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From Hearing Aids, Prostheses and Cochlear Implants to "Bionic" Feedback Phonation

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ABSTRACT

In Otorhinolaryngological medical practice therapeutic devices are used that are highly invasive and immersive. For aural and oral communication these could be hearing aids, prosthetics, implants or radio-electronic appliances that build up a bionic environment with apparent tendencies for virtualization. The popularization of such devices promotes the extensive use of Brain Computer Interfaces to both the scientific community and the consumer market. The use of bionic devices clinched with synapses of the nerves does not merely mingle input activity to brain activity, but also it provides a virtual channel for augmenting and manipulating speech communication, language communication and even further musical communication. The effects of bionic aural and oral communication when learning practices for the impaired in hearing are applied is encountered in terms of ability for speech perception and linguistic competence.

Keywords: Hearing Impairment, Hearing Aids & Implants, Speech Communication, Language Acquisition Competence

I. INTRODUCTION

Cochlear implants and digital hearing aids have elaborated a breakthrough that takes place in the fields of Medicine and Technology. They have proliferated enormous change in the education of the hard of hearing and deaf children, opening new horizons that allow the successful mainstreaming of new methods in the typical education classrooms, enhancing the potential of handicapped populations to participate in the educational procedures without being left behind due to their hearing loss.

The main prerequisite for their participation is the development of the oral and written language through which they will acquire the academic language proficiency. This competence will give them the opportunity to successfully participate in the academic curriculum.

The term deaf-muteness has been traced in antiquity in medical treatises assigned to Hippocrates and Aristotle, dealing formally and systematically with this disorder [1]. In newer times, the Swiss surgeon J. Amman in 1692 in Amsterdam argued that in most deaf-mute subjects the instrument of speech is perfect [2]. Since then, the difficulty in properly articulating speech for patients with hearing disorders in the acute set is conceived as a secondary derangement caused by heavy hearing loss, or deafness, diagnosed as a neonate hearing disorder, due to congenital causes, or as a perpetrating otoacoustic malady, that affects decisively a child's development for normal speech.

According to a recent definition by Hinchcliffe et al. a subject is considered suffering from deafness when he has been diagnosed with complete hearing loss in both ears [3]. In the case of a minimum acoustic perception, the subject is considered suffering from hearing loss.

The organ used by humans for hearing, balance and orientation is the ear. The ear is composed of three parts: the external ear, the middle and the inner ear (Fig. 1). The external ear consists of the auricle and the external auditory meatus. The auricle or pinna is mainly formed by the cartilaginous framework to which the skin is tightly applied, separated only by the perichondrium. The external auditory meatus has an approximate 3.7 cm long S-shaped course, extending to the tympanic membrane. The outer 1/3 is cartilaginous while the inner 2/3 is osseous, having the skin closely adherent to the osseous part. The tympanic membrane or eardrum consists of 3 layers, has an oval shape and is normally translucent. Points of interest on the tympanic membrane are the pars tensa, which is the largest part of the membrane, the pars flaccid, which is a small, lax triangular area above the lateral process of the malleus, the umbo, the light reflex, the handle and the lateral process of the malleus.

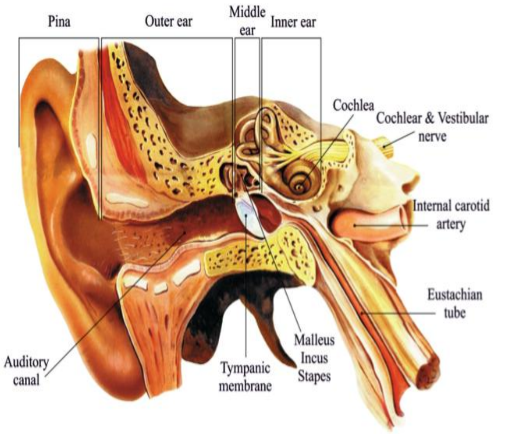

Fig. 1 Anatomy of the ear: The ear consists of the external ear, the middle and the inner ear. The main elements of each part are pointed with arrows.

The middle ear or tympanic cavity is a narrow cavity in the petrous part of the temporal bone and contains mainly the auditory ossicles. Anteriorly, the middle ear cavity communicates with the pharynx by the Eustachian tube, a 3.7 cm long bony and cartilaginous tube. Posteriorly it communicates with the mastoid antrum and the mastoid air cells. Conduction of sound through the middle ear is by way of the malleus, incus and stapes. The malleus is the largest of the auditory ossicles. It has a handle which is visible in otoscopy attached to the tympanic membrane, a head which articulates with the incus and a lateral process. The incus has a head, a short and a long process, which articulates with the stapes, the latter having a head a neck and a base, which is fixed in the oval window. Two muscles are associated with the ossicular chain and are useful in damping high frequency vibrations. These muscles are the stapedius, attached to the neck of the stapes and the tensor tympani, inserted into the handle of the malleus [4][5].

The internal ear consists of the bony labyrinth made up of a central vestibule, which communicates posteriorly with three semicircular ducts and anteriorly with the spiral cochlea (Fig. 2). The cavity encloses the membranous labyrinth, comprising the utricle and the saccule, which communicate with the semicircular canals and the cochlear canal. In each 2part of the membranous labyrinth there are specialized sensory receptor areas (maculae of utricle and saccule, ampullary crests of the semicircular canals, organ of Corti in the cochlea). The organ of Corti contains the auditory receptor cells. These are the outer and inner hair cells and they are surrounded by other structural and supporting cells [5][6][7].

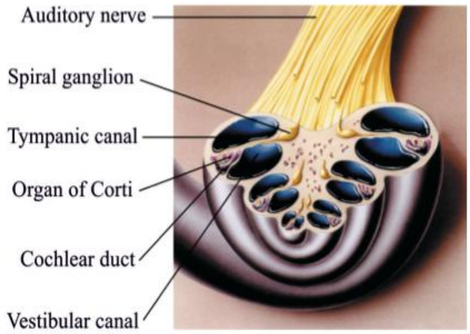

Fig. 2 Cross section of the cochlear duct. Scala tympani and scala vestibule are depicted as long as their relationship with the organ of Corti.

The term child hearing impairment refers to a reduced ability in perceiving acoustic emissions. It can be:

❖Conductive hearing loss, resulting from disruptions in the passage of sound from the external ear to the oval window. It can be caused by pathologies involving the external and middle ear (external auditory meatus, tympanic membrane, ossicular chain). Possible causes may be structural malformations and dysfunctions, traumatic injuries, the presence of foreign bodies, degeneration of stem cells. Conductive hearing loss is effectively amenable via surgical correction, or, in many milder cases, using pharmaceutical treatment [5].

❖Sensorineural hearing loss, a consequence of disruption in the passage of sound beyond the oval window. Such pathologies can be located to the auditory receptor cells of the cochlea and the eighth cranial nerve. It is clearly the most common type of hearing loss, resulting from cochlear or retrocohlear pathology. Sensorineural hearing loss is discriminated in inherited or acquired. Inherited impairments may be caused due to genetic factors or viral infections of the mother during pregnancy, like rubella, cytomegalovirus (CMV), toxoplasmosis, disorders of the endocrine system, hypothyroidism, diabetes mellitus, preeclampsia, other infections like HIV (Human Immunodeficiency Virus), syphilis, impaired renal function, radiotherapy or chemotherapy, and ototoxic drugs like antibiotics, loop diuretics, and some other 100 at least nonsteroidal anti-inflammatory drugs and chemotherapeutic agents. On the other hand, acquired hearing impairment results from perinatal diseases and epidemiology, like prematurity, asphyxia neonatorum, hyperbilirubinaemia, and post-natal disorders, like malignant, virulent infections that may follow birth, meningitis, ototoxic drugs, autoimmune diseases, serious injuries or damages of the inner ear, and acute otitis or chronic otitis media as result of infections of the middle ear [5].

❖Mixed hearing loss, which represents a mixture of both conductive and sensorineural hearing loss.

The term children with hearing impairment denotes a reduction in the ability to hear properly; it can be congenital or acquired, unilateral or bilateral, and it varies within the range of 25-95 dB HL (1 dB = decibel, HL = Hearing Level). Nearly all children with hearing loss experience disorders in their language and speech development process. When a child does not hear well, his ability to develop oral communication, language and social skills is seriously handicapped. To remedy this poignant situation, the child's cognitive development is enhanced by amplifying and supplementing his residual acoustic basis and by inclusive education in his early settings or primary school education.

II. COUPLING ORAL AND AURAL COMMUNICATION WITH PHONATION AND MULTIPLE INTELLIGENCE

Human speech and singing are considered to be acoustic signals with a dynamically varying structure in terms of frequency and time domain. Generally speaking, voice sounds are in the broader sense all the sounds produced by a person's larynx and uttered through the mouth. They may be speech, singing voices, whispers, laughter, snorting or grunting sounds, etc.

