# Lecture 3: Auditory Perception

## Part 1 of 3

# Anatomy and Physiology of the Auditory System

# Relevance


Cheung, S., Han, E., Kushki, A., Anagnostou, E. and Biddiss, E., 2016. Biomusic: An auditory interface for detecting physiological indicators of anxiety in children. *Frontiers in neuroscience*, *10*, p.401.

Wu, J., Liu, Q., Zhang, M., Pan, Z., Li, H. and Tan, K.C., 2021. HuRAI: A brain-inspired computational model for human-robot auditory interface. *Neurocomputing*, *465*, pp.103-113.

Serafin, S., Geronazzo, M., Erkut, C., Nilsson, N.C. and Nordahl, R., 2018. Sonic interactions in virtual reality: State of the art, current challenges, and future directions. *IEEE computer graphics and applications*, *38*(2), pp.31-43

Zhao, Y., Bennett, C.L., Benko, H., Cutrell, E., Holz, C., Morris, M.R. and Sinclair, M., 2018, April. Enabling people with visual impairments to navigate virtual reality with a haptic and auditory cane simulation. In *Proceedings of the 2018 CHI conference on human factors in computing systems* (pp. 1-14).

Geronazzo, M., Bedin, A., Brayda, L., Campus, C. and Avanzini, F., 2016. Interactive spatial sonification for non-visual exploration of virtual maps. *International Journal of Human-Computer Studies*, *85*, pp.4-15.

Betlehem, T., Zhang, W., Poletti, M.A. and Abhayapala, T.D., 2015. Personal sound zones: Delivering interface-free audio to multiple listeners. *IEEE Signal Processing Magazine*, *32*(2), pp.81-91.

# Learning Objectives

Provide an introduction to the structure and physiology of the auditory system, from the ear to the brain.

Provide a brief overview of the concepts such as pitch, loudness, localisation and their relevance to auditory processing including speech processing.

# Learning Outcomes

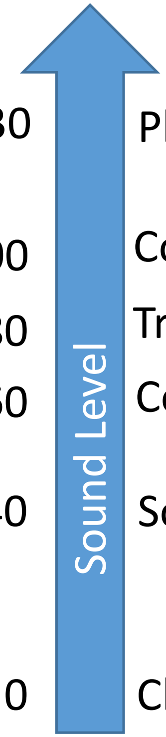
To be able to provide a description of the main areas of the auditory system, from ear to brain, relevant for the processing of auditory information.

The human auditory system is both complex and remarkable.

To understand how our auditory system works, let's pose some statements and questions and then investigate each element in more detail.

# Sound Level

**Typical Sound Levels (dBA)**



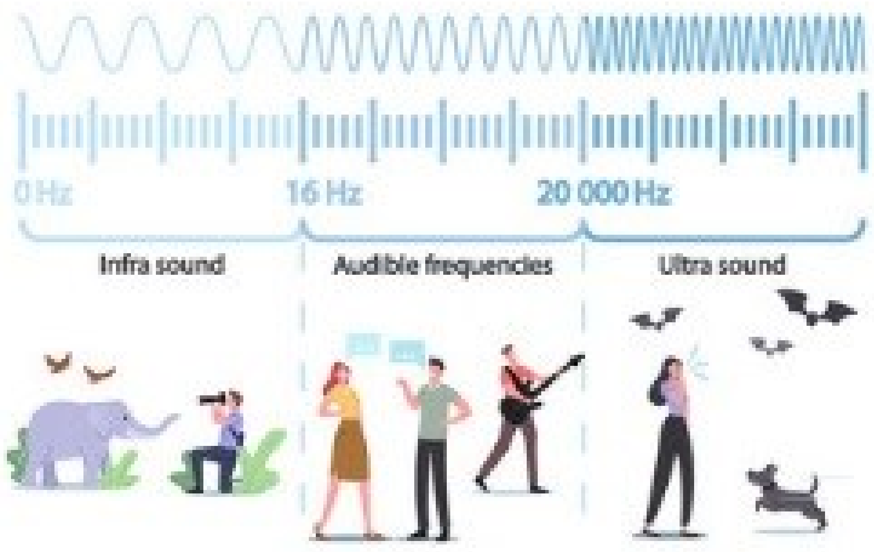

| | |
|---|---|
| 130 | Plane taking off (200 ft away) |
| 100 | Construction site |
| 80 | Train (100 ft away) |
| 60 | Conversation (3 ft away) |
| 40 | Soft whisper |
| 0 | Close to threshold of hearing |

<u>Sound level</u>

Statement: We can hear a wide variety of sounds from the quietest to the loudest.

Question: How is our auditory system able to process sound level information (which we subjectively describe as *loudness*) across such a large range of sound levels?

# Sound Frequency

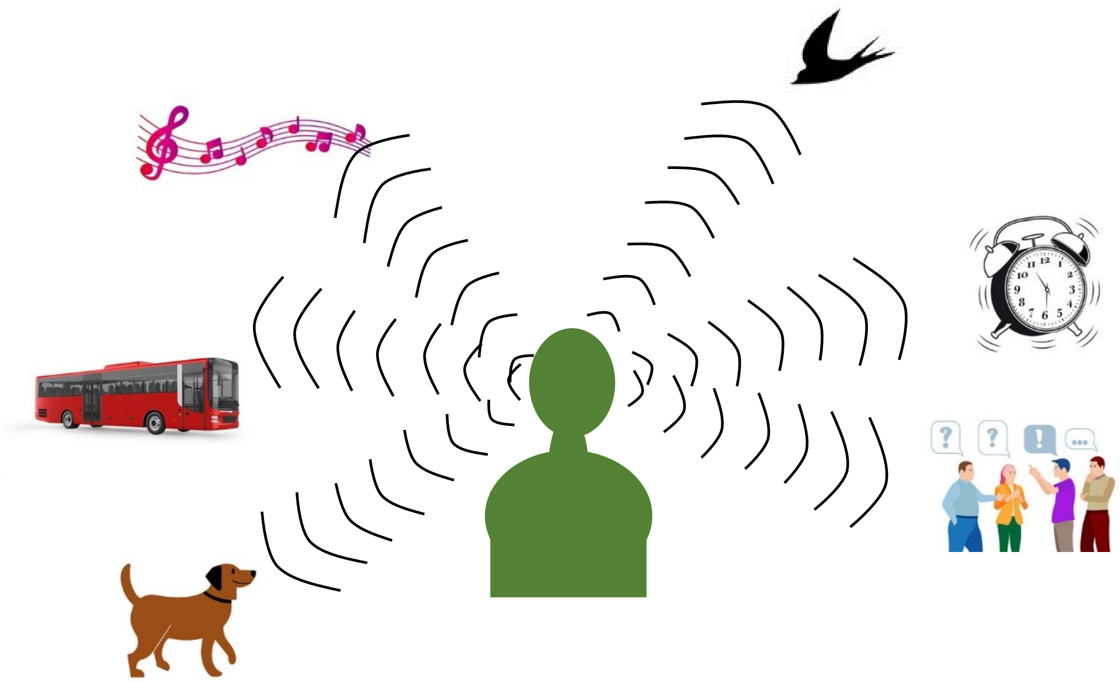



Sound frequency

Statement: We can hear a wide variety of sound frequencies, from low frequencies to high frequencies ~ 20 Hz to 20 kHz; including the frequencies important for speech processing.

Question: How does our auditory system process sound frequency information, and how do we perceive the *pitch* of sounds, which is important for speech processing as well as music perception?

# Sound Localisation



Sound localisation

Statement: We can detect sounds from behind, in front, above, and below.

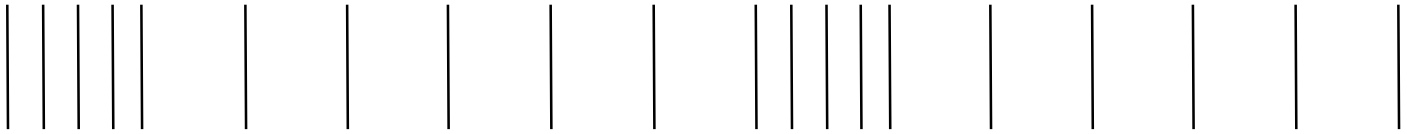
Question: How is the information from each ear and both ears combined in order for us to accurately judge where a sound is located in space?

# The Sound Stimulus

# The Sound Stimulus

Condensation:
Increase in
pressure

Rarefaction:
Decrease in
pressure

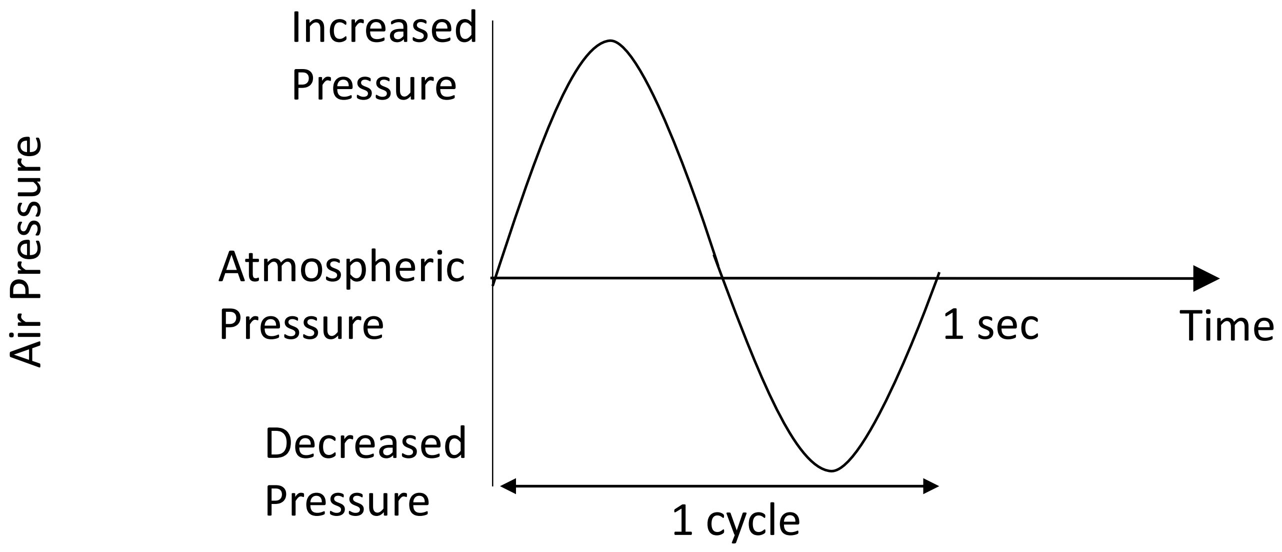


Object vibrations cause pressure changes in the air, water, or medium.

