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INSTITUT FÜR ANGEWANDTE PHYSIK - FACULTE DE MICROTECHNIQUE

MEMS : Enhancing human visual and auditory capabilities via biomimetics

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WIEN

WINTER 2017 - SUMMER 2018

MEMS : Enhancing human visual and auditory capabilities via biomimetics

Projectwork : Interactions with surfaces

Research on principles on the senses of seeing and hearing in humans and animals combined with identification of MEMS with respective abilities will yield a prototype of a device enhancing human visual and auditory senses.

Field of knowledge : Micro- and nano-technologies

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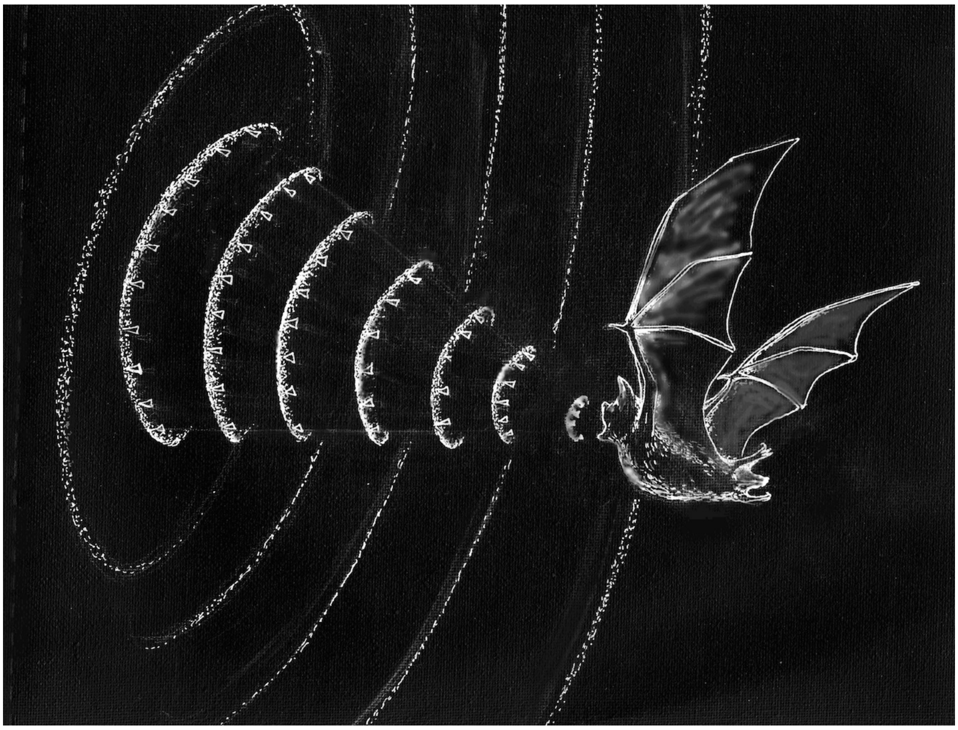

FIGURE 1 – Echolocation of bats

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RESUME

An animal species will survive only by exploiting every niche that allows him to take advantages on other species. In day-time, birds are predators of insects. In night-time, bats steal their role. This large group of mammals created an adequate substitute for vision. By using their larynx and ear for production of sound and the subsequent detection and discrimination of objects allow bats to see in complete darkness.

Human hearing capacities compared to bats are reduced but our seeing capacities are strong. We mostly use our eyes to see and check every information. A problem is that human seeing capacities are often tricked and limited by optic laws. For example, we're not able to see in deep or muddy water. Everywhere darkness is, a complicated problem awaits us. Society adapts itself to light up cities, caverns and dense forest. But there's remaining places like muddy water that our lights are not able to discover.

During this project work, we will discover how human hearing capacities are interesting for it's system's complexity and size. The anatomy of bat hear is also a complex system shaped in order to understand ultrasound frequency from his pinnae to his fovea. An interesting part on ultrasound emission will show that some bats adapt surroundings and emitted frequencies to understand them.

In order to discover the way ultrasound frequency works in general, two prototypes were successfully created. It shows fundamental laws and current applications of ultrasound use to see.

For a future human capability enhancement, limits of MEMS and NEMS systems, Greenwood's function properties and particularly interesting sensors will be depicted. A particular interest in the cochlear implant will give solutions and next challenges to lead next innovations on the way to an improved bionic man.

Nonetheless, this essay describes in detail all reflexions, deceptions and hope on my researches to enhance human visual and auditory capabilities via biomimetics using MEMS technologies.

Key words : MEMS, Biomimetics, Nanotechnologies, Seeing, Hearing, Night vision, Echolocation

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LIST OF ABBREVIATIONS AND ACRONYMS

MEMS	*Microelectromechanical systems*
NEMS	*Nanoelectromechanical systems*
EPFL	*Ecole Polytechnique Federale de Lausanne*
TUW	*Technische Universität Wien*
KTH	*Royal Institute of Technology in Stockholm*
FM	*Frequency Modulation*
CF	*Cumulative Frequency*
OHC	*Outer Hair Cell*
IHC	*Inner Hair Cell*
CVD	*Chemical Vapor Deposition*
PVD	*Physical Vapor Deposition*
ERB	*Equal Rectangular Bandwith*
VCC	*Alimentation Tension Continue*
LED	*Light-Emitting Diode*
GND	*Ground*
Tab.	*Table*
Fig.	*Figure*
Chap.	*Chapter*
Hz	*Hertz*

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1 INTRODUCTION

Human never stopped observing his environment. "Seeing is believing" is an idiom commonly used to describe our natural trust in any concrete evidence. This sense will always be used as a final check on an action. In case we heard a car coming, the common sense will be to turn our head in that direction to see if a car is really coming. It used to be a reflex or an instinct. This faculty is important for us but not as developed as other animals. Visual perception is the ability to interpret the surrounding environment. For humans, we will use light in the visible spectrum reflected by objects. The resulting perception is also known as visual perception, eyesight, sight, or vision.

As part of the project work "Interaction with Surfaces", I will need firstly to do some research on the senses in humans and animals. Then, I will need to build a prototype of a device that leads to improve human visual and auditory senses. These two senses can be used to improve each other. It's commonly known that in case of the loss of one of them, the subject will use the one working to replace that failing sense. Finally, I will identify some MEMS that could be used to an implementation in real life.

The paper following is organized into three sections. Firstly, humans and animals senses will be discussed. A particular attention will be on biological part like the human auditory system but also the acoustic bat emission system. Then, the second section will present prototypes of acoustics - visions. The different steps of analyses, which is based on ultrasound sensors, will be described by mathematical formulas and results. The last section will present MEMS and NEMS systems for a real-life implementation with ideas of future designs.

2 BIOLOGY AND NATURAL BEHAVIOR

2.1 Introduction

Acoustic sensors differ in some aspects from other types of sensors. For example, sensors in the electric field (Voltmeter, Ammeter...) will measure a quantity that humans are not used to measure. We are able to say very roughly a certain value describing these quantities. At least, we determine it by the way it hurt touching for example an electrified fences. In this experiment, touching is the only requirement.

It's different with human sensory perception. The physical variables are the sound pressure, the "mixture" of frequencies and the direction from which sound reaches the listener. Those main components that produce an acoustic perception are hardly described by any function or scale. Also, the relationship between variables depends very much on the individual.

In this chapter, we will discover all the complexity and characteristic of the human ear. We will also discuss capabilities of bat to hear and to emit ultrasound.

2.2 The human ear

Auditory or acoustic perception is the ability to perceive sound. Our ear is a very complex sense organ which will reveal fundamental capacities for auditions. We will firstly describe clearly main parts of the human hear : the outer ear, the middle ear and the inner ear.

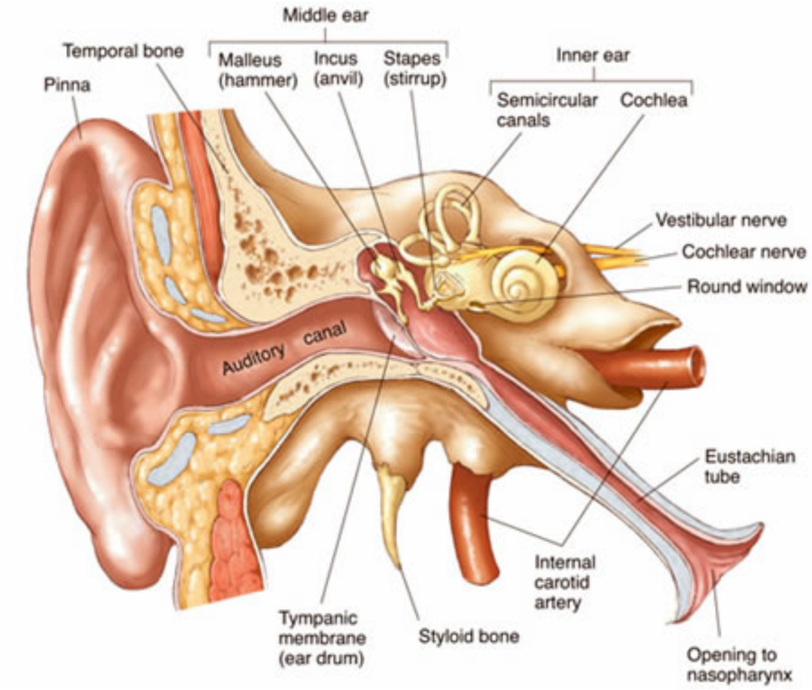


FIGURE 2 – Cross-section of the human ear : outer, middle and inner ear

2.2.1 Outer ear

The main functions of the outer ear (Auris externa) are capturing the sound but also generating frequency and direction-dependent maxima and minima in the spectrum, which are essential for direction detection. The ear canal constantly clean itself by secreting ear wax but also protect the sensitive eardrum thanks to a relatively long and narrow path.

Pinna The auricle or auricula is the visible part (Fig. 3) of the ear that resides outside the head. It is also called the pinna (pinnae in plural) which is more used in zoology. The importance of it will be

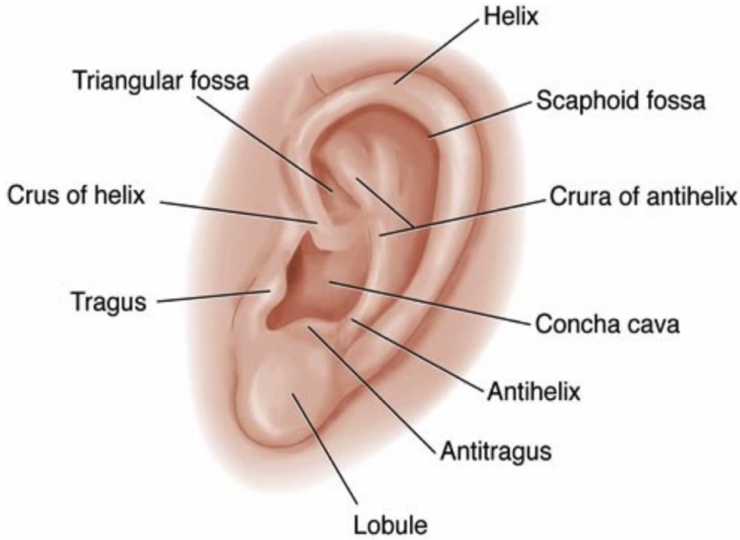


FIGURE 3 – Structure of the pinna : visible part of the outer ear

discussed in the next sections about bat ears.

2.2.2 Middle ear

The eardrum forms the boundary between outer and middle ear. It's a membrane around 100 μm thick with a diameter of approximately 10 mm. It represents the first transducer which converts the sound wave into a mechanical vibration.

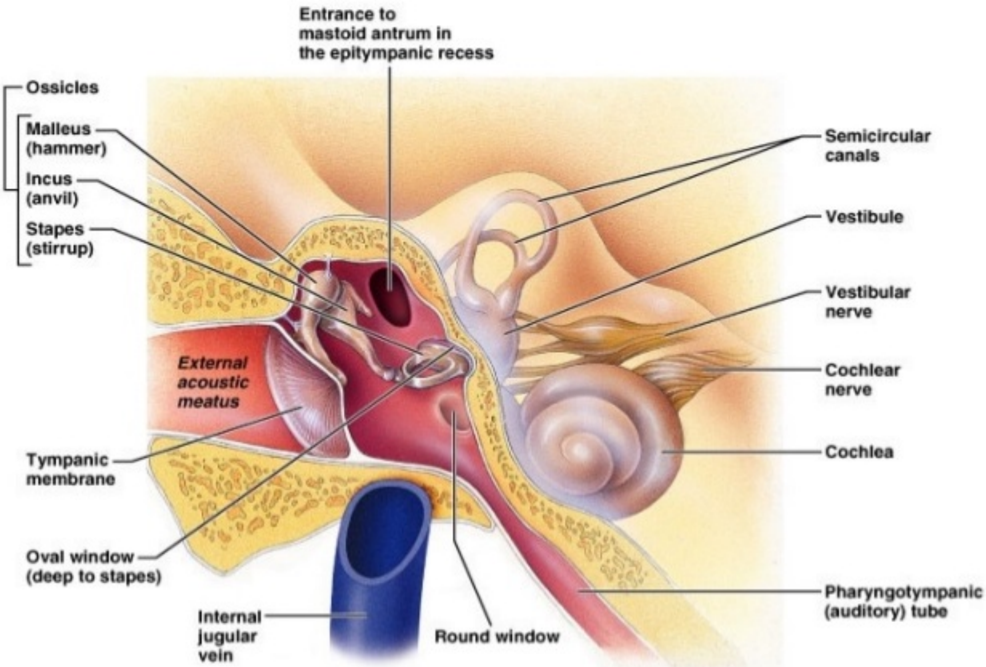


FIGURE 4 – Structure of the middle ear

The middle ear, also named Auris media, is an air-filled cavity. It's hermetically sealed by the tympanic membrane towards the outer ear. On the other side, it's closed by the oval window and the round window.

The middle ear has the difficult task to transform vibrations of the air into vibrations in liquids (Fig. 4 and Fig. 5). This change of the medium changes the acoustic impedance. An impedance will always reflect a ratio between quantities. A sound wave coming from air hitting a dense medium like water will be reflected at the interface according to :

$$\rho = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

Z_1 = acoustic impedance of air and Z_2 = acoustic impedance of water

At 25 ° C :

$$Z_1 = 410Ns/m^3$$

and

$$Z_2 = 1.5 \times 10^6 Ns/m^3$$

For the specified values, this result is $\rho = 0.9989$. It means that 99.9% of the energy would be reflected and only one thousandth of the sound intensity would reach the inner ear. It's an impressive coefficient but this leads only to the attenuation of $-30dB$.

To improve the situation, a lever mechanism plays an important role in the middle ear. Three middle ear bones are linked to create a chain of transmission improving the impedance matching essentially thanks to an area ratio aspect and some mechanical advantages. Prof. Keplinger (TU-Wien) script about "Sensors and Micro-system Technology" gives more details about this process (Keplinger, 2017).

Oval Window (Fenestra ovalis) The oval window separates the middle ear from the fluid-filled inner ear. The diaphragm is connected to the tympanic cavity, on the side of the middle ear the stirrup touches it and vibrates the diaphragm.

Round Window (Fenestra rotunda) Only the round window allows small fluid shifts within the inner ear. The membrane therefore moves opposite to the oval window.

2.2.3 Inner ear

In the transformation of the mechanical vibration of air to vibration of fluids and then into electrical nerve impulses, the inner ear is the part which houses the actual sensory cells (Keplinger, 2017).