No matter how these sounds are produced and what communication purposes they may serve, they are categorized to:

a. Voiced sounds that are produced in a person's larynx with a stream of air coming from the lungs and resonating the vocal cords. This stream continues to be modulated through its passage from the pharynx, mouth, and nasal cavity, resulting to an utterance in the form of speech or song.

b. Unvoiced sounds. Singing or utterance would be incomplete if unvoiced sounds where not produced. They do not come as a result of a vibration from the vocal cords, but as partial obstruction of the airflow during articulation.

The human ability to communicate relies on our capacity to coherently set up sequences of sounds that encode acoustically logical propositions. When voicing produces musical or singing sounds, then the articulated sounds of speech communication are enriched with phonation tuned up to melodic, definite pitches that are called notes or tones [6].

Not all people however produce the same notes in a uniform manner. A particular quality may be observed that gives the timbre of our voicing. Since the voice channel of each individual varies in morphology, and each subject may uniquely control its internal characteristics, virtually each one of us is capable to produce music with a unique quality, apart from its pitch and intensity. Even further, any malfunction or disease that affects the human organ, not to mention ageing, has impact on our ability to produce prosody or melody. Since the voice organ consists of the breathing apparatus, the vocal cords and nasal-oral passages, it is obvious that the process of phonation is a rather complex and multi-parametric phenomenon.

In any case, the capacity for oral and aural communication characterizes, especially in the first years of a child's development, not only its ability to share or exchange communication, but also its potential to acquire knowledge and skills [7]. Inability to apply an adequate magnitude of speech and language communication, although it seems to affect at first mainly the so called "social intelligence" qualities for the exchange of information between peers or the pedagogue, actually affects many developing capabilities that will not be apparently manifested till it is too late to remedy.

Although it is nowadays conceived that intelligence constitutes a characteristic that is demonstrated in various ways and dimensions, and therefore it is not feasible to standardize with rules a set of attributes that an individual must have in order to be marked as intelligent in a specific field of human activity, it is obvious that our schooling systems, at least in its early stages, particularly endows verbal aptitude. As schooling progresses, verbal aptitude extends from oral and aural communication to written correctness. Even further, it evolves to include logic and mathematical skills that are thought to be basic skills in elementary education. In parallel, schoolchildren are expected to start demonstrating linguistic efficiency that allows them to exhibit adequate mental ability to reasonably express their feelings, emotions and ideas [8]. The richness of their expression, their ability to comply with the rules of their language, and their intuitive knowledge of proper speech functions convolves to the overall organizational performance that constitutes the subject's linguistic competence.

The rather newly established theory of Multiple Intelligences (MI) emphasizes the different ways in which people can demonstrate aptitudes and performance for a specific intelligence or multiple intelligences [9]. So to say, by 1993 Gardner had already indicated the faults of the existent system of education which is mainly based on the logical and verbal intelligences, by contrasting the needs of many students with emphasized aspirations in other areas yet not adequately met [10].

As a result, the theory of MIs was promoted in various educational environments. For instance, it was pointed out that children with profound learning disabilities would be particularly deficient in manifesting verbal and logical competences [11].

Consequently, as Levine has pointed out in 2003 [12], the limited apprehension of intelligence alienates, or even worse expels many students from the schooling system. Even further, especially under stringent economic situations, many societies cannot afford the continuance of assistive instruction and fail to properly cope with disorders that cause difficulties in reading or interpreting words, but do not affect general intelligence.

The profiles of intelligences and their basic description defined by the MI theory are [13]:

- Verbal/linguistic – represents the primary means of communication amongst humans. It is reflected in symbolic thinking, language, reading, writing.
- Logical/mathematical – is used for data processing, pattern recognition, working with numbers, geometric shapes.
- Visual/spatial – navigation, map making, visual arts, architecture, perspective.
- Bodily/kinesthetic – reflects the precise self-body motion control, non-verbal emotion expression, dance, fine hand-eye coordination.
- Musical/rhythmic – recognition and use of rhythmic and tonal patterns, recognition of sound, speech and music instruments. It is used to interpret and create music.
- Natural – recognizing patterns in nature, classification of objects and types of wildlife.
- Interpersonal – the possibility of cooperation in small groups, communication with other people, individual's ability to recognize other people's intentions, mood, motivation, non-verbal signs.
- Intrapersonal – recognizing own abilities, capacities, feelings, emotional reactions, self-reflection, and intuition.

Evidence of existence of a theoretical ninth (existential) intelligence has not been clearly established [14], so it will not be considered.

The theory of multiple intelligences has spread waves of enthusiasm in various educational circles since it promotes both an individualized approach and practical application in teaching. Researchers thus recognize that by supporting multiple areas of activity they may enhance the students' mindset and better exploit it, especially amplifying its verbal and linguistic aptitude. MI theory increases learning efficiency by expediting instructors to direct further assistive education [15].

However, although the concept of multiple intelligences is important in understanding how people develop skills for visual and audio competences that are so crucial for multimedia expression and communication within today's ICT environments, linguistic competence is the monitoring tool that reveals a subject's subconscious and intuitive. Indeed, a system for measuring phonemic integration, morphosyntactic aptitude, and phraseology in addition to nomenclature vocabulary, without mistakes reveals a long-term capability, the command of language. So, not disregarding media education and literacy, classic literacy, as applied within a schooling system depicts mental ability that closely matches objective standards and measures like cerebral activity [16][17].

While in Human Computer Interaction (HCI) we talk about efficiency and effectiveness, that portray the ability to handle computer systems, smart phones and Internet of Things devices in a manner evoking admiration through magnitude, quality or particular skills in producing the intended results within a global network, in learning environments experts measure ability and competence in axes that demonstrate the scope of a person's knowledge [18][19]. In practice this means, that although aptitudes like advanced media education and management create an outermost layer for technical adeptness, a person's skills or proficiencies are more inner core achievements.

Hearing Loss and Deafness

Hearing loss in early childhood has as result the delay or reversal of speech communication. According to internationally acclaimed statistics, hearing loss in childhood fluctuates at the 4-5% of the general population. This figure applies to all types and all degrees for hard in hearing children. Even further, a 1-2‰ refers to sensorineural hearing loss on both ears [20].

Individual performances in hearing are measured in dB HL versus frequency (in Hz) diagrams. Within these diagrams, the crucial region, for medical reasons, lies between 125 and 8000 Hz, with the intensity of sound heard within the aural mechanism ranging from 10 up to 110 dB HL. The Hearing Threshold Level (HTL) determines the least intensity for sounds to be perceived for each frequency [3]. On the other end, the threshold of Pain delimits the boundary which when surpassed causes the feeling of pain on our ears. Usually it is about 120 dB HL.

The normal auditory experience in humans is confined between the Hearing Threshold Level and the Threshold of Pain. Although most acouometric tests use a variety of sounds between 20 and 20,000 Hz, with intensity anywhere within the audible range, three frequencies tap the significant disorders, as far as aural communication is concerned: 500, 1,000 and 2,000 Hz or, alternatively, 500, 1,000 and 4,000 Hz [21].

Usually clinicians depict the Hearing Threshold Level for each ear in audiograms like the one depicted in Fig. 3. The subject's hearing is tested with "pure tone audiometry" and the diagram produced indicates how well are perceived beeps and whistles in different frequencies. Test sounds range from soft sounds, barely heard, up to very loud sounds. Of course the lower hearing threshold is of crucial importance.

When the subject's hearing is measured with pure tones that are driven via headphones, this method is named air conduction audiometry. The audio signal follow the following route: via the air to the auditory canal, then through the tympanic membrane to the middle ear, and after that to the very delicate organ of hearing in the inner ear—the cochlea.

An alternative method for testing the cochlea's sensitivity is to place a small vibrator on the mastoid bone behind the ear and accordingly measure the subject's lower auditory threshold. In the latter case, the acoustic signals are directed to the inner ear structure via the bones of the skull. This method of finding out the acoustic threshold is obtained by bone conduction.

As mentioned in section I, hearing loss can be divided into two main categories, depending on the affected parts of sound transmission: Conductive hearing loss, and sensorineural hearing loss. If both impairments occur, then mixed hearing loss takes place, representing a combination of both conductive and sensorineural hearing loss.