E.g., Active loudspeaker diaphragm/striking a tuning fork:
Speaker diaphragm moves out: Air molecules pushed together (condensation), causing a slight increase in local density of molecules - -> increase in local air pressure.
Speaker diaphragm moves in: Air molecules spread out (rarefaction), causing a slight decrease in local density of molecules - -> decrease in local air pressure.

As this process is repeated: Alternating pattern of high- and low-pressure regions in the air, propagating the sound wave.

# The Sound Stimulus




Unit of sound frequency is Herts (Hz).
For example 1 cycle per second = 1 Hz

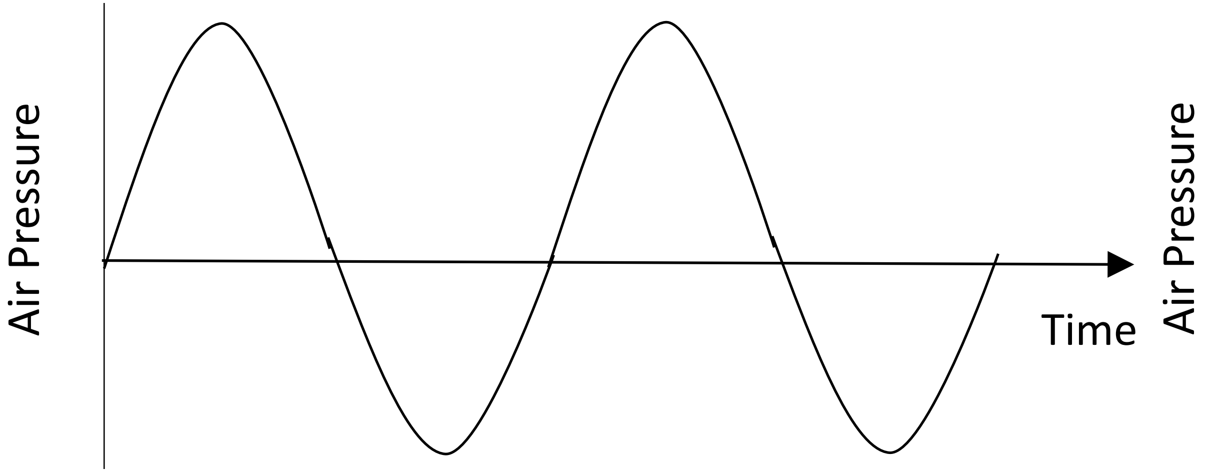
A pure tone (for example produced by striking a tuning fork).

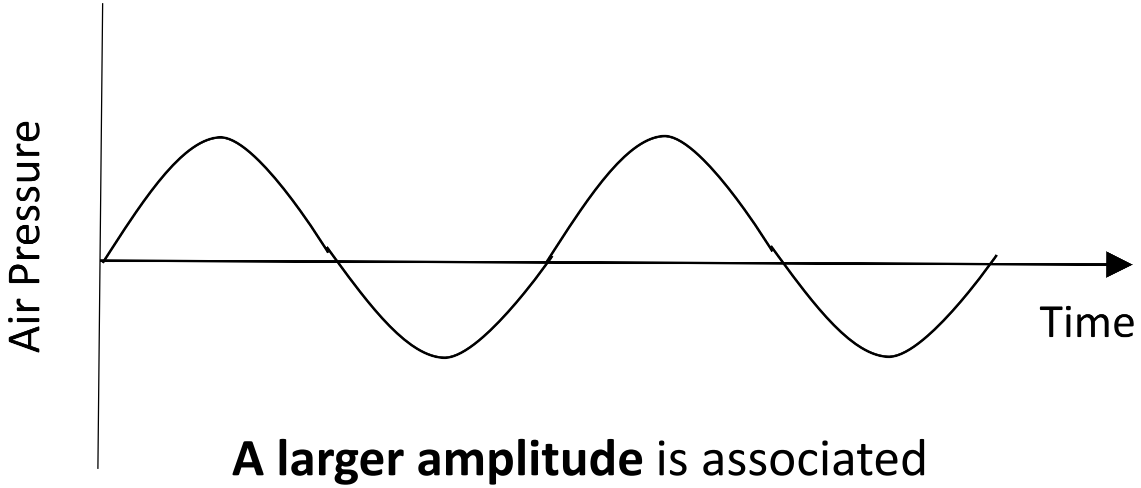
Pressure changes in the air occur in a pattern defined by a sine wave.

Amplitude- Size of pressure change.

Frequency: Number of times per second that the pressure changes repeat.

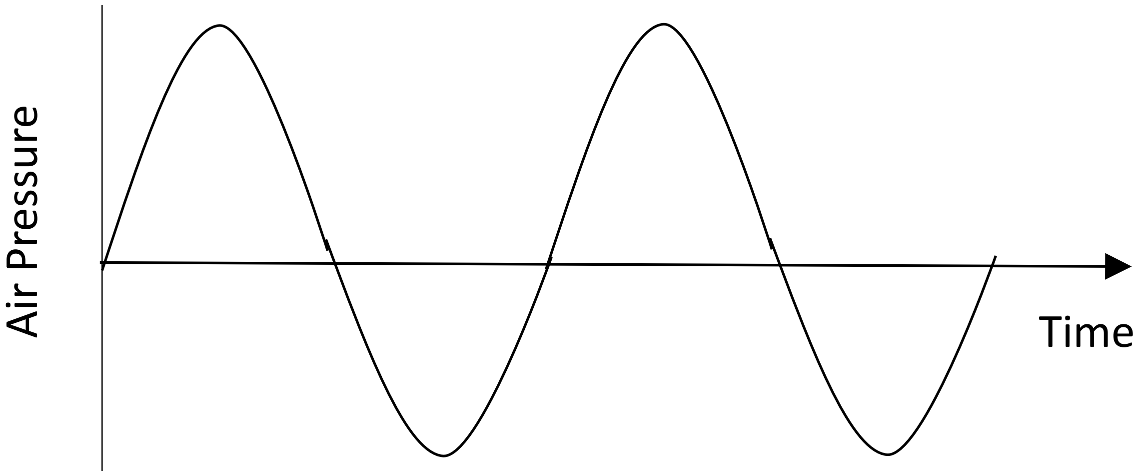
# Amplitude and Frequency (e.g., a pure tone)

