Auditive and Audiotactile Music Perception of Cochlear Implant Users

Martha Papadogianni-Kouranti

A Thesis presented for the degree of
Master of Science

Submitted to Prof.Dr. Stefan Weinzierl
Audiocommunication Group
Institut for Speech and Communication
Supervisor: Dr. Hauke Egermann

Technical University of Berlin
September 2014

Berlin, Germany

Dedicated to

all friends who patiently pretended to listen to my ideas..

Abstract

The subject of this thesis is the examination of possible influences of vibrotactile stimulation on melody and rhythm perception of children and adults with cochlear implants. For this purpose two experiments were conducted, in which the test subjects should assess whether given melodies[1] were the same or different. Seventeen child and nine adult participants were subjected to two different condition settings, audio only and audiovibrotactile. For the vibrotactile activation, a wooden chair was built from the author, which is able to transmit sound vibrations by using two bass shakers, placed underneath and behind the chair. The goal of the study was to investigate whether there is an improvement of melody and rhythm recognition rate from the participants, when additional vibrotactile information was applied. Results showed no significant differences in rhythm and melodic contour perception outcomes for adult participants, while there was a significant improvement of the melody recognition rate for child participants. Results indicate the importance of further investigation in the field of music perception with Cochlear implants by using audiovibrotactile excitation.

[1]The experimental stimuli were adapted from the Test Battery for Evaluation of Amusia (University of Montreál). For detailed report see Section4.2.1.

Zusammenfassung

In der vorliegenden Masterarbeit wird es untersucht, ob eine vibrotaktile Stimulation die Melodie- und/oder Rhythmuswahrnehmung von Kindern und Erwachsenen mit Cochlea Implantat verstärken könnte. Für diesen Zweck wurden zwei Experimente unter zwei unterschiedlichen Experimentsbedingungen durchgeführt: nur akustisch und audiovibrotaktil. Aufgabe der Versuchpersonen; siebzehn Kinder und neun Erwachsene, war es zu beurteilen, ob die dargebotenen Musikpaare gleich oder ungleich waren. Die vibrotaktilen Stimuli wurden durch einen von der Autorin gebaut Klangholzstuhl mit der Hilfe von zwei Bass-Shakers übertragen. Ziel der Studie wäre es zu zeigen, dass die zusätzliche vibrotaktile Schallinformation die Musikwahrnhemung von CI-Träger verbessert. Den Ergebnisse gemäß, gibt es eine signifikante Interaktion zwichen Stimulationsart und experimentalem Task für beide Teilnehmer-Gruppe. Die Melodie-Erkennungsrate von Kinder CI-Träger verbesserte sich signifikant, während die der Erwachsene nicht. Die Rhythmus-Erkennungsrate beider Gruppen war signifikant besser unter den zwei unterschiedlichen Stimulationen. Die Ergebnisse bestätigen daher, dass die vibrotaktile Stimulation die Musikwahrnehmung mit CIs fördern könnte. Es würde die Durchführung weiterer Experimente im Gebiet der Musikwahrnehmung von CI-Träger mit vibrotaktiler Stimulation empfohlen.

Erklärung

Hiermit erkläre ich an Eides statt gegenüber der Fakultät I der Technischen Universität Berlin, dass die vorliegende, dieser Erklärung angefügte Arbeit selbständig und nur unter Zuhilfenahme der im Literaturverzeichnis genannten Quellen und Hilfsmittel angefertigt wurde. Alle Stellen der Arbeit, die anderen Werken dem Wortlaut oder dem Sinn nach entnommen wurden, sind kenntlich gemacht. Ich reiche die Arbeit erstmals als Prüfungsleistung ein.

Martha Papadogianni-Kouranti

Berlin, den 15. September 2014

Acknowledgements

My deepest gratitude goes to my supervisor Dr. Hauke Egermann, who gave me the opportunity to conduct my thesis and always supported me with his knowledge and experience. I would like to express my warmest appreciation to Dr. Silvia Zichner and the team of the CIC-Coclear Implant Centrum of Berlin-Brandenburg, for their support, help and permission to perform my experiments in their house. Special thanks to Katharina Koch, forewoman of the wood-workshop of the University, Thanassis Lykartsis, Michael Stuetz from the Institute of Technical Acoustics TUB and Marten Seedorf. I wish to thank Prof. Dr. Stefan Weinzierl for accepting my thesis and directing my initial approaches. Finally i would like to convey my warmest thanks to my family and all friends who encouraged me and gave me always feedback when needed.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

The research on music perception of Cochlear Implant users (CI-users) has been developing during the last years. Most of the studies investigate the ability of melodic contour identification and timbre recognition, as well as emotional communication; rhythm and meter recognition are also examined. The results of those studies have shown that although CI-users perform nearly equally to normal hearing control groups at rhythm associated tasks, but they face great difficulties when they have to assess spectral related tasks ([8-10], [13], [15],[21-24], [31, [34], [35], [39], [40]).
Cochlear implants are medical prosthetics which can electrically stimulate the auditory nerve. These devices are placed in the inner ear of people with severe to profound hearing loss and are able to convey sound information when current hearing aids can provide no benefit. CIs are optimized for speech perception; therefore music perception of CI-users is problematic ([22], [23], [31]). Due to technical limitations, only coarse spectral information can be transmitted, resulting poor frequency resolution, i.e. limited sound perception.
All in all, the sense of hearing is strongly correlated with the perception of vibration ([1], [4], [5], [12], [14], [16], [20], [25-30], [33], [38]). Either consciously or unconsciously vibrotactile signals are permanent integrated with auditory inputs into one multimodal percept ([30], pp.1). This kind of sensory interplay initializes the subject of the following master thesis; the investigation of a possible enhancement of the music perception of people with cochlear implants through audio-vibrotactile excitation.

Many studies in the area of music perception of normal hearing people, examine the influence of vibrotactile inputs on several musical attributes, such as rhythm recognition, timbre identification, meter detection, loudness perception and polyphonic pitch. Their findings are important, as they indicate that vibrations have great influences on music perception. However, music perception of people with different types of hearing loss and especially of people with cochlear implants should be investigated isolated, because of the great particularities which are present.
Although research in the field of multi-modal interactions suggests that auditory and vibrotactile inputs are strongly correlated; audiotactile interactions are indicated by MEG recordings early in the cortical processing hierarchy [12]; furthermore, in [20] was shown that vibrotactile inputs are able to activate the human auditory cortex of congenitally deaf people; all of the studies which investigate the music perception of CI-users use airborne sound information. Only a small number of studies in the area of music perception of people with hearing difficulties or deaf people had made usage of vibrotactile stimulation ([4], [11], [16], [20], [33]).
One of the most important steps was the development of the "Emoti Chair" ([4], [16]). An audiotactile system which was developed in the Department of Psychology of Ryerson University in Canada [16] and is able to represent the audio information as tactile stimuli. In accordance with the auditory Model of Human Cochlear, a model of physical translation of the cochlear critical band filter on the back was created. Different frequency bands of a musical work were mapped to each of the loudspeakers on the back of the chair, processed so as to correspond to the frequency range of the sensitivity of the skin. The frequency discrimination ability with an artificial deafness degree was investigated and the results suggested that vibrotactile information can be used to support the experience of music information even in absence of sound ([4], [16]). Furthermore, it has been shown that participants were able to discriminate between vibrotactile inputs which differed in frequency by 1/3 of an octave.

The absence of empirical evidence from the field of audiovibrotactile music perception with CIs demands the conduction of more methodical approaches. Therefore,

the following study was conducted with the aim to fill some gap knowledge, still underlying the need for further research.
The thesis focusses on the rhythm, as well as the melody recognition rate of child and adult CI-users by making a comparison of their performance under two different experimental conditions; "audio only" and "audiovibrotactile" stimulation. The work focuses on the question; "Are simultaneously presented musical vibrations able to improve the music perception of cochlear implant users?".

The thesis is organized in six chapters; the first chapter introduces the general problematic and outlines the state of research. In the second chapter important theoretical fundamentals are described. The following chapter details the cochlear implant function and analyzes the music perception of CI-users. The experimental procedure is reported in chapter four and the results, as well as their interpretation are presented in chapter five. A final conclusion and proposals for future work can be found in the last chapter.

1.1 State of Research

The research of music perception of CI-Users has been developed the last decade in the topics of melody and rhythm recognition, as well as emotional identification. Most of the studies investigate the performance of Cochlear Implant users in comparison with normal hearing people, by using acoustical stimulation.
Donnely P., J., in [8] examines the ability of post-lingually deafened adults to identify polyphonic pitch. Their recognition rate is compared with that of normal hearing adults. The test stimuli are presented acoustically and consist of one, two and three simultaneous musical tones, both pure tones and played on the piano. The frequency range spanned one octave. The results present particularly lower scores of CI-users in identifying one, two ore three-tone-intervals than normal hearing subjects. The ability of CI users to discriminate polyphonic simultaneous tones is significantly poorer than that of normal hearing people. CI users perceive in many cases polyphonic pitches as one single tone. The limited frequency resolution that current

CI-devices can offer, leads to narrow presence of harmonical and spectral information. Consequently post-lingually CI-users face great difficulties in perceiving the harmonical content of musical performance.

The melodic contour identification of CI-adults is investigated in [10] by comparing the resulting data of the same subjects before and after musical training, while also comparing the results with those of familiar melody identification. CI performance is ranged widely, mirroring great inter-individual differences. Results indicate that melody identification is better when the distance between musical intervals increases and when rhythmical cues are presented. Familiar melody identification and contour identification are not correlated, but the latter is associated with vowel recognition performance. Musical training significantly improves the identification rate.

The study of [13] is of great interest, because it uses the children version of the Montreal battery of evaluation of musical abilities (MBEMA)[1]. Children and adolescents wearing unilateral CIs are tested in melody and rhythm recognition, as well as regarding their memory capacity. The stimuli are presented acoustically through an external loudspeaker. [13] focuses on the possible correlations between musical performance and age at implantation, furthermore investigates if the amount of residual hearing can improve musical performance. It is hypothesized that children with CIs perform better at rhythmical tasks, while they have greater difficulties at melody-relevant tests (scale, contour, interval). A comparison with a control group of NH-matched aged participants was made which shows that the music perception with CIs is far below that of normal hearing. The results confirm that CI-users melody recognition ability is poorer, in contrast to temporal-based tasks, like rhythm recognition. CI-users achieved significantly better scores at the memory test; according to these results [13] suggested that CI-users might use temporal, rather than spectral cues to identify melodies. Furthermore, the outcomes of both rhythm- and memory-test approved the hypothesis that greater residual hearing could en-

[1]The Musical Battery for Evaluation of Amusia (MBEA) is the most important and efficient tool for assessment of musical disorders in humans, developing parallel to the research progress. The MBEA Battery can be completed from adults and children after the age of 10 years ([36], pp.1) (see Section 4.2.1).

hance the perception of musical parameters, and emphasizes the significance of early auditory stimulation for improving the development of hearing processing.

The study of[15] investigates several tasks of sound perception abilities of prelingually deafened children: the clinical assessment of music perception, the consonant-nucleus-consonant (CNC) word recognition in quiet, the spondee reception threshold in steady-state noise (SRT) and measures using psychoacoustical approaches, the spectral ripple and the Schroeder phase discrimination. Additionally, he makes a comparison between the resultant data and existing data from previous studies testing postlingually deafened adults CI-users. In the study no correlations between results and age at implantation, as well as CI-experience are observed. CI-children users perform significantly worse on Schroeder-phase-discrimination, melody and timbre identification, compared to adults. The results of the other tasks of both groups are considered statistically equal. As possible explanation for the great differences between Schroeder-phase discrimination[2], and melody-timbre recognition, the incomplete development of central temporal processing strategies at children is given , whose abilities reach their maximum capacity after the age of 11. It is hypothesized that children and adults make usage of different temporal and spectral processing strategies. [15] suggests that the children population uses more its spectral sensitivity and not the immature temporal one.

In [21] is investigated the music perception of CI-Users in the neurophysiological level. To estimate the auditory cortical activations the PET-method (Positron emission tomography) is used. Ten postlingually deafened adults and ten normal hearing adults as control group are tested under the same conditions. The authors hypothesize that CI-users will present greater auditory cortex activation, than NH-group. Both groups are acoustically stimulated, in three different tasks: melody, rhythm and speech-recognition. The results showed that both groups perform their maxi-

[2]Schroeder-phase stimuli are time-reversed sound pairs with identical long-term spectra and minimal envelope modulations, i.e. they have different Acoustic temporal fine structure (TFS). TFS has been shown to be critical for good performance in difficult listening tasks, such as music perception; therefore, these stimuli have been used to measure sensitivity to TFS with minimal envelope cues ([9] pp.139)

mum on the rhythm-test, followed by the speech one. Melody recognition presents the lowest accuracy, especially for CI-Users, where it remains just above the chance levels. The PET-results demonstrate greater activity in the temporal cortices of CI-users, in comparison with normal hearing, for all three tasks. CI-users poorest activation is shown during the melody task, offering a possible explanation about their limited performance. In accordance with the speech-oriented development of CI-devices, the most significant activation is observed during the language task. [21] supports the need of further investigation, of how the activation of different brain areas and the performance in music and speech perception are correlated.

The article of [23] gives a review of the present research scene in the field of music perception of implant users and makes a report of the affects of cochlear implantation on perceptual abilities. Regarding listening preferences, results make clear that postlingually deafened CI-users with late implantation cannot appreciate and enjoy music as they did before. Many of CI-adults describe listening to music as disappointing and some of them classify musical sounds as noisy. On the other hand, prelingually or congenitally deaf children who were implanted in early ages develop their listening capacities based on the electrical-implant listening experience. Furthermore the results of this study indicate that CI-users performance is equivalent with this of NH in tests relative to temporal cues (rhythm and meter), compared with frequency related sound tasks. Especially pitch discrimination and timbre recognition abilities are limited. It is not clear on which attributes CI-users depend when they are called to discriminate tonal pitch, but is assumed that their ability is not one-dimensional, rather depends on a combination of different perceptual paths. Timbre is a multi-dimensional musical attribute. Cochlear implants cannot convey accurate timbre information, making the recognition of a musical instrument difficult. Furthermore, depending on the instrumental timbre, CI-users classify the pleasantness of different instrumental sounds, with those of higher frequencies, such as flute, to be often disappointing or even noisy. The melody identification includes pitch discrimination, timbre recognition, as well as rhythm and possible verbal perception. The research outcomes indicate that rhythm and verbal cues, as well as familiarity with the musical material, significantly improve successful melody identification. Moreover the

interindividual differences are mentioned, which are correlated with different factors, such as: age at implantation, anatomical characteristics of the inner ear and brain areas, exposure to sound, residual hearing, CI experience and processing algorithm. [23] stresses the benefits of musical training and its efectiveness to the enhancement of musical experience.

