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On the Relation of Electrophysiological Compound Action Potential (ECAP) Measurements and Perceptive Skills in Cochlear Implant (CI) Listeners

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Abbreviations

1I2AFC	One-Interval Two-Alternative Forced-Choice
3I3AFC	Three-Interval Three-Alternative Forced-Choice
A	Apical
ADIST	apical probe excitation distance
AMPDT	Adaptive Melody-Pattern-Discrimination Test
ART	Auditory Nerve Response Telemetry
B	Basal
BCDT	background contour discrimination threshold
BDIST	basal probe excitation distance
BP	Bipolar
CI	Cochlear Implant
cu	current unit
DIB	diagnose interface box
DIST	excitation distance
EAS	Electric-Acoustic Stimulation
ECAP	Electrically Evoked Compound Action Potential
hl	hearing loss
L50	50 % Speech Reception Threshold
LAPL	least acceptable perceived loudness
M	Medial
MAESTRO	MAESTRO CI Fitting and Diagnostic Software Version 6.0.1 by MED-EL
MDIST	medial probe excitation distance
MP	Monopolar

MSNF	Multi-Source Noise Field
N	Number
NaN	Not a Number
NERL	normalised ECAP response level
nt	Not Tested
OLSA	Oldenburger Satztest
P	Practice Session
pTP	Partial Tripolar
R	Repetition
SNR	Signal-to-Noise-Ratio
SoE	Spread of Excitation
SRT	speech reception threshold
SSS	Single-Stage Surgery
T	Test
TDDT	timbre difference discrimination threshold
TP	Tripolar
TSS	Two-Stage Surgery

Abstract

Background

Cochlear Implants (CIs) provide near normal speech intelligibility in quiet environments to individuals suffering from sensorineural hearing loss[1;2]. Perception of speech in situations with competing background noise and especially music appraisal[1] however are still insufficient[3]. Hence, improving speech perception in ambient noise and music intelligibility is a core challenge in CI research. Quantitatively assessing music intelligibility is a demanding task due to its inherently subjective nature. However, previous approaches have related electrophysiological measurements to speech intelligibility, a corresponding relation to music intelligibility, can be assumed. Recent studies have investigated the relation between results obtained from hearing performance tests and Spread of Excitations (SoEs) measurements[4;5]. SoE functions are acquired by measuring Electrically Evoked Compound Action Potentials (ECAPs) which represent the electrical response generated in the neural structures of the auditory nerve[6]. The parameters designed to describe SoE functions are used to estimate the dispersal of the electric field in the cochlea. The quality of spatial separation of the electrical field generated by adjacent electrodes are assumed to correlate with hearing performance measures[5].

Aim of study

This study investigated the relation of parameters derived by ECAP measurements and perceptive skills which aim to access the level of speech and music intelligibility in CI users. In addition, the ratings assessed in a questionnaire on self-rated music intelligibility were correlated to a test battery consisting of measures for speech reception threshold (SRT) in noise (Oldenburger Satztest (OLSA)) and music intelligibility (Adaptive Melody-Pattern-Discrimination Test (AMPDT)). We hypothesised that results from this test battery correlated to subjective ratings and measures describing SoE functions.

Methods

The patient collective covered 17 well-experienced bilateral CI listeners (8 females, 9 males) between the age of 14 and 77 years with a minimum CI experience of two years. Music enjoyment and self-rated musicality was evaluated by means of a questionnaire. The AMPDT included two psychoacoustic tests: timbre difference discrimination threshold (TDDT) and background contour discrimination threshold (BCDT). The accentuation of harmonics in a foreground melody created a background melody. Accentuation was realised by sound level increment, frequency detuning and onset asynchrony. Subjects had to detect target intervals comprising both foreground and background melody by discriminating timbre differences in a Three-Interval Three-Alternative Forced-Choice (3I3AFC) procedure. In a One-Interval Two-Alternative Forced-Choice (1I2AFC) proce-

dure, subjects had to classify the background melody's contour.
SoE was measured via a spatial forward-masking paradigm[6;7]. A basal, medial and apical recording electrode was measured. Probe electrodes were one electrode position apical to the recording. The width of normalised SoE functions was calculated at their 25 % and 50 % level (excitation distance (DIST)). Furthermore, exponential functions were calculated for SoE profiles with more than three data points for each side.
The OLSA assessed SRT in noise. The noisy environment was presented through an array of four loudspeakers (MSNF[8]). The *Fastl* noise-condition allows to make use of gap listening representing the temporal characteristics of speech as a fluctuating noise. The *OLnoise*-condition is a continuous noise resulting in a maximum portion of masking.

Results
We found that background melody contour classification (BCDT) is more challenging to CI users than the detection of small perceptual timbre differences (TDDT). Background melody contour classification was possible with harmonic accentuation by sound level increment whereas accentuation by onset asynchrony was more demanding. CI users failed in background melody contour classification obtained by frequency detuning.
SRTs assessed in the OLSA were significantly lower in the *OLnoise* than in the *Fastl* noise masking condition.
A number of N = 90 SoE functions were acquired from ECAP measurements, in which N = 48 showed a clearly present ECAP response. The DIST at the 25 % and 50 % level was narrower for the basal than for the apical and medial electrode. SoE functions showed asymmetric profiles with larger amplitudes towards the basal end of the cochlea.
Correlation analysis between the AMPDT, OLSA and DISTs showed no significant correlation. Correlation analysis between the AMPDT, OLSA and the questionnaire's results could not prove that musical activities (music listening, singing or playing instruments) improve music intelligibility. However, CI supply has restored the importance of music, self-rated musicality and musical enjoyment in this study's subjects.

Conclusions
The present study's results imply that CI listeners are only able to detect distinct timbre alterations throughout the course of a musical piece whereas they cannot discriminate background melodies hidden in a pattern of complex harmonic sounds.
Furthermore, SoE measurements do not seem to be an adequate tool to predict neither speech nor music intelligibility in CI listeners, contrary to our initial hypothesis. This finding is consistent with a number of studies who did not find a correlation between music or speech intelligibility and channel interactions assessed by SoE measurements[4;5].
It can be concluded that albeit CI supply restores musical enjoyment in patients with sensorineural hearing loss, music perception is still poor and does not significantly improve by regular musical activities such as listening to music, singing or playing instruments.

Zusammenfassung

Hintergrund

Cochlea Implantate (CI) erlauben Patienten mit sensorineuralem Hörverlust und günstigen Voraussetzungen ein nahezu normales Sprachverstehen in Ruhe[1;2]. Das Sprachverstehen im Störgeräusch und insbesondere die Hörqualität von Musik sind hingegen noch unzureichend[3] und stellen eine große Herausforderung dar. Die objektive Messung der Musikhörqualität ist aufgrund der individuell unterschiedlichen Empfindung anspruchsvoll. Der Zusammenhang zwischen elektrophysiologischen Messungen und Sprachdiskrimination ist Gegenstand aktueller Forschung - ein Zusammenhang mit Musikhörleistungen kann daher angenommen werden. Jüngste Studien haben die Zusammenhänge zwischen Sprachdiskriminationstests und Spread of Excitation (SoE) Messungen untersucht[4;5]. SoE Funktionen werden durch die Messung elektrisch evozierter Summenaktionspotenziale (ECAP) generiert. Diese repräsentieren die in den neuralen Strukturen des Hörnervs generierte elektrische Reizantwort[6]. Parameter zur Beschreibung der SoE Funktionen dienen der Abschätzung der Verteilung des elektrischen Feldes in der Cochlea. Es wird angenommen, dass die Güte der Trennung der elektrischen Felder benachbarter Elektroden mit den Ergebnissen psychophysischer Tests korreliert[5].

Fragestellung

Diese Studie untersucht den Zusammenhang zwischen aus ECAP Messungen abgeleiteten Parametern und Ergebnissen aus Sprach- sowie Musikdiskriminationstests bei CI-Nutzern. Es wird erwartet, dass CI-Nutzer mit selbst eingeschätzt guter Musikdiskrimination ein besseres Sprachverstehen im Störgeräusch zeigen und in musik-psychoakustischen Tests günstiger abschneiden. Es wird weiterhin angenommen, dass bei diesen CI-Nutzern eine selektivere Anregung der entsprechenden Neurone durch das CI besteht.

Methoden

An der Studie nahmen 17 erfahrene bilateral versorgte CI-Nutzer (8 weiblich, 9 männlich) im Alter von 14 bis 77 Jahren mit einer minimalen Nutzungsdauer von 2 Jahren teil.
Mit einem Fragebogen wurde die selbst eingeschätzte Musikalität sowie die Musikhörqualität vor und nach der CI Versorgung bewertet.
Durch ein psychoakustisches Verfahren (Adaptiver Melodien-Muster-Diskriminationstest (AMPDT)) wurde die Klangfarbendiskrimination (TDDT) und Hintergrundmelodiediskrimination (BCDT) geprüft. Die Akzentuierung Harmonischer in einer Vordergrundmelodie erzeugte eine Hintergrundmelodie. Die Teiltöne wurden im Pegel, in der Frequenz oder im zeitlichen Einsatzzeitpunkt variiert. Aufgabe war es, das Intervall mit gleichzeitiger Darbietung von Vorder- und Hintergrundmelodie durch Klangfarbenunterschiede in einem Three-Interval Three-Alternative Forced-Choice (3I3AFC) Verfahren

zu erkennen. In einem One-Interval Two-Alternative Forced-Choice (1I2AFC) Verfahren musste die Kontur der Hintergrundmelodie erkannt werden.
SoE Funktionen wurden durch ein Masker-Probe-Verfahren bestimmt[6;7]. Zur Messung wurden eine basale, mediale und apikale Elektrode verwendet. Die Testelektrode befand sich eine Position apikal der Aufnahmeelektrode. Die SoE Funktionen wurden über die "Breite" auf 25 %- und 50 % Niveau beschrieben (Exzitationsdistanz (DIST)). Zudem wurden für die SoE Funktionen Exponentialfunktionen berechnet.
Die Sprachverständlichkeitsschwelle (SRT) im räumlich getrennt dargebotenen Störgeräusch (Multi-Source Noise Field[8]) wurde im OLSA-Testverfahren bestimmt. Es wurden zwei Störgeräusche verschiedener Modulationscharakteristik verwendet.

Ergebnisse
Es zeigte sich, dass die Diskrimination der Hintergrundmelodie eine größere Herausforderung für CI-Nutzer darstellt als die Diskrimination von Klangfarbe. Die Akzentuierung durch Pegelerhöhung ermöglichte die Erkennung der Hintergrundmelodie, wohingegen dies durch Variation des Einsatzes nur teilweise gelang. Die CI-Nutzer scheiterten am Erkennen der Hintergrundmelodie durch Frequenzverstimmung.
Die im OLSA erfasste SRT war im *OLnoise*- signifikant niedriger als im *Fastl*-Rauschen. Aus der ECAP Messung wurden N=90 SoE Funktionen berechnet. Davon zeigten N=48 eine deutliche ECAP Antwort. Die Exzitationsdistanz war kürzer an der basalen im Vergleich zur apikalen und medialen Elektrode. Die SoE Funktionen zeigten in Richtung des basalen Endes der Cochlea asymmetrische Profile mit größeren Amplituden.
Die Korrelationsanalyse zwischen AMPDT, OLSA und DIST ergab keine signifikanten Korrelationen. Die Korrelationsanalyse konnte zudem nicht zeigen, dass musikalische Aktivitäten (Musik hören, singen oder Instrument spielen) die Musikdiskrimination beeinflussen. Jedoch konnte die CI-Versorgung die Bedeutung von Musik, die selbstevaluierte Musikalität und den Musikgenuss bei den Probanden dieser Studie wiederherstellen.

Schlussfolgerungen
Die Ergebnisse lassen den Schluss zu, dass es CI-Nutzern zwar möglich ist, deutliche Klangfarbenunterschiede während eines Musikstücks zu erkennen, die Konturen von Hintergrundmelodien jedoch nicht erkannt werden können. Entgegen der Hypothese scheinen SoE Messungen kein adäquates Messinstrument der Evaluierung von Sprach- oder Musikdiskrimination bei CI-Nutzern zu sein. Dies stimmt mit früheren Studien überein, die ebenso keine Korrelation zwischen Sprach- und Musikdiskrimination und der mit SoE Funktionen beschriebenen Frequenzkanalinteraktion zeigen konnten[4;5].
Es ist zu schlussfolgern, dass eine CI-Versorgung den Musikgenuss bei Patienten mit sensorineuralem Hörverlust wiederherstellt, aber die Musikdiskrimination immer noch mangelhaft ist und sich nicht signifikant durch regelmäßige musikalische Aktivitäten wie Musik hören, singen oder dem Spielen von Instrumenten verbessert.

Chapter 1: Introduction

According to the World Health Organization, 278 million people suffered from binaural profound hearing loss in 2005[9], a number that had to be corrected upwards in 2015 to 360 million people[10]. Presently, Cochlear Implants (CIs) are the only option to restore hearing in people with sensorineural hearing loss and are the most efficient neural prostheses available[2]. Owing to immense technical progress, CIs restore profoundly hearing impaired persons' ability of communication since the 1980s[3]. CIs nowadays allow their users an excellent speech intelligibility in quiet environments[1], after an initial adaptation phase of approximately 3 months[11–13]. This is quite remarkable considering that no more than supportive lip-reading was expected from the first generation CIs[14].

In modern society speech and sound are indispensable for communication and these technological developments provide deaf people with the ability of active participation[15]. Nonetheless, transmission of speech in situations with strong background noise is still not satisfying[3]. These difficulties in communication may derogate social contacts and emotional state up to identity shaping[16].

Music intelligibility however remains the most severely impaired task for CI users leading to a significantly diminished music enjoyment[1], that does not improve as easily as speech intelligibility as the inevitable result of daily exposure[17]. This seems easily comprehensible since music represents one of our human hearing's most complex performances.

Music is ranked directly after speech intelligibility for CI users[3], highlighting its significance in our life. This is not surprising since music serves as a very subtle device of communication uniting people across barriers of diverse languages and cultures. Therefore, music intelligibility cannot solely be reduced to what extent people can precisely distinguish melody, rhythm, and pitch[1].

Among the main worries of patients about to receive CIs is the potential loss of music appreciation they rejoiced in before their hearing loss[1]. This concern does not occur without reason: studies show that the majority of CI users perceive music as mechanical or even unpleasant[18]. A likely reason is that CI technology is unsurprisingly not able to adequately remodel the finely tuned tonotopic organisation of human cochleas - a miracle of nature. Depending on the manufacturer, CIs comprise up to 22 electrodes which are obliged to replace the loss of 3500 tonotopically arranged inner hair cells[19]. Hence only poor fine structure and pitch information can be conveyed even by modern CIs. Receiving incoming electric signals that encode auditory information from their assigned frequency bandwidths, independent electrodes stimulate surrounding nerve tissue that regularly process similar frequencies. Due to electric Spread of Excitation (SoE) evolving in this process, adjacent nerve tissue from different frequency spectra are being excited as well[20]. Hence, channel interactions occur via the stimulation of a larger population of neurons than the originally incoming sound in normal hearing otherwise would - much like a giant trying to play the piano rather than someone with dainty fingers. This circumstance might be to blame for CI recipients' poor music intelligibility[21].

These findings should provide a major incentive for technical research. A possible approach could be to fathom which characteristics of modern CIs and their users' strongly impaired hearing are leading to poor music intelligibility.

This study examines two main hypotheses. The first hypothesis is that subjects with bilateral CI supply who believe to have good music intelligibility score higher both in situations with severe background noise and in psychoacoustic music tests. This will be evaluated with the Oldenburger Satztest (OLSA)[22] and the Adaptive Melody-Pattern-Discrimination Test (AMPDT)[23]. In a questionnaire, the subjects will evaluate their music intelligibility.

The second hypothesis is that subjects achieving higher results in the OLSA and AMPDT test battery have a more selective neural excitation pattern produced by their CIs, which will be quantified by a spatial forward-masking paradigm SoE measurement.

Therefore, the objective of this study is to investigate the context of electrical intracochlear SoE, speech intelligibility in noise and music intelligibility in detail. Only in understanding these interactions there is a chance of enhancing technology leading to an improve of CI users' hearing abilities. As the number of 360 million people suffering from profound hearing loss worldwide in 2015[10] depicts, sensorineural hearing loss is a disease whose research must on no account be neglected. Moreover, these numbers are not likely to remain static as the population constantly grows older and we are exposed to dangerously high levels of noise daily caused by our society's modern lifestyle[24].
Due to these given reasons it is crucial to investigate the correlation of current CIs' technology with both objective tests assessing music and speech intelligibility and subjective musical enjoyment.

Chapter 2: Cochlear Implants

In order to retrace the motivation and objectives of this study, it is crucial to establish a well-founded understanding of CIs' history, technology and indication.

2.1 History of Cochlear Implants

The inventing progress of CIs has been an interdisciplinary collaboration between diverse groups such as engineers, otolaryngologists and neurosurgeons[25].

An abstract foundation for the invention of CIs was laid in 1748 by Benjamin Wilson who may claim to be the first to have electrically stimulated the ear of a deaf patient extra-auricularly[26] producing a slight thermal sensation from one ear to the other[27]. Fifty years later, the Italian physicist Alessandro Volta electrically stimulated his ear in a self-experiment resulting in an auditory sensation[28].

Goaded by those first experiments, scientists pushed the field forward in the following century[26]. The first patent pending for an electrical device stimulating a human's ear, the *electric osteophone* implemented by the American La Forest Potter, was dated in 1905[26]. Its intent was to electrically stimulate auditory brain cells in deaf people thereby igniting neglected auditory pathways[29].

A more radical approach towards today's' CIs was made in 1940 by the Americans Clark Jones, Stanley Smith Stevens and Moses Lurie[26]. They discovered inter alia the auditory nerve's response to electricity. An experiment showed that patients sensed a noise growing louder with rising current levels[30]. In 1950, the Swedish neurosurgeon Lundberg operatively stimulated a cochlear resulting in noise perception[26].

In 1939, Homer Dudley developed a synthesizer producing speech by reducing the human voice to its fundamental characteristics: its frequency range and spectral components. The so called "vocoder" is the foundation of modern speech processors in CIs[25].

In 1957, the electrophysiologist André Djourno and otolaryngologist Charles Eyriès from France were the first to stimulate the auditory nerve intra-auricularly in the auditory canal itself[26]. The patient claimed to detect an auditory sensation and could rudimentarily distinguish high and low frequencies, whereas speech could not be identified[25]. Although their experimental set-up cannot be considered as the first CI, their conclusion states that further development might result in the invention of electrical hearing[26].

Notwithstanding the ambitious approaches of electrical auditory nerve stimulation, the American team William House (otologist) and John Doyle (neurosurgeon) were the first to implant a device that could be characterised as a CI in 1961[26]. This device comprised a single electrode inserted in the scala tympani shortly afterwards replaced with an array of four channels. Although both devices created a vague sense of auditory input, they were soon afterwards removed since they caused oedema and impending infection due to high stimulation levels so[25]. However, due to a dispute concerning copyright the cooperation between Doyle and House quickly ended[26]. The Doyle brothers continued their work with otolaryngologist Frederick Turnbull until 1968[25].

In 1964, otolaryngologist Blair Simmons and engineer Robert White from Stanford University implanted an electrode array comprising 6 channels into a patient's modiolus[26]. This device can be considered as the first multichannel CI, although hearing tests in this patient were not very promising and Simmon stopped further implantation for the time being[25]. In the late 1960s, House continued his work on single-channel CIs with engineer Jack Urban. One of their primary goals was to develop implants not presenting health hazards to patients. Among their findings was the advantage of single-wire devices to multi-electrode devices[25].

Otolaryngologist Robin Michelson researched CIs in the late 1960s[25]. During an American Otological Society's meeting in 1971 he presented his work on implanting single-channel implants in several patients who where thus able to perform pitch identification below 600 Hz and to correctly identify speech, however without speech recognition[25]. Soon afterwards began a collaboration between Michelson, otolaryngologist Frank Sooy and neurophysiologist Michael Merzenich at the University of California at San Francisco (UCSF). After various animal experiments, Merzenich declared that a multichannel-device is obligatory for pitch perception marking a new period in CI research[25]. With the leading experts working collaboratively as well as competitively, devices now known as "CIs" have been established in the scientific community[26].

Until the early 1970s, the widely spread attitude towards CIs was that they would never be able to provide auditory skills useful in everyday life. This was substantiated by the fact that CIs then merely covered the cochlea's basal parts thus only enabling the perception of very high frequencies. Furthermore, current technique only provided dynamic ranges up to 6 dB which made it almost impossible to display regular speech patterns[25].

Due to the low success rate concerning speech intelligibility achieved with a single electrode CI, scientists ambitiously developed multichannel implants[26]. After an experimental session with 13 single-channel device implanted adults (11 implanted by House, 2 by Michelson) an evaluation by Robert Bilger from the University of Pittsburgh was published: Although patients could not understand spoken words, their lip reading, quality of life and own speech production significantly improved[25]. Goaded by these findings, House implanted a few thousand deaf patients with his *House/3M* single-channel implant until 1980[25].

However, other groups concentrated on the development of multi-electrode devices. Claude Henri Chouard, a student working in Charles Eyriès laboratory[25], inserted an implant comprising 7 electrodes. He justified this multichannel approach with the possibility of utilising the cochlear's tonotopic structure and therefore creating a hearing impression containing diverse frequency ranges[31]. Spured on by these findings, the Australian Graeme Clark investigated multichannel stimulation in cats. In 1978, he developed the first commercially available multichannel CI, marking the establishment of the Australian hearing company *Cochlear*[26]. Three years later he was able to prove that patients using these multichannel devices could partially understand speech without additional lip-reading. Not surprisingly, the *Nucleus Implant* received a commercial permission in 1985 for adults and for children from 2 years in 1990[25].

In the following years, eager attempts were made to improve speech intelligibility. Vast progress was made with the realization that exact tonotopic stimulation is key to hearing improvement. The most important demand on research during the first period of commercially established CIs was the development of implants transmitting speech satisfyingly. After vast technical progress, sensory deaf patients nowadays possess very good speech intelligibility with the help of modern CIs. Hence, the focus of CI research has shifted since the end of the 20th century: A new goal is to enable CI users to understand and enjoy music.

2.2 Cochlear Implant technology

The CI is a hearing aid designed for patients suffering from hearing loss due to both acquired or congenital etiologies of cochlear hair cell loss whose auditory nerves are still intact[32].

Figure 2.2.1 is a schematic drawing of the CI components. The device comprises implanted and externally worn components. Both microphone and speech processor are enclosed in a single housing worn at the pinna. The speech processor is connected to the emitting coil (transmitter) via a cable whereas the latter is magnetically held in place behind the ear. Its magnetic counterpart is the receiving coil (receiver) implanted subcutaneously. The remaining electric components are embedded in a bony indentation surgically countersinked behind the mastoid process. Finally, the electrode array is running through the middle ear in between facial nerve and chorda tympani. The array ends in the cochlea's scala tympani adjacent to the auditory nerve fibers' endings.[33].

The microphone receives acoustic sound which is transmitted to the speech processor. The latter converts the acoustic signal into an electrical neural excitation pattern individually adjusted to each patient with the help of stored programmes. Afterwards, this individual stimulation pattern is delivered to the emitting coil implanted subcutaneously via induction. Electric stimuli are further conveyed until reaching the electrodes which stimulate the acoustic nerve hence creating an auditory impression[33].

Various stimulation forms have been developed in order to make the auditory im-

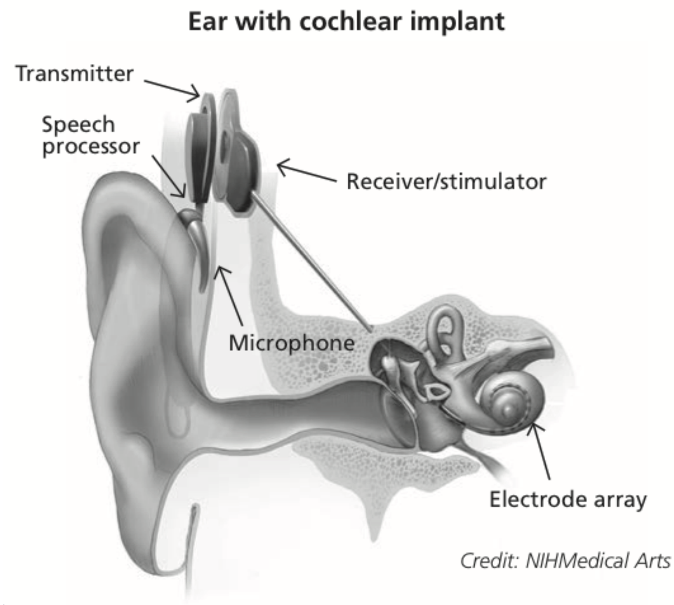


Figure 2.2.1: Schematic drawing of a Cochlear Implant[34].

pression created by CIs more natural. An electrical stimulus is defined by its current level flowing in or out of nerve tissue in a certain length of time. In order to avoid the likelihood of potentially harmful reactions in between tissue and electrodes it is crucial to use DC-free energy[33].

CIs circumvent the basilar membrane's complex function by electrically stimulating the auditory nerve[32]. Depending on the manufacturer, current multi-channel CIs comprise 8-22 electrodes and cover a large frequency bandwidth[33]. Whereas early devices comprising a single electrode only provided support in lip-reading, current multichannel implant techniques offer good speech intelligibility[32]. With the objective of making an efficient use of the cochlea's tonotopic arrangement, a stimulus in the area of a specific electrode evokes a pitch sensation corresponding to the location-dependent pitch sensation of a normal hearing person[33].

Modern CIs allow sense of hearing by band pass filtering the incoming sound spectrum. Hence, distinct sound spectrum parts activate their corresponding electrodes[32].

2.3 Indication

Ever since the CIs has been commercially introduced for adults in 1985, due to the implants' vast technical progress[35], its indication[35] is subject to constant alteration[36]. A first approval for the use of CIs in children was granted in 1990[36]. Other indication expansions such as implanting unilaterally in contrast to only bilaterally, implanting despite residual hearing, lowering the age limit for children and implanting persons with auditory malformations have been made[35].

In general, CIs are considered suitable for those patients with such profound sensorineural hearing loss that the use of other hearing aids is no longer auspicious[37].

Common indications for CIs are the following: postlingually deafened children, adolescents and adults; children, adolescents and adults with residual hearing; prelingually deaf children and perilingually deafened children with or without residual hearing. A CI supply as soon as possible after diagnosis of pre- oder perilingual deafness in children is crucial to avoid complications in speed acquisition. Other indications to be mentioned are the use of CIs in patients with a given unilateral CI indication and patients with tinnitus severely diminishing quality of life. CI supply is indicated in some selected cases of prelingually deafened adults. Testing the auditory nerve's and pathway's integrity and functionality prior to CI supply is mandatory[37].

2.4 CI provision conditions

All subjects in this study were users of bilateral CIs supply. Bilateral CI provision emerged at the end of the last century and is not funded by insurance companies for adults in most countries outside Germany. Several studies from the 1990s onwards could prove that bilateral CI implantation has a significant advantage over unilateral supply especially in directional hearing and tasks with speech presented with noise - listening tasks that require binaural interaction[38;39]. Similar advantages of bimodal CI use (unilateral CI supply and contralateral hearing aid supply) have been shown compared to unilateral CI use supply[40]. Bilateral implantation is considered the gold standard in prelingually deafened children since cortical patterns and binaural hearing develops more efficiently with acoustic information from both ears[41].

However, more alterations and expansion in the indication for CIs have been made. von Ilberg et al.[42] were the first research team to preserve residual hearing in the course of CI supply: a strategy called Electric-Acoustic Stimulation (EAS). This technique is suitable for patients suffering from profound high-frequency and mild low-frequency hearing loss amplifying high frequencies with the help of a CI and low-frequencies with a conventional hearing aid. Numerous studies have shown that EAS offers advantages for patients with residual hearing[42–44]. It appears that speech intelligibility in both quiet and noisy environments is significantly better with EAS than with bilateral CI supply[8;45–47]. Moreover, with EAS the transmission of fundamental frequency information is expanded compared to conventional CIs, which is important for pitch perception[2]. Hence, EAS users perform significantly better in melody recognition tasks than CI recipients[48;49].

2.5 Music perception and appraisal with Cochlear Implants

Compensating poor hearing abilities can easily be achieved in active conversations. Most words have one single predetermined meaning, and a sentence's meaning can often be concluded from its context. Furthermore, body language provides valuable information on the dialogue partners' emotional conditions and the relationship between them. Additionally, lip reading proves to be helpful in noisy conditions. Finally, there almost always remains the option of asking one's dialogue partner to repeat something left unclear.

As a rather abstract form of expression, music does not provide such opportunities. This especially applies to recorded music in contrast to live music[50;51]. In order to make technical advances in enhancing music intelligibility with CIs it is important to grasp the physical components making up music.

In simple terms, music can be described as a sequence of tones and complex tones having fundamental characteristics such as rhythm, pitch, melody and timbre[52].

Rhythm is the entity formed by successive tones and in between gaps with their specific durations[21]. In CIs, this information is presented via temporal stimulation patterns[3] - a strength of CIs in music transmission[21].

The recognition of melodies can solely be based on rhythm information. Admittedly, CI users are not as skilled in processing this information as normal hearing subjects are but still satisfactorily[3] so. Gfeller et al.[53] have developed a test battery (Adapted Primary Measures of Musical Audiation, PMMA) allowing the evaluation of rhythm recognition in CI users. Both the normal hearing control group and the CI patients achieved over 80% correct answers. A study by Brockmeier et al.[54] showed that normal hearing listeners on average achieve higher results than CI recipients in rhythm tasks, however not statistically significant.

Compared to speech, complex music comprises a larger range of fundamental frequencies and sound levels which makes music a more demanding listening task[51]. The cochlea's crucial mechanism for identifying pitch is its tonotopic organisation[55]. Whereas excursions of the basilar membrane's base near the oval window create the perception of high pitch, apical excursions near the helicotrema correspondingly create low pitch. Depending on the manufacturer, CIs comprise up to 22 electrodes which are obliged to replace the deafs' loss of 3500 tonotopically arranged inner hair cells[19]. Hence, rather degraded pitch information can be transmitted even by modern CIs. Independent electrodes, receiving incoming electric signals that encode auditory information from their assigned frequency band widths, stimulate surrounding nerve tissue that regularly process similar frequencies. However, the electric stimulation process is not as precise as the physiological stimulation process. This results in adjacent nerve tissue from different frequency spectra being excited as well[20]. This phenomenon is called Spread of Excitation.

The majority of currently applied electrode configurations in CIs is in a Monopolar (MP) mode. With MP configurations, electric current flows to an electrode in the cochlea with an extra-cochlear electrode used as an electrical grounding[56]. However, MP stimulation creates a relatively broad SoE in the cochlea[57]. Distinct electrodes are stimulated by incoming signals derived from their assigned frequency bands which in turn generate an electric field and stimulate adjacent neuronal tissue. The respective stimulated neuronal tissue is not clearly separated from its adjacent neuronal tissue stimulated by adjacent electrodes[20]. Hence, SoE severely limits frequency selectivity[21].