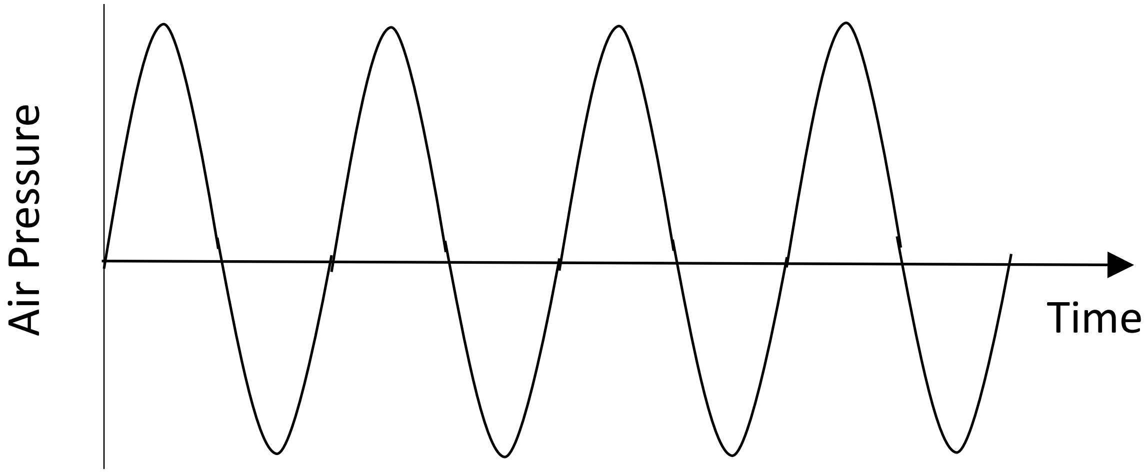


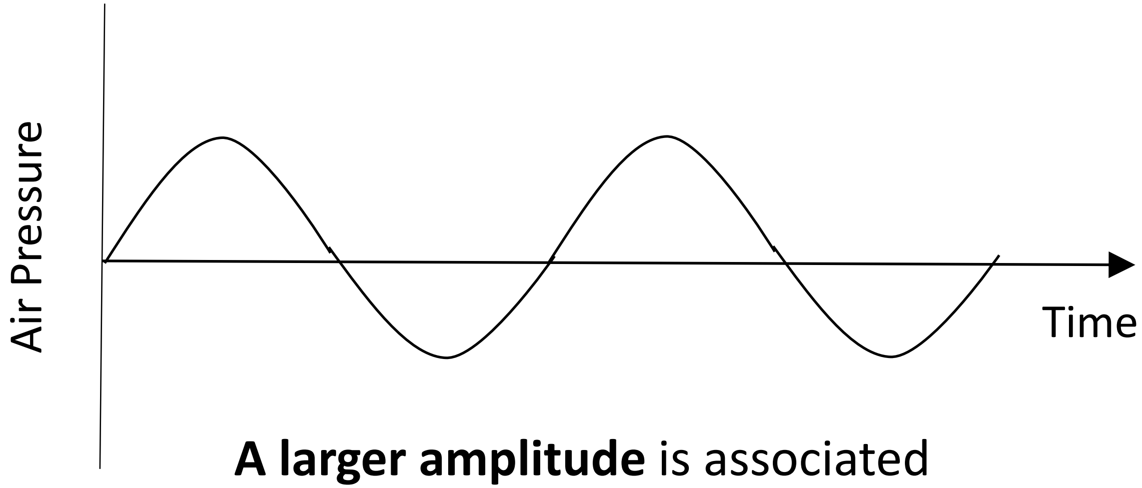



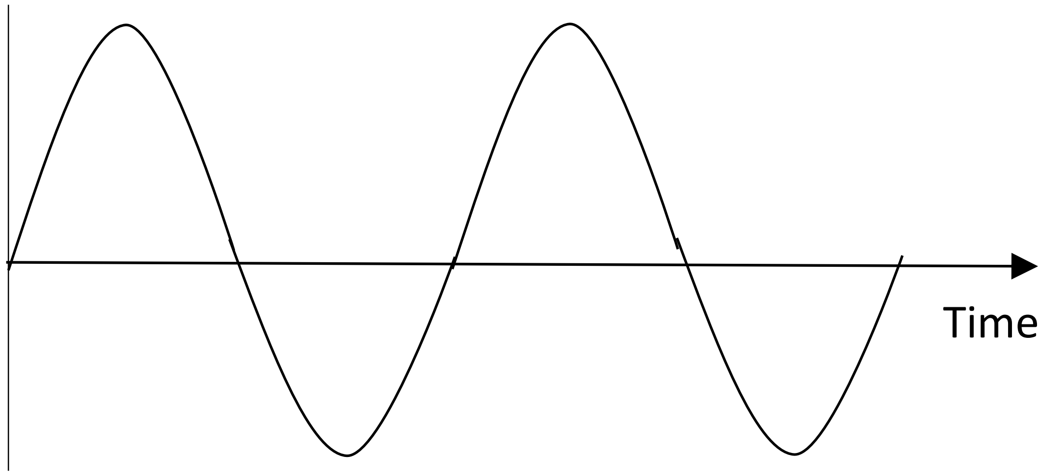

**A larger amplitude** is associated with the perception of greater **loudness**.

# Amplitude and Frequency (e.g., a pure tone)




**A larger amplitude** is associated with the perception of greater **loudness**.

**More cycles per second** = higher **sound frequency**. The repetition rate of a waveform is associated with the perception of **pitch**.

# Decibel Scale

The range from very quiet to very loud is extensive- so represented as decibels , a more manageable scale.

$$dB = 20 \times \log (p/P_o)$$

decibels

Sound pressure of the sound stimulus

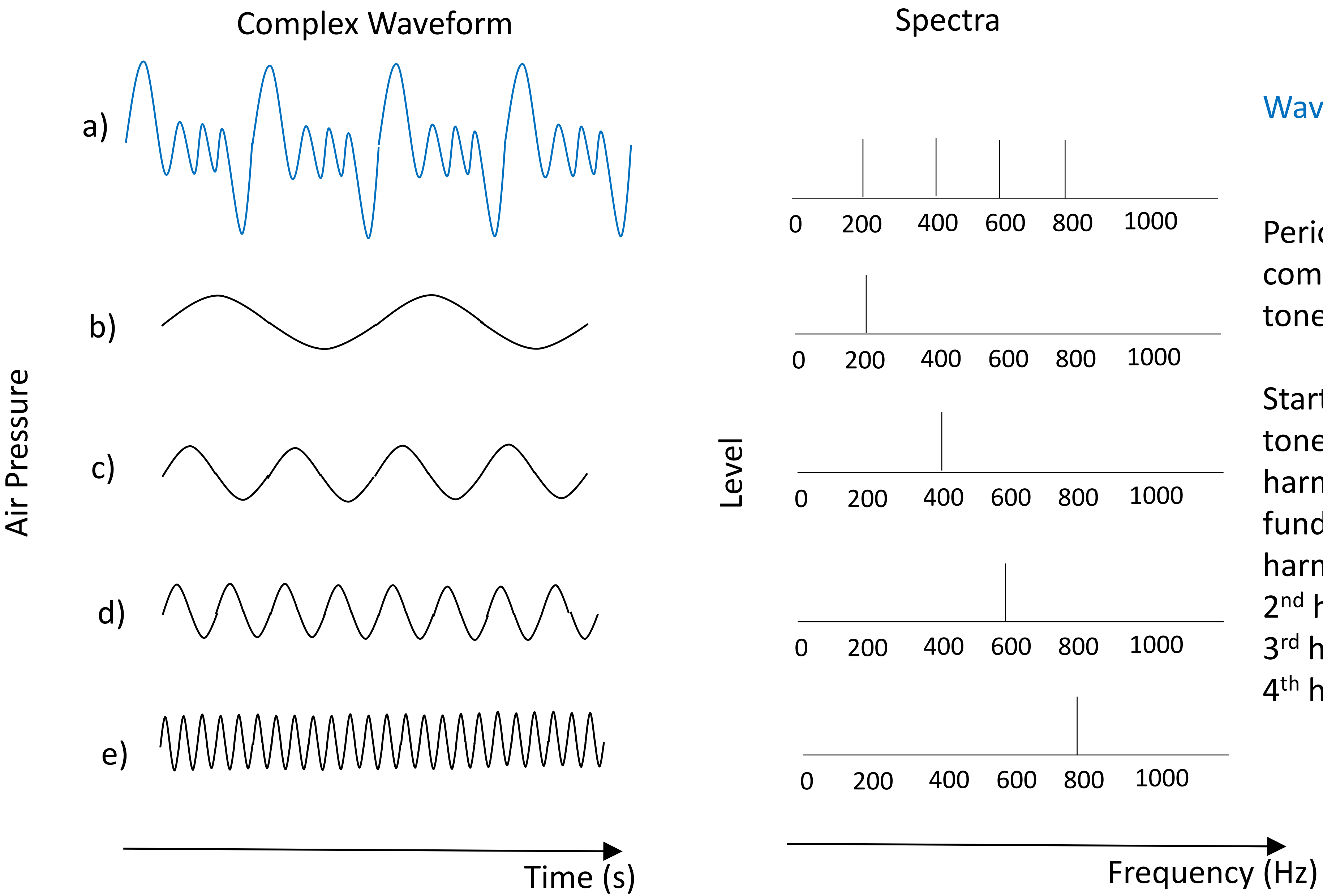
Standard sound pressure, usually 20 micropascals.

1 pascal is a unit of pressure.

20 micropascals is a pressure near the threshold of human hearing.

If the standard of 20 micropascals is used then the notation dB SPL is used (where SPL = Sound Pressure Level).

# Complex Sounds- e.g., Speech/Music/Environmental..




Waveform a) = b) + c) + d) + e)

Periodic complex sounds are comprised of a number of pure tones.

Start with a single 200-Hz pure tone (fundamental frequency/first harmonic). Add multiples of the fundamental frequency (higher harmonics).

