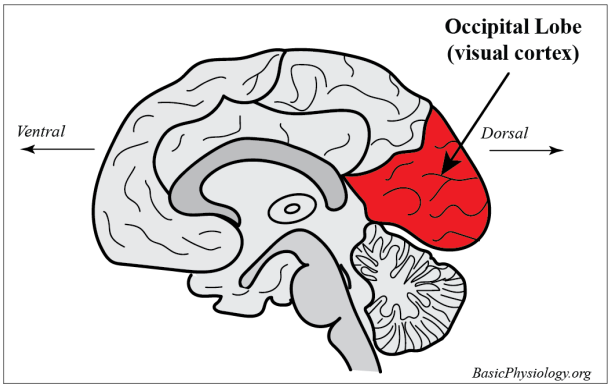
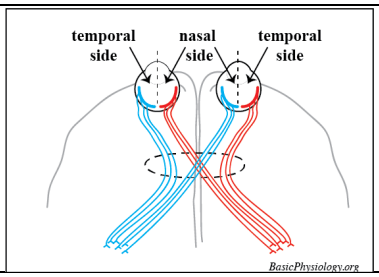
H. Central and Peripheral Vision:

Central vision: This is the vision as captured by the **fovea**. Most of the photoreceptors in the fovea are **cones** and practically every cone has its	**Peripheral Vision:** The remainder but largest part of the retina is covered by the rods, which are light sensitive but not colour sensitive.

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.	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).

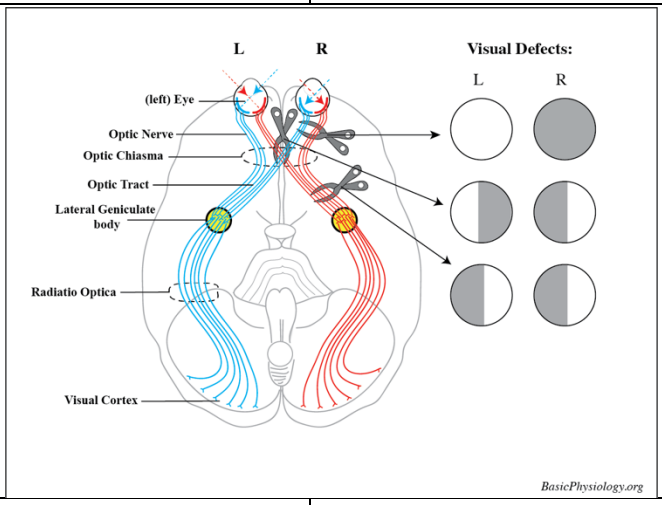
H.3.3.1.c. The Optic Nerve

A. Anatomy of the Optic Nerve.

<table>
<tr><td>1.
As you can guess, the optic nerve connects the retina of the eye to the brain.</td><td>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!</td></tr>
<tr><td>3.
But this connection between the eye and the brain is not as straightforward as you would expect.</td><td>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…</td></tr>
<tr><td>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.</td><td>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!</td></tr>
<tr><td> 
</td><td> 
</td></tr>
<tr><td>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.</td><td> 
</td></tr>
<tr><td>8.</td><td>9.</td></tr>
</table>

Why do these nerves cross-over like this? Nobody knows! But is, unfortunately for students, a fact.	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.	

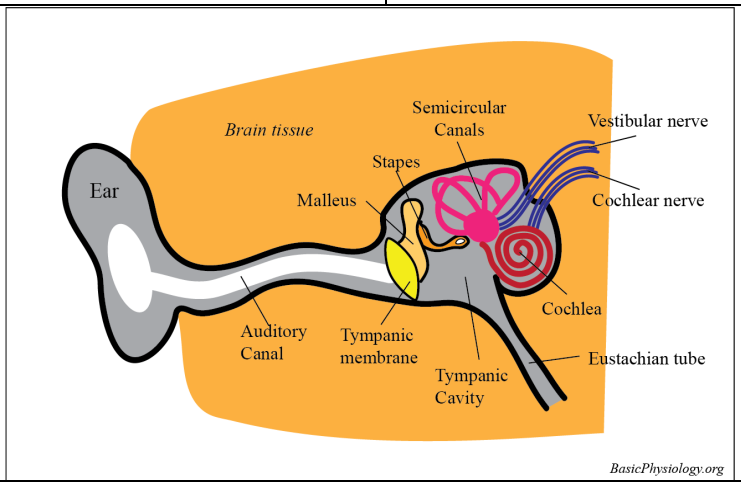
B. Visual defects

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*).

