Aus der Klinik und Poliklinik für Hals-, Nasen- und Ohrenheilkunde der Ludwigs-Maximilians-Universität München

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Design of a hearing test to evaluate the Comodulation Masking Release in Cochlear Implant users

[Entwurf eines Hörtests zur Bestimmung des Comodulation Masking Release bei Cochlea Implantat-Trägern]

Dissertation

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1. Introduction

1.1 History and problem description

Cochlear Implants (CI) are surgically implanted hearing devices that have been used for years as a normal clinical treatment in the otolaryngology for patients with a severe to profound congenital or obtained sensorineural hearing loss. CI's are currently the only clinical prostheses of a peripheral sense organ. The first CI concepts originated in the 1970's (Michelson *et al.*, 1973). The development began with single channel implants utilizing analogue signal processing and advanced until today to multi channel (12-22 channels) implants with highly developed high-rate pulsatile signal processing strategies, so called speech coding strategies, that try to mimic more and more auditory processes of the healthy ear (Battmer *et al.*, 2010; Buechner *et al.*, 2010; Schatzer *et al.*, 2010). In parallel, the surgical insert methods of implantation advanced (Hussong *et al.*, 2010; Kluenter *et al.*, 2010). With recent CI systems, implant users reach good speech recognition values in quiet of in average around 60% monosyllabic word recognition unilaterally [German Freiburger Einsilber (Laszig *et al.*, 2004)]. However, in steady state and even more in modulated noise or in a so called cocktail-party listening environment, the speech recognition of CI users is significantly reduced compared to normal hearing (NH) listeners. A release from masking in speech intelligibility tests trough the presentation of modulated interfering noise instead of steady state interfering noise, known in NH, could not be observed in many studies in CI users (Smith *et al.*, 2002; Qin and Oxenham, 2003; Brungart *et al.*, 2006; Loizou *et al.*, 2009; Li and Loizou, 2010). A monaural psychoacoustic effect, which in this context is described in literature, as a basic principle of auditory object segregation is the comodulation masking release (CMR). Particularly in a cocktail party listening environment, this effect seems to help NH to concentrate on a certain sound source, while the sounds of different sources are overlapping. The impact of CMR and the concluded across frequency processing of the auditory system for speech understanding in difficult hearing environments is widely discussed in the literature (Hall and Haggard, 1983; Hall *et al.*, 1984; Hall *et al.*, 1988; Grose and Hall, 1992; Florentine *et al.*, 1996; Verhey, 2008).

1.2 The Comodulation Masking Release

Fletcher (1940) introduced the concept of critical bands. He assumed that the part of noise that is effective in masking a test tone is the part of its spectrum lying near the tone. The order of steps of signal processing assumed by this model are i) an analysis of incoming sound by the auditory system by a bank of overlapping band-pass filters called “critical bands”, and ii) a determination of the threshold through the filter with the largest ratio between signal energy and masker energy, regardless of the temporal characteristics of the signals. For the derivation of critical bands see also Zwicker and Fastl (1999). But recent studies have shown that the detection of a sinusoidal signal masked by a narrow-band masker can be significantly improved by simultaneously presenting additional maskers at frequencies remote from the signal frequency, assumed the envelope fluctuations across frequencies are coherent i.e. comodulated (Hall *et al.*, 1984). Hall et al. (1984) have called this effect “comodulation masking release” (CMR). This effect cannot be described by the power spectrum model, as it involves a combination of information across critical bands and an influence of the temporal properties of the signals.

NH subjects benefit from this ability of the auditory system in hearing conditions with competing natural sounds, as for example human speech. The dominant modulation rates within narrow speech bands coincide with those for which CMR is maximal (Hall and Haggard, 1983; Florentine *et al.*, 1996; Nelken *et al.*, 1999). For hearing impaired subjects with a hearing loss of cochlear origin, the CMR is reduced. The reduction correlated significantly with reduced frequency selectivity (Hall *et al.*, 1988; Grose and Hall, 1996).

1.3 Aim of this work

Because of the potentially high significance of the CMR for speech reception under difficult acoustic conditions, especially in a cocktail party environment (Grose and Hall, 1992; Verhey, 2008), in which nearly all CI users report serious problems (Loizou *et al.*, 2009) the CMR in CI users is of high-interest.

The aim of this work was to design a hearing test, which is suited to experimentally evaluate the CMR in CI users. In the next step the test has been applied at NHs and CI patients of the *Klinikum der Universität München*, to evaluate if they are able to use the CMR mechanism to improve the perception of signals in noise with their speech processor in the usual hearing setting. All CI users were tested acoustically unilaterally with their own speech processor. As a reference group, NH were tested with the same test setups. Two signal parameters were varied in different experimental tests: i) the bandwidth of the noise maskers (see chapter 4.1 and 5.3.1) and ii) the spectral alignment of the noise maskers (see chapter 4.2 and 5.3.2). For signal presentation, three different methods were used: presentation via a) audio cable, b) headphones and c) in free field. Finally, the ability of CI users to discriminate adjacent electrodes in pitch was correlated with the individual height of CMR (see chapter 4.3 and 5.3.3).

1.4 Earlier studies concerning CMR in CI users

Results of simulated CI signal processing (vocoding) on speech reception in fluctuating maskers predict it as more detrimental in fluctuating interference than in steady state noise (Qin and Oxenham, 2003). This means that variable hearing in noise tests, as the German Oldenburger Satztest in interfering steady state noise, in which CI users reach signal to noise ratios in mean (sentence recognition 50% correct) at around +2.5 dB unilaterally (Baumann and Seeber, 2001) [NH around -7.1 dB (HoerTech GmbH, 25. Juli 2000)], don’t reflect every challenge of hearing in the normal daily acoustic environment. CI users are unable to receive masking release in speech intelligibility tests and the reasons are unclear (Li and Loizou, 2010). Anyhow electrical stimulation in cochlear implants seems to lead to central, across-channel temporal processing mechanisms (Chatterjee and Oba, 2004).

Further psychoacoustical data show that implant users could detect temporal fluctuations at frequencies up to 4000 Hz (Shannon, 1992). The principal ability for an across channel temporal processing and the good reception of amplitude modulation of CI users, especially at lower modulation frequencies, are the reason for the assumption in the present work, that the precondition for a CMR in CI users seems to exist.

This is supported by a study of Pierzycki and Seeber (2010) who investigated the contribution of the temporal fine structure (TFS) to CMR with unprocessed and vocoded stimuli in normal hearing. They found a significant CMR even when the TFS is removed through vocoding. However, the contribution of TFS to CMR is discussed inconsistently in the literature. Epp and Verhey (2009) make mainly envelope fluctuations responsible for CMR:

The only existing experimental work with CI users found in the literature (Wagner, 2002), implant users showed only a small CMR, compared to NH, in a within-channel experiment and no CMR in a band-widening experiment.

1.5 Neurophysiologic models for the CMR

Several conceptual models have been proposed to describe the neurophysiologic processes of CMR in NH. For example, Buus (1985) has hypothesized that the auditory system uses the information in the temporal minima of the masker envelope as cued by the frequency channels mainly excited by the comodulated flanking bands (dip-listening model). Other models assume that the auditory system correlates the output of different frequency channels [correlation model (Richards, 1987)] or has the ability to subtract the output of off-frequency filters from the filter centred at the signal frequency [across-frequency version of Durlach's (1963) equalisation-cancellation (EC) model]. Further models suggest that changes in the temporal waveform within a single filter can account for some aspects of CMR (Schooneveldt and Moore, 1989; Verhey *et al.*, 1999). It is unclear which, if any, of these models can be realized physiologically. However, recent physiological correlates of CMR have been found at different levels of the auditory pathway. Current hypotheses for the underlying neural mechanisms include wide-band inhibition or the disruption of masker modulation envelope response.

2. Cochlear Implants

2.1 General function

The reason for a hearing loss of cochlear origin often is a degeneration of inner hair cells (IHC) in the inner ear. These signal transducers transform the motion of the basilar membrane into nerve action potentials, which are delivered via the hearing nerve to the central nervous system. Often the degeneration of IHCs doesn't come with a loss of spiral ganglion cells (SGC) at the same time. As the moment of deafness isn't too long ago or because of other factors, the hearing nerve is still intact, the work of the IHCs can be approximately done by direct electrical stimulation of the spiral ganglion cells. The physical principle is a depolarisation of the nervous membrane of spiral ganglion cells via an electrical field, which is created by intracochlear electrodes, which are chirurgicaly inserted (see Figure 1), in reference to an extracochlear electrode.

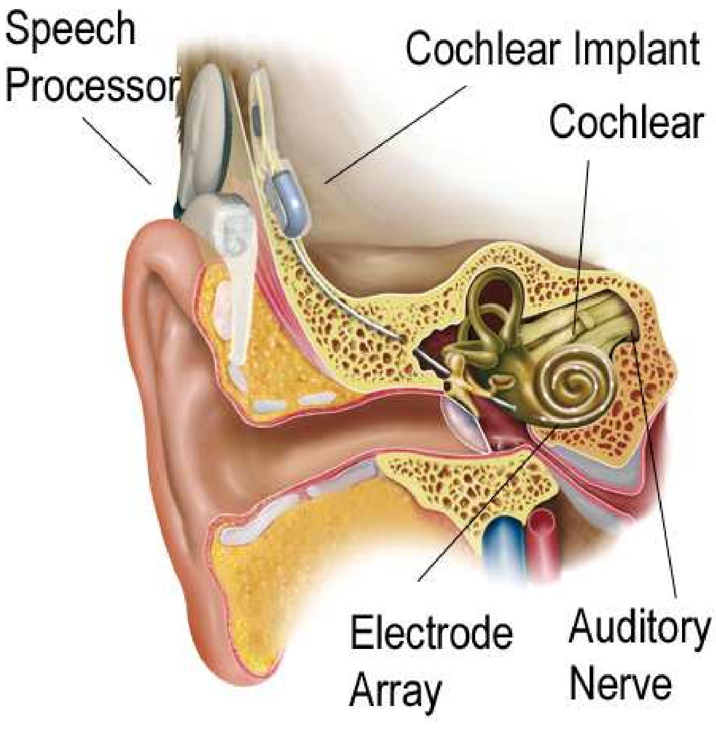

Figure 1: Human ear provided with a cochlear implant. Picture courtesy of the company of MED-EL.

When there is a current applied to an intracochlear electrode (typical stimulation currents per electrode are 10 µA up to 1.6 mA), the electrons flow from the negative to the positive pole (alternating between the reference electrode outside the cochlear and the intracochlear stimulation electrode in monopolar mode). An electrical potential difference depending on the tissue impedance of the surrounding medium is formed corresponding to Ohm's law:

$$U = I * Z \tag{1}$$

U: Voltage

I: Current

Z: Impedance

The potential difference provokes an electrical field. The relation between the electric potential U and the electric field E is given by the line integral (assumed static electrical field)

$$U = -\int_c Edl \tag{2}$$

C: arbitrary path connecting the point with zero potential to r

High field amplitudes lead to a depolarisation of the nervous membrane of spiral ganglion cells (Clark, 2003). The higher the potential difference, the bigger the electrical field, the more SGCs are depolarized. If enough SGCs are depolarized, the subject will have a soft hearing sensation. The bigger the potential difference is, the more SGCs are depolarized at the same time until the hearing sensation is getting loud.

To avoid remaining charge in the tissue around the intra cochlear electrodes biphasic pulses are used (see Figure 2).

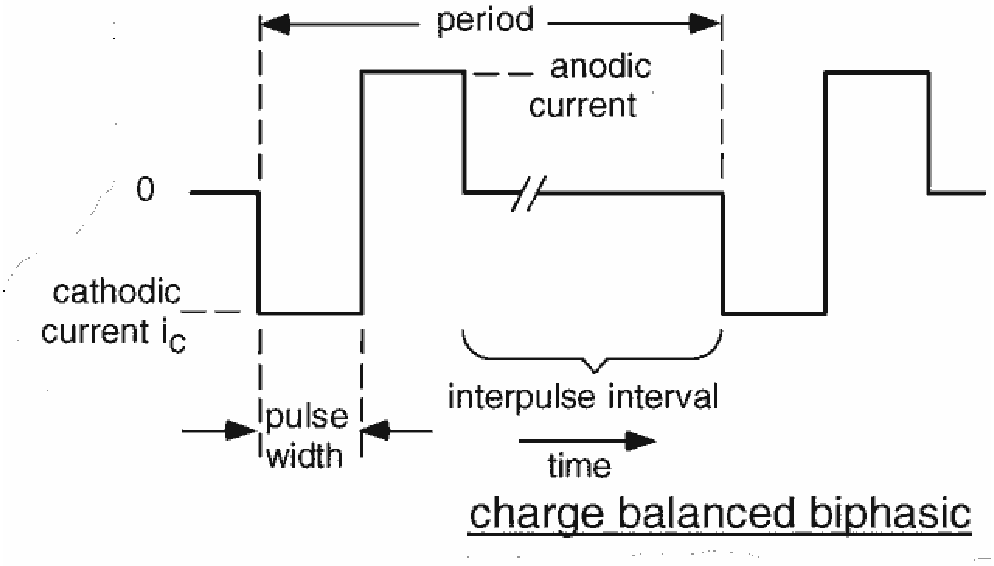

Figure 2: Schematic Biphasic Pulses (May, 2010)

Typical stimulation rates of biphasic pulses vary in the range of 900 – 3500 pulses per second (pps).

2.2 The CIS Speech Coding Strategy

The CIS (continuous interleaved sampling) speech coding strategy is a model for recent speech coding strategies, elucidated for example by the MED-EL HDCIS in the next chapter.

The first step of the signal processing is an amplifier, which attenuates incoming Signals from the microphone. The second step is an analogue-digital converter, that has to provide a sampling rate which more than the double of the highest band-pass cut off frequency [Shannon Theorem (Shannon, 1949)] later described in this chapter.

The subsequent step is the Automatic Gain Control (AGC) which cuts off acoustical information from the microphone under a certain sound pressure level (SPL - typically below 25 dB SPL). All signals over a certain sound pressure level (normally 65 dB SPL) will be compressed by the AGC. Furthermore, the AGC in recent cochlear systems reacts on the fluctuations of the acoustic signal in the temporal domain. A dual time constant compression system controls the system gain: a fast detector reacts on sudden intense transients (short attack and release times) and a slow detector to sense long-term environmental conditions (usual attack and release times of about 100 ms and 400 ms) (Stobich et al., 1999).

$$L_p = 20 * \log_{10}(\frac{p_{rms}}{p_{ref}}) dB \quad (3)$$

L_p: Sound pressure level in dB

P_{rms}: Root Mean Square of the sound pressure in Pascal

P_{ref}: Reference sound pressure 20 µPa

After that, the signal is going through a preemphasis-filter (for example: attenuation of frequency components under 1.2 kHz with 6 dB/octave). This filter magnifies consonants compared to vocals, whose spectral energy peak lies under 1.2 kHz.

The signal is now again filtered by a bank of overlapping band-pass filters (between 12 and 22 in number and normally higher than 2nd filter order). Typically, it covers a frequency range of about 200 to 8500 Hz. The bandwidth of the band-pass filter-bank increases to bigger center frequencies as an approximation of the tonotopic principle of the NH auditory system.

To extract the envelope of the band-pass-filter outputs envelope detectors are applied in every channel. This electronic circuit consists of a half wave rectifier and a low pass filter with a typical cut off frequency of about 200 Hz.

The Amplitude of the envelope determines the amplitude of the now following biphasic pulstrains in every channel, which are amplitude modulated by the envelope. To avoid clipping, the stimulation rate of the biphasic pulses is four times higher than the cut off frequency in the envelope detector (Clark, 2003; Zeng *et al.*, 2004). The stimulation rate over the different channels is normally the same, except for the recent FS-4 coding strategy of MED-EL (not discussed in this work).

The following step of signal processing is a static compression: a logarithmic transformation maps the relatively broad dynamic range of the acoustical envelope (120 dB at 1 kHz but already limited by the AGC) into the small dynamic range of electrically evoked hearing, which is in the range of 8 dB to 20 dB [User- and electrode-dependent (Clark, 2003; Zeng *et al.*, 2004)].

The mapping of the acoustical into the electrical dynamic range is realised by determination of the implant users personal electrical threshold and most comfortable level (MCL). These values are electrode dependent. The next step of signal processing is a compression function to map the sound information to the upper part of the electrical dynamic range. The output of the compression stage is transmitted to the implant via a transcutaneous inductive link. The channel output modulate biphasic pulse trains with the parameters pulsewidth, interphasegap, jitter and offset due to the sequential stimulation of multiple electrodes (Zeng *et al.*, 2004).

Biphasic, charge-balanced pulses are used to stimulate the hearing nerve fibres (Clark, 2003). The outputs of the 12 – 22 channels of the implant are organised tonotopically: deep inserted, apical electrodes in direction to the helicotrema lead to a perception of low frequencies and basal electrodes close to the cochleostomy lead to a high frequency perception (Clark, 2003; Zeng *et al.*, 2004).

In the CIS speech coding strategy typical low pass filter cut off frequencies of the envelope detectors are in the range of 200-400 Hz. The stimulation rate should be four or five times that high to avoid distortions in the neuronal activity pattern. Psychophysical experiments showed, that the Pitch Perception (“rate pitch”) is independent of the stimulation-rate, if the rate is 300 pps or higher (Clark, 2003).

The CIS-Speech Coding Strategy (see Figure 3) stimulates in a sequential way over the electrodes, which avoids channel interaction of adjacent electrodes.

The maximal stimulation rate often cannot be realised, because of high electrode-tissue impedances. If the current source gets into saturation (OOC: out of compliance), a higher loudness can only be realised by widening the pulse width t_{PW}.

$$Q=I \cdot t_{PW} \qquad (4)$$

Q: charge

I: current

t_{PW}: Pulse width

In this way more charge can be delivered to the neural membrane. But this results in a decrease of the stimulation rate.

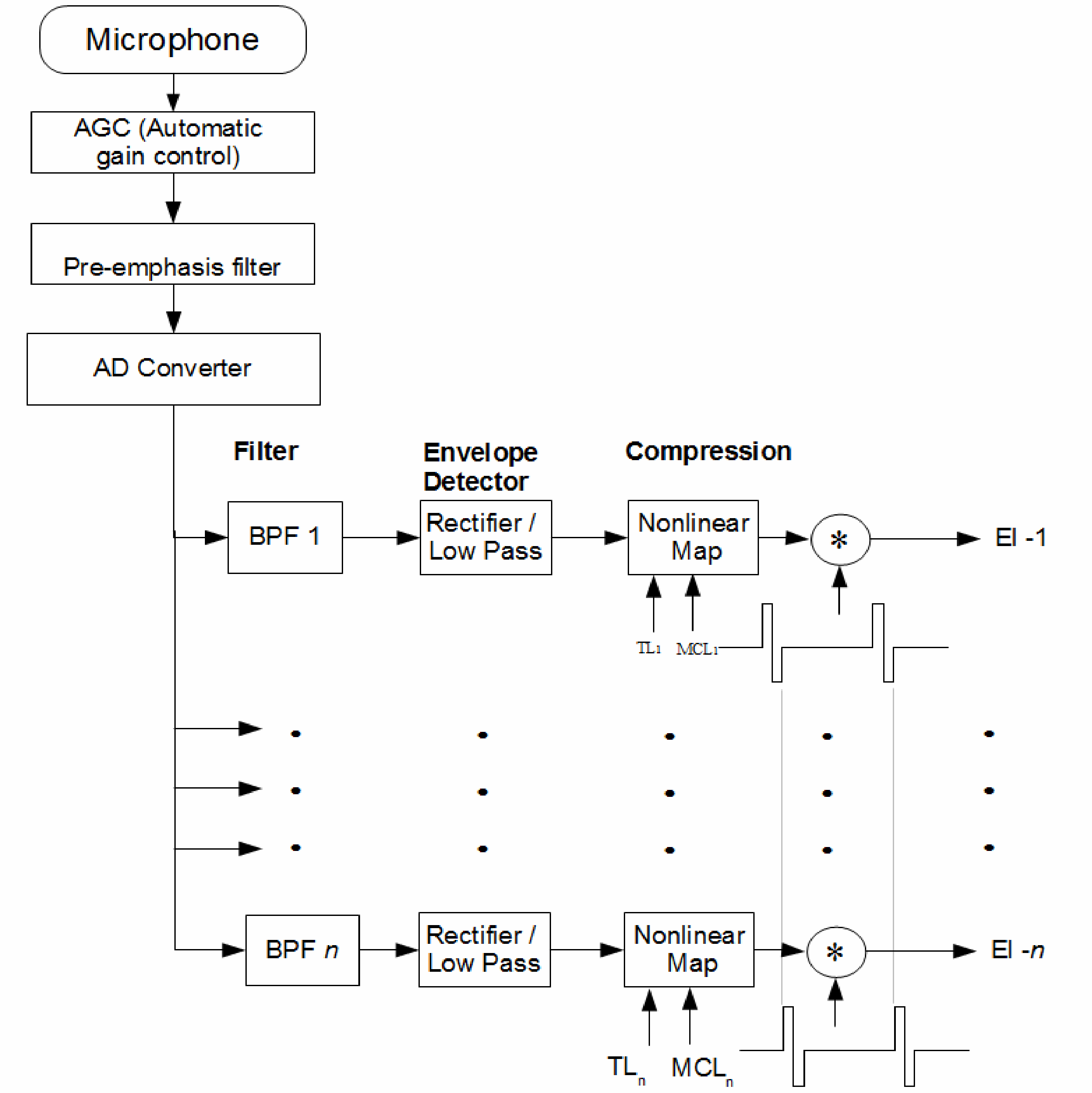

Figure 3: Block Diagram of the CIS Coding Strategy; BPF: Band-pass Filter; TL_n: Threshold at electrode n; MCL_n: Most Comfortable Level at electrode n; EL: Electrode; n: number of channels (Clark, 2003)

The band-pass filter bank imitates in a way the auditory filters of a NH ear, which are aligned in a tonotopic way. The number of channels is manufacturer-dependent (n=12…22).