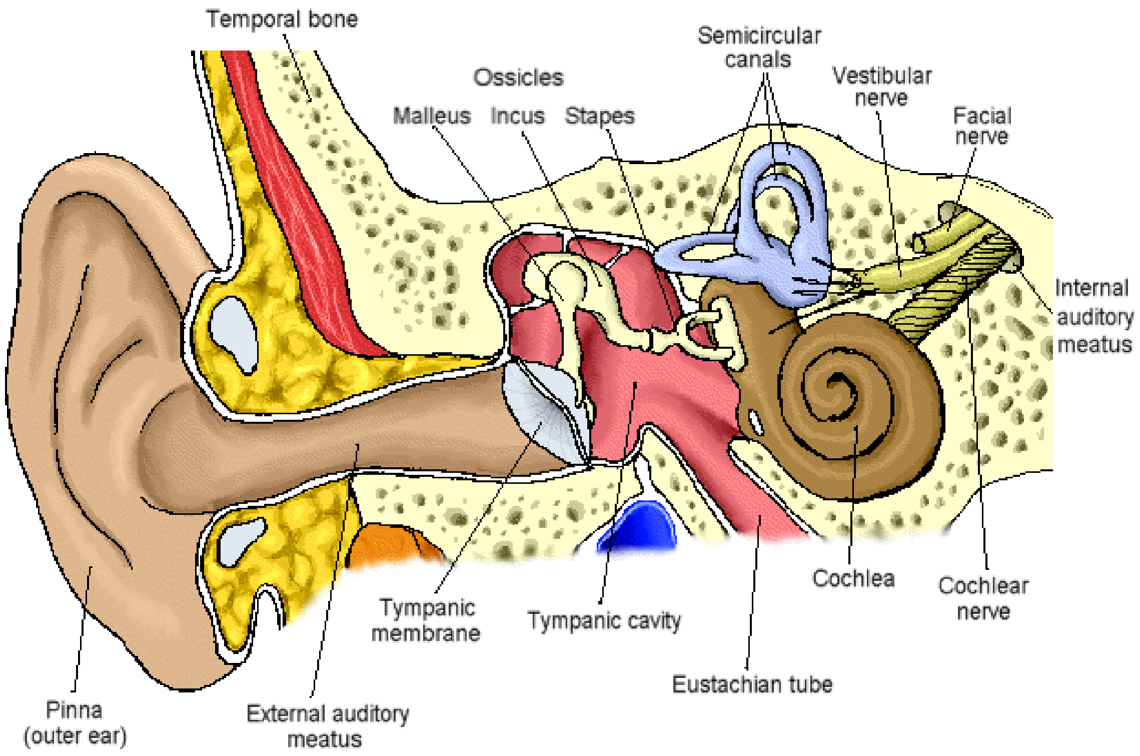
2nd harmonic tone = 400 Hz

3rd harmonic tone = 600 Hz

4th harmonic tone = 800 Hz

Anatomy and Physiology of the Auditory System

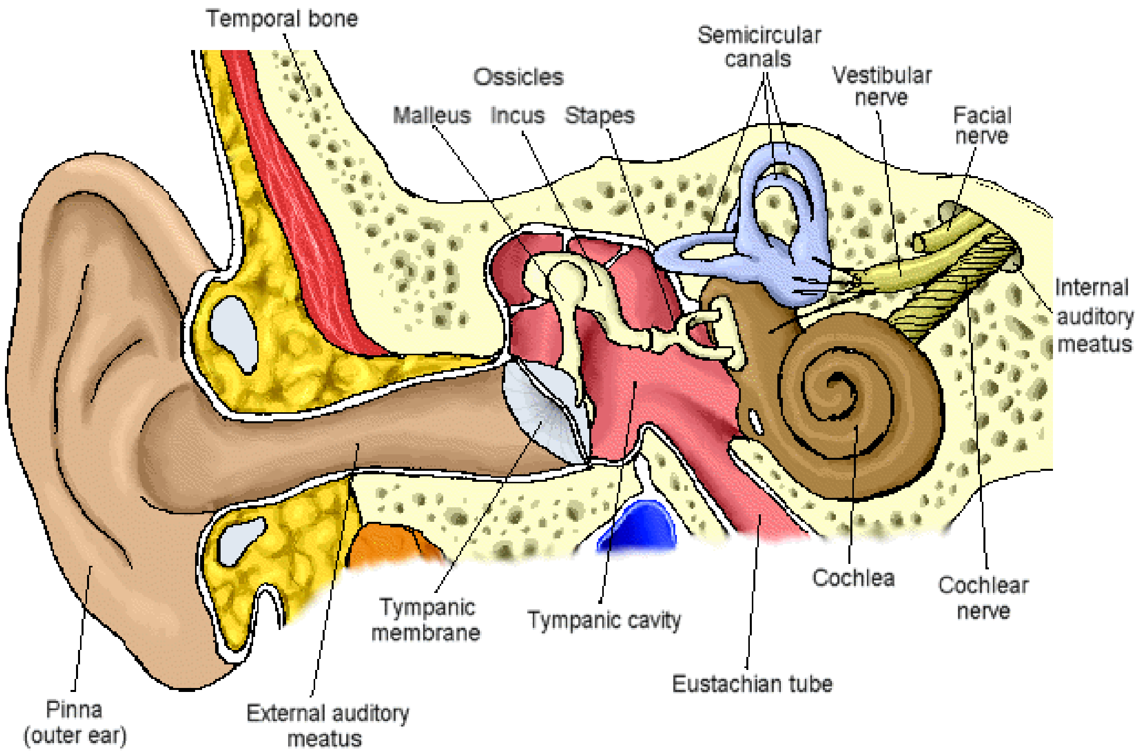
# The Ear




Delivery of sound [which may be pre-processed by the outer ear (pinna)] to the appropriate receptors in the inner part of the ear.

Transduction of the stimulus from pressure changes in the air into electrical signals in the auditory nerve.

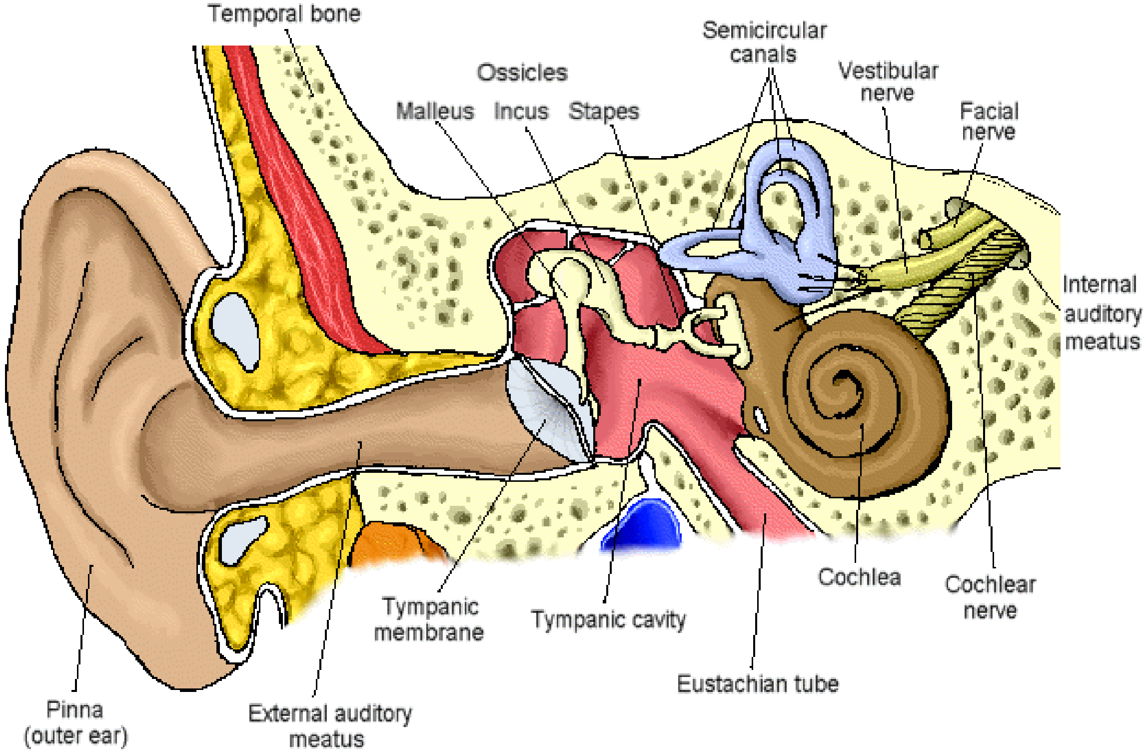
# Outer Ear




<u>Outer ear</u>
Pinna:
Acts as a funnel, to funnel sound into the ear canal and also acts as a filter.
External folds of the outer ear also help with the localisation of sounds.

Auditory canal (external auditory meatus):
Is terminated by eardrum.
Acts as an acoustic tube, closed at 1 end by the eardrum, boosting sensitivity in the range 1000-5000 Hz (range of the human voice).

# Middle Ear

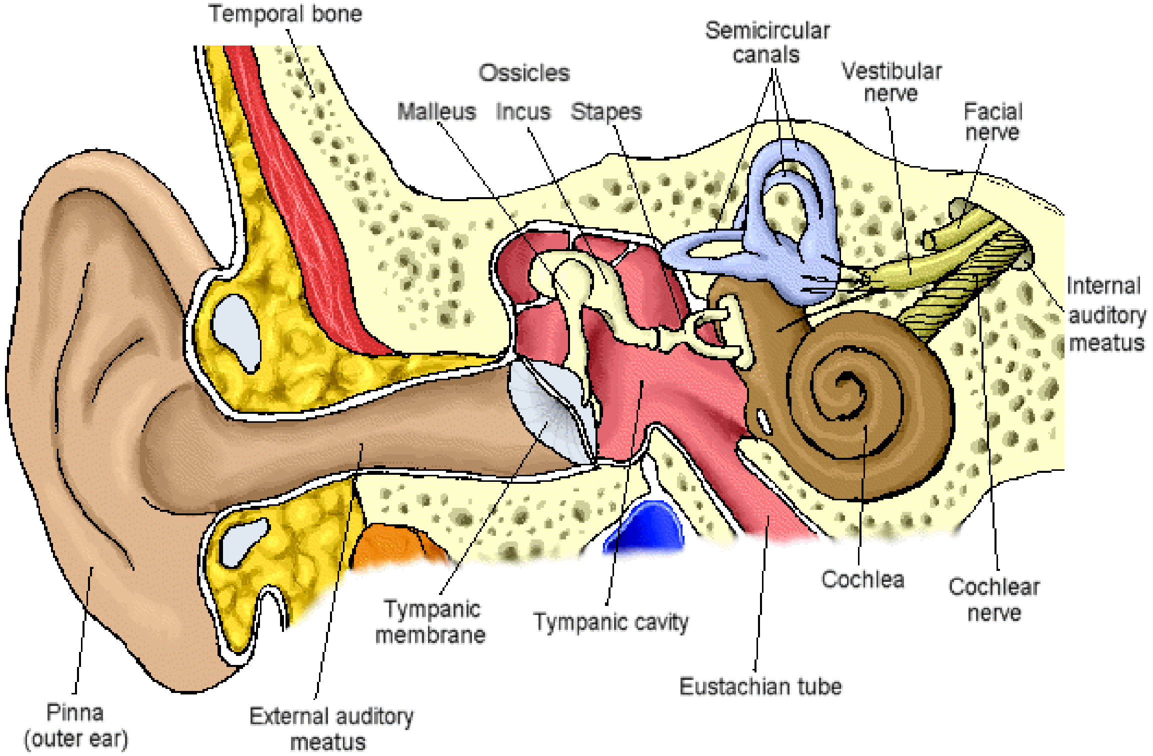



<u>Middle ear</u>
Consists of the eardrum, to which three small bones (called the ossicles), are attached.

Eardrum vibrates due to the sound, and this vibration is passed onto these 3 small bones which also vibrate. So the ear drum is responsible for changing pressure variations of incoming sound waves (through the ear canal) into mechanical vibrations of the 3 small bones.

Note: Since the eardrum seals the middle and outer ear, the Eustachian tube (which connects the middle ear to the oral cavity) is needed to equalize the pressures in these two cavities.

