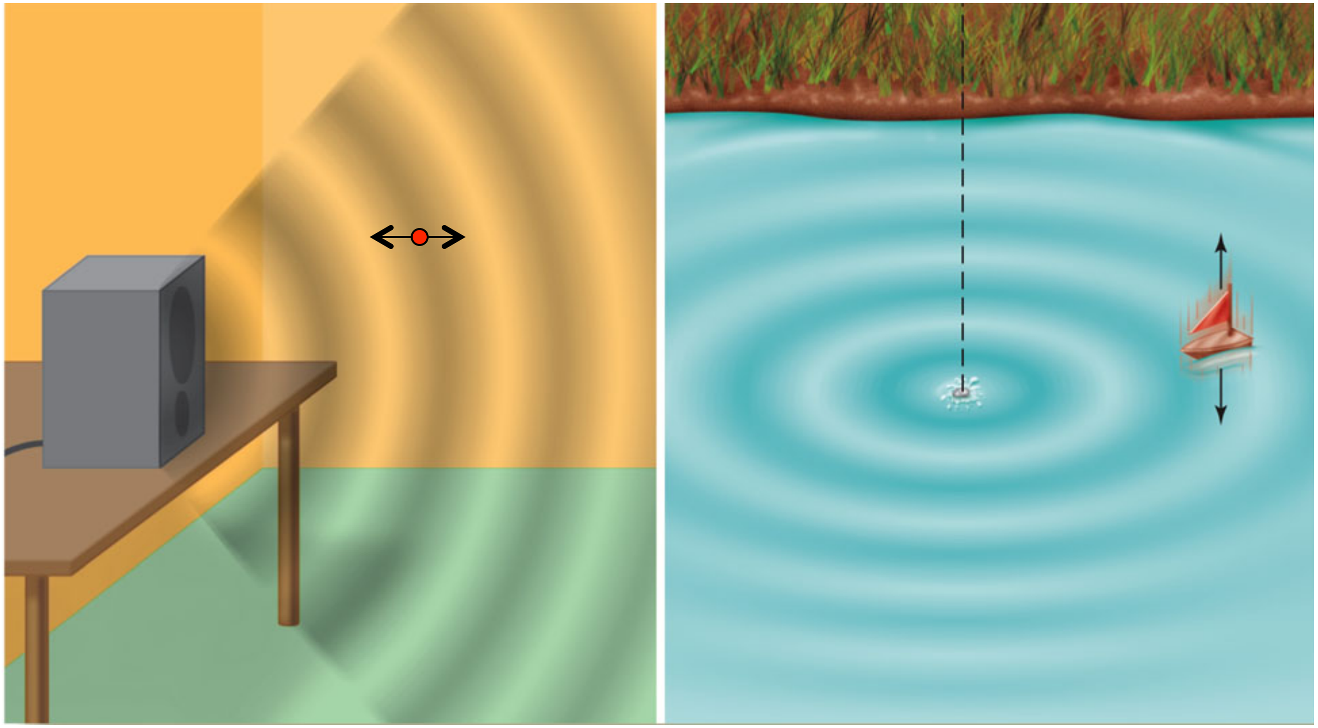
Sound, The Auditory System, and Pitch Perception

ELL788,

21ST Sept. 2016

How is sound produced?

- Loud speakers produce sound by
  - The diaphragm of the speaker moves out and in, pushing air molecules together and apart
  - The cycle of this process creates ‘sound waves’: alternating high- and low-pressure regions that travel through the air



How can we characterize a sound wave?

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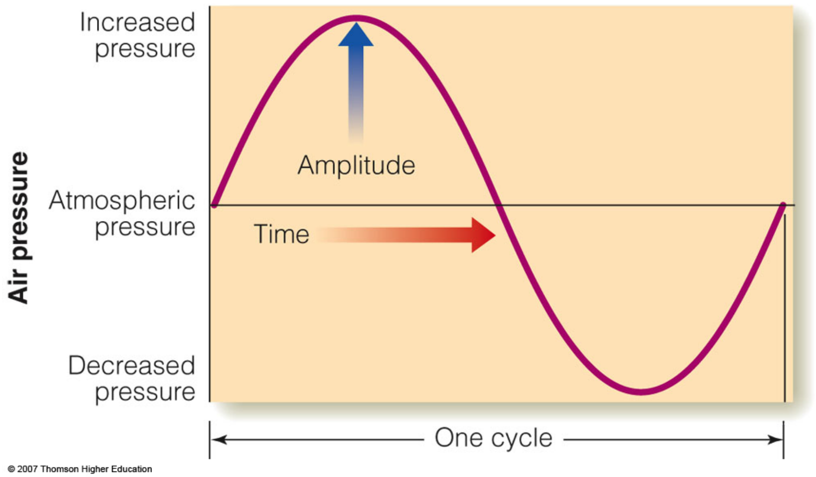
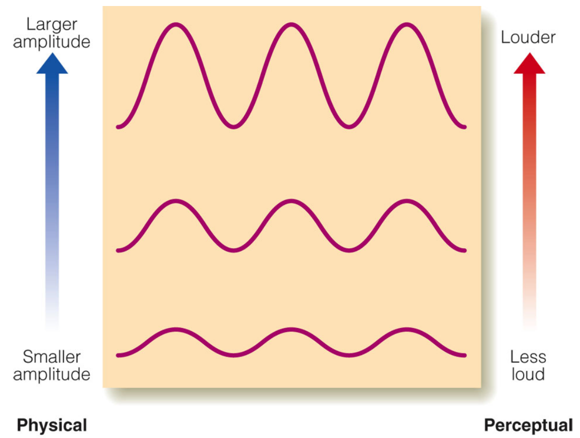
Characterizing Sound Waves



1. Amplitude - difference in pressure between high and low peaks of wave

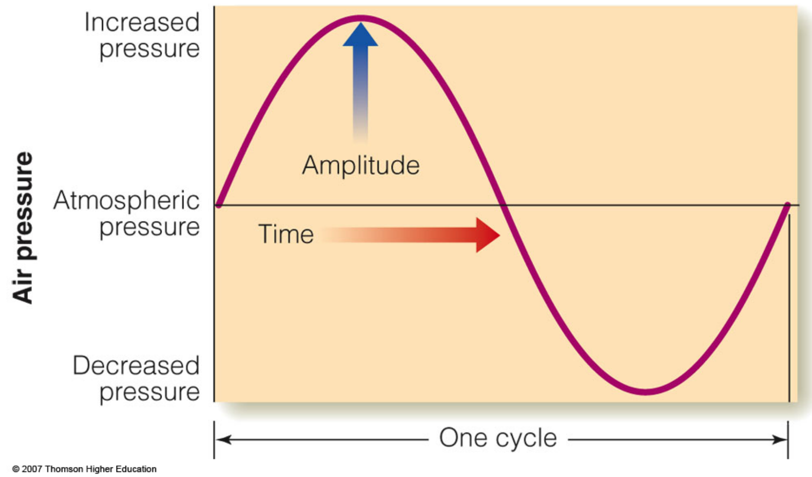
- Perception of amplitude is loudness
- Decibel (dB) is used as the measure of loudness
- Number of dB = 20 logarithm(p/p_o)



Relative amplitudes and decibels for environmental sounds

Sound	Relative amplitude	Decibels (dB)
Barely audible (threshold)	1	0
Leaves rustling	10	20
Quiet residential community	100	40
Average speaking voice	1,000	60
Express subway train	100,000	100
Propeller plane at takeoff	1,000,000	120
Jet engine at takeoff (pain threshold)	10,000,000	140
Spacecraft launch at close range	100,000,000	160