2.3 The MED-EL HDCIS Speech Coding Strategy

In this study the HDCIS Speech Coding Strategy from MED-EL is used to transform the acoustic stimuli into the stimulation pattern via the OPUS 2 speech processor and compatible implants [C40+, Pulsar, Sonata, Concerto] (see Figure 4).

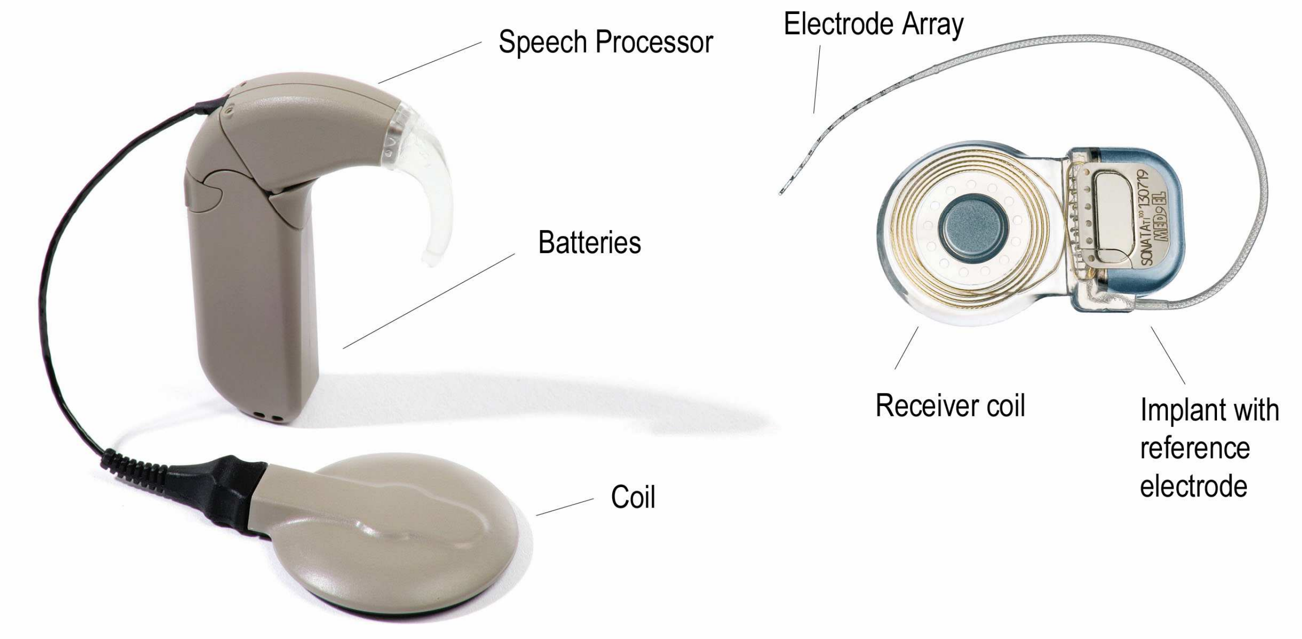

Figure 4: The OPUS 2 Speech Processor with one of the compatible implants, the SonataTi100. By courtesy of the company of MED-EL.

HDCIS is based on the CIS coding strategy. It uses 12 channels and electrodes. The filters are symmetric with the attributes in Table 1 (MED-EL, 2007).

Table 1: Band-pass Filter bank of the MED-EL OPUS 2 Speech Processor. The definite values vary from User to User (MED-EL, 2010)

	Lower Cut-Off Frequency f_{gu} in Hz	Center Frequency f_{gu} in Hz	Higher Cut-Off Frequency f_{gu} in Hz
Channel 1	100	149	198
Channel 2	198	262	325
Channel 3	325	409	491
Channel 4	491	602	710
Channel 5	710	851	999
Channel 6	999	1183	1383
Channel 7	1383	1632	1893
Channel 8	1893	2228	2574
Channel 9	2574	3064	3483
Channel 10	3483	4085	4698
Channel 11	4698	5656	6323
Channel 12	6323	7352	8500

Instead of a envelope detector described above, HDCIS uses the Hilbert Transform (Hilbert, 1912) to determine the envelope:

$$\hat{R}(t)=\frac{1}{\pi}\int_{-\infty}^{+\infty}\frac{R(u)}{t-u}du \qquad (5)$$

$\hat{R}(t)$: Hilbert transformed of R(t)

R(u): real time function

u: Integral Variable

t: Time

With equation 4 another notation can be written consisting of two orthogonal informations: the real time function and its Hilbert transformed (see also Figure 5):

$$R_n(t)=R(t)+j\hat{R}(t) \quad (6)$$

$R_n(t)$: analytical Signal

R(t): real time signal

t: Time

j: imaginary unit $j^2=-1$

The envelope which contains only the amplitude information of R(t) is determined by equation 7.

$$a(t)=\sqrt{(R(t))^2+(\hat{R}(t))^2} \quad (7)$$

a(t): Amplitude Distribution of the envelope

The fine structure (which isn't used in the HDCIS but in the FSP and FS4 speech coding strategy by MED-EL) contains only phase information and is determined by $\cos(\varphi)$,

$$\varphi=\arctan\left(\frac{\hat{R}(t)}{R(t)}\right) \quad (8)$$

φ : phase angle of the analytical signal

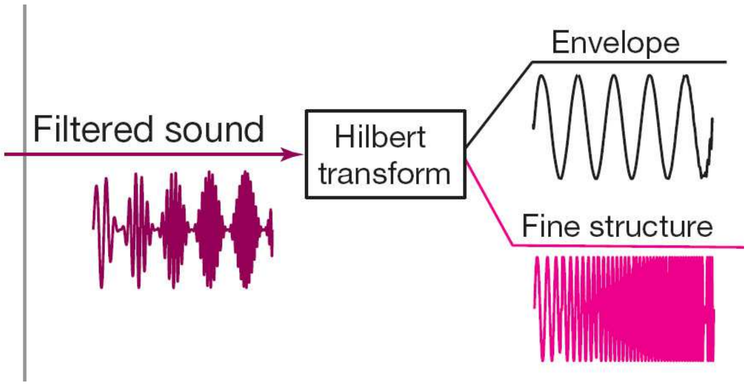

Figure 5: The Hibert transform as a mathematical tool to determine the envelope and the fine structure of a signal (Smith *et al.*, 2002)

In the OPUS 2 Speech Processor, the Hibert Transform is applied on every of the 12 band-pass filter outputs.

Vocoder experiments show, that only a relative small number of envelope channels (> 6) is necessary to reach a good speech reception (Smith *et al.*, 2002).

If in this work the FSP Strategy is mentioned, then, channel 1 and 2 can work with another algorithm than HDCIS. But higher channels addressed in this study (channels 3-8) work with even in the FSP strategy with HDCIS.

3. Different classes of CMR experiments and definition of CMR

There are two major classes of CMR experiments: the band-widening and the flanking-band test.

3.1 Band-widening Paradigm

In band-widening experiments the masker is either an unmodulated band-pass noise or an amplitude-comodulated noise with the same spectral content. Both are spectrally centred at the signal frequency.

In Figure 6 the left panel shows the detection thresholds of NH for unmodulated band-pass noise (open circles). The thresholds increase with increasing bandwidth of the masker. Beyond the critical band (dashed vertical line) the detection thresholds are independent of the masker bandwidth (Verhey *et al.*, 2003; Verhey, 2008). In the comodulated condition (closed circles) the thresholds are independent of the masker bandwidth until the critical band. Beyond the critical band the thresholds decrease. The CMR is defined by the difference of the recognition thresholds in the modulated and the unmodulated masker.

Hall et al. (1984) postulated, that the auditory system of NH is able to compare the masker envelope across frequency channels to produce a release from masking. Beyond that a smaller within channel effect is also measurable.

3.2 Flanking band Paradigm

In flanking band experiments the masker consists of a narrow band noise spectrally centred at the signal (On Frequency Masker – OFM) and of one or more narrow band noises spectrally remote to the signal, called flanking band (FB). In the first condition (open circles, Figure 6 b right) OFM and FB are uncorrelated modulated (the envelopes are different). In the second condition (closed circles, Figure 6 b right) OFM and FB are comodulated (the envelopes are equal). In both masking conditions the masker spectrum is the same. Outside the critical band of the signal, across frequency, there is a difference between the uncorrelated and the comodulated condition in detection threshold: the CMR. And also within channel, there is a CMR as the difference between the detection thresholds in the comodulated and uncorrelated condition.

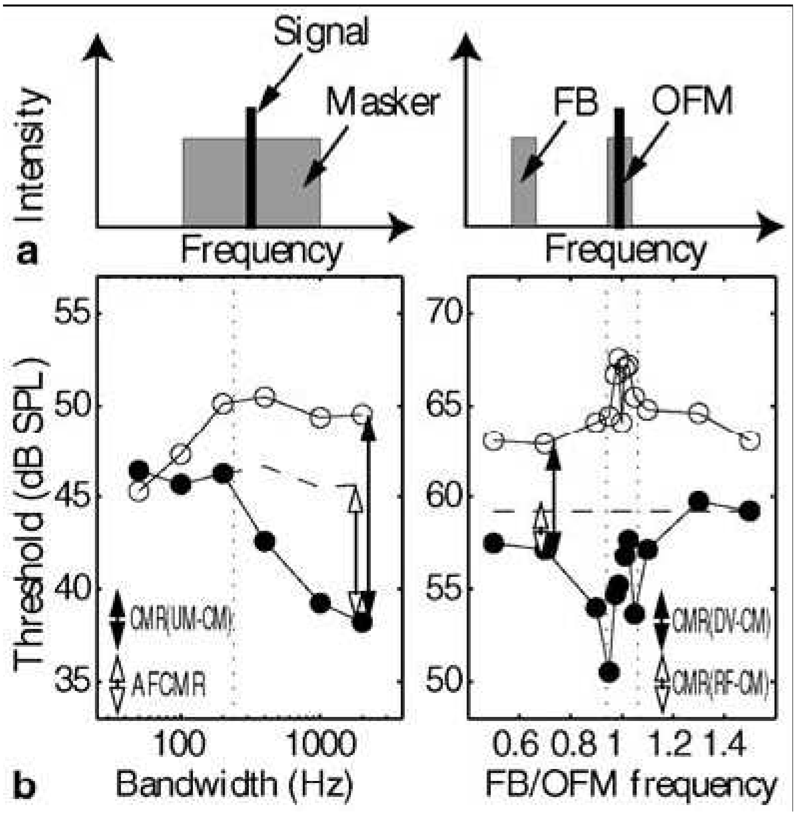

Figure 6: The two different classes of CMR experiments in NH: the left side contains the band-widening experiment (a) with experimental evaluated thresholds (UM=unmodulated, CM=comodulated, AFCMR=across frequency CMR) (b). On the right side the experimental principle of a flanking band test is shown (a). In (b) the threshold, when moving the flanking band from left to right, is illustrated (DV=uncorrelated, RF=reference condition only to OFM) (Verhey *et al.*, 2003).

In a flanking band test, the CMR can amount to 10 dB or more depending on the properties of the signal and the masker. The CMR in a flanking band test depends on various parameters e.g. the number of flanking bands, the masker type (e.g. sinusodial amplitude modulated tone, band-pass noise), the OFM bandwidth, the modulation depth and the spectrum level (Verhey *et al.*, 2003).

In this work only the flanking band paradigm was used to determine the comodulation masking release. The reason is the easier implementation and orientation of the OFM and FBs at the band-pass filter bank of the speech processor OPUS 2 of MED-EL. Anyhow, also the band-widening paradigm should be accomplishable on CI users.

3.3 Definition of CMR

In this work the flanking band paradigm was used to experimentally and acoustically evaluate the CMR in CI users and NH. The definition of CMR was taken out of the publication of Epp and Verhey (2009): Signal detection improves if the masker has coherent level fluctuations across frequency, i.e. is comodulated. A common reference to quantify CMR is a masking condition with the same masker spectrum as in the comodulated condition but with incoherent level fluctuations in different frequency regions (uncorrelated condition). The CMR is the difference between the detection thresholds in the uncorrelated and the comodulated condition.

4. Problem description and hypotheses

Generally, the main goal of this study was to compare the amount of comodulation masking release (CMR) in NH and CI users with their speech processor with their normal every day hearing program under the variation of several stimulus parameters. The CI users were used to their program for a longer period (usually more than 6 months). There have been no changes at this hearing program for this study.

On the other hand, the test setup was orientated at the program of the CI user in a way that all center frequencies of the narrow band noises used in the study were aligned at individual settings of the band-pass filter bank of the OPUS 2 of each CI user (see chapter 5.3.1 and 5.3.2).

4.1 Test 1: Dependence of CMR to bandwidth of the masking noise bands in a flanking band test

Figure 7 right describes how the CMR behaves when the OFM bandwidth is varied. The CMR has its maximum in NH for OFM bandwidths around 20-30 Hz.

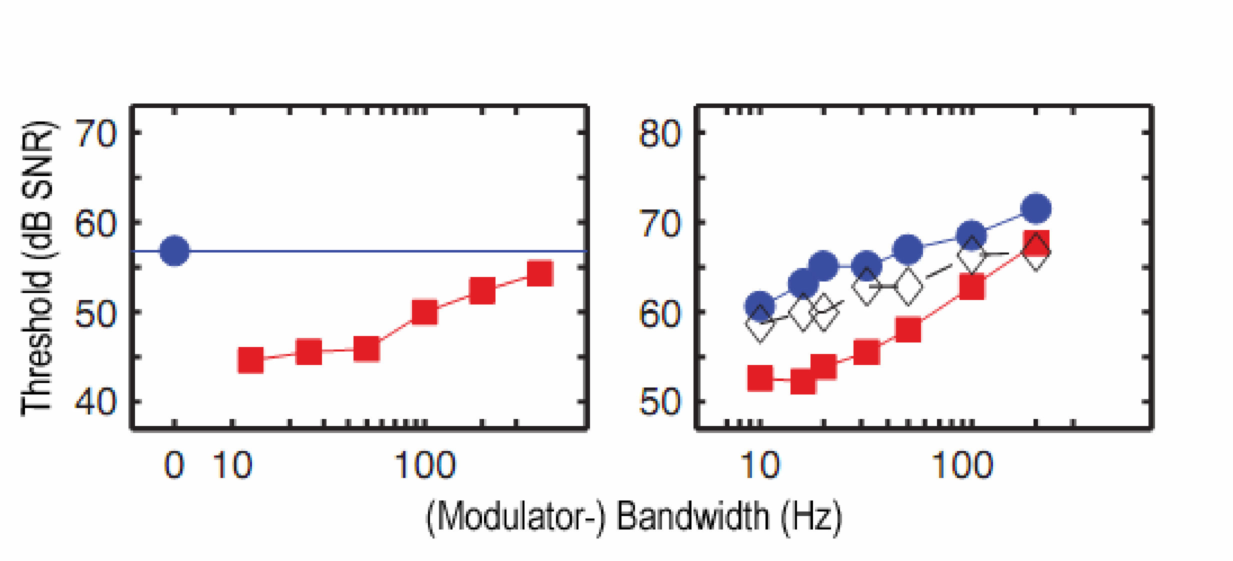

Figure 7: Threshold relative to OFM Level in a band-widening experiment (left) and a flanking band experiment (right). Blue circles represent threshold in the unmodulated (right) or uncorrelated (left) condition. Red squares represent threshold in the comodulated condition. Open diamonds represent the OFM only condition. The blue circles (right) represent the thresholds in a uncorrelated fice noise bands condition. In a band-widening experiment the CMR remains constant for modulation frequencies up to 50-60 Hz. For higher modulation frequencies the CMR gets smaller. In the flanking band experiment (right) the CMR is biggest for OFM bandwidth's around 20 Hz (difference between closed and opened symbols in the right picture) and gets smaller for higher modulation frequencies (Verhey, 2008).

The question in this test condition was if there is a dependence of the CMR to the bandwidth of OFM and FB's in CI users. For NH the dependence is shown in Figure 7. Therefore, the OFM- and FB-Bandwidths have been varied between 24 Hz and 48 Hz and a comparison between CI users and NH was accomplished. The center frequencies of OFM, FB, and the sinusoidal signal were orientated at the CI processors filter bank (channel 3,4,5,6,7).

4.2 Test 2: Dependence of CMR to spectral alignment of the masking noise bands in a flanking band test – Frequency shift condition

The bandwidth of the auditory filters in NH, the so called critical bands, are frequency-areas that are evaluated together (Zwicker, 1961). The bandwidths of the critical bands increase with increasing center frequency.

The power spectrum model (Fletcher, 1940) assumes that a NH listener trying to detect a sinusoidal signal in interfering noise uses the output of a single auditory filter whose center frequency is close to the signal frequency and has the highest signal to noise ratio. In this way, the NH auditory system is able to adapt to a change of center frequencies of narrow band maskers and sinusoidal signals presented in this work.

The question in this task was, if a frequency shift of OFM and FB's from the CI channel center frequencies between the channels has a disruptive effect on CMR in CI User, while in NH no or little alteration is expected (frequency shift condition). In the implant signal processing this frequency shift leads to a spectral spread which means, that adjacent channels carry the same information or rather multiple information of at least the two adjacent channels (see filter functions of the OPUS 2 in Figure 23).

4.3 Test 3: Correlation CMR with ability to discriminate electrode pitch

Hall et al. (1988) explored the CMR in listeners with a hearing loss of cochlear origin. They found that the CMR was reduced. These reductions in CMR are likely to be due in part to consequences of peripheral dysfunction such as reduced frequency selectivity and reduced temporal resolution.

The temporal resolution in CI listeners in rhythm discrimination tests is comparable to NH (Drennan and Rubinstein, 2008). This indicates a good transmission of envelope information of the acoustic signal via the signal processing of current cochlear implants. By contrast, the frequency selectivity of CI users is strongly reduced (Oxenham, 2008). Frequency selectivity in CI users suggests to be a product of place and timing cues. Place cues mean that electrodes close to the apex of the cochlea produce lower a pitch percept than electrodes closer to the base of the cochlea, depending of the spread of excitation in the cochlea and the number of surviving spiral ganglion cells in this area (Nelson *et al.*, 1995; Cohen *et al.*, 2003). Timing cues mean that the pitch percept is dependent on the pulse rate on each electrode (Zeng *et al.*, 2004). At stimulation rates beyond 200 – 300 pulses per second (pps), most CI users are no longer able to discriminate any difference in pitch – above this frequency the pitch perception is independent of the pulse rate (until approx. 3000 pps). In all current speech coding strategies the pulse rate per electrode lies in between 300-3000 pps.

The idea of this task was to test if there is any correlation between the ability of CI users to discriminate electrode pitch on electrodes 3-7 of the MED-EL implants Pulsar or Sonata by the normal stimulation rate (> 300 Hz) and the CMR height.

5. Method

5.1 Signals

Signal generation for the acoustic hearing test was realised with MATLAB (version R2009a) with a sampling rate of 44100 Hz (standard for CD audio). The modulated narrow band noises are realised with the multiplied noise method: white noise was filtered by a low pass of 12 Hz or 24 Hz and then multiplied in the time domain with a sinusoidal signal at the desired frequency. The result is a narrow band noise with a bandwidth of 24 Hz or 48 Hz, with a spectrum which is mirrored at the center frequency.

The mean modulation frequency of the noise band generated in this way corresponds to the upper cut-off frequency of the low pass. The low pass was realised by a FFT-rectangular shaped Band-pass filter (FFT: Fast Fourier Transformation). The main task of this filter is to eliminate all Frequency Bins outside the desired cut-off frequencies f1 and f2 in the Frequency Domain and mirrored at the Nyquist-Frequency (1/2* sampling frequency) all the Frequency Bins outside the frequencies f3 and f4. The real part of the inverse FFT is the desired low pass filtered noise.

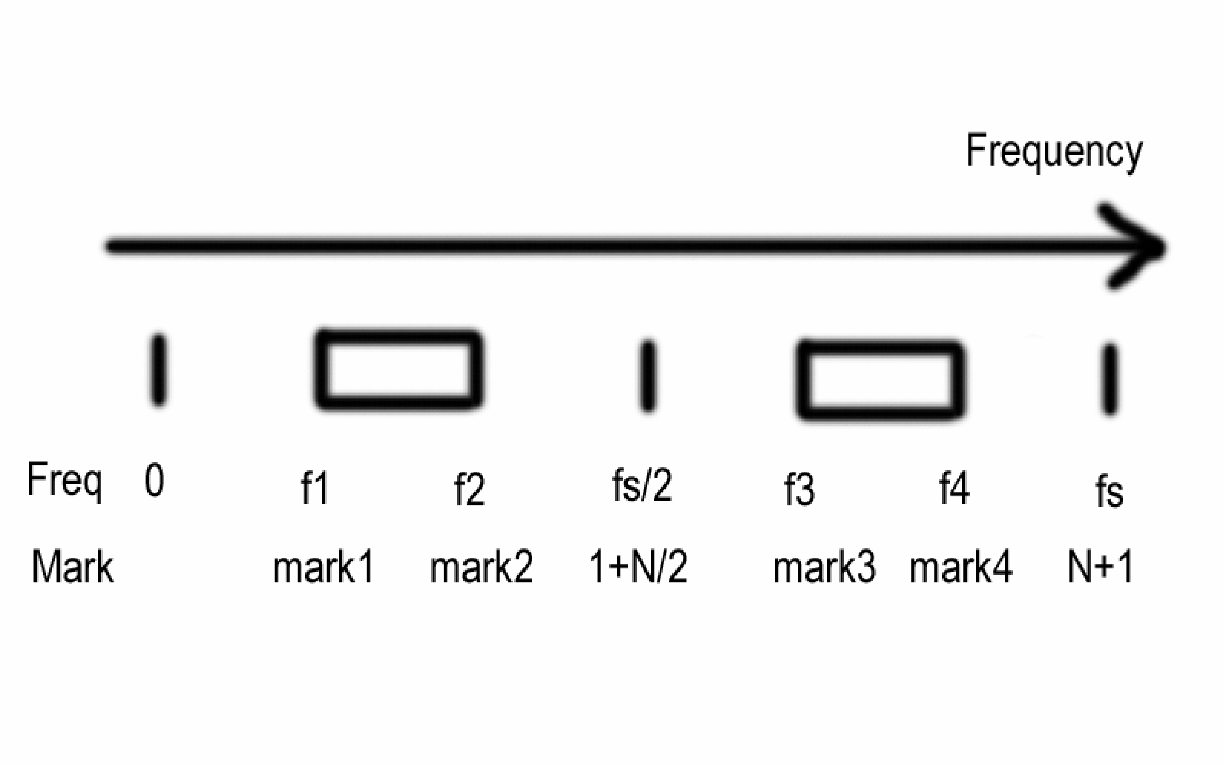

Figure 8: Principle of Filter functionality. Frequency bins outside f1-f2 and f3-f4 are set to 0. The real part of the inverse Fourier Transform is the desired time function. To refer the frequency band to the sampling frequency fs, it is necessary to calculate spectral marks: mark = 1+N*f/fs

The filter has rectangular shape in frequency domain, i.e., it has very steep slopes of approx. 300 dB damping within the bandwidth of 1 FFT-bin (Hansen, 2008).

