EQUIVALENT HEARING LOSS IN CHILDREN

I n a u g u r a l – D i s s e r t a t i o n

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„Nichts kommt von selbst. Und nur wenig ist von Dauer. Darum – besinnt Euch auf Eure Kraft und darauf, dass jede Zeit eigene Antworten will und man auf ihrer Höhe zu sein hat, wenn Gutes bewirkt werden soll.“

Willy Brandt[1]

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[1]Aus einem Grußwort an den Kongress der Sozialistischen Internationale in Berlin, 15. September 1992

II. ABSTRACT

Aim: Early intervention is the key to spoken language for hearing impaired children. A severe hearing loss diagnosis in a young child raises the urgent question on the type of optimal hearing aid device. But indication criteria differ not only from country to country, but sometimes from clinic to clinic.

As there is no recent data on comparing selection criteria for a specific hearing aid device, the goal of the Hearing Evaluation of Auditory Rehabilitation Devices (hEARd) project (Coninx & Vermeulen, 2012) evolved to collect and analyze interlingually comparable normative data on the speech perception performances of children with hearing aids and children with cochlear implants (CI). The hEARd project followed the Equivalent Hearing Loss concept of the 1990s (Snik et al., 1997a). The performance of CI users is interpreted in comparison to the performance of hearing aid users in relation to their degree of hearing loss. Collected data allows to derive an equivalent hearing loss (EHL) value. It can give an indication, from which level of hearing loss on a CI can offer statistically better speech perception in the used tests and up to which level a child benefits adequately from hearing aids compared to the average performance of children using hearing aids.

Method: In various institutions for hearing rehabilitation in Belgium, Germany and the Netherlands the Adaptive Auditory Speech Test AAST (Coninx, 2005) – amongst other tests of the BELLS software (Battery for the evaluation of listening and language skills) – was used in the hEARd project, to determine speech perception abilities in kindergarten and school aged children, using CI or hearing aids with a hearing loss acquired within their first year of life.

Achieved results in audiometric procedures such as speech perception in quiet or in noise as well as the performance when using high frequency speech material were matched to the unaided hearing loss values of children using hearing aids and compared to results of children using CI.

277 data sets of hearing impaired children were analyzed. Results of children using hearing aids were summarized in groups as to their unaided hearing loss values. The grouping was related to the World Health Organization's (WHO) grading of hearing impairment from mild (25–40 dB HL) to moderate (41–60 dB HL), severe (61-80 dB HL) and profound hearing impairment (80 dB HL and higher). These groups' performances were compared to the performances of children using CI.

Results: AAST speech recognition results in quiet showed a significantly better performance for the CI group in comparison to the group of profoundly impaired hearing aid users as well as the group of severely impaired hearing aid users. The same trend could be observed in the performance of high frequency speech material. However the CI users' performances in speech perception in noise did not vary from the hearing aid users' performances who have a profound or severe hearing loss.

Within the collected data analyses showed that children with a CI show an equivalent performance on speech perception in quiet as children using hearing aids with a "moderate" hearing impairment. The CI users' performance on speech perception in noise appeared poorly compared to their overall performance.

Conclusion: The test battery turned out to be a useful diagnostic tool to evaluate the performance on auditory speech perception skills in hearing impaired children. It allows a comparison of performances based on different parameters such as type of technical hearing aid device.

For the daily educational routine it can be concluded that especially children using hearing aids with hearing losses greater than 60 dB have distinctly greater difficulties in the auditory perception of speech compared to children with lower hearing losses or children using CI. Speech perception in an educational environment needs to be ensured. Educational concepts as well as the optimization of technical devices should be topics in the ongoing consultation of child and family.

This is one task that needs to be addressed by the field of educational audiology as well as a necessary reevaluation of outcomes with upcoming developments of technical hearing devices.

Motivation: Frühe Intervention ist der Schlüssel zu gesprochener Sprache für Kinder mit Hörbeeinträchtigung. Die Diagnose hochgradig Schwerhörig bei einem kleinen Kind bringt die dringende Frage nach der optimalen technischen Hörhilfenversorgung mit sich. Jedoch variieren Indikationskriterien nicht nur zwischen verschiedenen Ländern, sondern gegebenenfalls schon zwischen unterschiedlichen Kliniken.

Die Zielsetzung des Projektes "hearing evaluation of auditory rehabilitation devices" – kurz des hEARd Projektes (Coninx & Vermeulen, 2012) – entwickelte sich aufgrund mangelnder aktueller Daten zu Auswahlkriterien spezifischer technischer Hörhilfen; interlingual vergleichbare Normdaten zu auditiven Fähigkeiten der Sprachwahrnehmung von Kindern mit Hörgeräten und Cohlea Implantaten (CI) zu erheben. Das hEARd Project basiert auf dem Konzept des „Äquivalenten Hörverlustes" (equivalent hearing loss - EHL) der 90er Jahre (Snik et al., 1997a). Die Performance von CI Nutzern wird im Vergleich zur Performance von Hörgeräte Nutzern im Zusammenhang zu deren unversorgten Grad des Hörverlustes interpretiert. Die erhobenen Daten ermöglichen die Ableitung eines äquivalenten Hörverlust Wertes (EHL Wertes). Dieser kann eine Indikation darüber geben, von welchem Hörverlust an ein CI statistisch gesehen eine verbesserte Sprachwahrnehmung in den eingesetzten Testverfahren bieten kann und bis zu welchem Hörverlust ein Kind adäquat von seinen Hörgeräten profitiert, verglichen mit der durchschnittlichen Performance von Kindern mit Hörgeräten.

Methode: In verschiedenen Einrichtungen zur Hörrehabilitation in Belgien, Deutschland und den Niederlanden wurde der Adaptiv Auditive Sprachtest AAST (Coninx, 2005) – neben weiteren Tests der BELLS Software (Battery for the evaluation of listening and language skills) – im Rahmen des hEARd Projektes eingesetzt, um die Fähigkeiten zur Sprachwahrnehmung bei Kindern im Kindergarten- und Schulalter, welche CI oder Hörgerät nutzen und einen Hörverlust innerhalb des ersten Lebensjahres erlitten, zu erfassen.

Die Resultate der audiometrischen Untersuchungen, welche unter anderem Sprachverstehen in Ruhe und im Störgeräusch, sowie das Verstehen von Material mit erhöhten hochfrequenten Sprachanteilen umfassten, wurden in ein Verhältnis zum unversorgten Hörverlust der Kinder mit Hörgeräten gesetzt und dann mit den Ergebnissen der Kinder mit CI verglichen. 277 Datensätze hörgeschädigter Kinder wurden analysiert. Ergebnisse der Kinder mit Hörgeräten wurden in Gruppen nach unversorgtem Hörverlust zusammengefasst. Die Gruppierung erfolgte in Anlehnung an die Einteilung nach Schweregrad der Hörbeeinträchtigung der WHO von geringgradiger (25–40 dB HL) über mittelgradige (41-60 dB HL) hin zu hochgradiger (61-80 dB HL) und an Taubheit grenzender Schwerhörigkeit (80 dB HL und höher). Die Ergebnisse dieser Gruppen wurden mit den Ergebnissen der Kinder mit CI verglichen.

Ergebnisse: Die Ergebnisse des AAST in Ruhe zeigten ein signifikant besseres Sprachverstehen der CI Gruppe im Vergleich zur Gruppe der an Taubheit grenzend scherhörigen Hörgerätenutzer, sowie der hochgradig schwerhörigen Hörgerätenutzer. Dieser Trend konnte auch in den Ergebnissen zum hochfrequenten Sprachmaterial beobachtet werden. Die Ergebnisse der CI-Träger beim Sprachverstehen im Störgeräusch unterschieden sich jedoch nicht von denen der Hörgeräteträger mit an Taubheit grenzender oder hochgradiger Schwerhörigkeit.

Im Rahmen der Datenanalyse konnte gezeigt werden, dass Kinder mit einem CI äquivalente Ergebnisse im Sprachverstehen in Ruhe erreichten, verglichen mit Hörgeräte-versorgten Kindern, welche mittelgradig hörbeeinträchtigt sind. Die Leistung der CI-Träger beim Sprachverstehen im Störgeräusch erschien im Vergleich zum gesamten Abschneiden jedoch schwach.

Fazit: Die Testbatterie erwies sich als nützliches diagnostisches Instrumentarium zur Evaluation von Fähigkeiten zur auditiven Sprachwahrnehmung bei Kindern mit Hörbeeinträchtigung. Das Test-Set ermöglicht den Vergleich von Ergebnissen hinsichtlich verschiedener Parameter, wie zum Beispiel die Art der technischen Hörhilfenversorgung.

Für den pädagogischen Alltag kann geschlussfolgert werden, dass vor allem Kinder mit Hörgeräten und einem Hörverlust über 60 dB deutlich größere Schwierigkeiten in der auditiven Verarbeitung von Sprache haben, als Kinder mit geringeren Hörverlusten oder Kinder mit Cochlea Implantat. Sprachwahrnehmung im schulischen Kontext muss entsprechend abgesichert werden. Pädagogische Konzepte, sowie eine Optimierung der technischen Hörhilfen sollten Thema der fortlaufenden Beratung des Kindes und seiner Familie sein.

Dies ist eine Aufgabe im Bereich der pädagogischen Audiologie, wie aber auch die notwendige Reevaluation von Ergebnissen, welche mit zukünftigen Entwicklungen technischer Hörhilfen erreicht werden können.

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VI. Abbreviations

AAST .... Adaptive Auditory Speech Test
AAST CN............... Adaptive Auditory Speech Test in noise (continuous noise)
AAST HF .... Adaptive Auditory Speech Test high frequency test set
AAST QT .... Adaptive Auditory Speech Test in quiet
BELLS.................... Battery for the Evaluation of Listening and Language Skills
CI............................ cochlear implant
dB .... decibel
dB HL..................... decibel hearing level
EHL .... equivalent hearing loss
ELFRA-1................ Elternfragebogen für die Früherkennung von Risikokindern
hEARd.................... hearing evaluation of auditory rehabilitation devices
Hz .... Hertz
kHz .... Kilo Hertz
K-ABC .... Kaufman-Assessment Battery for Children
mFAST................... multi Frequency Animal Sound Test
NHS........................ newborn hearing screening
PTA .... pure tone audiometry
SNR .... signal to noise ratio
SRT......................... speech recognition threshold
TTT F .... TiTaTu fricative subtest
TTT P .... TiTaTu plosive subtest
TTT V..................... TiTaTu vowel subtest
WHO .... World Health Organization
WRIST .... Word Recognition in Sentences Test

1. INTRODUCTION

Max and Anna have come with their parents to an audiological center. Anna is 10 months old. She did not pass the newborn hearing screening and further diagnosis confirmed a profound hearing impairment. The recent appointment is about informing the family on the planned procedure of sequential cochlear implantation. Anna's parents have known the audiological center for several years because her older brother Max is also hard of hearing.

The newborn hearing screening was just instated at the time Max was born six years ago, but unfortunately not executed at this clinic at that time. Max was diagnosed with a moderate hearing impairment of approximately 50 dB HL when he was 26 months old. Regular monitoring of his auditory and verbal development with hearing aids showed a progressive hearing loss over the years.

At this point in time, Max's language development, especially the development of expressive vocabulary, is age adequate. However, the ability of adapting and interpreting certain morphological principles (markings of plural or verb conjugations) appears slightly below the age related standards.

This past summer Max entered primary school, where he is supported by a teacher from the school for the hearing impaired once a week. His teachers are well-informed about his hearing impairment and the use of hearing aids and wireless communication devices implemented in the classroom. They report that Max is doing well and meets the requirements of the curriculum.

Following his last audiological test, it was stated that the average hearing loss had increased up to approx. 75 dB. The unaided hearing threshold in the last audiogram decreased from 55 dB HL at 250 Hz down to 90 dB HL at 8 kHz. In the current aided speech audiogram with his Phonak Naída III UP hearing aids, Max could understand 0% of the words presented at 50 dB, 50% at 65 dB and 70% at 80 dB (binaural test). This is a decrease since the last test six months ago.

Within the decision-making process for Anna's cochlear implantation, the parents asked if Max was becoming a candidate for an implantable hearing aid device, since his hearing loss was increasing, resulting in poorer speech perception results. However, they also wondered if this was the right time and if the step from hearing aid to a cochlear implant (CI) was necessary. Or, if better hearing was possible with new hearing aids or even a new hearing aid fitting.

This is just one example of an actual background behind the question, if a CI is the right technical hearing device for a child. These thoughts lead to the question of probable outcome in the development of understanding speech with a CI instead of a hearing aid. In the past 30 years of development in the field of cochlear implantation to aid children with hearing impairment, these questions have been repeatedly asked, but have not yet been answered with certainty.

1.1 MOTIVATION: PERSPECTIVE FROM DAILY PROFESSIONAL ROUTINE

The diagnosis "hearing impaired child" can raise questions as well as fears in parents. They are confronted with medical information and different options, and have to make a decision at the end.

After the diagnosis, an immediate first hearing aid fitting is recommended to offer optimal auditory access to spoken language as soon and as long as possible. While closely watching the auditory gain, specifically a child's listening and speech development, sufficiency of the hearing aid provision needs to be discussed and closely monitored. In cases of insufficient auditory gain, the result of a profound or progressive hearing impairment, a CI can be presented as a medical hearing aid device. The parents' decision process ends with a decision for or against an implantation surgery for this specific hearing aid device.

While choosing an optimal hearing device, such as a CI or hearing aid, questions about probable long-term outcomes in terms of auditory speech, perception skills, and spoken language development are raised. In this estimation, many aspects are to be factored in. The question, what kind of device should be chosen to allow a young child best auditory access to spoken language, is difficult to answer in many cases. The selection criteria differ not only from country to country, but sometimes from clinic to clinic.

One goal of the hearing evaluation of auditory rehabilitation devices (hEARd) project was to collect and interpret data on the auditory speech perception skills in children with hearing impairment, using acoustically or electrically stimulating hearing devices.

The concept of assessing and comparing results of children using hearing aids and children using CIs in a standardized way evolved from the equivalent hearing loss (EHL) concept of the 1990s.

1.2 OVERVIEW

In this dissertation, results of the hEARd project have been provided as normative data, which can be used as a measure of efficacy of the different types of hearing devices at different levels of auditory speech perception skills.

Following a brief look into the development of hearing aids and CIs in the past 30 years, the state of the art in the project's participating countries is presented in **Chapter 2** as in terms of selection criteria on hearing device provision.

Chapter 3 deals with the presentation and discussion of available speech tests in pediatric audiology. This project also uses the Adaptive Auditory Speech Test (AAST) as an intra-European test for speech audiometry.

The development of the hEARd project and its study design are introduced in the process (**Chapter 4**). It focuses on the included subtests as part of the Battery for the Evaluation of Language and Listening Skills (BELLS). BELLS is a test battery capturing the developmental state of auditory (speech) perception skills in children with hearing aids and CIs.

Research questions, formulated at the beginning of the project (**Chapter 5**), are answered on the basis of data collected from the hEARd project. Analyses are presented in **Chapter 6**, followed by their evaluation in **Chapter 7**.

Further questions which have sprung up in the course of the project have resulted in the development of new speech test material for pediatric use. The design and development of the Word Recognition in Sentences Test (WRIST) is documented in **Chapter 8**, including the results of preliminary data collection.

While concluding this dissertation in **Chapters 9** and **10**, project outcomes and their controversial aspects are discussed in the context of recent scientific discourse and possible consequences for educational and therapeutic practice.

1.3 ORIGINAL AIM OF EHL STUDY IN THE 90S

In the early 1990s, results in the development of auditory speech perception skills of the profoundly hearing impaired and deaf children using CIs seemed remarkable in some cases. Even age appropriate spoken language development could be reported, but due to the broad spectrum of influential factors, the performances were hardly comparable (Snik et al., 1997b).

In 1997, the research group around Snik in Nijmegen presented results of a comparison between performances in auditory speech perception of children using CI and performances of hearing impaired children using hearing aids. A standardized assessment procedure was developed to document the long-term hearing development of children with CI.

The performances of children with hearing aids having different degrees of hearing loss formed the basis of the comparison. Within the assessment battery, speech perception was to be measured at different levels of difficulty and complexity (Snik et al., 1997a). It started at a basic level with closed-set discrimination tasks, including meaningful words of different lengths, and the same task with nonsense words. This was followed by closed-set word identification tasks at different levels of difficulty (different word lengths; same word length). At the highest level, the test battery included an open set word recognition test. Listed according to increasing difficulty, three scores were obtained from the test battery: basal speech perception score, word identification score, and open set speech recognition score.

Performances were summarized to a percentage value (percent correct) for each score. For the hearing aid group, a correlation between performance level and degree of hearing loss could be shown. Lower the hearing loss, the better the percentage value. In Figure 1, regression curves between the three score categories and hearing loss of hearing aid users are shown.

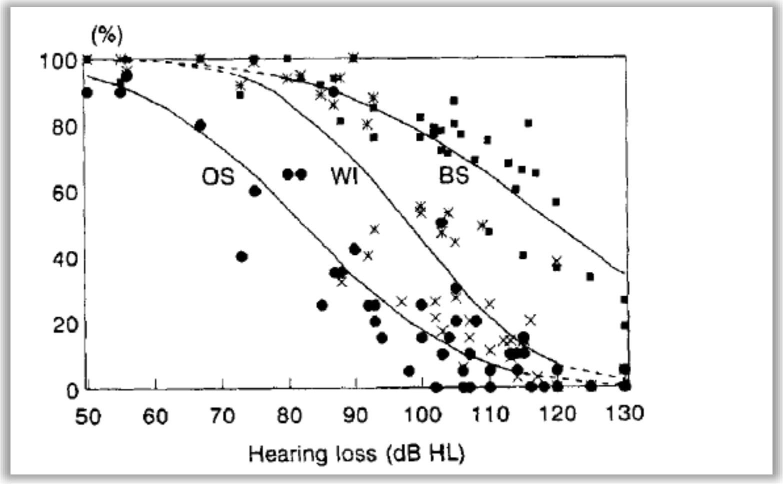

Figure 1:EHL scores (Snik et al., 1997a)

For these three scores an equivalent hearing loss score could be derived. Based on the performance of hearing aid users with unaided hearing loss between 50 dB and 130 dB, an expected performance value for auditory speech perception tasks was available, based on PTA data. This correlation could also be interpreted backwards; the scores achieved in the speech based test battery could give an estimate of the level of hearing loss that enabled a child using hearing aids to perform comparably.

This also allowed the interpretation of the speech perception performance of CI users to equal the abilities of hearing aid users. As the CI user's performance was also tested using the same standards, the performances of these two groups could be compared. Beyond this comparison, a normative value for hearing aid users was established, allowing an interpretation of performance within a group of comparable hearing losses, instead of a typical comparison with the performance of normal hearing children.

1.4 HEARD PROJECT

The main question, forming the basis of the hEARd project, was how children using CIs are performing in terms of auditory perception and processing of speech today, after approximately 30 years of technical and medical development, and increasing numbers of cochlear implantations. Kral and O'Donoghue speak of 80,000 implantations in children worldwide in an article published in October 2010 (Kral & O'Donoghue, 2010).

The question of a cochlear implantation versus an ongoing hearing aid provision depends on the probable "better" speech perception outcome with the CI as for example mentioned in the AWMF guidelines in Germany. To estimate this outcome, a comparison between children with hearing aids and children with CIs seemed reasonable. Since the level of hearing impairment is one of the most influential factors in the decision process, the degree of hearing loss was to be taken into account in the comparison of performances.

The concept of the described EHL project offered an evaluation of performances as well as a comparison regarding the degrees of hearing loss. The design of the previous EHL concept was to be reinvestigated in today's clientele of pediatric users of hearing devices. A cross-lingual, intra-European design of data assessment was chosen to addresses the problem of low prevalence of hearing impairment within countries with lower population, therefore affecting results of nationwide research. To accumulate an intra-European recent evidence-based data collective, language differences in European member states and different test materials and procedures had to be overcome by the right choice of test material in the project.

Besides the comparison of performances of children using different types of technical hearing aid devices, the collected data was to be used as a recent normative value to interpret performances within groups of children with similar hearing losses. Therefore, a test battery was to be designed which would allow an evaluation of any child's performance in speech perception abilities with its specific hearing aid.

Regarding future technical and medical advances, another criterion in the development of a test battery was the potential of re-testing the auditory speech perception skills of a new/ the next generation of children using CIs and hearing aids. For example in Germany, the recently implemented newborn hearing screening is an influential factor, so is the re-testing of the same cohort at a different age.

These thoughts and questions were combined in the research topics that were officially addressed in the "hearing evaluation of auditory rehabilitation devices project"[2] (Coninx & Vermeulen, 2012).

[2] Official Project name: Development of an intra-European Auditory Speech Perception standard for hearing impaired subjects with conventional/digital hearing instruments, hybrid devices or CIs

This dissertation discusses the above mentioned points of research, using the data collected within the project.

The project's time frame stretched from the beginning of 2011 until August 2013. Data collection for the here presented analyses started in 2012 and proceeded until 2014.

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2. ADVANCES IN TECHNICAL HEARING DEVICES

2.1 CI SYSTEMS - THEN AND NOW

First, CI systems were used as implantable hearing aids in deaf individuals who did not benefit from acoustically amplifying devices, such as conventional hearing aids to perceive hearing impressions. The devices were developed, following the example of the natural effect of the inner ear, more specific, the hair cells, transforming an acoustical signal into electrical impulses, to stimulate the fibers of the auditory nerve and thereby sending a signal up the central auditory system, creating a hearing impression (Lenarz, 2008).

CI systems skip the described natural hearing processes up to the inner ear and conduct electrical impulses in the cochlear to directly reach the hearing nerve fibers converging in the modiolus of the cochlear (Lenarz, 2008; Kral & O'Donoghue, 2010; Wilson & Dorman, 2008).

As a new type of hearing aid device for deaf people in the late 1970s and early 1980s, the use of the first CIs system was set at a very basic level:

> *"The device provides auditory stimulation to individuals with hearing disorder and helps in* ***identifying environmental sounds such as the ringing of the phone****."*

(Tobin, 1976)

> *"Last month, the Food and Drug Administration (FDA) approved the implantation of an electronic device that simulates the cochlea's transforming function and may enable 60,000 to 200,000 profoundly deaf adults in the United States* ***to hear sounds such as sirens and automobile horns"***

(Benowitz, 1984)

Looking at the different functions of hearing described by Richtberg (1980), a CI at that point could enable a deaf person to regain the “alarming” and “orientation” functions of hearing. However, Burian mentions in his report on first experiences with CI in 1979 that he expects a quick development, hopefully soon enabling speech recognition with new developments in CI research (Burian, 1979). The communication function of hearing, set as a goal in cochlear implantation, was reached in a few cases. Banfai. for example, mentions a development towards open set speech recognition in 20% of the observed cases up to 1984 (Banfai et al., 1984).

From early developmental research in the 1960s and 1970s to the first commercial implantations in the 1980s, CIs still were not a common hearing aid device in the early 1990s, but at the same time not rare anymore (Souliere et al., 1994). The first pediatric patient being implanted with a Nucleus CI system, received the device in 1987 (Cochlear Ltd., 2016b). By 1992, 5,000 people had been implanted worldwide with a NUCLEUS CI system by today’s Australian company Cochlear (Cochlear Ltd., 2016c). O’Donoghue remarks that in 2000, about 10,000 children had been fitted with CIs worldwide (O'Donoghue et al., 2000).

In the Netherlands, the numbers of implantations are reported by the CI centers to the independent platform Onafhankelijk Platform Cochleaire Implantatie (OPCI) annually. In 2014, 177 children and 364 adults were reported to have been implanted in the Netherlands (Onafhankelijk Platform Cochleaire Implantatie, 2016a). The platform refers to an overall number of 1,855 implantations in children and 4,098 implantations in adults up to and including the year 2014 (Onafhankelijk Platform Cochleaire Implantatie, 2016b).

In this paper, the focus is on today’s two most prominent companies distributing CI systems worldwide. This decision is based on numbers published by Ingeborg Hochmair in September 2013 on the official MedEl homepage, presenting Cochlear with 26,674 sold systems and MedEl with 14,027 systems in between June 30, 2012 and June 30, 2013 (Hochmair-Desoyer, 2013). Other companies are “Advanced Bionics, owned by Sonova, Switzerland; Neurelec, owned by William Demant, Denmark; Nurotron, China; and other minor activities” (cf. ibid.).

First multi-channel devices:

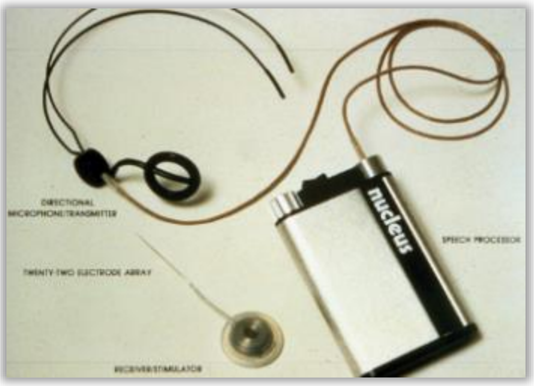

Figure 2: First FDA approved NUCLEUS Cochlear Implant System of 1985 for commercial use (Cochlear Ltd., 2016a)

Figure 3: MEDEL Cochlear Implant System of 1982 (MED−EL Elektromedizinische Geräte Gesellschaft m.b.H., 2016a)

Devices seen within the hEARd project:

Figure 4: Nucleus 5 system of 2009 by COCHLEAR (Cochlear Ltd., 2016d)

Figure 5: Maestro system of 2010 by MEDEL (MED−EL Elektromedizinische Geräte Gesellschaft m.b.H., 2016c)

Devices in 2016:

Figure 6: Nucleus 6 system of 2013 by COCHLEAR (Cochlear Ltd., 2016e)

Figure 7: Synchrony system of 2014 by MEDEL (MED−EL Elektromedizinische Geräte Gesellschaft m.b.H., 2014)

Looking at the first CI systems from the early 1980s in Figure 2 and Figure 3 and comparing them to the frequently seen devices within the hEARd project seen in Figure 4 and Figure 5, as well as the newest systems available in 2016 seen in Figure 6: Nucleus 6 system of 2013 by COCHLEAR and Figure 7, the technical progress is obvious. The very basic function of CI systems, however, has not changed. The system contains of two main parts - the implant itself and the speech processor, which is worn externally today mostly behind the ear (see Figure 8).

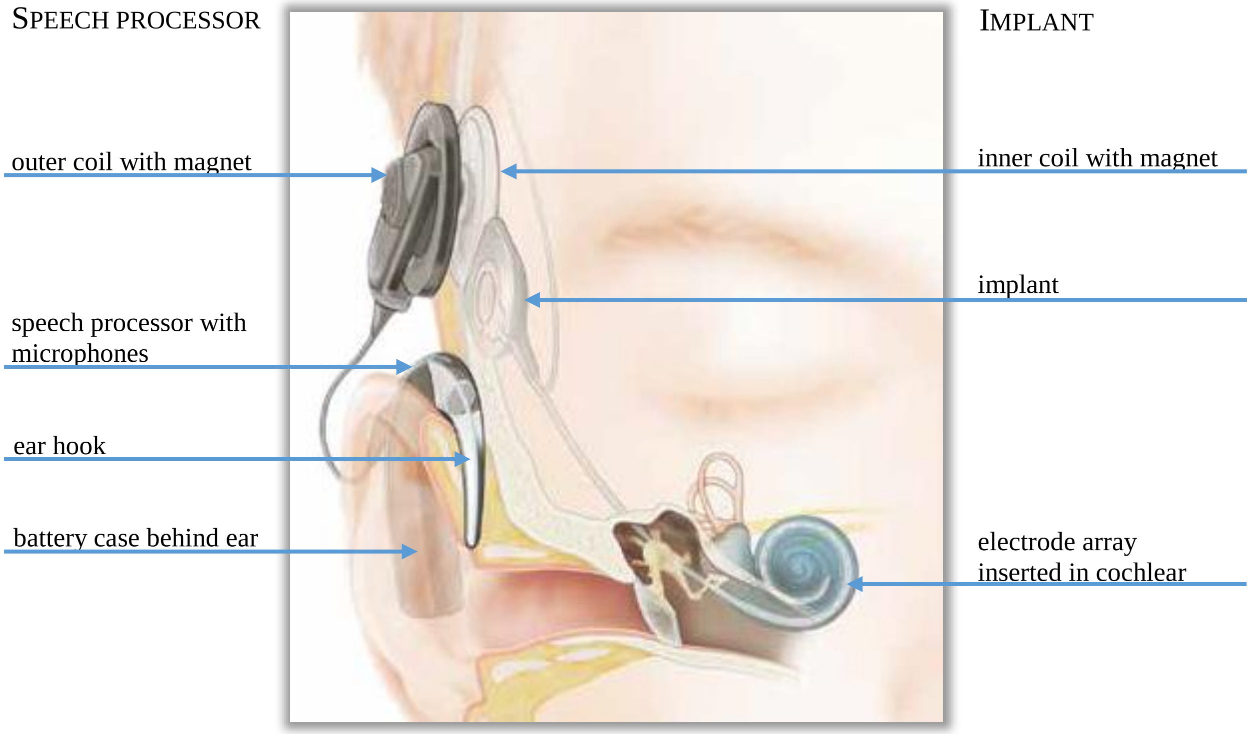

Figure 8: Illustration of CI system (Cochlear Ltd., 2014b)

Starting with the speech processor, the acoustical signal is captured by the microphone(s) and then digitalized. The digital signal is transformed into electrical signals, which carry temporal- and frequency-based aspects, as well as the intensity of the initial acoustical signal following specific coding strategies. This signal is transferred to the implant via inductive transmission, from the outer coil that is connected to the processor via cable to the inner coil of the implant (Hochmair & Hochmair-Desoyer, 1981). The electrical signal is then decoded and transformed into electrical pulse patterns. These patterns initiate the activation of electrical stimulation by the implant's electrodes allowing the direct stimulation of the auditory nerve fibers and ultimately creating a hearing impression (Stark & Helbig, 2011).

Each electrode stimulates a fixed part in the tonotopically organized cochlear (Banfai et al., 1984). Direct stimulation especially in the basal areas of the cochlear leads to hearing impressions in the high frequency sound range (Wilson & Dorman, 2008).

Stimulation through amplification devices in this frequency range was hardly possible at the time of the first CI systems (Levitt, 1987) and still is a great challenge in today's hearing aid technology (see Chapter 2.2). To create highly differential hearing impressions, the assumption seems reasonable that a higher number of electrodes mean better discrimination of sound frequencies. Over the years, the increase of electrodes has reached a limitation due to overlapping stimulation within the cochlear (Wilson & Dorman, 2008; Lenarz, 2008).