Thus, channel interactions in CIs occur due to the stimulation of a larger population of neurons than the same acoustic signal in physiological cochleas normally do. Since the acoustic signal is processed in predetermined frequency band widths, harmonic complex tones' components may not be resolved hence destroying the sensation of harmonicity[51].

In order to improve CI patients' speech and music intelligibility, a reduction of channel interactions is the aim of current research[20].

Another factor contributing to poor pitch perception is a potential mismatch between the electrode array's frequency intracochlear placement and the individual cochlea's tonotopic order necessarily resulting from surgery. Since electrode arrays are mostly not fully exploiting the cochlea's length, lower frequencies are being paired with tonotopically higher frequencies in the cochlea[51]. Pitch perception however relies on low-frequency hearing, an ability that is hardly preserved with standard CIs. Thus, both SoE and frequency mismatches are held responsible for CI users not possessing normal hearing subjects' finely graduated frequency discrimination[21].

According to various studies[21;58], CIs at least have to comprise 64 electrodes for conveying music almost naturally. In contrast, merely four electrodes are necessary for speech intelligibility in quiet environments[21;59]. Several studies have shown that normal hearing listeners can on average perceive pitch differences of one semitone whereas CI recipients on average need intervals of at least eight semitones to detect a change in pitch[60;61]. Just as music intelligibility in general, pitch perception performance varies strongly among CI users with some being able to detect differences of a single semitone[60].

A common approach to assess melody intelligibility are familiar melody recognition tasks. The results vary broadly from not being able to recognise any melody to perfectly identifying all[21;60]. However, the recognition of even well known melodies may be rather difficult for CI recipients, owing to long periods of profound hearing impairment prior to implantation. Therefore, numerous studies on melody recognition were implemented basing on assigning well known melodies to presented test stimulus patterns[21]. For example, Galvin et al.[62] developed a test which examined melodic contour identification. The test comprises nine different melodies of distinct patterns (ascending, descending, descending-ascending etc.) presented with simple stimuli. The normal hearing control group correctly identified 90% of all given melodies whereas CI users could only do so in 50%.

Timbre perception in CI recipients is rather poor[62–64]. Timbre is a characteristic of musical signals and allows us to distinguish different instruments - e.g., piano and violin - generating a sound with identical fundamental frequency and loudness [21]. Furthermore, timbre recognition relies on both frequency and temporal envelope information [21]. Temporal information in CIs is typically transmitted via the waveform's temporal characteristics that stimulate each electrode - in this process, music's fine-structure information is mostly getting lost [51].

Heng et al. [65] reported that if CI recipients and a normal hearing control group were offered both frequency and temporal envelope information to identify instruments, CI users would merely use temporal envelope information. In addition to their test battery with simple stimuli, Galvin et al. [62] investigated timbre perception by playing the aforementioned melodies with six different instruments (organ, glockenspiel, trumpet, clarinet, violin and piano). Just as reported for rhythm perception, normal hearing subjects scored higher than CI users (80% versus 60% correct answers).

As discussed above, CI users' performance in perceiving music's fundamental characteristics of pitch and timbre is poor. This emphasises the need for further research on CI technology to improve music intelligibility.

2.6 Hearing performance related to objective measures

In spite of music being the more demanding listening task, speech perception can be put in direct contrast. Both speech perception in noise and music perception require the listener to perceive differences in pitch [66] which is achieved by high spectral resolution - a technical feature that is still very limited in CIs [1;67;68]. Speech perception in quiet in contrast does not rely as much on pitch perception and is therefore relatively well kept in CI users [66].

Various studies investigate the relation of speech perception in noise and music perception in CI recipients. Gfeller et al. [69] compared three groups of normal hearing adults, standard CI recipients and EAS users in a familiar melody recognition and pitch ranking task and correlated results with a speech reception threshold (SRT) task in noise. EAS listeners achieved significantly higher scores in pitch ranking compared to subjects using regular CI devices. Against expectations, no significant intraindividual correlation was found between pitch ranking and speech perception in noise, which the authors related to the small number of participants [69]. Cullington and Zeng [70] compared bilateral CI recipients' and bimodal CI users' performance in a speech in noise test and a music task inter alia by testing pitch perception. Analysis of intraindividual performance showed no significant correlation between the SRT in noise task and the music test.

To further analyse this, we hypothesise that subjects with bilateral CI supply who rate themselves as possessing good music intelligibility score higher both in situations with severe background noise and in psychoacoustic music tests. This will be evaluated with the Oldenburger Satztest (OLSA) and the Adaptive Melody-Pattern-Discrimination Test (AMPDT). The subjects will evaluate their music intelligibility in a questionnaire.

In daily clinical practice, an objective tool to predict performance in difficult listening tasks such as speech perception in noise and music perception would clearly be very useful. It could be used to check the functionality of new developments in CI technology.

Various studies investigated whether reduced channel interactions assessed by Spread of Excitation measurements are a predictor of good perceptive skills and vice versa. Srinivasan et al.[71] found a significant improvement of performance in speech perception in noise tasks with Partial Tripolar (pTP) stimulation compared to Monopolar stimulation. Several studies have shown that TP stimulation modes produce less channel interactions than Monopolar (MP) stimulation modes[57;72–74]. However, Srinivasan et al.[71] could not find a significant correlation between the degree of improvement in speech perception and the degree of current focusing reducing SoE. Similarly, Padilla and Landsberger[75] investigated whether subjectively perceived simple stimuli sound quality could estimate the degree of reduction in SoE achieved by current focusing. Results showed that a significant correlation exists between reduced SoE and subjects describing the sound of applied stimuli as rather "clean" than "dirty"[75].

To find out whether SoE is a crucial factor to CI recipients' poor music perception, Spahr et al.[76] tested 10 normal hearing adults' hearing performance in musical tasks such as melody recognition and frequency discrimination. To imitate CI recipients' difficult listening condition, Spahr et al.[76] simulated SoE via manipulating the rate of amplitude reduction. They found that all musical tasks' test results worsened with simulating current spread[76].

Therefore, the second hypothesis is that subjects achieving higher results in the OLSA and AMPDT test battery have a more selective neural excitation pattern produced by their CIs. This will be objectified by a forward masking SoE measurement.

Chapter 3: Material and methods

This scientific study follows the ethical principles defined in the World Medical Association's (WMA) Declaration of Helsinki from 1964 and has been approved by the University of Frankfurt's medical ethics committee (ethics committee number 380/2014).

3.1 Subjects

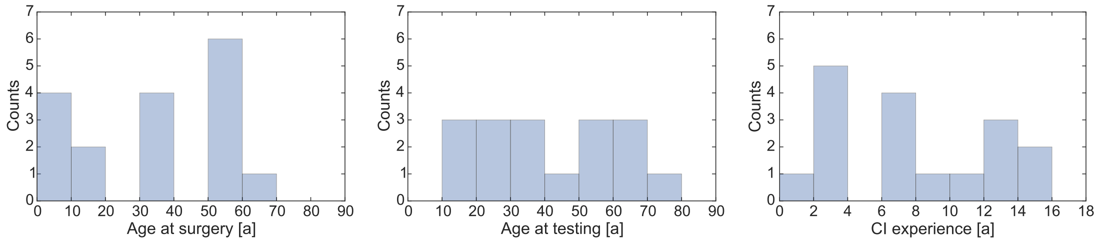
All subjects who participated in the study are listed in the data bank for CI users of the University Hospital Frankfurt's department for Audiology. Likewise, they were implanted in the corresponding Department of Otolaryngology. The patient collective covered 17 subjects with bilateral CI usage and a minimum CI experience of 2 years.

With 8 female and 9 male subjects the gender distribution was nearly uniform. The oldest subject was 77.9 years and the youngest 14.6 years old. Further information on the patients are listed in table 3.1.1. The subjects for the present study were chosen according to given audiometric reports and their highly developed speech intelligibility in noise environments.

Four subjects were prelingually deaf whereas 13 subjects were postlingually deaf. For further information on the subjects' hearing loss etiology see table B.0.1. For matters of data privacy there are no subject names listed in the study. The number associated with each subject represents the order they were tested.

3.2 Implanted devices and electrode material

All patients were provided with CI devices by the Austrian hearing implant company MED-EL but used different types of both implants and electrodes (table B.0.1).



(a) **(b)** **(c)**

Figure 3.1.1: Histograms: Age distribution for **(a)** surgery, **(b)** at testing and years of **(c)** CI experience.

	Patient population
Number of patients (N)	17
Females (N)	8
Males (N)	9
Maximum age [a]	77.9 a
Age (mean) [a]	41.6 a
Minimum age [a]	14.6 a
CI experience (arithmetic mean) [a]	8.0 a

Table 3.1.1: Subject demography

3.3 Experimental set-up

3.3.1 Adaptive Melody-Pattern-Discrimination Test

The Adaptive Melody-Pattern-Discrimination Test (AMPDT) was conducted in a soundproof auditory booth in the University Hospital Frankfurt's department of Audiology. The subjects completed the test binaurally with their own speech processors. No alterations of their processors' standard settings were undertaken.

The subjects were seated in the exact centre of the auditory booth. A "KS Digital C5 Tiny" loudspeaker with the ear to membrane distance $d_{\mathrm{em}} = 160\,\mathrm{cm}$ was mounted in the fronting wall's centre. The distance from the speaker membrane's centre to the floor was $d_{\mathrm{mf}} = 135\,\mathrm{cm}$. Stimulus level was set at 70 dB SPL (sound pressure level) in the approximate position of the subjects' ears. A touch-screen terminal positioned in front of the subjects' chair served as the control panel. The experiment was controlled using custom written MATLAB software (2007b version 7.5, The MathWorks, Inc., Natick, Massachusetts).

3.3.2 Spread of Excitation

The Spread of Excitation (SoE) test was conducted in an office room within the University Hospital Frankfurt's department of Audiology. MAESTRO, the hearing implant company's CE-certified standard-fitting-software was used to measure SoE. Each ear was tested separately.

At the beginning of each SoE measurement run, a psychoacoustic measurement was conducted to determine each subject's individual least acceptable perceived loudness (LAPL). The hearing implant company MED-EL defines the LAPL as the loudest sound level at which one can comfortably hear. A visual analogue scale ranging from 0 (no sound) to 10 (far to loud) served the investigator and subject as an indication to determine the individual LAPL. An "8" on the visual analogue scale was predetermined with the aspirated LAPL. Identifying the individual LAPL was the only part in the SoE where the response of the subject was required.

Control of stimulation and receiving electrodes were executed via a diagnose interface box (DIB) coil. The subjects' processors were not used.

3.3.3 Speech perception in noise measurement

The Oldenburger Sentence Test (OLSA) was conducted in the same auditory booth described above.
The subjects completed the test binaurally with their own speech processors in their preferred daily life setting. No alterations of their processors' standard settings were undertaken.

The subjects were seated in the exact centre of the auditory booth. Speech signal presentation was realised through a loudspeaker array lined up at the wall facing the subject with a constant sound pressure level of 65 dB.
The noise was created by an array system including 128 loudspeakers creating a Multi-Source Noise Field (MSNF). The latter consisted of four independent virtual speakers set up in each corner of the auditory booth simulating a natural noise environment[8].

A touch-screen terminal positioned in front of the subjects' chair served as the control panel. Speech intelligibility was assessed in two different noise conditions.

- **CCITT-Noise:** This noise comprises frequencies up to 22 kHz and contains almost no temporal fluctuation. Furthermore, it has no informational masking property[8].
- **Fastl-noise**[77]: This noise type depicts the temporal characteristics of speech and creates the opportunity of gap listening. This is achieved by amplitude modulation of the CCITT-noise with randomised modulation frequency. The modulation spectrum distribution of Fastl-noise has its maximum at 4 Hz correlating with the amplitude-modulation statistics of German language. It serves as a single competing speaker stimulation without any informational masking[8].
- **OLnoise:** The noise originally used in the OLSA is synthesized by time-shifted parts of the mixed test sentences.

3.4 Study schedule

All subjects received invitation letters and appointments were made individually by telephone or email. All tests were conducted in the Department of Audiology in the University Hospital Frankfurt. The appointments lasted for approximately 3-4 hours depending on individual breaks and speed.

Initially, the instructor explained the planned procedure including possible risks and insurance matters. The subjects signed a consent form stating their participation in the study was voluntarily and could be ended without any further explications necessary. The subjects received an expense allowance and signed a receipt. All subjects completed three psychoacoustic tests in the fixed order listed below:

i. The Adaptive Melody-Pattern-Discrimination Test (AMPDT)

ii. Spread of Excitation (SoE) Test

iii. Oldenburger Sentence Test OLSA

A fixed order was chosen since both AMPDT and OLSA require a high level of concentration whereas no active participation is needed in the SoE measurement. Therefore, the SoE measurement was taken between the two demanding tasks. In order to familiarise the subjects with the AMPDT and OLSA procedures, a test run preceded each test. The patients' task was to type in their answers using the touch-screen terminal. During the test runs the instructor stayed with the patients in the auditory booth to assure the explained test procedure was completely understood.

The SoE measurement is a passive test during which the subjects's only task was to state whether the loudness of the presented stimulus elicited the sensation of uncomfortable loudness.

3.5 Test procedure

3.5.1 Adaptive Melody-Pattern-Discrimination Test

Two different psychoacoustic measures were assessed with the AMPDT paradigm[23]. The first experiment investigated the timbre difference discrimination threshold (TDDT) by means of an adaptive Three-Interval Three-Alternative Forced-Choice (3I3AFC) test.

Hereby, one of the two foreground melodies (A or B, each consisting of sequentially presented six harmonic-complex sounds, see figure 3.5.1) was randomly selected and repeatedly presented in three consecutive intervals. In one randomly chosen interval, one of the harmonics of each harmonic complex sound was accentuated (target presentation, 3I3AFC procedure). This created the auditory impression of a second "hidden" melody - the "background melody". The subject's task was to detect the target interval by discrimination of small perceptual timbre differences. By adaptive steering of the amount of accentuation of the target harmonics, the threshold needed to discriminate distinct timbre differences was assessed (timbre difference discrimination threshold (TDDT)).

The pause duration between consecutive harmonic complex sounds was $t_\mathrm{p} = 100\,\mathrm{ms}$. The duration of a harmonic complex sound was $t_\mathrm{hcs} = 200\,\mathrm{ms}$ in melody A and alternately $t_\mathrm{hcs} = 200\,\mathrm{ms}$ and $t_\mathrm{hcs} = 300\,\mathrm{ms}$ in melody B.

The second psychoacoustic measure investigated a more complex perceptual task, namely the identification of the melodic contour of the background melody (background contour discrimination threshold (BCDT)). In the second experimental setup, two randomly chosen equal foreground melodies were consecutively presented. The second melody comprised either a descending or an ascending background contour (melody, see figure 3.5.1), which was generated by accentuation of single harmonics in the harmonic complex sound melodic foreground pattern. After presentation, the subject was forced to state whether an ascending or descending background contour was present (One-Interval Two-Alternative Forced-Choice (1I2AFC) procedure). The level of accentuation was adaptively controlled in order to assess the so called background contour discrimination threshold (BCDT).

Accentuation of the harmonics was realised by alternating three different parameters (figure 3.5.2):

- sound level increment (ΔL)
- frequency detuning (Δf)
- onset asynchrony (Δt_{on})

The AMPDT's condition "sound level increment" assessed how much more intense (ΔL, in dB) the background melody had to be compared to the foreground melody to enable timbre difference discrimination (3I3AFC) and background contour discrimination (1I2AFC). Applying to both of these conditions, small dB results corresponded to high scores since subjects hence needed the background melodies only to be little louder than the foreground melodies to master the given tasks. Thus, whenever results of this condition were numerically positively correlated with other tests in which high numeric scores represent high scores, Pearson correlation coefficients (r-values) would be negative. For better understanding, in those cases all r-values were multiplied by -1.

The AMPDT's condition "frequency detuning" assessed the degree of frequency detuning Δf necessary to enable timbre difference discrimination (3I3AFC) and background contour discrimination (1I2AFC). In this study, the foreground melody was altered by raising its frequency measured in percent of the melody's key note. This generated the background melody. Hence, low percentage test results represented higher scores than high percentage test results since the subjects needed the background melody to be only slightly altered in order to fulfil the given tasks. Hence, same as for condition "sound level", r-values are multiplied by -1 in those cases where positive correlations were represented by a negative r-value.

The AMPDT's condition "onset asynchronism" assessed the minimum time Δt_{on} necessary for the background melody to start before the foreground melody to enable timbre difference discrimination (3I3AFC) and background contour discrimination (1I2AFC).

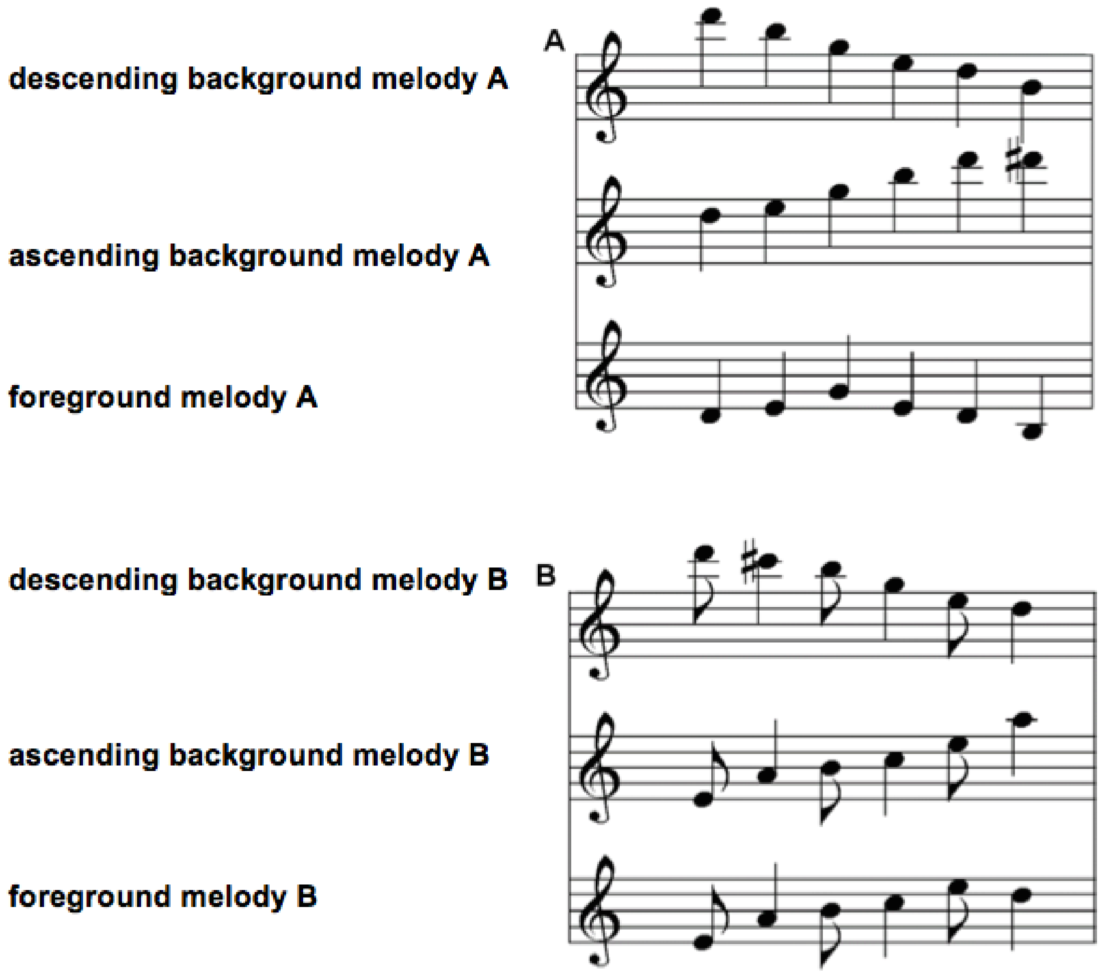


Figure 3.5.1: Foreground melodies A and B with ascending and descending background melodies appearing in the AMPDT.

The result was given in ms, with the negative algebraic sign indicating the earlier start of the background melody. Hence, low results in the millisecond range represented low discrimination thresholds.

The test battery was conducted sequentially for each parameter. Five patients were tested in the order $\Delta L - \Delta f - \Delta t_{\text{on}}$ and 4 patients in the sequence $\Delta f - \Delta L - \Delta t_{\text{on}}$ to investigate possible test sequence effects.

Both 3I3AFC and 1I2AFC test were repeated once and preceded by a practice session and will not be further analysed. The practice session contained 5 runs and was not adaptive and was therefore presented with the following start parameter settings: 15 dB ($3I3AFC_{\Delta L}$), 20 dB ($1I2AFC_{\Delta L}$), 30 % (Δf), −25 ms (Δt_{on}). Figure A.0.1 shows the practice session's results for each test condition.

Tests sessions both for the 3I3AFC and 1I2AFC tasks were adaptive following a 2down-1up rule. In the event of a wrong answer, the harmonics' modification was increased in order to make the difference the subject had to identify more obvious. If the

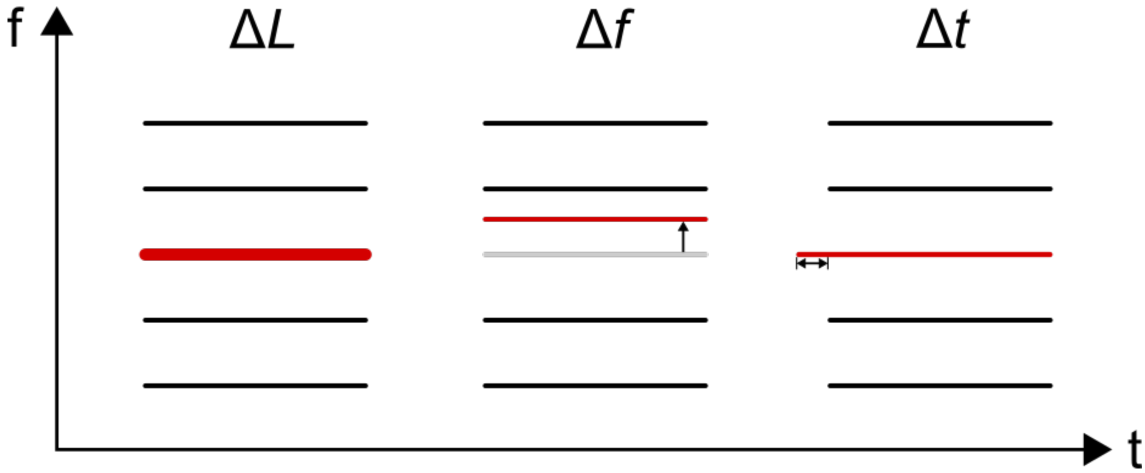


Figure 3.5.2: Schematic diagram displaying the background melodies' creation in the AMPDT. Background melodies were computed by accentuating respectively one harmonic in each harmonic-complex sound: either by sound level increment (ΔL), frequency detuning (Δf or by onset asynchrony (Δt_{on}). The AMPDT is an adaptive test that assessed degree of alteration in the background melodies necessary for the detection of timbre differences (TDDT) or the background melody's contour (BCDT).

subject answered a test run correctly, the following run was presented with the same level of modification as the previous one. If answered correctly again, the harmonics' modification was accordingly decreased resulting in the next run to be more difficult. A test run automatically ended after 12 turning points with a turning point being completed after two correct and one wrong answer given consecutively or in reverse order. The first 4, the middle 2 and the last 6 turning points were associated with the same modification interval. Harmonics were modified after one wrong or two correct answers as explained above. These intervals were 4 dB / 2 dB / 1 dB in parameter ΔL, 8 % / 4 %/ 2 % in parameter Δf and −8 ms / −4 ms/ −2 ms in parameter Δt_{on}. The subjects' final TDDT or BCDT was the average value of the last 6 turning points' discrimination thresholds.

In case a subject did not achieve 12 turning points, the test either terminated after a maximum of 50 runs or after reaching a predetermined maximum modification parameter (20 dB, 50 % or −80 ms). As a result of the explanation above, at least 6 reached turning points were obligatory to evaluate a test.

3.5.2 Spread of Excitation

The SoE measurement conducted in this study used Electrically Evoked Compound Action Potentials (ECAPs). ECAP are a telemetry of electrically evoked compound action potentials measured by the CI hardware. These represent the electrical response to acoustic stimuli generated in the spiral ganglion[6]. In daily clinical practice, ECAPs are used during CI surgery to estimate the neural response threshold. ECAPs were measured by the Auditory Nerve Response Telemetry (ART) in the MAESTRO programme.

In this study, SoE was measured via a spatial forward-masking paradigm[6;7]: Stimuli of identical level were time-shiftedly applied to fixed probe electrodes and masker electrodes proceeding along the electrode array[7]. A biphasic stimulus with a pulse duration of 30 µs and an interphase gap of 2.1 µs were used. With a time interval of 400 µs, the stimulus was initially applied to the masker electrode and afterwards to the probe electrode. The ECAP generated by the stimulus applied to the probe electrode was captured at the recording electrode which was one electrode step basal to the probe. After 400 µs, the auditory nerve's fibers excited by the masker stimulus were still refractory. In case masker and probe electrode were the same or nearby electrodes, the probe electrode's ECAP could therefore either not be elicited or was at least very small due to the refractory period. Hence, ECAPs grow with increasing masker and probe electrode distance (Figure 3.5.3). Thereby the ECAP measured at the recording electrode is a description of the masking impact the masker electrode has on the probe by the overlap of both excitation areas[7]. ECAPs thus illustrate the degree of spatial selectivity of adjacent electrodes[5].

The stimulus level assessed in the described way is the least acceptable perceived loudness (LAPL) [cu]. Current unit (cu) is a unit introduced by the hearing implant company MED-EL, whereupon 1 cu is approximately 1 µA.
In the present study, in each CI a basal, medial and apical electrode were used as probe electrodes with their adjacent electrodes serving as recording electrodes. Usually, probe electrodes were E3 (apical), E6 (medial) and E9 (basal) unless exactly those were deactivated in a subject's map. The electrodes used in the SoE measurement are listed in table B.0.2.

For each probe electrode, 6 masker electrodes in each direction of the electrode array were used including the probe electrode as a masker itself. Thus, the masker electrode varied its location from -6, -5, -4, -3, -2, -1, 0, +2, +3, +4, +5 and +6 electrode steps on the array counted from the probe electrode. The recording electrode one step basal from the probe electrode (+1) was not used as a masking electrode. The possible number of masker electrodes was limited by the electrode array's length of 12 electrodes. As the probe electrodes are fixed and the masker electrodes proceed along the array during the SoE measurement, the number of discharged ECAPs corresponded to the number of masker electrodes used. The result of the SoE measurement was a plot of ECAPs amplitude vs. masker electrode. Amplitudes were calculated by subtracting the negative from the next positive peak of the response[5] (Figure 3.5.4). The SoE function is characterised by its slope. A steep slope is indicative of a more localised electrical field distribution in the cochlea[20].

Another investigated area of application for SoE measurements is to detect electrode positions: Grolman et al.[78] found that SoE measurements are a useful tool to detect electrode array tip foldovers. Furthermore, SoE measurements may help to predict or explain CI recipients' performance and may therefore be a tool to control modifications

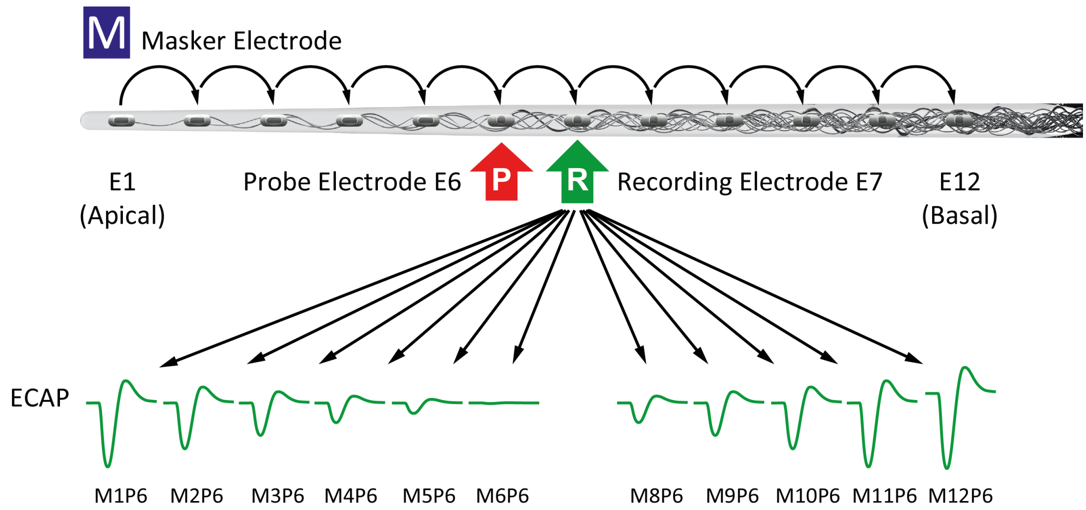


Figure 3.5.3: Schematic illustration of ECAP formation from the medial probe (P) electrode 6 during the SoE measurement. ECAPs were computed via a spatial forward-masking paradigm. Fixed probe electrode locations with recording (R) electrode being the adjacent basal electrode were used. Masker (M) electrodes varied along the array throughout the measurement. The closer masker and probe were, the stronger was the resulting masking effect depicted by a smaller ECAP response (green graphs). Small masking effects represent small channel interactions and hence higher spatial selectivity.
(P= probe electrode; R= recording electrode; M= masker electrode)

of sound processing strategies for improving listening performance[79].

3.5.3 Speech Perception in noise measurement

The Oldenburger Satztest's (OLSA, Hörtech GmbH, Oldenburg) is a sentence matrix test to measure a person's speech reception threshold (SRT) in noise[22].

The subjects' task was to listen to sentences comprising five words with the schematic form name - verb - numeral - adjective - object binaurally with their standard speech processors' programmes. All sentences were presented in noise.

Test sentences were randomly arranged from a pool of 50 words with 10 alternatives in each word group. The investigator chose one of twenty test lists with each list containing 20 test sentences. As the test sentences were randomly arranged they mostly were devoid of meaning. This intended circumstance is excellent for a test in clinical practice: the subjects are consequently unable to remember sentences or conclude their answer based on assumptions.