Characterizing Sound Waves



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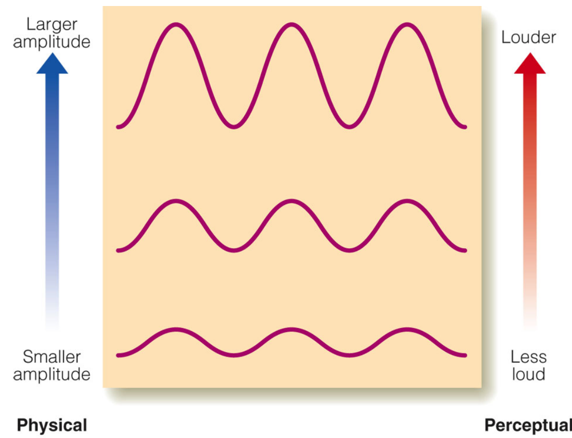
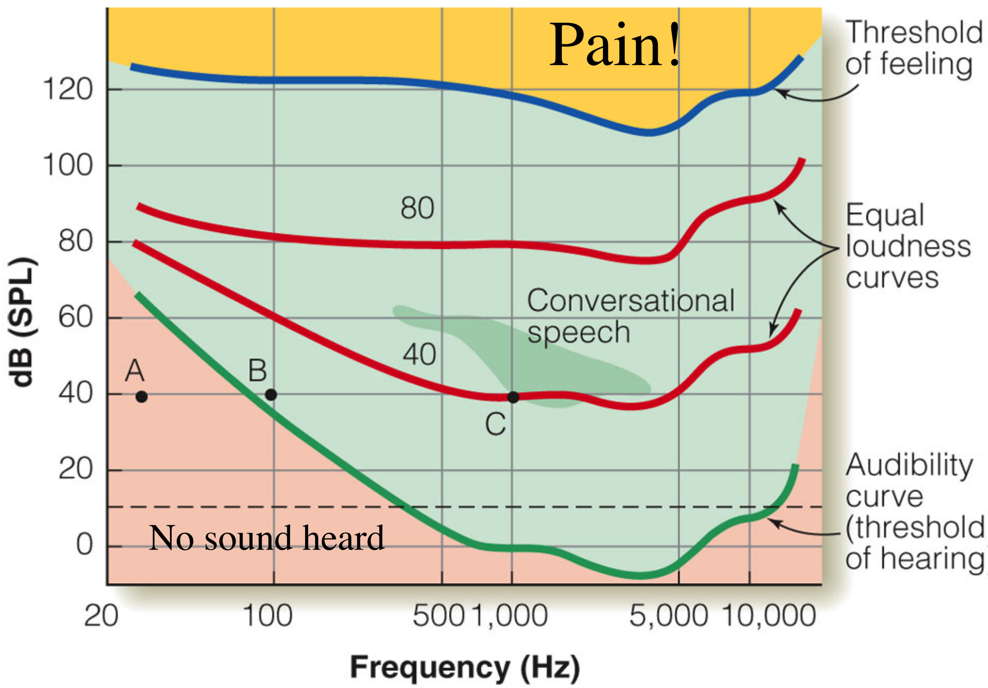


2. Frequency - number of cycles within a given time period

- Measured in Hertz (Hz) - 1 Hz is 1 cycle per second
- Frequency is perceived as pitch
- We can hear only a small range of sound frequencies

Range of Hearing

- Human hearing range - 20 to 20,000 Hz
- Sensitivity changes as a function of frequency (like the csf)
- Audibility curve - shows the threshold of hearing
  - Changes on this curve show that humans are most sensitive to 2,000 to 4,000 Hz



Is pitch and loudness all there is for describing sound perception?

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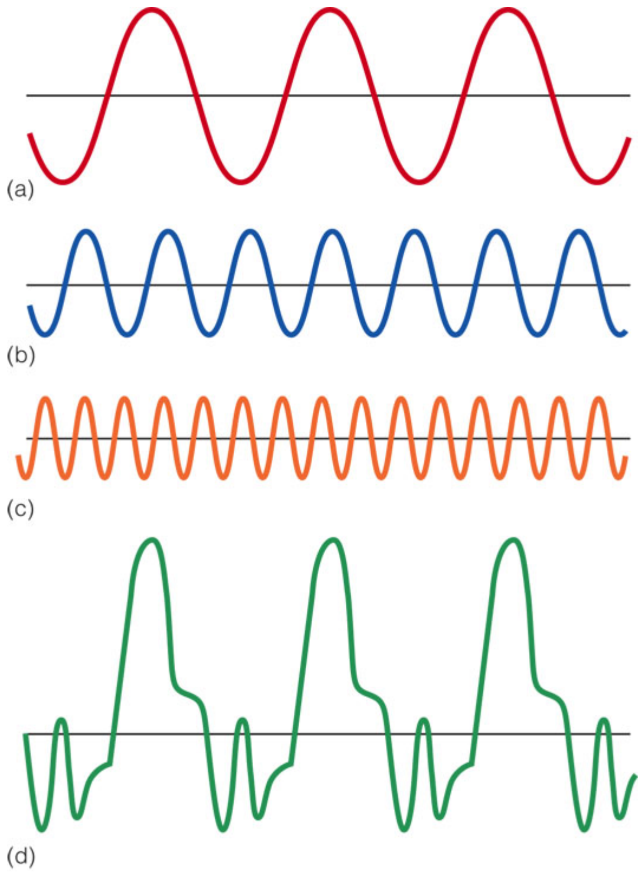
Sound Quality: Timbre

- All other properties of sound except for loudness and pitch constitute timbre
- Timbre is created partially by the multiple frequencies that make up complex tones
  - Fundamental frequency is the first harmonic
  - Musical tones have additional harmonics that are multiples of the fundamental frequency

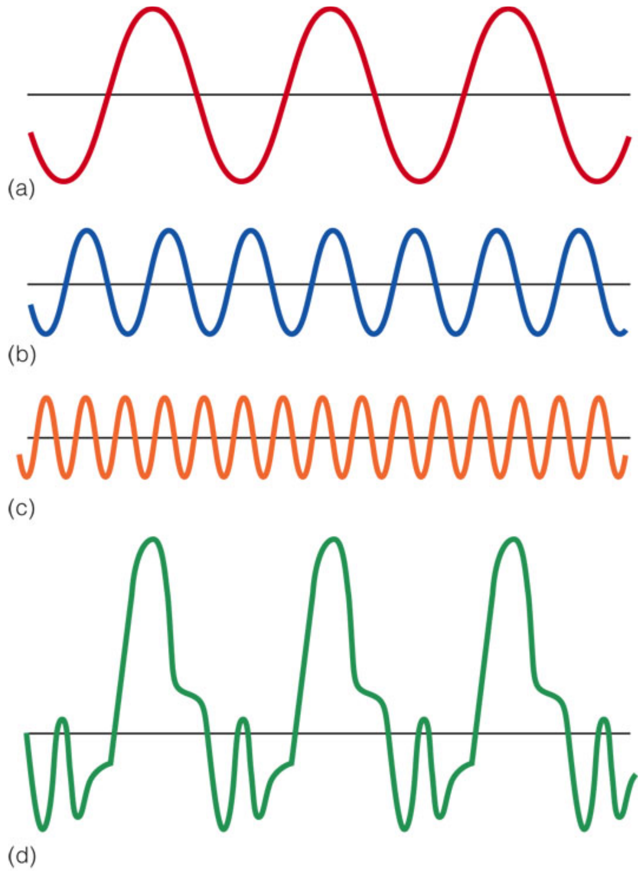
Sound Quality: Timbre

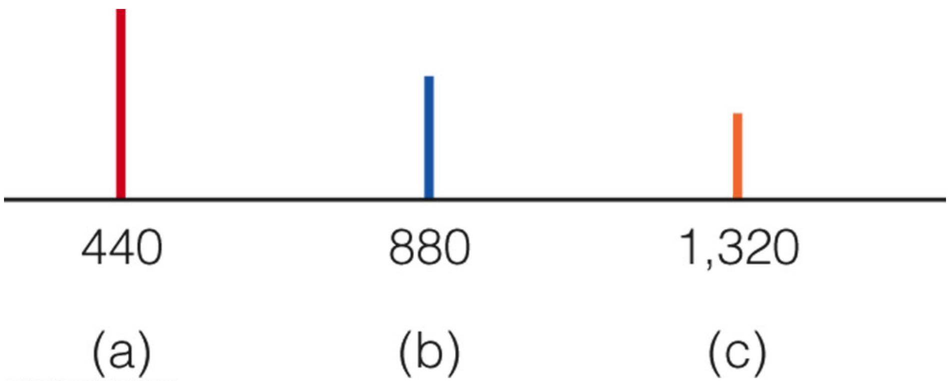
- Additive synthesis - process of adding harmonics to create complex sounds