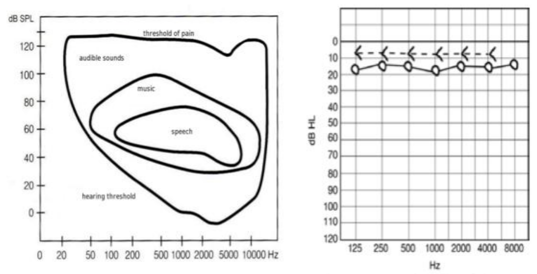

Fig. 3 Left: The frequency characteristics of hearing in dB measuring Sound Pressure Levels. Right: Pure tone audiograms for normal hearing: air audiometry (o) and bone conducted audiometry (<)

Hearing loss is discriminated in 6 levels. In Table 1 the degrees of hearing disorder are depicted:

Table 1 Quantifying taxonomy of hearing level audiometry evaluation

Level of Hearing	Hearing loss in dB HL
Normal	0 - 20
Mild	21 - 40
Moderate	41 - 60
Moderately Severe	61 - 80
Severe	81 - 95
Profound & Deafness	> 90

Pure tone audiometry for producing audiograms is performed in an audiometric test room, where the subject’s face should be clearly visible to the tester. When the test is observed from outside the audiometric test room the subject should be monitored through a window or a TV monitor. Excessive ambient noise can affect test results, thus it is recommended not to perform the test if the ambient noise is >35dB. Both ears are tested for air conduction firstly at 1,000Hz and then at 2,000Hz, 4,000Hz, 8,000Hz, 250Hz and 500Hz. A reference level of 0 dB HL conventionally represents normal hearing across the entire frequency spectrum.

Some basic thresholds are the following:

- Threshold of hearing 0 dB
- Whisper from 1m distance 30 dB
- Normal conversation 60 dB
- A shout 90 dB
- Discomfort 120 dB

The interpretation of the audiogram provides information not only for the quality of any potential hearing loss (conductive, sensorineural or mixed) but for the level of hearing loss as well (Fig. 4). Generally, normal hearing is considered to be >20dB, while mild hearing loss is > 40dB [5].

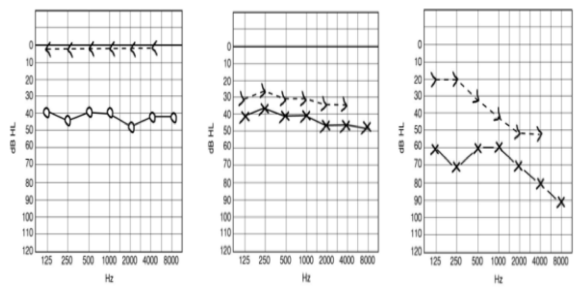

Fig. 4 Left: Conductive hearing loss with an obvious air bone gap in its pure tone audiogram. Center: Sensorineural hearing loss audiogram. Right: Mixed hearing loss.

For sensorineural hearing loss, a more adaptive to the task method is used: Tympanometry, which is part of acoustic impedance testing along with acoustic reflexes. It is an objective test that measures the mobility (compliance) of the tympanic membrane and the middle ear system. The sound transmission from the external ear to the middle ear is optimal when the pressure in the ear canal is the same as the middle ear. The compliance of the tympanic membrane is measured as a function of mechanically varied air pressure in the external auditory meat us and so the middle ear pressure is indirectly measured [22](Fig. 5, left). For more details on how accurate diagnosis can take place in medical terms, see Stavrakas et al. [5].

A very interesting test is speech audiometry, which offers a very realistic representation of an individual's hearing as it involves single-syllable words rather than pure tones. The subject repeats every word addressed to him, and his performance is determined by a score representing the percentage of the words that he has correctly identified. In other words, speech audiometry is a method to assess auditory discrimination [23].

Fig. 5 Left: A typical tympanogram. Right: Speech audiogram patterns. Retrocochlear lesions can be identified by the "roll-over" phenomenon.

Speech audiometry is delivered to only one ear using headphones or free-field to both ears. The optimum discrimination score (ODS) is the highest score achieved (maximum is 100%). The speech-reception threshold (SRT) is the sound level at which the individual obtains 50% of the score. The half peak level (HPL) is the sound level at which the individual obtains his/her ODS. Half peak level elevation (HPLE) is the difference between the HPL of the tested individual and normal individuals [5].

Under normal circumstances, speech audiometry yields a sigmoid curve, like the one seen in Fig. 5, right. In conductive hearing loss the curve is displaced towards the right and in sensorineural hearing loss, speech discrimination deteriorates with increased sound levels, according to the "roll-over" phenomenon that reveals damages like retrocochlear lesions.

Brain-Computer Interfaces and Sound Perception

Hearing Although the general public's pictorial perception for a Brain Computer Interface is mingled between the image of an EEG cap (an electrode studded cap that reads brain activity) and a portable device like Oculus rift, in recent proceedings a more subtle schematic view has been emerging with devices like cochlear implants that input activity to brain activity [24].

Generally speaking, there are two kinds of BCIs [25]:

a. **Invasive**
This category of products, undoubtedly the flagship of interfaces, produce overwhelming immersion into what brain activity projects. In audio matters, such devices offer state of the art multi-track digital input capabilities and thus they simulate and gradually replace the sound input of the outside world.

b. **Non-Invasive**
Not so immersive, they need some training via biofeedback, and their bandwidth is rather limited. They act more like assistive devices and do not totally replace a handicapped organ or instrument. It is obvious that the hardwiring of Figs. 7 and 8, indeed resemble the beginnings of electromechanical interfaces. Subtle operations and engineering methods take place as any malfunction or any unguided penetration may induct erroneously the electrode into the posterior semicircular.

With the advent of medical technology, a new form of interfaces has been put up, that of "augmentation". As body parts are failing to function properly and restoration to a healthy state seems inefficacious, prosthetics are used to rehabilitate vital bodily functions. In certain occasions the term bioelectronics, aka bionics is used. For severe hearing loss that has to do with failure of the outer or middle ear to function properly, bionic devices like those seen in Fig. 6 are used.

Fig. 6 Hearing aids for rather severe hearing loss. Left and Center: Bone Anchored Hearing Aids (BAHA), implantable systems for treatment of hearing loss with direct bone sound conduction. Right: Envoy Esteem™, a totally implantable hearing device with speech processor taking advantage of the tympanic membrane for collecting the sound vibrations instead of using a synthetic microphone.

Under normal circumstances the most easily recognizable hearing aid is the digital hearing aid. However, augmentation usually has to do with more advanced devices, both in medical fitting and processing power terms. For instance, for patients older than 5 years of age, suffering from developmental disorders like dysplasia of the outer or middle ear, failure of tissues to develop or malfunctions that cause aplasia, chronic inflammations of the outer ear, like otitis externa, which affects the passage of the outer ear, or otitis media, that distresses the middle ear, otosclerosis of the ossicles in the middle or inner ear, due to limited mobility, problematic fixation or overgrowth, it is obvious that digital hearing aidscannot be a viable solution.

In such cases, and especially for aural atresia or chronic ear-drainage, a Bone Anchored Hearing Aid (BAHA) can be used, as seen in Fig. 6, left and center. In medical terms, BAHAs are secured firmly on the mastoid bone and externally function more or less like most hearing aids. However, in structural terms it is different. It does not use a membrane for converting sound waves into electrical energy, but it rather induces a very solid microsystem that produces vibrations within the bone it is anchored on [21].

We may see two variations of it in Fig. 6. The former operates on the mastoid bone while the latter, as seen in Fig. 6, right, is connected with the incus of the middle ear, or in some cases, it may replace him. In both cases the acoustic irritation of the cochlea is caused by vibrations that come via the ossicles of the middle ear and not the normal auditory meatus (which leads to the tympanic membrane and bones). This osseous conduction of vibrations seems to be a more natural alternative to the audiologic solution offered by the usual hearing aids. However, it demands surgical intervention in order to place the sound processor inside the scull, and neat manipulation when assembling the sensor and driver with the middle ear ossicles.

Undoubtedly, the top of the line for bionic audiological technology is the Cochlear Implant (CI).

In strict terms a CI is an electronic device that restores partial hearing to individuals with severe to profound hearing loss; these people normally would not benefit from a conventional hearing aid. Conventionally, as the American Academy of Otolaryngology [26] puts it “is surgically implanted in the inner ear and activated by a device worn outside the ear. Unlike a hearing aid, it does not make sound louder or clearer. Instead, the device bypasses damaged parts of the auditory system and directly stimulates the nerve of hearing, allowing individuals who are profoundly hearing impaired to receive sound”.

It is obvious that the hardwiring seen in Fig. 7, image on the left and center, is overwhelmingly analogous with advanced electromechanical interfaces. Subtle operations and engineering methods take place as any malfunction or any unguided penetration may induct erroneously the electrode into the posterior semicircular canal damaging the facial nerve, or creating an unsupervised electrode contact within the vestibulocochlear nerve. The implant, seen in Fig. 7, left, is comprised of antenna, magnet, receiver stimulator in titanium casing, electrode array with electrode contacts, apical and basal, spaced at 2.4 mm intervals. Usually the electrode array that is implanted is about 30 mm long and 1.3 mm wide at its base concluding to some 0.8 mm at its apical end.