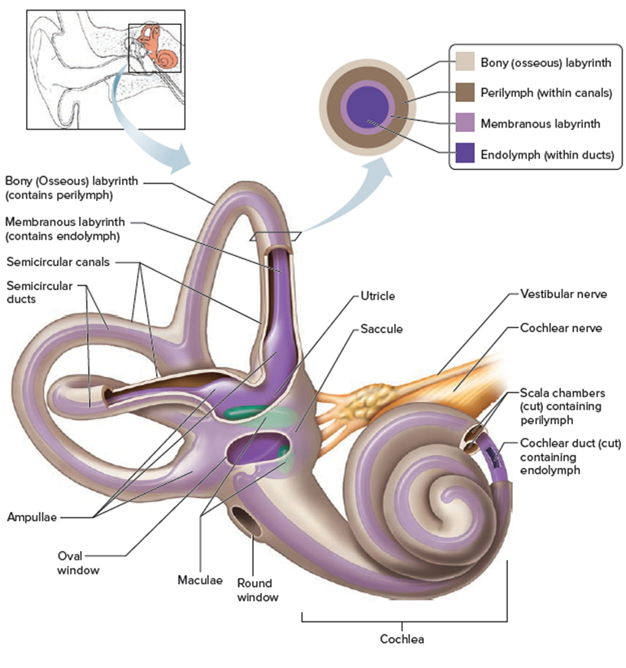


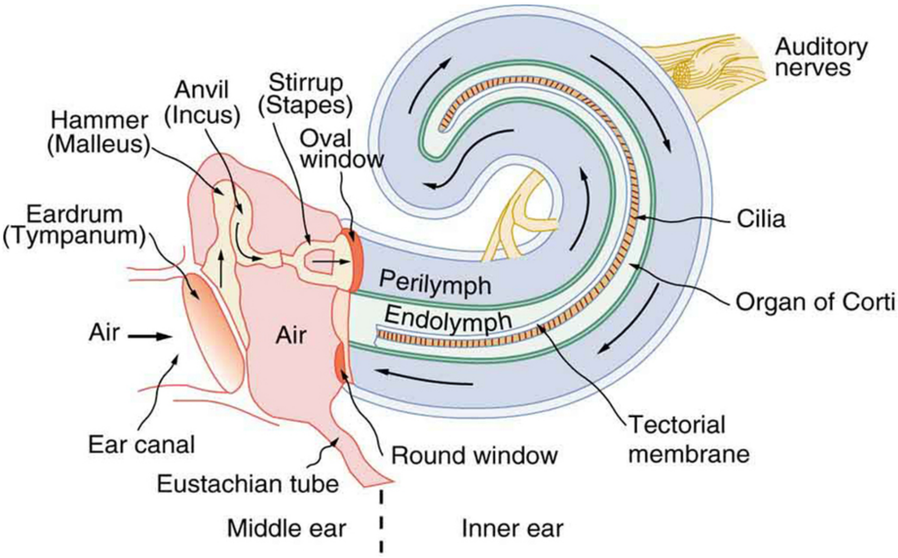
FIGURE 5 – Structure of the inner ear

Inside the inner ear, the mechanical vibrations of the oval window are converted into nerve impulses (Fig. 5).

The inner ear is a hollow space in the temporal bone. This bone is the hardest material in the body after the dental enamel in order to protect nerves going directly to the brain. In the system of "membraneous labyrinth" 5, passages are filled with an aqueous fluid : the endolymph. This labyrinth consists of the three semicircular membranous ducts, which are required for the three axes of the sense of balance. It's a natural inertial sensor.

2.2.3.1 Cochlea

FIGURE 6 – Structure of the cochlea



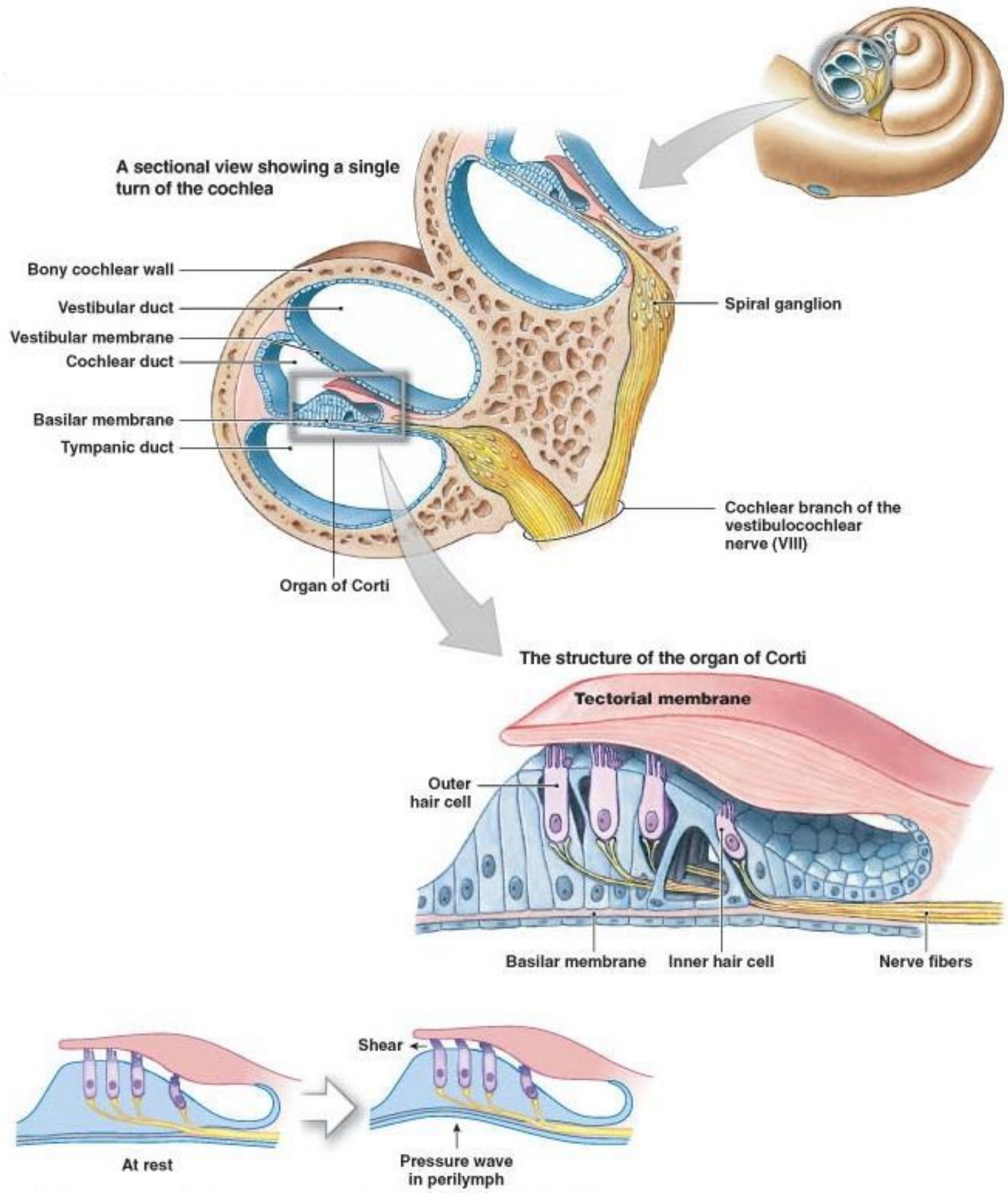
When the oval window is forced inward, as shown, a pressure wave travels through the perilymph in the direction of the arrows, stimulating nerves at the base of cilia in the organ of Corti.

The cochlea has the size of a pea and from the outside looks like a tiny little snail shell. But inside of this tiny little organ are all sorts of little structures that work together to turn sound into hearing. The cochlea is a coiled tube about 3 mm in diameter and 3 cm in length if uncoiled (Lumen, 2018). The oval window, the start of the vestibular duct, is connected to the Stirrup (Stapes) on the side of the middle ear. A vibration of the stapes causes a vibration of the oval window. The liquid behind the window must be free to vibrate. We can see easily see (Fig. 6) that waves propagate along the vestibular duct from the oval window to the round window which creates vibration and activates the auditory nerves.

2.2.4 A natural microphone in the human hearing system

Inside the inner ear (Fig. 5), the actual microphone of the hearing system is the Organ of Corti (Fig. 7). It has been named after Alfonso Corti who discovered the receptor area in the inner hear in 1851.

FIGURE 7 – Structure of the organ of Corti



Pressure waves in the perilymph lead to shifts in the tectorial membrane and the bending of the hair cells. The hair's location in the cochlea are seen at the bottom of that picture.

The sound waves running out in the vestibular duct and running back to the tympanic duct cause deformations of the membranes enclosing these channels. This membrane overlies the hair cells (Fig. 6 and Fig. 7). We name hairs an excrescence of the cells, normally referred as stereocilia. The hair cells are arranged in multiple rows on the basilar membrane.

The cochlea is divided in areas : frequencies of sound waves interact with different locations on the structure. This way of analyzing sounds is referred to as the place-coding theory of pitch (Fig. 8). The place theory is usually attributed to Hermann Helmholtz, though it was widely believed much earlier (Lightfoot, 1897). The place where a frequency is encoded is mainly dependent on physical characteristics of the basilar membrane in the cochlea. Every part is sensitive to a slightly different frequency then the next. This is caused by gradual variations in the stiffness and width of the basilar membrane, among other less important factors like hair cell length and so forth. The specific physical characteristics determine what specific resonant frequency a particular part of the basilar membrane has. Hence, incoming sounds are torn apart with standing waves, where each frequency results in a standing wave at a particular spot in the cochlea.

The base of the cochlea, closest to the outer ear, is the stiffest and narrowest. Here, the high-frequency sounds are decoded. The apex, or top, of the cochlea is wider and much more flexible and loose and functions as the transduction site for low-frequency sounds. So on one side, it will only respond to high-pitched sounds (like a bird's chirp), while on the other end it only responds to low-pitched sounds (like the beat of a drum).

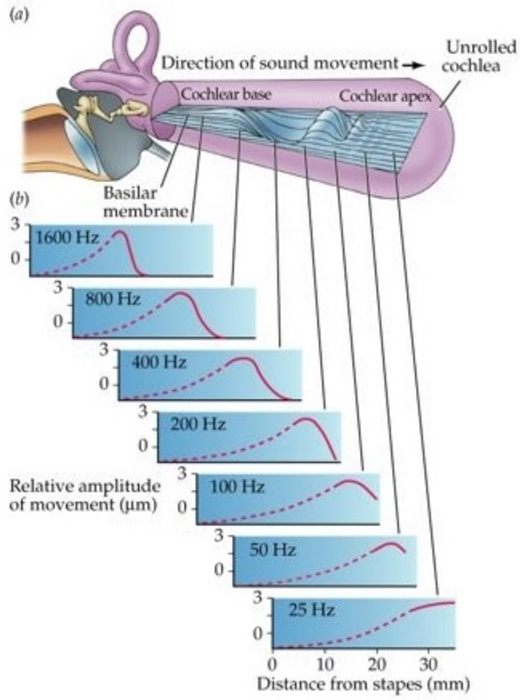


Figure 8 – Frequency zone of the cochlea from base to apex

2.2.4.1 Stereocilia

Stereocilia are groups (Fig. 10 and Fig. 9) of auditory hair cells. It's generally arranged in three rows of graded lengths. In addition to thin tip links which are involved in the mechano-transduction process, stereocilia are attached by transverse (/lateral) links, both in the same row and from row to row (Neuroreille, 2016).

The deflection of the stereocilia causes stretch-sensitive ion channels to open. These are non-selectively permeable to cations and are located at the base of the tip links, with 1 or 2 channels per tip link. Displacement of the stereocilia causes the cation channels to open : potassium (K+) enters the hair cell, causing it to depolarise. At the same time, another cation, calcium (Ca2+), also enters the cell. The electrical nerve signal can be sent.

2.2.4.2 Outer hair cells

The length of OHC's cell body are about $50\mu m$ (Gebeshuber ; Rattay ; Gitter, 1997), cylindrical in shape with a diameter of $10\mu m$ (Gebeshuber ; Rattay ; Gitter, 1997), and are approximately 15000. These outer hair cells are arranged in 24 groups and each group is responsible for its own frequency range. The outer hair cells role is not to send nerve impulses towards the brain (efferent cells). At the slightest deflection of the cells, the entire cell body is elongated or damped down by the outer hair cells. This

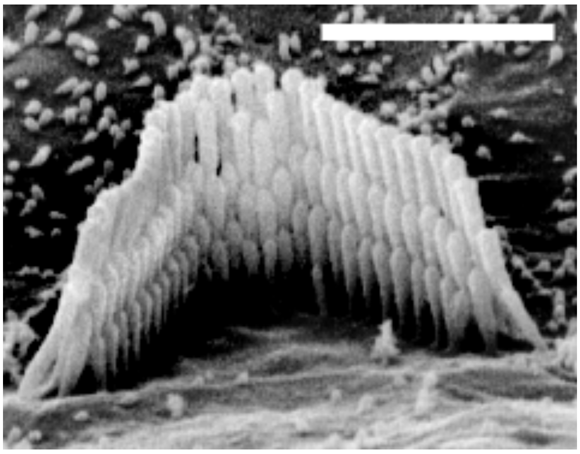


FIGURE 9 – "W" pattern of stereocilia's outer hair cells by M. Lenoir

called the cochlear amplifier because the actual sensory cells, the inner hair cells, are moved more and thus also get stimulated more and at the same time the frequency selectivity of the areas increases.

The elongation can be up to $2\mu m$. Some interesting and funny videos (Tapia, 2007) show hair cells dancing to the beat of some rock song thanks to scanning electron microscope by Dr. Fernando Cordova Tapia.

2.2.4.3 Inner hair cells

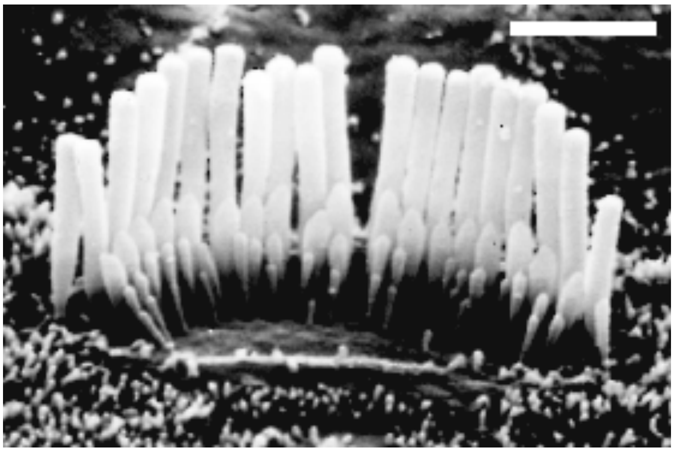


FIGURE 10 – Linear pattern of stereocilia's inner hair cells by M. Lenoir

The length of IHC's cell body are about $20\mu m$ (Gebeshuber ; Rattay ; Gitter, 1997), cylindrical in shape with a diameter of $8\mu m$ (Gebeshuber ; Rattay ; Gitter, 1997), and are approximately 3600. Their role is to produce the electrical signals that go through the auditory nerve to the auditory cortex of the brain (afferent never fibers) : 95% of the fibers of the auditory nerve that project to the brain arise from this subpopulation.

2.2.5 Disfunctions

Firstly, hair cells share with neurons inability to proliferate (Neuroreille, 2016), they are differentiated. This means that the final number of hair cells is reached very early in development (around 10 weeks of fetal gestation) ; from this stage on our cochlea can only lose hair cells.

Then, the cilia of the hair cells can also stick together, be bet or be completely missing which results in more or less hearing loss. It's also possible for a person to perceives noises like high-frequency whistle. A current theory assumes that destruction of hair cells, which will cause a partial hearing loss, leads to "under-stimulation" of neurons in the auditory cortex and in consequence to hyperexcitability of the hair cells (Keplinger, 2017).

2.3 The bat ear

2.3.1 Echolocation

2.3.1.1 Discovery of echolocation

We can ask ourselves why the bats are not using day-vision. Here, the process of evolution struck for providing a living for all creatures.

Bats are well-adapted to their environment : our environment when the day is gone. Chiroptera preferred using the rich food resources of the night by specializing in the audition. They emit short sounds and listen to the echoes returning from potential prey. Then, the bat's auditory system analyzes spectral and temporal parameters of echoes for detecting, locating and identifying a target.

In 1944, Griffin called echolocation this acoustical way of perceiving the outer world (Griffin, 1974) . At a time when animal thinking was a topic deemed unfit for serious research, Griffin became a pioneer in the field of cognitive ethology, starting research in 1978 that studied how animals think. His observations of the sophisticated abilities of animals to gather food and interact with their environment led him to conclude that animals were conscious too.

