Hearing abilities measured with the Hearing in Noise Test (HINT)

Studies on normal hearing and cochlear implant users

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Abbreviations

ASA	Auditory scene analysis
AVCN	Anteroventral cochlear nucleus
dB SPL	Decibel (dB) sound pressure level
CF	Characteristic frequency
CI	Cochlear implant
CI ₁	First side cochlear implant
CI ₂	Second side cochlear implant
CI _{BI}	Bilateral cochlear implants
CN	Cochlear nucleus
DCN	Dorsal cochlear nucleus
ESP / ESP-N	Early Speech Perception test / ESP test in Norwegian
HA	Hearing aid
HINT	Hearing in Noise test
ILD	Interaural level difference
ITD	Interaural time difference
JND	Just-noticeable differences
LSO	Lateral superior olive
MGB	Medial geniculate body
MLD	Masking level difference
MSO	Medial superior olive
NF	Noise Front
NL	Noise Left
NR	Noise Right
OUS	Oslo University Hospital
PI	Performance intensity
PVCN	Posteroventral cochlear nucleus
RMS	Root mean square
SD	Standard deviation
SNR	Signal-to-noise ratio
SRM	Spatial release from masking
SRT	Speech Reception Threshold
SSQ	Speech Spatial and Qualities of Hearing scale

List of publications

Paper I

Myhrum, M., Moen, I. (2008). The Norwegian hearing in noise test. *Int J Audiol*, 47, 377-378 (Myhrum et al. 2008)

Paper II

Myhrum, M., Tvete, O., Heldahl, M. G., et al. (2016). The Norwegian Hearing in Noise Test for Children. *Ear Hear*, 37, 80-92 (Myhrum et al. 2016)

Paper III

Myhrum, M., Strøm-Roum, H., Heldahl, M.G., Rød vik, A.K., Eksveen, B., Landsvik, B., Rasmussen, K., Tvete, O.E. Sequential bilateral cochlear implantation in children – outcome of the second CI and long-term use. (Accepted with minor changes 2nd August 2016, *Ear Hear*)

Paper IV

Myhrum, M., Heldahl, M.G., Jablonski, G.E., Tvete, O.E. Self-Assessed Speech, Spatial, and Qualities of Hearing Scores (SSQ) and Speech Perception in Adult Cochlear Implant Recipients (*Journal of Speech, Language, and Hearing Research*, Submitted in July 2016)

The papers will be referred to by their Roman numerals.

Preface

The overall purpose of the thesis was to develop a Hearing in Noise test (HINT) in Norwegian, and apply the test via headphones to normal-hearing adults. The subsequent purpose was to develop a pediatric version of the test and apply adult and pediatric versions of the test from speakers in free-field, to normal hearing adults and children. Speaker presentation is necessary when the test is to be used with hearing aid (HA) and cochlear implant (CI) users. Earlier studies have shown effects of maturation, therefore children aged from 6 to 13 years old were included.

The test was then used in two different CI population studies. The first CI study used the Hearing in Noise test (HINT) to investigate the advantage of two CIs in a subgroup of a pediatric CI population who had received sequential CIs. This study also investigated the use and benefit of a second CI in the total cohort.

The other CI study used the HINT to describe the hearing ability of an adult CI study group. A questionnaire for self-assessment of hearing abilities was translated from English into Norwegian and was used in the latter study to describe a self-assessed, subjective measure of hearing abilities. The relationship between HINT results (objective measure) and questionnaire results (subjective measure) was investigated.

The HINT is a validated English test using sentences in background noise. It has been used in several CI studies, and has been implemented in several languages and with pediatric versions, and was the basis for the Norwegian version used in the studies here. The Speech, Spatial and Qualities of Hearing scale (SSQ) is a validated English hearing ability self-assessment questionnaire and was selected for use in these studies. The SSQ was originally developed in English, translated into other languages and validated, and used to study hearing abilities in the hearing impaired. It is used in an increasing number of CI studies.

The studies in the thesis were prospective, except for the pediatric CI study which was a combination of a retrospective longitudinal cohort study and a prospective study of a subgroup of the cohort. The number of participants in the normal-hearing studies was based on the inclusion number in similar studies in other languages, in addition to our own sample power calculations. The normal-hearing studies were necessary, to obtain Norwegian norms and to compare results with other languages. The investigation of maturation effects on speech in noise was a supplement to earlier research in other languages, but testing of speech in noise in an anechoic chamber with speech and noise

spatially separated gained new insight in the field. The CI studies included a large number of participants (160 in the pediatric and 152 in the adult study). The retrospective, longitudinal, pediatric CI cohort study is unique since the population is from a country's only pediatric CI center, and includes all children who underwent sequential CI in the study period. There was also a long follow-up after implantation, longitudinally followed for at least 5 years after second CI surgery. In the adult CI study, a large number of CI users assessed themselves using the SSQ, and a disability profile could be calculated and compared to SSQ profiles in other CI studies using the SSQ in other languages, though the other studies included fewer participants. The adult CI study provided new insights by combining subjective and objective measures in a large study group.

Another important overall purpose was to integrate the HINT in the array of tests used to assess speech perception in CI users. This had a clinical purpose, but also meant that data could be used in future studies. Systematic collection according to test protocol and database storage of clinical test results will make it easy to retrieve data in subsequent studies.

1 Background

1.1 Introduction

Speech in the presence of disturbing sounds is sometimes challenging and sometimes perception of speech will be impossible. In addition to individual hearing abilities, speech intelligibility is dependent on the type, level and other characteristics of the disturbing sounds. Individuals with hearing impairment generally perceive less in the presence of background noise than normal-hearing individuals, even if the hearing loss audibility is partly compensated for with a hearing aid (HA) or a cochlear implant (CI).

Sensorineural hearing impairment, the most common form of hearing loss, is typically associated with dysfunction of the inner ear (cochlea). In a cochlear hearing loss, the auditory signal processing is changed, altering sound perception in a complex nonlinear manner. Percepts of timbre and loudness are distorted. Characteristics of sensorineural hearing impairment are reduced sensitivity (hearing level is elevated), abnormal growth of loudness (loudness recruitment), reduced frequency selectivity and temporal resolution, and this leads to degraded supra-threshold hearing.

A moderate to severe hearing loss compensated for with either a HA or a CI will make the sounds audible, but the phrase “I can hear, but I can’t understand” is common, especially when hearing in background noise. Hearing the sounds is not enough to make the words intelligible. The deficit in the signal processing leads to reduced intelligibility of speech sounds, especially difficult in the presence of background noise. Loudness recruitment, reduced frequency sensitivity and reduced temporal resolution are examples of supra-threshold deficits.

There are 250 000 to 300 000 with hearing impairments in Norway, 3500 to 4000 of them are profoundly deaf (numbers according to www.snl.no). At Oslo University Hospital, as of December 2015, 679 adults have received a CI on one side (unilateral CI), 91 (13%) of whom have received a sequential CI on the contralateral side and have CIs on both sides (bilateral CIs). In Bergen, 265 adults have received CIs, 53 (20%) of whom have bilateral CIs. In Trondheim, 220 adults have received CIs, 24 (11%) of whom have bilateral CIs. Oslo University Hospital is the only hospital in Norway performing CI surgery on children. As of December 2015 and since the first surgery in 1988, the total number of children who have received CIs is 628. Of those, 251 have received sequential bilateral CIs and 224 have received simultaneous bilateral CIs (76% of the children have bilateral CIs). As of April 2014, around 350 000 people have CIs, with 50 000 of them implanted bilaterally. In 2013, more

than 51 000 CIs were sold globally, with 55% of them going to children (Lecture by Ingeborg Hochmeier, founder and CEO of MED-EL Medical Electronics:<https://news.usc.edu/61752/lasker-lectures-cover-the-development-of-cochlear-implants/>)

Speech recognition in background noise is difficult for many hearing-impaired people and for most CI users. At some point in noisy environments, everybody – including normal-hearing individuals – will experience difficulty with speech recognition. The following will give an understanding of how normal-hearing individuals hear and especially how they recognize speech in background noise. Mechanisms of normal hearing and the auditory pathways are described. CI technology is introduced, and ways to measure hearing in noise abilities are provided.

A substantial part of this Background chapter refers to the book by Celestia (2015). In this book, Chapter 1 on auditory pathways is written by Pickles (Pickles 2015) with reference to his book (Pickles 2013), and Chapter 3 on the development of the auditory system is written by Litovsky (Litovsky 2015).

1.2 Auditory pathways

The auditory signal is a one-dimensional, time-dependent sound pressure wave received by each ear. The sound spectrum is changed through resonance filters in the outer and middle ear, and the impedance is transformed. There is an impedance matching between the air and the fluid in the cochlea since the area of the ear drum is larger than the stapes footplate which makes the middle ear act as a hydraulic press. The lever arm of the malleus is somewhat longer than that of incus, giving another factor in pressure increase.

The cochlea performs sound detection and a high resolution frequency analysis. Inner hair cells in the cochlea act as simple sensory receptor cells. The inner hair cells stimulate the auditory nerve fibers to action. Their responses are fundamental for the later stages of the auditory pathways: The auditory brainstem, midbrain and the cortex have multiple and interrelated functions, both parallel and overlapping pathways. The issues of sound processing in the outer and middle ear, and the following signal processing in the cochlea and the central auditory system, are described briefly in the following section.

The peripheral auditory system consists of the outer ear, middle ear and inner ear. The central auditory system extends from the cochlear nucleus up to the primary auditory cortex.

1.2.1 The outer and middle ear

A normal ear transforms sound pressure waves into nerve impulses. The human ear can be divided in three parts: the outer ear which is the pinna and the outer ear canal, the middle ear which begins with the eardrum at the end of the ear canal, and contains the three tiny bones, called the ossicles, and the inner ear which contains the sensory organs for hearing and balance. The cochlea is the hearing part of the inner ear. The anatomical parts of the human ear are illustrated in Figure 1.

Figure 1 Illustration of the human ear and how sounds enter the pinna (1), move through the ear canal and strike the ear drum. The sound waves cause the ear drum to vibrate, and thereby the three bones (ossicles) within the middle ear (2). The vibrations move through the fluid in the cochlea (3) and mechanical sound waves are converted to electrical signals which are transferred to the brain via the hearing nerve (4). (The illustration is provided by Cochlear, Copyright Cochlear Limited ©)

Sound diffracts around the torso, the head and around the pinna, and is additionally filtered due to the shape of the pinna before it reaches the ear canal. The width and length of the ear canal will further change the spectrum of the sound. Typically, the ear canal transfer function shows a peak of about 10-15 dB of around 3000 Hz (Shaw 1974). The tympanic membrane (ear drum) is at the end of the ear canal, and the sound pressure wave makes the ear drum vibrate at the same frequency as the sound. The ear drum separates the outer and middle ear. From the ear drum, the sound propagates through the middle ear, which consists of three small bones (ossicles), the malleus, incus and stapes. The stapes transfers sound from the middle ear to the inner ear (cochlea) via the oval window into the cochlea. The middle ear transmits the sound or the acoustical energy to the inner ear. The impedance is transformed due to the area difference between the larger ear drum and the smaller oval window and

the length difference between the longer arm of the malleus and the shorter arm of the stapes. The size differences amplify the pressure reaching the oval window compared to the pressure at the ear drum. The sound signal transferred to the cochlea is a filtered and impedance transformed version of the sound signal which reached the outer ear (Nakajima et al. 2009).

Absolute threshold

The auditory absolute threshold to detect sound corresponds to a power of the order 10^{-18} W absorbed by the inner ear (Rosowski 1991). At threshold, about 300 ms is used to make a decision. Thus, the energy detection threshold is 3×10^{-19} J. The efficiency of transmission through the outer and middle ear to the inner ear gives a variation in the hearing threshold over the range 450 Hz to at least 10 kHz. Other factors come into play outside this frequency range. Commonly, 20 kHz is taken as the upper frequency limit of hearing in young children, 15 kHz in young adults (Pickles 2015). Below 1 kHz the threshold rises gradually as the stimulus frequency is lowered.

1.2.2 The inner ear (cochlea)

The inner ear (cochlea) is a spiral fluid-filled tube with 2.5 turns. The overall width is 1 cm and height 0.5 cm. The cochlea/tube has three chambers or scalae, spiraled around the central core, the modiolus. The modiolus contains the auditory nerve and many of the blood vessels. The basilar membrane is a membrane between the scalae, 35 mm long. The organ of Corti is located on top of the basilar membrane. The organ of Corti consists of receptor (sensory) cells (hair cells) and the tectorial membrane.

The vibration of stapes at the oval window makes the mechanical motion propagate from the oval window, from the base towards the apex of the cochlea. The propagation makes the basilar membrane vibrate, and a traveling wave is produced on the basilar membrane. The wave peaks close to the base for high-frequency stimuli and closer to the apex for lower frequency stimuli. The traveling wave was originally measured by Bekesy in animal and human cadavers (Von Békésy 1960). As was first demonstrated by von Bekesy (Von Békésy 1960; Von Békésy et al. 1989), the mechanical action of the cochlea produces a frequency-to-place transformation. Later studies showed that the traveling wave was larger and more sharply tuned. A review is provided in Robles et al. (2001). The neural response of each fiber of the auditory nerve is highly frequency specific, and stimulus frequency to which each fiber is most sensitive, is referred to as the characteristic frequency (CF) for that fiber. This ‘tonotopic’ representation of sound is preserved at virtually all levels of

auditory processing. In addition, fibers with low CF are synchronized to the detailed time structure of low-frequency sound.

Outer and inner hair cells are two types of sensory cells identified inside the cochlea. The vibration of the hair cells causes the bristles (stereocilia) on the hair cell tips to brush against the tectorial membrane. The mechanical impulses are converted into electrical energy. The hair cells act as tiny transducers that convert mechanical energy into electrical energy. Low-frequency sounds are converted close to the apex and high-frequency sounds closer to the base. The transformation of mechanical vibration into an electrochemical change is referred to as a forward transduction.

The outer and inner hair cells have a different anatomy and function. The outer hair cells have in addition to the forward transduction, a mechanical role in reverse transduction (efferent pathway). Their bundles of stereocilia (60-120 per hair cell) are relatively stiff and have a motile (ability to move spontaneously) cell body. The active process of the outer hair cells is driven by the protein prestin contained in the walls of the hair cells, and the active process gives the mammalian cochlea the high sensitivity which allows detection of very low sound intensities over a wide range of frequencies. The inner hair cells act more directly as simple sensory receptor cells. Inner hair cells activate the fibers of the auditory nerve; about 95% of the fibers of the auditory nerve arise from the inner hair cell population (afferent pathway).

Nerve fibers at the base of the cochlea are tuned to high frequencies, and fibers innervating the apex are tuned to low frequencies. For low-frequency sounds, nerve fibers are preferably activated in one phase of the stimulus, and the responses of the auditory nerve fibers are likely to be phase-locked to the individual cycles of the stimulating waveform. When the stimulus frequency is raised above 1 kHz, the phase locking gradually decreases. At 5 kHz, the nerve fibers are likely to fire with nearly equal probability at all phases of the waveform. Both site and timing of its action potentials can convey information about the stimulus frequency, but there is no consensus as to what extent the two cues contribute (Pickles 2015).

1.2.3 Central auditory system

The auditory system deals with very rapid temporal fluctuations of the order of a few tens of microseconds. However, to extract stimulus from background noise, the neuronal circuits (e.g. lateral inhibition) have uncertainties of the order of milliseconds. Pickles (2015) suggests that the complexity in the auditory system is because these two types of analysis are incompatible, and the auditory system has multiple parallel and overlapping pathways, as illustrated in Figure 2. The pathways are divided in the auditory nerve to the cochlear nucleus (CN) as:

1. Ventral auditory stream of the brainstem. Temporal information with a high accuracy (e.g. sound localization by comparing responses at the two ears). From the anteroventral cochlear nucleus (AVCN) where precision of temporal information is further enhanced, the pathway divides into
 - a. The medial superior olive (MSO): timing of the stimuli at the two ears is analyzed.
 - b. The lateral superior olive (LSO): intensities of the stimuli at the two ears are compared.

Fibers travel through the lateral lemniscus with its two nuclei, one of which (the dorsal nucleus) serves to increase accuracy, contrast and dynamic range of the localization information by crossed inhibitory inputs.

2. Dorsal auditory stream of the brainstem. Analysis of patterns of activity measures the mean response rates over populations of neurons. (Multiplicity of functions: signals are extracted based on a complex spectral analysis and timing accurately preserved in the broadband stimuli). Complex patterns of the stimuli are extracted in the dorsal cochlear nucleus. The posteroventral cochlear nucleus (PVCN) takes both timing and spectral analyses, mostly for the dorsal stream, but also for the ventral auditory stream.

Fibers travel through the ventral nucleus of the lateral lemniscus which apparently is not involved in binaural sound localization since it does not receive input from binaural MSO and LSO.

Results from the analyses in the two pathways are combined in the inferior colliculus and in later stages both combined and refined. The tonotopic organization is preserved in both the AVCN and the DCN divisions of the CN, and in the higher auditory structures.

The medial geniculate body (MGB) is part of the auditory thalamus and represents the auditory thalamic relay between the inferior colliculus (midbrain) and auditory cortex (cerebral cortex). The spatial, spectral and temporal features are further integrated to form neural coding of “auditory objects” which is presented to the auditory cortex. There is a close two-way interaction between the MGB and the auditory cortex and some consider it as one unit. To analyze the stimulus transformations in MGB itself is therefore difficult (Pickles 2015).

Figure 2 The main ascending pathways of the brainstem. Many minor pathways are not shown. DNLL, dorsal nucleus of the lateral lemniscus; IC, inferior colliculus; MGN, medial geniculate body; VNLL, ventral nucleus of the lateral lemniscus; MSO, medial superior olivary nucleus; LSO, lateral superior olive; MNTB, medial nucleus of the trapezoid body; AVCN, anteroventral cochlear nucleus; PVCN, posteroventral cochlear nucleus. (Permission granted by Pickles (Pickles 2013)).