THE IMPLANT: The basis of the device is the array of electrodes that are surgically inserted into the cochlear's scala tympani, part of the actual implant. The electrode arrays in the above shown models from the 1980s differ from the presented, commonly used implants in Figure 5 and Figure 7 in diameter and in the number of electrodes. Comparing the above shown Nucleus implants, the number of electrodes is consistent. The diameter of the electrode array decreased to 0.6 mm – 0.3 mm in the CI422 implant with slim straight electrode (Cochlear Ltd., 2014a). The CI 512 implant itself is as thin as 3.9 mm (Cochlear Ltd., 2009).

Depending on the condition of the cochlear to be implanted as well as a surgeon's preference, amongst other factors, today the actual electrode for a patient can be chosen out of a variety. Cochlear, for example, offers four different types of electrode arrays (Cochlear Ltd., 2013).

THE SPEECH PROCESSOR: Processors of today's so called "digital age" are managing these same processes as did the first ones. However, the necessary equipment has shrunk in size. At the same time, it provides additional options to process the initial acoustical signal, comparable to features like "noise reduction", "focus setting" and other settings that are also found in today's hearing aid technology (Vaerenberg et al., 2014; Stark & Helbig, 2011). The newest generation of speech processors enables the user to connect wireless accessories directly to the speech processor in an often more stable and differential way than the long established transmission via the telecoil (Cochlear Ltd., 2016f) with its unique set of problems (Levitt, 2007).

The course of stimulation through the electrodes in the cochlear is, as mentioned above, derived from the initial acoustical input that is analyzed and processed by the speech processor. The coding of acoustical speech signals by the speech processor as well as the transformation into electrical pulses has improved over the years. Today, more than one type of speech coding strategy can be used for an implant system, with specific strategies per company (Vaerenberg et al., 2014).

OUTCOME - THEN AND NOW

Burian describes in his overview of "clinical observations in electrical stimulation of the ear" his 1979 experiences of deaf patients using CI with one-channel electrodes. An improvement of understanding speech through lip-reading was described by the patients. However, in cases of implanted single-channel electrodes by the Vienna research group, the implant system did not enable the patients to understand spoken language through strict auditory stimulation (Burian, 1979).

Improvements were achieved in the development and use of multi-channel electrodes. One of the first MedEl implant system recipients from 1979 using a multi-channel electrode was even able to understand words and sentences without any visual cues in 1980 (Hochmair Desoyer et al., 1980).

Looking at the descriptions from the first group of implanted individuals in the 1980s, using MedEl CI systems, their hearing impressions are diverse. Tests of speech recognition showed extremely different results (see Figure 9) which were often non-reproducible.

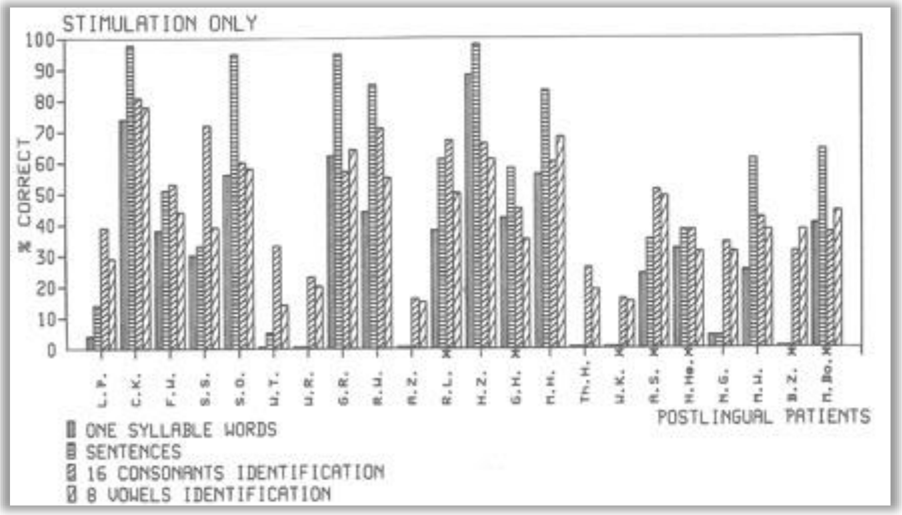

Figure 9: Speech reception in first MEDEL CI recipients in 1985 (MED−EL Elektromedizinische Geräte Gesellschaft m.b.H., 2016b)

A good 30 years later, patients visiting CI centers, as part of their daily routine, show how the development of auditory speech perception skills in deaf children has changed over time.

There are children who have had an implantation within their first two years of life, who visit a regular primary school, perceive spoken language in classes with more than 20 students and show age appropriate literacy development.

There are young children in kindergarten, who react to spoken language in acoustically challenging situations, locate speakers, and noises from any place in a room and develop spoken language almost at the same pace as their peers.

And, there are teenagers participating in sports, understanding instructions from a distance, listening to music in their free time, and talking to their friends on the phone like any other boy or girl their age.

It is difficult or impossible to predict the exact outcome and auditory development after cochlear implantation for each individual, as it is hardly ever possible to predict a child's development in general, but auditory perception of speech with a CI system is a realistic goal in many cases today.

2.2 HEARING AID SYSTEMS - THEN AND NOW

Figure 10: Oticon Digi Focus Compact from 1996 (Bauman, 2015)

Looking at the quite similar hearing aids appearing behind the ear, which had been released for commercial use within the past decades (see Figure 10, Figure 11, Figure 12, Figure 13), several milestones in development should be mentioned.

The basic function of a microphone perceiving an acoustical input, the hearing aid amplifying this signal, and finally the output of the amplified acoustical signal through a loudspeaker/receiver into the ear canal has not changed. In this very rough description, the main difference between hearing with a CI and hearing with a hearing aid becomes clear:

While the implant system converts an acoustical signal into an electrical one, the hearing aid simply "manipulates" an acoustical signal, input and output remain equal in terms of mode (acoustic).

ANALOG HEARING AIDS: Commercially distributed conventional hearing aids from the 1980s used the analog technology of signal processing. In cases of analog signal, the acoustical signal is captured by a microphone, transformed into electrical voltage, filtered, and amplified via electrical processing (electrical circuit elements only). The amplified signal is again transformed into an acoustical signal, which is delivered by a small loudspeaker into the ear canal (Marangos & Schipper, 1999).

The fitting to specific and individual needs can only be reached in a very basic way.

DIGITALLY PROGRAMMABLE HEARING AIDS: An important step towards fully digital hearing aids was the development of digitally programmable hearing aids that still use analog technology, but a more complex amplification system. These hearing aids contain a digital controller that operates the amplification system. This controller is programmed digitally by an external computer software. This option became more important as multi-channel hearing aids became available. After the initial conversion and amplification, the signal is "split" into frequency bands by the use of multiple filters (number of channels is based on number of filters and differs in between hearing aids). For each filtered signal, a specific fitting is possible, addressing frequency specific fitting that match an individual's hearing loss (Marangos & Schipper, 1999).

The first commercially available hearing aids of this type became available by the end of the 1980s (Levitt, 1987; Marangos & Schipper, 1999). These contain a memory system which permits the saving of different settings that can be programmed by the external software.

FULLY DIGITAL HEARING AIDS: The first fully digital hearing aids became available in the 1990s. Levitt mentions Widex Senso (available in 1996) and Oticon DigiFocus as the first commercially successful fully digital hearing aids.

The opportunity of digital sound processing (DSP) allowed the development of specific signal processing strategies addressing several problems that until then could not have been removed in a satisfying manner with analog technology. This included the cancellation of feedback especially in cases of high amplification concerning high frequencies, the reduction of noise and a more specific and individual fitting meeting the needs of a patient – more accurate hearing thresholds and comfortable levels throughout the frequency spectrum (Levitt, 2007; Prinz et al., 2002; Valente et al., 1998; Kerckhoff et al., 2008). The advantages were reported by adults as well by children (Valente & Mispagel, 2008; Prinz et al., 2002).

In comparison to the analog system, in digital hearing aids the acoustical signal is captured by the microphone (or several microphones), initially amplified and then converted into a digital signal. The DSP takes place. Following the DSP, the digital signal is converted again back into an analog signal, which – after final amplification – is delivered via loudspeaker towards the ear canal. The digital manipulation of the initial signal allows even more specific fittings. More and more options of DSP strategies have been developed in the past 20 years. Starting with frequency specific amplification, non-linear frequency transposition became available as well as more distinct strategies of noise reduction or even options of wireless communication in between bilaterally worn hearing aids or in between hearing aids and additional technical hearing devices (Kerckhoff et al., 2008).

Figure 11: Phonak Naida III UP (© Phonak AG, 2009)

WITHIN THE HEARD PROJECT one of the most frequently seen digital hearing aids in children was the Phonak Naida hearing aid with the sound recovery option. Addressing the problem of amplification within high frequencies, Phonak developed a specific sound processing strategy called "soundrecover". With "soundrecover", the acoustical signal is analyzed and then follows a non-linear frequency transposition, to recreate the high frequency input in a lower frequency as a better perceivable output (Glista et al., 2009).

Figure 12: Oticon Sensei (Oticon GmbH, 2013)

Figure 13: Phonak Sky Q (© Phonak AG, 2013)

STATE OF THE ART high end digital hearing aids for children are for example the Phonak Sky or Oticon Sensei hearing aids. Besides the options of several features such as frequency transposition (Phonak) long available noise reduction, wireless options on connecting further equipment or binaural connections, this generation of hearing aids aims for a more distinct and clear amplification in higher frequencies. The goal is set to widen the frequency range that can be amplified in a clear way, preventing distortion. The Oticon Sensei BTE 90 hearing aid shows a possible amplification of almost 50 dB SPL in the area of 9500 Hz in ear simulator measurements, according to IEC 60118-0 (1983), 60711 (1981), and DIN 45605

(Oticon GmbH, 2013). The crucial factor of amplification in high frequencies is influenced in an improved way[3].

Like the above mentioned “soundrecover” feature of Phonak, hearing aid companies have developed more features that analyze the acoustical surrounding of the hearing aid user. This is possible in the unilateral use of a hearing aid, but offers even more complex options in the bilateral interaction of hearing aids. Sound signals are classified into useful sound or disturbing sound. Depending on the situation, the hearing aid systems can evaluate the most efficient way of reducing background noise while adjusting the spatial area of microphone perception. For example, at the dinner table with a communication partner sitting across from the hearing aid user, the hearing aid system could use a focus or zoom function through the directional microphones. In a classroom situation with speakers from all directions, an omnidirectional orientation would automatically be chosen by the hearing aid system (© Phonak AG, 2010).

The predictability of these automated settings is to be debated, however, features like automated reduction of noise is a standard sound processing strategy to be found in today’s digital hearing aids and is finding a way into the signal processing strategies of CI systems as well (MED−EL Elektromedizinische Geräte Gesellschaft m.b.H, 2014).

From an educational and therapeutic point of view, the use of the mentioned sound processing features in children needs to be discussed. This in terms of a possible prevention from natural learning processes within the hearing development vs. an optimized perception of speech, by the reduction of ambient noises, as a crucial factors in language development.

2.3 CI INDICATION TODAY

Today after 30 years of experience and ongoing research there is no strict international standard that could answer the questions of which patient has an indication for a CI today. There is no definite checklist that sums up to a yes or no decision. The final choice depends on several factors and individual circumstances. However, there are certain criteria that are known to have an influence on and are to be considered when trying to predict the outcome.

[3] Previous model Oticon Safari BTE Super Power 900 allowed possible amplification of approx. 50 dB SPL in the area of 6500 Hz in ear simulator measurements according to IEC 60118-0 (1983), 60711 (1981), and DIN 45605 Oticon GmbH (2016) ; Oticon GmbH (2016).

2.3.1 DEGREE OF HEARING LOSS/ HEARING IMPAIRMENT

One great point of reference for or against cochlear implantation is the degree of hearing loss/ impairment.

Based on a WHO report from 1991 (World Health Organization, 1991) on the prevention of deafness and hearing impairment, the grades of hearing impairment follow the classification presented in Table 1. The classification is based on hearing loss in the better ear, derived from the average of the audiometric ISO values of 500 Hz, 1 kHz, 2 kHz, and 4 kHz (Mathers et al., 2000).

pure tone average of 500 Hz, 1 kHz, 2 kHz, 4 kHz	grade of hearing impairment
<25 dB HL	no impairment
25–40 dB HL	mild impairment
41-60 dB HL	moderate impairment
61-80 dB HL	severe impairment
>80 dB HL	profound impairment

Table 1: Grades of hearing impairment

A profound impairment or deafness in the better ear is a strong indication for a CI (Kral & O'Donoghue, 2010).

2.3.2 PHYSICAL CONDITIONS AND ETIOLOGY OF HEARING LOSS

Primarily, a patient’s global physical condition must be stable to undergo the surgical procedure.

One of the requirements allowing a successful implantation is the condition of the cochlear itself. Malformations of the cochlear, for example, can complicate the insertion of the electrode array during surgery. However, a malformation or dysplasia of the cochlear is no contraindication per se and the post-operative speech perception can develop adequately (Buchman et al., 2004; Buchman et al., 2004; Sennaroglu, 2010; Miyamoto et al., 2005). In cases of cochlear ossification as well as dysfunction or even aplasia of the auditory nerve, only poor effects could be reported post cochlear implantation. Due to the probable poor outcome, it can be a surgeon’s decision to see these physical conditions as contraindicative for a cochlear implantation (Colletti et al., 2004).

2.3.3 INFLUENTIAL FACTORS

Besides the above mentioned conditions for or against cochlear implantation, there is more anamnestic information in adults and children that can be used as predictive factors for the outcome after implantation.

DURATION OF HEARING LOSS

As an important influencing factor, the duration of hearing loss must be taken into account. Research shows that speech recognition in post-lingual deafness develops better the sooner the implantation takes place. Different results in performance after cochlear implantation after progressive hearing losses can be explained by the duration of impaired speech perception prior to implantation (Peterson et al., 2010; Klop et al., 2007).

LEVEL OF SPOKEN LANGUAGE ACQUISITION AT THE TIME OF HEARING LOSS/ DEAFNESS (PRE-, PERI-, POST-LINGUAL)

It has been shown that the already achieved level of language acquisition has great impact on the auditory understanding of language via CI.

The goal of auditory understanding of spoken language after implantation has limitations after years of pre-lingual deafness (Kral, 2009; Peterson et al., 2010).

Different outcomes can be seen in adults being deaf over decades who completed auditory based spoken language development and those who never had auditory access to spoken language. The greater the knowledge of spoken language acquired through the auditory system before implantation, shown in results of pre-operative speech audiometry, the better the outcome after implantation (Klop et al., 2007).

EARLY INTERVENTION

Since the implementation of newborn hearing screenings in many European countries – including Flanders in 1998 (Raeve & Lichtert, 2012), Germany in 2009 (Brockow et al., 2014), Netherlands in 2006 (van der Ploeg, C. P. B. et al., 2012) – the diagnosis of a profound hearing loss or deafness is formed and verified within the first months of life (Matulat et al., 2014; Brockow et al., 2014; Brockow et al., 2014).

If there are no recognizable developmental stages of hearing or signs of initiating speech and language development through the use of hearing aids, a cochlear implantation is the method of choice to provide auditory access to spoken language (Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen, 2012). Several studies show that an early implantation has a significant impact in reaching an age appropriate development of hearing skills and spoken language abilities. This is in case of a child's regular global development and health.

Maturation of the auditory pathway and its sensitive periods have been analyzed to find the appropriate time of hearing aid provision and intervention. Sharma et al. (2011) found in their research "a sensitive period for optimal central auditory development of about 3.5 years in childhood" (Sharma & Campbell, 2011), which is comparable to the findings of (Kral, 2009).

The sooner spoken language is perceived through the auditory system, the better. The higher the acoustic quality of the perceived signal, the better it is. The effect of early intervention through early cochlear implantation can be shown for different levels of hearing development as well as different levels of language development.

EARLY RECEPTIVE AND EXPRESSIVE LANGUAGE DEVELOPMENT: (Niparko et al., 2010) found for young children (under five years of age) that the receptive and expressive development of language (repeatedly analyzed at different times pre- and post-implantation with the Reynell Developmental Language Scales) presented itself in a correlation to the age of cochlear implantation, with a better development corresponding to a younger age of implantation.

RECEPTIVE AND EXPRESSIVE VOCABULARY: Several studies show a correlation between the receptive vocabulary score determined with the Peabody Picture Vocabulary test (Dunn & Dunn, 2007) and the age of implantation. In the studies, a cochlear implantation before the second birthday led to a better test result in comparison to results of the later implanted group of children (Connor et al., 2006; Hayes et al., 2009; Percy-Smith et al., 2013; Streicher, 2011).

The analysis of expressive vocabulary (Boons et al., 2012) found that children who received a CI before their second birthday performed significantly better than children of an older implantation age.

PHONOLOGICAL DEVELOPMENT: Within their German study (Kral et al., 2014) found that children implanted within the first year of life showed a development closest to the phonological development of normal hearing children.

GRAMMAR: (Nikolopoulos et al., 2004) found a correlation between better grammar comprehension and early cochlear implantation.

In a study by (Nittrouer et al., 2014) the appearance of certain morphological and syntactical features was examined in speech samples of cochlear implanted children. The variance in outcomes within this group could be explained at a significant level by the age of implantation. The difficulties in morpho-syntactical development of hearing impaired children even in cases of mild to severe hearing impairment is emphasized in a recently presented study by Tomblin et al. as well (Tomblin et al., 2015).

READING SKILLS: Several authors conducting international research in the U.S. (Fagan et al., 2007), in the Netherlands (Vermeulen et al., 2007), in Germany (Streicher, 2011) and the UK (Archbold et al., 2008; Johnson & Goswami, 2010) found results in testing (comprehensive) reading skills in groups of children using CIs. The results showed a correspondence between early implantation (i.e. Fagan mentioning a mean of around 2.5 years) for significantly better performance.

This is only an excerpt of available results from research focusing on the correlation between early intervention in terms of early cochlear implantation for the group of (congenitally) profoundly hearing impaired children and their spoken language development.

Intervention before the second birthday in comparison to later intervention often showed significant differences that led to better performance of children implanted at an early age.

However, using an implant is more risky than using a hearing aid and the question can be raised, how early is early enough for implantation. In determining an exact time frame for cochlear implantation to achieve the most beneficial outcome in terms of spoken language development, some studies show that there seems to be no significant difference within age groups of children who had been implanted before their second birthday (Boons et al., 2013; Connor et al., 2006). Others find a significant difference in language development at approximately kindergarten age in between groups of children implanted in their first year of life and children implanted in their second year of life. However, the limitation of earlier implantation is set by the necessity of a certain diagnosis of the level of hearing impairment (Nicholas & Geers, 2013).

Other factors such as the residual hearing before implantation (Nicholas & Geers, 2006) as well as the socio-economic status of the parents, educational background of the mother, and multilingual upbringing (other spoken language in the family than test language or sign language instead of spoken language) seem to have a strong impact on the spoken language development in *early* implanted children as well (Nicholas & Geers, 2013; Boons et al., 2013).

2.3.4 INDICATION CRITERIA, COSTS AND COVERAGE BY HEALTH INSURANCE – STATE OF THE ART IN PARTICIPATING EUROPEAN COUNTRIES

BELGIUM

In 2013, Leo De Raeve and Annelies Wouters summarized the accessibility to CIs in Belgium at the time. The cost of one cochlear implantation is covered by the Belgian National Institute for Health and Disability Insurance (referred to the Belgisch Staatsblad 1994 by (Raeve & Wouters, 2013). Indication criteria include a bilateral hearing loss of at least 85 dB at 500 Hz, 1 kHz, and 2 kHz, an auditory evoked brainstem response at peak V no sooner than at 90 dB HL and also an insufficient benefit using hearing aids. In cases of post-lingual deafness, the result of a monosyllabic speech test is also taken into account with the restriction of a phoneme score of 30% or less at 70 dB (referred to the Belgisch Staatsblad 2006 by (Raeve & Wouters, 2013). Bilateral implantation is only covered for children below the age of 12, in cases of auditory neuropathy or meningitis with ossification. The insurance coverage for a second CI extends up to the age of 18 (referred to the Belgisch Staatsblad 2010 by (Raeve & Wouters, 2013). The cost for the implemented multidisciplinary rehabilitation following an implantation in Belgium is covered by health insurance up to the age of 18. Adults have a financially covered access of two years for multidisciplinary rehabilitation (or monodisciplinary therapy as speech or auditory therapy).

GERMANY

In Germany, indication criteria concerning cochlear implantation have been summarized by the "Deutsche Gesellschaft für Hals- Nasen- Ohren- Heilkunde, Kopf- und Hals-Chirurgie e. V." in a guideline with multidisciplinary participation of the "Deutsche Gesellschaft für Phoniatrie und Pädaudiologie e.V.", "Deutsche Gesellschaft für Audiologie", "Deutsche Gesellschaft für Neuroradiologie", as well as the "Berufsverband Deutscher Hörgeschädigtenpädagogen" and the "Deutsche Cochlear Implant Gesellschaft e.V.".

The updated guideline from 2012 recommends that there is in principle an indication of CI for adults and children with a post-lingual acquired profound hearing loss or deafness. In cases of pre-lingual acquired profound hearing loss or deafness in adults, an implantation is only recommended in certain cases. For children with a pre-lingual or peri-lingual acquired profound hearing loss or deafness, an implantation is recommended as early as possible. The implantation for children with residual hearing begins with a hearing aid fitting and a close observation of the child's auditory development with it.

The final indication is presented by the surgeon, but is formed by multidisciplinary diagnostic results and analysis of the anamnestic information.

If there is an indication for both ears, a bilateral implantation is possible (Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen, 2012).

Cases of unilateral profound hearing impairment or deafness are not a contraindication (Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen, 2012).

Zahnert and Schulze mention rough audiometric guidelines to evaluate a hearing loss for a possible indication. If in a fixed level word test (usually the Freiburger Einsilber for German adults) only 30% (or in certain cases less than 50%) of the speech material is identified correctly despite optimal hearing aid provision, it can be interpreted as a sign for cochlear implantation. No perception in a pure tone audiogram below 50 dB using optimal hearing aid provision can be seen as an influencing factor as well.

In infants and toddlers, objective audiometry has to be used and interpreted. No response in BERA measurements of 1 kHz and higher frequencies below 90 dB can be seen as a strong indicator for CI (Zahnert & Schulze, 2009).

The German statutory health insurance covers, beside the costs of the actual CI system, costs of the pre-operative diagnostic procedures, the implantation surgery, the hospital stay, and the post-operative rehabilitation program. A CI is categorized as a medical device, specifically an "active implantable medical device". Hearing aids, on the other hand, are categorized as medical aids that follow different restrictions in reimbursement and financing by the SHI companies.

NETHERLANDS

Indication criteria in the Netherlands for a first CI are comparable to those in Germany. A hearing loss of 80 dB and higher as well as results of less than 50% correct responses in speech audiometry are mentioned as rough guidelines for a CI (Onafhankelijk Platform Cochleaire Implantatie, 2016c).

The final decision is made by a surgeon from a multidisciplinary team in one of the eight ENT clinics with a CI-team (Onafhankelijk Platform Cochleaire Implantatie, 2016c).

Health insurance in the Netherlands covers the cost of the first CI. In cases of deafness due to meningitis, a second implant is also covered. Since 2012, bilateral implantation is financed in cases of pre-lingual deafness for children up to the age of five (van Eijndhoven et al., 2012), in some cases for children up to the age of 18. Also, exceptions in financial coverage of a second CI are sometimes made in cases of deaf-blindness.

Battery supply is not included.

An annual check-up at the implanting clinic is mentioned as necessary.

2.4 HEARING AID INDICATION TODAY

2.4.1 BELGIUM

Reimbursement of hearing aid devices by Belgian health insurance companies is handled in individual ways. However, guidelines are formulated in the nomenclature of the Rijksinstituut voor ziekte- en invaliditeitsverzekering RIZIV (Rijksinstituut voor ziekte- en invaliditeitsverzekering RIZIV, 2015b).

Bilateral hearing aid provision can be reimbursed in cases of at least 40 dB in for an average hearing loss over the frequencies of 1, 2, and 4 kHz in each ear.

When using a hearing aid, the result in speech audiometry testing in quiet should show a gain of 5 dB in SRT measurements (threshold at which 50% of the speech material is identified correctly) or the intelligibility of speech material at a fixed level of intensity has to be improved by 5%.

In a test for auditory localization, binaural hearing aid use should show an improved result of at least 10% or 10° (depending on the test).

A new hearing aid prescription can be given after three years for children and five years for adults.

Several exceptions are listed within the nomenclature addressing cases of hearing losses of less than 40 dB, as well as new hearing aid provision sooner than the above mentioned time frames. Consideration of results for tests of speech perception in noise are mentioned amongst other exception guidelines (Rijksinstituut voor ziekte- en invaliditeitsverzekering RIZIV, 2015b).

The choice of an adequate hearing aid is based on the evaluation of a standardized questionnaire, the Client Oriented Scale of Improvement (COSI) – vragenlijst (Rijksinstituut voor ziekte- en invaliditeitsverzekering RIZIV, 2015a), amongst other anamnestic and diagnostic data.

A strict protocol for the process of hearing aid provision is to be followed, describing the functional responsibilities of ENT doctors and hearing aid acousticians/ dispensers.

Reimbursement values differ depending on unilateral or bilateral provisions, but also depending on the patient's age:

- 1136,11 € reimbursement for unilateral provision in children under the age of 18
- 2250,37 € reimbursement for bilateral provision in children under the age of 18
- 666,00 € reimbursement for unilateral provision in adults over the age of 18
- 1318,27 € reimbursement for bilateral provision in adults over the age of 18

An ear mold is included as well as regular maintenance of the hearing aid and a two year warranty. Battery supply is not covered (Prijzenobservatorium - Instituut voor de Nationale Rekeningen, 2014).

2.4.2 GERMANY

In Germany, the criteria that have to be met for the prescription of a hearing aid are summarized in the German guidelines on aiding devices. Reimbursement by the SHI companies is handled in diverse ways. However, the Gemeinsamer Bundesausschuss formulated a new resolution on the matter in 2012, last adapted in 2015 (Gemeinsamer Bundesausschuss, 2015).

Bilateral hearing aid provision should be reimbursed in cases of a hearing loss of at least 30 dB in the better ear for at least one frequency in between 500 Hz and 4 kHz. In addition, the unaided result of speech audiometry testing in quiet should not be higher than 80% at a fixed level of intensity of 65 dB.

Using a hearing aid, the result in speech audiometry testing in quiet should improve by 20 percent points. Binaural hearing aid use should show an improved result of at least 2 dB, signal to noise ratio, for speech audiometry testing in noise.

Unilateral hearing aid provision in cases of unilateral hearing losses should be reimbursed in cases of a hearing loss of at least 30 dB in the poorer ear for at least one frequency in between 500 Hz and 4 kHz. In addition, the unaided result of speech audiometry testing in quiet should not be higher than 80% at a fixed level of intensity of 65 dB.

Using a hearing aid, the result in speech audiometry testing in quiet should improve by 20 percent points, masking needs to be used in the contralateral ear. Binaural testing with the hearing aid should show an improved result of at least 2 dB, signal to noise ratio, for speech audiometry testing in noise with a special test set up.

A new hearing aid prescription can be given after five years for children and six years for adults.

For children, age specific test material should be used for speech audiometry. If participation in the audiometric procedure (pure tone and speech audiometry) is not possible due to age or development, an objective procedure should be chosen. In specific cases, hearing aids can be reimbursed for children with hearing losses below the above mentioned thresholds, if speech perception in noise is severely limited.

The process of adequate hearing aid devices in children as well as regular monitoring of their auditory development is to be accompanied by a pediatric audiological institution.

The association of German SHI formulated new contribution values for reimbursement of hearing aids in adults:

- In treating profound hearing impairment 786,86€ for the first hearing aid, an additional 629,49€ for the second one, in cases of binaural treatment (GKV-Spitzenverband, 2012).
- In treating hearing impairment below the profound degree 733,59€ for the first hearing aid, an additional 586,87€ for the second one, in cases of binaural treatment (GKV-Spitzenverband, 2013).

Battery supply is not covered by the SHI. Partial reimbursement of ear moldings is covered separately. Based on these guidelines, health insurance companies have individual contracts with hearing aid distributing facilities. Therefore, the reimbursement of hearing aids for adults and a hearing aid's exact cost varies and is depending on the health insurance company and the hearing aid dispenser.

Reimbursement for children is usually 100%, including battery supply and ear moldings (Beauftragte der Bundesregierung für die Belange behinderter Menschen, 2016).

2.4.3 NETHERLANDS

Similar to the German system, guidelines for hearing aid provision have been formulated by the National Health Care Institute of the Netherlands (Zorginstituut Nederland, 2016).

A hearing loss of 35 dB indicates hearing aid assessment. About 25% of the cost is to be covered by the hearing aid user, which includes the cost of ear moldings. However, the exact amount of reimbursement is dependent on the individual health insurance policy contract.

Before the initial step of determining the hearing loss by audiometric measurements, a questionnaire on the patient's needs and challenges is to be filled out. Based on the outcome, the best fit out of five existing categories of hearing aids is determined (category one – simple technology up to category five – complex technology). The use of the classification system has been reviewed by the University of Amsterdam (Brons & Dreschler, 2014) and the National Health Care Institute of the Netherlands (2015).The cost of a hearing aid from the determined category will be reimbursed according to the above mentioned criteria.

The choice of an adequate hearing aid provision in children as well as regular monitoring of auditory development is to be accompanied by an audiological center.

Starting January 2016, hearing aid provision for children up to the age of 18 is covered by health insurance without the patient having to pay part of it.

3. SPEECH AUDIOMETRY FOR INTRA-EUROPEAN USE

Perceiving speech through the auditory system is the basis of spoken language acquisition. An impaired hearing ability influences auditory speech perception. With speech audiometry, it is possible to see how well speech is perceived despite the impairment, for example with the use of certain hearing aid devices.

The use of speech audiometry compared to pure tone audiometry gives information on the auditory perception skills in a more meaningful context. The ability of understanding speech is often the most important goal in the process of providing a hearing aid device. In the context of evaluating the effectiveness of a hearing aid device, speech appears as a reliable variable of measurement (Gemeinsamer Bundesausschuss, 2015).

To compare auditory speech perception performances in children on an intra-European level, comparison on an interlingual level must be possible. The results of speech perception tests used in the participating countries are not necessarily comparable at a lingual level. Also, the way in which the test is implemented differs not only from country to country, but often from one institution to another. Some tests are carried out as open set tests, some use picture templates, some use different sets of age based and therefore often limited vocabulary, not to mention different extent of material or even level of language complexity, such as sentence or word material.

In this chapter, commonly used tests from the field of pediatric speech audiometry in Dutch/ Flemish (participation of institutions in the Netherlands and the region Flanders in Belgium) and German language have been summarized and evaluated as to their use in an interlingual context, mainly their comparability.

3.1 SPEECH MATERIAL

To choose the “right” speech material for speech audiometry, there should be clarity on what should be tested.