Commonly the signals last a few milliseconds and comprise a wide frequency band ranging from as little as 16 kHz up to 150 kHz. These FM components may be preceded or followed by short constant frequency parts.

According to signal theory, an «echolocating» bat is even able to select a certain sound structure best adapted to the environmental situation. Indeed, it appears that some bats are not restricted by a specific environment. A few species have become specialized for detecting and analyzing distinct acoustical features of their prey in order to overcome auditory environmental constraints.

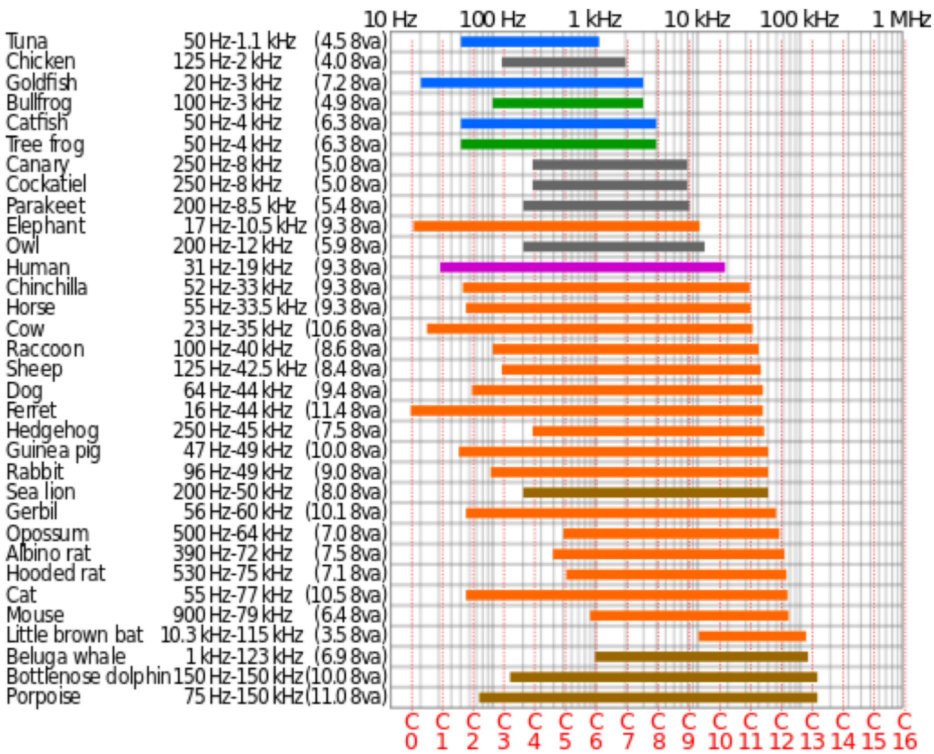


FIGURE 11 – Frequency of hearing of different species

But, in order to characterize generally echolocation, bats use different frequencies modulated calls and consequently assesses the echo when the call bounce back. The spectrum of echoes is affected by the shape of a target, but also by its distance, motion and location. All of that is sent in the transmitting and receiving waves and mixed by interference among overlapping echoes reflected by concomitant clutter (Simmons ; Saillant, 1995) (Makarczuk *et al.*, 2011).

2.3.1.2 Basic formulas about echolocation

Even if difficulties are important to describe some natural principles with accurate formulas, the process of echolocation can be mathematically explained. The formula of target distance (Ulanovsky, 2012) will be useful for our prototypes of echolocation :

$$R = \frac{cT}{2}$$

The formula of Doppler shift(Ulanovsky, 2012) is also interesting :

$$f_r = f_e \left(1 + 2\frac{v}{c}\right)$$

The factors $\frac{1}{2}$ and 2 in these equations are due to the two-way travel. The different terms are explained in the following list :

R = target range [m].

c = speed of sound in air ≈ 340 m/s.

T = pulse-echo delay [s].

f_r = frequency as received in the bat's ears [Hz].

f_e = frequency emitted from bat's mouth (or bat's nose) [Hz].

v = bat's flight speed [m/s].

2.3.2 Emission

2.3.2.1 Characterizing bats thanks to echolocation

The physical effects of sound propagation in air make echolocation a rather short-range orientation system.

Bats hunting within dense foliage or close to any structured background should have difficulties in detecting prey. The background reflects a multitude of echoes so that any structure of an echo is more or less lost and the relevant echo from a prey masked by noise. The horseshoe bats can hunt close to foliage or walls in what would appear to be an echo-cluttered area. Focusing echolocation on a unique acoustical feature might overcome these difficulties in an echo-cluttered environment.

Regarding to these definitions,

— CF : frequency range of the constant frequency part of the echoes.

— FM : frequency range of the final frequency modulated part of the echoes.

we can define two types of bats which use echolocation :

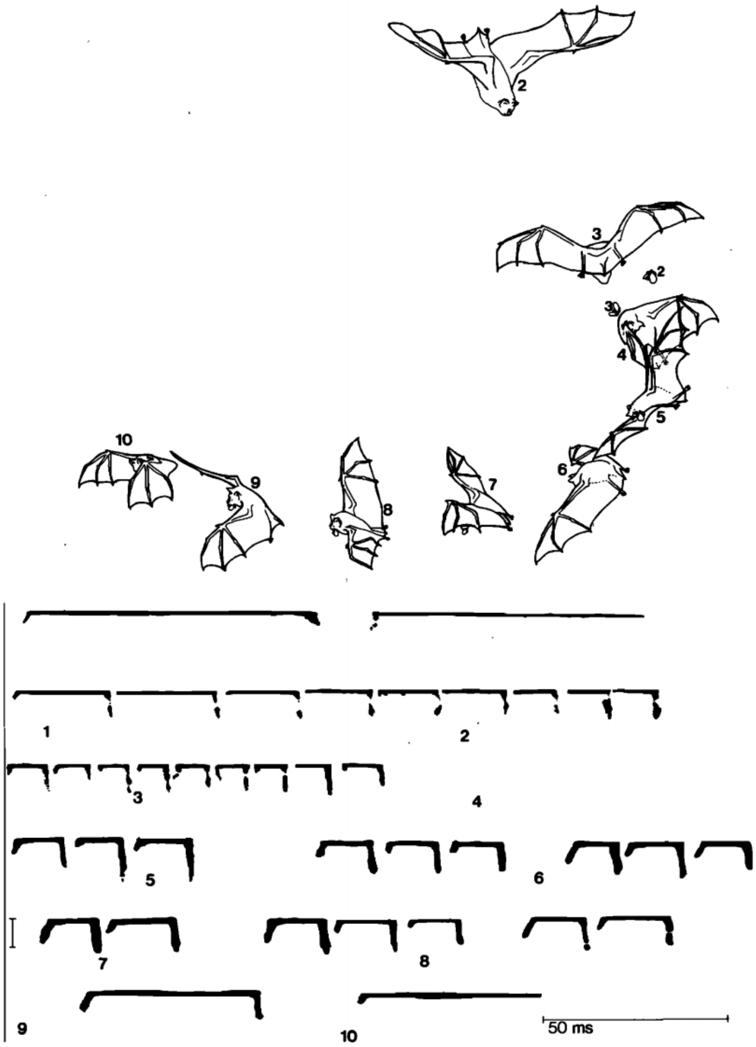
FM bats (Ulanovsky, 2012) are able to discriminate jitter in target range down to $< 400ns$ (less than 0.1 mm). This extraordinary temporal resolution (together with the 10μs behavioral resolution) is far below the rise-time of action potentials.

CF–FM bats (Ulanovsky, 2012) can compute the Doppler shift (target velocity). They can also detect Doppler modulations caused by the insect's wing flutter and these bats can even tell apart different insect species based on their different flutter rate.

2.3.2.2 Hunting frequency of bats

In the year 1980, G. Neuweiler published a paper explaining how bats adapted themselves for the detection of motions (Neuweiler ; Bruns ; Schuller, 1980). A particularly interesting part describes the emission of bats during hunting : from detection of prey to starting of the digestion process.

Figure 12 – Emission of "echolocating" horseshoe bat catching a moth



Spectrograms of the echolocation sounds emitted during flight are shown below. Numbers indicate identical timings as in the flight path (frame No. 1 is not shown, no signal). Sequence from No. 1 to No. 10 lasts about 0.9 s. ***Constant frequency part : 82 kHz.***

As we can see in the figure (Fig. 12), the horseshoe bat (CF/FM bat) conspicuously and invariably emits pure tone echolocation signals of about 83 kHz. Since the pure tone is terminated by a short downward FM sweep (every line is decreasing at the end of the signal) and the pulse duration is long, the emitted signals are classified as long CF/FM. Neuweiler mention that a pure tone is less suited for time coding, but has a narrowly peaked maximum in the velocity axis (Neuweiler ; Bruns ; Schuller, 1980). We realize that the movement sensitivity of echolocation is brought about by induced modulations in the echoes reflected from potential prey.

We also recognize categories of hunting frequencies by changes in echolocation calls during the closing-in on the insect :

Larger bandwidth gives better accuracy in estimating the target range (mathematical theory of sonar : see formulas in the last section).

Higher rate of calls implies higher update rate, allows better tracking of the moving target.

Shorter call duration shows smaller overlap between outgoing call and incoming echo, allows tracking insects at closer ranges.

2.3.3 Anatomy of the bat ear

2.3.3.1 Pinnae

Next to wings, the external ear is called pinnae. The pinnae are among the most conspicuous features of many species of bats. Throughout the several different species of bats, in this study are represented 47 species of bats from 13 families, the Pinnae can have different shapes.

There are at least three reasons why the Chiroptera offer excellent possibilities for examining the role of the external ear in acoustic behaviour.

First, regarding to our subject, there is two different "types" of bats : "echolocating" and "non-echolocating" bats. There's a big difference with the well-developed echolocation of the Microchiroptera and the Megachiroptera. Second, echocolation is a trait in some bats but not all species use the same approach to echolocation and some do not depend upon echolocation to find their prey. Finally, there are also some differences among the Microchiroptera from conspicuous pinnae to smaller ones.

Bat's acoustic receivers, including their pinnae, are one central component in maximising the distance over which they can hear because sound propagation make echolocation a short-range system.

Using a moveable loudspeaker and an implanted microphone, a research team (Obrist *et al.*, 1993) composed of Canadian and German scientists discovered which role pinna has in bat ears.

They compared pinna gain, directionality of hearing and inter-aural intensity differences in "echolocating" and "non-echolocatings" bats, in species using different echolocation strategies and in species that depend upon prey-generated sound to locate their targets.

A calibration microphone and a measuring amplifier were used to measure sound pressure levels. A sine wave generator, a power amplifier and an electrostatic speaker were used for sound production.

The idea that drove me to that article was to understand what is the role of the bat's ear in echolocation. We can see in the results from M. K. Obrist (Obrist *et al.*, 1993) that the pinna has a first task to sort the frequency. We can imagine that the task is then easier for the brain to decode them.

2.3.3.2 Auditory cortex and fovea

There are prominent characteristics of the auditory cortex of CF-FM bat. Firstly, there is delay tuned neurons which are neurons specialized only on certain ranged targets (Suga ; O'Neill, 19 Oct 1979). In the frequency-modulated-signal processing area of the auditory cortex of the mustache bat (Pteronotus parnelli rubiginosus), neurons respond poorly or not at all to synthesize orientation sounds or echoes alone but respond vigorously to echoes following the emitted sound with a specific delay from targets at a specific range.

Then, the cochlea (Neuweiler ; Bruns ; Schuller, 1980) of the horseshoe/mustache bat has an acoustical fovea (Fig. 14) built into the organ of Corti. The fovea deals with the echo-carrier frequency and results in an extremely fine frequency resolution within the narrow frequency range of 82 to 86 kHz. It is centered around the dominant harmonic of the bat call. This fovea frequency band is vastly overrepresented throughout the ascending auditory pathways. Onto the peripheral adaptations several neuronal specializations are superimposed and they converge towards the same direction.

CF-FM bats are also taking advantages of this dominant harmonic for other frequencies. Ulanovsky (Ulanovsky, 2012) names it the Doppler shift compensation behavior. "Mustached bats" and "Horseshoe bats" shift their frequency (Fig. 14) to keep the frequency of the echo inside the narrow frequency tuning of their neurons.

Figure 13 – Different species and their own frequencies characteristics

Species	PRES	FM (kHz)	CF (kHz)	H	nH	DU (ms)	PL	BF (kHz)
Peropteryx macrotis	A	80–15			7	3–4		
Rhynchonycteris naso	A	105–70	105	2	2	5		
Saccopteryx bilineata	A	47–40	45–50	2	3	6		40–45
Taphozous hildegardae	A	35–25		2	4	5		
Asellia tridens	A	115–90	111–124			11–3		
Cloeotis percivali	A	221–183	212			3		
Hipposideros caffer	A	150–130	145			8		
Hipposideros lankadiva	F	70–60	70	4	5	8		
Cardioderma cor	A	100–25			4		x	
Megaderma lyra	F	120–30			5	1	x	40–15
Molossus pretiosus	A	*35–15*						
Mormopterus jugularis	A	*90–20*						
Otomops martiensseni	A	17–10	15–13	1	2	30–5		
Tadarida brasiliensis	F	70–30	45	1	2	7		
Tadarida macrotis	A	30–17	21/35	1	3	20/12		
Tadarida pumila	A	*55–35*	*55–35*	1	2			
Mormoops megalophylla	A	50–40	60–50	1/2	3	8–2		
Pteronotus gymnonotus	A	60–40	55–50	2	4	2		60–40
Pteronotus parnellii	A	60–45	60	2	3	38–6		
Pteronotus personatus	A	82–60	82	2	3	3–5		
Natalus micropus	A	*80–40*			2–3			
Noctilio albiventris	AF	75–57	75–65			8–6		
Noctilio leporinus	A	CF–28	56–59			6–3		60–30
Nycteris grandis	A	96–60			3	2	x	
Nycteris thebaica	A	97–61		2?	2	2	x	
Artibeus lituratus	A	100–50		1	3	1		
Carollia brevicauda	A	120–25			3	1		80–40
Desmodus rotundus	A	100–35			2	1–2		10–25
Glosophaga soricina	A	126–73				2–0.5		70–50
Micronycteris megalotis	A	120–70		1	1	1		
Phyllostomus discolor	AF	80–40						
Phyllostomus elongatus	A	*90–50*						
Trachops cirrhosus	A	120–20			3		x	
Pteropus giganteus	A	No echoloc.						
Rousettus aegyptiacus	A	80–15			1	1		20–8
Rousettus amplexicaudatus	A	80–15			1	1		50/10
Rhinolophus clivosus	A	100–50	100/70	2				
Rhinolophus eloquens	A	*100–60*	*100–80*	*≥2*	*>2*			
Rhinolophus rouxii	F	75–55	79–72	2	4	46		
Rhinopoma hardwickei	A	60–20	35	2	4	8		35
Antrozous pallidus	F	49/70–26			2	2	x	20–15
Eptesicus fuscus	AF	42–22		1	2–3	11		55+20
Lasiurus borealis	F	49–30		1	3–4	10		
Lasiurus cinereus	F	29–17		1	3–4	10		
Miniopterus natalensis	A	100–40		1	2	5		50–40
Myotis evotis	F	80–50	63/50	1	1	1	x	
Myotis nigricans	A	120–60				2		

FM : dominant spectral range of frequency-modulated echolocation call components. CF : dominant spectral range of narrow-band or constant-frequency echolocation call component. H : number of the harmonic with main energy (fundamental=first harmonic). nH : total number of harmonics. DU : signal duration. PL : x if known to locate prey by passive listening to prey-generated noises. BF : best frequency, the frequency of best hearing.

Finally,we can find cortical fields and so determine computational maps with areas in the bat brain :

— FM–FM areas : neurons specializing in computing pulse-echo delay (target range).

— CF–CF areas : neurons specializing in computing Doppler magnitude (target velocity).

2.4 Conclusion

Along this chapter, we discovered the human auditory system depicting all the stages of our hearing sense. We went from outer, middle and inner ear to tiny natural sensors like inner hair cells contained in our cochlea. We also talked about the bat ear and it’s echolocation capabilities from emission to reception.

