Auditory System

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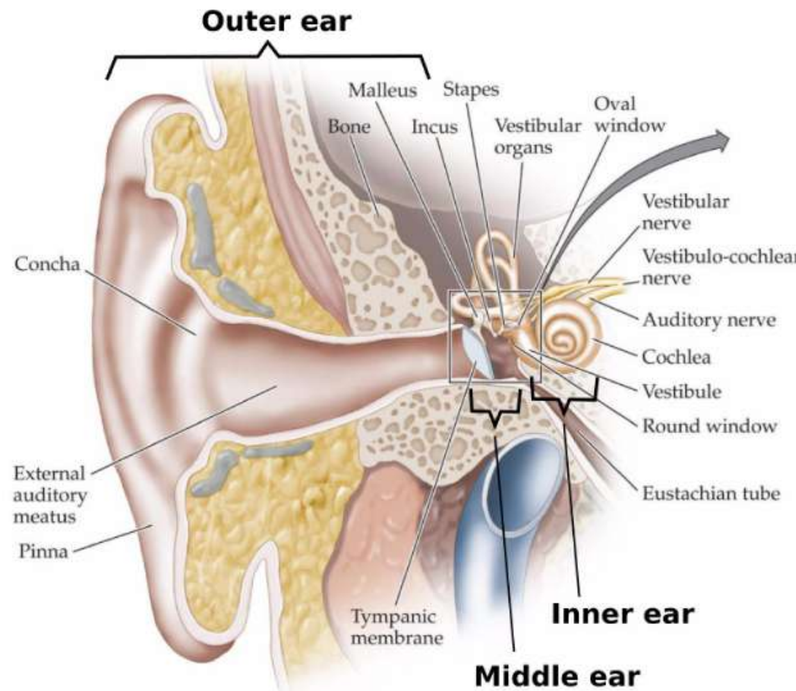
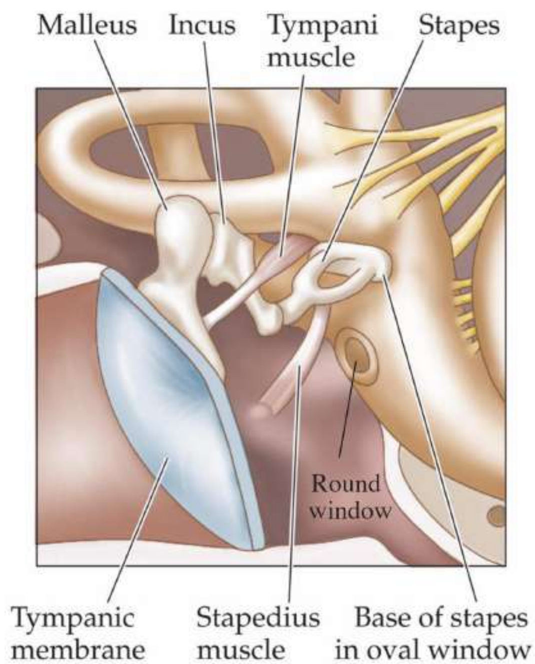
The humans auditory system consists of the outer ear, the middle ear, the inner ear, and the auditory sensory nerve pathway.



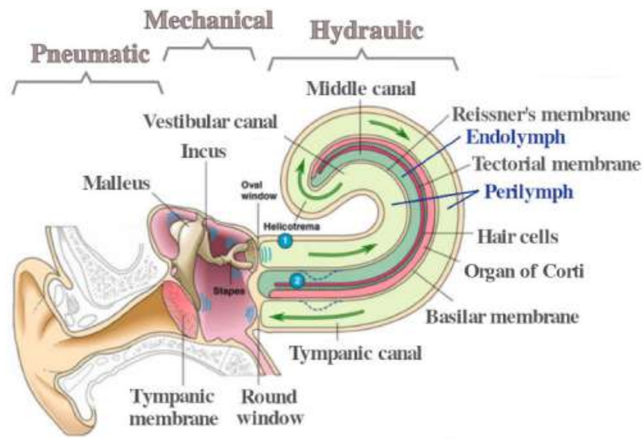
The **outer ear** funnels sound vibrations to the eardrum. The folds of cartilage surrounding the ear canal are called the pinna. Sound waves are reflected and attenuated when they hit the pinna, and these changes provide additional information that helps the brain determine the sound direction. The outer ear also increases the sound pressure in the middle frequency range (between 3 and 12 KHz).