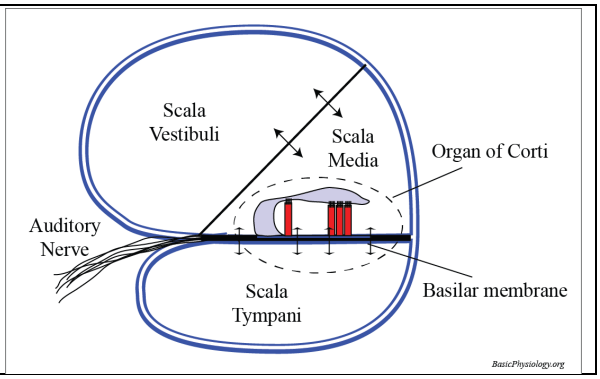


B. Middle Ear:

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:	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.
These ossicles work as **levers**; thereby **magnifying** the amplitude of the sound waves (approximately 20x).	
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.	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.
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**.	5. These muscles contract by reflex, when there is a loud noise, to pull at the ossicles and to prevent them of getting dislodged.

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**.

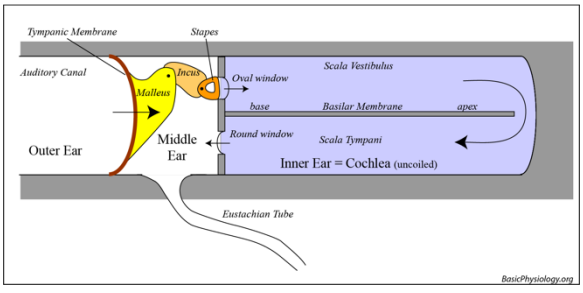
3.
The **scala media** and **scala vestibuli** work together. Between these two and the **scala tympani**, there is the **basilar membrane**.

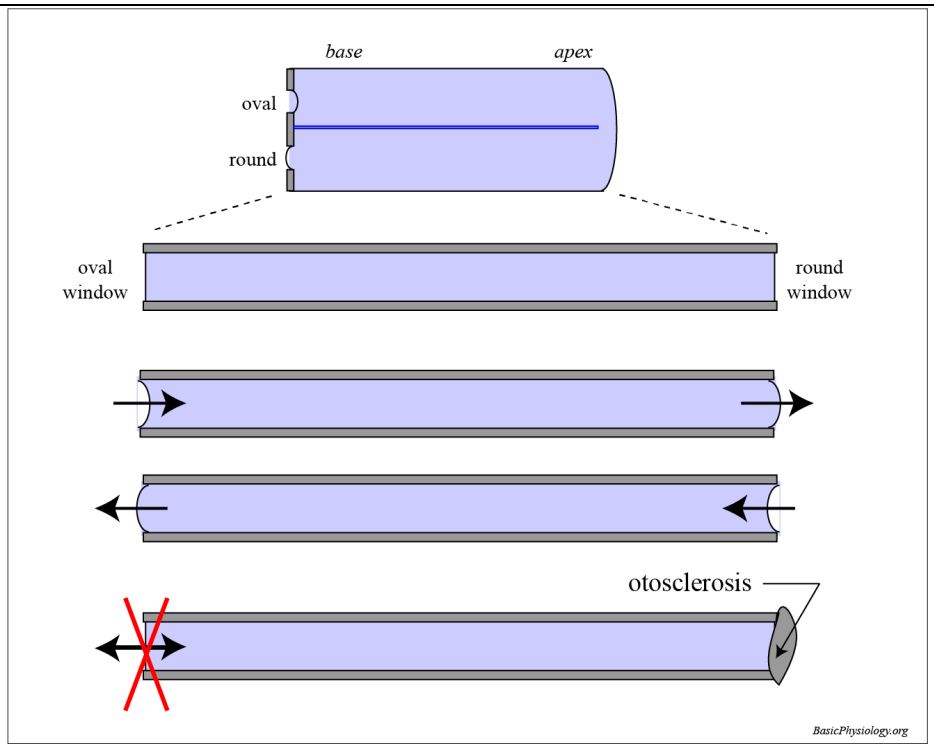
4.
On this basilar membrane, the sensor of the ear, the **organ of Corti** is located.

