Sound and the Ear

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9.35

HEARING

Sound - when objects in the world vibrate, they transmit acoustic energy through surrounding medium in the form of a wave.

The task of the ears is to measure the soundwave and transmit it to the brain.

The task of the brain is to interpret this signal, and use it to figure out what's out there in the world.

Sound waves are longitudinal, consisting of regions of high and low pressure that move away from the sound source.

(Image removed due to copyright considerations.)

Some facts about sound:

It needs a medium to carry it.

Speed of sound is proportional to density of medium.
-at room temp, sound in air moves at 343 meters/second
-in water, 1500 meters/second

Speed is independent of intensity.

Intensity falls off with distance.

Sound can travel around objects.

Sound level (intensity) is measured in decibels. Intensity is the energy transmitted per second (i.e. the power) through a unit area.

The auditory system can deal with a huge range of sound intensities, so instead of talking about intensity directly we use a log scale of the ratio between two sound intensities.

One bel indicates a ratio of 10:1, so
number of bels = $\log_{10}(I1/I0)$

But bels are too big! So we use decibels, which are a tenth as big:
number of decibels = $10 \log_{10}(I1/I0)$

So increasing the sound level by 10 dB means a tenfold increase (in intensity).

Increasing the sound level by 20 dB means a hundredfold increase.

number of decibels = $10 \log_{10}(I1/I0)$

When we say a rock concert is 120 dB, this is implicitly measured with reference to an agreed upon reference sound level, I0.

I0 was chosen to be close to the minimum detectable sound level for humans.

0 dB is defined to be this sound level.

When we measure sound levels with respect to this standard reference (e.g. with a sound meter), we say the sound is 120 dB SPL, for instance.

Intensity is proportional to the square of pressure, so also:

number of decibels = $20 \log_{10}(P1/P0)$

0 dB Threshold of hearing
10 dB Normal breathing

30 dB Soft whisper

50 dB Quiet conversation

70 dB Busy traffic

90 dB Shouting

110 dB <--- prolonged exposure can cause hearing loss
120 dB Propeller plane at takeoff

140 dB Jet at takeoff, threshold of pain

160 dB Instant perforation of eardrum, 10^{16} times something at 0 dB.

Although sound waves are longitudinal, we represent them as amplitude (pressure) vs. time.

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Please see: Sekuler, Robert and Blake, Randolph.
Perception (Fourth edition).
New York: McGraw-Hill, 2001.
Figure 9.2, p. 295.

It's often more convenient and useful to represent sound waves in terms of the frequencies they contain.

Remember Fourier analysis:
any signal can be built out of sines and cosines.

E.g. a square wave:

(Images removed due to copyright considerations.)

Review of wave terminology:

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Frequency is the inverse of the period, and is measured in Hz.

1 Hz = 1 cycle per second, i.e. one period per second.

Humans can hear sounds between 20 and 20,000 Hz.

Filters change the frequency content of a signal.

Lowpass, bandpass, and highpass filters are three important types.

(Image removed due to copyright considerations.)

Natural sounds often have interesting structure when broken down in the frequency domain.

Instruments of a particular class (wind instruments, say), when played at a given pitch, all generate the same frequencies, just with different relative amplitudes.

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The amplitude of the harmonics (also called overtones) play a big role in timbre - how things sound (oboe vs. clarinet vs. flute).

The pitch of an instrument is conveyed by the fundamental,or lowest frequency (mostly), and the timbre by the amplitude of the overtones. But more on that later.

Often the frequency composition of natural sound sources changes over time. So instead of just plotting the amplitude spectrum for the whole signal, we plot the amplitude spectrum as a function of time.

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A shotgun blast

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THE EAR

The ear exists to turn soundwaves into electrical signals to send to the brain. Each part serves a specific function.

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Functional schematic of the ear:

(Image removed due to copyright considerations.)

The Outer Ear

The pinna (floppy thing on each side of head)
- funnel sound into ear
- humans can't move theirs, unfortunately
- helps us localize sound by filtering sound differently depending on where sound is coming from

Auditory canal
- has a resonance at 3000 Hz

Eardrum (tympanic membrane)
- in humans it is about 0.5 cm in diameter
- umbrella-like structure, pretty sturdy

The Middle Ear

The middle ear transmits the eardrum's vibrations to the oval window, which transmits them to the fluid-filled cochlea.

The ossicles - three smallest bones in body, the size of letters on a page.
hammer, anvil, and stirrup

What is the point? Why not get rid of eardrum and have airborne vibrations directly impact the cochlea?

(Image removed due to copyright considerations.)

The function of the middle ear: impedance matching.

Because water is denser than air, it offers more resistance to movement.

So at an air-water boundary, most of the incoming sound is reflected rather than transmitted. There is a 30 dB loss in sound level.

(Image removed due to copyright considerations.)

The oval window is 20 times smaller than eardrum, so same force exerts more pressure, compensating for change in impedance.

Impedance matching, continued.

This only works if the air pressure in the middle ear is the same as the atmospheric pressure outside the eardrum (otherwise you lose energy at the eardrum instead).

So the Eustachian tube equalizes the pressure every time you swallow (it is connected to the throat).

This is what is happening when your ears pop.

(Image removed due to copyright considerations.)

The acoustic reflex

The other function of the middle ear.

The eardrum and stirrup bone (part of the ossicles) are each equipped with tiny muscles that contract in the presence of loud sounds.