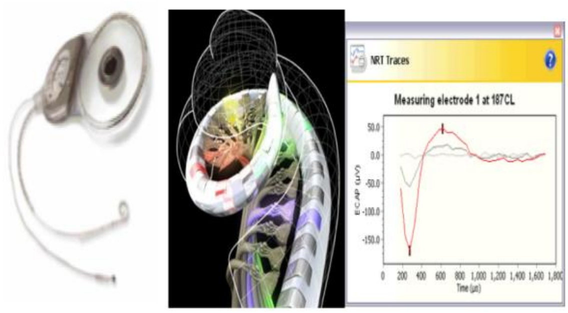

Fig. 7 The cochlear implant pictorially: Left, the device, Cochlear’s Nucleus Freedom™; Center: penetration and placement within the ear; Right, measurement and calibration of electrode polarization, in µV, after its successful synapse with the acoustic nerve.

CIs are applicable for both children and adults with bilateral, severe to profound sensorineural hearing loss, who cannot take advantage of the use of powerful hearing aids and have not managed to improve their oral communication skills by a prescribed speech therapy. In this manner, the early stimulation of the acoustic Central Nervous System, especially in pre-school ages, may well lead to improved acoustic memory and sound discrimination.

Indications and preoperative requirements for cochlear implantation include a complete medical history and physical examination, medical valuation, audiologic examinations, CT and MRI scans to evaluate the cochlea and the auditory nerve, psychological tests, speech evaluation and enrolment in oral education program.

Methodical follow-up and mapping of the implant are assumed, more frequently in children, along with specialized speech therapy. Each new mapping is evaluated according to the record of the patient with regard to the acoustic perception of sounds and speech and the discrimination of individual elements of phonation based on a protocol that the authors we have created for the needs of Greek language. It should be noted at this point that these kind of protocols are language specific, and therefore generic rules should be applied with some caution for trans-linguistic codification [26].

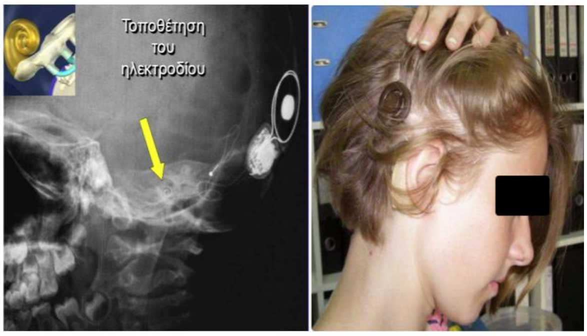

Fig. 8 Applying a Cochlear Implant to a child at the AHEPA hospital, as seen with a CT head cross-section (left), and as it seen from outside (right).

Cochlear implants do not restore normal hearing; they just provide a *representation* of sound. An inner ear problem, usually leads to sensorineural impairment or nerve deafness. In most situations, the hair cells are damaged and do not function. Even though various auditory nerve fibers may be intact and can transmit electrical impulses to the brain, these nerve fibers are unresponsive due to hair cell damage [27]. It is generally accepted that if severe sensorineural hearing loss cannot be put right with medical treatment, then the road towards cochlear implantation is wide open (Fig. 9).

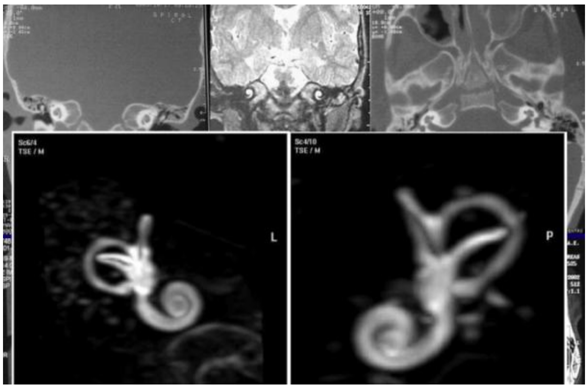

Fig. 9 The Cochlear Implant as seen in various CT post-surgical sections.

Modern cochlear implants come with as many as 24 electrodes, whereas, as seen in Fig. 7, center, the hearing process employs approximately 16,000 cells inside the cochlea. However, the human brain is able to adapt to the new representation of sounds, to a certain degree typically after a year [28].

For post-lingually deaf subjects, the initial sounds are portrayedas robotic, fuzzy, cartoonish, or similar to a noisy street. After post surgical training and calibration, performed by the doctor, most users are able to recognize voices, and enhance lip reading. Interestingly, after recent technological advances, many young patients that do not suffer from congenital malfunctions are able to retain and comprehend speech and languagewithout extravagant effort.

Therefore, the surgeon's role is not merely confined to linking nerves with a stimulating mechanism or by properly parameterizing the implantable nerve simulator. The doctor is the one that directs the motor mechanism for producing speech. In this point a "interdisciplinary" group of scientists is involved, trying to visualize the "big picture" that comes out of thousand of synapses linked with bioelectronics.

The subject bearing a cochlear implant does not react on the basis of what he hears; in reality he reconstructs sounds based on what his mind thinks sounds should be morphed in for speech production. Moreover, he will be prompted one way or the other to try his skills in music reproduction, and more specifically in singing.

Surgeons try to model the absence of auditory feedback by monitoring poor laryngeal function in terms of voice quality, frequency and intensity [24]. Although surgeons play a key role in proper speech communication for cochlear implanted subjects, it is the speech therapist that will develop his phonological skills and the applied linguistics expert who will advance his language pedagogy.

All these therapies are applied in parallel: After training and calibration, performed by the doctor, most users are able to recognize voices, and enhance lip reading. Many, after recent advances, are able to retain and comprehend speech and language.

The process of sound transmission into the cochlea can be identified as a flow process: sound is transformed into electrical signals. The processor then samples, processes and maps the signals to specific locations within the cochlea, depending on the waveform frequency spectrum. The accuracy and scalability upon which medics and computer scientists calibrate the sound – transfer mechanism, implies the degree of immersion, i.e. the trip from non-invasive to fully invasive "motor" mechanisms (Fig. 10).

Starting from the physicians point of view, rehabilitation strategies apply "low level programming" on the frequency induction of synapses, map with many electrodes the frequency bands, and use low or high frequencies to trigger the nerves. Along with the speech expert and the linguist, a combined team of specialists interacts with the subject's bionic parts, programming the Advanced Combination Encoder (ACE) of the CI to adjust better to the environmental activities.

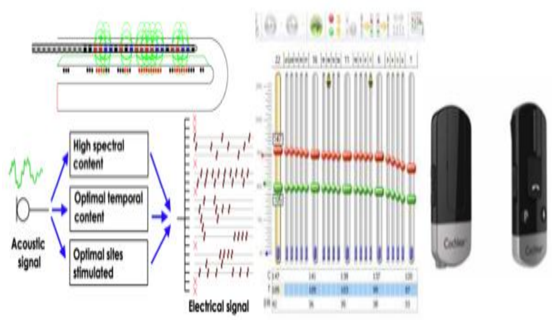

Fig. 10 The CI as a bioelectric amplifier and equalizer, enacting Advanced Combination Encoders (ACE), or short range radio receiver and emitter (Far right, the Cochlear™ Wireless Mini Microphone and Cochlear™ Wireless Phone Clip).

Indeed, although a patient with CIs is somewhat handicapped and unfortunate, on the other hand, he is experiencing a unique situation where inference mechanisms deploy advanced computer technology and bionics in order to induce fluent verbal communication [29].

III. EDUCATING CHILDREN WITH SEVERE HEARING LOSS

In Europe, the starting point in the education of hearing impaired people is signaled in 1555 from the Spanish monk Pedro Ponce de León, which educated a small number of deaf children in reading, in writing and in speech. In 1620, a second Spanish, priest Juan Pablo Boncet, who continued the effort of Pedro Ponce, wrote the first book on the education of hearing impaireds titled "Reducción de lasletras y arte paraenseñar a hablar a los mudos", in which he portrays an "oral" and "manual" method for training the deaf. For the English speaking world, in 1664 philosopher and physician John Bulwer published the first book on deaf children education that emphasized on enhancing aural communication with lip reading alongside gesture.

In 1680 Scottish intellectual George Dalgerno supported in his book "Didascalocophus or the Deaf and Dumb man's tutor" that the deaf individuals have the same possibilities of learning with the ones that can hear. He introduced learning methods that were widely used for many years. In 1767 Thomas Braidwood in Edinburgh established the first school for deaf children, the Braidwood Academy for the Deaf and Dumb in Grove House, deploying a combined method with oral and sign language elements.

The same era in Holland, the Swiss origined John Conrad Amman applied a special method in small number of learners with noble origin, suffering from hearing impairments, which was developed on two axes, "articulation" and "lip reading", aiming to capacitate non verbal deaf persons to both articulate speech and comprehend aural communication.