If speech audiometry is used to analyze the performance of understanding speech in daily life, a natural test situation seems reasonable. Sentences can be seen as a natural speech stimulus in comparison to single phonemes. In daily life, sentences and not phonemes or single words constitute speech.

If speech audiometry is used to show how well certain phonemes of a language are perceived using a specific hearing aid, a sentence test is not very different. Since the intelligibility of a sentence is influenced by many top down processes, such as language development and cognitive skills, it cannot be determined with certainty if the intelligibility is based on the top-down processes or the auditory perception of the input, the bottom-up process.

The task of correct identification of words with existing similar words such as “*Fall*” (“*Ball*”, “*Hall*”, “*All*”) is more sensitive to the perception skills on a phoneme level.

SPEECH MATERIAL IN TESTING CHILDREN

The decision to choose the “right” material for speech audiometry in children is not only strongly dependent on a child’s linguistic development, but also cognitive development, especially related to age.

Speech material in the available and later on described tests differs from the use of phonemes, monosyllables, digits, spondees or phrases up to the use of sentences.

The more complex the speech element, the higher will be the redundancy. The smaller the element, the lower will be the redundancy. A sentence, for example, offers a higher redundancy to a language than just a monosyllabic word. The intelligibility of different speech elements is connected to a child’s linguistic knowledge. This includes the language development on a phonological, semantical/ lexical as well as morphological/ syntactical level.

The influence on speech material of different levels of complexity is described in the following[4].

Single **phonemes** being the smallest meaningful element of a language, have the lowest redundancy. The task of identifying a single phoneme can only be supported by a top-down process of knowing and expecting phonemes that are available in a language. For example, the phoneme // is hardly represented in German.

The repetition of phonemes can be conditioned even in young children, for example using sounds of animals or objects that are of interest to a child and represent specific phonemes (/s/ matching a snake).

At the level of **syllables**, morphological rules that are characteristic of a language apply, allowing only specific phonological sequences in a morpheme. Two plosives, for example, do not follow one after the other in a German morpheme. Certain phonemes, such as voiceless and voiced plosives can be differentiated easier when presented in a consonant-vowel combination. Therefore, auditory presentation of phonemes in a syllabic pattern is preferred sometimes.

The redundancy increases when **words** are used. Even if a word consists of only one syllable, it has a semantical meaning. Using the existing word /tal/ and the pseudo word /pal/ as an example, the actual word has a higher intelligibility due to its semantical meaning. So, even if the first phoneme is not perceived correctly, the word can still be identified correctly.

The length of a word can increase its intelligibility, due to the decreasing number of existing words of a certain length.

When testing children picking up the example of "*Fall*", "*Ball*", "*Hall*", "*All*" for speech audiometry with words, the word "*Hall*" as in "echo" or "reverberation" is hardly part of a child's vocabulary before kindergarten. The meaning of the word "Ball", however, is known even by very young children[5]. In the set of the above mentioned words, the intelligibility can

[4] Examples will refer to German language.

[5] The word "*Ball*" is part of the German questionnaire ELFRA-1 Grimm & Doil (2006) that screens for irregularities in the early spoken language development around a child's first birthday.

hardly be seen as equal. This example illustrates a great difficulty in choosing appropriate speech material for children, due to the different development of vocabulary in each child.

Digits, as one specific group of words, offer a very high intelligibility due to the limitation of possibilities (only 10 digits in the metric system). An auditory identification task of digits can be performed by children even with limitations in the spoken language development (Wilson et al., 2008).

To avoid influencing a child's semantic/ lexical development, nonsense words can be used. However, the task of repeating **nonsense words** can be seen as a strange task to some children, especially young children. In using nonsense words in speech audiometry, the refusal of repetition can be seen as a risk, as well as the repetition of an existing word matching the presented nonsense word instead of the nonsense word itself (/bal/ instead of /pal/).

When **sentences** are used as a natural test material, the task can be as complex as the repetition of the whole sentence or be set at a lower level, asking for the repetition of just one word in the sentence. If a task requires the repetition of all words in a sentence, it is not only testing the auditory perception skills, but also auditory memory. Some tests use **phrases** of only a few words to keep the influence of auditory memory minimal.

The semantical context within a sentence can be used as a top-down process to fill a lack of auditory perception. The meaning of the word "car", for example, excludes certain verbs following it such as "loves" (which can be lexically grouped into "human behavior only") or "rains" (the verb "rain" has no valence including a subject except "it"). The influence of semantic/ lexical knowledge should be kept to a minimum in the sentence material to focus on the testing of auditory skills.

For phrases or sentences as test material, morphological and syntactical information increase the intelligibility as well. Knowledge of the syntactical patterns of a language provides information on the analysis of a sentence (example of the English strict subject-verb-object pattern). For example, the correspondence between a subject and a verb gives information on the morphological structure of the verb. This information can be obtained without fully perceiving all auditory information about the verb, especially the final phonemes. Presenting several phrases or sentences in the same syntactical pattern increases the intelligibility even more.

3.2 SPEECH RECOGNITION THRESHOLD

The American Speech-Language-Hearing Association (ASHA) defined a comparable value of measurement with the term SRT – speech recognition threshold (former speech reception threshold) as the "minimum hearing level for speech" that enables a person to recognize 50% of the presented speech test material. The recognition task is defined as a task of choosing one stimulus out of "a closed set of choices" (American Speech-Language-Hearing Association, 1988).

As a critical point in the evaluation of frequently used tests in speech audiometry, it can be seen that the task in a test itself often differs from actual recognition. The development of a person's vocabulary can influence the results of speech audiometric tests. For example, if only an auditory stimulus is presented and no reference frame is given, as in closed set tests that give many options to focus on. Therefore, the SRT value in some tests indicates the threshold at which a person "understands" 50% of the presented speech material instead of "recognizes" 50% of the material. In children, this factor is even more crucial due to language development, especially when looking at the complexity of the speech material. This aspect of language development, mainly the vocabulary, is addressed in the presented tests in different ways and will be mentioned in the description of each test.

CLOSED SET TESTS VERSUS OPEN SET TESTS:

In the context of "recognition" versus "understanding" the terms "closed set" tests and "open set" tests are commonly used (Brandy, 2001; Lyregaard, 1997). The recognition task in a closed set test can be solved easily since there is a limitation of possible responses, as well as a certain chance level. "Understanding" a speech stimulus with no additional information on the possible input in an open set test is more difficult. In cases of limited language development or a low hearing status, a closed set test might be more sensitive. This is because an open set would result in a bottom effect; the task is too difficult, all responses are incorrect, despite a possible improvement or decrease in the hearing status. In cases of normal language development and a good hearing status, an open set test might be more sensitive. This is because a closed set test would result in a ceiling effect; the task is too easy, all items are identified correctly, despite a possible improvement or decrease in the hearing status.

RESPONSE MODE:

One should also be aware of the fact that a difference in the task leads to a difference in the response mode as well. An example of a closed set recognition task would be the use of a picture template that requires only a pointing response from a child. In this type of setting, no verbal response is necessary, excluding responses marked as "wrong" by the test leader, due to a verbal response that might seem incorrect because of the child's deficits in the spoken language acquisition (expressive phonological development), but not because of his/her's hearing abilities.

3.3 SPEECH TESTS IN NOISE

Adults having a hearing impairment often express difficulties in hearing in a noisy environment. This "noise" could also be other speakers in a group.

To understand speech in noise, complex activities of auditory speech perception and processing are necessary. On the other hand, it is equally important to perceive even the smallest segments of a speech stimulus in noise. Not perceiving a certain group of phonemes, such as fricatives, for example, can exclude key information that is necessary for intelligibility and understanding (Kompis, 2004).

Looking at the surroundings in daily life, mostly there is a "noisy" environment of some kind, especially in a child's life. In speech audiometry, many tests focus on the perception abilities of speech in quiet. The results of a test in quiet are a very important factor in the evaluation of a hearing aid device. Health insurances in Germany, for example, use a comparison of a word test at a fixed level of intensity as an indication criterion for or against a specific hearing aid (Gemeinsamer Bundesausschuss, 2015). However, the performance in quiet does not necessarily mean that the performance in a noisy environment is equally good. Results of a speech audiometry test in noise give more information on the performance in daily life.

For children who acquired a hearing impairment pre- or perilingually, the aspect of perceiving speech in noise becomes even more crucial. Due to the still ongoing spoken language development, the quality of the input should be optimal. In noise this is not given. Therefore, a hearing device should always be evaluated for its actual aid in a noisy environment. In Germany's guidelines on aiding devices (Gemeinsamer Bundesausschuss, 2015), this aspect has recently been included as a criterion for the reimbursement of one hearing aid in comparison to another one, which might offer the same support in a speech test situation in quiet, but less support in noise.

Furthermore, speech tests in noise can give information on auditory processing disorders. While the perception and processing of speech in quiet is mostly successful, the disorder can lead to a weak performance in a speech test in noise (Lehnhardt, 2001).

For speech audiometry tests in noise, the SNR gives a value on the span between the necessary intensity of the speech signal – for the recognition of 50% of the offered speech material – and the noise signal.

3.4 AVAILABLE TESTS IN BELGIUM, GERMANY, AND THE NETHERLANDS

3.4.1 TESTS FOR SPEECH AUDIOMETRY IN BELGIUM

Representing the audiological association of the Netherlands (Nederlandse Vereniging voor Audiologie) Snik, Neijenhuis, Crul, and Lamoré summarized available and commonly used tests for speech audiometry in children in Dutch and Flemish. Their selection is not limited to tests of the following two lists (Snik et al., 2016).

- ASSE – Auditory Speech Sounds Evaluation (Govaerts et al., 2006)
- De Brugse lijsten (Bosman et al., 1995; Wouters et al., 1994; Hammer et al., 2013).
- BLU lijsten – Brugge Leuven Utrecht lijsten (Bosman et al., 1995; Wouters et al., 1994; Hammer et al., 2013).
- LINT – Leuven Intelligibility Number Test (van Wieringen & Wouters, 2008)
- LIST – Leuven Intelligibility Sentence Test (van Wieringen & Wouters, 2008)
- 'Vlaamse opnamen voor spraakaudiometrie' Translated *Göttinger* lists (Wouters et al., 1994)
- 'Vlaamse opnamen voor spraakaudiometrie' *NVA* lists (Wouters et al., 1994)

3.4.2 TESTS FOR SPEECH AUDIOMETRY IN THE NETHERLANDS

- AAST – 'adaptive auditory speech test' (Coninx, 2005; Coninx, 2006a)
- NVA lijsten – selected lists for children from the word lists constructed by Bosman 1989 for the Nederlandse Vereniging voor Audiologie (Bosman et al., 1995)
- PAS – De Peuter Adaptieve Spraakdrempelbepaling test (Weersink-Braks et al., 1997)
- pDIN – *pediatric* digits-in-noise test (Smits et al., 2013; Kaandorp et al., 2015)
- Plomp-zinnen – specific version for children (Plomp & Mimpen, 1979)
- SAP(-R) – spraakaudiometrie met plaatjes test (revised) constructed by Crul 1994 (Snik et al., 2016)
- Versfeld-zinnen – specific version for children (Versfeld & Dreschler, 2002)

3.4.3 TESTS FOR SPEECH AUDIOMETRY IN GERMANY

Currently, German speech perception tests for the use of speech audiometry in children and adults are being reevaluated by a committee of the DIN (Kinkel, 2015). The following presented tests for pediatric use are available for purchase and used in a clinical routine and have been part of scientific discourse (Kollmeier, 2009):

- AAST – Adaptive Auditory Speech Test (Coninx, 2005; Coninx, 2006a)
- Freiburger Einsilber (Hahlbrock, 1970)
- Göttinger Kindersprachverständnistest (Gabriel, 1976)
- Mainzer Kindersprachtest (Biesalski et al., 1974)
- OLKI – Oldenburger Kinderreimtest (Wagener et al., 2006)
- OLKISA – Oldenburger Kindersatztest (Wagener & Kollmeier, 2005)

The above mentioned tests for the use of speech audiometry, some especially developed for children, follow different concepts that are described in the chapter.

3.5 TESTS AT A FIXED LEVEL OF INTENSITY

Tests in the field of speech audiometry are often carried out by presenting a list of stimuli at a fixed level of intensity and measure the intelligibility of the stimuli in percent correct.

In clinical practice, tests at fixed levels of intensity are often carried out, not only to derive the SRT, but to monitor the development of speech recognition/ understanding with hearing aid devices at certain levels of intensity, e.g. at 60–70 dB, representing the “normal” loudness level of spoken language. Often, another value at a higher intensity level is derived, to see if a device allows better “understanding” with increasing loudness, which is a crucial factor especially in hearing aid fittings.

The SRT can be derived from tests at fixed levels as well. If a test does not result in a 50% value, the SRT of 50% can be calculated using the Spearman-Kärber Method (Miller & Ulrich, 2001) from two results at different levels of intensity - the test result at a fixed level of intensity where less than 50% of the speech material has been referred to correctly and the result at a level of intensity where more than 50% of the material has been referred to correctly.

The speech audiometry tests can be analyzed as to the score of correctly identified phonemes in one list or the score of correctly identified words in one list. In Germany, usually the word score is derived from a test, in the Netherlands and Belgium it is often the phoneme score. In Belgium, a phoneme score of 70 dB is one of the indication criteria for or against the reimbursement of a cochlear implantation (Raeve & Wouters, 2013).

Available tests matching the profile mentioned above will be described in the following.

The “**Auditory Speech Sounds Evaluation**”(ASSE) is a battery of preverbal tests.

The ASSE battery includes a discrimination task for pairs of speech sounds. A background sound is presented and then replaced by a different sound, the stimulus sound. After conditioning the child to the background sound, a reaction is observed when the actual stimulus sound is presented. A verbal response is not necessary. After trial runs, the discrimination task should be carried out for a minimum of seven suggested pairs of speech sounds. For certain sets of speech sounds, there is normative data available for children as young as 10 months.

The ASSE battery includes an identification of speech sounds. A speech sound stimulus has to be identified on a template with corresponding pictures of objects or actions representing the sounds (e.g. picture of a snake for the sound /s/) or on a template with corresponding pictures that show the matching visemes. Again, a verbal response is not necessary. For certain sets of speech sounds, there is normative data available for children as young as two (Govaerts et al., 2006).

The “**Brugse lijsten**” contains 20 test lists. Each list has 17 monosyllabic words. The test has no age dependent subtests and is designed for adults. No picture templates are used. A test list is presented at a fixed level of intensity. The response mode is the verbal repetition of each word. The Brugse lijsten are usually used in quiet (Bosman et al., 1995; Wouters et al., 1994; Hammer et al., 2013).

The “**BLU lijsten**” contains 15 test lists. Each list has 10 by-syllabic words per list, more specifically spondee-words. The test has no age dependent subtests and is designed for adults. No picture templates are used. A test list is presented at a fixed level of intensity. The response mode is the verbal repetition of each spondee. The BLU lijsten can be used in quiet and also in noise (Bosman et al., 1995; Wouters et al., 1994; Hammer et al., 2013).

The “**spraakaudiometrie met plaatjes test**” contains 10 test lists. Each test list has, 10 monosyllabic words from a total of 20 monosyllabic words.

The SAP test is suggested to be used for children in the age group of three and a half to seven years for testing in quiet; from six years onwards for testing in noise. Each word stimulus is offered while presenting a corresponding picture set of four drawn items, representing the offered word and three more words that contain the same vowels as the target word.

A test list is presented at a fixed level of intensity. The response mode is pointing at the matching picture after each stimulus, no verbal response is necessary. The SAP can be carried out in quiet and in noise (Snik et al., 2016).

The “**selected NVA lists**” contain 15 test lists. Each test list has 12 monosyllabic words per list, from a total of 66 monosyllabic words.

The NVA lists are suggested to be used for children six years and above.

The material is presented by a male speaker. A test list is presented at a fixed level of intensity. The response mode is the verbal repetition of each word. Typically, the NVA lists are not carried out in noise (Bosman et al., 1995).

The NVA lists have been developed in the Netherlands, but also a version recorded by a Flemish speaker is available, due to different ways of pronouncing certain phonemes in the Netherlands and Flanders (Hammer et al., 2013).

The "**Mainzer Kindersprachtest"** contains five test lists including five monosyllabic and five by-syllabic words per list. The test is divided into three age dependent subtests.

The Mainzer I is suggested to be used for children between the ages of three and four. It includes 10 words. A matching picture template can be used if strict auditory presentation is too difficult.

The Mainzer II is suggested to be used for children between the ages of four and six. It includes a total of 25 words. It can be used with picture templates, including the set from the Mainzer I and two more with eight pictures each.

The Mainzer III is suggested to be used for children between the ages of six and eight. It includes a total of 50 words. No picture templates are used.

The material is presented by a female speaker. The response mode is the verbal repetition of each word or depending on the subtest, pointing to a picture. Typically, the Mainzer is not carried out in noise (Biesalski et al., 1974).

The "**Göttinger Kindersprachverständnistest**" contains 10 test lists. Each test list has 10 monosyllabic words. The test is divided into two age dependent subtests.

The Göttinger I is suggested to be used for children between the ages of three and four. It includes 20 words. The use of picture templates is possible, if strict auditory presentation is too difficult. The target word is represented as one picture out of a set of four pictures (representing words with the same vowel as the target word).

The Göttinger II is suggested to be used for children between the ages of five and six. It includes a total of 100 words. No picture templates are used.

The material is presented by a male speaker. A test list is presented at a fixed level of intensity. The response mode is the verbal repetition of each word or dependent on the subtest, pointing to a picture. Typically, the Göttinger is not carried out in noise (Gabriel, 1976).

The "**Oldenburger Kinderreimtest**" contains 10 test lists. Each test list has 12 by-syllabic words. Normative data is available for children in primary school for the first, second, third, and fourth grade.

Each word stimulus is offered while presenting a corresponding picture set of three drawn items, representing the offered word and two more words that differ from the target word in only one phoneme (Wagener et al., 2006).

In the presentation of all words, the emphasis is on the first syllable. The material is presented by a male speaker. A test list is presented at a fixed level of intensity. The response mode requires pointing at the matching picture, no verbal response is necessary. The OlKi was developed for use in quiet, but can also be used in noise (Steffens, 2007).

The "**Freiburger Sprachverständnistest – Einsilber**" contains 20 test lists. Each list has 20 monosyllabic words. The test has no age dependent subtests and has been designed for adults. No picture templates are used. The material is presented by a male speaker. A test list is presented at a fixed level of intensity. The response mode is the verbal repetition of each word. Typically, the Freiburger is not carried out in noise (Hahlbrock, 1970; Hahlbrock, 1953).

For tests at a fixed level of intensity, there is one influencing factor, especially when testing children. For each value, at a certain level of intensity, 10 to 20 words are to be identified. To keep a constant level of motivation and concentration can be challenging when several fixed level values are to be derived. Also, the task can be frustrating for a child if the chosen intensity level doesn't enable the child to understand the presented material. A 10% score on a 10 item list is to be interpreted as nine incorrect responses of which the child is probably aware of.

Therefore, it is important to choose the right speech material that matches a child's individual level of spoken language development.

Tests like the Mainzer I address the very early vocabulary of children and are important tools to measure auditory speech perception skills at an early stage of spoken language development.

However, selecting a speech audiometry test based on language development, especially vocabulary, leads to the problem of comparability of tests with different levels of complexity. In an evaluation of the hearing status, aided by a hearing device, the immediate test result has to be compared to the previous test. Different levels of complexity, such as closed set test vs. open set test (e.g. Göttinger I and Göttinger II) need to be factored in in order to interpret the test results.

3.6 ADAPTIVE SPEECH TESTS

Modern tests in the field of speech audiometry for children also include adaptive test profiles, to derive the SRT in quiet or the SNR for speech tests in noise.

The tests presented in the following adapt the intensity level of the offered speech stimuli according to the answer. A correct response usually results in the following stimulus being presented at a lower level. A false response results in the presentation of the following stimulus at a higher level. By adaptively measuring the SRT, the test duration can be shortened significantly, meeting the needs of children as test subjects, considering a lower attention span in a test situation. The adaptive procedure also addresses the aspect of the awareness on false responses as mentioned above.

The "**Leuven intelligibility numbers test**" (LINT) was not specifically developed for children, but for hearing impaired individuals with limitations in spoken language skills. It consists of 40 lists. Each list has10 numbers (numbers from 1-100).

The test material is presented by two female speakers as well as two male speakers (10 lists per speaker). The response mode demands repetition of the presented numbers. Typically the LINT can be carried out in quiet and in noise. Adaptively the test goes on until 50% of the numbers are identified correctly, thereby measuring the SNR of 50%, testing in quiet is carried out at a fixed level of intensity (van Wieringen & Wouters, 2008).

The “**Leuven intelligibility sentence test**” was also not specifically developed for children, but for hearing impaired individuals who had difficulties with speech presented at a faster pace, usage of complex language, and limitations in auditory memory. It consists of 35 lists. Each list has 10 sentences of varying length.

The test material is presented by a female speaker. The response mode demands repetition of the presented sentence. The LIST can be presented in quiet or in noise. Adaptively, the test goes on until 50% of the sentences are identified correctly, thereby measuring up to an SNR of 50%. Testing can also be carried out at a fixed level of intensity.

The development of a test set suitable for children is planned. This set will be selected from the existing LIST sentences (van Wieringen & Wouters, 2008).

The “**De Peuter Adaptieve Spraakdrempelbepaling test**” (PAS) contains eight test lists. Each list includes 10 monosyllabic words from a total of 26 monosyllabic words.

The PAS test is suggested to be used for children as old as two. Each word stimulus is offered while presenting corresponding figures/ toys. The target word itself is presented in a carrier phrase, such as “take the HORSE”.

The response mode entails identifying the matching figure; no verbal response is necessary. The PAS is usually carried out in quiet. Adaptively, the test continues until 71% of the words are identified correctly, thereby measuring an SRT of 71% (Weersink-Braks et al., 1997).

The “**digits-in-noise-test *for pediatric use***” (*p*DIN) follows the same concept as the digits-in-noise-test for adults (Smits et al., 2013) and the basic principle of the digit-triplet-test carried out as a screening for adults on the phone (Smits et al., 2004).

The *p*DIN test is suggested to be used for children from the age of three and a half. Single digits from one through nine are presented to the child.

The material is presented by a male speaker. The digits are to be repeated verbally or the response can be carried out by pointing at a template of the numbers/digits. Typically the *p*DIN is carried out in noise. Adaptively, the test continues until 80% of the digits are identified correctly, thereby measuring the SNR (Smits et al., 2013; Kaandorp et al., 2015).

The "**Plomp zinnen**" test, which was not specifically developed for children, consists of 10 lists. Each list includes 13 sentences of varying length (four through seven words).

It is suggested to be used for children 12 years and above. The syntactical structure differs within the sentences.

The response mode is repetition of the presented sentences. The Plomp sentences are presented in noise. Adaptively, the test continues until 50% of the sentences are identified correctly, thereby reaching the SNR of 50% (Plomp & Mimpen, 1979).

The "**Versfeld zinnen**" test, which was not specifically developed for children, consists of 38 lists. Each list includes 13 sentences of varying length.

It is suggested to be used for children 12 years and above. The syntactical structure differs within the sentences.

The test material is presented by a female speaker, as well as a male speaker. The response mode is repetition of the presented sentences. The Versfeld sentences are presented in noise. Adaptively, the test continues until 50% of the sentences are identified correctly, thereby measuring an SNR of 50% (Versfeld & Dreschler, 2002).

The test may also be modified and used to evaluate children of six to seven years. The child is not to repeat the whole sentence, but a keyword from the sentence (Snik et al., 2016).

The “**Oldenburger Kindersatztest**” (OlKiSa) contains 10 test lists including 14 phrases that are derived from a total of 21 possible words, always presented in the same three-element pattern; number – adjective – object. The phrases have no semantic context.

The OlKiSa follows the same concept as the “Oldenburger Satztest” for adults (Wagener et al., 1999c; Wagener et al., 1999a; Wagener et al., 1999b).

Normative data is available for children between four and nine years and for first, second, third, and fourth grade of primary school.

The test can be carried out with the presentation of a template showing all possible words (seven words per position in the phrase). The material is presented by a male speaker. The response mode is repetition of the presented phrase or pointing at the matching words to avoid the necessity of a verbal response. Typically, the OlKiSa can be carried out in quiet and in noise. Adaptively, the test is continues until 50% of the phrases are identified correctly, thereby measuring an SRT or the SNR of 50% (Wagener & Kollmeier, 2005).

As mentioned before, the difference between a recognition task in a closed set test setting and the understanding of stimuli in an open set test setting is to be factored in while interpreting the results of different tests.

3.7 CHOOSING AAST

The “**adaptive auditory speech test**” (AAST)– (Coninx, 2005; Coninx, 2006a) follows the example of the “monosyllabic adaptive speech test” (MAST) of Mackie und Dermody (Mackie & Dermody P, 1986). As a computer-based speech audiometry test for children as young as three to four years, the AAST can be used as a diagnostic tool to adaptively determine the SRT. It can also be carried out in noise to adaptively determine the SNR.

Each word has to be identified out of six representing pictures – as shown in Figure 14 – presented on a computer screen, touch screen or on a printed out card. The test duration is short and takes an average of about two minutes for one ear.

Figure 14: Test screen of basic German version of AAST (2005)

After the presentation of the auditory stimulus starting at 65 dB, the child has to identify the matching picture. The response is carried out by clicking or pointing on the screen or picture card. A stimulus identified correctly is followed by a stimulus of lower intensity (by one step, 5 dB), automatically decreased by the software. After an incorrect identification, the intensity is increased (by two steps, 10 dB). The presentation of the words is random. Within one test run not every single presented stimulus is evaluated. Only the critical turning points from a correct to a false response are factored in, to calculate the actual test score. Three reversal points from correct to incorrect response are derived and used by the software to calculate the threshold of 50% speech recognition. After the third incorrect answer, the test is finished. To avoid the evaluation of responses that have been falsely given due to learning effects, the four initial responses are not factored in and the intensity continues at 65 dB for these four initial stimuli.

Due to its adaptive strategy and the response mode, the test shows high motivational factors meeting the needs of even the youngest children (Coninx, 2006a).

The AAST has been adapted from German to Dutch (v.s.) and Polish (Coninx et al., 2007) amongst other languages. For each language, the same criteria have been followed in the selection of speech material with preference given to spondee-words, if existent in a language.

CRITERIA MET IN THE DEVELOPMENT OF THE AAST IN DIFFERENT LANGUAGES

A crucial step in the development of AAST versions for different languages is the choice of words. Using the AAST as a standardized test material, comparable at an interlingual level, the word selection criteria must be met for each language.

Regarding requirements to be fulfilled by speech material in audiometric tests mentioned by Hudgins (1947), the following aspects should be evaluated for a speech test:

- Knowledge of the speech material
- Representing a large variety of phonemes within the material as well as representing language specific frequency of occurrence of phonemes
- Homogeneous test material in terms of intelligibility

These aspects will be addressed for the AAST in the following.

SPEECH MATERIAL – SPONDEES

The expression "spondee-word" also refers to "spondaic-word" or simply "spondee". This word group is implemented in the history of speech audiometry. In the 1970s, ASHA presented guidelines to determine the threshold of speech reception, referring to spondee-words as suitable speech material to determine the speech reception threshold (1988).

Spondees offer a high intelligibility and reference to natural spoken language compared to speech material, such as nonsense words. Due to the characteristic of spondees to be compound words, consisting of two words, each having a meaning, the redundancy is high (Lyregaard, 1998). For a compound word to be considered a spondee, its structure needs to be disyllabic. Just like monosyllabic words, spondees follow a strict prosodic pattern. Each spondee consists of two monosyllabic words. Both syllables are stressed equally. The advantage of spondees in comparison to monosyllables is that greater phonological material is offered. More phonological characteristics can be covered with fewer spondees when used in speech audiometry.

The spondee word lists W-1 und W-2 des Central Institute for the Deaf (Young et al., 1982) have been evaluated as to their psychometric function (performance intensity function) of correct response (in %) to stimulus intensity (in dB SPL) resulting in a slope growing 10% per dB step between the marks of 20% and 80% (Kruger & Kruger, 1997).

Within the Dutch, English, and German basic versions of the AAST amongst others, spondees are used. The use of trisyllabic words in speech audiometry instead of spondees in languages where no spondees exist (e.g. Mandarin) has been evaluated more recently, with the result of a comparable function of growth (Nissen et al., 2005) legitimizing the use of trisyllables instead of spondees to assess the SRT value. Trisyllabic words are used in the Mandarin version of the AAST.

VOCABULARY – CHOICE OF WORDS

Since the AAST has been developed for children as young as three and four, the words that are chosen for a test list, should be implemented in the receptive vocabulary of children at that age. For the adaption into different languages it should be taken into account that the development of a child's vocabulary is connected to cultural influences, a simple translation of words is not necessarily appropriate.

Regional differences in naming a certain object can also be problematic and should be avoided. The existing words for "carrot" in Germany include "Karotte", "Möhre", "Mohrrübe", "Gelbe Rübe" or "Wurzel". A similar problem exists with polysemous words, such as the German word "bank", which has two meanings, the bank as a financial institution and the bench as a place to sit down.

The aim is to ensure a semantical independence within the word in order to avoid a response based on semantical analysis instead of auditory analysis. This could happen if certain words originate from one lexical group (e.g. animals: dog, cat, cow, goat) and the remaining words from another. Words from one group could be confused (e.g. dog, cat), words with no semantical connection could be falsely ruled out or be perceived as an irregularity, thereby influencing the response.

PHONOLOGICAL PROPERTIES

The prosodic pattern within a list of words used in a test set for speech audiometry should not vary, the variety of a language's phonemes should, however, be represented. The frequency of occurrence of language specific phonemes should be considered. Comparison of the occurrence of every single phoneme is not necessary, groups of phonemes can be compared instead, categorized by the mode of articulation as vowels, plosives, fricatives, nasals, laterals, vibrants, etc. (Hall, 2000; Ashby & Maidment, 2005).

Due to the use of spondees instead of monosyllables a larger number of phonemes are represented in an AAST word set of only six. The group based phoneme balancing has been part of the development of the AAST versions in different languages (Coninx et al., 2007). The equal prosodic pattern is given by the speech material (spondees) as mentioned above.

ILLUSTRATIONS

The chosen words should be easily illustrated. Even if the task is not to describe or name the illustrated objects, but to identify a picture matching the previous auditorily presented word, the illustration should be distinct. Names of objects as test words are therefore to be preferred over actions, since an action cannot necessarily be illustrated in an unambiguous way.

Furthermore, the chosen words should not be too specific. The German words “Buntstift” (colored pen) and “Schulbuch” (school book) are spondees which can be expected to be found in a child’s receptive vocabulary. However, they represent items of the lexical subcategories of the words “Stift” (pencil) and “Buch” (book). Visualizing these specific differences can be challenging. A mismatch between the actual auditory stimulus (school book) and the child’s interpretation of the visual stimulus (book) could lead to misunderstandings influencing the test outcome.