The OLSA assessed the SNR (given in "dB SNR") level by means of an adaptive procedure, where 50 % Speech Reception Threshold (L50) [dB] was present. The Signal-to-Noise-Ratio (SNR) gave information about whether noise may be louder than speech enabling the subjects to correctly understand 50% of the sentences or speech had to be louder than noise in order to do so. The noise was presented at the fixed level of 65 dB whereas the speech signal's level was varied according to the subject's performance

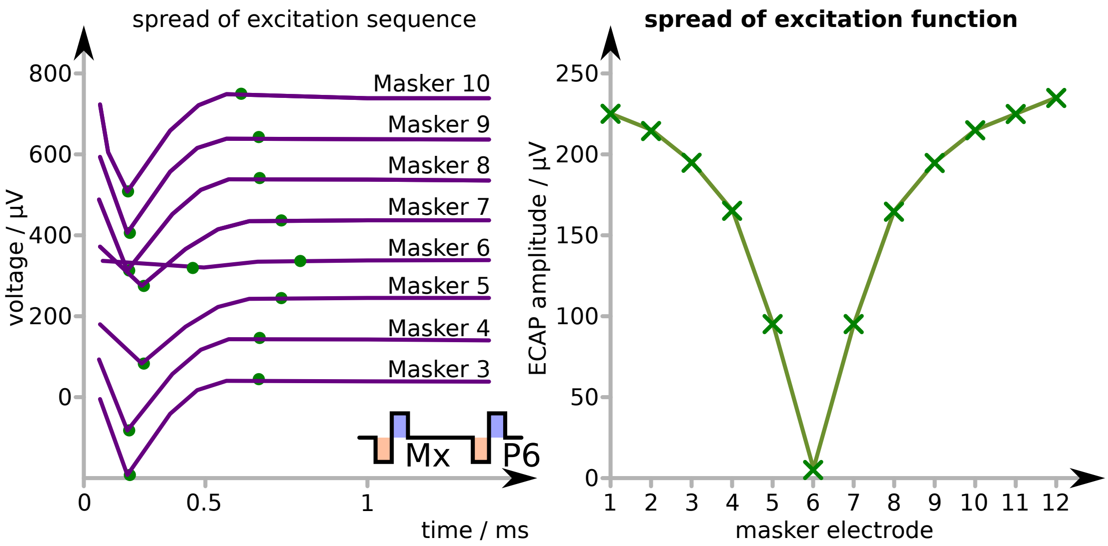


Figure 3.5.4: Schematic illustration of computing a SoE function of probe (P) electrode 6 during the SoE measurement. ECAPs were computed via a spatial forward-masking paradigm. The closer masker and probe were, the stronger was the resulting masking effect depicted by a smaller ECAP amplitude (distance between the highest and lowest voltage values in each purple graph). The SoE function (green graph) is formed by plotting the masker electrodes against their associated ECAP amplitudes (purple graphs).
Graphic by courtesy of MED-EL, Austria

to compute individual SRT. Due to application problems, four data sets are missing ($L50_{Fastl,P}$; $L50_{Fastl,T}$ and two times $L50_{OLnoise,T}$).

Negative signs imply that the speech signal may be quieter than the noise signal whereas positive signs mean that the speech signal had to be stronger than the noise signal to fulfil said task. Thus, whenever good results in the OLSA and other tests in which high numeric scores represent good results were positively related, Pearson's r-values would be negative. For better understanding, in those cases all Pearson's r-values were multiplied by -1.

In the present study, speech and noise were transmitted through different loudspeaker arrangements. With the objective of creating a natural noise environment, a Multi-Source Noise Field (MSNF) was utilised. The MSNF's design is an arrangement of four loudspeaker arrays creating four different noise sources presented simultaneously (figure 3.5.5). These loudspeakers were located in the corners of the auditory booth. Speech signal was presented by a loudspeaker at a distance of 165 cm directly in front of the subject[8].

Additionally, two different noise characteristics (Fastl-noise[77] and OLnoise, see figure 3.5.6) were utilised in this study. Prior to the measurement all subjects completed a practice session in the *Fastl* condition in order to familiarise themselves with the test procedure.

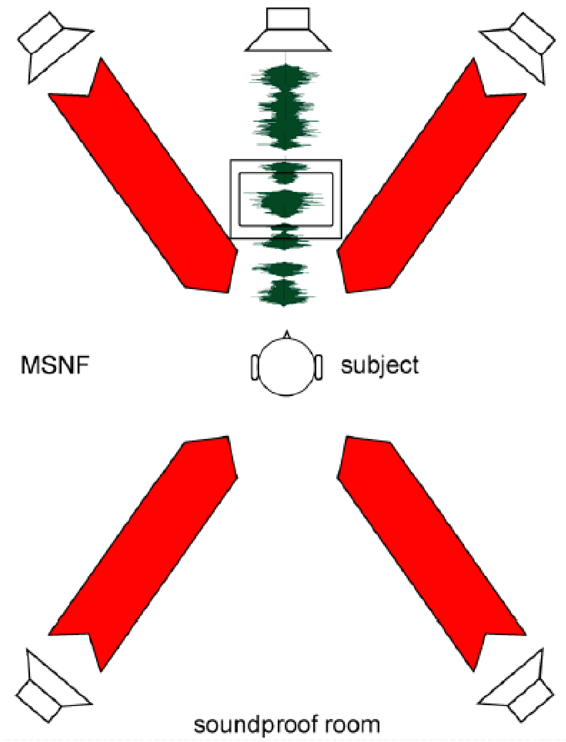


Figure 3.5.5: Schematic diagram of the Multi-Source Noise Field (MSNF) condition. The subject was seated in a soundproof room surrounded by an arrangement of four loudspeakers located in the corners of the room. The speech signal was presented with a loudspeaker directly in front of the subject.
Source: Rader et al. [8]

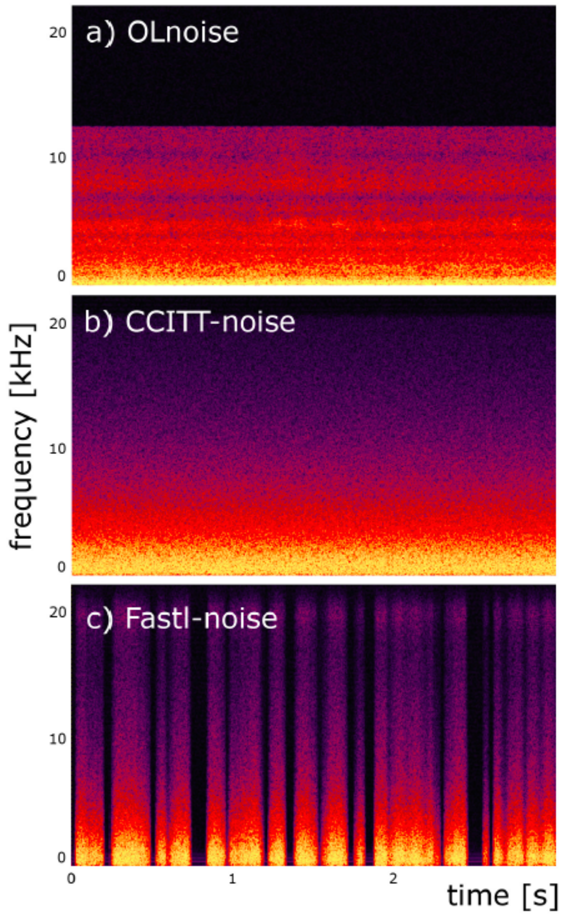


Figure 3.5.6: Time/frequency plots of OLnoise, CCITT- and Fastl-Noise[8] frequency patterns utilised in the speech in noise test OLSA.
Fastl-noise has a frequency range of 0 - 22 kHz and is derived from the CCITT-noise via amplitude modulation. This alteration represents the temporal characteristics of speech. Fastl-noise's maximum in temporal distribution is located at 4 Hz corresponding to the amplitude-modulation statistics of German language.
OLnoise is generated by randomly overlapping the OLSA's test sentences. The frequency spectrum of the OLSA is equivalent to the OLnoise's from 150 Hz - 12.6 kHz. Thereby, very effective masking is achieved.
Source: Rader et al.[8]

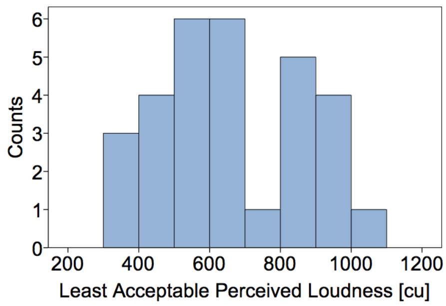


Figure 3.6.1: Histogram: Least acceptable perceived loudness (LAPL) [cu] in the SoE measurement.

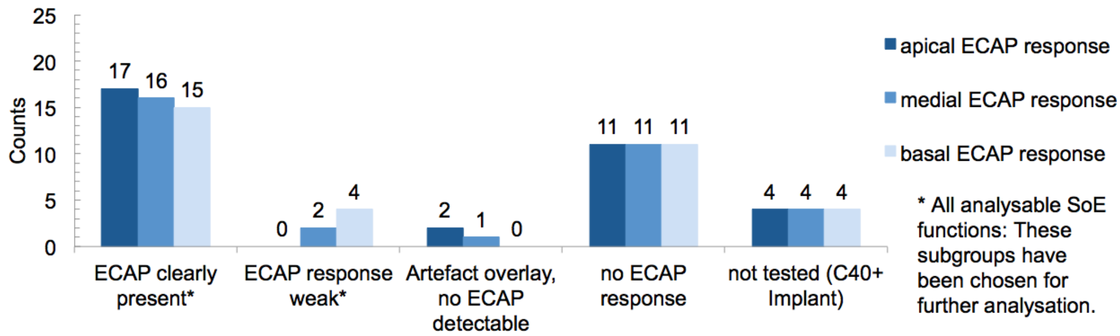


Figure 3.6.2: Bar graph of ECAP response categories (n=90). The category "ECAP measurement not supported" comprises all Combi 40+ implants.

3.6 Spread of Excitation analysis

The SoE measurement was performed on almost all subjects since the Combi 40+ device does not support SoE measurements. As there were 4 Combi 40+ devices among the subjects' CIs (one Combi 40+ device on the right hand side; 3 Combi 40+ devices on the left hand side), 30 ears had undergone the SoE measurement. Hence, a total number of N = 90 SoE profile functions were recorded. Among the acquired SoE functions were N = 54 with a present ECAP response and N = 48 with a clearly present ECAP response (see 3.6.2). The SoE measurement was performed unilaterally in 4 patients.

Prior to the actual SoE measurement, the subjects' individual least acceptable perceived loudness (LAPL) was determined for each side. The stimulation level's median was 638.50 cu, the maximum was 1011.00 cu and the minimum was 350.00 cu (see figure 3.6.1). An Independent-Samples T Test showed that stimulation levels for each subject's right and left CI device are not statistically different from one another ($p = 0.74$).

As described in subsection 3.6.2, a classification of all ECAP responses was established. Figure 3.6.2 shows a bar graph of the categorised ECAPs classes. Individual SoE functions depending on place of stimulation are shown in figure B.0.3.

3.6.1 Artefact reduction methods

ECAP measurements were corrected for artefacts originating from the capacitive nature of the CI system according to public procedures (P Spitzer 2014, personal communication).

The ECAP measuring procedure used in MAESTRO is called Auditory Nerve Response Telemetry (ART). ART offers two different methods of artefact reduction. These methods are "Alternating Stimulation" and "Zero Amplitude Template" (see figure 3.6.3).

After the application of an electrical stimulus, the charging and discharging progress of the capacitive elements generates an electrical field with exponentially decaying field strength. Since this induced electrical artefact is several orders of magnitude stronger than the small neural response, this electrical artefact dramatically decreases the ECAP response's quality. To prevent this, the SoE measurements apply a biphasic stimulation pattern depicted in figure 3.6.3a (anodic-cathodic (S) or cathodic-anodic stimulation sequence (B)). The artefact is removed by averaging measurements of both stimulation sequences (figure 3.6.3a) without modifying the ECAP signal. The artefact reduction method is called "Alternating Stimulation".

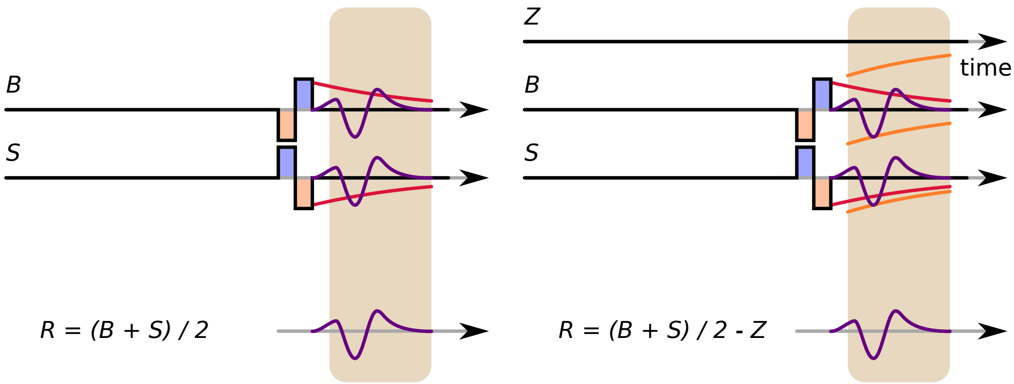
In addition, a procedure named "Zero Amplitude Template" is available to further reduce the residual electrical artefact. The CI's amplifier produces an artefact itself. To measure this artefact, voltage is measured at the recording electrode without prior stimulation (Z). This artefact (Z) is then subtracted from the equation resulting from "Alternating Stimulation" ($R = (B + S)/2 - Z$, see figure 3.6.3b). This procedure was used for each ECAP in all SoE measurements.

3.6.2 ECAP response quality and exponential functions

Due to largely varying results, a classification of all collected ECAP responses into five categories was necessary:

- ECAP clearly present
- ECAP response weak
- Artefact overlay, no ECAP detectable
- no ECAP response
- ECAP measurement not supported (C40+ Implant)

In the data analysis only those SoE functions categorised as "ECAP clearly present" and "ECAP response weak" were regarded which make up 54 out of all 90 SoE functions (see examples in figure 3.6.4). In the following, those two categories will be summarised



(a) Alternating stimulation **(b)** Zero Amplitude Template

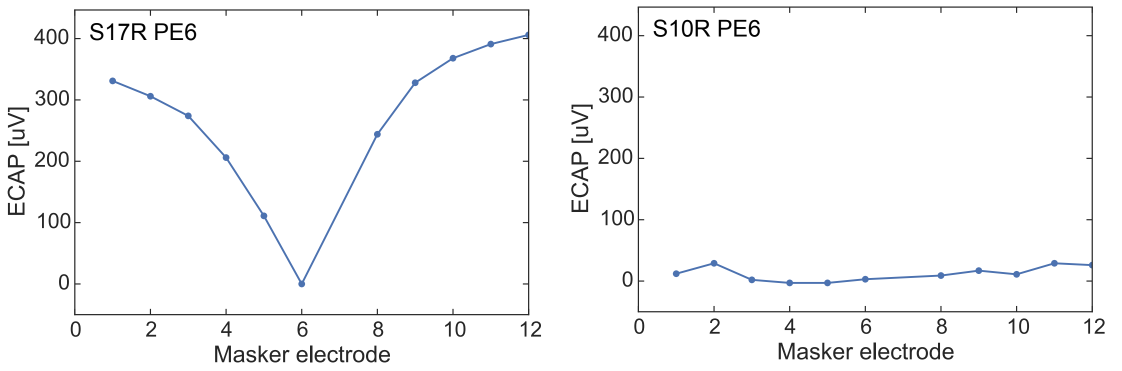
Figure 3.6.3: Artefact reduction strategies in the SoE measurement.
(a) Alternating stimulation: Electrodes in CIs operate as capacitors. The electrode's discharging progress results in an exponentially declining voltage curve. To prevent this from producing an artefact reducing the ECAP response's quality, the SoE measurement is run with an "Alternating Stimulation".
(b) Zero Amplitude Template: The CI's amplifier produces an artefact itself. To measure this artefact, voltage is measured at the recording electrode without prior stimulation (Z). This artefact (Z) is then subtracted from the equation resulting from "Alternating Stimulation" ($R = (B + S)/2 - Z$, see figure 3.6.3b).
Graphic by courtesy of MED-EL, Austria

as "ECAP response present".
One of the approaches to analyse the SoE functions was to establish parameters defining exponential functions which approximately display the SoE functions' courses. Each SoE function was depicted by two exponential functions: one exponential function represents the SoE function's left hand (towards the electrode's apex) and the other plots the SoE function's right hand side (towards the electrode's base).

An exponential function was applied to approximate the course of the SoE measurements:

$$ECAP = c - a \cdot e^{\frac{-|m-p|}{u}} \tag{3.1}$$

Variable c is equatable to the maximum ECAP possible for large distances between probe and masker electrode. The difference between variables c and a describes the exponential function's minimum. The SI Unit of variables c and a is μV.
Variable p represents the probe electrode's number ($p = 6$ for probe electrode 6). Variable m represents the masker electrode's number. The term $-m - p$ thus describes the distance between masker and probe electrode measured in number of electrode steps. If the masker electrode has a lower number than the probe electrode, the term $-m - p$ is negative.



(a) **(b)**

Figure 3.6.4: Examples for SoE functions that were chosen for further analysis (categories **(a)** "ECAP clearly present" (S17, Probe 6, right ear) and **(b)** "ECAP response weak" (S10, Probe 6, right ear). (S = Subject)

Variable u depicts the exponential function's slope: The smaller the absolute value of u, the steeper the e-function's slope is. A steep slope represents a more localised electrical field's distribution in the cochlea[20].
Figure 3.6.5 displays two exemplary exponential functions. Table B.0.3 displays the subjects values for each variable c, a and u.

The coordinate points' SI unit forming all SoE functions is μV. In order to make all SoE functions easier to compare, all SoE functions were normalised by dividing all μV values by the respective function's maximum. Hence, the normalised function's maximum is always 1. Figure 3.6.6 contrasts all medial probe's SoE functions in their unaltered (figure 3.6.6a) and normalised (figure 3.6.6b) versions.
The normalised SoE functions' values are displayed in table B.0.4.

3.6.3 Excitation Distances

In order to analyse the results of the SoE measurements, informative parameters had to be calculated. A procedure formerly proposed by Busby et al.[4] was applied to calculate the broadness of normalised SoE functions at the 25 %, 50 % and 75 % normalised ECAP response range ($\mathrm{DIST}_{0.25,\mathrm{A/B/AB}}$; $\mathrm{DIST}_{0.5,\mathrm{A/B/AB}}$; $\mathrm{DIST}_{0.75,\mathrm{A/B/AB}}$; DIST = excitation distance; A = Apical; B = Basal; AB = A + B). Three distances were measured: primarily the apical half of the SoE function's point of intersection with the horizontal line at 25 % (50 % and 75 %) to the point of intersection from the horizontal line with the vertical at the SoE function's minimum ($\mathrm{DIST}_{0.25/0.5/0.75,\mathrm{A}}$), secondly the respective distance at the basal half ($\mathrm{DIST}_{0.25/0.5/0.75,\mathrm{B}}$) and finally the sum of both distances ($\mathrm{DIST}_{0.25/0.5/0.75,\mathrm{AB}}$). Measurements of excitation distances were taken at the normalised SoE functions. In this study, said 25 % (50 % and 75 % levels were called "normalised ECAP response level (NERL)".

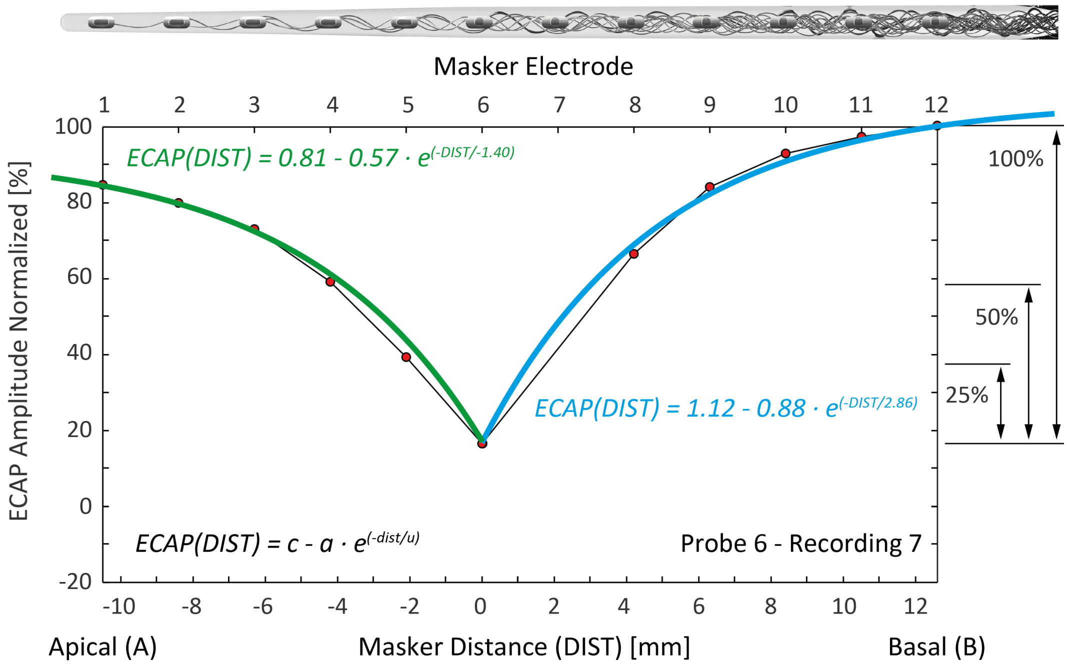


Figure 3.6.5: Schematic diagram of SoE functions represented by exponential functions. The red coordinate points represent the measured ECAP responses and form the SoE function. Based on these ECAP responses, exponential functions have been fitted.
Intracochlear SoE is characterised by the distance (excitation distance (DIST)) the exponential functions frame at their 25 % and 50 % level.

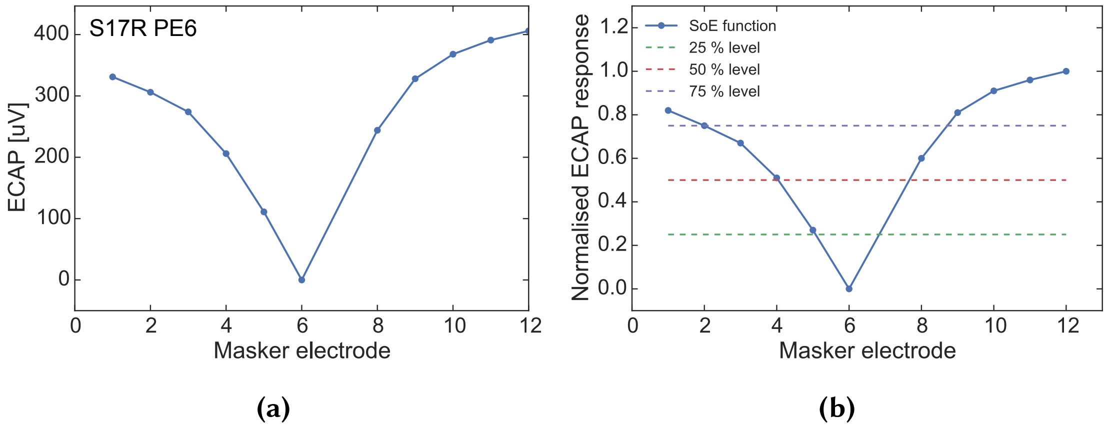


Figure 3.6.6: Unaltered vs. normalised SoE functions for the medial probe electrode.
(a) unaltered medial probe SoE functions and **(b)** normalised medial probe SoE functions.
(S 17, probe 6, right ear)

Electrode type	Active Stimulation Range [mm]	excitation distance [mm]
$FLEX_{28}$	23.1	2.1
$FLEX_{soft}$	26.4	2.4
Standard	26.4	2.4
$FLEX_{24}$	20.9	1.9
Compressed	12.1	1.1
Medium	20.9	1.9

Table 3.6.1: The manufacturer's (MED-EL) information on the respective active stimulation ranges of all tested electrodes.

DIST calculations were accomplished for both electrode number and electrode contact distance in mm. The latter was calculated in respect of the manufacturer's information on the active stimulation range of the individual electrode array (see table 3.6.1 and equation 3.2). Figure 3.6.7 outlines this data analysis method. Further data analysis will use electrode distances in mm. Hence, short DISTs represent narrow SoE patterns, which is assumed to be associated with higher spectral resolution.

$$\text{excitationdistance [mm]} = \frac{\text{Electrode length}}{11} \cdot \text{Electrode distance} \tag{3.2}$$

3.7 Questionnaire

To compare the subjects' objective test results from the AMPDT, SoE measurement and OLSA with subjective information, a questionnaire was developed for this study. All subjects (N=17) completed the questionnaire before the test battery. The questionnaire enquires about self-assessments in musicality and the extent of pleasure the subjects experience from listening to music.

A selection of questions from the "Munich Music Questionnaire - (MUMU)"[80] was chosen. The 25 questions of the latest version gather information about how listening to music is individually perceived and whether musical education has been experienced (instruments, vocals). The selected questions were arranged in three categories: music in everyday life, music intelligibility and musical education, The questionnaire's full version is listed in the appendix (C).
Using a questionnaire that concentrates on emotional aspects seems sensible visualising that music highly contributes to emotional well-being in most people's lives.

Albeit all questions followed a closed-ended question type, there are three different subtypes to be distinguished:

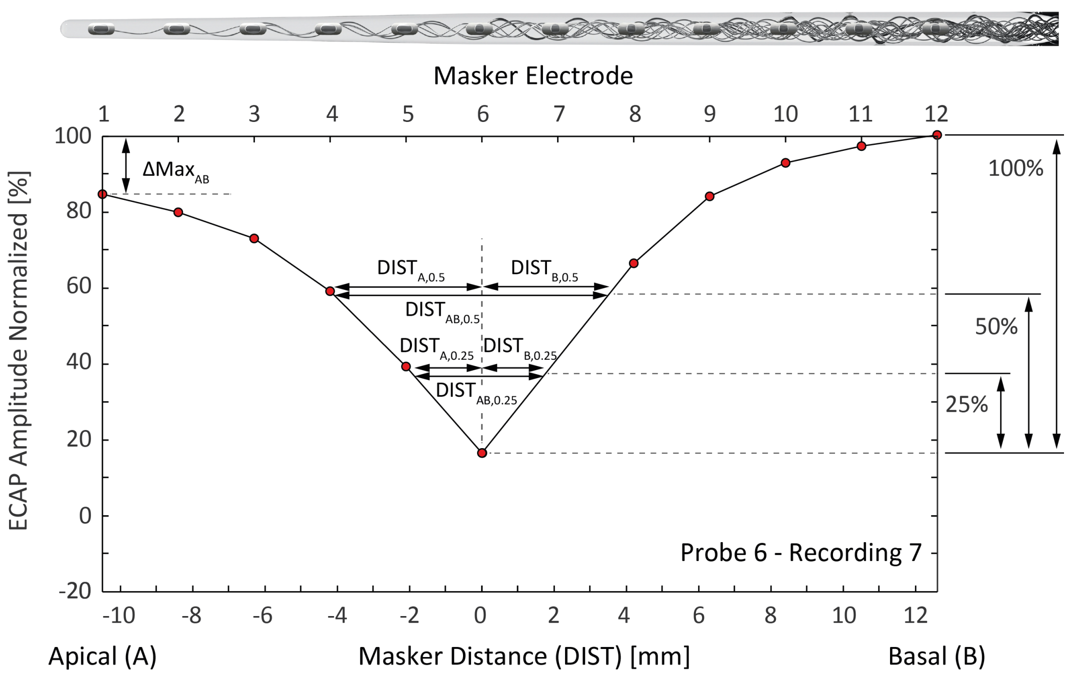


Figure 3.6.7: Schematic diagram of SoE data analysis: Measurement of the DISTs at the SoE function's 25 %, 50 % and 75 % NERL. Another approach of data analysis is measuring the difference between the basal and apical side of the SoE function's respective maximum given in μV (ΔMax_{BA}). (NERL = normalised ECAP response level; DIST = excitation distance)

i. polar questions (single choice and yes-no questions)

ii. self-assessment scales from 1-10

iii. multiple-choice questions (this question type always offers the possibility of adding an individual answer along with the preformed ones ticking "other".)

3.8 Statistics

After finishing data collection, the data were entered into Excel (Microsoft Excel for Mac 2011. version 14.4.7) and transferred to SPSS (version 22 for Mac OS X) for statistical evaluation. To make the data anonymous, the subjects were assigned numbers from 1-17.

Multiple comparisons increase the risk of falsely rejecting a null hypothesis (type I error, multiple comparisons problem). Thus, whenever data analysis required multiple comparisons, the Bonferroni method was applied to adjust significance levels. With N representing the number of compared pairs, the adjusted significance level was described by $p^{\star} < \frac{\alpha}{\mathrm{N}}$.

As the name implies, the Adaptive Melody-Pattern-Discrimination Test is an *adaptive* test with the subjects' results being determined by calculating the arithmetic means' from the last six test runs. The OLSA is an adaptive test as well with the subjects' results being determined by calculating the speech signal's sound level in dB to be able to recognise 50 % of the sentences. Negative signs imply that the speech signal may be less intense than the noise signal whereas positive signs mean that the speech signal needs to be stronger than the noise signal to fulfil said task.

All excitation distances assessed in the SoE measurement were computed with the technical graphing programme IGOR pro (version 6.34).

Chapter 4: Experimental results

This chapter lists the results of the psychoacoustic tests (AMPDT and OLSA), the SoE measurement, and the questionnaire.

4.1 Adaptive Melody-Pattern-Discrimination Test

Under the 3I3AFC condition, the subject's task was to detect the interval comprising the target melody with altered harmonic structure (timbre difference discrimination threshold (TDDT)). The 1I2AFC model on the other hand tested the subjects' ability to recognise melody patterns - in this study's case whether the background melody pattern is ascending or descending (background contour discrimination threshold (BCDT)).

The AMPDT measurements were additionally assessed with a normal hearing control group of 8 subjects aged between 23 and 60 years (6 female, 2 male)[81].

Since the complete test battery approximately lasted 3-4 hours and a rather demanding level of concentration was necessary, not every subject was able to complete all tests. The investigator decided individually whether the subject was able to complete the test battery. Table A.0.3 shows the number of participants in each AMPDT test variation.

Boxplots A.0.2, A.0.3 and A.0.4 show the collapsed results of Test (T) and Repetition (R). Table A.0.2 shows all individual results. Guess probabilities are 33 % for the 3I3AFC model and 50 % for the 1I2AFC model.

4.1.1 Learning effect

To maximize a given test's objectiveness and repeatability, potential learning effects should be avoided or properly accounted for.

Therefore, a Paired-Samples T Test (for normally distributed measured value differences) and a Wilcoxon-Test (for not normally distributed measured value differences) were used to investigate whether the difference between the T and R run's results of each parameter (ΔL, Δf and Δt_{on}) in the 3I3AFC and 1I2AFC model is statistically significant. A statistically significant difference indicating a learning effect was not present in any test condition (see table 4.1.1). This proves the retest's high reproducibility. However, the average discrimination threshold improved to a small extent between Test and Repetition run in all conditions except for condition 3I3AFC$_{\Delta f}$: The average potential gain of learning is 1.48 dB in condition 3I3AFC$_{\Delta L}$, 0.89 dB in condition 1I2AFC$_{\Delta L}$, 2.77 % in condition 1I2AFC$_{\Delta f}$, -1.87 ms in condition 3I3AFC$_{\Delta t_{on}}$ and -6.97 ms in condition 1I2AFC$_{\Delta t_{on}}$.