The ability of prelingually deafened Japanese children to recognize familiar television theme songs is examined in [34]. The children should identify a known melody under three different versions: one original, one original with no lyrics and one instrumental, where only the main melody (theme) is played. The results show that the children are able to recognize the melody of the original versions. They fail to identify familiar songs when the lyrics are removed or when only the main melody is heard. They hypothesize that this is mainly due to the fact that: music perception of CI-users relies more on temporal rather than spectral cues[3]; and CI-technology is optimized for speech understanding, it is expected that CI-users can more easily recognize familiar melodies, when the lyrics are present. The resultant data ratify these expectations.

In [39] the ability of child CI Users in identifying familiar songs and TV theme songs is examined. Additionally, their singing capacity and their listening preferences are investigated. The results are compared with those of normal hearing age-matched children. For the familiar-song-recognition-task, the children should recognize a familiar song under three different conditions: one with the original piece and two instrumental versions, the first of which presents the original song without vocals and the second the main theme-melody played on the piano. CI-users performance is significantly poorer than NH children, for all tasks. The information amount and the resultant performance of both groups are strongly correlated and similarly distributed: Both NH-children and child implant users achieve better results when they assess the original version, followed by the original without vocals, while they face great difficulties when stimulated by the synthesized melody. For recognizing the TV-song-themes the same three versions are produced again (but the main melody

[3]Nonetheless the recognition of a melody depends significantly on pitch cues.

is played by flute). [39] makes a comparison between a group of Canadian 4 to 11 year-old CI users and the results of [33] of a group of Japanese children 4 to 9 years of age. As stated above, the Japanese children perform above chance levels only with the original versions, while only chance ability is shown for the other two. On the contrary the Canadian children are able to identify the songs also from the melody (flute) versions. Possible explanations are that the Canadian have greater exposure to music; moreover that different timbres (piano and flute) could likely influence the perceptual accuracy of the children . In [39] child-CI users sing their favorable songs. The same are sung also from NH-children and the results are compared. Both groups performed well with regard to the rhythmical content. However implanted children use only a narrow frequency range when reproducing the tonal pitches, reflecting the limitations of spectral processing. This study aims furthermore to draw parallels between children and adult implant users, suggesting that the latter face more difficulties in music processing, while children are capable to enjoy music and show greater engagement.
The study of [40] examine the capacity of prelingually deafened children to recognize emotion in music and speech. All child-CI-users have bilateral implants. A control group of age-matched normal-hearing children is also investigated. Two emotions are identified: hapiness and sadness. It is shown that the experience with the cochlear implant leads to better performance for both tasks. The child CI-users perform above chance levels, but their rate is far below those of normal hearing children. It is assumed that child-CI users can poorly recognize tonal pitch variations in a way to be able to identify emotion in music; using more likely amplitude or/and temporal, than spectral cues.

To summarize, research studies indicate that CI-users perform equivalent to NH subjects on rhythm-related activities, but face great difficulties when asked to judge spectral content associated tasks. Technical limitations of current CI models in processing strategies of spectral cues cannot provide accurate conveyance of musical information, making melody recognition and timbre identification a challenge for many CI-users. Moreover subjects individual properties, musical training and

sound experience influence their perceptual capacity.

The above mentioned studies offer great knowledge about music perception of CI-users, both for child and adult patients for many different fields of research. However, considering that until now[4] none of those has investigated the music perception with CIs by using vibrotactile stimulation; moreover in accordance with the approved sensory interactions between tactile and auditory inputs, this thesis focuses on the compensation of the lower frequencies whose resolution is no longer possible after the implantation, with the ambition that the latter will reinforce the overall music perception of CI-users.

The experimental procedure consists of two tests which investigate musical attributes under two different stimulation types: audio only and audiovibrotactile. An improvement of melody and rhythm recognition rate is expected when additional vibrotactile information is applied. The main idea of the study is that the compensation of the lower frequencies below 190 Hz (which cannot be conveyed after the implantation) might enable an enhancement of the overall music perception. A great improvement of the rhythm perception is not expected, thus CI-users are able to perceive temporal information relative accurate. On the other hand, melody recognition rate is aimed to be significantly reinforced. The null Hypothesis H_0 states that no effect will be present, expecting no difference between the mean performance of the participants when stimulated under the two different conditions. The alternative Hypothesis H_A supports the goal of this thesis by suggesting that the mean performance of the participants under the two different stimulations is not equal and will be enhanced under audiovibrotactile stimulation. The results will be analyzed with a repeated-measures analysis of variance in SPSS [45].

[4] Due to the individual literature survey.

Chapter 2

Fundamentals

In this chapter an introduction to the auditory processing of normal hearing listeners is reported. Moreover, a brief overview of the fundamental elements of the vibration perception, and how auditory and vibrotactile inputs interact, is given. Finally, both melody and rhythm perception for normal hearing people are described in the last section.

2.1 Auditory Processing

The Auditory Processing of normal hearing listeners consists of two different stages: The preprocessing of the sound in the peripheral system and the neural processing where the sound information is encoded into auditory sensations ([43], p.23).
The peripheral system includes the head and the ear of the listener; their anatomy influence significantly the receptible sound information ([43], p.23). The human ear consists of three parts: the outer ear, the middle ear and the inner ear. Each of them fulfills a different function.

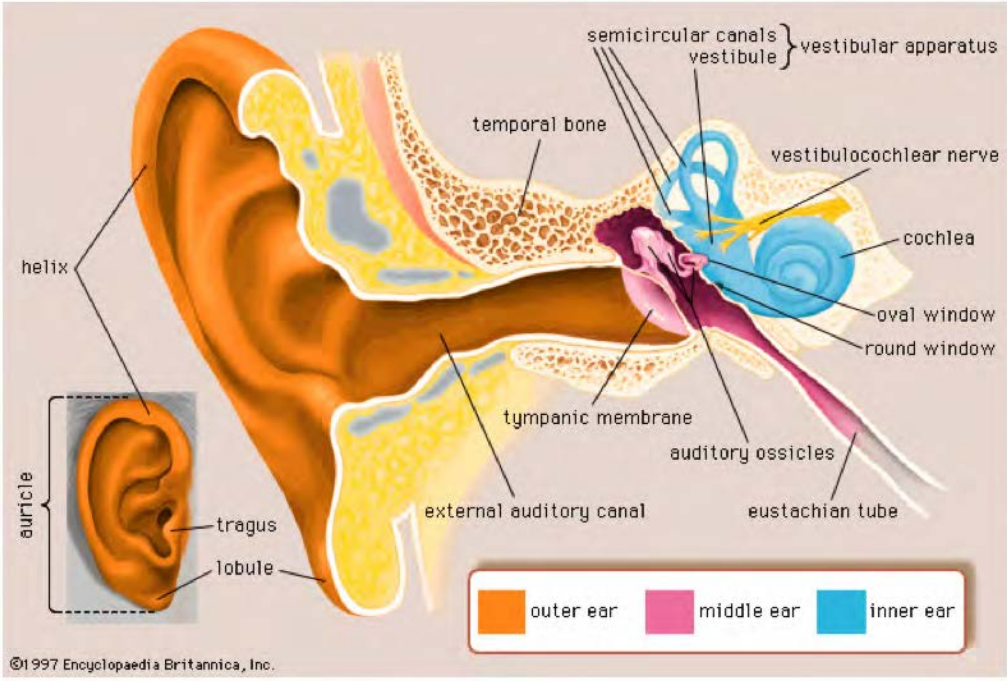

Figure 2.1: Schematic drawing of the different ear parts; [43]

The outer ear consists of the pinna, the auditory canal and the eardrum. It is responsible for the collection of the sound waves, their pre-amplification, i.e. enhancement of the sound intensity by a factor of two or three and the sound localization in the auditory scene.

Sound waves enter the auditory canal and travel to the eardrum. Through the multiple reflections at the tunnel they provide maximum sensitivity regions. The auditory canal can be pictured as a $\lambda/4$ resonator with resonance frequencies between 2 and 5 kHz, the most important frequency range for speech perception and discrimination. At the end of the auditory canal is the eardrum (tympanic membrane), which separates the middle from the outer ear. The eardrum is a very thin membrane (about 0.1mm), which immediately starts to vibrate after receiving (and reflecting) the amplified sound waves ([43], p.23).

The middle ear, an air-filled cavity, is on the inner side of the eardrum and contains three tiny ossicles, which transmit the sound waves to the oval window of the inner ear. These ossicles are the malleus, incus and stapes (or commonly hammer, anvil and stirrup) and follow the Law of Lever, amplifying the sound vibrations by a factor

of about two or three before transmitting them to the inner ear. The most important function of the middle ear is that it performs an energy transformation, from the air in the canal to the liquid in the inner ear (acoustical impedance). Furthermore, it compensates the pressure difference between the cavity and the enviroment through the eustachian tube, which connects the middle ear with the nasopharynx ([43], p.24-25).

The inner ear consists of two parts with different functions: the cochlea who is responsible for the processing of the auditory information and the semicircular canals, which communicate with the cochlea and are correlated with the sense of equilibrium. The cochlea converts the sound energy into neural (electrical) impulses. The Cochlea is a coiled tube with about 2.75 turns filled with perilymph, a liquid with high viscosity. It consists of two parallel channels, the scala tympani and the scala vestibuli. The lamina spiralis, a bony projection where the basilar membran is attached, separates the scala tympani from scala vestibuli. Between them a thin membrane called Reissner´s membrane defines the scala media. Scala vestibuli and scala tympani are coupled through the Helicotrema ([43], p.26).

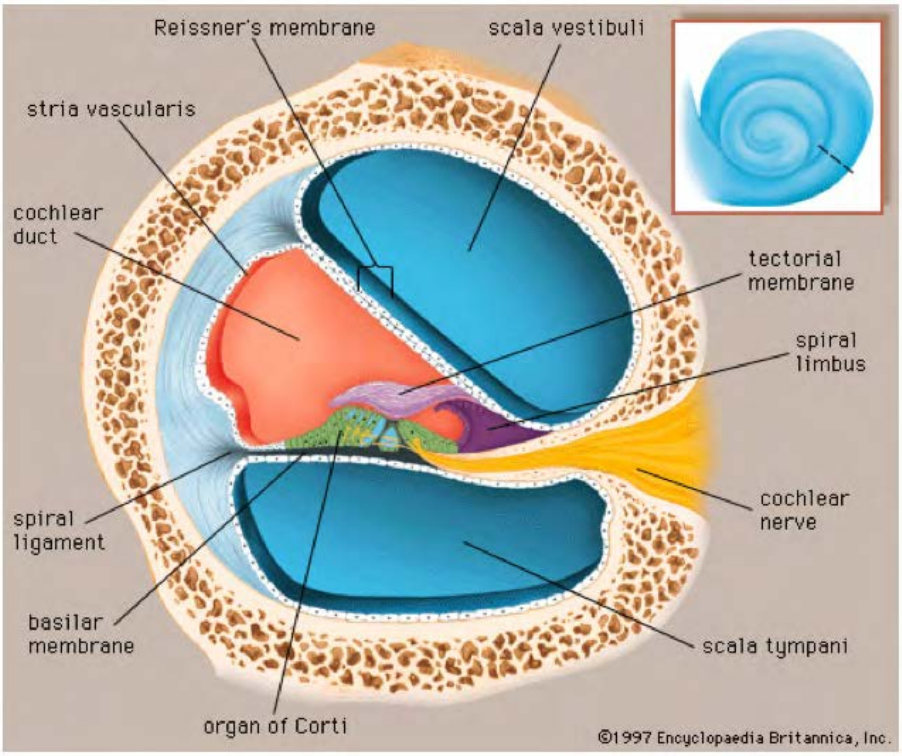

Figure 2.2: Cross section of the Cochlea; [44]

When the sound vibrations reach the oval window, they induce pressure oscillations in the fluids of the cochlear (perlilymph and endolymph). These followingly displace the basilar membrane, a structure which separates the cochlea along is length, from the resting position. The mechanical properties of the basilar membrane (BM) alter along its length. Near the oval window the BM is stif and narrow, while near the helicotrema wider and flexible [Wil08]. The pressure difference travels in the form of a progressive/travelling wave along the BM from the oval window to the other end "Helicotrema". The amplitude of the travelling wave is not constant. The maximum excitation depends on the frequency of the sound wave and defines the pitch perception. On the BM the traveling wave begins with low amplitude near the oval window. The amplitude increases steadily up to a maximum and then rapidly decreases. Higher frequencies reach their maximum (peak) near the oval window (base), whereas lower frequencies near to helicotrema (apex). The sound propagation is associated with specific places on the basilar membran, therefore the term frequency-to-place (place theory) conversion for the frequency encoding (see fig. 2.3).

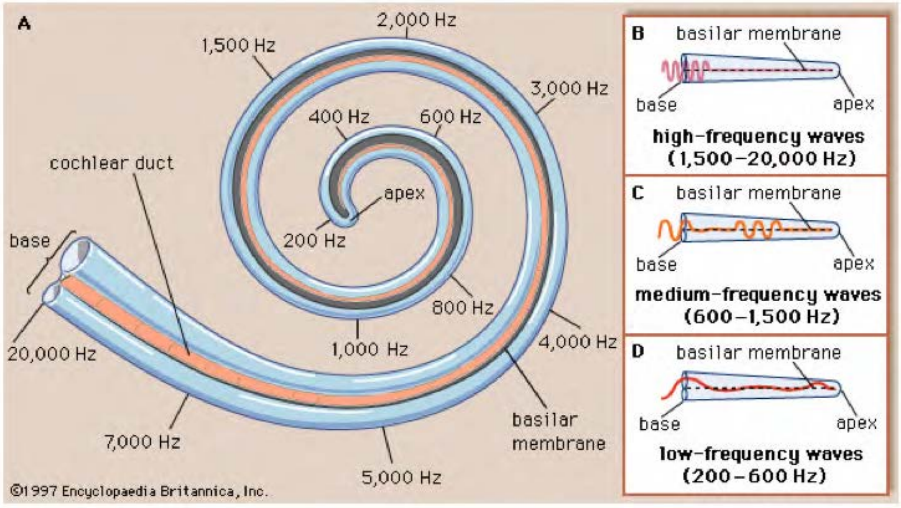

Figure 2.3: Stimulation of the basilar membrane; [44]

On the basilar membrane, the organ of Corti is placed. There, the mechanical stimuli are converted into neural signals by the 16000 to 20000 (30000) sensory receptor-cells which are placed on it. These are sensory transducers (called hair cells), organized in two groups: the outer and the inner hair cells. The bottom of the hair cells is attached on the basilar membrane. On their surface they have projections of different lengths, called stereocilia. The stereocilia transform the mechanical energy of the sound waves into electrical signals, which excite the auditory nerve: The vibrations after a sound excitation cause a shearing force between the basilar membrane and the tectorial membrane, which lies above it. As a result, the hair cells change their length. This deformation of the cells caused by the deflection of the basilar membrane leads to the release of action potentials, i.e. electro-chemical impulses, which are transmitted to the auditory center by the nerve fibers ([43], p.27-30).