# Middle Ear

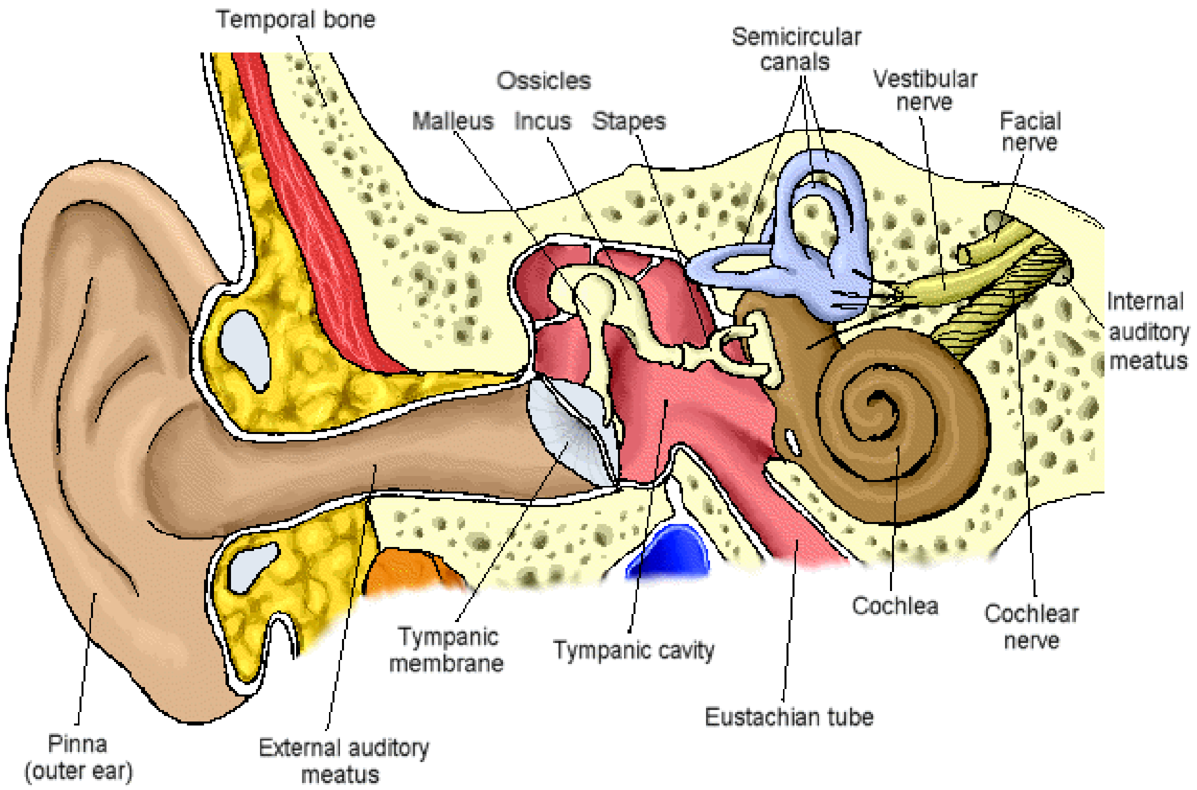



The Ossicles of the middle ear:
Malleus (hammer)
Incus  (anvil)
Stapes (stirrup)
The stapes attaches to the oval window of the coiled structure called the cochlea.

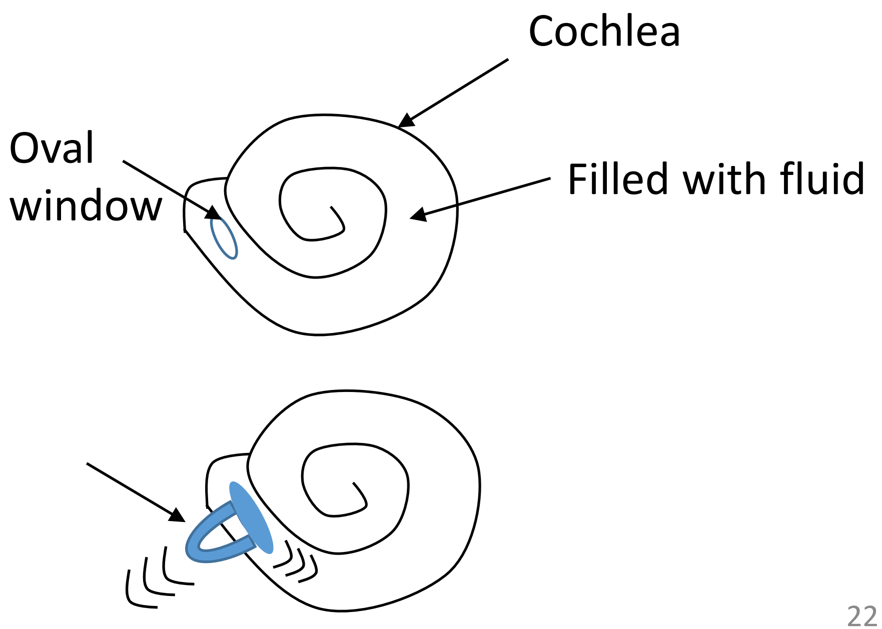
The ossicles transform small changes in pressure exerted by a sound wave, to a much greater pressure at the oval window of the cochlea. This assists the transmission of vibrations from the non-fluid-filled middle ear to the fluid-filled cochlea of the inner ear.

E.g., The lever action in the ossicles provides a factor of about 1.5 in force multiplication.

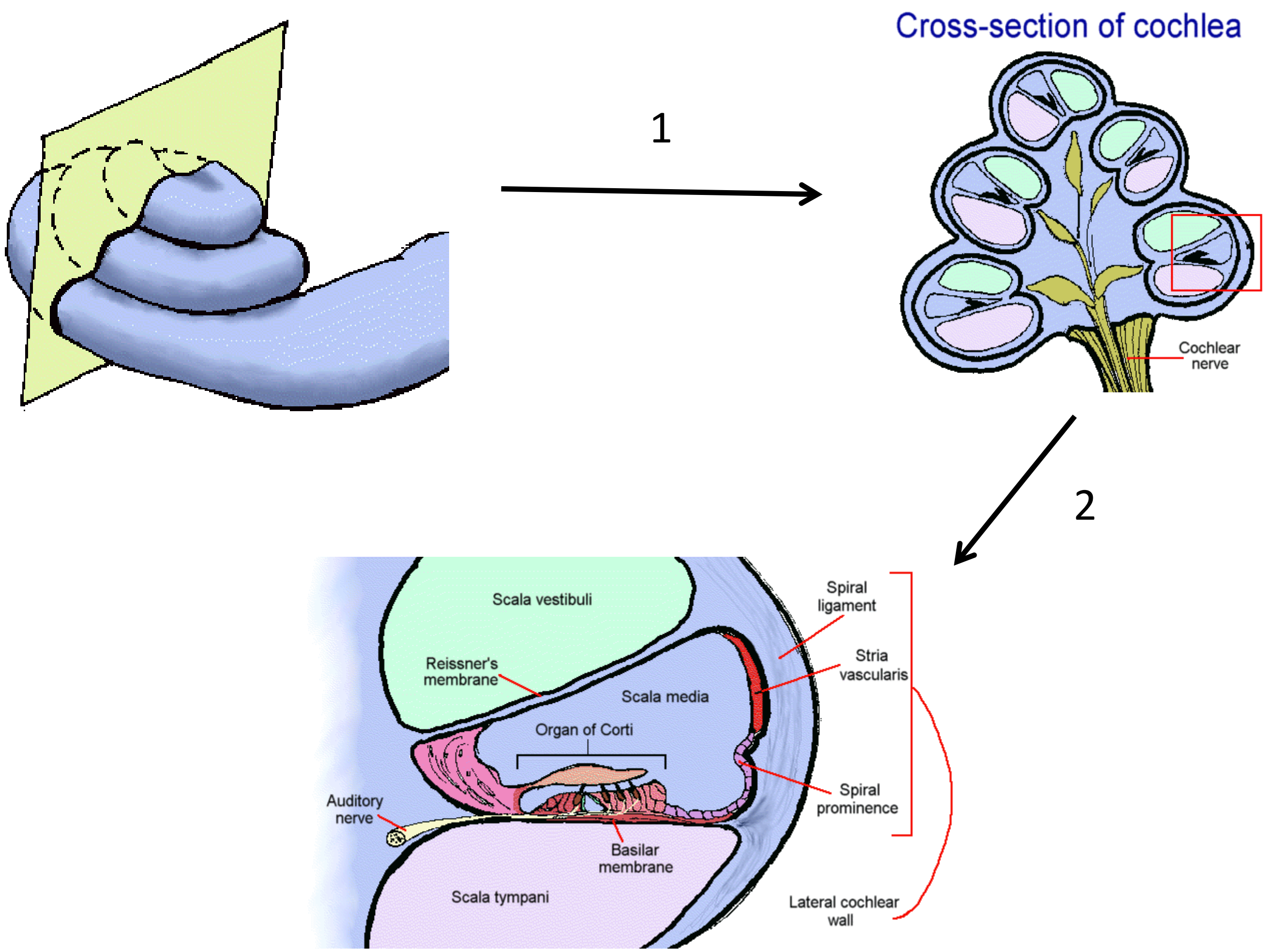
# Inner Ear




Inner ear: The cochlea is a bony coiled structure filled with fluid. The cochlea transforms pressure variations into neural impulses.
The stapes attaches to the oval window of the cochlea.
Vibrations passed on by the stapes of the middle ear are transmitted to the fluid of the cochlea via the oval window.



# The Cochlea of the Inner Ear




Cochlea: Bony coiled structure, filled with fluid.

3 main areas separated by 2 membranes.

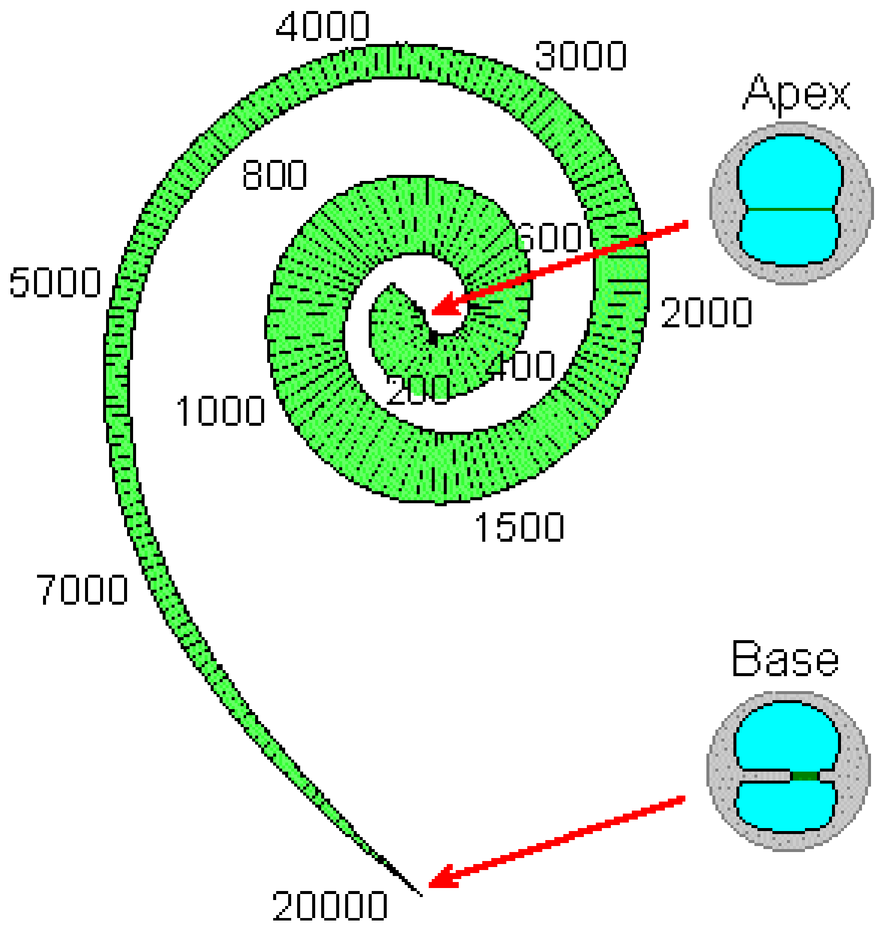
3 areas are: Scala vestibuli, Scala media, Scala tympani.

