Psychoacoustics

1st lesson

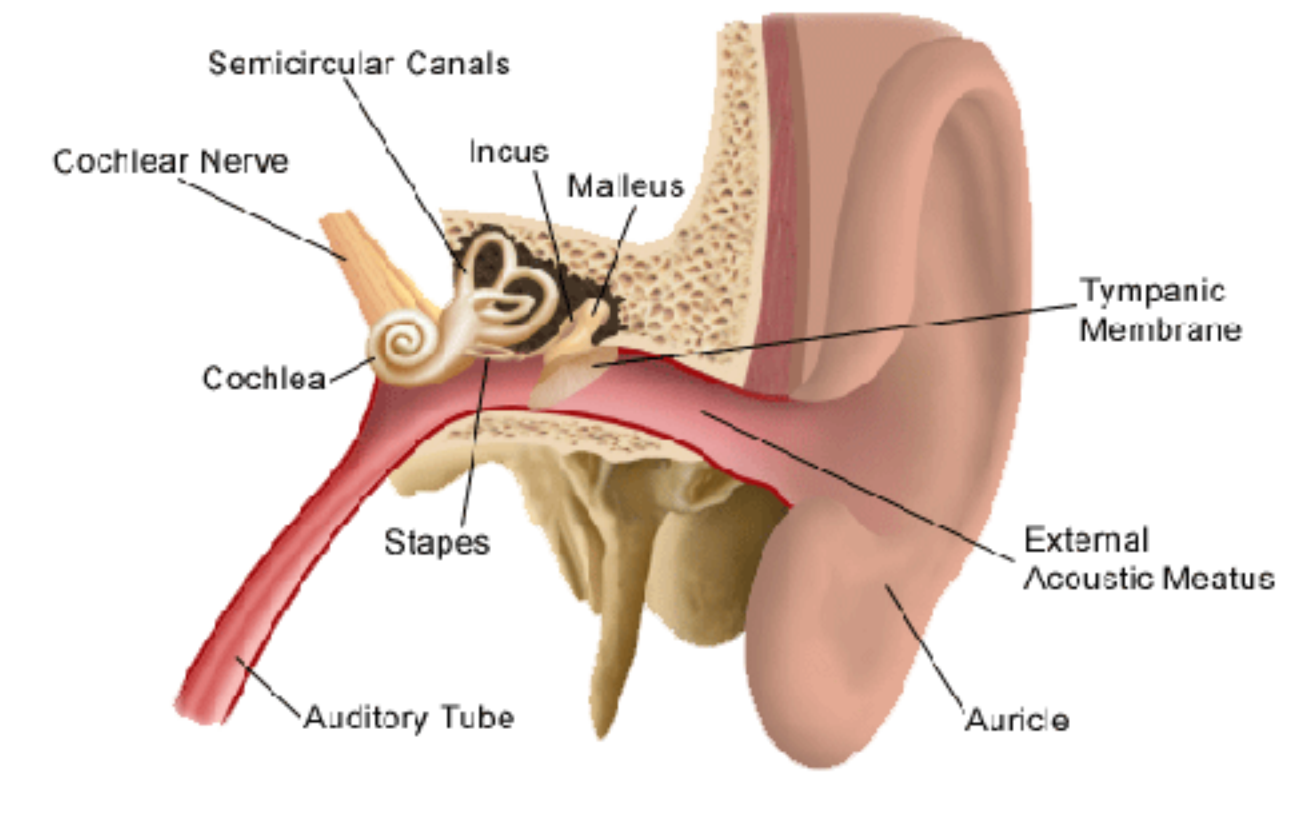
Reference:

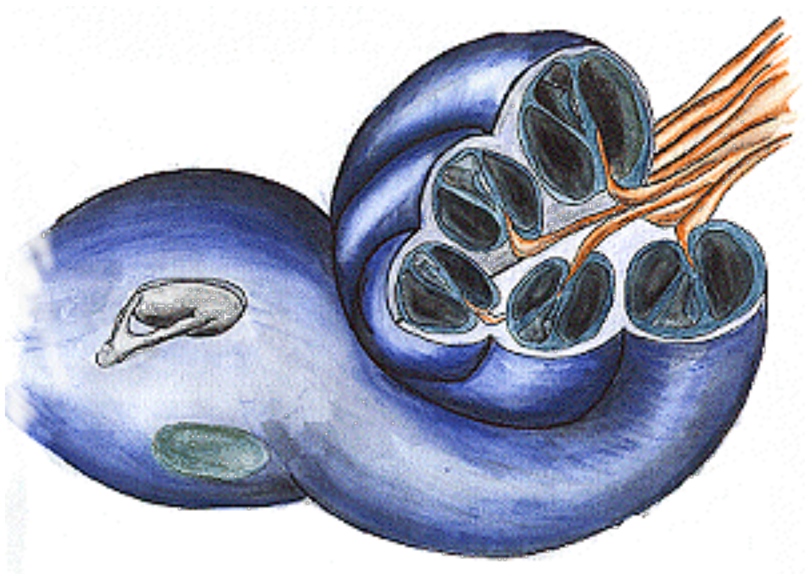
http://web.fbe.uni-wuppertal.de/fbe0014/ars_auditus/

Animation:

https://www.youtube.com/watch?v=PeTriGTENoc

Anatomy of the Ear



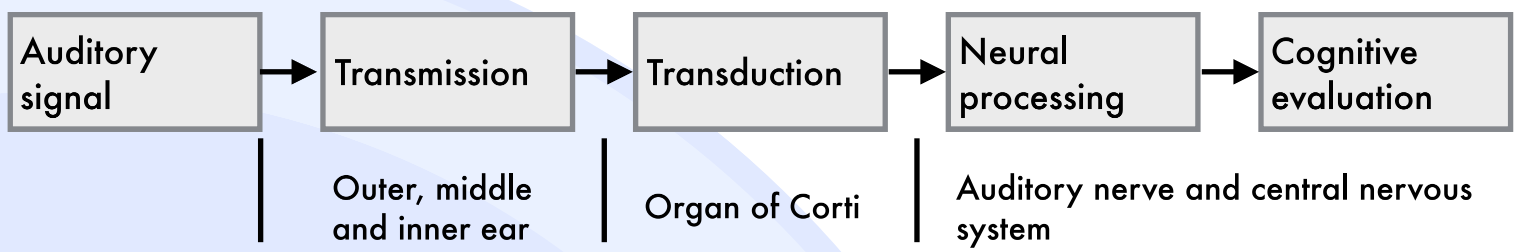


The **outer ear** consists of the auricle (pinna) and the external auditory canal. It fulfills the function of sound transmission from the environment to the middle ear. The boundary to the middle ear is given by the eardrum, which is brought into mechanical vibrations by the transmitted sound waves. The forms of the auricle and auditory canal have a considerable influence on the way the auditory system transmits sound.

The **middle ear** transmits the vibrations of the eardrum to the inner ear. It consists of the eardrum, the auditory ossicles, which are called malleus, incus and stapes, the air-filled tympanic cavity and the middle ear muscles.

The **inner ear**, the cochlea ("snail"), is where the actual hearing process takes place. The cochlea contains the transformation organ with the sensory cells, which transduces the vibrations transmitted through the middle ear into nerve impulses. These are directed to the brain via the auditory nerve. This is followed by the last step of the hearing process: neural processing.

Transfer functions of the Ear



Hearing consists of the operations of transmission, transduction and neural processing of an auditory stimulus. Each of these processes can be represented by separate stages and, apart from neural processing, can be described by a corresponding transfer function.

Sound generated by a sound source reaches the two eardrums. At this point, the sound event is described by the two **ear signals,** and the eardrum is understood as the physical point of entrance for the auditory signal. Already at this point, depending on the frequency, different ear signals occur, which are described by the **free-field transfer function (**FFTF**;** aka free-field-to-eardrum transfer function (FETF) or head-related transfer function (HRTF)) and the **interaural transfer function**.

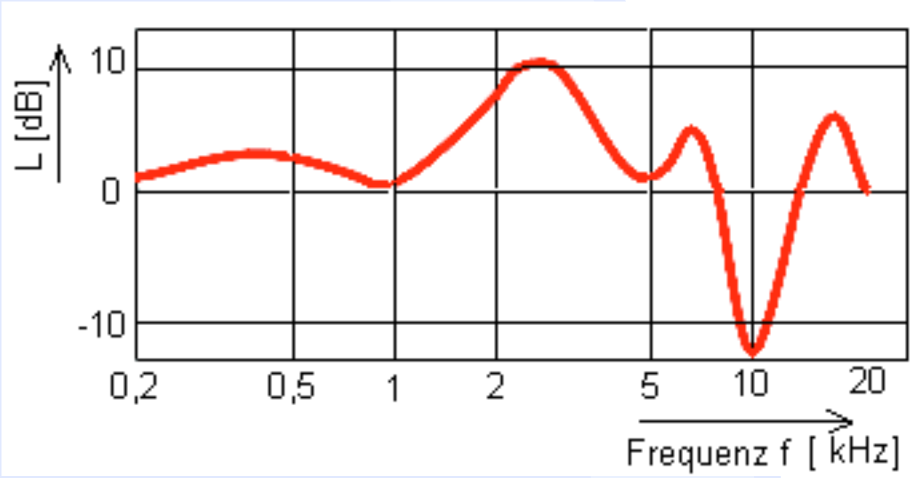
The description of the stimulus transmission is made with the help of the transfer functions of

- outer ear
- middle ear and
- inner ear

A last term in the description of the hearing process (for which a transfer function can be specified) is given by the **transfer function of the transduction of the auditory signal**. There is a direct relationship between the tonotopic organization of the basilar membrane and the primary auditory cortex.