The transmission of auditory information to the brain via the nerve fibres constitutes the primary auditory pathway. The filtering and processing of sound information takes place at the secondary and the central auditory pathways. However, "the understanding of information processing, especially in higher center of the brain, is still incomplete" ([43], p.60); a clear description of the interconnections between the stimulus perception and its final sensation is not possible. The tonotopic organization of the basilar membrane is proceeded to the brain which is arranged tonotopic:

The nerve fibres "tend to maintain their spatial relations to one another" ([43], p.59); different frequency responses are therefore organized systematically "according to location in all centres of the brain" ([43], p.59).
Sound information is decoded firstly (as stated above) in the primary auditory pathways. However, auditory messages are processed also in non-primary auditory pathways. There the decoding of different sensory inputs is reported ([32], p.86). The main function after the collection of different input information is the filtering of those which must be processed first and the simultaneous abstraction of any other present stimuli; i.e. the focus on the most vital task. Existing neurons of the non-primary pathways respond to sound information, as well as to other sensory inputs, such as tactile or visual stimulation. Through the reticular formation[1] the sound input is collected and processed with the other sensory stimuli [31]. Research on cross-modal interactions between the auditory and the somatosensory systems indicate that non-primary auditory pathways are involved in hearing processing [32] p.86.

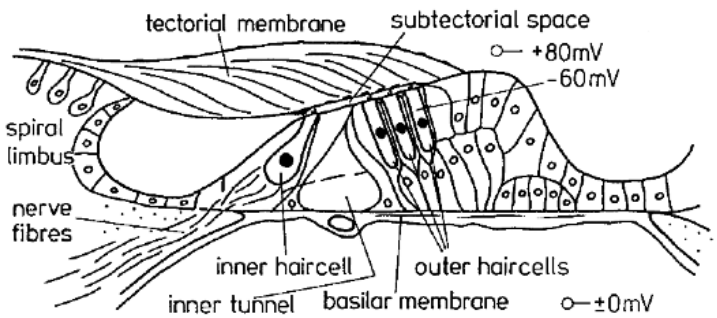

Figure 2.4: Schematic Drawing of The Corti-organ; [43], pp. 27.

2.2 Vibration Perception

Sound is not only audible, but it also can be felt through different sensory pathways ([32], p.86). Hearing sound is possible via air or bone conduction, while feeling sound through several activities of our somatosensory system, i.e. kinesthetic, haptic and

[1]The reticular formation is a structure of nerve pathways which enables the transmission of information produced by sound, smell, touch and other sensory modalities ([7], p.380).

tactile processes.

The perception of vibration cannot be separated from the sense of touch. The human body does not have special receptors just for the vibration sensation [3]. Vibration sensation can be categorized into the "Whole-Body-vibrations" and the "Hand-transmitted-vibrations" sections. The absolute sensoric thresholds, as well as the limens of JNDs differ significantly between different subjects ([1-3], [26], [27]). Individual factors affect the perception of vibration, such as body posture, structure of the skin, structure of the epidermis and dermis, body temperature and body resonances. The resonance areas of the body are modeled theoretically and are coupled with the direction and the frequency of the input vibrations. Furthermore the perception of vibration is correlated with stimulus duration and contact force. The difference thresholds are strongly frequency dependent, presenting an increasing JND-value when frequency also increases [3].

Sound perception is related to the cutaneous senses of the somatosensory system like touch, pressure and vibration. There are different receptor types (sensors) in the skin (epidermis and dermis) capable to convey specific information. Of foremost interest in respect to the vibration sensation are the Pacinian Corpuscles. These mechanoreceptors are located in the dermis, i.e. deep in the skin and are able to adapt rapidly and recognize an input signal of some μm magnitude. A normal somatosensory system perceives vibrations in a frequency range of 0.4 to 1000 Hz. Between 100 and 300 Hz, 1-2 μm vibrations enough to stimulate the Pacinian corpuscles and activate the vibration sensation ([4], p.155). The detectable frequency range differs between the mechanoreceptors.

Receptor	Receptor Type	Field Diameter	Frequency Range	Sensed Parameter
Merkel Disks	SAI	3-4 mm	DC-30 Hz	Local skin curvature
Ruffini Endings	SAII	>10 mm	DC-15 Hz	Directional skin stretch
Meissner Corpuscles	FAI	3-4 mm	10-60 Hz	Skin stretch
Pacinian Corpuscles	FAII	>20 mm	50-1000 Hz	Unlocalized vibration

Figure 2.5: Basic Characteristics of mechanorecpetors in human skin; available online $http://bdml.stanford.edu/twiki/bin/view/Haptics/VibrationOrForce.html$.

Pacinian corpuscles reach their maximum at around 250 Hz, while they can less

easily perceive frequencies below 50 Hz.

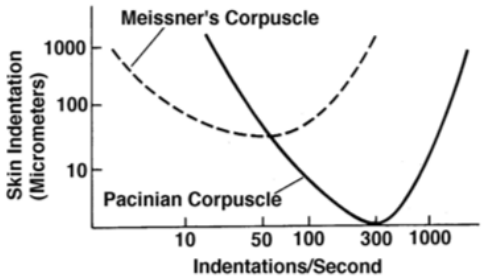

Figure 2.6: Perception Threshold of Pacinian Corpuscles; available online *http://neurobiography.info/t.*

Somatosensory and auditory inputs are considered to be strongly correlated; Non-primary pathways are activated both by auditory inputs and signals carried from the cutaneous receptors ([7], p.380). Research in audiotactile interactions determines a multisensory potential of the human auditory cortical areas for tactile processing ([1], [4], [5], [12], [14], [16], [20], [25-30], [33], [38]). The cross-modal interplay is indicated by activations of both the somatosensory and auditory cortices in early stages of perceptual processing[2]. (Vibro)tactile percepts are integrated with auditory information to one multi-modal process ([5], p.1157-1160).

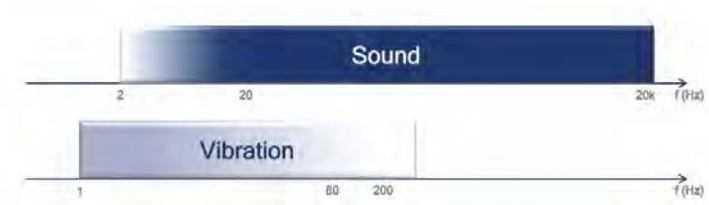

Figure 2.7: Overlapped Frequency Regions: Sound and Vibration Sensations; [26], pp. 4.

Tactile inputs are able to activate the human auditory cortex, even of congenitally deaf people [20]. The auditory cortex is capable to discriminate between different vibration frequencies. However for normal hearing people the auditory information dominates, when tactile and audio inputs share similar frequencies [16].

[2][21]indicates, that vibrotacitle stimuli alone can activate the human auditory cortex. MEGs have shown, that the first responses to vibrations take place in the primary somatosensory cortex, followed by the auditory cortices and then the secondary somatosensory cortex.

The vibrotactile sense is poorer compared with auditory processing, when judging frequency differences.

Vibrotactile stimulation significantly influences the auditory perception of several musical attributes , as well as emotional communication and the enjoyment of music. In accordance to loudness perception (isophone curves), the perception threshold of body vibrations and the JNDs are subjective. In [3] the measured JNDs for whole-body vibrations have shown that between 5.4 and 40 Hz the discrimination ability of frequency increases with increasing frequency in accordance with the relationship 0.34*f-1.25 Hz. For frequencies above 40 Hz no study has been conducted yet.

Additional musical vibrations can improve especially rhythm and meter perception. They seem also to enhance positively the quality of musical performance[3].

2.3 Music Perception

The importance of experiencing music extends both to a psychological and a biological level. Emotional and social intelligence (alienation), self confidence and self esteem are strongly connected with music perception. Music can activate the pleasure centers in the human brain, induce and communicate emotions. When listening to music, both sides of brain are used [17],[4] improving the development of multiple intelligence. Moreover music has a therapeutic role, not only for psychological supporting, but also for curing illnesses. Musical education affects the development of a childs brain emotionally (expression, communication, emotional maturity), physically (motor capacities), spiritually (memory capacity, discrimination abilities, attention) and academically (greater performance). Furthermore, it can improve critical thinking and team-working [17].

Music is able to convey emotions. The emotional communication has some universal common characteristics, but also depends on cultural and social factors[5]. Therefore,

[3]For more detailed report see: ([1-4], [14], [25-30], [38])

[4]Brain interconnections

[5]The interpretation of emotions conveyed by music is based also on social patterns, which are bequeathed to people during social communication

exposure to music significantly influences the cognitive, social and emotional development of a child.

Music perception is a complex cognitive, learning and behavioral process, which consists of many different mental, psychological, social, somatosensoric and motoric components. Music processing is structured, filtered and analyzed hierarchically in the human brain. Conveying musical information is divided into different levels, from low level, which are the four basic perceptual musical characteristics, i.e. timbre, loudness, pitch and duration, to high level properties such as interpretation, expectations or musical intentions.
Spectral, temporal and amplitude cues contribute to the sound processing. The organized differentiation of temporal patterns forms the sense of rhythm, while the sequencing of tonal pitches the melody identification. Contrary to speech perception, music involves more complex processes, according to the complexity of musical stimuli. The basic musical attributes are associated with different musical properties. Changes on the note-durations convey different rhythmical information, whereas variations in timbre indicate different instruments. However, musical experience combines all these characteristics into one entity [17].

Melody

Melody is defined as a rhythmical organized sequence of musical tones, in a manner that they produce a musical entity ([17], [23]). Its definition involves that melody recognition is correlated both with spectral and temporal cues[6]. Additionally, individual properties like musical experience and training, sociocultural characteristics, psychological parameters and listening preferences significantly affect the perceptual stage. Melody recognition is primarily connected with pitch perception. Pitch processing is based on both pattern-organization strategies and temporal-related mech-

[6]Different factors which affect melody recognition are melodic contour identification, rhythm perception, tempo, timbre, phrasing, dynamics, texture and articulation.

anisms [23]. The mechanism of excitation of the basilar membrane, when stimulated by sound is very complex: Complex tones activate simultaneously many different positions on the membrane, which however vibrate in a specific tact, that defines the fundamental frequency of the input signal. In order to perceive the pitch of a complex sound, the auditory system must extract this fundamental frequency ([17], [23]). This process requires both the spatial mechanism, i.e. frequency resolution and analysis into the involved components, and the extraction of the temporal pitch information as mentioned above. The perceived sensation is formed both from the peak of the basilar membrane and the temporal schema of the cells activation [23]. The auditory mechanism acts like a bandpass filter, separating the complex enviromental sounds into its components. Frequency selectivity[7], stream segregation and frequency fusion are products of filtering and analyzing an input sound signal into its frequency components and compensating the meaningful cues [23]. The recognition of a melody in a musical context is correlated with this capacity, depending on the number of different sound streams (musical lines and different instruments). The order of the overtones of a fundamental frequency is significant for pitch identification, with the lower harmonics being more important: "The pitch of a complex tone is based on the spectral pitch of its lower components" ([43], p.120).
In some cases the phenomenon of virtual pitch appears. This is defined as the situation in which the fundamental frequency and eventually some of the lower harmonics are missing, but the human auditory mechanism allows the perception of the missing[8] fundamental.

[7]The width of the auditory filters plays significant role to the ability of frequency selectivity. As a result, CI-users present limited selectivity because of the increased filter bandwidths (in some situations NH have the half bandwidth [23].

[8]For detailed report [43], Chapter Five.

Rhythm

Rhythm is the temporal organization of music [14], [23]. It defines a serial pattern of different durations. The temporal organization is primarly indicated from two parameters: periodicity and patterning. Rhythm perception requires the activation of overlapping brain areas. Auditory and motoric pathways are activated and sychronized to an input rhytmical pattern. Fundamental components of temporal organization are meter, tempo, and beat, which must not be confused with rhythm [14]. Rhythm involves all these parameters, forming a single entity. Rhythmic perception is part of the elementary music processing ability. Human response to rhythm and its different periodicities (beats) is an automatic sychronized motor reaction, even possible by infants. Contrary to melody, rhythm is an independent musical feature. Hence, no other attribute is required for its perception. While auditory pathways are important for processing the frequency related cues, rhythm can additionally activate the somatosensory system mechanisms through the vibrotactile sensation. Consequently, it can be easily recognized even by hard of hearing or deaf people [14], [17], [23], .

Chapter 3

Cochlear Implants

3.1 Hearing Loss

The term hearing loss points to many situations of different degrees of disability to perceive auditory information.

The diagnosis of the type and the degree of hearing loss depends on the performance of hearing sensitivity by auditory testing. To measure the hearing acuity the Decibel Unit (dB) is used. The threshold is defined at 0 dB, where normal hearing young adults can perceive a tone of specific frequency and intensity level. For children the range of normal hearing exhibits up to 20 dB of the defined thresholds. Depending on the acuity demonstration of sound intensity different levels of hearing loss are classified: mild ($20 - 40$ dB), moderate ($41 - 55$ dB), moderately severe ($56 - 70$ dB), severe ($71 - 90$ dB) and profound (> 90 dB). Due to the performance of frequency perception, the severity of hearing loss is classed as low (< 500 Hz), middle ($501 - 2000$ Hz) or high(> 2000 Hz). Apart from the degree and frequency range of hearing loss additional components are determined, such as type of loss, time of onset, and causality [32].

Hearing loss can remain stable or be progressive. According to which area of the auditory processing mechanism is damaged, different types are determined: Conductive hearing losses (tymbanic membrane, ear canal) influence more often the whole

frequency range at the same level and do not lead to relentless losses. Hearing aids can be used and in some cases medical treatment can be possible. Sensorineural Hearing losses refer to either damaged sensory hair cells of the inner ear or inactive neural parts of the primary auditory pathway. The degree of loss extends between mild and profound. The frequency perception alternates in the spectrum. Therefore sound amplification can provide limited enhancement. Mixed hearing loss occurs when both types, i.e. conductive hearing loss and sensorineural hearing loss are present. Central hearing loss is hard to cope with, as in this case nerves or nuclei of the auditory center are damaged.
The time of onset refers to acquired or congenital hearing loss. The causality is either genetic (hereditary) or non-genetic (enviromental). Congenital hearing loss or deafness can arise as a consequence of hereditory and genetic factors, infections and / or complications during pregnancy or during the neonatal period. Occasionally they can be correlated with the presence of a syndrome such as Down, Usher, or Alport [32].