In Germany, the same period, Samuel Heinicke introduced a method for developing oral skills for the impaired in hearing, paying emphasis on lipreading. Heinicke's findings where further elaborated by Friedrich Maritz Hill who managed to establish an Internationally acclaimed oral communication system.

For the French speaking world, Charles Michel, Abbot de l' Éppée and Roch-Ambroise Cucurron Sicard somewhere around 1760 developed an instructional method of signs ("signes méthodiques") language. Their communication system was arranged with a combination of systematized signsand a gestural alphabet. What was interesting with their method was the fact that it promoted the evidence of feelings, thus being the precursor of sensory and aesthesia based education.

On the other side of the Atlantic, in 1817 was founded the first American School for the Deaf, in Hartford, Connecticut, by Thomas Hopkins Gallaudet. Laurent Clerc, a deaf Frenchman, served as its first instructor. For instruction he used a signed communication, so in practice teaching was conducted in English using a variant of the French sign language. Gallaudet travelled to Europe in 1815 to further re-examine the method used by the Braidwood family in England, based on oral communication, along with the sign language promoted by l' Éppée and at the Institution Nationale de Sourds-Muets à Paris. However, the Braidwoods rejected Gallaudet offer to franchise him with their method within a few months of training, and therefore he altered his plans that were based on combining the best elements of two "worlds". He embraced the French method, and returned to USA with Clerc, a Sicard's disciple, and relied their teaching method to the newly established American School for the Deaf on a variant of the French sign language. As Clerc was getting more proficient with the English language, they started introducing apart from sign language classes for deaf, classes for hearing men who wanted to study deaf educations, setting the foundations for what is now the Gallaudet University.

For these reasons, the early American schools for the deaf distanced themselves from the instruction for oral communication; they mainly emphasized in promoting the American Sing Language (ASL) along with written English as a platform for achieving personal and professional language goals.

However, between 1860 and 1900 the interest for oral methods prevailed. Horace Mann, having visited schools for deaf in Germany and Britain in 1844, authored a report promoting the success story of the oral methods, over sign languages. Indeed, it was a turning point. In 1867 two new schools were introduced: the School for Deaf in Lexington, NY, and the Clarke Institution for Deaf-Mutes, in Massachussetes. Gardiner Hubbard, the founder of the Clarke School, engulfed not only deaf pupils, but also hard-in-hearing and post-lingually deaf subjects, not to talk about other groups of non-impaired in hearing students [30].

This was more or less the trajectory for establishing special education departments for impaired in hearing students. The principles laid down by the founding fathers of education for the deaf or hard in hearing subjects were promulgated to most major languages.

3.1 The Modern context for Training the Impaired in Hearing

In modern times hearing aids are widely spread, and therefore special education takes full advantage of prosthetic or bionic devices. Therefore, the specific gravity for this training does not ponder on developing sign-language communiqué skills, but on ameliorating the hearing capacity of the ill healthed students and trying to gradually affiliate them with the norm of oral and aural communication used in mainstream public schools.

In 1998 Yoshinaga - Itano and his fellow researchers [31] conducted a survey on 72 children diagnosed with hearing loss or deafness at the first 6 months of their life, and with a second group of 78 subjects whose impairment was detected after the age of 6 months. It was obvious from the results of this survey that children which were early enough diagnosed had achieved better in language communication terms in comparison to the ones whose therapeutic intervention commenced after the age of 6 months.

Tur-Kaspa and Dromi on the other hand focused their study [32] on the morpho-syntactic development of orally trained deaf or hard-in-hearing children speaking Hebrew. The scientific results obtained out of this research demonstrated that the linguistic ability of these children failed to mark grammatical agreement when matching the singular or plural with the gender of verbs and nouns for subject verb agreement or adjective-noun agreement.

Taeschner and his associates [33] conducted a survey on children between 11 and 15 years of age speaking Italian. Their findings demonstrated that deaf and impaired in hearing children often made mistakes when matching articles and nouns. Even further, subjects were picking articles in accordance with the last vowel of the noun, a mistake that was not observed with children that enjoyed normal hearing. In the research conducted by Friedman and Sztermanin in 2006 [34] the comprehension of relative clauses with subjects and objects for deaf and hard-in-hearing children between 7.7 and 11.3 years of age, the target group appeared to have lesser linguistic competence in comparison to the normal probability distribution for children with no hearing defects. They also found a strong correlation between the age of the first medical intervention and the linguistic accomplishments. Children that had received hearing aids before the age of 8 months achieved significantly better than those that had rectified their hearing at a later stage.

A similar survey was conducted in a similar language, the French language. Delage in 2008 obtained observation results from the spontaneous language communication of deaf and hard in hearing children aged between 6 and 12. Her findings showed that the impaired in hearing subjects made significantly more mistakes when forming compound sentences containing locative pronouns replacing the complementizer and propositions in comparison to normally hearing children [35].

When it comes to children using CIs, it has been internationally accepted in recent years that the unique technological accomplishments achieved can effectively assist a deaf or seriously impaired in hearing child to perceive sounds, to understand speech communication and to develop high level linguistic skills.

As it has been explained, CIs bypass the outer and middle ear structures and trigger directly the hearing nerve, i.e. the eighth pair of cranial nerves, or the vestibulocochlear nerve. This is achieved by conveying sensory impulses from the speech processor directly to the brain. In several researches conducted worldwide it has been made clear that hard-in-hearing children with cochlear implantations develop oral communication skills faster in comparison to impaired children that do not benefit from their use [8][36][37][38]. Even further, in some cases cochlearly implanted children managed to carry out a linguistic activity as efficiently as did children with normal hearing [37][39].

In a research conducted by Szagun in 2004 on deaf or seriously impaired in hearing children using cochlear implants and communicating in German, it was statistically measured that they had similar typical performance in statistical comparison with children enjoying normal hearing [40]. The test fields of Szagun's research were focused on inflectional plural and the morphology of affixes. She examined the acquisition of case and gender on an implanted group of subjects according to the productive rules of the German language grammar. She concluded that impaired children failed within the grammatical structure of a sentence in different manner compared to normally hearing children and in some occasions their performance was inferior. In a research conducted by Okalidou in 2010 [41], a Greek girl aged 4 years and 5 months was closely monitored shortly after having undergone cochlear implantation. Although she was performing poorly in speech communication, after the operation she demonstrated a steep increase in both her phonological performance and the number of the properly uttered words.

3.2 Comparison of Language Development for Children with CI vs. Children with Hearing Aids

Since the cost of cochlear implantation is a multitude bigger than that of ordinary hearing aids, a number of researches focussed on the comparison of speech and language communication levels achieved by populations using solely hearing aids versus populations using cochlear implants. Although such researches would be pointless some decades earlier, the recent advances in sound amplification performed by hearing aids, the fervent progress on both cochlear implantation technology and post surgical training, and mainly the development of interdisciplinary academic work on how to evaluate, monitor and rehabilitate, impaired children undergone cochlear implantation presents gives evidence of significant findings [42][43][44].

Going back as early as 1993, Osberger, Maso and Sam compared the comprehensibility and speech intelligibility for groups of children using Hearing Aids (Has) and CIs [45]. It was obvious then, that according to this research, that the oral, lingual and phonic ability to articulate proper sounds was comparatively much better when cochlear implantation was chosen as a rehabilitating method.

Indeed, McConkey et al. in1995 committing a similar, long lasting research [46] came to similar outcomes when comparing the understandability of speech communication for children using CIs versus children using HAs. In this research it was demonstrated that the aptitude for proper speech communication was increasing with time for children using CIs, while for children using hearing aids it was having a more slow progress.

A similar research by Van Lierde et al. in 2005 focused on the articulation patterns for both children using CIs and HAs [47]. The formation of clear and distinct sounds seemed to be statistically much better for the CI group of children. The inability of the Has populated group for uttering speech sounds with clarity was evidently due, more or less, to severe phonetic and phonological disorders.

In another research accomplished again between populations of children using CIs versus HAs, Tobey et al. concluded in 1994 which factors are associated with the development of speech production skills in young children with CIs [48]. The research group wanted to record how impaired in hearing children could imitate nonwords given to them. What is important in this research is that the prosody and voice characteristics of children with CIs were developing better than the other group with HAs. It seemed that implanted children enjoyed better speech perception alongside precision in reproduction, when spontaneous speech was encountered.

Even further, Miyamoto et al. in their 1996 research concerning speech intelligibility [36], concluded that children with CI perform better than children who use conventional HAs. The evaluation was performed by panels of listeners who analyzed recorded speech samples monitoring progress over 6-month lapses of time.