2 membranes are Reissner's membrane and Basilar membrane.

When stapes vibrates against the oval window, pressure waves are transmitted down the scala vestibuli, introducing ripples in the basilar membrane.

Mechanical vibrations of the *basilar membrane* are converted to electrical impulses in the auditory nerve via the organ of Corti.

# The Basilar Membrane in the Cochlea




Mechanical vibrations of the *basilar membrane* are converted to electrical impulses in the auditory nerve. How?

Each sound frequency stimulates the basilar membrane at a particular location along it depending on the membrane's stiffness..

High-frequency sounds create greater amplitude ripples on the basilar membrane near the oval window (where the membrane is narrow and stiff)- i.e., near the base.

Low-frequency sounds create greater amplitude ripples on the basilar membrane at the far end (where the membrane is slack), i.e., near the apex

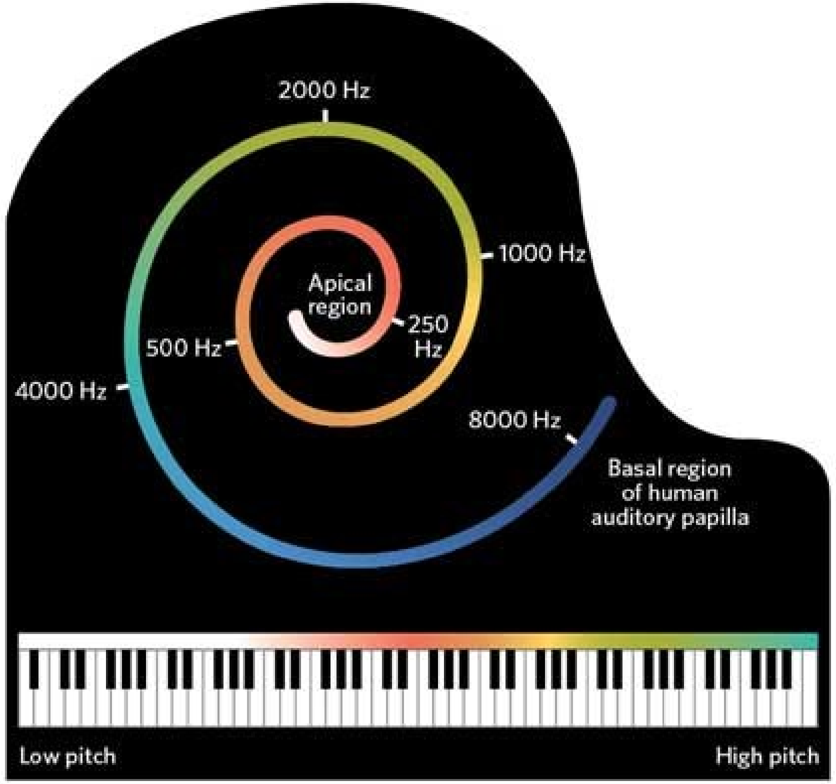
The nerves associated with each region then transmit neural information about the activity in that specific region, i.e., specific to that sound frequency.

# Questions [10 mins]

Would it be possible to hear different sound pitches at each ear?- and how could this affect the design of an audio interface?

Would sound need to be delivered solely through a headphone- could other means be used?

# Basilar membrane vibrations



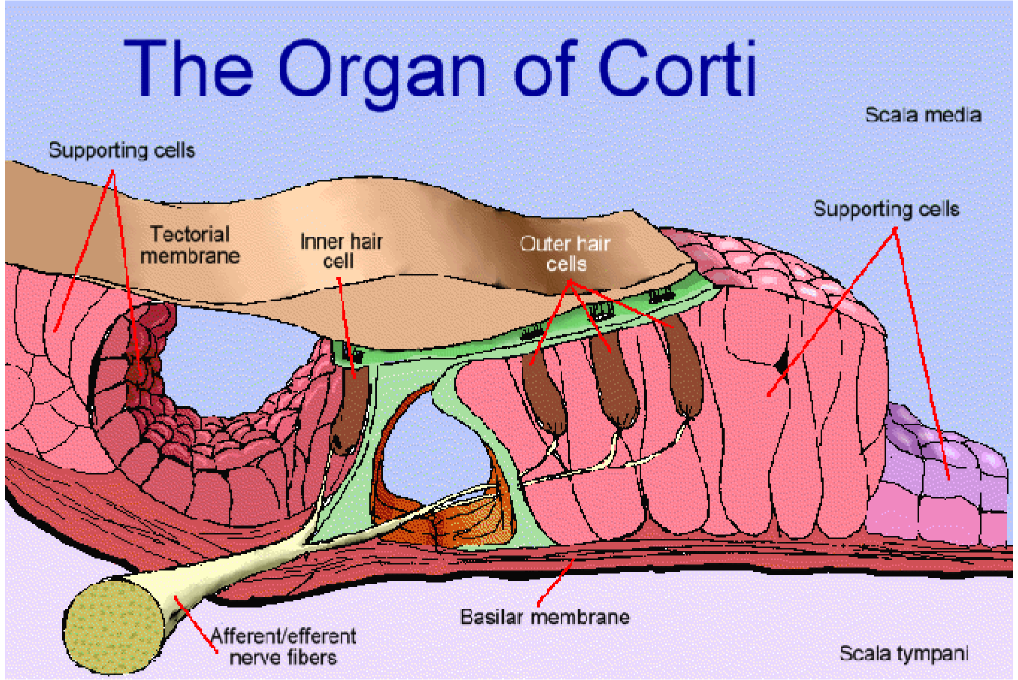

Each sound frequency stimulates the basilar membrane at a particular location along it and the nerves associated with each location on the basilar membrane then transmit neural information about activity in that specific location, i.e., specific to that sound frequency.

Activation and vibration of the basilar membrane caused by the sound input is often described as the first point of *sound frequency analysis*.



Image accessed (28/2/17): http://www.the-scientist.com/?articles.view/articleNo/43806/title/Aural-History/

# Basilar Membrane Vibration is Converted into Electrical Impulses



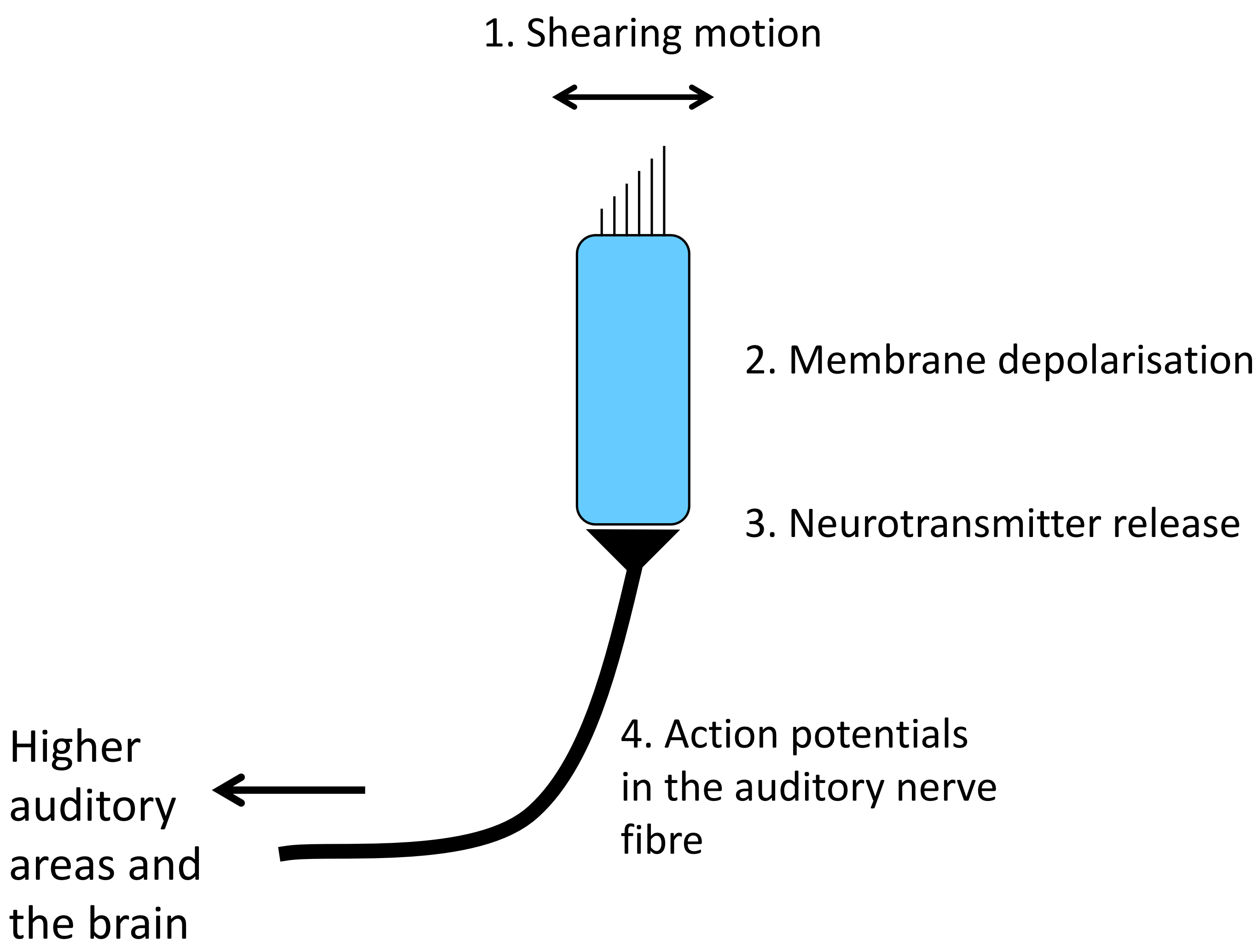

<u>Organ of Corti</u>

Basilar membrane at the bottom.
Inner hair cells
Outer Hair cells
Hair cells have short hairs (stereocillia) on top.
Shorter tectorial membrane sitting on top of the hair cells
Nerve fibres are attached to the inner and outer hair cells

So, what happens when the basilar membrane vibrates?