3.2 Cochlear Implants

3.2.1 Description

In cases of sensorineural hearing loss, when hair cells in the inner ear or nerve pathways are damaged, conventional hearing aids cannot provide significant improvement. These types of hearing losses affect the hearing ability of specific frequencies. Thus, only amplification by increasing the intensity sound level cannot enhance hearing. Instead, people may perceive distorted sound. For these situations cochlear implantation is useful ([22], [23], [31], [42]). Although CIs cannot restore normal hearing, they can give a deaf or hard of hearing person the opportunity of representing and understanding the acoustical enviroment, and more important being able to communicate [23].

A CI is an electronic medical prosthetic, that gives the possibility of hearing, to people with moderate to profound sensorineural hearing loss. People with pre- or

post-linguistic sensorineural hearing loss can get monaural or bilateral implantation when they present moderate to profound sensorineural hearing loss and cannot have real benefit from only sound amplification through hearing aids. A necessary requirement for implantation is that the parts of the central nervous system which are associated with auditory processing should present no damage. The cochlear implant cannot completely replace the function of the damaged cells, but instead can electrically stimulate groups of active neurons around the cochlea, thus helping to achieve sound perception. Speech recognition and sound identification can be accomplished even with few electrodes on the cochlear implant [23].

A CI consists of two parts, one inside the head of the user and one external visible, which is placed behind the ear, attached on the skin of the head. Both include more components, such as microphone headset, speech processor, transmitter, receiver/stimulator and electrode array ([22], [23], [31], [42]) .

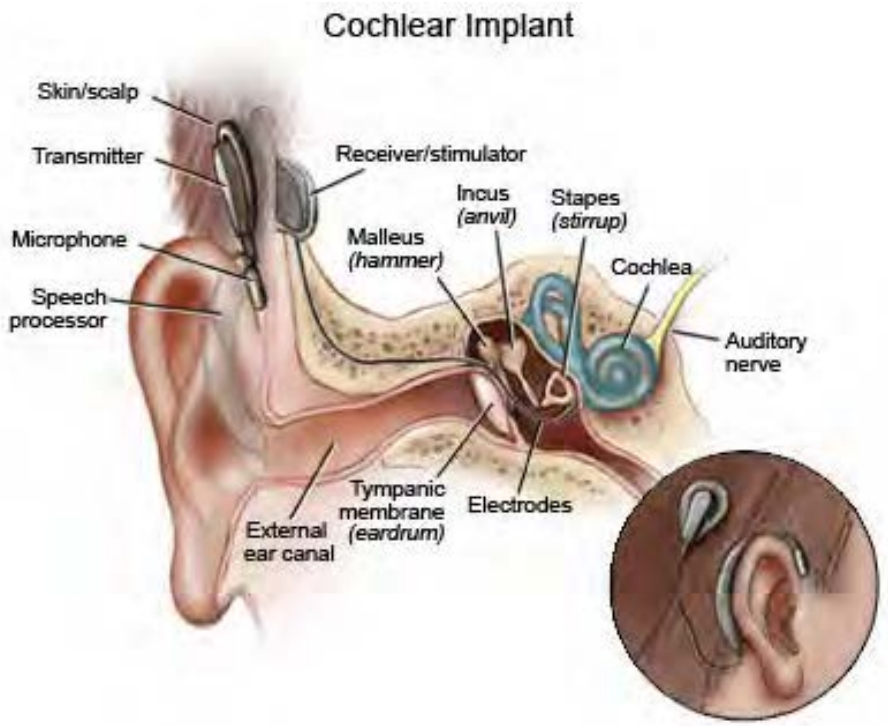

Figure 3.1: Schematic drawing of the Cochlear Implant, [31] pp.2.

3.2.2 Function

The function[1] of CIs is to bypass damaged ear-regions and directly excite surviving regions in the auditory nerve. The external sound processor records through a microphone the enviromental sounds and digitizes them into coded signals. These are transmitted to a coil, which propagates sound waves across the skin to the sound processor of the internal part. The internal device is placed under the skin just behind the ear, receives the radio frequency signals from the sound processor and converts them into electrical currents, which via the electrode array, are capable to activate the auditory nerve. During this stage, the input signals are decomposed into their spectral components, according to the cochlea-function of normal-hearing processing, so that the electrodes send the pulses to different regions of the auditory nerve (simulation of the tonotopic arrangement). Depending on the device model, the number of the electrodes differs between 4 and 22 (that means less than 1% of the number of hair cells of the inner ear). Multichannel cochlear implants exploit the frequency-to-place conversion for signal processing, i.e. electrodes of the device which are near the oval window are stimulated with high frequencies, while electrodes near the helicotrema with lower frequencies. The resulting sound perceived by the CI-user depends on the speech-processing strategy which is used. There are different strategies which determine the electrical conversion of the input sound information into electrical currents ([23], p.173).

[1]For detailed information of cochlear implant function see [22] and [23]

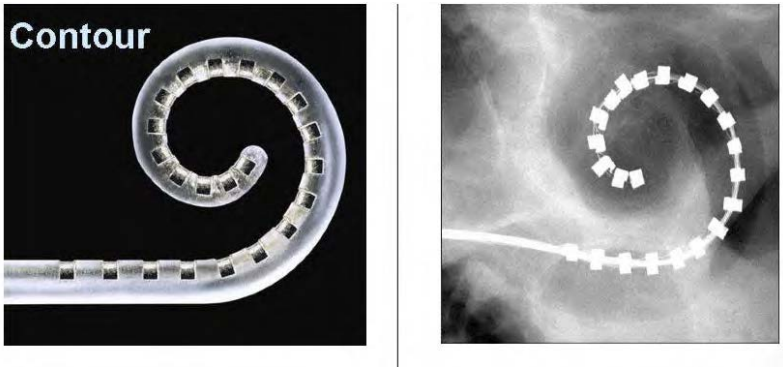

Figure 3.2: Nucleus Contour CI24; Image Courtecy of Cochlear.

The sense of hearing with a cochlear implant is not the same as in the case of normal hearing, since only limited spectral information is transferred. Speech understanding in noise and music perception remain challenging, provided that not only technological limitations, but also individual properties, like temporal processing capabilities and variability in speech and music recognition rate are strongly correlated. The efficacy of CIs depends on the age of onset of hearing loss and duration, age at implantation, cochlear implant experience, possible residual hearing, training, structure of the cochlea and device characteristics [23].

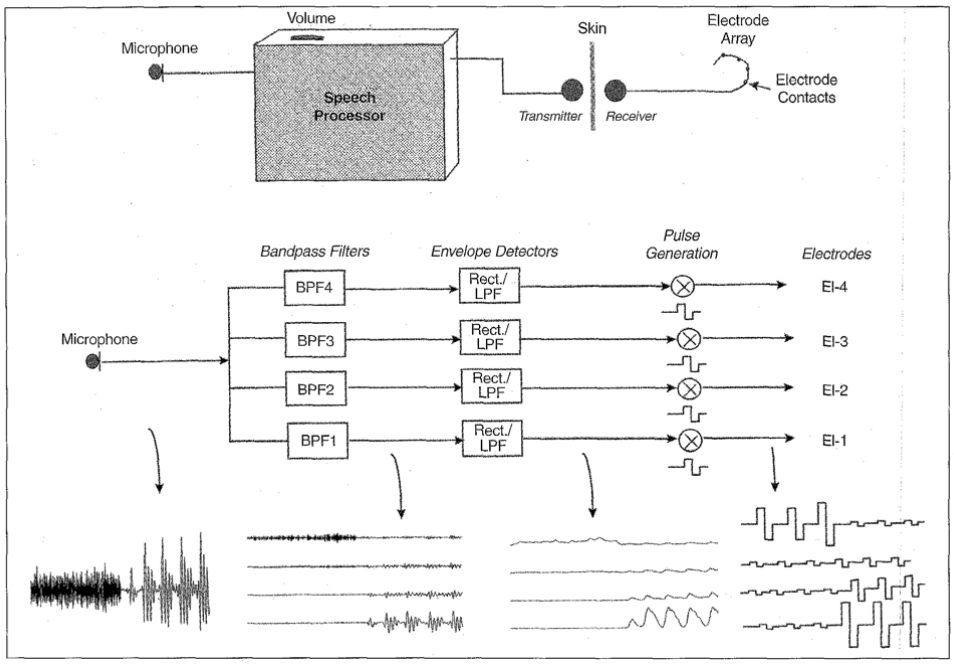

Figure 3.3: 4-Channel cochlear implant operation. The signal is recorded from an external microphone. Followingly is bandpass-filtered and divided into 4 channels. The envelopes of the bandpass-filtered waves are rectified and low-pass filtered. Through electrical pulse generation the sound signals are transmitted to the 4 electrodes. [22], pp.104.

3.2.3 Technical Challenges

Technical challenges are present at different stages, such as the design of the electrodes array, the stimulation type, the signal-processing algorithms and the number of effective channels. Interactions (interferences) and spectral masking along the electrodes of the array are commonly responsible for sound distortion. Non-overlapping of different channels contributes to the best possible frequency resolution [22].

CIs are designed primarily for helping people perceive and discriminate speech. Therefore, speech perception in quiet enviroment is relative quick and easily feasible for the most CI-Users ([8-10], [13], [15], [21-24], [31], [34], [35], [39], [40]).

The musical acoustical content in music is complex and demands different signal processing strategies compared to speech ([23], p.170). Current models of CI-devices are able to transmit frequency regions, which are important for speech understanding

(especially the range between 2 and 5 kHz), while the transmission technology of those parameters which contribute to music perception, especially to melody recognition, pitch discrimination and timbre identification, needs further development The identification of pitch contour remains the biggest challenge for many CI-users ([8-10], [13], [15], [21-24], [31], [34], [35], [39]). The inaccuracy of the representation of the tonotopic function as a result of the coarse frequency resolution affects the pitch perception ([23], p.177). The implanted electrode array cannot stimulate precisely the nerve cells, but can mimic the order of frequency mapping, from the apex to the base of the cochlear [42]. The frequency resolution depends on the number of the electrodes , as well as on the distance between them. It is unclear how many channels should be ideally activated to perform better resolution, as a result of the numerous factors involved (see section 3.2.2). Bilateral electrical stimulation may benefit sound perception, thus CI-users are capable to adjust interaural temporal and intensity differences, which are responsible for sound localization and sound-information-discrimination. Moreover, when lower frequencies are transferred acoustically, while middle and higher frequencies electrically by the electrodes, an improvement of perceptual capacities could be achieved.

3.3 Music Perception with Cochlear Implants

The musical performance of CI-users present great interindividual differences, which depend on several components: Average duration of implant experience, duration of hearing impairment before implantation, exposure to speech and musical experiences, model of CI, bilateral or unilateral implantation, number of operating[2] nerve cells and residual hearing[3], ([8-10], [13], [15], [21-24], [31], [34], [35], [39], [40]) . Furthermore, the anatomy of the inner ear, the cooperation of the different parts (and the brain) and the anatomy of the central auditory pathways of each user[4], play an

[2]The number of active (surviving) auditory nerves depends on the cause of hearing loss.

[3]Some patients retain an amount of residual hearing, still in different frequency ranges.

[4]The anatomy of the cochlear play here an important role. Depending on its structure, the electrode array can be completely or partly inserted, stimulating differently the auditory nerve.

important role to the sound processing stage ([22], [23], [42], [46]). As a result, both the perceptual capacity and the enjoyment of music of CI-users varies significantly.

Music perception is based on both temporal and spectral cues ([17], [23], [46]). Although temporal characteristics can be more easily recognized, the transmitted spectral information of the complex acoustical features cannot be conveyed accurately. However the perception and the enjoyment of music are not necessarily correlated [23]. There is an important distinction between post- and prelingually deafened CI-patients, as well as between users with different CI-experience and duration of hearing loss before the implantation. CI-adults who received their implants (unilateral or bilateral) in older ages cannot enjoy and appreciate musical experience as they did before and they require greater effort, compared to children. The reason is that the human brain is capable to recall past musical experiences, which are stored in the memory-processing brain areas. Consequently CI-adults are facing difficulties while trying to adapt and adjust their novel hearing reality [22].
The ability of CI-users to perceive music is reduced with increasing amount of musical information. They can easily identify rhythmical cues (temporally associated cues), but poorly discriminate between different timbres or polyphonic pitch [8]. CI users are stimulated electrically, while NH and people with hearing aids, acoustically. Spectral information, important for melody recognition, pitch discrimination and timbre identification are represented in a totally different way for CI-users:

"Pitch perception for electrically stimulated hearing via a CI relies on place and/or temporal cues to provide fundamental frequency (F_0) information. The preservation, coding, and effective use of these cues all play important roles in the perception of pitch with a CI. Factors such as poor frequency resolution, a frequency mismatch between the CIs spectral analysis filters and the corresponding stimulated places in the cochlea, and the distance separating the stimulating electrodes from the target neural populations may affect CI users ability to use place-pitch cues". [46], p. 266.

The auditory streaming ability of CI- users is also limited. Due to the periph-

eral Channeling theory the auditory streaming of different channels depends on the area of excitation of the basilar membrane. The more the stimulated areas overlap, the more difficult it is to discriminate the different channels, and the stimuli are perceived as one stream. The spread of the electrical current in a cochlear implant (CI) causes the stimulation of a wide area around each electrode. Therefore, according to the Peripheral Channeling theory, hearing impaired listeners should show a reduced ability to stream [24].

Two factors appear to significantly affect the recognition of musical parameters: the familiarity with the musical material; and the speech recognition/discrimination rate of the user ([23], p.184). When the musical pieces are known or have been heard several times and when they are accompanied from lyrics, CI-users recognition improves [34]. For identifying perceived emotion in music, although it stays unclear which mechanisms CI-patients use, [40] suggests that they rely certainly more on rhythmical patterns than spectral cues. Speech perception capacity plays also here an important role.

According to [Wil08] a simultaneous acoustical and electrical stimulation enhance the musical perceptual capacity. Furthermore, the melody recognition ability and timbre classification are improved in comparison with electrical stimulation only.

Despite of the presented interindividual differences and technical design limitations, personal effort during the rehabilitation period after the implantation affects the improvement of perceptual capacity and enjoyment of musical information ([23], [46]).

Chapter 4

Methods

This chapter reports the conducted methodological approach. It begins with a description of the experimental system and a brief report of the sound wave propagation in wood. The second section includes the experimental design and performing.