More recently, in 2008, Geers et al., presented long-term outcomes of cochlear implantation on the schooling process [49]. They focused on the correlation of improved auditory access with factors like speech perception, language and reading of 85 North American adolescents. They concluded that CIs have a long-term positive impact on school performance.

In the of research of Tomblin et al. in 1999 [39] two separate groups of hearing impaired children were examined. The former was using CIs while the latter employed digital HAs.

The primary measure of competence for language development was the assessment for sentence comprehension. For children with CI experience, a mean percentile rank of 92.2 was achieved, with SD = 15.74. On contrast to this, the group with HAs scored on average 50, demonstrating a profound bias for cochlear implantation.

As the researchers concluded with, "despite the fact that these data do not resolve the controversy concerning the use of CIs with congenitally deaf children, they do demonstrate that these devices are providing the gains in linguistic development promised by the previously demonstrated improvements in audibility, speech perception, and speech production."

The research of Löhle et al.[50] had already given another dimension to this research: As faster and as earlier children suffering from heavy hearing loss or deafness, are implanted, the better it is. This was one of the first researches that correlated speech recognition, speech production and speech intelligibility with age. Although humans do not have many memories from their early stages of development, and generally speaking many parents believe that as years pass by children with impairments will catch-up with, in practice linguistic competencies heavily time dependent.

In 2010 Baudonck et al. [51] cleared out how parents participate in developing the linguistic skills of their impaired in hearing children. As it was demonstrated, if parents were early enough activated to seek implantation as a final solution, the average competence of their siblings in speech perception was very close to that of normal in hearing populations. On the contrary, children with HAs scored obviously worse results.

IV. PROBLEM FORMULATION AND EVALUATION RESULTS

As it has been accepted in contemporary literature, within various linguistic frames, Cochlear Implants help heavily impaired in hearing children develop linguistic skills better than those children using digital Hearing Aids.

In addition, this specific research focuses on the evaluation of:

- linguistic profiling and competence for children suffering heavy hearing loss, using CIs.
- Linguistic profiling and competence for children suffering heavy hearing loss, using HAs.
- The intergroup and within the group differences and trends.

The sample group of this research, which was conducted from September 2012 until December 2014 was a group of 140 children suffering from moderately severe or severe hearing loss, and therefore experiencing developmental delays in their schooling advancement. All children were offered free appropriate public education, which included apart from their normal schooling load a special education program aiming to ameliorate their speech and language communication skills without using a sign language, under public supervision and direction. Furthermore, an individualized support program was launched focusing on the aural and oral communication rehabilitation, supported by a multidisciplinary scientific group under the auspices of the Cochlear Implantation Center at the University Hospital AHEPA, Aristotle University of Thessaloniki, Greece.

68 of these children comprised the CI group, while 72 were using HAs. For the 68 children of the CI group, 35 of them commenced remedying their hearing impairment with HAs, and gradually they shifted to CIs, while 33 of them were using CIs from the beginning.

For the children of the HA group, pure tone audiometry was conducted periodically for the four basic frequency bands in hearing: 500 Hz, 1kHz, 2 kHz, and 4kHz. Their average hearing loss was about 80 dB HL, ranging from 60 dB HL up to 100 dB HL - see Table I).

The gender distribution of the working group was also evenly split: 71 were boys and 69 were girls.

Their age spectrum was as follows: 45 children were aged between 4 and 8, 95 were between 8 and 15 - see Table 2.

Table 2 Statistical indices for the children participating in the survey.

	Age (months)	Time Interval using HAs (months)	Time Interval using CIs (months)	Age (in months) when CIs were implanted	Age when Hearing Impairment was diagnosed (months)	Age when they started using HAs (months)
Mean $\bar{x}$	107	77	62	40	19	26
Median M_a	97	77	54	39	18	20
Standard Deviation s	35	39	32	19	10	14
Min Value	48	15	15	9	1	1
Max Value	179	165	130	94	36	48

The educational profile of overall the children within Greece attending special education schooling can be seen in Table 3.

Table 3 Special Education indices for Greece, school year 2011-12, according to the Directorate for Special Education, Ministry of Education.

Formal Education Stage	N	%
Early Childhood Education- (Preschool)	38	7.7
Elementary Education	220	44.8
Secondary Education	233	47.5
Total	**491**	**100**

According to the figures of Table 3, the 140 subjects that participated in this survey constituted the 28.5% of all pupils receiving Special Education in Greece.

For conducting the survey, three alternative models for testing linguistic development were used:

- Applebee's System for assessing narrative stages, and generally testing the acquisition of language features [52].
- The Λ-α-Τ-ωTest of Linguistic Aptitude, which is an adapted form of phonological, morphosyntactic and semantic assessments that give a standardized evaluation for Greek speaking subjects [53].
- The Detroit Test of Learning Aptitude - the oldest and most disreputable assessment in special education for measuring the general aptitude of young children [54].

All these tests have been extensively used quite a while both in Greece and worldwide, therefore plentiful statistical norms have been produced allowing the research group to correlate psychometric theory data with the linguistic aptitude assessments of the impaired children groups. However, measurements are language dependent, and for this reason internationally acclaimed tests have always a specific language profile.

The statistical results that will be presented are in standard score values.

4.1 Comparison of Narrative Skills Development between Children Using CIs and HAs

In order to assess the narrative skills of the impaired, Applebee's Structure Model Analysis of Narratives was used.

Narration is a cognitive process, based on observation and experience, which depends on the ability of a child to express his knowledge in an organized way [55]. For this, he has to recount his personal experience, relating past, present or future events, sorted out in timelines. The main activity that will be described, whether factual or invented for the purpose of narration, systematizes story telling as logical sequence of events.

The cohesion of the plot, the character development and the control over the vocabulary elements that makes a narrative more illustrative and precise in its details, provide information on the subject's ability to develop communicative competence.

The results obtained out of 119 monitored children were processed using the Independent Sample T-test and were normalized, demonstrating a statistically inferred linguistic behavior in favor of the group using CIs. As seen in Table 4, the assumption of homogeneity is met, with Levene's test the equality of variances producing F = 11.9 and Sig. < 0.001, thus there is adequate statistical evidence to conclude that CIs clearly enhance narrative skills.

The clearly evident statistical difference in aptitude shown in Fig. 11 demonstrates a kind of shift in the ability to handle evaluative and contextual components, as far as narration is concerned. Narration, as a cognitive process, involves developmental milestones in acquiring the skills for conceptually organizing the acquired personal experience of facts, for correlating events in time based relations (timelines) and causal conjunctions, for establishing and integrating the main idea with a sensitive, cohesive and logical manner.

As seen in Fig. 11, impaired in hearing children using CIs demonstrate on average better performance by 0.9 (normalized) degrees in the mastery of structural patterns as far as narration is concerned.

Table 4 Correlating the HAs group with the CIs Group on one metric value as far as Narration Skills are exhibited with Applebee's structural tests.

N = 119		Narrative Competence
Hearing Aids Group (N=60)	Mean (HA)	2.9
Cochlear Implants Group (N=59)	Mean (CI)	3.8
	F	11.9
	Sig.	**p < 0.001**

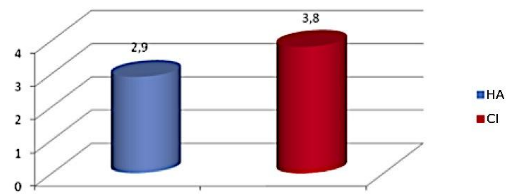

Fig. 11 The difference in narrative ability between groups of impaired-in-hearing children with CIs and HAs, according to Applebee's Structure Model Analysis tests.

Therefore, a more exhaustive research focuses on the contribution of constituent factors that on the whole establish the natural ability to narrate.

Thus, the evaluation of a child's ability to give a spoken account or to deliver description with reasoning is assessed quantitatively with the following criteria:

- Heaps: they demonstrate the subject's ability to bring together a set, a collection of unrelated ideas, facts or events that may be cohesive enough to build up a meaningful story.
- Sequences: It is the arrangement in particular order of events, topics or characters that potentially may develop into a concrete theme. They demonstrate a subject's ability to arrange stimuli, memories or ideas according to a pattern or method.
- Primitive narratives: like sequences, they contain a central evolution line. However, in addition to that they provide multiple connection nodes that links narrative elements not only on the basis of input through the senses and observation, but via the cognitive evaluation of their properties and functions. As a result, they enrich sequences with perceptually similar coupled, connected or related events. Applebee's model presumes that children process stories like a collection of complementary or interrelated events convolving around a central, topic or character. They demonstrate the subject's competence in concentrating their interest towards in forming a basic narration.
- Unfocused chains: It does not contain a central character or theme. However, albeit the absence

of a central evolution line, the collected events are logically or causally linked sharing some common characteristics. Children may be still using sensory input, apart from their cognitive contribution, to form chains of events, put in proper order as far as their time or causal attributes are concerned. However, on the whole the structure produced has a rather limited degree of cohesion, lacking a central character or thematic subject, although it may be quite extended in their narrative discourse.