Since there was no statistically significant difference between Test (T) and Repetition (R), averaged results obtained from the two runs in each condition will be analysed in the following. Figures A.0.1, 4.1.1, 4.1.2 and 4.1.3 illustrate the collapsed average

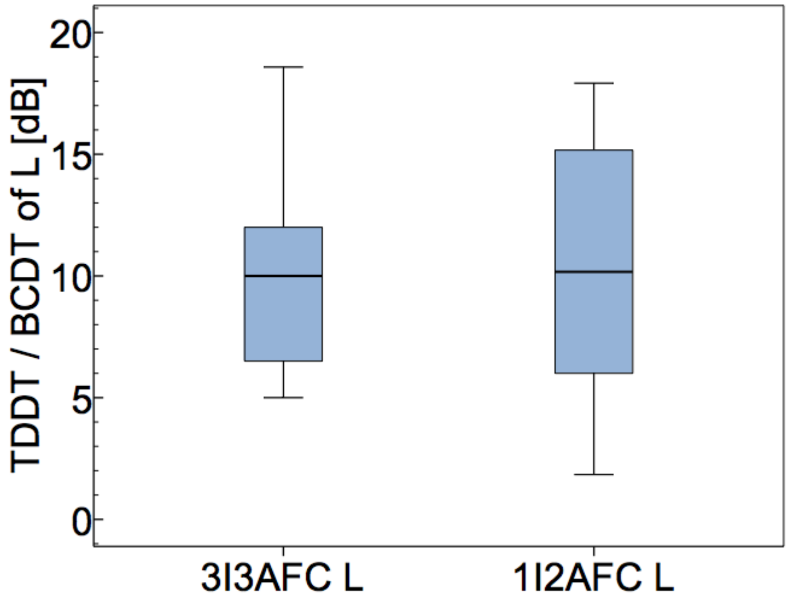


Figure 4.1.1: Boxplot charts: Collapsed average timbre difference discrimination threshold (TDDT) and background contour discrimination threshold (BCDT) depending on sound level increment of the harmonic (ΔL). For the number of participating subjects see table A.0.3.

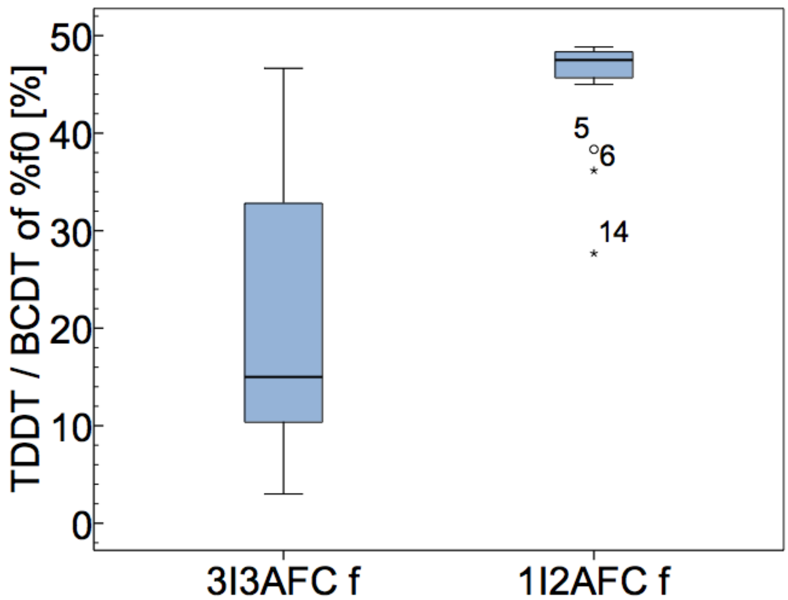


Figure 4.1.2: Boxplot charts: Collapsed average timbre difference discrimination threshold (TDDT) and background contour discrimination threshold (BCDT) depending on frequency detuning of the harmonic (Δf). Numbering of outliers (°) and extreme values (*) represent the number associated with each subject for matters of data privacy (see section 3.1). For the number of participating subjects see table A.0.3.

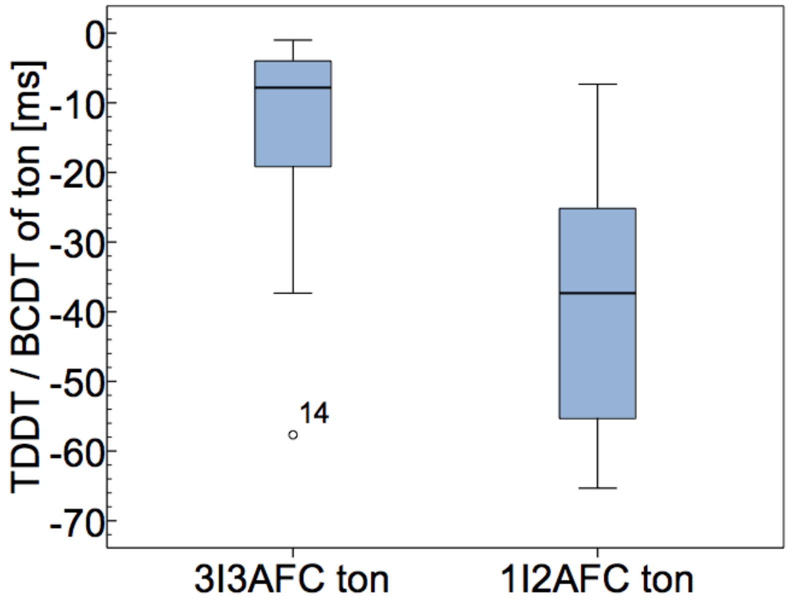


Figure 4.1.3: Boxplot charts: Collapsed average timbre difference discrimination threshold (TDDT) and background contour discrimination threshold (BCDT) depending on onset asynchrony of the harmonic (Δt_{on}). Numbering of outliers (°) and extreme values (*) represent the number associated with each subject for matters of data privacy (see section 3.1). For the number of participating subjects see table A.0.3.

discrimination threshold in the AMPDT's conditions. Table A.0.2 shows all individual results.

4.1.2 Sound level increment

Figure 4.1.1 shows discrimination thresholds depending on sound level increment of the harmonic. The 3I3AFC$_{\Delta L}$ conditions' median is 10.00 dB, maximum is 18.58 dB (Subject 12) and minimum is 5.00 dB (Subject 13). The median in condition 1I2AFC$_{\Delta L}$ is 10.17 dB. The discrimination threshold ranges between 1.84 dB (Subject 11) to 17.92 dB (Subject 14). The median in condition 1I2AFC$_{\Delta L}$ in the normal hearing control group was 2.5 dB[81].

4.1.3 Frequency detuning

Figure 4.1.2 shows discrimination thresholds depending on frequency detuning of the harmonic. The median in condition 3I3AFC$_{\Delta f}$ is 15.00 %. Discrimination thresholds range from 46.65 % (Subject 16) to 3.00 % (Subject 2). The median of condition 1I2AFC$_{\Delta f}$ is 47.5 % (below chance level). Discrimination thresholds range from 48.84 % (Subject 4) to 27.67 % (Subject 14). The median in condition 1I2AFC$_{\Delta f}$ in the normal hearing control group was 1.7 %[81].

Subjects were able to identify the distinct timbre difference introduced by frequency detuning (3I3AFC procedure) but unable to identify the background melody pattern

Test condition	Paired-Samples T Test			
	Mean difference	t	df	p
3I3AFC$_{\Delta L}$	1.48	1.51	16	0.15
1I2AFC$_{\Delta L}$	0.89	1.16	16	0.26
3I3AFC$_{\Delta f}$	-1.24	-0.57	16	0.58
1I2AFC$_{\Delta f}$	2.77	1.18	15	0.26
3I3AFC$_{\Delta t_{on}}$	-1.87	-1.65	9	0.13
1I2AFC$_{\Delta t_{on}}$	-6.97	-1.59	9	0.15

Table 4.1.1: Paired-Samples T Test and Wilcoxon-Test: Investigation of possible learning effects from the Test to Repetition run of each AMPDT condition. No statistically significant difference indicating a learning effect was present (all $p>0.05$). The SI unit of values listed in this column is the one applying to each condition (ΔL [dB]; Δf [%]; Δt_{on} [ms].) See subsection 4.1.1 for further explanation.

(1I2AFC procedure). The median of condition 1I2AFC$_{\Delta f}$ (47.5 %) converges to the inherent lower limit of the test (50 %). Further frequency detuning would result in strong convergence to the next higher harmonic. Clear outliers are subjects 6 and 14. Subject 6 was implanted at the age of 18 in a Single-Stage Surgery whereas subject 14 was implanted at the age of 52 with an interval of 1.78 years (see table B.0.1 for all subjects' age at surgery).

4.1.4 Onset asynchrony

Figure 4.1.3 shows discrimination thresholds depending on onset asynchrony of the harmonic. In the 3I3AFC$_{\Delta t_{on}}$ condition subjects achieved −8.92 ms as a median. Discrimination thresholds range from −57.67 ms (Subject 14) to −1 ms (Subject 5 and 6). The median of condition 1I2AFC$_{\Delta t_{on}}$ is −37.33 ms. Discrimination thresholds range from −65.33 ms (Subject 2) to −7.33 ms (Subject 11). The median in condition 1I2AFC$_{\Delta t_{on}}$ in the normal hearing control group was −4.3 ms[81].

Again, subjects were able to identify the distinct timbre difference introduced by onset asynchrony (3I3AFC condition) whereas they experienced difficulties in identifying the background melody pattern (1I2AFC condition).

4.1.5 3I3AFC versus 1I2AFC

At first glance it seems easier to detect target intervals by small timbre differences (3I3AFC) than to indicate the correct pattern of the target background melody (1I2AFC) (see figures 4.1.1, 4.1.2 and 4.1.3), as suggested by the 3I3AFC and 1I2AFC test's results.

In each test condition (ΔL, Δf, Δt_{on}), the average discrimination threshold was lower

Test condition	Paired-Samples T Test				
	Mean difference	t	df	p	
$3I3AFC/1I2AFC_{\Delta L}$	-0.92	-0.63	16	0.54	
$3I3AFC/1I2AFC_{\Delta f}$	-25.05	-6.50	16	<0.01	*
$3I3AFC/1I2AFC_{\Delta t_{on}}$	23.63	4.01	12	<0.01	*

Table 4.1.2: 3I3AFC compared to the 1I2AFC condition results. On average the subjects always achieved lower discrimination thresholds in the 3I3AFC test.
* Significant differences

in the 3I3AFC condition: mean $3I3AFC_{\Delta L}$ = 9.90 dB, mean $1I2AFC_{\Delta L}$ = 10.82 dB; mean $3I3AFC_{\Delta f}$ = 19.98 %, mean $1I2AFC_{\Delta f}$ = 45.03 %; mean $3I3AFC_{\Delta t_{on}} = -15.74$ ms, mean $1I2AFC_{\Delta t_{on}} = -38.30$ ms.
On average, in condition ΔL the BCDT (1I2AFC task) is 0.92 dB higher than the TDDT (3I3AFC task). However, this difference is not statistically different ($p = 0.54$, see table 4.1.2). In condition Δf, the BCDT (1I2AFC task) exhibits a 25.05 % larger mistuning than the TDDT (3I3AFC task). This difference is statistically highly significant (p<0.01). Likewise, TDDT (3I3AFC task) is highly significantly lower than the BCDT (1I2AFC task) in condition Δt_{on}: the background melody needs to start 23.63 ms earlier in the 1I2AFC than in the 3I3AFC test ($p < 0.01$) (see table 4.1.2).

4.1.6 Impact of mode of surgery

In the present study, 4 subjects among 17 underwent a Single-Stage Surgery (SSS) receiving both of their CI at once. The remaining 13 patients received their CIs sequentially (Two-Stage Surgery (TSS) group). It may be of interest whether the surgery (sequential vs. simultaneous) has an impact on clinical outcome such as music intelligibility. One may hypothesise patients adapt more quickly to electrical hearing if both ears are provided with CIs simultaneously. Table A.0.4 lists the number of participants divided according to mode of surgery in each AMPDT condition. In the TSS group, the average time difference between first and second implantation was 2.18 years ranging from 0.13 years to 5.13 years. Figure B.0.2 shows discrimination threshold depending on mode of surgery.

On average, the SSS subject group had lower discrimination thresholds in 5 out of 6 tested conditions: $1I2AFC_{\Delta L}$ (mean SSS = 9.52 dB; mean TSS =11.22 dB), $3I3AFC_{\Delta f}$ (mean SSS =16.40 %; mean TSS =21.08 %), $1I2AFC_{\Delta f}$ (mean SSS =44.80 %; mean TSS =45.11 %), $3I3AFC_{\Delta t_{on}}$ (mean SSS $=-11.5$ ms; mean TSS $=-17.43$ ms) and $1I2AFC_{\Delta t_{on}}$ (mean SSS $=-20.44$ ms; mean TSS $=-43.65$ ms). These differences were however not statistically significant (Independent-Samples T Test, all $p > 0.05$, see table 4.1.3).

In condition $3I3AFC_{\Delta L}$ the TSS subjects achieved lower TDDT (mean SSS = 12.75 dB;

Test condition	t	df	p	Mean difference
3I3AFC$_{\Delta L}$	1.68	15	0.08	3.73
1I2AFC$_{\Delta L}$	-0.53	15	0.61	-1.70
3I3AFC$_{\Delta f}$	-0.90	14.52	0.38	-4.68
1I2AFC$_{\Delta f}$	-0.09	15	0.93	-0.31
3I3AFC$_{\Delta t_{on}}$	0.59	12	0.57	5.93
1I2AFC$_{\Delta t_{on}}$	2.00	11	0.07	23.21

Table 4.1.3: Independent-Samples T Test for Equality of Means: Mean difference between the Single-Stage Surgery and Two-Stage Surgery group's discrimination thresholds the AMPDT. Subjects in the Single-Stage Surgery (SSS) group had slightly lower discrimination thresholds than the Two-Stage Surgery (TSS) group in all conditions except for 3I3AFC$_{\Delta L}$. This finding is not statistically significant (all p>0.05).

mean TSS = 9.02 dB). This difference, however, was not statistically significant (Independent-Samples T Test, $p > 0.05$, see table 4.1.3).

4.2 Spread of Excitation

4.2.1 Excitation distances

The total SoE width at the 25 % normalised ECAP response level (NERL) was narrower for the basal (median of BDIST$_{0.25,\mathrm{AB}}$= 3.15 mm) than for the apical (median of ADIST$_{0.25,\mathrm{AB}}$ = 6.03 mm) and the medial probe (median of MDIST$_{0.25,\mathrm{AB}}$ = 5.88 mm). The same effect was observed at the 50 % NERL (median of ADIST$_{0.5,\mathrm{AB}}$ = 8.97 mm; median of MDIST$_{0.5,\mathrm{AB}}$ = 5.61 mm; median of BDIST$_{0.5,\mathrm{AB}}$ = 9.94 mm, see table 4.2.1).

SoE functions (except for the medial probe at 25 % NERL, see table 4.2.1) showed asymmetric profiles with larger amplitudes towards the basal end of the cochlea.

The majority of SoE functions do not show perfect symmetry and therefore sometimes have a very low maximum at their apical/ basal side compared to the other. In the course of measuring excitation distances (DISTs) (see subsection 3.6.3), it was therefore not possible to find intersection points at the 25 %, 50 % and 75 % NERL for all conditions. Table 4.2.2 lists all available intersection points. It is obvious that the Apical DIST always produces less intersection points at the NERL than the Basal DIST. A possible reason for this might be that the electrode array is more densely arranged at its apical than basal end due to the anatomic narrowness of the cochlea's helicotrema. For further data analysis therefore only the medial probe excitation distances (MDISTs) will be analysed. Furthermore, the distance created by the difference between the basal and apical side of the SoE function's respective maximum given in μV (ΔMax_{BA} was determined, see equation 4.1).

Excitation distance	**[mm]**
$\mathrm{ADIST}_{0.25,\mathrm{B}}$	3.81
$\mathrm{ADIST}_{0.25,\mathrm{A}}$	2.36
$\mathrm{ADIST}_{0.25,\mathrm{AB}}$	6.02
$\mathrm{MDIST}_{0.25,\mathrm{B}}$	2.66
$\mathrm{MDIST}_{0.25,\mathrm{A}}$	2.67
$\mathrm{MDIST}_{0.25,\mathrm{AB}}$	5.88
$\mathrm{BDIST}_{0.25,\mathrm{B}}$	1.99
$\mathrm{BDIST}_{0.25,\mathrm{A}}$	1.15
$\mathrm{BDIST}_{0.25,\mathrm{AB}}$	3.15
$\mathrm{ADIST}_{0.5,\mathrm{B}}$	5.55
$\mathrm{ADIST}_{0.5,\mathrm{A}}$	2.40
$\mathrm{ADIST}_{0.5,\mathrm{AB}}$	8.97
$\mathrm{MDIST}_{0.5,\mathrm{B}}$	4.92
$\mathrm{MDIST}_{0.5,\mathrm{A}}$	4.11
$\mathrm{MDIST}_{0.5,\mathrm{AB}}$	9.94
$\mathrm{BDIST}_{0.5,\mathrm{B}}$	3.56
$\mathrm{BDIST}_{0.5,\mathrm{A}}$	2.30
$\mathrm{BDIST}_{0.5,\mathrm{AB}}$	5.61

Table 4.2.1: Excitation distances (DISTs, medians) at all normalised ECAP response levels (NERLs). (ADIST = apical probe excitation distance; MDIST = medial probe excitation distance; BDIST = basal probe excitation distance)

Distance [mm]	Number of estimations
$MDIST_{0.25,B}$	18
$MDIST_{0.25,A}$	17
$MDIST_{0.25,AB}$	17
$MDIST_{0.5,B}$	18
$MDIST_{0.5,A}$	13
$MDIST_{0.5,AB}$	13
$MDIST_{0.75,B}$	18
$MDIST_{0.75,A}$	7
$MDIST_{0.75,AB}$	7

Table 4.2.2: Number of available intersection points for all measured excitation distances (DISTs) at the 25 %, 50 % and 75 % NERL. (MDIST = medial probe excitation distance; NERL = normalised ECAP response level)

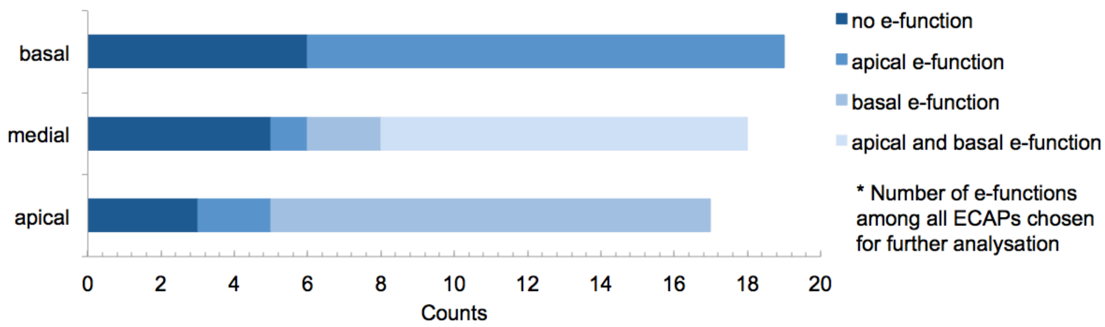


Figure 4.2.1: Exponential functions found for all clearly present ECAP responses, N=55 (categories "ECAP clearly present" and "ECAP response weak").

$$\Delta Max_{BA} = Max_B - Max_A \tag{4.1}$$

4.2.2 Exponential functions

Since exponential functions could only be described for SoE functions having at least 3 coordinate points, the majority of exponential functions could be defined for the implants' medial probes (see figure 4.2.1). This is due to the circumstance that the ART measurement procedure stopped after recording 6 electrode positions to both the electrode array's apex and base. Hence only the medial probes' results will be regarded in the following.

SoE parameter	Sig. (2-tailed)	Mean difference
ΔMax_{BA}	0.38	-68.98
$MDIST_{0.25,B}$	0.55	-0.69
$MDIST_{0.25,A}$	0.27	-1.13
$MDIST_{0.25,AB}$	0.23	-1.82
$MDIST_{0.5,B}$	0.35	-1.40
$MDIST_{0.5,A}$	0.30	-2.84
$MDIST_{0.5,AB}$	0.18	-4.85

Table 4.2.3: Independent-Samples T Test for Equality of Means: SoE results grouped according to first and second implanted ears. No statistically significant difference in the medial probe excitation distances of first and second implanted CIs in the SoE measurement is present. (MDIST = medial probe excitation distance)

4.2.3 Analysis of intra patient Spread of Excitation with respect to mode of surgery

Figure 4.2.2 and 4.2.3 display the statistics of all measured DISTs and ΔMax_{BA} for all analysis groups.

As outlined before, most bilateral CI users were sequentially implanted with a significant time delay between the surgeries. Commonly the side with residual or profound deafness is implanted first. The different prerequisites may impact the pattern of Spread of Excitation.
Table B.0.5 lists all means of the SoE measurement results for the firstly and second implanted ear. The firstly implanted ears always show smaller excitation distance means at all 25 % and 50 % levels and therefore narrower SoE patterns: ΔMax_{BA} (mean first CI = 68.40 µV; mean second CI = 137.38 µV); $MDIST_{0.25,B}$ (mean first CI = 2.62 mm; mean second CI = 3.31 mm); $MDIST_{0.25,A}$ (mean first CI = 2.56 mm; mean second CI = 3.97 mm); $MDIST_{0.25,AB}$ (mean first CI = 5.18 mm; mean second CI = 7.01 mm); $MDIST_{0.5,B}$ (mean first CI = 3.93 mm; mean second CI = 5.33 mm); $MDIST_{0.5,A}$ (mean first CI = 4.57 mm; mean second CI = 7.42 mm); $MDIST_{0.5,AB}$ (mean first CI = 8.31 mm; mean second CI = 13.16 mm).
However the Spread of Excitation difference is not significant and hence dependent on chance (all p values "Sig. 2-tailed" >0.05, see table 4.2.3).

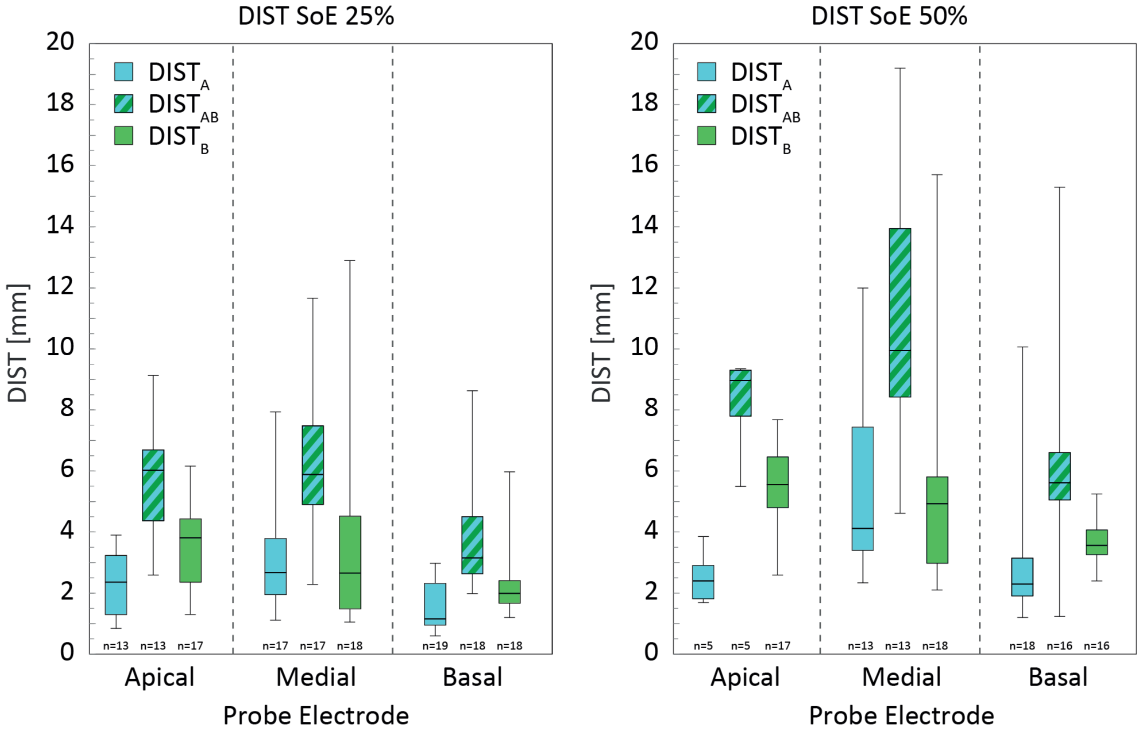


Figure 4.2.2: excitation distance (DIST) dependence on place and normalised ECAP response level. Boxplots named "DIST$_A$" represent the excitation distances (DISTs) in mm depicted for the SoE functions' apical side at the 25 % (left diagram) and 50 % (right diagram) NERL. Likewise, boxplots named "DIST$_B$" represent DISTs at the SoE functions' basal side and boxplots labelled "DIST$_{AB}$" those DISTs that are framed by both the apical and basal SoE functions' sides. Figure 3.6.7 graphically shows these parameters. (NERL = normalised ECAP response level)

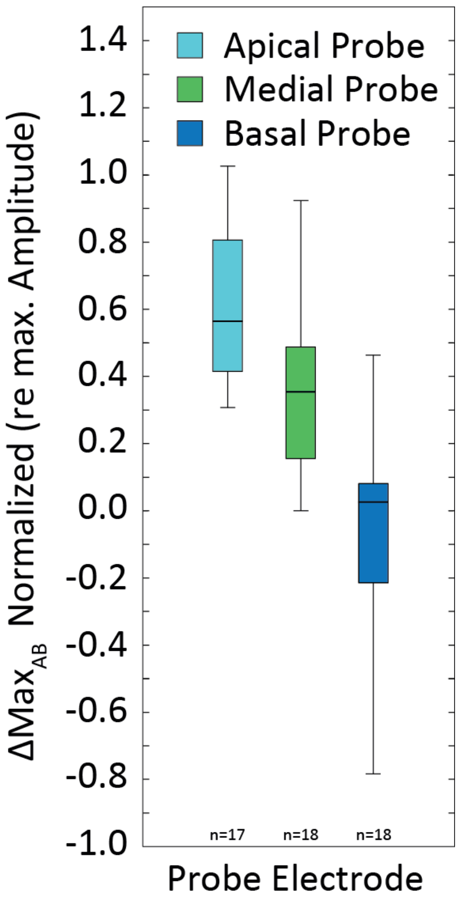


Figure 4.2.3: Boxplot diagram: $\Delta\mathrm{Max}_{\mathrm{BA}}$. The term $\Delta\mathrm{Max}_{\mathrm{BA}}$ describes difference between the basal and apical side of the SoE function's respective maximum given in μV. Figure 3.6.7 graphically shows these parameters.

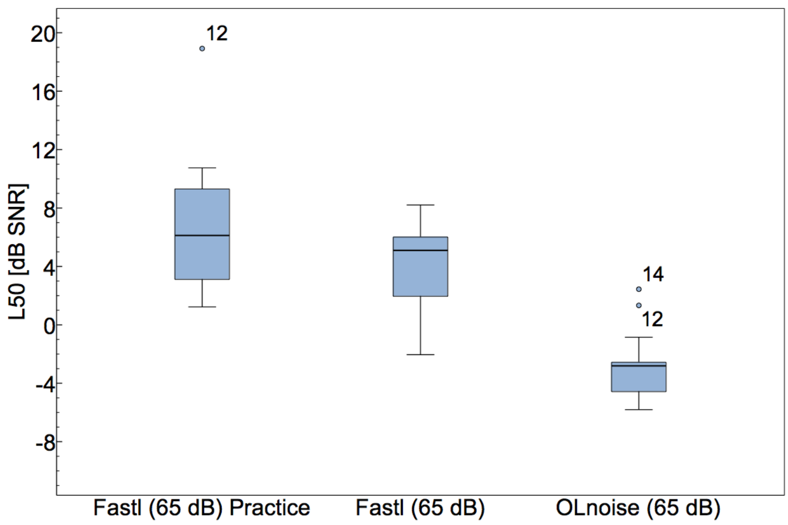


Figure 4.3.1: Boxplot charts: OLSA Practice Session (P) and Test (T) speech reception thresholds (SRTs) from conditions $L50_{Fastl, P}$, $L50_{Fastl, T}$ and $L50_{OLnoise, T}$. Numbering of outliers (°) and extreme values (*) represent the number associated with each subject for matters of data privacy (see section 3.1).
(P = Practice Session; T = Test)

	Performed N	**Not performed N**	**All N**
$L50_{Fastl}$	16	1	17
$L50_{OLnoise}$	15	2	17

Table 4.3.1: Number (N) of participants in both OLSA noise conditions. Due to application problems, the OLSA test has not been completed by all subjects. (L50 = 50 % Speech Reception Threshold)

4.3 Speech perception in noise

Maximum, median and minimum 50 % Speech Reception Thresholds of the practice session ($L50_{Fastl, P}$) are 18.9 dB SNR, 5.1 dB SNR and 0.9 dB SNR. The actual test run always started in the condition *Fastl* noise ($L50_{Fastl, T}$). Maximum, median and minimum L50s are 8.2 dB SNR, 5.2 dB SNR and −2.0 dB SNR. In the second test run ($L50_{OLnoise, T}$), maximum, median and minimum L50s are 2.4 dB SNR, −2.8 dB SNR and −5.8 dB SNR. Results are shown in figure 4.3.1 as boxplots. Table 4.3.1 shows the number of participants in both OLSA conditions.

4.3.1 *OLnoise* versus *Fastl*-noise

As shown in figure 4.3.1, it is obvious that the average SRT in modulated noise (*Fastl*) is higher compared to the unmodulated condition (*OLnoise*). On average, SRT was 4.0 dB SNR (mean) in the *Fastl* condition and −3.0 dB SNR (mean) in the *OLnoise*

Test condition	Sig. (2-tailed)	Mean difference
$L50_{Fastl}$	0.17	-1.8
$L50_{OLnoise}$	0.95	-0.1

Table 4.3.2: Independent-Samples T Test for Equality of Means: Mean difference between the Single-Stage Surgery and Two-Stage Surgery's speech reception threshold (SRT) in the OLSA. Subjects in the Single-Stage Surgery (SSS) group had slightly lower SRTs than the Two-Stage Surgery (TSS) group. This finding is not statistically significant (both p>0.05). (L50 = 50 % Speech Reception Threshold)

condition. Hence, the speech stimulus needs to be more intense in *Fastl* noise whereas the speech stimulus may be less intense in the *OLnoise* condition. The observed speech reception threshold difference between both conditions is statistically highly significant (Paired-Samples T Test, $p < 0.001$; mean difference = 6.9 dB SNR).