4.1 Experimental System

Figure 4.1: The experimental Chair

4.1.1 Some Words about Wood

The quality of the wood depends more on its purpose of use than on objective attributes. Its use spreads in many different sectors such as the building of musical instruments, furniture industry, flooring, paper products and many more. In accordance with the various uses, different quality degrees are demanded. Therefore it is plausible to refer to the mechanical and physical properties, as well as to the chemical/biological characteristics of different wood species parallel with the pur-

pose of use. Wood is an orthotropic anisotropic[1] material, with unique mechanical properties in all three directional axes of a cartesian coordinate system. Most of the mechanical and physical properties of wood are density dependent. For the vibration of wooden plates the Young's Elasticity Module E and the Shear Module G play an important role, determining the acoustical behaviour of the material ([6], [41]). Furthermore, the side hardness N influences the sound propagation, according to the type of stimulation, inducing sound transmission by contact or impact [41]. An additional factor that significantly affects the acoustical properties of wood are the enviromental conditions. Wood has the ability of reaction and adaptation to the enviromental changes, thus its properties alternate in accordance with moisture and temperature levels. The material properties that are relevant to the acoustical conduct of a wood are significantly correlated with moisture [6]. Components which are important when examining wood species, such as sound speed, sound radiation coefficient, characteristic impedance and intensity are defined from different relations between the Young Modulus and the density [41]. Another important component is the loss coefficient, which represents the degree of mechanical energy converted to heat because of internal friction and does not depend on density and E. The eigenfrequencies which arise are also determined by the moisture, the density, the side hardness, the E-modulus and the loss coefficient, but furthermore are strongly correlated with the geometry and kind of the material. The shape and proportions of the dimensions, as well as the type of sound excitation influence the appearance of eigenfrequencies and the form of eigenmodes [41].

4.1.2 Sound Wave Propagation in Wood

The sound propagation depends on the E-modulus, the density, and on geometrical characteristics. The sound speed in wood depends on the direction of propagation. It presents the highest velocity parallel to the grain on the longitudinal axis [18]. Provided that the wavelength of the transferred sound is large compared with the thickness of the solid, then sound transmission in wood is dispersive, i.e. differ-

[1] The anisotropy of wood describes the subjectivity of a sound signal to dispersion and absorption, that are different and vary in all three dimensions x,y,z.

ent frequencies are conveyed with different speeds along the material [19]. When a wooden piece is excited from a sound source different types of waves are generated. Three different kinds co-exist: longitudinal (compressional), shear (transverse) and bending (flexural), which are described from the following equations [([19], pp. 190)]:

$$(2\mu + \lambda) \cdot \frac{\partial^2 \xi}{\partial x^2} = \rho_0 \cdot \frac{\partial^2 \xi}{\partial t^2} \tag{4.1.1}$$

$$\mu \cdot \frac{\partial^2 \eta}{\partial x^2} = \rho_0 \cdot \frac{\partial^2 \eta}{\partial t^2} \tag{4.1.2}$$

$$\mu \cdot \frac{\partial^2 \zeta}{\partial x^2} = \rho_0 \cdot \frac{\partial^2 \zeta}{\partial t^2} \tag{4.1.3}$$

Where ξ, η and ζ displacement components ρ density, λ and μ elastic constants (called Lamé constants ([18],pp. 42]))

Between two solids that are attached the propagating sound wave from the one medium to the other produce both (longitudinal and transverse) reflected and refracted waves. The produced wave field is complex and requires: equal sound pressures and equal normal displacements. Furthermore, "..that not only components of the particle velocity are continuous at the plane $x = 0$, but also the normal stress σ_{xx} and the shear stress σ_{xy}", ([19], pp. 194). However, when the sound waves are transferred perpendicularly, then the longitudinal waves are missing [Kut].

In this study the vibrotactile sensation on the chair is correlated with transversal sound waves that are produced by the attached bass-shakers which afterwards excite perpendicularly the wooden plates. Thus a brief report on bending waves gives some theoretical information about their nature.

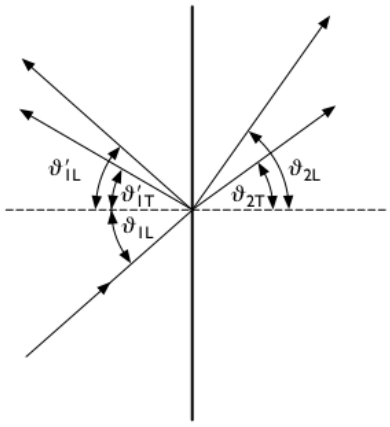

Figure 4.2: Reflexion and refraction at the interface between two solids; [Kut] pp. 194.

Bending Waves

Bending (also called flexural) waves are not acoustic waves. They are generated in solids and cause a crosswide (transversal) deformation of the structure. Their velocity is smaller compared to longitudinal and transversal waves, but they transfer more energy, constituting the most significant producer of acoustic wave radiation (audible sound/structure borne sound) in neighboring media [19]. Their dispersive behaviour complicates their physical description[2]. Dispersive means that each frequency component propagates with different velocity. Bending waves have a frequency dependent speed. Assuming that the wooden surface has free boundaries and it is free of forces, then for low frequencies the phase and the group velocities of bending waves are given from the equations 4.1.4 and 4.1.5 ([19], pp. 203).

$$c_B = \omega / k_B = \sqrt{\omega} \cdot \sqrt[4]{\frac{B}{m'}} \tag{4.1.4}$$

[2]Bending waves require four independent variables: the displacement perpendicular to the plate, its spatial derivative, the bending moment D and a transverse force F, ([19], pp. 202])

$$c'_B = \frac{d\omega}{dk_B} = 2\sqrt{\omega} \cdot \sqrt[4]{\frac{B}{m'}} = 2c_B \tag{4.1.5}$$

where:
B the bending stiffness of the plate given by $B = \frac{d^3}{12} \cdot \frac{Y}{1-n^2}$,
m' the specific mass equal to $m' = \rho_0 d$, and
k_B wavenumber of the bending wave.

However, when a plate is surrounded by another medium and especially because of the lateral displacements which accompany the propagation of bending waves, then sound radiation occurs [19]. According to [19] there are two requirements which must be fulfilled: the radiated waves must be plane waves and the frequencies of the bending waves that occur when a surface is excited, must agree with those of the audible radiated frequencies in the air. For every plate there is a critical frequency ω_c, above which the plate radiates significantly stronger than below:

$$\omega_c = c^2 \sqrt{\frac{m'}{B}} \tag{4.1.6}$$

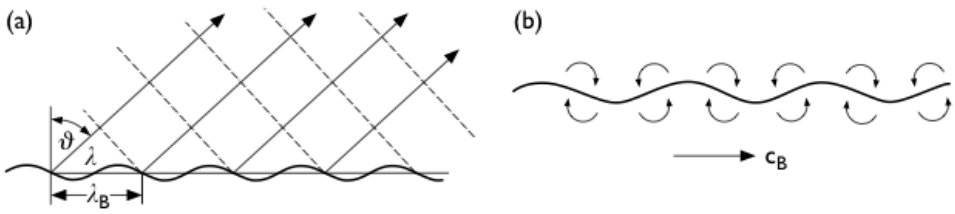

Figure 4.3: "Reaction of the adjacent air to a bending wave travelling on a plate: (a) above the critical frequency: radiation of a sound wave, (b) below the critical frequency: local air flows"; ([19], pp. 194).

The phase velocity is defined as ([19], pp. 204):

$$c_B = c\sqrt{\frac{\omega}{\omega_c}} = c\sqrt{\frac{f}{f_c}} \tag{4.1.7}$$

4.1.3 Chair Manufacture

The wooden plates of the chair are excited by two bass shakers which are attached under the seat and behind the back of the chair. The used model is the Bass Pump 8 from Sinus Live Company (frequency range $5 - 100$ Hz)[3]. The construction of the chair required a plausible choice of wood species[4]. The plates and the arms of the chair should be made of a wood kind that transmits as well as possible middle and low frequencies. With regard to musical acoustics it is better to use hard wood for lower frequency propagation, which presents good shock resistance and limited weight ([6], [41]).

For both vibrating plates of the chair, white-ash-wood was chosen (back and seat). Ash is hard, strong and dense, but relatively light compared with other hard woods, such as beech. Acoustically it transmits efficiently middle and lower frequencies, therefore is often used for the body of bass-strings or guitars.

The supporting parts, between that the ash-plates are stapled[5], are beech boards. The European Beech Wood is hard, robust and shows good bending capacities. It has many different uses, such as flooring, boat building, musical instruments and furniture. On the inner surface of the boards elastic band was applied, so that no significant friction between them and the plates can occur.

For the arms maple Wood was used. This kind is used brightly for the back and the sides of the body in string instruments and guitars. The produced sound is bright and balanced. Maple belongs to the hard wood species, but is much lighter than other types of the family. It presents middle to low internal dampening, high density, high characteristic impedance and mild stiffness.

All other parts were made from pine wood, which is elastic and soft. Due to its low

[3]Information Online: http://www.basspump.de/ .

[4]Information online: $http://www.holzlexikon.modellskipper.de/Holzarten_Abschnitt_A/Holzarten_in_alphabe$

[5]The seat and the back are not screwed together, but wedged between four pieces of beech wood, in order to vibrate with the less possible distortion.

characteristic impedance allows the bending waves to travel on the chair surfaces without corrupting or considerably damping the sound communication between the different system parts.

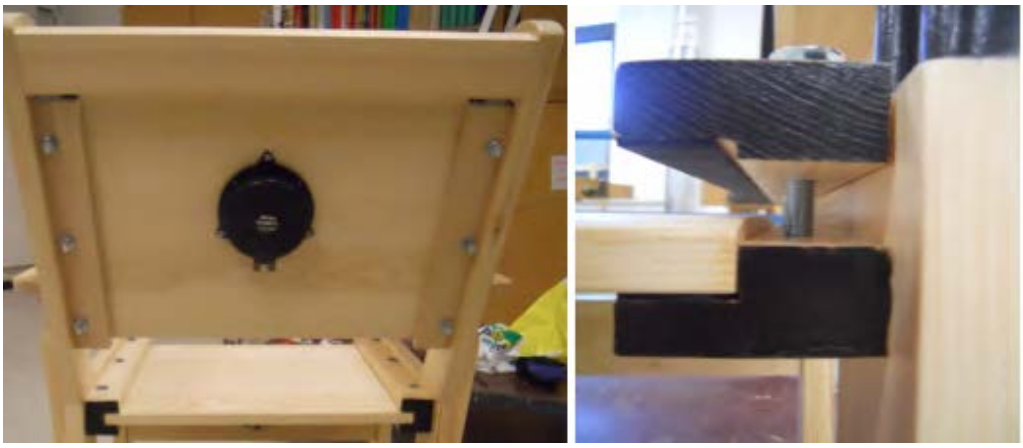

Figure 4.4: left: The back of the chair; right: The wooden plate of the seat.

4.2 Experimental Design and Performing

4.2.1 Stimuli

Both tests adapted the music test batteries for evaluation of Amusia, developed by the University of Montreal.

Since 1987, a group from the Department of Psychology, International Laboratory of Brain, Music and sound Research of the University of Montreal, works on the development of a Battery of Musical clips, with the purpose to investigate several musical disabilities in adults and children. The composed Musical Battery for Evaluation of Amusia (MBEA) is the most important and efficient tool for assessment of musical disorders in humans, developing parallel to the research progress. The MBEA Battery can be completed from adults and children after the age of 10 years ([36], pp.1).

However, for evaluating musical abilities in young children, MBEA is considered inefficient, due to the long duration and large number of stimuli. Therefore the group

introduced in 2013 a new tool, the Montreal Battery of Evaluation of Musical Abilities (MBEMA) in childhood. This Battery is particularly novel, but depending on the fact that is based on MBEA, whose efficacy and validity have been tested both with normal hearing subjects and CI-users, it was judged as the most appropriate musical material for the Master Thesis experimental purposes.

The adaptation from the MBEA was achieved by reducing the number of the stimuli and their duration, as well as by using 10 different instrumental timbres. MBEMA is divided into two versions, one full, which consists of 5 separate test categories: rhythm, memory, melodic contour, interval and scale and one short version, which comprises the same stimuli-sets of rhythm and memory as the full version, but combines scale, interval and contour into one melody-test . Each test is constituted of 20 melody-pairs, that can be the same or different. In [36] the validity of both versions is experimentally investigated. Results show that both are convenient for evaluating musical abilities, but also for pointing out perceptual disparities between children from different cultural background and possessing different musical education.

Melody and Rhythm Test with Children

For the melody and the rhythm tests, 40 musical clips from the abbreviated version[6] of the Montreal Battery of Evaluation of Musical Abilities (MBMA) in childhood were used.

As mentioned above, the melody test of the abbreviated version used here collapses scale, contour and interval comparisons. In the scale test, one out-of-key note replaces one of the original melody. Contour presents changes in pitch direction, while remaining in the same key. The melody-pairs of the interval comparisons differ in one note, but keep the melodic contour and key. The rhythm test is constituted of the same melodies as in the melody test, but the duration of a single tone is different, altering the rhythmical organization, while the meter remains the same.

[6]The version is freely available in www.brams.umontreal.ca/short/mbea-child.

The stimuli are computer-generated with an average duration of 3.5 sec/ melody. All melodies are monophonic and composed following the tonal system of western music, in 10 different keys, played by 10 different midi instruments.

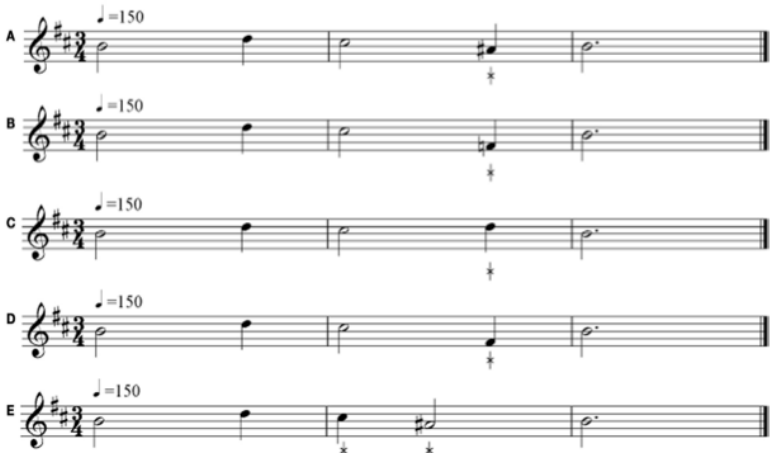

Figure 4.5: (A) is the original melody. In (B) is presented the scale comparison, in (C) the contour alternative, in (D) the single interval note and in (E) the rhythmical variation. ([36], pp.3).

Different Contour and Rhythm Test with Adults

For the evaluation of the melody and rhythm recognition rate of adults, the tasks of different contour and rhythm of the Montreal Battery for Evaluation of Amusia were used. Each test consists of 31 pairs, and has a total duration of ca. 10 minutes. All melodies are monophonic, computer-generated with piano timbre, composed according to the Western music system of tonality.

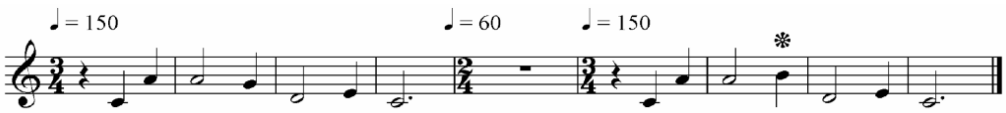

Figure 4.6: Score of an example for different contour discrimination.