- Focused chains: They do have a logical evolution of events and usually they involve a key character. They resemble pretty much the narratives that adults produce, and therefore they have a similarity with "adventures" of real or imaginary people and events, lacking however the perspective of a meaningful plot with some degree of realism.
- True narrative: It convolves indeed around a character or a thematic contexture, having a plausible plot. There is a regarded problem, a possible event or outcome that persistently proceeds towards a climactic point, while the composition of events is logically, emotionally and focally admissible. According to the Applebee model, true stories commence to be accomplishable from the age of five, and gradually, within a year or two, they become the dominant methodology for organizing narrations.
- Complex stories: multiple embedded commentaries that illustrate an underlying structure with a plan subject to causality, reaction in a contrasting form and thematic setting.

Diagrammatically, a schematic representation for the stages of child narrative development is exhibited in Fig. 12. Evaluation and skill development aims to enhance particular abilities, that emerge as an outcome of special education.

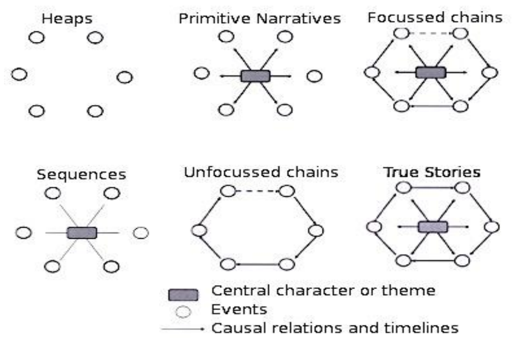

Fig. 12 Schematic conceptualization of plot, thematic coherence and sequence of events for Child Narrative Development.

The results obtained from the two test groups, one having children being assisted with digital HAs and the other comprised of children having CIs, are presented in detail in Table 5.

Table 5 Comparison of the Level of Narrative competence for the HA group and CI group of impaired in hearing children.

	Level of Narrative Competence	HA Group	CI Group	Total
1	Heaps	14	8	22
2	Sequences	10	13	23
3	Primitive Narratives	20	5	25
4	Unfocused Chains	6	7	13
5	Focused Chains	7	9	16
6	True Narrative	2	14	16
7	Complex Stories	1	3	4
	Total	**60**	**59**	**119**

This set of data is illustrated in Fig. 13, demonstrating a tendency for better Linguistic Competence at the advanced levels of Narrative Analysis, in favor of the CI treatment.

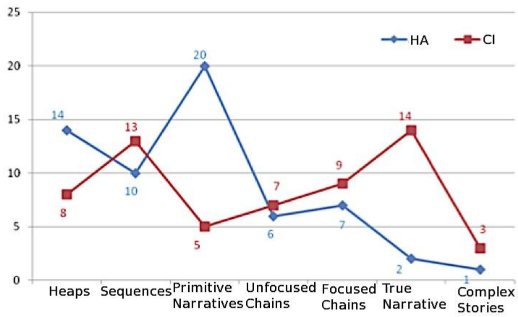

Fig. 13 Comparison between the groups of children using CIs and HAs for the achieved levels of Narrative Competence, according to Applebee's Structure Model Analysis tests.

Although the analysis scheme focused on Narrative skills gives and edge to the CI treated group, it does provide a conjunction with the bionic, i.e. electromechanical and operational background of the implantation in terms of processing power.

4.2 Comparison of Linguistic Aptitude Skills Between Children Using CIs and HAs

When it comes to assess the Linguistic Competence, the intuitive knowledge of the rules of their mother tongue language comes to surface.

The psychometric test Λ-α-T-ω (L-a-T-o - Language Acquisition Competence Test, Level II) is an adopted version to the Greek language of the theoretical foundations for measuring the acquisition process in reception, organization and expressive language [7][56][57]. It provides composites for three language modalities: the conceptual, the grammatical (organizational) and the phonological.

This methodology takes into account the input system for aural communication, which

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comprises of audio channels of communication along with visual proceedings and gestures that support linguistic intuitive knowledge.

More specifically, three sub systems are taken into account, when performing the tests of this analysis model:

- The reception system, used for aural communication acquisition. It does not take into account only the perceived information by the senses, i.e. the aural input mainly, but it also includes a preprocessing stage that entails the understanding of phonological information into full speech processing and communication.
- The organizational system that gives children the potential to organize input information by correlation. i.e. by establishing a relationship between internal psychological processes that exist within the working memory. In terms of language communication, this sub-system stirs a child's memory and/or subconscious understanding, which holds the intuitive knowledge of the rules of his language, and gives him the mental ability to provide out of the perceived phonological information the strategic encounter of language communication, i.e. meaning and concepts.
- The expressive system that assesses the ability to produce meaningful oral communication. In a child's advancement, meaningful vocal sounds are organized in words, then in sentences, later in concepts. By schooling, a learner is capable for the proper arrangement of words and phrases articulating well-formed sentences. Syntactic dexterity may evolve further with education and personal study into more accomplished performing skills in oral communication, afterwards in command of written language communication and for some even in musical competences with singing.

In HCI terminology, it becomes apparent that the Human Processor Model [58],that was first established in mid 1980's, provides a perceptional equivalent in computer terms for the mental, sensory and emotional activity that takes place for aural communication (Fig. 14).

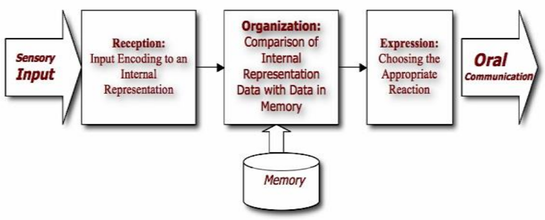

Fig. 14 The Model Human Processor with aural input and oral output channelling for speech and language communication.

Indeed, the Model Human Processor describes in computer architecture terms the mental activity exercised for competent aural and oral communication, providing a workable simulation for analyzing how human cognition responds in a HCI manner with the plethora of incoming signals that trigger the human body respond to external or internal stimuli by performing an action.

As a result, in the literature of the impaired-in-hearing, evaluation of the receptive or expressive vocabulary data of a subject may be committed, attempting to mark out the boundary of words, in qualitative or quantitative terms, eventually evaluating his aural and oral communication potential [59].

In any case, as far as linguistic competence is concerned, all these three subsystems exercise processing power and are linked with three upper layer observable elements of linguistic vocal development:

- the phonological, which evaluates the phonoprosodic linguistic vocalizations, i.e. the ability of a subject to encode and decode the phonemes of his language, with proper intonational and rhythmic conduct, according to acoustic rules of duration and pitch [60].
- the semantic or conceptual, which assesses the child's ability to conceptualize aural and oral communication, by giving meaning to vocal sounds and relation between words.
- the moprhosyntactic, which evaluates how well a child can perceive and elaborate syntactically correct sentences.

The evaluation results over the two groups of impaired in hearing children according to the Λ-α-Τ-ω test are presented in Table 6.

Discrimination has been made for CI users, on medical grounds, of when they commenced using cochlear implantation.

Table 6 Synoptic comparison of the dispersion mean values for the L-a-T-o Language Acquisition Competence Test for groups of children with HAs and CIs (consisting of two subgroups).

N=140		Reception System (standard score)	Organizational System (standard score)	Expressive System (standard score)	Phonological Element (standard score)	Conceptual Element (standard score)	Morphosyntactic Element (standard score)	**Total** (standard score)	Quotient of Linguistic Competence
HA	Mean $\bar{x}$	3.2	4.8	3.7	3.9	4.2	3.3	22.2	62.3
Initially HA and afterwards CI	Mean $\bar{x}$	3.6	6.4	4.1	4.0	4.4	4.4	23.2	66.2
CI from the beginning	Mean $\bar{x}$	5.3	7.5	5.1	5.4	6.3	5.2	34.5	74.5
	F	7.5	4.6	3.3	4.6	5.2	3.8	9.4	5.2
	Sig.	$p < 0.01$	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.01$	$p < 0.05$	$p < 0.001$	$p < 0.01$

Pictorially the boost that special education trainees receive is shown in Fig. 15.

As testing gets more detailed, as far as language acquisition competence is concerned, the clear edge of using CIs is becomes apparent, especially when the Organizational System is encountered.

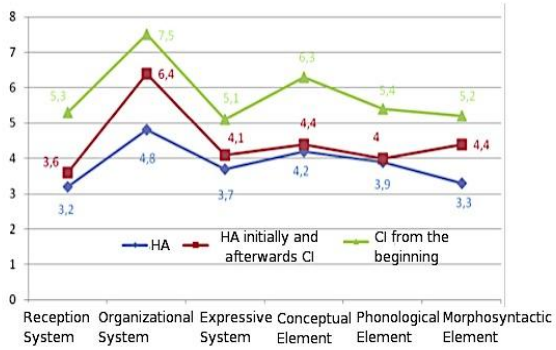

Fig. 15 Pictorial comparison of groups of children under special education using HAs and CIs (two subgroups) according to the L-a-T-o psychometric tests.