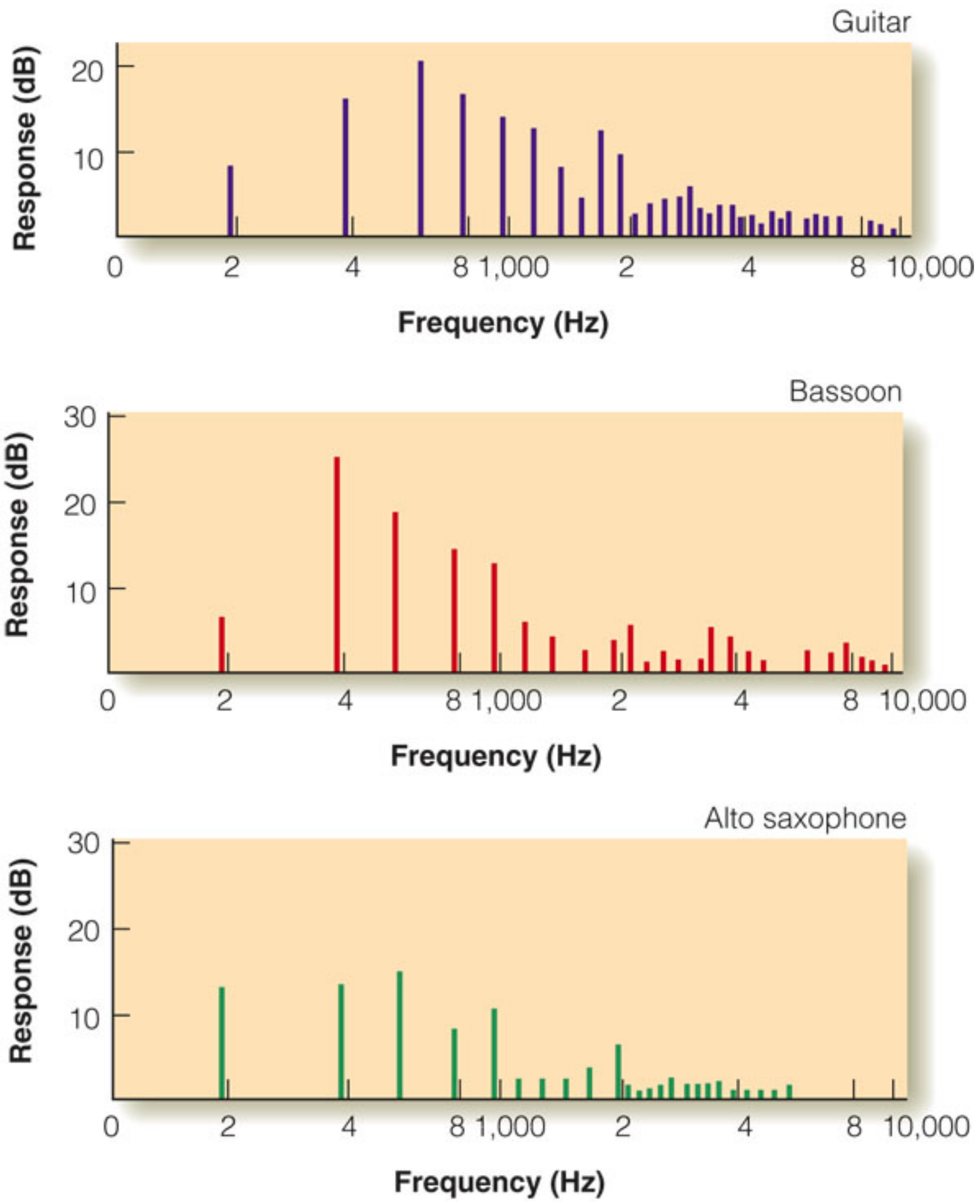
Additive synthesis. (a) Pressure changes for a pure tone with frequency = 440 Hz. (b) The second harmonic of this tone, with a frequency of 880 Hz. (c) The third harmonic, with a frequency of 1,320 Hz. (d) The sum of the three harmonics creates the waveform for a complex tone.

Frequency spectrum - display of harmonics of a complex sound





The frequency spectrum for the tone on the left. The heights of the lines indicate the amplitude of each of the frequencies that make up the tone.



Frequency spectra for a guitar, a bassoon, and an alto saxophone playing a tone with a fundamental frequency of 196 Hz. The position of the lines on the horizontal axis indicates the frequencies of the harmonics and their height indicates their intensities.

How are sound waves converted into percepts?

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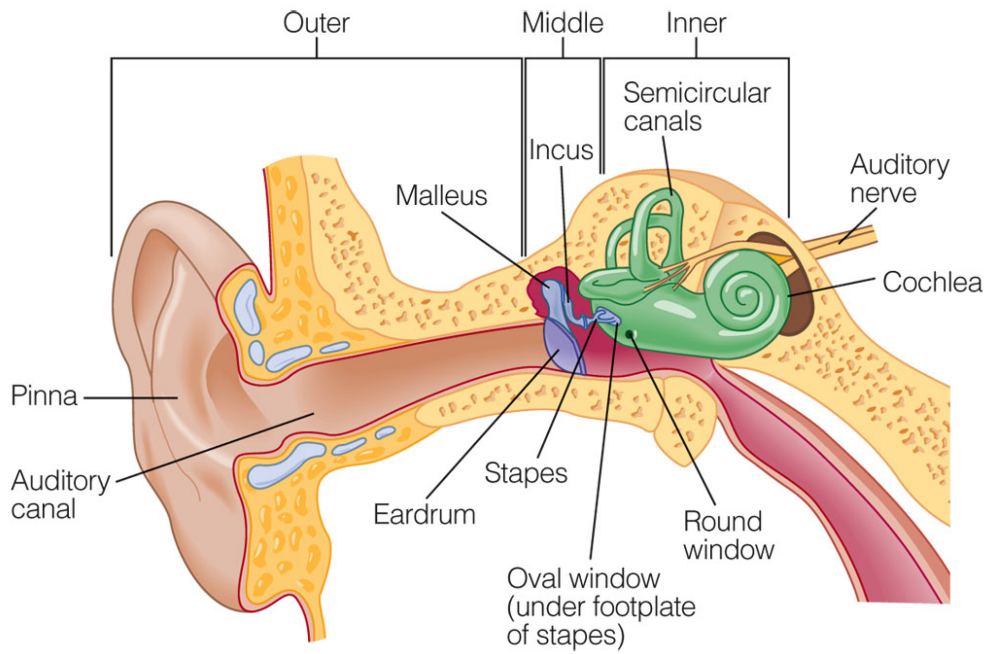
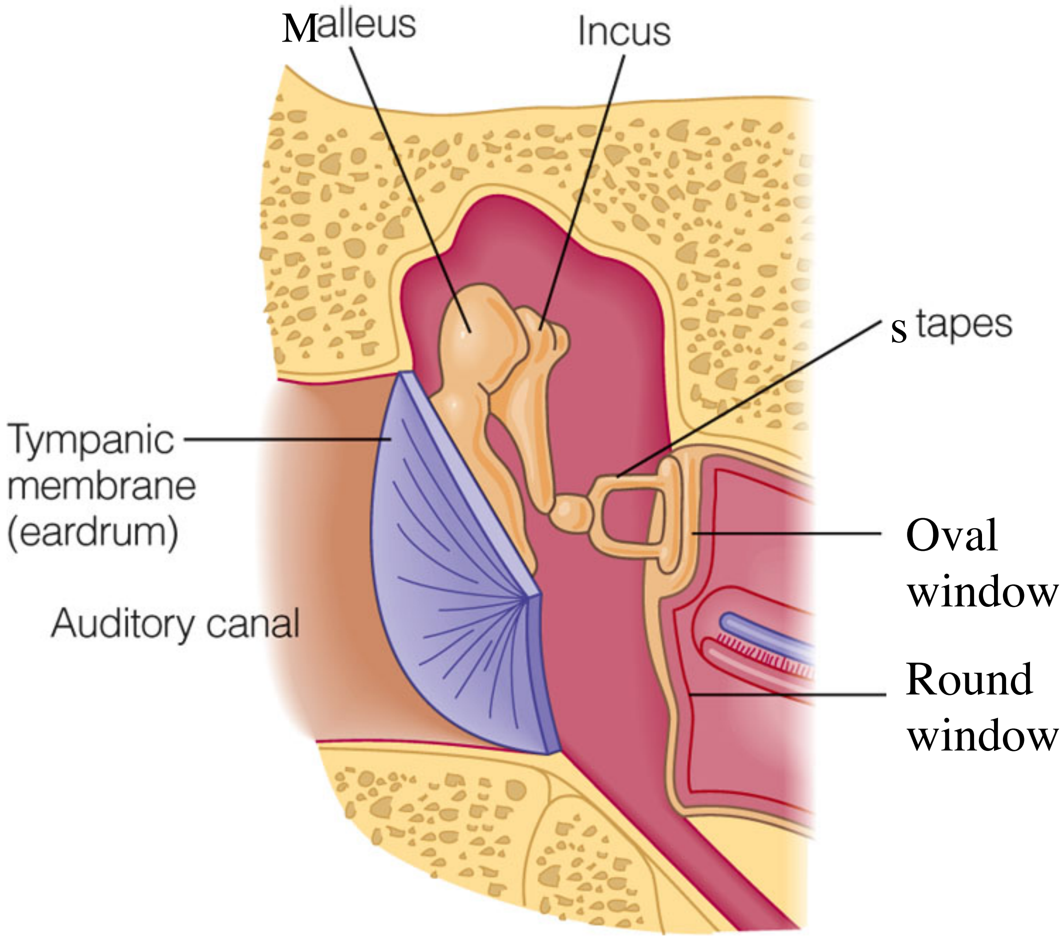
The Ear

Outer ear - pinna and auditory canal

- Pinna helps with sound location
- Auditory canal - tube-like 3 cm long structure
  - Protects the tympanic membrane at the end of the canal
  - Resonant frequency of the canal amplifies frequencies between 2,000 and 5,000 Hz



The middle ear. The three bones of the middle ear ('ossicles') transmit the vibrations of the tympanic membrane to the inner ear.