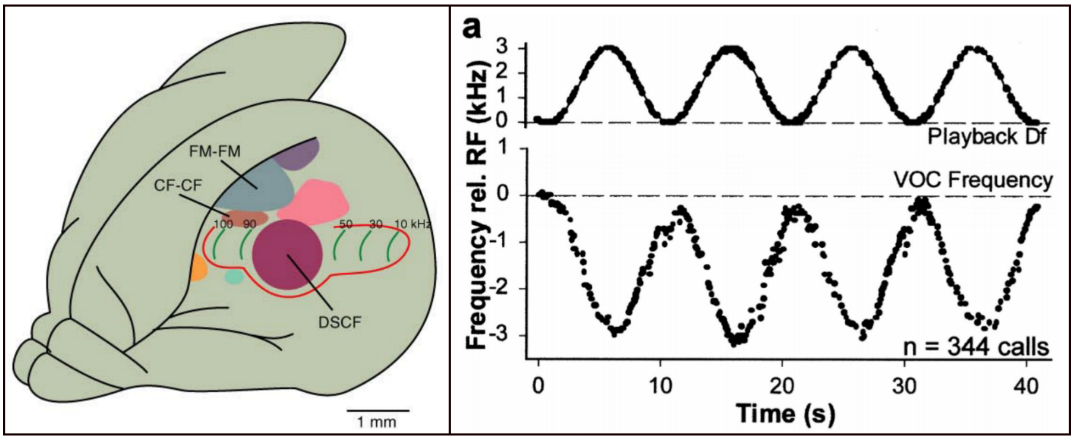


FIGURE 14 – "Auditory fovea" specialized in detecting rapid Doppler modulations and Doppler shift compensation in horseshoe bats (Smotherman et al., 2003)

3 PROTOTYPING

3.1 First prototype : two sensors HC-SR04

Components :

— 2 sensors HC-SR04
— 1 Arduino Uno
— 2 red LEDs
— 2 resistors 330 Ohm
— 1 computer with Arduino
— Wires, breadboard, USB-cable...

In this prototype, I tried to get used to the ultrasound sensor HC-SR04 (Bachelard, 28 Novembre 2015). This sensor provides 2 cm to 400 cm of non-contact measurement functionality with a ranging accuracy that can reach up to 3 mm. Each HC-SR04 module includes an ultrasonic transmitter, a receiver and a control circuit. The sensor is using ultrasound frequency to detect his surroundings by sending from the transmitter waves and getting the waves bouncing back at the receiver.

There are only four pins that you need to worry about on the HC-SR04 : VCC (Power), Trig (Trigger), Echo (Receive), and GND (Ground).

The goal of that prototype was also to find errors, calibrate and limit the differences of the sensors.

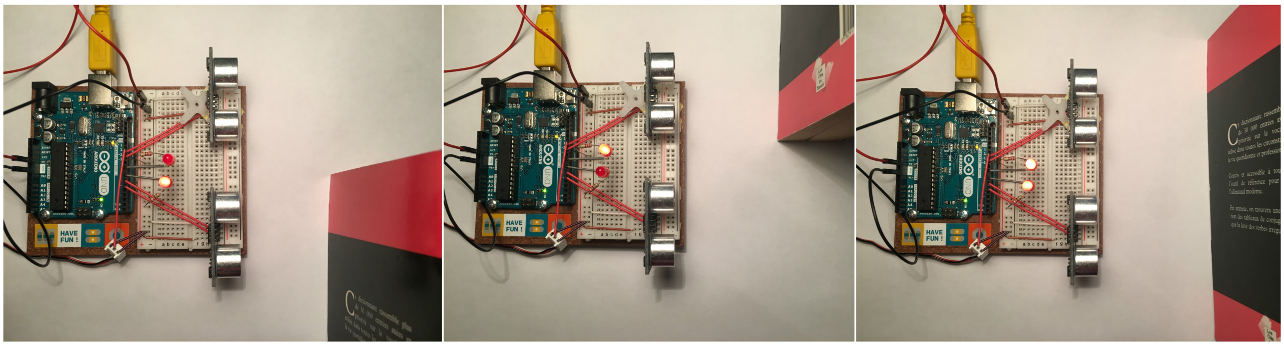


FIGURE 15 – First prototype reacting to different scenarios

The program of the prototype 1 is available in the Annex. All program is explained directly along the code. We used two sensors and programmed them in order to light up one LED in case an object is closer than 10 cm to a sensor. Each sensor is connected to his on LED. We can see different scenarios in the figure (Fig. 15) :

1. A book is less than 10 cm away of the lower sensor. The corresponding LED lights up. The upper sensor detects objects (his range is around 4 meters) that are more than 10 cm away so the corresponding LED is off.
2. A book is less than 10 cm away of the upper sensor. The corresponding LED lights up. The lower sensor detects objects that are more than 10 cm away so the corresponding LED is off.
3. The two sensors are detecting a book placed less than 10 cm away. The two LEDs lights up.

The following terminal (serial monitor) (Fig. 16) shows different information that we can get with that prototype. This picture is also showing different scenarios : zero, one or two LEDs on. It's important to note that in the first and last case, where the two sensors are detecting the book, the distance difference of 1 cm can come from a short angle difference, perturbations or a small difference in components.

Thanks to that prototype and the distance displayed (Fig : 16), we realize that the accuracy of the sensor is limited by the proximity (height) of our table. When the sensor is too near from a flat

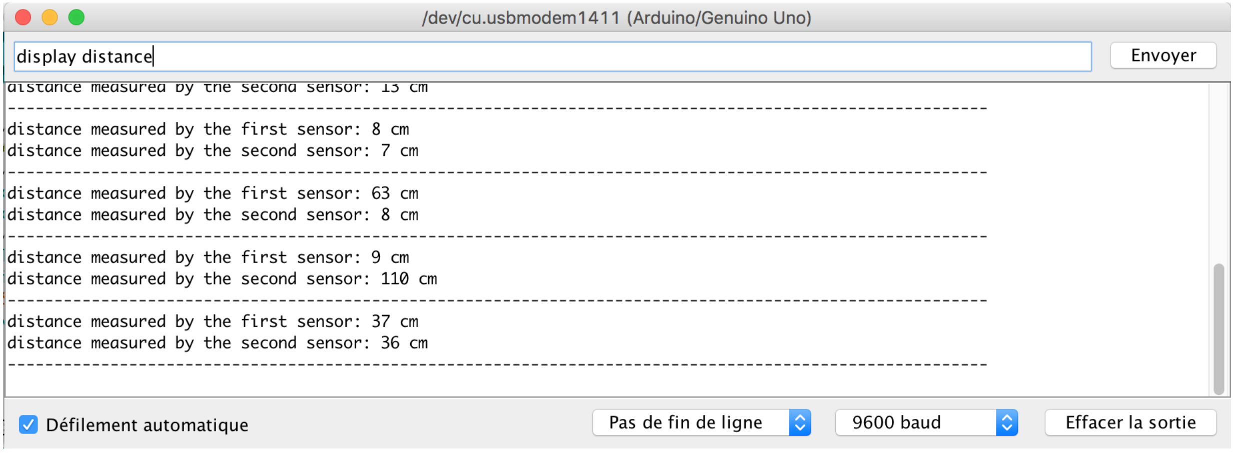


FIGURE 16 – Arduino's terminal gives informations about the distance with the instruction "display distance"

surface, some waves will be reflected after a certain distance of traveling. In order to solve that problem, the sensor will be elevated by a 3D mount and a step-by-step motor in the next prototype.

3.2 Second prototype : sonar

Components :

- 1 sensor HC-SR04
- 1 Arduino Uno
- 1 mount (self 3D printed) for sensor HC-SR04
- 1 step-by-step motor (5V)
- 1 computer with Arduino and Processing
- Wires, breadboard, USB-cable...

For the second prototype (Fig. 17), we will exploit two different software : Arduino and Processing. On one side, Arduino will be used to pilot the motor and get information from the system. It will manage the interactions between the computer and the electromechanical system. On the other side, Processing will only be computer-based. It will use the serial monitor's information to display a sonar. The Arduino's serial monitor is sending angle and distance of the object seen by the ultrasound sensor HC-SR04. Then processing apply this information to display an image of a sonar with complementary calculated information (Fig. 18).

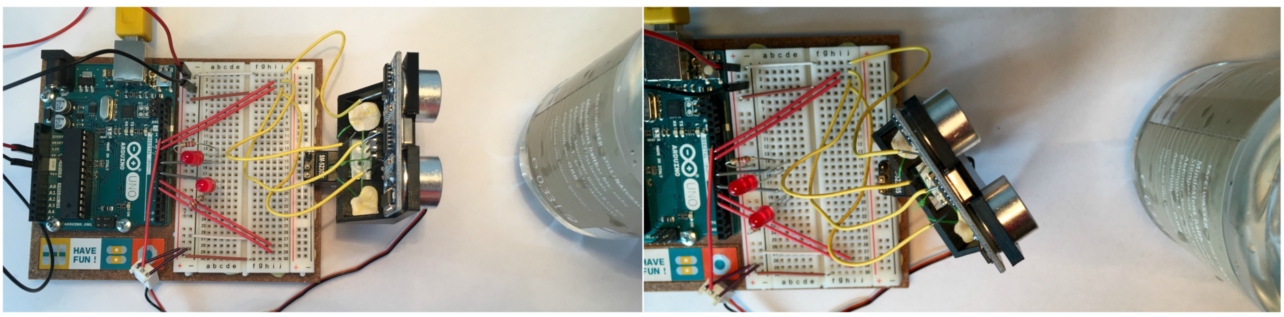


FIGURE 17 – Second prototype at different angles of rotation

The program of the prototype 2 is available in the Annex. A bottle (Fig. 17) has been chosen for the target in order to get different distances making a rounded shape on the sonar. The sensor is displayed with two different positions (angle difference of the stator's position). The motor will rotate from 15 to 165 degrees and then the way back.

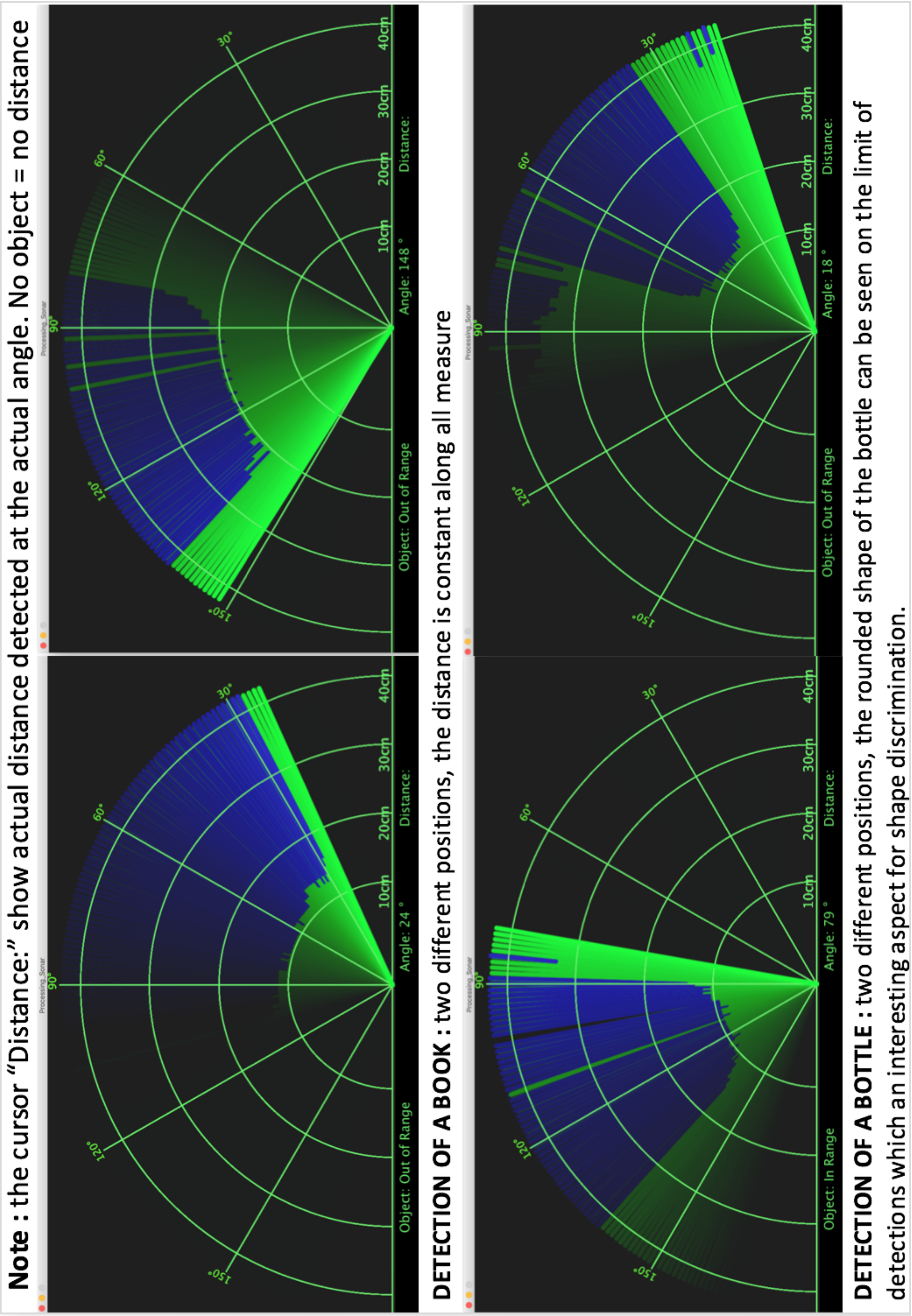


Figure 18 – Second prototype reacting to different scenarios with the sonar running on Processing

4 IMPROVING HUMAN HEARING AND VISION : MEMS AND NEMS

4.1 Introduction

In the first chapter, this paper explained human auditory system. Our ear can be separated in three parts. In our inner ear, the cochlea contains a membrane that vibrates when a sound strikes it. It has specific areas along its length that vibrate in response to specific sound frequencies. So if the waves are too slow or too fast, our ears will not be sensitive enough to hear the sound. And the membrane is simply not long enough to accommodate sounds more than 20,000 Hz.

Table 1 – Overview table of different species

Animals	Min. frequency [Hz]	Max. frequency [Hz]	Range [Hz]	Comment
Human	20	20000	19980	$\simeq$ hability of the chimp
Bat	3000	120000	11700	useful for echolocation
Dolphin	1000	130000	129000	echolocation similar to bats
Porpoise	75	150000	149925	largest range known

Value given by (IHP, 2015)

As we can see in the table (see Tab. in Chap. 4.1), Dolphins are further species that utilize echolocation to determine the position of objects and for communication (Makarczuk *et al.*, 2011). It enables the marine mammals to "see" in a much more complex way than it might seem.

Despite human hearing system cochlea, we studied the bat hearing system and discovered that several other hearing system (see Tab. in Chap. 4.1) are also able to work with a bigger range. In the next section, we will try to imagine a system improving human hearing based on MEMS and NEMS.

A first idea was to create a non-integrated system with a simple hearing aid capable of getting ultrasound frequency. Then, a processor will transform them into sounds from frequencies possible to hear. Finally, a sequence of signals will act the start of the transmission and the end of it in order to recognize the incoming modified sounds. But this system suffered from a lack of innovation and interest.

My main idea of enhancing human capabilities with body integrated system was driven by the lecture of "On the Way to the Bionic Man - A Novel Approach to MEMS Based on Biological Sensory Systems" (Karman *et al.*, 2011) by Ille C. Gebeshuber and Salmah B. Karman helped by several other authors either from Vienna University of Technology in Austria or universities and institutes in Malaysia. MEMS that is skillfully added to the human body can provide additional perception data. But the challenge here will be to provide valuable data. MEMS generated data should be readily understandable information. It should also be like an add-on within an already existing sensory bandwidth for the user. The article (Karman *et al.*, 2011) also mention three methods to reach these goals. Firstly, the expensive method adds information to the upper or lower end of the sensory bandwidth. The additive method enhances the original information by transforming it. Finally, the last method is the mutative method that completely reformats the available information. My solution will follow the expensive method by increasing the range of human auditory capabilities.