1.2.4 The auditory cortex

The auditory cortex is divided into a number of different regions. Broadly it can be divided into the primary area and the peripheral area (or belt area). The primary area receives input from the ventral auditory system via the MGB and is thought to have a precise tonotopic map. The belt areas receive more diffuse information from the belt areas of MGB, mainly from its dorsal and medial divisions.

Definition of areas in the auditory cortex has been undertaken in primates/cats, but is more difficult in human beings. Recent functional magnetic resonance imaging (fMRI) studies have confirmed some of the findings in some subcortical areas while other studies show differences across studies and observations that these might be species-dependent (Moerel et al. 2015). Current data suggests that the three fields of the core are tonotopically organized (Barton et al. 2012), and further frequency-selective representations have been found outside these areas (subcortical areas like the inferior colliculus and MGB) (Barton et al. 2012; Moerel et al. 2012; Moerel et al. 2015).

In the auditory cortex, auditory field maps are defined by the combination of tonotopic organization, representing the spectral aspects of sound, and orthogonal periodotopic organization representing the temporal aspects of sound (i.e. period or temporal envelope). A periodotopic map is organized from short to long temporal receptive fields, orthogonal to the tonotopic organization (Barton et al. 2012). Converging evidence imaging and measurements forms the basis for the definition of 11 auditory field maps across core and belt areas of the human auditory cortex (Brewer et al. 2016) .

1.2.5 Descending pathways (the centrifugal system)

The auditory system has pathways that run in the reverse direction, i.e. from the auditory cortices to the MGB and the inferior colliculus, as illustrated in Figure 3. The centripetal system conveys information from the auditory periphery to the central systems whereas the centrifugal system is a rich set of descending pathways. The descending pathways can modify the response of the ascending system.

Figure 3 Major descending pathways of the auditory system. In general, the descending pathways end on neurons in areas surrounding the nuclei associated with the ascending system. The branching and joining of arrows does not necessarily mean that fibers branch or join. CN, cochlear nucleus; COCB, crossed fibers of the olivocochlear bundle; DNLL, dorsal nucleus of the lateral lemniscus; IC, inferior colliculus; lat, lateral component of the olivocochlear bundle; VNLL, ventral nucleus of the lateral lemniscus; MSO, medial superior olivary nucleus; LSO, lateral superior olive; MNTB, medial nucleus of the trapezoid body; PVCN, posteroventral cochlear nucleus (Permission granted by Pickles (Pickles 2013))

1.3 The auditory system and auditory processing

Auditory processing starts with peripheral mechanisms which encode sound, and proceeds to more complex stages where the sound processing leads to perception and auditory object recognition. Inputs from the left and right ears combine in stages or in several synapses after the initial synapses in the cochlea.

Generally, the peripheral system encodes the sound stimuli based on temporal, spectral and intensity cues. Complex combinations of those cues are extracted,

and assignment of auditory features into meaningful stimuli, such as music and speech, occurs at more central levels of the auditory pathways, including the role of non-auditory processing.

1.3.1 Coding of auditory features (loudness and pitch)

Perceived pitch and loudness are two basic auditory attributes which are subjective responses to auditory features like sound frequency and intensity, aspects of detection of sound (frequency dependent) and discrimination of frequency and intensity.

Loudness is the perceptual correlate to sound intensity, but is dependent on other acoustical parameters, such as frequency, bandwidth, temporal duration and fluctuations, and whether presentation of stimulus is monaural or binaural (Rohl et al. 2012; Uppenkamp et al. 2014). Non-auditory factors like context effects and personality (e.g. anxiety) can affect loudness.

Within the peripheral auditory system, the hypotheses are that neurons fire more to a louder sound (firing rate increases) and that more neurons fire to a louder sound (number of active neurons increases).

Pitch is an important cue when segregating sound sources. A just-noticeable difference (JND) in the frequency of pure tones can be as low as 0.2% in the frequency range from 500 to 2000 Hz (Moore 1973). Within the peripheral auditory system, there are two “classical” ways in which a pure tone might be coded, one using place and one using time code (Oxenham 2013). The place representation is based on the mechanical frequency analysis and the mapping of frequency to place mapping in the cochlea. Every place along the basilar membrane has its own “characteristic frequency”. This tonotopic organization is maintained in the auditory pathways up to the primary auditory cortex. A potential neural code for pitch of pure tones is provided. The second potential code is the “temporal” code. Action potentials or spikes are generated in the auditory nerve and tend to be phase-locked to the period of the sinusoid. The time intervals between successive spikes could be potential representations of frequency. Since the frequency limit of phase-locking reduces from 2-4 kHz (measured in other mammals, (Palmer et al. 1986)) to 100-200 Hz in the auditory cortex (Wallace et al. 2000), most researchers believe that the timing information code must be transformed to some form of place- or rate-based code (Oxenham 2013).

Just as with pure tones, the models for pitch extraction in complex tones are generally divided into place and time (and place-time). Place models assume that pitch is extracted from the lower harmonics (Cohen et al. 1995; Goldstein

1973; Terhardt 1974; Wightman 1973). Temporal models use the autocorrelation or an all-interval spike histogram to evaluate the time intervals between auditory nerve spikes (Cariani et al. 1996; Meddis et al. 1997; Meddis et al. 2006). One of the place-time (spatio-temporal) models uses a spatial network of coincidence detectors to calculate the coincident timing between neurons with harmonically related characteristic frequencies (Shamma et al. 2000; Zhang et al. 2001). The spatio-temporal representation is consistent with available physiological evidence, and the model is more robust than the rate-place representation at high stimulus levels (Cedolin et al. 2010).

A sound signal can be decomposed into temporal envelope and temporal fine structure. For the low-frequency bands, the neural responses are highly synchronized to the fine structure, but for the higher frequencies biophysical properties limit the tempo of the neural responses. The temporal representation is limited by jitter in the synaptic transmission; the upper limit of phase-locking in humans is as yet unknown, but the phase-locking begins to weaken above 4-5 kHz in most mammals (Moon et al. 2014). In humans, the lack of perceptual phase sensitivity above 1.5 kHz is often modeled as a lack of synchronized firing above 1.5 kHz. The place representation is based on mechanical frequency-to-place mapping in the cochlea and is limited by cochlear frequency resolution.

The central processing of pitch means a degradation in the temporal representation of pitch, there is a neural tuning to temporal envelope, and it is questioned whether there are “pitch neurons” in the auditory cortex. Many questions remain concerning how auditory cortical neurons encode the percept of pitch (Bizley et al. 2010).

1.3.2 Masking and auditory segregation

The ability to recognize what one person is saying when others are speaking simultaneously has stimulated research in psychoacoustics, auditory scene analysis and attention. It includes research on the early processing and selection of speech. In the psychoacoustic literature the term “masking” is used for all types of sound competitors or interferers.

Important effects like mutual masking of sounds and unmasking occur in binaural listening at the peripheral and brainstem levels. These effects can be predicted in psychoacoustic models. The grouping of sounds is the subsequent processing stage, interacting with attention. Auditory scene analysis (ASA), a model for the basis of auditory perception, tries to understand how sound is organized into perceptually meaningful elements (Bregman 1990). For speech

sounds, the more specific “cocktail-party” effect was first described by Cherry (1953).

In Bronkhorst (2015), the term “grouping” is used instead of “auditory scene analysis” since ASA also refers to attentional effects. Bronkhorst (2015) described two different tasks which are performed when a target speech is extracted from a multi-talker mixture, *segregation* and *streaming*. Segregation separates the target from other speech. Streaming connects sound elements across time. Bregman (1990) referred to segregation as *simultaneous* organization and streaming as *sequential* organization. Bregman (1990) also introduced “primitive” (“bottom-up” ASA) and “schema-based” (“top-down” ASA) grouping, but did not link attention to the schema-based grouping. The primitive grouping takes place pre-attentively while the schema-based grouping makes use of specific stored sound patterns.

Two “popular” types of grouping cues are based on voice characteristics and spatial separation of target and noise. More complex processing is required with speech recognition, to process lexical, syntactic, or semantic information of sounds. Examples of cues that will probably affect grouping are speaking style, timbre, linguistic variability (native or non-native), and various contextual types of information (for example, semantic, syntactic, and coarticulatory information).

When several sounds are presented, the sounds can be perceived as either one coherent sound or as several distinct sounds. The sounds may share some dimensions or features, and the formation appears to depend on acoustic parameters like frequency, spatial location, fundamental frequency of the talker, spectrum and temporal onsets and offsets. Auditory stream formation appears to be dependent on acoustic parameters (frequency, spatial location, talker’s gender, spectrum and common temporal onsets and offsets) (Bregman 1990). Developmental changes in the ability to segregate auditory streams are found well into school-age years (Sussman et al. 2007).

1.3.3 Masking and unmasking of speech sounds

The multiple acoustic cues are all used to interpret and understand speech. Their relative contributions in speech perception in quiet and in noise have been investigated in several studies. Moon and Hong (2014) refer to studies investigating the contribution of multiple acoustic cues and their relative contributions in speech perception in quiet and in noise (Drullman 1995; Hopkins et al. 2010; Hopkins et al. 2008; Lorenzi et al. 2006; Shannon et al. 1995; Won et al. 2007; Xu et al. 2005). In particular, the contribution of fine structure and its importance in hearing-impaired listening and in CI

stimulations are discussed (Moon and Hong 2014; Oxenham 2013), in which Oxenham (2013) argues that “much of the recent evidence suggesting the importance of temporal fine structure processing can also be accounted for using spectral (place) or temporal-envelope cues”.

At the peripheral and brainstem levels, important effects occur, like mutual masking of sounds and “unmasking” as a result of binaural listening. Similar components reach both ears and effective unmasking is achieved through suppression. An important variable in unmasking is the signal-to-noise ratio (SNR). The SNR is the difference in dB between target sentence level and noise level. Plomp (1977) showed that a typical cocktail party has SNR equal to 0 dB.

Several factors will influence the masking and unmasking of speech. Bronkhorst (2015) described the most important or relevant factors as: target speech, spectral differences between target and noise and the spatial configuration between the two, fluctuations or modulations of the noise, the environmental acoustics, and the hearing ability of the listener. Different types of masking and maturation of the unmasking abilities are described in the following.

Energetic masking

The peripheral interference is called energetic masking, to distinguish it from informational masking which refers to masking that cannot be accounted for by peripheral mechanisms.

Energetic masking can have different characteristics, but shares features with the target (signal), and is typically accounted for in the peripheral auditory system. Steady-state noise is often assumed to produce mainly energetic masking due to overlapping excitation patterns on the basilar membrane (Fletcher 1940).

There is a rapid maturation for hearing signals in noise, and the maturation is faster for the high-frequency than the low-frequency thresholds (He et al. 2010). Several studies show that children require a more advantageous SNR than adults for speech recognition in relatively steady state noise (Elliott 1979; Hall et al. 2002; Litovsky 2005; Nishi et al. 2010; Nitttrouer et al. 1990; Wightman et al. 2005) . Most children achieved adult-like performance by at least 10 years of age (Eisenberg et al. 2000; Elliott 1979; Nishi et al. 2010), also shown in the findings of McCreery et al. (2011), although the latter study also showed that, compared to adults, children did not experience greater degradation in speech recognition when high-frequency bandwidth was

limited. The finding supports the need for maximizing high-frequency audibility, in particular for young children developing linguistic knowledge.

Informational masking

Informational masking refers to masking that cannot be accounted for by peripheral mechanisms. Informational masking might indicate that the listener is confused about which features of the sound belong to the target and which to the masker (Durlach et al. 2003). The listener will not know which aspects of sound (spectral, temporal or other features) to ignore in the masker. Informational masking is also explained by interference that cannot be explained by reduced audibility (Arbogast et al. 2002; Bronkhorst 2015; Brungart 2001). Speech maskers produce substantial informational masking in addition to energetic masking, and the masker effects decrease as the number of talkers in the masker increase. The latter effect is probably caused by the resulting masker being less confusable with the target speech and thus producing less informational masking.

The more similar the speech signal and the masker signal, the more likely there is for informational masking to occur. The most extreme example would be the same voice expressing two messages at the same sound pressure level and from the same speaker.

Larger and more prolonged age effects were found in studies using informational compared to energetic masking. Larger performance gaps are found between adults and children for speech maskers compared to steady-state noise maskers (Bonino et al. 2013; Corbin et al. 2016; Hall et al. 2002; Wightman et al. 2003; Wightman and Kistler 2005). School-aged children (under 10 years old) showed elevated speech detection thresholds relative to adults in two-talker speech, but not in speech-shaped noise (Leibold et al. 2016). Consonant identification in a speech-shaped noise was found to be adult-like for 11- to 13-year-olds, but significant child-adult differences were found even for the oldest group of children in consonant identification in a two-talker masker (Leibold et al. 2013). It is suggested that errors with the two-talker masker reflect failures in sound segregation.

Backward masking and auditory maturation

Another parameter when studying masking is presentation order of target and noise. Backward masking is studied by presenting the signal before the noise, and involves a central mechanism that weights information from the two sound sources. Simultaneous masking is adult-like by age 6-10 years while backward masking is significantly worse in children compared to adults. It has been suggested that the temporal resolution is involved in backward masking

and the ability is improved during childhood (Hartley et al. 2000). Results showed that, measured by masking, frequency resolution reached adult-like performance by 6 years of age whereas temporal resolution developed beyond 10 years of age.

Modulated noise maskers

In steady-state noise, peaks of the speech will contribute to intelligibility and recognition is usually predictable. If the noise is amplitude modulated the listening condition is more complex.

As summarized by Freyman et al. (2012), compared to those with normal hearing, the hearing impaired take less advantage of the temporal “valleys” and “dips” or “glimpses” when the masker is amplitude modulated. Proposed explanations are reduced audibility, temporal masking, reduced peripheral compression, and higher SNRs used in the tests, which makes masker fluctuations less useful.

The slope of the psychometric function for speech intelligibility is the rate of intelligibility change with level. MacPherson et al. (2014) quantified the range of slope changes in the psychometric functions for different listening conditions in 885 psychometric functions from 139 studies. Modulated maskers included all maskers with temporally fluctuating amplitude, regardless of the type and spectral shape of modulation. Their analyses demonstrated that masker type affected the slope of the psychometric function: speech maskers gave shallower slopes than static noise maskers and amplitude-modulated noise maskers. Surprisingly, the amplitude-modulated noises did not give substantially shallower slopes than the static noise maskers, as might be expected by the “glimpsing” argument which states that dips of locally increased SNR allow the listener to glimpse the target speech signal. However, as explained in the paper, a wide range of maskers fell into the category of modulated depth, that is, depths ranging from 1 to 48 dB and modulation rates from 1 to 100 interrupts per second. Howard-Jones et al. (1993) found that fluctuations with relatively long durations (> 200 ms) gave shallower psychometric functions than non-modulated maskers.

The precedence effect / reverberations

In reverberant rooms, sound reaches the listener along a direct path and a time delayed path due to reflections from walls and various objects. Perceived location is mainly based on the first-arriving sound, referred to as the precedence effect (Wallach et al. 1949). Summaries of earlier studies are provided in the article written by Litovsky et al. (1999), and for studies published thereafter in the review article by Brown et al. (2015). Steven

Colburn et al. (2006) illustrated that interaural differences are complicated in reverberant environments, and concluded that functional hearing abilities in anechoic and reverberant environments might give different results. It was also speculated that the effects of various amounts of reverberation could be different for listeners with normal hearing and listeners with hearing loss.

There are several studies of the precedence effect, most often looking at simple stimulus, but even if simple stimuli are used, the simulations probably indicate potential difficulties in realistic, reverberant listening situations. Implication of the finding in a study reported by Litovsky (2015) is that, compared to adults, children have more difficulty in perceptual weighting of spatial cues arriving from the direct and delayed paths (sources and their reflections).

Factors for successful identification

The intelligibility of a talker can be degraded by maskers. Spectral overlaps between talker and masker give an energetic masking; the audibility of the target is reduced. Other aspects of masking are generally referred to as informational masking. Similarity between talkers is a particularly strong driver of informational masking; the talker and masking words are confusing. Knowledge of schemas for target and masker will play a role in identification of the target words, e.g. knowledge of semantic context and prosody will play a role. Familiarity with the talker voice and the masker will also be a factor of reducing informational masking. Not only the voice quality of the talker, but also where and when to listen, will affect the unmasking. These are top-down processes to segregate and stream target from a masker (Carlile et al. 2015).

1.4 Binaural hearing

Binaural hearing is the ability to extract auditory information using two ears. Binaural hearing is useful in sound-source localization, in signal detection in noise (binaural unmasking), and in sound-source grouping and segregation. Binaural processing is an essential component of ASA.

When listening in noise and when locating where sounds are coming from, listeners utilize the acoustic cues arriving at both ears. Effects have been studied in relation to binaural cues and bilateral benefits.

Binaural cues

Spatial and binaural hearing takes advantage of the acoustic cues arriving at the two ears. Sound sources arriving from the side will reach the two ears at different times, and with different intensity. The interaural time difference (ITD), when a sound is 90° to the right, will depend on the size of the head, but is about $660\ \mu\text{s}$ for a human head of typical size. Typically, below 1500 Hz, the listener can effectively utilize the time difference. At typically high frequencies, the head creates a head shadow of the sound since the head is large compared to the wavelength of the incoming sound, producing substantial reflection rather than diffraction of the incoming sound waves. The near ear will have a greater intensity than the far ear, and we have an interaural level difference (ILD) between the two ears. The ILDs are frequency dependent and can be as large as 20 dB sound pressure level (dB SPL).

The duplex theory for sound localization is a century old, first formalized by Strutt (later Lord Rayleigh) (Strutt 1907). The idea is that sound localization is based on ITD at low frequencies and ILD at high frequencies. The duplex theory view of ILD as an exclusively high-frequency cue has persisted, but physiological studies have characterized ILD coding neurons sensitive to the tonotopic frequency span, including the low frequencies (Jones et al. 2015). For example, low-frequency sound near the head (especially $< 1\ \text{m}$) can generate large ILDs (10 dB) due to dispersion rather than frequency-dependent head shadowing (Brungart et al. 1999; Kim et al. 2010).