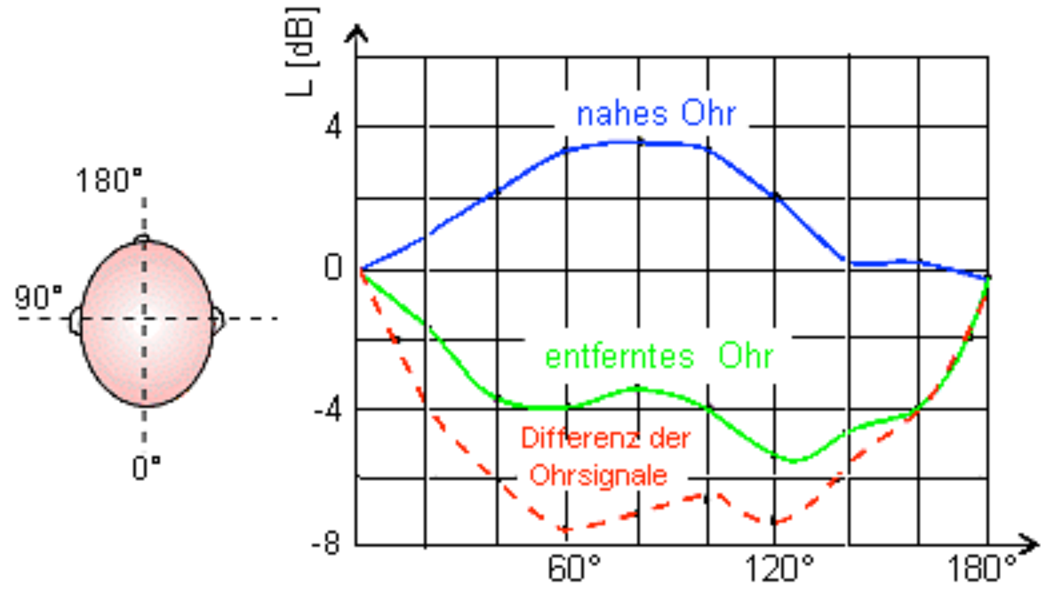
Outer Ear

The sources of sound in the human environment provide all kinds of acoustic information. However, the sound signals generated are already changed on the way to the outer ear by the reflection and diffraction of sound waves on the human body.
Therefore, so-called ear signals are used for a clear description of the auditory events. The ear signals are the sound pressure signals which arise directly in front of the eardrums. In this way one can regard the eardrums as physical inputs of the hearing, no matter how the ear signals are generated by the external sound sources.
The ear signals are described with the so-called free-field transfer function.

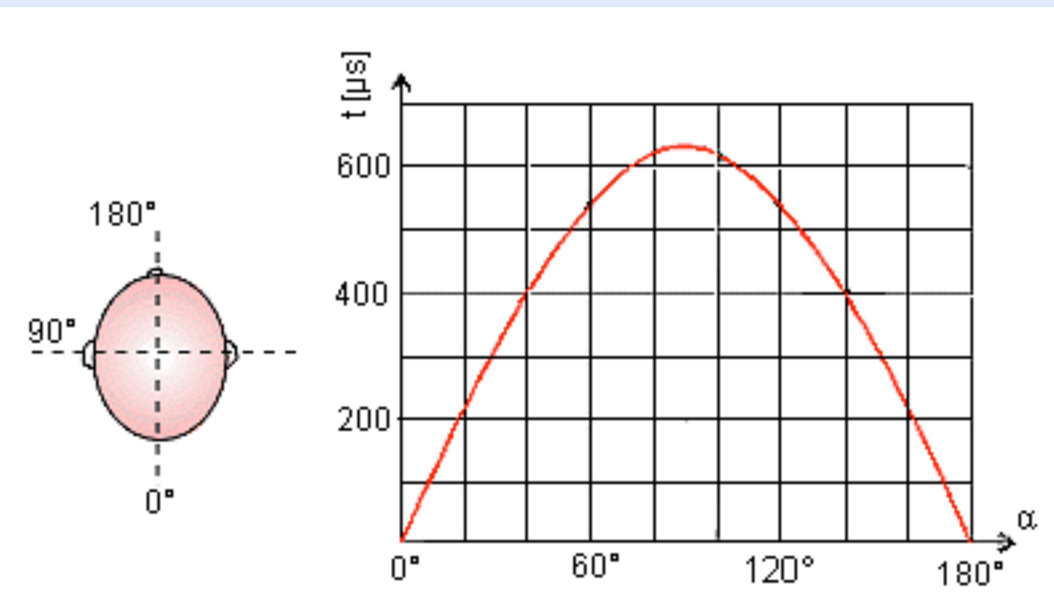


The ear signals which occur in front of the eardrums differ from the sound signal which would have existed in the absence of the person. The differences are caused by diffraction phenomena of the sound waves on the body of the hearing person. The sound field, which is present in the absence of the person, is called a free-field. Its characteristics can be described solely by the geometrical arrangement and the type of sound sources. The difference between the free-field signal and the resulting ear signal is described by the free-field-to-eardrum transfer function. This is shown in the figure above for a frontal sound source. The free-field-to-eardrum transfer function depends on the direction and distance of the sound source and the individual anatomical dimensions.

Interaural Transfer Function

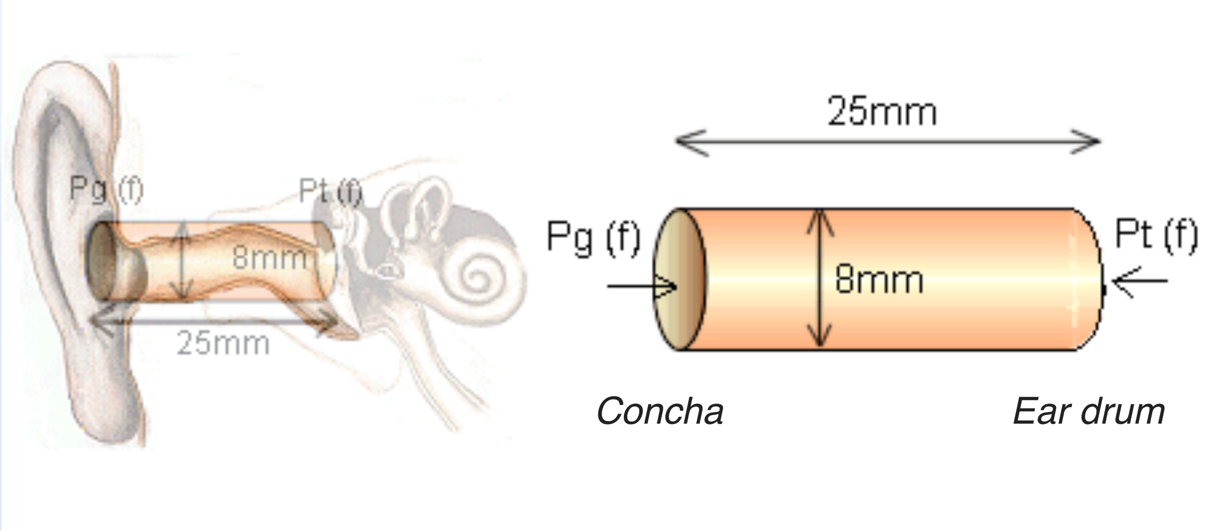


If a sound source is located exactly in front of or behind the hearing person, the same ear signals are applied to both eardrums. This changes, however, if the position of the sound source no longer lies in front of the person. In this case, a different ear signal occurs on the eardrum due to the different geometrical position of the ears to the sound source, as well as by the head, which is a "sound barrier". This difference is described by the so-called interaural transfer function. The adjacent graphic describes the interaural transfer function for the sound event as a function of the angle of incidence of the sound waves. The function shown applies to sound events in the frequency range between 500 Hz and 2500 Hz. For higher frequencies, the function is at lower levels due to the sound shadow formed by the head.



Apart from shading, there is also a second interaural effect: the interaural time difference (ITD). Time differences play an important role in terms of spatial hearing and sound source localization, in conjunction with the frequency-dependent shading of the sound at the head. The propagation delay between the ears as a function of the angle of incidence is shown in the adjacent diagram.