4.2 Definition of MEMS and NEMS

Over the next decade, major industrial and scientific trends that emerged will influence not only how manufacturing will be done, but also what is manufactured. The size of many manufactured goods continues to decrease, resulting in ultra-miniature electronic devices and new hybrid technologies. The newly designed advanced materials and manufacturing processes will be built at the nanoscale.

Micro and Nano Electro-Mechanical Systems is a rapidly growing field building upon the existing silicon processing infrastructure and techniques to create micro/nano-scale devices or systems. MEMS/NEMS devices integrate physical, chemical, and even biological processes in micro- and millimeter-scale technology packages. MEMS/NEMS devices now are used as product differentiators in market areas such as automotive, aerospace, electronics instrumentation, industrial process control, appliances, biotechnology, healthcare, office equipment, and telecommunications. Unlike conventional integrated circuits, micro/nano devices can have many functions including sensing, communication, and actuators. On the horizon is the development of mass nanomanufacturing technologies which will require new techniques for design, fabrication, manufacturing, process measurement and control using the latest scientific breakthrough.

4.2.1 Micro Electro-Mechanical Systems (MEMS)

Micro-electromechanical systems (MEMSnet, 2016) (STMielectronics, 2018), MEMS, is the technology of moving microscopic devices. MEMS are made up of components between 1 and 100 micrometers in size (i.e., 0.001 to 0.1mm), and MEMS devices generally range in size from 20 micrometers to a millimeter (i.e., 0.02 to 1.0mm). They usually consist of a central unit that processes data (the microprocessor) and several components that interact with the surroundings such as micro-sensors. Because of the large surface area to volume ratio of MEMS (Wikipedia, 2018c), forces produced by ambient electromagnetism,like electrostatic charges and magnetic moments are important design considerations. The forces produced by fluid dynamics, for example surface tension and viscosity, are also more important design considerations than with larger scale mechanical devices.

Fabrication of MEMS The materials used for MEMS manufacturing (Fig. 19) are silicon, polymers, ceramics and metals. Each of them has their own characteristic even if Silicon is the material used to create most of the integrated circuits.

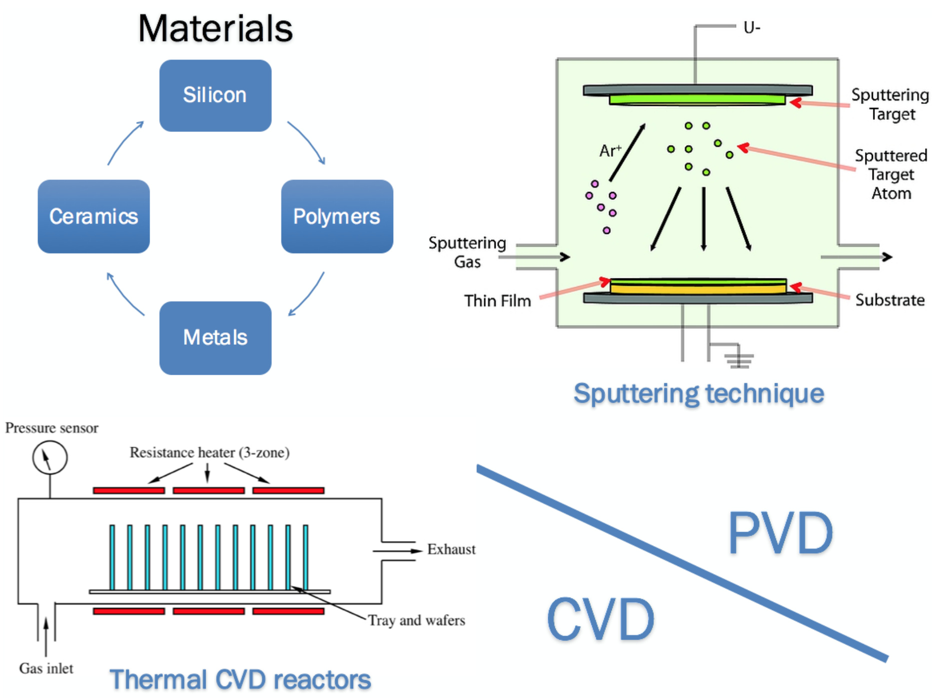


FIGURE 19 – Fabrication of MEMS

There's also two MEMS basic processes (Fig. 19) that I would like to talk about. On one side, the Physical Vapor Deposition (PVD) is a collective set of processes used to deposit thin layers of material, typically in the range of few nanometers to several micrometers. PVD processes are environmentally friendly vacuum deposition techniques consisting of three fundamental steps :

— Vaporization of the material from a solid source assisted by the high temperature vacuum or gaseous plasma.
— Transportation of the vapor in vacuum or partial vacuum to the substrate surface.

— Condensation onto the substrate to generate thin films.

On the other side, chemical vapor deposition (CVD) is a chemical process used to produce high quality, high-performance, solid materials. In typical CVD, the wafer, which is the substrate, is exposed to one or more volatile precursors, which react and/or decompose on the substrate surface to produce the desired deposit. Frequently, volatile by-products are also produced, which are removed by gas flows through the reaction chamber. Now, we will change our scale and go from MEMS to NEMS.

4.2.2 Nano Electro-Mechanical Systems (NEMS)

Nano Electro-Mechanical Systems (Wikipedia, 2018d), NEMS, are made up of components between 1 and 100 nanometers in size (i.e., 0.001 to 0.1mm), and NEMS devices generally range in size from 20 nanometers to a micrometer (i.e., 0.02 to 1.0mm). NEMS are MEMS scaled to sub-micrometer dimensions, to exploit the mechanical degree of freedom on the nanometer scale. In this size regime, it is possible to attain extremely high fundamental frequencies while simultaneously preserving high mechanical responsiveness. This combination of attributes translates directly into high force sensitivity, operability at ultra-low power, and the ability to induce non-linearity with very modest control forces, leading to potential payoffs in a diverse range of fields from medicine to biotechnology.

Many of the commonly used materials for NEMS technology (Fig. 20) have been carbon-based, specifically diamond, carbon nanotubes and graphene.The low friction of those materials, allows practically frictionless bearings and has thus been a huge motivation towards practical applications in NEMS, such as nano-motors, switches, and high-frequency oscillators.

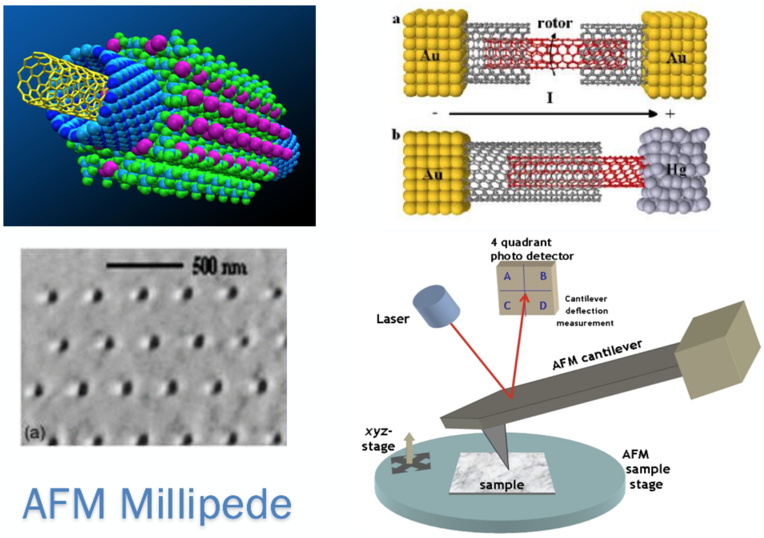


FIGURE 20 – Example of NEMS applications

4.3 Greenwood function

4.3.1 Greenwood function used for humans

The Greenwood function (Wikipedia, 2016) correlates the position of the hair cells in the inner ear to the frequencies that stimulate their corresponding auditory neurons.

$$f = \int_0^x \Delta f_{cb} = A(10^{ax} - K)$$

— f is the characteristic frequency of the sound in hertz.

— A is a scaling constant between the characteristic frequency and the upper frequency limit of the species.

— a is the slope of the straight-line portion of the frequency-position curve, which has shown to be conserved throughout all investigated species after scaling the length of the cochlea.

— x is the fractional length along the cochlear spiral measured from the apical end of the cochlea to the region of interest ($0 < x < 1$).

— K is a constant of integration that represents the divergence from the log nature of the curve and is determined by the lower frequency audible limit in the species.

Empirically derived in 1961 by Donald D. Greenwood, the relationship has shown to be constant throughout mammalian species when scaled to the appropriate cochlear spiral lengths and audible frequency ranges.

Greenwood provided coefficients for humans of $A = 165.4$, $a = 2.1$ (if x is expressed as a proportion of total basilar membrane length), and $k = 0.88$ (to give a lower frequency limit of 20 Hz). To get an explicit curve of the typical range of human hearing (Fig. 21) :

$$f_1 = A(10^{\frac{a}{b}x} - K)$$

with $b = 35$ mm, the mean human size of human cochlea. $\frac{a}{b} = \frac{2.1}{35} = 0.06$. Then, x can be displayed in millimeters. The code (Maple program) is available in the appendix.

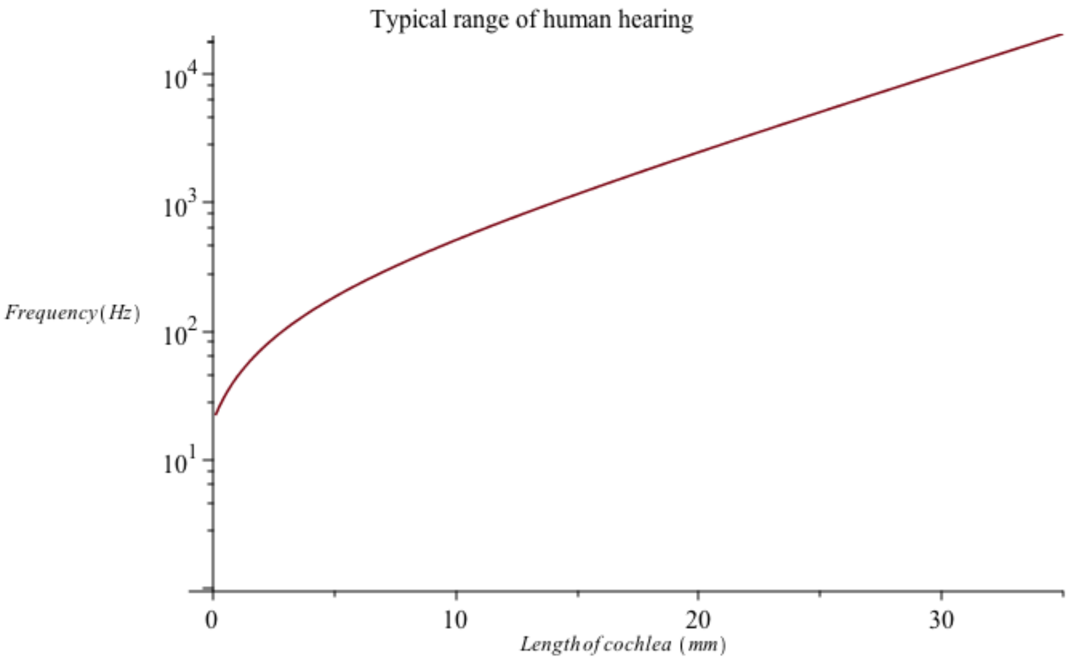


Figure 21 – Typical range of human hearing with Maple

As we can see, at a distance of $35mm$ in the cochlea which is the apex, we reach a frequency of $f_1(35) = 20677$ Hz.

4.3.2 Greenwood function used for animal species

In 1990, Greenwood published a new article named "A cochlear frequency-position function for several species - 29 years later" (Greenwood, 1990). In his report, we can find several values for other species than humans to use with the greenwood function (Greenwood, 1990) (Liberman, 1982). All values have been modified for a result in Hertz.

At the conclusion, Greenwood (Greenwood, 1990) points out also a limit about the function and the experiment done with it. Since possible cochlear frequency-position is dependent on the accuracy of the available physiological frequency-position data, it has been unfortunate that the data came from

TABLE 2 – Overview table of different species values for Greenwood function

Animals	A : scaling constant	a : slope	$\frac{a}{b}$: slope [mm]	K : divergence
Human	165.4	2.1	$\frac{2.1}{35} = 0.06$	0.88
Cat	456	2.1	$\frac{2.1}{25} = 0.084$	0.8
Guinea pig	0.35	2.1	$\frac{2.1}{18.5} = 0.011$	0.85
Monkey	0.36	2.1	$\frac{2.1}{25.6} = 0.082$	0.87
Mouse : Mongolian gerbil	0.400	2.1	$\frac{2.1}{12.1} = 0.174$	0.85

The value of guinea pig, monkey, mouse are done for a ***measurement in kilohertz.*** *The correct conversion has been done with Maple to get graphs. b is the mean cochlea size of each species given by (Greenwood, 1990).*

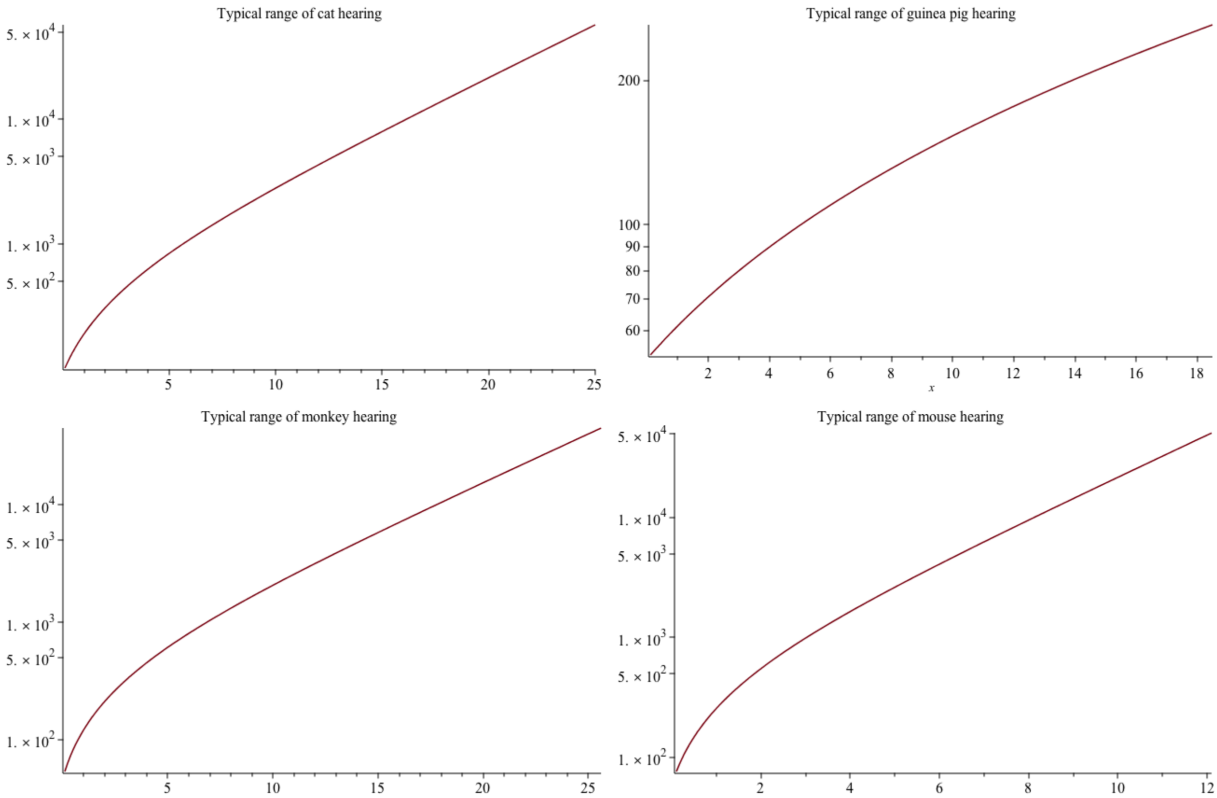


FIGURE 22 – Range of species cited in the table with Maple

dead species, with the particularity of only cat data with alive animals from Prof. Liberman (Liberman, 1982). From the research that has been carried out, Greenwood concludes that the function is valid for any animal. The main factors are the scaling constant A, the divergence K, b the length of the cochlea and a which his conserved throughout all investigated species with the method of Greenwood.