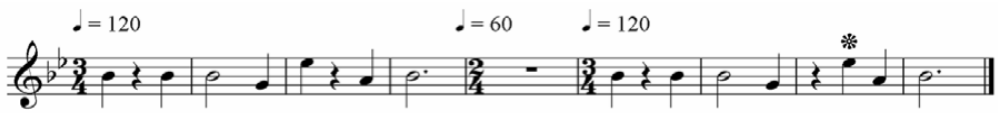

Figure 4.7: Score of an example for rhythm recognition.

In the different contour discrimination task, the pitch direction of the second melody may differ from the previous in ascending or descending direction.
In the rhythmical task the duration of two adjacents tones can differ, but the number of musical notes, as well as the same meter, are maintained.

4.2.2 Subjects

All subjects were recruited through the Cochlear Implant Center of Berlin-Brandenburg (CIC). Participants were compensated 10 Euro for their participation.

Child-Cochlear Implant Users

Seventeen prelingually deafened children and adolescents (7 male and 10 female) were recruited from the CIC and participated in the experiment. The criteria of recruitment included bilateral implantation with more than 6 months experience. Not all of the subjects received their implants simultaneously. For right ear implantation the mean duration of CI-experience was 7.6 years and for left ear 5.6. As an independent variable the average of both values was calculated (mean=7). The participants were between the ages of 5.4 and 16.3 years old (mean=11.4, range=10.9). All subjects attended ordinary schools and were able to communicate verbally. Six participants had musical experience (35.3%)[7](mean=2.6 years).
The degree of hearing capacity was determined by the most recent audiometric tests of the subjects in decibel units. The values are the mean hearing thresholds (dB) for the frequency range between 250 Hz and 8 kHz. The optimal hearing situation for cochlear implants is placed between 10 and 30 dB. Except for one participant (5.9%), all subjects presented values between 18.2 and 28.3 dB (mean=22.5 dB).

[7]Three of them take drums lessons, two piano and one flute.

The etiology of deafness was unknown for the most of the children. Detailed participant information is listed in figures 4.10 and 4.11: gender, age, age at right and left ear implantation respectively, as well as etiology, % recognition rate at speech tests and dB scores of audiogram individual tests are reported. Most of the subjects used Nucleus 24 Contour Implants with CP810, CP910 and Freedom Processors.

Code	Gender	Age	Age Right Implant	Age Left Implant	Etiology
CI1	f	13.4	4.6	1.1	From birth (unknown)
CI2	m	5.4	0.7	0.7	From birth (unknown)
CI3	f	6.9	1.4	1.4	From birth (unknown)
CI4	f	13.8	5.1	6.9	From birth (unknown)
CI5	f	11.1	9.7	9.7	Meningitis
CI6	f	12.7	6.2	2.1	Dysplasie
CI7	m	7 .0	4.0	4.0	From birth (unknown)
CI8	f	16.3	2.2	7.8	From birth (unknown)
CI9	m	5.7	2.8	2.8	From birth (unknown)
C10	m	13.3	3.3	5.2	From birth (unknown)
CI11	f	13.4	6.3	6.5	From birth (unknown)
CI12	m	15.1	2.5	6.1	From birth (unknown)
CI13	m	10.8	2.1	2.9	From birth (unknown)
CI14	f	16.2	3.0	8.3	From birth (unknown)
CI15	m	8.7	5.2	5.2	From birth (unknown)
CI16	f	16.3	2.7	9.8	From birth (unknown)
CI17	f	7.2	2.4	2.4	From birth (unknown)

Table 4.1: Individual Properties I; Child Participants

Code	Audiogram (dB)	Speech Recognition	CI-Model	Processor
CI1	18.6	No Data	Nucleus CI24RE	Freedom
CI2	22.5	92.9	Nucleus CI24RE	Freedom, CP 810
CI3	19.6	89	Nucleus CI24RE	Freedom
CI4	22.8	94.5	Nucleus CI24RE	Freedom
CI5	21.8	78.1	Nucleus CI24RE	Freedom
CI6	22.9	96	Nucleus CI24RE	Freedom
CI7	25.4	No Data	Nucleus CI 512	CP 810
CI8	19.2	81	Nucleus CI24RE	Freedom
CI9	32.5	No Data	Nucleus CI24RE	Freedom, CP910
CI10	18.2	92	Nucleus CI24RE	CP 810
CI11	24.3	82.7	Nucleus CI24RE	Freedom
CI12	19.9	88	Nucleus CI24RE	Freedom
CI13	20.5	No Data	Nucleus CI24RE	Freedom
CI14	22.3	37.5	Nucleus CI24RE	Freedom
CI15	28.3	No Data	Nucleus CI24RE	Freedom
CI16	20.4	No Data	Nucleus CI24RE	Freedom
CI17	22.9	44	Nucleus CI24RE	Freedom, CP910

Table 4.2: Individual Properties II: Child Participants

Adult-Cochlear Implant Users

Nine adults (7 female and 2 male) CI-users participated at the second experiment. Four of them were born deaf, and five were postlingually deafened. The etiology for the prelingually deafened adults was unknown, except for one case of genetical irregularity. One adult had an unilateral implant, and was therefore asked to shut down the hearing aid and to cover the unimplanted ear. The participants were between 24.1 and 69.9 years old (range=45.7 , mean=47.9). Only one was implanted bilaterally simultaneously; the CI-experience was calculated as above taking the average value of right and left implantation and defining the mean for all participants. Four adults (44%) had amateur musical experience, with an average duration of 10.8

years and standard deviation 17.51[8] . Their hearing abilities were determined as in the first experiment, by examining their dB scores in the individual audiograms. All subjects presented values between 20 and 30 dB, except one (43.5 dB). In tables III and IV the demographic data, as well as individual properties are mentioned.

Code	Audiogram (dB)	Speech Recognition	CI-Model	Processor
E1	22.9	28.7	Nucleus CI Harmony	Freedom
E2	22.8	37.5	Nucleus CI24RE	CP 910
E3	29.7	51.2	Nucleus CI24RE	CP 810
E4	20.7	55.1	Nucleus CI24RE	CP 810
E5	43.5	61.5	MED-EL	OPUS 2XS
E6	26.8	59.1	Nucleus CI24RE	CP 810
E7	24.1	39.0	Nucleus CI24RE	Freedom, CP 810
E8	26.3	63.0	Nucleus CI24RE	Freedom, CP 910
E9	28.6	65.0	Nucleus CI24RE	CP 810

Table 4.4: Individual Properties II: Adult Participants

4.2.3 Test Procedure

Both experiments were conducted at the Cochlear Implant Centrum of Berlin-Brandenburg. The participants were tested individually. All participants used their own processors without making any changes. A MATLAB algorithm was developed for the reproduction of the audio(vibro)tactile signals. The stimuli were played by a touch-screen Laptop (Levono ThinkPad S230u) and were transferred to an amplifier through a TASCAM audio/MIDI interface, model US 122 MK II of Teac Corp.. The signals were amplified with a Stereo amplifier of Pioneer Electronics Corp., model A221 and presented in the sound field through an external single loudspeaker of Arcus Elektroakustik GmBH, model TS 100 and the bass shakers.

[8]One adult had long musical experience, since childhood and some none.

The loudness range oscillated between 60-65 dB.

During the audio only condition the original stimuli were presented from the loudspeaker, positioned 1.2 m in front of the subjects at zero degrees azimuth. For the vibrotactile stimulation the original signals were transposed 2 octaves lower with the pitch-shifting algorithm of the open source tool Audacity[9]. Afterwards the vibrotactile signals were sychronized and bounced into one stereo signal with their corresponding originals by using the LogicPro8 tool[10]. The vibrotactile stimuli were in real time RMS normalized and low-pass-filtered with a second order Butterworth filter (Cut-off frequency at 250 Hz). The frequency range of the stimuli extends between B1 (61.74 Hz) and B5 (987.7 Hz)[11].

The transposition of the audio clips changed their timbre quality. The focus of the experiments is to evaluate the melody and rhythm recognition rate with and without additional vibrotactile stimulation. Thus no additional filtering was performed to eliminate the timbres of the occured lowered signals.

All tasks were presented as same/different (yes/no) method. The test-subjects (children and adults) were given pairs of melodies and had to assess whether these sounded the same or not. A target melody was played followed by a 2 sec. silence and then the comparison melody was presented. The participants were forced to give an answer for all pairs even if they were unsure about the correctness of their response.

To avoid weariness or/and learning effects the order of stimuli presentation was randomized. Furthermore the order of the test administration differed across the subjects.

[9] http://audacity.sourceforge.net/about/

[10] http://support.apple.com/kb/sp533

[11] As basis A 440 Hz is taken.

Pre-test

During pre-test the children heard four example-pairs and were asked to assess if they were sounded same or different. If it was necessary the participants had the opportunity to listen to more examples. The tested pictures presented at the melody and rhythm test were created by the author in accordance with the proposed pictures of the MBEMA.

Figure 4.8: Visual Stimuli produced by the author for the discrimination between "same=Gleich" and "different=Ungleich".

To determine the discrimination abilities of the children two visual warm-up tests took place. The children were given a "same/different" child game and were asked to match the proper pairs.

Chapter 5

Results

5.1 Children

To analyze the data of child participants a two-way repeated-measures ANOVA was conducted with the type of stimulation (2 levels) and the different experimental tasks (melody and rhythm) as within-subjects factors (independent variables). The age of the participants, as well as their audiogram scores were analyzed as covariates. As none of the children had considerable musical training, music experience was not introduced as a covariate.

Figure 5.1 shows the estimated marginal mean performance of the four different experimental conditions. Although the mean performance was enhanced under audiovibrotactile stimulation the ANOVA indicates that this difference was not significant.

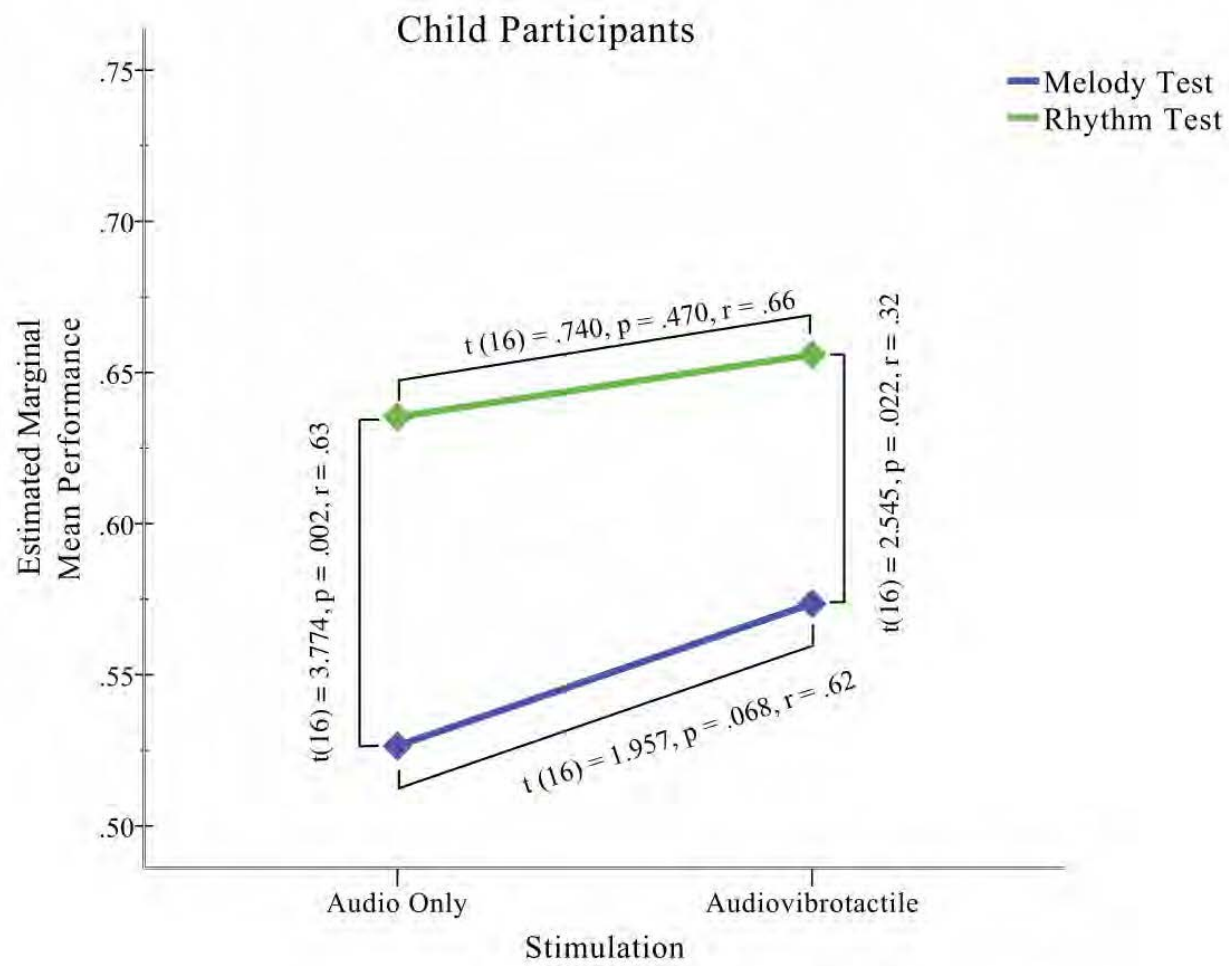

Figure 5.1: Estimated Mean Performance of child CI-Users separated by task and stimulation type.

Results showed that there was no significant effect for the two different stimulations, nor the different tasks alone. Furthermore, there was no significant interaction effect between stimulation type and age of the participants, between stimulation and individual audiogram scores, as well as between task and audiogram scores. Although the F-value was > 1 for the interaction between experimental task and age of the participants the effect was not significant.

On the other hand there was a significant interaction effect between stimulation and task tested. ANOVA indicated also that there were significant interaction effects between stimulation, task and age of the participants, as well as between stimulation, task and participants individual performances at audiogram tests (see table 5.1).

The results described above suggest that there was no influence of stimulation type and of experimental task on the recognition rate of the participants, but the interaction effect between different stimulation and task, as well as stimulation x task x age and stimulation x task x audiogram scores were significant. This interaction appear to reflect the enhancement of the melody recognition rate of the participants under the audiovibrotactile condition, always considering of the covariates which affected the results. It is critical that ANOVA revealed significant interaction effects with age and audiogram scores, but there was no main significant effect both of age and audiogram scores when tested with stimulation and task. Paired-sample t-tests showed that the probability that child participants performed significantly better at rhythm tasks under the two conditions was $p = .002$ for audio only stimulation and $p = .022$ for audiovibrotactile. The different performances at the rhythm task occurred likely by chance, whereas for the melody task the probability that the difference was due to chance was .068 (two-tailed) (see Figure 5.1).

