Section 1.1 : The ear as a sensor

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Presentation and initial test

I

A. Introduction

Objectives

The objectives of this section is to:

- Succinctly present the general mechanisms of human hearing
- Introduce the physical mechanisms and the transduction phenomena that happen in the ear, which can be seen, basically speaking, as an electro-mechanical-acoustic transducer
- Introduce the tools associated with sensors (transfer functions, sensitivity, input/output laws)
- Link the auditory perception of sound intensity with objective indicators (physical phenomena)

Requirements

The required notions for this section are:

- Transfer functions (input/output laws)
- Classical mechanics

B. Exercice : Initial Test

Here is a general schematic of the human ear that will be studied in more detail later on.

Observe the different parts of this schematic by moving the cursor over the image (outer ear, middle ear, inner ear).

This will help you reply to the initial test of this section.

The ear is composed of three distinct parts that are visible on the previous image.

To which physical domains are the different parts associated? (fill in the following table):

	Fluid	Solid	Electrical
Outer ear	1	2	3
Middle ear	4	5	6
Inner ear	7	8	9

- ☐ **Zone 1**
- ☐ **Zone 2**
- ☐ **Zone 3**
- ☐ **Zone 4**
- ☐ **Zone 5**
- ☐ **Zone 6**
- ☐ **Zone 7**
- ☐ **Zone 8**
- ☐ **Zone 9**

C. Requirements test

Exercice 1

Does the pinna/concha amplify sound ?

- ○ Yes
- ○ No

Exercice 2

Are we equally sensitive to every audible frequency ?

- ○ Yes
- ○ No

Exercice 3

The ear drum never vibrates.