4.3.3 Method of Lepage : finding new constant for Greenwood function

In our case, a human with a bigger frequency range doesn't exist. Some people can have a slightly better range than others but no one is able to exceed bats capacities, for example. Then no data are available for it.

If frequency-position data is not available via Greenwood (Greenwood, 1990) or other experimental analysis, equal rectangular bandwidth (ERB) data can be used to derive the Greenwood warping constants. As shown in Clemins and Johnson (Clemins ; Johnson, 2006), if the ERB data is fit by the linear equation :

$$ERB = \alpha(\beta f + \varrho)$$

then the necessary Greenwood constants can be derived by :

$$A = \frac{1}{\beta}$$
$$a = \alpha\beta log(e)$$
$$k = \varrho$$

While frequency-position data is preferred, and ERB data is a good secondary method for determining the Greenwood warping constants, there is a third option if neither of those experimental data is available. Lepage (Charles ; Tobias, 2017) has shown that the value of the Greenwood value is near constant $k = 0.88$ in most mammalian species. We're going to use this work which is the most suitable for our case. The necessary Greenwood constants can be derived directly from a maximum and minimum frequency range for the species via :

$$k = 0.88$$
$$A = \frac{F_{min}}{1-k}$$
$$a = log_{10}\left(\frac{F_{max}}{A} + k\right)$$

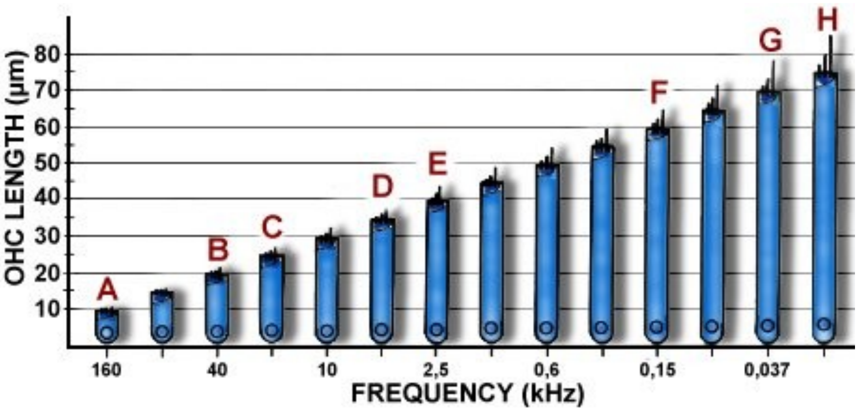
Thanks to Lepage's work, we will be able to pre-design in the next sections a cochlea regarding to the frequency we want to reach.

4.4 Simulating outer hair cells and inner hair cells

4.4.1 Size of outer hair cells and inner hair cells

MEMS and NEMS are well known for their tiny size. But they are human made which limit their size of creation. Nature skills are famous for the complexity of their miniature creations. While Outer Hair Cells (OHC) diameter keeps a constant value (7 μm), their length regularly varies according to frequency.

FIGURE 23 – OHCs from different mammalian species



OHC are not transmitting electrical signal to brain but place IHC in a good shape to do it (Fig. 10 and Fig. 9).

In the human cochlea (Pujol, 2017), a 25 μm basal OHC (C) is found at a place which codes for 20 kHz ; conversely a 70 μm OHC (G) is found apically at the site coding for a very low frequency (< 100 Hz).

Other notes about Fig. 23 :

— A = shortest OHC in basal turn of a bat cochlea (at a place coding for 160 kHz).

— B = basal OHC from a cat cochlea (at a place coding for 40 kHz).

— D = OHC of a guinea pig cochlea (at a place coding for 5 kHz).

— E = OHC of a guinea pig cochlea (at a place coding for 2.5 kHz).

— F = OHC of a guinea pig cochlea (at a place coding for 150 Hz).

— H = apical OHC from a rat cochlea (at a place coding for 15 Hz)

A precise size of an IHC was not found during my researches.

4.4.2 Micro pressure sensor

Regarding to the operation condition of our ears, we would replace an OHC/IHC by an electrical pressure sensor. An interesting comparison between an OHC and one human system can be done. For example, a pressure sensor from STMicroelectronics (STMicroelectronics, 2018) is never smaller than 1 mm^3. Here are a few examples :

TABLE 3 – Overview table of different sensors from STMicroelectronics

Type	Dimensions [mm]	Volume [mm^3]	Pressure range [hPa]	Current consumption [μA]
LPS25H	$2.5 * 2.5 * 1$	6.25	260 to 1260	25-4
LPS22HB	$2 * 2 * 0.76$	3.04	260 to 1260	12-1
LPS33HW	$3.3 * 3.3 * 2.9$	31.5	260 to 1260	1

FIGURE 24 – Sensors presented from STMicroelectronics

The dimensions of those sensors are considered small. But compared to the dimensions of a human IHC, it's way too big.

— OHC mean volume (assimilated to a cylinder) : $\pi r^2 h = \pi \times 7^2 \times 40 = 6157 \mu m^3 = 6.157 \times 10^{-6} mm^3$

— Smallest volume in our MEMS senors : $3.04 mm^3$ which around 500 000 bigger than the volume of an OHC.

If we want to replace each OHC by a MEMS sensors, the size of our cochlea seems compromised.

4.4.3 Nano pressure sensor

However, some promising technologies are showing up. Even if they're not already commercialised, those technologies will probably compete actual technologies in the next years. Graphene is an ideal material for use in nanoelectromechanical system (NEMS) applications, thanks to its low density and high strength.

In 2013, from KTH in Sweden, Max Lemme and colleagues published an article (Lemme ; Nikholaus, 2006) on the development of graphene based pressure sensors.

In recent papers, the research group have shown the superior pressure-sensing ability of graphene NEMS sensors over competing technologies. The graphene sensor (Graphenea ; Azonano, 2014) is fabricated

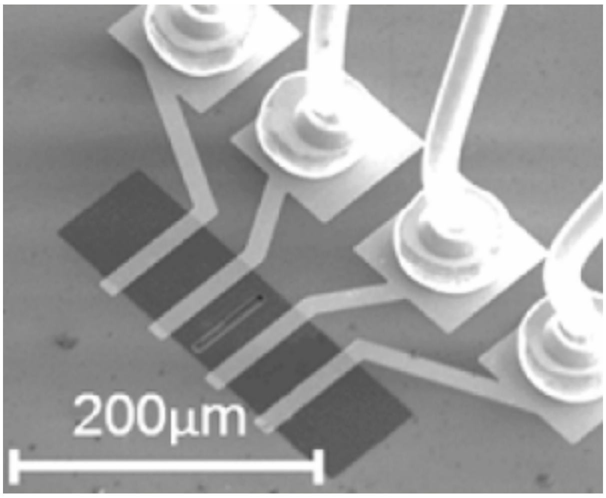


FIGURE 25 – Graphene NEMS pressure sensor consisting of a single graphene layer suspended above a trench in the substrate

by cutting open a trench in a silicon dioxide substrate followed by the deposition of a graphene sheet over the trench. The graphene suspends freely like a drum membrane above the trench (Fig. 26). The sensor has a cross-sectional area of only 65 by $6\mu m$.

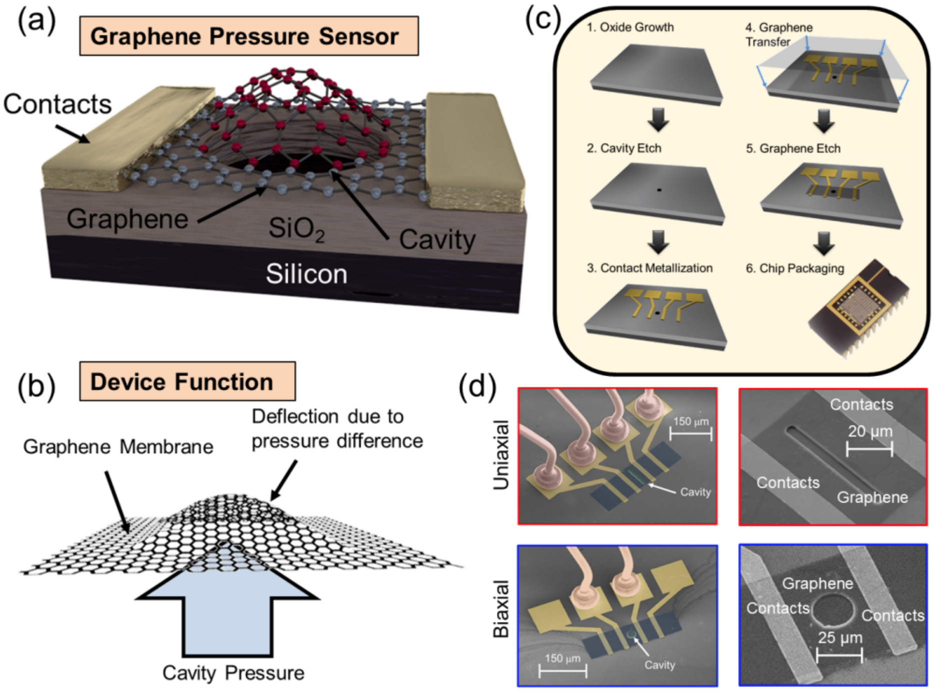


FIGURE 26 – Graphene NEMS pressure sensor : process, function, fabrication, views

a) *Schematic of the pressure sensor used. The red area represents the active area of the device.*

b) *Representation of membrane functionality. As the pressure outside the cavity varies, it causes a deflection and straining of the graphene membrane, thereby changing its electronic properties.*

c) *Fabrication process flow starting with SiO2 growth on a silicon substrate followed by RIE cavity etching. Metal contacts are then patterned followed by the transfer of graphene. The graphene is patterned using a mask in combination with O2 plasma etching. Finally, devices are wire bonded and placed into a chip package.*

d) *Color-enhanced SEM of a sensor device. In the SEMs the graphene is shaded in blue, the cavity in green, the electrodes and contact pads in yellow, and the bond wires in orange. To the right of each color enhanced SEM is an SEM showing a close-up of the cavity region for the corresponding devices.*

The bulging of the graphene sheet (Fig. 26) is determined through the piezoelectric property of the nanomaterial. This piezoelectric property causes the electrical resistance variation under strain. The increase in pressure causes a decrease in the resistance, which, in turn, increase current.

4.5 Partial cochlear implant : improving a technique

4.5.1 Actual cochlear implant

Cochlear implants (NIDCD, 2017) bypass the normal hearing process (Fig. 31) ; they have a sound processor that resides on the outside of the skin (and generally worn behind the ear) which contains microphones, electronics, batteries, and a coil which transmits a signal to the implant. The implant has a coil to receive signals, electronics, and an array of electrodes which is placed into the cochlea, which stimulates the cochlear nerve.

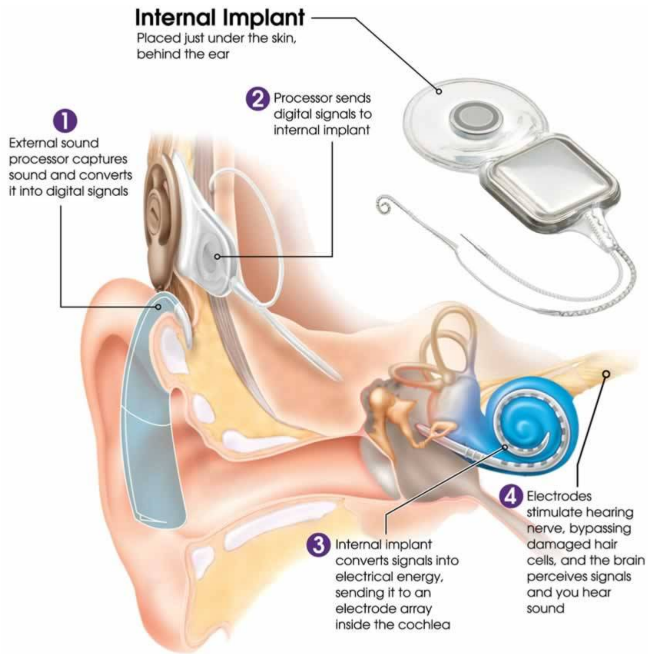


FIGURE 27 – Functioning of an cochlear implant with internal and external parts

The patient's psychology and his experiences with his deafness will affect his result with a cochlear implant (Wikipedia, 2018b). Adults deeply deaf from birth and people deaf since a long time meet more difficulties than young children. Young children tend to have a very high capacity of adaptation. The cochlear implant also has one other main limit (Wikipedia, 2018a) : it's not working in case of a surdity made by a missing vestibulocochlear nerve (auditory vestibular nerve). It can only transmit some auditory information if the nerve is only damaged.

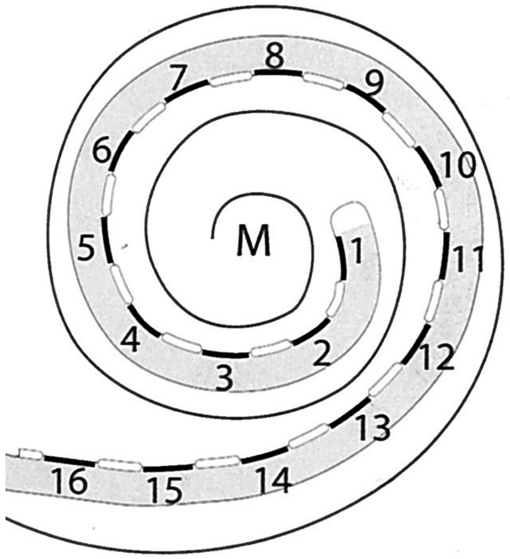
4.5.2 Improvement of a cochlear implant in order to improve the range of hearing

Without any modifications on a cochlear implant, we already know that the integration to adults is difficult. We can imagine that the difficulty of adults for new implantation is maybe linked to the cochlear growth that stops around the first birthday. That's why a rapid implementation is important.

Since the implant bypass the OHC/IHC system, an interesting idea will be to add more channels to the implant with the corresponding ultrasound microphone integrated in the external sound processor. Normally in the cochlea, the IHC/OHC system communicates information to the nerves depending on frequency-zone. In this improvement, the nerves in each zone will be less specified because of the remaining size of the cochlea. The nerves will transmit electrical pulses to the brain that will step by step learn how to decode it including the new frequency. The extraordinary plasticity of the human brain (Karman *et al.*, 2011) will allow the user to adapt himself to a new intercepted acoustic environment.

In this case, the modified zones are calculated for $F_{min} = 20$ Hz and $F_{max} = 120000$ Hz of hearing. The position of the microphone for the external processor will be chose according to these data.

Figure 28 – Position related to frequency in the cochlea



Note : *Greenwood function (Greenwood, 1990) shows that increment of frequency is not linear in the cochlea.*

Table 4 – Table of position related to frequency in the cochlea

Zone	1	2	3	4	5-16 : increment per zone
Normal zone[Hz]	100	200	400	700	⊗ increment is not linear !
Modified zone[Hz]	0-7500	7500-15000	15000-22500	22500-30000	$\simeq$ 7500

4.6 Complete cochlear implant : creating a new technique

4.6.1 Sensor's integration for a normal range of hearing

The "partial" cochlear implant (Wikipedia, 2018a) is visible and bypass the normal hearing process. In order to maintain the hearing process and minimize the size of the visible part of the system, an idea will be to copy the process of OHC/IHC and to replace the defected cochlear inside the inner ear. We will replace the IHC with pressure sensors. The implant of sensors will permit us to improve our auditory range perception if wanted.