To summarize, the stimulation condition influences the individual performances depending on task tested. Moreover, the recognition rate of the subjects is affected from other independent variables (covariates) when the interaction between task x stimulation is considered.

Child participants performed significantly better at rhythmical than melodic tasks in the different experimental conditions. The lowest group performance was observed under the "audio only" stimulation for the melody test. The mean score was just above chance levels. While rhythm recognition presented no significant improvement, melody recognition ability was significantly enhanced (p = .068, two-tailed) when vibrotactile stimulation was added.

	ANOVA	Child	Participants	(N = 17)	
Factor	F-values	df	p	η^2	Test Power
Within-Subjects Effects					
Stimulation	.039	1	.845	.003	.054
Stimulation*Age	.002	1	.965	.000	.050
Stimulation*Audiogram	.001	1	.976	.000	.050
Task	.003	1	.954	.000	.050
Task*Age	2.228	1	.158	.137	.285
Task*Audiogram	.073	1	.791	.005	.057
Stimulation*Task	6.012	1	.028	.300	.626
Stimulation*Task*Age	5.437	1	.035	.280	.583
Stimulation*Task*Audiogram	5.099	1	.040	.267	.556
Between-Subjects Effects					
Intercept	10.33	1	.006	.43	.85
Age	.10	1	.760	.007	.06
Audiogram	1.18	1	.300	.08	.17

Note. $p < .05$; two-tailed

Table 5.1: Two-way repeated measures ANOVA: Child Results

To examine whether the ANOVA-indicated different performances resulted by chance, $post - hoc$ tests for all possible task-combinations were applied (see fig. 5.1).

5.2 Adults

A two-way repeated-measures ANOVA was also conducted for the analysis of the adult participants results. The experimental stimulation types (2 levels) and the musical tasks were analyzed as within-subjects factors. The age of the participants,

the audiogram scores, as well as the individual CI-experience were analyzed as covariates. The adult group consisted of four adults with long musical experience and five adults with no musical experience (mean = 10.56 years; std = 18.28). Thus musical experience was introduced as between-subjects factor.

Figure 5.2 illustrate the marginal estimated means for adults. Rhythm perception decreased slightly under audiovibrotactile stimulation.

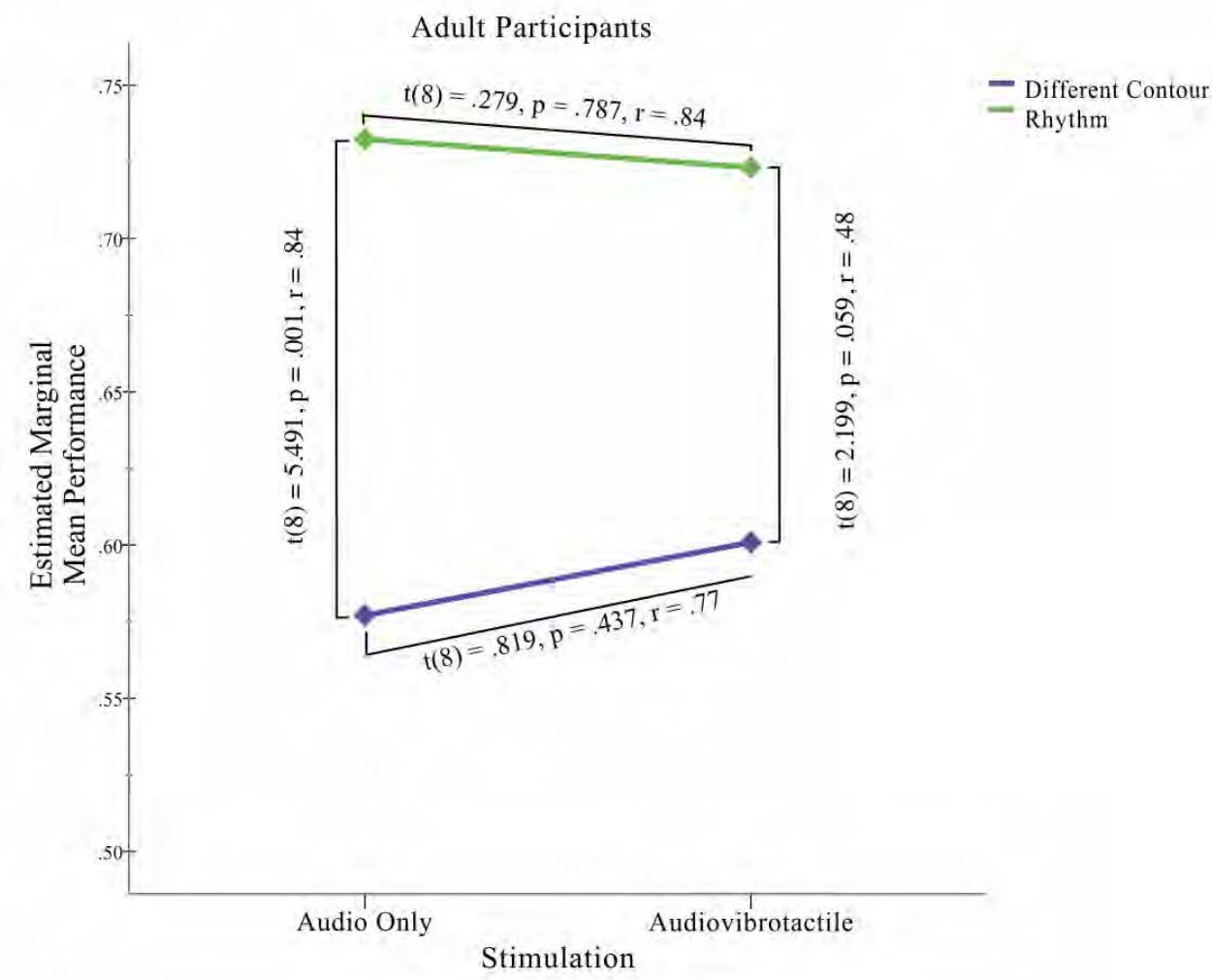

Figure 5.2: Estimated Mean Performance of adult CI-Users.

	ANOVA	Adult	Participants	(N = 9)	
Factor	F-values	df	p	η^2	Test Power
Within-Subjects					
Stimulation	.055	1	.83	.014	.054
Stimulation*Age	1.325	1	.31	.249	.146
Stimulation*CI-Experience	1.540	1	.28	.278	.162
Stimulation*Audiogram Scores	1.685	1	.26	.296	.172
Stimulation*Music Experience	1.566	1	.28	.281	.164
Task	.039	1	.85	.010	.053
Task*Age	1.447	1	.29	.266	.155
Task*CI-Experience	1.050	1	.36	.208	.126
Task*Audiogram Scores	.983	1	.38	.197	.121
Task*Music Experience	1.149	1	.34	.223	.133
Stimulation*Task	7.161	1	.05	.642	.528
Stimulation*Task*Age	5.975	1	.07	.599	.461
Stimulation*Task*CI-Experience	8.679	1	.04	.685	.604
Stimulation*Task*Audiogram Scores	.134	1	.73	.033	.060
Stimulation*Task*Music Experience	.207	1	.673	.049	.065
Between-Subjects					
Intercept	35.611	1	.004	.90	.99
Age	3.522	1	.134	.47	.303
CI-Experience	15.640	1	.017	.80	.84
Audiogram	1.014	1	.371	.202	.123
Music Experience	.771	1	.430	.162	.106

Note. $p < .05$; two-tailed

Table 5.2: Two-way repeated measures ANOVA: Adult Results

Similar to child' results ANOVA indicated a significant interaction effect between stimulation and task tested. There was also a significant interaction effect between stimulation x task x CI-experience. A moderate interaction effect was shown be-

tween stimulation x task x age. ANOVA revealed no significant main effects both of stimulation and of task. There were no significant interaction effects between: Stimulation and age, stimulation and CI-experience, stimulation and audiogram scores, stimulation and music experience. Similarly, ANOVA indicated no significant interaction effects between: Task and age, task and CI-experience, task and audiogram scores, task and music experience; stimulation x task x audiogram scores, stimulation x task x music experience. The tests of between-subjects effects showed a main significant effect on the recognition ability of the participants which depended on the stimulation type and the task tested. Moreover, the recognition rate depended significantly on individual CI-experience by within-subjects interaction of stimulation type and experimental task.

The rhythm perception of adult participants was significantly better compared to different contour recognition rate on both experimental manipulations and t-tests indicated that the different performances occurred by chance with a probability $p = .001$ for the audio only and $p = .059$ for the audiovibrotactile stimulation (see fig. 5.3). At the different contour task, adults presented a slight improvement when they were audiovibrotactile stimulated, while their performance at rhythm recognition task decreased when vibrotactile information was added. Both were not significant.

In comparison with child implant users adult participants achieved higher scores in all experimental tasks .

Both groups performed significantly better at rhythmical tasks compared to melodic and different contour tasks respectively (see fig. 5.1 and table 5.3). For the children group there was quantitative interactions between the experimental condition and the different tasks tested; melody and rhythm perception were both enhanced under audiovibrotactile stimulation; however rhythm perception. The age of the participants was not significantly correlated with any of the two within-subjects factors. The audiogram scores were correlated with the children performance at rhythm task under audiovibrotactile stimulation.

		Correlations			
		Child Participants		(N = 17)	
		Audio Only		Audiovibrotactile	
Factor		Melody	Rhythm	Melody	Rhythm
Age	r	-.065	.410	.109	.332
	p	.803	.102	.678	.193
Audiogram	r	-.249	-.293	-.111	-.510
	p	.335	.255	.673	.037

Note. $p < .05$; two-tailed

Table 5.3: Correlation Table: Child Participants

For the adult group the interactions between the tasks and the stimulations were qualitative, thus rhythm perception decreased when additional vibrotactile information was conveyed and melody recognition improved. The association between the duration of cochlear implant use (CI-Experience) and the performance of the adult group (N = 9) was negative and statistically significant for all tasks (see table 5.4). Furthermore, the rhythm recognition rate of the adults was significantly correlated with their age. No other significant correlations were presented.

		Correlations			
		Adult Participants		(N = 9)	
		Audio Only		Audiovibrotactile	
Factor		Contour	Rhythm	Contour	Rhythm
Age	r	.579	.568	.223	.730
	p	.102	.110	.564	.026
CI Experience	r	-.677	-.859	-.835	-.674
	p	.045	.003	.005	.047
Audiogram	r	.015	-.056	-.018	.063
	p	.969	.887	.963	.872
Music Experience	r	.292	.554	.100	.592
	p	.445	.122	.798	.093

Note. $p < .05$; two-tailed

Table 5.4: Correlation Table: Adult Participants

5.3 Interpretation

A great intersubject variability was present in the results. Interindividual differences are connected with device characteristics, duration of implant use, age of participants, age at implantation and possible musical experience.

Although most of the participants are implanted with the CI-Model Nucleus 24 with either Freedom or CP810 and CP910 speech processors, the hearing processing parameters cannot be equally adjusted. The functional frequency resolution that can be captured by the existing nerve cells of the inner ear, the allocation of the input spectral components, the stimulation rate, as well as the electrode configuration are different for each participant. Hence, input signals are processed uniquely and the magnitude of differences may contribute to the variation between the individual performances ([22], [23]).

The temporal processing strategies of CI devices are able to convey temporal cues relatively accurate ([22], [23], [31], [42]). This could explain the fact that the rhythm

task presented slight differences on both groups under the two different stimulation types. This could also be explained, by taking on consideration the fact that the participants achieved their top performance.

Previous studies have investigated melody recognition, discrimination and identification, as well as rhythm perception using mainly acoustical inputs ([8-10], [13], [15], [21-24], [31], [34], [35], [39], [40]) . The majority of those studies focused on the comparison between a control group of normal hearing people and CI-users and concluded that the two groups had similar performance at rhythmical tasks. However, CI-users achieved considerably lower scores in spectral processing associated tasks. Although the present study made no comparison with normal hearing people, the results of the CI-groups came to an agreement with the previous studies when the results of the audio only condition are considered: CI-users performed significantly better at temporal task (rhythm) than spectral related tasks (melody).

As stated in chapter 3.3 pitch perception remains the most challenging factor for most CI-Users. Pitch resolution afforded by cochlear implants is limited. CI-users of the present study could not easily exhibit the recognition threshold of less than 4 semitones. Only the participants who achieved the highest scores at melody/different contour tasks, 75% (Child Participants) and 87,1% (Adult Participants), were able to recognize a minimal difference of 2 semitones. Although the experimental stimuli were monophonic, all participants reported great difficulties when judging the pitch associated tasks. Both the poor frequency resolution and the temporal envelope processing, which is limited between (maximal) 22 frequency bands, complicate the pitch perception ability of CI-Users.

Another important influence factor is the sensitivity of vibration perception, which varies across individuals. As it is presented in section 1.2, the frequency range, the receptive field, as well as the sensory adaptation and perception among the different mechanoreceptors differ. Not only the physiological factors, but also psychological components play an important role to the perception of vibrations [30]. The transfer characteristic of the vibrating plates is strongly correlated with individual properties of the participants; this is defined by Altinsoy in [2] as the Body-Related-Transfer Function (BRTF). However, due to lack of equipment in this experiment the trans-

fer functions were not measured. Some of the participants reacted positively when vibrotactile stimulation was presented, while others reported that the stimulation type had no effect on their perceptual capacity.

In very few input signals a slight asynchrony between audio and vibrotactile stimuli occured on account of the reproduction way of the vibratory stimuli. However, "for a plausible multi-sensory .. experience, it is important that input from all sensory systems is integrated into one unifield percept" ([30], pp.2). Some stimuli presented a fine delay that might have affected the recognition rate of some participants. Especially, for adults with musical experience, this asynchrony might have contributed to a performance reduction only for the rhythm task, when vibrotactile stimulation was added.

Differences in the performance of child and adult participants were presented at all tasks. Although postlingually deafened CI-users are likely to face greater difficulties in recognizing spectral features compared to prelingually deafened users [46], they achieved better results. According to [13], improved music perception in adults with later year's implants compared to children with pre-lingual onset of deafness, may have occured due to the fact that adults once stimulated by acoustical sound information have developed some auditory pathways, that can be activated by implants. On contrary, children with no acoustical sound experience cannot process the same amount of spectral and temporal cues which are important for music understanding. Although implant devices are able to accommodate these cues, prelingually deafened child users lack of relevant processing strategies. Furthermore, [15] suggested that children have not completely developed their temporal sensitivity until the age of 11 years old. Consequently, temporal cues cannot be processed precisely. Another statement was proposed by [13]; the results of this study have shown that increasing age at implantation influenced greatly the performance of the participants. Residual hearing and exposure at acoustical sound experience in early development could enhance the music perception with later cochlear implantation.

