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The Biophysical Function of the Human Middle Ear

Janos Vincze[1] | Gabriella Vincze-Tiszay [1]

[1]Health Human International Environment Foundation, Budapest, Hungary

Abstract

The man perceives a part of the sounds with his organ of hearing which is of threefold setting up. The external ear is composed of the pavilion and the external auditory meatus (bore of hearing), then the middle ear (tympanum) sets up with the ear-drum membrane. In its cavity are to be found the auditory ossicles: the hammer (malleus), anvil (incus) and stapes, as sound conductors connecting the ear-drum with the oval window of the inner ear. Inside the oval window, the internal ear is filled up with fluid in which the balance-sensory organ (the semicircular canals) and the auditory organ, the cochlea take place. From here starts the auditory nerve to carry the stimulus of the cochlea to the auditory centre of our brain. It is our {auditory} organ of hearing to perceive speech and music. The evolution and continuous development of speech decisively contributed to the human race to emerge from the other living species, indeed, also the individual formation of speech essentially contributes to the explosion-like development of the child's way of thinking.

1 | INTRODUCTION

According to general experience, sounds with a larger intensity are louder. Loudness, which is a subjective, psychophysical quantity, has to be distinguished from the previously discussed intensity, which is an objective physical quantity. The former characterizes the strength of the stimulus, while latter the strength of sensation.

Loudness on one hand depends on the physical intensity, and on the hand on the frequency of sound. (1) However, identical changes of intensity correspond to non-identical changes of sound sensation, since as discussed previously the ear is only able to receive physical stimuli across 13 orders of magnitude. It was thought for a long time that the ear gave a logarithmic response to a change of intensity (Weber-

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Fechner's law). (2) However, according to accurate measurements the intensity dependence of strength (loudness) on subjective sound sensation is actually a power function.

The vibrating amplitude of air in the case of sounds which are just audible is extremely small i.e. about ten times smaller than the diameter of hydrogen atom (10^{-11} m). Remarkably, it has been calculated that this displacement is only about 30% larger that the noise amplitude caused by the random thermal fluctuations of air. (3) [3] Therefore evolution did not create an organ of hearing with a pointlessly large sensitivity, since we would hear only the thermal noise of air if the ear were more sensitive. (4)

You have to tell the little child many times the name of an object and its different forms described with the given word have to be seen far too often. The small child – by developing the concept of a chair – was not enough to see only one chair and attach the word „chair" but it had to be done with many chairs different in colour, shape and size in theory all over the word. After forming the concept, the word shall attach to such features of the object characterizing all those objects which belong to the same conceptual circle. This happend to the little child, too. As long as the concept of the chair hasn't been formed he had to find out from many other similar objects that those are out of the question (didn't belong to the „chair"). In the first period of evolving the speech, the child cannot express his thoughts, wishes in full sentences, just marked by one word. „The full-sentence speech" shall develop as the child recognizes the link between the single objects and actions. The perfect accuracy won't be achieved but for a long time. (5) The discrimination from other objects, of course, usually won't succeed quickly and perfectly. Forming a concept evolves as a result of a long development. There are concepts, ideas to be developed, widened, supplemented for a lifetime in substantial interpretation.

The structure of the ear is shown in Figure 1.

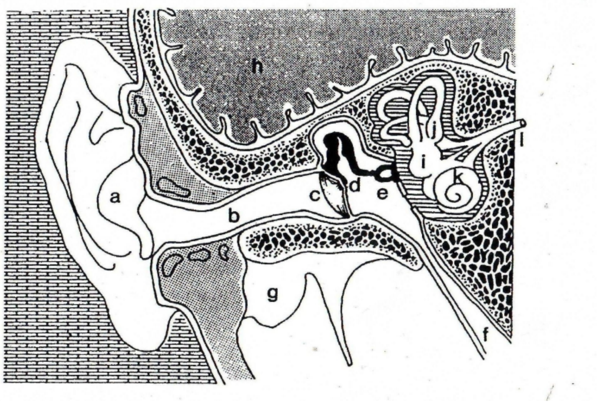


FIGURE 1: Schematic section of the ear.