The resulting spectra of a Band-pass filtered narrow band noise at 700 Hz with a bandwidth of 24 Hz and 48 Hz is illustrated below in figure 9:

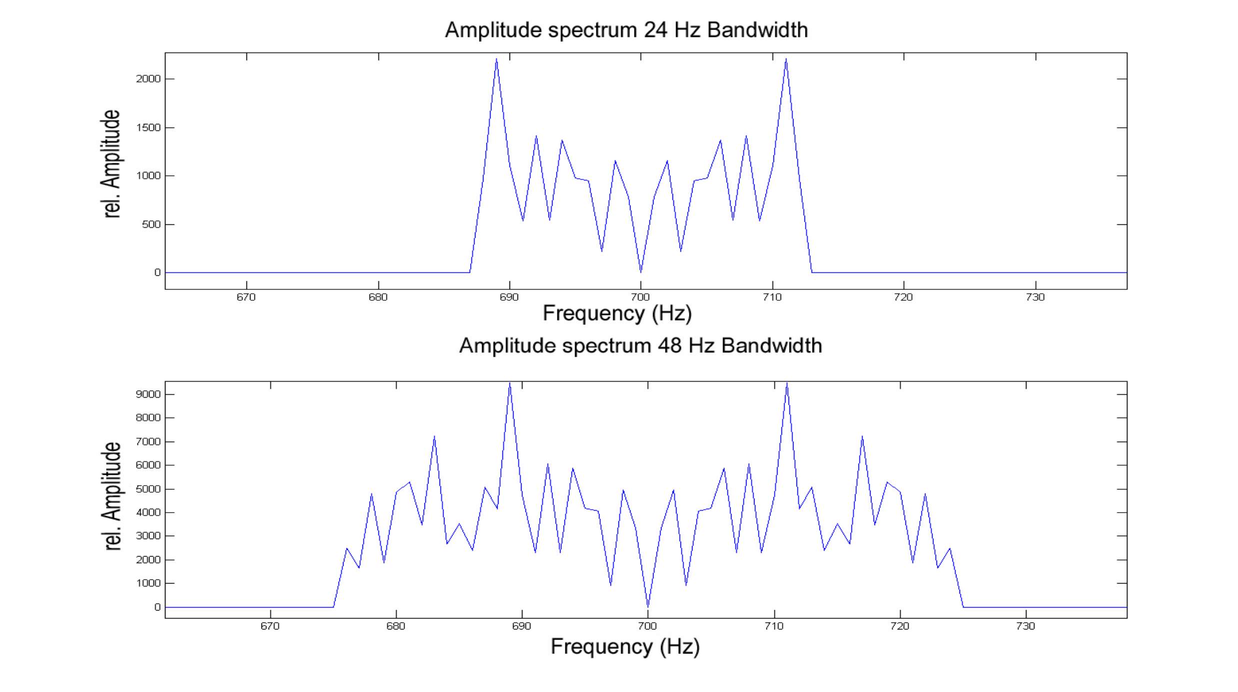

Figure 9: Spectra of a narrow band noise generated with the multiplied noise method. Up: bandwidth 24 Hz, Bottom: bandwidth 48 Hz.

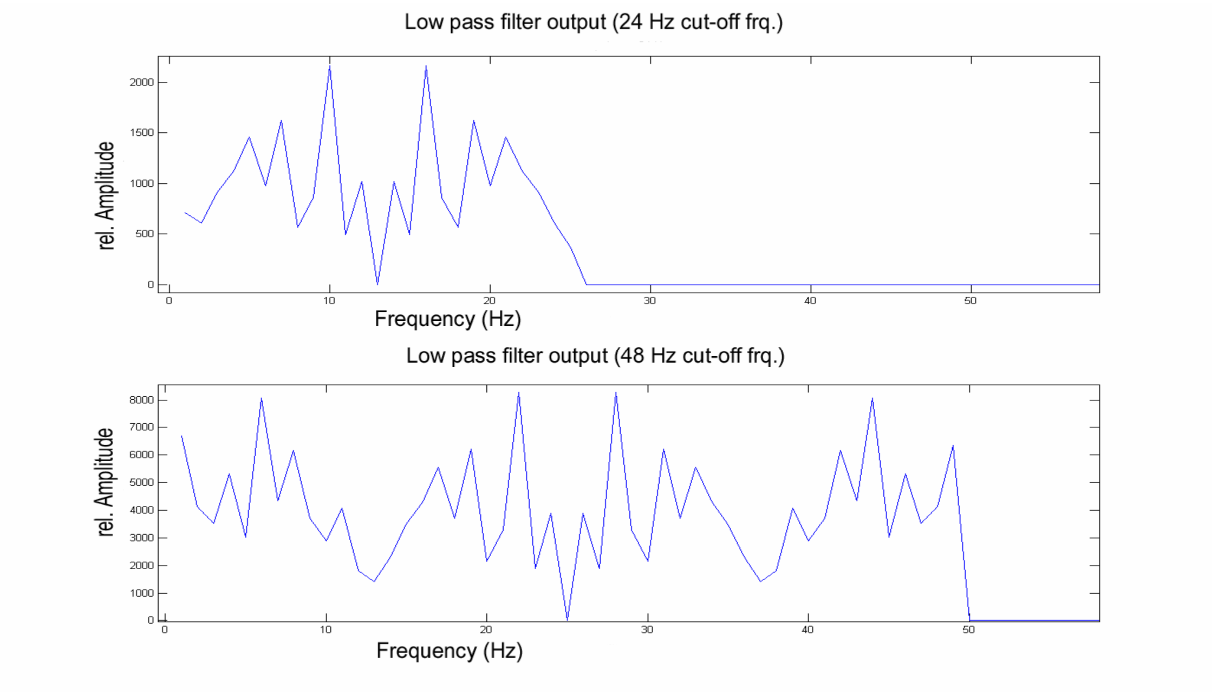

Figure 10: Spectra of the low pass noise with the different bandwidths (top: 24 Hz, bottom: 48 Hz).

To create different narrow bands noises at different center frequencies with the same envelope (see Figure 11), it is possible to multiply (multiplied noise) the same low pass noise (see Figure 10) with different sinus frequencies in the time domain (Epp and Verhey, 2009). The resulting narrow noise bands (resp. masking bands or masker) have the same spectrum in the comodulated and the incoherent modulated (uncorrelated) condition (see Figure 12). Thus, the masker energy is the same.

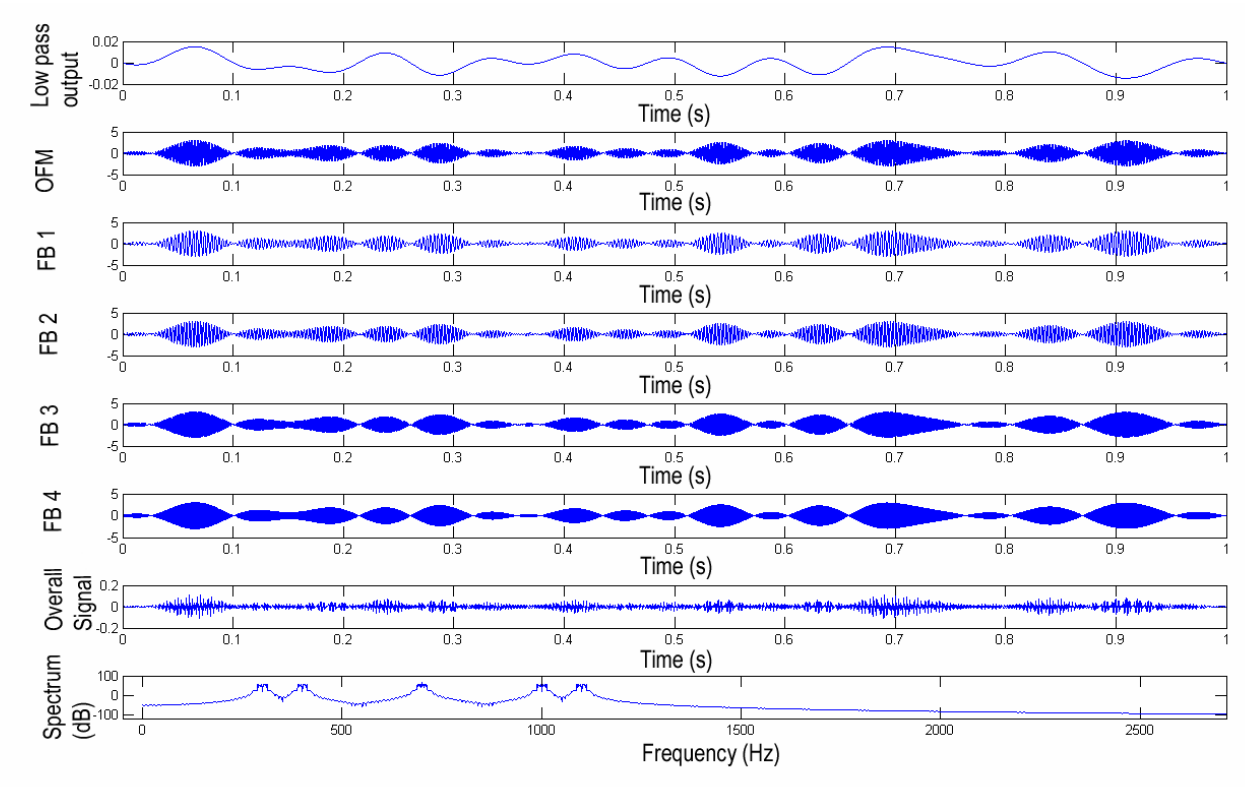

Figure 11: Comodulated Noise Bands: The low pass output is shown at the topmost row. Beneath there are the 5 narrow bands noises, modulated with the low pass envelope. The envelopes of the 5 masking noise bands are coherently modulated (comodulated). In the second lowest row there is the added signal and in the lowest row the spectrum of all noise bands with the center frequencies of 300, 400, 700,1000,1100 Hz.

Epp and Verhey (2009) have used similar center frequencies of the narrow band noises (300,400,700,1000,1100 Hz) in NH to avoid within-channel cues in CMR. In case of the CI users the center frequencies of the narrow band noises were determined by the band pass filter bank of the OPUS 2 Speech Processor (channels 3,4,5,6,7).

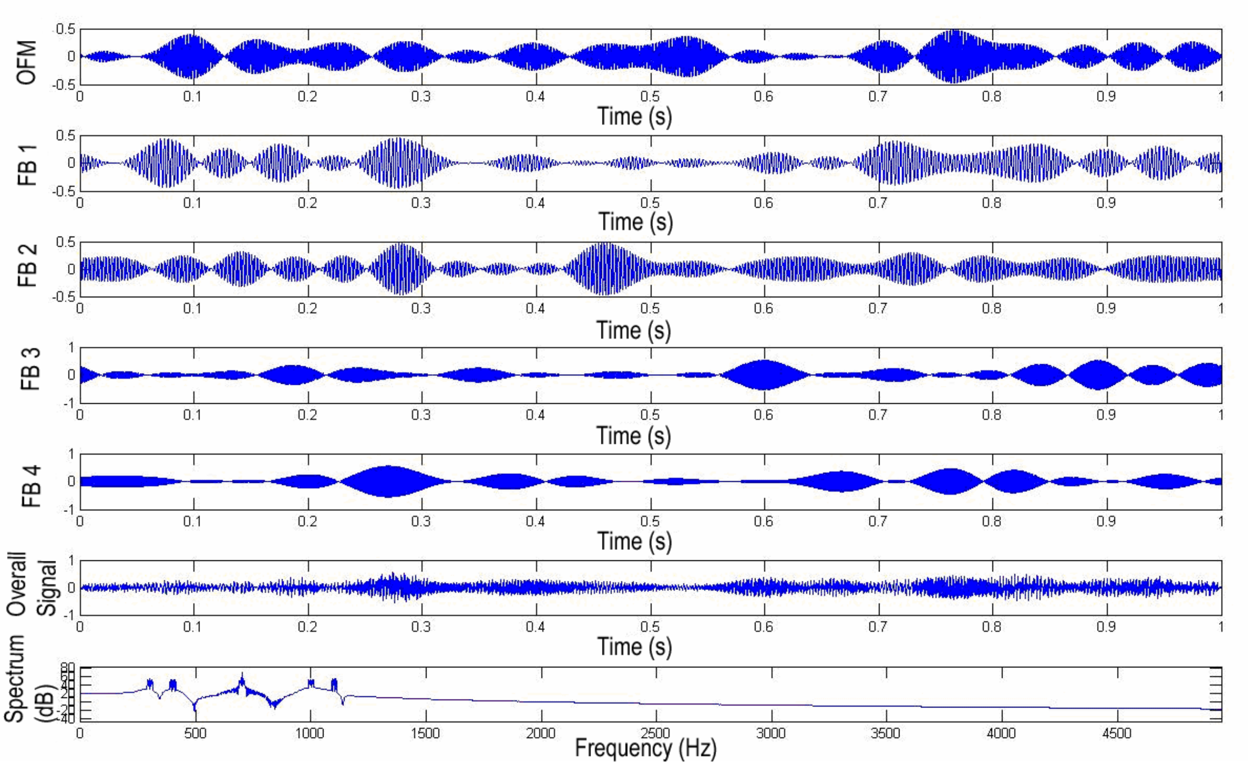

Figure 12: Uncorrelated modulated noise bands: For generation of the incoherently modulated noise bands in the top 5 rows, the low pass filter described above was multiple used for each channel. Resulting the envelopes across channels aren't identical. The level fluctuations in different frequency regions are incoherent (uncorrelated condition). In the second lowest row there is the added signal and in the lowest row the spectrum of the added signal with all noise bands with the center frequencies of 300, 400, 700,1000,1100 Hz as used in the study of Epp and Verhey (2009)

The modulation depth of the generated noise bands is 1. The envelope statistic is shown in Figure 13.

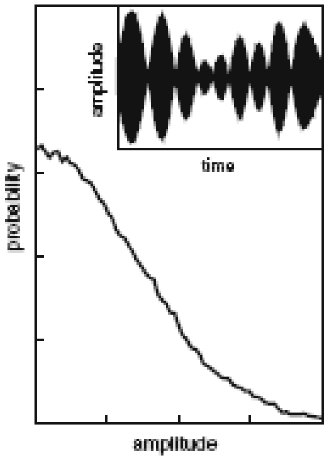

Figure 13: Envelope amplitude statistics of the noise masker generated with the modulated noise method. The distribution corresponds to the positive half of a Gaussian distribution (Epp and Verhey, 2009).

The signal that has to be identified by the test subjects is a sinusoidal sound of a discrete frequency at the center frequency of the central noise band, the OFM. In all following experiments the amplitude of the sinusoidal signal was varied in certain steps and the amplitude of the masking noise bands was held constant as described in chapter 5.3. The CMR is the difference between the detection threshold in the uncorrelated masking bands and the comodulated masking bands.

$$CMR = Detection\_Threshold_{uncorrelated}(dB\_SNR) - Detection\_Threshold_{comodulated}(dB\_SNR) \quad (9)$$

The signals were scaled by the Root Mean Square (RMS) Value: the noise bands are added and scaled on a RMS of 1:

$$Signal_{RMS=1} = \frac{Signal}{\sqrt{\sum_{i=1}^{n} \frac{Signal(i)^2}{N}}} \quad (10)$$

i: Index

n: Samples

N: Number of Samples

After that, a scaling down to the desired Sound Pressure Level (dB_SPL) was realised by

$$Signal_{Scaled} = Signal_{RMS=1} * 10^{\frac{dB\_SPL - 100}{20}} \quad (11)$$

dB_SPL: desired Sound Pressure Level in dB

The sound pressure level of the sinusoidal signal was scaled in the same way, but separately and presented at an independent value with a specific signal to noise ratio (SNR).

$$\Delta L_{SNR} = 20 * \log_{10}(\frac{P_{Signal}}{P_{Noise}}) = 20 * \log_{10}(P_{Signal}) - 20 * \log_{10}(P_{Noise}) = L_{Signal}(dB) - L_{Noise}(dB) \qquad (12)$$

The sound pressure level was calibrated by a B&K Measuring Amplifier Type 2610 in case of the Headphones Sennheiser HD 280 pro with an Artificial Ear B&K Type 4152 with a calibration Sinus Tone of 1 kHz. The sound pressure level of the Loudspeaker Edirol MA-10A for the free field measurements had been calibrated using the B&K Type 1613 in a distance of 1 m (calibration Sinus Tone of 1 kHz).

The signal on- and offset (raised cosine function) was applied by to avoid clicking noises.

$$w(n) = 0.5 * (1 - \cos(\frac{\pi * t}{T})) \qquad (13)$$

W(t): raised cosine function

t: time

T: 0.8 s

5.2 Psychoacoustics

5.2.1 AFC Paradigm

A three Alternative Forced Choice (AFC) paradigm was used to determine the threshold of the sinus tone in the masking noise bands. Therefore three masking noise complexes were played after each other with a pause of 0.5 sec in between. Only one of this three contained the sinus tone. After playing the tones the test subject was forced to choose in which of the three noise complexes the tone was (see Figure 14). The test subject was instructed to guess the answer if he/she did not hear the tone. To be familiar with the test procedure, the test subject heard three examples with given answers at the beginning of each test. After each input of the test subject there was a confirmation via a text message at the computer screen, whether the answer was right or wrong. The test subject was informed at anytime about the progress of the whole test procedure via text messages on the computer screen. At half-time the test subject was prompted to do a rest period of 5 – 10 minutes.

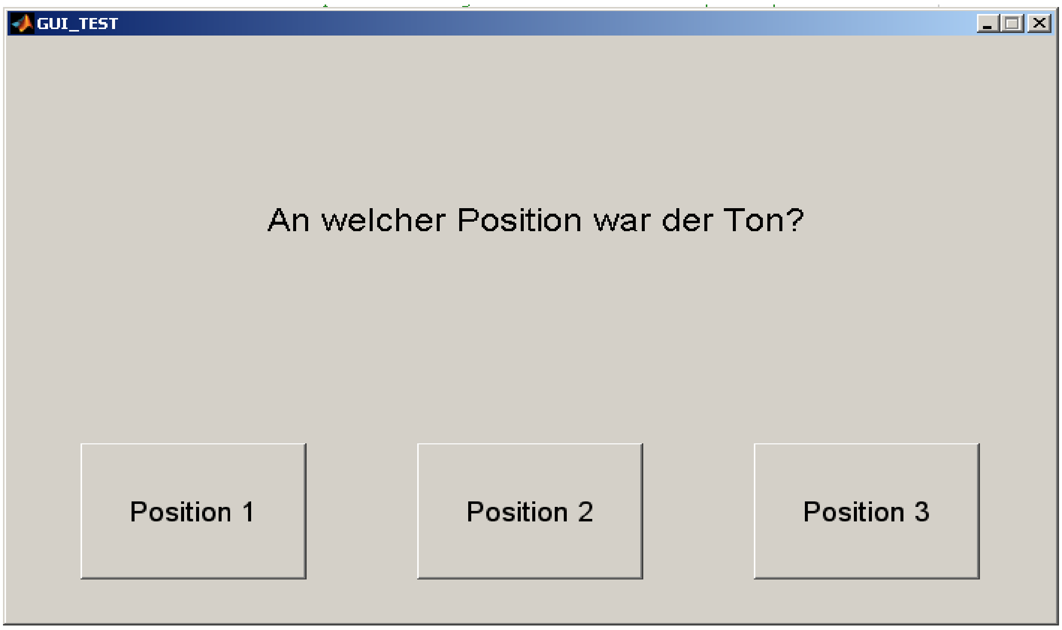

Figure 14: The test subjects had to choice at which position the sinus tone in the three stimuli was (Matlab Graphical User Interface –GUI)

5.2.2 Up-Down Procedure

A *two-down one-up procedure* as described by Levitt (1971) was used to determine the threshold of the sinus tone in the noise complex, according to the 70.7 % confidence level of the psychometric function (see Table 2).