Short hairs (stereocilia) on top of the inner hairs cells bend when the basilar membrane vibrates in response to sound. Bending of the stereocillia generates a receptor potential inside the hair cell, which leads to generation of electrical nerve impulses in the auditory nerve attached to the cell. These nerve fibres are then responsible for propagating the electrical impulses via connections of fibres to higher-processing areas of the auditory system and eventually the brain for further processing.

# Inner Hair Cell in a Bit More Detail

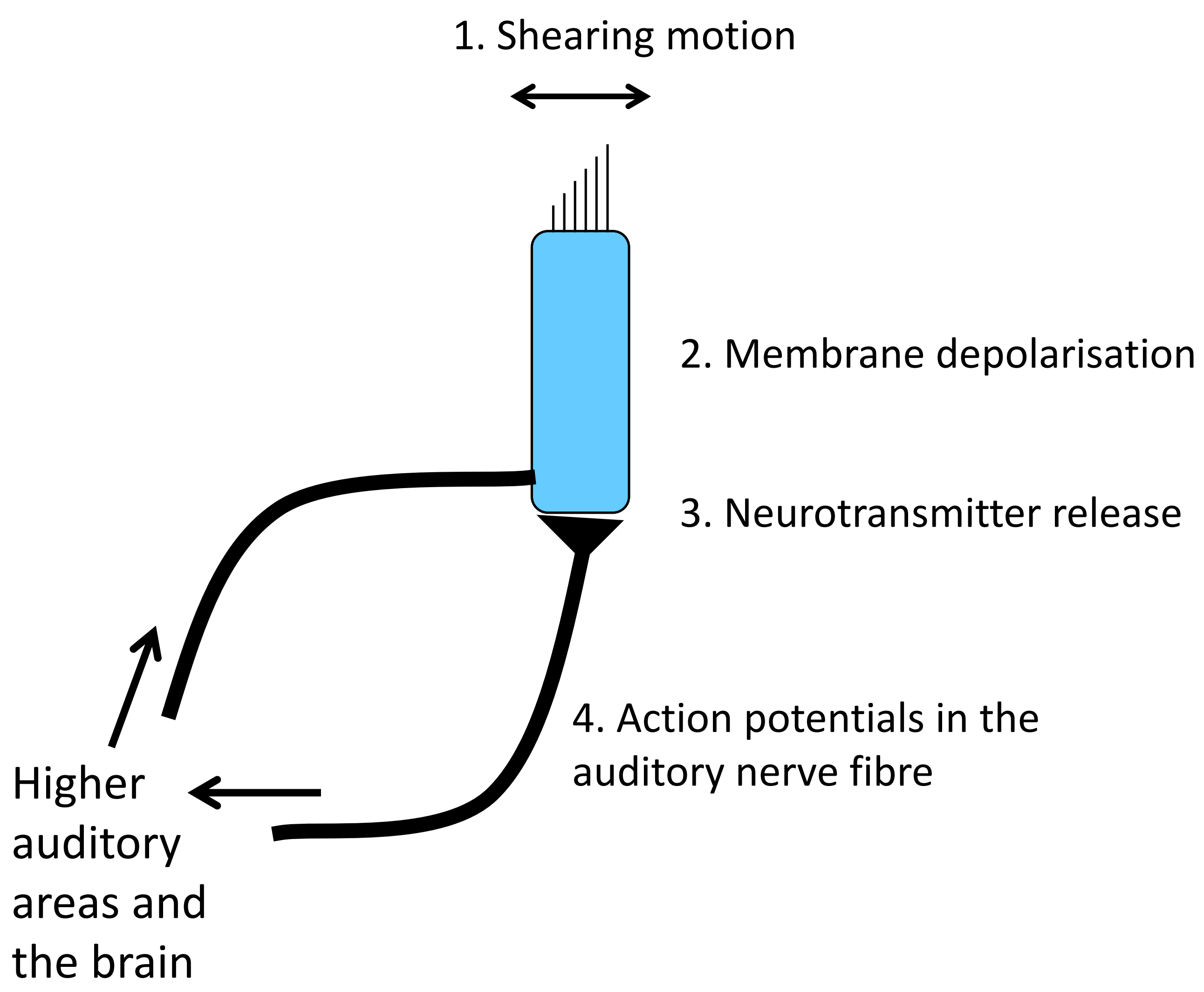



Vibrations of the basilar membrane cause the stereocilia (small hairs on top of the cell) of the inner hair cells to bend.

This bending causes membrane depolarisation, causing neurotransmitter release.
This then leads to generation of action potentials in the auditory nerve fibres attached at the base of the cell.

In this way auditory stimulation information is sent via the auditory nerve to the brain.

# What About Outer Hair Cells?

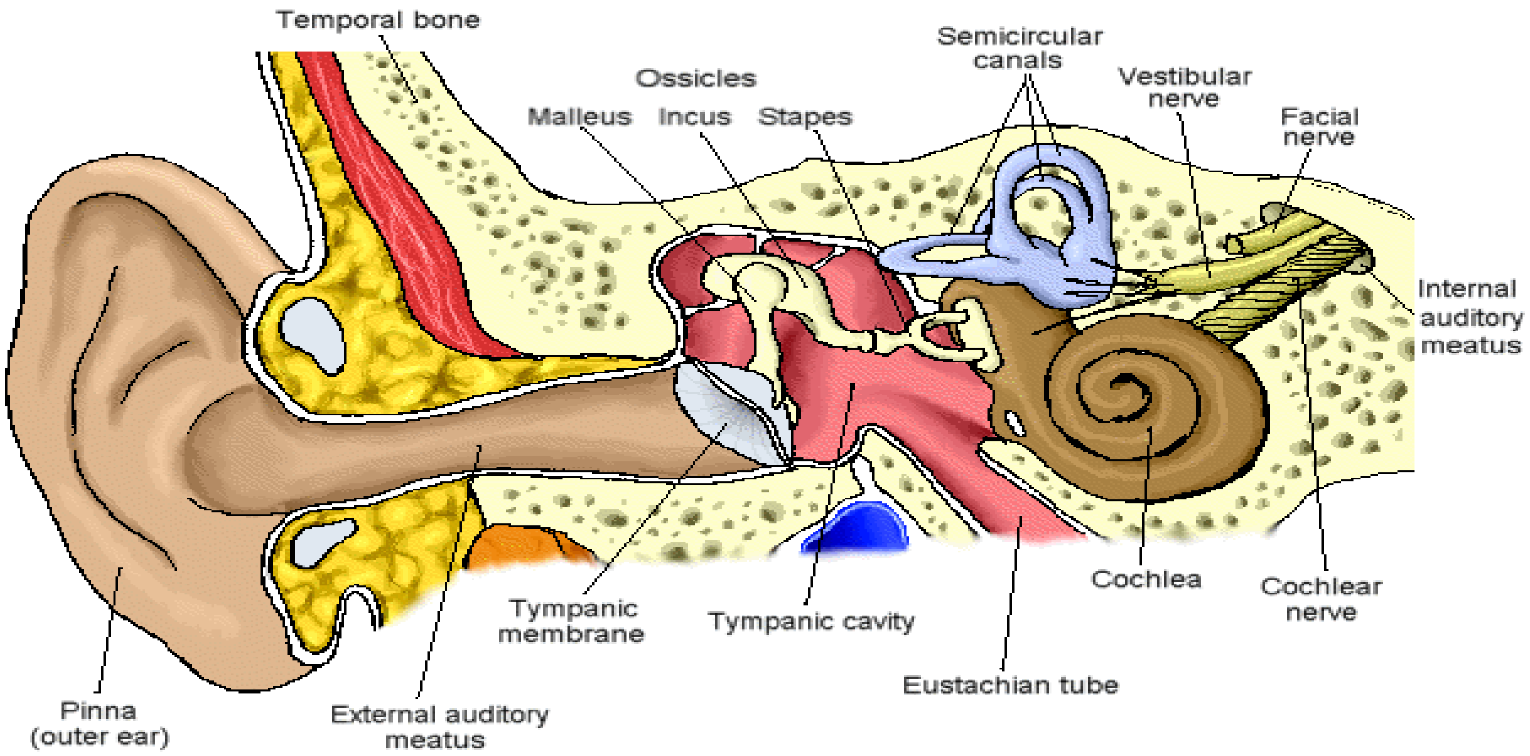



Interestingly, outer hair cells have plenty of nerve fibres that are bringing back electrical information **from the** brain to the cell.

Information **from the higher auditory areas, including the brain** is passed down to these cells – this information can be used to **amplify** the response of the basilar membrane.

How do they amplify the basilar membrane response? Outer hair cells are <u>**motile**</u>- I,e., they can stiffen and move in response to the vibration, in that way they can amplify and sharpen the vibrational response of the basilar membrane.