Equality should not only be found in the intelligibility of the auditorily presented stimuli, but also in the visual representation of the presented words. Drawings and photographs or colored and black and white illustrations should not be combined. Representing five out of six words as photographs and one as a drawing could lead a child to the conclusion that visual categorization is the expected task. It could even influence the child’s response mode indirectly.

Additionally, the size of the presented pictures used should be used appropriate. The size of each object should be comparable. If an object is presented in a context e.g. a boy playing football as a representation of the word football or the lower part of a face to represent the word mouth, the object of interest (football, mouth) should be emphasized or marked in some way, to prevent a false association (to the boy; to the face or chin). If it is necessary to illustrate the word in a context, the principle of distinctiveness is to be regarded.

Regarding the various aspects of test procedures of speech audiometry in children discussed in this chapter, the following attributes can be summarized for the AAST:

OBJECTIVITY is optimized by the choice of words with regard to the vocabulary development of young children, excluding semantical influences. Individual language development and cognitive development are kept to a low level.

The standardized procedure of the AAST with minimal influence of the test leader (as in false interpretation of verbal responses) raises the objectivity as well.

Furthermore, the influence of worsening motivation and concentration is kept at a low level due to the self-explanatory completion and relatively short duration of the test itself.

Due to the visual presentation of six pictures in a circle and a honeycomb like pattern, a visual preference is kept low.

RELIABILITY is regarded by the adaptive procedure and the random presentation of test words. A previously observed learning effect has been addressed by adding more trial runs of stimuli that are not calculated into the actual test result. Test-rest reliability has been shown in the analysis of normative data (Coninx, 2005).

Analyses of additional testing showed that a stable result can be derived from three “reversal points” (Coninx, 2008).

VALIDITY was analyzed in a sample of 82 hearing impaired children using hearing aids, in which it could be shown that the AAST is an adequate test to evaluate the efficacy of hearing aids.

The guessing level cannot be prevented completely due to the closed set procedure with a choice of six options. This effect has been addressed by adding an additional honeycomb with a question mark into the center of the six picture honeycomb circle on the test screen. The test person is encouraged to click or point at the question mark when a stimulus is not understood correctly.

Validity is also preserved by the fact that the AAST word sets for each language are limited to six words usually within a young child’s vocabulary. The word selection criteria are the same for each language specific test set. The testing of lexical development in addition to the testing of auditory speech recognition is kept to a minimum. To derive the SRT, a recognition task is to be expected and provided by the AAST (closed set test). Due to the response mode, the AAST does not examine the intelligibility of a child's spoken language in addition to the testing of auditory speech recognition.

SYNOPSYS

Addressing the qualities of a test that could be used as an interlingually comparable, stable and standardized measuring instrument, the AAST

- is available in several languages, including Dutch and German
- offers speech material of adequate use for speech audiometry
- is an adaptive procedure, therefor time efficient and preventing a ceiling effect
- can be carried out in quiet and in noise
- as a closed set test it is suitable for young children
- meets common criteria of test quality (objective, valid, reliable)
- as part of the BELLS software, allows to perform other tests that are available within the same software. It can also be installed on laptops with only a little additional hardware

4. DEVELOPMENT AND PROTOCOL OF THE hEARd PROJECT

4.1 PARTICIPATING PARTNERS

A broad spectrum of institutions in Belgium, Germany, and the Netherlands, such as schools for the hearing impaired, clinics as well as hearing aid acousticians collected and contributed data for this project. Children visiting these different institutions represent the heterogeneous performance spectrum. The hypothesis behind this thought is the assumption that children with more difficulties in their hearing and spoken language development frequently visit to CI centers and schools for special education. Children with fewer problems in their spoken language development are often part of an inclusive educational setting and have clinical appointments only for annual checkups.

Data from the following centers was used in the presented analysis:

- CIC Wilhelm Hirte, Hannover (CI center)
- Johannes-Vatter-Schule, Friedberg (school for the hearing impaired)
- Radboud UMC, Nijmegen (audiological center and CI center)
- Institut für Audiopädagogik/ Praxis der Ohrwurm, Solingen (auditory rehabilitation practice)
- Landesförderzentrum Hören und Sprache, Schleswig (school and rehabilitation center for the hearing impaired)
- Centrum voor Ambulante Revalidatie Sint-Lievenspoort, Gent (rehabilitation center for the hearing impaired)
- Audiologisch Centrum, Eindhoven (audiological center)
- Köttgen Hörakustik, Köln (hearing aid acoustician)
- Deutsche HörZentrum Hannover (DHZ) der HNO-Klinik der MHH, Hannover (ENT clinic)

4.2 INCLUDED PARTICIPANTS

For an intra-European pool of comparable data set, certain inclusion criteria were considered for the participating children.

4.2.1 AGE

The focus was on children aged four to 10. The AAST, which serves as the main test for assessing skills of auditory speech perception used in the hEARd project, the applicability is suggested for children as old as four years. The norm data based on the performance of children with normal hearing showed a high variance in children younger than four.

Therefore, children younger than four and older than ten were not required to be tested.

4.2.2 HEARING LOSS

The study focused on the development of auditory speech perception skills in children with pre-lingual binaural hearing impairment. Since the universal newborn hearing screening had not been implemented in Germany, a participating country since the beginning of 2009, the strict inclusion criterion was a diagnosed hearing impairment within the first year of life. Cases where a hearing loss was diagnosed at a later point and early onset within the first year of life could only be suspected were excluded.

The possible influence of a previous normal auditory development, including spoken language acquisition, was ruled out as a factor influencing the speech perception skills within the project. Cases of unilateral hearing losses had been excluded for this reason.

Most conductive hearing losses appear temporarily as an ear infection (Zahnert, 2011), the effect on auditory speech perception would also have to be interpreted as temporary. To prevent a false evaluation of a hearing aid device (in this case hearing aids) due to a temporal conductive hearing loss, a tympanometric test before the actual testing for the hEARd study was suggested. In case of an irregular finding, this was to be marked on the questionnaire/ information sheet for each participating child.

The etiology of the hearing loss, if known as well as the specific age of diagnosis was to be marked as well. Overall, all types of technically aided hearing losses (acquired within a child's first year of life) could be included in the testing.

4.2.3 Aiding with technical hearing device

It was expected that the participating children had some experience with their recent hearing aid device. Testing after a recent provision with a new device or immediately after a new fitting was to be avoided. If possible, an opinion on the tested child's recent fitting of the hearing aid device was to be given.

All information regarding the hearing aid device was to be documented for later analysis:

- type of hearing aid device used in the testing – type of hearing aid or CI
- type of first hearing aid device – type of hearing aid or CI
- child's age of first fitting

The study focused on the evaluation of different types of hearing aid devices. Although bone-conducting hearing aids as well as bone-anchored hearing aids are used in children as well, it was not suggested or specifically expressed to test children with conductive hearing losses.

4.2.4 Communication mode

To evaluate auditory speech perception skills, possible influencing factors need to be documented to be later on analyzed, such as the possible effects of unfamiliarity with the speech material due to limitations in the spoken language development on the semantic/ lexical level (receptive vocabulary). Limitations in language development that probably would not originate in auditory perception skills could be second language acquisition or a communication system that uses no auditory access.

Therefore, the communication mode was to be documented, in terms of whether a child was using sign language or spoken language and if the spoken language was the target language spoken in the country of testing. Owing to the fact that information on the familiar communication mode used by the child most of the time, was not always available and obvious in interaction with the test adviser, the communication mode or specific spoken language between the child and his/her parents was to be documented as well.

4.2.5 ADDITIONAL HANDICAP

The definition of an additional handicap is based on the definition of a handicap, which again is defined in diverse ways, often based on the impairment experienced. Within the hEARd study, an additional handicap was defined as any kind of impairment or illness, beside the hearing loss, which could influence the speech perception skills or the performance on the AAST.

Examples include impaired cognitive development or attention deficit disorders that could influence language development, as well as visual or motoric impairment that could influence the implementation of the actual test.

In cases of an additional handicap as defined above, children were not to be excluded from the study, since a large proportion of hearing losses occur in combination with an additional impairment or illness (Zahnert, 2011). The information on a diagnosed or suspected additional handicap (as defined above) was to be documented in the questionnaire.

4.2.6 EDUCATIONAL SETTING

Children visiting schools for special education as well as children in an inclusive school setting were to be included, to maintain heterogeneity. This included preschoolers as well.

4.3 BELLS SOFTWARE

The BELLS software offers the possibility to implement several subtests within one software, for different levels of auditory perception.

The BELLS software including the subtests described in the course of this chapter was implemented at the institutions participating in the hEARd study. Therapists, teachers, audiologists, audiometrists or other staff members working at the above mentioned institutions were introduced to the software (if it had not been already used) and informed of the test protocol. A standardized manual was given to the test leaders. First, trial runs were usually overseen by personnel administering the hEARd project.

For each child, a profile (including name and birthday) was created in the BELLS software. Within this profile, all performed subtests including the questionnaire were documented.

Testing was to be carried out “unilaterally” with the hearing aid device. In cases of bilateral provision with a hearing aid, bilateral cochlear implantation or bimodal aiding, the evidently better side was to be tested. Unilateral testing of the contralateral could be carried out additionally.

4.3.1 SPEECH RECOGNITION THRESHOLD– AAST QUIET

To collect data on a child’s speech perception skills in quiet, the AAST was to be performed to arrive at the 50% speech recognition threshold.

4.3.2 SNR – AAST NOISE

A speech test in noise should be performed to get a better understanding on a child’s ability of the auditory perception of speech in situations of daily life (see Chapter 2.3).

As mentioned above, the basic AAST test set can also be used to assess the SNR between a 65 dB steady state noise and the adapted speech signal at which 50% is correctly identified.

Following the initial test in quiet, the words are already implemented and the test setting is established, minimizing the influence of learning effects within the test set in noise.

4.3.3 SPEECH RECOGNITION IN A HIGH-FREQUENCY RANGE – AAST HIGH FREQUENCY

The problems and limitations of amplifying hearing aid devices in a high frequency range is of great interest in pediatric audiology. To counteract the negative influence on spoken language development caused by limited auditory perception of certain phoneme groups, such as fricatives, an optimized hearing aid provision should be aimed at.

To evaluate the performance in perception of speech material containing these phoneme groups, special AAST test sets had been developed. These sets contain a total of six words that can be differentiated only in single phonemes (fricatives and voiceless plosives).

For the above mentioned reasons, the so-called AAST HF (high frequency) test sets had been implemented in the hEARd test protocol.

4.3.4 PHONEME DISCRIMINATION – TITATU

For an even more specific evaluation on phoneme discrimination skills, the TiTaTu test (Coninx, 2006b) has been adapted to be implemented in the BELLS software to be part of the hEARd test protocol. In comparison to other tests focusing on the phoneme perception skills, such as monosyllabic speech tests, the TiTaTu uses consonant-vowel combinations that need to be matched.

After presentation of the target stimulus (represented by a smiley in the center), the matching stimulus has to be identified from a set of four possibilities (represented by four surrounding smileys). The stimuli are presented at a fixed level of intensity of 70 dB.

The child can compare the target stimulus and the four offered choices numerous times by clicking on the representing smileys. A choice is made by matching two smileys via drag and drop in either direction (stimulus-smiley on chosen-option-smiley or chosen-option-smiley on stimulus smiley).

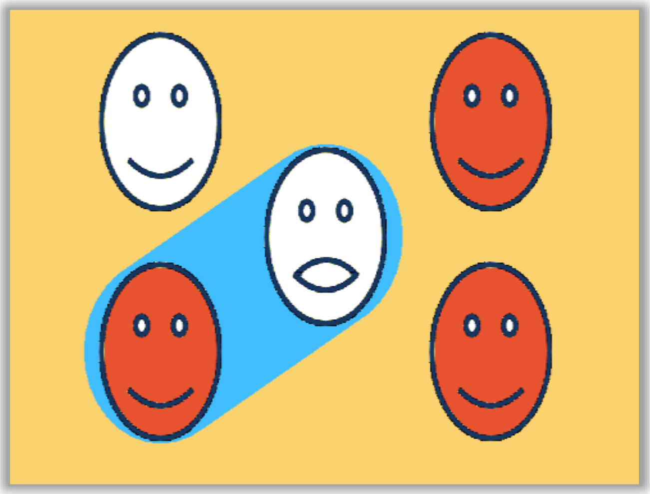

Figure 15: TiTaTu test screen

Three subtests are available and implemented in the software:

- TiTaTu vowel set (TTT V): consonant /t/ in combination with changing vowels/ vowels and diphthongs for Dutch version
- TiTaTu plosive set (TTT P): changing plosives in combination with vowel /a/
- TiTaTu fricative set (TTT F): changing fricatives in combination with vowel /a/

The chosen phonemes differ in German and Dutch based on the frequency of occurrence in each language.

4.3.5 TONAL THRESHOLDS – MFAST

The multi frequency animal sound test mFAST was developed as a test alternative for pure tone audiometry in children. Its advantage is the adaptive procedure of assessing four thresholds for frequency specific stimuli around the main frequencies of 500 Hz, 1 kHz, 2 kHz and 4 kHz (Offei, 2013). Furthermore, the frequencies are visually represented by four animals.

Figure 16: mFAST test screen

The frequency specific stimuli had been manipulated to match the natural sounds of these four animals (see picture) - the cow representing a frequency range of around 500 Hz, the dog representing a frequency range of around 1 kHz, the cat representing a frequency range of around 2 kHz, and the bird representing a frequency range of around 4 kHz.

In addition to the latest available pure tone audiogram of a child included in the hEARd study, the mFAST result could give information on the frequency specific auditory perception skills. This was assessed with a test specifically developed for children keeping in mind their needs within audiological testing.

Comparable to the AAST, mFAST derives the threshold of each stimulus by adaptively increasing the intensity of a stimulus after an incorrect response and decreasing the intensity after a correct response. Automatically, thresholds of the four frequency dependent stimuli are assessed by offering the stimuli in changing order, starting with the presentation of each stimulus at a level of 65 dB three times, as trial runs, to avoid learning effects (see Chapter 2.4). Then, those three intensity levels pre-stimulus are factored in to the final result, at which an incorrect answer is given.

4.3.6 QUESTIONNAIRE

Information on the above mentioned aspects (Chapter 3.2) was to be implemented in a specially designed digital questionnaire. This questionnaire could be filled out within the BELLS software as part of a patient's profile. However, a printout was available on request.

Optimally, a staff member working with the child on a regular basis should be involved in the assessment in cooperation with the parents.

The questionnaire was to be filled out based on a child's medical file and most recent diagnostic information, which should in any case include:

- current hearing aid device
- information on additional handicap
- information on dominant communication mode
- latest unaided audiogram for hearing aid users
- result of the latest open set speech test at a fixed level of around 60–70 dB
- information on the educational setting

4.4 CALIBRATION WITHIN PARTICIPATING INSTITUTIONS

To assure a comparable test environment within all participating institutions, the same calibration guidelines for the test software had been followed. Within all institutions the calibration had been carried out by the same staff using the same measuring equipment.

4.5 ETHICAL APPROVAL

The hEARd project was approved by the ethical committee of the European Commission. Participating centers gained ethical approval as to their institution's regulations.

Before data assessment, a randomized ID number was assigned to each participating child. Within the center, a child's name was documented in the software and kept available for further analysis. While processing the collected data for evaluation within the hEARd project, the ID number and not the name was exported.

5. RESEARCH QUESTIONS AND HYPOTHESES

Following the data assessment the subsequent questions should be addressed. Hypotheses are to be analyzed.

5.1 HOW DO CHILDREN AT DIFFERENT LEVELS OF HEARING IMPAIRMENT USING HEARING AIDS PERFORM IN THE ADAPTIVE AUDITORY SPEECH TEST?

Coninx describes, in a presentation of study outcomes in 2006, a correlation between AAST SRT values of hearing impaired children using hearing aids and their average unaided hearing loss of 500 Hz, 1 kHz, and 2 kHz (in the better ear). To use the collected data from the hEARd project as a normative collective from a recent study in a time of further developed technical hearing devices, means of performances within groups of certain degrees of hearing loss should be evaluated.

H1: Analysis of the hEARd project data shows that ***AAST*** *SRT values of hearing impaired children using hearing aids correlate to their unaided hearing loss pure tone average of 500 Hz, 1 kHz, and 2 kHz in one ear; better SRT in smaller HL.*

5.2 ABOVE WHICH LEVEL OF HEARING LOSS DOES A CI OFFER BETTER SPEECH PERCEPTION IN QUIET THAN A HEARING AID?

Addressing the main question of the hEARd project, this research question evolves naturally. Within the individual subtests of AAST, data should be analyzed regarding the different hearing devices, different levels of hearing loss, and their outcomes. Based on the current indication criteria for cochlear implantation (see Chapter 2.3), as in degree of hearing loss, better speech perception with a CI in comparison to cases of profound hearing impairment/ deafness aided with an amplifying device. This expectation is to be confirmed by the test results.

In recent scientific discourse, the extension of cochlear implantation to cases of severe hearing impairment or even cases of residual hearing is of keen interest. This was even discussed at the 12th European Symposium on Pediatric Cochlear Implantation in 2015 (Lesinski-Schiedat et al., 2015; Manrique Rodriguez, 2015; Nikolopoulos et al., 2015). Looking at these discussions, the test results of the group of severely hearing impaired children in the hEARd study should be analyzed as well. Therefore, the following hypotheses should be analyzed.

H2: Children using a cochlear implant (group CI) achieve better results in the ***AAST QT*** *in unilateral testing than children using a hearing aid with a hearing loss*

- *higher than 80 dB(group HA IV).*
- *between 61 dB and 80 dB (group HA III).*

5.3 DO CIS OFFER BETTER PERFORMANCE OF SPEECH PERCEPTION IN NOISE THAN HEARING AIDS?

The use of speech audiometry in noise, especially in the pediatric field, has been discussed in Chapter 3.3.

With the AAST CN, the ability of speech perception in noise is tested within the hEARd project. Therefore, the following hypotheses should be analyzed.

H3: Children using a cochlear implant (group CI) achieve better results in the ***AAST CN*** *in unilateral testing than children using a hearing aid with a hearing loss*

- *higher than 80 dB(group HA IV).*
- *between 61 dB and 80 dB (group HA III).*

5.4 ARE THERE CORRELATIONS BETWEEN PTA VALUES IN THE HIGH FREQUENCIES, AND THE AAST AND TITATU SUBTESTS USING HIGH FREQUENCY SPEECH MATERIAL

The limited auditory perception of high frequency ranges has a negative influence on the auditory perception of certain elements of speech compared to lower frequencies, such as various groups of phonemes, including voiceless plosives (stops) and especially fricatives as illustrated in Figure 17.

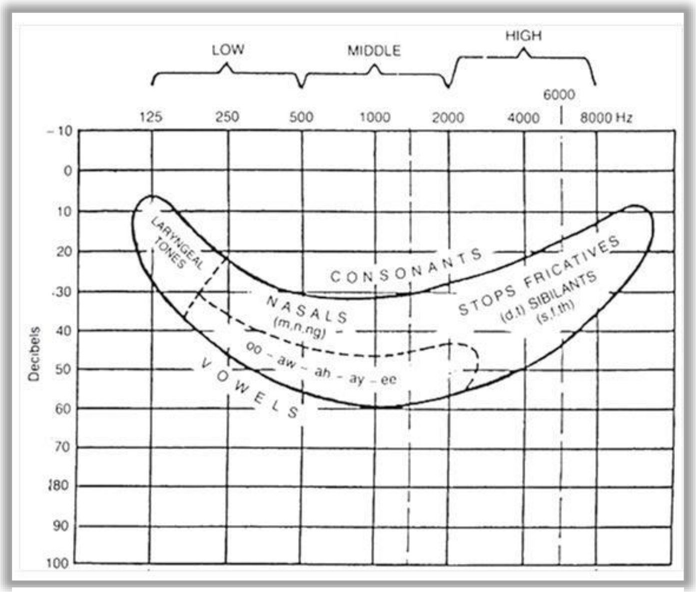

Figure 17:"Field of speech" by Ballantyne 1970 (Lyregaard, 1997)

In the English language, fricatives and plosives are the two most frequently appearing groups of consonants (Mines et al., 1978). The differential perception of phonemes and fricatives is of most importance in a child's language acquisition. In the English language, the development of grammatical structures is influenced by the auditory perception of fricatives. The fricative/s/ is partially responsible for the understanding of morphological and syntactical principles, for example the conjugation of verbs or the use of plural in nouns.

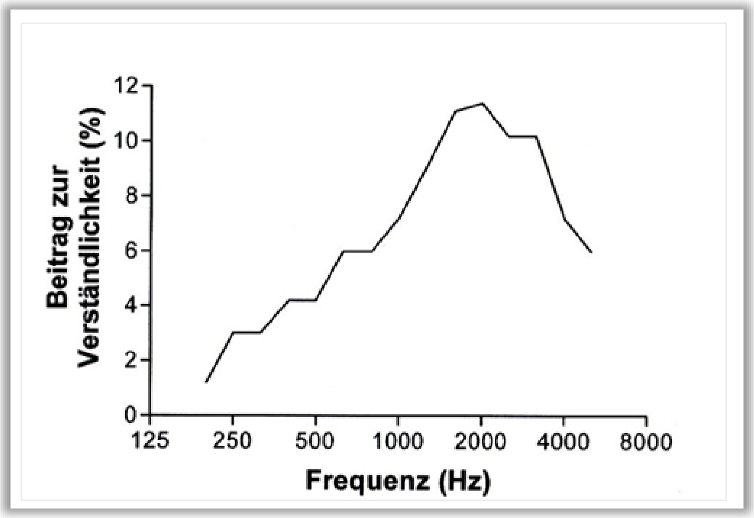

Figure 18: Frequency dependent influence on speech recognition based on the ANSI-Norm (1969) in Kompis (2004)

Figure 18 provides an overview of the ability to hear specific frequency ranges to understand spoken German language. It shows the strong influence of high frequencies above 1 kHz in comparison to the lower frequencies below 1 kHz.

Average hearing loss values as defined by the WHO for the classification of hearing impairment, focus on the following frequency thresholds: 500 Hz, 1 kHz, 2 kHz, and 4 kHz. In scientific research, PTA values of 500 Hz, 1 kHz, and 2 kHz are often used as well. If auditory perception in the higher frequency range is of importance in perceiving specific speech signals, the above mentioned PTA values don't seem to be suitable in addressing this factor of influence. Within the hEARd test battery, different subtests are used to obtain data on the perception of high frequency speech material. An analysis should be conducted to see whether there is a correlation in between the specific subtests, such as the AAST HF, TiTaTu plosive or TiTaTu fricative set and unaided PTA values of the high frequencies. Therefore, the following hypotheses should be analyzed.

H4: A correlation can be found in between the results of the ***AAST HF,*** *the* ***TiTaTu P****,*
the ***TiTaTu F*** *and the average unaided PTA values of*

- *2 kHz and higher*
- *4 kHz and higher*

as in; higher average PTA values resulting in poorer subtest results for the group of hearing aid users.

5.5 IS THERE A SIGNIFICANT DIFFERENCE BETWEEN CI USERS AND HA USERS IN DISCRIMINATING AND IDENTIFYING HIGH FREQUENCY SPEECH MATERIAL?

The possibility of amplification in high frequencies with hearing aids are limited (Turner & Cummings, 1999). High amplification in high frequencies is often described as uncomfortable hearing impressions. For example, a range of the previously mentioned 2007 Phonak Naida III UP, a commonly used high power hearing aid for children, presents itself with an amplification of up to 50 dB in the area of 5 kHz in ear simulator measurements (citation data sheet). Even though advantages in auditory speech perception skills by using the *sound recover* option in children have been shown (Bagatto et al., 2008), there are limitations set by the degree of high frequency hearing loss (Leifholz et al., 2013).

CI systems allow a stable stimulation within the highest frequencies due to the tonotopical order in the cochlear. No matter how far the insertion of the electrode array[6], a stimulation in the basal area of the cochlear is usually possible, allowing the perception of high frequency sounds - environmental sounds as well as speech sounds.

Therefore, one could assume that CI users profit in understanding speech compared to hearing aid users with hearing losses in the high frequency range. The following hypotheses should thus be analyzed.

H5.1: Children using a cochlear implant (group CI) achieve better results in the ***AAST HF*** *in unilateral testing than children using a hearing aid with a hearing loss*

- *higher than 80 dB(group HA IV).*
- *between 61 dB and 80 dB (group HA III).*

The performance of hearing aid users should be compared to the performance of CI users for the TiTaTu subtests on plosives and fricatives. Therefore, the following hypotheses should be analyzed.

[6] also shorter electrode arrays as in electric acoustical stimulation Gantz et al., (2005)

*H5.2: Children using a cochlear implant (group CI) achieve better results in the **TiTaTu test** in unilateral testing than children using a hearing aid with a hearing loss*

- *higher than 80 dB (group HA IV) in the **plosive** subtest.*
- *between 61 dB and 80 dB (group HA III) in the **plosive** subtest.*
- *higher than 80 dB (group HA IV) in the **fricative** subtest.*
- *between 61 dB and 80 dB (group HA III) in the **fricative**.*

5.6 ARE THERE CORRELATIONS BETWEEN WORD SCORES AND PHONEME SCORES IN SPEECH PERCEPTION TESTS AT A FIXED LEVEL OF INTENSITY AND AAST WORD SCORES AND TITATU PHONEME SCORES

Open set speech audiometry testing is often carried out at a fixed level of intensity. Speech is to be offered at levels that represent an intensity of spoken language in a daily context. These levels vary around 65 dB SPL. The advantages and disadvantages of open set speech testing are discussed in Chapter 3.

Test results from the hEARd data should be correlated to the documented open set speech test results, collected from the participating institutions. This will help to to see whether the AAST as a test addresses the critical factors described in Chapter 3 and is as sensitive to performances of auditory speech perception in quiet as the open set word tests at a fixed level of intensity. Therefore, the following hypotheses should be analyzed.

H6.1: A correlation can be found between the word scores of open set speech tests at a fixed level of intensity and the results of the

- ***AAST QT** (the better the AAST QT result, the higher the word score).*
- ***AAST HF** (the better the AAST HF result, the higher the word score).*

H6.2: A correlation can be found in between the phoneme scores of open set speech tests at a fixed level of intensity and the results of the

- ***TiTaTu V** (the better the TiTaTu V result, the higher the phoneme score).*
- ***TiTaTu P** (the better the TiTaTu P result, the higher the phoneme score).*
- ***TiTaTu F** (the better the TiTaTu F result, the higher the phoneme score).*

6. STUDY OUTCOMES, STATISTICAL ANALYSES

6.1 INCLUDED DATA

At the end, 277 individual hEARd test results (no. of ears tested) were available for further analysis. In 43 cases, an additional handicap that could influence speech perception or the performance in a test, was marked as diagnosed or suspected by the test leader. In 24 cases, the communication system was marked as sign language or influenced by sign language (e.g. communication mode used between child and parents).

Both above mentioned groups were excluded from further analysis, to focus on the auditory perception skills of spoken language, by limiting other influential factors. In the following analysis, 220 ears were included.

For statistical analysis, hearing aid users were grouped to their unaided average hearing loss values derived from the frequencies of 500 Hz, 1 kHz, 2 kHz, and 4 kHz. Table 2 shows the number of tested ears, supplied with a hearing aid in groups, referring to the grades of hearing impairment by the WHO. Following this model, groups HA I, HA II, HA III, and HA IV could be categorized as groups of mild, moderate, severe, and profound hearing impairment.

Group	PTA	HI	N
HA	<25 dB HL		2
HA I	25–40 dB HL	mild	21
HA II	41–60 dB HL	moderate	58
HA III	61–80 dB HL	severe	21
HA IV	>80 dB HL	profound	11
∑			113
CI	profound HI/deafness		107
∑			220

Table 2: HEARING DEVICE GROUPS - number of tested ears with a hearing aid in groups as to their unaided PTA and number of tested ears with a CI

Further analysis excluded two cases of unaided hearing losses below the 25 dB PTA value.

The IBM software SPSS 23 was used to perform the statistical data analysis.

Looking at the results of the hEARd subtests within the formed groups, the Kolmogorov Smirnov test and Levene's test showed that the data was not normally distributed and that the groups formed above had heterogeneous variances.

Therefore, non-parametric tests were used for further analyses.

6.2 COMPARABILITY OF THE TEST RESULTS[7]

First, the analysis focused on the comparability of the test results per center. Due to the comparable test development for different languages and the mentioned calibration procedures within participating centers, no significant differences based on these factors were expected in between the performances per center or language.

6.2.1 CENTERS

The Kruskal Wallis test was used to test for differences in between the groups/centers for each subtest.

Performances in the tests AAST QT, AAST CN, TTT F, mFAST cow, mFAST dog, mFAST cat differed significantly in between certain centers. However, looking at the mean results per subtest, no center showed an overall better or poorer performance for *all* subtests in comparison to another center.

The major differences between centers can be explained by the expected difference in performance due to the type of institution (compare Chapter 4.1).

Looking at the different groups of hearing aid users as to their degree of hearing impairment, as well as the CI users individually, the comparisons in between the centers yield different results. Again, the Kruskal-Wallis test was performed. Comparison of the means of each of the five hearing device groups in between the centers shows that the means within all four hearing

[7] In the following, AAST results refer to SRT values in dB SPL for AAST QT and AAST HF; to SNR values in dB SPL for AAST CN

aid groups are comparable within the centers, as are the performances of CI users. Only for the TTT F subtest a significant difference in between centers could be found within the CI group.

Since this is the only effect that has been found in between centers, it is unlikely that there is an overall difference in between centers based on calibration differences.

6.2.2 LANGUAGES

While comparing performances as per language, an analysis with the Man Whitney *U* test shows a significant difference (p=0.031) for the AAST in quiet. The same test material is used in the AAST in noise, where the difference was of no significance.

Looking at the different groups of hearing aid users as to their degree of hearing impairment, as well as the CI users individually, the comparisons in between the languages yield different results. Again, the Man Whitney *U* test was performed. Comparison of the means of each of the five hearing device groups in between the languages shows that the means within the groups HA I, HA III, and HA IV are comparable in between languages.

The performance of group HA II shows a significant difference in between languages for subtest AAST CN (p=0.045) and also for subtest AAST HF (p=0.042). Better results were achieved in the German subtests. As mentioned above, the AAST QT uses the same speech material as the AAST CN, but no significant difference can be found in between languages within group HA II, suggesting that this difference is not based on a different level of difficulty in the speech material for each language.

The performance of group CI shows a significant difference in between languages for subtest AAST QT (p=0.007). Again, this difference does not seem to originate at a different level of difficulty of the word set, since in this case better results were achieved in the Dutch subtest.

The performance of CI users, however, shows a significant difference (p=0.003).

Since significant differences have not been found in a systematic way in between languages, it is unlikely that there is an overall difference in between results based on incomparable speech test material.