Table 2: Condition and probability for the 2-down 1-up strategy of Levitt (1971)

X: Stimulus level

P(X): Probability for a correct answer

Condition for „Up“	Condition for „Down“	Probability P(Down)	Confidence Level
+- or -	++	$[P(X)]^2$	P(X)=0,707

5.2.3 Adaptive threshold convergence

The test stopped after 12 reversal points starting at +10 dB signal to noise ratio (SNR). After 3 initial +10 dB stimuli, the step-width decreased after the 5. reversal point from 8 dB to 4 dB, after the 6^{th} reversal point to 2 dB and after the 8^{th} reversal point to 1 dB (see Figure 15).

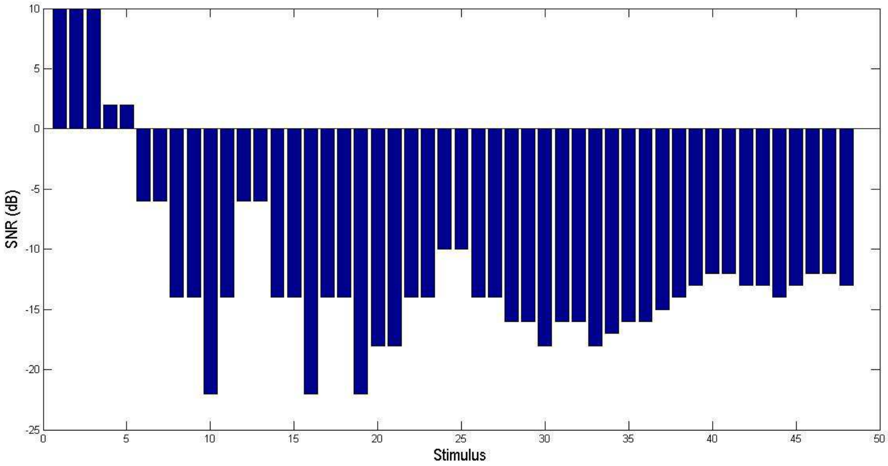

Figure 15: Two-down 1-up method of test subject CI07M1987 in the comodulated condition, test sequence 1, bandwidth 24 Hz, centred narrow band noises with center frequencies according to the center frequencies of the cochlear implant’s filter bank.

The threshold was calculated as the arithmetic mean of the last 4 reversal points. Each threshold determination was repeated three times (see chapter 5.3.2).

5.3 Realisation of test procedures

5.3.1 Test 1: Dependence of CMR to bandwidth of the masking noise bands in a flanking band test

The signal generation of the masking noise bands (modulated noise) implicates an increasing bandwidth by increasing the modulation rate. The medium modulation rate corresponds to the cut off frequency of the low pass filter, thus half of the bandwidth of the noise band (Verhey, 2008). This is a consequence, of the amplitude-spectrum of the low pass filtered noise with the filter described in chapter 5.1 Signals is mirrored at the y-axis (see Figure 9). This is a characteristic of the Fast Fourier Transform (FFT) used for signal filtering.

Two different test conditions were accomplished:

a) Signal delivery via headphones (NH) and audio cable (CI Users)

In this test condition, the acoustic stimuli were presented unilaterally to one ear (NH) via headphones or to one speech processor (CI-Users) via the MED-EL audio cable (see chapter 5.5).

The sound pressure level was not fixed: to every subject, test stimuli (OFM with 24 Hz bandwidth at 700 Hz center frequency) were presented with different sound pressure levels, so that a loudness growth function could be established as can be seen in Figure 16.

This procedure was orientated towards the german *Oldenburger Hörfeld* (http://www.hearcom.eu/prof/DiagnosingHearingLoss/AuditoryProfile/OMAModuleAcalos/05-kls-Kategoriale-Lautheitsskalierung-ger.pdf, 2010). In brief the *Oldenburger Hörfeld* creates loundness growth functions depending on the subjective perceived loudness of the test subject in different frequency bands through free field presentation of (unmodulated) narrow band noises at different sound pressure levels and different center frequencies. The task for the test subject is to enter his/her perceived subjective loudness after each presented stimulus at an artificial scale from 0 (not perceived) to 50 (uncomfortable loud).

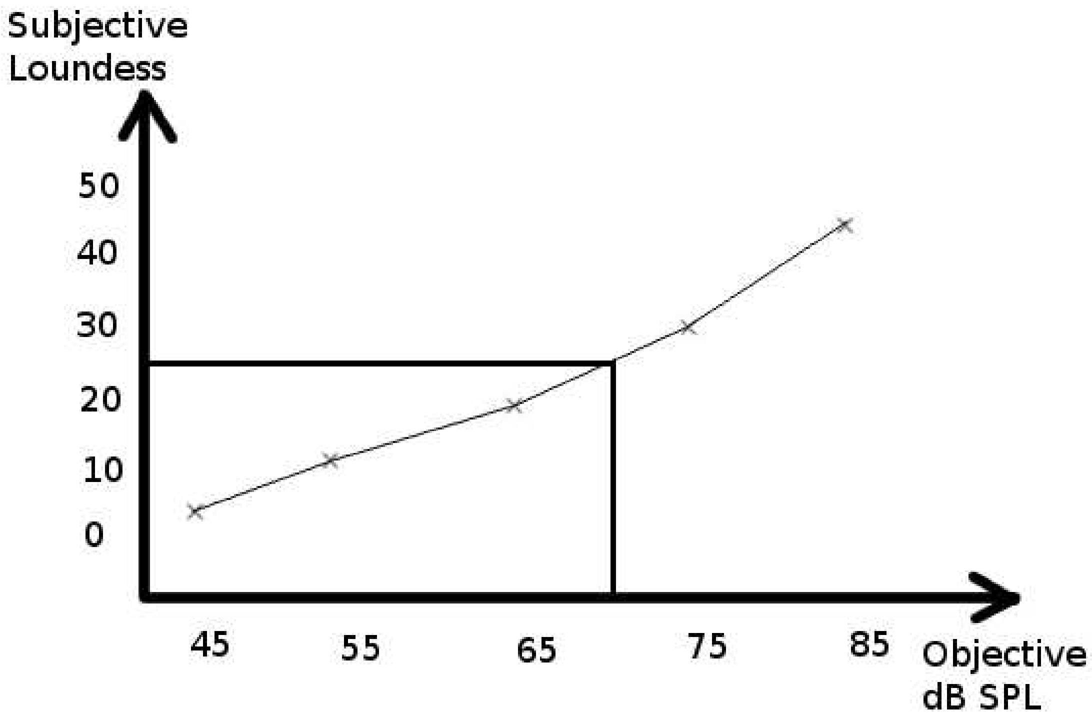

Figure 16: Loudness Growth Function of Subject CI19W1974. This evaluation of the best loudness was accomplished with every test subject in test condition: Dependence of CMR to bandwidth of the masking noise bands. The used sound pressure level for the whole following test was determined by the equivalent SPL to the subjective value of 25 which corresponds to comfortable loudness (http://www.hearcom.eu/prof/DiagnosingHearingLoss/AuditoryProfile/OMAModuleAcalos/05-kls-Kategoriale-Lautheitsskalierung-ger.pdf, 2010).

The center frequencies of OFM, FB and the sinusoidal signal was presented at center frequency of channel 3,4,5,6,7 of the filter bank of each CI user. The parameters of the filter bank were elected with the Maestro Fitting Software of MED-EL (Version 3.1). The test sequences are shown in Table 3.

Table 3: Test Sequences in the bandwidth of the masking noise bands-test. Every detection threshold was determined 3 times. The arithmetic medium over the three detection threshold sequences was used as the final detection threshold at this bandwidth.

Test Sequence	Threshold Test	Bandwidth of OFM and FB's (Hz)
1	Comodulated	24 (1)
2	Uncorrelated	48 (1)
3	Comodulated	48 (1)
4	Uncorrelated	24 (1)
5	Uncorrelated	48 (2)
6	Comodulated	48 (2)
7	Comodulated	24 (2)
8	Uncorrelated	24 (2)
9	Comodulated	48 (3)
10	Uncorrelated	24 (3)
11	Comodulated	24 (3)
12	Uncorrelated	48 (3)

Figure 17: Exemplary demonstration of the measuring station for the audio cable condition. The tests took place in the normal fitting room in the *Klinikum der Universität München*.

For the assurance of a galvanic isolation of the speech processor connected via audio cable to the Computer, all CI users were tested with a computer notebook with disconnected power supply in rechargeable battery mode (see Figure 17).

b) Signal delivery in free field

In this test condition the acoustic stimuli were presented unilaterally to NH and CI-users in free field via an Edirol MA-10A Speaker in S0N0 condition, distance to listener one meter. sound source in eye height (see Figure 18). The sound pressure level of the acoustic stimuli was fix at 65 dB SPL in one meter distance from the sound source.

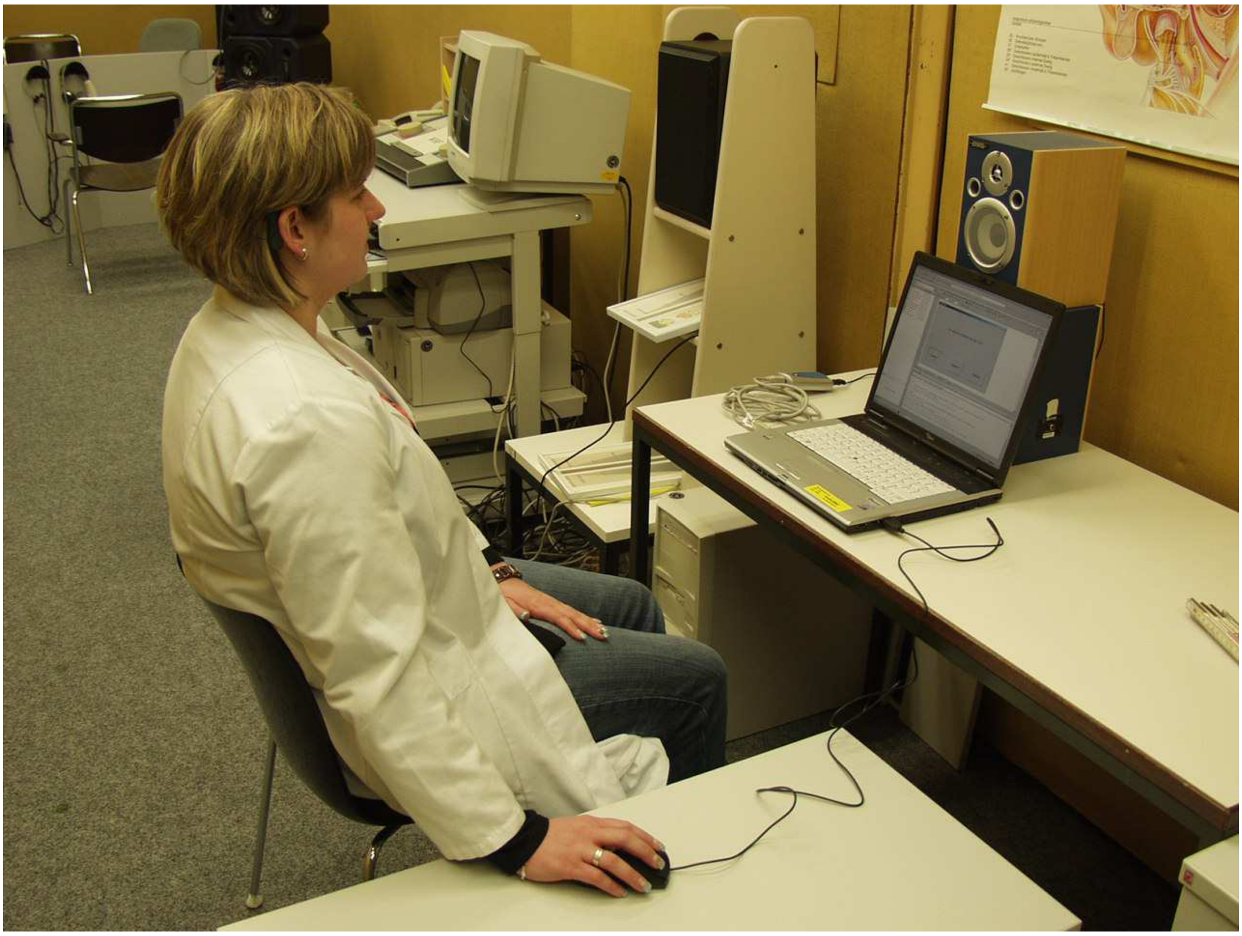

Figure 18: Exemplary demonstration of the measuring station for the frequency shift condition. The acoustic stimuli were presented in eye hight in S0N0 condition. The distance between ear and loudspeaker was 1m. The tests took place in a sound isolated audiometric cabin in the *Klinikum der Universität München*.

5.3.2 Test 2: Dependence of CMR to spectral alignment of the masking noise bands in a flanking band test – frequency shift condition

To evaluate how the CMR depends on how the center frequencies of the masker noise bands and the sinus tone are arranged (see chapter 4.2), three different test conditions were accomplished:

a) OFM condition

To evaluate if there is an across frequency processing in CI users (a comparison at higher neuronal stage of multiple CI channels – in analogy to critical bands in NH - with different center frequencies in one ear), the first test condition mainly determines within channel cues: the masker consists of only one modulated narrow band noise with a bandwidth of 24 Hz presented at the center frequency of a CI Channel. The sinus tone is situated at the center frequency of the masker (resp. CI Channel). This masker is called On Frequency Masker (OFM). In this condition the threshold of the sinus tone in the modulated OFM was measured (see Figure 19).

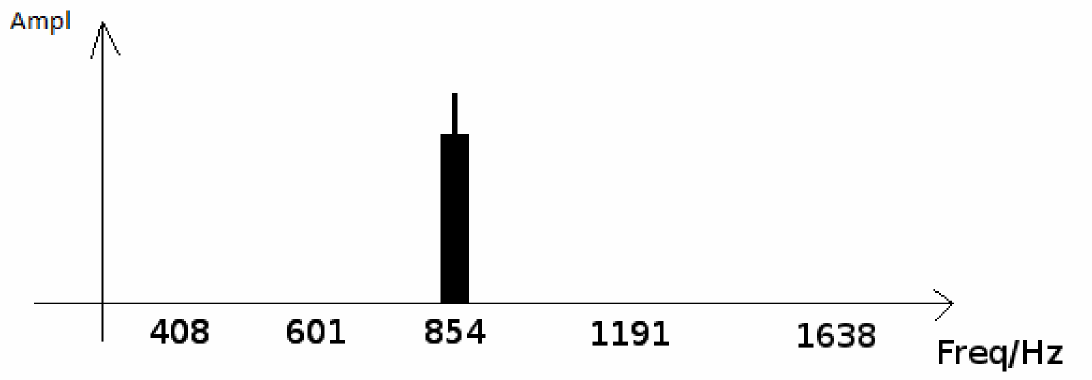

Figure 19: In the OFM condition only one noise band and a sinus tone at his center frequency is presented at the center frequency of channel 5 (CI users with the MED-EL OPUS 2 Speech Processor and FSP or HDCIS strategy) or at 854 Hz (NH)

Because of the overlap of adjacent bands in the OPUS 2 band-pass filter bank the OFM is not strictly just a within channel stimulus (see Figure 23). But with the request to test the CI user with his/her normal every day listening program, this circumstance can not be avoided.

b) OFM+FB condition

In this test condition four Flanking Bands (FB) were added to the OFM. To measure a CMR the OFM and FB are presented comodulated or uncorrelated. The difference of the thresholds of the sinus tone in these noise complexes is the CMR. The OFM and the FB are presented at the center frequencies of the CI channels 3, 4, 5, 6, 7 (see Table 1). In the case of NH subjects the center frequencies were the same over all NH at 854 Hz (OFM), 408 Hz (FB1), 601 Hz (FB2), 1191 Hz (FB3) and 1638 Hz (FB4) (see Figure 20).

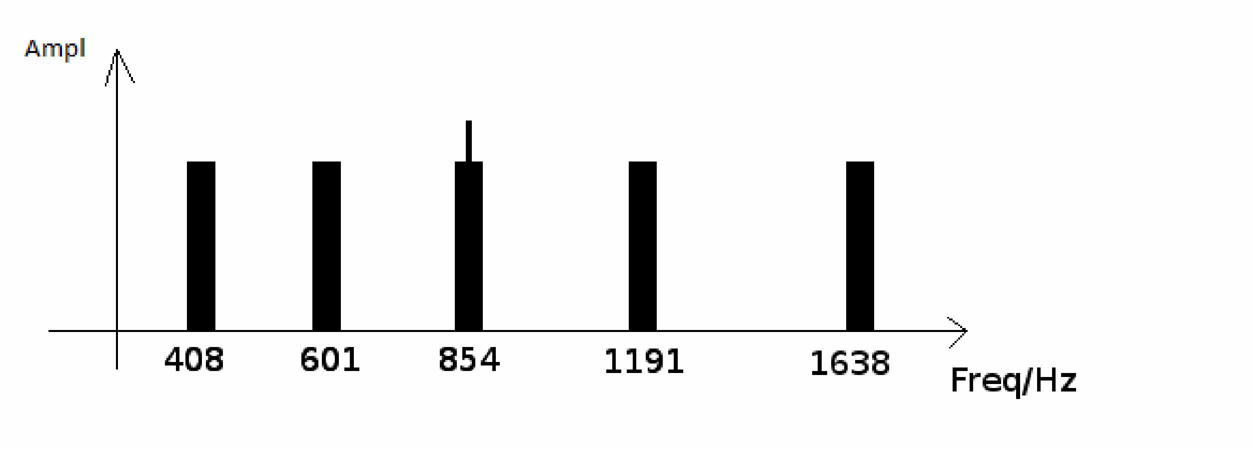

Figure 20: Flanking Bands are added to the OFM. The signal is further on at the center frequency of the OFM. The FB's are presented either comodulated or uncorrelated at the center frequencies of the channels 3,4,6,7 (CI users with the MED-EL OPUS 2 Speech Processor and FSP or HDCIS strategy) or at the fix center frequencies 408, 601,1191 and 1638 Hz (NH).

To evaluate if there is a high part of across frequency processing with this alignment of noise bands in NH, the distance of the OFM center frequency to the flanking bands is considered in Figure 21.

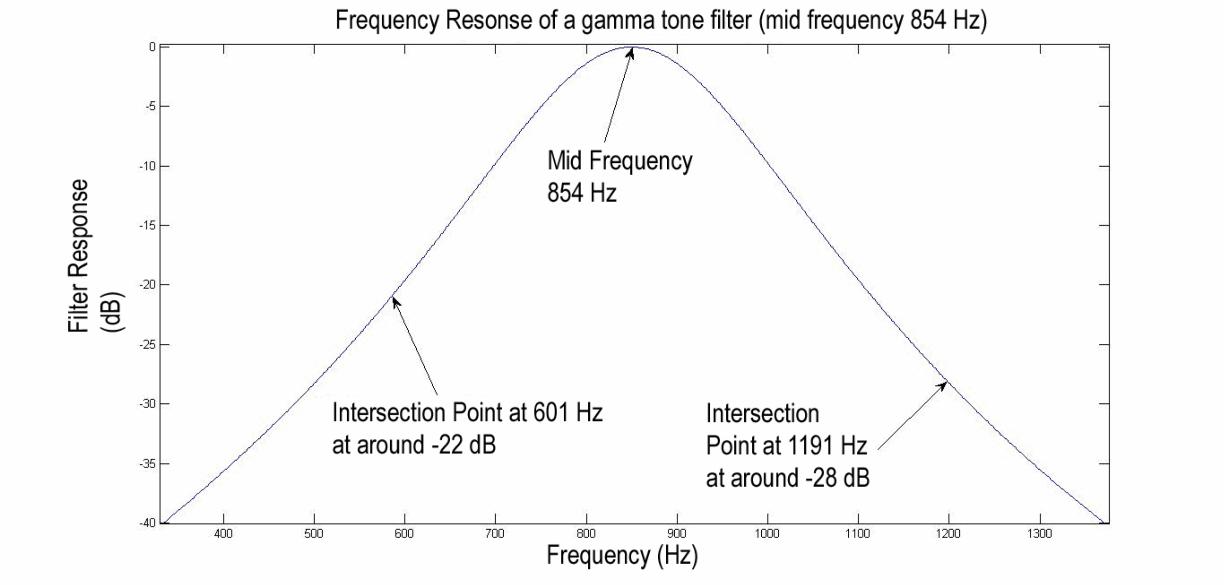

Figure 21: A fourthorder gammatone filter represents by approximation the normal hearing auditory filter at the center frequency of 854 Hz (bandwidth of the critical band 150 Hz). The damping of the adjacent flanking bands is in minimum 22 dB. So a mainly across frequency processing is assumed.

The frequency selectivity and thus the precondition for an across frequency processing in CI users is determined on the one hand by the alignment of the OPUS 2 band-pass filter bank, the gain applied to signal parts falling in adjacent filters (Maplaw). On the other hand and independent of the band-pass filter bank of the speech processor it is determined by the superposition of the electrical fields provoked by the alternating stimulation on the different adjacent intra cochlear electrodes to the same external reference electrode (in monopolar mode, which is today the most common stimulation setting across all CI systems of the different manufacturers, see Figure 22). The superposition of the electrical fields of different electrodes can lead to a depolarisation of similar populations of hearing nerve fibres. In this case, none or only little additional spectral information can be transmitted by the stimulation of adjacent electrodes (place pitch <-> temporal pitch). Temporal information on the other hand can furthermore convey additional information also in this case (Zeng, 2002).

The necessary current amplitude per electrode to depolarise enough hearing nerve fibres for a comfortable hearing sensation depends on various factors: the intra cochlear electrode impedance, the distance from the electrode to the hearing nerve, the number of surviving spiral ganglion cells and the subjective need of loudness determined by the CI user. There are some ideas how a better electrode selectivity could be achieved (O'Leary *et al.*, 2009).