(Scala = Italian for staircase)

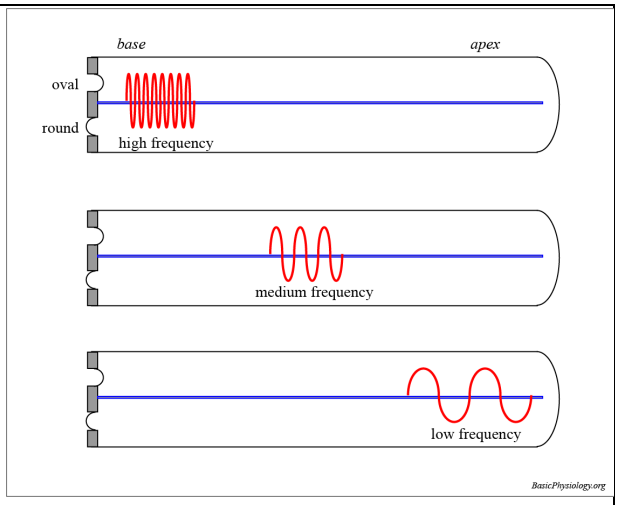
5.
The **inner ear** can be described as a single tube which starts at the oval window and ends at the round window. This tube is filled with fluid. If the membrane of the oval window is pushed inwards, by a sound vibration, then the round window membrane, at the other end of the tube, is pushed outward. 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).





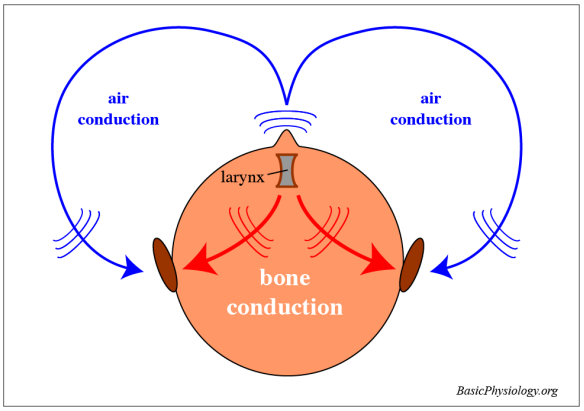
7.
The **basilar membrane** will vibrate when the fluid in the upper and in the lower scala's vibrate. But the basilar membrane is not the same (homogeneous) along its length. Rather, it contains fibers that are short and stiff in the base and long and slender in the apex.
Therefore, the basilar membrane 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):

<table>
<tr><td colspan="2">1.
Deafness can be caused by an abnormality in the outer ear, the middle ear or the inner hear.</td></tr>
<tr><td>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.</td><td>3.
Abnormalities in the cochlea (the inner ear) or in the nerves are called Nerve deafness or Sensorineural deafness.</td></tr>
<tr><td>4. Audiogram:

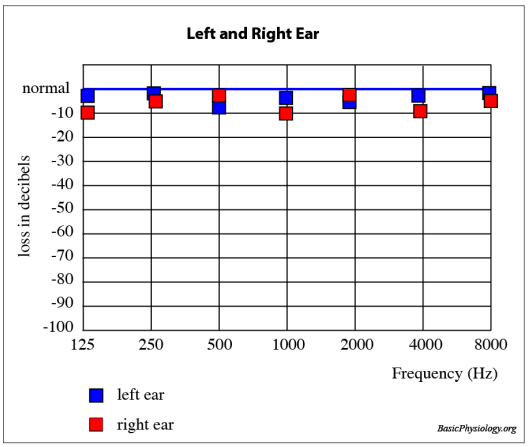
An audiogram is a measurement of how well we can hear. This is tested by producing sound at different frequencies and at different amplitudes and plotted in a graph (= audiogram). Furthermore, we can test, separately, air and bone conduction.</td><td>5.
In air conduction, sound is perceived through the 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.</td></tr>
<tr><td colspan="2">6.
This distinction makes it possible to differentiate between conduction deafness and nerve deafness (see below).</td></tr>
</table>

B. Normal Audiograms:

<table>
<tr><td>1. Audiogram:

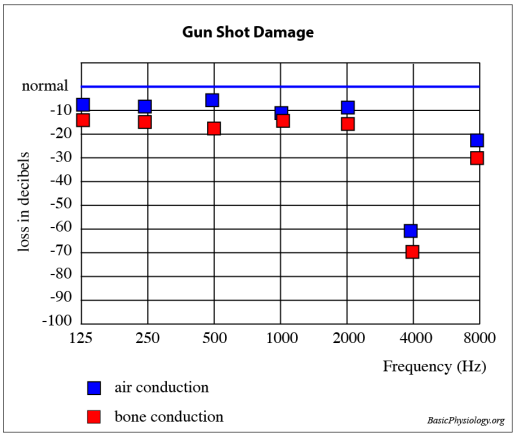
An audiogram is a graph that plots the threshold levels for hearing sounds at different frequencies, usually from 125 to 8000 Hz. These levels are expressed in decibels (dB) on a logarithmic scale.</td><td>2.
The audiogram is measured for both ears separately (with earphones) and by comparing air conduction and bone conduction. Bone conduction is induced</td></tr>
</table>

Zero dB represents threshold for normal healthy people.	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:

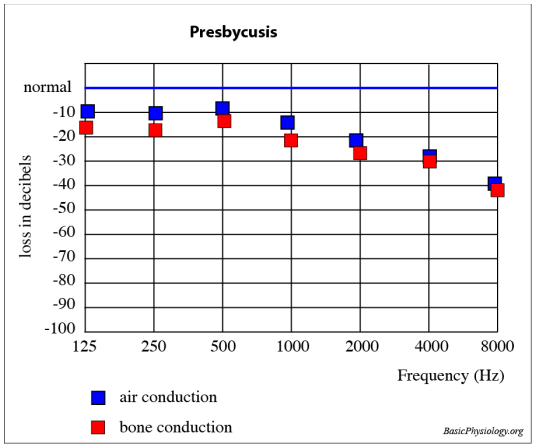
1. Gun-shot damage:

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.



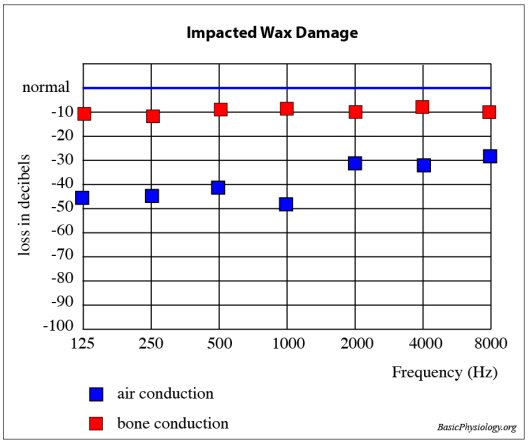
2. Presbycusis:

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!).



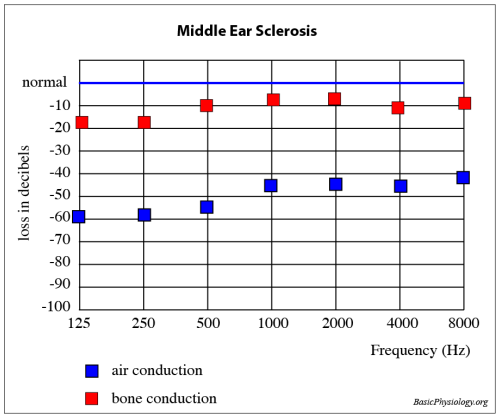
3. Impacted Wax:

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).



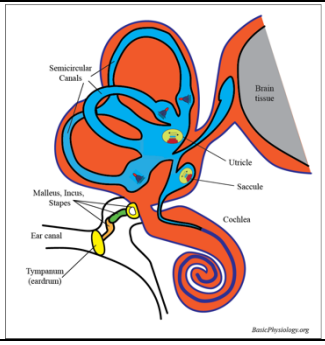
H.3.3.3. Equilibrium

A. Introduction:

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.

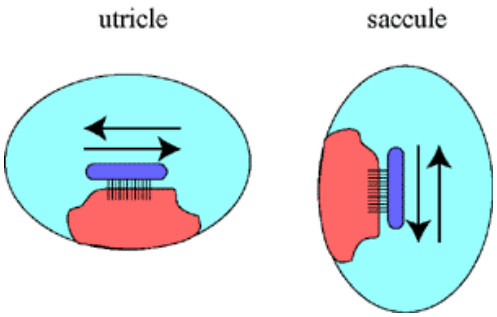
2.
Just a reminder of the most important structures in the vestibuli, adjacent to the outer ear, the middle ear and the cochlea. Not the location of two structures at the base of the semi-circular canals; the utricle and the saccule, and that of the crista-ampullaris in the three semi-circular canals