6.3 EHL SCALES DERIVED FROM AAST RESULTS

The following results have been achieved on an average within the groups described in Chapter 6.1. Most test results are available within the group of CI users. Looking at the groups of hearing aid users, most results are available for group HA II. Only a few results are available for group HA IV, which can be explained by fewer children being aided with an amplifying hearing device, but instead already having a CI.

Hearing device groups		AASTQT	AASTCN	AASTHF
HA I	Mean	27,581	-10,976	37,756
	N	21	21	16
	Std. Deviation	5,6852	3,1084	10,7581
HA II	Mean	32,124	-9,591	41,702
	N	58	57	45
	Std. Deviation	8,9072	4,5364	11,3654
HA III	Mean	42,830	-5,815	53,440
	N	20	20	10
	Std. Deviation	9,2969	6,4395	15,7064
HA IV	Mean	45,991	-6,580	55,114
	N	11	10	7
	Std. Deviation	14,1351	7,7723	17,1917
CI	Mean	33,608	-7,908	41,349
	N	107	107	106
	Std. Deviation	5,9039	3,7018	11,7554
Total	Mean	34,106	-8,398	42,304
	N	217	215	184
	Std. Deviation	8,8003	4,6073	12,5354

Table 3: Results on AAST subtests for groups of hearing devices

For the AAST QT, this group also shows a rather high standard deviation.

While comparing the three AAST subtests, the AAST HF results showed a high standard deviation for all groups of hearing devices, which can be explained by the speech material, which differs from the subtest in quiet and in noise (see Table 3).

6.3.1 AAST IN QUIET

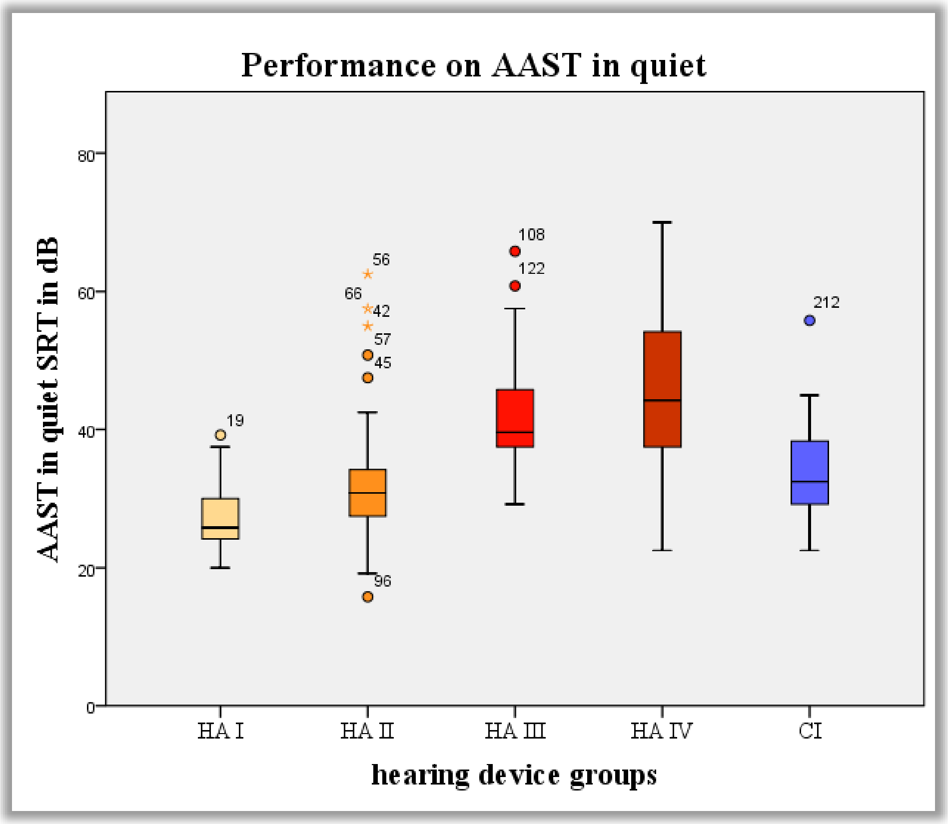

Figure 19: Comparison of SRT results of hearing aid groups and CI group for the AAST in quiet

In Figure 19, the performance of the hearing aid groups I, II, III, IV, and CI group for the AAST in quiet is shown. In this distribution, the CI group and hearing aid group II (moderate hearing impairment) appear to perform alike, whereas hearing aid group III and IV (severe and profound hearing impairment) seem to perform poorer.

The Kruskal Wallis test showed significant differences in between the means achieved in the groups of hearing aid users and CI users for the AAST QT ($p<0.001$). To compare the differences between a pair of groups to look for significance, the Man Whitney *U* test was performed, with the critical value of 0.5 being adapted by using the Bonferroni Correction, as two comparisons were performed. Analyses show that the CI group performed significantly better not only than the hearing aid group IV (HL >80 dB) with a critical value of $p=0.001$, but also significantly better than hearing aid group III (HL 61–80 dB) with a critical value of $p<0.001$.

6.3.2 AAST IN NOISE

Results of the **AAST in noise** shown in Figure 20 present the SNR values reached by each group. Looking at the graph it appears that the CI group does not perform better than hearing aid group IV or hearing aid group III and not quite as good as hearing aid group II.

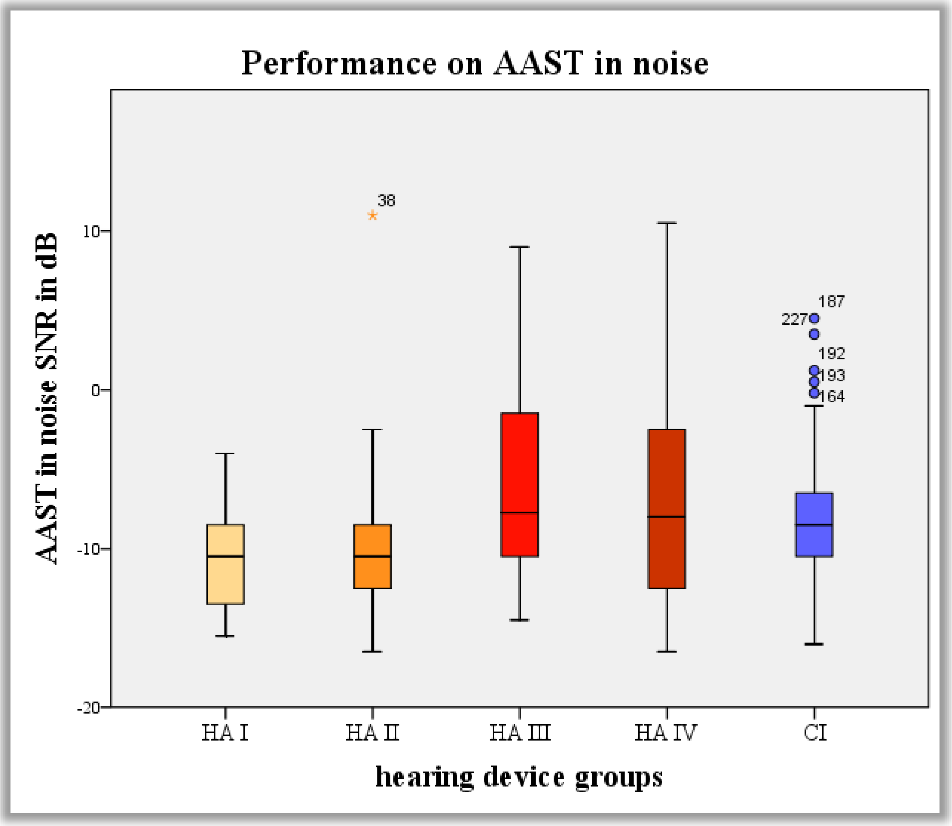

Figure 20: Comparison of SNR results of hearing aid groups and CI group for the AAST in noise

The Kruskal Wallis test showed significant differences in between the means achieved in the groups of hearing aid users and CI users for the AAST CN (p=0.001). To compare the differences between the CI group and a specific hearing aid group to look for significance, the Man Whitney *U* test was performed, with the critical value of 0.5 being adapted by using the Bonferroni Correction, as three comparisons were performed. Analyses show that the CI group, in fact, did not perform significantly better than hearing aid group IV (HL >80 dB) or hearing aid group III (HL 61–80 dB). However, hearing aid group II (HL 41–60 dB) did not perform better than the group of CI users either.

6.3.3 AAST IN HIGH FREQUENCIES

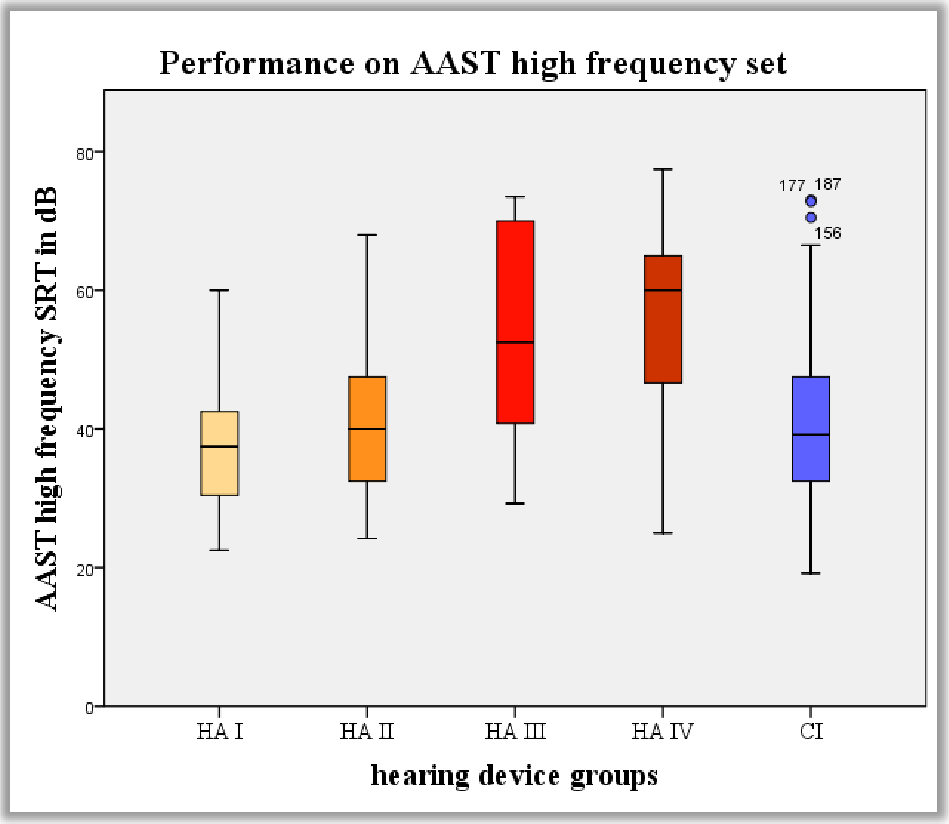

Figure 21: Comparison of SRT results of hearing aid groups and CI group for the AAST high frequency set

Looking at Figure 21, showing the SRT values derived from the AAST high frequency test set, also presented in quiet, the CI group again seems to perform better than hearing aid groups III and IV.

The Kruskal Wallis test showed significant differences in between the means achieved in the groups of hearing aid users and CI users for the AAST QT (p=0.015). To compare the differences between a pair of groups to look for significance, the Man Whitney *U* test was performed, with the critical value of 0.5 being adapted by using the Bonferroni Correction, as two comparisons were performed. Analyses show that the CI group performed significantly better not only than hearing aid group IV (HL >80 dB) with a critical value of p=0.025, but also significantly better than hearing aid group III (HL 61–80 dB) with a critical value of p=0.015.

6.4 PHONEME DISCRIMINATION MEASURED WITH TITATU

Comparing the TiTaTu values for the above mentioned groups of hearing aid users and the group of CI users, the number of executed tests per group show a strong variance (see Table 4). For this reason, the hearing aid users have been grouped into unaided hearing losses (average 500 Hz, 1 kHz, 2 kHz, 4 kHz) of 25–60 dB and hearing losses greater than 60 dB for further analyses.

Group	PTA	N TTT V	N TTT P	N TTT F
HA I	25–40 dB HL	7	7	6
HA II	41–60 dB HL	20	18	19
HA III	61–80 dB HL	5	5	6
HA IV	>80 dB HL	5	5	5
CI	profound HI/deafness	81	71	71
∑		118	106	107

Table 4: No. of tested ears with hearing aid in groups as to their unaided PTA and no. of tested ears with CI in TiTaTu subtests

6.4.1 TITATU SUBTESTS ON PLOSIVES AND FRICATIVES

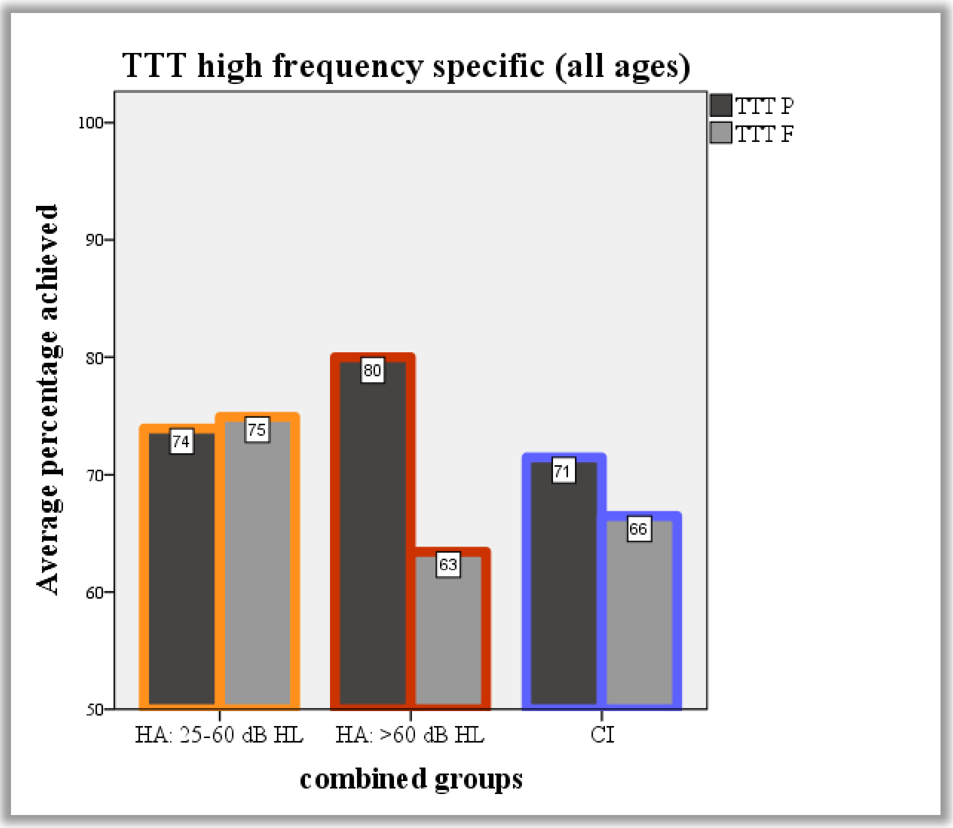

Figure 22: Results on TTT P and TTT F for combined groups of hearing aid users and CI users

Comparisons of the means achieved in the TiTaTu plosive and TiTaTu fricative subtests by the two groups of children one using hearing aids, and the other group CIs showed no significant difference in performing the Kruskal-Wallis test.

The results illustrated in Figure 22 show no specific trend. However, the CI users appear to perform poorly, especially in the discrimination of plosives, compared to other groups.

One factor that could be influencing the discrimination ability between the two groups of phonemes, is a possible delay in phonological development of hearing impaired children (Kral et al., 2014). This factor was addressed in an age dependent analysis. Results were compared and analyzed for children of six years and older (see Table 5).

Group	N TTT P		N TTT F	
	age >=6	age <6	age >=6	age <6
HA: 25–60 dB HL	19		19	
	14	5	15	4
HA: >60 dB HL	8		9	
	8	0	9	0
CI	48		46	
	34	14	33	13

Table 5: Age dependent number of children that performed TTT high frequency specific[8].

Illustration of the age dependent modified TiTaTu results show similar performances for all three groups in the discrimination on the TiTaTu plosive subtest (see Figure 23).

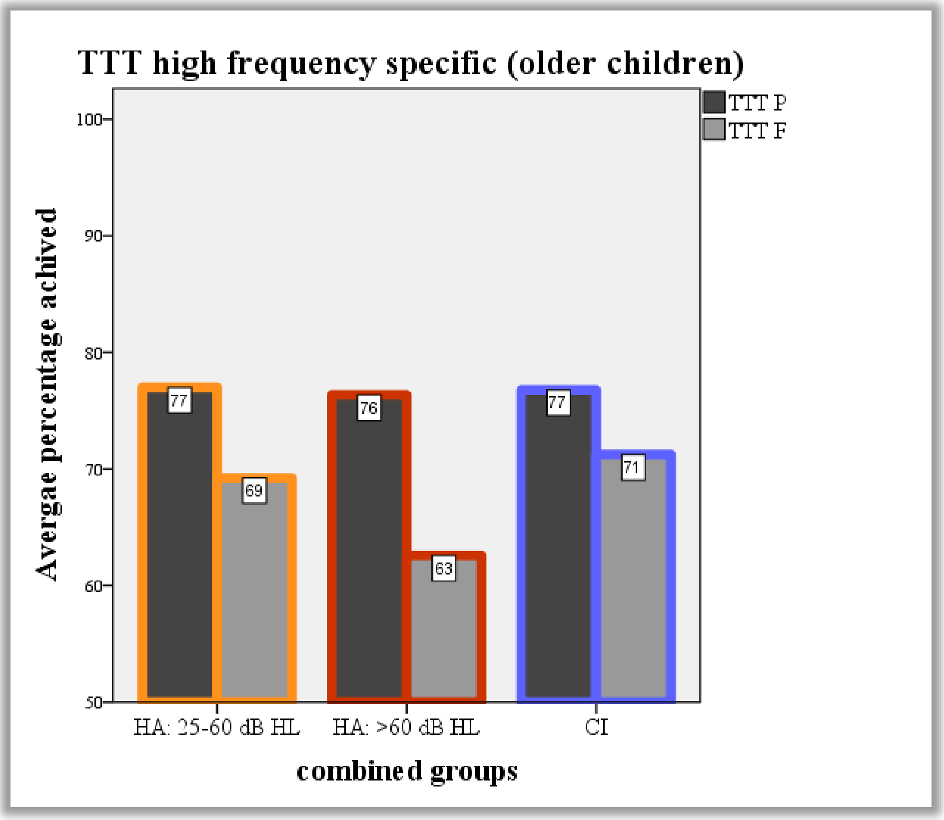

Figure 23: Results on TTT P and TTT F for combined groups of hearing aid users and CI users of the age of 6 and older

Results of the TiTaTu fricative subtest indicate that cochlear implanted children of six years and older indicate a better competence of discriminating fricatives than children with hearing losses greater than 60 dB at the age of six and above (see Figure 23).

[8] Birthday not available for all cases mentioned in Table 5

The differences in between the combined hearing device groups (of children of six years and older) in performances analyzed with the Kruskal-Wallis test are not of significance for either subtest (TTT P, TTT F).

The performance of the younger group of children was analyzed as well, but included only the group of children with hearing losses between 25 and 60 dB and the group of children with CI. All children performing the TiTaTu subtests with a hearing loss greater than 60 dB were older than five years.

The performances of hearing aid users (25–60 dB HL) and CI users under the age of six was not of significant difference for the TTT P, but showed a strong variance (p=0.069) for the TTT F (analyzed with the Man Whitney *U* test). Here, those with hearing aids fared better than CI users.

Comparison of the performances of children younger than six years (see Figure 24) and the older group (see Figure 23) of the same degree of hearing loss/ hearing device suggests an improving development in the discrimination abilities in both analyzed TiTaTu subtests for CI

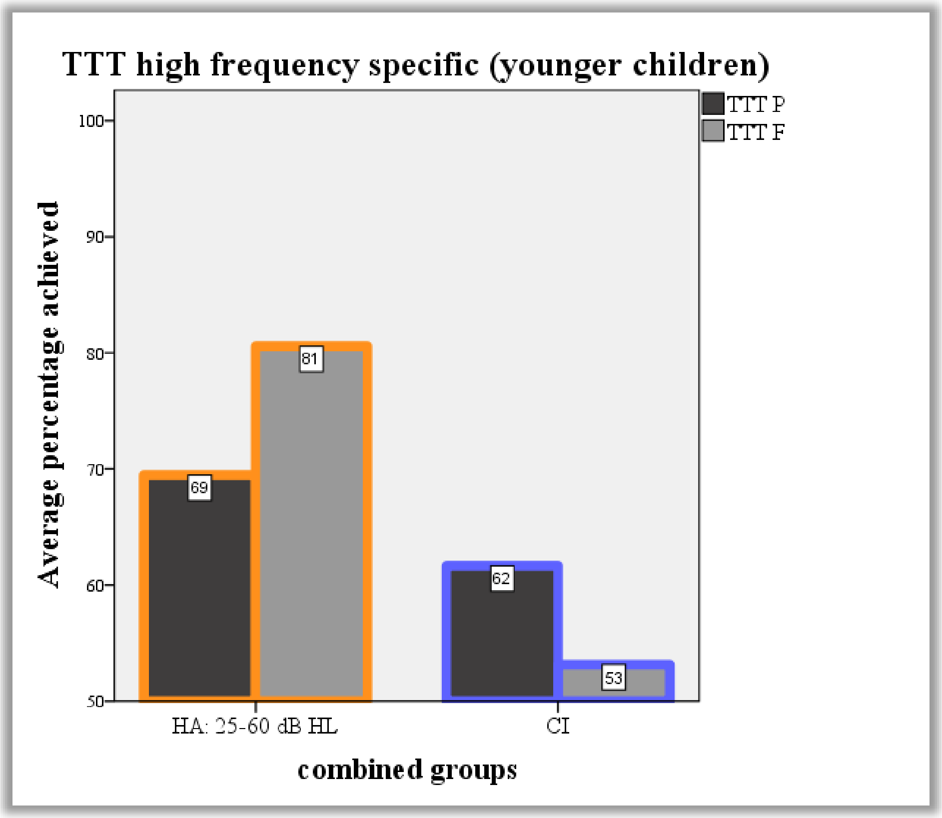

Figure 24: Results on TTT P and TTT F for combined groups of hearing aid users and CI users younger than six years of age

users. The difference analyzed with the Man Whitney *U* test in between the two age groups of CI users is of significance with p=0.034 in the TTT P results and p= 0.031 in the TTT F results.

The difference of performances between the younger and older group of children with hearing losses between 25 and 60 dB (analyzed with the Man Whitney *U* test) is of no significance.

6.4.2 TITATU SUBTEST ON VOWELS

Results of hearing aid users and CI users on the TiTaTu vowel subtest have been combined into the groups defined in the beginning of Chapter 6.4.

Analyses have been performed using the Kruskal Wallis test with no significant difference in between the formed groups.

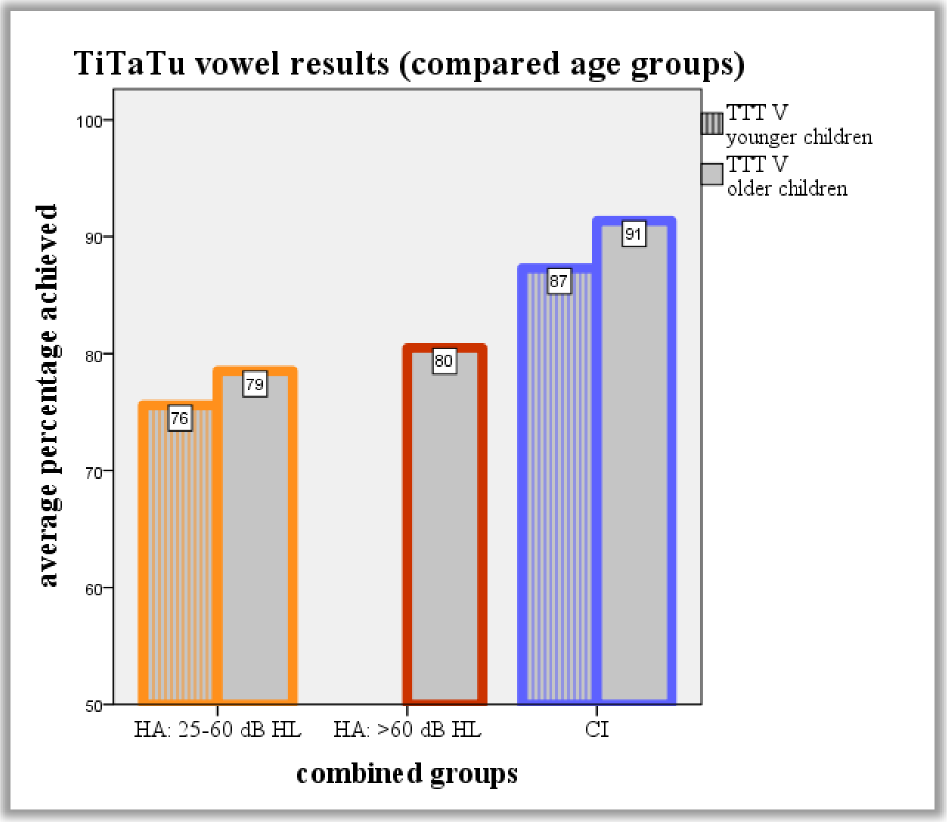

Figure 25: Results on TTT V for combined groups of hearing aid users and CI users categorized by age

Further analyses have been performed to look for differences between younger and older children as defined in Chapter 6.4.1 using the Man Whitney *U* test. For the above mentioned groups related to degree of hearing loss and CI, there is no significant age related improvement in performance on the TiTaTu vowel subtest (see Figure 25). Also, there is no significant difference in between the hearing device groups for children younger than six years or in between the hearing device groups for children of six years and above.

6.4.3 TITATU OVERVIEW

Comparing performances on all three TiTaTu subtests regarding the two groups of hearing aid users as to their "combined" hearing loss and the group of CI users, the discrimination of vowels seems to be easiest, followed by the discrimination of plosives and last fricatives (see Figure 26).

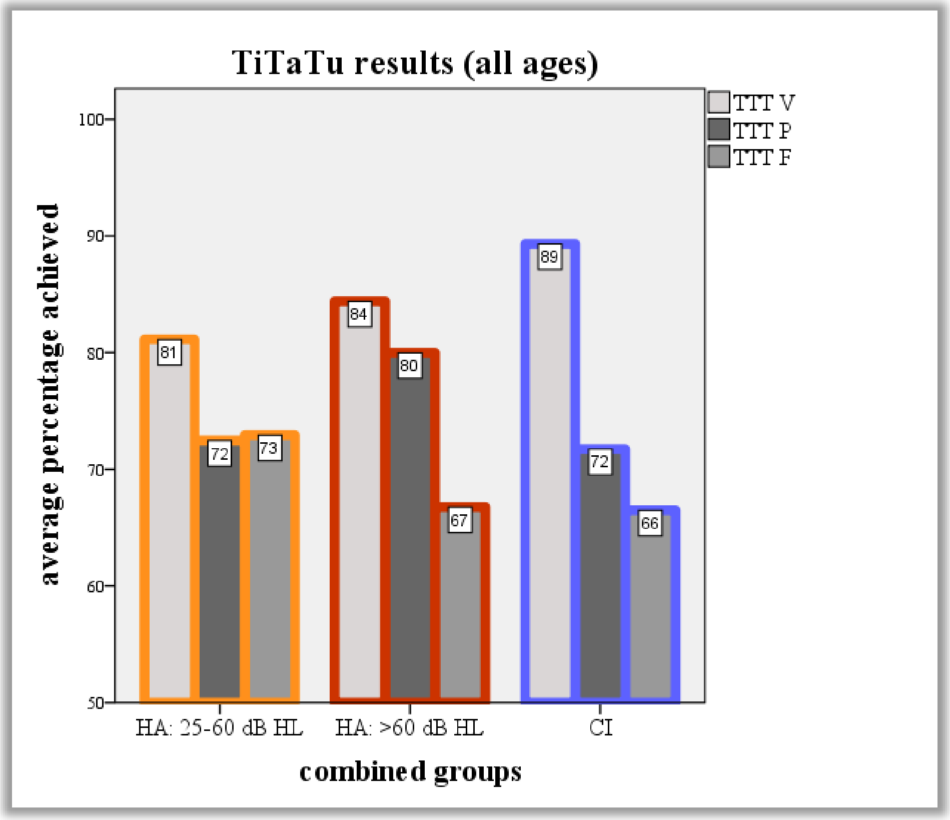

Figure 26: Results on TTT subtests for combined groups of hearing aid users and CI users

6.5 WORD SCORES AND PHONEME SCORES IN SPEECH TESTS AT A FIXED LEVEL OF INTENSITY VS. AAST AND TITATU RESULTS

Correlations between the mentioned subtests included in the BELLS used in the hEARd project, and documented data of speech tests at a fixed level of intensity have been evaluated. As the data is not normally distributed, nonparametric correlation analysis has been carried out using Spearman correlation.

6.5.1 CORRELATION TO AAST

Spearman correlation showed a significant relation between the performances in the **AAST QT** and the achieved word scores on speech tests at a fixed level of intensity, with r_s= -.448. The correlation is significant at the 0.01 level (1-tailed).

No significant relation was found in between the AAST QT results and the phoneme scores of speech tests at a fixed level of intensity.

A significant relation was found in between the **AAST CN** results and the word scores of speech tests at a fixed level of intensity, with r_s= -.383. The correlation is significant at the 0.01 level (1-tailed).

No significant relation was found in between the AAST CN results and the phoneme scores of speech tests at a fixed level of intensity.

A significant relation was found in between the **AAST HF** results and the word scores of speech tests at a fixed level of intensity, with r_s= -.327. The correlation is significant at the 0.01 level (1-tailed).

No significant relation was found in between the AAST HF results and the phoneme scores of speech tests at a fixed level of intensity.

6.5.2 CORRELATION TO TITATU

Spearman correlation showed a significant relation between the performance in the **TTT V** and the achieved word scores of speech tests at a fixed level of intensity, with r_s= -.448. The correlation is significant at the 0.05 level (1-tailed).

No significant relation was found in between the **TTT P** results and the word scores of speech tests at a fixed level of intensity.

No significant relation was found in between the **TTT F** results and the word scores of speech tests at a fixed level of intensity.

No significant relation was found in between any set of TTT results and phoneme scores of speech tests at a fixed level of intensity. However, the number of data sets available was limited to 20.

6.6 MFAST RESULTS

In the hEARd project, the mFAST results were used as information on the gain reached through the use of a hearing aid in four main frequency bands (500 Hz, 1 kHz, 2 kHz, 4 kHz).

Due to the small number of available mFAST results in the groups HA I (n=9), HA III (n=8), and HA IV (n=6), the groups of hearing aid users were combined as described in Chapter 6.4 to groups of hearing losses of 25–60 dB and hearing losses greater than 60 dB.