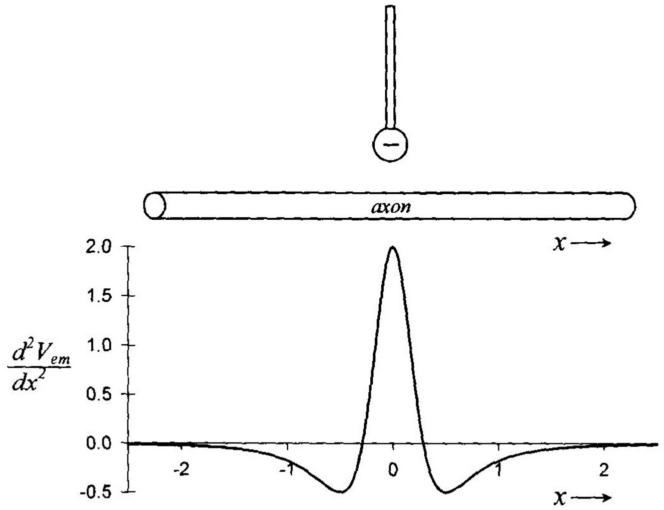

Figure 22: The activating function of a cathode over an axon of a neuron. Vem(x) is the electrical potential dependent of the distance of maximal excitation in rel. units (Zeng *et al.*, 2004).

The experimental measured frequency responses of the OPUS 2 in standard settings are shown in Figure 23.

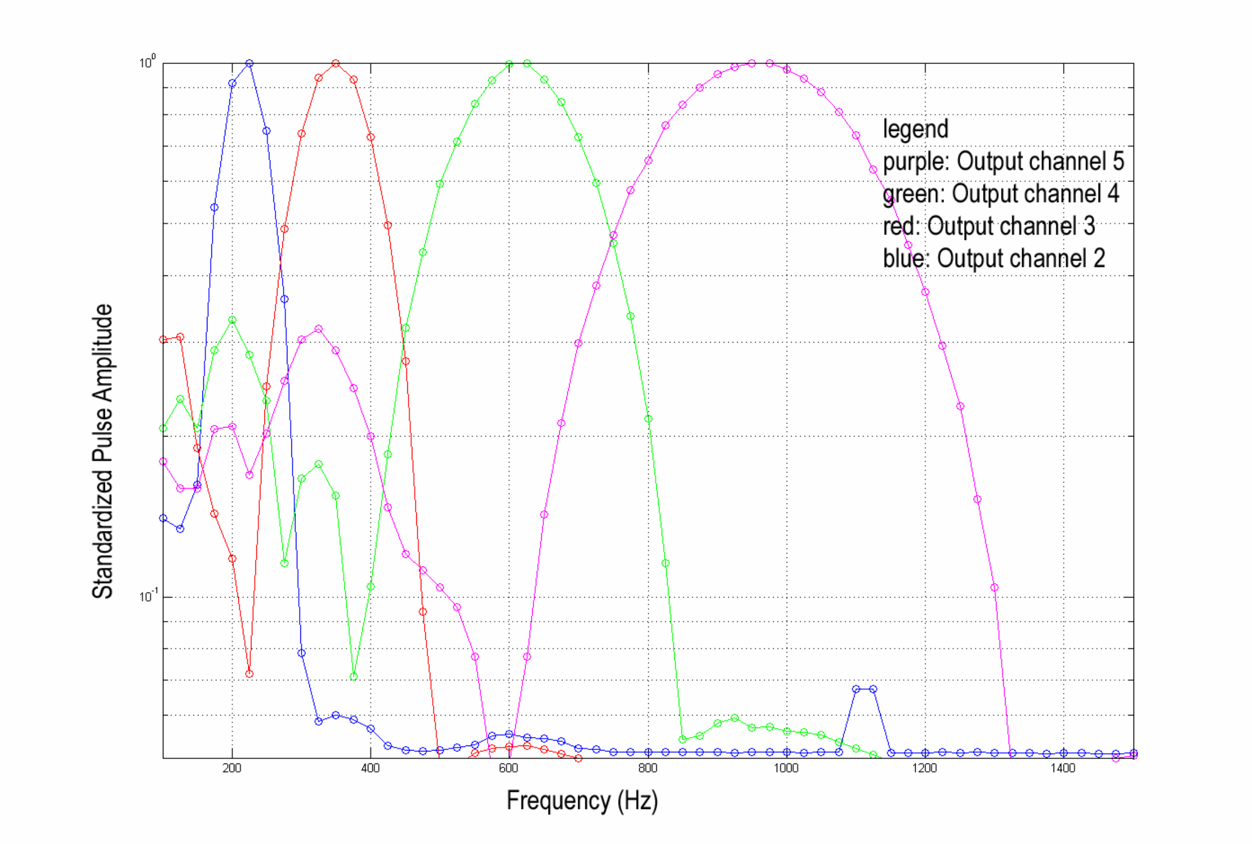

Figure 23: Measured frequency responses (input: discrete sweep of pure tones in 25 Hz distance shown as circles) of the CI channels 5 purple, center frequency 854 Hz) and CI channels 4, 3 and 2 (measured with a I100 Detector Box Prototype of MED-EL).

High ripples to apical could be observed (-4.77 dB) at the n-2 channel. The frequency responses are yielded with an artificial flat map (threshold 0 qu, most comfortable level 20 qu) and the standard band-pass filter bank of the OPUS 2 with FSP. Inputs were sequential sinusoidal tones of constant level in 25 Hz steps from 100 Hz to 1500 Hz.

The measuring station is shown in Figure 24. The acoustic stimuli were delivered to the speech processor via headphones. The stimuli were presented unilaterally to CI users and NH. The measurement took place in the fitting room of the Klinikum der Universität München, without any visual or acoustical disruption of the test course.

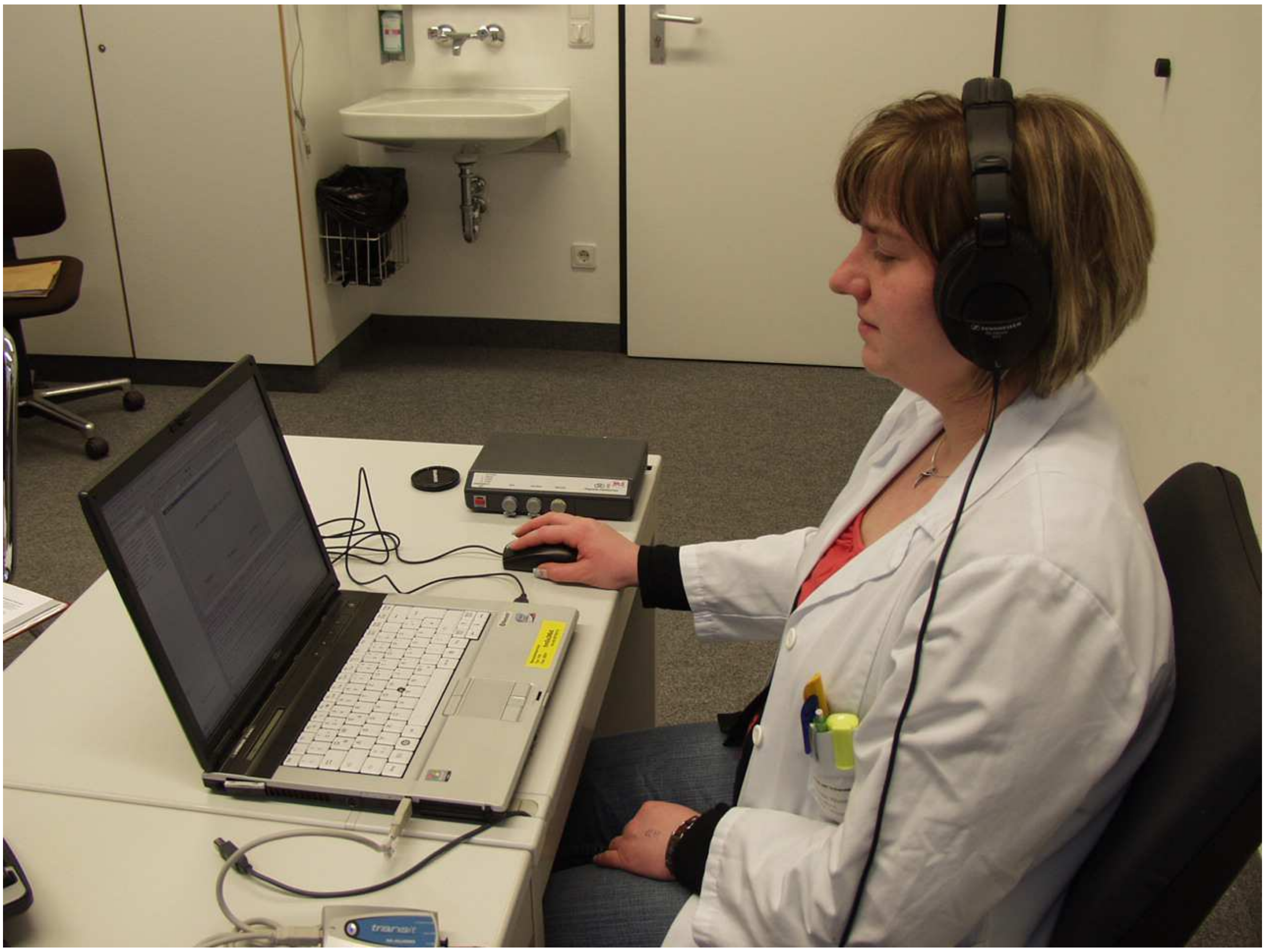

Figure 24: Exemplary demonstration of the measuring station for the frequency shift condition. The tests took place in the normal fitting room in the Klinikum Großhadern.

c) Frequency shift condition

In the last test condition, the center frequencies of the noise maskers (OFM+FB) and the sinus tone are shifted between the CI channels center frequencies (see Figure 25). Also in this condition, a CMR is measurable as a difference in detection threshold of the sinusoidal signal in comodulated or uncorrelated modulated narrow noise bands (see definition in chapter 3.3).

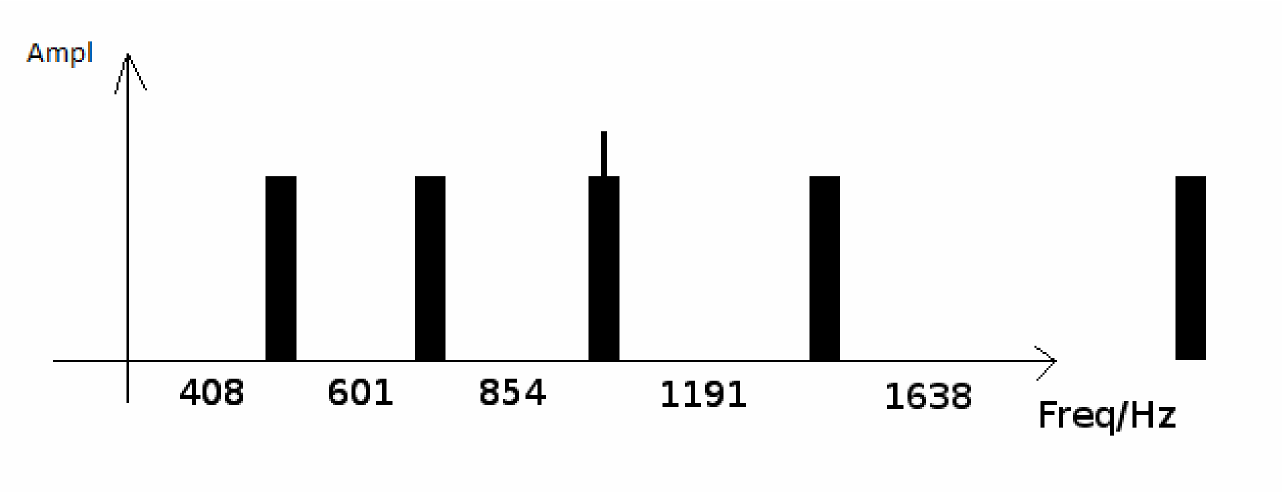

Figure 25: In the Frequency shift condition the OFM, FB and the sinus tone are shifted between the CI channels. For NH the center frequencies are 504,5, 727,5, 1022,5, 1414,5, 1935,5 Hz.

Every threshold was determined three times. The final threshold in each condition was calculated as the arithmetic mean over the three thresholds. The test order of all 15 single tests is pictured in

Table 4.

Table 4 Test sequences in the frequency shift procedure

Test sequence	Threshold test
1	Comodulated OFM+FB
2	Uncorrelated OFM+FB
3	Uncorrelated Frequency Shift
4	Comodulated Frequency Shift

5	Only OFM
6	Uncorrelated OFM+FB
7	Comodulated OFM+FB
8	Comodulated Frequency Shift
9	Uncorrelated Frequency Shift
10	Only OFM
11	Uncorrelated OFM+FB
12	Comodulated OFM+FB
13	Comodulated Frequency Shift
14	Uncorrelated Frequency Shift
15	Only OFM

The headphones were calibrated with the masking noise complex in the uncorrelated OFM+FB condition to 70 dB SPL. This level was held constant while the level of the pure tone in the OFM varied.

5.3.3 Test 3: Correlation CMR with ability to discriminate electrode pitch

Hall et al. (1988) measured a reduction of the CMR in hearing impaired people with hearing loss of cochlear origin in a band-widening experiment. 1996 similar results were obtained in a flanking band experiment (Grose and Hall). The reduced CMR correlated significantly with reduced frequency selectivity concordant with the hypothesis that the across-frequency difference cue used in CMR is diminished by poor frequency selectivity. Hall et al. (1988) suggest further, that a good frequency selectivity is a requirement, but not a guarantee for a large CMR.

In this study the ability of CI users to discriminate adjacent electrodes using place pitch was established with the Maestro Fitting Software of MED-EL by giving single channel bursts at MCL level with a duration of 300 ms at the CI users usual stimulation rate (typically between 700 -1800 pps, depending on the required charge and the electrode impedance measured before this test) on different electrodes as shown in Table 5. The question for the CI user after presenting the two single channel stimuli was: “*Which of the following two tones has the higher pitch?*”

Table 5: Test sequences to evaluate the ability of CI users to discriminate adjacent electrodes in pitch

Channels stimulating after each other
3-4
4-5
5-6
6-7
7-8
4-3
5-4
6-5
7-6
8-7
In common: 5 pitch steps

When all tones could be discriminated by the CI user in the correct tonotopic order, the maximum score in the electrode pitch test was reached. This corresponds to the number five. If the two electrodes could only be discriminated in one of the two cycles the score reduces in one step.

5.4 Overview of the test conditions

In table 6 the test conditions with additional information are presented.

Table 6: Overview of the test conditions

General Test Method					Flanking Band Experiment		
Underling Test Method			Bandwidth of the masking noise			Spectral alignment of the masking noise bands	Ability to discriminate electrode pitch
Signal Presentation	free field		audio cable (CI users) / Headphones (NH)			headphones (CI users & NH)	
Signal Setup	24 Hz Band-width condition	48 Hz Band-width condition	24 Hz Band-width condition	48 Hz Band-width condition	OFM condition	OFM+FB condition	Frequency shift condition
Sound Pressure Level	Sound Pressure Level: fixed at 65 dB SPL		Sound Pressure Level: variable (scaled by User)			Sound Pressure Level: fixed at 70 dB SPL	
Test Subjects	6 NH, 8 CI users		5 NH, 8 CI users			7 NH, 11 CI users (Electr. Discr. 15 CI users)	

5.5 Signal generation & presentation

5.5.1 Computer and Software

For signal generation Matlab 2009a in the basis version was used on a Fujutsu Siemens Notebook Type Lifebook E series.

5.5.2 Soundcard

An external Soundcard type MAUDIO USB (max. sampling depth 24 Bit, max. sampling frequency 96 kHz) was used for all experiments.

5.5.3 Equipment

Audio cable

For the tests in the audio cable conditions a MED-EL audio cable in the red version (damping of the microphone signal: -32 dB) was used to deliver sound stimuli directly via the FM input to the speech processor OPUS 2. The galvanic isolation was realised by running the notebook with the rechargeable battery (plugged off the external power).

Speakers

An Edirol MA-10A speaker was used to present the acoustic stimuli in an S0N0 condition (signal and noise out of the same source and in front of the test-subject).

Headphones

Sennheiser HD 280 pro headphones were used to present the acoustic stimuli unilaterally without a hearing aid or speech processor in the contra lateral ear.

In case of good residual hearing on the non implanted side, this ear was provided with earplugs Type Bilsom 303S (medium damping 33 dB). In NH the stimuli were delivered unilaterally. The contra lateral ear was provided with earplugs (see above) and the headphone speaker was turned away from this ear.

5.6 Data analysis

The yielded data was analyzed with SPSS Version 18.0. Because of the relatively small number of test subjects, the Mann-Whitney-Test with a significance level of 0.05 was applied. All p values are two sided.

In case of the comparison of means of two variables in one control sample, the t-test with a significance level of 0.05 was used (results of the frequency shift condition; chapter 6.2).

5.7 Test subjects

The test subjects vary from test to test. There have never been two same test subjects.

NH subjects were in general employees of the *Klinik und Poliklinik für Hals-Nasen-Ohrenheilkunde of the Klinikum der Universität München*. All NH subjects had to verify their hearing abilities with a recent audiogram. In the frequency range between 100 Hz – 8 kHz the thresholds had to stay between 0 and -20 dB.

The CI users were all implanted and rehabilitated in the *Klinik und Poliklinik für Hals-Nasen-Ohrenheilkunde of the Klinikum der Universität München*. In general the CI users come in a later phase after implantation once a year. After the clinical medical,, the technical control and the control of speech understanding, CI users with the OPUS 2 Speech Processor were asked if they want to participate in the CMR study. The study was authorized by the ethics commission of the clinic. The period since implantation was at least 6 months in all CI test subjects.

5.7.1 Normal Hearing

Test 1: Dependence of CMR to bandwidth of the masking noise bands

In Table 7 and Table 8 the NH test subjects are listed.

Table 7: NH test subjects in the headphones test condition of the bandwidth variation experiment

number	test subject	gender	age (years)
1	NH01W1983	female	27
2	NH02M1990	male	20
3	NH03W1974	female	36
4	NH04M1942	male	68
5	NH05M1986	male	24
6	NH06M1979	male	31

Table 8: NH test subjects in the free field test condition of the bandwidth variation experiment

number	test subject	gender	age (years)
1	NH07M1985	male	25
2	NH08W1989	female	21
3	NH09W1990	female	20
4	NH10M1942	male	68
5	NH11M1990	male	20

Test 2: Dependence of CMR to spectral alignment of the masking noise bands in a flanking band test

In Table 9 the NHs who participated in the test are listed.

Table 9: NH test subjects in the spectral alignment of the masking noise bands experiment

Number	test subject	gender	age (years)
1	NH12W1962	female	48
2	NH13M1986	male	24
3	NH14W1990	female	20
4	NH15W1982	female	28
5	NH16W1976	female	34
6	NH17M1986	male	24
7	NH18M1979	male	31

Test 3: Correlation CMR with ability to discriminate electrode pitch

This test conditions was accomplished only by CI users, not by NH.

5.7.2 CI-Users

All CI users were implanted and attended at the *Klinikum der Universität München*,, Munich, Germany.

Test 1: Dependence of CMR to bandwidth of the masking noise bands

In Table 10 and Table 11 the CI subjects who participated in this test condition are listed.

Table 10: CI test subjects in the audio cable test condition of the bandwidth variation experiment

number	test subject	gender	age (years)
1	CI01M1940	male	70
2	CI02W1970	female	40
3	CI03M1929	male	81
4	CI04M1950	male	60
5	CI05M1940	male	70
6	CI06W1950	female	60
7	CI07W1953	female	57
8	CI08W1988	female	22

Table 11: CI test subjects in the free field test condition of the bandwidth variation experiment

number	test subject	gender	age (years)
1	CI09W1948	female	62
2	CI10W1977	female	33
3	CI07W1953	female	57
4	CI11M1930	male	80
6	CI13M1948	male	62
7	CI14W1966	female	44
8	CI15W1990	female	20

Test 2: Dependence of CMR to spectral alignment of the masking noise bands in a flanking band test

In Table 12 the CI subjects who participated in this test condition are listed.

Table 12: CI test subjects in the spectral alignment of the masking noise bands experiment

number	test subject	gender	age (years)
1	CI16M1930	male	80
2	CI17M1940	male	70
3	CI18M1946	female	64
4	CI19W1974	female	36
5	CI20M1929	male	81
6	CI21M1939	male	71
7	CI22M1987	male	23
8	CI23M1971	male	39
9	CI24W1936	female	74
10	CI25M1946	male	64
11	CI26W1990	female	20

Test 3: Correlation CMR with ability to discriminate electrode pitch

The test subjects in Test 3 were the same as in Test 2 in Table 12. The results were gained during the experiment of Test 2, except for the CI users in Table 13 (additionally for this test condition):

Table 13: Additionally to the CI subjects in Table 12, this two CI users have participated in Test 3.

number	test subject	gender	age (years)
12	CI27W1942FSP	female	68
2	CI28M1940FSP	male	70

6. Results

6.1 Results of Test 1: Dependence of CMR to bandwidth of the masking noise bands in a flanking band test

6.1.1 Headphone/audio cable condition

In Table 14 the results of NH in test 1 are shown.

Table 14: Thresholds and Comodulation Masking Releases of NH in test 1 with headphones (unilateral). Each threshold of each test subject is the arithmetic mean over three test sequences (see Table 3). The SNR is referred to all five noise bands.