The Transfer Function of the External Ear Canal

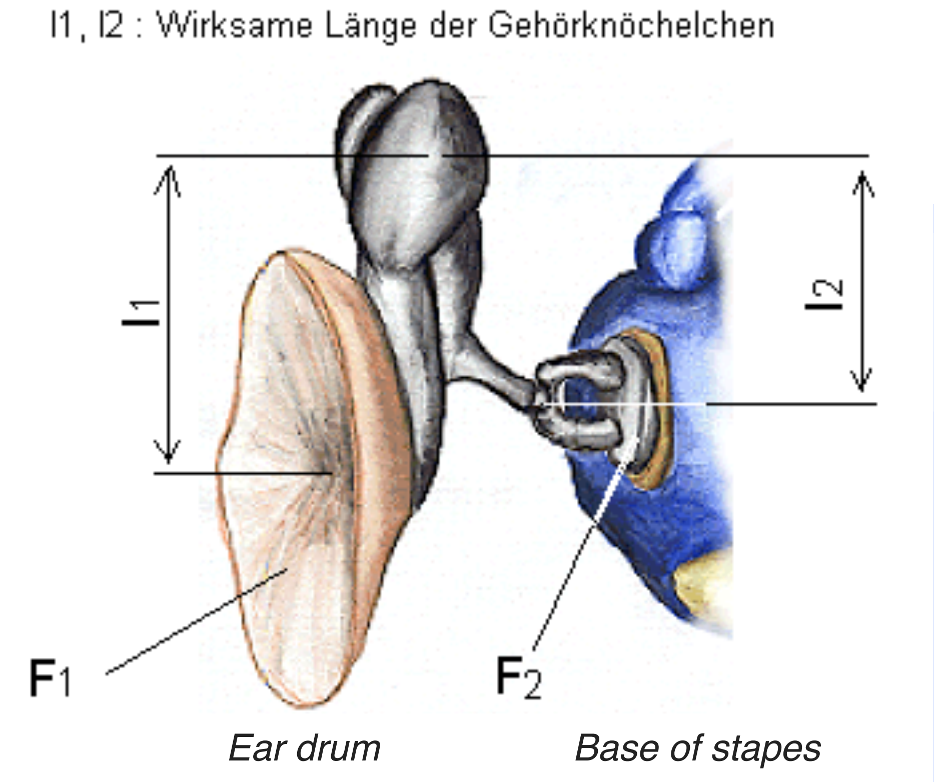


For a mathematical description, the external auditory canal can be considered as a tube with a length of 25 mm and a width of 8 mm.

The transfer function is described by the ratio of the sound pressure at the eardrum Pt (f) to the sound pressure at the input of the auditory canal Pg (f). Since both the sound pressure on the eardrum and the sound pressure at the input of the auditory canal depend on the frequency, the transfer function formed therefrom is also frequency-dependent.

The behavior of the transfer function is largely influenced by the final impedance of the auditory canal (acoustic wave resistance), that is, the impedance of the eardrum.

The transfer function derived from this model has a maximum at the frequency f = 3430 Hz. The maximum of the transfer function at this point also means a maximum of the sensitivity of hearing. This sensitivity increase can be shown as function of the resting threshold. In the range of the frequency specified (3430 Hz), the values are lowered. Therefore, a lower sound level is required in order to trigger a hearing sensation.



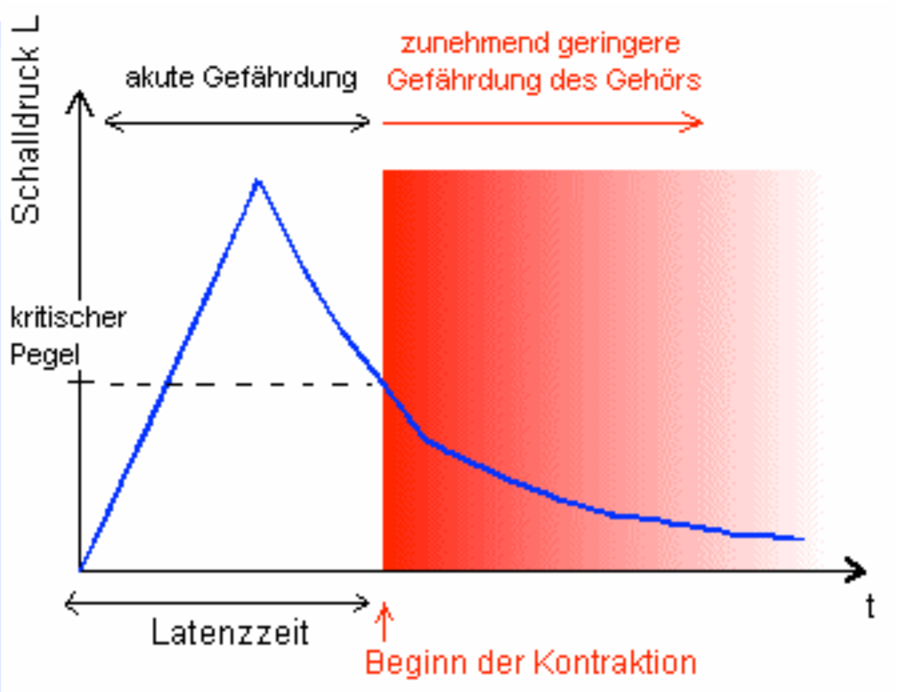
Impedance Matching in the Middle Ear

The outer ear and the tympanic cavity are filled with air, the inner ear are filled with the perilymph and endolymph, water-like fluids. When vibrations are transmitted from the outer ear to the inner ear, there is therefore a change in the sound-transmitting medium and thus a transition between two different acoustic impedances.
Theoretically, due to the different sound wave resistances of the two media, about 98% of the incident sound waves would be reflected at the interface between air and water and thus lost for the hearing process.
In order to avoid these reflection losses, an adaptation of the sound wave resistances, a so-called impedance adaptation, must be performed in the middle ear. For this purpose, a pressure elevation at the oval window is necessary in comparison to the pressure at the eardrum.
The adjustment process is carried out mainly by

- the area ratio of eardrum to the base of the stapes and
- the length ratios of the effective levers of the chain of ossicles

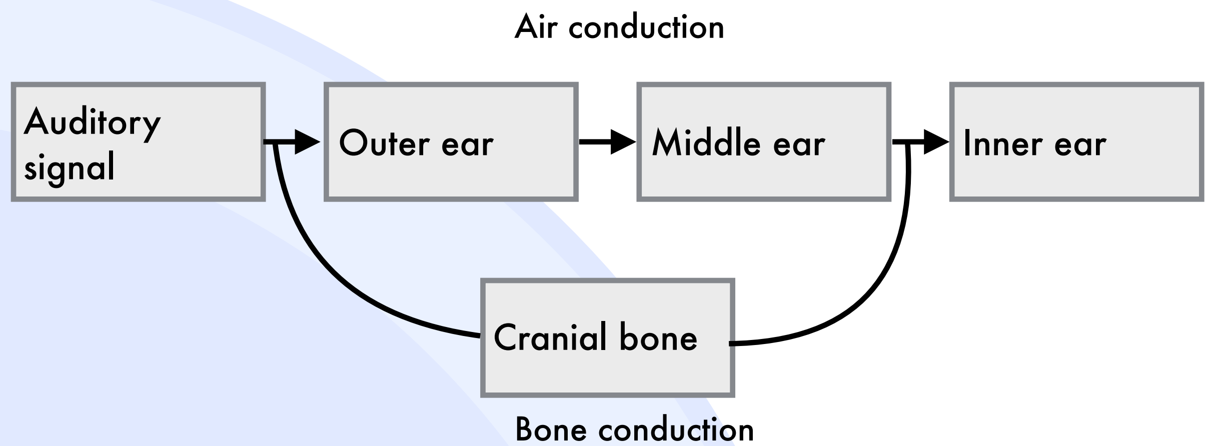
Through the process of impedance conversion only about 40% instead of 98% of the sound waves are being reflected. This corresponds to an absorption of approximately 60% of the sound waves arriving at the eardrum.
The pressure on the oval window of the inner ear (vestibule) is about 22 times higher than the pressure on the eardrum by the mechanism of impedance matching.