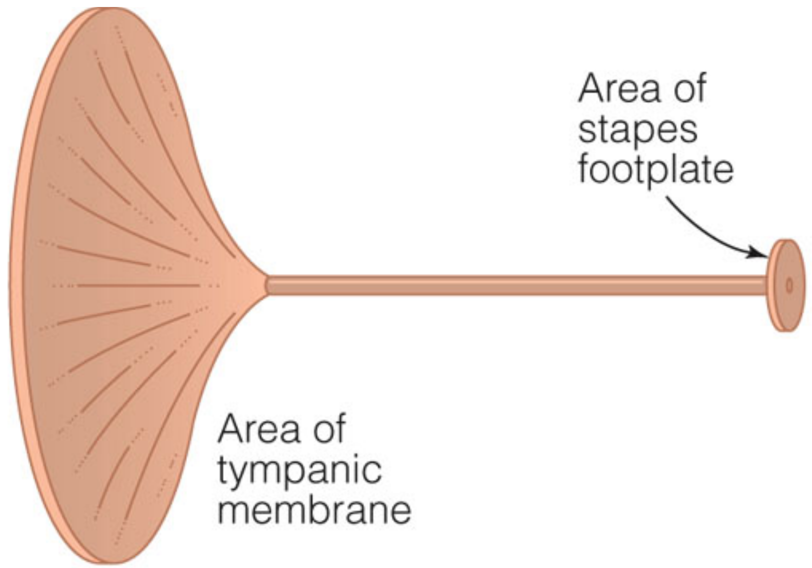
Why have a middle ear at all? Why doesn't the tympanic membrane connect directly to the cochlea?

Function of Ossicles

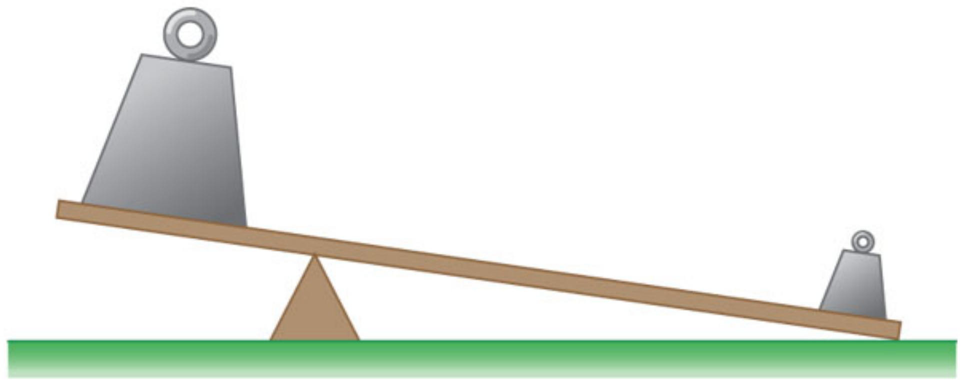
- Outer ear is filled with air
- Inner ear is filled with fluid that is much denser than air
- Pressure changes in air transmit poorly into the denser medium
- Ossicles act to amplify the vibration for better transmission to the fluid

How do the ossicles accomplish amplification?

How the ossicles amplify vibrations:



(a)



(b)

What is the mechanism for sound transduction into nerve impulses?

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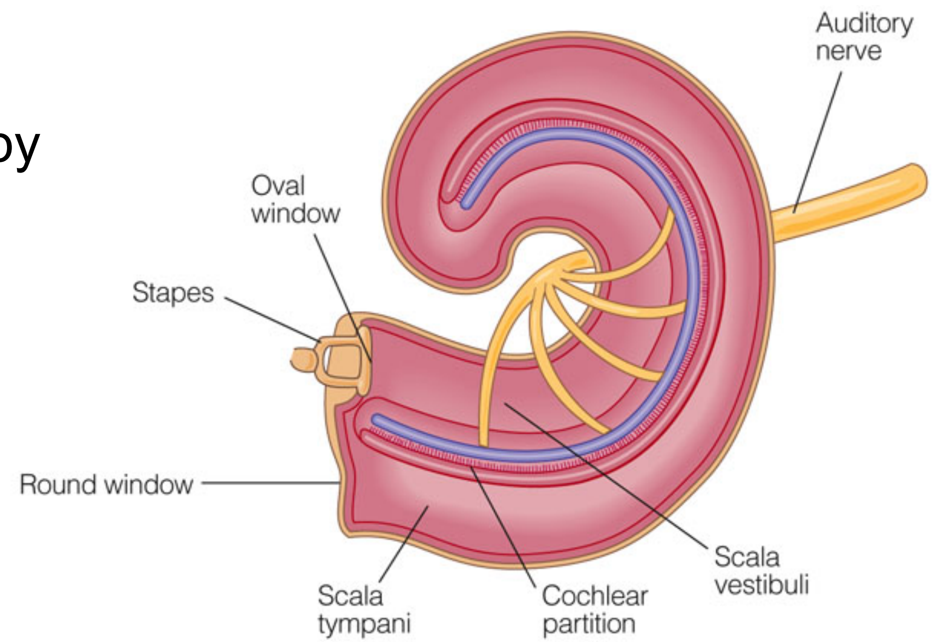
The Inner Ear

- Main structure is the cochlea
  - Fluid-filled snail-like structure set into vibration by the stapes
  - Divided into the scala vestibuli and scala tympani by the cochlear partition
  - Cochlear partition extends from the base (stapes end) to the apex (far end)
  - Organ of Corti contained by the cochlear partition



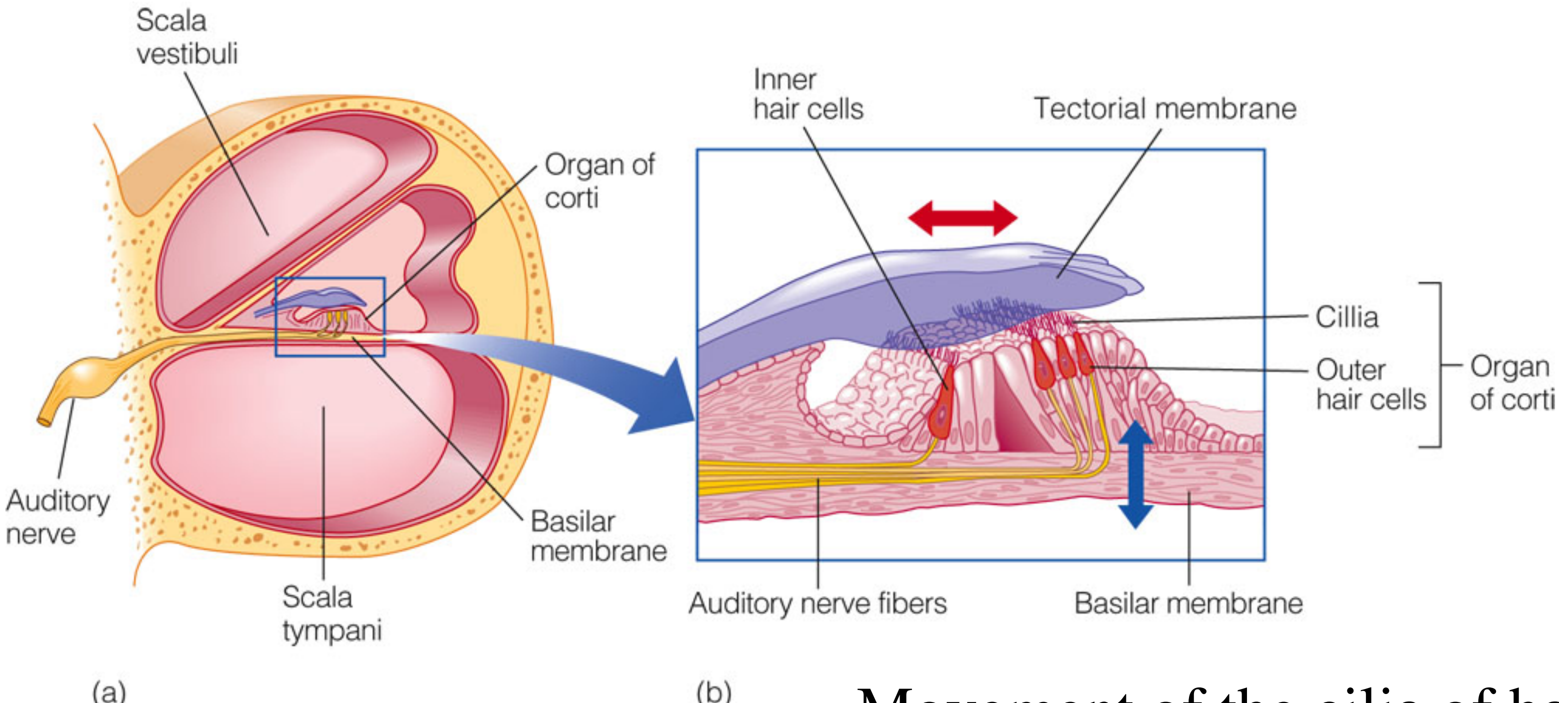
(a)

(b)

Why?