Test subject	Threshold uncorrelated 24Hz (dB SNR)	Threshold comodulated 24Hz (dB SNR)	Threshold uncorrelated 48 Hz (dB SNR)	Threshold comodulated 48 Hz (dB SNR)	CMR 24Hz (dB)	CMR 48Hz (dB)
NH01W1983	-5.7	-18.8	-6.5	-17.9	13.1	11.5
NH02M1990	-6.8	-15.3	-7.3	-14.5	8.5	7.2
NH03W1974	-0.1	-15.1	-4.9	-14.7	15.0	9.8
NH04M1942	-8.7	-20.4	-9.5	-20.1	11.7	10.6
NH05M1986	-9.9	-22.9	-10.9	-23.0	13.0	12.1
NH06M1979	-5.6	-20.6	-9.1	-18.9	15.0	9.9
Arithmetic Mean	-6.1	-18.9	-8.0	-18.2	12.7	10.2
Standard Deviation	3.4	3.1	2.2	3.3	2.4	1.7

In Table 15 the results of CI users in test 1 are listed. All CI users were tested with their everyday hearing program with speech coding strategy FSP. All noise bands and the sinusoidal signal are centred on the center frequencies of the individually arranged band-pass filter bank of each CI user. The SNR is referred to all five noise bands.

Table 15: Thresholds and Comodulation Masking Releases of CI users in test 1 yielded with the audio cable (unilateral). Each threshold of each test subject is the arithmetic mean over three test sequences (see Table 4).

Test subject	Threshold uncorrelated 24Hz (dB SNR)	Threshold comodulated 24Hz (dB SNR)	Threshold uncorrelated 48 Hz (dB SNR)	Threshold comodulated 48 Hz (dB SNR)	CMR 24Hz (dB)	CMR 48Hz (dB)
CI01M1940	-9.1	-16.6	-6.5	-15.3	7.5	8.8
CI02W1970	-0.5	-15.4	-5.8	-13.9	14.9	8.1
CI03M1929	0.5	-12.9	-1.5	-16.5	13.5	15.1
CI04M1950	-2.5	-15.9	-4.0	-12.8	13.4	8.8
CI05M1940	5.1	-2.5	3.3	-3.2	7.6	6.5
CI06W1950	10.1	-5.9	8.3	-3.0	16.0	11.3
CI07W1953	-2.5	-12.9	-2.6	-12.9	10.3	10.3
CI08W1988	-2.5	-14.1	-5.7	-6.0	11.6	0.3
Arithmetic Mean	-0.2	-12.0	-1.8	-10.5	11.8	8.6
Standard Deviation	5.7	5.1	5.2	5.5	3.2	4.2

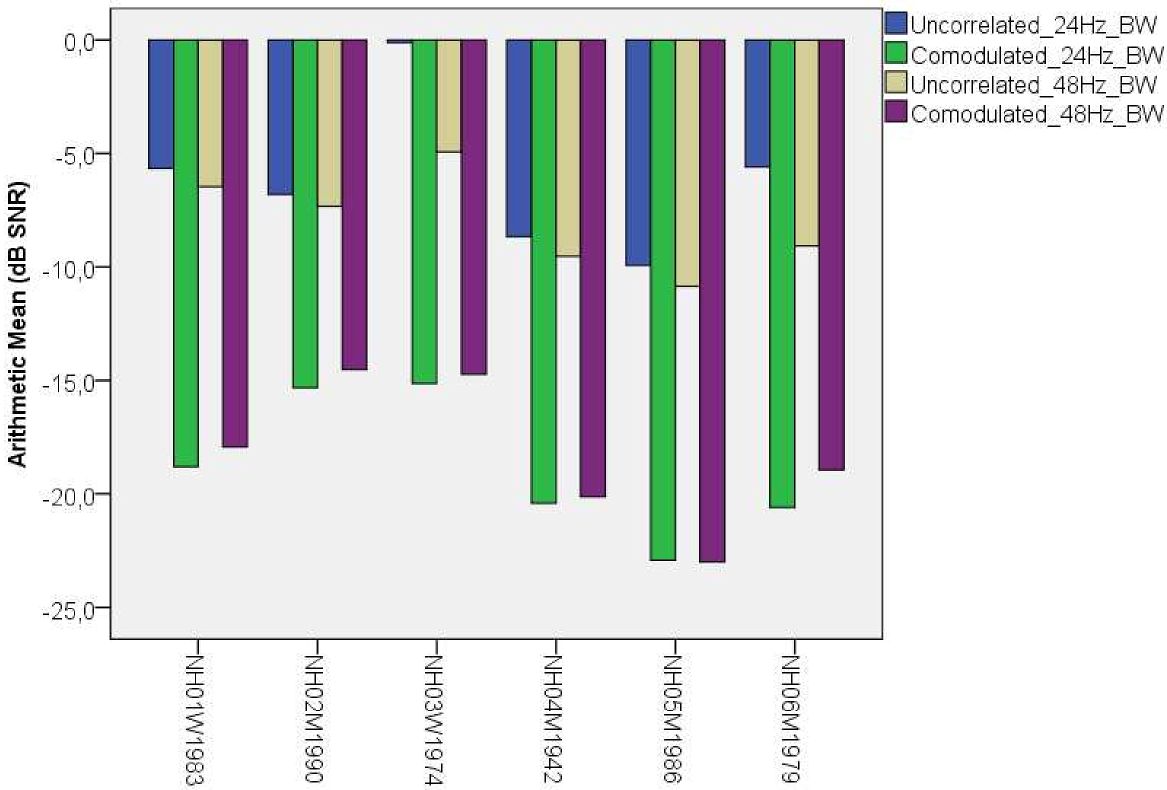

Figure 26: Thresholds of NH in Test 1 over the Bandwidths 24 Hz and 48 Hz in the <u>headphone/audio cable</u> condition. Each threshold of each test subject is the arithmetic mean over three test sequences (see Table 3). The SNR is referred to all five noise bands.

NH reached relatively homogenous hearing thresholds (Figure 26) in the uncorrelated and the comodulated conditions. The arithmetic means and the standard deviations of the thresholds can be found in Table 14. For a detailed analysis of the results see chapter 7.

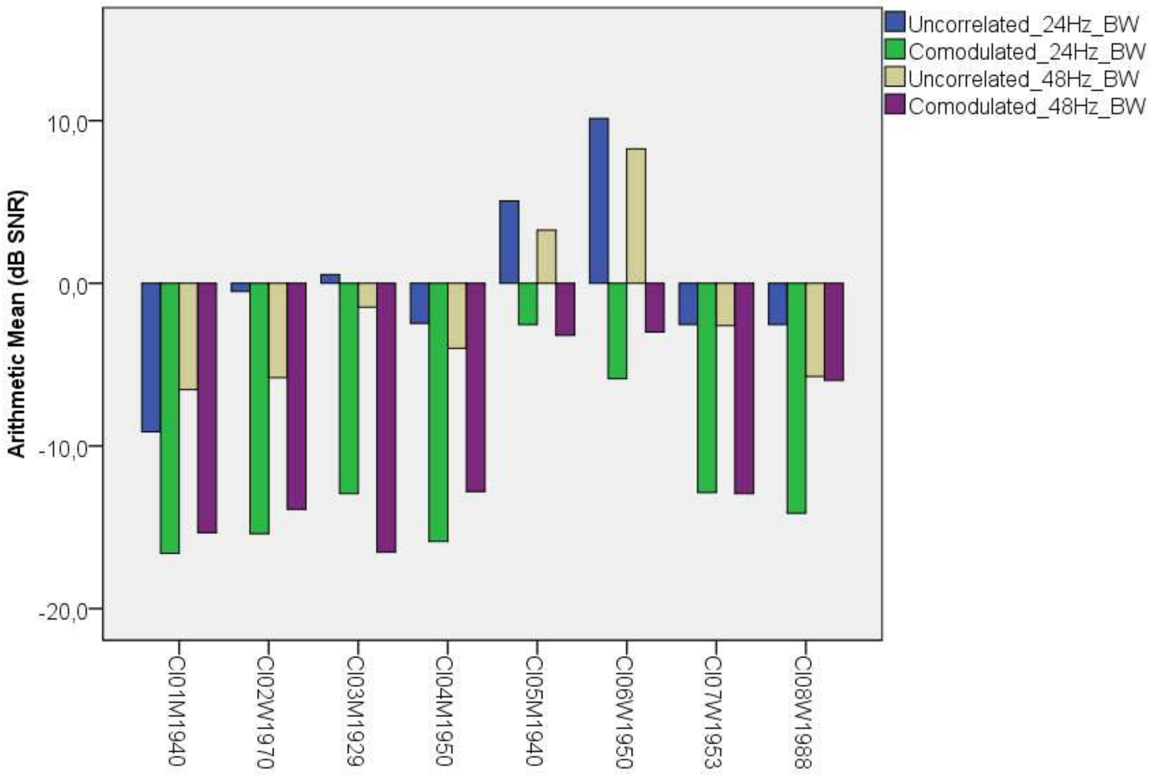

Figure 27: Thresholds of CI users in Test 1 over the two bandwidths 24 Hz and 48 Hz in the headphone/audio cable condition. Each threshold of each test subject is the arithmetic mean over three test sequences (see Table 3). The SNR is referred to all five noise bands.

CI users reached more inhomogeneous hearing thresholds (Figure 27) in the uncorrelated and the comodulated conditions than NH. Especially the inter subjective variance was bigger. The arithmetic means and the standard deviations of the thresholds can be found in Table 14. For a detailed analysis of the results see chapter 7.

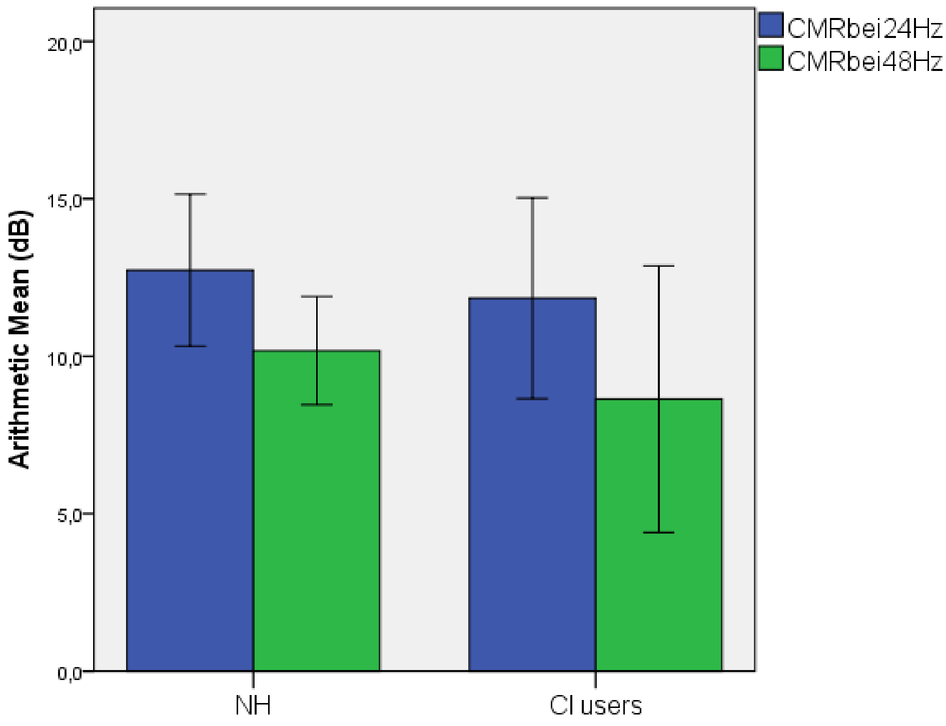

Figure 28: Comodulation Masking Releases of NH (N=6) and Cochlear Implant users (N=8) in test 1 in the <u>headphone/audio cable</u> condition at two bandwidths (Zirn et al., 2010a). Error bars depict 1 SEM.

The standard deviation in CI users is higher than in NH.(see Figure 28).

6.1.2 Free Field Experiments

The results of NH in this test condition are listed in Table 16.

Table 16: Thresholds and Comodulation Masking Releases of NH in Test 1 in free field (unilateral). Each threshold of each test subject is the arithmetic mean over three test sequences (see Table 8).

Test subject	Threshold uncorrelated 24 Hz (dB SNR)	Threshold comodulated 24 Hz (dB SNR)	Threshold uncorrelated 48 Hz (dB SNR)	Threshold comodulated 48 Hz (dB SNR)	CMR 24 Hz (dB)	CMR 48 Hz (dB)
NH07M1985	-8.10	-27.60	-7.3	-21.30	19.50	13.90
NH08W1989	-8.5	-16.7	-8.8	-16.3	8.2	7.5
NH09W1990	-3.2	-14.9	-7	-12.6	11.7	5.6
NH10M1942	-5.7	-17.7	-11.2	-15.3	12	4
NH11M1990	-6.7	-15.7	-8.1	-21.2	9	13
Arithmetic Mean	-6.4	-18.5	-8.5	-17.3	12.1	8.8
Standard Deviation	2.1	5.2	1.7	3.8	4.5	4.4

In all NH there was a difference between the threshold in the uncorrelated and the comodulated condition. In the bandwidth experiments no threshold in the OFM only condition were measured (see Figure 29).

In Table 17 the results of CI users in Test 1 in free field are listed. All CI users were tested with their everyday-hearing-program with speech coding strategy FSP. All noise bands and the sinusoidal signal are centred on the center frequencies of the individually arranged band-pass filter bank of each CI user. The SNR is referred to all five noise bands.

Table 17: Thresholds and Comodulation Masking Releases of CI users in Test 1 yielded in free field (unilateral). Each threshold of each test subject is the arithmetic mean over three test sequences (see Table 11).

Test subject	Threshold uncorrelated 24 Hz (dB SNR)	Threshold comodulated 24 Hz (dB SNR)	Threshold uncorrelated 48 Hz (dB SNR)	Threshold comodulated 48 Hz (dB SNR)	CMR 24 Hz	CMR 48 Hz
CI09W1948	2.9	-10.3	3.3	-14.7	13.2	18
CI10W1977	1.7	-6.5	6.4	-6.7	8.2	13.1
CI07W1953	0.2	-12.4	-2.3	-12.3	12.6	10.1
CI11M1930	-2.6	-6.1	-3.3	-5.3	3.5	2
CI13M1948	4.3	1.3	6.4	4.1	3	2.3
CI14W1966	-6.7	-8.3	-5.6	-7.8	1.6	2.2
CI15W1990	1.3	2.3	1.3	2.5	-0.9	-1.3
Arithmetic Mean	0.2	-5.7	0.9	-5.7	5.9	6.6
Standard Deviation	3.7	5.6	4.8	7.0	5.5	7.1

The CI test subjects show a difference between the uncorrelated and the comodulated condition (see also Figure 30).

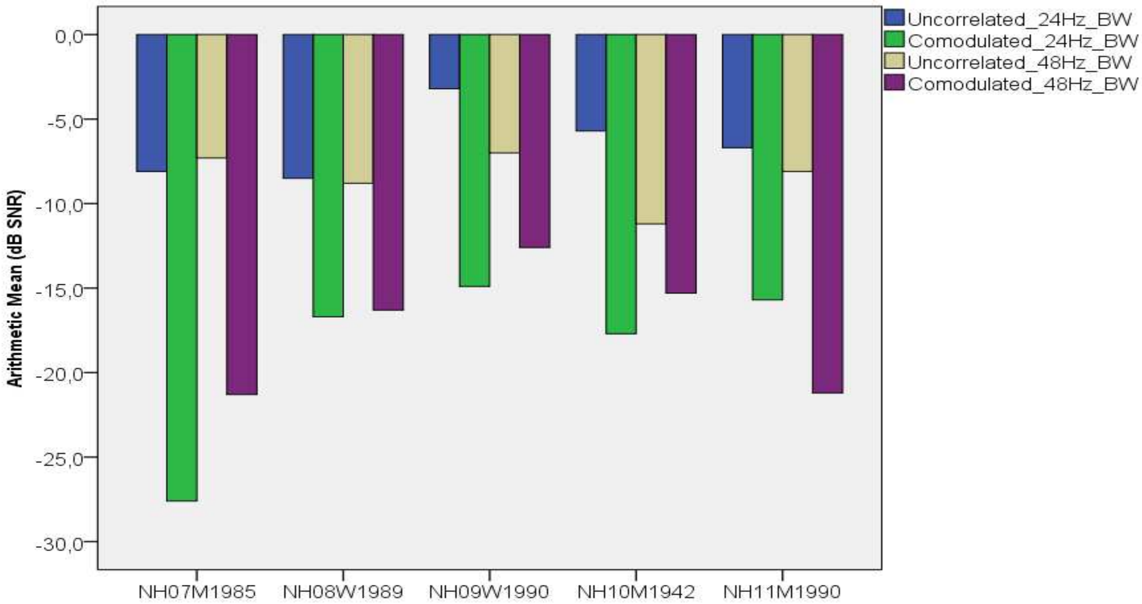

Figure 29: Thresholds of NH in Test 1 over the bandwidths 24 Hz and 48 Hz in free field. Each threshold of each test subject is the arithmetic mean over three test sequences (see Table 8). The SNR is referred to all five noise bands.

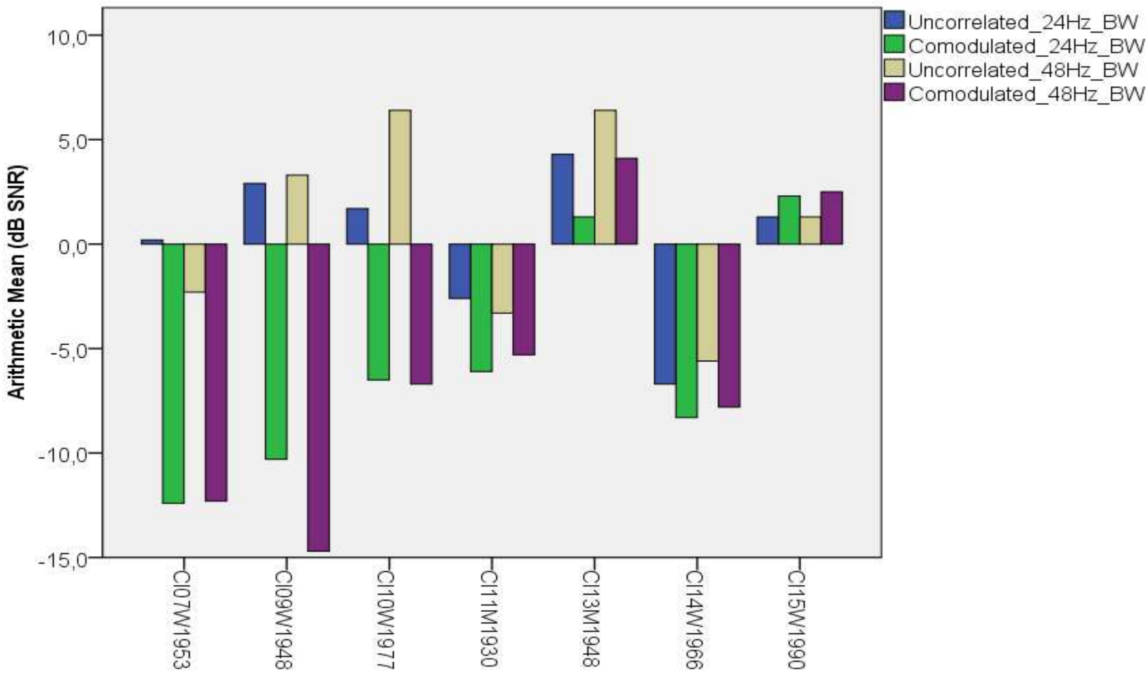

Figure 30: Thresholds of CI users in Test 1 over the two Bandwidths 24 Hz and 48 Hz in free field. Each threshold of each test subject is the arithmetic mean over three test sequences (see Table 11). The SNR is referred to all five noise bands.

The CMR in test 1 in free field of NH and CI users are shown in Figure 31.

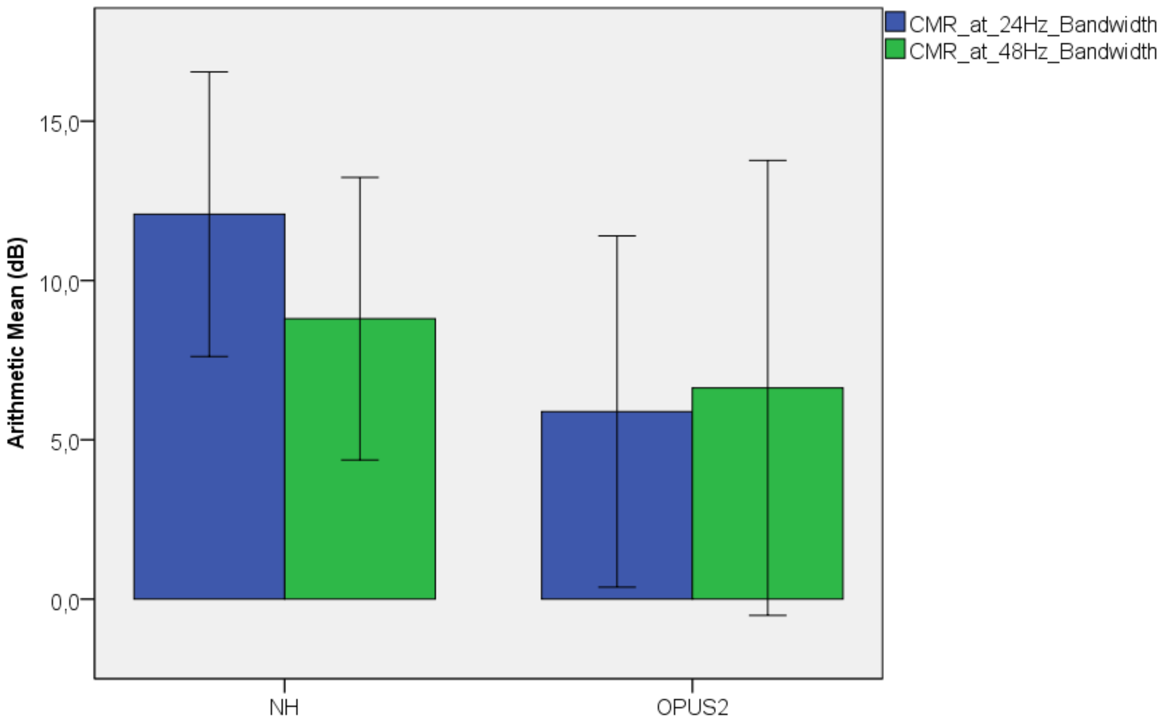

Figure 31: Comodulation Masking Releases of NH (N=5) and OPUS 2 users (N=8) in Test 1 in the free field condition at two bandwidths (Zirn et al., 2010a). Error bars depict 1 SEM.