Binaural processing is complex. The likely first sites of analysis of the binaural cues are the MSO for ITDs, LSO for ILDs, and DCN for spectral-shape cues. It is generally assumed that low-frequency ITDs are processed in the MSO and high-frequency ILDs are processed in the LSO. For many years, the brainstem mechanisms of ITD sensitivity (in the MSO) have been explained by the Jeffress model (Jeffress 1948), a set of delay lines and coincidence detectors to compute a temporal cross-correlation function. Since

speech is amplitude modulated, the ITD cues will be available in the timing of the envelopes of the speech signal.

To quantify binaural abilities, the JND in the ITD and ILD can be used. For low-frequency stimuli, the best listeners typically achieve ITD JNDs of about 15 μ s, and ILD JNDs of about 0.5 dB at all frequencies (Steven Colburn et al. 2006).

Thus, interaural differences in sound waveforms are: ILDs, ITDs, and interaural cross-correlation and the energy difference in the waveforms. Generally, they can all be considered as a function of sound frequency. These binaural cues depend on many acoustic factors. Interaural differences are complex patterns in acoustical environments with reverberations and multiple sources (Steven Colburn et al. 2006). The complex patterns are interpreted through complex processes which include both top-down and bottom-up factors. Studies have investigated how binaural cues are affected by reverberations (Gourevitch et al. 2012; Mlynarski et al. 2014).

In addition to binaural cues, sound reaching the eardrum interacts with the head and the outer ears, acting as frequency filters, so that the sound is modified. This frequency modification makes it possible to determine sound source localization in the vertical plane.

Binaural unmasking

Generally, when target and masker have interaural parameters that are different, binaural detection of the target can have a large advantage compared to monaural detection. These advantages are described as masking level differences (MLDs).

Binaural unmasking is used in different listening aspects, but the focus in the following is the binaural cues for segregating target speech from competing noise (or competing speech interferers). In normal hearing a complex set of auditory computations are involved when segregating target speech from competing noise. It involves monaural and binaural processing and depends on features of the noise (Culling et al. 2004; Hawley et al. 1999; Hawley et al. 2004).

Spatial cues are used in source segregation, and speech intelligibility normally increases when target speech and noise are horizontally separated. The separation of target and noise along horizontal azimuth lowers the threshold for detecting the target over a wide range of frequencies (Freyman et al. 1999; Saberi et al. 1991). The lower thresholds are mainly a head shadow effect for high-frequency sounds and binaural interaction for low-frequency sounds.

Zurek (1993) considered only the audibility component in his model of binary speech recognition, and the model explains successfully other speech-in-noise data, e.g. (Bronkhorst et al. 1988; Freyman et al. 1999).

The difference in threshold for detecting signals in the presence of noise collocated with the signal and spatially separated from the signal, is called a spatial release from masking (SRM) (Arbogast et al. 2002; Hawley et al. 1999; Hawley et al. 2004). Litovsky (2015) reviewed SRM data from several studies, with SRM values ranging from a relatively small 3-5 dB up to quite large values of 10-12 dB, depending on the stimulus, type of masker and task. SRM is largest when target and masker are more confusable, e.g. maskers with a more similar voice as target will have larger SRM (Misurelli et al. 2012). Speech maskers gave overall higher SRM magnitudes than primarily energetic noise maskers (Jones et al. 2011). High informational masking (higher when masker speech is the same gender or the same talker) gave larger magnitude of the SRM relative to energetic noise maskers (Balakrishnan et al. 2008; Brungart 2001). Freyman et al. (2001) compared noise maskers which were understandable and not understandable (two-talker reversed speech or non-native), and found that spatial release was not limited to understandable noise.

1.5 Development of the auditory system

The maturation of auditory perception has a sensory component in the auditory system which matures, and a non-sensory component which includes attention, cognition and memory. Auditory perception is therefore age-dependent with individual variability within age. Maturation on behavior on auditory tests is seen into the late teenage years (Fischer et al. 2004; Maxon et al. 1982).

Physiologic responses in the central auditory pathways are, for example, measured using event-related potentials. Different or missing characteristics of the responses for adults and children might reflect the immaturity found in behavioral studies. Neural maturity for central processing of complex information continues to mature beyond ages 6-8 years. Cortical maturation extends into the late teenage years (Coch et al. 2005; Litovsky 2015).

Behavioral testing and psychoacoustics

A research review on how the human auditory system develops, is described by Litovsky in the work by Celesia (Celesia 2015), and includes what aspects of sound are perceived by infants and children and the ways in which sounds are interpreted at higher levels of neural coding. Also discussed is how perception can be measured reliably through behavioral testing, and how testing methods must vary through the lifespan. With infants, thresholds for

hearing sounds at different frequencies can be found by observer-based techniques where changes of the infant's behavior to stimuli are observed. Children from around 3 years old can use a computerized, interactive test environment, and studies for the last 20 years have used data programs to study auditory maturation in children.

Litovsky provided data (Celesia 2015) with a summary of auditory development findings which show an age range during which the different perceptual abilities are known to be mature, and in which perceptual abilities are moderately mature, but for which additional research may be required. Litovsky identified four perceptual abilities which needed additional research: loudness perception, simultaneous masking, comodulation masking release and informational masking. Loudness perception is mature to a certain extent in range from 6 months to early school age. Maturation of simultaneous masking, comodulation masking release and informational masking are fairly mature from preschool age, and continue to mature into middle school age, with informational masking continuing to mature into the teenage years.

Age of development and desirable age of intervention in deaf children

The auditory system can change significantly due to lack of sensory input, and degeneration will occur both peripherally and centrally (Shepherd et al. 2006). Degradation of neural ganglion cells will follow after a prolonged period of auditory deprivation (Leake et al. 1988). When profound deafness occurs in the early developmental period, it seems to result in loss of normal tonotopic organization of the primary auditory cortex. However, studies show that the loss can be reversed after reactivation of afferent input (Kral et al. 2009).

Auditory deprivation can be divided into two mechanisms (Litovsky 2015):

- 1) Peripheral mechanisms which are more easily deprived and less likely to recover their function.
- 2) Central auditory mechanisms are easily influenced by deprivation and likely dysfunctional as a result of hearing loss, but more likely to recover their function.

Some functions can be recovered with training and rehabilitation. Questions arise as to which developmental stimulatory deprivation might lead to disrupted structural development, and whether listeners are able to organize incoming information after the auditory system is reactivated.

This reactivation occurs with CIs which provide hearing through electric stimulation of the auditory nerve. Several studies have found that differences

in cortical or auditory pathways are likely to contribute to the variability in CI outcome (Wilson et al. 2008a, 2008b).

There is evidence that earlier intervention with a HA or CI will improve outcomes, and outcomes are maximized if stimulation is provided at an early stage in spoken language development (Niparko et al. 2010; Wilson and Dorman 2008a). The longitudinal multicenter study results provided in the paper by Niparko et al. (2010) were not determinative, but age at implantation (groups < 18 months, 18-36 months, > 36 months) and residual hearing were associated with rate increases in acquisition of spoken language. Wie (2010) found that the majority of children receiving bilateral CIs between ages 5 to 18 months developed language skills within the normative range over longitudinal follow-up in intervals up to 48 months of implant use.

When it comes to single sided deafness, some research studies in animal models (Kral et al. 2013) and humans (Gordon et al. 2013) show possible irreversible aural preferences. In bilaterally deaf children who receive a CI in one ear and have a prolonged stimulation in the other ear, adaptation of the second side CI is found to be difficult (Galvin et al. 2009).

1.6 Cochlear implants (CIs)

A substantial part of the theory of CIs is by Sheperd et al. from Chapter 16 in the book by Celesia (2015). In a paper by Wilson and Dorman (2008a), the “remarkable past and brilliant future” of CIs is described, and provides a brief history of the CI, a present status report, limitations, and new directions for CI research. Design of CIs in aspects of normal hearing, components of CI systems and stimuli or processing strategies are described in another article by the same authors (Wilson and Dorman 2008b).

1.6.1 Introduction

CI technology takes advantage of the tonotopic organization of the cochlea. An electrode array is inserted into the scala tympani to electrically stimulate sectors of the auditory nerve via populations of residual spiral ganglion nerve cells. The CI transmits important speech cues to the auditory brain, including loudness (intensity), pitch (site of the cochlea) and temporal cues with information about the speech envelope dynamics. Speech is divided into discrete frequency bands and mapped to specific electrodes.

1.6.2 CI systems

A CI system (Figure 4) consists of an external sound processor and an implanted device of combined receiver and stimulator, including an electrode array of platinum electrodes.

Figure 4. Illustration of cochlear implant system with a sound processor (1), a coil (2) to transmit digitally-coded sound from processor to the implanted device (3). The implanted device receives the signals and converts them into electrical impulses which are sent along the electrode array placed in the cochlea. The electrodes in the cochlea stimulate the hearing nerve (4). (The illustration is provided by Cochlear, Copyright Cochlear Limited ©)

The sound processor picks up sound from the environment through an internal microphone, typically analyzes the frequency content and maps the acoustic parameters into appropriate electrical charge levels (intensity levels) and stimulation sites in the cochlea (which electrodes to stimulate). The processor has a power source to run the frequency analyzer and power to transmit to the implanted device. Power and data from the external processor is delivered by an inductive link to the implanted receiver-stimulator.

There are several sound-processing algorithms available, but all are based on Fourier transform or a bank of parallel band-pass filters (McDermott et al. 1992; Wilson et al. 1991). High frequencies are assigned to electrodes near the base of the cochlea, lower frequencies assigned to the more apical electrodes.

The implanted device consists of a receiver coil (to receive power and data), a decoder (data decoded to produce current waveform), a charge delivery system and an electrode array of platinum electrodes located in the cochlea. The current waveforms stimulate the spiral ganglion nerve cells.

1.6.3 Electrical stimulation

Loudness in CIs (Seligman et al. 2011) is encoded by both current amplitude and pulse duration. The spiral ganglion nerve cells are sensitive to changes in both. The resting transmembrane potential of spiral ganglion nerve cells is -60 mV, and the electrical stimulation of the neural tissue initiates action potentials.

Electrical stimulation is achieved via a series of electrochemical reactions that convert the charge carriers from electrons (in the electrode) to ions (in the electrolyte) (Ranck 1975). Normal physiological processes are undertaken once the action potentials are initiated. Charge recovery using biphasic pulses are non-linear, and to correct for charge imbalance and minimize electrochemical reaction products, additional techniques are used (Patrick 1990; White 1980). Phase duration is typically 10-40 μ s, and the pulse rate typically between 600-2000 Hz per channel. Pulses are delivered sequentially. The overall pulse rate varies, for the Cochlear system the overall pulse rate is for example 14 400 pulses per second.

The most common electrode configurations are monopolar and bipolar electrode geometries. Bipolar stimulation uses a neighboring electrode (separated by at least one electrode) as the return electrode, and neural excitation is produced in a relatively localized pattern. However, since there is current shunting between electrodes, thresholds are quite high. Monopolar stimulation is a more efficient electrode configuration and uses a single scala tympani electrode of a larger surface and a return electrode located outside the cochlea. However, spread of neural activation is larger with monopolar compared to bipolar stimulation (van den Honert et al. 1987). Multipolar electrode stimulation has improved spatial selectivity (Bierer et al. 2010) and may have clinical application.

One spiral ganglion nerve cell can be activated by multiple electrodes since stimulating channels overlap considerably. Stimulation from an electrode in the scala tympani is spatially broad due to the conductive nature of the fluid-filled inner ear (Black et al. 1981; Snyder et al. 2004; van den Honert and Stypulkowski 1987). For the same reason, electrode stimulations are typically done sequentially.

1.6.4 Stimulation strategies

The stimulation strategy is the algorithm in which sound is converted into series of electric impulses and determines which electrodes to activate in each stimulation cycle or sound frame. Frequently used strategies are Continuous Interleave Sampling (CIS) and Advanced Combination Encoder (ACE)

(Kiefer et al. 2001; Wilson and Dorman 2008b; Wilson et al. 1991). In CIS, all frequency bands are stimulated in sequence for each frame of sound. Variations of CIS are used in all major CI manufacturers, but CIS (or HiRes) is default in the Advanced Bionics implants (Advanced Bionics Corp) which have 16 intracochlear electrodes (HiRes) and the MED-EL device (Medical Electronics GmbH of Innsbruck, Austria) which has 12 electrodes.

The ACE strategy is the default strategy for the Cochlear device (Cochlear Ltd of Lane Cove, Australia), and is based on a so-called *n-of-m* principle in which 8-12 channels of 22 frequency bands are stimulated in each frame of recorded sound. Only the largest amplitude frequency bands are stimulated.

In addition to these fixed channel stimulating strategies, there is a virtual channel technique (Koch et al. 2004) which uses current steering to control the electrical interaction. Advanced Bionics is the first manufacturer to commercialize the virtual channel technique (HiRes 120).

During the past several years, there is increased interest in representing the sound's "fine structure" (FS) or "fine frequency" information in CIs. The mathematician Hilbert showed century ago that signals can be decomposed into a slowly varying envelope and a high-frequency fine-structure. The FS processing (FSP) strategy of two manufacturers (MED-EL and Advanced Bionics) uses the timing of positive zeros crossings in the output from the lower frequency bands.

1.6.5 Clinical performance with CIs

CIs in children demonstrate greater benefit with earlier intervention and shorter duration of deafness (Bond et al. 2009). Results from a multicenter study (Dettman et al. 2016) support provision of implants to children younger than 12 months (with severe to profound hearing loss) to optimize speech perception and subsequent language acquisition and speech production accuracy. Results appeared promising in the Norwegian pediatric CI study (Wie 2010), which investigated the ability to develop complex expressive and receptive spoken language after receiving bilateral CIs at between 5 to 18 months.

Long duration of sensorineural hearing loss is presumably associated with loss of spiral ganglion nerve cells and/or reduced plasticity of the central auditory pathway. The great majority of CI recipients obtain substantial benefit, but CI users generally find it difficult to understand speech in competing noise. Considerable research and development is undertaken to improve sound processing in these difficult listening situations.

1.7 Speech perception tests

Speech perception is a measure of a listener's correct identification of a speech message. Correct identification depends on the listener's ability to receive and interpret the various components of speech (French et al. 1947; Jorgensen et al. 2013). Recognition and interpretation of speech depends on the intensity of the sound at the ear, and the intensity of masking sounds. Speech perception is usually expressed as a percentage of phonemes, words or sentences correctly identified, but can also be expressed as a signal-to-noise ratio (SNR) at threshold for correctly identified words or correctly identified sentences. The SNR at threshold for 50% correctly identified sentences is frequently used as the outcome measure. Several factors affect speech intelligibility (1.3.3 Masking and unmasking of speech sounds).

1.7.1 Common speech perception in noise tests

“HiST taleaudiometri” is a Norwegian speech audiometry set (Øygarden 2009). It consists of five-word sentences, three-word utterances, monosyllabic words, and numerals. The five-word sentences are of the form (name-verb-numeral-adjective-noun), similar to the sentence type used in the Swedish speech audiometry (Hagerman 1982). Noise was developed from the speech material. The three-word utterances are of the form (numeral-adjective-noun). The noise can be used together with the five- and three-word utterances for speech recognition threshold in noise measurements. The presentation of utterances is reduced in level until not recognized correctly. The threshold is calculated from the number of words recognized correctly in each list. Noise can be applied from five surrounding speakers in azimuth directions 0° , $\pm 45^\circ$ and $\pm 135^\circ$.

Some of the most common sentence-in-noise tests (Wilson et al. 2007) are the Connected Sentence Test (CST; Cox et al. (1987)), the Hearing in Noise Test (HINT) (Nilsson et al. 1994), the Quick Speech-in-Noise Test (QuickSIN, Killion et al. (2004)), and the Bamford-Kowal-Bench Speech-in-noise Test (BKB-SIN; Niquette et al. (2003)). Words as target stimuli instead of sentences are used in the Words-in-Noise test (WIN, (Wilson 2003; Wilson et al. 2005)).

In the development of the AzBio sentence lists (Spahr et al. 2004; Spahr et al. 2012), CI simulation was used to estimate the intelligibility of individual sentences, and the test is used in the clinical evaluation of hearing-impaired listeners and CI users. Pediatric AzBio sentence lists are also available (Spahr et al. 2014). The sentence lists are presented in multi-talker noise with SNRs dependent on the subject's monosyllabic word scores.

1.7.2 Hearing in Noise test (HINT)

HINT uses sentences as target and an adaptive procedure developed by Nilsson et al. (1994) based on the work of Plomp et al. (1979). An overview of the assessment of speech intelligibility in noise with the HINT is described by Soli et al. (2008). The Speech Reception Threshold (SRT) is defined as the mean presentation level in quiet or in noise at which the listener can repeat 50% of the sentences correctly. The SRT in noise is usually expressed as a SNR. The test is presented under headphones using head-related transfer functions (HRTFs) to simulate free-field conditions or via speakers in a sound field. The noise is a speech-spectrum noise which can be added from one of three directions: Noise Front (NF, speech and noise in front at 0° azimuth), Noise Right (NR, speech in front and noise at 90° azimuth) and Noise Left (NL, speech in front and noise at 270° azimuth). A test setup is illustrated in Figure 5. A measure of SRM is obtained from the difference between the NR and NF thresholds and between the NL and NF thresholds.

Sentence materials similar to the American English HINT sentences (Nilsson et al. 1994) are available in other languages such as Dutch (Plomp and Mimpen 1979), German (Kollmeier et al. 1997) and Canadian French (Vaillancourt et al. 2005). The average SRT in noise for the Swedish sentences (headphone presentation and noise fixed at 65 dB SPL) was -3.0 dB SNR (SD = 1.1) (Hallgren et al. 2006), and for the Danish sentences the average SRT was -3.15 dB SNR (SD = 1.0) (Nielsen et al. 2009).