4.3.2 Impact of mode of surgery

As 4 subjects among 17 underwent a Single-Stage Surgery (SSS) receiving both of their CI at once, it may be of interest whether the surgery (sequential vs. simultaneous) has an impact on the most important clinical outcome parameter: speech intelligibility (see chapter 4.1.6 for the impact on music intelligibility). One may hypothesise patients adapt more quickly to electrical hearing if both ears are provided with CIs simultaneously.

On average, the Single-Stage Surgery (SSS) group's SRT was 2.6 dB SNR and the Two-Stage Surgery (TSS)'s SRT 4.4 dB SNR in modulated noise ($L50_{Fastl}$). Likewise, the SSS group's SRT was -3.0 dB SNR and the TSS group's SRT -2.9 dB SNR in the unmodulated noise ($L50_{OLnoise}$). The SSS group demonstrated slightly lower SRT in both noise conditions compared to the TSS group. This finding is not statistically significant (Independent-Samples T Test, $p > 0.05$, see table 4.3.2).

4.4 Questionnaire

After examining the questionnaire's results in detail, some questions were excluded from final evaluation. These are questions 1.2, 1.3, 1.4, 3.3 and 3.5: they explored under what circumstances the subjects listen to music, why they listened to music, which musical genres they listen to, which instruments they play, and at which locations they sing. These questions were not expected to contribute to the investigation of the hypotheses. Said questions' results are listed in section C.1.

Question 1.1: Music Listening habits before and after CI surgery

How often do you listen to music or how often have you been listening to music?

Question	N	Mean	Std. dev.
Q 1.1.1 (before hl)	12	7.8	1.8
Q 1.1.2 (diagnose)	12	4.4	2.4
Q 1.1.3 (with CI)	17	7.3	2.6

Table 4.4.1: Question 1.1: How often do you listen to music or how often have you been listening to music? (1.1.1) before hearing loss (before hl); 1.1.2) with hearing loss, without CI (diagnose); 1.1.3) currently (with CI))
Means of all subquestions of question 1.1 and Number of subjects (N) having answered. The given answers are based on an analogue scale from 1-10, with 1 corresponding to "never" and 10 corresponding to "often". (Std. dev. = Standard deviation; hl = hearing loss)

1.1.1) How often have you listened to music before the onset of your hearing loss?

1.1.2) How often have you listened to music after your hearing loss without your CI?

1.1.3) How often do you currently listen to music since receiving your CI?

Question 1.1 had to be answered on the basis of an analogue scale from 1-10, with 1 corresponding to "never" and 10 corresponding to "often". The answers clearly depended on the subject's personal interpretation of "often" and "never". Table 4.4.1 shows the means of all subquestions. Five subjects did not answer questions 1.1.1 and 1.1.2 since they suffered from congenital deafness and therefore could not answer these questions.

To investigate whether the subjects' personal evaluation of how often they listen to music statistically differs concerning the time before their hearing loss (Q 1.1.1), with their hearing loss but without a CI (Q 1.1.2) and today (Q 1.2.3), a Paired-Samples T Test has been calculated. Table 4.4.2 shows the test's results.
The results indicate the frequency of music listening has significantly decreased from the subjects' time with normal hearing to the time with hearing loss without CI supply (Mean difference = 3.36; $p < 0.01$). Furthermore, the frequency of music listening has significantly increased from the time period with hearing loss without CI supply to today (Mean difference = -3.00; $p < 0.01$).

Question 2.1: Perceived Quality of Music

How does music generally sound with your CI?

Question 2.1 had to be answered on the basis of a Likert scale scale from 1-10, with 1 corresponding to "unnatural" and 10 corresponding to "natural" in subquestion 2.1.1 and "unpleasant - pleasant"; "indistinct - distinct"; "reverberant - clear" and "tinny - less tinny" for subquestions 2.1.2-2.1.5 respectively. Table 4.4.3 shows the means of all sub-

Question pair	Mean difference	t	df	p	
Q 1.1.1/ Q 1.1.2 (before hl/ diagnose)	3.36	4.20	10	<0.01	*
Q 1.1.1/ Q 1.1.3 (before hl/ with CI)	0.08	0.10	11	0.93	
Q 1.1.2/ Q 1.1.3 (diagnose/ with CI)	-3.00	-3.15	11	<0.01	*

Table 4.4.2: Question 1.1: How often do you listen to music or how often have you been listening to music?
Paired-Samples T Test: Comparison of means for subquestions Q 1.1. See text for explanation.
* Significant differences

Question	Quality	N	Mean	Std. dev.
Q 2.1.1	unnatural/ natural	14	7.5	2.2
Q 2.1.2	unpleasant/ pleasant	17	8.4	2.3
Q 2.1.3	indistinct/ distinct	16	6.7	2.7
Q 2.1.4	reverberant/ clear	16	9.0	1.4
Q 2.1.5	tinny/ less tinny	16	8.6	1.5

Table 4.4.3: Question 2.1: How does music generally sound with your CI?
Means of all subquestions of question 2.1 and Number of subjects (N) having answered. The given answers are based on a Likert scale scale from 1-10, with 1 corresponding to "unnatural" and 10 corresponding to "natural" in subquestion 2.1.1 and "unpleasant - pleasant" in 2.1.2; "indistinct - distinct in 2.1.3"; "reverberant - clear in 2.1.4" and "tinny - less tinny in 2.1.5". (Std. dev. = Standard deviation)

questions.

Question 2.2: Importance of music before and after CI surgery

What role does music play in your life?

2.2.1) What role did music play in your life before the onset of your hearing loss?
2.2.2) What role did music play in your life after your hearing loss without your CI?
2.2.3) What role does music currently play in your life since receiving your CI?

Question 2.2 had to be answered on the basis of a Likert scale scale from 1-10, with 1 corresponding to "none" and 10 corresponding to "a major role". Subquestions 2.2.1 and 2.2.2 have not been answered by those subjects suffering from congenital hearing loss. Table 4.4.4 shows the means of all subquestions.

To find out whether the importance of music to the subjects has decreased after their hearing loss, a Paired-Samples T Test has been calculated. The test's results are listed in

Question	N	Mean	Std. dev.
Q 2.2.1 (before hl)	12	8.1	2.1
Q 2.2.2 (diagnose)	12	5.7	2.9
Q 2.2.3 (with CI)	17	7.9	2.4

Table 4.4.4: Question 2.2: What role does music play in your life? (2.2.1) before hearing loss (before hl); 2.2.2) with hearing loss, without CI (diagnose); 2.2.3) currently (with CI)) Means of all subquestions of question 2.2 and Number of subjects (N) having answered. The given answers are based on a Likert scale scale from 1-10, with 1 corresponding to "none" and 10 corresponding to "a big role". (Std. dev. = Standard deviation; hl = hearing loss)

Question pair	Mean difference	t	df	p	
Q 2.2.1/ Q 2.2.2 (before hl/ diagnose)	2.36	2.61	10	0.03	*
Q 2.2.1/ Q 2.2.3 (before hl/ with CI)	0.00	0.00	11	1.00	
Q 2.2.2/ Q 2.2.3 (diagnose/ with CI)	-2.25	-3.08	11	0.01	*

Table 4.4.5: Question 2.2: What role does music play in your life?
Paired-Samples T Test: Comparison of means for subquestions Q 2.2. See text for explanation.
* Significant differences

table 4.4.5. The results indicate the importance of music has significantly decreased from the subjects' time with normal hearing to the time with hearing loss without CI supply (Mean difference = 2.4; p = 0.03). Furthermore, the importance of music has increased from the time period with hearing loss without CI supply to today (Mean difference = -2.3; p = 0.01).

Question 2.3: Musicality before and after CI surgery

How do you estimate your musicality?

2.3.1) How do you estimate your musicality prior to your hearing loss?
2.3.2) How do you estimate your musicality after your hearing loss without your CI?
2.3.3) How do you currently estimate your musicality since receiving your CI?

Question 2.3 had to be answered on the basis of a Likert scale scale from 1-10, with 1 corresponding to "very good" and 10 corresponding to "not good". Subquestions 2.3.1 and 2.3.2 have not been answered by those subjects suffering from congenital hearing loss. Table 4.4.6 shows the means of all subquestions.
To find out whether the subjects' self-rated musicality has decreased after their hearing loss, a Paired-Samples T Test has been calculated. The test's results are listed in table 4.4.7. The results indicate that musicality has significantly decreased from the sub-

Question	N	Mean	Std. dev.
Q 2.3.1 (before hl)	12	7.1	3.1
Q 2.3.2 (diagnose)	12	4.4	3.1
Q 2.3.3 (with CI)	17	6.2	2.3

Table 4.4.6: Question 2.3: How do you estimate your musicality? (2.3.1) before hearing loss (before hl); 2.3.2) with hearing loss, without CI (diagnose) ; 2.3.3) currently (with CI)) Means of all subquestions of question 2.3 and Number of subjects (N) having answered. The given answers are based on a Likert scale scale from 1-10, with 1 corresponding to "very good" and 10 corresponding to "not good". (Std. dev. = Standard deviation; hl = hearing loss)

Question pair	Mean difference	t	df	p	
Q 2.3.1/ Q 2.3.2 (before hl/ diagnose)	2.80	2.66	10	0.02	*
Q 2.2.1/ Q 2.3.3 (before hl/ with CI)	0.60	1.63	11	0.13	
Q 2.3.2/ Q 2.3.3 (diagnose/ withCI)	-2.10	-2.93	11	0.01	*

Table 4.4.7: Question 2.3: How do you estimate your musicality?
Paired-Samples T Test: Comparison of means from questions 2.3. See text for explanation.
* Significant differences

jects' time with normal hearing to the time with hearing loss without CI supply (Mean difference = 2.8; $p = 0.02$). Furthermore, musicality has increased from the time period with hearing loss without CI supply to today (Mean difference = -2.1; $p = 0.01$).

Question 3.1: Musical Education

Did you receive any musical education outside of school?

3.1.1) Did you receive any musical education outside of school?
3.1.2) For how long did you receive musical education outside of school?

Subquestion 3.1.1 has a single-choice answering pattern consisting of "Yes" and "No". The given answers for question 3.1.2 are "less than three years"; "more than three years"; "other". Tables 4.4.8 and 4.4.9 list the results of all subquestions. 64.70 % of the subjects received music education outside of school and 35.30 % did not. 81.80 % of the subjects having received musical education outside of school did so for more than 3 years and 18.20 % for less than 3 years. A number of 8 subjects from those 9 who received musical education outside of school approximately stated the duration of their musical education in years. Musical education among those subjects was on average 13.4 years ranging from 4 to 24 years.

	Percent of cases
Yes	64.70
No	35.30

Table 4.4.8: Question 3.1: Did you receive any musical education outside of school? Number of Responses (N) and percent of cases of question 3.1.1. 64.70 % of the subjects received music education outside of school and 35.30 % did not.

	Percent of cases
less than three years	18.20
more than three years	81.80

Table 4.4.9: Question 3.1: Did you receive any musical education outside of school? Number of Responses (N) and percent of cases of question 3.1.2. 81.80 % of the subjects having received musical education outside of school did so for more than 3 years and 18.20 % for less than 3 years.

Question 3.2: Instrument playing habits before and after CI surgery

Do you play an instrument or have you ever played one?

3.2.1) Did you play an instrument as a child?
3.2.2) Did you play an instrument before the onset of your hearing loss?
3.2.3) Did you play an instrument after your hearing loss without your CI?
3.2.4) Do you currently play an instrument after your hearing loss since receiving your CI?

Question 3.2 had to be answered on the basis of a Likert scale scale from 1-10, with 1 corresponding to "never" and 10 corresponding to "often". The answers naturally depended on the subject's personal interpretation what is corresponding to "often" and "never". Table 4.4.10 shows the means of all subquestions. Five subjects did not answer questions 3.2.1, 3.2.2 and 3.2.3 since they suffered from congenital deafness therefore could not answer these questions.

To investigate whether the time subjects spend playing an instrument has changed throughout their stages of hearing loss, a Paired-Samples T Test has been calculated. The test's results are listed in table 4.4.11. Although the subjects played instruments less frequently during their childhood than as adults prior to their hearing loss, the difference is not significant ($p = 0.28$). Furthermore, they played instruments more frequently during their childhood than after the onset of their hearing loss without a CI, but again not significantly ($p = 0.10$). However, they significantly played instruments more frequently as adults prior to their hearing loss than with the onset of their hearing loss without a

Question	N	Mean	Std. dev.
Q 3.2.1 (child)	12	4.8	3.9
Q 3.2.2 (before hl)	12	5.9	3.7
Q 3.2.3 (diagnose)	12	3.0	3.5
Q 3.2.4 (with CI)	17	3.4	3.2

Table 4.4.10: Question 3.2: Do you play an instrument or have you ever played one?
(3.2.1) as a child (child); 3.2.2) before hearing loss (before hl); 3.2.3) with hearing loss, without CI (diagnose); 3.2.4) currently (with CI))
Means of all subquestions of question 3.2 and Number of subjects (N) having answered. The given answers are based on a Likert scale scale from 1-10, with 1 corresponding to "never" and 10 corresponding to "often". (Std. dev. = Standard deviation; hl = hearing loss)

CI ($p = 0.03$). Furthermore, the subjects (highly) significantly play instruments less frequently today than during their childhood ($p = 0.04$) and as adults prior to their hearing loss ($p < 0.01$). The test results state that the subjects today play instruments less frequently than with the onset of their hearing loss without a CI, however not significantly ($p = 0.44$).

Over half of the subjects received a musical education outside of school (see table 4.4.8). It may be of interest how their habits of playing instruments has changed in the course of their hearing loss and CI implantation. Naturally subjects who received a musical education play instruments more often than subjects who did not in all stages of their hearing loss (see table 4.4.12). Subjects who did not receive a musical education did not play music instruments more or less frequently in any stage of their hearing loss. Those who did receive a music education played instruments significantly more often as children and as adults prior to their hearing loss than today with CI supply (see table 4.4.13).

Question 3.4: Singing habits

Do you sing or did you sing?

3.4.1) How often did you sing before the onset of your hearing loss?
3.4.2) How often did you sing after your hearing loss without your CI?
3.4.3) How often do you currently sing since receiving your CI?

Question 3.4 had to be answered on the basis of a Likert scale scale from 1-10, with 1 corresponding to "never" and 10 corresponding to "often". The answers naturally depended on the subject's personal interpretation of what is corresponding to "often" and "never". Table 4.4.14 shows the means of all subquestions. Five subjects did not answer questions 3.4.1 and 3.4.2 since they suffered from congenital deafness and therefore could

Question pair	Mean difference	t	df	p	
Q 3.2.1/ Q 3.2.2 (child/ before hl)	-1.08	-1.13	11	0.28	
Q 3.2.1/ Q 3.2.3 (child/ diagnose)	1.70	1.79	10	0.10	
Q 3.2.1/ Q 3.2.4 (child/ with CI)	2.00	2.37	11	0.04	*
Q 3.2.2/ Q 3.2.3 (before hl/ diagnose)	3.00	2.64	10	0.03	*
Q 3.2.2/ Q 3.2.4 (before hl/ with CI)	3.10	3.14	11	<0.01	**
Q 3.2.3/ Q 3.2.4 (diagnose/ with CI)	0.20	0.80	11	0.44	

Table 4.4.11: Question 3.2: Do you play an instrument or have you ever played one? Paired-Samples T Test: Comparison of means from all subquestions 3.2. See text for explanation. (hl = hearing loss)
* Significant differences **Highly significant differences

	Question	N	Mean	Std. dev.
No musical education	Q 3.2.1 (child)	4	1.05	1.00
	Q 3.2.2 (before hl)	4	3.75	4.27
	Q 3.2.3 (diagnose)	5	1.20	0.45
	Q 3.2.4 (with CI)	6	1.67	1.63
Musical education	Q 3.2.1 (child)	8	6.50	3.74
	Q 3.2.2 (before hl)	8	7.00	3.16
	Q 3.2.3 (diagnose)	7	4.29	4.15
	Q 3.2.4 (with CI)	11	4.41	3.51

Table 4.4.12: Question 3.2 according to musical education: Do you play an instrument or have you ever played one? (3.2.1) as a child (child); 3.2.2) before hearing loss (before hl); 3.2.3) with hearing loss, without CI (diagnose); 3.2.4) currently (with CI))
Means of all subquestions of question 3.2 and Number of subjects (N) having answered according to musical education. The given answers are based on a Likert scale scale from 1-10, with 1 corresponding to "never" and 10 corresponding to "often". (Std. dev. = Standard deviation; hl = hearing loss)

	Question pair	Mean diff.	t	df	p	
No m.e.	3.2.1/ 3.2.2 (child/ before hl)	-2.25	-1.00	3	0.39	
	3.2.1/ 3.2.3 (child/ diagnose)	0.50	1.00	3	0.39	
	3.2.1/ 3.2.4 (child/ with CI)	0.50	1.00	3	0.39	
	3.2.2/ 3.2.3 (before hl/ diagnose)	2.75	1.29	3	0.29	
	3.2.2/ 3.2.4 (before hl/ with CI)	2.75	1.29	3	0.29	
	3.2.3/ 3.2.4 (diagnose/ with CI)	0.20	1.00	4	0.37	
m.e.	3.2.1/ 3.2.2 (child/ before hl)	-0.50	-0.52	7	0.62	
	3.2.1/ 3.2.3 (child/ diagnose)	2.43	1.66	6	0.15	
	3.2.1/ 3.2.4 (child/ with CI)	2.75	2.34	7	0.05	*
	3.2.2/ 3.2.3 (before hl/ diagnose)	3.14	2.19	6	0.07	
	3.2.2/ 3.2.4 (before hl/ with CI)	3.25	2.88	7	0.02	*
	3.2.3/ 3.2.4 (diagnose/ with CI)	0.14	0.42	6	0.69	

Table 4.4.13: Question 3.2 according to musical education: Do you play an instrument or have you ever played one?
Paired-Samples T Test: Comparison of means from all subquestions 3.2 according to musical education. See text for explanation.
(Mean diff = Mean difference; m.e. = musical education; hl = hearing loss)
* Significant differences

Question	N	Mean	Std. dev.
Q 3.4.1 (before hl)	12	5.8	3.6
Q 3.4.2 (diagnose)	12	3.9	2.9
Q 3.4.3 (with CI)	17	3.8	3.0

Table 4.4.14: Question 3.4: Do you sing or did you sing? (3.4.1) before hearing loss (before hl); 3.4.2) with hearing loss, without CI (diagnose); 3.4.3) currently (with CI))
Means of all subquestions of question 3.4 and Number of subjects (N) having answered. The given answers are based on a Likert scale scale from 1-10, with 1 corresponding to "never" and 10 corresponding to "often". (Std. dev. = Standard deviation; hl = hearing loss)

Question pair	Mean difference	t	df	p	
Q 3.4.1/ Q 3.4.2 (before hl/ diagnose)	2.00	2.4	10	0.04	*
Q 3.4.1/ Q 3.4.3 (before hl/ with CI)	2.00	2.90	11	0.02	*
Q 3.4.2/ Q 3.4.3 (diagnose/ with CI)	0.10	0.11	11	0.92	

Table 4.4.15: Question 3.4: Do you sing or did you sing?
Paired-Samples T Test: Comparison of means of all subquestions 3.4. See text for explanation. (hl = hearing loss)
* Significant differences

not answer these questions.

To assess whether the subjects' singing habits varied throughout the stages of their hearing loss, a Paired-Samples T Test has been calculated (see table 4.4.15).
Subjects indicate they had sung more often prior to their hearing loss than with the onset of their hearing loss without CI supply which has proven to be statistically significant (p = 0.04). Furthermore, they statistically sing less today than prior to their hearing loss (p = 0.02). Cumulative, all subjects had sung more often with the onset of their hearing loss without CI supply than today, however this finding is not statistically significant (p = 0.92).

4.5 Correlations

4.5.1 Correlation of self rated musical skills and speech intelligibility

Initiating the present study, we hypothesised low or high discrimination thresholds in music intelligibility measured in the 1I2AFC and 3I3AFC test would correlate with good or poor speech intelligibility as assessed by the OLSA. To examine this hypothesis, a 2-tailed Pearson product moment correlation and a 2-tailed Spearman's rank corre-

Test pair		N	p		r	R^2
$3I3AFC_{\Delta L}$	- $L50_{Fastl}$	16	0.57		0.16	0.03
$3I3AFC_{\Delta L}$	- $L50_{OLnoise}$	15	0.09		0.45	0.20
$1I2AFC_{\Delta L}$	- $L50_{Fastl}$	16	0.28		0.29	0.08
$1I2AFC_{\Delta L}$	- $L50_{OLnoise}$	15	0.44		0.21	0.04
$3I3AFC_{\Delta f}$	- $L50_{Fastl}$	16	0.64		0.13	0.02
$3I3AFC_{\Delta f}$	- $L50_{OLnoise}$	15	0.60		0.15	0.02
$1I2AFC_{\Delta f}$	- $L50_{Fastl}$	16	0.80		-0.07	<0.01
$1I2AFC_{\Delta f}$	- $L50_{OLnoise}$	15	0.24		-0.32	0.10
$3I3AFC_{\Delta t_{on}}$	- $L50_{Fastl}$	13	0.04	*	0.57	0.32
$3I3AFC_{\Delta t_{on}}$	- $L50_{OLnoise}$	12	<0.01	**	0.72	0.52
$1I2AFC_{\Delta t_{on}}$	- $L50_{Fastl}$	12	<0.01	**	0.72	0.52
$1I2AFC_{\Delta t_{on}}$	- $L50_{OLnoise}$	11	0.01	*	0.73	0.53

Table 4.5.1: Pearson product-moment correlation: calculated between 3I3AFC/ 1I2AFC conditions and OLSA conditions. See subsection 4.5.1 for further explanation.
* Significant correlation (without Bonferroni correction); ** Highly significant correlation (without Bonferroni correction); L50 = 50 % Speech Reception Threshold; N = Number of pairs in correlation analysis

lation have been calculated to compare all 1I2AFC and 3I3AFC test conditions with all OLSA conditions.

No significant correlation was present in most of the tested pairs, but some selected pairs show significant correlations (see table 4.5.1 for all correlations). Test condition $L50_{OLnoise}$ is (highly) significantly ($p < 0.01$) positively correlated ($r = 0.72$) with condition $3I3AFC_{\Delta t_{on}}$ and with condition $1I2AFC_{\Delta t_{on}}$ ($p = 0.01$; $r = 0.73$), meaning that lower discrimination thresholds in conditions $3I3AFC_{\Delta t_{on}}$ and $1I2AFC_{\Delta t_{on}}$ are correlated with lower SRT in the $L50_{OLnoise}$ condition. OLSA condition $L50_{Fastl}$ is significantly positively correlated ($p = 0.04$; $r = 0.57$) with condition $3I3AFC_{\Delta t_{on}}$ and highly significantly positively correlated with condition $1I2AFC_{\Delta t_{on}}$ ($p = 0.01$; $r = 0.72$).

Since multiple comparisons were carried out, the Bonferroni method was applied to adjust significance levels. With N = 12 compared pairs (6 AMPDT variations and 2 OLSA parameters), the adjusted significance level $p* < \frac{\alpha}{N}$ is $p* < \frac{0.05}{12} \approx 0.004$. With respect to the adjusted level of significance, no significant correlation between the AMPDT and OLSA test results is present.

4.5.2 Correlation of music and speech intelligibility to Spread of Excitation

This study's objective was not only to investigate potential correlations between CI users' speech and music intelligibility but also between the latter and intracochlear neural masking as measured via SoE. It was hypothesised that performance measures (as assessed by the AMPDT and OLSA) would correlate with SoE. Reduced neural interaction and consequently enhanced discrimination is reflected by a narrower Spread of Excitation which is attributable to a SoE function's relatively short DIST at the 25 % and 50 % NERL.

To examine this hypothesis, a 2-tailed Pearson product moment correlation has been calculated for 1I2AFC, 3I3AFC and OLSA test conditions with the respective medial probe excitation distances (MDISTs) at the 25 % and 50 % NERL ($DIST_{0.25/0.5;\, A/B/AB}$) and the distance created by the difference between the basal and apical side of the fit function's respective maximum given in μV (ΔMax_{BA}). Analysis for data on the 75 % NERL did not show sufficient intersection points due to the asymmetry of the SoE functions and was therefore disregarded.

As visible in table D.0.1 no significant correlation between the AMPDT, OLSA and SoE was present.

4.5.3 Correlation of surgery interval to speech and music intelligibility

As described in subsections 4.1.6 and 4.3.2, the 4 simultaneously implanted subjects achieved lower discrimination thresholds in 5 out of 6 AMPDT conditions and lower speech reception thresholds (SRTs) in all OLSA conditions. To further determine the impact of the surgery interval, a Pearson product-moment correlation was calculated. No significant correlation between surgery interval on the one hand and OLSA and AMPDT results on the other hand was present (see table 4.5.2).

Correlation analysis was repeated for the subgroup of 4 subjects who had been implanted during their early childhood (1 to 6 years) against all other subjects. No significant correlation was found indicating that children who had a shorter interval between surgeries achieved lower discrimination thresholds in the AMPDT or lower speech reception thresholds in the OLSA (see table D.0.2).

4.5.4 Correlation of LAPL, ECAP response quality and excitation distance

As depicted in subsection 3.6.2, all collected ECAPs have been classified into categories according to response quality. To identify possible disruptive factors, it may be of interest whether measurement related factors such as least acceptable perceived loudness (LAPL) have an influence on ECAP response quality and electrical field's dispersal depicted by excitation distances (DISTs).

Correlation pair		N	p	r	R^2
$3I3AFC_{\Delta L}$	- Surgery interval	13	0.48	0.21	0.04
$1I2AFC_{\Delta L}$	- Surgery interval	13	0.12	-0.46	0.21
$3I3AFC_{\Delta f}$	- Surgery interval	13	0.96	0.02	<0.01
$1I2AFC_{\Delta f}$	- Surgery interval	13	0.61	0.16	0.03
$3I3AFC_{\Delta t_{on}}$	- Surgery interval	10	0.96	-0.02	<0.01
$1I2AFC_{\Delta t_{on}}$	- Surgery interval	10	0.58	0.20	0.04
$L50_{Fastl}$	- Surgery interval	13	0.61	0.16	0.03
$L50_{OLnoise}$	- Surgery interval	12	0.91	-0.04	<0.01

Table 4.5.2: Pearson product-moment correlation calculated between 3I3AFC/ 1I2AFC conditions, OLSA conditions and surgery interval. Absence of significant correlation.
N = Number of pairs in correlation analysis; L50 = 50 % Speech Reception Threshold

Test condition		N	p		r
LAPL	- $ECAP_A$	30	<0.01	**	0.48
LAPL	- $ECAP_M$	30	<0.01	**	0.66
LAPL	- $ECAP_B$	30	<0.01	**	0.60

Table 4.5.3: Spearman's rank correlation calculated between least acceptable perceived loudness (LAPL) and ECAP response quality (see subsection 3.6.2). High or low LAPLs are significantly associated with good or poor ECAP response quality. See subsection 4.5.4 for further explanation. (A = Apical probe electrode ; M = Medial probe electrode ; B= Basal probe electrode)
** Highly significant correlations

Figure 4.5.1 shows the relation between ECAP response quality and LAPL. ECAP response quality and LAPL levels are significantly positively correlated (Spearman's rank correlation): high or low LAPLs are associated with good or poor ECAP response quality (see table 4.5.3). This indicates that measurements conducted with low stimulation levels (individually determined least acceptable perceived loudness) result in rather poor ECAP response quality.

Furthermore, the correlation between LAPL and excitation distances (DISTs) was analysed. A significant positive correlation between LAPL and medial probe excitation distances (MDISTs) at the apical 50 % NERL ($MDIST_{0.5,A}$; $p = 0.04$; $r = 0.59$) was present.

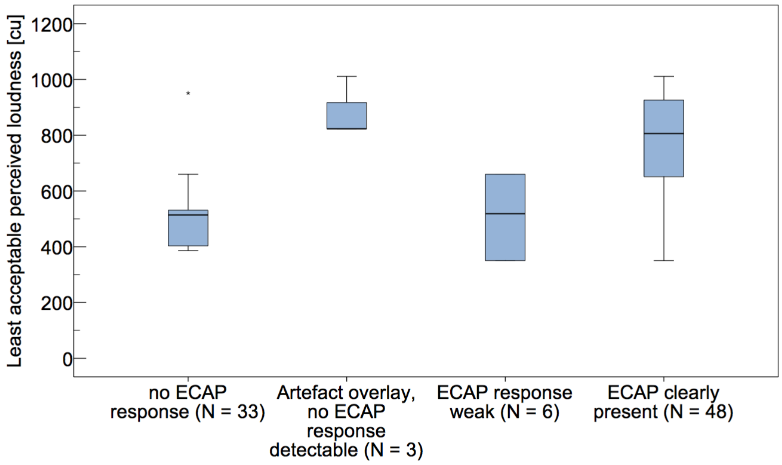


Figure 4.5.1: LAPL stimulating levels depending on ECAP response quality as determined by the investigator. Collapsed data assessed for apical, medial and basal electrodes.

Correlation pair	**N**	p		r	R^2
CI experience [a] - $\mathrm{MDIST}_{0.5,\mathrm{A}}$	13	0.02	*	0.66	0.44
CI experience [a] - $\mathrm{MDIST}_{0.5,\mathrm{AB}}$	13	<0.01	**	0.74	0.55

Table 4.5.4: Pearson product-moment correlation: Significant correlations between CI experience, subject age at surgery/ test and Spread of Excitation. See subsection 4.5.5 for further explanation. (MDIST = medial probe excitation distance; a = years)
* Significant correlations ** Highly significant correlations

4.5.5 Correlation of subject age and CI experience to SoE, music and speech intelligibility

There are various factors that might contribute to music intelligibility, speech intelligibility and electrical field's dispersal in the cochlea in CI listeners. Apart from individual musicality, among these might be subject age at surgery, actual age and CI experience in years. To determine these factor's impacts on music intelligibility, a 2-tailed Pearson product moment correlation was calculated. No significant correlation was present (data not shown).

The subjects' CI experience is significantly positively correlated with $\mathrm{MDIST}_{0.5,A}$ ($p = 0.02$; $r = 0.66$) meaning that subjects with relatively short CI experience show more narrow SoE patterns than subjects with longer CI experience. The same applies to excitation distance $\mathrm{MDIST}_{0.5,AB}$ ($p < 0.01$; $r = 0.74$, see table 4.5.4).

An explanation for this finding might be that patients with longer CI use might tolerate higher current levels (LAPL). However, no significant correlation between subjects' CI experience and least acceptable perceived loudness (LAPL) could be found ($p = 0.13$, $r = -0.29$).