# What Causes a Hearing Impairment?




Auditory nerve dysfunction

Loss of cochlear hair cell function, through ageing or loud noise exposure

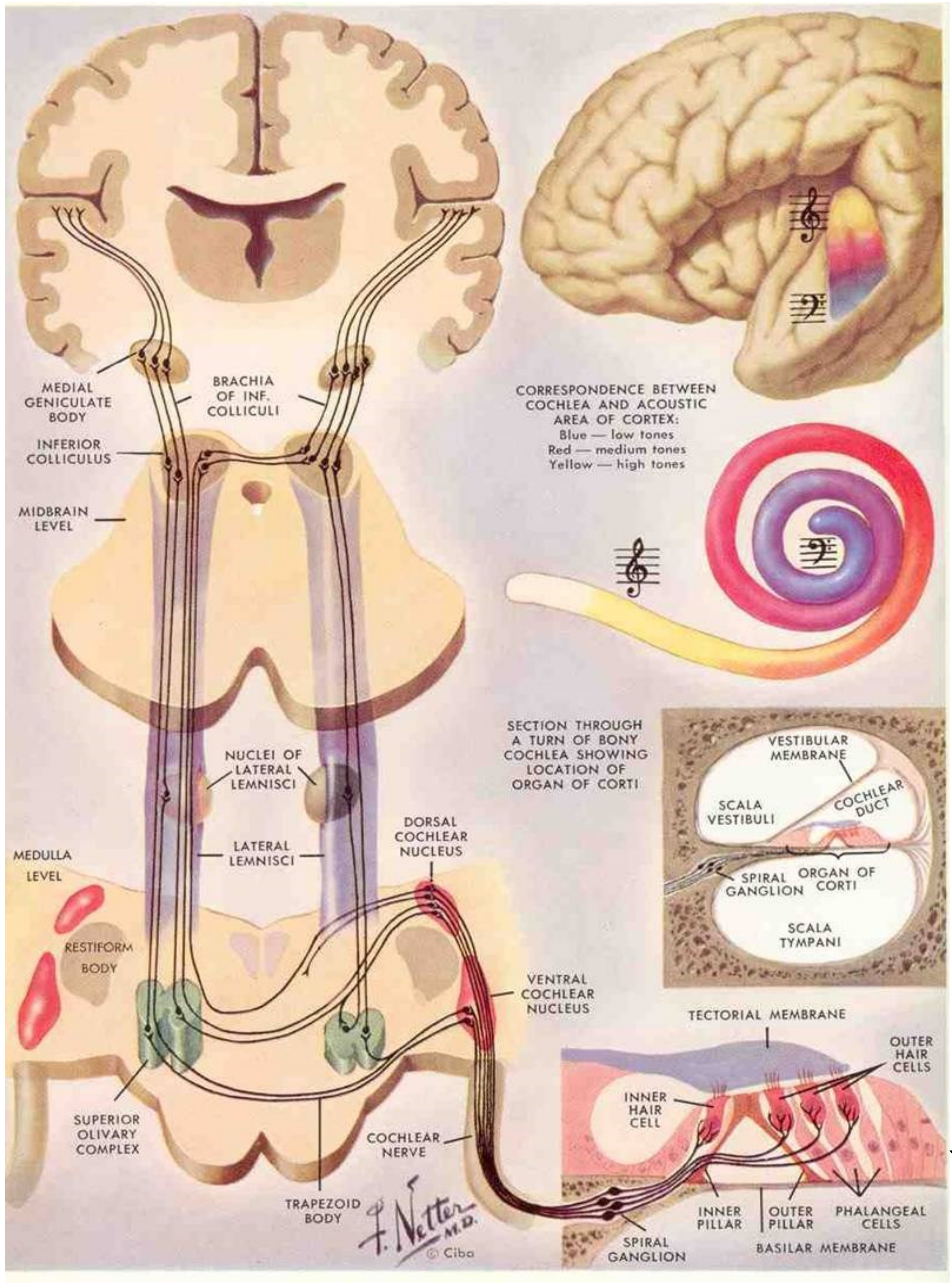
Ear canal blockage

Ear drum rupture or stiffening

Ossicle stiffening

Some impairments can also be due to dysfunction at higher levels of the auditory system/brain

# The Auditory Pathway



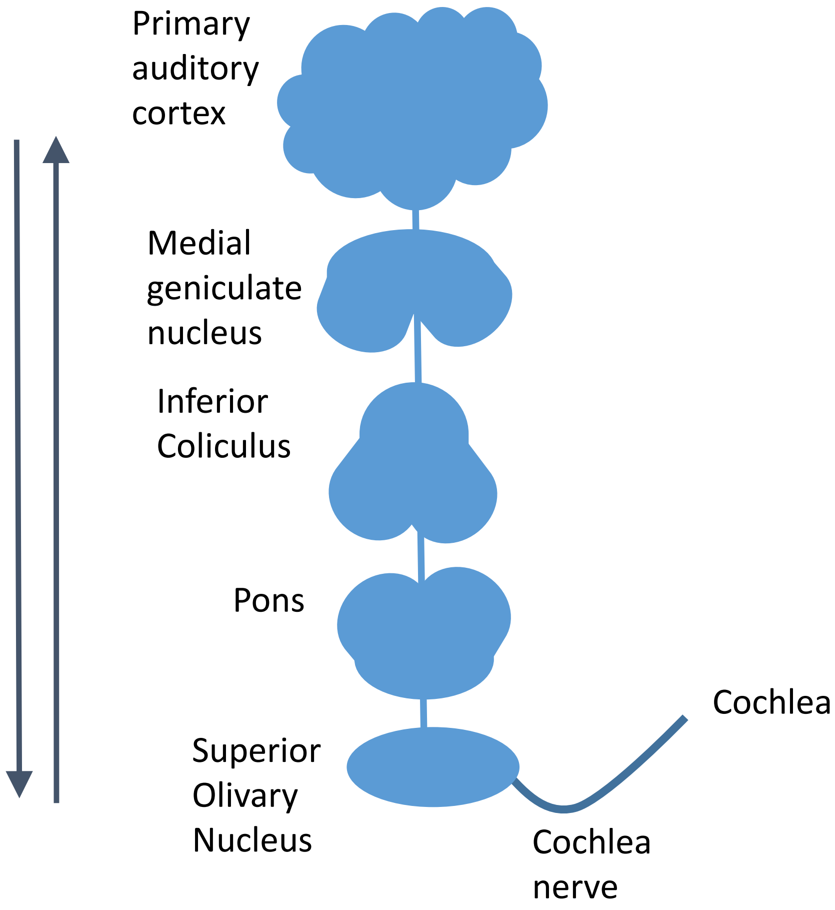

Auditory Forebrain:
Cortex
Medial Geniculate Nucleus

Auditory Brainstem:
Inferior Colliculus
Lateral Lemniscus
Superior Olive
Cochlear Nucleus

Cochlear level:
Spiral Ganglion
Cochlear Nerve

Cochlea

# Simplifying



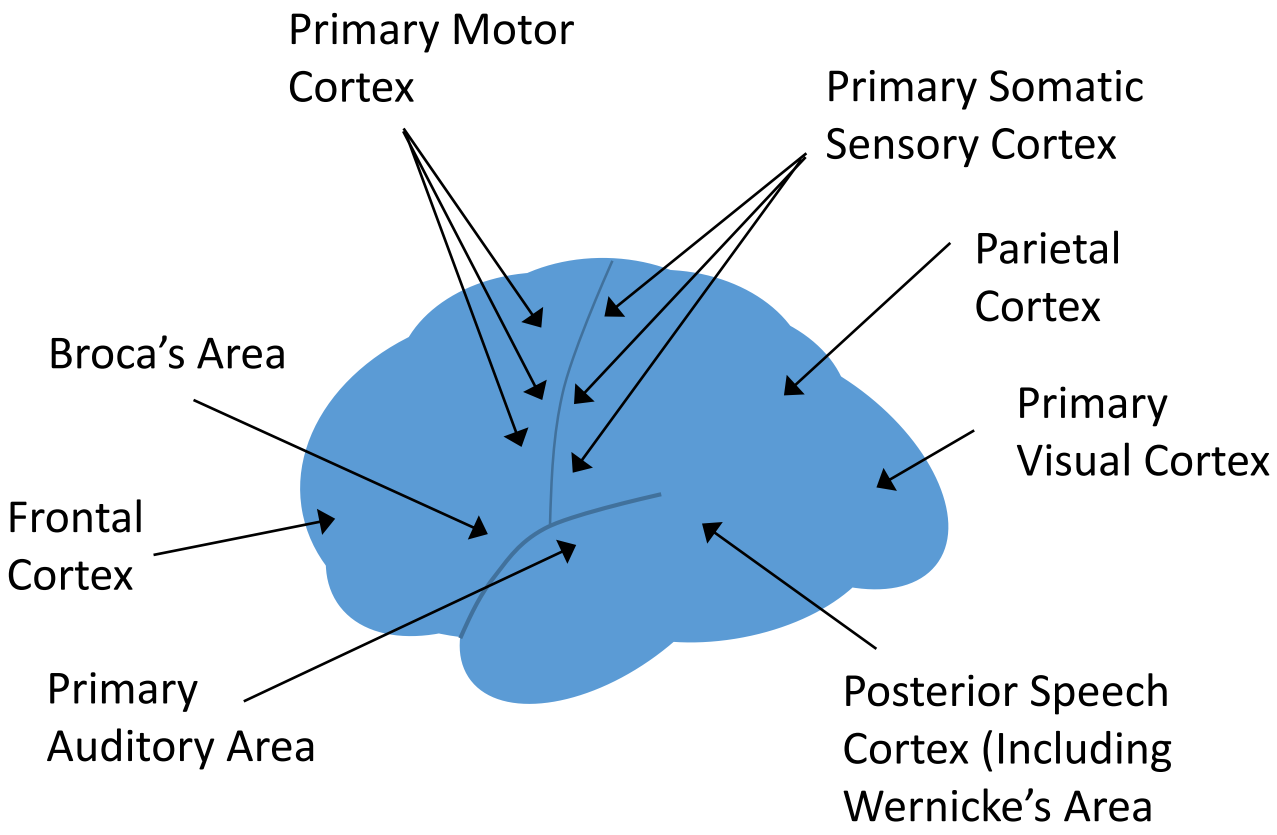

Higher-level

Music, Language, speech

Lower-level

Loudness, Pitch, Localisation….

# Auditory Cortex of the Brain




Main area of the brain responsible for auditory processing – Primary auditory area, in the temporal lobe and neighbouring regions.

Other areas are specialised for processing speech and language.

Also areas in the parietal and frontal lobes are activated by both auditory and visual stimuli.

# Summary

Sound waves are described by their time-series and spectra. Periodic complex waves can be composed of component sinewaves.

Sound waves propagate through the ear canal and cause the eardrum to vibrate, causing vibration of the 3 small bones (ossicles) of the middle ear.

The stapes small bone of the middle ear, transmits these vibrations through the oval window of the cochlea. This causes pressure variations within the fluid of the cochlea, setting in motion the basilar membrane.

The vibrations of the basilar membrane cause the stereocilia of the hair cells to transmit electrical impulses to the brain via the auditory nerve.

Different regions of the brain are involved in processing simple and more complex auditory information, as well as audio-visual information

# Resources

<u>Essential</u>:

Sensation and Perception 8th edition (book), p259-289; 291-309; 311-327.