B. The Utricle and the Saccule:

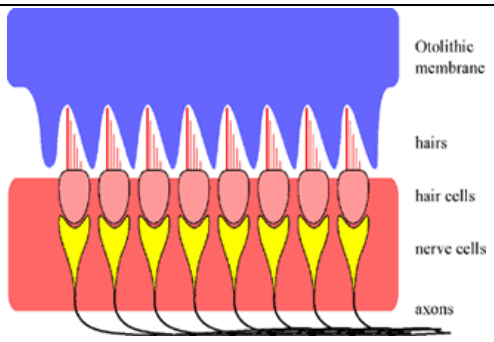
1. The Utricle and the Saccule:

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.



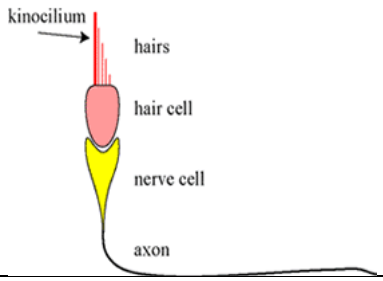
2. The Macula:

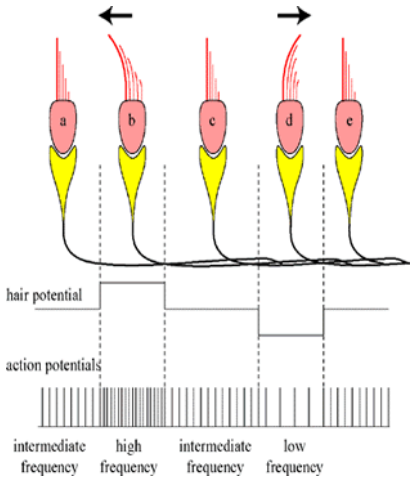
The macula is the sensor in these two organs. It essentially consists of a row of **hair cells**. The hairs are connected to a gelatinous mass called the **otholithic** membrane. The other side of the hair cell is connected to a nerve. This is the beginning of the vestibular nerve.



3. The Hair Cell:

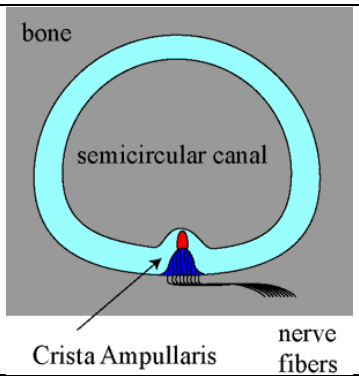
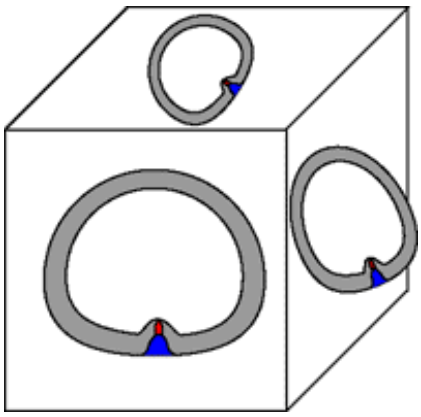
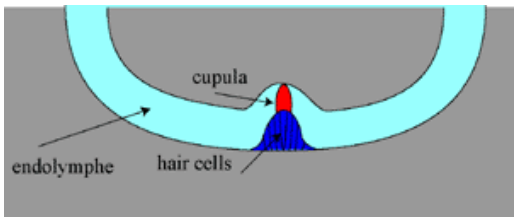
In contrast to the hair cells in the cochlea, there is also an orientation in the configuration of the hairs in the macula. One of the hairs is longer and thicker than the others. This special hair is called