Protection of the Inner Ear against Loud Sound



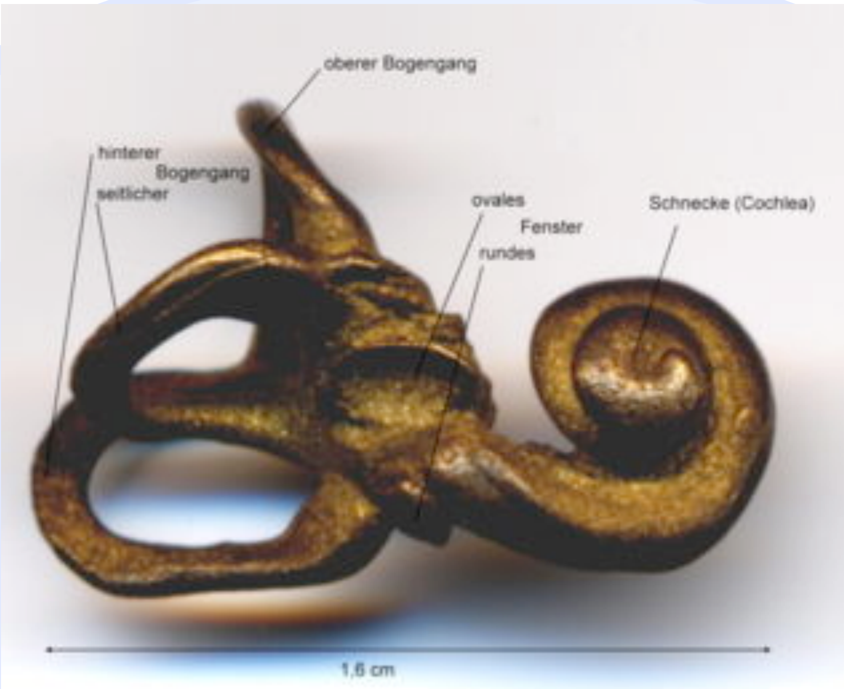
If the sound energy transmitted from the environment exceeds a certain value, the contraction of the middle ear muscles occurs. Hence, the tympanic membrane is more strongly strained. As a result, the reflection of the sound waves on the eardrum is increased and the deflection of the stapes is restricted. Due to the reduced deflection and the increasingly reflected portion of the incoming sound waves, the sensory cells located in the inner ear are protected against damage caused by excessive sound pressure amplitudes. Both muscles require a certain response time (latency) until they contract. This time depends on the sound intensity and is about 35 ms at high and up to 150 ms at low sound pressure levels. For this reason, the middle ear muscles fulfill only an insufficient protection of the inner ear from suddenly occurring loud sound events, e.g. blasts. This is due to the fact that the increase in the sound pressure level of a sound event takes place in a shorter time period than the response time of the middle ear muscles. In this case, the sound event reaches the inner ear with a high level that may damage the sensory cells, before the middle ear muscles contract. A suddenly occurring auditory signal of sufficiently high volume can lead to irreparable damage to the sensory cells in the inner ear. In this context, one speaks of an acoustic shock or a blast injury. Such sounds arise e.g. when setting off a firecracker or firing a gunshot.

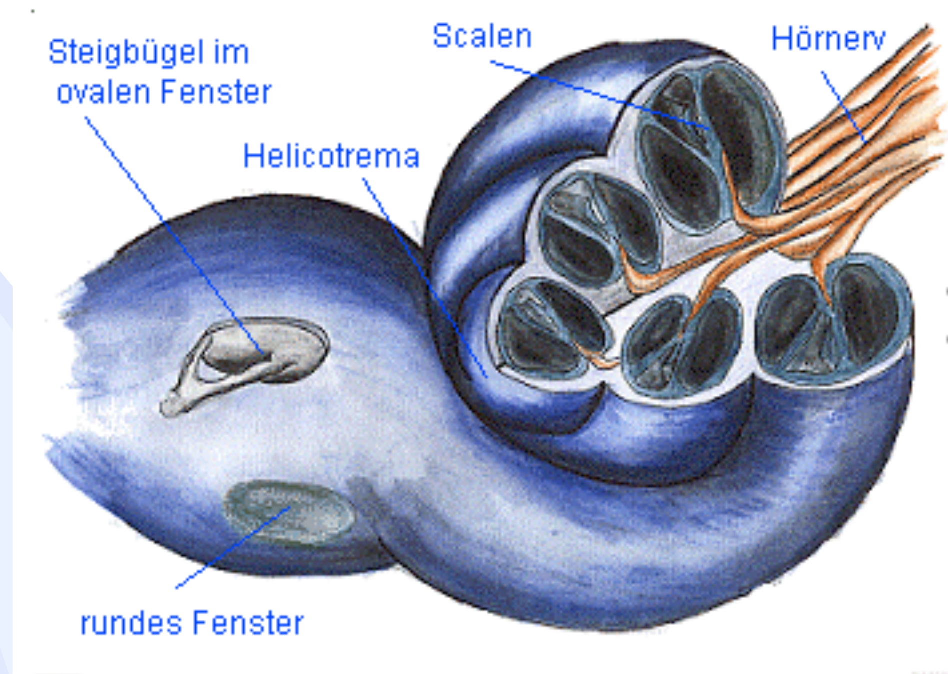
Beethoven’s Trauma



The previously described path of the sound transmission via the outer and middle ear to the inner ear is referred to as air conduction. In addition to air conduction, however, there is still a second mechanism of the transmission, the so-called bone conduction. In the same way as the eardrum, the skull bone is also excited by the sound waves coming from the environment to mechanical vibrations. These vibrations of the cranial bone are called bone sounds and are transmitted directly to the inner ear. The path through outer ear and middle ear is thereby circumvented. In daily life, bone conduction hardly plays a role, except for hearing of one's own voice. This is because the proportion of bone sound is approximately 50 dB below the air sound level for all frequencies. The effect of bone conduction on the hearing of one's own voice is known to anyone who has once heard a tape recording of his or her voice. It appears alien, while others can not detect anything unusual.

Inner Ear





The inner ear contains the organ of balance (semicircular canals) and the actual organ of hearing, which is called cochlea because of its shape. Both organs together are called the labyrinth. The organ of balance is connected with the cochlea, but it plays no part in the hearing process, so it is not considered here.
The actual hearing process takes place in the inner ear by transforming mechanical vibrations into nerve impulses via
• stimulus distribution to the sensory cells (travelling-wave theory) and
• stimulus transformation,
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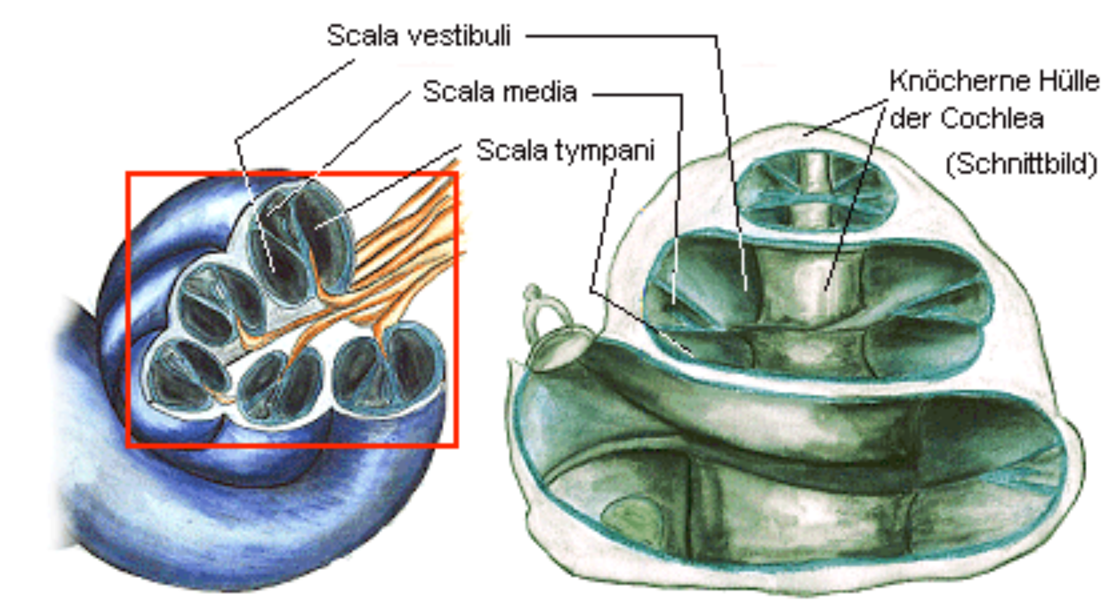
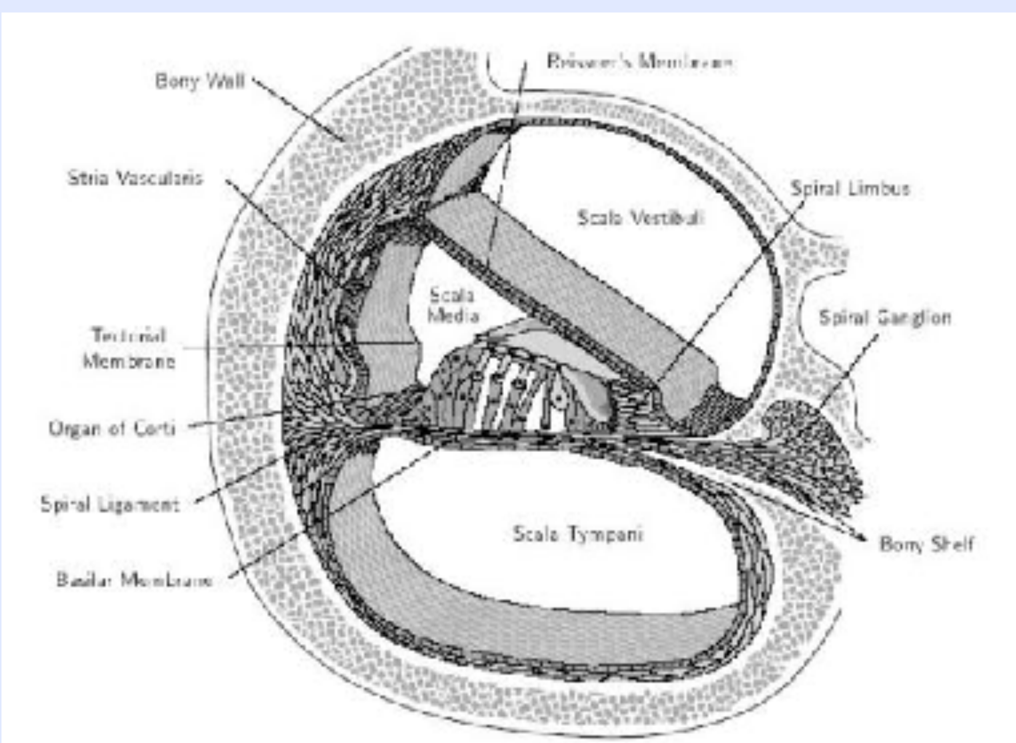
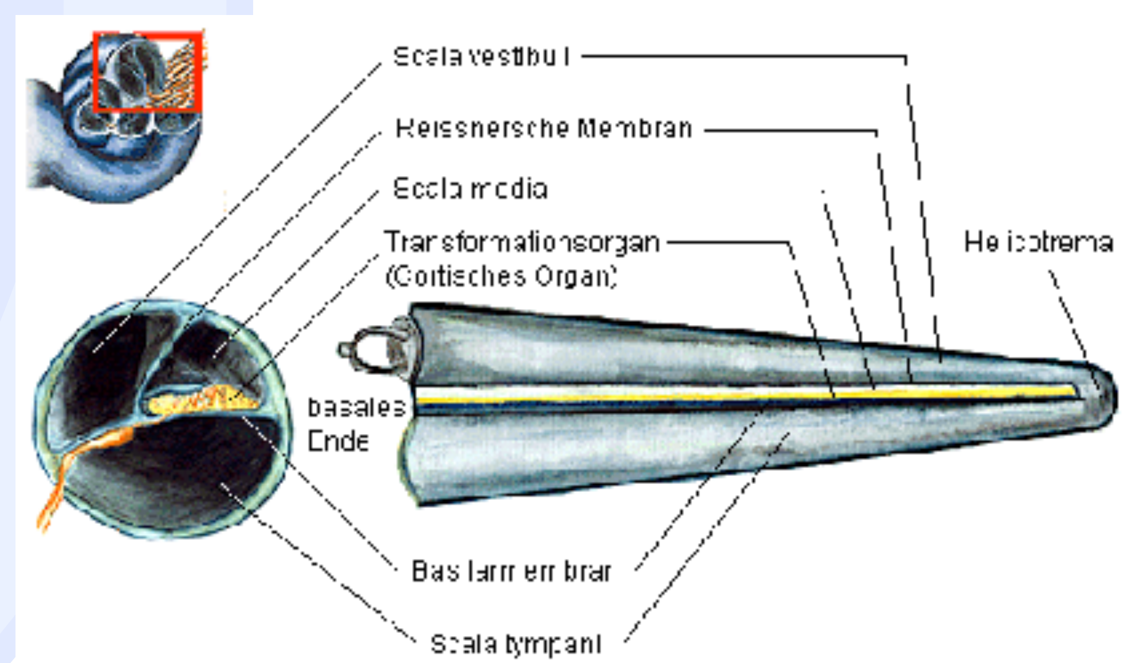
Cochlea