To investigate the impacts of the LAPL on speech reception threshold (SRT), a

Correlation pair		N	p		r	R^2
Age at test [a]	- $L50_{Fastl}$	16	0.02	*	-0.59	0.35
Age at surgery [a]	- $L50_{Fastl}$	16	0.05	*	-0.51	0.26
Age at test [a]	- $L50_{OLnoise}$	15	<0.01	**	-0.66	0.44
Age at surgery [a]	- $L50_{OLnoise}$	15	0.03	*	-0.55	0.23

Table 4.5.5: Results of a Pearson product-moment correlation calculated between factors CI experience, subject age at surgery/ test and the OLSA's results. See subsection 4.5.5 for further explanation. (a = years; SRT = speech reception threshold)
* Significant correlations ** Highly significant correlations

2-tailed Pearson product moment correlation was calculated. Only significant correlations are given in table 4.5.5. Test parameter $L50_{Fastl}$ is significantly negatively correlated with the subjects' actual age ($p = 0.02$; $r = -0.59$) and with their age at surgery ($p = 0.05$; $r = -0.51$), meaning that younger subjects and subjects who received their CIs at a younger age achieved lower SRTs in the $L50_{Fastl}$ condition.
Likewise, test parameter $L50_{OLnoise}$ is highly significantly negatively correlated with the subjects' age on the test ($p < 0.01$; $r = -0.66$) and significantly negatively correlated with their age by receiving their CIs ($p = 0.03$; $r = -0.55$). These findings indicate again that younger subjects and subjects who received their CIs at a younger age achieved lower SRTs in both speech in noise tests.

4.5.6 Correlation of frequency of music listening to speech and music intelligibility

It may be of interest whether listening to music frequently (music questionnaire's question 1.1) improves speech and music perception performance. In a Pearson product-moment correlation no significant correlation was present between results of question 1.1, discrimination thresholds of the AMPDT or speech reception thresholds (SRTs) of the OLSA (data not shown).

4.5.7 Correlation of music appraisal to SoE, speech and music intelligibility

As outlined in section 4.4, the CI subjects reported degraded appraisal of music as assessed by question 2.1 of the music questionnaire. This might also be related to intracochlear electrical field's dispersal or speech and music intelligibility. A Pearson product-moment correlation between AMPDT, OLSA and SoE results was calculated. Significant correlations are listed in table 4.5.6.

Results of question 2.1.4 and excitation distance $\mathrm{MDIST}_{0.25,AB}$ are significantly positively correlated ($p = 0.02$; $r = 0.58$), indicating that broader excitation distances go

Correlation pair		N	p		r	R^2
Q 2.1.1 (unnatural/ natural)	- $3I3AFC_{\Delta L}$	14	0.02	*	0.61	0.29
Q 2.1.2 (unpleasant/ pleasant)	- $3I3AFC_{\Delta L}$	17	<0.01	**	0.62	0.41
Q 2.1.2 (unpleasant/ pleasant)	- $\Delta Max_{BA,norm.}$	18	<0.01	**	-0.60	0.36
Q 2.1.2 (unpleasant/ pleasant)	- $L50_{OLnoise}$	15	0.03	*	0.56	0.31
Q 2.1.4 (reverberant/ clear)	- $MDIST_{0.25,AB}$	16	0.02	*	0.58	0.33
Q 2.1.4 (reverberant/ clear)	- $MDIST_{0.5,AB}$	12	0.02	*	0.65	0.42

Table 4.5.6: Pearson product-moment correlation calculated between 3I3AFC/ 1I2AFC conditions, OLSA conditions, medial probe excitation distance and Question 2.1. Only significant test pairs are shown (no Bonferroni correction). See subsection 4.5.7 for further explanation. (norm. = normalised; SRT = speech reception threshold; MDIST = medial probe excitation distance)
* Significant correlations ** Highly significant correlations

along with "less reverberant" music perception. Question 2.1.4 and excitation distance $MDIST_{0.5,AB}$ are significantly positively ($p = 0.02$; $r = 0.65$) correlated, resulting in the same finding. Distance $\Delta Max_{BA,norm.}$ ist highly significantly negatively correlated ($p < 0.01$; $r = -0.60$) with Question 2.1.2 which indicates that rather symmetric SoE functions are associated with rather "pleasant" music perception.

Question 2.1.2 and test condition $3I3AFC_{\Delta L}$ are highly significantly positively correlated ($p < 0.01$; $r = 0.62$), which suggests that subjects achieving lower TDDTs in the $3I3AFC_{\Delta L}$ test rate music as "pleasant". Question 2.1.1 and test condition $3I3AFC_{\Delta L}$ are significantly positively correlated ($p = 0.02$; $r = 0.61$) which implies that subjects rating the sound of music as more "natural" achieved lower TDDTs in test condition $3I3AFC_{\Delta L}$.

The significant positive correlation ($p = 0.03$; $r = 0.56$) between test condition $L50_{OLnoise}$ and question 2.1.2 implies that subjects achieving low SRTs in continuous noise perceive the sound of music as rather "pleasant".

After Bonferroni correction with the adjusted significance level of $p* < \frac{\alpha}{N}$ is $p* < \frac{0.05}{60} \approx 0.0008$ no significant correlation between all investigated factors is present.

Likewise for correlation of Question 2.1 and the OLSA parameters, the adjusted significance level of $p* < \frac{0.05}{10} \approx 0.005$ leads to no significant correlation.

4.5.8 Correlation of importance of music to speech and music intelligibility

The assumption of a relation between the importance of music in life and music appraisal or speech intelligibility was investigated by means of calculation of a Pearson product-moment correlation between AMPDT, OLSA and question 2.2. Only one test pair (Q 2.2.3 and $L50_{OLnoise}$) turned out to be significant. This result indicates that subjects with higher importance of music in life since receiving their CIs achieved lower

SRTs in test condition $L50_{OLnoise}$ ($p = 0.05$; $r = 0.52$).

However, after Bonferroni correction no significant correlation between the OLSA test and Question 2.2 is present (adjusted significance level $p* < \frac{0.05}{6} \approx 0.008$).

4.5.9 Correlation of self evaluated musicality to speech and music intelligibility

To analyse whether the subjects' self evaluation of their own musicality correlates to higher music appraisal and speech intelligibility (as assessed by the AMPDT and OLSA), a Pearson product-moment correlation was calculated. However, no significant correlation was present (data not shown).

4.5.10 Correlation of instrument playing and singing to speech and music intelligibility

To assess out whether subjects playing instruments or who often times sing achieved higher scores in this study's test battery, a Pearson product-moment correlation was calculated correlating the questionnaire's results with the subjects' results from the AMPDT and OLSA. No significant correlation between singing and speech or music intelligibility was present.

Only one test pair (Q 3.2.4 and $\mathrm{L50_{Fastl}}$) turned out to be significant. This results indicates that subjects playing instruments more often since having received their CIs achieved lower SRTs in test condition $L50_{Fastl}$ than subjects who rarely or never play an instrument ($p = 0.04$; $r = 0.52$; N=16). The frequency of playing instruments does not correlate with performance in the AMPDT.

However, after Bonferroni correction no significant correlation between the OLSA test and Question 3.2.4 is present (adjusted significance level $p* < \frac{0.05}{8} \approx 0.006$).

4.5.11 Correlation of music appraisal and individual music perception

Subjects who listen to music more frequently may perceive the sound of music as more pleasant and natural than those who rarely listen to music. To investigate this, a Pearson product-moment was calculated between parameters derived by the music questionnaire. Significant correlations are listed in table C.1.1.

CI recipients who frequently listened to music prior to their hearing loss perceive the sound of music as highly significantly more natural ($p < 0.01$; $r = 0.73$), pleasant ($p < 0.01$; $r = 0.74$) and clear ($p < 0.01$; $r = 0.80$). Subjects who listened more frequently to music before CI surgery perceive the sound of music as significantly more natural ($p = 0.04$; $r = 0.61$). Those CI recipients who perceive the sound of music as rather natural rated music as rather important during their hearing loss prior to CI implantation ($p = 0.04$; $r = 0.59$) and today with their CIs ($p < 0.01$; $r = 0.79$). The same pattern applies to perceiving music as rather pleasant (hearing loss without CI: $p = 0.04$, $r = 0.59$; today: $p = 0.02$, $r = 0.56$). To CI recipients who perceive music as rather clearly, music was highly significantly more important to prior to their hearing loss than to recipients who do not perceive music as clearly ($p < 0.01$; $r = 0.80$).

Chapter 5: Discussion

5.1 Summary of results

The present study investigated the relation of Electrically Evoked Compound Action Potential (ECAP) measurements, perceptive skills such as speech and music intelligibility and music appraisal in a cohort of 17 highly trained and experienced bilateral CI users.

The first hypothesis on the relation between music appraisal and perceptional skills was evaluated with the Oldenburger Satztest (OLSA) and the Adaptive Melody-Pattern-Discrimination Test (AMPDT). Music appraisal was assessed by means of a questionnaire.

According to the second hypothesis of the study, subjects scoring higher in the OLSA and AMPDT test battery should show a more selective neural excitation pattern which was assessed by a Spread of Excitation (SoE) measurement.

5.1.1 The relation of electrophysical properties and perceptive skills

The basic expectation of the present study was that advanced music and speech intelligibility is associated with narrow SoE patterns. Due to reduced channel interactions reflected by narrower SoE patterns, enhanced listening might be enabled. The impact of electrode channel interactions were assessed by means of SoE measurements and the calculation of a number of parameters to describe the pattern of intracochlear masking (excitation distances (DISTs)). Correlation analysis between the AMPDT, OLSA and DISTs showed no significant correlations.

5.1.2 The relation of musical education, music appraisal and perceptive skills

Another hypothesis was that subjects with a formal musical education, a self-rated high music intelligibility and musicality would perform higher both in the AMPDT and OLSA. This study could not confirm that musical activities such as listening to music, singing or playing instruments improve music intelligibility. Self-rated musicality as well did not correlate to the performance measures investigated in the present study. However, CI supply did restore the general importance of music, self-evaluated musicality and the will to listen to music in the present study's subjects. Therefore, this hypothesis can only partly be confirmed.

Subjects with lower SRT in continuous noise (*OLnoise*) seem to play instruments more often after CI supply ($p = 0.04$; $r = 0.52$). However, the Bonferroni adjusted significance level $p^* < \frac{0.05}{8} \approx 0.006$) was not reached. The frequency of playing instruments does not correlate with performance in the AMPDT.

CI users who presently rate music as rather important had significantly lower SRTs in test $L50_{OLnoise}$ ($p = 0.05$; $r = 0.52$). However, the Bonferroni adjusted significance level was not reached either ($p^* < \frac{0.05}{6} \approx 0.008$).

Subjects who perceive music as rather pleasant (question 2.1.2) had highly significantly lower TDDTs in condition 3I3AFC$_{\Delta L}$ ($p < 0.01$; $r = 0.62$), and those who experience the sound of music as natural (question 2.1.1) had significantly lower TDDTs in condition 3I3AFC$_{\Delta L}$ ($p = 0.02$; $r = 0.61$). Subjects who experience the sound of music as rather pleasant (question 2.1.2) had significantly lower SRT in continuous noise (*OLnoise*; $p = 0.03$; $r = 0.56$).

We further considered a potential relation between SRT in noise and music intelligibility. Many AMPDT conditions were correlated with lower SRT in noise. Lower SRT in the continuous noise condition (*OLnoise*) were highly significantly correlated with lower discrimination thresholds in conditions 3I3AFC$_{\Delta t_{on}}$ ($p < 0.01$; $r = 0.72$) as well as 1I2AFC$_{\Delta t_{on}}$ ($p = 0.01$; $r = 0.73$). Lower SRT in modulated noise condition (*Fastl*) was significantly correlated with lower TDDTs in condition 3I3AFC$_{\Delta t_{on}}$ ($p = 0.04$; $r = 0.57$) and highly significantly correlated with lower BCDTs in condition 1I2AFC$_{\Delta t_{on}}$ ($p < 0.01$; $r = 0.72$). However, after Bonferroni correction with the adjusted significance level of $p^* < \frac{0.05}{12} \approx 0.004$ no significant correlation between all investigated factors is present.

It can be concluded that although CI supply restores music appreciation in patients with sensorineural hearing loss, accurate music perception is still poor and does not significantly improve by regular musical activities such as listening to music, singing or playing instruments.

5.1.3 Adaptive Melody-Pattern-Discrimination Test

Although the subjects on average showed lower discrimination thresholds in the repeated trial, the difference between results obtained from two consecutive runs were not statistically significant. This finding excludes a learning effect and implies high test reproducibility.

The subjects on average achieved lower discrimination thresholds in the 3I3AFC than in the 1I2AFC task, which was highly significant in test conditions Δf and Δt_{on} (both $p < 0.01$). Hence, background melody contour classification is more challenging to CI users than the detection of small perceptual timbre differences (TDDT). Background melody contour classification was possible with harmonic accentuation by sound level increment (ΔL) whereas accentuation realized by onset asynchrony (Δt_{on}) was more demanding. CI users failed in background melody contour classification obtained by frequency detuning (The median of condition 1I2AFC$_{\Delta f}$ converged to the test related limit of possible frequency detuning (50 %)). This implies that CI listeners are mostly only able to detect distinct timbre alterations throughout the course of a musical piece whereas they cannot discriminate background melodies hidden in a pattern of complex harmonic sounds.

In the present study, 4 subjects among 17 underwent a Single-Stage Surgery (SSS) receiving both of their CI at once. The remaining 13 patients received their CIs sequentially (Two-Stage Surgery (TSS) group). It may be of interest whether the surgery (sequential vs. simultaneous) has an impact on clinical outcome such as music intelligibility. One may hypothesise patients adapt more quickly to electrical hearing if both ears are provided with CIs simultaneously. The analysis of the impact of the surgical interval on music intelligibility on average showed lower discrimination thresholds in 5 out of 6 AMPDT conditions in the SSS group, however not significantly so. The lacking significance might be owed to small size of the study group.

According to Looi et al.[51], the "accurate perception of Western music requires the listener to discriminate frequency modulations as small as 6 %, which corresponds to approximately one semitone". Results of the AMPDT showed that most subjects were not able to perceive frequency detuning of the accentuated harmonic below 15 % (median of test condition $3I3AFC_{\Delta f}$) implying the majority of subjects were not able to detect timbre differences introduced by frequency detuning. Only 4 out of 17 subjects showed discrimination thresholds below 6 % detuning (3 out of 4 implanted early in childhood).

Correlation analysis between subjects' age and AMPDT discrimination demonstrated that no significant correlation was present between actual subject age, age at surgery, CI experience and music intelligibility. This is consistent with the results reported by Gfeller et al.[17] and Gfeller et al.[82] who found that music intelligibility does not improve with longer CI experience.

5.1.4 Spread of Excitation

A total number of N = 90 SoE profile functions were recorded, in which N = 48 showed a clearly present ECAP response (see 3.6.2). The total SoE width at the 25 % normalised ECAP response level (NERL) was narrower for the basal probe electrode (median of $BDIST_{0.25,AB}$= 3.15 mm) than for the apical (median of $ADIST_{0.25,AB}$ = 6.03 mm) and the medial electrode (median of $MDIST_{0.25,AB}$ = 5.88 mm). The same effect was observed at the 50 % NERL (median of $ADIST_{0.5,AB}$ = 8.97 mm; median of $MDIST_{0.5,AB}$ = 5.61 mm; median of $BDIST_{0.5,AB}$ = 9.94 mm, see table 4.2.1).

SoE functions (except for the medial probe at 25 % NERL, see table 4.2.1) showed asymmetric profiles with larger amplitudes towards the basal end of the cochlea.

The stimulation level applied in the SoE measurement (LAPL) varied strongly interindividually. Correlation analysis revealed that ECAP response quality (see subsection 3.6.2) was associated with higher LAPL. As a consequence, stimulus characteristics need to be improved to increase LAPL. A significant correlation between CI experience and LAPL was absent meaning that prolonged CI experience does not foster toleration of high stimulation levels. We further assumed that high LAPL levels are associated with broad SoE function patterns since poorer neural survival requires higher stimulation levels[7;83]. However, since there was only one significantly positive correlation between stimulation level (LAPL) and medial probe excitation distance (MDIST), there is little evidence to support this assumption.

The analysis of the impact of the surgery interval was carried out to investigate whether the first CI showed different excitation patterns compared to the second one. The first CI average DISTs was smaller at all levels and therefore displayed more narrow SoE than the second CI. However, this finding was not statistically significant. This might be related to the small size of the study group.

5.1.5 Speech perception in noise

The OLSA's aim is to objectify speech intelligibility in a noisy environment reflecting listening tasks in everyday life: for instance being part of a conversation in a crowded noisy room or public address announcements at railway stations at the arrival of a train.

Subjects achieved highly significantly lower SRT with *OLnoise* masking compared to the *Fastl* modulated noise condition. In order to understand how challenging the OLSA is for CI recipients, it is important to be aware of the average SRT normal hearing control groups achieve in this test. Rader et al.[8] assessed SRT by application of the OLSA in a similar MSNF loudspeaker set-up with *OLnoise* and *Fastl*-noise. Apart from different groups of CI users (EAS, bimodal, uni- and bilateral) they presented results obtained in a normal hearing control group. In all tested conditions the normal hearing control group had lower SRTs than the CI groups. Furthermore, the normal hearing control group exclusively had negative average SRTs indicating that the speech signal could always be lower than the noise signal to complete the test. Normal hearing were able to utilise noise-free gaps as occurring in the *Fastl*-noise whereas noise signal interruptions had a disturbing effect on CI users' listening process. *Fastl* noise allows to make use of gap listening representing the temporal characteristics of speech as a fluctuating noise. *OLnoise* is a continuous noise resulting in a maximum portion of masking. Findings both of the present study and reported by Rader et al.[8] consolidate the finding that CI recipients experience large difficulties in demanding listening tasks due to the inability of utilising temporal gaps. This illustrates how challenging conversations in noisy environments are to CI listeners[8].

The analysis of the impact of the surgical interval on SRT showed lower SRT in both noise conditions in the SSS group. The difference to the TSS group was not significant, which might be owed to the small size of the study group.

Furthermore, statistical correlation between subjects' age and their SRT proved that younger subjects achieved (highly) significantly lower SRT in both noise conditions ($L50_{Fastl}$: $p = 0.02$; $r = -0.59$; $L50_{OLnoise}$: $p < 0.01$; $r = -0.66$). Subjects who received their CIs at a younger age achieved significantly lower SRT in both noise conditions ($L50_{Fastl}$: $p = 0.05$; $r = -0.51$; $L50_{OLnoise}$: $p = 0.03$; $r = -0.55$).

5.1.6 Questionnaire on music perception and musical activities

A potential drawback of the questionnaire data might be that in some cases, personal over- and underestimation may play a decisive role. Therefore, some results may give no scientific evidence but develop an idea of how appraisal of music or practice of music has changed throughout the process of hearing loss and subsequent rehabilitation.

The questionnaire's results indicate that CIs are able to restore the subject's music listening habits they had prior to their hearing loss. The subjects' frequency of music listening has highly significantly decreased from when they were normal hearing to their hearing loss without CI supply ($p < 0.01$). This finding is consistent with results from the "Iowa Musical Background Questionnaire" used in a study by Gfeller et al.[82]. The subjects highly significantly listen to music more often with CI supply than after the onset of their hearing loss without their CIs ($p < 0.01$; Question 1.1, see tables 4.4.1 and 4.4.2). The same pattern applies to the general importance of music and their musicality: music was significantly less important to the subjects after the onset of their hearing loss ($p = 0.03$; Question 2.2). Music regained its role in the subjects' lives after implantation meaning that music is presently with CI supply equally important as before profound hearing loss ($p = 1.00$, see tables 4.4.4 and 4.4.5). The subjects' self-rated musicality has significantly decreased after the onset of profound hearing loss ($p = 0.03$; Question 2.3). However, they feel that with CI supply their musicality has reached the same level as before the onset of their hearing loss ($p = 0.13$, see tables 4.4.6 and 4.4.7). However, indistinctness in musical sound quality was pointed out as the biggest drawback even with CI supply (Question 2.1.3, see table 4.4.3).

Although CI support is able to restore musical listening habits, and the subjective importance of music and musicality, (see tables 4.4.6 and 4.4.7), the subjects do not sing and play instruments as much as before their hearing loss. Subjects played instruments most often as adults with normal hearing. From that time on, they significantly played instruments less frequently: at the onset of their hearing loss ($p = 0.03$) and even after CI rehabilitation (highly significantly, $p < 0.01$, question 3.2, see tables 4.4.10 and 4.4.11). As well as playing instruments, singing is a musical activity severely affected by hearing loss and follows the same decreasing pattern in frequency as playing instruments (Question 3.4, see tables 4.4.14 and 4.4.15). Especially subjects who received a formal musical education play instruments less frequently even after CI rehabilitation (see tables 4.4.12 and 4.4.13). A possible reason why this musically well educated subgroup "gave up" on playing instruments might be that they are highly disappointed in the CI musical sound experience compared to their once well developed musical comprehension. In contrast, instrument playing habits of subjects who did not receive a formal musical education were neither significantly affected by ongoing hearing loss nor CI supply (see tables 4.4.12 and 4.4.13).

5.2 Relation of study results to previously reported data

Music is a crucial medium of communication especially in terms of emotional aspects and may increase quality of life. Therefore it is a major concern of CIs' research to improve CI users' access to music which they rank at second place in personal importance[3].

5.2.1 The relation of electrophysical properties and perceptive skills

The relation of speech and music intelligibility to channel interactions as measured by SoE is a common assumption in CI research[56;71;75]. To support CIs' technical progress in terms of music intelligibility, it is useful to find a method that objectifies possible effects caused by new technical developments. SoE measurements, as performed it in this study, would be favourable in terms of objectifying music intelligibility: the only task the tested person has is sitting more or less still for the duration of the test which takes about 1-2 minutes per ear. The reduction of channel interactions might be monitored by SoE measurement and support CI rehabilitation[20].

However, the results of this study do not provide sufficient evidence that parameters assessed with SoE measurements relate to CI users' music or speech intelligibility.

Several previous studies on the potential dependency of outcome and intracochlear tonotopic neural resolution came to the same conclusion[4;5]. Hughes and Abbas[5] had to reject their hypothesis that narrow SoE patterns and therefore small channel interactions would be associated with high performance in an electrode pitch-ranking task as well as in speech intelligibility tasks. Busby et al.[4] applied similar SoE parameter extraction techniques (except the usage of linear best-fit lines between data points for measuring distances) and assessed pitch ranking. Again, no correlation between SoE parameters and pitch-ranking results was reported.

Goehring et al.[84] applied SoE measurements to predict the potential benefit of virtual channels generated by current steering. With current steering, adjacent electrodes are stimulated sequentially or simultaneously. The resulting ECAP should be generated by a slightly different neuronal population compared to separate stimulation of adjacent electrodes[83]. In contrast to the present study, Goehring et al.[84] measured a different trait of the SoE function: A method introduced by Hughes[85] called *spatial separation (Σ)* that measures the overall difference between two adjacent electrode's SoE ECAPs. Goehring et al.[84] hypothesised that larger Σ values are associated with more efficient virtual-channel perception allowing more precise pitch ranking. However, Goehring et al.[84] came to the conclusion that the measurement of spatial separation is not useful to identify CI users with enhanced pitch ranking while using virtual channels. Hence, Goehring et al.[84] pointed out that parameters derived by ECAP measurements are not suited to predict individual performance in psychoacoustic tasks. One reason might be that SoE measurements in general apply higher stimulation levels and low frequency single-pulse stimuli whereas psychoacoustic studies make use of pulse-train stimuli and rather low current levels[84].

Aside from the relation of estimated ECAP parameters to music intelligibility, their relationship to speech intelligibility was examined in previous studies.

Likewise, Hughes and Abbas[5] did not find a relation between ECAP channel interactions, different measures of speech intelligibility and the ability to discriminate pitch between electrodes in a psychophysical pitch ranking task. Hughes and Stille[20] hypothesised that high scores in speech intelligibility tasks would correlate with less psychophysical and physiological forward masking, which had to be rejected. Psychophysical forward masking was measured in a three-interval two-alternative forced-choice task where the presentation of masker and probe together had to be detected from presentations of the masker alone[20]. Physiological forward masking was measured via ECAPs[20].

The 17 subjects have been chosen for the present study according to given audiometric reports and highly developed aided speech intelligibility in noise environments. This circumstance may present both an advantage and a potential drawback of this study. Due to the selection criteria, the study group form a homogeneous collective. Due to the small variance of results, this limits the calculation of possible correlations. However, with the AMPDT being a rather demanding hearing performance test a sufficient variance of results for correlation analysis is given.

Considering the present results on the relation between measures of ECAP forward masking and speech in noise discrimination, the hypothesis that narrow SoE function patterns (small DISTs) are a prerequisite for enhanced speech and music intelligibility must be rejected. This finding is supported by the data obtained in previous studies discussed above.

5.2.2 The relation of musical education, music appraisal and perceptive skills

We hypothesised that subjects who received a musical education and practice music themselves in the present in any form, scored higher in the AMPDT and OLSA. For normal hearing adults, musical training has a positive influence on speech and music intelligibility via altered auditory cortical representation[86], an effect especially found in musicians[87]. Parbery-Clark et al.[88] reported that normal hearing musicians scored significantly higher in speech-in-noise-perception tests than normal hearing non-musicians. These findings allow the speculation that this effect is also present in CI recipients.

In the present study, subjects who have a self-rated high musicality and stated they either had played or still play instruments frequently or sing did not perform considerably better in the OLSA or the AMPDT compared to those without a noteworthy musical background.

Recent studies report controversial findings on the impact of musical education on speech and music intelligibility. Arehart et al.[89] did not find any significant difference between neither melody nor timbre recognition regarding the subjects' musical skills. Gfeller et al.[17] however reported significant correlations between their *Complex Melody Recognition Test (CMR)* and *Iowa Musical Background Questionnaire (IMBQ)* indicating that CI recipients engaged with music scored higher in the *CMR*. Furthermore, Gfeller et al.[17] postulates that "easygoingly" listening to music on a day-to-day basis does not have any significant influence on CI recipients' music recognition skills - intensified musical skills training would be the only factor improving music intelligibility. This was also discovered by Driscoll et al.[11], who let their normal hearing subjects complete a 5 week music instrument recognition training programme at their own home computers. It contained 3 training sessions per week for only 12 minutes. Instruments were presented in a CI simulation. A significant improvement in instrument recognition could be observed after the training programme was completed. Furthermore, Driscoll et al.[11] found that subjects with a musical education scored higher in the tests. Brendel et al.[14] implemented a questionnaire which assesses CI recipients' subjective music and speech intelligibility and compared it to speech performance in quiet and noise (Hochmair-Schulz-Moser sentence test[90]): A correlation of speech perception to self-assessment scores of speech intelligibility was reported, but not to scores of subjectively rated music intelligibility. Fuller et al.[86] compared the results of various questionnaires on musical training, CI implantation's influence on quality of life and subjectively rated hearing performance with a speech intelligibility test in quiet. They hypothesised that a profound musical education would correlate with improved listening skills. However, no such correlation was found.

Contrary to the initial hypothesis, the present data did not support the assumption that a strong musical education is associated with high scores in challenging speech and music intelligibility tests such as the OLSA and AMPDT. There are two potential reasons explaining this unexpected outcome. Firstly, the questions derived from the *Munich Music Questionnaire*[80] may be too unspecific to assess the individual musical education. Secondly, a more profound reason may be that prolonged auditory deprivation during complete deafness without any access to music may be sufficient for the loss of a once obtained musical sense[86].

5.2.3 Impact of age on speech and music intelligibility

The results of the present study did not show any significant correlation between actual subject age, age at surgery, CI experience and music intelligibility. CI experience did not correlate to speech intelligibility either. Younger subjects and subjects who received their CIs at a younger age achieved significantly lower SRTs in both OLSA conditions.

Arehart et al.[89] hypothesised that older CI users experience more difficulties than younger CI recipients in timbre and melody recognition, the latter due to their reduced ability to make use of temporal cues and the resulting dependence on envelope information only. Simulating CI and EAS hearing (Electric-Acoustic Stimulation, the combination of a conventional CI for high frequencies and a hearing aid for residual low-frequency hearing), Arehart et al.[89] compared two groups of younger and older normal hearing subjects and their performance in melody recognition. Their findings confirm their hypothesis that melody recognition skills decline with age, just as the present study's results show. Similar findings on the relation between age and melody recognition were reported by Gfeller et al.[17].

As already mentioned, frequency discrimination of at least 6 %[51] is required to perceive Western music's melodic structure accurately, which most subjects could not. Three subjects showed exceptionally high frequency discrimination. Two of them received their CIs prelingually and one during early childhood. All of the older subjects were postlingually deafened and some underwent a period of time during which they might already have benefited from CI supply. Consequently, one may hypothesise that the auditory pathway of adults receiving CI supply due to postlingual deafness is adapted to process acoustic hearing. Electric hearing as used in CIs, however, provides the brain with different input - input, whose processing it needs to learn. Postlingually deafened adults may therefore adapt to more simple input such as speech and rhythm information with electric hearing - the processing of fine structure such as pitch and timbre however is more difficult to learn. Prelingually deafened children with CI supply on the other hand developed all of their cortical processing patterns with the input of electric hearing. This circumstance might explain why two prelingually deafened subjects scored higher in the AMPDT's frequency discrimination tasks.

5.2.4 Impact of surgery type on speech and music intelligibility

Subjects from the SSS group achieved lower discrimination thresholds in 5 out of 6 AMPDT conditions and lower SRTs in all OLSA parameters, and although not statistically significant, this circumstance is quite peculiar. One may hypothesise that the lacking significance is due to the small size of the study group (N=17). A small sample size increases the risk of making statistic error type II - in this case to miss a possibly present difference between both surgery type groups. Especially in condition Δt_{on} only 10-14 subjects - depending on the test run - participated.

So far, only a few studies have investigated the impact of surgery interval on performance measures. Gantz et al.[91] performed a clinical follow up of 10 patients with asymmetrical hearing impairment who underwent bilateral implantation in a single surgery. The united response from all patients during their first CI fitting was that both CIs together generated a much better hearing impression. Gantz et al.[91] suspected that a possible reason for the advantage of binaural CIs in listening situations with a single sound source (just as in the AMPDT) might be both ears acting reciprocally and complementing one another in the neuronal and cortical area.

Chapter 6: Outlook

Even though science has made tremendous progress in further developing CIs, these technical devices have a relatively short clinical history of under 40 years. Hence, it is not surprising that neither individual patient factors leading to high or low hearing performances, nor all key levers in CI design with the capability of improving the latter have been identified yet. Therefore, it is crucial to investigate unutilised possibilities to improve current CI technique and to train their recipients. Especially since other factors contributing to poor hearing performance such as neuronal survival and tissue impedance in the array's surrounding can hardly be altered[51;52]. The following chapter gives an overview of a current approach to improve CI recipients' hearing abilities.