- ○ True
- ○ False

General presentation of the human ear

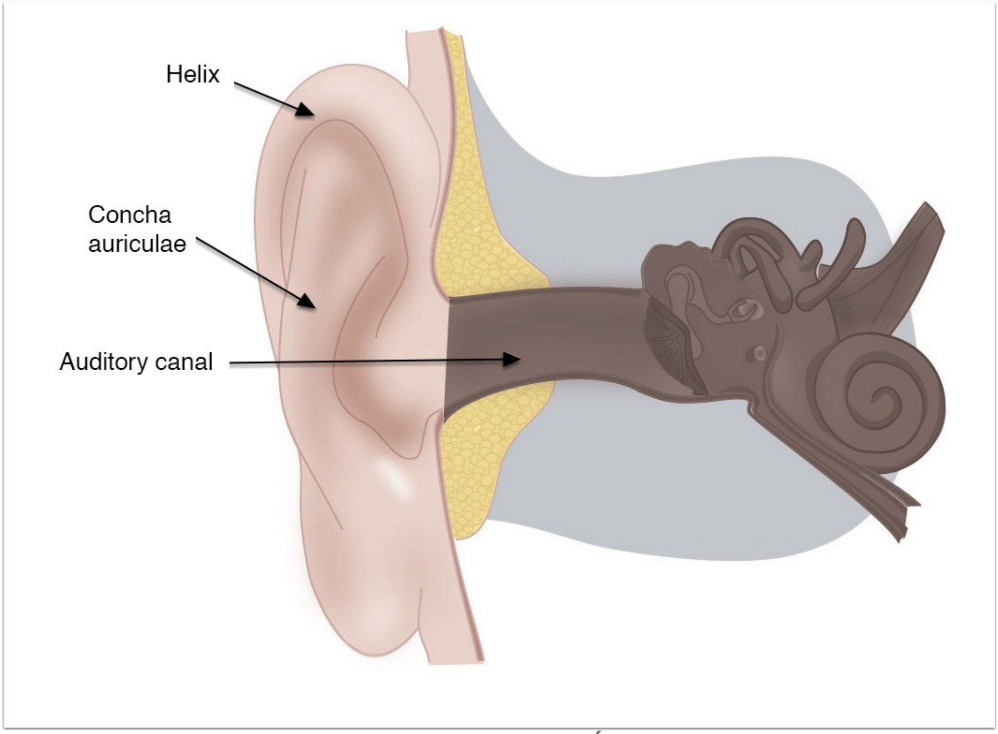
II

- The ear transforms an acoustic pressure (stimulus) into an electrical impulse that is sent to the brain (perception).
- The stimulus results from the ear drum being excited by a pressure variation in the air.
- Step by step description of the animation:
  - A pressure difference in the air vibrates the ear drum: **acoustic-mechanical transduction**
  - These vibrations are transmitted via the ossicles (hammer, styrup and anvil) to the oval window of the cochlea.
    One of the functions of the ossicles is to increase the energy transfer from the exterior (air medium) to a liquid medium in which sits the inner ear, and in particular, the cochlea (this is often called impedance matching)
  - What follows is the vibration of the organs of the inner ear, and in particular the specialised cells that transmit the information to the brain.
    This corresponds to a:
    mechanical-electrical transduction.

The outer ear

III

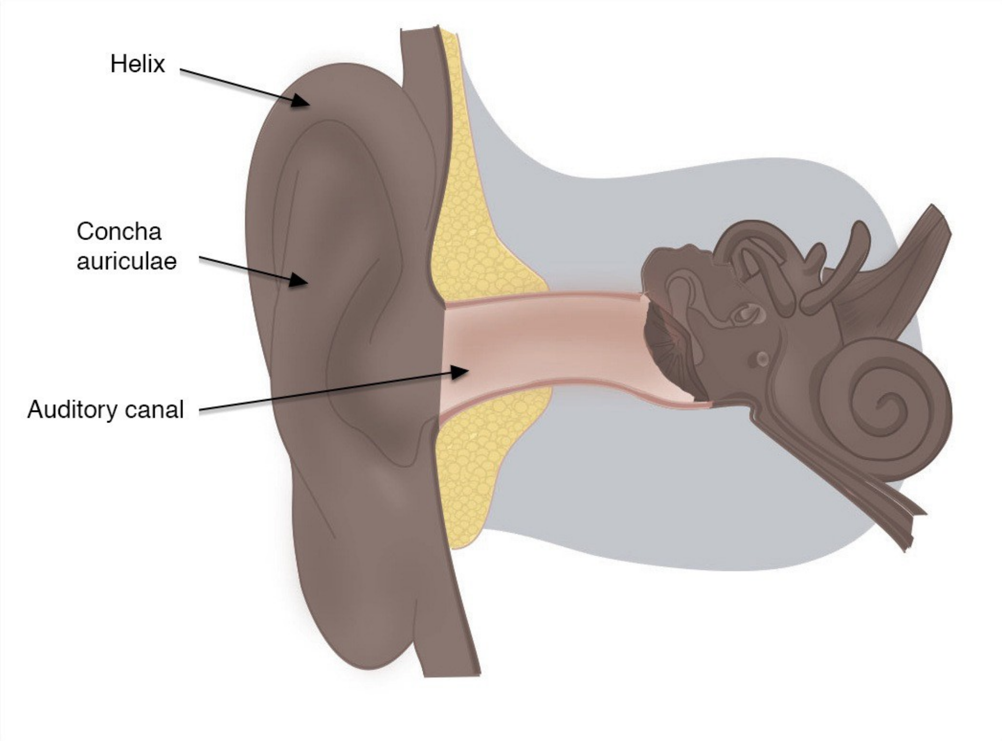
The pinna and the concha: an acoustic horn



Schematic created by Éric Bavu

- Main role in sensing, and channeling exterior sounds towards the ear canal and ear drum.
- Concha-pinna: Impedance matching (optimisation of the transfer to the ear canal).
- Amplifying (resonances). Concha: resonance around 5000 Hz.

The ear canal : the resonator



Schematic created by Éric Bavu

To understand the resonator concept, see section 2.3 - part 2[1], chapter "propagation in a long tube", with examples.

- The ear canal behaves like a tube closed on one side (by the ear drum), and open at the other.
- This type of tube is called a wave guide, which exhibits resonances depending on its length.