The cochlea consists of a bony sheath, which contains three spirally wound conical chambers. These chambers are filled with a lymph-like fluid, and are called scala vestibuli, scala media, and scala tympani.
For better illustration, the spiral is shown in the unrolled state. The round and oval windows are located at the base of the cochlea, the helicotrema (the location where the tympanic duct and the vestibular duct merge) at its apex. The spiral is approximately 30 mm long and tapers during its course from 0.9 mm to 0.3 mm in diameter. Scala vestibuli and scala media are separated by Reissner's membrane; scala media and scala tympani by the basilar membrane. The organ of transduction (organ of Corti) is located on the basilar membrane. Here the actual hearing process, the transduction of mechanical vibrations into nerve impulses, takes place. The basilar membrane changes its mechanical properties during its course from the basal to the apical end by decreasing stiffness. At the same time the basilar membrane widens from 1/6 mm to 1/2 mm. This change in mechanical properties is an important prerequisite for the dispersion of sound to separate frequencies spatially

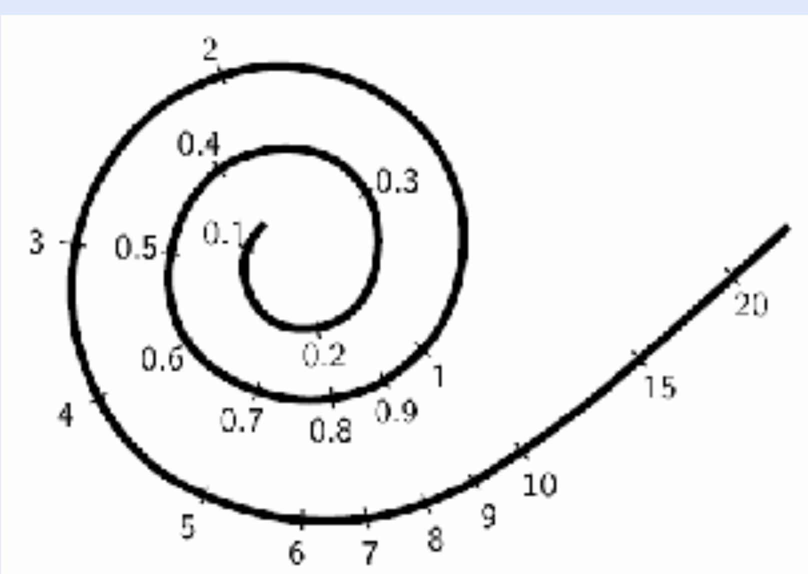


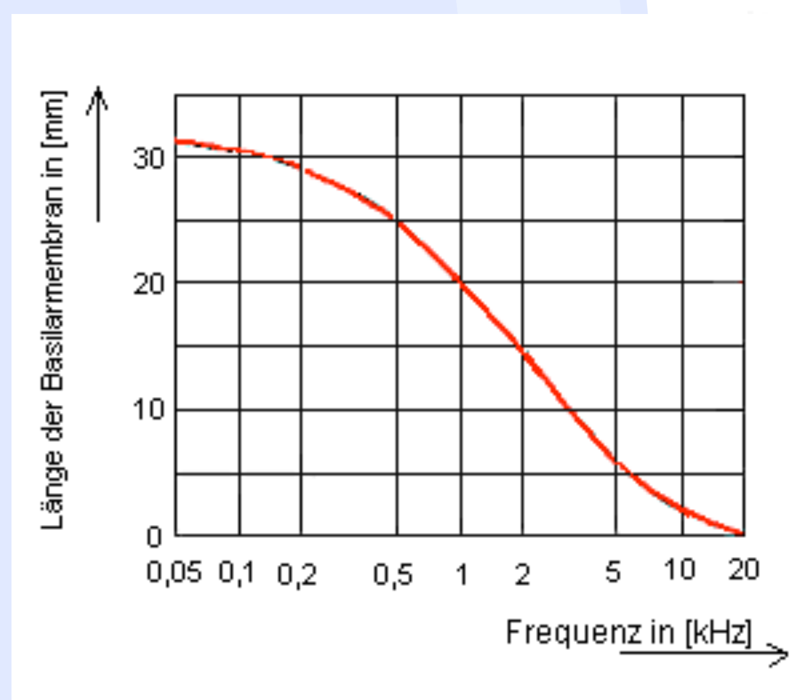


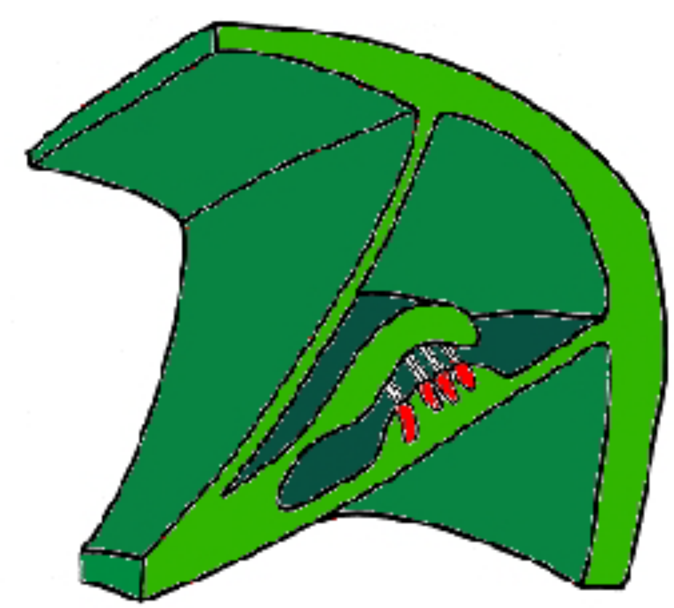
Traveling-wave Theory

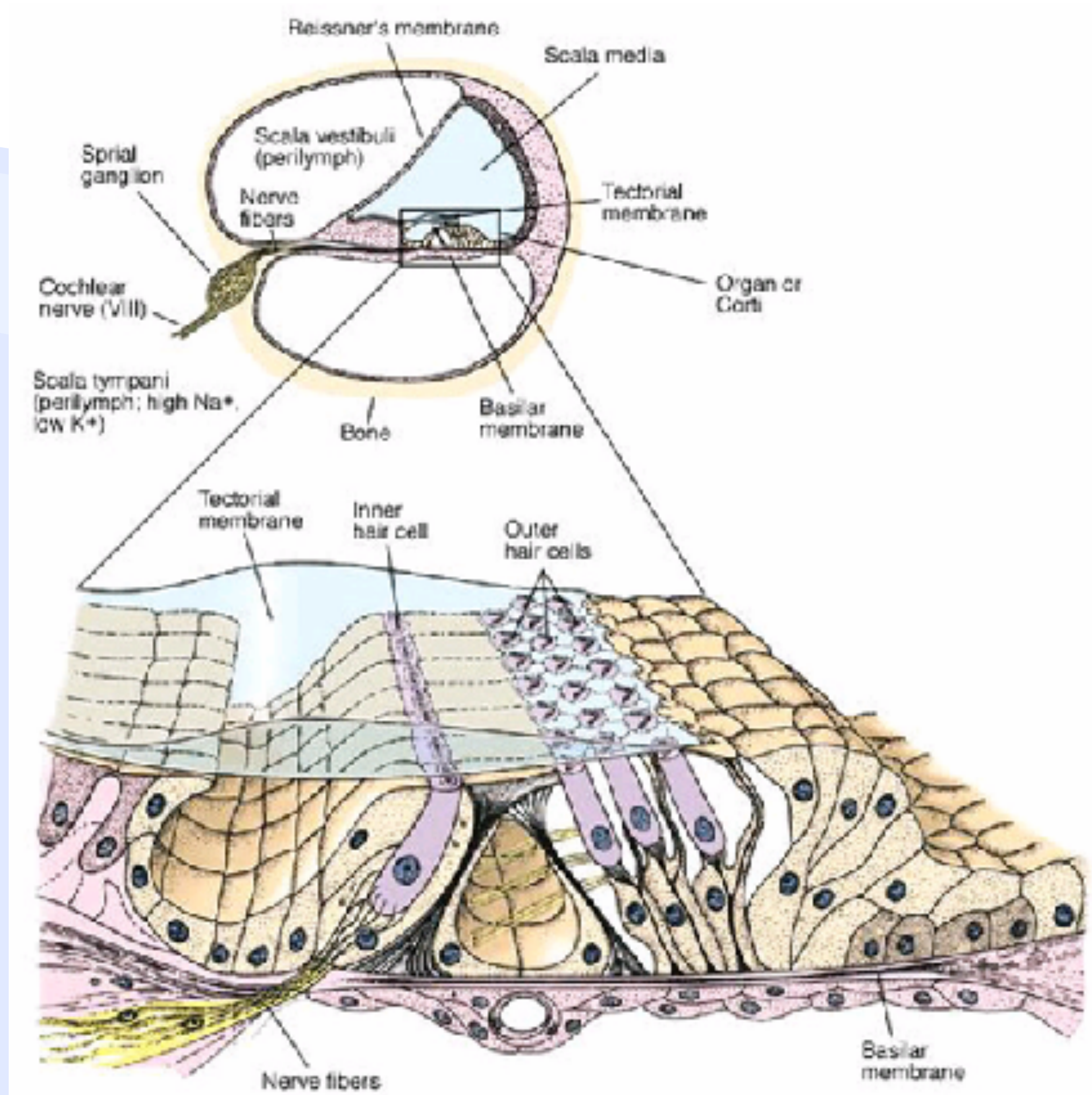