6.1 Current focusing and current steering

Current focusing and current steering are presently used CI stimulation strategies to overcome poor spectral resolution caused by the limited number of effective frequency channels reduced by neural channel interactions[72;92;93].

The current stimulation technique in CIs is Monopolar (MP). However, monopolar stimulation creates a relatively broad SoE in the cochlea[57]: the distinct electrodes are stimulated by incoming signals derived from their assigned frequency bands which in turn generate an electric field and stimulate adjacent neuronal tissue. The thereby stimulated neuronal tissue is not clearly separated from its adjacent neuronal tissue stimulated by neighbouring electrodes[20]. Hence, channel interactions severely limit the amount of perceptually distinguishable frequency channels[21]. Although modern CI technology offers up to 22 physical channels depending on the manufacturer, not more than 8 spectral channels can be conveyed due to channel interactions[56].

Current focusing is an approach to limit channel interactions by altering the CI's stimulation mode. Apart from the conventional MP methodology, other currently realised stimulation modes are Bipolar (BP), Tripolar (TP) and Partial Tripolar (pTP) electrode configuration which are distinct from one another in terms of electrode wiring. In MP constellations, electric current flows to the selected active electrode inside of the cochlea with an extra-cochlear electrode serving as reference[56]. In BP mode, the reference is a neighbouring intracochlear electrode and in TP mode two parallel connected electrodes are wired as reference[92]. Partial tripolar stimulation operates similarly as TP stimulation except for an additional extra-cochlear reference that creates the possibility of delivering the current to intra- and extra-cochlear references in adjustable fractions[56].

Several studies have shown that TP stimulation modes produce the smallest electrical field dispersal followed by BP and MP stimulation modes[57;72–74]. However, the advantage of a smaller SoE is achieved at a cost: to achieve equal levels of loudness, higher current stimulation levels are required[94] which in turn generate broader electrical field's dispersal[95]. Although the idea of current focusing is very promising, a number of studies have found no improvement in neither speech nor music intelligibility compared to conventional MP stimulation[96;97]. In contrast to this finding by Mens and Berenstein[96] and Berenstein et al.[97], a recent study by Zhu et al.[92] could show that neural spatial selectivity is significantly higher with BP and TP modes than with MP stimulation. This was shown by comparing MP, BP and TP stimulation modes intraindividually in psychophysical forward masking tasks. Zhu et al.[92] hypothesised that a possible reason for this finding might be varying neuronal survival within the subjects: current focusing and thus stimulating only a small amount of nerve fibres in regions with a higher amount of degenerated neural tissue would entail no advantage over broad stimulation in the same area. As recent studies do no agree on whether current focusing has a positive influence on speech and music intelligibility[92] or not[96;97], Landsberger et al.[56] compared physiological to psychophysical spatial selectivity with either broad or focused stimulation intraindividually. They found that only those CI recipients showing a narrower SoE in pTP than MP stimulation modes at the same sound level could benefit from higher spatial selectivity achieved by current focusing in psychophysical tests[56].

Alongside attempts to reduce Spread of Excitation by altering electrode configuration (current focusing), current steering is an approach to increase the number of feasible frequency channels by stimulating adjacent electrodes sequentially or simultaneously. The combined stimulation excites a slightly different neuron population than the separate stimulation of adjacent electrodes could do which results in the perception of "virtual channels"[83]. Furthermore, using different current sources and therefore steering the electrical field's maximum allows to create more than one virtual channel between two adjacent physical electrodes[83]. In a study by Hughes et al.[83], current was equally split between neighbouring physical electrodes.

A number of studies showed that additional intermediate pitch information could be received by current steering[93;98], however it was hypothesised that analogous to current focusing not all CI recipients would profit from additional virtual channels[93]. Hence, several authors have tried to establish tests that could possibly predict the number of perceptually separable (virtual) pitch channels for an individual CI recipient[84;99]. Hughes et al.[83] investigated spatial separation between adjacent physical electrodes and their intermediate virtual channels by measuring the degree of separation between the ECAP SoE patterns. The authors demonstrated that the SoE pattern of virtual channels is located between the location of physical electrodes and that spatial separation of SoE functions is larger between physical electrodes than from a physical electrode to an adjacent virtual channel. These findings would indicate that the creation of virtual channels with their required characteristics is technically feasible: additional frequency channels located between already existing channels represented by physical electrodes[83].

As both current steering and current focusing aim at the solution of a very similar problem in present CI technique, several studies have investigated the combination of both methods[100;101]. Srinivasan et al.[100] investigated whether virtual channels could be used more successfully by reducing channel interactions via current focusing and found that a stimulation mode similar to pTP stimulation (quadrupolar stimulation) produces virtual channels with narrower SoE patterns than with MP stimulation. Although Srinivasan et al.[100] also found that an inappropriate current level was necessary for successful current focusing, they suggested that longer phase durations and lower stimulation rates could compensate for this deficit. Likewise, Landsberger and Srinivasan[101] reported that virtual channels could be more precisely perceived with quadrupolar than MP stimulation in a psychophysical task.

Although further research is mandatory, these findings suggest that current steering and current focusing might be helpful to overcome poor spectral resolution in CIs - at least for some CI recipients.

Chapter 7: Conclusion

In conclusion, the basic expectations of the present study could not be confirmed. The present study's results imply that CI listeners are only able to detect distinct timbre alterations throughout the course of a musical piece while they cannot discriminate background melodies hidden in a pattern of complex harmonic sounds.

No significant correlation between frequency of music listening, playing instruments, singing and speech or music intelligibility was present. Furthermore, the subjects' self-rated musicality did not significantly correlate with neither speech nor music intelligibility tasks.

It can be concluded that although CI supply restores music appreciation in patients with sensorineural hearing loss, accurate music perception is still poor and does not significantly improve by regular musical activities such as listening to music, singing or playing instruments.

ECAP measurements do not seem to be an adequate tool to predict neither speech nor music intelligibility in CI listeners, contrary to our initial hypothesis. Perceptional skills assessed in the AMPDT and OLSA did not correlate with a more selective neural excitation pattern which was calculated from the average width of the SoE function resulting from the acquisition of ECAP measurements. This finding is consistent with a number of studies who did not find any correlation between music or speech intelligibility and the degree of channel interactions as assessed by SoE measurements[4;5].

Despite this, intracochlear SoE might still hold the potential to assess CI recipients' qualification in terms of speech and music intelligibility. However, it might be that SoE measurements depicting peripheral neuronal activity are no adequate tool for a comparison with subjective psychoacoustic listening tasks that additionally rely on central processing[4;5].

Appendix A: Adaptive Melody-Pattern-Discrimination Test

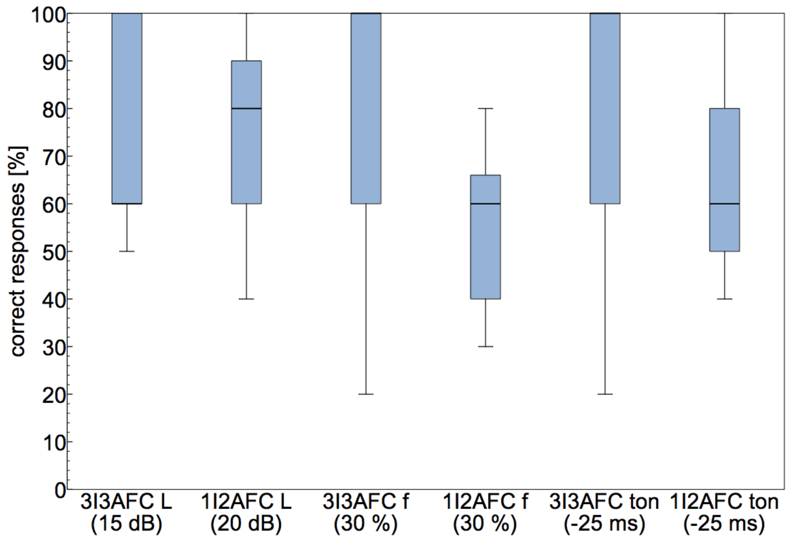


Figure A.0.1: Boxplot charts: Proportion of correct responses in the Practice Sessions (Ps) depending on the 3I3AFC or 1I2AFC condition. For the number of participating subjects see table A.0.3.

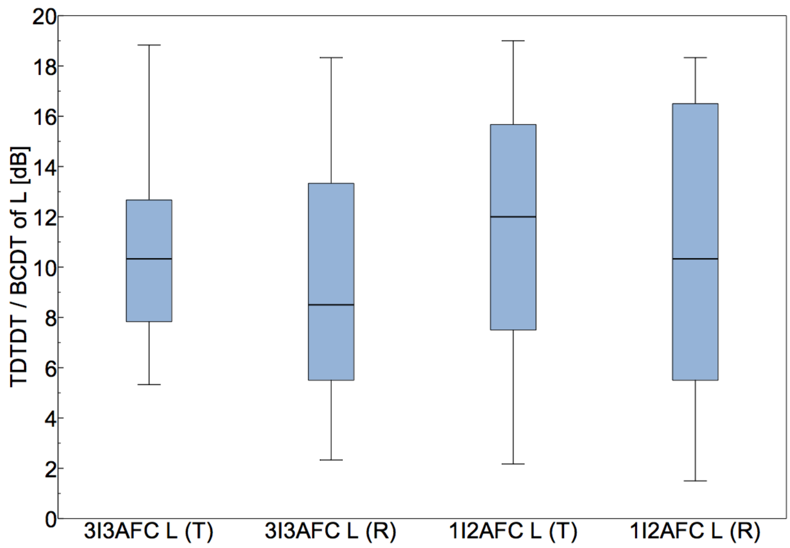


Figure A.0.2: Boxplot charts: Collapsed Test (T) and Repetition (R) timbre difference discrimination threshold (TDDT) and background contour discrimination threshold (BCDT) depending on sound level alteration (ΔL). For the number of participating subjects see table A.0.3.
(T = Test; R = Repetition)

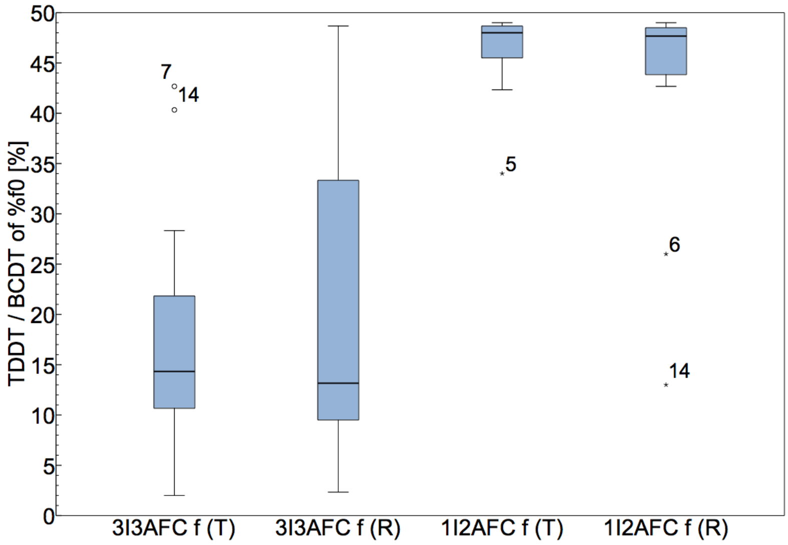


Figure A.0.3: Boxplot charts: Collapsed Test (T) and Repetition (R) timbre difference discrimination threshold (TDDT) and background contour discrimination threshold (BCDT) depending on frequency alteration (Δf). The subjects were able to identify detuning, however unable to identify the melody pattern. Clear outliers are subject 6 and 14 in the repetition of condition $1I2AFC_{\Delta f}$. Subject 6 was implanted at the age of 18 in a Single-Stage Surgery whereas subject 14 was implanted at the age of 52 with an interval of 1.78 years. For the number of participating subjects see table A.0.3. (T = Test; R = Repetition)

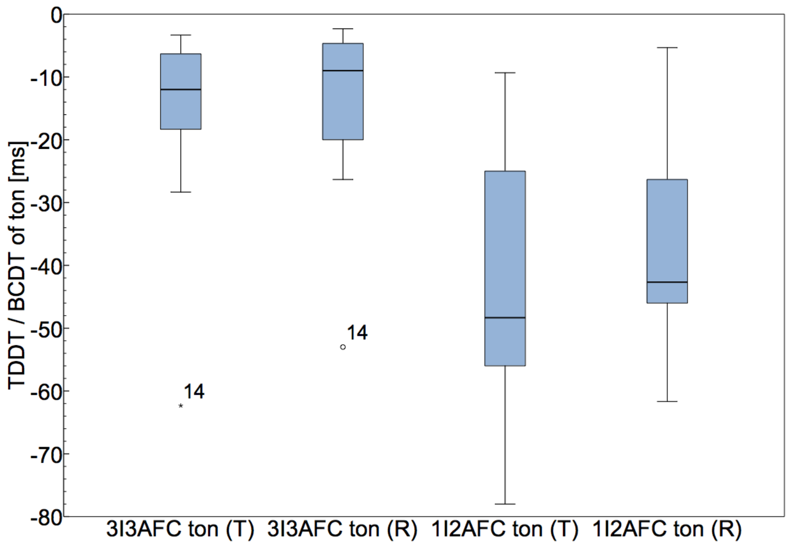


Figure A.0.4: Boxplot charts: Collapsed Test (T) and Repetition (R) timbre difference discrimination threshold (TDDT) and background contour discrimination threshold (BCDT) depending on part tone asynchrony (Δt_{on}). The subjects were able to identify detuning, however unable to identify the melody pattern. For the number of participating subjects see table A.0.3.
(T = Test; R = Repetition)

S	$3I3AFC_{\Delta L}$ [1]	$1I2AFC_{\Delta L}$ [1]	$3I3AFC_{\Delta f}$ [2]	$1I2AFC_{\Delta f}$ [2]	$3I3AFC_{\Delta t_{on}}$ [3]	$1I2AFC_{\Delta t_{on}}$ [3]
01	7.25	10.17	12.15	47.50	nt	nt
02	6.50	10.09	3.00	45.84	-5.67	-65.33
03	6.42	14.25	17.70	46.34	-37.33	-32.67
04	12.00	17.92	24.30	48.84	-10.00	-16.00
05	10.00	17.67	18.30	38.34	-1.00	-25.17
06	14.25	9.08	15.00	36.17	-1.00	-11.33
07	9.34	13.42	45.70	48.17	nt	nt
08	11.25	14.59	32.80	48.84	-19.17	-41.17
09	11.50	6.00	10.35	45.00	-27.33	-48.50
10	12.42	15.17	5.65	48.34	-7.83	-55.34
11	10.42	1.84	34.15	47.50	-10.50	-7.33
12	18.58	7.92	14.30	48.50	-29.67	nt
13	5.00	3.75	6.30	48.50	-3.83	-60.34
14	14.17	17.58	36.30	27.67	-57.67	-63.34
15	5.25	16.25	5.00	46.67	-4.00	-37.33
16	7.75	5.09	46.65	47.67	nt	nt
17	6.17	3.17	12.00	45.67	-5.34	-34.00

Table A.0.1: Individual average results of all 3I3AFC and 1I2AFC variations.
(nt = Not Tested)
[1] [dB]
[2] [% dB SNR]
[3] [ms]

S	Test	3I3AFC$_{\Delta L}$ [1]	1I2AFC$_{\Delta L}$ [1]	3I3AFC$_{\Delta f}$ [2]	1I2AFC$_{\Delta f}$ [2]	3I3AFC$_{\Delta t_{on}}$ [3]	1I2AFC$_{\Delta t_{on}}$ [3]
01	**T**	10.33	10.33	12.33	48.67	nt	nt
	R	4.17	10.00	12.00	46.33	nt	nt
02	**T**	7.00	12.00	3.67	48.67	-5.67	-65.33
	R	6.00	8.17	2.33	43.00	nt	nt
03	**T**	7.33	15.67	19.67	45.00	-37.33	-32.67
	R	5.50	12.83	15.67	47.67	nt	nt
04	**T**	8.00	17.83	14.33	48.67	-12.00	-20.33
	R	16.00	18.00	34.33	49.00	-8.00	-11.67
05	**T**	11.50	18.83	20.33	34.00	-1.00	-27.67
	R	8.50	16.50	16.33	42.67	nt	-22.67
06	**T**	15.17	7.83	20.00	46.33	-1.00	-11.33
	R	13.33	10.33	10.00	26.00	-1.00	nt
07	**T**	12.17	14.67	42.67	48.67	nt	nt
	R	6.50	12.17	48.67	47.67	nt	nt
08	**T**	14.00	12.50	28.33	49.00	-18.33	-42.67
	R	8.50	16.67	37.33	48.67	-20.00	-39.67
09	**T**	14.00	7.50	11.00	42.33	-28.33	-51.00
	R	9.00	4.50	9.67	47.67	-26.33	-46.00
10	**T**	11.33	12.33	2.00	47.67	-6.33	-56.00
	R	13.50	18.00	9.33	49.00	-9.33	-54.67
11	**T**	8.83	2.17	23.33	47.00	-12.00	-9.33
	R	12.00	1.50	45.00	48.00	-9.00	-5.33
12	**T**	18.83	10.33	14.33	48.33	-29.67	nt
	R	18.33	5.50	14.33	48.67	nt	nt
13	**T**	6.50	5.83	10.33	48.67	-5.33	-78.00
	R	3.50	1.67	2.33	48.33	-2.33	-42.67
14	**T**	12.67	16.83	40.33	42.33	-62.33	-65.00
	R	15.67	18.33	32.33	13.00	-53.00	-61.67
15	**T**	5.33	19.00	6.33	48.67	-3.33	-48.33
	R	5.17	13.50	3.67	44.67	-4.67	-26.33
16	**T**	7.83	4.50	48.33	nt	nt	nt
	R	7.67	5.67	45.00	47.67	nt	nt
17	**T**	10.00	3.33	12.00	46.00	-7.00	-25.00
	R	2.33	3.00	12.00	45.33	-3.67	-43.00

Table A.0.2: Individual results of all 3I3AFC and 1I2AFC variations. (T = Test; R = Repetition; nt = Not Tested)
[1] [dB]
[2] [% dB SNR]
[3] [ms]

		Performed (N)	Not performed (N)	All (N)
$3I3AFC_{\Delta L}$	T	17	0	17
	R	17	0	17
$1I2AFC_{\Delta L}$	T	17	0	17
	R	17	0	17
$3I3AFC_{\Delta f}$	T	17	0	17
	R	17	0	17
$1I2AFC_{\Delta f}$	T	16	1	17
	R	17	0	17
$3I3AFC_{\Delta t_{on}}$	T	14	3	17
	R	10	7	17
$1I2AFC_{\Delta t_{on}}$	T	13	4	17
	R	10	7	17

Table A.0.3: Number (N) of results in all AMPDT variations. Due to the long test session duration requiring a high level of concentration, not every subject completed the whole test battery (see column "not performed").
(T = Test; R = Repetition)

			Performed (N)	Not performed (N)	All (N)
$3I3AFC_{\Delta L}$	T	SSS	4	0	4
		TSS	13	0	13
	R	SSS	4	0	4
		TSS	13	0	13
$1I2AFC_{\Delta L}$	T	SSS	4	0	4
		TSS	13	0	13
	R	SSS	4	0	4
		TSS	13	0	13
$3I3AFC_{\Delta f}$	T	SSS	4	0	4
		TSS	13	0	13
	R	SSS	4	0	4
		TSS	13	0	13
$1I2AFC_{\Delta f}$	T	SSS	4	0	4
		TSS	12	1	13
	R	SSS	4	0	4
		TSS	13	0	13
$3I3AFC_{\Delta t_{on}}$	T	SSS	3	1	4
		TSS	7	6	13
	R	SSS	4	0	4
		TSS	10	3	13
$1I2AFC_{\Delta t_{on}}$	T	SSS	3	1	4
		TSS	10	3	13
	R	SSS	2	2	4
		TSS	8	5	13

Table A.0.4: Number (N) of participants in all AMPDT variations divided according to operation type (SSS= Single-Stage Surgery; TSS = Two-Stage Surgery). All subjects having recieved both of their CIs in a single surgery are in the Single-Stage Surgery group and all those subjects who had separate surgeries are in the Two-Stage Surgery group.
(T = Test; R = Repetition)

Appendix B: Spread of Excitation

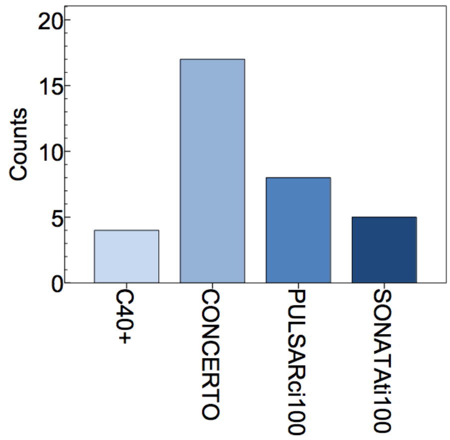


Figure B.0.1: Bar graph showing the devices. Number (N) of CI devices. With 17 participants in total, 34 ears could have been tested. Combi 40+ implants do not support backward telemetry ECAP measurements.

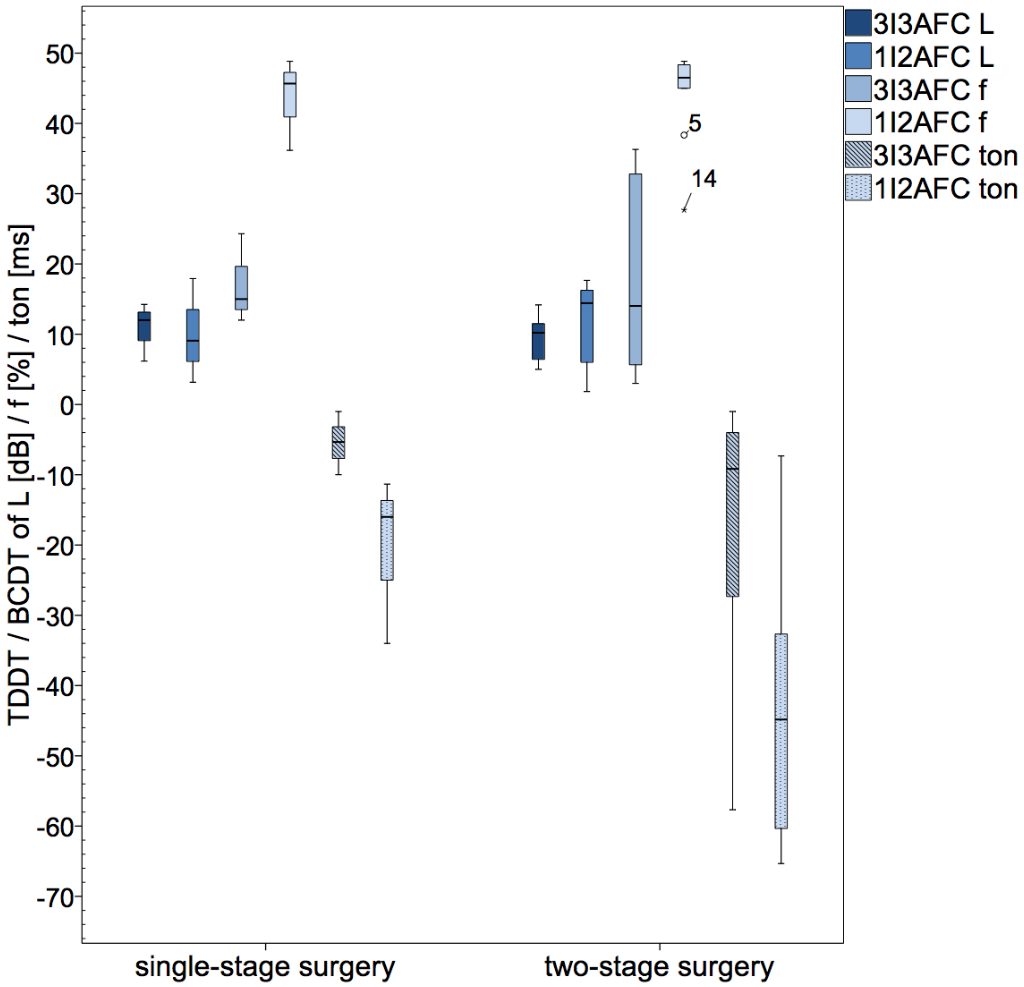


Figure B.0.2: Boxplot charts: Comparison of the Single-Stage Surgery (SSS) and Two-Stage Surgery (TSS) group's discrimination thresholds in all conditions. Numbering of outliers (°) and extreme values (*) represent the number associated with each subject for matters of data privacy (see section 3.1).

subject	CI type		electrode type		aetiology	onset of hl	age at surgery [yr]	FMS^1 [%]		CI exp. [yr]	
	left	right	left	right				left	right	left	right
01	CONCERTO	CONCERTO	FLEXsoft	FLEX28	progressive hl	postlingual	53	100	80	2.7	1.8
02	SONATAti100	SONATAti100	Standard	FLEXsoft	progressive hl	postlingual	57	80	85	6.5	4.0
03	PULSARci100	CONCERTO	Standard	Standard	hl during infancy	prelingual	3	40	65	8.8	13.6
04	CONCERTO	CONCERTO	FLEX28	FLEX28	congenital auditory defect	postlingual	38	95	100	1.6	1.6
05	PULSARci100	CONCERTO	FLEX24	FLEX28	hl during childhood	postlingual	17	80	80	7.2	2.0
06	PULSARci100	PULSARci100	Medium	Compressed	meningitis	postlingual	18	90	35	6.5	6.5
07	CONCERTO	CONCERTO	FLEX28	FLEXsoft	progressive hl	postlingual	58	60	70	2.0	3.0
08	C40+	PULSARci100		Standard	progressive hl	postlingual	51	90	90	11.5	6.9
09	SONATAti100	SONATAti100	Standard	Standard	progressive hl	postlingual	50	85	90	5.7	6.4
10	C40+	CONCERTO	Standard	FLEXsoft	meningitis	prelingual	1	100	100	13.6	13.5
11	CONCERTO	CONCERTO	FLEXsoft	FLEXsoft	progressive hl	postlingual	38	100	95	2.5	2.9
12	CONCERTO	PULSARci100	FLEX28	Standard	progressive hl	postlingual	64	70	65	13.5	13.5
13	CONCERTO	C40+	FLEXsoft	Standard	congenital deafness	prelingual	2	90	100	13.1	15.2
14	PULSARci100	PULSARci100	Standard	Standard	hl during childhood	postlingual	52	65	65	9.4	7.6
15	C40+	SONATAti100	Standard	Standard	congenital auditory defect	prelingual	6	100	100	15.4	13.1
16	CONCERTO	CONCERTO	FLEX28	FLEX28	progressive hl	postlingual	36	90	90	2.9	1.1
17	CONCERTO	CONCERTO	FLEX28	FLEX28	congenital auditory defect	postlingual	33	90	85	2.2	2.2

Table B.0.1: CI type specification, hearing loss aetiology, last available results of the Freiburger Monosyllabic Test at 65 dB speech level an CI experience (hl = hearing loss; CI exp. = CI experience).

[1] Freiburger Monosyllabic Test at 65 dB speech level

Subject	basal		medial		apical	
	left	**right**	**left**	**right**	**left**	**right**
01	9	9	6	6	3	3
02	9	9	6	6	3	3
03	9	9	6	6	3	3
04	9	9	6	6	3	3
05	8	9	4	6	1	3
06	9	9	6	6	3	3
07	9	9	6	6	3	3
08	nt	9	nt	6	nt	3
09	9	11	6	9	3	6
10	nt	9	nt	6	nt	3
11	9	9	6	6	3	3
12	9	9	6	6	3	3
13	9	nt	6	nt	3	nt
14	9	9	6	6	3	3
15	nt	9	nt	6	nt	3
16	9	9	6	6	3	3
17	9	9	6	6	3	3

Table B.0.2: Probe and recording electrodes in the SoE test (nt = Not Tested, ECAP measurement not supported (C40+ Implant)).

S	Ear	e-functions		min	max	lhs:c	lhs:a	lhs:u	rhs:c	rhs:a	rhs:u
		apical	basal								
01	r	✓	✓	37.00	437.00	174.00	1.78	-1.37	435.00	0.00	1.01
01	l		✓	68.00	252.00	0.00	0.00	0.00	208.00	0.00	0.01
04	r	✓	✓	37.00	397.00	416.00	44.77	-2.75	472.00	2703.98	3.30
04	l	✓	✓	-8.00	292.00	227.00	38.00	-0.93	339.00	2587.24	3.00
11	r	✓	✓	40.00	258.00	138.00	2.48	-1.60	249.00	0.00	0.95
11	l		✓	29.00	303.00	0.00	0.00	0.00	314.00	5159.04	2.02
13	l	✓	✓	32.00	175.00	501.00	346.68	-19.01	156.00	0.00	0.07
14	l	✓	✓	29.00	241.00	136.00	8.78	-2.43	247.00	17612.64	1.37
15	r	✓		-30.00	929.00	417.00	2.85	-1.20	0.00	NaN	NaN
16	r	✓	✓	0.00	205.00	188.00	1.10	-1.16	183.00	0.00	0.03
16	l	✓	✓	81.00	193.00	197.00	13.91	-2.84	185.00	0.00	0.07
17	r	✓	✓	0.00	406.00	401.00	45.49	-2.75	446.00	5616.60	2.37
17	l	✓	✓	-26.00	222.00	284.00	107.65	-5.51	261.00	3104.64	2.54

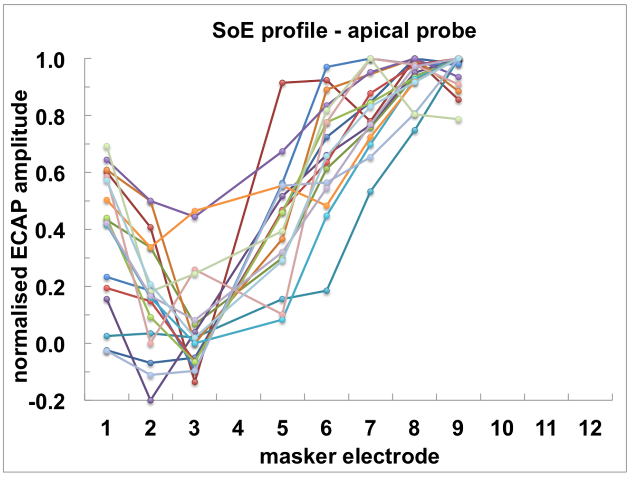
Table B.0.3: Exponential functions' parameters (S = Subjects; r = right; l = left; lhs = the graph's left hand (apical) side; rhs = the graph's right hand (basal) side; max = maximum of the e-function [μV]; min = minimum of the e-function [μV]; c = maximum ECAP possible for large distances between probe and masker electrode [μV]; a = the difference between variables c and a ($c - a$) describes the exponential function's minimum [μV]; u = depiction of the exponential function's slope; NaN = Not a Number).