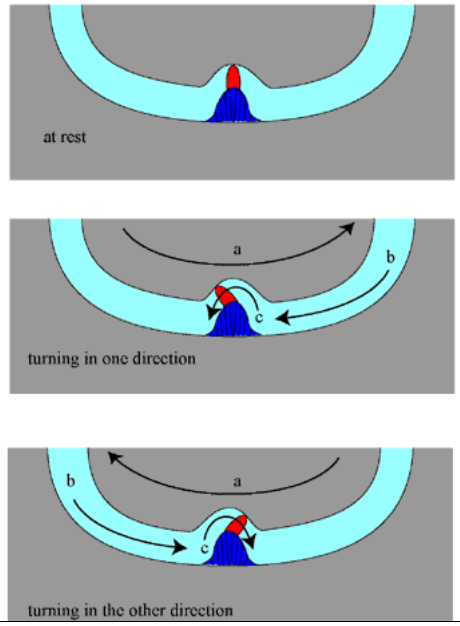
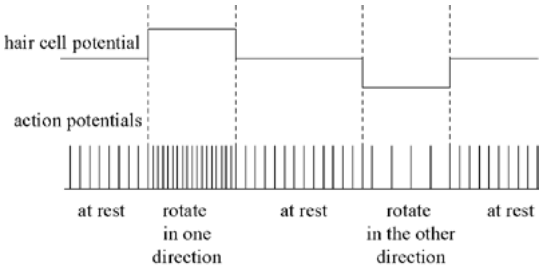


a **kinocilium** (plural kinocilia) and is, as it were, a point of reference for these hairs.	
4. How does it work? When the head starts to move in one direction, the otolithic membrane will move in the opposite direction. This is due to the **inertia** of the **otolith**. Because the hair cells move 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

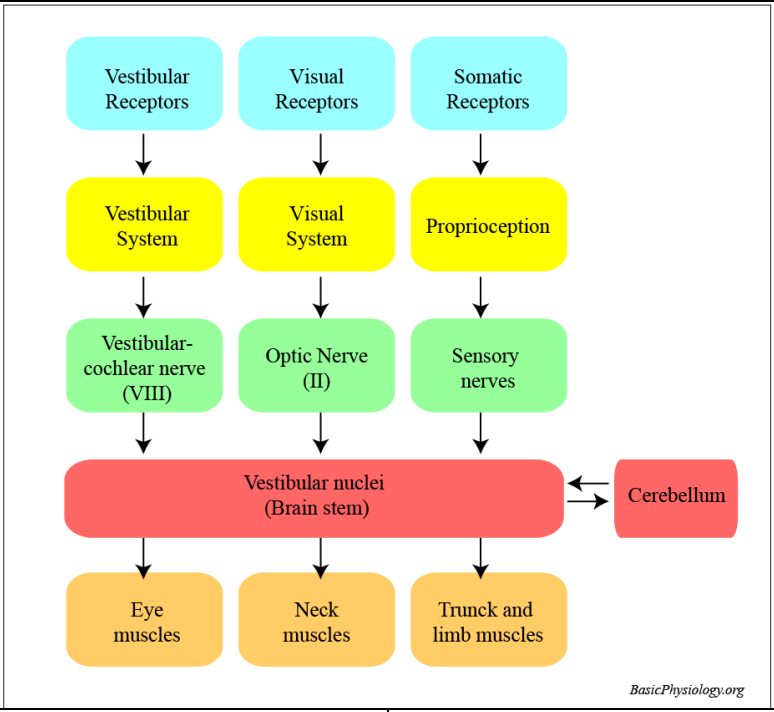
velocity (=acceleration or deceleration) that shifts the otoliths and that is what we feel.	decreases, then it can report how **much** (the change in frequency) and in which **direction** (accelerating or decelerating).

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.

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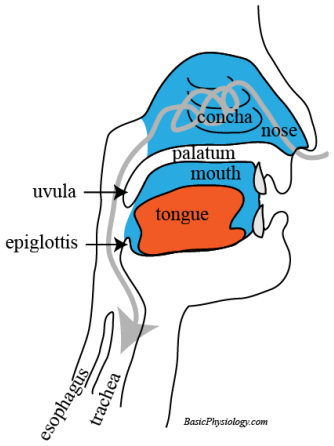
7. When are we in balance? We are in balance when the information from the three systems agree with each other. For example, suppose that you are in an elevator which looks outside (as in some expensive hotels) and you go up in that elevator. Then your **eyes** tell you that you are going up, your **sacule** 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:	**10. Why so severe?**
The symptoms of motion sickness are quite **severe**: 1. nausea 2. vomiting 3. pallor 4. rapid breathing 5. sweating	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 adequately to danger. Whatever causes this mis-information must **STOP** immediately. Hence, **motion sickness**is really incapacitating.