The movements of the stapes on the oval window cause a fluid displacement or pressure change in the cochlea. This causes the basilar membrane to vibrate. Due to these vibrations, migrating waves are formed on the basilar membrane, which propagate from the oval window to the helicotrema and form their amplitude maximum at a frequency-dependent location: sounds of high frequency close to the oval window, low frequency sounds near the helicotrema. The diagram below shows the location of the maximum deflection as a function of frequency.

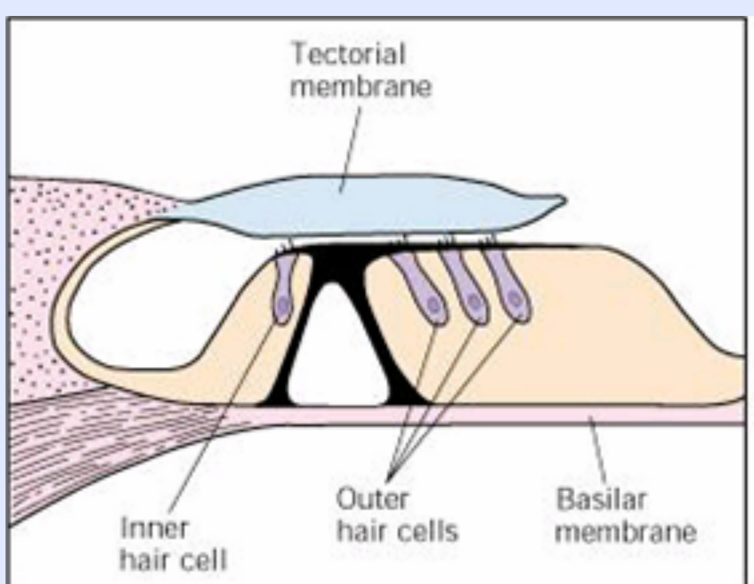
The relative movement between the basilar membrane and the tectorial membrane occurs at the location of the amplitude maxima. This leads to a tangential shearing of the hair cells. The hair cells react by producing nerve pulses, which are directed via the fibers of the auditory nerve to the neural processing stages in the brain. This process can be illustrated by an animation. Since the location of the amplitudes maximum on the basilar membrane is dependent on the frequency of the sound event, each frequency is unambiguously assigned to a particular location of the basilar membrane. The traveling wave forming on the basilar membrane is the last event of the hearing process, in which the sound absorbed from the environment can still be detected as a mechanical vibration. After transduction, the complicated neural processing begins, whose functioning has not yet been elucidated in all details.

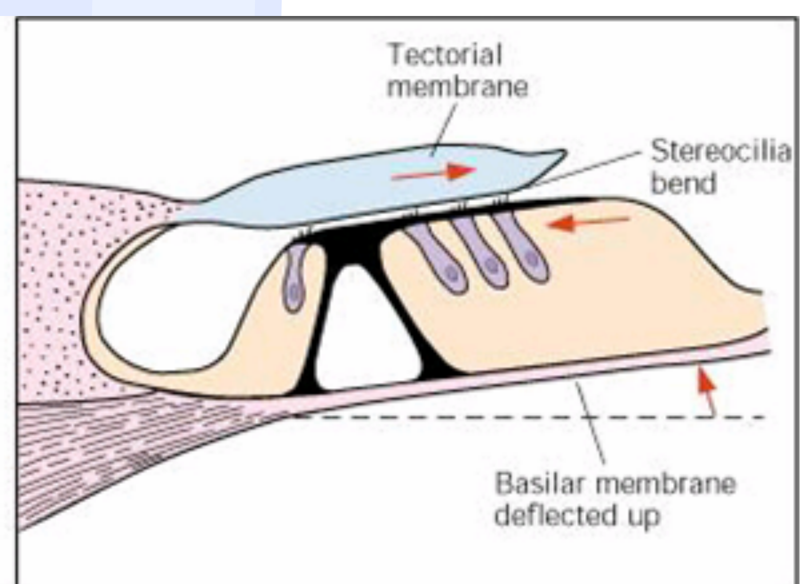







Reissner's membrane
Scala media
Scala vestibuli (perilymph)
Sprial ganglion
Nerve fibers
Tectorial membrane
Organ of Corti
Cochlear nerve (VIII)
Scala tympani (perilymph; high Na+, low K+)
Bone
Basilar membrane
Tectorial membrane
Inner hair cell
Outer hair cells
Nerve fibers
Basilar membrane