Sample sizes of the combined HA groups as well as the CI group, their results on the mFAST stimuli and the corresponding unaided PTA values are documented in Table 6.

Groups		500 Hz	COW	1 kHz	DOG	2 kHz	CAT	4 kHz	BIRD	N
HA	Mean	37	24	45	30	48	35	49	31	47
25–60 dB HL	SD	11	9	12	9	11	15	14	14	
HA	Mean	74	30	78	34	80	43	80	38	14
>60 dB HL	SD	18	12	14	10	13	12	15	15	
CI	Mean	-	32	-	36	-	36	-	32	86
	SD	-	10	-	13	-	13	-	12	

Table 6: Average results of combined HA groups and CI groups on mFAST in relation to the average frequency related unaided PTA scores

The illustrated mFAST results of the combined groups of hearing aid users and the group of CI users (see Figure 27) indicate that the CI users performed equally on the identification of all four frequency corresponding animal sounds. For hearing aid users, the identification threshold seems to increase in higher frequency ranges. This effect seems to be greater for the group of hearing aid users with hearing losses above 60 dB HL.

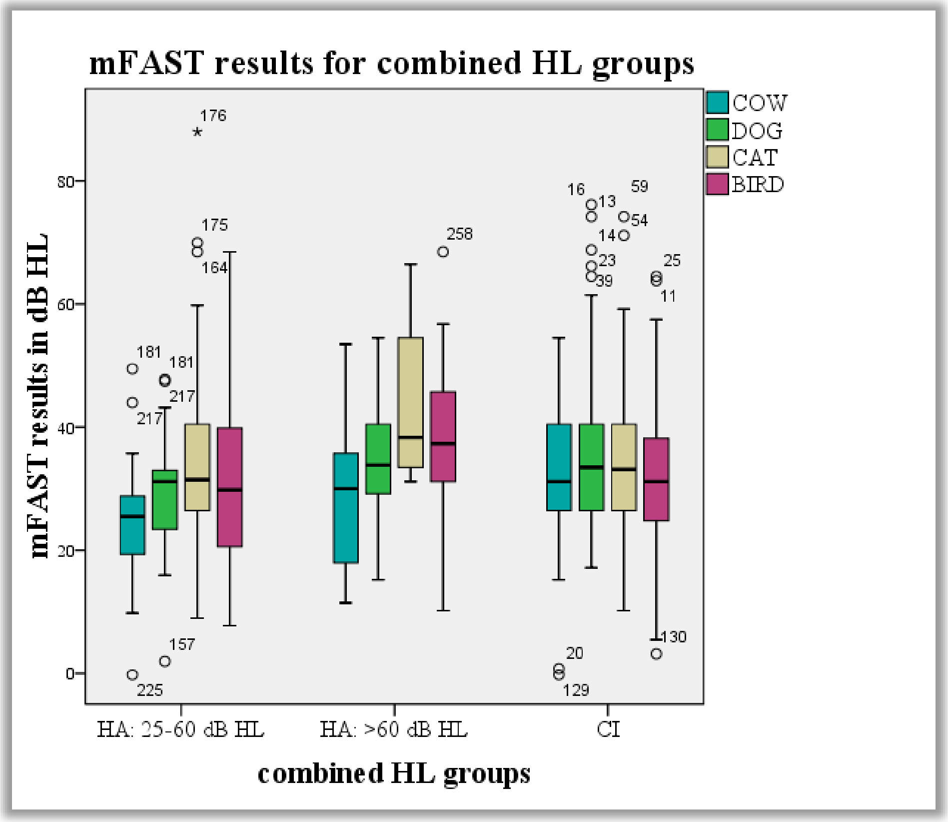

Figure 27: Performance of combined HL groups on mFAST

6.7 SENSITIVITY TO HIGH FREQUENCY PERCEPTION

			AASTHF	TTT P	TTT F	CAT	BIRD	PTA 2-8 kHz	PTA 4-8 kHz
Spearman's rho	AASTHF	Correlation Coefficient	1,000	-,357*	-,067	,568**	,681**	,400**	,403**
		Sig. (1-tailed)	.	,016	,347	,000	,000	,000	,000
		N	80	36	37	63	63	80	80
	TTT P	Correlation Coefficient	-,357*	1,000	,444**	-,435**	-,365*	,046	,073
		Sig. (1-tailed)	,016	.	,004	,005	,017	,396	,336
		N	36	36	34	34	34	36	36
	TTT F	Correlation Coefficient	-,067	,444**	1,000	-,165	-,076	-,170	-,151
		Sig. (1-tailed)	,347	,004	.	,168	,330	,157	,187
		N	37	34	37	36	36	37	37
	CAT	Correlation Coefficient	,568**	-,435**	-,165	1,000	,686**	,297**	,299**
		Sig. (1-tailed)	,000	,005	,168	.	,000	,009	,009
		N	63	34	36	63	63	63	63
	BIRD	Correlation Coefficient	,681**	-,365*	-,076	,686**	1,000	,271*	,303**
		Sig. (1-tailed)	,000	,017	,330	,000	.	,016	,008
		N	63	34	36	63	63	63	63
	PTA 2-8 kHz	Correlation Coefficient	,400**	,046	-,170	,297**	,271*	1,000	,971**
		Sig. (1-tailed)	,000	,396	,157	,009	,016	.	,000
		N	80	36	37	63	63	113	113
	PTA 4-8 kHz	Correlation Coefficient	,403**	,073	-,151	,299**	,303**	,971**	1,000
		Sig. (1-tailed)	,000	,336	,187	,009	,008	,000	.
		N	80	36	37	63	63	113	113

*. Correlation is significant at the 0.05 level (1-tailed).

**. Correlation is significant at the 0.01 level (1-tailed).

Table 7: Results of correlation analyses for high frequency specific subtests for hearing aid users

To analyze the sensitivity of specific subtests of the BELLS – AAST HF, TTT P, TTT F – to hearing losses in high frequencies for the group of hearing aid users, nonparametric correlation analyses have been carried out using the Spearman correlation.

Significant relations were found in between unaided PTA average values of 2–8 kHz and results of AAST HF, with r_s= .400. The correlation is significant at the 0.01 level (1-tailed).

Significant relations were found in between unaided PTA average values of 4–8 kHz and results of AAST HF, with r_s= .403. The correlation is significant at the 0.01 level (1-tailed).

No significant relations were found in between unaided PTA average values of 2–8 kHz and results of TTT P or TTT F.

No significant relations were found in between unaided PTA average values of 2–8 kHz and results of TTT P or TTT F.

As for the correlation between results of the mFAST subtests representing the aided tonal thresholds of the high frequency bands of 2 kHz (stimulus CAT) as well as 4 kHz (stimulus BIRD) and the AAST HF, TTT P, and TTT F subtests, Spearman correlation analyses was performed as well.

Significant relations were found in between aided thresholds of CAT and results of AAST HF, with r_s= .568. The correlation is significant at the 0.01 level (1-tailed).

Significant relations were found in between aided thresholds of BIRD and results of AAST HF, with r_s= .681. The correlation is significant at the 0.01 level (1-tailed).

Significant relations were found in between aided thresholds of CAT and results of TTT P, with r_s= .435. The correlation is significant at the 0.01 level (1-tailed).

Significant relations were found in between aided thresholds of BIRD and results of TTT F, with r_s= .365. The correlation is significant at the 0.05 level (1-tailed).

No significant relations were found in between aided thresholds of CAT or BIRD and results of TTT F.

7. EVALUATION AND DISCUSSION OF RESEARCH QUESTIONS

7.1 HOW DO CHILDREN AT DIFFERENT LEVELS OF HEARING IMPAIRMENT USING HEARING AIDS PERFORM IN THE ADAPTIVE AUDITORY SPEECH TEST?

H1: Analysis of the hEARd project data shows that ***AAST*** *SRT values of hearing impaired children using hearing aids correlate to their unaided hearing loss pure tone average of 500 Hz, 1 kHz and 2 kHz in one ear; better SRT in smaller HL.*

This hypothesis can be accepted. A significant correlation could be found. The lower the unaided hearing loss, the better the AAST SRT value achieved on the AAST in quiet.

Interpreting this correlation, it can be assumed that the average AAST QT performance per average hearing loss, indicated by the trendline in Figure 28, can be used as a guideline on expectable performance with a hearing aid.

Coninx showed in 2005 the validity of the test as a proper tool, to evaluate a child's hearing aid assessment and fitting (with results referring to the testing of bilaterally aided children). The increase of average AAST QT performance from approx. 20–25 dB SPL for hearing loss values of 30 dB to 45–50 dB SPL for hearing loss values of 100 dB appears similar in this study (compare Figure 28 and 29).

Nonetheless, as did the study of 2005, this study also included children that achieved AAST QT results higher than 50 dB, therefore poorer than the expected lowest performance (see also Table 3). In these cases, further analyses and evaluation is needed to identify the factors that influence the perception of speech, especially since these children live in an auditory communication environment and the perception of speech is not influenced by an additional handicap (see Chapter 6.1).

Overall, the performance of children with hearing aids and different levels of hearing loss has contributed to recent robust normative data. Some children performed very well in spite of a moderate to profound hearing loss, but there were also children who performed poorer than expected, although their hearing loss was mild to moderate.

These cases are of great interest for further and individual evaluation, especially regarding the fitting of the hearing aid, as well as the applied educational and therapeutic concepts.

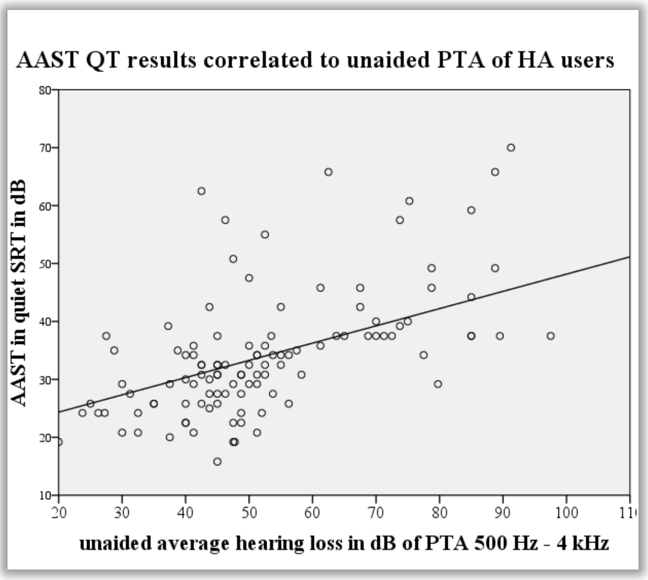

Figure 28: AAST QT results correlated to unaided PTA of HA users

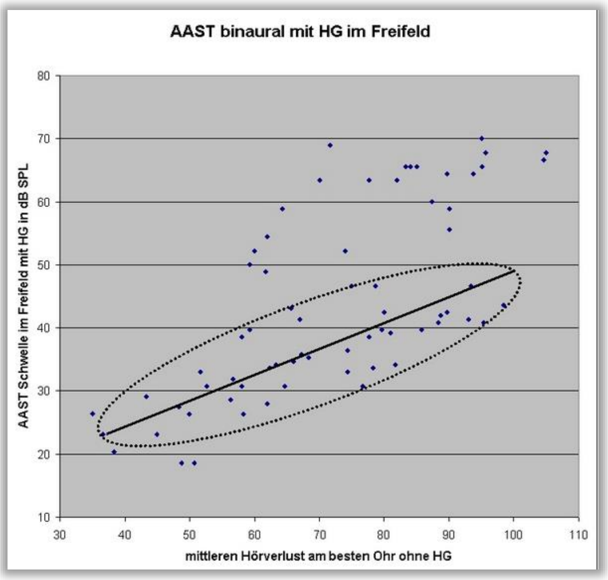

Figure 29: AAST QT results correlated to unaided PTA of HA users (Coninx 2005)

7.2 ABOVE WHICH LEVEL OF HEARING LOSS DOES A CI OFFER BETTER SPEECH PERCEPTION IN QUIET THAN A HEARING AID?

*H2: Children using a cochlear implant (group CI) achieve better results in the **AAST QT** in unilateral testing than children using a hearing aid with a hearing loss*

- *higher than 80 dB(group HA IV).*
- *between 61 dB and 80 dB (group HA III).*

This hypothesis can be accepted. A significant difference could be found for the groups of hearing aid users from group HA III as well as group HA IV in comparison to the CI group, which performed significantly better on the AAST QT. The CI group performed equivalent to the group HA II on the AAST QT.

Looking at different areas of speech perception such as the discrimination of different phoneme groups as tested within the TiTaTu subtests this effect could not be shown to be significant. When analyzing the TiTaTu subtest results for children of six years and older, a tendency of better performance of the CI group, in comparison to the group of hearing aid users with hearing losses higher than 60 dB was observed.

Carrying out speech audiometric tests in quiet, it can be concluded from the above mentioned results that children with hearing aids and hearing losses higher than 60 dB perform poorer than children with CIs.

7.3 DO CIS OFFER BETTER PERFORMANCE OF SPEECH PERCEPTION IN NOISE THAN HEARING AIDS?

H3: Children using a cochlear implant (group CI) achieve better results in the ***AAST CN*** *in unilateral testing than children using a hearing aid with a hearing loss*

- *higher than 80 dB(group HA IV).*
- *between 61 dB and 80 dB (group HA III).*

This hypothesis has to be rejected. No significant difference was found in between the test results of the group HA III as well as group HA IV in comparison to the CI group.

The performance of the CI group on speech perception in noise appears low in comparison to their "overall" performance within the project. Speech perception in noise seems to be a great challenge for children using CI.

Further analysis should include test results from a bilaterally aided setup, especially in noise, but also in quiet to compare the effect. Also, closer analyses on hearing aid fittings and CI fittings should follow, to look for influences by specific features, such as noise reduction.

7.4 ARE THERE CORRELATIONS BETWEEN PTA VALUES IN THE HIGH FREQUENCIES AND THE AAST AND TITATU SUBTESTS USING HIGH FREQUENCY SPEECH MATERIAL

H4: A correlation can be found in between the results of the ***AAST HF,*** *the* ***TiTaTu P****, the* ***TiTaTu F,*** *and the average unaided PTA values of*

- *2 kHz and higher*

- *4 kHz and higher*

as in; higher average PTA values resulting in poorer subtest results for the group of hearing aid users.

This hypothesis can partially be accepted. The relation between unaided PTA values of 2–8 kHz as well as 4–8 kHz is significant to the AAST HF results. There is no significant relation between the unaided PTA values mentioned above and the TTT subtests.

For children using hearing aids it can be concluded that the AAST HF is an adequate measuring tool to evaluate the auditory speech perception skills of speech elements in the high frequency range. Although no correlation could be found between the unaided hearing losses in the higher frequencies (as defined above) and the TiTaTu subtests regarding the high frequency phonemes, a correlation analysis between the TTT P and aided tonal thresholds in these frequencies assessed with mFAST resulted in significant findings.

To evaluate a hearing aid fitting within these high frequencies, the AAST HF appears to be a highly sensitive test. The TiTaTu can give additional information on the perception of specific phoneme groups.

7.5 IS THERE A SIGNIFICANT DIFFERENCE BETWEEN CI USERS AND HA USERS IN DISCRIMINATING AND IDENTIFYING HIGH FREQUENCY SPEECH MATERIAL?

H5.1: Children using a cochlear implant (group CI) achieve better results in the ***AAST HF*** *in unilateral testing than children using a hearing aid with a hearing loss*

- *higher than 80 dB (group HA IV).*
- *between 61 dB and 80 dB (group HA III).*

This hypothesis can be accepted. A significant difference could be found for the groups of hearing aid users from group HA III as well as group HA IV in comparison to the CI group, which performed significantly better on the AAST HF. The CI group performed equivalent to the group HA II on the AAST HF.

*H5.2: Children using a cochlear implant (group CI) achieve better results in the **TiTaTu test** in unilateral testing than children using a hearing aid with a hearing loss*

- *higher than 80 dB (group HA IV) in the **plosive** subtest.*
- *between 61 dB and 80 dB (group HA III) in the **plosive** subtest.*
- *higher than 80 dB (group HA IV) in the **fricative** subtest.*
- *between 61 dB and 80 dB (group HA III) in the **fricative**.*

This hypothesis has to be rejected. The CI users do not perform better than hearing aid users with unaided hearing losses above 60 dB. Analysis within the groups defined above was not performed due to the low number of test results. Overall, the group of CI users does appear to perform mostly equivalent to the groups of hearing aid users. Also, the results are very heterogeneous and partially show age dependent effects.

The advantage of perception in the high frequency range does not seem to influence the ability of discriminating phonemes, when relating the AAST HF results to the TTT P and TTT F results.

The TiTaTu results for the sets of plosive and fricative discrimination showed a poor performance of the CI users. Overall, the discrimination on the vowel set was easiest for all groups, followed by discrimination of plosives and most difficult for the group of fricatives. A possible effect of ongoing phonological development was addressed in an age dependent analysis. Comparing performances of the above mentioned groups (HA groups and CI) for children over the age of five, results appeared to show a positive development with age within the CI users.

Overall, the performances on the three TiTaTu subtests seem to relate to the observations on phonological development in general. One possible factor of influence could be an effect of delayed phonological development for hearing impaired children in specific. Cochlear implanted children in this study show, on an average, an improved performance on the TiTaTu plosive test set at an older age. This observation relates to studies on phonological development in cochlear implanted children (Kral et al., 2014). The production of fricatives seems to be most difficult within the groups of phonemes in the study of (Stelmachowicz et al., 2004) which is supported by findings of (Eisenberg, 2007). The study of (Kral et al., 2014) shows that two out of the five most frequently assessed deficient processes for the tested group of cochlear implanted children using the PLAKSS test, were related to the phoneme group of plosives. Processes included devoicing and fronting.

Differentiating voiced and voiceless plosives is a necessary auditory ability to perform the TiTaTu plosive subtest correctly, since it included the phonemes /p,t,k,b,d,g/. A problem that has been mentioned to be of influence in cochlear implanted children's language development is the perception of sonority and the production of sonorant speech material. The speech material that needs to be identified in the AAST HF differs in fricatives mostly, but also in voiceless plosives.

The presented data shows that the TiTaTu plosive set addresses the described problem of plosive discrimination in CI users.

7.6 ARE THERE CORRELATIONS BETWEEN WORD SCORES AND PHONEME SCORES IN SPEECH PERCEPTION TESTS AT A FIXED LEVEL OF INTENSITY AND AAST WORD SCORES AND TITATU PHONEME SCORES

H6.1: A correlation can be found in between the word scores of open set speech tests at a fixed level of intensity and the results of the

- ***AAST QT*** *(the better the AAST QT result, the higher the word score).*
- ***AAST HF*** *(the better the AAST HF result, the higher the word score).*

This hypothesis can be accepted. A significant relation was found in between the AAST QT as well as the AAST HF results and the word scores of speech tests at a fixed level of intensity.

As a correlation in between the AAST QT/ AAST HF and word scores of speech tests at a fixed level of intensity, the AAST can be seen as a suitable and sensitive test for the evaluation of hearing devices. One advantage in testing children is the comparability over a long period of time. The performance is independent from further language development, especially vocabulary (see Chapter 3).

Choosing between an adaptive test like the AAST and a speech test/ word test at a fixed level of intensity depends nonetheless on several factors, mainly the diagnostic goal. A test at a fixed level of intensity ise suitable when the performance at a certain intensity is of interest, for example, the perception of speech at a lower level, for example 50 dB. This allows an interpretation on speech perception in daily situations, such as understanding speech over distance. For this type of evaluation, testing of more natural speech material – sentences for example – could, however, be more suitable than words.

Further analyses showed that the AAST QT results and phoneme scores – as used in Belgium and the Netherlands – correlate in a significant way. Looking at the illustration of this correlation in Figure 30, the tendency of a ceiling effect can be seen for the phoneme scores. At the same time, the results of the AAST QT differ strongly from the performance on the open set speech test in some cases. Children perceiving 100% of the presented phonemes, achieve AAST SRT results, varying between 20 dB and almost 50 dB. At the same time, there are children who perform poorly on the open set speech test and achieve AAST SRT values in the lowest area. These findings should be analyzed further to find possible influencing factors, such as age and language development.

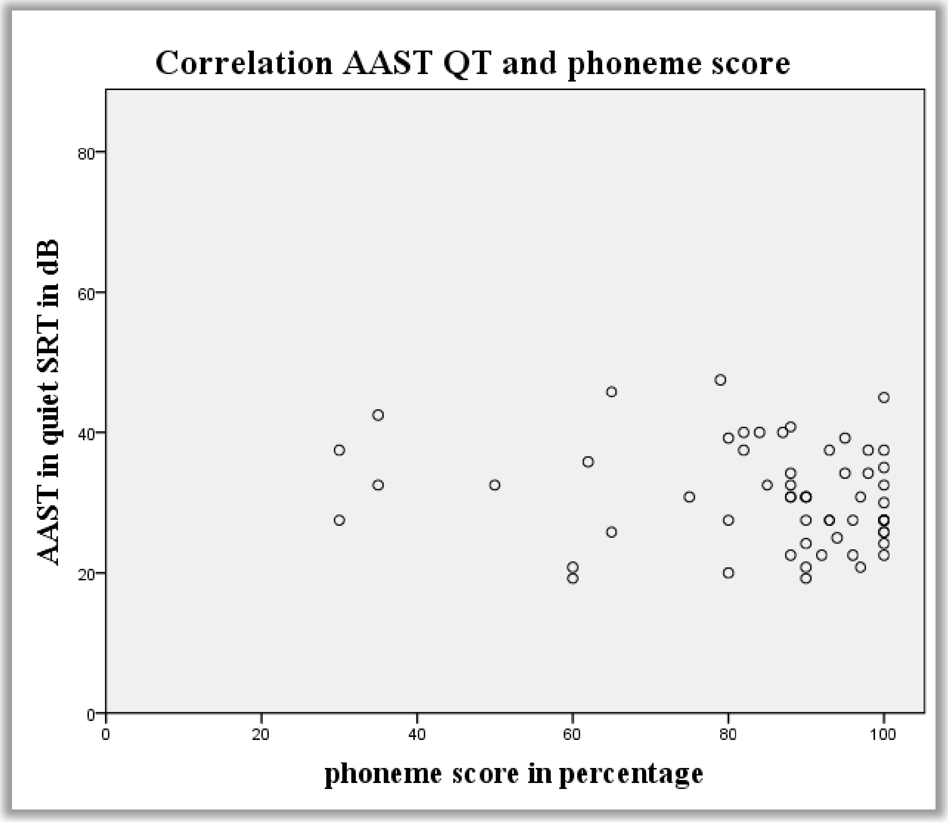

Figure 30: Correlation of AAST QT results vs. phoneme scores on speech tests at fixed level of intensity

H6.2: A correlation can be found in between the phoneme scores of open set speech tests at a fixed level of intensity and the results of the

- ***TiTaTu V** (the better the TiTaTu V result, the higher the phoneme score).*
- ***TiTaTu P** (the better the TiTaTu P result, the higher the phoneme score).*
- ***TiTaTu F** (the better the TiTaTu F result, the higher the phoneme score).*

This hypothesis has to be rejected. No significant relation was found in between the TiTaTu subtest results and the phoneme scores of speech tests at a fixed level of intensity.

Further analyses with a larger data set appear necessary to look for possible relations in between the mentioned tests. However, the above mentioned effects of age and phonological development in general should be taken into account when evaluating the TiTaTu results.

8. FURTHER RESEARCH – DEVELOPMENT OF WRIST

8.1 BACKGROUND – TESTING "HIGHER" LEVELS OF HEARING

Within the preparation of the hEARd study, another question came to mind. From the daily clinical routine in interpreting speech audiometric test results it seems that there are children with similar results, e.g. in their SRT measurements, maybe even in the speech audiometry tests in noise. However, when it comes to a higher linguistic level, there seem to be great differences in the (auditory) abilities of understanding spoken language in daily life.

For therapeutic practice we need more information on what functional auditory perception skills a child can use in meaningful daily situations, such as school, kindergarten or free time activities. Discourse conveys a lot of information and from the existing speech audiometric test material it cannot certainly be said, how a child perceives these.

The available data of (speech) audiometric test material collected within the hEARd project gives information about *detection* skills (detection threshold of pure tones), *identification* skills (e.g. identification of animal sounds – mFast; consonant-vowel combinations – TiTaTu; words in a closed set – AAST) and *speech recognition of words in an open set* (e.g. Freiburger, Göttinger, Mainzer; NVA word lists).

8.1.1 HEARING IN DAILY LIFE – "UNDERSTANDING" SENTENCES

As a linguistically more complex audiometric test material sentences come to mind, to give a better impression of a child's competence in hearing and understanding spoken language in daily life. A common example for a sentence test is the Oldenburger Kinder Satztest which is described in Chapter 2. Compared to daily life speech, the material still seems unnatural, since the sentences are not meaningful because there is no relation between a subject and a predicate.

The HSM as well as the Göttinger sentence material for German language offer more complexity, as do the Plomp or Versfeld sentences for speech audiometry in the Netherlands, or the LIST for Dutch test material in Belgium. The sentences seem natural and follow a complex and varying syntactical structure, comparable to daily speech.

The ability to recognize sentences, based on auditory perception skills, is facilitated by higher linguistic and cognitive skills and does require more than merely the simple recognition of words presented in isolation, which is a common task in standard auditory speech perception procedures (see Chapter 3). The above mentioned tests address adults more than they address children. Owing to their still ongoing language development, often delayed due to hearing impairment, the material is too difficult for many children.

Delays and difficulties in spoken language development of hearing impaired children need to be regarded as important influential factors in using more complex sentence based speech audiometric material.

Within the hEARd project in auditory perception evaluation a wide range of perception abilities has been assessed. To assess the functional auditory benefit of a device in more demanding listening environments, the incorporation of a more complex speech test using sentences appears to be a reasonable extension of the hEARd test protocol.

8.1.2 AUDITORY SKILLS IN ANALYZING SENTENCES

To analyze the competence of hearing and understanding of spoken language in daily life the perception of continuous speech (and continuous speech in noise) should be assessed.

For that reason, the new developed test material uses a more complex level of speech, in this case sentences.

The meaning of a sentence is understood by analyzing the meaning of words in the sentence. To analyze the meaning of a word, it needs to be perceived auditorily as one unit within the sentence. It can be concluded that one important auditory skill in interpreting sentences is the auditory segmentation of single words out of the speech flow.

When the meaning of the words in a sentence has been analyzed, the context as a relation of the words needs to be interpreted. Linguistic and cognitive developments influence this ability. However, words as units within a sentence need to be kept in the auditory memory until an interpretation based on (linguistic) knowledge is successful. The development of auditory memory can be concluded to be another highly important auditory skill in interpreting sentences.

8.1.3 SEGMENTATION – AUD. MEMORY

DEVELOPMENT OF SEGMENTATION SKILLS:

Looking at the acoustical properties of speech, supra-segmental properties have a great impact on the development of auditory speech perception in children. Prosodic elements of speech are perceived even before birth (Schröder & Höhle, 2011).

The skill of segmentation develops early in normal hearing children. The strategy initially seems to develop out of the analysis of prosodic patterns of a language as well as other factors (Jusczyk et al., 1999) by focusing on the recognition of word boundaries. Recognizing such a boundary seems easiest due to a short pause after each word. In natural speech, however, co-articulation influences this aspect. Also, pauses after syllables can be observed. Another prosodic attribute in identifying word boundaries within the speech flow is the intonation, which on a word level – depending on a language – is often connected to the metric structure of a word, e.g. the commonly trochee in English and German. Knowledge of phonetic and morphological structures in terms of frequency of occurrence and possible combinations within a language is to be mentioned as another influential factor for the development of segmentation abilities (Jusczyk et al., 1999).

The syntactical nature of a sentence puts the emphasis on certain words (independent from the metric properties of these words) in comparison, by increasing intensity and/or change in frequency of one's voice.

As shown in research of (Newman et al., 2006); (Schröder & Höhle, 2011; Jusczyk et al., 1999), early segmentation abilities interact with the development of a child's vocabulary, which as a counter-effect supports the segmentation skills through top-down processes (familiar words are easier to detect and segment than unfamiliar words). The (early) skill of auditory segmentation also seems to have an impact on the knowledge of syntactical structures and is a meaningful component of the phonological awareness.

SEGMENTATION SKILLS IN HEARING IMPAIRED CHILDREN:

Based on the acquisition of early segmentation skills due to knowledge of metric properties of words within a language, we would expect this skill to not be sufficiently developed in hearing impaired children. Especially, the "schwa"-syllables, typical of the language and the metric structure of many German words, are not emphasized in speech and often undergo co-articulation with voiced consonants such as labials and nasals, which have little acoustical intensity. The acquisition of knowledge about phonetical and morphological structures is likely to be influenced by hearing impairment as well, especially in word endings (see above). The perception of word boundaries seems to be complicated in cases of hearing impairment; therefore, one could expect the development of segmentation skills to be influenced by hearing impairment.

On the other hand, we know that for individuals with hearing impairment the focus on target words within sentences is the most commonly used strategy in the auditory analysis of sentences to follow a conversation. With this strategy first the semantic topic of a conversation can be deduced quickly. Even though the strategy is not sufficient when it comes to a complete interpretation of a sentence, since the syntactical analysis gives detailed information about the true meaning of it (negation, temporal marks etc.), research shows that hearing impaired adults use these strategies in analyzing language/sentences in the opposite order than normal hearing individuals (Friederici et al., 2010; Hahne et al., 2012).

Looking at the impact on different linguistic levels and their development, an early diagnostic and training of auditory segmentation skills seems necessary as it is one probable factor to explain the differences in performance in terms of understanding spoken language as well as being part of spoken language development.

Talking to hearing impaired adults about the speaking characteristics of their communication partner, they often prefer slow speakers – not unnaturally slow but not hasty – with a good pronunciation –not unnaturally but no mumbling. Segmentation of words out of the speech flow seems to be a persistent problem for a hearing impaired person, which substantiates a focus on this skill in audiometric testing.