The muscle contraction stiffens the eardrum and restricts the movement of the ossicles, thereby damping the vibrations passed to the inner ear.

This is thought to help prevent damage to the inner ear.

It only partially works - sudden, intense sounds (gunshots) get through before the muscles can contract.

Interim summary:

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The Inner Ear

Semicircular canals - for balance

Cochlea - receptor organ for hearing

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Please see: Sekuler, Robert and Blake, Randolph.
Perception (Fourth edition).
New York: McGraw-Hill, 2001.
Figure 9.11, p. 306.

The cochlea, unrolled:

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Please see: Sekuler, Robert and Blake, Randolph.
Perception (Fourth edition).
New York: McGraw-Hill, 2001.
Figure 9.1, p. 306.

Basic idea: vibrations at oval window cause basilar membrane to wiggle. These wiggles cause the hair cells in the Organ of Corti to fire. The electrical signals are carried up the auditory nerve to the brain.
The details of the cochlea have been difficult to study, because it is a very tiny mechanical device that does not function in vitro.

Another view of the cochlea, unrolled. Note that the vestibular and tympanic canals are connected at the apex of the cochlea.

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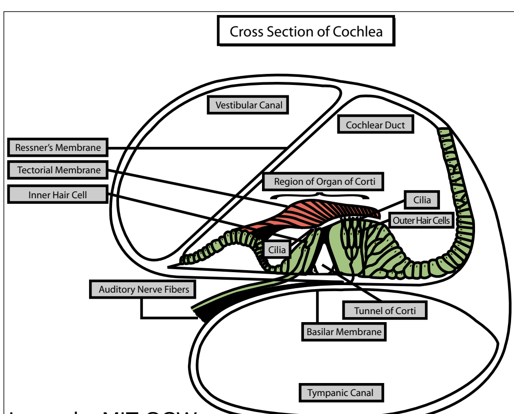

Image by MIT OCW.

Big question: how does the basilar membrane wiggle in response to sound?

Early theory (due to Rutherford): whole thing moves at once, like a diahragm.

Problem: basilar membrane varies in thickness and stiffness:

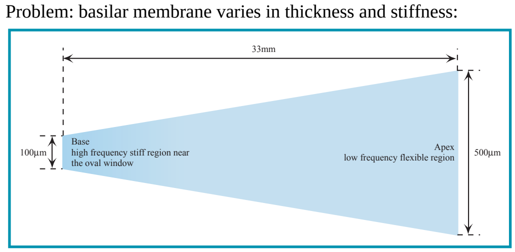

Image by MIT OCW.

The basilar membrane was hard to study because of its size and delicate nature.

Georg von Bekesy discovered how the basilar membrane works, by constructing a crude model of the cochlea:

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Please see: Sekuler, Robert and Blake, Randolph.
Perception (Fourth edition).
New York: McGraw-Hill, 2001.
Figure 9.17, p. 313.

Bekesy's observation:

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Perception (Fourth edition).
New York: McGraw-Hill, 2001.
Figure 9.18, p. 314.

Frequency sensitivity changes as you move along the basilar membrane, due to its mechanical properties.

Vibrations of the oval window, and the pressure changes in the cochlear fluid that result set up a traveling wave on the basilar membrane.

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Please see: Sekuler, Robert and Blake, Randolph.
Perception (Fourth edition).
New York: McGraw-Hill, 2001.
Figure 9.19, p. 315.

The wave peaks in different places depending on its frequency content.

Two examples of traveling waves:

High frequency Low frequency

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Figure 9.19, p. 315.

Movement of the basilar membrane causes the hair cells to move against the tectorial membrane, which causes the cilia to bend.

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When the cilia bend, the hair cells release neurotransmitter onto synapses with auditory nerve fibers that send signals to the brain.

But because only part of the basilar membrane moves for a given frequency of sound, each hair cell and auditory nerve fiber signal only particular frequencies of sound.

(Image removed due to copyright considerations.)

Different auditory nerve fibers encode different frequencies:

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Please see: Sekuler, Robert and Blake, Randolph.
Perception (Fourth edition).
New York: McGraw-Hill, 2001.
Figure 9.23, p. 321.

The cochlea is doing a frequency analysis of the sound signal!

One complication - there are two kinds of hair cells.

Inner hair cells are the ones that synapse with auditory nerve fibers.

Outer hair cells are more numerous than inner hair cells, but serve mainly to amplify the motion of the basilar membrane, and sharpen its tuning.

(Image removed due to copyright considerations.)

Weird feature of the ear: otoacoustic emissions

Mechanics of the ear work in reverse, too.

So if basilar membrane moves on its own, this will produce a sound.

You can hear these sounds in most people (2/3) if you listen to their ear in a quiet room (emissions are about 20 dB).

They are thought to be due to the amplifying functions of the outer hair cells.

You can also hear emissions in response to a sharp click
(outer hair cells amplify motion, don't stop immediately)

Summary of The Ear

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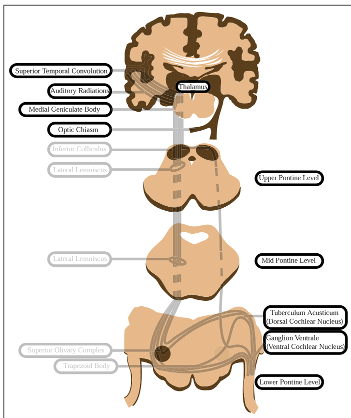

On to the brain…

The subcortical auditory pathways are much more complicated than those for vision.

Image by MIT OCW.