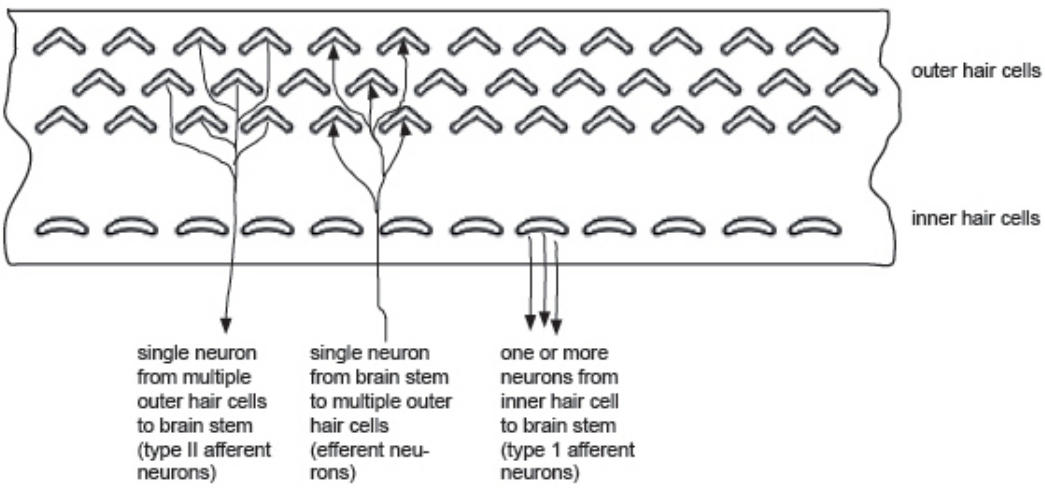


Figure 29 – Arrangement on the basilar membrane of OHC and IHC

Two models for our calculations are now offered to us. The first one is to be considered that we want to use current technology of sensors. This technique implies that our cochlea and our inner ear can be bigger than the one we actually have. The second one is to consider that the size of our inner ear is limited by the size of the structure around it ; the size of our cochlea is fixed. This technique implies that our sensors need to fit in a certain space.

The arrangement on the basilar membrane (Fig. 29) explain to us how we have to arrange our sensors to detect sound. Expecting that our sensors will be sufficient amplified, we do not need any outer hair cells acting like actors to place them in the right position like the inner hair cells. So the only sensors we need are pressure sensors to replace IHC. In order to place our sensors more easily, we will dispose of them in a line on the cochlea one next to the other one.

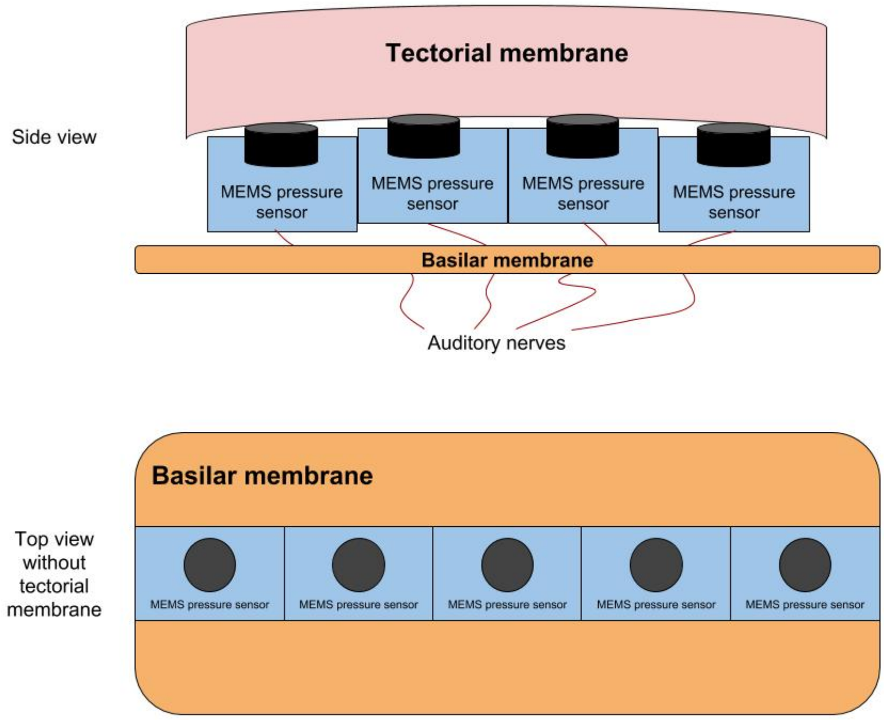


FIGURE 30 – Implementation of complete cochlear implant's idea with MEMS pressure sensor

Mean cochlear duct length depends on a lot of factors. For example, it has been shown that population from Asia and Africa doesn't have the same mean size of cochlear ducts. We will continue to consider a length of 35 mm. We should now remember that the cochlea is about the size of a pea and from the outside looks like a tiny little snail shell. But inside of this tiny little organ are 3600 IHC transmitting electrical signals to our brain. In order to keep our hearing acuity, we will have to replace each of them by a sensor. Thanks to the results given by the last chapters, we can fill up this table (Tab. in Chap. 4.6.1) :

TABLE 5 – Overview table to design cochlear sensors

	1^{st} : **LPS22HB**	2^{nd} : **NEMS**	3^{th} : constant cochlea
Nbr sensors = Nbr IHC	3600	3600	3600
Sensor size	$2 * 2 * 0.76mm$	$6 * 64\mu m$	**0.01 mm** $= 10\mu m$
Side used	$2mm$	$6\mu m$	/
Size of cochlea	**7200mm = 7.20m**	**21.6mm**	35mm

Regarding the result, the first sensor will create a giant cochlea. It is a sensor that is currently used in industry. Coming from Pr. Lemme (Lemme ; Nikholaus, 2006), the second sensor shows impressive results. It's still important to qualify them : the side used was the smaller one and this type of device may require a gap with the device close to it. Finally, in case we want to integrate sensors in our ear and in the same time keeping the same size as our cochlea, the maximal length of our sensor is $0.01mm = 10\mu m$.

We can also check the width of the cochlea (Rask-Andersen *et al.*, 2012). The mean width of the cochlea is around 800μm. In that case, our first sensor is not adapted to it for the width either. Our second sensor is still possible to integrate. According to the real in-ear IHC placement, it can also be possible to do two or more lines of sensors instead of one line of it on the basilar membrane. This can lead to a better acuity but also a bigger electrical consumption.

4.6.2 Sensor's integration for a modified range of hearing

4.6.2.1 Integration of NEMS pressure sensor

From the outcome of our investigation it is possible to choose the second sensor in order to create an improved hearing system. Since the acuity of our sensors will decrease if the range of frequency grows, we can decide to use the total length of cochlea to add more sensors.

$$\frac{35 \cdot 10^3}{6} \simeq 5833$$

If we choose a cochlea of 35 mm, we will dispose of 5833 sensors of $6 * 64\mu m$. Otherwise, if we choose a cochlea of 21.6 mm, we will dispose 3600 sensors which is the accurate number of IHC.

4.6.2.2 Application of Lepage's method

Thanks to the work of Lepage (Charles ; Tobias, 2017) already mentioned in the last sections, we can create a model based on the wanted characteristics.

In order to start using "echolocation", we have to reach the ultrasound frequency. Using the table (Tab. in part 4.1) giving bats capabilities, we find $F_{minBAT} = 3000$ Hz and $F_{maxBAT} = 120000$ Hz. If we want to continue hearing all the frequencies that we are able to use nowadays, we choose $F_{min} = 20$ Hz and $F_{max} = 120000$ Hz.

Using the code (Maple program) of the Greenwood function available in the appendix, we get the following result (Fig. 31) :

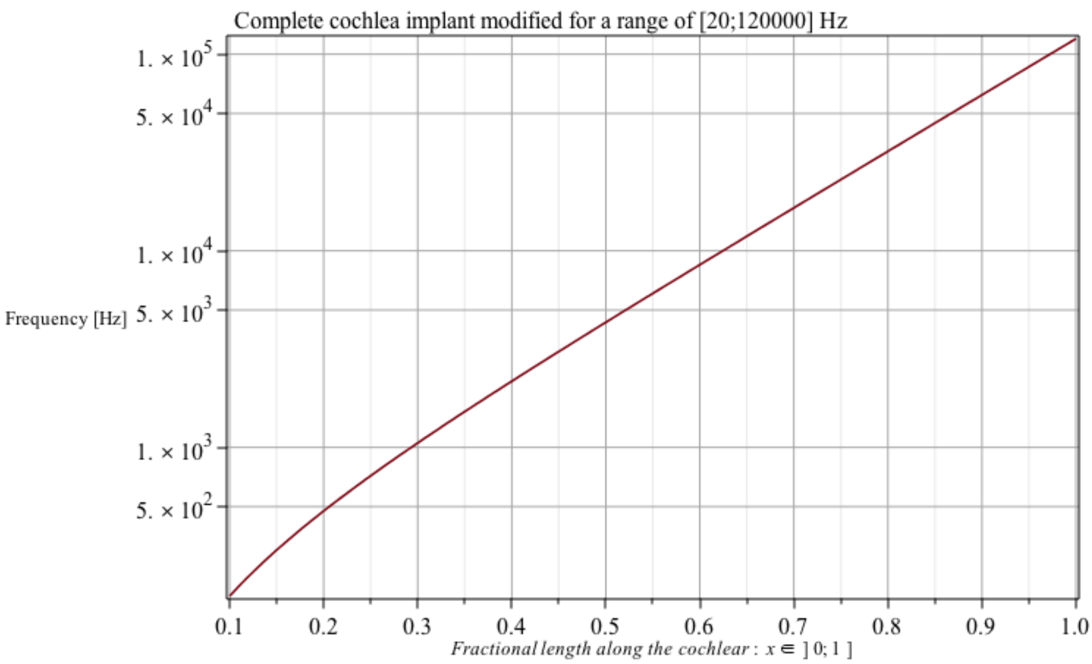


FIGURE 31 – Complete cochlea implant for a modified range

Thanks to Lepage formulas, we have :

$$k = 0.88$$

$$A = \frac{F_{min}}{1-k} = \frac{20}{1-0.88} = \frac{500}{3} \approx 166.666$$

$$a = log_{10}\left(\frac{F_{max}}{A} + k\right) = log_{10}\left(\frac{120000}{\frac{500}{3}} + 0.88\right) = 2.858$$

On the x scale, we have the fractional length along the cochlear. In order to get the length at which a certain frequency is reached, we have to define a size for our complete cochlea implant.

For 3600 sensors with a cochlear length of 21.6mm and 5833 sensors with a cochlear length of 35 mm using sensors of $6 * 64\mu m$, we get (Fig. 32 and Fig. 33) :

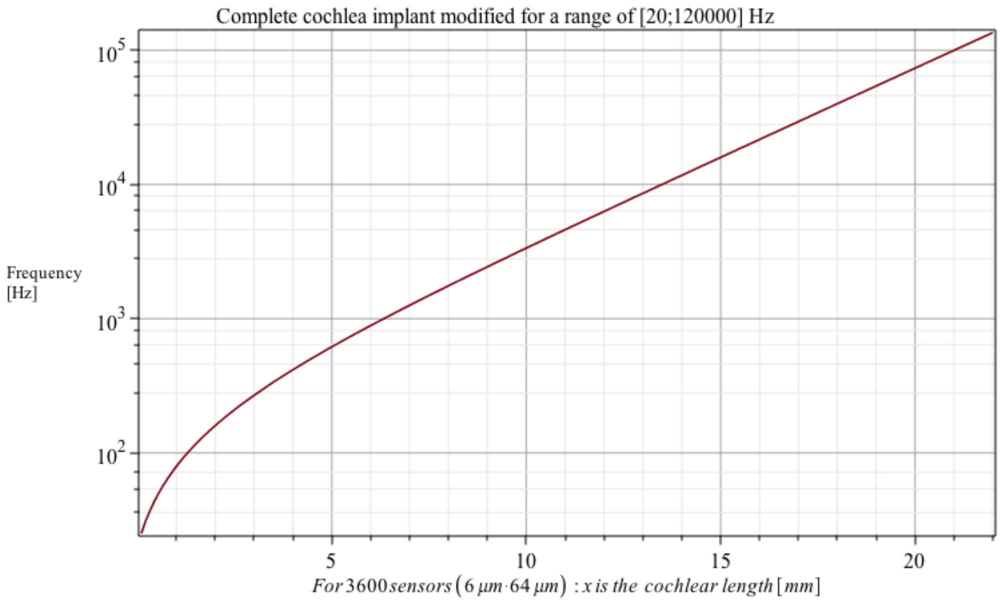


Figure 32 – Graph of dependence between frequency and depth in complete cochlea implant with 3600 sensors

Figure 33 – Graph of dependence between frequency and depth in complete cochlea implant with 5833 sensors

4.6.3 Problems and limits

In order to use sensors, we need to provide a power supply that can add complexity to our solution. If we want to keep our system not visible, several methods are offered to us with for each of them there are pros and cons. An inductive charging or a battery located inside the body like the ones used for a pacemaker is the most common idea. We can also think about unreasonable ideas like sensors powered by the waves of sound itself.

Other solutions are possible to imagine in order to hide the device with MEMS microphone at the limit between outer ear and middle ear. However, those solutions were less interesting to study because the solution of "partial" cochlear implant already exists and the task will only consist to hide it.

Based on the results already discussed in the first chapter, we know that OHC, IHC and the auditory nerves stop growing very soon. In case we lose some, they will not be replaced. In order to avoid problems depicted before like inefficiency ones if integrated to adults, we can imagine implantation during the first year after birth for creating auditory nerves ready to decode our cochlear information because his solution prevents problems of inefficiency of the device if integrated to adults. This idea creates some ethical problems that our essay will not be able to solve.

Even if our system is interesting, we're now meeting more fundamental problems than technology. Human body evolution is a very long time process. The idea of skipping some steps is dangerous and the means of science are limited in that case.

4.7 Conclusion

Along this chapter, we discovered fundamentals of MEMS and NEMS system. Greenwood's function permitted us to create a mathematical model based on existing measurements in order to calculate date for our own systems. Our selection of current sensors copying hair cells makes us realize that some improvements are still needed to reach our human sensors size. Finally, we described two different systems to enhance human hearing competences with their own attributes.

5 CONCLUSION

Animal species and humans are exploiting their best facets to take advantages on our world. In order to move inside this world, human are using seven senses. They are dependent on their sense of seeing to find their way. Compared to humans, bats are dependent of emitting and receipting ultrasound waves : the echolocation. This impressive capacity is interesting for numerous applications and would help us to visit still hidden surroundings.

In this essay, we discovered the human and bats auditory system depicting all the stages of the hearing sense. Then, we created two concrete prototypes showing a variety of interesting ultrasound usages. Lastly, we investigated innovative approaches leading to enhance human capabilities.

This essay involves wavering feelings on the need and desire to improve human constituents. Evolution is an impressive feature of biology but it’s long lasting process annoy our actual need of speed. Science has reached nowadays a point where human devices implementations are possible to create. Even if the subject has still some secrets for science, the biggest question remaining is not scientific but philosophic. We can ask yourself if researches are driven by the best intentions. In a world where top-notch technologies are shared between privileged people only, a bionic man with new capacities will revolutionize our last worldwide common components : our senses.

6 ANNEX

6.1 Maple's program

- f is the characteristic frequency of the sound in hertz.
- A is a scaling constant between the characteristic frequency and the upper frequency limit of the species.
- a is the slope of the straight-line portion of the frequency-position curve, which has shown to be conserved throughout all investigated species after scaling the length of the cochlea.
- b is the length of the cochlea from the base to the apex.
- x is the length along the cochlear spiral measured from the apical end of the cochlea to the region of interest.
- K is a constant of integration that represents the divergence from the log nature of the curve and is determined by the lower frequency audible limit in the species.
- M is the maximal value showed by the graph along y (frequency).