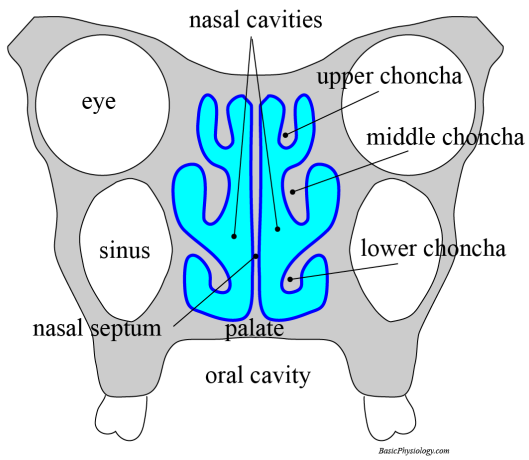
H.3.3.4. Smell

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

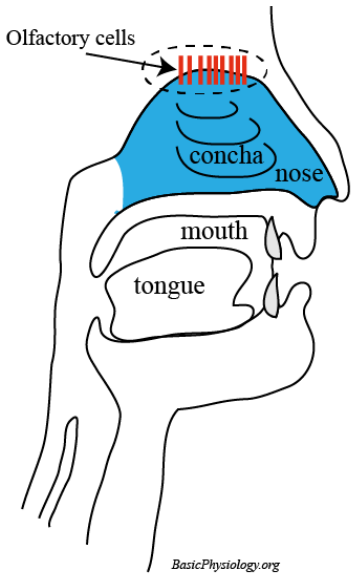
<table>
<tr><td>1.
As air flows into the body, during inspiration, it flows through the following structures:
1. nasal cavity
2. oral cavity
3. pharynx
4. larynx
5. trachea
6. bronchial tree</td><td>2.
During the inspiration, the inspired air is modified as follows:
a. The airways clean the air from 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.</td></tr>
<tr><td>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.</td><td rowspan="2"> 
</td></tr>
<tr><td>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.</td></tr>
</table>

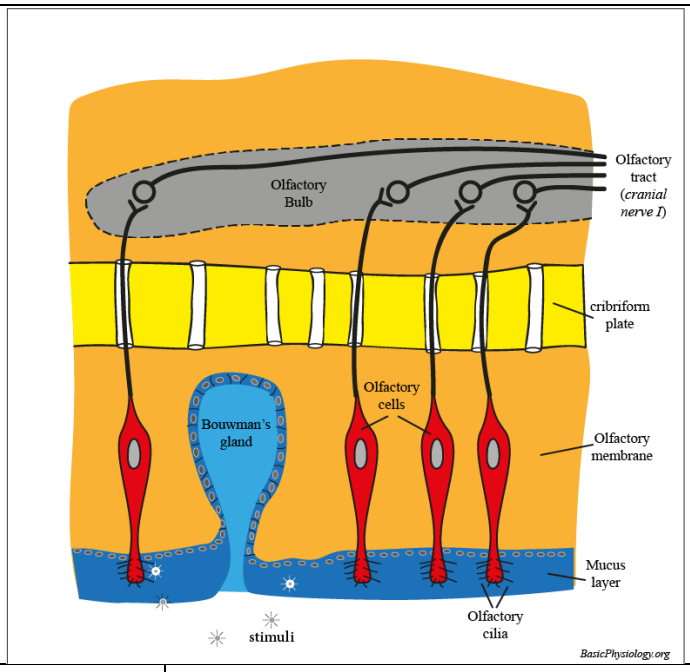
B. The Nasal cavity:

<table>
<tr><td>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).</td><td></td></tr>
</table>

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	5. The influx of sodium ions will depolarize the	6. As the olfactory cell is actually a nerve cell, the

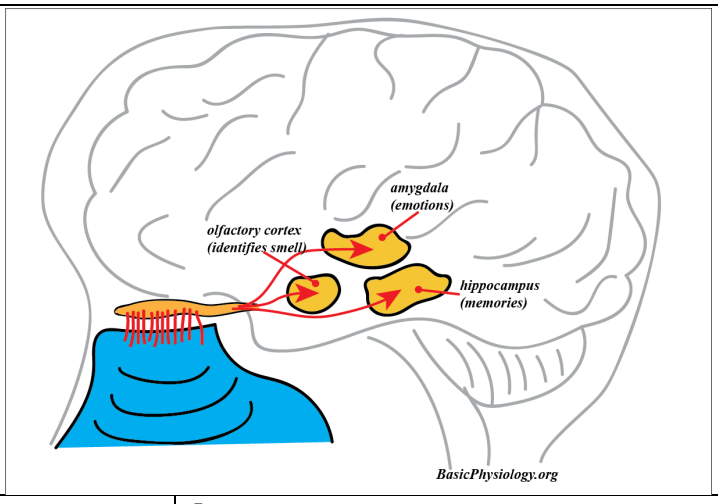
cyclase) which opens sodium-channels.	olfactory cell and if that reaches threshold, will induce one or more action potentials. If the smell is strong, there will be more action potentials.	action potential will propagate along the un-myelinated axon towards the olfactory bulb.