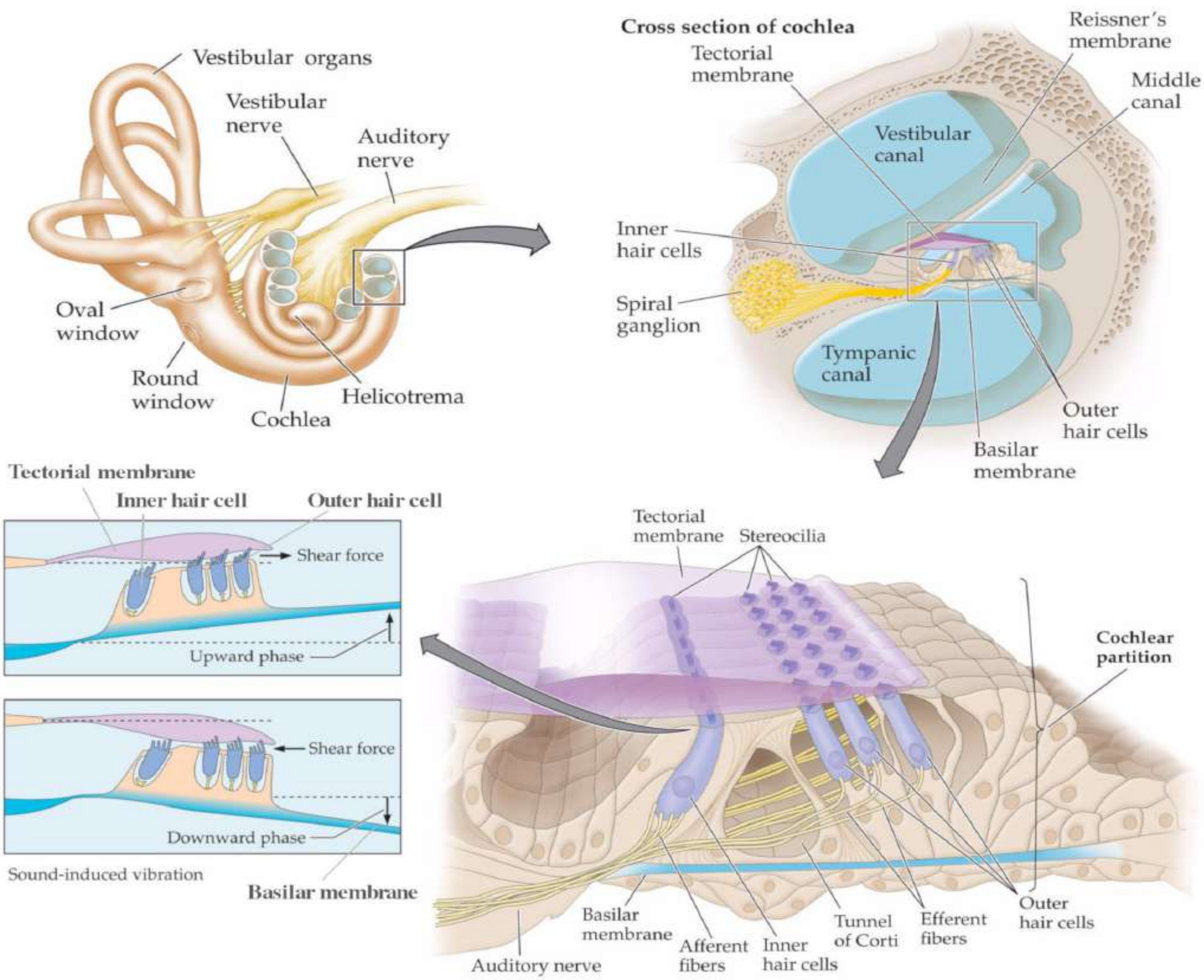
The **middle ear** is an air-filled chamber from the tympanic membrane (ear drum) to the oval window, which are connected by three ossicles (small bones). The three auditory ossicles are the malleus (hammer), incus (anvil) and stapes (stirrup). These ossicles act as a lever, converting the lower-pressure eardrum sound vibrations into higher-pressure sound vibrations at the smaller membrane of the oval window. The surface area of the eardrum is approximately 55 mm^2, while the faceplate of the stapes has a surface area of about 3.2 mm^2. Because pressure is force per unit area, the reduction from a larger area to a smaller area means an amplification of the pressure by about 17 times (55 / 3.2). Higher pressure is necessary at the oval window because the inner ear beyond the oval window contains liquid rather than air. The stapedius reflex of the middle ear muscles helps protect the inner ear from damage by reducing the transmission of sound energy when the stapedius muscle is activated in response to a loud sound. The eustachian tube is a canal that connects the middle ear to the nasopharynx. It controls the pressure within the middle ear, making it equal with the air pressure outside the body.