AUDITORY MEMORY:

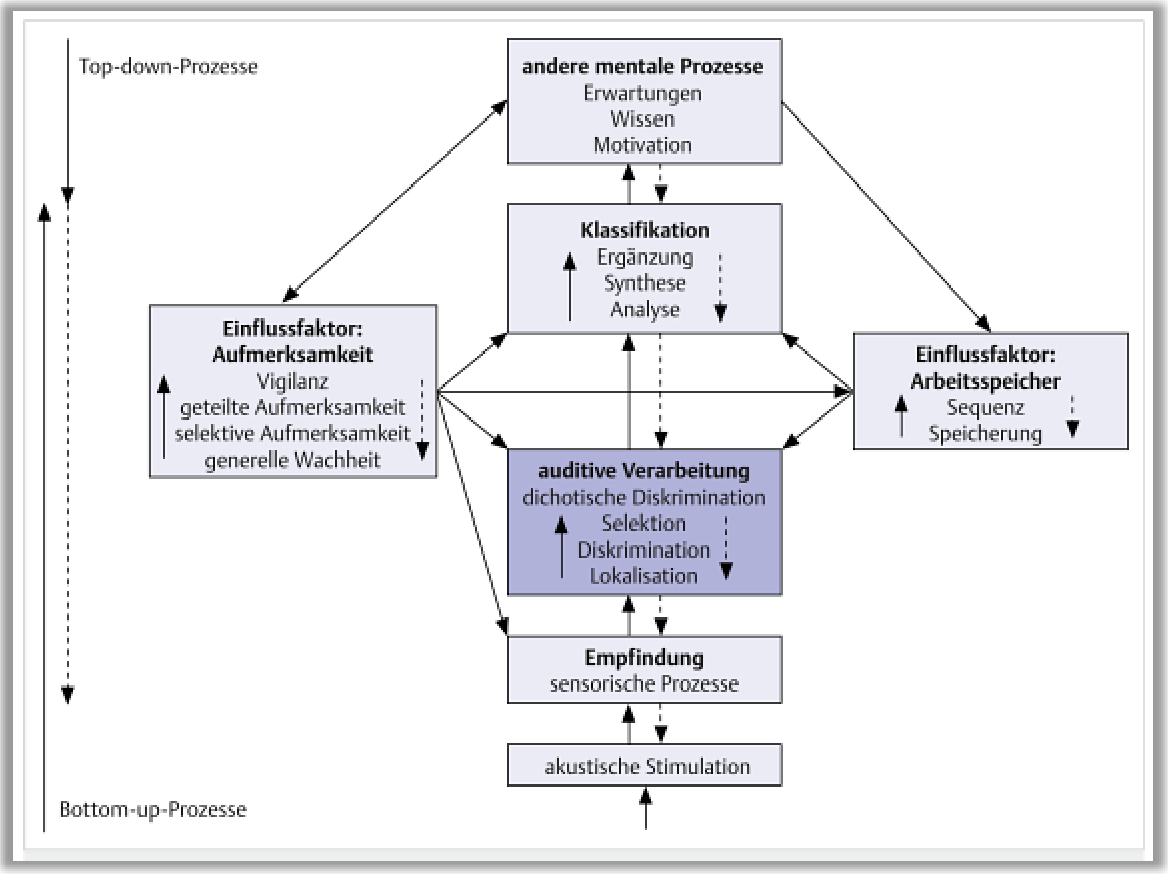

Figure 31: Model of auditory processing, its influential factors and following classification processes (Lauer 2014)

Using the model of auditory processing by (Lauer, 2014), presented in Figure 31, the interaction of bottom-up-and top-down-processes is described. The superordinated top down-process (linguistic) knowledge plays a part in analyzing acoustical stimuli, based on basic cognitive competences, as well as the necessary linguistic input, to acquire this knowledge.

Looking at the required auditory processes in analyzing sentences as a more complex speech material, perception as the peripheral part of hearing is followed by auditory processing and the capacity of auditory memory of perceived linguistic information, therefore more central parts of hearing and central processing in general.

In the interpretation of a sentence or even an ongoing conversation, an influential factor is the ability to keep the perceived auditory information in the working memory long enough to proceed with processing, classification, and final interpretation. The auditory input needs to be memorized long enough to be matched to its meaning. With more than one fact is available, a sensible connection between two words needs to be found, to interpret the information correctly.

In hearing impaired children and adults the analysis of bottom up information is complicated based on the fact that the information is usually incomplete or compromised. When fragments of the auditory perceived language are missing, a longer comparison of the auditory input with the available mental lexicon is necessary, to find words fitting the context to comprehend the meaning of a sentence. The working memory is occupied more intensely.

Understanding this difficulty is important, as studies show that the auditory memory is often poorly developed in hearing impaired children (Dawson et al., 2002).

8.1.4 CRITERIA FOR DEVELOPMENT OF A COMPARABLE SENTENCE TEST AS PART OF BELLS

Available sentence tests as the ones mentioned above are often too complex for children with difficulties in language development due to three main factors (amongst others):

- Not all words used are in a child's **vocabulary**
- Complex **syntax**
- Sentences are too long to be kept in **auditory memory**

Verbal repetition for the above mentioned reasons is highly problematic, the aspect of impaired expressive phonological development is not even considered.

The restrictions in the use of available sentence tests formed the criteria in the development of a test usable in the BELLS software, comparable in different languages that assess auditory skills of children in understanding *more complex speech material*.

The main goal of the test is to assess the auditory segmentation skills and auditory memory skills of children in continuous meaningful speech. The construction of the test aims to assess these two abilities while minimizing the strains on cognitive and linguistic capacities.

Requirement 1: BELLS compatible test design

In all hEARd tests, each auditory stimulus is associated with and represented by one picture. The test should be carried within a similar format due to the same positive aspects of response mode, guessing chance, child's motivation, and time efficiency, as well as the child's familiarity with the test mode.

Requirement 2: Avoid language testing

The test should provide information on the segmentation skill, not the vocabulary. The target words to be segmented out of a speech flow should be within a child's vocabulary. Furthermore, a semantic/ lexical connection between the target word and the sentence should be avoided, to focus on auditory skills, not interpretation based on linguistic knowledge.

Requirement 3: Validity – test for auditory segmentation and memory

Hearing impaired children have more difficulties in the segmentation of words out of a sentence than normal hearing children. They also have a limited auditory memory in comparison to normal hearing children. The test needs to show this effect, to document different developmental stages of this skill.

Requirement 4: Offer different levels of difficulty

Following the prosodic pattern of a sentence, segmentation of a target word is easier, if the pattern is consistent. To analyze the word segmentation skill in natural speech flow, the used sentences should vary in their syntactical structure and their length, not falling below a certain number of words per sentence, to keep up the difficulty of the task. At the same time, the syntactical structure should not be too complex, to meet the linguistic competences of children aged four years and above.

8.2 WRIST – WORD RECOGNITION IN SENTENCES TEST

The listed requirements have been considered in the development of the Word Recognition in Sentences Test – WRIST.

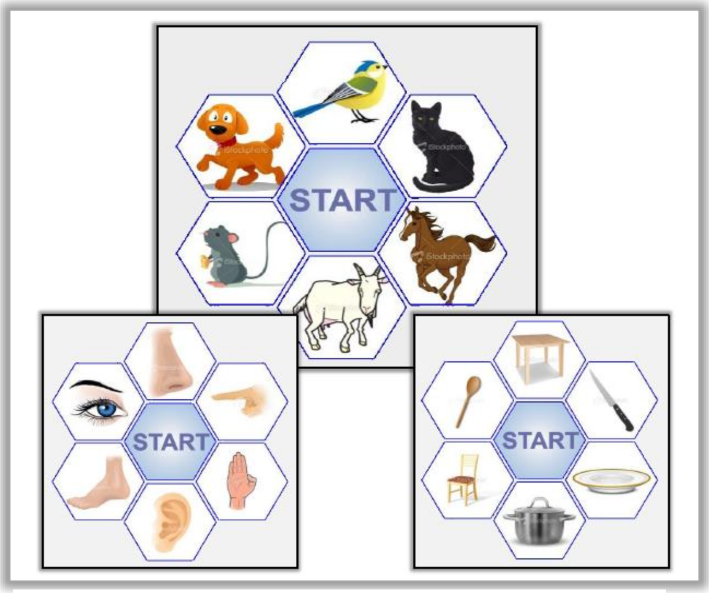

Figure 32: German test sets WRIST

The test layout is based on the AAST interface. Six pictures represent six simple target words with a high probability of being known to children four years and above. These words are all derived from one semantic field. One or more of the target words appear in sentences of different levels of complexity which are offered to the child acoustically. The child responds by clicking on one or more of the pictures. All stimuli are presented at a level of intensity that is comfortable to the child. Adjustments can be made between 65 dB, 70 dB, and 75 dB. Speech examples are presented to fit the level of intensity prior to the actual testing.

The WRIST offers auditory segmentation and memory tasks at different levels of difficulty and complexity. It tries to assess the individual interaction between segmentation skills and auditory memory in a child using different test settings:

- ➔ Focus on segmentation; participation of auditory memory kept to a minimum
- ➔ Focus on auditory memory; necessity of segmentation kept to a minimum
- ➔ Combining segmentation skills and auditory memory in one task

These different levels of segmentation and/or auditory memory abilities are assessed in four different WRIST subtests.

SEGMENTATION I:	single word segmentation in strict syntactical structure
SEGMENTATION II:	single word segmentation in varying syntactical structure
SEGMENTATION III:	multiple word segmentation in varying syntactical structure
AUDITORY MEMORY:	auditory memory of keyword strings in a sentence pattern

To avoid learning effects in retest situations, the test material is available in a variety of semantically themed test sets; “animals”, “body parts”, and “kitchen utensils” are examples of German test sets as seen in Figure 32. Only one of the themes is presented to an individual participant in one test session.

The keywords within one test set are of different lengths and prosodic structure. In the German version, the stimuli within a group consist of three disyllabic words and three monosyllabic words.

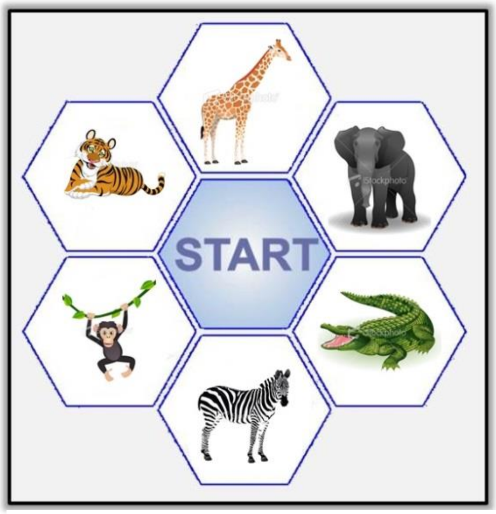

Figure 33: WRIST test screen for English test set “zoo animals“

In the English version, the stimuli within a theme consist for example of three disyllabic words and three trisyllabic words (Figure 33).
The following description of the test construction refers to examples of the English test set.

8.2.1 SEGMENTATION I (SEG I)

Single word segmentation in strict syntactical structure

The aim of this level is to verify if the target words/ keywords used in the subtests, are within the receptive vocabulary (spoken language) of the child and to assess whether the words can be segmented and identified in a relatively easy sentence environment (keyword as last word in a simple short carrier phrases). Also, the child gets familiar with a test environment.

TASK: Identify one keyword out of a simple sentence.

STIMULI: Six phrases (sentences as well as questions) are presented using the same simple syntactical structure. One keyword is presented per phrase, always represented as the last word. The phrases are of inviting character referring to the response mode.

EXAMPLE:

Show the ***tiger.***

Where is the ***elephant?***

RESPONSE: The child is to point or click at the picture corresponding to the keyword.

TEST RESULT: The result is given in percent correct.

8.2.2 SEGMENTATION II (SEG II)

Single word segmentation in varying syntactical structure

THE AIM of this level is to assess the skill of segmenting a keyword out of continuous meaningful speech.

TASK: Identify one keyword out of a more complex sentence.

STIMULI: Twelve sentences are presented, either made up of independent clauses, or dependent clauses. All information in the sentence is necessary to identify the correct keyword. Context information on itself is not enough to deduct which word is the correct stimulus. In each sentence at least three keywords are plausible. Within the list of sentences, the keyword in each sentence is positioned as differently as possible. However, they are not placed either at the start or at the end of the sentence as the perception on these positions seems to be easier.

There are two levels of difficulty concerning the stimulus presentation; stress on keyword as a lower demand on the segmentation skill – stress on a different word, as a higher demand on the segmentation skill. Six sentences are presented per level of difficulty (stressed – unstressed) leading to two sentences per keyword. All stimuli are presented randomly.

EXAMPLE A – stress on keyword (SEG II A):

The little ***chimpanzee*** *has soft fur.*

Yesterday I saw a ***tiger*** *at the zoo.*

EXAMPLE B – stress different word (SEG II B):

The little ***chimpanzee*** *has soft fur.*

Yesterday I saw a ***tiger*** *at the zoo.*

RESPONSE: The child is to point or click at the picture corresponding to the keyword.

TEST RESULT: The result is given in percent correct.

8.2.3 SEGMENTATION III (SEG III)

Multiple word segmentation in varying syntactical structure

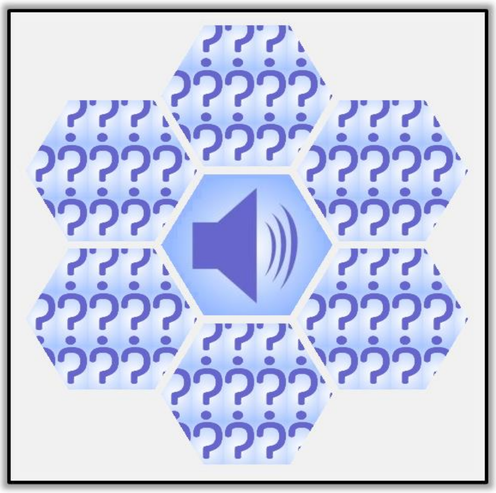

Figure 34: "Hidden" test screen in auditory memory task of WRIST

THE AIM of this level is to assess the skill of segmenting two keywords out of continuous meaningful speech; auditory memory skills are involved increasingly.

TASK: Identify two or three keywords out of a more complex sentence.

STIMULI: Two levels of difficulty are implemented. At the first level, two keywords are to be segmented out of each sentence. At the second level, three keywords are to be segmented out of each sentence. The sentences are either made up of independent clauses or dependent clauses.

All information in the sentence is necessary to identify the correct keyword. Context information by itself is not enough to deduct which word is the correct stimulus. In each sentence, interchanging of the keywords remains a plausible sentence. Within the list of sentences, the keywords are positioned as differently as possible. For each level, six sentences are available and each keyword is presented twice.

EXAMPLE A – two keywords (SEG III A):

*The **zebra** and **giraffe** both live in the jungle.*

*Look, the **chimpanzee** is sitting with the **elephant** that is eating.*

EXAMPLE B – three keywords (SEG III B):

*The **zebra** and **giraffe** both look at the **tiger** in the crate.*

*In the morning they first fed the **tiger**, then the **crocodile,** and then the **giraffe**.*

RESPONSE: The child is to point or click at the pictures corresponding to the keywords.

TEST RESULT: The number of recognized words determines the test result; the order of the chosen words is documented, but has no influence on the result, since the auditory memory is influencing this task, but the testing is addressing segmentation skills. The result is given in percent correct.

8.2.4 AUDITORY MEMORY (AM)

Auditory memory of keyword strings in a sentence pattern

THE AIM of this level is to assess the auditory memory span for keywords that are presented in a close to natural speech flow.

TASK: Identify as many keywords as possible in the presented order out of a natural speech flow.

STIMULI: Strings of keywords (varying number of syllables in the words; equally spread and mixed in one list) that are spoken in natural sentence prosody and conversational speed. The last word is preceded by the word “and” to obtain a more natural sentence pattern. During the auditory presentation of a stimulus, the picture set is hidden to avoid the use of visual cues or strategies by the child (see Figure 34).

The length of the stimuli increases or decreases following an adaptive procedure. The first item consists of two keywords. Following a correct identification, in the right order of the keywords, the next stimulus consists of one more keyword. The length of the string of keywords is increased to a maximum of six. After a mistake, two keywords less are presented in the next string, with a minimum of two. In one word string, each key word is presented only once. Strings of keywords are presented randomly. After five subsequent mistakes the test is finished.

EXAMPLE:

Elephant *and* ***zebra.***

Tiger, giraffe, *and* ***chimpanzee.***

Crocodile, zebra, tiger, *and* ***giraffe.***

RESPONSE: The child is to point or click at the pictures corresponding to the keywords in the same order as they have been presented. The number of recognized words determines the test result; the order of the chosen words is documented, but has no influence on the result, since the auditory memory is influencing this task, but the testing is addressing segmentation skills.

TEST RESULT: The result is given as a threshold of auditory memory span of keywords calculated from the adaptive procedure, similar to assessment of results in the AAST.

8.3 PRELIMINARY RESULTS

In a preliminary study, 40 normal hearing children and 17 children with hearing impairment have been tested with the WRIST in German kindergartens.

The group of hearing impaired children was extremely heterogeneous. They differed in age, type of hearing aid device used, degree and onset of hearing loss, as well as spoken language development and global development. However, the heterogeneity of the group could give information if the WRIST was too difficult for a certain clientele or if it could be used for children from the age of four years despite their unique background.

Within the group of normal hearing children, spoken language development, and a possible influence of bilingual upbringing was not assessed before testing.

All children tested were between the ages of four and six years (see Table 8).

Age	NH	HI
4;00–4;05	3	0
4;05–4;11	1	0
5;00–5;05	14	3
5;06–5;11	15	7
6;00–6;05	7	5
6;06–6;11	0	2
∑	40	17

Table 8: Number of normal hearing children (NH) and hearing impaired children (HI) in age groups

In evaluating the performances of the two groups, statistically significant correlations or differences could not be found in all explorative analyses, partially due to the low number of individuals tested in the group of the hearing impaired. However, the following trends can be observed.

SEGMENTATION SKILLS:

Overall, the degree of difficulty seems to increase within the subtests for auditory segmentation, as anticipated. The segmentation of one keyword out of a carrier sentence seems to result in a ceiling effect for the group of normal hearing children.

For the hearing impaired group there appears to be a higher difficulty in the segmentation of words from within the center of a sentence (SEG II) than from the end of a sentence (SEG I), see Figure 35. This effect has been observed by (Seidl & Johnson, 2006). However, a simpler syntactical pattern in subtest SEG I could be another reason for this effect in this group.

For the hearing impaired group as opposed to the normal hearing group, it also appears to be a factor of influence whether a target word in a sentence is emphasized or not. A difference appears to exist in between results of subtest SEG II A (stress on keyword) and subtest SEG II B (stress on other word) for the group of hearing impaired children (see Figure 35). This difference is not significant.

The level of difficulty seems to increase from the task of segmenting one word (SEG II) to the segmentation of more than one word (SEG III) out of a sentence. There is a significant difference for the group of hearing impaired children in between the performance of the two subtests (p=0.000), this significance is also found within the group of normal hearing children (p=0.000).

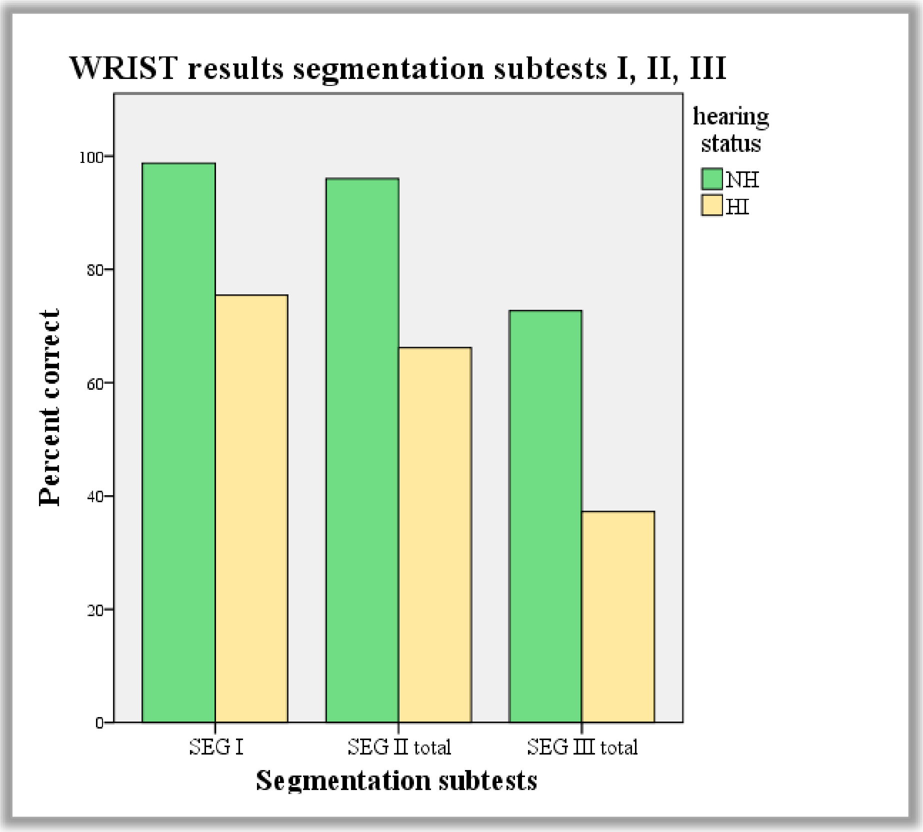

Figure 35: WRIST results segmentation subtests I, II, III

A difference in performance is to be found for segmentation tasks of two words (SEG III A) and the segmentation of three words (SEG III B) out of a carrier sentence. This effect is significant for normal hearing children (p=0.000). For the hearing impaired group, the difference between the subtests shows a large effect, but no significance for $p<0.05$ (p=0.064).

Overall, the group of hearing impaired children performs significantly poorer in all five subtests on auditory segmentation of words within sentences than the group of normal hearing children of similar age (see Figure 36).

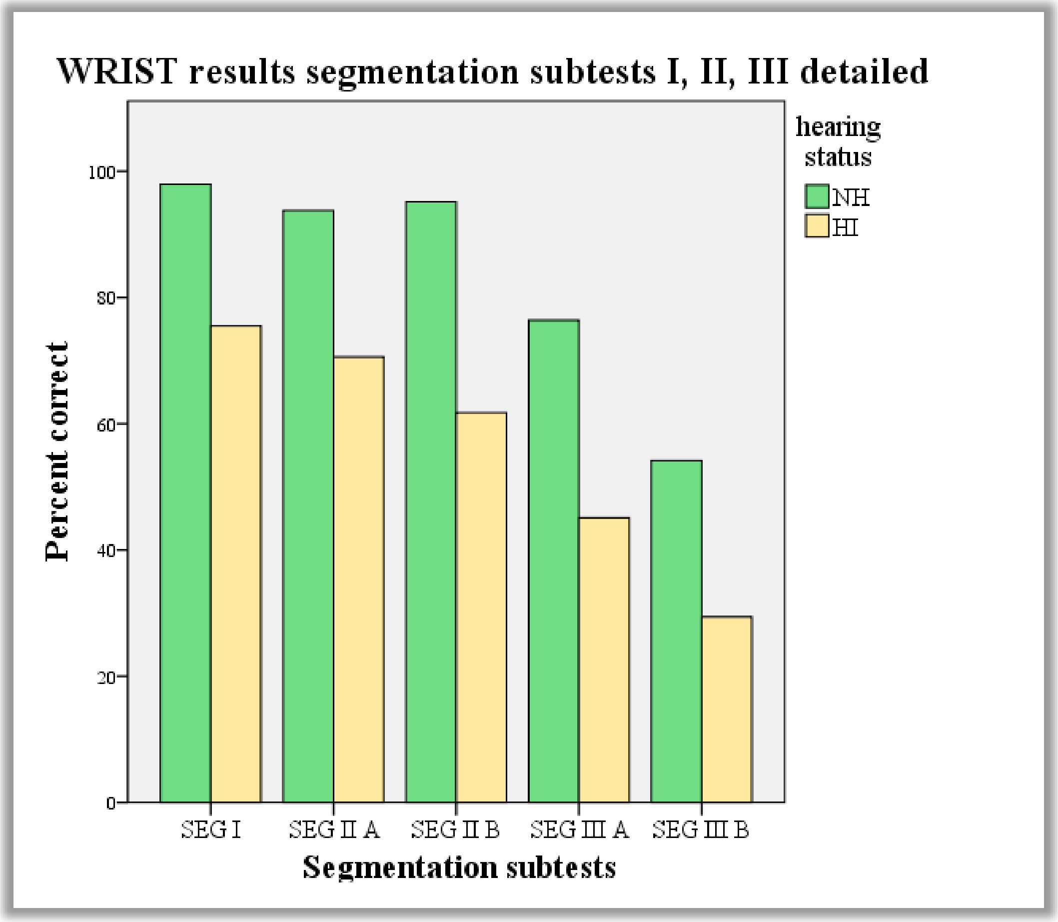

Figure 36: Results of WRIST segmentation subtests

AUDITORY MEMORY:

In analyzing the results on auditory memory span assessed with the WRIST subtest AM it appears that the normal hearing group of children performs better than the group of hearing impaired children. The majority of normal hearing children (approximately 50%) were able to correctly repeat a string of four keywords in terms of clicking/ pointing at the corresponding pictures in the order of the previously auditorily perceived words, maintaining the order of presentation. The majority of hearing impaired children (approximately 50%) gave a correct response to strings of two keywords (see Figure 37).

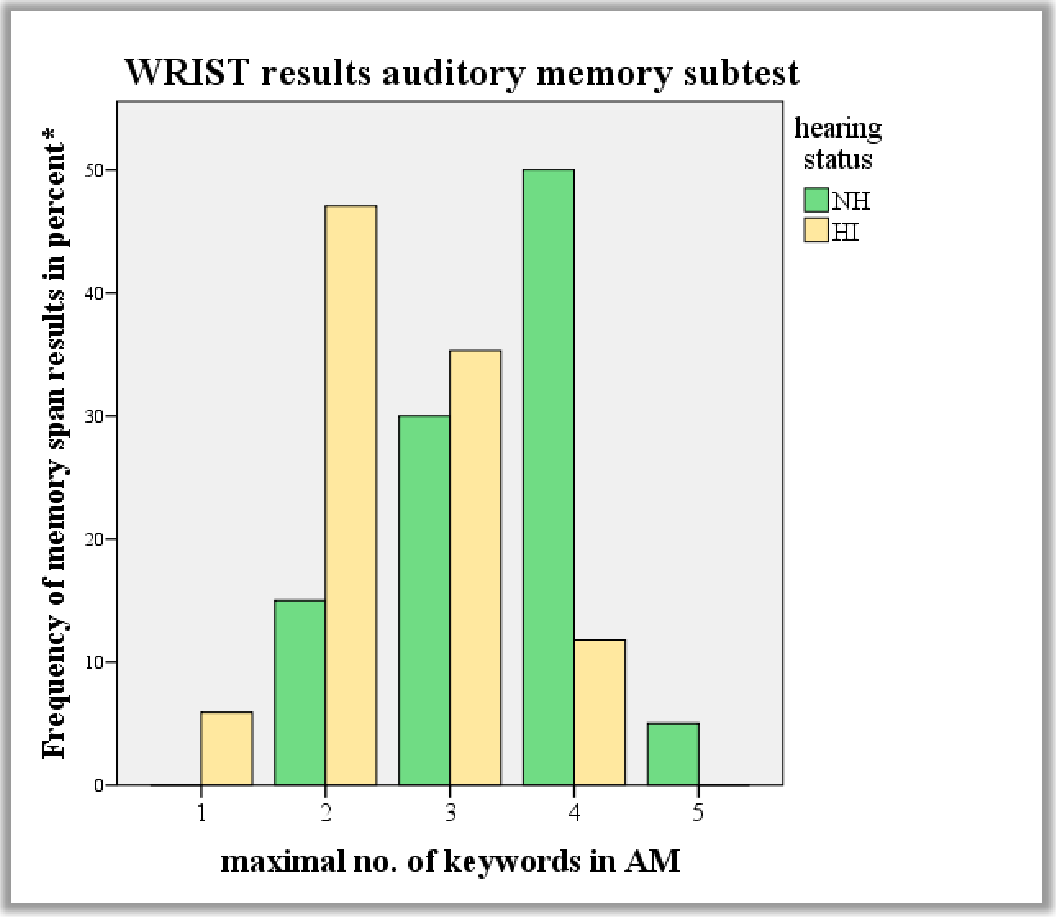

Figure 37: Results of auditory memory span subtest in WRIST

The difference in performance on the WRIST auditory memory subtest is of significance between the group of normal hearing and hearing impaired children.

For existing tests in the field of assessing the auditory memory span – for example, the Mottier test or the subtest repeating numbers in the Kaufman Assessment Battery for children – age effects have been shown (Kaufman et al., 2009; Wild & Fleck, 2013). Due to the low prevalence of normal hearing children of varying ages participating in the test, no significance could be found in the correlation of age and performance on the AM subtest.

OBSERVATIONS:

On an average the duration for all subtests was approx.15 minutes which appears to be too long, especially if the WRIST is performed as one test out of a test battery. Observing the test situations, children seemed to be less motivated when reaching subtest SEG III. Some asked when the test would get over or wanted to be done or did not want to proceed.

Many children performing the WRIST by pointing at a picture card, automatically chose a verbal response mode in subtest AM. Observing the test situation, it could be seen that children often repeated the word string quietly or whispered. The challenging part of the task seemed to be the response mode of clicking or pointing in the right order. Following the “hidden screen” during auditory presentation of the keyword string, it seemed to be difficult for the children to find the matching pictures.

8.4 CONCLUSION

OBJECTIVITY is optimized by the chosen language material described above. Keeping semantical influences to a minimum and regarding the vocabulary development of young children, especially in terms of the chosen keywords is very vital.

The standardized procedure in the pattern of the AAST with minimal influence of the test leader (as in false interpretation of verbal responses) raises the objectivity as well.

The influence of decreasing motivation and concentration should, however, be reevaluated. The self-explanatory completion and adaptive procedures are positively influencing factors. On the other hand, the average duration of 15 minutes for all subtests appears to be too long. The criteria for adaptively ending the subtests on segmentation after a certain amount of wrong responses could be discussed. Also, the reduction and combination of subtests SEG II A and SEG II B could be an option.

RELIABILITY has been tried to be addressed by the fact that the WRIST sentences for each subtest follow the same construction criteria in the different word sets that are available for retest situations. In further data assessment, the comparability of the different test sets needs to be evaluated.

To derive the SRT, a recognition task is to be expected and provided by the AAST (closed set test). Due to the response mode, the AAST does not examine the intelligibility of a child’s spoken language in addition to the testing of auditory speech recognition. Test-rest reliability has been shown in the analysis of normative data (Coninx, 2006a).

VALIDITY has been analyzed in a small and very heterogeneous sample of hearing impaired children and a small group of normal hearing children of different ages. Further testing is necessary to establish strong normative data regarding age effects.

The six chosen keywords can usually be found within a young child's vocabulary. The testing of lexical development is kept to a minimum.

The guessing level cannot be prevented completely due to the closed set procedure with a choice of six options, as it is mentioned for the AAST as well. In subtests SEG II and SEG III as well as AM, the guessing level could be decreased by including the possibility of word repetition in the test material.

Due to the visual presentation of six pictures in a circle and a honeycomb like pattern, a visual preference is kept low. However, the choice of six pictures that need to be chosen in a specific order for subtest AM seems to create a level of difficulty of a visual task instead of the aspired auditory testing. Minimizing the visual response options to four pictures and adapting the speech stimuli should be part of future reevaluation.

Within the first data assessment all children at a kindergarten age were able to perform the WRIST; only one child per group did not complete the test. For the hearing impaired group, this was a child with an additional handicap.