Cross-section of the cochlea

Organ of Corti



Movement of the cilia of hair cells generates nerve impulses.

Marquis Alfonso Corti (1822-1888), an Italian nobleman, histologist, and anatomist.
In Italian, the word "corti“ means "short"

How do the nerve fibers code for sound frequency?

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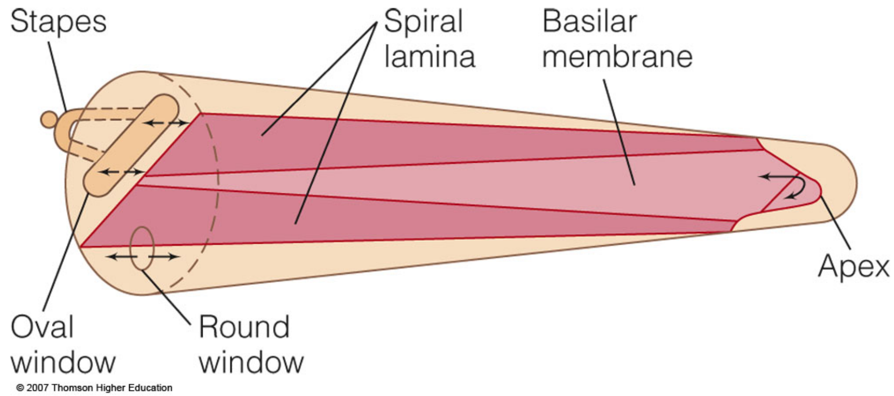
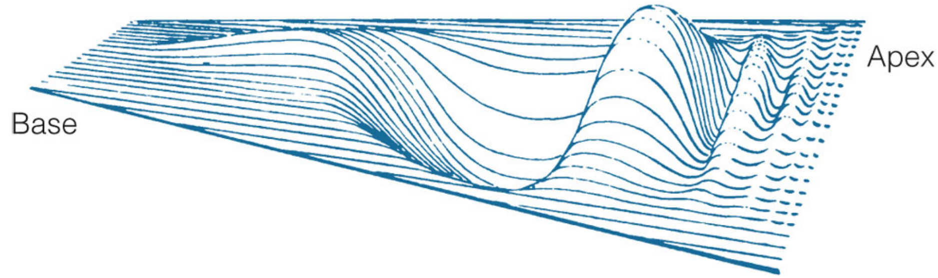
Békésys’ Place Theory of Hearing

- Frequency of sound is indicated by the place on the organ of Corti that has the highest firing rate
- Békésy determined this in two ways
  - Direct observation of the basilar membrane in a cadaver
  - Building a model of the cochlea using the physical properties of the basilar membrane

Békésys' Place Theory of Hearing - continued

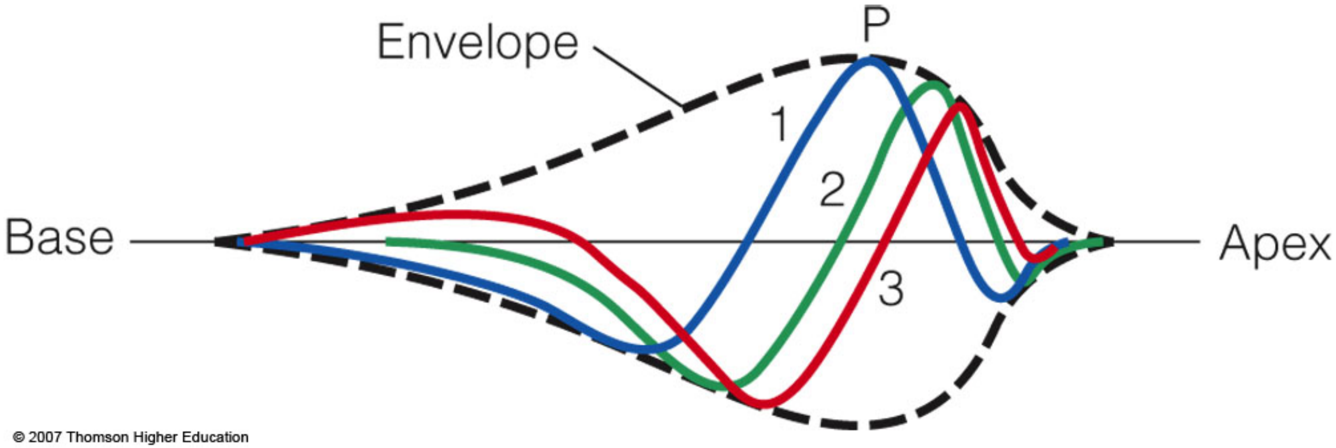
- Physical properties of the basilar membrane
  - Base of the membrane (by stapes) is
    - 3 to 4 times narrower than at the apex
    - 100 times stiffer than at the apex
- Both the model and the direct observation showed that the vibrating motion of the membrane is a traveling wave





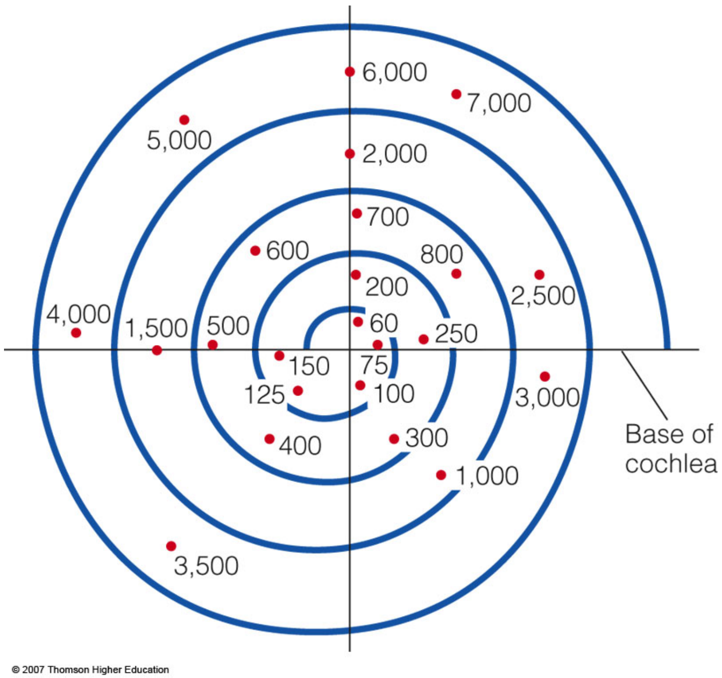
Békésys' Place Theory of Hearing - continued

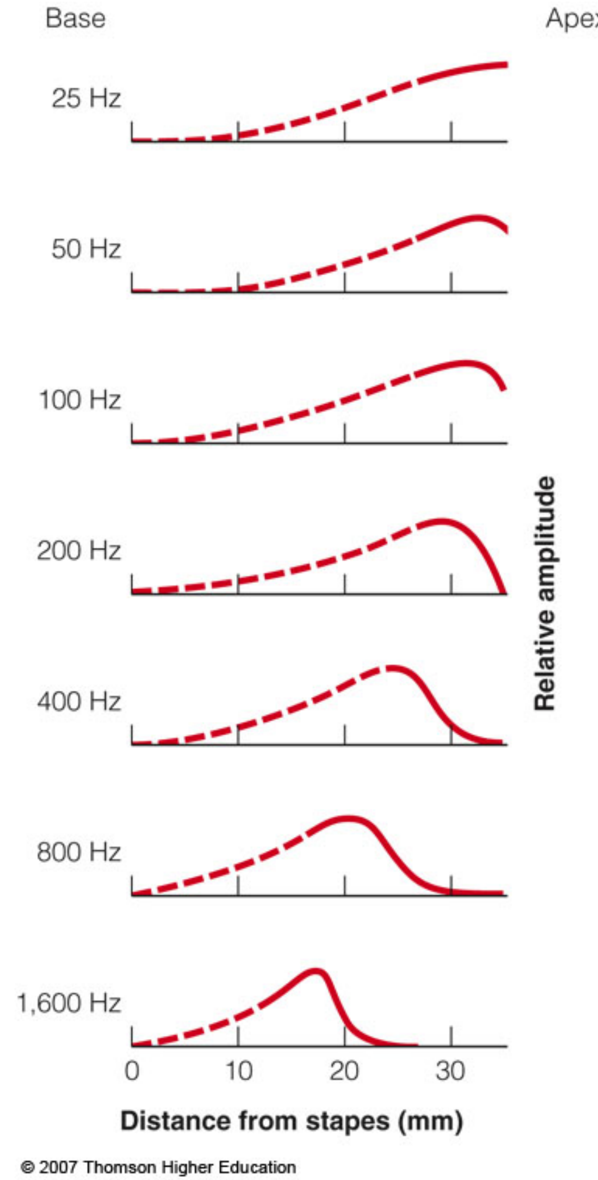
- Envelope of the traveling wave
  - Indicates the point of maximum displacement of the basilar membrane
  - Hair cells at this point are stimulated the most strongly leading to the nerve fibers firing the most strongly at this location
  - Position of the peak is a function of frequency