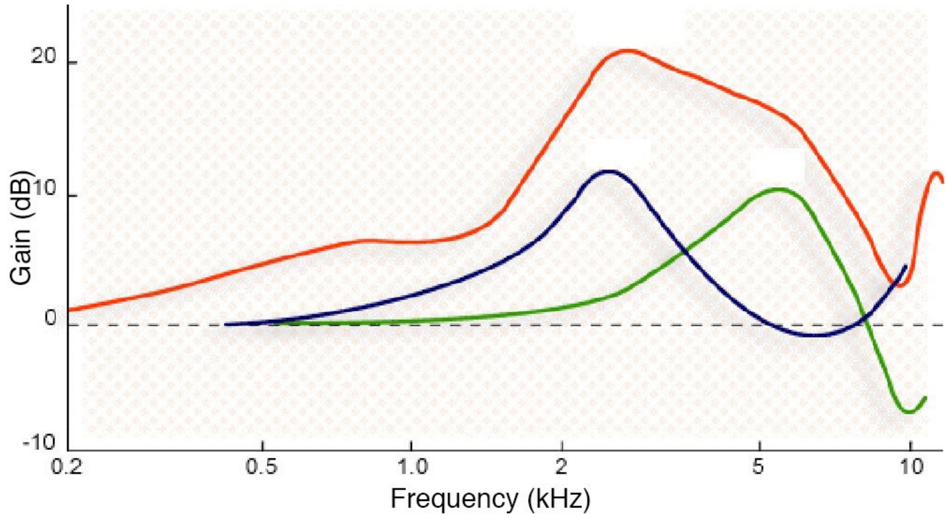
  This is like a organ pipe, with the note depending on the length of the tube.
- The resonance frequency of the ear canal can be found at around 3400 Hz. This is a quarter wave resonance, thus the length of the tube and the frequency can be linked. If l_c is the tube length: $f = \frac{c}{4l_c}$, with $c = 343 m.s^{-1}$ the speed of sound in the air.
- We can therefore see that the ear is most sensitive to frequencies between 1 kHz and 4 kHz (This mostly being due to the outer ear).
- The ear drum is the element that separates the middle and outer ear.

Total amplification due to the outer ear.

The blue curve represents the amplification due to the ear canal (maximal around 2500 Hz), the green curve represents the amplification due to the pinna and concha (maximal around 500 Hz), and the red curve represents the total amplification of the outer and middle ear.

We can see that the sensitivity depends mostly on the amplifications by the outer ear, as the red curve is very close to the sum of the green and blue curves. The remaining amplification is provided by phenomena in the middle and inner ear.

1 - ../../Grain2.32en/co/module_M2G3-2_6.html



Schematic created by Éric Bavu

The middle ear

IV

A. The ear drum

- The ear drum is a thin, light and elastic membrane. Its surface is around 60mm², and its thickness is around 100 microns.
- This membrane is excited by an acoustic wave, guided and amplified by the ear canal.
- The ear drum is comparable to a microphone membrane.
- The ear drum creates what is called a coupling (or an acoustical-mechanic transduction) (see *section 3.1*[2] for a more detailed explanation)
- The ear drum transforms acoustic pressure p and volume velocity $w = S\,v$, where S is the canals diameter, and v the acoustic velocity (see definitions in *section 1.2*[3]) in the ear canal into mechanical force and velocity through the middle ear to the inner ear.