Chapter 6

Conclusions

This experimental study investigated a possible enhancement of music perception of people with CIs when additional vibrotactile excitation was applied, by comparing their performances under two different experimental conditions; audio only and audiovibrotactile. The goal of the study was to show an improvement of melody and rhythm recognition ability when sound vibrations were presented.

The statistical analysis model of the resultant data has shown that both child and adult participants achieved significantly higher scores at the rhythmical tasks under the two different experimental conditions. Moreover, the vibrotactile manipulation improved the melody recognition rate of child CI-users significantly. Adults performed better at the different contour task under audiovibrotactile stimulation; however the difference was not significant.

The effect of the audiovibrotactile stimulation on the recognition rate of the subjects was small. This fact reflects the difficulties of analyzing the results and proving their statistical significance. Familiarity with this novel unnatural listening experience, which is more complex compared to audio listening, might contribute to achieve larger effects than the observed ones. In view of familiarity with music experience (with or without sound vibrations) ([23], [34]) regular contact with musical activities could be able to affect the recognition capacity. A training period with this specific type of vibrotactile stimulation, as well as with simple sound signals, such as monophonic musical intervals, could improve pitch and rhythm discrimination ability ([23], [46]). Listening to specific melodic schemata using different timbres

might also enhance the perception of spectral cues.

Another parameter which could influence the recognition rate of the participants is the vibration sensation. Sound vibrations were transmitted into the human body through the middle back and the seat. Although sound waves could be perceived also through the arms and the hands of the participants, the two contact points where the BassPumps were attached dominated. Considering the psychoacoustical nature of vibration perception, further investigation of the proper contact and application areas of the excitation should be realized. The different receptive fields, as well as the sensory adaptation of the skin mechanoreceptors affect the recognition ability of the participants. A development of a vibrotactile system in harmony with the function of the different mechanoreceptors might lead to an achievement of better results ([3], [4], [16], [26], [30], [31], [33]).

Furthermore, the signal processing of the experimental stimuli is of great importance ([22], [23], [35], [42]). Different frequency transposition areas were applied before settling on the final processing strategy. In future works various frequency transposition areas, as well as filtering applications should be examined. Additionally, further development of signal processing strategies in accordance with the processing algorithms of implant devices could contribute to an improvement of music transmission ([22], [23], [35], [42]).

Considering the small number of participants the external validity of the conducted experiment cannot be credited. The problems due to the great interindividual differences of the CI-users are emphasized by the findings ([8-10], [13], [15], [21-24], [31], [34], [35], [39], [40]). As mentioned in 3.2, parameters such as CI-experience, duration of past acoustical sound experience, age of the participants, differences of the anatomy of the inner ear and technical characteristics of the device (processing strategies, electrodes activation), have an impact on the subject homogeneity. To eliminate intersubject variability the participants were recruited with predefined requirements: more than six months experience with the device and bilateral implantation. However, the results indicate a great influence of individual differences and underline the importance of controlling for independent variables/covariates which influence the outcomes.

This study constitutes an initial approach in the field of vibrotactile music perception of people with cochlear implants. It provides empirical evidence, confirming the general statement that sound vibrations are able to enhance musical experience. However, because of different factors, such as the limited participants number, the nature of the experimental stimuli and the application areas of sound vibrations, the observed effects were not large enough to allow the establishment of using such a new listening technology.

The importance of future work is pointed out with respect to the difficulties mentioned in the conclusions.

Bibliography

[1] Altinsoy M.E., Merchel S. (2010), *Cross-Modal Frequency Matching: Sound and Whole-Body vibration*, in Nordahl, R.;Serafin, S. : Fontana, F.; Brewster, s. (Eds.), Haptic and Audio Interaction Design, LNCS 6306, pp 37-45, Berlin: Springer.

[2] Altinsoy M.E., Merchel S. (2011), *BRTF (Body related Transfer Function) and Whole-Body Vibration Reproduction Systems*, presented at: AES 130th Convention, London UK,13-16 May.

[3] Bellmann A. M. (2002), *Perception of whole-Body Vibrations: From Basic experiments to effects of seat and steering-wheel vibrations on the passengers comfort inside vehicles*, Doctorthesis, Department of Physics, University of Oldenburg, Germany.

[4] Branje, C. J., Karam, M., Maksimowski, M., Fels, D. I., Russo, F. A., (2010). *Vibrotactile display of music on the human back*, Proceedings of the International Conferences on Advances in Computer-Human Interactions, pp. 154-159, Saint Maarten, Antilles.

[5] Bresciani, J., P., Ernst, O., M., (2007), *Signal reliability modulates auditory-tactile integration for event counting*, Max-Planck-Institute for Biological Cybernetics, Tuebingen, Germany , available online at: http://ftp.tuebingen.mpg.de/kyb/bresciani/papers/bresciani07.pdf

[6] Brémaud, I., (2012), *Acoustical properties of wood in string instruments soundboards and tuned idiophones: Biological and cultural diversity*, pub-

lished in: Journal of the Acoustical Society of America 131, (2012), DOI : 10.1121/1.3651233, pp 807-818.

[7] Brodal, P., (2004), *The Central Nervous System: Structure and Function*, Oxford University Press, 2004.

[8] Donnelly P. J., Guo B. Z., Limbel C. J. (2009), *Perceptual fusion of polyphonic pitch in cochlear implant users*, In Journal Acoustical Society of America, November 2009.

[9] Drennan, R., W., Longnion, K., J., Ruffin, C., Rubinstein, T., J., (2008), *Discrimination of Schroeder-Phase Harmonic Complexes by Normal-Hearing and Cochlear-Implant Listeners*, In: Jaro Journal of the Association for Research in Otolaryngology, DOI: 10.1007/s10162-0070107-6, JARO 9: pp 138-149.

[10] Galvin J.J., Fu Q. J., Nogaki G. (2007), *Melodic Contour Identification by Cochlear Implant Listeners, Division of Communication and Auditory Neuroscience*, Published in final edited form as: Ear Hear; 28(3),pp 302-319, June 2007.

[11] Giordano M., Wanderley M.M. (2013), *Perceptual and Technological Issues in the Design of Vibrotactile Augmented Interfaces for Music Technology and Media*, Oakley and S.Brewster (Eds,), pp 89-98, Springer-Verlag Berlin-Heidelberg.

[12] Gobbelé R., Schuermann M., Forss N., Juottonen K., Buchner H., Hari R. (2003), *Activation of the human posterior parietal and temporoparietal cortices during audiotactile interaction*, published in NeuroImage 20, Academic Press, pp 503-511.

[13] Hopyan T., Peretz Is., Chan L.P., Papsin B.C., Gordon K.A. (2012), *Children using cochlear implants capitalize on acoustical hearing for music perception*, ORIGINAL RESEARCH ARTICLE, published in Frontiers in Psychology - Auditory Cognitive Neuroscience, October 2012, Volume 3, Article 425 - 1.

[14] Huang J., Gmable D., Sarnlertsophon K., Wang X., Hsiao S. (2012), *Feeling Music: Integration of Auditory and Tactile Inputs in Musical Meter Perception*, available online at: http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0048496

[15] Jung K. H., Won J.H., Drennan W.R.,Jameyson E., Miyasaki G., Norton S.J., Rubinstein J.T. (2012), *Psychoacoustic Performance and Music and Speech Perception in Prelingually Deafened Children with Cochlear Implants*, In: Audiol Neurotol 2012; 17: pp 189-197.

[16] Karam, M., Fels, I., D., Russo, F., (2009), *Designing the Model Human Cochlea: An Ambient Crossmodal Audio-Tactile Display*, Ryerson University, Science of Music, Auditory Research and Technology (SMART), published in: $IEEE$ Transactions on Haptics, Vol.2, No.3, July-September 2009, pp 160-169.

[17] Koelsch, S., Walter, A. Siebel, (2005), *Towards a neural basis of music perception*, in $TRENDS$ in Cognitive Sciences, VOL. 9, NO. 12, December 2005.

[18] Kuttruff, H. (2007), Acoustic variables and basic relations, *Acoustics: An Introduction*, pp 34-68, Taylor & Francis, 2007.

[19] Kuttruff, H. (2007), Sound waves in isotropic solids, *Acoustics: An Introduction*, pp 190-208, Taylor & Francis, 2007.

[20] Levänen S., Jousmäki V., Hari R. (1998), *Vibration induced auditory cortex activation in a congenitally deaf adult*, published in Current Biology, pp 869-872.

[21] Limb C.J., Molloy A.T., Jiradejvong P., Braun A.R. (2010), *Auditory Cortical Activity During Cochlear Implant-Mediated Perception of Spoken Language, Melody, and Rhythm*, In: Jaro Journal of the Association for Research in Otolaryngology, JARO 11: pp 133-143.

[22] Loizou, C., P.,. (1998), *Mimicking the Human Ear: An Overview of Signal-Processing Strategies for Converting Sound into Electrical Siganls in Cochlear*

Implants, Published in: *IEEE* Signal Processing Magazine, DOI:1053-5888/98, pp. 101-130.

[23] Looi, V. (2008), *The Effect of Cochlear Implantation on Music Perception: A Review*, in: OTORINOLARINGOL, Vol. 58, No.4, pp 169-190.

[24] Marozeau, J., Innes-Brown, H., Blamey, J., P., (2013), *The Acoustic and Perceptual Cues affecting Melody Segregation for listeners with Cochlear Implant*, available online: http://journal.frontiersin.org/Journal/10.3389/fpsyg.2013.00790/abstract.

[25] Merchel S., Leppin A., Altinsoy M.E. (2009), *Hearing with your body: The Influence of Whole-body Vibrations on Loudness Perception*, presented at: 16th International Congress on Sound and Vibration, ICSV16, Krakw, 5-9 July, Poland.

[26] Merchel S., Altinsoy M.E. (2009), *Vibratory and Acoustical Factors in Multimodal Reproduction of Concert DVDs*, in M.E. Altinsoy, U. Jekosch, and S. Brewster (Eds.): HAID 2009, LNCS 5763, pp 119-127, Springer-Verlag Berlin-Heidelberg.

[27] Merchel S., Stamm M., Altinsoy M.E. (2011), *Just-Noticeable Frequency Differences for Whole-Body Vibrations*, presented at: Inter-Noise, Osaka Japan 4-7 September.

[28] Merchel S., Stamm M., Altinsoy M.E. (2011), *Equal Intensity Contours for Whole-body Vibrations Compared with Vibrations Cross-Modally Matched to Isophones*, in Cooper E., Brewster S., Ogawa H., Kryssanov V.K. (Eds.), Haptic and Audio Interaction Design 2011, LNCS 6851, Berlin: Springer.

[29] Merchel S., Stamm M., Altinsoy M.E. (2011), *Tactile Identification of Non-Percussive Music Instruments*, presented at: Forum Acusticum 2011, Aalborg, 27.June-1.July Denmark.

[30] Merchel S., Altinsoy M.E. (2013), *Auditory-Tactile Music Perception*, in: Proceedings of Meetings on Acoustics, Vol. 19, 015030, DOI: 10.1121/1.4799137, Acoustical Society of America.

[31] Moctezuma, A., (2011), *An Overview of Cochlear Implant Systems*, University of Illinois, published in: BIOE 414, pp 1-20.

[32] Moller, R., A., (2000), Anatomy of the Auditory Nervous System, *Hearing: Its Physiology and Pathophysiology*, pp 75-93, Academic Press, 2000.

[33] Nanayakkara, S. C., Taylor, E., Wyse L., Ong S. H. (2009), *An enhanced musical experience for the deaf: design and evaluation of a music display and a haptic chair*, in: Proceedings of the 27th international Conference on Human Factors in Computing Systems (Boston, MA, USA, April 04 - 09, 2009). CHI '09. ACM, pp 337-346, New York.

[34] Nakata T., Trehub S.E., Mitani C., Kanda Y., Shibasaki A., Schellenberg G. E. (2005), *Music Recognition by Japanese Children with Cochlear Implants*, in the Journal of PHYSIOLOGICAL ANTHROPOLOGY and Applied Human Science, 24: pp 29-32.

[35] Nobbe, A., (2004), *Pitch Perception and Signal Processing in electric Hearing [Tonhöhenwahrnehmung und Signalverarbeitung bei elektrischem Hören]*, Doctoral Dissertation, available online: http://edoc.ub.uni-muenchen.de, Medizinische Fakultät der Ludwig-Maximilians-Universität, München, 2004.

[36] Peretz, I., Gosselin, N., Nan, Y., Caron-Caplette, E., Trehub, E., S., (2013), *A novel tool for evaluating children's musical abilities across age and culture*, ORIGINAL RESEARCH ARTICLE, published in: Frontiers in Psychology - Auditory Cognitive Neuroscience, July 2013, Volume 7, Article 30.

[37] Schmidt, H., C., F., & Schaible, H., G., (2000), Somatosensorik, *Neuro- und Sinnesphysiologie*, pp 227-256, 4.Auflage, Springer Verlag Berlin-Heidelberg.

[38] Schürmann, M., Caetano G., Jousmäki V., and Hari R. (2002), *Hands help hearing: Facilitatory audiotactile interaction at low sound-intensity levels*, DOI: 10.1121/1.1639909, pp. 830-832, Acoustical Society of America.

[39] Trehub, S., E., Vongspaisal, T., Nakata, T., (2009), *Music in the Lives of Deaf Children with Cochlear Implants*, published in: The Neuroscience and Music III-Disorders and Plasticity, DOI: 10.1111/j.1749-6632.2009.04554, pp. 534-542, NY Academy of Sciences.

[40] Volkova A.,Trehub S., Schellenberg G.E., Papsin B.C., Gordon K.A. (2012), *Children with bilateral cochlear implants identify emotion in speech and music*, published in: Cochlear Implants International, VOL. 0, NO. 0.

[41] Wegst, G., K., U., (2006), *Wood for Sound*, Max-Planck-Institut für Metallforschung, published in: American Journal of Botany 93(10), pp 1439-1448.

[42] Wilson, S., B., Dorman, M.m F., (2008), *Cochlear Implants: Current Designs and future Possibilities*, in: Journal of Rehabilitation Research & Development (JRRD), Vol. 45, No.5, DOI: 10.1682/JRRD.2007.10.0173, pp 695-730.

[43] Zwicker, E., Fastl H., (2007), Information Processing in the Auditory System, *Psychoacoustics: Facts and Models*, pp 23-61, Third Edition, Springer-Verlag Berlin-Heidelberg.

[44] Encyclopaedia Britannica: http://www.britannica.com/EBchecked/topic/288499/inner-ear

[45] Field, A., (2009), *Discovering Statistics Using SPSS (and sex and drugs and rock'n'roll)*, Third Edition, SAGE Publications Ltd.

[46] Looi, V., McDermott, H., McKay, C., Hickson, L., (2008), *The effect of cochlear implantation on music perception by adults with usable pre-operative acoustic hearing*, published in: International Journal of Audiology, VOL. 47, NO. 5, DOI: 10.1080/14992020801955237, pp. 257-268.