The WRIST turned out to be suitable for children at ages four and upwards. It gives information on word segmentation abilities in fluent speech at different levels of difficulty and also on the auditory memory span. Its correlation to other auditory measurements such as SRT values should be evaluated as well as a possible correlation to diagnostic results on language development. Additional testing is to be carried out to analyze age dependent effects on all subtests, especially the AM.

From analyses of the first WRIST results, the test appears to be compatible to the set goal of using a test for the assessment of auditory skills in understanding meaningful daily speech, suitable for hearing impaired children. The WRIST has been developed as an integral part of the BELLS software.

The development of the WRIST rose from an idea formed within the phase of developing the hEARd test protocol. First, data could be assessed with a proto type of a German test set. Since no additional test appointments were to be made for participants within the hEARd project, first

WRIST results could not be assessed from the already included participants. Due to the length of the hEARd test battery described in Chapter 3, the WRIST was not added to the obligatory test battery.

9. DISCUSSION : REVIEW AND PROSPECTS

9.1 REEVALUATION OF COMMON INDICATION CRITERIA FOR COCHLEAR IMPLANTATION

Indication criteria for pediatric cochlear implantation differ, as documented in the introductory chapters of this dissertation. Audiometric criteria have changed over the past decade. The precondition of total deafness or a strict average hearing loss of 90 dB and greater has been reevaluated and adapted.

LOWER AUDIOLOGICAL IMPLANTATION CRITERIA FOR COCHLEAR IMPLANTATION?

Within this dissertation it was shown that children using CI perform equivalent to children with a moderate hearing loss of 41–60 dB in perceiving speech in quiet. From an audiological point of view, this indicates a probable better or at least equivalent performance after cochlear implantation for children with hearing losses higher than 60 dB.

On the other hand, it is of no doubt that a cochlear implantation is an invasive procedure and it has been established in Chapter 2 that the indication for a CI should not only depend on audiological criteria. Based on the presented findings, it should not be concluded that a CI is the optimal hearing device for all children with hearing losses of 60 dB and higher.

At the same time, it becomes obvious that indication criteria strictly based on audiological restrictions, such as a minimum hearing loss of 80 dB will not meet the individual needs of a pediatric patient.

Recent research discusses approaches of cochlear implantation in cases of lower hearing losses, high frequency hearing losses, residual hearing, and single sided deafness (Skarzynski et al., 2006; Lesinski-Schiedat et al., 2015; Nikolopoulos et al., 2015; Manrique Rodriguez, 2015; Skarzynski et al., 2014).

The common ground in these types of cases of extended indication criteria for a cochlear implantation is however the multidisciplinary diagnosis, as referred to in the German guidelines on implantable hearing devices (Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen, 2012; Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen, 2012).

EDUCATIONAL CONSEQUENCES

It is established that the success of a CI provision depends on several factors including, but not limited to the audiological status of a patient, whether the patient is a child or an adult (see Chapter 2). The process of auditory development with a CI is at the same time influenced greatly by the rehabilitation concept following the CI provision (Streicher, 2011).

Regarding this information and the possible adaption of implantation criteria, the need of a competent guidance and consultation of educational and therapeutic personnel becomes obvious. This is not only for a post-operative rehabilitation, but also for pre-operative observations on a child's development.

The impact of a changed audiological status is first observed in a daily context. To support a family in the decision process for a CI, professionals in an educational/ therapeutic context need to be sensitive to a family's needs while at the same time providing information on options and possibilities. Recent evidence based information, such as that made available by data assessed in this study, can give perspective.

9.2 PERFORMANCE IN NOISE

One aspect of great interest in the evaluation of the presented data is the performance of children using CI when perceiving speech in noise.

In comparison to their overall performance on the test battery, the performance in noise appears to be surprisingly poor and not significantly better than the performance of severely to profoundly impaired hearing aid users.

Possible reasons for this and options to address this problematic effect will be discussed in the following.

BILATERAL VS. UNILATERAL TESTING

The recognition of speech in noise is likely to be influenced in a positive way, when the stimulus is presented binaurally. Effects of binaural hearing processes have been researched and discussed (Gilkey, 1997)(Litovsky et al., 2009a; Litovsky et al., 2009b).

The speech test in noise performed in the presented study has been carried out in a unilateral test situation which could be of influence. On the other hand, all children in the study have been tested unilaterally, including children with severe to profound hearing impairment, which performed significantly poorer than the CI group in speech tests in quiet.

Further analyses and research should include a comparison of test results in binaural and unilateral testing for the mentioned hearing device groups. An improvement in perceiving speech in noise is to be expected. However, it would be of interest to analyze, whether the previous discrepancy in between hearing aid users with severe to profound impairment and CI users could be observed.

TYPE OF NOISE SIGNAL

Another aspect of influence could be the used setting for the speech test in noise. The used noise signal was a steady state noise signal, adapted to the frequency range of the speaker presenting the test items within the software. Looking at the results, presented in Chapter 6, all children appeared to perform poorly in the test, which could be due to the “difficult” choice of noise signal. Fluctuating noise signals in comparison offer a better perception of speech (Festen, 1990). Also, the used setting of speech and noise being applied from one direction could be of influence in comparison to a more natural test setting of speech and noise being applied from different directions.

These options of a different application of the noise signal could be analyzed in further analyses as mentioned above.

SIGNAL PROCESSING STRATEGIES IN HEARING DEVICES

A factor that should be evaluated thoroughly in further data assessment should be the use of signal processing strategies. The options of processing strategies, addressing the reduction of ambient noise, are various for hearing aids as well as the newest CI systems, as shortly discussed in earlier chapters.

In this study, the use of such strategies in present fittings of the tested hearing devices has not been assessed sufficiently. A comparable test situation for all participants was and is hardly possible, due to missing information of these settings for each child. A precondition in further testing should be discussed, in terms of no use of noise reducing settings. However, some of these settings are implemented in the hearing devices in an automated way and cannot be turned off manually.

In further analyses, a more specific protocol on the actual hearing device and its settings should be implemented.

EDUCATIONAL CONSEQUENCES

The presented findings are surprising on the one hand, but reflect quite well the reports of adult hearing impaired patients. Speech recognition in noise is often mentioned as one of the greatest challenges in daily life.

Looking at the daily challenges for hearing impaired children, the acoustic surroundings are often extremely challenging in terms of a noisy environment (school, kindergarten, playground etc.).

The findings of this study should raise awareness of this difficulty and result in addressing this problem in each child’s educational and therapeutic concept. Conditions in the educational setting should be optimized, in terms of reduction of ambient noise and development as well as improving coping strategies, to guarantee the best auditory input of verbal information (Picard & Bradley, 2001).

The use of additional technical devices, such as equipment for wireless transmission in a classroom using a microphone connected to the hearing device (e.g. Phonak Roger system), needs to be discussed, in terms of effectiveness and also when it comes to reimbursement of these devices by health insurance.

At the same time the development of natural listening strategies in a challenging acoustic environment needs to be addressed in therapeutic concepts as well. Again, it is necessary for educational and therapeutic professionals to closely monitor the child’s development in this specific field, to allow a natural development of necessary auditory skills, while assuring the optimal perception of speech in an educational environment.

9.3 REGULAR EVALUATION OF RECENT HEARING DEVICES DUE TO ONGOING TECHNICAL DEVELOPMENT

The design of the hEARd study turned out to be a suitable measuring instrument, to document the state of a child's development of auditory speech perception skills using a certain hearing aid device.

Nonetheless, it must be clear that normative data for the evaluation of technical hearing devices needs to be reevaluated in recent cycles. The rapid development of technical hearing devices provides new possibilities in shorter time frames. As presented in Chapter 2, devices seen in the implementation of the hEARd project have already been replaced by newer models, for hearing aids as well as for CI systems.

In establishing and evaluating this normative database, the presented test battery could easily be used for data assessment at regular intervals, allowing comparison and analyses of possible advantages by technical progress.

FURTHER TESTING OF MORE COMPLEX PERCEPTION AND PROCESSING SKILLS (WRIST)

In addition to the used tests, mainly the different AAST test sets, to derive information on SRT and SNR values, as well as tonal thresholds with the mFAST, the relation to the perception of linguistic elements, such as phonemes is of interest and should be evaluated in further analyses.

As a new development the WRIST was presented. When addressing daily needs and challenges of hearing impaired children, the use of more natural speech material for audiological assessment seems reasonable. In the development of the WRIST, as described in Chapter 8, first preliminary data showed that the test could be used in children at kindergarten age. Comparable data of performances in normal hearing children has been assessed. The initial tests of hearing impaired children showed a sensitivity of the WRIST towards the development of auditory processing strategies, such as segmentation skills or the development of auditory memory skills. The WRIST addresses not only auditory perception of speech material such as words, but the next higher level. These details are of great interest for educational practice. As the basis for understanding complex spoken language, the development of segmentation skills and auditory memory can be assessed in a precise way, regarding and monitoring small developmental steps.

Further data assessment in hearing impaired children is necessary at this point.

DIAGNOSTIC USE IN ADULTS

The present study focused on the assessment of audiological development in children using different types of hearing devices. As it has been discussed before, two main goals are to be met in audiological diagnostic procedures- to evaluate the individual development of a patient and to compare the individual hearing status to a norm group.

These aspects are, however, not only of importance in the hearing device provision of hearing impaired children, but also in the process of aiding hearing impaired adults.

When a child is diagnosed as hearing impaired, a regular evaluation of his/her hearing status is an established procedure in health care systems. When provided with a hearing device, the evaluation of this device is to be carried out by pediatric ENT specialists or specialized audiological centers (Gemeinsamer Bundesausschuss, 2015).

With this diagnosis many professionals become involved, especially in cases of more severe impairment, such as institutions for early intervention, kindergarten, schools, schools and teachers for special education, speech therapists and more. In optimal cases, a tight network is evaluates the child’s development in different settings. Anomalies in auditory development is likely to be observed in this kind of setting and can be addressed adequately.

For hearing impaired adults there is no thorough tracking of the auditory development. Challenges in hearing are different for adults and the auditory development with a certain aiding device needs to be evaluated as well, for example, the function of hearing devices in different environments of a daily context, such as at the workplace.

A closer focus is set on the development of auditory abilities with a CI, which is often observed by specialized clinics or audiological centers, due to the fact that the CI is an implantable medical device with the need of regular medical examination.

The auditory development with hearing aids is often not observed as thoroughly. Optimal fittings are not achieved in many cases, resulting in minimal benefits and cases of hearing aids not being worn. The provision of a hearing aid is often only monitored by a hearing aid acoustician. Annual checkups after provision are a suggestion. The acoustician may even remind the patient of an appointment, but the need is often not as obvious, as it is with an implantable device. Also, no additional institutions are involved, as in the rehabilitation process of hearing impaired children. For hearing impaired adults using hearing aids, it is in their own interest to keep the hearing aid system optimally fitted and maintained.

A standardized test battery could therefore be of use for the evaluation of a hearing aid provision in adults. Besides the documentation of an individual's development, as in long term evaluation of hearing aid use, a normative data pool could also give information on the average goals that can be set to be achieved with a certain device in cases of certain hearing losses.

The process of initial provision and fitting could be evaluated on an evidence base and be presented as more transparent to a patient. Normative data could give information on ways of addressing for example, common age related hearing losses. Typically used hearing aids could be evaluated to an appropriate function in different settings of daily life. Also, information could be concluded, on whether hearing aids covered by health insurance (see Chapter 2.4) are sufficient or don't meet the needs in terms of an adequate performance as to degree of hearing loss.

In cases of cochlear implantation, a comparable norm would be of interest that evaluates not only the initial pre-operative degree of unaided hearing loss, but also the important factor of pre-operative duration of hearing loss (Green et al., 2005). A bilateral set up as mentioned above would be of great importance, to focus on the coverage of a second CI in countries like Belgium and the Netherlands.

Overall, it can be summarized that the auditory development of adults using hearing devices should be addressed in regular normative evaluation procedures, as presented in this study as well. Normative values are of specific importance since only a few institutions are involved in the provision of hearing devices for adults. At the same time, adults should be provided with information on probable outcomes, as they have to cover the cost of many hearing devices themselves.

EDUCATIONAL CONSEQUENCES

Interpretation of audiological test results needs to take place in comparison to previous performances, to evaluate personal development. At the same time, results should be evaluated to normative values as well. It is one of the tasks to be met by educational and therapeutic professionals in the field of hearing impairment to interpret and evaluate these results in a meaningful daily context. Conclusions for the adaption of the surrounding setting as well as therapeutic concepts need to be drawn by educational and therapeutic staff. A diagnosis and normative interpretation of a test result is of little use, when not addressed on a daily basis. As part of an interdisciplinary diagnosis, audiological information should be interpreted promptly, as it is the basis for further advances in a patient's auditory development, to set adequate goals, and develop individual concepts that can be put into action.

10. CONCLUSION

10.1 SUMMARY OF RESULTS

Within this dissertation it was shown that children of school going age who were diagnosed with hearing impairment within their first year of life, show different levels of performance in terms of their skills in auditory speech perception. These performance levels show a correlation to the unaided hearing loss and to the type of technical hearing aid device used by the child.

Furthermore, results of this analyses indicated that not only could profoundly hearing impaired children benefit from a CI in terms of their auditory speech perception skills, but – within the presented test setting –severely hearing impaired children with a hearing loss of more than 60 dB could also benefit. Children in this study using CI show a performance equivalent to children using hearing aids with moderate hearing impairment.

Within the processes of choosing an optimal technical hearing aid device for a child, especially an implantable one, audiometric results need to be monitored closely. Although audiometric criteria for or against cochlear implantation cannot and should not replace a multidisciplinary diagnosis, a regular reevaluation of common standards as in audiometric guidelines indicating cochlear implantation, is necessary, regarding the rapid development of technical devices.

In the process of evaluating study outcomes for hearing impaired children using hearing aids, normative data for the AAST could be established for groups related to the grading of hearing impairment by the WHO as in mild, moderate, severe, and profound hearing impairment.

10.2 ANTICIPATION FOR EDUCATIONAL PRACTICE

An adequate fitting of hearing devices – no matter if cochlear implant or hearing aid – is of great importance. As Tomblin points out, not only children with severe to profound hearing losses are at risk of delays or even impairment of language development (Tomblin et al., 2015). Even in cases of mild to moderate hearing losses optimal provision and fitting of hearing devices is to be set as a goal for a multidisciplinary practice to give hearing impaired children optimal auditory access to spoken language.

Monitoring a child's auditory development in relation to its perception and production of spoken language is a task that needs to be addressed within the field of educational audiology.

In addition to audiological data that should be assessed regularly, there is the need to interpret these results in the context of each child's personal environment. Information that can be received in an educational and therapeutic context, such as kindergarten, school and of course a child's home, allow the evaluation of auditory development in a holistic way.

This can be the interpretation of a poor audiometric test result due to a child's lack of participation after a school day. Evaluating the development of auditory memory and segmentation skills not only based on the audiological status, but also on the child's daily environment as in auditory input. Or the knowledge of new concepts in speech therapy that are focusing on the discrimination and production of plosives, which result in better performance on specific audiometric tests.

A multidisciplinary network monitoring the auditory and global development of a hearing impaired child, facilitates prompt reactions to anomalies in the process. Thus ensuring optimal auditory access to spoken language.

10.3 DAILY PROFESSIONAL ROUTINE – COCHLEAR IMPLANT FOR MAX?

Interpreting the results that Max achieved in recent audiological test procedures – including the unaided hearing loss level – in the context of findings presented in this dissertation, a cochlear implant could offer an improvement in his auditory speech perception skills.

Looking at the described situation as in auditory status and language development, as well as other influential factors, Max did profit from regular diagnostic procedures on his auditory development. Changes in the hearing status could be addressed directly.

Regarding the increasing challenges in the educational context, the cochlear implantation could enable Max to maintain his hearing status at the level he has achieved so far and develop further auditory and linguistic skills on that basis.

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VII. APPENDIX

I. WRIST – GROUPS OF KEYWORDS AND PICTURES

GERMAN VERSIONS:

1) animals

1 syllable	*2 syllables*
Pferd	Vogel
Maus	Katze
Hund	Ziege

2) body parts

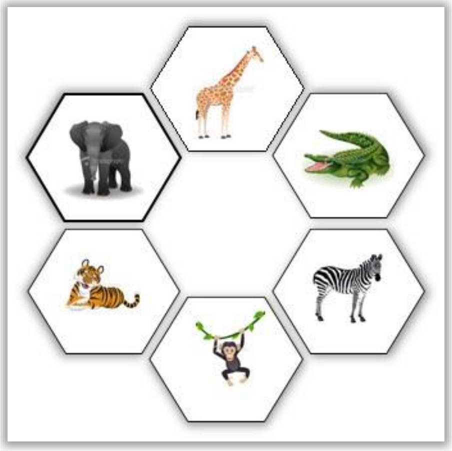
1 syllable	*2 syllables*
Hand	Nase
Ohr	Finger
Fuß	Auge

3) kitchen supplies

1 syllable	*2 syllables*
Tisch	Messer
Topf	Teller
Stuhl	Löffel

ENGLISH VERSIONS:

1) zoo animals



2 syllables	*3 syllables*
tiger	elephant
zebra	crocodile
giraffe	chimpanzee

2) farm animals

1 syllable	*2 syllables*	
dog	rabbit	
bird	chicken	
mouse	hedgehock	no pictures available yet

3) body parts

1 syllable	*2 syllables*	
hand	finger	
foot	shoulder	
nose	eyebrow	no pictures available yet

4) kitchen supplies

1 syllable	*2 syllables*	
spoon	table	
knife	napkin	
chair	oven	no pictures available yet

II. WRIST – SEGMENTATION I

German: animals

1. Zeige den **Hund**.
2. Wo ist die **Maus**?
3. Zeig mir das **Pferd**.
4. Wo ist die **Katze**?
5. Zeig mir den **Vogel**.
6. Zeige die **Ziege**.

German: body parts

1. Zeig mir die **Hand**.
2. Wo ist der **Fuß**?
3. Zeige das **Ohr**.
4. Zeige die **Nase**.
5. Wo ist der **Finger**?
6. Zeig mir das **Auge**.

German: kitchen supplies

1. Zeige den **Teller**.
2. Zeige den **Stuhl**.
3. Wo ist der **Tisch**?
4. Zeig mir das **Messer**.
5. Zeig mir den **Topf**.
6. Wo ist der **Löffel**?

English: zoo animals

1. Show me the **tiger**.
2. Where is the **zebra**?
3. Can you show the **giraffe**?
4. Where is the **elephant**?
5. Can you show the **crocodile**?
6. Show me the **chimpanzee**

III. WRIST – SEGMENTATION II

German: animals

1. Schau mal, der **Hund** läuft *lustig* umher.
2. *Mein* Lieblingstier ist eine **Maus**, genau wie mein Kuscheltier.
3. Hörst du, ein **Pferd** kann ganz schön laut sein!
4. Ich wünsche mir eine **Katze** von meinen Eltern zum *Geburtstag*.
5. Der kleine **Vogel** hat *ganz* schön Hunger.
6. Ich habe geträumt, dass ein **Hund** in meinem Zimmer war.
7. Sowas, das Fell von der **Ziege** ist ja ganz weich.
8. *Gestern* habe ich ein **Pferd** gesehen.
9. *Guck mal*, die **Katze** geht über die Wiese.
10. Mein Freund hat eine **Maus** zu Hause.
11. Ich gebe der **Ziege** gerne *Futter*.
12. *Ich* wünsche mir einen **Vogel** als Haustier.

German: body parts

1. Ich habe mir die **Hand** eingeklemmt.
2. Kevin hat einen kleineren **Fuß** als Marvin. Der Junge hat einen kleineren **Fuß** als sein Vater.
3. Ich sehe mein **Ohr** im *Spiegel*.
4. Auch viele Tiere haben eine **Nase**, aber sie sehen unterschiedlich aus!
5. Ich habe mir den **Finger** ganz fest gestoßen.
6. Mir tut der **Fuß** *so* weh.
7. Der *Doktor* sagt, mein **Auge** ist gesund.
8. Ich habe mich an meiner **Hand** beim *Fallen* verletzt.
9. Im *Winter* ist mein **Finger** oft kalt.
10. Siehst du, an meinem **Ohr** bin ich nicht kitzelig.
11. Ich hatte am **Auge** schon mal einen Verband.
12. Schau mal, die **Nase** von dem Baby ist so klein.

German: kitchen supplies

1. Beim Aufräumen ist mir ein **Messer** *heruntergefallen*, oh je.
2. Ich habe versucht einen **Löffel** zu *malen*, das war schwer!
3. Nach dem Spülen wird das **Messer** wieder weggeräumt.
4. Nach dem Essen muss der **Topf** gespült werden.
5. *Ich* habe einen **Stuhl**, extra für Kinder.
6. Wir machen den **Tisch** nach dem Essen sauber.
7. Der große **Teller** ist *sehr schwer*.
8. Ich habe meinen eigenen **Löffel**, der ist bunt.
9. Ich habe auch einen **Stuhl**, der ist rot.
10. *Gestern* haben wir einen neuen **Topf** gekauft.
11. Weißt du, Mamas **Teller** ist größer als meiner.
12. Es gibt *einen* **Tisch** in unserer Küche.

English: zoo animals

1. Look there, the **elephant** is eating much leaves.
2. Listen, the **tiger** makes a lot of noise.
3. I wish I could have a **chimpanzee** as my pet
4. The baby of the **tiger** is such a cute little thing.
5. The man was riding a **zebra** in the circus.
6. The food of the **chimpanzee** is high in the trees.
7. They are feeding the **crocodile** in the zoo now.
8. You know, the fur of a **giraffe** feels really soft.
9. I think, the **crocodile** like to play in the water.
10. I like to look at the **giraffe** when I visit the zoo.
11. A little **chimpanzee** is very playful you know.
12. In the jungle the **zebra** is the fastest animal.

IV. WRIST – SEGMENTATION III A

German: animals

1. Eine **Ziege** und auch ein **Hund** leben auf unserem Bauernhof.
2. Weißt du, das **Pferd** und die **Ziege** fressen gerne Gras.
3. Schau mal, die **Vogel** und die **Maus** leben in einem Käfig.
4. Bei meiner Freundin habe ich eine **Katze** und ein **Pferd** gestreichelt.
5. Ich habe einen **Hund** als Haustier, aber ich wünsche mir einen **Vogel**.
6. Unsere Nachbarn haben eine **Maus** und eine **Katze**.

German: body parts

1. Hihi, ich halte Papas **Auge** zu mit meiner **Hand**.
2. Ich habe ein Pflaster am **Finger** und einen Verband am **Fuß,** weil ich gestern gestürzt bin.
3. Oh nein, man sieht nur mein **Ohr** auf dem Foto, und ein Stück meiner **Nase**.
4. Wenn ich Inline-Skates fahre, brauche ich auch einen Schützer für **Hand** und **Finger.**
5. Mit dem **Auge** kann ich sehen und mit der **Nase** kann ich riechen.
6. Ich hatte die Windpocken und alles vom **Fuß** bis hin zum **Ohr** hat gejuckt.

German: kitchen supplies

1. Den Kakao rührst du mit dem **Löffel** um, aber nicht mit dem **Messer**!
2. Im **Topf** ist noch Soße, die fülle ich mir mit dem **Löffel** auf die Nudeln.
3. Ich habe einen eigenen **Stuhl,** mit dem ich in unserer Küche am **Tisch** sitze.
4. Der **Tisch** in unserer Küche ist aus Holz, aber mein **Stuhl** ist aus Plastik.
5. Neben dem **Messer** liegt auf der Arbeitsplatte noch ein kleiner **Teller**.
6. Mein **Teller** steht im großen Schrank, im kleinen Schrank steht ein **Topf**.

English: zoo animals

1. The **giraffe** eats a lot and the **zebra** is a hungry animal.
2. In the jungle the **tiger** makes a lot of noise and the **chimpanzee** too.
3. The large **crocodile** likes the water as much as the **elephant.**
4. I like to have a baby **tiger** and a **zebra** at home.
5. The **chimpanzee** and the **crocodile** are living in the zoo.
6. In the circus the **elephant** and the **giraffe** are dressed up.

V. WRIST – SEGMENTATION III B

German: animals

1. Schau mal, der **Vogel** sitzt bei der **Ziege** und dem **Pferd** auf der Wiese.
2. Die **Katze** beobachtet den **Vogel** und die **Maus** auf der Wiese.
3. Der **Hund** und die **Katze** schlafen mit dem **Pferd** im Stall.
4. Eine kleine **Maus** macht andere Geräusche als eine **Ziege** oder ein **Hund**.
5. Wir haben drei Haustiere Oscar, den **Hund** und Lilly, die **Katze** und Flitzi, die **Maus**.
6. Meine Mama füttert immer erst den **Vogel**, dann die **Ziege** und dann das **Pferd**.

German: body parts

1. Im Winter sind mein **Fuß**, meine **Nase** und meine **Finger** immer kalt.
2. Zum Karneval male ich mir die **Nase**, mein **Ohr** und mein **Auge** bunt an.
3. Dein **Ohr** ist viel kleiner als dein **Fuß** oder deine **Hand**.
4. Ich stehe vorm Spiegel und sehe meinen **Finger**, meine **Hand** und mein **Auge**.
5. Wenn ich erkältet bin, tun meine **Nase** und mein **Ohr** weh und mein **Auge** brennt.
6. Ich schnipse mit dem **Finger**, klatsche in die **Hand** und stampfe mit dem **Fuß**.

German: kitchen supplies

1. Heute Morgen habe ich alle **Messer** und **Teller** auf den **Tisch** gelegt.
2. Zu jedem **Stuhl** der am **Tisch** steht, stelle ich einen **Teller** hin.
3. Wenn ich koche, stehe ich auf einem **Stuhl** und rühre mit dem **Löffel** im **Topf**.
4. Mama spült zuerst den **Teller**, danach den **Topf** und das **Messer** zum Schluss.
5. Wenn ich mit dem **Löffel** auf einen **Topf** oder den **Stuhl** haue, mache ich Musik.
6. Vor dem Essen ist es meine Aufgabe, **Messer** und **Löffel** auf den **Tisch** zu legen.

English: zoo animals

1. In the circus the clown, the **zebra** and the **giraffe** are playing with the **chimpanzee**.
2. The caretaker feeds the **tiger** in the zoo, and the **elephant** and the **crocodile**.
3. The strong **tiger** makes a different noise than the **crocodile** and **zebra** do.
4. In the jungle the **elephant** and the **chimpanzee** like the sun, just like the **giraffe**.
5. I like to look at the **crocodile** and the **elephant** in the zoo, and to the **zebra**.
6. My mother does not like a **giraffe** or a **tiger** and not even a **crocodile**.

VI. WRIST – AUDITORY MEMORY

Sentence material is built up from the following word- order sequences.

German: animals

Hund	Katze	Maus	Pferd	Vogel	Ziege
Pferd	Vogel	Ziege	Hund	Katze	Maus
Vogel	Maus	Hund	Ziege	Pferd	Katze
Ziege	Pferd	Katze	Vogel	Maus	Hund
Katze	Ziege	Pferd	Maus	Hund	Vogel
Maus	Hund	Vogel	Katze	Ziege	Pferd
Pferd	Vogel	Hund	Ziege	Maus	Katze
Katze	Ziege	Maus	Pferd	Vogel	Hund
Vogel	Pferd	Ziege	Maus	Hund	Katze
Hund	Maus	Vogel	Pferd	Katze	Ziege

German: body parts

Auge	Finger	Fuß	Hand	Nase	Ohr
Hand	Nase	Ohr	Auge	Finger	Fuß
Nase	Fuß	Auge	Ohr	Hand	Finger
Ohr	Hand	Finger	Nase	Fuß	Auge
Finger	Ohr	Hand	Fuß	Auge	Nase
Fuß	Auge	Nase	Finger	Ohr	Hand
Hand	Nase	Auge	Fuß	Finger	Ohr
Auge	Ohr	Finger	Nase	Hand	Fuß
Nase	Fuß	Hand	Auge	Ohr	Finger
Ohr	Auge	Finger	Fuß	Hand	Nase

German: kitchen supplies

Löffel	Messer	Teller	Tisch	Topf	Stuhl
Tisch	Topf	Teller	Stuhl	Messer	Löffel
Topf	Teller	Löffel	Tisch	Stuhl	Messer
Löffel	Tisch	Messer	Topf	Teller	Löffel
Messer	Stuhl	Tisch	Teller	Löffel	Topf
Teller	Löffel	Stuhl	Messer	Topf	Tisch
Stuhl	Teller	Löffel	Topf	Tisch	Messer
Messer	Topf	Tisch	Löffel	Stuhl	Teller
Tisch	Löffel	Messer	Stuhl	Teller	Topf
Stuhl	Tisch	Teller	Löffel	Topf	Messer

English: zoo animals

Tiger	Elephant	Zebra	Giraffe	Crocodile	Chimpanzee
Giraffe	Crocodile	Chimpanzee	Tiger	Elephant	Zebra
Crocodile	Zebra	Tiger	Chimpanzee	Giraffe	Elephant
Chimpanzee	Giraffe	Elephant	Crocodile	Zebra	Tiger
Elephant	Chimpanzee	Giraffe	Zebra	Tiger	Crocodile
Zebra	Tiger	Crocodile	Elephant	Chimpanzee	Giraffe
Giraffe	Crocodile	Tiger	Chimpanzee	Zebra	Elephant
Elephant	Chimpanzee	Zebra	Giraffe	Crocodile	Tiger
Crocodile	Giraffe	Chimpanzee	Zebra	Tiger	Elephant
Tiger	Zebra	Crocodile	Giraffe	Elephant	Chimpanzee

VII. WRIST – T -TEST FOR DIFFERENCES BETWEEN SEGMENTATION SUBTESTS FOR HEARING IMPAIRED GROUP

Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	SEG II A	70,5882%	17	21,67421%	5,25677%
	SEG II B	61,7647%	17	28,11479%	6,81884%
Pair 2	SEG III A	45,0980%	17	34,24012%	8,30445%
	SEG III B	29,4118%	17	31,47387%	7,63354%
Pair 3	SEG II total	66,1765%	17	21,54424%	5,22525%
	SEG III total	37,2549%	17	28,58310%	6,93242%

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	SEG II A & SEG II B	17	,489	,046
Pair 2	SEG III A & SEG III B	17	,513	,035
Pair 3	SEG II total & SEG III total	17	,722	,001

Paired Samples Test

		Paired Differences					t	df	Sig. (2-tailed)
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper			
Pair 1	SEG II A - SEG II B	8,82353%	25,76446%	6,24880%	-4,42333%	22,07039%	1,412	16	,177
Pair 2	SEG III A - SEG III B	15,68627%	32,52701%	7,88896%	-1,03757%	32,41012%	1,988	16	,064
Pair 3	SEG II total - SEG III total	28,92157%	19,79005%	4,79979%	18,74646%	39,09668%	6,026	16	,000