Pediatric HINT versions are available in a number of languages, and age-specific normative data have been established for the American English and Canadian French versions (Nilsson et al. 1996; Vaillancourt et al. 2008). In both of these studies, children's performance increased with age and reached adult-like values when the children were about 12 years old.

Figure 5 HINT test setup for Noise Front (NF) and Noise Right (NR). HINT, Hearing in Noise test.

1.7.3 Speech perception tests Oslo University Hospital (OUS)

An overview of some of the currently used speech perception tests is provided in Table 1. These tests are applied at CI user follow-ups at OUS. The HINT has become a standard clinical tool; speech recognition in quiet and in noise is assessed. Sentences presented from speakers are used to form word recognition scores in quiet, and SRTs in noise are collected if the word scores are above 75-80%. The HINT is used in the assessment of CI candidacy, and at follow-ups after implantation.

Integration of HINT in the clinical assessment protocol was one of the clinical objectives of the thesis. The HINT is included in this overview to give a complete picture of current speech perception test protocol.

Table 1 Speech perception tests administered at OUS. All tests except the ESP-N are administered in an anechoic chamber.

Speech Perception Tests

Early Speech Perception test – Norwegian equivalent (ESP-N)

(Moog et al. 1990; Wie et al. 2007)

Closed set test with spondaic and monosyllabic words. The test uses word stimulus with appropriate pictorial response alternatives. Test administrator uses his own voice. The test results are ordinal categories from 1-5: detection (category 1), pattern perception (category 2), some word identification (category 3), at least 50% closed-set word identification (category 4) and at least 75% closed-set word identification (category 5).

Monosyllable Tests

Words are presented at 65 dBA level from a loudspeaker in an anechoic chamber, 2 meters in front of the patient.

Phonetically Balanced Word Lists (PB-N)

(Øygarden 2009)

Nine lists of 50 monosyllabic words.

Phonetically Balanced Word Lists – Kindergarten (PBK-N)

(Haskins 1949; Øygarden 2009)

Three lists of 50 monosyllabic words. Alternatively, 25 words are used.

IOWA sentence test

An audio visual sentence test with sentences spoken at a relatively slow speech rate, and with four different speakers. Sentences are derived from the English BKB sentences (Bench et al. 1979) The test can be assessed with video to allow for lip reading. (Teig et al. 1993)

Norwegian Hearing in Noise Test (HINT) for adults and children

(Myhrum and Moen 2008; Myhrum et al. 2016; Soli and Wong 2008)

Sentences presented in quiet at 65 dBA level (% word score). Speech Reception Threshold (SRT) collected in an anechoic chamber with 60 dBA fixed speech spectrum noise and noise directions: Noise Front (NF), Noise Right (NR) and Noise Left (NL).

1.8 Speech, Spatial and Qualities of Hearing scale (SSQ)

Subjective assessment of hearing ability in everyday life can be a useful complement to objective forms of evaluation. Particular deficits in auditory skills are experienced as disabilities on an individual basis. Experienced hearing disability is subjective and is not necessarily correlated to objective measurements of disability. Subjective assessment can also be used to measure changes in skill level when, for example HA or CI is fitted or training is provided. Individually experienced benefit can be measured using a questionnaire.

1.8.1 SSQ for adults

The SSQ (Gatehouse et al. 2004; Noble et al. 2004) is a self-reporting questionnaire, originally designed for adults. It covers speech perception in quiet conditions and in spatial hearing situations, localization tasks, and the quality aspects of speech (naturalness, clarity, differentiation ability, and music perception). The questionnaire is comprised of 3 parts: speech hearing, spatial hearing, and qualities of hearing, over a total of 49 questions with a self-rating scale from 0 to 10 for each question, with 0 representing complete inability with regard to the item in question and 10 representing perfect ability.

The SSQ was originally validated using an interview format (Gatehouse and Noble 2004), but self-administration has since been used in several studies (Banh et al. 2012; Dwyer et al. 2014; Laske et al. 2009; Noble et al. 2008; Noble et al. 2009). The reliability of the interview and self-administration formats was found to be comparable (Singh et al. 2010).

The SSQ has been used for self-assessment of hearing in different CI population groups (Dwyer et al. 2014; Mertens et al. 2013; Quentin et al. 2006; Reeder et al. 2014). All of the studies with the exception of that by Mertens et al. looked at the benefit of a sequential second side CI, finding improvements on the SSQ. The greatest improvement was in the spatial domain. Reeder et al. (2014) found that the increase in SSQ scores with bilateral CIs followed a superior bilateral performance to either ear alone, on measures of speech recognition in quiet and noise, and localization. Thus, objective measures and subjective measures both indicated bilateral benefit. In a study by Laske et al. (2009), a group of bilateral CI users had on average higher SSQ scores than a group of unilateral CI users (matched for age, gender, and CI experience), but the difference was not significant. In a study by Zhang et al. (2015), the SSQ was administered to adults with simultaneous CIs and results were compared longitudinally. The SSQ scores improved up to 12 months postimplantation.

1.8.2 SSQ for children

Galvin et al. (2013) adapted child, parent, and teacher versions of the SSQ. Some items were deleted and some wording changed in the adapted version. A minimum age of 11 years for the child version and 5 years for the parent and teacher versions was suggested. Observation periods were introduced prior to ratings. Instruction indicates interview-style administration to describe and clarify listening scenarios and demonstrate the ruler-style response format.

Parents rated the performance for their child in a study by Galvin et al. (2015). The children were from 5 to 9 years old and had been using bilateral CIs since they were on average 2.8 years old. Higher ratings for speech perception were associated with an earlier age at first implant. Higher ratings for spatial hearing were associated with more bilateral experience. Higher ratings for other qualities of hearing were associated with an earlier age at first implant and a shorter time between implants.

Within-participant comparisons following sequential bilateral implantation was done in a study by Galvin et al. (2016). Ratings were generally unrelated to age at first CI, inter-implant interval or age at bilateral implantation. Performance in bilateral mode was hypothesized to be better in the speech perception items involving group conversation or background noise, all spatial hearing items and qualities of hearing scale focusing on the segregation of sounds or on listening efforts. For the group, parent ratings were higher in the participants with bilateral CI for all of the speech perception and spatial hearing items. Ratings were not higher for listening effort-related items. The authors concluded that larger participant groups and the inclusion of children implanted at a younger age and with less delay between implants are important to gain a more powerful analysis.

The SSQ for parents has been used in studies to compare performances for children with unilateral CI versus bilateral CIs, making between-participant (Beijen et al. 2007; Lovett et al. 2010; Sparreboom et al. 2012) and within-participant comparisons (Galvin et al. 2010; Galvin et al. 2007; Kim et al. 2013; Sparreboom et al. 2012). A bilateral compared to unilateral advantage was found in all SSQ domains (Lovett et al. 2010), although in the study by Beijen et al. (2007), this advantage was only found in the spatial domain. However, the study had only five participants in each group. In the studies where data on unilateral CI and postoperatively after reception of a second side CI were collected, SSQ ratings were generally higher.

2 Thesis aims

This chapter presents the motivation for and aims of the thesis. The research and clinical objectives are summarized. It ends with an outline of the thesis.

2.1 Motivation

The chain leading to successful implant outcomes includes candidate selection, surgery, fitting, rehabilitation or training, and use. To measure the quality of the outcome we need to assess the CI users' performances. For most CI recipients, the perception of spoken language is the goal and assessment of speech recognition is performed regularly at follow-ups. First of all, for adults and parents, systematic assessment of their own or their child's hearing ability is important. Secondly, clinicians use test results to control quality of the CI adjustments and results give guidelines for rehabilitation. Third, test results are used as research variables.

Speech intelligibility tests are intended to assess the ability to hear in quiet and background noise. The speech materials vary from phonemes or simple sounds, to words without meaning, monosyllable words, disyllables, short sentences and natural sentences. The longer the material, the more redundancy in the target speech; good cognitive abilities and language knowledge will make the speech easier to perceive when the material is redundant. In a natural sentence, when some words are not heard, we can guess which words are missing from the content. In a simple sound test it would be impossible to guess the target stimuli. We need to hear the exact sound. Different maskers are used in speech intelligibility tests. Typically, speech spectrum noise maskers or speech from different talkers are used. The noise can be stationary or modulated. Some tests are applied with a fixed SNR and the percentage correctly repeated words are used for the test results. Adaptive tests measure the SRT by varying the SNR and estimate the threshold for which 50% of the sentences are repeated correctly. The latter tests can be applied to normal hearing and the hearing impaired who have close to 100% word score in quiet conditions.

A clinically based motivation for the thesis was that the test battery used in the assessment of CI users needed to incorporate more difficult speech perception tests since ceiling effects were pronounced in these tests when presented in quiet conditions. In the design phase of the thesis, there were no validated tests to measure hearing in noise ability in the Norwegian language.

2.2 Aims of the thesis

The first aim of the thesis was to develop a speech perception test to measure the abilities to recognize spoken language when there is background noise and use the test to measure abilities for normal-hearing children and adults.

The Hearing in Noise Test (HINT) is a test based on the response of sentences presented in noise. The test is adaptive, and can be used to measure speech intelligibility in noise, abilities in the range from normal hearing to hearing impaired where there is close to 100% intelligibility when there is no background noise. The output of the test is a Speech Reception Threshold (SRT). The HINT is used in many countries, and is a preferred speech intelligibility measure in clinical practices and research studies.

A clinical objective of the thesis was to implement HINT assessment in clinical practice to follow the outcome of CIs in patients who had their CI surgery at Oslo University Hospital and who regularly attend follow-ups at the hospital. The follow-ups consist of technical adjustments of the CI sound processor. In follow-ups in children, speech and language therapists monitor and give advice for further rehabilitation concerning communication, and tests are necessary to validate outcome. The results from the tests are used both as quality indicators, and as research parameters.

A research objective was to investigate speech perception outcome in a retrospective longitudinal cohort study of sequential bilateral CI in children. A subgroup of participants from this retrospective study was included in a research study to look at the bilateral benefits of CIs when listening to sentences in background noise. In the cohort study, the HINT was used descriptively. In the research study, the HINT was used in different test conditions to compare speech recognition with single (unilateral) and two (bilateral) CIs.

Another aim of the thesis was to translate a validated questionnaire for self-reporting measure of auditory abilities from English into Norwegian using a back-translation procedure. The questionnaire Speech Spatial and Qualities of Hearing scale (SSQ) is a user feedback scheme to report auditory abilities. The original questionnaire is in English. The final SSQs for adults and for children are to be used in the clinic and in research.

The last research objective was to investigate objective (monosyllable score and HINT test results) and subjective measures (self-assessment using SSQ) to evaluate hearing ability in an adult CI population.

2.3 Summary of objectives

The main research objective for this thesis was to:

Measure hearing in noise ability with the HINT. In addition, a self-assessment of hearing abilities was used (SSQ). Study groups are normal hearing and CI users.

This research objective was divided into sub-goals:

- Develop a speech recognition test in noise for adults: HINT in Norwegian
- Translate into Norwegian the self-assessment form of the English version of the SSQ
- Collect norms or reference values for HINT under headphones
- Collect norms or reference values for HINT for test presented from speakers in two different rooms, one anechoic and one with slight reverberations
- Develop HINT for children
- Collect norms for HINT for age groups from 6 to 14 years old and investigate maturation effects.
- Use HINT in a CI research project to evaluate bilateral benefit for speech recognition in noise. Participants were sequentially implanted; received CI as a child and a second-side CI from 3 months to 19 years later
- Investigate the objective measures of speech recognition in quiet and noise (monosyllables in quiet and HINT) and the subjective self-assessed SSQ in an adult CI population

The clinical objective was divided into sub-goals:

- Implement HINT assessment in clinical practice (CI users).
- Use SSQ questionnaire in clinical practice (CI users).
- Collect HINT and SSQ data for ongoing studies, “tie up clinical practice and research for joint benefit”. Use the same test protocol and variables in clinical practice and in research studies.

To combine research and clinical practice is important so the clinical objective is included.

2.4 Thesis outline

The thesis is a collection of papers. The four appended papers constitute the research contributions of this thesis; two of them in their original publication format and two in their submitted format.

The rest of the thesis is organized in chapters, in which the current chapter gives an introduction to the thesis. Chapter 1 presents background information to create an understanding of the complex mechanisms involved when listening in background noise and in which the binaural listening with two ears is important. The development of the auditory system is introduced since a developmental trend is observed for listening in noise. CI technology is then concisely described. Some speech perception in noise tests are listed, whilst HINT is described in more detail. There are several questionnaires to assess hearing abilities, but the only one described in this thesis, is the SSQ scale questionnaire, which is the one we have translated into Norwegian and which was applied to participants in the study described in Paper IV. None of the articles in the thesis use the pediatric version of the SSQ, but the SSQ for children is described since there are ongoing studies using this questionnaire in the pediatric CI population (these studies are described in Chapter 7).

Chapter 3 summarizes the Material and Methods in all four papers, followed by Results, and findings in the papers are discussed in Chapter 5. Methodological considerations are discussed in Chapter 5.4 and a General discussion is presented in Chapter 5.5. Conclusions are found in Chapter 6. Appendix contains SSQ questionnaires in Norwegian, adult and child versions.

3 Materials and methods

3.1 Overview

An overview of papers with study details on HINT test conditions and study groups is provided in Figure 6.

Figure 6 Overview of papers with study details on HINT test conditions and study groups. CI, cochlear implant; NH, normal-hearing; HINT, Hearing in Noise test; SSQ, Speech, Spatial and Qualities of Hearing Scale: Q, quiet; NF, Noise Front; NR, Noise Right; NL, Noise Left.

3.2 Terms used

The term objective assessment of hearing ability was used in this thesis to mean objective outcome measure in contrast to the participant's subjective self-assessment. The objective outcome measures are speech perception test results. This is worth mentioning since objective assessment is often used in objective measurements like auditory brain stem responses in which user feedback/repetition is not required.

The terms speech intelligibility, speech perception or speech recognition are often used to describe the outcome measure of responses to speech tests. All three terms are used to describe behavioral testing for which words or sentences presented from speakers are to be repeated.

3.3 Summary of material and methods in each paper

3.3.1 Norwegian Hearing in Noise test (Paper I + II)

An overview of the development of the HINT test materials

An overview of the stages in the development of the HINT test materials is provided in Figure 7.

Figure 7 Overview of the development of HINT test materials. HINT, Hearing in noise test; NH, normal-hearing.

The development of HINT in Norwegian followed a protocol of 7 steps.

1. Preparation of 900 sentences, 700 selected from ratings of naturalness.
2. Audio recording of 700 sentences using a male speaker.
3. Synthesis of speech spectrum shaped noise.
4. With sentences and the noise available, normal-hearing participants were tested to estimate a performance-intensity (PI) function which gave us the expected increase in percentage word score per 1 dB increase in the SNR (65 dB noise level). The PI function was estimated from the mean percentage scores of three different SNRs.
5. Equalization of sentences to make each sentence equally difficult to hear in noise. This means we had to tune the sound level of each sentence individually, such that the mean score when listening in a specific noise level was approximately the same for all sentences.
6. Lists of sentences were created from the equalized sentences. Lists were phonemically balanced.
7. List reliability and norms were collected.

Adult Hearing in Noise test and headphone norms (Paper I)

Paper I describes the development of the Norwegian HINT and collection of adult headphones norms. Since Paper I is compressed, some additional study details are described.

Nine-hundred sentences of 4 to 15 syllables were constructed. Seven native Norwegian speakers rated the sentences from 1 to 5 with 1 being an unnatural sentence and 5 being a natural sentence. About eighty percent of the sentences were scored as 5 by all the reviewers or were scored as 5 by all but one reviewer. Seven hundred sentences were recorded by a male speaker. A speech spectrum noise file was created from the recorded Norwegian sentences as described in the Soli and Wong study (Soli and Wong 2008).

The performance-intensity (PI) function was estimated for nine subjects. At 70% word intelligibility, the estimated SNR was -4.5 dB and the PI function slope was 9.2% per one dB change in the SNR. The equalization of the 700 recorded sentences searched for the sentence SNR that gave the sentence a 70% score, starting with the SNR equal to -4.5 dB for each of the sentences. A total number of 55 normal-hearing participants took part in the sentence equalization procedure. Twenty subjects participated in each round of sentence equalization, listening to 350 sentences each. The mean correctly repeated word responses for each sentence were calculated. The root mean square (RMS) values for the sentences that scored less than 70% were increased and similarly reduced if the mean scores were higher than 70%. The change in a sentence RMS should follow the 10% word response change per one dB change in RMS.

After the second round of testing and RMS sentence adjustments, 242 sentences scored on average 70.9% (SD = 6.0%), ranged between 60% and 82%. The average sentence RMS value was -4.8 dB SNR (SD=1.4 dB), with all RMS values within ± 2.8 dB of the average level.

HINT for children and developmental norms in free-field (Paper II)

Twelve 10-sentence HINT lists for children were created. When using 10-sentence lists, at least two SRTs must be collected and averaged. Norms were collected for adults and children aged 5-13 years old in two different rooms, an anechoic chamber and an audiometric test room, using noise levels 55, 60 or 65 dBA. Over 200 were tested in the NF condition and close to 100 of them were tested additionally in the NR and NL test conditions. The NR and NL scores were averaged to yield a Noise Side (NS) score.

3.3.2 Pediatric CI participants with sequential CI₂ (Paper III)

From June 2003 to January 2009, 181 sequential CI surgeries were performed at Oslo University Hospital on patients who had their first implant (CI₁) as a child and sequential second contralateral (CI₂) from 0.2 to 19.1 years after the first. The study investigated use and outcome of the CI₂ cohort. Group mean age at CI₁ surgery was 4.6 years (SD=3.4), and the mean age at CI₂ surgery was 9.3 years (SD=4.3). Observation times were a minimum of five years after the sequential surgery. A flow chart of the cohort population is provided in Figure 8. The analyses applied are also indicated. Twenty-nine participants were included in a study to evaluate bilateral benefit of speech in noise using the HINT.