4.3 Comparison of Detroit Test of Learning Aptitude Linguistic Aptitude Skills between Children Using CIs and HAs

The Detroit Test of Learning Aptitude (DTLA) comprises a series of psychometric procedures that assess linguistic aptitude by measuring cognitive ability on accomplishing language tasks, attention investigation, or motor abilities (i.e. manual dexterity as a motor enhanced composite).

The basic concept of the test comes in various formats, depending on the language used and the number of sub tests carried out.

Detroit Test's Primary version 3 (DTLA-P:3) for the Greek Language comprises some 115 questions on test Articulation, Digital Sequences, Oral tests, Conceptual Matching, Design reproduction, Digit sequences, Draw-a-Person, Letter Sequences, Motor Directions, Object Sequences, Oral Directions, Picture Fragments, Picture Identification, Sentence Imitation, and Symbolic Relations.

For this research, a newer, enhanced version was used, DTLA-4, emphasizing on certain psychometric variables tested by performance in finding and sorting Word Opposites, Design Sequences, Sentence Reproduction, Letter Reproduction, Story Construction, Design Reproduction, Basic Information, Symbolic Relations, Word Sequences and Story Sequences.

It is obvious that this test methodology extensively examines various factors, some of them diametrically different, ranging from theoretical composites to psychological characteristics while others give emphasis on linking manual dexterities with intellectuality.

The results obtained after thoroughly testing the groups of children using HAs and CIs are presented in Table 7. They were processed statistically using one-way ANOVA with post-hoc group comparisons according to Scheffe test.

Table 7 Synoptic comparison of the dispersion mean values for the DTLA-4 methodology for groups of children with HAs and CIs.

N=140		Verbal Composite (standard score)	Non Verbal Composite (standard score)	Attention Enhanced (standard score)	Attention Reduced (standard score)	Motor Enhanced Composite (standard score)	Motor Reduced Composite (standard score)	**Total** (standard score)	Quotient of Linguistic Competence
HA	Mean $\bar{x}$	3.9	5.3	4.8	5.0	5.6	3.9	28.7	69.3
Initially HA and afterwards CI	Mean $\bar{x}$	5.5	4.7	5.2	5.5	4.4	29.4	68.9	5.5
CI from the beginning	Mean $\bar{x}$	4.6	7.3	5.2	5.7	6.3	5.3	34.2	76.2
	F	1.1	5.0	0.3	0.4	0.7	2.7	1.3	2.2
	Sig.	N.S.	$p < 0.01$	N.S.	N.S.	N.S.	$p < 0.05$	N.S.	N.S.

A pictorial representation of the received data is seen in Fig. 16.

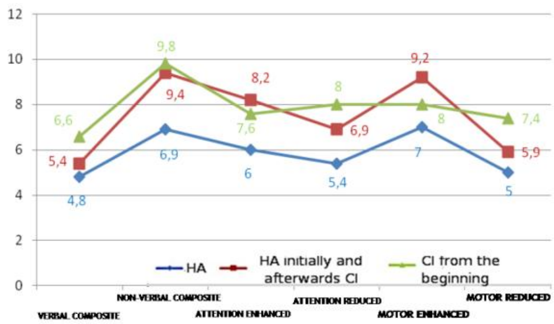

Fig. 16 Comparison between the groups of children using CIs and HAs according to the DTLA-4 norm-referenced measure of psychometric functions in language, attention and motor composites.

The results in Fig. 16 cannot give a clear edge on CI users as far as verbal composites are involved. For the Verbal Composite, i.e. the knowledge of words and their use, it does not seem that CI users outperform HA users. The same can be said about the Attention Enhanced Composite that evaluates concentration, attending and short memory capacity. When long-term memory recalls are encountered (as evaluated by the Attention-Reduced Composite subtests), and even further, when Motor Composites are considered, the results are mixed.

However, it is obvious by these measurements for assessing mental states and performance skills that CI users do unanimously much better in developed aptitudes for non-verbal communication.

This practically means that CI users excel in finding symbolic relations in designs or patterns, in visual discrimination and fast recall of objects from their memory bank, and speedy information processing.

As a result, the topic of optimal level mental processing is set up. The existence of bionic equipment is enhancing simultaneous processing, and therefore asks for an adjustment of the processing model depicted in Fig. 14. It is obvious that cochlear implantation, along with highly immersive and invasive audiovisual and kinetic devices deploy a BCI that more or less revamps the Human Processor Model [58] of the mid 1980's by adding a blend of virtual reality sensing.

A more realistic approach on how feedback or parallel auditory and visual input are handled can be seen in the model of Fig. 17.

Indeed, the initial model proposed by Card, Moran and Newell, provided a workable simulation in computer architecture terms for analysing how human cognition responds in a HCI manner with the plethora of incoming signals that trigger the human body to respond to what humans see, hear, or become aware of something through the senses. This triggering mechanism combines external and internal stimuli in provoking action, making use of complex level motor dexterities.

At this point, prosthetics and implanted devices offer a potential that did not exist, in the original 1986 model, which could not envisage the possibility of desirable future characteristics [61] like an "audio processor" or a "graphics processor" apart from the Central Processing Unit.

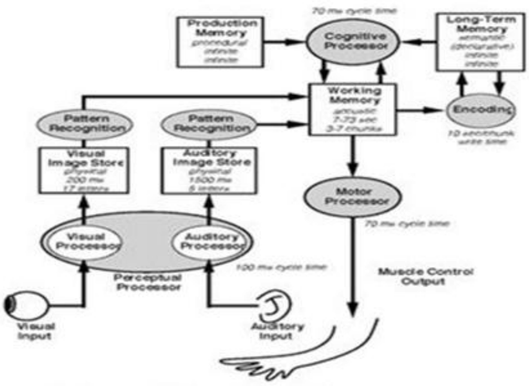

Fig. 17 The revamped Human Processor Model. (Cropped from https://blombladivinden.wordpress.com)

This new approach propels theories that take into account special capacities that enable individuals to display exaggerated performances and skills, which cannot be explained in depth by the theories of intellectual performance based solely on a person's reasoning ability.

Prosthetics, bionics and augmentation devices allow subjects to readily experience an augmented virtual reality that gives them, although handicapped and impaired in normal physiological values, the possibility to experience the production of sensual impressions stimulated by "parts" of their body, or provoked by other senses. As a result they may have differential ability achievements and simultaneous processing experiences that add "intelligence" to their normal, sequential conceptual ability.

How fast this bionic feedback is associated in terms of neurophysiology with organic brain synapses that affect the functioning intelligence is an object of ongoing research [24][62].

V. CONCLUSION

Hearing loss in young children results in language development disorders. Various researches in a multitude of languages have shown that cochlear implantation improves the linguistic competence of the impaired. In order to evaluate the linguistic development of children that used cochlear implants and compare it with that of children that used hearing aids the Structure Model Analysis of Narratives by Applebee, the Psychometric Test of Language Acquisition Competence (L-a-T-o) adjusted to the Greek language and practice, and the Detroit Test of Learning Aptitude (DTLA-4) were used.

Subjects of prolong study study were 140 children with severe to profound sensorineural hearing loss who were enrolled in mainstream school settings and used oral speech in order to communicate. 68 of them used a cochlear implant, 35 of these children used hearing aids initially and they underwent cochlear implantation later and 33 used a cochlear implant from the beginning.

Data analysis revealed that the group of cochlear implants users and the group of hearing aids users were equivalent in terms of learning acquisition competence. However, it was revealed that the cochlear implant users exhibited improved development in the three linguistic systems (reception, organization – production) and in the three linguistic forms (semantic, syntactic and phonological) compare to the hearing aids users.

The cochlear implant users had improved competence compare to the hearing aids users in producing and organizing their written narrative language according to the Structure Model Analysis of Narratives by Applebee.

Both learning acquisition competence and linguistic development of the subjects were enhanced compare to their chronological age in all the fields of their cognitive and linguistic development.

All groups of subjects, the group that used hearing aids initially and then underwent cochlear implantation, the group that used a cochlear implant from the beginning, and the group that used hearing aids, were equivalent according to their learning acquisition competence. It was found that the group that used a cochlear implant from the beginning exhibited improved linguistic development in comparison of the rest of the groups.

The linguistic competence of the examined children was correlated with the enhanced Model Human Processor in an attempt to correlate the impact of bionic devices on the feedback of phonation, as far as speech and language communication are concerned.

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