> $f := A\left(10\hat{}\left(\left(\frac{a}{b}\right)\cdot x\right) - K\right)$

$$f := A\left(10^{\frac{a\,x}{b}} - K\right) \quad (1)$$

> $plot(f, x = 0.1\,..b, y = 0.1\,..M)$

FIGURE 34 – Maple code for Greenwood function

> $f := 165.4(10\hat{}(0.06\cdot x) - 0.88)$

$$f := 165.4\;10^{0.06x} - 145.552$$

> $plot(f, x = 0.1\,..35, y = 0.1\,..20000)$

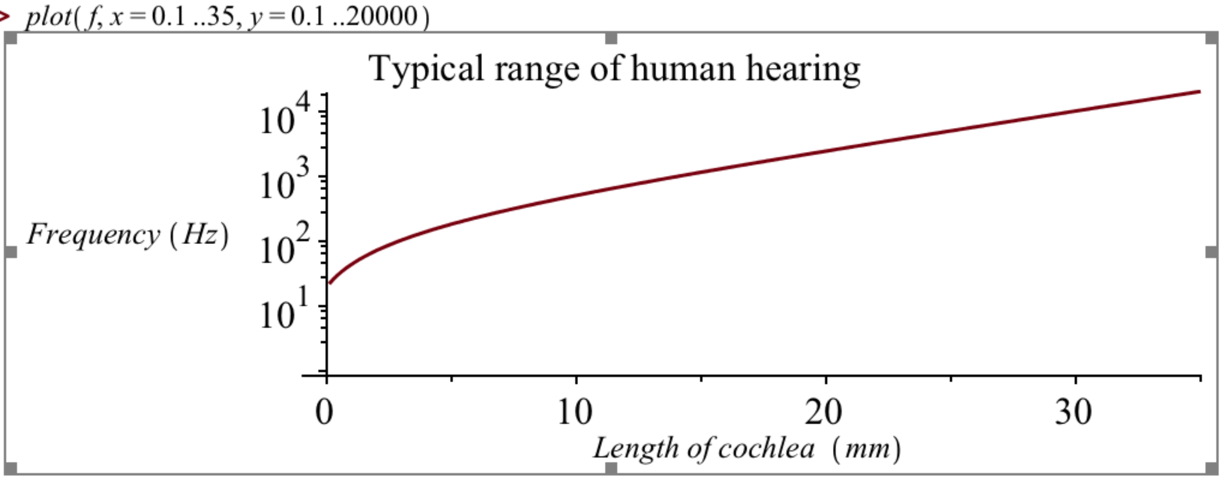


FIGURE 35 – Application of Maple code with human data

6.2 Arduino's program

6.2.1 Prototype 1 : two sensors HC-SR04

```
/*******************************************************************************
 * - Date            : 23/03/2017                 *
 * *****************************************************************************/

/*-------------------------------------------------------------------------------|
 This code allows you to know the distance between an Ultrasonic sensor and an object |
 I used two Ultrasonic sensors so you can place them in two different sides to know  |
 if there is any object near                                                      |
 --------------------------------------------------------------------------------|*/
//Start :
//Pins that we will use for the first ultrasonic sensor
//-------------------------------------------------------------------------------
#define trigPin1 10
// All pins adjusted for Arduino UNO used in the projectwork
#define echoPin1 11
// we'll use this pin to read the signal from the first sensor
#define LED_first_ping 8
//--------------------------------------------------------------------------------

//Pins that we will use for the second ultrasonic sensor
//-------------------------------------------------------------------------------
#define trigPin2 5
#define echoPin2 6
#define LED_second_ping 7
//---------------------------------------------------------------------------------

//used variables
//--------------------------------------------------------------------------------
long duration, distance, UltraSensor1, UltraSensor2;
//we will use these variable to store and generate data

char data;
String SerialData="";
//---------------------------------------------------------------------------------

//Make the setup of your pins
//---------------------------------------------------------------------------------
void setup()
{// START SETUP FUNCTION
Serial.begin (9600);
//we will use the serial data transmission to display the distance value
//on the serial monitor

// setup pins first sensor
pinMode(trigPin1, OUTPUT);       // from where we will transmit the ultrasonic wave
pinMode(echoPin1, INPUT);              //from where we will read the reflected wave
pinMode(LED_first_ping, OUTPUT);      // from where we will control the LED
```

```
//setup pins second sensor
pinMode(trigPin2, OUTPUT);
pinMode(echoPin2, INPUT);
pinMode(LED_second_ping, OUTPUT);


//initialize the LED status
digitalWrite(LED_first_ping,LOW);
digitalWrite(LED_second_ping,LOW);
}// END SETUP FUNCTION

//write the code in the loop function
void loop()
{
// START THE LOOP FUNCTION
SonarSensor(trigPin1, echoPin1);
// look bellow to find the definition of the SonarSensor function
UltraSensor1 = distance;
// store the distance in the first variable
SonarSensor(trigPin2,echoPin2);
// call the SonarSensor function again with the second sensor pins
UltraSensor2 = distance;
// store the new distance in the second variable

while(Serial.available())
{
  delay(10);
  data=Serial.read();
  SerialData+=data;
}

if(SerialData=="display distance")
{
// display the distances on the serial monitor for the first sensor
//-----------------------------------------------------------------------------
Serial.print("distance measured by the first sensor: ");
Serial.print(UltraSensor1);
Serial.println(" cm");
//---------------------------------------------------------------------------
//display the distance on the serial monitor for the second sensor
//------------------------------------------------------------------------------
Serial.print("distance measured by the second sensor: ");
Serial.print(UltraSensor2);
Serial.println(" cm");
Serial.println("----------------------------------------------------------------");
//-------------------------------------------------------------------------------
}

SerialData="";
// make condition to control the LEDs
if(UltraSensor1 <=10)// if distance is less than 10 Cm turn the LED ON
//distance can be easily changed here
```

```
{
  digitalWrite(LED_first_ping,HIGH);
}
else                // else turn the LED OFF
{
  digitalWrite(LED_first_ping,LOW);
}

// do the same thing for second sensor ,
//distance also have to be changed here
if(UltraSensor2 <=10)
{
  digitalWrite(LED_second_ping,HIGH);
}
else
{
  digitalWrite(LED_second_ping,LOW);
}
}//END LOOP FUNTION

// SonarSensor function used to generate and read the ultrasonic wave
void SonarSensor(int trigPinSensor,int echoPinSensor)
//trigPIN and the echoPIN in the function
{
  //START SonarSensor FUNCTION
  //generate the ultrasonic wave
//----------------------------------------------------------------------------------
digitalWrite(trigPinSensor, LOW);// put trigpin LOW
delayMicroseconds(2);// wait 2 microseconds
digitalWrite(trigPinSensor, HIGH);// switch trigpin HIGH
delayMicroseconds(10); // wait 10 microseconds
digitalWrite(trigPinSensor, LOW);// turn it LOW again
//---------------------------------------------------------------------------------

//read the distance
//--------------------------------------------------------------------------------
duration = pulseIn(echoPinSensor, HIGH);
distance= (duration/2) / 29.1;
// IMPORTANT : divide the duration by two because the wave travel back and forth
}// END SonarSensor FUNCTION

/****************************--- END ---***************************/
```

6.2.2 Prototype 2 : sonar Arduino

```
/*****************************************************************************
 * - Date            : 01/04/2017                  *
 * ***************************************************************************

/*-------------------------------------------------------------------------------|
 This code allows you to use an Ultrasonic sensor in order to simulate a sonar
 (distance, angle, ...)                            |
```

```
 Here, I used : one Ultrasonic sensor HC-SR04, one servomotor 5V, one 3D printed
 structure to hold the servo                       |
 ---------------------------------------------------------------------------------*/
//Start :
//Pin used for an Arduino UNO

// Includes the Servo library
#include <Servo.h>
// Defines Tirg and Echo pins of the Ultrasonic Sensor
const int trigPin = 10;
const int echoPin = 11;
// Variables for the duration and the distance
long duration;
int distance;
Servo myServo; // Creates a servo object for controlling the servo motor
void setup() {
  pinMode(trigPin, OUTPUT); // Sets the trigPin as an Output
  pinMode(echoPin, INPUT); // Sets the echoPin as an Input
  Serial.begin(9600);
  myServo.attach(12); // Defines on which pin is the servo motor attached
}
void loop() {
  // rotates the servo motor from 15 to 165 degrees
  for(int i=15;i<=165;i++){
  myServo.write(i);
  delay(30);
  distance = calculateDistance();
  // Calls a function for calculating the distance measured by the Ultrasonic
  //sensor for each degree

  Serial.print(i); // Sends the current degree into the Serial Port
  Serial.print(","); // Sends addition character right next to the previous
                     //value needed later in the Processing IDE for indexing
  Serial.print(distance); // Sends the distance value into the Serial Port
  Serial.print("."); // Sends addition character right next to the previous
                   //value needed later in the Processing IDE for indexing
  }
  // Repeats the previous lines from 165 to 15 degrees
  for(int i=165;i>15;i--){
  myServo.write(i);
  delay(30);
  distance = calculateDistance();
  Serial.print(i);
  Serial.print(",");
  Serial.print(distance);
  Serial.print(".");
  }
}
// Function for calculating the distance measured by the Ultrasonic sensor
int calculateDistance(){

  digitalWrite(trigPin, LOW);
```

```
  delayMicroseconds(2);
  // Sets the trigPin on HIGH state for 10 micro seconds
  digitalWrite(trigPin, HIGH);
  delayMicroseconds(10);
  digitalWrite(trigPin, LOW);
  duration = pulseIn(echoPin, HIGH);
  distance= duration*0.034/2;
  //Calculate the distance using the returned sound wave travel time in microseconds
  return distance;
}

/****************************--- END ---***************************/
```

6.3 Processing's program

6.3.1 Prototype 2 : sonar Processing

```
/*******************************************************************************
 * - Date             : 01/04/2017                   *
 * *****************************************************************************
/*-----------------------------------------------------------------------------|
 This code allows you to use an Ultrasonic sensor in order to simulate a sonar
 (distance, angle, ...)                                                        |
 Processing will use the serial monitor's informations to display              |
 a sonar. The arduino's serial monitor is sending angle and distance of the object
 seen by the ultrasound sensor HC-SR04. Then processing use these informations
 to display an image of a sonar with complementary informations.
 Check : Arduino is ON with UNO plugged in the computer
 -----------------------------------------------------------------------------*/

import processing.serial.*; // imports library for serial communication
import java.awt.event.KeyEvent;
import java.io.IOException;

Serial myPort;

// defines variables
String angle="";
String distance="";
String data="";
String noObject;
float pixsDistance;
int iAngle, iDistance;
int index1=0;
int index2=0;
PFont orcFont;
void setup() {

 /*SCREEN RESOLUTION*/

 size (1280, 716); //optimal for presentation
```

```
  //size (300, 300); //better for testing : CPU is less used

  smooth();
  myPort = new Serial(this,"/dev/cu.usbmodem1411", 9600);
  // starts the serial communication with the arduino

  //Note : the /dev/cu.usbmodem1411 can change depending on the computer.
  //This specification work only with iOS : /dev/cu.usbmodem1411

  myPort.bufferUntil('.');
  // reads the data from the serial port up to the character '.'.
  //So actually it reads this: angle,distance.
}
void draw() {

   //COLOR

   fill(109, 241, 111); // green color

   //---//

   //Not needed copied from hackster.io projects
   // simulating motion blur and slow fade of the moving line
   noStroke();
   fill(0,4);
   rect(0, 0, width, height-height*0.065);

   //COLOR

   fill(109, 241, 111); // green color

   //---//

   // functions for drawing the radar
   drawRadar();
   drawLine();
   drawObject();
   drawText();
}
void serialEvent (Serial myPort) { // starts reading data from the Serial Port
   // reads the data from the Serial Port up to the character '.'
   // and puts it into the String variable "data".
   data = myPort.readStringUntil('.');
   data = data.substring(0,data.length()-1);

   index1 = data.indexOf(","); // find the character ',' and puts it into the variable "index1"

   angle= data.substring(0, index1);
   // read the data from position "0" to position of the variable index1
   //or thats the value of the angle the Arduino Board sent into the Serial Port

   distance= data.substring(index1+1, data.length());
```

```
  // read the data from position "index1" to the end of the data : value of the distance

  // converts the String variables into Integer
  iAngle = int(angle);
  iDistance = int(distance);
}
void drawRadar() {
  pushMatrix();
  translate(width/2,height-height*0.074); // moves the starting coordinats to new location
  noFill();
  strokeWeight(2);

  //COLOR

  stroke(109, 241, 111); // green color

  //---//

  //Drawing of the radar//

  // draws the arc lines
  arc(0,0,(width-width*0.0625),(width-width*0.0625),PI,TWO_PI);
  arc(0,0,(width-width*0.27),(width-width*0.27),PI,TWO_PI);
  arc(0,0,(width-width*0.479),(width-width*0.479),PI,TWO_PI);
  arc(0,0,(width-width*0.687),(width-width*0.687),PI,TWO_PI);
  // draws the angle lines
  line(-width/2,0,width/2,0);
  line(0,0,(-width/2)*cos(radians(30)),(-width/2)*sin(radians(30)));
  line(0,0,(-width/2)*cos(radians(60)),(-width/2)*sin(radians(60)));
  line(0,0,(-width/2)*cos(radians(90)),(-width/2)*sin(radians(90)));
  line(0,0,(-width/2)*cos(radians(120)),(-width/2)*sin(radians(120)));
  line(0,0,(-width/2)*cos(radians(150)),(-width/2)*sin(radians(150)));
  line((-width/2)*cos(radians(30)),0,width/2,0);
  popMatrix();
}
void drawObject() {
  pushMatrix();
  translate(width/2,height-height*0.074); // moves the starting coordinats to new location
  strokeWeight(9);
  //stroke(255,10,10); // red color
  stroke(50,50,210);
  pixsDistance = iDistance*((height-height*0.1666)*0.025);
  // covers the distance from the sensor from cm (send by the arduino) to pixels (for the screen)
  // limiting the range to 40 cms
  if(iDistance<40){
    // draws the object according to the angle and the distance
  line(pixsDistance*cos(radians(iAngle)),-pixsDistance*sin(radians(iAngle)),
  (width-width*0.505)*cos(radians(iAngle)),-(width-width*0.505)*sin(radians(iAngle)));
  }
  popMatrix();
}
void drawLine() {
```

```
  pushMatrix();
  strokeWeight(9);
  stroke(30,250,60);
  translate(width/2,height-height*0.074); // moves the starting coordinats to new location
  line(0,0,(height-height*0.12)*cos(radians(iAngle)),-(height-height*0.12)*sin(radians(iAngle)
  // draws the line according to the angle
  popMatrix();
}

void drawText() { // draws the texts on the screen

  pushMatrix();
  if(iDistance>40) {
  noObject = "Out of Range";
  }
  else {
  noObject = "In Range";
  }
  fill(0,0,0);
  noStroke();
  rect(0, height-height*0.0648, width, height);

  //COLOR

  fill(109, 241, 111); // green clear color

  //---//

  textSize(25);   //modify text size, normally 25

  text("10cm",width-width*0.3854,height-height*0.0833);
  text("20cm",width-width*0.281,height-height*0.0833);
  text("30cm",width-width*0.177,height-height*0.0833);
  text("40cm",width-width*0.0729,height-height*0.0833);
  textSize(25); // normally 40
  text("Object: " + noObject, width-width*0.875, height-height*0.0277);
  text("Angle: " + iAngle +" *", width-width*0.48, height-height*0.0277);
  text("Distance: ", width-width*0.26, height-height*0.0277);
  if(iDistance<40) {
  text("         " + iDistance +" cm", width-width*0.225, height-height*0.0277);
  }
  textSize(20);
  fill(98,245,60);
  //Attention, space and enter in the next instruction for presentation
  translate((width-width*0.4994)+width/2*cos(radians(30)),
  (height-height*0.0907)-width/2*sin(radians(30)));
  rotate(-radians(-60));
  text("30*",0,0);
  resetMatrix();
  translate((width-width*0.503)+width/2*cos(radians(60)),
  (height-height*0.0888)-width/2*sin(radians(60)));
  rotate(-radians(-30));
```

```
  text("60*",0,0);
  resetMatrix();
  translate((width-width*0.507)+width/2*cos(radians(90)),
  (height-height*0.0833)-width/2*sin(radians(90)));
  rotate(radians(0));
  text("90*",0,0);
  resetMatrix();
  translate(width-width*0.513+width/2*cos(radians(120)),
  (height-height*0.07129)-width/2*sin(radians(120)));
  rotate(radians(-30));
  text("120*",0,0);
  resetMatrix();
  translate((width-width*0.5104)+width/2*cos(radians(150)),
  (height-height*0.0574)-width/2*sin(radians(150)));
  rotate(radians(-60));
  text("150*",0,0);
  popMatrix();
}
```

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