S	Ear	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12
01	r	0.35	0.40	0.40	0.33	0.21	0.08	NaN	0.84	0.99	1.00	0.95	NaN
01	l	NaN	0.53	0.42	0.46	0.27	0.31	NaN	0.80	1.00	0.84	0.74	0.75
04	r	0.82	0.85	0.80	0.58	0.23	0.09	NaN	0.51	0.82	0.88	0.92	1.00
04	l	0.76	0.70	0.83	0.70	0.47	-0.03	NaN	0.46	0.80	0.89	0.88	1.00
06	l	-0.03	-0.10	0.00	0.03	0.08	-0.05	NaN	0.28	0.46	0.61	0.89	1.00
08	r	0.55	0.42	0.24	0.05	-0.14	0.00	NaN	0.57	0.78	0.97	0.88	1.00
10	r	0.41	1.00	0.07	-0.10	-0.10	0.10	NaN	0.31	0.59	0.38	1.00	0.90
11	r	0.47	0.51	0.49	0.50	0.22	0.16	NaN	0.86	0.95	0.93	0.93	1.00
11	l	0.45	0.27	0.23	0.25	0.10	0.17	NaN	0.73	0.81	0.95	0.94	1.00
13	l	0.75	0.68	0.58	0.42	0.22	0.18	NaN	0.94	0.80	0.91	0.82	1.00
14	r	0.51	0.45	0.15	0.33	0.14	0.00	NaN	0.40	0.80	0.86	0.83	1.00
14	l	0.54	0.39	0.62	0.20	0.37	0.12	NaN	0.77	1.00	0.96	0.98	NaN
15	r	0.50	0.42	0.39	0.27	0.33	-0.03	NaN	0.11	0.50	0.71	0.89	1.00
16	r	0.94	0.78	0.90	0.82	0.46	0.00	NaN	0.92	0.85	0.81	0.88	1.00
16	l	0.97	0.80	0.78	0.79	0.58	0.42	NaN	1.00	0.98	0.88	0.98	NaN
17	r	0.82	0.75	0.67	0.51	0.27	0.00	NaN	0.60	0.81	0.91	0.96	1.00
17	l	0.67	0.56	0.56	0.25	-0.01	-0.12	NaN	0.40	0.96	0.95	0.97	1.00

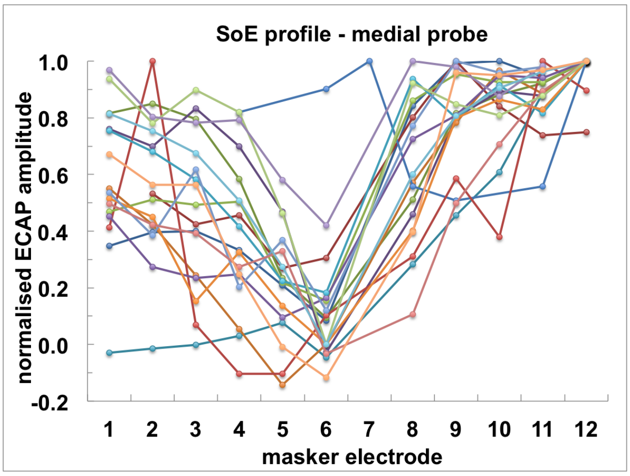
Table B.0.4: Normalised values of all analysable SoE functions. (S = Subject; r = right; l = left; M=Masker Electrode; NaN = Not a Number).

		ΔMax_{BA}	$MDIST_{0.25, B}$	$MDIST_{0.25, A}$	$MDIST_{0.25, AB}$	$MDIST_{0.25, B}$	$MDIST_{0.5, a}$	$MDIST_{0.5, AB}$
first implanted ear	Mean	68.40	2.62	2.56	5.18	3.93	4.57	8.31
	N	5.00	5.00	5.00	5.00	5.00	3.00	3.00
	Std. Dev.	61.05	1.80	0.71	1.99	1.69	1.98	2.47
second implanted ear	Mean	137.38	3.31	3.97	7.01	5.33	7.42	13.16
	N	8.00	8.00	8.00	8.00	8.00	6.00	6.00
	Std. Dev.	158.75	2.05	2.06	2.81	2.90	4.02	5.21
implanted simultaneously	Mean	226.00	4.90	2.32	5.22	6.88	4.01	8.68
	N	5.00	5.00	4.00	4.00	5.00	4.00	4.00
	Std. Dev.	361.84	4.59	1.04	1.41	4.95	1.3	1.40

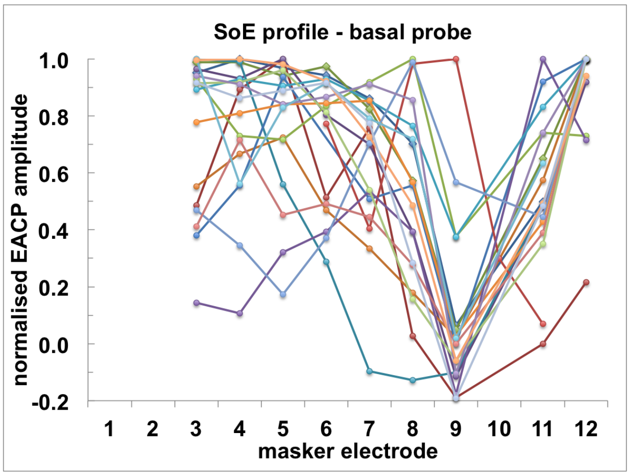
Table B.0.5: All means of the SoE test results split up according to initially and second implanted ear. The first implanted ears always show smaller excitation distance means at all 25 % and 50 % levels and therefore narrower SoE patterns. (MDIST = medial probe excitation distance; A = apical; B = basal; Std. Dev. = Standard deviation; N = Number)



(a)



(b)



(c)

Figure B.0.3: Normalised SoE functions of the ECAP response quality category "ECAP response present" (see subsection 3.6.2) for apical, medial and basal probe electrodes. In the measurement of the apical electrode, 17 SoE functions are listed in the category "ECAP response present", 18 for the medial electrode and 19 for the basal electrode. Each graph displays a SoE function.
(a) apical probe, **(b)** medial probe and **(c)** basal probe.

Appendix C: Questionnaire

Surname, Given name:	Patient ID:
Date of birth:	Datum:

Please take a few moments to fill in this questionnaire.
Your answers will be treated absolutely anonymously. Thank you very much for your participation!

1) MUSIC IN EVERYDAY LIFE

1.1) How often do you listen to music or how often have you been listening to music?

1.1.1) How often have you listened to music before the onset of your hearing loss?

Often	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Never
	10	9	8	7	6	5	4	3	2	1	

1.1.2) How often have you listened to music after your hearing loss without your CI?

Often	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Never
	10	9	8	7	6	5	4	3	2	1	

1.1.3) How often do you currently listen to music since receiving your CI?

Often	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Never
	10	9	8	7	6	5	4	3	2	1	

1.2) Under what circumstances do you listen to music?

1.2.1) Under what circumstances have you listened to music before the onset of your hearing loss?

☐ In the background ☐ Actively (concerts etc.) ☐ I like to play music myself. ☐ Other: ______________________

1.2.2) Under what circumstances have you listened to music after your hearing loss without your CI?

☐ In the background ☐ Actively (concerts etc.) ☐ I like to play music myself. ☐ Other: ______________________

1.2.3) Under what circumstances are you currently listening to music since receiving your CI?

☐ In the background ☐ Actively (concerts etc.) ☐ I like to play music myself. ☐ Other: ______________________

1.3) Why do you listen to music?

1.3.1) Why have you listened to music before the onset of your hearing loss?

☐ For pleasure ☐ Professional reasons ☐ Emotional satisfaction ☐ To improve my mood

☐ To dance ☐ To stay awake ☐ Other: ______________________________________

1.3.2) Why have you listened to music after your hearing loss without your CI?

☐ For pleasure ☐ Professional reasons ☐ Emotional satisfaction ☐ To improve my mood

☐ To dance ☐ To stay awake ☐ Other: ______________________________________

1.3.3) Why are you currently listening to music since receiving your CI?

☐ For pleasure ☐ Professional reasons ☐ Emotional satisfaction ☐ To improve my mood

☐ To dance ☐ To stay awake ☐ Other: ______________________________________

1.4) Which musical genres do you listen to?

1.4.1) Which musical genres have you listened to before the onset of your hearing loss?

☐ Classical Music ☐ Opera/ Operetta/ Vocals ☐ Religious Music

☐ Rock/ Pop ☐ Jazz/ Blues ☐ R&B/ Soul

☐ Folk/ Country Music ☐ Hip Hop/ Rap ☐ Alternative/ Indie

☐ Metal ☐ Techno/ House ☐ Beat-Music

☐ Other: ____

1.4.2) Which musical genres have you listened to after your hearing loss without your CI?

☐ Classical Music ☐ Opera/ Operetta/ Vocals ☐ Religious Music

☐ Rock/ Pop ☐ Jazz/ Blues ☐ R&B/ Soul

☐ Folk/ Country Music ☐ Hip Hop/ Rap ☐ Alternative/ Indie

☐ Metal ☐ Techno/ House ☐ Beat-Music

☐ Other: ____

1.4.3) Which musical genres are you currently listening to since receiving your CI?

☐ Classical Music ☐ Opera/ Operetta/ Vocals ☐ Religious Music

☐ Rock/ Pop ☐ Jazz/ Blues ☐ R&B/ Soul

☐ Folk/ Country Music ☐ Hip Hop/ Rap ☐ Alternative/ Indie

☐ Metal ☐ Techno/ House ☐ Beat-Music

☐ Other: ____

2) MUSIC PERCEPTION

2.1) How does music generally sound with your Cochlear Implant?

Natural	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Unnatural
	10	9	8	7	6	5	4	3	2	1	
Pleasant	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Unpleasant
	10	9	8	7	6	5	4	3	2	1	
Distinct	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Indistinct
	10	9	8	7	6	5	4	3	2	1	
Clear	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Reverberant
	10	9	8	7	6	5	4	3	2	1	
Less tinny	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	More tinny
	10	9	8	7	6	5	4	3	2	1	

2.2) What role does music play in your life?

2.2.1) What role did music play in your life before the onset of your hearing loss?

A big role	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	None
	10	9	8	7	6	5	4	3	2	1	

2.2.2) What role did music play in your life after your hearing loss without your CI?

A big role	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	None
	10	9	8	7	6	5	4	3	2	1	

2.2.3) What role does music currently play in your life since receiving your CI?

A big role	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	None
	10	9	8	7	6	5	4	3	2	1	

2.3) How do you estimate your musicality?

2.3.1) How do you estimate your musicality prior to your hearing loss?

Very good	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Not good
	10	9	8	7	6	5	4	3	2	1	

2.3.2) How do you estimate your musicality after your hearing loss without your CI?

Very good	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Not good
	10	9	8	7	6	5	4	3	2	1	

2.3.3) How do you currently estimate your musicality since receiving your CI?

Very good	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Not good
	10	9	8	7	6	5	4	3	2	1	

3) MUSICAL EDUCATION

3.1) Did you receive any musical education outside of school?

3.1.1) Did you receive any musical education outside of school?

☐ Yes ☐ No

3.1.2) For how long did you receive musical education outside of school?

☐ Less than 3 years ☐ More than 3 years ☐ Other: ______________________

3.2) Do you play an instrument or have you ever played one?

3.2.1) Did you play an instrument as a child?

Often	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Never
	10	9	8	7	6	5	4	3	2	1	

3.2.2) Did you play an instrument before the onset of your hearing loss?

Often	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Never
	10	9	8	7	6	5	4	3	2	1	

3.2.3) Did you play an instrument after your hearing loss without your CI?

Often	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Never
	10	9	8	7	6	5	4	3	2	1	

3.2.4) Do you currently play an instrument after your hearing loss since receiving your CI?

Often	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Never
	10	9	8	7	6	5	4	3	2	1	

3.3) Which instruments have you ever played or are you playing now?

3.3.1) Which instruments have you played before the onset of your hearing loss?

☐ Recorder
☐ Transverse flute
☐ Clarinet
☐ Saxophone
☐ Trumpet
☐ Piano
☐ Accordion
☐ Guitar
☐ Bass
☐ Violin
☐ Drums
☐ A different instrument:
____

3.3.2) Which instruments did you play after your hearing loss without your CI?

☐ Recorder
☐ Transverse flute
☐ Clarinet
☐ Saxophone
☐ Trumpet
☐ Piano
☐ Accordion
☐ Guitar
☐ Bass
☐ Violin
☐ Drums
☐ A different instrument:
____

3.3.3) Which instruments are you currently playing since receiving your CI?

☐ Recorder
☐ Transverse flute
☐ Clarinet
☐ Saxophone
☐ Trumpet
☐ Piano
☐ Accordion
☐ Guitar
☐ Bass
☐ Violin
☐ Drums
☐ A different instrument:
____

3.4) Do you sing or did you sing?

3.4.1) How often did you sing before the onset of your hearing loss?

Often	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Never
	10	9	8	7	6	5	4	3	2	1	

3.4.2) How often did you sing after your hearing loss without your CI?

Often	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Never
	10	9	8	7	6	5	4	3	2	1	

3.4.3) How often do you currently sing since receiving your CI?

Often	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	Never
	10	9	8	7	6	5	4	3	2	1	

3.5) If you sing or did sing, indicate where?

3.5.1) Where did you sing before the onset of your hearing loss?

☐ In a choir
☐ In the car
☐ At home, by myself
☐ In religious institutions
☐ With friends
☐ Other: ____

3.5.2) Where did you sing after your hearing loss without your CI?

☐ In a choir
☐ In the car
☐ At home, by myself
☐ In religious institutions
☐ With friends
☐ Other: ____

3.5.3) Where do you currently sing since receiving your CI?

- ☐ In a choir
- ☐ In the car
- ☐ At home, by myself
- ☐ In religious institutions
- ☐ With friends
- ☐ Other: ____

Please note additional information.

Thank you for your contribution!

C.1 Results

Question 1.2
Under what circumstances do you listen to music?

1.2.1) Under what circumstances have you listened to music before the onset of your hearing loss?
1.2.2) Under what circumstances have you listened to music after your hearing loss without your CI?
1.2.3) Under what circumstances are you currently listening to music since receiving your CI?

All subquestions had the following multiple-choice answering pattern: In the background; I like to play music myself; Actively (concerts etc.); Other; Never; Hearing loss as a child (only 1.2.1 and 1.2.2). Table C.1.2 shows the results of all subquestions.

Question 1.3
Why do you listen to music?

1.3.1) Why have you listened to music before the onset of your hearing loss?
1.3.2) Why have you listened to music after your hearing loss without your CI?
1.3.3) Why are you currently listening to music since receiving your CI?

All subquestions have the following multiple-choice answering pattern: For pleasure; Professional reasons; to improve my mood; to stay awake; to dance; emotional satisfaction; other; never; hearing loss as a child (only 1.3.1 and 1.3.2). Table C.1.3 shows the results of all subquestions.

Question 1.4
Which musical genres do you listen to?

1.4.1) Which musical genres have you listened to before the onset of your hearing loss?
1.4.2) Which musical genres have you listened to after your hearing loss without your CI?
1.4.3) Which musical genres are you currently listening to since receiving your CI?

All subquestions have the following multiple-choice answering pattern: Classical Music; Opera/ Operetta; Religious Music; Rock/ Pop; Jazz/ Blues; R&B/ Soul; Folk/ Country Music; Hip Hop/ Rap; Alternative/ Indie; Metal; Techno/ House; Beat-Music; Other; None; Hearing loss as a child (only 1.4.1 and 1.4.2). Table C.1.4 shows the results of all subquestions.

Correlation pair		N	p		r	R^2
Q 1.1.1 (frequency before hl)	- Q 2.1.1 (unnatural/ natural)	12	<0.01	**	0.73	0.53
Q 1.1.1 (frequency before hl)	- Q 2.1.2 (unpleasant/ pleasant)	12	<0.01	**	0.74	0.54
Q 1.1.1 (frequency before hl)	- Q 2.1.3 (indistinct/ distinct)	12	<0.01	**	0.80	0.64
Q 1.1.2 (frequency diagnose)	- Q 2.1.1 (unnatural/ natural)	12	0.04	*	0.61	0.37
Q 2.2.2 (importance diagnose)	- Q 2.1.1 (unnatural/ natural)	12	0.04	*	0.59	0.35
Q 2.2.3 (importance with CI)	- Q 2.1.1 (unnatural/ natural)	14	<0.01	**	0.79	0.62
Q 2.2.2 (importance diagnose)	- Q 2.1.2 (unpleasant/ pleasant)	12	0.04	*	0.59	0.35
Q 2.2.3 (importance with CI)	- Q 2.1.2 (unpleasant/ pleasant)	17	0.02	*	0.56	0.31
Q 2.2.1 (importance before hl)	- Q 2.1.3 (indistinct/ distinct)	12	<0.01	**	0.80	0.65

Table C.1.1: Pearson product-moment correlation: Significant correlations between music appreciation and individual music perception. See subsection 4.5.11 for further explanation.
* Significant correlations ** Highly significant correlations

	Q 1.2.1	Q 1.2.2	Q 1.2.3
	Percent of Cases	Percent of Cases	Percent of Cases
In the background	52.9	11.8	64.7
Actively (concerts etc)	58.8	29.4	62.5
I like to play music myself.	41.2	17.6	37.5
Other	0	0	0
Never	0	29.4	6.3
Hearing loss as a child	29.4	29.4	nan

Table C.1.2: Number of Responses (N) and percent of cases of question 1.2. (NaN = Not a Number)

	Q 1.3.1	Q 1.3.2	Q 1.3.3
	Percent of Cases	Percent of Cases	Percent of Cases
For pleasure	64.7	47.1	94.1
For professional reasons	0	0	0
To improve my mood	41.2	29.4	64.7
To stay awake	11.8	11.8	23.5
To dance	35.3	35.3	47.1
Emotional satisfaction	52.9	29.4	82.4
Other	0	0	11.8*
Never	0	23.5	0
Hearing loss as a child	29.4	29.4	nan

Table C.1.3: Number of Responses (n) and percent of cases of question 1.3. (nan = not a number)
*1.3.3: 2 Two subjects are listening to music "for practising with the CI"

	Q 1.4.1 Percent of Cases	Q 1.4.2 Percent of Cases	Q 1.4.3 Percent of Cases
Classical Music	18.8	23.5	58.8
Opera/ Operetta	25.0	11.8	35.3
Religious Music	12.5	17.6	17.6
Rock/ Pop	50.0	41.2	88.2
Jazz/ Blues	25.0	23.5	52.9
R&B/ Soul	31.3	23.5	52.9
Folk/ Country Music	31.3	17.6	41.2
Hip Hop/ Rap	12.5	5.9	29.4
Alternative/ Indie	0	5.9	17.6
Metal	6.3	5.9	17.6
Techno/ House	12.5	5.9	23.5
Beat-Music	37.5	17.6	35.3
Other	18.8*	5.9**	23.5***
None	0	23.5	0
Hearing loss as a child	31.3	29.4	nan

Table C.1.4: Number of Responses (n) and percent of cases of question 1.4. (nan = not a number)
* Two subjects liked to listen to "German folk music" and one to "audio plays" prior to their hearing loss;
** One subject liked to listen to "German folk music" after the onset of his/her hearing loss without a CI;
***Three subjects like to listen to "German folk music" and one to "Meditative Music".

	Q 3.3.1 Percent of Cases	Q 3.3.2 Percent of Cases	Q 3.3.3 Percent of Cases
Recorder	23.5	0	0
Transverse Flute	0	0	0
Clarinet	5.9	0	0
Saxophone	5,9	0	0
Trumpet	11.8	0	5.9
Piano	17.6	11.8	29.4
Accordion	11.8	0	0
Guitar	5.9	5.9	11.8
Bass	0	0	5.9
Violin	5.9	0	0
Drums	0	0	5.9
Other	5.9*	11.8**	5.9***
None	11.8	47.1	58.8
Hearing loss as a child	29.4	29.4	nan

Table C.1.5: Number of Responses (n) and percent of cases of question 3.3. (nan = not a number)
* One subject liked to play "electric organ" prior to her/his hearing loss
** One subject liked to play "electric organ" and another "Flugelhorn" after the onset of his/her hearing loss without a CI
*** One subject likes to play "Flugelhorn"

Question 3.3
Which instruments have you ever played or are you playing now?

3.3.1) Which instruments have you played before the onset of your hearing loss?
3.3.2) Which instruments did you play after your hearing loss without your CI?
3.3.3) Which instruments are you currently playing since receiving your CI?

All subquestions have the following multiple-choice answering pattern: Recorder; Transverse Flute; Clarinet; Saxophone; Trumpet; Piano; Accordion; Guitar; Bass; Violin; Drums; Other; None; Hearing loss as a child (only 3.3.1 and 3.3.2). Table C.1.5 shows the results of all subquestions.

Question 3.5
If you sing or did sing, indicate where?

	Q 3.5.1 Percent of Cases	Q 3.5.2 Percent of Cases	Q 3.5.3 Percent of Cases
In a choir	29.4	11.8	0
In religious institutions	17.6	17.6	11.8
In the car	29.4	17.6	35.3
With friends	29.4	17.6	23.5
At home, by myself	23.5	17.6	41.2
Other	11.8*	11.8**	23.5***
Never	17.6	29.4	35.3
Hearing loss as a child	29.4	29.4	nan

Table C.1.6: Number of Responses (n) and percent of cases of question 3.5. (nan = not a number)
* One subject used to sing in a non-professional band prior to his/her hearing loss and another "with familiy"
** Two subjects liked to sing "with familiy" after the onset of their hearing loss without a CI
*** Three subjects like to sing "with familiy" and another lullabies for his/her children

3.5.1) Where did you sing before the onset of your hearing loss?

3.5.2) Where did you sing after your hearing loss without your CI?

3.5.3) Where do you currently sing since receiving your CI?

All subquestions have the following multiple-choice answering pattern: In religious institutions; In the car; With friends; at home, by myself; Other; None; Hearing loss as a child (only 3.5.1 and 3.5.2). Table C.1.6 shows the results of all subquestions.

Appendix D: Correlations

Table D.0.1: Pearson product-moment correlation: All correlations between 3I3AFC/ 1I2AFC conditions, OLSA conditions and SoE. High levels of performance in $1I2AFC_{\Delta t_{on}}$ are significantly correlated with narrow $MDIST_{0.5,A}$ ($p = 0.05$) and $MDIST_{0.5,AB}$ ($p = 0.02$). No significant correlations were found between DISTs and the OLSA results (MDIST = medial probe excitation distance)

Correlation pair	p	r	R^2
$3I3AFC_{\Delta L}$ - MAX_{AB}	0.54	0.15	0.02
$3I3AFC_{\Delta L}$ - $MDIST_{0.25,A}$	0.82	0.06	<0.01
$3I3AFC_{\Delta L}$ - $MDIST_{0.25,B}$	0.18	0.33	0.11
$3I3AFC_{\Delta L}$ - $MDIST_{0.25,AB}$	0.70	0.10	0.01
$3I3AFC_{\Delta L}$ - $MDIST_{0.5,A}$	0.88	-0.05	<0.01
$3I3AFC_{\Delta L}$ - $MDIST_{0.5,B}$	0.08	0.42	0.18
$3I3AFC_{\Delta L}$ - $MDIST_{0.5,AB}$	0.75	0.1	0.01
$1I2AFC_{\Delta L}$ - MAX_{AB}	0.89	0.03	<0.01
$1I2AFC_{\Delta L}$ - $MDIST_{0.25,A}$	0.16	-0.36	0.13
$1I2AFC_{\Delta L}$ - $MDIST_{0.25,B}$	0.70	0.10	0.01
$1I2AFC_{\Delta L}$ - $MDIST_{0.25,AB}$	0.73	-0.09	<0.01
$1I2AFC_{\Delta L}$ - $MDIST_{0.5,A}$	0.25	0.35	0.12
$1I2AFC_{\Delta L}$ - $MDIST_{0.5,B}$	0.41	0.21	0.04
$1I2AFC_{\Delta L}$ - $MDIST_{0.5,AB}$	0.10	0.47	0.22
$3I3AFC_{\Delta f}$ - MAX_{AB}	0.74	-0.08	<0.01
$3I3AFC_{\Delta f}$ - $MDIST_{0.25,A}$	0.93	0.02	<0.01
$3I3AFC_{\Delta f}$ - $MDIST_{0.25,B}$	0.08	-0.43	0.18
$3I3AFC_{\Delta f}$ - $MDIST_{0.25,AB}$	0.13	-0.38	0.14

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Table D.0.1 – continued from previous page

Correlation pairs	p	r	R^2
$3I3AFC_{\Delta f}$ - $MDIST_{0.5,A}$	0.66	-0.14	0.02
$3I3AFC_{\Delta f}$ - $MDIST_{0.5,B}$	0.09	-0.41	0.17
$3I3AFC_{\Delta f}$- $MDIST_{0.5,AB}$	0.16	-0.41	0.17
$1I2AFC_{\Delta f}$ - MAX_{AB}	0.14	-0.36	0.13
$1I2AFC_{\Delta f}$ - $MDIST_{0.25,A}$	0.92	0.03	<0.01
$1I2AFC_{\Delta f}$ - $MDIST_{0.25,B}$	0.43	-0.20	0.04
$1I2AFC_{\Delta f}$ - $MDIST_{0.25,AB}$	0.73	0.09	<0.01
$1I2AFC_{\Delta f}$ - $MDIST_{0.5,A}$	0.10	-0.48	0.23
$1I2AFC_{\Delta f}$ - $MDIST_{0.5,B}$	0.43	-0.20	0.04
$1I2AFC_{\Delta f}$ - $MDIST_{0.5,AB}$	0.31	-0.30	0.09
$3I3AFC_{\Delta t_{on}}$ - MAX_{AB}	0.98	-0.01	<0.01
$3I3AFC_{\Delta t_{on}}$ - $MDIST_{0.25,A}$	0.86	-0.05	<0.01
$3I3AFC_{\Delta t_{on}}$ - $MDIST_{0.25,B}$	0.30	-0.30	0.09
$3I3AFC_{\Delta t_{on}}$ - $MDIST_{0.25,AB}$	0.54	-0.19	0.04
$3I3AFC_{\Delta t_{on}}$ - $MDIST_{0.5,A}$	0.30	0.34	0.12
$3I3AFC_{\Delta t_{on}}$ - $MDIST_{0.5,B}$	0.33	-0.28	0.08
$3I3AFC_{\Delta t_{on}}$ - $MDIST_{0.5,AB}$	0.61	0.17	0.03
$1I2AFC_{\Delta t_{on}}$ - MAX_{AB}	0.21	-0.36	0.13
$1I2AFC_{\Delta t_{on}}$ - $MDIST_{0.25,A}$	0.46	-0.22	0.05
$1I2AFC_{\Delta t_{on}}$ - $MDIST_{0.25,B}$	0.51	-0.19	0.04
$1I2AFC_{\Delta t_{on}}$ - $MDIST_{0.25,AB}$	0.89	-0.05	<0.01
$1I2AFC_{\Delta t_{on}}$ - $MDIST_{0.5,A}$	0.18	0.44	0.19
$1I2AFC_{\Delta t_{on}}$ - $MDIST_{0.5,B}$	0.58	-0.16	0.03

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Table D.0.1 – continued from previous page

Correlation pairs	p	r	R^2
$1I2AFC_{\Delta t_{on}}$ - $MDIST_{0.5,AB}$	0.21	0.41	0.17
$L50_{Fastl}$ - MAX_{AB}	0.44	-0.21	0.04
$L50_{Fastl}$ - $MDIST_{0.25,A}$	0.13	-0.41	0.17
$L50_{Fastl}$ - $MDIST_{0.25,B}$	0.39	-0.23	0.05
$L50_{Fastl}$ - $MDIST_{0.25,AB}$	0.10	-0.45	0.20
$L50_{Fastl}$ - $MDIST_{0.5,A}$	0.72	0.12	0.01
$L50_{Fastl}$ - $MDIST_{0.5,B}$	0.39	-0.23	0.05
$L50_{Fastl}$ - $MDIST_{0.5,AB}$	0.74	-0.12	0.01
$L50_{OLnoise}$ - MAX_{AB}	0.89	-0.04	<0.01
$L50_{OLnoise}$ - $MDIST_{0.25,A}$	0.48	-0.21	0.04
$L50_{OLnoise}$ - $MDIST_{0.25,B}$	0.34	-0.27	0.07
$L50_{OLnoise}$ - $MDIST_{0.25,AB}$	0.22	-0.35	0.12
$L50_{OLnoise}$ - $MDIST_{0.5,A}$	0.31	0.36	0.13
$L50_{OLnoise}$ - $MDIST_{0.5,B}$	0.42	-0.23	0.05
$L50_{OLnoise}$ - $MDIST_{0.5,AB}$	0.77	0.11	0.01

Correlation pair		N	p	r	R^2
$3I3AFC_{\Delta L}$	- Surgery interval	4	0.36	0.64	0.41
$1I2AFC_{\Delta L}$	- Surgery interval	4	0.98	0.02	<0.01
$3I3AFC_{\Delta f}$	- Surgery interval	4	0.15	0.85	0.72
$1I2AFC_{\Delta f}$	- Surgery interval	4	0.23	0.77	0.59
$3I3AFC_{\Delta t_{on}}$	- Surgery interval	4	0.20	-0.80	0.64
$1I2AFC_{\Delta t_{on}}$	- Surgery interval	4	0.27	0.73	0.53
$L50_{Fastl}$	- Surgery interval	4	0.12	-0.88	0.77
$L50_{OLnoise}$	- Surgery interval	4	0.61	-0.39	0.15

Table D.0.2: Pearson product-moment correlation calculated between 3I3AFC/ 1I2AFC conditions, OLSA conditions and surgery interval for the subgroup of 4 subjects who had been implanted during their early childhood (1 to 6 years). Absence of significant correlation.
N = Number of pairs in correlation analysis

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Schriftliche Erklärung

Ich erkläre ehrenwörtlich, dass ich die dem Fachbereich Medizin der Johann Wolfgang Goethe-Universität Frankfurt am Main zur Promotionsprüfung eingereichte Dissertation mit dem Titel

On the Relation of Electrophysiological Compound Action Potential (ECAP) Measurements and Perceptive Skills in Cochlear Implant (CI) Listeners

in der Klinik für Hals-Nasen-Ohrenheilkunde unter Betreuung und Anleitung von Prof. Dr.-Ing. Uwe Baumann mit Unterstützung durch Dr.-Ing. Tobias Rader ohne sonstige Hilfe selbst durchgeführt und bei der Abfassung der Arbeit keine anderen als die in der Dissertation angeführten Hilfsmittel benutzt habe. Darüber hinaus versichere ich, nicht die Hilfe einer kommerziellen Promotionsvermittlung in Anspruch genommen zu haben.

Ich habe bisher an keiner in- oder ausländischen Universität ein Gesuch um Zulassung zur Promotion eingereicht. Die vorliegende Arbeit wurde bisher nicht als Dissertation eingereicht.

Frankfurt am Main	25.08.2017	
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