6.2 Results of Test 2: Dependence of CMR to spectral alignment of the masking noise bands in a flanking band test

NH

The results in test condition 2 of NH were widely homogeneous (see Table 17 and Figure 32).

Table 18: Thresholds and Comodulation Masking Releases of NH in Test 2. Each threshold of each test subject is the arithmetic mean over three test sequences (see Table 4). The SNR is referred to one noise band (all thresholds).

Test subject	side	Threhold OFM only (dB SNR)	Thres-hold uncorrel. OFM+FB (dB SNR)	Thres-hold comodul. OFM+FB (dB SNR)	Thres-hold uncorrel. FreqShift (dB SNR)	Thres-hold comodul. FreqShift (dB SNR)	CMR OFM+FB (dB)	CMR FreqShift (dB)
NH12W1962	right	0.7	0.5	-11.6	2.2	-9.7	12.1	11.9
NH13M1986	left	miss. Value	0.6	-11.9	0.1	-14.1	12.5	14.1
NH14W1990	right	0.8	1.9	-11.9	5.7	-2.9	13.9	8.7
NH15W1982	right	-1.4	-0.3	-10.1	0	-7.7	9.9	7.7
NH16W1976	right	1.7	2.9	-8.4	2.9	-11.1	11.3	13.9
NH17M1986	right	1.5	2.8	-11.9	5.6	-11.6	14.7	17.2
NH18M1979	right	0.5	0.9	-13.6	0.2	-16.2	14.5	16.4
Arithmetic Mean		0.6	1.3	-11.4	2.4	-10.5	12.7	12.8
Standard Deviation		1.1	1.2	1.6	2.5	4.3	1.8	3.6

The threshold in the OFM only condition stays in medium 0.7 dB lower than the threshold in the condition with flanking bands OFM+FB and then decreases in the comodulated condition. All thresholds are referred to one noise band. The correction factor is in approximation 7 dB (assuming the energy in the 5 noise bands is equal):

$$L_{dB} = 10 * \log_{10}\left(\frac{1 * Signal}{5 * Noise}\right) = 10 * \log_{10}\left(\frac{Signal}{Noise}\right) + 10 * \log_{10}\left(\frac{1}{5}\right) = 10 * \log_{10}\left(\frac{Signal}{Noise}\right) - 7 \quad (14)$$

When referred to one noise band in all conditions, the hearing thresholds increase slightly from the OFM only to the uncorrelated OFM+FB condition and decrease to the comodulated OFM+FB condition. The relative difference between the uncorrelated and comodulated Thresholds, thus the CMR, however is not affected by this calculation.

The standard deviation increases in the frequency shift condition. It is assumed, that this increase decreases by increasing the number of test subjects. The CMR on the other hand stays approximately constant in the OFM+FB condition compared to the frequency shift condition.

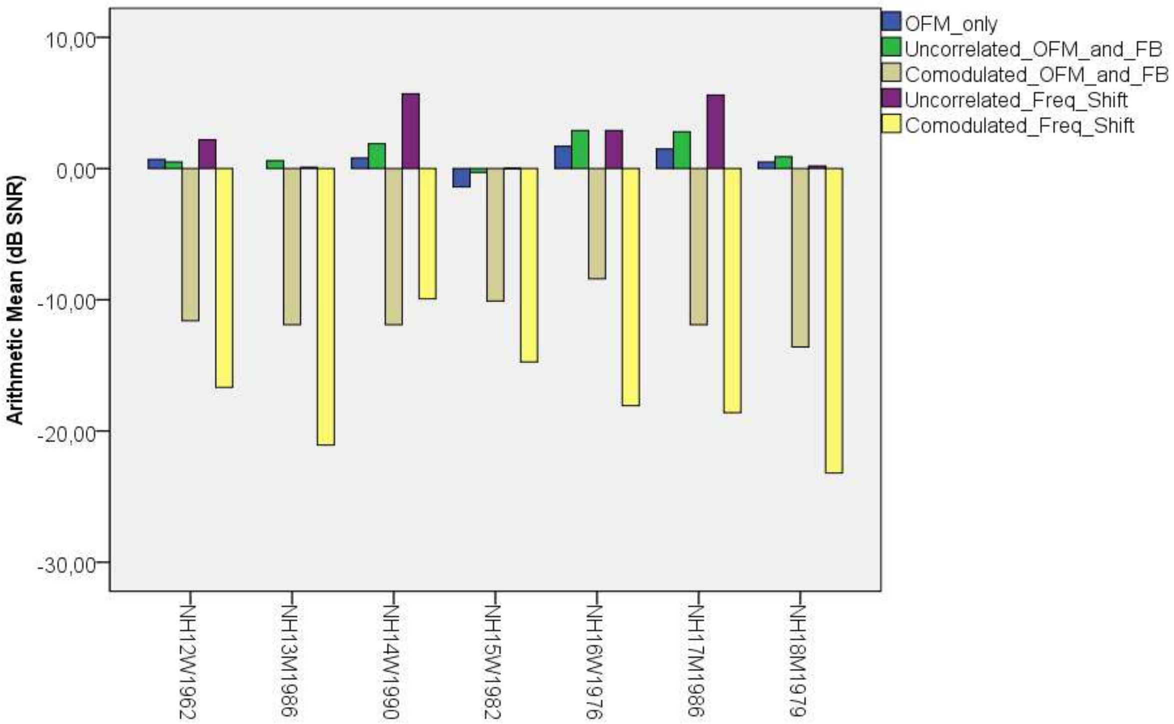

Figure 32: Thresholds of NH in Test 2. Each threshold of each test subject is the arithmetic mean over three test sequences (see

Table 4). The SNR is referred to one noise band (all thresholds).

CI users

Beyond the thresholds and the CMR, further parameters of the CI users have been recorded and evaluated, as the subjective loudness at a presentation sound pressure level of 70 dB, the stimulation rate (which depends on the CI users map thresholds- and most comfortable values and the electrode impedances), the results in the German Oldenburger Satztest and the dynamic range on channel 5.

Table 19: CI users with settings, results of the German Oldenburger Satztest (OLSA) and their subjective loudness (Range 0-50), see Figure 16.

Test_Subject	Coding strategy	Subjective loudness (between 0..50)	StimRate (pps)	OLSA (dB SNR)	Dynamic range on channel 5 (cu)
CI16M1930FSP	FSP	30	1003	Miss. value	Miss. Value
CI17M1940FSP	FSP	30	1818	-1.5	570
CI18M1946FSP	FSP	Miss. value	1523	4.65	708
CI19W1974FSP	FSP	30	562	-0.3	909
CI20M1929FSP	FSP	Miss. value	781	2.5	784
CI21M1939FSP	FSP	35	1515	0.7	729
CI22M1987FSP	FSP	30	1174	-1.6	1481
CI23M1971FSP	FSP	30	1093	-3.35	605
CI25M1946FSP	FSP	25	1523	4.5	708
CI24W1936FSP	FSP	30	770	1.4	735
CI26W1990FSP	FSP	30	1550	-0.2	1410

The subjective loudness over all test subjects is approximately homogeneous at a comfortable level of around 30.

Table 20: Thresholds and Comodulation Masking Releases of CI users in Test 2. Each threshold of each test subject is the arithmetic mean over three test sequences (see

Table 4). The SNR is referred to one noise band (all thresholds).

Test_Subject	Threshold OFM_only (dB SNR)	Threshold Uncorrelated OFM+FB (dB SNR)	Threshold Comodulated OFM+FB (dB SNR)	Threshold Uncorrelated FreqShift (dB SNR)	Threshold Comodulated FreqShift (dB SNR)	CMR OFM+FB (dB)	CMR FreqShift (dB)
CI16M1930FSP	Miss. value	6.9	9.1	4.3	8.8	-2.2	-4.5
CI17M1940FSP	Miss. value	9.5	-1.4	12.6	6.3	10.9	6.3
CI18M1946FSP	Miss. value	16.9	5.1	14.3	5.0	11.8	9.3
CI19W1974FSP	6.9	8.3	-1.5	12.1	4.1	9.7	7.9
CI20M1929FSP	2.1	8.3	-4.4	5.1	-7.6	12.7	12.7
CI21M1939FSP	-0.5	1.2	-6.9	-0.5	-10.9	8.1	10.4
CI22M1987FSP	4.1	0.5	-12.2	4.5	-6.9	12.7	11.5
CI23M1971FSP	0.4	0.5	-9.5	-0.4	-8.1	10.0	7.7
CI25M1946FSP	4.3	17.5	6.3	13.6	2.0	11.2	11.6
CI24W1936FSP	10.1	9.1	3.3	10.0	1.2	5.8	8.8
CI26W1990FSP	4.2	5.5	-5.3	6.7	-5.6	10.9	12.3
Arithmetic Mean	4	7.7	-1.6	7.5	-1.1	9.2	8.5
Standard Deviation	3.4	5.8	6.9	5.4	6.9	4.3	4.8

The threshold in the OFM only condition stays in medium 3.3 dB lower than the threshold in the condition with flanking bands OFM+FB. The difference is bigger than in NH (see Table 20).

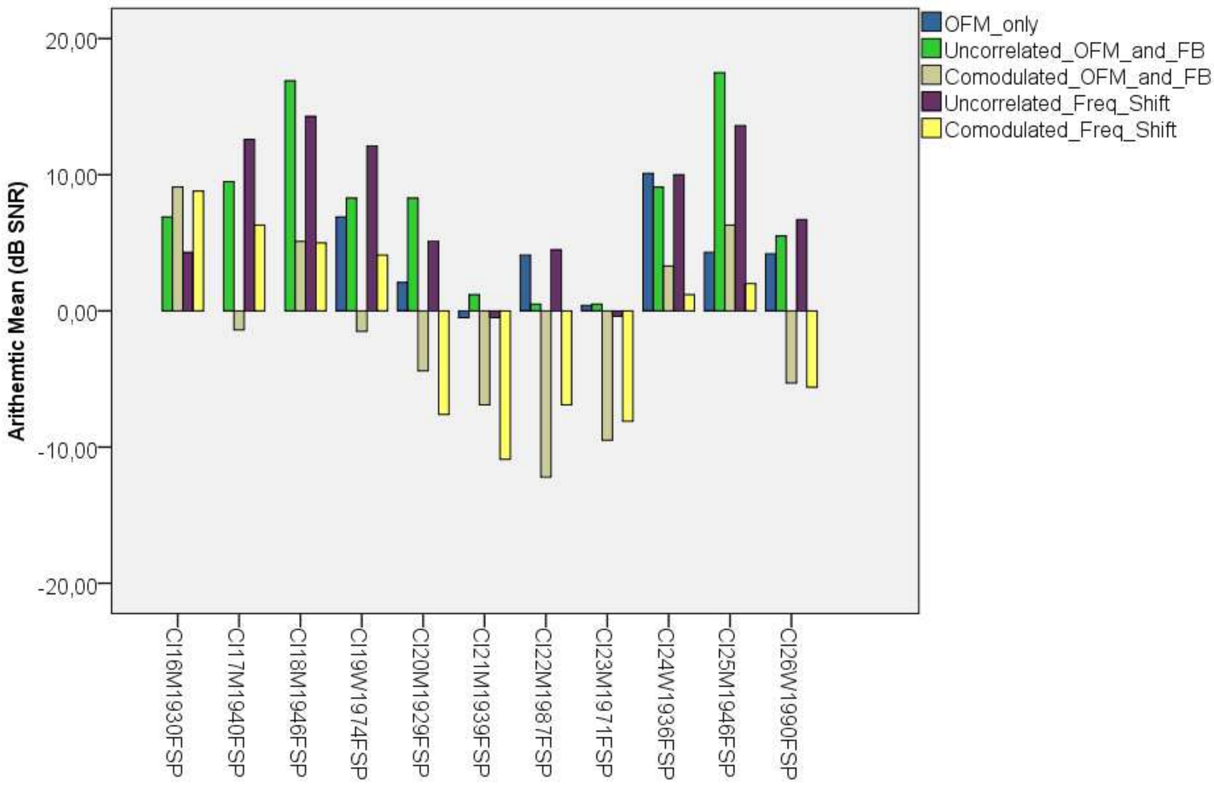

Figure 33: Thresholds of CI users in test 2. Each threshold of each test subject is the arithmetic mean over three test sequences (see

Table 4). The SNR is referred to one noise band (all thresholds).

The thresholds are not as homogenous in CI users as in NH (Figure 33). Anyhow, even with the variable thresholds, a difference between the uncorrelated and the comodulated threshold, thus a CMR can be observed in most of the CI users.

Test Subject CI23W1971FSP achieves thresholds that are approx. comparable to the thresholds of NH. In contrast, CI user CI16M1930FSP shows an increase of recognition threshold when comodulated flanking bands are added compared to the OFM only condition. This is a strongly non-NH like behaviour. Anyway, a difference between uncorrelated and comodulated threshold is also observable in this CI user.

The thresholds CI users pointed out, were nearly as reproducible (mean intra individual standard deviation of the three threshold approaches overall CI users: 2.3 dB) as the thresholds of NH (mean standard deviation: 1.9 dB).

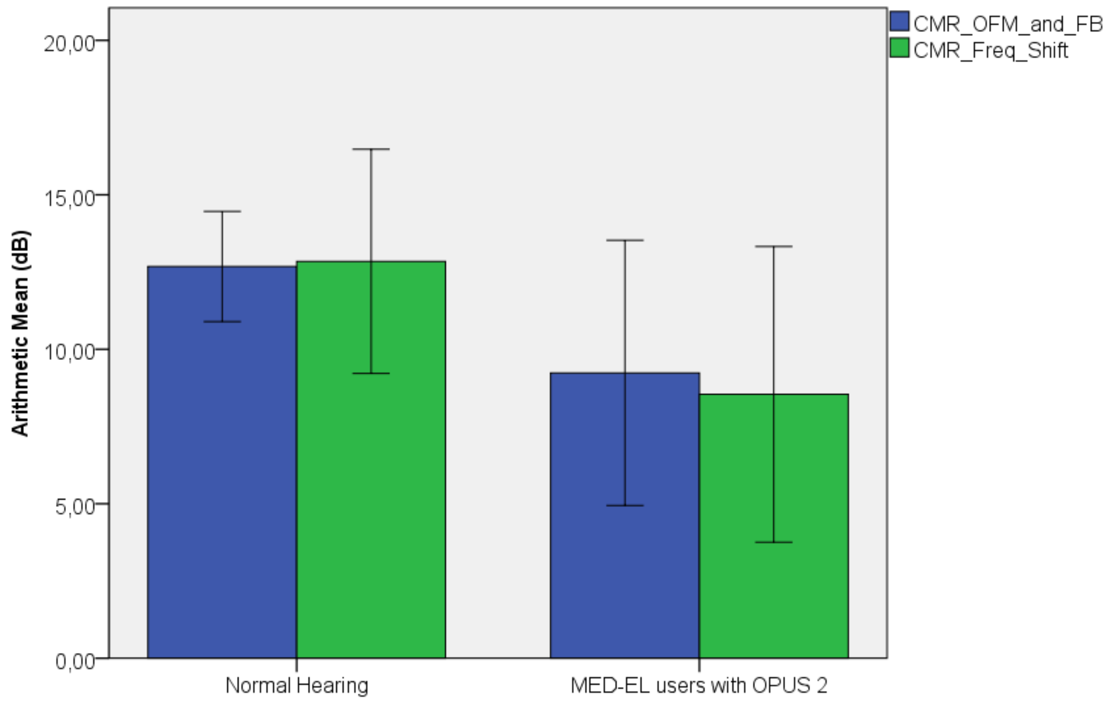

Figure 34: CMR as the difference between the uncorrelated and the comodulated threshold in the OFM+FB and the Frequency Shift test. The results of NH (N=7) is showed on the left. The results of MED-EL OPUS 2 (N=11) users is shown on the right (Zirn et al., 2010b) . Error bars depict 1 SEM.

The arithmetic mean of the CMR in NH is 12.7(+-1.8) dB in the OFM+FB condition and 12.8(+-3.6) dB in the Frequency Shift Condition (see Figure 34).

6.3 Results of Test 3: Correlation CMR with ability to discriminate electrode pitch

The results of the third test condition are listed below in Table 21.

Table 21: CI users, their CMR and their ability to discriminate adjacent electrodes in pitch

Test Subject	CMR OFM+FB	Electrode Discrimination (max_5)
CI16M1930FSP	-2.2	5
CI17M1940FSP	10.93	5
CI18M1946FSP	11.8	4
CI19W1974FSP	9.73	miss. value
CI20M1929FSP	12.67	5
CI21M1939FSP	8.13	5
CI22M1987FSP	12.67	4
CI23M1971FSP	10	5
CI25M1946FSP	11.2	4
CI24W1936FSP	5.8	3
CI26W1990FSP	10.87	3

In Figure 35 the CMR of each CI user is shown over the ability of the CI user to discriminate adjacent electrodes in pitch. Most of the test subjects were able to discriminate all electrodes in the correct order (see chapter 5.3.3). Furthermore, in the figure the regression line is implemented.

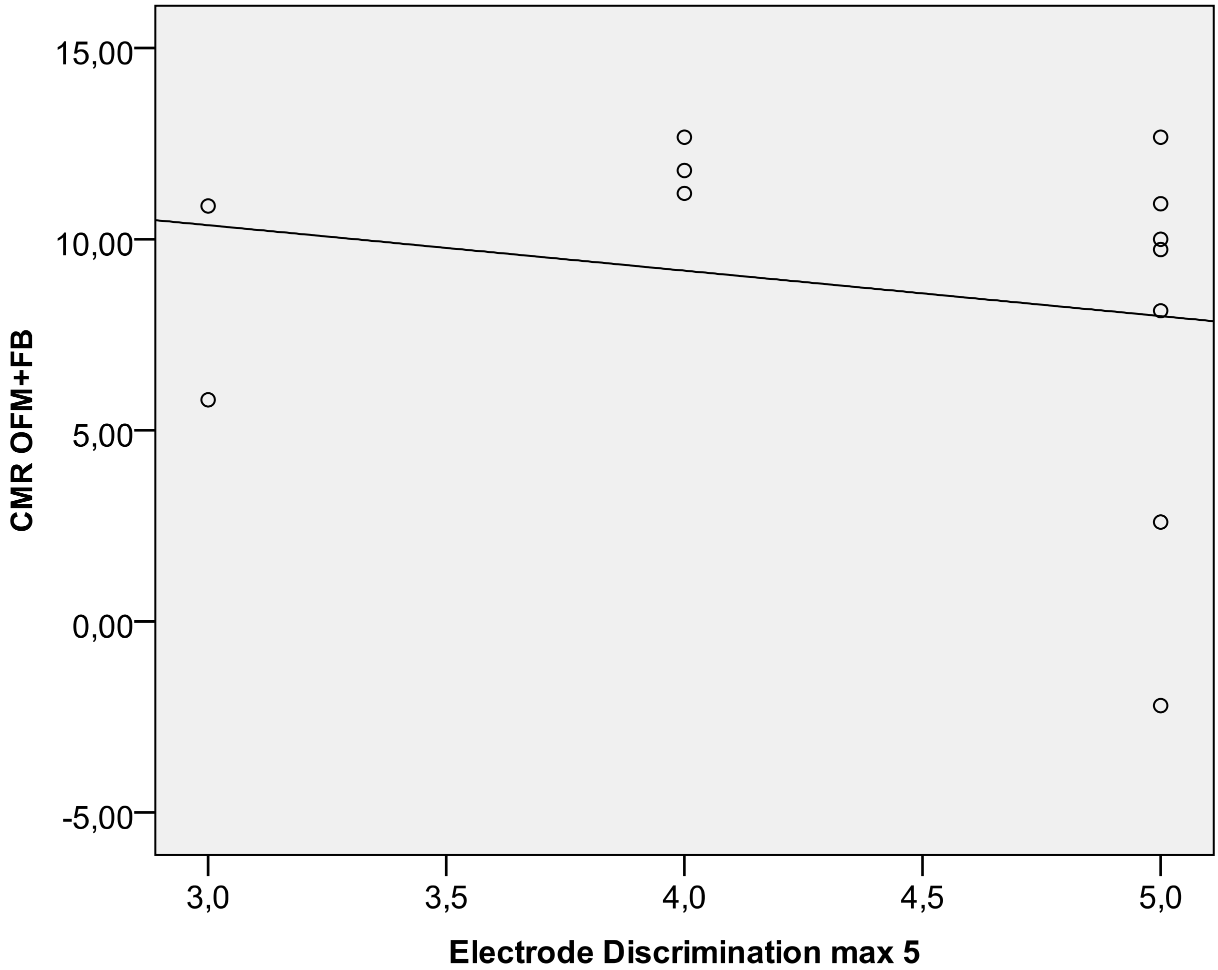

Figure 35: Dependence of CMR to the ability of the CI user to discriminate adjacent electrodes in pitch. The Pearson correlation factor is r=-0.21.

7. Discussion

7.1 Dependence of CMR to bandwidth of the masking noise bands in a flanking band test

Headphone/audio cable condition

This test condition was the first approach to investigate a CMR in CI users with the OPUS 2 Speech Processor with the HCDIS or FSP Strategy compared to NH. The found detection thresholds in NH conform to literature data [with respect to the correction factor equation (14) of 7 dB] (Epp and Verhey, 2009).