Figure 8 Flow chart of the cohort and participants included in the retrospective and prospective studies. The aims of the studies are indicated.

Recognition scores of monosyllables were used to measure the outcomes with either CI alone or with bilateral CIs (CI_{BI}). The Early Speech Perception test (ESP-N) was used if the monosyllable and HINT tests were too difficult. The patients were divided into four groups depending on their current use of CI₂ (non-, little, part time and all-day-users).

Twenty-nine patients were tested with HINT in bilateral and “best CI” test conditions. Bilateral effects were calculated:

- “Summation NF” = SRT CI_{best} (noise front) – SRT CI_{BI} (noise front)
- “Head shadow” = SRT CI_{best} (noise to CI_{best}) – SRT CI_{BI} (noise to CI_{best})
- “Squelch” = SRT CI_{best} (noise contralateral CI_{best}) – SRT CI_{BI} (noise contralateral CI_{best})

3.3.3 Adult CI participants (Paper IV)

The Norwegian SSQ was translated from the English version using a back-translation procedure. Adult CI users (n=152) assessed their hearing abilities using the SSQ questionnaire which has a scale from 0 to 10. Demographics of the participants are shown in Table 2. Participants with bilateral CIs were compared to participants with unilateral CIs or with a HA contralateral to a CI.

Table 2 Demographics of the 152 participants.

	BCI (n = 29)	HCI+UCI (n = 123)
Age at 1st CI [years]		
Mean (SD)	46.2 (14.2)	57.1 (16.2)**
Median (Range)	44.7 (20.6–78.2)	57.1 (23.9–90.1)
Age at 2nd CI [years]		
Mean (SD)	51.0 (15.0)	
Median (Range)	48.7 (21.6–80.9)	
Age at assessment [years]		
Mean (SD)	54.2 (15.1)	61.4 (15.5)*
Median (Range)	51.5 (28.1–82)	62.8 (26.5–91.2)
Gender, n (% female)	n = 21 (72%)	n = 78 (63%)
Implant Type n = (N-M-A)^a	n = (9-16-4)	n = (74-43-11)

a) Nucleus (N), Medel (M), Advanced Bionics (A)
 *) or **) Denotes significantly (p < 0.05) or (p < 0.01) different mean compared to BCI group (t-test)
 CI: Cochlear implant, BCI: Bilateral CI recipients, HCI: CI in one ear and hearing aid in contralateral ear, UCI: Unilateral CI recipients.

Mean results for SSQ domains (Speech, Spatial, and Qualities) and 10 subscale scores, were compared to results obtained from other CI populations; subscale items are provided in Table 3. Subjective scores were compared to the monosyllable test score in quiet and SRT in noise using the HINT, and the predictors of SSQ scores were investigated.

Table 3. Domains and subscales of the Speech, Spatial, and Qualities of Hearing questionnaire (SSQ).

SSQ Domain	SSQ Subscale	SSQ Items
Speech	Speech in Quiet (SiQ)	2,3
	Speech in Noise (SiN)	1, 4-6
	Speech in Speech Contexts (SiSCont)	7-9, 11
	Multiple Speech Streams (MultStream)	10,12,14
Spatial	Localization (Loc)	1-6
	Distance and Movement (DisMov)	7-13, 15, 16
Qualities	Segregation of Sounds (SegSnds)	1-3
	Identification of Sound and Objects (IdSnd)	4-7, 13
	Sound and Quality and Naturalness (Qlty)	8-12
	Listening Effort (Eff)	14, 18

As suggested by Gatehouse and Akeroyd (2006), the following items were excluded from the subscales: Speech domain: item 13; Spatial domain: items 14 and 17; Qualities domain: items 15, 16, and 17.

4 Results

4.1 Norwegian Hearing in Noise test (Papers I+II)

HINT headphone norms were collected for 60 native, adult Norwegians with normal hearing. HINT normative data were collected for 219 children and adults, and in two different test rooms. Selected norms are provided in Table 4.

Table 4 HINT headphone norms and speaker presentation normative data in two different rooms.

Participant details			Summary of group mean HINT SRTs		
Experiment and participant groups	N	Age (yrs)	Quiet (dBA)	NF (dB SNR)	NS (dB SNR)
		Mean (SD)		Mean (SD)	
Paper I NH participants					
HINT under headphones and 65 dBA noise					
Adults	60	29.9 (7.0)	17.5 (2.9)	-3.2 (1.0)	-10.4 (1.0)
Paper II NH participants					
HINT in the anechoic chamber and 55 dBA noise					
Adults	17	27.7 (6.7)	15.0 (2.1)	-3.9 (1.0)	-11.6 (1.0)
9-yr-olds (13g, 7b)	20	9.4 (0.3)	20.3 (3.7)	-3.2 (0.9)	-8.0 (1.0)
8-yr-olds (6g, 6b)	12	8.2 (0.2)	-	-2.2 (0.5)	-7.3 (0.8)
7-yr-olds (5g, 4b)	9	7.3 (0.4)	21.6 (3.9)	-2.1 (0.8)	-7.5 (0.9)
6-yr-olds (12g, 14b)	26	6.0 (0.3)		-0.8 (1.3)	
Paper II NH participants					
HINT in the anechoic chamber and 60 dBA noise					
Adults	19	27.6 (7.1)	15.5 (2.9)	-3.7 (0.8)	-11.8 (0.9)
13-yr-olds (6g, 6b)	12	13.1 (0.2)	16.6 (1.6)	-3.3 (0.6)	-9.7 (0.9)
6-yr-olds (9g, 9b)	18	6.0 (0.3)	24.5 (3.2)	-0.3 (0.9)	-5.7 (1.5)
Paper II NH participants					
HINT in the audiometric test room and 65 dBA noise					
Adults	14	33.0 (8.4)	-	-3.0 (0.8)	-10.2 (1.2)
12-yr-olds (15g, 8b)	23	12.5 (0.3)	-	-2.4 (1.3)	-7.7 (1.0)
9-yr-olds (16g, 12b)	28	9.7 (0.2)	-	-1.8 (0.8)	-
7-yr-olds (7g, 8b)	15	7.7 (0.3)	-	-0.5 (1.4)	-

HINT, Hearing in Noise test; SRT, Speech Reception Threshold; NF, Noise Front; NS, Noise Side; SRM, Spatial Release of Masking (NF – NS); SD, Standard deviation.

Adult SRTs were about 3 dB lower than those for 6-year-olds, corresponding to 25-30% better intelligibility for adults around threshold. NF SRTs in the anechoic chamber improved by 0.7 dB per year over an age range of 5-10 years. Using a PI slope 8-10% per dB, the estimated increase in percent word intelligibility was 4-7% per year.

Figure 9 is a copy of a figure in Paper II, and displays scatterplots of NF SRTs and age, NS SRTs and age, and calculated linear regression lines. Boxplots for the adult results collected in the anechoic chamber are also displayed.

Figure 9. Scatterplots of Noise Front (NF) and Noise Side (NS) SRTs versus age and boxplots for the adult results. The SRTs were collected in the anechoic chamber with noise levels 55 dBA (plotted as *circles*) and 60 dBA (plotted as *diamonds*). The NF results are plotted *grey shaded* and the NS are *open circles* or *open diamonds*. The *solid lines* are linear regression lines ($R^2 = 0.68$ for NF and $R^2 = 0.40$ for NS). The results for adults are plotted as boxplots. The boxes go from the first quartiles to the third quartiles, and the whiskers go from the smallest non-outlier to the largest non-outlier. An outlier was considered to be outside 1.5 times the interquartile range. The arrows in the figure are pointing to the longitudinal data, obtained when the children were 8 and 13 years old.

4.2 Pediatric CI participants with sequential CI₂ (Paper III)

This retrospective longitudinal cohort study assessed the outcomes over a minimum 5-year follow-up after placement of a second contralateral CI (CI₂) in 160 subjects. In a subgroup (n=29), the bilateral benefits of speech recognition in noise were also examined.

Based on onset of deafness and language acquisition before implantation, two study groups were analyzed. Group A (n=110) consisted of prelingually deaf children (severe to profound) with no or little acquired oral language before implantation; group B (n=50) consisted of prelingually deaf children with acquired language before implantation, in addition to perilingually and postlingually deaf children. Speech perception test results are provided in Table 5.

Table 5 Speech perception test results of CI₁, CI₂, and CI_{BI}. Test results reflect the best achieved CI₂ score.

Speech Perception Test Results	Group A Mean (SD) median (range) or ESP-N distribution	n	Group B Mean (SD) median (range) or ESP-N distribution	n
Age when tested [years]	12.4 (3.6) 12.1 (5.3–24.5)	100	14.2 (4.3) 13.8 (7–32.2)	44
CI₁ test results:				
ESP-N category	1 in category 3 3 in category 4 7 in category 5	11	1 in category 5	1
Monosyllables [%]	75.9 (16.4) 80 (18–100)	87	76.3 (19.7) 84 (4–98)	42
CI₂ test results:				
ESP-N category	1 in category 1 4 in category 2 3 in category 3 10 in category 4 13 in category 5	31	3 in category 4 2 in category 5	5
Monosyllables [%]	56.9 (24.0) 60 (4–96)	67	64.3 (20.8) 68 (12–98)	37
CI_{BI} test results:				
ESP-N category	4 in category 4 7 in category 5	11	1 in category 5	1
Monosyllables [%]	78.9 (14.5) 80 (26–100)	90	81.1 (16.7) 87 (30–100)	42
* Test results were collected at least 2 years after CI ₂ implantation, except for 12 patients who were tested within 2 years of CI ₂ use, as described in the text. CI, cochlear implant; CI ₁ , first side CI; CI ₂ , second side CI, CI _{BI} , bilateral CI; SD, standard deviation; ESP-N, Early Speech Perception test/ESP test in Norwegian				

In general, patients were more likely to choose not to use CI₂ after some time if it did not become comparable to CI₁. Our data show that 25% of prelingually deaf subjects with no or little acquired oral language before implantation and 10% of subjects with pre-implantation language acquisition did not use CI₂ ≥ 5 years after surgery.

Twenty-nine patients were tested with HINT in bilateral and “best CI” test conditions. Test results are provided in Table 6. When analyzing the total results for groups A and B, the summation effect in the noise front condition, was 0.2 dB and not significant ($p = 0.53$). The head shadow effect of adding a second CI was 3.5 dB ($p < 0.001$). The squelch calculations showed a bilateral disadvantage of 1.2 dB ($p = 0.02$) when the second CI was added to the noise side.

Table 6. HINT tests to measure bilateral benefits.

HINT test results of CI_{BI} and CI_{best} (CI₂ is CI_{best} in 6 cases)	From group A (n=19) Mean (SD) (range)	From group B (n=10) Mean (SD) (range)
Age CI ₁ [years]	2.1 (0.7) (1.0–3.4)	6.5 (4.1) (1.9–15.8)
Age CI ₂ [years]	5.4 (2.3) (1.2–10.1)	8.3 (4.1) (2.7–16.4)
Age when tested [years]	11.4 (1.9) (8.2–14.7)	13.7 (3.6) (9.4–20.9)
Duration since CI ₂ surgery	6.1 (1.1) 5.9 (4.6–7.9)	5.4 (0.7) 5.3 (4.5–6.7)
Monosyllable test score, CI _{best} [%]	88.2 (5.1) (80–100)	85.1 (8.7) (66–96)
Monosyllable test score, CI _{poorest} [%]	78.5 (9.9) (64–96)	75.6 (9.1) (62–92)
HINT sentences [%] CI _{BI}	97.6 (3.5) (89–100)	95.1 (4.7) (87–100)
HINT sentences [%] CI _{best}	94.9 (8.1) (69–100)	97.6 (2.6) (94–100)
HINT noise front SRT [dB SNR] CI _{BI}	2.6 (2.4) (-0.7–7.7)	3.0 (1.9) (1.2–6.3)
HINT noise front SRT [dB SNR] CI _{best}	2.6 (2.2) (-0.2–8.8)	3.7 (2.7) (0.2–8.9)
“Summation NF” effect		
HINT noise in front [dB SNR]	0.0 (1.6) (-3.1–3.0)	0.7 (1.5) (-1.0–3.4)
“Head shadow” effect		
HINT noise towards CI _{best} [dB SNR]	3.2 (2.4) (-1.5–7.1)	3.4 (2.8) (0.2–9.6)
“Squelch” effect		
HINT noise contralateral to CI _{best} [dB SNR]	-1.0 (2.3) (-7.8–2.7)	-0.5 (1.8) (-4.0–1.7)
HINT, Hearing in Noise test; CI, cochlear implant; CI ₁ , first side CI; CI ₂ , second side CI, CI _{BI} , bilateral CI; SD, standard deviation; SRT, Speech Reception Threshold; SNR, Signal-to-noise ratio		

4.3 Adult CI participants (Paper IV)

The speech perception test results for the adult CI users are provided in Table 7. The SSQ domain and subscale scores are provided in Table 8.

Table 7 Speech perception test results for adult CI users.

Speech perception tests	BCI n = 29	HCI+UCI n = 123
Monosyllable score [%]	n = 27	n = 96
Mean (SD) Median (Range)	70.0 (17) 74.0 (32-92)	64.0 (19.1) 68.0 (15-96)
Slower speech rate sentences [%]	n = 4	n = 36
Mean (SD) Median (Range)	80.8 (1.5) 80.0 (80-83)	65.3 (24.8) 69.5 (10-100)
HINT sentences in quiet [%]	n = 25	n = 73
Mean (SD) Median (Range)	88.4 (14.0) 95.0 (55-100)	86.5 (14.1) 90.0 (47-100)
HINT NF SRT [dB SNR]	n = 20	n = 58
Mean (SD) Median (Range)	5.6 (4.7) 3.6 (-1.4-16)	5.9 (3.6) 3.8 (0.1-13.6)

None of the means were significantly different between groups ($p > 0.05$).

SD, standard deviation; HINT, Hearing in Noise test; SRT, Speech Reception Threshold; SNR, Signal-to-noise ratio; CI: Cochlear implant, BCI: Bilateral CI recipients, HCI: CI in one ear and hearing aid in contralateral ear, UCI: Unilateral CI recipients.

Table 8. SSQ scores for adult CI users. The self-rating scale is from 0 to 10.

SSQ Domain or Subscale	BCI n = 29	HCI+UCI n = 123
Speech Domain		
Mean (SD) Median (Range)	4.9 (2.2) 4.9 (0.6-9.0)	4.1 (1.8)* 3.8 (0.5-8.2)
95% CI of mean	4.0-5.7	3.7-4.4
Spatial Domain		
Mean (SD) Median (Range)	5.0 (2.4) 5.3 (0.8-8.8)	3.8 (2.1)**(##) 3.6 (0.2-9)
95% CI of mean	4.1-6.0	3.4-4.2
Qualities Domain		
Mean (SD) Median (Range)	7.0 (2.0) 7.4 (2.3-10)	5.7 (2.0)**(##) 6.0 (0.5-9.8)
95% CI of mean	6.2-7.8	5.4-6.1
Speech in Quiet (SiQ)		
Mean (SD) Median (Range)	7.9 (2.2) 8.0 (1.1-10)	6.9 (2.2)* 7.1 (1-10)
Speech in Noise (SiN)		
Mean (SD) Median (Range)	4.3 (2.3) 4.3 (0-8.5)	3.6 (2.1) 3.3 (0.3-8.3)
Speech in Speech Cont. (SiSCont)		
Mean (SD) Median (Range)	5.3 (2.8) 5.3 (0.6-10)	4.1 (2.2)* 4.0 (0-10)
Multiple Speech (MultStream)		
Mean (SD) Median (Range)	2.7 (2.2) 2.3 (0-8.4)	2.4 (1.9) 2.0 (0-8.2)
Localization (Loc)		
Mean (SD) Median (Range)	5.3 (2.8) 6.3 (0-9.5)	3.6 (2.6)**(##) 3.5 (0-9.8)
Distance and Movement (DisMov)		
Mean (SD) Median (Range)	4.6 (2.6) 5.0 (0-9.1)	3.7 (2.1)* 3.7 (0.2-9.4)
Segregation of Sounds (SegSnds)		
Mean (SD) Median (Range)	7.7 (2.2) 8.3 (2.9-10)	6.2 (2.6)**(##) 6.7 (0-10)
Identification of Sound and Objects (IdSnd)		
Mean (SD) Median (Range)	6.9 (2.4) 7.4 (0.9-10)	5.9 (2.2)* 6.4 (0.6-10)
Sound and Quality and Naturalness (Qlty)		
Mean (SD) Median (Range)	7.9 (2.3) 8.5 (1.6-10)	6.4 (2.3)**(##) 6.9 (0.3-10)
Listening Effort (Eff)		
Mean (SD) Median (Range)	5.0 (2.7) 5.1 (0-10)	4.2 (2.5) 4.0 (0-10)

*) or **) Denotes significantly ($p < 0.05$ or < 0.01) different mean compared to BCI group
 #) or ##) Denotes significantly ($p < 0.05$ or < 0.01) different mean compared to BCI group when corrected/adjusted for age.

CI: Cochlear implant, BCI: Bilateral CI recipients, HCI: CI in one ear and hearing aid in contralateral ear, UCI: Unilateral CI recipients.

The mean SSQ subscale scores for participants with bilateral CI were consistently higher than for participants with unilateral CI and significantly higher for subscales concerning location and distance/moving objects. The group effect (bilateral versus unilateral) was significant for the Spatial and Qualities domains after adjusting for age and monosyllable score. The trends in our observed scores matched those from studies of other CI populations. Generally, age and monosyllable scores were predictors for the SSQ scores.

4.4 HINT results across study groups (Papers II, III, IV)

The HINT NF results of participants in Paper II, III, and IV are provided in Table 9. The only participants in Paper III with HINT results provided in the paper were those who participated in the HINT study to measure bilateral advantages of two CIs and who were required to have 60% score on monosyllables. Those were high-performing participants. Therefore, the HINT results of the participants in the retrospective study of Paper III are provided in the table. These results were not provided in the Paper.