Evidence for the Place Theory

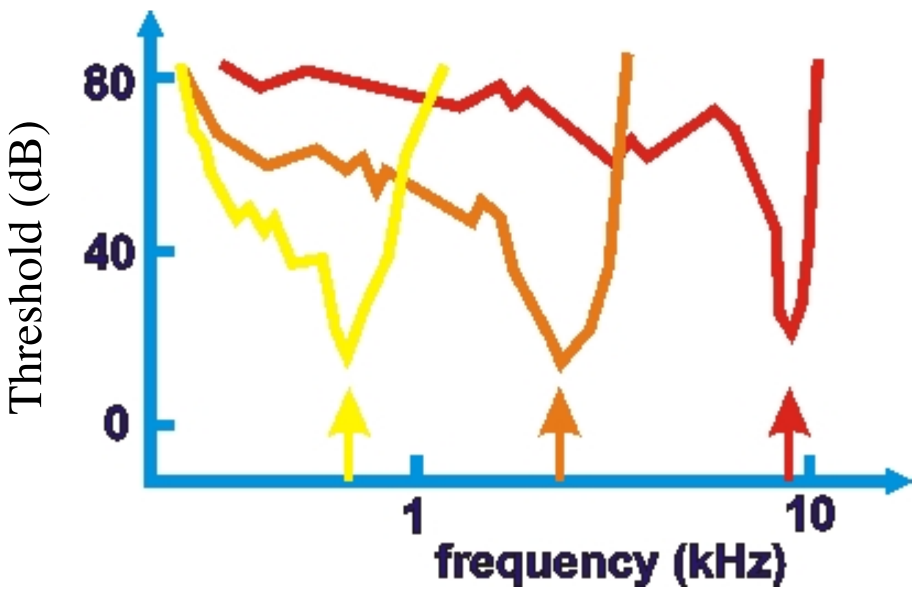
- Tonotopic map
  - Cochlea shows an orderly map of frequencies along its length
    - Apex responds best to low frequencies
    - Base responds best to high frequencies





The corresponding nerve fibers exhibit sharp frequency tuning curves…

- Neural frequency tuning curves
  - Pure tones are used to determine the threshold for specific frequencies measured at single neurons
  - Plotting thresholds for frequencies results in tuning curves
  - Frequency to which the neuron is most sensitive is the characteristic frequency



http://www.youtube.com/watch?v=1JE8WduJKV4&feature=related

How does the place theory encode complex tones?

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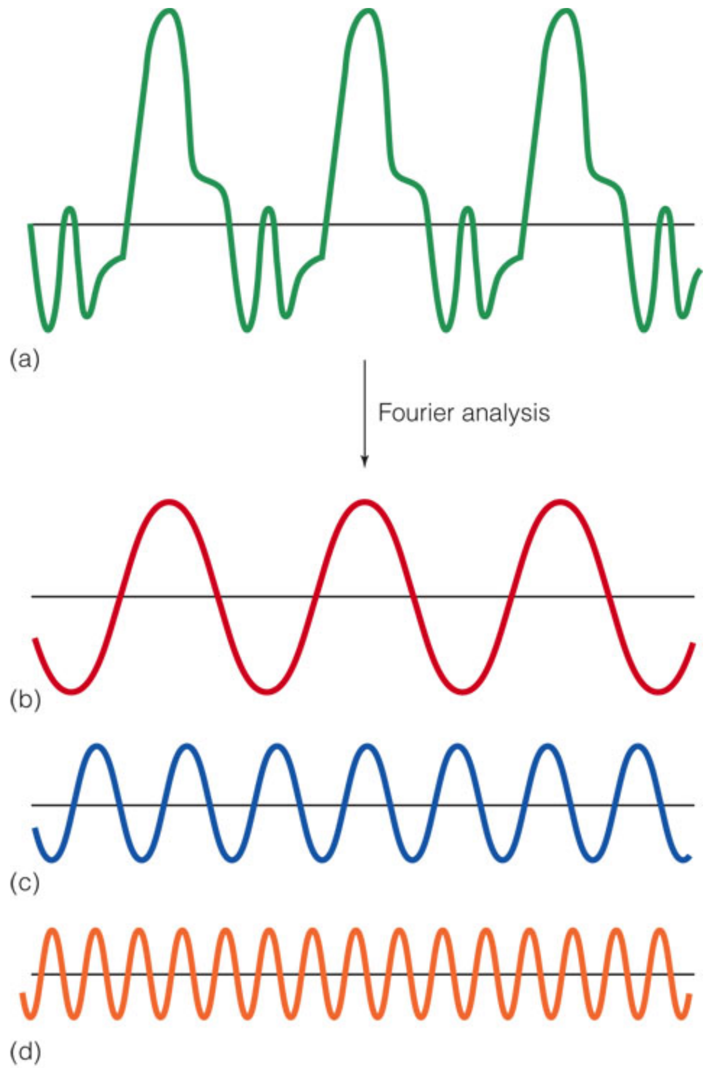
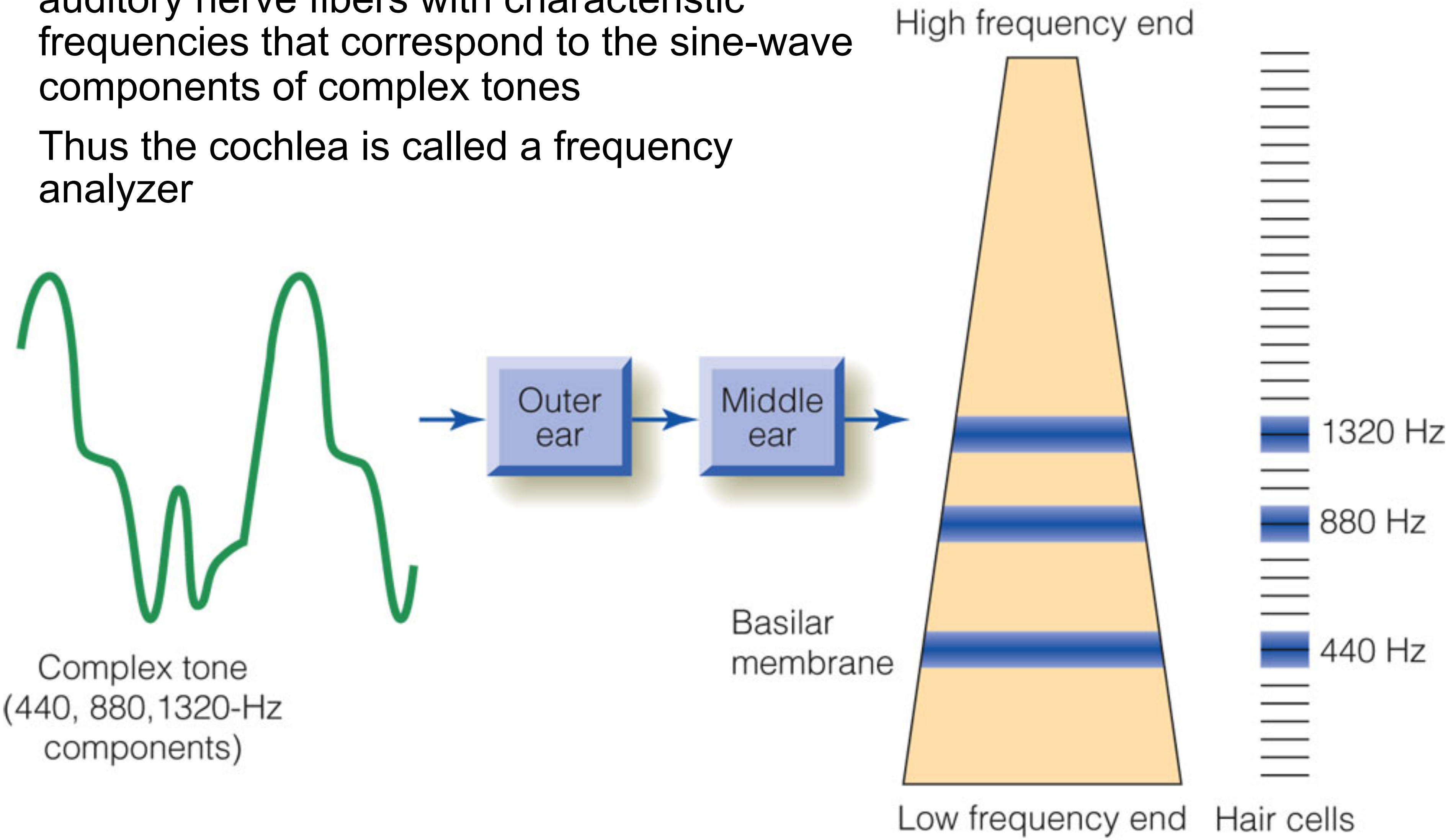
Response of Basilar Membrane to Complex Tones

- Fourier analysis - mathematic process that separates complex waveforms into a number of sine waves



Research on the response of the basilar membrane shows the highest response in auditory nerve fibers with characteristic frequencies that correspond to the sine-wave components of complex tones

Thus the cochlea is called a frequency analyzer



What lies beyond the cochlea?