Tectorial membrane
Inner hair cell
Outer hair cells
Basilar membrane


Tectorial membrane
Stereocilia bend
Basilar membrane deflected up

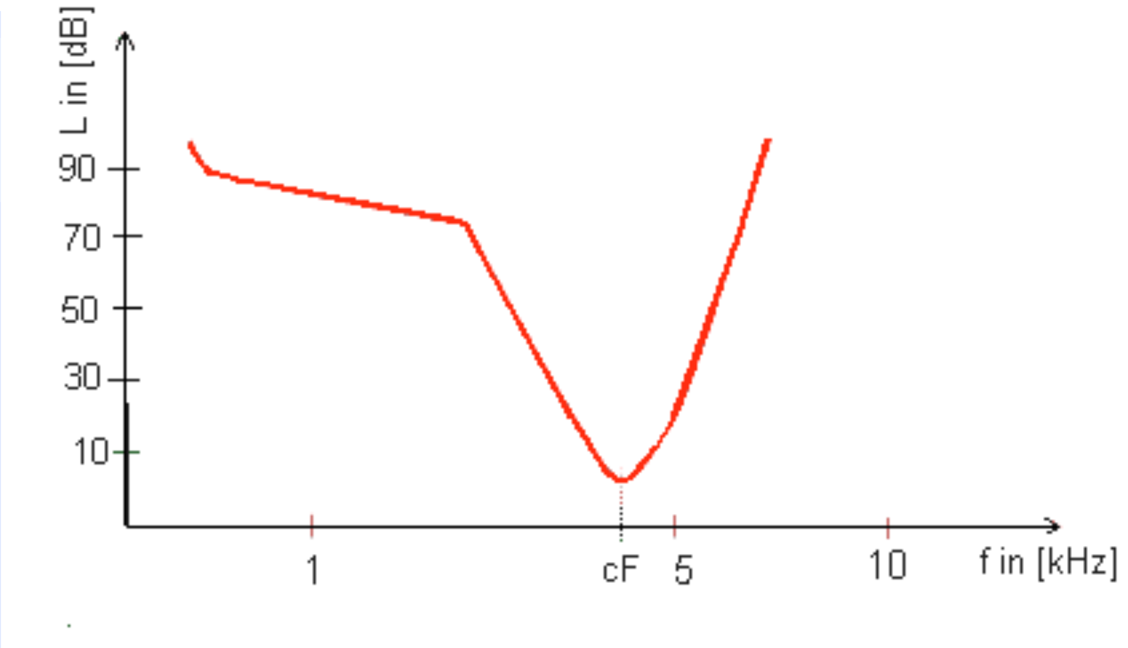
Neural Processing

After a sound event has traveled through the outer and middle ear and has been transducer into electrical nerve impulses in the inner ear, the last and most complicated part of the hearing process follows: neural processing,.

The processed auditory information is transmitted by the auditory nerve in its entirety. Theoretically, an acoustic stimulus can be described by looking at all activities of the auditory nerve in the same way as it can be described completely by its physical properties,.

The sensory cells of the basilar membrane deliver to the nervous system patterns of neural excitation. The physical characteristics of the sound signal are encoded into these patterns. They are now being processed by the nervous system, so that they can be consciously perceived and analyzed for their information content.

Transfer Functions of Sensory Transformation



When the action potentials, that is, the nerve impulses of the individual nerve fibers, which contact the inner hair cells, are shown, the number of pulses occurring per time unit is strongly dependent on the frequency of the stimulating sound. Each fiber of the auditory nerve, which contacts an inner hair cell on the basilar membrane, has a so-called best frequency (characteristic frequency cF). The characteristic frequency is the frequency at which a sinusoidal produces a maximum pulse sequence frequency at minimum amplitude. If the threshold curve of a nerve fiber is plotted as a function of the sound pressure level, the so-called tuning curve of the nerve fiber is obtained. The nerve fibers are highly frequency-selective. If the ear is exposed to a frequency which differs from the characteristic frequency, the fiber can not be activated at all or only with the aid of a higher sound pressure level if the stimulating frequency is sufficiently close to the characteristic frequency.

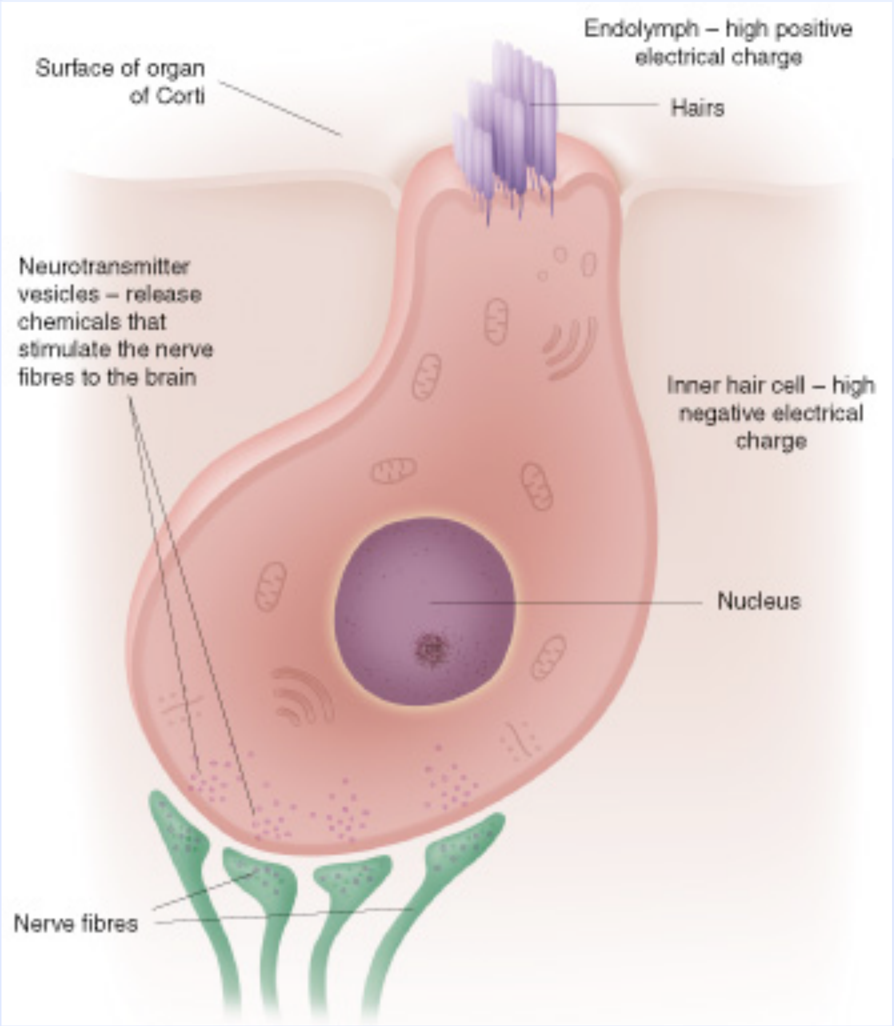
If the response of the individual fibers to a complex sound event is plotted as tuning curves, then a representation of the spectral analysis of the sound signal is obtained. The cochlea is therefore a frequency analyzer. There is a transfer function with bandpass characteristics between the stapes and each point on the basilar membrane, so that each point of the basilar membrane can be characterized by the frequency of the associated bandpass.