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:

1. The olfactory bulb contains glomeruli, in which thousands of axons from the olfactory cells synapse to.	
2. In addition, there are other nerve cells, such as the mitral cells that receive the axons from the olfactory cells.	

3. The nerve cells in the glomeruli send their axon, though the olfactory tract towards several centres in the brain.	

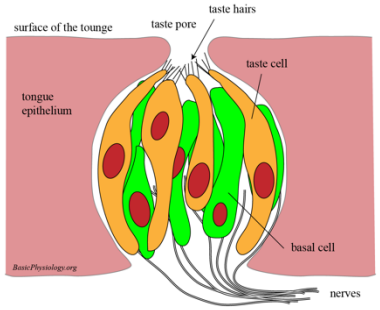
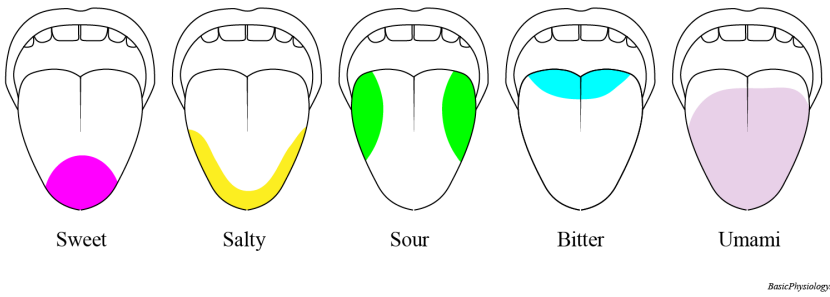
4. The olfactory bulb and the olfactory tract together form **cranial nerve I** (= the first nerve). Further on in the brain, the tract divides into several parts.	5. One part of the tract radiates to the **olfactory cortex,** (which identifies the recoded smell).
6. Another tract connects to the **hippocampus** area (which stores the smell memories!)	7. Other fibres go to the **amygdala** region. This area is important because there the smell stimuli are associated with **emotions**!

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

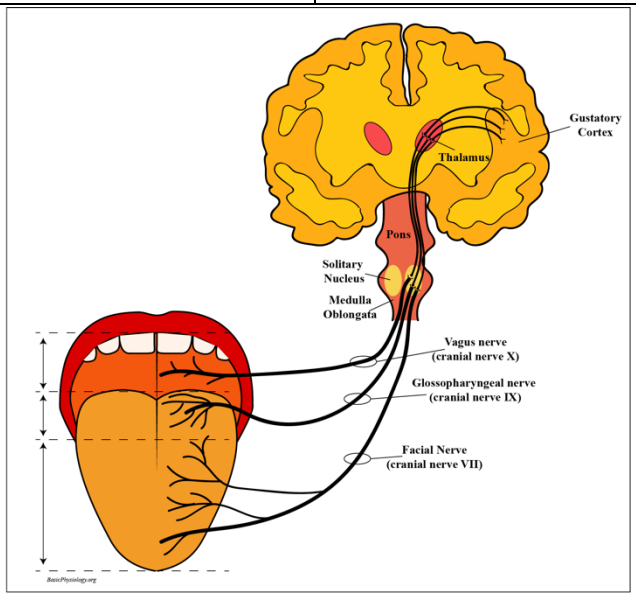
A. The tongue *(copied from E.2. The Mouth and the Nose)*

1. *The tongue is a skeletal muscle, attached at one end to the bones of the skull.*	*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.*
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.*	
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.*	*5.* *Because these taste cells don't live very long, 5-10 days max, they are constantly being replaced by the accompanying base cells.*
	
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	10. From the brainstem, the nerve fibres travel to the solitary nucleus in the thalamus, and from there, they ultimately reach the gustatory

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.	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.	10.

The tongue also plays an important role in swallowing food, but also in speaking and it even helps in cleaning the teeth.	And… oh yes… the tongue also plays an important role in human eroticism; French kissing and licking!!!

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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