What is the organization of the neural pathway for audition?

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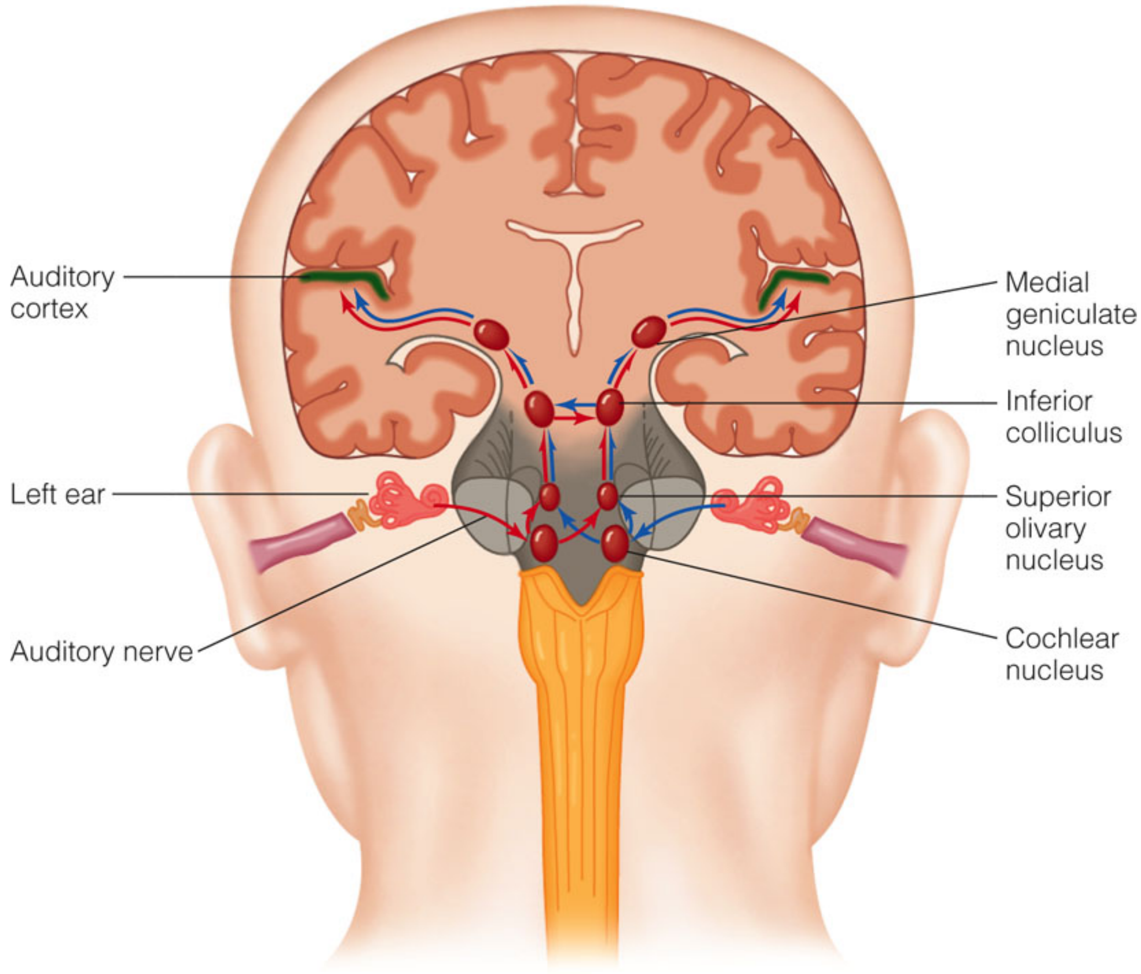
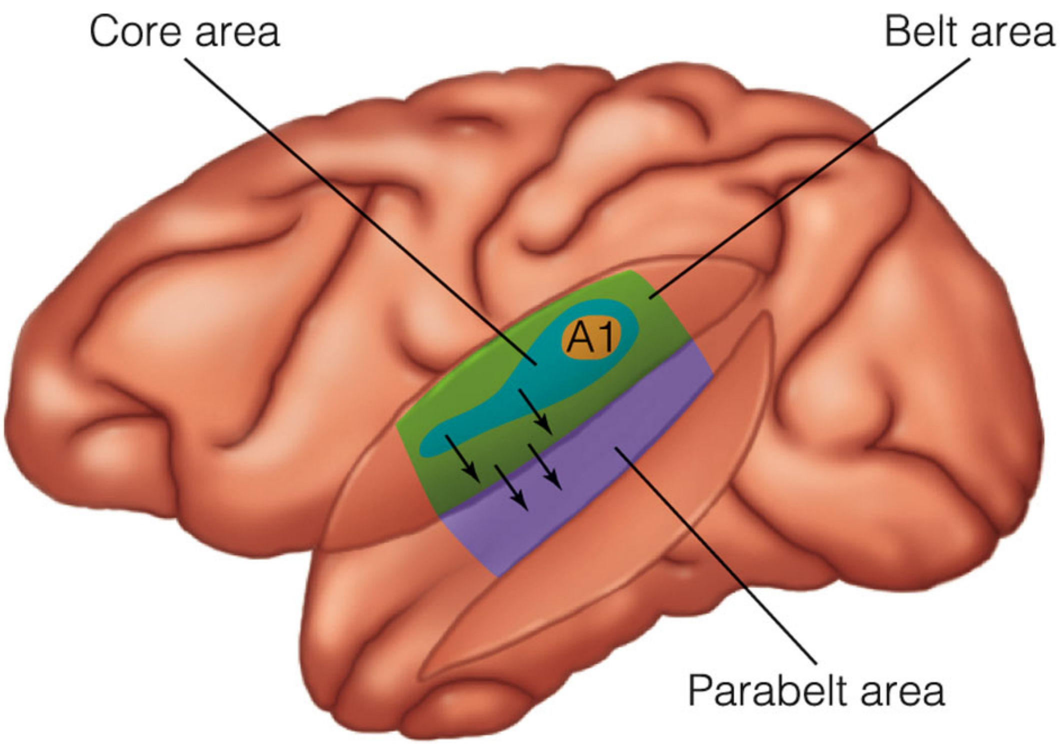
Pathway from the Cochlea to the Cortex



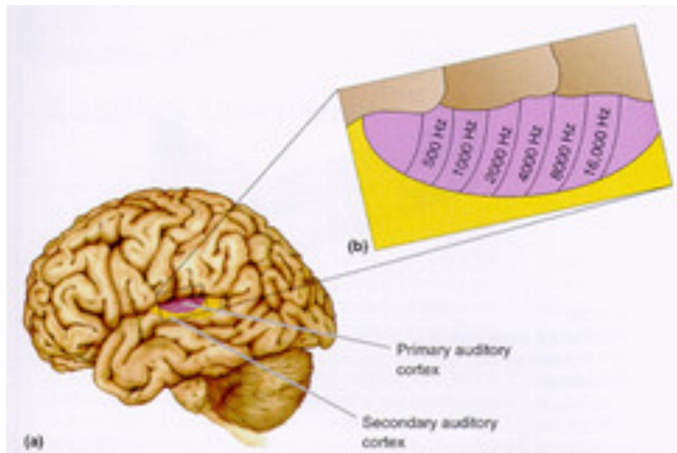
Auditory Areas in the Cortex

- Hierarchical processing occurs in the cortex
  - Neural signals travel through the core, then belt, followed by the parabelt area
  - Simple sounds cause activation in the core area
  - Belt and parabelt areas are activated in response to more complex stimuli made up of many frequencies