Table 9. HINT NF results across study groups in Paper II, III, and IV.

HINT in the anechoic chamber and 60 dBA noise			
Participant groups	n	Age (yrs) Mean (SD) (range)	NF (dB SNR) Mean (SD) (range)
Paper II			
Normal-hearing participants			
Adults	19	27.6 (7.1)	-3.7 (0.8)
13-yr-olds	12	13.1 (0.2)	-3.3 (0.6)
6-yr-olds	18	6.0 (0.3)	-0.3 (0.9)
Paper III			
CI participants with sequential bilateral CIs, monosyllable score > 60% with either CI			
Group A	19	11.4 (1.9) (8-15)	2.6 (2.4) (-0.7–7.7)
Group B	10	13.7 (3.6) (9-21)	3.0 (1.9) (1.2–6.3)
Paper III Participants^{*)}			
CI participants with sequential bilateral CIs			
Word score of HINT sentences in quiet:			
Group A	75	Word score:	87% (13) (53-100)
Group B	43	Word score:	83% (20) (32-100)
Group A	61	13.9 (2.7) (9-23)	5.4 (4.5) (-0.7–16.8)
Group B	33	16.4 (3.9) (10-27)	4.4 (3.9) (-1.0–14.9)
Paper IV			
Adult CI participants with unilateral or bilateral CIs			
Group BCI	20	54 (15) (28-82)	5.6 (4.7) 3.6 (-1.4-16)
Group HCI+UCI	58	61 (16) (27-91)	5.9 (3.6) 3.8 (0.1-14)

^{*)} Results were not included in Paper III

HINT, Hearing in Noise test; SD, standard deviation; NF, Noise front; SNR, Signal-to-noise ratio; CI, cochlear implant, BCI, bilateral CI; HCI, HA contralateral to CI, UCI, unilateral CI Group A consisted of prelingually deaf children (severe to profound) with no or little acquired oral language before implantation; group B consisted of prelingually deaf children with acquired language before implantation, in addition to perilingually and postlingually deaf children.

5 Discussion

5.1 Norwegian Hearing in Noise test (Papers I+II)

The results for normal-hearing adults are in general agreement with other studies. Summary of the normative data for the HINT languages are provided in Table 10 (from (Soli and Wong 2008)).

Table 10 Summary of normative adult headphone data for HINT languages (Soli).

Summary of SRT normative data for HINT languages				
Language	Quiet (dBA)	NF (dB SNR)	NR (dB SNR)	NL (dB SNR)
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
American English	15.6 (3.1)	-2.6 (1.0)	-10.1 (1.3)	-10.1 (1.3)
Brazilian Portuguese	15.3 (3.5)	-4.6 (0.8)	-12.1 (1.0)	-12.2 (0.8)
Bulgarian	24.2 (7.5)	-4.0 (1.5)	-9.7 (3.8)	-10.2 (3.9)
Canadian French	16.4 (3.8)	-3.0 (1.1)	-11.5 (1.2)	-11.3 (1.4)
Cantonese	19.4 (3.1)	-4.0 (0.9)	-10.9 (1.0)	-11.0 (0.8)
Castilian Spanish	14.6 (3.2)	-3.6 (1.2)	-11.8 (1.2)	-12.1 (1.0)
Japanese	16.8 (3.1)	-5.3 (1.4)	-12.2 (1.4)	-12.5 (1.4)
Korean	18.6 (3.0)	-3.3 (1.0)	-10.8 (1.1)	-10.5 (1.2)
Mainland Mandarin	14.7 (1.5)	-4.3 (0.6)	-11.7 (0.9)	-11.7 (0.8)
Malay	20.2 (3.4)	-4.7 (0.8)	-12.4 (1.0)	-12.4 (1.0)
Norwegian	17.5 (2.9)	-3.2 (1.0)	-10.3 (1.1)	-10.4 (1.1)
Taiwanese Mandarin	19.4 (3.1)	-4.0 (0.9)	-10.9 (1.0)	-11.0 (0.8)
Turkish	25.9 (2.2)	-3.9 (0.9)	-11.8 (1.1)	-12.1 (1.0)
Average	18.4 (3.3)	-3.9 (1.0)	-11.2 (1.3)	-11.3 (1.3)

HINT, Hearing in noise test; SRT, Speech Reception Threshold; NF, Noise Front; NR, Noise Right; NL, Noise Left; SD, Standard deviation.

Normal-hearing children and adults were tested with sentences presented from speakers, and in two different rooms, one anechoic and one with slight reverberations. The anechoic room is a room used for clinical follow-up testing of CI users so results will also serve as norms for the hearing impaired using HAs and CIs, for which headphone testing is not applicable.

Developmental trends in the HINT NF condition were found in both rooms for two independent study groups, from ages 5.5 to 10 years in the anechoic chamber, and from ages 7 to 10 years in the audiometric room. The Noise Side (NS) test results showed a developmental trend from 5.5 to 13 years (anechoic chamber).

Children reached adult performance at a younger age in the NF condition compared with the NS test condition. This is in agreement with other studies. However, in the present study we found that the developmental trend in the anechoic chamber was slightly different compared to studies in slightly

reverberant rooms. Developmental trends seemed to be affected by room type or rather reverberation time.

Since adults have larger heads and torsos they might benefit more than children from spatial separation in an anechoic chamber than in an audiometric test room since the head shadow and binaural unmasking effects will not be impaired by reflections when reverberations are not present. It is hypothesized that fewer cues available to separate the target from the competition will more likely increase the spatial advantage with age (Ching et al. 2011). Fewer cues in the anechoic chamber might have influenced the spatial advantage with age compared with the spatial advantage with age in the audiometric test room studies. Combined effects of noise and reverberation on speech recognition performances of normal-hearing children and adults were studied by Neuman et al. (2010), with speech and noise presented from the front. Future studies should look at developmental trends under conditions of noise and reverberation, and with speech and noise spatially separated. Developmental trends might be different when speech and noise are spatially separated since reverberation introduces extra cues.

More limited language experience will lower the chance of guessing the correct sentence when not heard properly. Thus, language skills might have an effect on the developmental trend in the NF test condition. Limited language experience, however, should equally influence the NF and NS test conditions and cannot explain the lower SRM observed for children.

Sanes et al. (2011) described auditory perceptual skills as emerging from auditory perceptual maturation through adolescence. Further, that the age at which adult-like performance is reached on different auditory perceptual skills varies tremendously across the skills.

The NS test condition requires more complex auditory skills compared with the NF test condition since the auditory inputs to the two ears are different. The complexity can explain why adult values were reached earlier in the NF test condition compared with the NS test condition. Similarly, auditory complexity is increased when slight reverberations are present and can explain why adult NF values were reached earlier in the anechoic chamber compared with in the audiometric test room.

5.2 Pediatric CI participants with sequential CI₂ (Paper III)

The discussion in this paragraph will focus on the use of HINT in the research study described in the paper.

Bilateral effects such as summation, head shadow and squelch were calculated. Bilateral advantage for speech recognition in noise was mainly obtained for the condition with noise near the “best CI”; the addition of a second CI offered a new head shadow benefit. A small mean disadvantage was measured when the noise was located opposite to the “best CI”. However, the latter was not significant since the significance level was set to $p=0.01$.

We observed a negative squelch effect, whereby adding a CI₂ on the side with poorest SNR makes bilateral listening more disadvantageous than the unilateral listening mode. Since the disadvantage was only close to significant, further studies with greater statistical power should evaluate this effect. Litovsky et al. (2012) showed a similar mean disadvantage of 2–3 dB in the bilateral listening mode. Other pediatric bilateral CI studies (Chadha et al. 2011; Murphy et al. 2011; Nitttrouer et al. 2013; Sheffield et al. 2015; van Deun et al. 2010) have found head shadow effects, but with unchanged or minimal summation and squelch effects. However, the stimuli and noise must be considered when comparisons are made across studies. The potential benefit of binaural cues might depend on stimuli and type of noise. In addition, squelch and summation effects are small, even for normal-hearing listeners (Bronkhorst and Plomp 1988; Bronkhorst et al. 1989).

One major issue with testing in unilateral and bilateral conditions during the same test session is that the unilateral test condition is less familiar to the participant, and the condition is likely to be worse. Ideally, testing in unilateral conditions should have been preceded by a daily listening period in the unilateral condition of at least 2–3 weeks. However, in this group of participants with sequential implants, we considered the use of CI₁ to be relatively familiar. This would probably be a more important issue when investigating participants with simultaneous bilateral implants.

5.3 Adult CI participants (Paper IV)

The SSQ scores of the participants with unilateral CIs were quite similar to those in other studies of similar CI populations (Dwyer et al. 2013; Mertens et al. 2013); generally, all mean differences were less than 1 point. The trends of the scores of the present bilateral CI group were compared to a bilateral CI group in which the participants assessed their hearing before and some time after the second side implantation. The absolute values in our bilateral CI group were generally lower.

The differences between the SSQ scoring of the present bilateral CI group versus that of Dwyer’s bilateral CI group were especially large (mean difference (d) equal to or larger than 1.5); for the Speech domain (d = 1.5),

the SiN ($d = 1.9$), MultStream ($d = 2.1$), and Eff ($d = 1.6$). This could indicate that the present bilateral CI participants found these listening situations to be more difficult than the bilateral CI participants in the Dwyer study.

Therefore, either the bilateral CI participants in Dwyer's study were strictly better in these listening situations, or their self-assessed scores were higher than the present bilateral CI participants, because they subjectively felt that they had less hearing disability compared to when they had done the test as unilateral CI recipients. Thus, participants took the same assessment multiple times, which could have affected their later results.

Other longitudinal studies in adults with sequential bilateral CIs have also found increased scores in all SSQ domains after receiving the second implant (on average an increase from 1 to about 3 points, generally largest in the Quality domain) (Quentin et al. 2006; Reeder et al. 2014). However, in a cross sectional study comparing SSQ scores of unilateral and bilateral CI participants (groups were matched for age, CI experience, and gender), SSQ ratings were higher in the bilateral group, but the difference was not significant (Laske et al. 2009).

5.4 Methodological considerations

When measuring speech perception in noise, there are several available tests in English and other languages. The HINT has been used in several studies involving CI participants, and the HINT has been implemented in several languages. The Norwegian HINT was developed after a protocol which has been used for a number of different languages. This is an advantage from a clinical point of view. It means that in a multilingual society similar tests will be available in a number of different languages. It will also enable cross-language and bilingual studies of speech perception. Multicenter studies can use similar tests. Cross language studies, again, could improve the basis for rehabilitation.

If other Norwegian speech perception in noise tests had been available in the design phase, these tests would have been included and used in addition to the HINT. The "HiST taleaudiometri" is now available and should be used as a supplementary test in clinical practice and in research studies. Addition of several tests will also increase validity when results from the different tests are compared.

Self-assessment of hearing can be done in different ways, and there are several questionnaires available. We considered only validated questionnaires, even though we found several of the questions in the SSQ a little imprecise. For

example, to the first question “You are talking with one other person and there is a TV on in the same room. Without turning the TV down, can you follow what the person you’re talking to says?”, several responders said “It depends on the volume setting of the TV”. SSQ was selected and used without modifications so that results can be compared across languages.

The SSQ questionnaire was translated from English into Norwegian. The English version of the SSQ has been validated. No validation was performed for the translated version. However, the questionnaire was independently translated back into English and checked by a co-author of the original article. This task was to verify that the intended meaning was preserved, increasing the likelihood that responses from different languages could be compared. Originally, the questionnaire is assessed in interviews, but self-administration has been used in several studies (as described and cited in Paper IV). If the questionnaire is to be used as a clinical assessment tool, the interview format is too time consuming. To compare results, either interview or self-assessment should be used consistently. A shorter version of the SSQ could be considered; a 12-item version (SSQ12) was developed and evaluated by Noble et al. (2013).

Limitations

The HINT was the only speech in noise test applied in the studies, and the only test we use as a clinical tool to assess speech in noise abilities. The HINT results give indications of the hearing in noise ability, but other tests will cover other aspects of functional hearing in noise. The validity of the HINT cannot be measured with the SSQ questionnaire since the self-assessment is subjective and will depend on hearing history etc.

Validity issue

Sentence stimuli have high validity in order to provide reflection of a listener’s speech recognition. However, the type of noise applied in speech perception tests might not reflect the listener’s real life experience for listening in background noise. For example, the noise applied might not reflect the real-life noise masking experienced in busy restaurants with multiple talkers or in departure and arrival halls at airports. Real world situations will have modulated background noise, and reverberations will alter the speech recognition.

The HINT uses sentences as target and the noise is an unmodulated speech spectrum shaped signal, with frequency components similar to the average of the sentences’ frequency components. The noise is applied from specific directions (from front and either side) which are often not the case in real life.

The HINT uses sentences which require attention and working memory for correct repetition, in addition to recognition. Furthermore, sentence recognition and repetition require mastery of language and linguistic knowledge. Thus, hearing is not the only ability tested in a sentence recognition test.

Reliability issue

When the word score in quiet is less than 100%, HINT test-retest reliability might be lower since some words in noise might not have been recognized even if presented in undisturbed test conditions. This might give less reliable test results for the hearing impaired compared to those with normal hearing. Test-retest reliability measures for normal-hearing adults and children (Paper II) had standard deviation of repeated SRT estimates equal to 0.7 dB for adults, 0.8 dB for 9-year-olds, and 1.1 dB for 6-year-olds (The average of two SRTs were used when the pediatric lists were used.) Test-retest measures should also be collected and investigated for CI users.

Time issue

In a clinical follow-up at OUS, tests are applied to guide rehabilitation and control CI functionality, test speech perception and language development. In addition, CI users, particularly children, participate in several research studies. A regular follow-up visit lasts for 1.5-2 hours. Even if visits are extended when participating in research studies, time consumption is a challenge. When children are tested, motivation and concentration will influence test results, and thereby reliability and validity of the results.

The PhD design included tests to investigate bilateral advantage. The design protocol included HINT applied from all three noise directions in bilateral and unilateral test conditions. This protocol was applied to several participants, but often clashed with other testing in other research projects or the protocol was too extensive for some children. This might give a selection bias of participants.

5.5 General discussion

Use of HINT to measure hearing in noise ability and bilateral effects

The HINT seems suitable to partly quantify hearing in noise ability, or functional hearing. It measures sentence recognition in quiet and in noise, and testing is conducted binaurally. The Norwegian adult headphone norms were in agreement with norms found in other languages. In free-field, the developmental trends we found were similar to that found in other languages. To recognize 50% of the sentences correctly, the SNR threshold was higher for 6-year-olds compared to 9-year-olds. When noise was applied from either

left or right, the developmental trend of lower SNR thresholds was seen up to age 13 years. Noise from the side requires more complex auditory processing, which is developed later. When comparing results, it is important to consider age, and comparison must be made with normal-hearing peers.

The HINT is a speech recognition test with noise classified as energetic masking; unmasking occurs mainly in the peripheral auditory system. Other tests using informational masking should therefore be applied as a supplement to test both auditory perceptual and central processing levels. Furthermore, other noise directions or surroundings should be used, not only either the left or the right sides. Reverberation is another important acoustical component when it comes to functional hearing. Only small reverberations will interfere and alter the ability to understand speech in background noise, as observed for normal-hearing participants in a room with only slight reverberations described in Paper II. Therefore, studies should use supplemental tests to measure speech recognition in background noise and with controlled reverberation settings.

Litovsky (2015) identified the need for additional research on the developmental effect of informational unmasking. The developmental effect of informational masking in CI users would be of great interest, as would comparison of age effects on energetic and informational masking in relation to the CI, particularly with reference to the effect of implantation age. Since the HINT has energetic masking effects, we would need Norwegian informational masking tests as well. The effect of reverberation on speech recognition outcome should also be assessed, and should be included in the clinical assessment of CI users.

In Paper III, the advantage of CI₂ and bilateral advantage was investigated. A close to significant mean disadvantage was found when noise was applied to the second CI side, introducing a bilateral disadvantage. Future studies with more statistical power should investigate bilateral effects to detect listening conditions that were beneficial or disadvantageous. Also, similar test conditions should be applied to other study groups, e.g. to a study group consisting of prelingually deaf receiving simultaneous bilateral CIs early, for example the study group of children receiving simultaneous bilateral CIs between ages 5 to 18 months described by Wie (2010) with findings that language skills development was within normal for the majority of children. Adults with bilateral CIs should also be studied using the same tests to compare bilateral advantages across study groups. There are ongoing studies to investigate some of these effects, as described in Chapter 7.

HINT is a valuable tool in an audiological test battery for CI candidacy considerations and tests quality whilst following audiological development, particular that of hearing in noise ability. Speech intelligibility tests which include reverberation, informational masking and modulated noise masker must however be considered. Addition of several tests will also increase validity when results from the different tests are compared.

Data collection and clinical assessment

OUS is the only hospital in Norway where pediatric CI surgery is performed. The study population in Paper III is a cohort of one country's complete pediatric CI population with sequential bilateral CIs (period 2003-2008). Therefore, the study data is unique. Study clinical test variables were collected at follow-ups at OUS. Clinical test protocols are used at OUS, but test protocols are not completed or consistent at all follow-ups since 1) protocols are revised and changed and 2) clinical considerations and the individual CI user's needs are met. Some test results were therefore missing in Paper III. Obviously, missing test results will always exist in a retrospective study. Nevertheless, sometimes a missing test result provides better information than an invalid or unreliable test result in a more strict test regime. In addition, studies like the retrospective studies in Paper III, can be more effective and give answers not found in more selective study populations with fewer participants. It shows the importance of coordinating research studies and clinical practice, and the value of using the same test protocols in both clinical assessment and research studies. When the data collection in research studies is made during clinical follow-ups, the study design has to consider clinical practice and clinical needs.