2 - ../../Grain3.1en/index.html
3 - ../../Grain1.2en/index.html

B. The ossicles of the middle ear

Anatomy

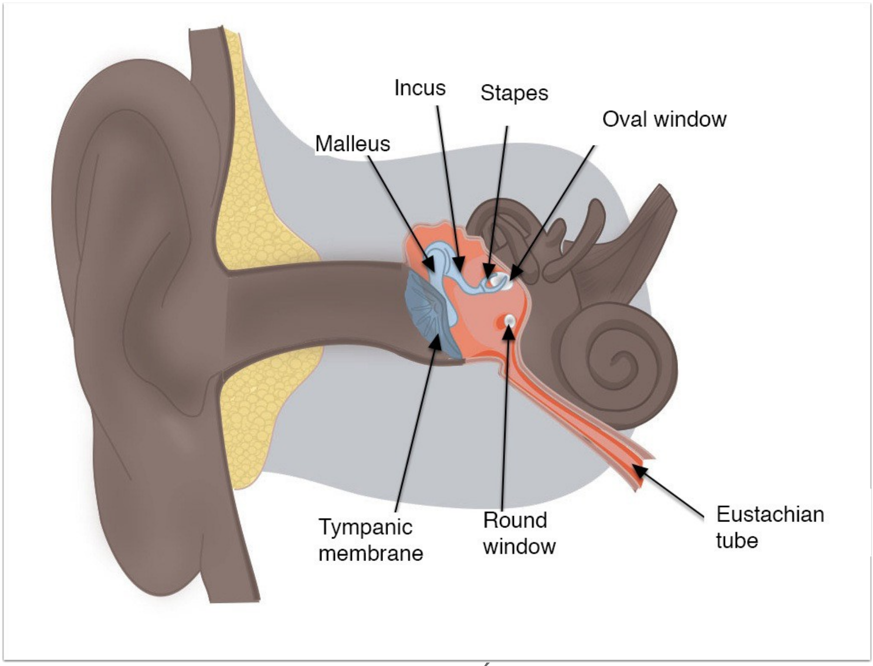


Image credit : Éric Bavu

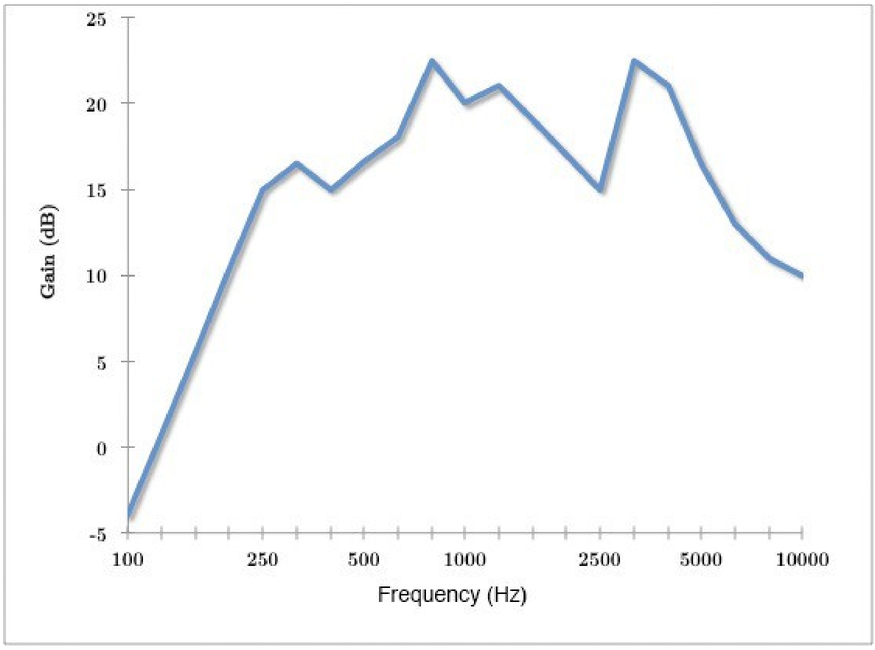
- Essentially a link between the inner and outer ear.
- Used to efficiently transmit vibrations from an air medium to a liquid medium.

Role

- The role of the ossicles is that of impedance matching (p/v) between the air and the perilymph (the fluid). Basically, this means that they simplify the energy transfer between these two media. This is needed because the input impedance of the endolymph is around 5000 times that of air, thus a mechanism is required to facilitate the energy transmission. Link to impedances : *section 2.3.2*[4].
- Without these ossicles, the transmission to the inner ear would be 100 times less efficient.
- Remark : This impedance matching depends on the frequency, this signifies that the transmission to the inner ear is not as efficient for every frequency (illustrated in the following schematic).