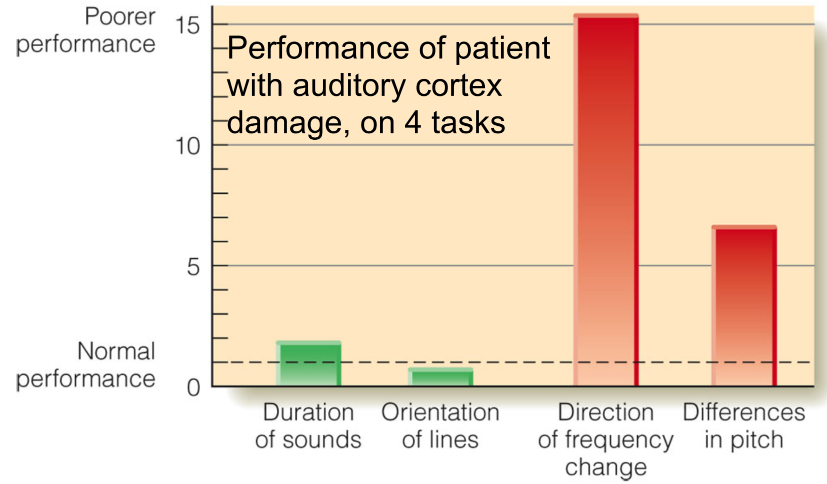
Auditory Areas in the human Cortex

- Brain scans in humans
  - Tasks that require pitch recognition activate core area. A tonotopic map is evident in A1.



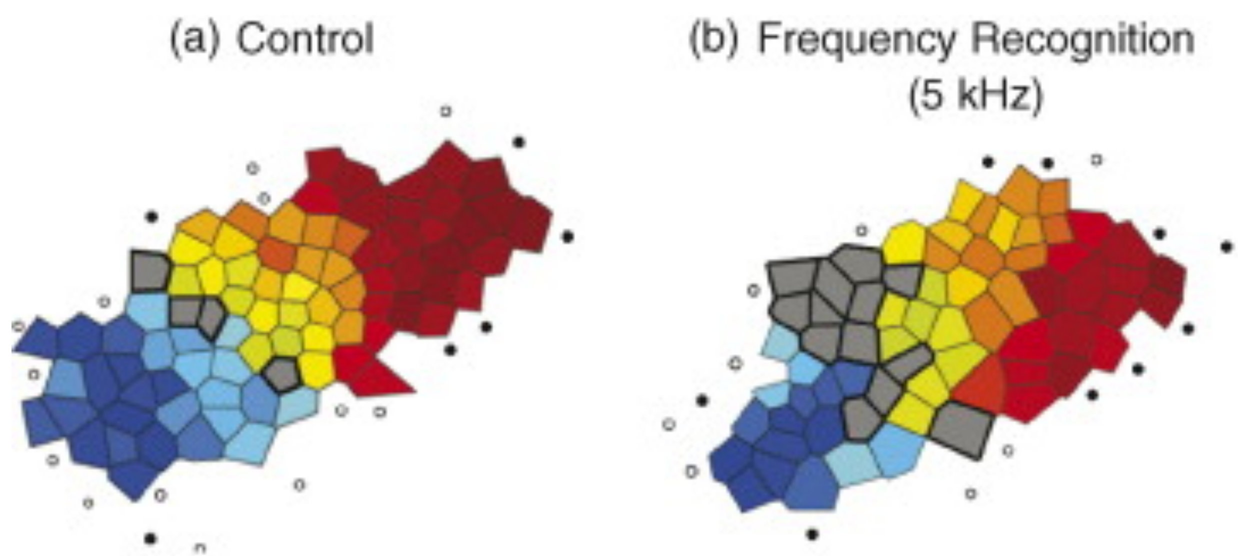
  - Tasks that require recognition of complex stimuli activate areas equivalent to the parabelt area in monkeys
  - Thus, stimuli that are more complex are processed farther "downstream" in the nervous system

Cases of humans with brain damage to this area show perception difficulties with pitch



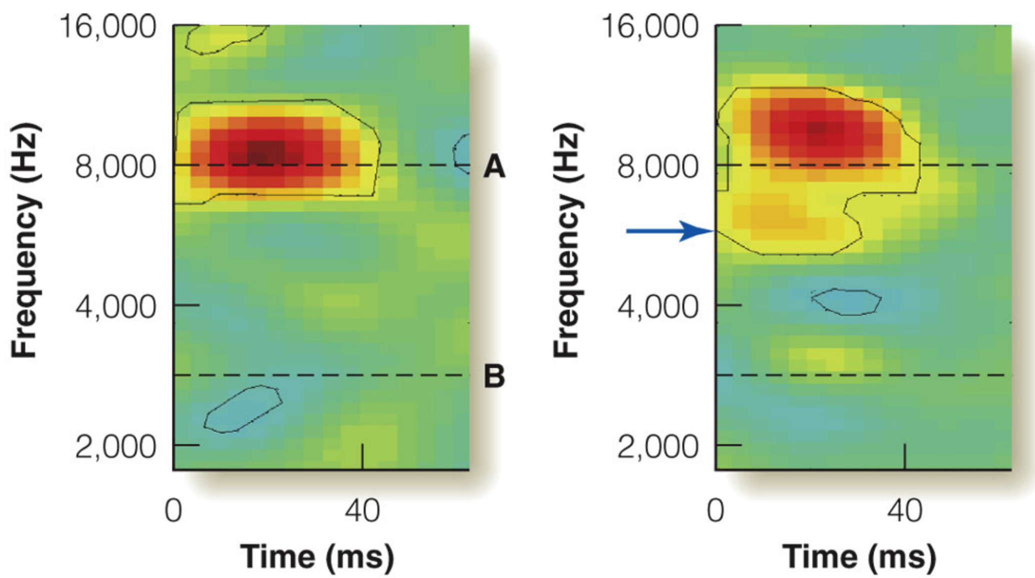
Effect of training on tonotopic maps

- Rats trained to recognize 5kHz frequency



Effect of Experience on the Auditory Cortex

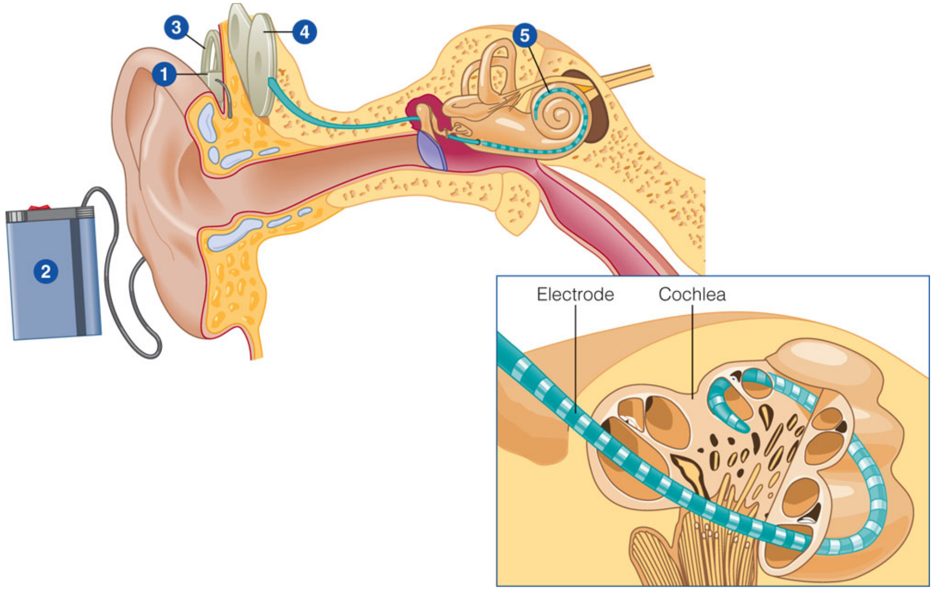
- Musicians show enlarged auditory cortices that respond to piano tones and stronger neural responses than non-musicians
- Experiment by Fritz et al. (2003) *Nat. Neurosc.*
  - Marmosets were trained to lick a water spout in response to a pure tone embedded within a stream of complex tones
  - Neurons became quickly tuned to the target frequency and maintained the effect for hours after the testing session



(a) Before training (b) After training

Cochlear Implants

- Electrodes are inserted into the cochlea to electrically stimulate auditory nerve fibers
- The device is made up of
  - A microphone worn behind the ear
  - A sound processor
  - A transmitter mounted on the mastoid bone
  - A receiver surgically mounted on the mastoid bone



Cochlear Implants - continued

- Implants stimulate the cochlea at different places on the tonotopic map according to specific frequencies in the stimulus
- These devices help deaf people to hear some sounds and to understand language
- They work best for people who receive them early in life

http://www.youtube.com/watch?v=WDDfGMuofuw&feature=related