Symbols: a: auricle, b: external auditory canal, c: eardrum, d: middle ear with auditory bones, e: stapes in the oval window, f: Eustachian tube towards the oral cavity, g: and its black patched area) bone, h: brain,

i : vestibula, j: semicircular canals, k: cochlea (white parts are membranous, hatched parts are a bony maze), l: nerve running to the brain.

It is our {auditory} organ of hearing to perceive speech and music.

The characteristics of the sound waves

The waves can be classified in two big categories: (6)

- longitudinal waves when the oscillations of the particles take place in the direction of propaga-tion of the wave;

he phase velocity c for longitudinal waves in a solid medium is given by the following formula:

$$c = \sqrt{\frac{b}{E}\cdot\frac{(3-\varrho)\mu}{I}}$$

where: E - modulus of elasticity, ρ - density, μ - Poisson's ratio.

- transversal waves when the oscillations take place on a perpendicular direction on the one of the propagation of the wave.

The phase velocity (c) of the transverse wave is calculated by the following formula:

$$c_l = \sqrt{\frac{E}{\rho_0 \cdot (3 - 6\mu)}}$$

Comparing the two formulas, we can conclude that the phase velocity of longitudinal waves is always higher. (7) Using the value interval of the Poisson number, the ratio of the velocities of the two phases changes in the following interval:

$$c_l / c_t \in [2{,}15 - 9{,}7]$$

The sounds are longitudinal waves which propagate in continuous environments and if they reach the human's hearing organ, in certain conditions, they produce hearing sensations. (8) The description and the characterization of the sounds is based on three main characteristics: height, intensity and quality, to which the following physical sizes correspond: frequency, amplitude and harmonic constitution. (9)

The height of a sound is determined by the frequency of an acoustic wave (ν), namely the number of os-cillations that the sound wave performs in the time unit. The higher the sound frequency, the „higher" the human ear perceives them. (10)

According to the frequency, the sounds classify as follows:

– infrasounds, $\nu < 16$ Hz;

– proper sounds, 16 Hz $< \nu <$ 20 kHz,

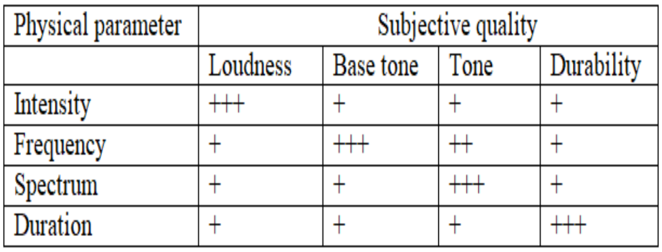
– ultrasounds, $\nu >$ 20 kHz.

The infrasounds and the ultrasounds cannot be per-ceived by the human ear.

The frequency range of hearing varies greatly from individual to individual; it is rare for a person to be able to hear the full hearing range of 16 to 20,000 Hz. The ear is relatively insensitive to low-frequency sounds; for example, at 100 Hz its sensi-tivity is roughly 1,000 times lower than at 1,000 Hz. The sensitivity of high-frequency sounds is greatest in infancy and gradually decreases throughout life, making it difficult for an adult to hear sounds above 12,000 Hz. (11)

Loudness mainly depends on the sound pressure, but the duration and spectrum of the sound also influence the development of loudness sensation. The sense of pitch depends mainly on frequency, but shows a slight dependence on sound pressure and duration. Table 1 illustrates the dependence of sound sensation quality on physical parameters. (12)

TABLE 1: Dependence of sound qualityon physical parameters



Physical parameter	Subjective quality			
	Loudness	Base tone	Tone	Durability
Intensity	+++	+	+	+
Frequency	+	+++	++	+
Spectrum	+	+	+++	+
Duration	+	+	+	+++

+ = weakly dependent ++ = moderately dependent,+++ = highly dependent.