The middle ear can be considered as an impedance adapter - without it about 98% of energy would be reflected back. This is the same idea as the impedance matching between a microphone and a pre-amp. The input impedance of the pre-amp needs to match with that of the microphone in order to achieve the optimal signal-to-noise ratio. An animation of the sound wave propagation in the middle ear is available at <http://www.cochlea.eu/en/ear/middle-ear>.

The **inner ear** contains the cochlea, which is a spiral tube coiling about 2.5 turns. It forms a cone approximately 9 mm in diameter at its base and 5 mm in height. When stretched out, the spiral tube is approximately 30 mm in length. The base of the stapes couples vibrations into the cochlea via the oval window, which vibrates the perilymph liquid and causes the round window to bulb out as the oval window bulges in. There are three canals of the cochlea. The vestibular canal extends from oval window at base of cochlea to helicotrema at the apex. The tympanic canal extends from the helicotrema at the apex to the round window at the base of the cochlea. The middle canal is sandwiched between the vestibular and tympanic canals and contains the cochlear partition. The three cochlear canals are separated by two membranes. The Reissner's membrane is a thin sheath of tissue separating the vestibular and middle canals in the cochlea. The basilar membrane is a plate of fibers that forms the base of the cochlear partition and separates the middle and tympanic canals in the cochlea.