4 - ../../Grain2.32en/index.html

Remark : transfer function of the middle ear



Movement of the ossicles in the middle ear

Stapedius reflex (protection mechanism)

- If a sound is detected by the brain at more than 80 dB SPL, the information is transmitted to the nucleus of the brainstem
- A reflex feedback loop orders the contraction of certain muscles, this rigidifies the ossicular chain of the middle ear
- Due to this rigidification, the energy transmitted to the inner ear is reduced
- This mechanism protects the hair cells of the inner ear from damage by high intensity sounds

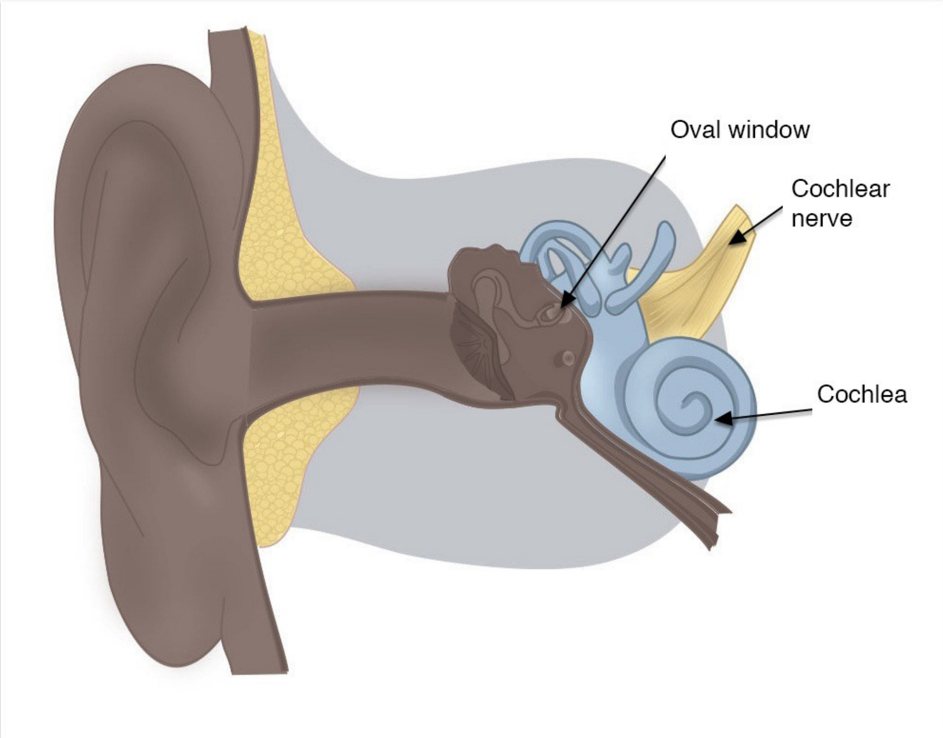
Caution : this reflex is limited!

- it can tire (rapidly)
- it only works for frequencies under 2000 Hz
- the vibrations in the the cochlea are only reduced by a factor of 10 (20 dB maximum)
- this mechanism only intervenes after around 30 ms because of the reflex latency. Thus, the intensity of impulses is rarely reduced

The inner ear

V

The cochlea, the sensory organ of hearing



The **cochlea** is a spiral-shaped organ in which the sound pressure waves are transformed into electrochemical impulses.

The transformation into electrochemical impulses

- The oval window, excited by the stapes (stirrup), transmits an acoustic wave to the fluids in which sit the different organs of the inner ear (in the cochlea).
- The inner ear has two functions: it is responsible for sound detection and balance (not studied here).
- Specialised cells, connected to the brain via **nerves**, are oscillated by the wave in the fluids. These cells transmit an electrical impulse to the brain with every agitation, the mechanical vibration of the oval window is therefore transformed into a nervous influx.
- The cochlea therefore performs a **mechanical-electrical transduction**.