The phase velocity (c) of the transverse wave is calculated by the following formula:

$$c_l = \sqrt{\frac{E}{\rho_0 \cdot (3 - 6\mu)}}$$

Comparing the two formulas, we can conclude that the phase velocity of longitudinal waves is always higher. (13) Using the value interval of the Poisson number, the ratio of the velocities of the two phases changes in the following interval:

$$c_l / c_t \in [2{,}15 - 9{,}7]$$

The sound intensity **I**, is defined as sound energy **E** , which crosses the surface unit **S**, in the time unit t,

$$I = \frac{E}{S \cdot t} = \frac{P}{S}$$

where **P** is power and the measurement unit for the sound intensity is:

$$[I] = \frac{J}{m^2 s} = \frac{W}{m^2}$$

The sound intensity depends on the power of the sound source and the distance from the source, be-cause the sound intensity decreases with the x dis-tance, due to the absorption of the sound according to the relation: (14)

$$I = I_0 e^{-\beta \cdot x}$$

where β is the absorption coefficient, which depends on the nature of the environment and it physical conditions.

The level of the intensity of the sound sensation depends both on the sound intensity and the frequency of sound. (15) For sounds of the same frequency, the intensity of the sound frequency is given by Weber-Fechner's law:

$$L = \log \frac{I}{I_0}$$

where I_0 is the reference intensity. In order to define the reference intensity a sound with the frequency of 1 kHz is considered usually. The measure unit for the level of the sound intensity **I**, is called bel (B), (the intensity corresponding to zero bels) but the submultiple is used more often:

$$1\,dB = 10^{-1} B$$

in which case the level of the sound intensity is written:

$$L = 10 \lg \frac{I}{I_0} (dB)$$

The level of the minimum sound intensity which causes sounds perceivable by the human ear is called sensitivity threshold. The level of the maximum sound intensity for which the sounds do not produce painful effects or temporary or permanent deafness is called painful sensation threshold. (16) These two thresholds depend both on the sound frequency and the sound intensity. The human ear perceives sounds with intensities ranging between 0 and 140 dB. Table 2.shows examples of sound intensity for various sound categories.

TABLE 2: The value of soundintensity

Sound	L (dB)
The leaves sre rusting	10
Low-toned conversation	30
Normal conversation	65
Street noise	90
Orchestral noise	100
Engined aircraft (at 3 m)	120

The human ear perceives two sounds which have the same intensity, but different frequencies, as two sounds of different intensity which shows the necessity of introducing a new sizes called hearing intensity (N). The hearing intensity represents the level of sound intensity measured in dB for a sound with a frequency of 1 kHz assessed by a normal physiological listener. (17) The measure unit for the hearing intensity is the phon.

The quality is another feature of the sound which allows it to differentiate two sounds which have the same frequency and the same sound intensity and this characteristic is determined by the type of sound source. The sound issued by a source is not a simple sound, but it is formed of several simple sounds which have different frequencies. The sound with the lowest frequency is called fundamental sound and the other sounds whose frequency is equal with an integer multiple of the fundamental frequency, is called superior harmonic, the number and the energetic distribution of these harmonics determines the sound quality and allows us to distinguish the sounds from one another. (18)

The previously enumerated proprties refer to the pa-rameters which characterize the sound in itself. Since the sound must propagate to reach the hearing organ, the propagation parameters are also important. They are: the speed of sound, the acoustic impedance, the reflection coefficient.

The propagation speed v, of the sound depends on the propagation environment

$$v = \sqrt{\frac{E}{\rho}}$$

where: **E** – elasticity module and ρ environment density. For liquid environments the compressibility coefficient χ is used, which is the reverse of the elasticity module and the propagation speed can be written

$$v = \sqrt{\frac{1}{\chi\rho}}$$

Examples of the values of the propagation of the sound in various environments are written in the table 3.

TABLE 3: Velocity of sound in thedifferent mediums

Medium	Velocity of sound (m/s)
Air (20° C)	343
Water	1435
Glycerine	1750
Steel	5100
Copper	3400
Stone	5000
Lead	1300
Wood	3000–4000
Caoutchouc	45

The propagation of the sound waves determines pres-sure variations. The difference between the pressures existing in the environment is called sound pres-sure. (19)

The acoustic impedance **z** is the size which is used in the case when the wave is not plan or there are energy dispersions, the pressure and the speed are not in the phase anymore. This size is given by the relation:

$$\Delta p = \rho \cdot v \cdot \upsilon$$

In these relations ρ is the environment density and v is the sound propagation of the sound and ν is the sound frequency.