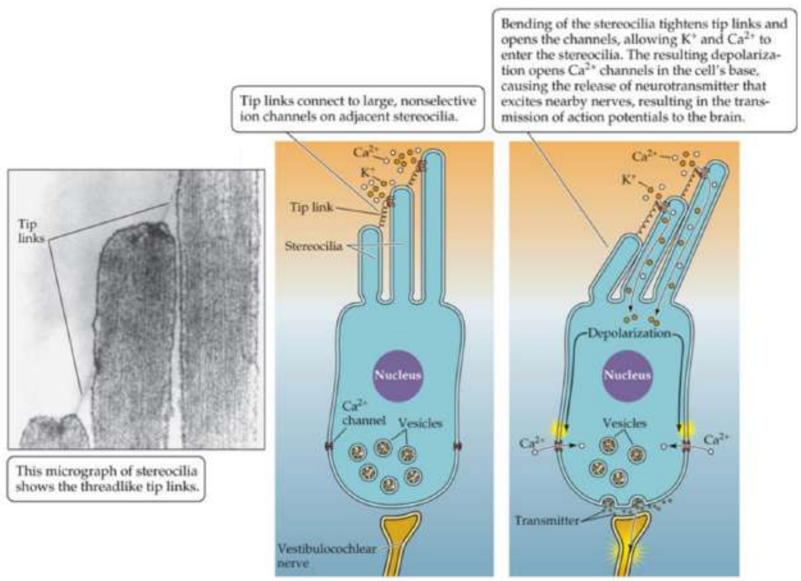




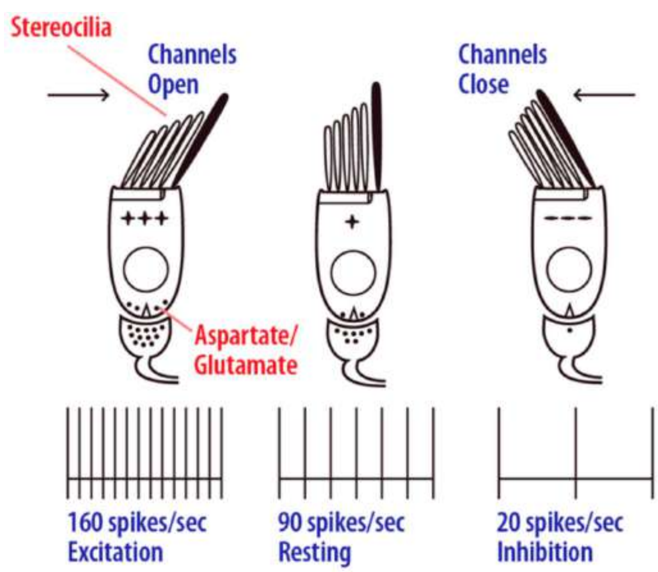
The vestibular canal and the tympanic canal are filled with the perilymph, and are connected at the helicotrema, the apex of the cochlear. The middle canal is filled with the endolymph. Perilymph has a similar ionic constituents to the extracellular fluid: high concentration of sodium (Na+) and low concentrations of potassium (K+) and chloride (Cl–). Endolymph has ionic concentrations similar to intracellular fluid: high concentrations of potassium and chloride.

The organ of Corti is a structure on the basilar membrane of the cochlea that is composed of hair cells and dendrites of auditory nerve fibers. Movements of the cochlear partition are translated into neural signals by structures in the organ of Corti. Hair cells are cells that support the hairlike extensions called stereocilia, which transduce mechanical movement in the cochlea into neural activity sent to the brain stem. Some hair cells also receive input from the brain. Hair cells are arranged in four rows that run down length of basilar membrane: one row of inner hair cells and 3 rows of outer hair cells. The human cochlea contains on the order of 3,500 inner hair cells and 12,000 outer hair cells at birth. The tectorial membrane is a gelatinous structure, attached on one end, that extends into the middle canal of the ear, floating above inner hair cells and touching outer hair cells.

Vibrations cause displacement of the tectorial membrane, which bends stereocilia attached to hair cells and causes the release of neurotransmitters. The tip of each stereocilium is connected to the side of its neighbor by a tiny filament called a tip link. Stereocilia regulate the flow of calcium and potassium ions into and out of the hair cells.

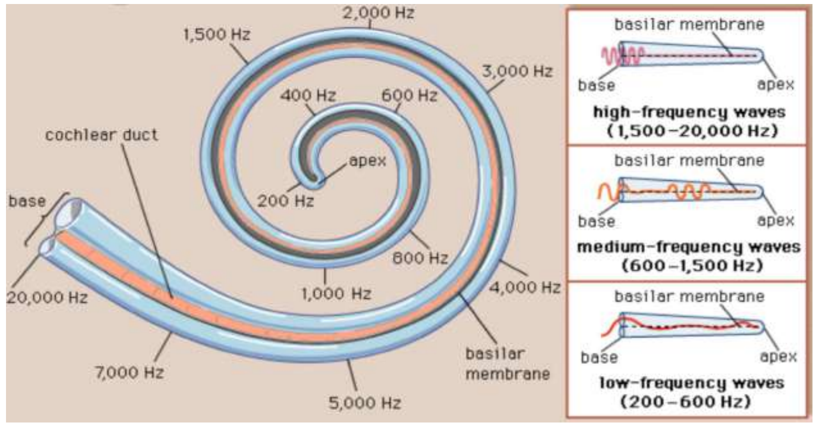


The inner hair cells convey almost all information about sound waves to the brain using afferent fibers. The outer hair cells receive information from the brain using efferent fibers, which can make parts of the cochlear partition stiffer. This makes the responses of inner hair cells more sensitive and more sharply tuned to specific frequencies.