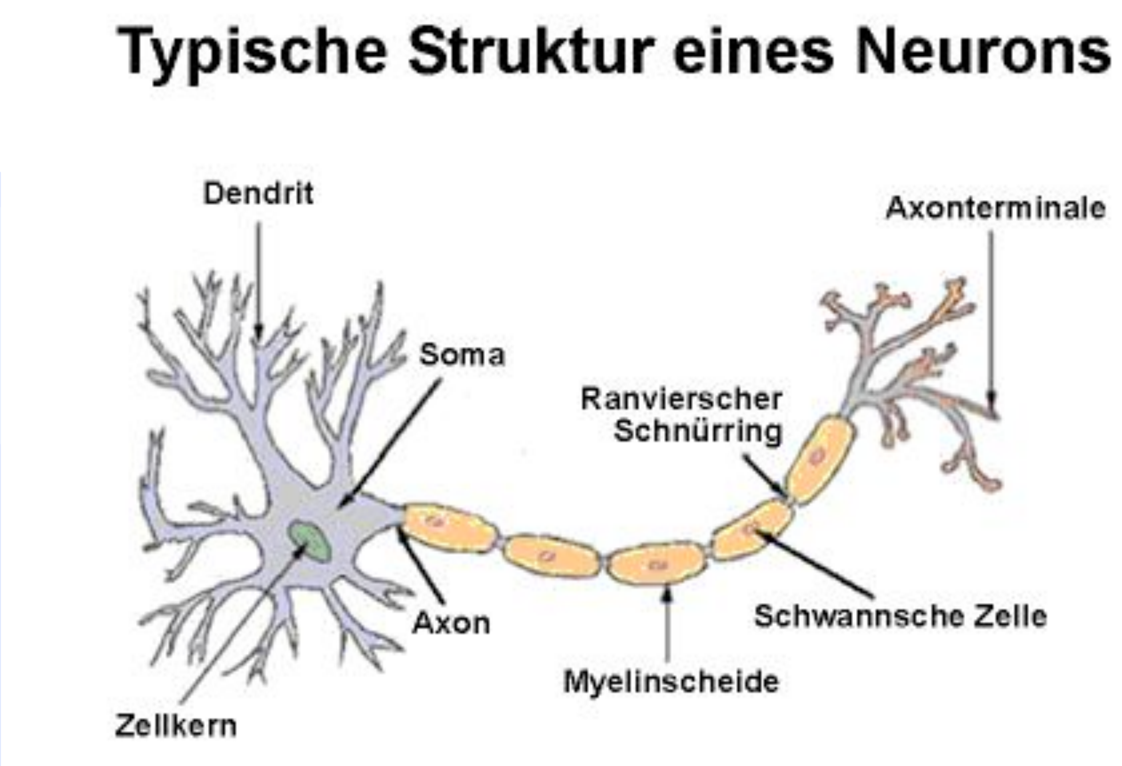
The Nervous System

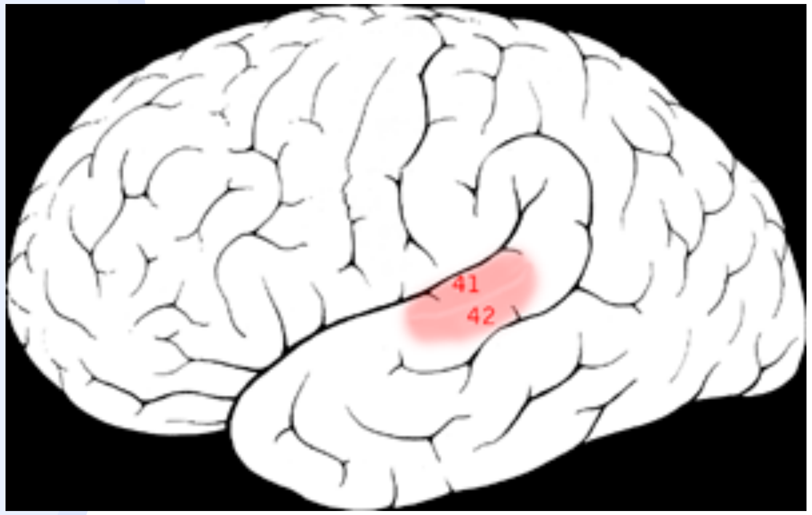
Physiologically, the nervous system is the structure formed by the spinal cord and the brain. The nervous system is used to receive, organize and evaluate messages from the environment. On the basis of the information obtained from these messages, it controls in a complex process, the perception, learning, movement and the behavior of the organism. Technically speaking, the nervous system can therefore be regarded as an information processing machine that receives tens of thousands of signals from the sensory organs within a fraction of a second and transmits thousands of signals to the brain. The signals are processed by a complicated system of neuronal circuits, which are formed by the neurons. A neuron is only a component of a combination of over 10 billion nerve cells in the human brain, which are connected by very complex, largely dynamic structures.

The neuron represents the functional and structural unity of the nervous system. Neurons are specialized somatic cells, which have the special property of being able to conduct nerve impulses (neural excitations). They are therefore used for information transmission and processing. It is clear from these tasks that a nerve cell must be able to receive, and to pass on, neural signals from other nerve cells. To this aim, the nerve cell is provided with two types of protrusions, the dendrites and the axon. The axon typically conducts electrical impulses away from the neuron's cell body, the dendrites and the soma act as the receivers. The transmission of the message between the nerve cells is carried out by the synapses.

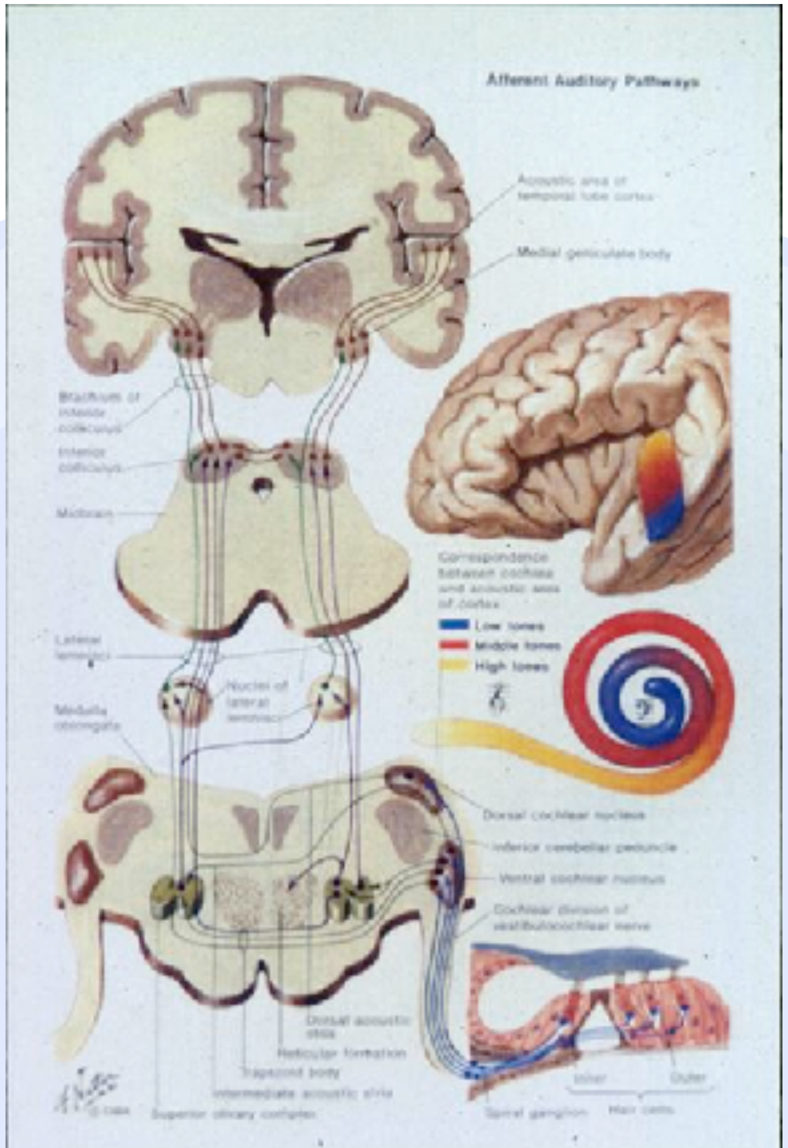
The basic neural output consists of an individual neural impulse. These nerve impulses are electrical voltage pulses and are referred to as action potentials (AP).
The signal of a neuron, that is, the single AP, is of no importance. Only a complex signal resulting from the neuronal impulses of an entire fiber bundle, can be processed into a sensible percept.
The neural information is determined by the frequency or the temporal distribution with which the individual pulses are created.
The decision as to whether a neuron will release an AP due to the incoming information is decided by an integration process (https://upload.wikimedia.org/wikipedia/commons/2/23/Neuron_action_potential.webm).

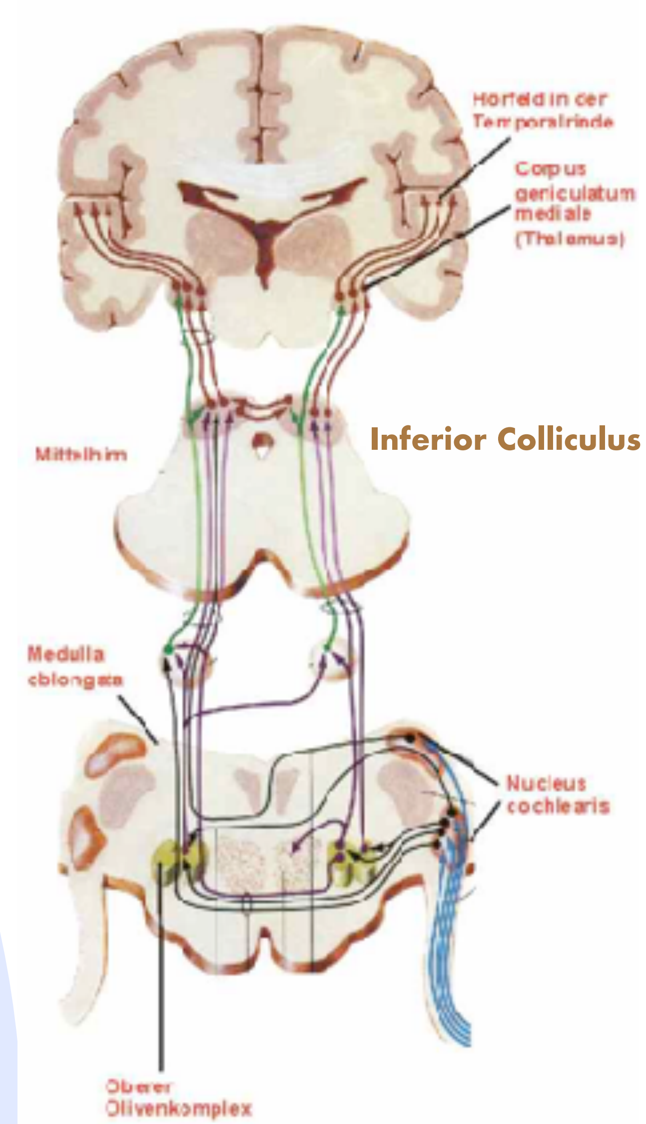






http://en.wikipedia.org/wiki/Action_potential





From the spiral ganglion in the cochlea, the sensory fibers run first to the cochlear nucleus in the brainstem. The acoustic information is already being processed at this stage by lateral inhibition, for instance. If an inner hair cell is activated by a relatively loud sound, adjacent cells (which actually encode higher and lower frequencies) can also be activated. In the cochlear nucleus the transmission of the signal of these co-activated cells can be suppressed. This improves frequency separation.

At the next stage, in the superior olivary complex, information is collected from both cochleas. Here, temporal differences between the fibers from both ears are evaluated in order to locate the direction of a sound source.

After passing through the cerebrum, where, among other things, directional hearing is improved in the inferior colliculus, the auditory information reaches the thalamus (medial geniculate nucleus), from where the auditory cortex (primary and secondary auditory cortex) and is reached, coming into consciousness.