The anatomical structure of the middle ear

The middle ear consists of the tympanic cavity. It is a cavity in the shape of a prism inside the pyramid. Six of its walls are usually described: Paries jugularis. The lower wall separates it from the fossa jugularis visible from the outside at the base of the pyramid. Paries tegmentalis. The upper wall is formed by the tegmen tympani of the temporal bone. It borders the cranial cavity. Paries caroticus. The anterior wall is behind the canalis caroticus. Paries mastoideus. The posterior wall faces the processus mastoideus. There is a larger opening in it that leads to the cavity system of the processus mastoideus. In addition, a small, conical protrusion (erninentia pyramidalis) is visible, through which the tendon of a small muscle (musculus stapedius) appears. The outer wall (aries membranaceus) is mostly made up of the eardrum.

The inner wall (paries labyrinthicus) separates it from the inner ear. There are two small openings on it: the upper oval window, the lower circular window. The former fits the base of the stapes, while the latter is closed by a connective tissue membrane, the membrana tympani secundaria. (20)

At the corners of the anterior and inner walls, a bony canal runs towards the top of the pyramid: the canalis musculotubarius. The canal is divided by a thin bone plate into an upper smaller and a lower larger part. There is small muscle in the upper half of the canal, while the lower, larger passage is the initial, bony section of the Eustache tube.

In the middle ear there is an air column of length d between the eardrum and the circular window, which is an integer (n) multiple of the half-wavelength ($\lambda/2$) of the standing wave formed here. Frequency of vibrations (ν_n) in the air column of the middle ear.

$$\upsilon_n = n \cdot \frac{c}{2d}$$

where c – speed of sound wave propagation in the air. The significance of the air column in the middle ear is minimal, because it is mainly the auditory ossicles that play a role in this. (21)

Auditory ossicles

There are three tiny bones in the tympanic cavity between the eardrum and the oval opening.

a) Malleus 6–8 mm. The head (capitulum), the neck (collum) and projections can be distinguished on it. The strongest of the latter is the handle (manubrium), which has merged with the eardrum, causing stria mallearis on it.

b. Incus 7 mm. A body and two protruding crura can be separated on it. The body forms a joint with the head of the malleus. Its short crus points backwards, its long crus runs parallel to the handle of the malleus, behind this formula. The lower part widens (processus lenticularis) and forms a joint with the head of the stapes.

c. Stapes 3x3 mm2. On the third auditory bone, a head (capitulum), two crura and a base (basis) are distinguished. The head fits into the lenticular process of the incus and the base fits into the oval window.

The auditory bones are connected through joints to each other. The handle of the malleus has grown together with the eardrum, and the base of the stapes is secured to the oval window by a circular strip. In this way, the bones connect the eardrum to the inner ear. The vibrations of the eardrum are taken over and transmitted to the inner ear. If the eardrum moves as a result of the vibration of the sound waves, the base of the stapes will be pressed or retracted into the fenestra oval. (22)

The muscles of the tympanic cavity. In the tympanic cavity we find two fine little striated muscles. The stapes muscle (m. stapedius) is a 6.3 mm long muscle that originates from the pyramidal process of the tympanic cavity and adheres to the neck of the stapes.

It is innervated by the facial nerve. It pulls the stapes out and back. The tensor tympani is a 25 mm long muscle that originates in the musculotubarius canal and adheres to the root of the malleus handle after a break of nearly 90°. Its nerve is the branch of the trigeminal nerve. It pulls the malleus up and inwards. The two muscles contract together, making the auditory bone chain tighter. The function of said muscles reduces sound transmission, so they have a protective effect, but they also have a tuning role, as their increased contraction ensures that the ear adapts to high tones, and their relaxation ensures that the eardrum adapts to deep tones. (23)

The muscles of the tympanic cavity as well as the ligament systems of the auditory ossicles hold the auditory ossicles in a special position.

It is true that the pressure of the fluid system of the inner ear increases with the increased tone of the muscles, but this phenomenon has no significant effect on the sound transmission.