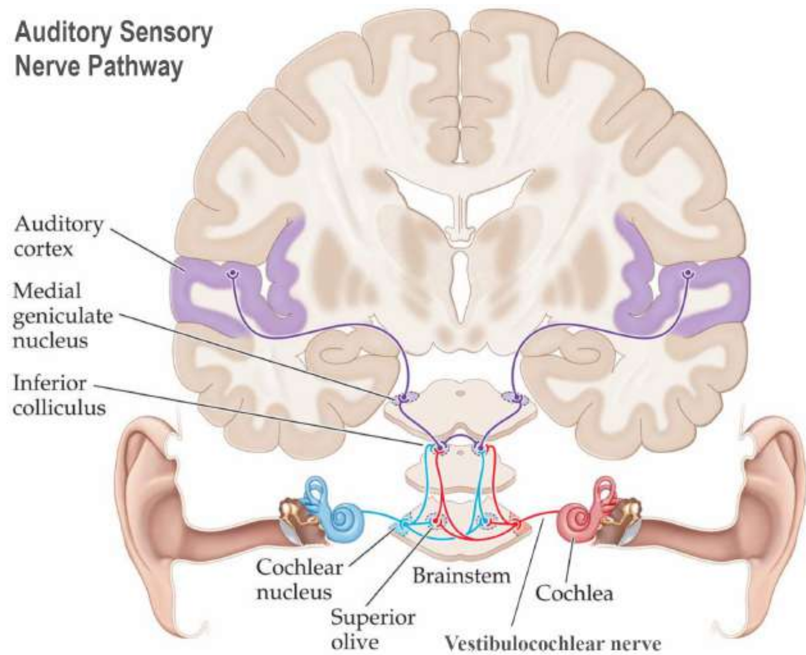


At rest, hair cells release some neurotransmitter (aspartate and glutamate), producing a spontaneous firing rate of action potentials in the innervating afferent fibers (such as 90 spikes/s). When the stereocilia are displaced toward the kinocilium (a specialized cilia), the cell is depolarized (more positive) and the afferent firing rate is increased (such as 160 spikes/s). When the stereocilia are displaced away from the kinocilium, the cell is hyperpolarized (more negative) and the afferent firing rate is decreased (such as 20 spikes/s).

The cochlea senses different frequencies on the basis of the place along the organ of Corti. Low frequency sound waves travel farther than high frequency sound waves do. Thus, high Frequency sounds cause stronger vibrations near the oval window, and low frequency sounds cause stronger vibrations near the helicotrema. The frequency distribution along the cochlear is shown on the right.

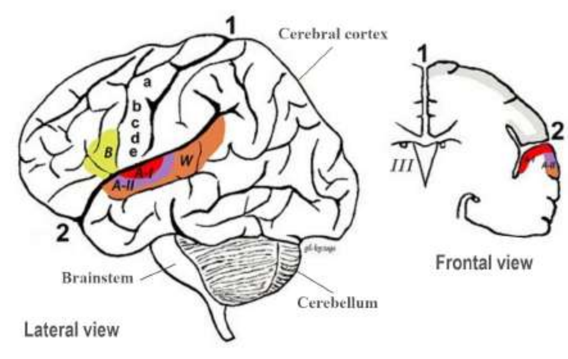


The **auditory sensory nerve pathway** conveys the special sense of hearing. Sound information travels from the cochlear nuclei in the organ of Corti of the inner ear (cochlear hair cells) to the central nervous system, carried by the vestibulocochlear nerve.



The superior olivary in pons (part of the brainstem) is the first convergence of the left and right cochlear pulses. The superior olivary complex is a 14-neuron network that normalizes sound levels between the ears and determines the sound location.

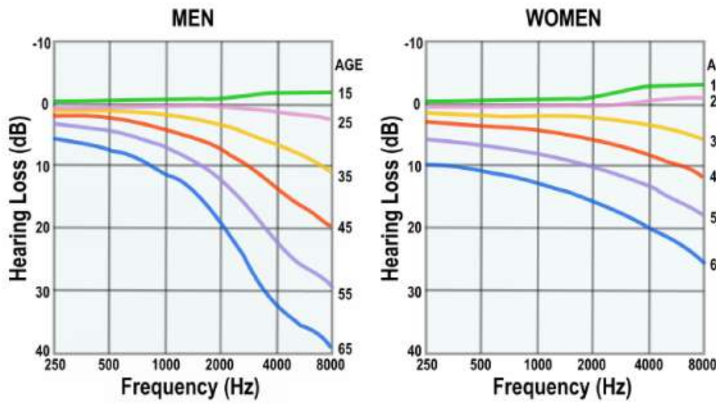
The inferior colliculus is located in the midbrain (upper part of the brainstem) and serves as a nearly obligatory relay neuron in the ascending auditory system. It acts to integrate information from the superior olivary and cochlear nucleus before sending it to the thalamus and cortex.