Paper IV describes a research study where clinical assessment is combined with research data collection. The same speech recognition test scores (monosyllable test score, HINT percentage word score on sentences in quiet, and HINT NF SRT) are used as clinical follow-up and research variables. The test results were collected in addition to the self-assessment (and self-administered) SSQ questionnaire. In the study period, 152 participants answered the SSQ questionnaire. This is a large number of participants compared to the number in other similar studies. Of the 152 participants, 123 (81%) had a monosyllable test score, 98 had HINT percentage score in quiet, and 78 had obtained a HINT NF test score. Of the 20 participants who had only HINT percentage score and not NF SRTs, 11 had word scores of HINT sentences below 75%, which is below the recommended score for HINT SRT testing (according to the test protocol). However, nine had word scores above 75% and could probably have been tested in the HINT NF test condition.

Twenty-five had monosyllable test scores and not HINT test scores, but were tested with slower speech rate sentences (IOWA). However, fifteen obtained from 80-100% word score on the IOWA sentences, and could probably have been tested with HINT sentences as well. The decision to test with slower speech rate sentences is a clinical decision, and at the same time a pitfall for the research study since data will be missing and analysis results will be less robust/reliable. The clinician might have considered the HINT test too difficult, or there might have been time issues related to the decision to test only IOWA sentences.

In an adult CI population, it is generally easier to complete the test protocol, compared to a pediatric CI population. However, sometimes the clinician chooses not to apply difficult tests since the CI user's feeling of success in the test situation is preferred over a low score on a difficult test. On the other hand, from a research point of view, inclusion of all ranges of results is important. Results might be biased with these results missing in the data set.

In the Paper IV study, monosyllable scores were missing in 29 (19%) of the participants. The feeling of failure is less with monosyllables than sentences since one single word can be repeated if heard even if not identified correctly. Therefore, the reason for not testing monosyllables is usually time issue related – either the CI user does not have time, or the clinician has no time for testing, or the test room is occupied.

Objective outcome measure and self-assessed SSQ scores

We found that the monosyllable scores predicted to some degree the SSQ scores, except for in the Spatial domain. Whether the participant came from the bilateral CI group or the HA contralateral to CI+unilateral CI group there was a significant effect in the Spatial and Qualities domains, but the magnitude of the effect was small, and the mean differences between the two groups ranged from below 1 to just above 1 point on the SSQ scale.

The objective measure of recognizing speech in noise, i.e., the HINT NF, correlated with the scores in the Speech and Spatial domains, and in the subscales concerning listening in background noise. However, the correlation coefficients were small, and the HINT NF score explained only 6% of the variation in these self-rated SSQ subscales. Since the HINT NF is a demanding test, it can be applied only to high-performing CI users who have relatively good speech perception, so the range of participants was restricted. When comparing the SSQ results between the participants who were tested with HINT NF and those who were not tested with HINT NF, the mean SSQ scores were significantly better in the “HINT NF group” for all SSQ domains

except the Spatial domain scores, which were still better, but not significantly so.

The age at assessment and objective speech perception scores predicted the self-assessed SSQ scores to a lesser degree. Other factors explaining the variation in SSQ scores were not investigated. It is likely that the history of hearing ability before implantation will contribute to the self-assessed hearing ability with a CI. Even though they might not be objectively better in the listening situations in question, participants going from a very poor hearing situation with HAs into a much better hearing situation with CIs will probably score themselves better than the ones who started off with a higher ability, and thus received a smaller benefit from their CIs. In other words, because the objective improvement in their hearing ability is greater, their subjective self-assessment becomes higher. In addition, the patient's expectation regarding the outcomes of implantation and whether they were fulfilled is probably an independent factor for predicting SSQ scores.

In Paper IV, HINT NF results correlated with the SSQ items related to hearing in noise, but explained only a low percentage of the variation in the SSQ scores. CI users who did not obtain HINT SRTs, the majority of them because the test was too difficult, had significantly lower average SSQ scores. In Paper IV, correlation between monosyllables and SSQ Speech domain was $r=0.50$ ($n=123$) and between HINT NF and SSQ Speech domain $r= 0.25$ ($n=68$), probably because the number of participants was larger in the first ($n=123$), and thus included a broader range of listening performances.

Studies using the SSQ questionnaire should be conducted on participant groups other than adult CI users and effects of objective outcome measures and age should be further investigated. When SSQ is assessed in longitudinal studies the effect of repeated assessment must be considered (as discussed in Paper IV).

Results across study groups

The subgroup of participants who were tested with HINT in the research study in Paper III was selected based on a monosyllable score above 60% so the group cannot be compared to the other groups directly. Their HINT NF scores were on average 2.6 and 3.6 dB, while the average score in the two groups A and B in Paper III was 5.4 and 4.5 dB (results summarized in Table 9). The average scores in the participant groups of adult CI users in Paper IV were also 5.6 in the bilateral CI group and 5.9 in the unilateral CI group.

It is interesting to compare mean HINT SRTs and mean monosyllable scores in the two groups: a 3 dB increase in mean SRT followed a 18% decrease in monosyllable score and a 10% decrease in word scores on HINT sentences (98% and 88% respectively in the two study groups). There are ceiling effects in both the monosyllable scores and the HINT in quiet scores, but these are more pronounced in the sentence test compared to the monosyllables. Since monosyllables can be applied to a large range of listeners, and ceiling effects are less than with sentences, the monosyllable test score is a useful test variable.

The HINT adaptive testing (SRT outcome) can be applied when the speech perception of sentences in quiet is close to 100% (>75% according to our test protocol). Thus, only the high-performing CI users can obtain HINT thresholds (SRTs). The ceiling effect obtained in quiet listening conditions is spread along HINT thresholds from near to normal hearing (-1 dB SNR is close to adult norms) up to 16 dB SNR, which is a high SNR. HINT NF SRTs correlate with monosyllable scores. However, the monosyllable test can be applied for a larger range of speech perception abilities than the HINT NF, and is an important test supplement.

Clinical assessment of the hearing in noise ability

Currently, the HINT is used as a clinical assessment tool to follow the outcome of CIs in patients who attend regular follow-ups at OUS. The HINT results are used to measure hearing in noise ability and to give guidelines for rehabilitation for CI recipients. Other hearing in noise tests should be applied as a supplement to measure other aspects of functional hearing. Available Norwegian speech in noise tests are included in “HiST taleaudiometri” as described in Section 1.7.1. The noise can be applied from surrounding speakers and the speech can consist of three-word utterances instead of sentences, and is therefore applicable for children younger than 5-6 years, 6 years old being the recommended lower age limit for applying the HINT. The “HiST Taleaudiometri” has tests in quiet and in noise, using three-word-utterances, and would be a valuable speech perception test supplement to monosyllables and sentences.

6 Conclusions

6.1 Norwegian Hearing in Noise test (Papers I+II)

The Norwegian HINT test results can be compared to test results of HINT in other languages. The test can be used to test hearing ability in noise in clinical settings and research studies. Since the Norwegian speaking population is relatively small, around 5 million, it is particularly important to have across-language comparable tests.

The children's version of the HINT makes it possible to use the HINT in clinical settings to get a better impression of the hearing capabilities in real-life situations for children with different types of hearing impairments, for HA users and for CI users. The HINT will enable differentiation of performers ranging from normal hearing to hearing impaired who perform reasonably well in quiet conditions. Their reduced performance in noise compared with their normal-hearing peers can be expressed as a SNR loss.

Children appear to achieve adult-like performance in NF conditions in non-reverberant environments around or before the age of 9 years. In the NS condition all age groups were significantly poorer than adults, indicating that children do not achieve adult-like SRM until after they are 13 years old.

The results show the importance of testing speech perception in controlled noise and controlled reverberation settings. A small reverberation might affect the results of hearing impaired subjects more strongly than those with normal hearing, and the combined effects of noise and reverberation should receive further study.

6.2 Pediatric CI participants with sequential CI₂ (Paper III)

The main contribution of our paper is the finding that, in general, patients were more likely to choose not to use their second CI (CI₂) after some time if it did not perform comparably to the first implant (CI₁). In prelingually deaf children with no or little acquired oral language before implantation, increased inter-implant intervals predicted poorer CI₂ speech perception results and increased the risk of not using CI₂.

The study emphasizes the importance of close counselling over a long-term follow-up period, along with individual considerations regarding motivation and parental support, to achieve good outcomes.

In the assessment of tests without noise (monosyllable test) the bilateral benefit was either non-significant or in cases of statistical significance, the

mean effect was small. Ceiling effects might have occurred in unilateral and bilateral test conditions when tests were applied in quiet conditions.

Using HINT, we were unable to measure a bilateral advantage when sentences and noise came from the same speaker. When sentences and noise appeared from different speakers (90° apart), a bilateral advantage was measured when the bilateral compared to the unilateral condition added the second CI on the opposite side of the noise. Addition of a second CI on the ipsi side of the noise, produced a poorer HINT result so the mean effect was a bilateral disadvantage, but this disadvantage effect was only close to significant.

6.3 Adult CI participants (Paper IV)

The pattern of SSQ responses in the present CI population was similar to those in other studies with similar CI populations. The bilateral CI recipients scored themselves higher than unilateral CI recipients, but the effect was only significant for the Spatial and Qualities domains after adjusting for age and monosyllable scores.

Both objective and subjective measures should be used to evaluate hearing ability. We found that the objective measures explained some of the variation in perceived hearing disability. We found that age at assessment and monosyllable score explained 35% of the variation in experienced hearing disability in the Speech and Qualities domains. The monosyllable scores explained 9% of the variation of the experienced hearing disability in the Spatial domain, and while age did not predict self-assessment in this domain, participants with bilateral CIs felt less disability than the participants with unilateral CIs.

The HINT NF test results correlated with the scores in the Speech and Spatial domains, and in the subscales concerning listening in background noise. However, the correlation coefficients were small, and the HINT NF score explained only 6% of the variation in these self-rated SSQ subscales.

The relatively small magnitudes of the effects indicate that other factors than speech perception scores are involved in explaining the variation in SSQ; these factors can be individually based and the experienced auditory skills might be based on personal preferences. Deficits in auditory skills are experienced as disabilities on an individual basis, and routine clinical assessment to evaluate hearing should include self-assessment.

6.4 HINT in clinical practice

One clinical objective was to implement HINT assessment in clinical practice. HINT has been integrated in the clinical assessment protocol for CI users at OUS as part of the CI outcome “quality check”. The HINT is used in the assessment of CI candidacy, and at follow-ups after implantation.

HINT is assessed regularly at follow-ups. Adults, older children, and parents of younger children are given feedback on their own or their child’s hearing ability in noise measured with HINT, and their HINT results can be compared to the HINT norms of normal-hearing peers. Also, we have gained an understanding of what would be good or acceptable results for the different groups of CI users (e.g. grouping based on onset of deafness, implantation age etc). However, data must be further investigated to gain a scientific understanding of the HINT results from different CI user groups and with independent variables such as onset of deafness, length of deafness, implantation age and what range of HINT results to expect.

The HINT results are used to give guidelines for rehabilitation and document, for example, the need for class room audio systems. Also, HINT results are systematically stored in a local CI database, and can be retrieved in future studies.

7 Future perspectives

There are several ongoing studies at OUS which use the HINT and the SSQ. The studies which originate from this thesis are listed below, with research objectives and subgoals:

- Evaluate bilateral benefit for speech recognition in noise in participants who received simultaneous bilateral implants as children, and compare results to those with sequential implants (study group in Paper III). The data collection is almost complete.
- Evaluate bilateral benefit for speech recognition in noise in adult participants with bilateral implants, and compare results to the pediatric population. The data collection is almost complete.
- Investigate the objective measures of speech recognition in quiet and noise and the subjective self-assessed SSQ in a pediatric CI population. The data collection is complete.
- Under consideration is a follow-up study of the participants in Paper III, who were sequentially implanted, that is received a CI as a child and a second-side CI from 3 months to 19 years later. We are deliberating an intervention study to motivate the non-users of CI₂ to have a new CI₂ fitted and subsequently follow a rehabilitation program.

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8 Appendix

8.1 SSQ questionnaire in Norwegian

SSQ-skjema

The Speech, Spatial, and Qualities of Hearing Scale)

(Utviklet av William Noble & Stuart Gatehouse)

Svar på spørsmålene nedenfor, og gå deretter til spørsmålene om hørsel

Navn: _____

Fødselsdato: _____

Dagens dato: _____

<i>Merk av for ett av alternativene for venstre side og ett av alternativene for høyre side:</i>	Venstre side	Høyre side
Jeg bruker ikke høreapparat eller CI	☐	☐
Jeg bruker høreapparat	☐	☐
Jeg bruker CI	☐	☐
Nåværende bruk:	☐ Hele dagen ☐ Bare på skole/jobb ☐ Annet: _____	☐ Hele dagen ☐ Bare på skole/jobb ☐ Annet: _____

Råd om besvarelse av spørsmålene

Spørsmålene nedenfor gjelder aspekter ved dine evner og opplevelser når det gjelder å høre og lytte i ulike situasjoner.

For hvert spørsmål setter du et merke, for eksempel et kryss (x), et eller annet sted på skalaen som vises etter hvert spørsmål. Skalaen går fra 0 til 10. Hvis du setter et merke ved 10, betyr det at du ikke har noen som helst problemer med å gjøre eller oppleve det som beskrives i spørsmålet. Hvis du setter et merke ved 0, betyr det at du er helt ute av stand til å gjøre eller oppleve det som beskrives.

Eksempel: Spørsmål 1 gjelder det å ha en samtale med en annen person samtidig som TV-en står på. Hvis du er i stand til dette, setter du et merke mot høyre side av skalaen. Hvis du kan følge ca. halvparten av samtalen i en slik situasjon, setter du merket ca. midt på skalaen, og så videre.

Vi antar at samtlige spørsmål dreier seg om ting du opplever i hverdagen, men hvis et spørsmål beskriver en situasjon som ikke gjelder deg, krysser du av i boksen "Gjelder ikke". Skriv også en merknad ved siden av spørsmålet som forklarer hvorfor situasjonen ikke gjelder deg.

SSQ-skjema (Del I: Oppfattelse av tale)

1. Du snakker med en annen person og TV-en står på i samme rom. Kan du følge med på hva den andre personen sier, uten å skru ned TV-lyden?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
2. Du snakker med en annen person i en stille, teppebelagt stue. Kan du følge med på hva den andre personen sier?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
3. Du er en del av en gruppe på fem personer som sitter rundt et bord. Stedet er ellers rolig. Du kan se alle de andre i gruppen. Kan du følge med på samtalen?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
4. Du er en del av en gruppe på fem personer i en travel restaurant. Du kan se alle de andre i gruppen. Kan du følge med på samtalen?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
5. Du snakker med en annen person. Det er kontinuerlig støy i bakgrunnen, for eksempel en vifte eller rennende vann. Kan du følge med på hva den andre personen sier?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>

SSQ-skjema (Del 1: Oppfattelse av tale, forts.)

6. Du er en del av en gruppe på fem personer i en travel restaurant. Du KAN IKKE se alle de andre i gruppen. Kan du følge med på samtalen?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
7. Du snakker med en annen person på et sted med mye ekko, for eksempel i en kirke eller i ventehallen på en jernbanestasjon. Kan du følge med på hva den andre personen sier?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
8. Kan du ha en samtale med en person når en annen person snakker, og denne personen har samme stemmeleie som personen du snakker med?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
9. Kan du ha en samtale med en person når en annen person snakker, og denne andre personen har et annet stemmeleie enn personen du snakker med?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
10. Du lytter til noen som snakker til deg, samtidig som du prøver å følge med på nyhetene på TV. Kan du følge med på hva begge personene sier?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>

SSQ-skjema (Del 1: Oppfattelse av tale, forts.)

<p>11. Du snakker med en person i et rom der mange andre personer snakker sammen. Kan du følge med på hva personen du snakker med, sier?</p>	<div> <div>Ikke i det hele tatt</div> <div> <div>0</div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div> <div>7</div> <div>8</div> <div>9</div> <div>10</div> </div> <div>Uten problemer</div> </div> <div> <div>Gjelder ikke</div> <div>☐</div> </div>
<p>12. Du er i en gruppe, og samtalen veksler mellom ulike personer. Kan du enkelt følge med i samtalen uten å miste starten på det hver enkelt person sier?</p>	<div> <div>Ikke i det hele tatt</div> <div> <div>0</div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div> <div>7</div> <div>8</div> <div>9</div> <div>10</div> </div> <div>Uten problemer</div> </div> <div> <div>Gjelder ikke</div> <div>☐</div> </div>
<p>13. Kan du enkelt ha en samtale i telefonen?</p>	<div> <div>Ikke i det hele tatt</div> <div> <div>0</div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div> <div>7</div> <div>8</div> <div>9</div> <div>10</div> </div> <div>Uten problemer</div> </div> <div> <div>Gjelder ikke</div> <div>☐</div> </div>
<p>14. Du lytter til noen i telefonen, og en person ved siden av deg begynner å snakke. Kan du følge med på hva begge to sier?</p>	<div> <div>Ikke i det hele tatt</div> <div> <div>0</div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div> <div>7</div> <div>8</div> <div>9</div> <div>10</div> </div> <div>Uten problemer</div> </div> <div> <div>Gjelder ikke</div> <div>☐</div> </div>

SSQ-skjema (Del 2: Rom og retning)

1. Du er utendørs på et ukjent sted. Du hører noen som bruker en gressklipper. Du kan ikke se hvor. Hører du umiddelbart hvor lyden kommer fra?	<div>Ikke i det hele tatt</div> <div>0 1 2 3 4 5 6 7 8 9 10</div> <div>Uten problemer</div> <div>Gjelder ikke ☐</div>
2. Du sitter rundt et bord eller på et møte med flere andre personer. Du kan ikke se alle. Vet du hvor en person er så snart vedkommende begynner å snakke?	<div>Ikke i det hele tatt</div> <div>0 1 2 3 4 5 6 7 8 9 10</div> <div>Uten problemer</div> <div>Gjelder ikke ☐</div>
3. Du sitter mellom to personer. En av dem begynner å snakke. Vet du umiddelbart om det er personen til venstre eller til høyre som snakker, uten at du må se etter?	<div>Ikke i det hele tatt</div> <div>0 1 2 3 4 5 6 7 8 9 10</div> <div>Uten problemer</div> <div>Gjelder ikke ☐</div>
4. Du er i et ukjent hus. Det er stille. Du hører en dør slå igjen. Hører du umiddelbart hvor lyden kommer fra?	<div>Ikke i det hele tatt</div> <div>0 1 2 3 4 5 6 7 8 9 10</div> <div>Uten problemer</div> <div>Gjelder ikke ☐</div>
5. Du er i trappen i en bygning med etasjer over og under deg. Du kan høre lyder fra en annen etasje. Hører du umiddelbart hvor lyden kommer fra?	<div>Ikke i det hele tatt</div> <div>0 1 2 3 4 5 6 7 8 9 10</div> <div>Uten problemer</div> <div>Gjelder ikke ☐</div>

SSQ-skjema (Del 2: Rom og retning, forts.)