Another specific formula of the tympanic cavity is the Eustache tube (tuba auditiva), the narrow channel that connects the tympanic cavity to the pharynx. A bony and cartilaginous section can be distinguished on it. (24) The semicanalis tubae auditivae, located in the temporal bone, forms the bony part. Attached to this is the cartilaginous section outside the skull base.The cartilage of the eardrum is open downwards in a V-shape, supplemented by a connective tissue plate into a complete channel. The cavity of the canal is wider in children, usually closed in adults, only opened by the contraction of the muscles ad-hering to it at times. In this way, the Eustache tube partly serves to ventilate the tympanic cavity and partly compensates for the difference in air pres-sure between the tympanic cavity and the outside world. (25) The mucous membrane of the tympanic cavity also spreads into the Eustache tube and lines it. The walls and formulas of the tympanic cavity are covered by a mucosa consisting of a cylindrical epithelium and a loose connective tissue beneath the epithelium.

Biophysical modeling of the sound conduction of the auditory ossicles

It plays an acoustic role, transforming external sound vibrations, amplifying them and then transmitting them to the fluid system of the inner ear. It protects the inner ear from excessive sound effects.

The deflections of the eardrum are transferred to the base of the stapes by the lifting action of the auditory bone chain. Due to the fact that the functional surface of the eardrum is 55 mm^2 and that of the stapes base is 3.2 mm^2, the pressure at the base of the stapes is 18 times higher than that of the eardrum (55: 3.2 = 17). This ratio corresponds to a 24.5 dB increase in sound pressure. To this must be added 2.2 dB, since one crus of the auditory bone chain (one arm of the elevator) is one handle of the malleus, the other crus (the other arm of the elevator) is the long crus of the incus, 1.3 times longer than the handle of the malleus. Thus, the voice guidance system of the middle ear: It causes a pressure increase of 24.5 + 2.2 = 26.7 dB. From all this we can conclude that the middle ear acts as a mechanical transformer.

The auditory ossicles can be considered as rigid bars and thus the sound waves propagate in a longitudinal form. In this case, the wave equation

$$\frac{\partial^2 \Phi}{\partial t^2} = c^2 \cdot \frac{\partial^2 \Phi}{\partial x^2}$$

The phase velocity c for longitudinal waves in a solid medium is given by the following formula:

$$c = \sqrt{\frac{E}{\rho} \cdot \frac{1}{(3-6)\mu}}$$

where: E - modulus of elasticity, ρ - density, μ - Poisson’s ratio.

With their reflex contraction, the m.stapedius and m.tensor tympani stiffen the auditory bone chain(70–80 dB sound above the hearing range) and re-duce the amplitude of the system vibrations (~ 10 s delay) - the reflex mainly reduces the transmission of deep sounds – n. facial paresis – causes hyperacusis.

The stapes base moves around two axes: (26)

- for weaker sounds - rotates around its transverse axis (Fig. 2.a.);

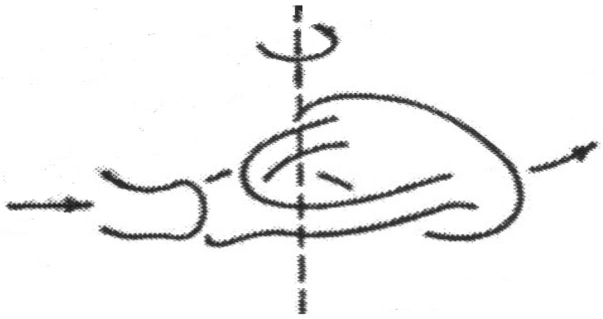


Figure. 2.a.

- in case of a strong sound - it moves around its longitudinal axis, then the amplitude of vibration is smaller (Fig. 2.b).

Figure. 2.b.

We have three (3) auditory ossicles because, with their spatial location (27) , the middle ear is able to amplify weak sounds and at the same time is able to attenuate high-intensity sounds.

Summary:

1. The eardrum vibrates from the sound waves
2. Auditory ossicles amplify the stimulus
3. In an oval window, the vibration is transmitted theto fluid space of the inner ear
4. It vibrates the basilar membrane
5. What is pressed against the membrane tectoria
6. The stereocilliums of the hair cell bend, ion channels open
7. Hair cell depolarizes
8. Stimulus is dissipated in cerebrospinal fluid VIII (vestibulocochlearis)
9. Temporal lobe primary auditory cortex (Brodman 41, 42)
10. Association pathways: speech comprehension (Wernicke area)

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