Lateral view (left) showing the distribution of A-I and A-II and Wernicke's area (W). Auditory cortex projects to the regions of the frontal lobe involved in motor function for speech (a), the lips (b), jaw (c), tongue (d), larynx (e) and Broca's area (B). Frontal view (right) showing A-I inside the Sylvian fissure and Heschl's gyrus. 1 - Interhemispherical fissure. 2 - Sylvian fissure.

The medial geniculate nucleus is part of the auditory thalamus and represents the thalamic relay between the inferior colliculus and the auditory cortex. The thalamus is at the top of the brainstem that serves several functions such as relaying of sensory signals, including motor signals to the cerebral cortex, and the regulation of consciousness, sleep, and alertness. It is thought that the medial geniculate nucleus influences the direction and maintenance of attention.

The human auditory cortex can be studied using functional magnetic resonance imaging (fMRI), and is divided into more than a dozen different regions surrounding Heschl's gyrus in the superior part of the temporal lobe. Primary auditory cortex (A-I) is situated in the posterior third of the superior temporal gyrus, next to Wernicke's area (W). A-I is the central region of the auditory cortex and receives direct projections from the ascending auditory pathway, particularly the ventral region of the medial geniculate body in the thalamus. Secondary auditory cortex (A-II) is located more rostrally in the temporal lobe, which includes the Wernicke's area, an important region in language function. Wernicke's area is specifically for language development.

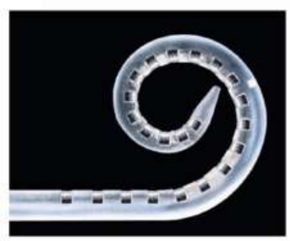


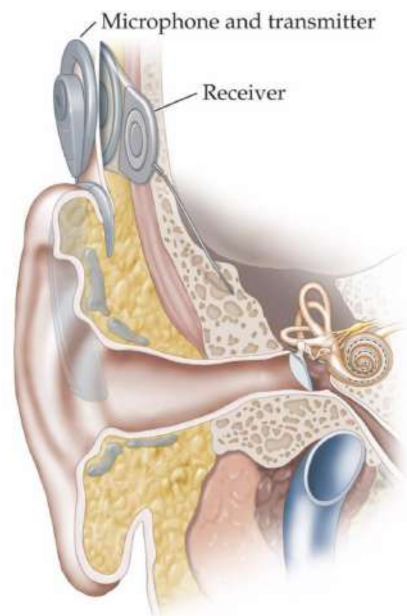
Normal Hearing Loss

Normal hearing loss due to aging consists of a gradual decrease in high frequency sensitivity over time (see chart of the right). Acquired hearing loss for a specific narrow frequency band can be caused by substantial (cumulative) exposure to a sound of a strong intensity.

Cochlear Implant

A cochlear implant is a surgically implanted neuroprosthetic device that provides a sense of sound to a person with severe sensorineural hearing loss. Bypassing the outer and middle ears, the sound sensation comes from the sound that is converted to electric signals which directly stimulate the auditory nerve. The brain adapts to the new mode of hearing, and eventually can interpret the electric signals as sound and speech.





The outside unit contains a microphone, electronics, a digital signal processor, battery, and a coil transmitting signals across the skin. The inside unit has a coil to receive signals, electronics, and an array of electrodes placed into the cochlea to stimulate the cochlear nerve.

From the early days of implants in the 1970s and the 1980s, speech perception via an implant has steadily increased. Many users of modern implants gain reasonable to good hearing and speech perception skills post-implantation, especially when combined with lipreading. One of the challenges that remain with these implants is that hearing and speech understanding skills after implantation show a wide range of variation across individual implant users. Factors such as duration and cause of hearing loss, how the implant is situated in the cochlea, the overall health of the cochlear nerve, but also individual capabilities of re-learning are considered to contribute to this variation, yet no certain predictive factors are known. In children with severe to profound hearing loss, implants have shown to positively contribute to spoken language development.

Despite providing the ability for hearing and oral speech communication to children and adults with severe to profound hearing loss, there is also controversy around the devices. Much of the strongest objection to cochlear implants has come from the Deaf community. For some in the Deaf community, cochlear implants are an affront to their culture, which as some view it, is a minority threatened by the hearing majority.