Conclusion exit test

VI

A. Summary

- This lecture is a general introduction to human hearing
- The three domains of physics that contribute to electroacoustics have been shown (electrical, mechanical, acoustical)
- The different energy transformations explained here are introduced as **electroacoustic transductions**
- The efficiency of the components of the auditory system depends on the frequency, this has for effect a hearing sensitivity relative to frequency

Further reading : equal loudness curves

- The **equal loudness curves** (see the following graph) are obtained by inverting the sensitivity curves of the ear (see for example the amplification curves) for different excitation levels
- The graph shows the gain to be applied (in dB) to a signal of frequency f for the human ear to perceive the same sound intensity for each frequency.

  Put another way, for the ear to perceive every frequency in the audible spectrum at, for example, 45 phons and taking 4000 Hz (40 dB) as the reference frequency

  this is the amplification applied to a selection of frequencies:

  20 Hz: around 60 dB

  50 Hz: around 45 dB

  125 Hz: around 30 dB

  315 Hz: around 15 dB

  800 Hz: around 5 dB

  3000 Hz: around 5 dB

  5000 Hz: around 0 dB

  12500 Hz: around 20 dB

  Therefore, loudness measures a sensation, not an excitation.

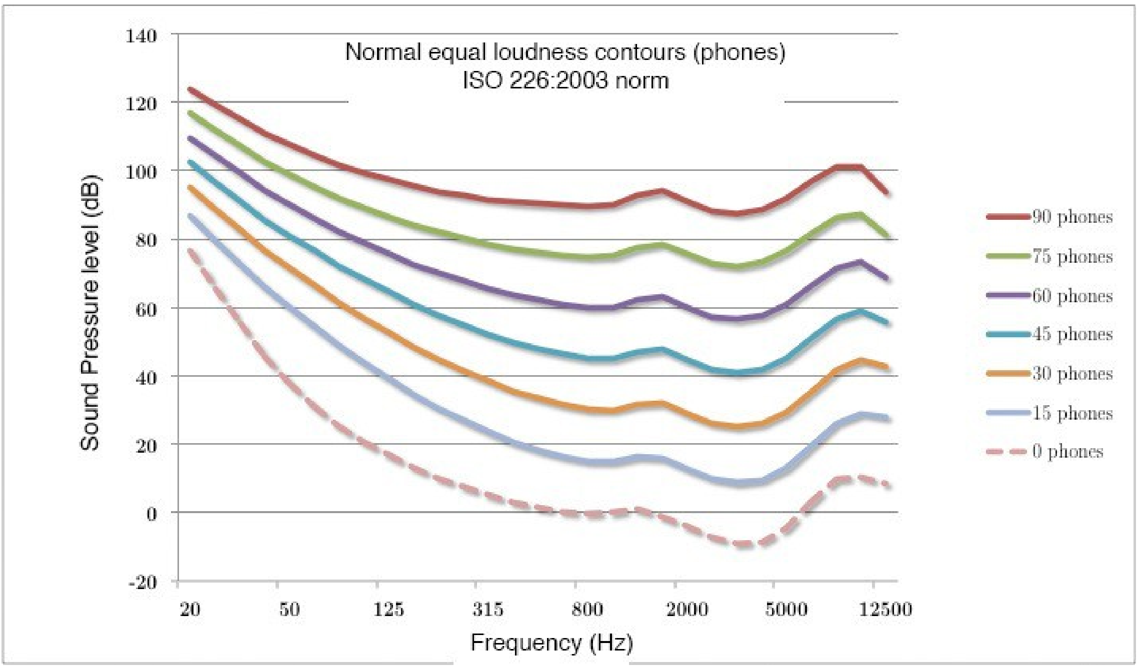


Image credit : Eric Bavu

B. Test what you know

Exercice 1

The pinna/concha resonates at frequencies lower than the auditory canal.

- ◯ Yes
- ◯ No

Exercice 2

The ossicles transmit information to the brain via nerves.

- ◯ True
- ◯ False

C. Exercise

Calculate the length lc of the ear canal, knowing that the quater wave resonance frequency is $fc = 3400Hz$

Answer : $l_c = \frac{c}{4f_c} = 2.5cm$ if we consider that $c = 343m.s{-}1$

Bibliography

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