6. Du er utendørs. En hund bjeffer høyt. Hører du umiddelbart hvor den er, uten at du må se etter?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
7. Du står på fortauet i en travel gate. Kan du umiddelbart høre hvilken retning en buss eller lastebil kommer fra, før du ser den?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
8. Kan du ute på gaten si hvor langt unna en person er, basert på lyden av stemmen eller fottrinnene?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
9. Kan du si hvor langt unna en buss eller lastebil er, basert på lyden?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
10. Kan du si hvilken retning en buss eller lastebil beveger seg i, basert på lyden – fra venstre mot høyre eller fra høyre mot venstre?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>

SSQ-skjema (Del 2: Rom og retning, forts.)

<p>11. Kan du si hvilken retning en person beveger seg i, basert på lyden av stemmen eller fottrinnene – fra venstre mot høyre eller fra høyre mot venstre?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
<p>12. Kan du si om en person kommer mot deg eller går fra deg, basert på stemmen eller fottrinnene?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
<p>13. Kan du si om en buss eller lastebil kommer mot deg eller går fra deg, basert på lyden?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
<p>14. Virker det som om lydene av ting du kan høre, heller er inne i hodet ditt enn ute i omgivelsene?</p>	<p><i>Inne i hodet mitt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Ute i omgivelsene</i></p> <p>Gjelder ikke ☐</p>
<p>15. Viser det seg at lyder fra personer eller ting du kan høre, men ikke umiddelbart kan se, er nærmere enn forventet når du får øye på dem?</p>	<p><i>Mye nærmere</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Ikke nærmere</i></p> <p>Gjelder ikke ☐</p>

SSQ-skjema (Del 2: Rom og retning, forts.)

<p>16. Viser det seg at lyder fra personer eller ting du kan høre, men ikke umiddelbart kan se, er lenger unna enn forventet når du får øye på dem?</p>	<div> <div> <div>Mye lenger unna</div> <div> <div>Ikke lenger unna</div> </div> </div> <div> <div>0</div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div> <div>7</div> <div>8</div> <div>9</div> <div>10</div> </div> <div> <div>Gjelder ikke</div> <div></div> </div> </div>
<p>17. Har du inntrykk av at lyder er nøyaktig der du forventet at de skulle være?</p>	<div> <div> <div>Ikke i det hele tatt</div> <div> <div>Uten problemer</div> </div> </div> <div> <div>0</div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div> <div>7</div> <div>8</div> <div>9</div> <div>10</div> </div> <div> <div>Gjelder ikke</div> <div></div> </div> </div>

SSQ-skjema (Del 3: hørselskvalitet)

1. Tenk på når du hører to ting samtidig, for eksempel vann som renner i en vask, og en radio som står på. Har du inntrykk av at disse lydene er atskilt fra hverandre?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10 <i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
2. Når du hører flere lyder samtidig, har du da inntrykk av at de høres ut som én enkelt, sammensatt lyd?	<p><i>Sammensatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10 <i>Ikke sammensatt</i></p> <p>Gjelder ikke ☐</p>
3. Du er i et rom, og det er musikk på radioen. En annen person i rommet snakker. Kan du høre stemmen atskilt fra musikken?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10 <i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
4. Synes du det er enkelt å gjenkjenne ulike personer du kjenner, basert på lyden av stemmene deres?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10 <i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
5. Synes du det er enkelt å skjelne mellom ulike musikkskykker som du kjenner?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10 <i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>

SSQ-skjema (Del 3: hørskvalitet, forts.)

<p>6. Hører du forskjell på ulike lyder, for eksempel bil og buss eller vann som koker i en kasserolle og mat som stekes i en stekepanne?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
<p>7. Kan du skjelne mellom de ulike instrumentene som spiller når du lytter til musikk?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
<p>8. Høres musikken tydelig og naturlig ut når du lytter til musikk?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
<p>9. Høres dagligdagse lyder du enkelt kan høre, tydelige ut (ikke uklare)?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
<p>10. Høres stemmen til andre personer tydelig og naturlig ut?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>

SSQ-skjema (Del 3: hørselskvalitet, forts.)

11. Høres dagligdagse lyder kunstige eller unaturlige ut?	<p><i>Unaturlige</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Naturlige</i></p> <p>Gjelder ikke ☐</p>
12. Høres din egen stemme naturlig ut for deg?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
13. Kan du enkelt vurdere en annen persons humør basert på lyden av stemmen?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Uten problemer</i></p> <p>Gjelder ikke ☐</p>
14. Må du konsentrere deg nøye når du lytter til noen eller noe?	<p><i>Må konsentrere meg nøye</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Trenger ikke konsentrere meg</i></p> <p>Gjelder ikke ☐</p>
15. Må du anstrenge deg veldig for å kunne høre hva som blir sagt i en samtale med andre?	<p><i>Stor anstrengelse</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Ingen anstrengelse</i></p> <p>Gjelder ikke ☐</p>

SSQ-skjema (Del 3: hørselskvalitet, forts.)

16. Kan du enkelt høre hva sidepassasjeren sier når du er sjåfør i en bil?	<div>Ikke i det hele tatt</div> <div> <div>0</div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div> <div>7</div> <div>8</div> <div>9</div> <div>10</div> </div> <div>Uten problemer</div> <div>Gjelder ikke</div> <div>☐</div>
17. Kan du enkelt høre hva sjåføren sier når du sitter i passasjerstet foran?	<div>Ikke i det hele tatt</div> <div> <div>0</div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div> <div>7</div> <div>8</div> <div>9</div> <div>10</div> </div> <div>Uten problemer</div> <div>Gjelder ikke</div> <div>☐</div>
18. Kan du lett ignorere andre lyder når du prøver å lytte til noe?	<div>Ikke lett ignorere</div> <div> <div>0</div> <div>1</div> <div>2</div> <div>3</div> <div>4</div> <div>5</div> <div>6</div> <div>7</div> <div>8</div> <div>9</div> <div>10</div> </div> <div>Lett ignorere</div> <div>Gjelder ikke</div> <div>☐</div>

8.2 SSQ questionnaire for children in Norwegian

SSQ-skjema for barn med nedsatt hørsel

The Speech, Spatial, and Qualities of Hearing Scale)

(Basert på SSQ for voksne, utviklet av William Noble & Stuart Gatehouse, endringer av Karyn Galvin)

Svar på spørsmålene nedenfor, og gå deretter til spørsmålene om hørsel

Navn: _____

Fødselsdato: _____

Dagens dato: _____

Merk av for ett av alternativene for venstre side og ett av alternativene for høyre side:	Venstre side	Høyre side
Jeg bruker ikke høreapparat eller CI	☐	☐
Jeg bruker høreapparat	☐	☐
Jeg bruker CI	☐	☐
Nåværende bruk:	☐ Hele dagen ☐ Bare på skole/barnhage ☐ Annet: _____	☐ Hele dagen ☐ Bare på skole/barnhage ☐ Annet: _____

Råd om hvordan du svarer på spørsmålene

Besvares sammen med en voksen

Spørsmålene handler om hvordan du syns du hører og hvordan du lytter i ulike situasjoner.

For hvert spørsmål setter du et merke, for eksempel et kryss (x), et eller annet sted på skalaen som vises etter hvert spørsmål. Skalaen går fra 0 til 10. Hvis du setter et merke ved 10, betyr det at du ikke har noen som helst problemer med å høre eller klare det som beskrives i spørsmålet. Hvis du setter et merke ved 0, betyr det at du er helt ute av stand til å høre eller klare det som beskrives.

Eksempel: Spørsmål 1 gjelder det å ha en samtale med en annen person samtidig som TV-en står på. Hvis du klarer å snakke med noen andre samtidig som TV-en står på, setter du et merke mot høyre side av skalaen. Hvis du hører ca. halvparten av samtalen mens TV-en står på, setter du merket ca. midt på skalaen, og så videre.

Vi tror spørsmålene handler om noe du har opplevd, eller som likner på noe du har opplevd. Kanskje er det noe du opplever hver dag. Men hvis et spørsmål beskriver en situasjon som ikke gjelder for deg, krysser du av i boksen "Gjelder ikke". Skriv også en merknad ved siden av spørsmålet som forklarer hvorfor situasjonen ikke gjelder deg.

Section A: Tale

1. Du snakker med mamma eller pappa, og TV-en står på i samme rom. Forstår du hva mamma eller pappa sier til deg, uten at du må skru ned lyden på TV-en?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p><i>Maximum</i></p> <p>☐ Vilje ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>
2. Du snakker med en person i et stille rom med teppe. Forstår du hva den andre personen sier til deg?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p><i>Maximum</i></p> <p>☐ Vilje ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>
3. Du er en del av en gruppe på omtrent fem personer som sitter rundt et bord. Det er et rolig sted. Du kan se alle de andre i gruppen. Forstår du hva gruppen snakker om?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p><i>Maximum</i></p> <p>☐ Vilje ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>
4. Du er en del av en gruppe på omtrent fem personer som sitter rundt et bord. Det er et støyende rom, for eksempel et travelt klasserom der elevene beveger seg rundt og snakker. Du kan se alle i gruppen rundt bordet. Forstår du hva gruppen snakker om?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p><i>Maximum</i></p> <p>☐ Vilje ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>
5. Du snakker med en person. Det er støy i bakgrunnen, for eksempel rennende vann eller en vifte. Forstår du hva den andre personen sier til deg?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p><i>Maximum</i></p> <p>☐ Vilje ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>

Section A: Tale

6. Du er en del av en gruppe på ondtrent fem personer som sitter rundt et bord. Det er et støyende rom, for eksempel et travelt klasserom der elevene beveger seg rundt og snakker. Du kan ikke se alle i gruppen rundt bordet. Forstår du hva gruppen snakker om?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>
7. Du snakker med noen på et sted med mye ekko, for eksempel i en forsamlingsal på skolen. Forstår du hva den andre personen sier?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>
8. Du snakker med en person i et rom der mange andre snakker sammen. Forstår du hva den andre personen sier?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>
9. Du snakker med en gruppe venner, og alle snakker etter tur. Forstår du hva som blir sagt, uten å miste starten hver gang en ny person begynner å snakke?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>
10. Er det enkelt for deg å snakke i telefonen med en venn, mamma eller pappa?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>

Section B: Rom og retning

1. Du er utendørs på et sted du ikke har vært før. Det kommer høy lyd fra en gressklipper eller et fly som du ikke kan se. Hører du med én gang hvor lyden kommer fra?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p>	<p><i>Uten problemer</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Maximum</i></p>	☐ Ville ikke høre det ☐ Vet ikke ☐ Gjelder ikke
2. Du er en del av en gruppe på omtrent fem personer som sitter rundt et bord. Du kan ikke se alle i gruppen. Vet du hvor en person er så snart vedkommende begynner å snakke?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p>	<p><i>Uten problemer</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Maximum</i></p>	☐ Ville ikke høre det ☐ Vet ikke ☐ Gjelder ikke
3. Du sitter mellom to venner. En av dem begynner å snakke. Vet du med én gang om det er vennen til venstre eller til høyre for deg som snakker, uten å se etter?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p>	<p><i>Uten problemer</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Maximum</i></p>	☐ Ville ikke høre det ☐ Vet ikke ☐ Gjelder ikke
4. Du er hjemme, og det er stille. Mamma eller pappa roper på deg fra et annet rom. Vet du hvor de er uten å se etter?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p>	<p><i>Uten problemer</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Maximum</i></p>	☐ Ville ikke høre det ☐ Vet ikke ☐ Gjelder ikke
5. Du er utendørs. En hund bjeffer høyt. Hører du med én gang hvor den er, uten at du må se etter?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p>	<p><i>Uten problemer</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Maximum</i></p>	☐ Ville ikke høre det ☐ Vet ikke ☐ Gjelder ikke

Section B: Rom og retning

<p>6. Du står på fortauet i en travel gate. Du kan høre en buss eller lastebil. Vet du med én gang hvor den kommer fra, for du ser den?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det ☐ Vet ikke ☐ Gjelder ikke</p>
<p>7. Du kan høre en buss eller lastebil. Hører du om den kommer mot deg eller beveger seg bort fra deg?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det ☐ Vet ikke ☐ Gjelder ikke</p>
<p>8. Du hører stemmer eller fottrinn. Hører du om personen kommer mot deg eller beveger seg bort fra deg?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det ☐ Vet ikke ☐ Gjelder ikke</p>
<p>9. Du kan høre en buss eller lastebil. Vet du hvilken retning den beveger seg i (for eksempel fra venstre mot høyre eller fra høyre mot venstre) basert på lyden?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det ☐ Vet ikke ☐ Gjelder ikke</p>
<p>10. Du hører stemmer eller fottrinn. Vet du hvilken retning personen beveger seg i (for eksempel fra venstre mot høyre eller fra høyre mot venstre) basert på lyden?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det ☐ Vet ikke ☐ Gjelder ikke</p>

Section B: Rom og retning

<p>11. Du kan høre en buss eller lastebil. Kan du høre hvor langt unna den er?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p><i>Maximum</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>
<p>12. Du hører stemmer eller fottrinn. Kan du høre hvor langt unna personen er?</p>	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p><i>Maximum</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>
<p>13. Virker det som om lyden av ting du kan høre, er inne i hodet ditt og ikke ute i virkeligheten? Hvis du for eksempel kan se en hund som bjeffer på den andre siden av gaten, høres det ut som om hunden er på den andre siden av gaten, eller høres det ut som om lyden er inne i hodet ditt?</p>	<p><i>Inne i hodet mitt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Ute i virkeligheten</i></p> <p><i>Maksimum</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p>

Section C: Hørselskvalitet

1. Du er i et rom der det spilles musikk. Noen begynner å snakke. Merker du at noen har begynt å snakke (selv om du kanskje ikke hører hva vedkommende sier)?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p> <p><i>Maximum</i></p>
2. Tenk på når du kan høre to lyder samtidig, for eksempel vann som renner på badet og en radio som står på, ELLER en lastebil som kjører forbi og lyden av banking på døren. Hører du dette som to separate lyder?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p> <p><i>Maximum</i></p>
3. Vet du hvilket familiemedlem som snakker basert på lyden av stemmen, selv om du ikke kan se hvem det er?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p> <p><i>Maximum</i></p>
4. En sang du kjenner, spilles på radioen eller på en CD. Er det enkelt for deg å si hvilken sang det er, bare ved å lytte?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p> <p><i>Maximum</i></p>
5. Hører du forskjell på lyder som ligner litt på hverandre, for eksempel en bil og en buss ELLER remende vann og en vifte?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> <p><i>Uten problemer</i></p> <p>☐ Ville ikke høre det</p> <p>☐ Vet ikke</p> <p>☐ Gjelder ikke</p> <p><i>Maximum</i></p>

Section C: Hørselskvalitet

6. Kan du legge merke til humøret til en person (glad, sint, lei seg) bare ved å lytte til stemmen?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p>☐ Uten problemer ☐ Vil ikke høre det</p> <p>☐ Vet ikke ☐ Gjelder ikke</p>
7. Må du konsentrere deg nøy når du lytter til noen eller noe?	<p><i>Prøver veldig hardt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maksimum</i></p> <p>☐ Prøver ikke hardt ☐ Vet ikke</p>
8. Når du er på tur og sitter i passasjeret foran i bilen, er det da enkelt å forstå hva sjåføren sier til deg?	<p><i>Ikke i det hele tatt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maximum</i></p> <p>☐ Uten problemer ☐ Vil ikke høre det</p> <p>☐ Vet ikke ☐ Gjelder ikke</p>
9. Må du prøve hardt å forstå hva andre sier?	<p><i>Prøver veldig hardt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maksimum</i></p> <p>☐ Prøver ikke hardt ☐ Vet ikke</p>
10. Kan du enkelt ignorere andre lyder når du prøver å lytte til noe?	<p><i>Ikke enkelt</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i> <i>Maksimum</i></p> <p><i>Enkelt</i></p> <p>☐ Vet ikke ☐ Gjelder ikke</p>

Section C: Hørselskvalitet

Svar på disse spørsmålene hvis du bruker implantat eller høreapparat på begge ører

<p>11. Virker alt for stille hvis høyre cochleaimplantat/høreapparat er slått av og venstre cochleaimplantat/høreapparat ikke skrur opp eller ned?</p>	<div style="display: flex; justify-content: space-between;"> <div style="text-align: center;"> <p><i>For stille</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> </div> <div style="text-align: center;"> <p><i>Ikke for stille</i></p> <p>☐ Vet ikke</p> <p><i>Maksimum</i></p> </div> </div>
<p>12. Virker alt for stille hvis venstre cochleaimplantat/høreapparat er slått av og høyre cochleaimplantat/høreapparat ikke skrur opp eller ned?</p>	<div style="display: flex; justify-content: space-between;"> <div style="text-align: center;"> <p><i>For stille</i></p> <p>0 1 2 3 4 5 6 7 8 9 10</p> <p><i>Minimum</i></p> </div> <div style="text-align: center;"> <p><i>Ikke for stille</i></p> <p>☐ Vet ikke</p> <p><i>Maksimum</i></p> </div> </div>