The transmission of the stimuli via audio cable to the CI users Speech Processor should avoid a loss of stimulus quality due to transformation to an acoustical signal by a sound source and a retransformation to an electrical signal by the speech processors microphone.

Concerning the results of CI users, it is not surprising, that a high intersubjective variance can be observed, like in many experimental studies with CI users. The big differences of the preconditions for the electrical hearing, due to different case histories of hearing impairment before implantation, can be one reason for this (Blamey *et al.*, 1996). The detection thresholds found in this test condition in CI user are in mean 6-8 dB higher than in NH.

In contrast, it is remarkable that in every tested subject in the reviewed group a difference in detection threshold between the comodulated and the uncorrelated condition was measurable, despite the high intersubjective variance of the absolute thresholds. In all of the 8 tested CI users the threshold in the uncorrelated condition was lower than in the comodulated condition.

The difference of these two thresholds, thus the CMR, is in the 24 Hz Bandwidth test condition (Mann-Whitney-U-Test, $p=0.6$), as well as in the 48 Hz test condition (Mann-Whitney-U-Test, $p= 0.3$) not significantly smaller in CI users than in NH. The standard deviation of CI user's results is in contrast nearly twice as big as in NH.

The dual time constant compression (slow and fast acting), working in the OPUS 2 speech processor (Stobich et al., 1999), seems to handle the variation of the bandwidth/modulation frequency of the masking noise bands in an adequate way: the reduction of CMR through the increased bandwidth/modulation frequency in CI users is similar to NH.

Free Field

To avoid a falsification of the results because of the different stimuli delivery in CI users (audio cable) and in NH (Headphones) and through the loudness scaling procedure according to the Oldenburger Hörfeld paradigm, the next test course tested the CMR in free filed with a fixed presentation level of 65 dB SPL for NH and CI users.

The results at 24 Hz bandwidth for NH barely changed, the CMR in the 48 Hz bandwidth condition decreased about 1.4 dB. It is assumed, that this decrease at 48 Hz bandwidth can be accounted to the relative small number of NH tested in free field (five subjects). Further, it is assumed that an increasing number of NH test subjects will lead to similar results like in the headphones/audio cable test course in the 48 Hz test condition discussed above. The absolute thresholds in the uncorrelated and the comodulated test condition barely changed in NH because of the different stimuli delivery.

In CI users, the different stimuli delivery led nearly to a bisection of the results in the 24 Hz test condition and to a clear decrease of the results in the 48 Hz bandwidth test condition (around 2 dB less). It is assumed that this decrease can be mainly accounted to the in mean reduced presentation level in reference to the audio cable test course described above. Furthermore the acoustical attributes of the room, although audiometric cabin, are probably not the best for this kind of hearing test (for example standing waves).

Despite of the overall higher detection thresholds and the higher standard deviations in free field in CI users, an advantage of the detection thresholds in the comodulated condition in reference to the uncorrelated test condition with the same spectrum level, was measurable, too. The only exception is test subject CI15W1990. For her, the threshold increased from the uncorrelated to the comodulated test condition. This can be assumed as a runaway value. The trend also for CI users is different: 6 out of 7 test subjects show a clear reduction in threshold from uncorrelated to comodulated.

7.2 Dependence of CMR to spectral alignment of the masking noise bands in a flanking band test

In this test course al detection thresholds in chapter 6.2 are referred to one noise band with respect to the correction factor of equation (14) of 7 dB. This conversion makes a comparison of the thresholds in the OFM only and the OFM+FB and accordingly the frequency shift condition easier.

The measured detection thresholds of NH conform to literature (Epp and Verhey, 2009). A small increase of detection threshold through the addition of uncorrelated flanking bands could be seen (mean comparison t-test of paired samples, OFM only-uncorrelated$_{OFM+FB}$, $p=0.02$).

But if presented comodulated, the addition of flanking bands leads to a clear advantage in detection threshold: 12.7 dB better in the OFM+FB condition (mean comparison t-test of paired samples, uncorrelated-comodulated, $p<0.01$) and 12.8 dB better in the frequency shift condition (mean comparison t-test of paired samples, uncorrelated-comodulated, $p<0.01$). Thus, there is no difference in NH if the noise bands and the signal are centred at the frequencies 408/601/854/1191/1638 Hz (OFM+FB condition) or 504.5/727.5/1022.5/1414.5/1935.5 (frequency shift condition). This was expected as discussed in chapter 4.2. The detection thresholds agreed to the measured thresholds in the headphones condition of chapter 6.1.1 (with respect to the correction factor equation (14) of 7 dB).

An interesting fact is that the thresholds CI users pointed out, were nearly as reproducible (mean intra individual standard deviation of the three threshold approaches overall CI users: 2.3 dB) as the thresholds of NH (mean standard deviation: 1.9 dB).

Not every CI user was able to do OFM only condition, because this is a difficult task for CI users and needs intense concentration to complete. It is assumed, that the reason is the tonal sound of one narrow noise band which masked the sinusoidal signal. In the subjects where the OFM only detection threshold could be measured, no significant change through the addition of uncorrelated flanking bands could be seen (mean comparison t-test of paired samples, OFM only-uncorrelated$_{OFM+FB}$, $p=0.23$).

But same as in NH a comodulated presentation of OFM and FB’s leads to a clearly better detection threshold of the sinusoidal signal in noise (mean comparison t-test of paired samples, $uncorrelated_{OFM+FB}$-$comodulated_{OFM+FB}$, $p<0.01$).

Same in the frequency shift condition (mean comparison t-test of paired samples, $Uncorrelated_{Freq\_Shift}$ - $Comodulated_{Freq\_Shift}$, $p<0.01$)

The CMR in the OFM+FB condition is worse in CI users than in NH (Mann-Whitney-Test $p=0.01$). Same in the frequency shift condition (Mann-Whitney-Test $p=0.05$).

The mean comparison between the CMR in the OFM+FB condition and the frequency shift condition resulted in a non significant difference (mean comparison t-test of paired samples, CMR_{OFM+FB}-CMR_{freq_shift}, $p=0.35$).

The main problem in this test course was the reduced frequency selectivity of CI users versus NH, as discussed in chapter 5.3.2. Both the band-pass filter bank and the superposition of electrical fields of adjacent electrodes lead to a spectral spread of the excitation pattern. That is the reason why not only one channel of the CI system will stimulate in the OFM only condition. As can be seen in Figure 23, at least the two adjacent channels will stimulate additionally to the central channel because of the overlapping filter functions and the amplification by the compression function Maplaw. In this way the envelopes generated in adjacent channels will be comodulated. This distorts the results in the OFM only condition. Under the premise to test the CI users with their normal everyday hearing program in an acoustic test, this distortion is not avoidable.

Furthermore and independent to this limitation of the band-pass filter bank, the question is, if adjacent electrodes really stimulate different spiral ganglion populations. If this is not the case, an assumption about an across frequency processing is not permitted. To answer this question, the next test course ‘Correlation CMR with the ability to discriminate electrode pitch’ (results in chapter 6.3) had the goal to differentiate between the electrodes by subjective pitch on electrodes 3-7.

The relatively small change of the CMR from the OFM+FB condition to the frequency shift condition commends that both, the stimuli delivery in the OFM+FB condition and in the frequency shift condition result in a broad banded excitation pattern. The assumption that the presentation of the stimuli exactly between the center frequencies of the CI channels leads to a change in CMR is highlighted as wrong.

7.3 Correlation CMR with ability to discriminate electrode pitch

Referring to chapter 7.2 the topic of this question was, if the magnitude of the CMR correlates with the ability of the CI user to discriminate adjacent electrodes in pitch as described in chapter 5.3.3

The pearson correlation factor is r=-0.21. Therefore, only a low correlation between the magnitude of the CMR and the ability of the CI user to discriminate adjacent electrodes in pitch could be proven.

A significant correlation could have been an evidence for a real Across Frequency Processing as a base for CMR in CI users. The reviewed test subjects did not show this correlation.

To evaluate the origin of this problem it is necessary to change the band-pass filter bank in a way that the overlap of adjacent filter functions is reduced. Then the question if the magnitude of the CMR correlates with the ability of the CI user to discriminate adjacent electrodes in pitch can be considered more objectively. But the problem originated by the superposition electrical fields provided by adjacent electrodes, which can lead to channel interaction, still remains.

7.4 General discussion

Generally, the results indicate that CI users with the MED-EL OPUS 2 Speech processor and the Pulsar or Sonata Implant show a difference in detection threshold between the uncorrelated and the comodulated test condition in an acoustic test, thus a CMR. This could be approved in all test conditions.

An adequate presentation level and the usual AGC settings are important factors for the accruement of a significant CMR in CI users. An experiment with one CI user in AGC off setting compared to standard AGC settings showed a profound reduction of CMR.

An interesting aspect is the detection attribute: CI users and NH partly used distinct detection attributes for differencing between the stimuli. NH normally could hear a tone inside the noise maskers in one of the three test stimuli per cycle, whereas CI users often just heard a difference between the test stimuli with the sinusoidal signal and the noise maskers compared to the other two with noise maskers only.

However, by definition this detection attribute difference between NH and CI users does not affect the CMR. The test challenge can be successfully completed by using one or both of the two discrimination attributes. Nevertheless, some CI users maintained to hear a tone inside the noise maskers after a period of practise during the test course.

There are some limitations of the test setup, which come by the acoustical presentation and the following signal processing of the speech processor: the stimulation even in the OFM only condition gets relatively broad banded because of the overlapping band pass filters in the speech processor. That is why the detection thresholds in the OFM only condition have to be considered with attention. To avoid this problem, further work on the CMR topic with non-acoustical stimuli presentation through a research interface, which is making single channel stimulation under exact control of the pulses possible, is planned.

Another aspect, which comes by acoustic presentation and signal processing in the speech processor and is influencing the threshold in the uncorrelated test condition is: an affection by an adverse superposition of the electrical fields arising from adjacent intracochlear electrodes and reaching the same population of spiral ganglion cells. So for example a dip in the amplitude modulation in the OFM channel can be filled not by the tone but by the electrical field of an adjacent electrode, when one of the FBs reaches a maximum at exactly this time. This then is clearly not a process of the central nervous system but a peripheral process due to the overlap of electrical stimulation.

In the only other experimental work concerning the CMR in CI users with a related test paradigm from Wagner (2002) within-channel cues had been in the focus. Wagner used an OFM and only 1 FB of 25 Hz bandwidth and presented it inside the same CI channel (center frequency around 2 kHz). In this way, only within-channel cues are available, no across-channel cues. Wagner could only observe a small CMR. According to previous findings (Nelson and Jin, 2004) more spectral channels seem to lead to a higher masking release in CI users.

8. Summary

8.1 Summary and further prospects

Today’s Cochlear Implant (CI) systems offer a great choice to many profoundly hearing impaired or deaf people who suffer from damage to the inner ear, allowing them to (re-)enter the acoustical world. In mean an increase of speech intelligibility in quiet to around 60 % mono syllables (unilaterally German Freiburger Einsilber) 6 months after implantation can be achieved (Laszig *et al.*, 2004). Social rehabilitation and an enormous increase in the quality of life for patients can often be accomplished by this clinical therapy.

However, a caveat exits: speech intelligibility of CI users in challenging listening environments, like modulated noise or interfering talkers is worse than of NH. In speech intelligibility tests CI users in contrast to NH receive no release of masking through modulated interfering noise instead of steady state interfering noise and the reasons are unclear (Qin and Oxenham, 2003; Stickney *et al.*, 2004; Loizou *et al.*, 2009; Li and Loizou, 2010; Cullington and Zeng, 2011).

A basic ability of the healthy auditory system of NH in this context is the facilitation of the detection of tones in noise by comodulated envelope fluctuations in different frequency regions (Hall and Haggard, 1983; Hall *et al.*, 1984; Hall *et al.*, 1988; Grose and Hall, 1992; Verhey *et al.*, 2003; Epp and Verhey, 2009). Natural sounds and human speech offer comodulated structures (Florentine *et al.*, 1996; Nelken *et al.*, 1999).

Hall et al. (1984) have labelled this psychoacoustical phenomenon Comodulation Masking Release (CMR). The dominant modulation rates within narrow speech bands coincide with those for which CMR is maximal (Hall and Haggard, 1983; Florentine *et al.*, 1996; Nelken *et al.*, 1999).

The topic of this work was to design a hearing test, which is suitable to evaluate the CMR in CI users. The next step was to question if CI users show a comodulation masking release in a flanking band experiment in an acoustic test by the use of their speech processor in the normal everyday hearing setting. As a reference group NH were tested with the same test setups.

The test setup included the determination of several detection thresholds:

First, as a reference condition the detection threshold of a sinusoidal signal was determined as a signal to noise ratio in an amplitude modulated narrow band noise (On Frequency Masker – OFM) at the center frequency of the CI systems speech processor.

Further, in the CMR test condition four adjacent amplitude modulated noise bands (Flanking Bands – FB) of the same bandwidth as the OFM were added on adjacent center frequencies of the band-pass filter bank of the speech processor. OFM and FB were either uncorrelated modulated or coherently modulated (comodulated). The masker spectrums of the uncorrelated and comodulated noise bands were identical. The CMR is defined as the difference in threshold of the sinusoidal signal in the uncorrelated and in the comodulated masker (Epp and Verhey, 2009).

Two parameters of the masking narrow noise bands were varied: i) the bandwidth and ii) the spectral arrangement. As a reference, NH were tested in each test condition.

The i) increased bandwidth (24 Hz to 48 Hz) results in a smaller CMR in NH (N=6) and CI users (N=8). The arithmetic mean of the CMR in NH were 12.7 dB (24 Hz) and 10.2 dB (48 Hz), CI user 11.8 dB (24 Hz) and 8.6 dB (48 Hz). The signal was presented with headphones to NH and audio cable to the CI users speech processor.

The same test condition in free field led to lower CMR's in CI users (N=8). The reason for this behaviour is probably mainly due to the fixed presentation level of 65 dB SPL in free field compared to the user defined comfortable level of test condition using the audio cable.

The second parameter varied in the next test condition was the ii) spectral arrangement of the masking narrow band noises by a fixed bandwidth (24 Hz) which means a spectral shift of all masking noise bands and the sinusoidal signal between the CI channel center frequencies. The presentation level was also fixed at 70 dB SPL (delivery via headphones to NH and CI users). The results indicate no big influence of the spectral arrangement of the OFM and FB's in NH (12.7 dB in the OFM+FB condition and 12.8 dB in the Frequency shift condition, N=7) as in CI users (9.2 dB in the OFM+FB condition and 8.5 dB in the frequency shift condition, n=11).

It is assumed that the speech processors band-pass filter bank, whose filter functions are over lapping, and independent to this, the superposition of the electrical fields provided through the adjacent intra cochlear electrodes lead both to a broad spectral excitation, which makes a clear correlation of CMR to spectral arrangement of the narrow noise bands impossible.

Finally, this assumption is supported through the further test condition: the correlation of the CMR to the ability of CI users (N=13) to discriminate adjacent electrodes in pitch. There could only be achieved a low correlation (r=-0.21).

In summary, the designed acoustic hearing test is suitable for testing the CMR in CI users and in NH. The test results are surprising because literature references (Wagner, 2002; Qin and Oxenham, 2003) didn't predict a CMR in CI users. This work could show, that under the described test conditions and with this test setup, CI users can show a CMR. According to literature a relatively broad banded stimulation (Nelson and Jin, 2004) and a relatively high presentation level seems to be important requirements for a CMR in CI users.

To prove a real across frequency processing in CI users, an acoustical test with it's limitations (given band pass filter bank with overlapping filter functions of the speech processor) is unsuitable. Further tests with narrow filter functions under exact control of the stimulation pulses are necessary to answer this question.

8.2 Zusammenfassung und Ausblick

Heutige Cochlea Implantat (CI)-Systeme eröffnen vielen hochgradig schwerhörigen oder tauben Menschen, die unter einem Innenohrschaden leiden, die Möglichkeit in die akustische Welt zurückzukehren. Taub geborenen Kindern steht in vielen Fällen sogar eine annähernd normale Sprachentwicklung offen. Im Mittel kann durch die CI-Versorgung 6 Monate nach Implantation eine Steigerung des Einsilberverstehens in Ruhe auf ca. 60% (Erwachsene, postlingual ertaubt, unilateral, Freiburger Einsilber) erzielt werden (Laszig et al., 2004). Soziale Rehabilitation und ein enormer Zugewinn an Lebensqualität können in vielen Fällen durch diese Form der klinischen Therapie erreicht werden.

Trotz dieser Erfolge der CI-Therapie besteht für Implantat-Träger im Vergleich zu Normalhörenden (NH) das Problem eines reduzierten Sprachverstehens in komplexen akustischen Umgebungen, wie z.B. modulierten Störgeräuschen oder konkurrierenden Sprechern. In Sprachverständnistests im Störgeräusch erfahren CI-Träger im Gegensatz zu NH keine Maskierungsreduktion (engl. Masking Release) durch modulierte, anstelle stationärer Störgeräusche. Die Begründung hierfür ist bis heute unklar (Qin and Oxenham, 2003; Stickney et al., 2004; Loizou et al., 2009; Li and Loizou, 2010).

Eine basale Fähigkeit des gesunden auditorischen Systems von NH ist in diesem Zusammenhang die akustische Objekttrennung von sich überlagernden Spektren unterschiedlicher Geräuschquellen durch synchrone Pegelschwankungen in unterschiedlichen Frequenzkomponenten des jeweiligen akustischen Objekts (beispielsweise ein Sprecher). Die vorliegende Arbeit untersucht die Sensitivität für synchrone (komodulierte) Pegelschwankungen von CI-Trägern im Vergleich zu NH anhand eines psychoakustischen Effektes: des Comodulation Masking Release (CMR) (Hall and Haggard, 1983; Hall et al., 1984; Hall et al., 1988; Grose and Hall, 1992; Verhey et al., 2003; Epp and Verhey, 2009). Natürliche Umweltgeräusche und Sprache besitzen komodulierte Strukturen (Florentine et al., 1996; Nelken et al., 1999). Die dominanten Modulationsfrequenzen in komodulierten Bereichen von Sprache entsprechen denen, für die der CMR maximal wird (Hall and Haggard, 1983; Nelken et al., 1999). Ein Innenohrschaden führt zu einem reduzierten CMR. Dies wird in der Literatur auf die verringerte Frequenzselektivität von Innenohrschwerhörigen zurückgeführt (Hall et al., 1988).

Das Thema dieser Arbeit war der Entwurf eines Hörtest, welcher für die Evaluation des CMR bei CI-Trägern geeignet ist. Im Fokus des nächsten Schritts stand die Frage, ob CI-Träger einen CMR in einem Flankenbandexperiment in einem akustischen Test unter Nutzung ihres Sprachprozessors mit Alltagshörprogramm zeigen. Als Referenzgruppe wurden NH mit dem jeweils gleichen Testsetup getestet.

Das Testsetup beinhaltete die Bestimmung verschiedener Mithörschwellen:

Erstens wurde als Referenzbedingung die Mithörschwelle eines sinusförmigen Signals in einem schmalbandigen, amplitudenmodulierten (d.h. mit aufgeprägter Pegelschwankung) Verdecker mit der Mittenfrequenz des Sinustons (On Frequency Masker – OFM) bestimmt. Die Mittenfrequenz von Signal und Verdecker lag auf der Mittenfrequenz des Kanals fünf des CI-Systems (Hersteller MED-EL, siehe Kapitel 5.3.2 sowie Abbildung 19). Bei NH lag die Signal- und Mittenfrequenz bei 854 Hz (einer typischen Mittenfrequenz des Kanals 5 bei diesem CI-System).

Zweitens wurden in der CMR Testbedingung vier spektral benachbarte amplitudenmodulierte Verdecker (Flankenbänder – FB) mit denselben Pegelschwankungen und gleicher Bandbreite wie der OFM zeitgleich zum OFM und dem zu erkennenden Signal dargeboten. Die Mittenfrequenzen der FB orientierten sich an den Mittenfrequenzen der benachbarten Kanäle des CI-Systems. Um den CMR zu bestimmen, wurden OFM und FB entweder unkorreliert moduliert oder komoduliert dargeboten und jeweils die Mithörschwelle des Tons bestimmt. Die Verdeckerenergie war in beiden Fällen gleich groß, die zeitliche Struktur aber unterschiedlich (siehe Abbildungen 11 und 12 in Kapitel 5.1). Bei NH zeigt sich bei zeitgleicher Darbietung von komodulierten FB zum OFM und Signal eine Reduktion der Mithörschwelle des Signals um 10-15 dB gegenüber der unkorrelierten Darbietung (Hall et al., 1984, Verhey et al., 2003). Durch die Addition von Störgeräuschenergie kann sich also bei entsprechender zeitlicher (komodulierter) Struktur die Mithörschwelle eines Signals in Verdeckungssituationen verbessern. Dieser zunächst paradox klingende Effekt wird in der Literatur auf unterschiedliche Arten definiert (siehe für Details: Verhey et al., 2003). In dieser Arbeit wurde die Definition von Epp und Verhey (2009) verwendet: der CMR entspricht der Differenz der Mithörschwelle eines Sinustons im unkorrelierten gegen komodulierten Verdecker bei gleicher Verdeckerenergie.

Darüber hinaus wurden zwei Parameter der schmalbandigen Verdecker variiert: i) Bandbreite und ii) spektrale Anordnung.

Die in i) veränderte Bandbreite (von anfangs 24 Hz auf 48 Hz, siehe Kapitel 5.3.1) resultiert in einem reduzierten CMR bei NH (N=6) und CI-Trägern (N=8). Die arithmetischen Mittelwerte des CMR in NH waren 12,7 dB (24 Hz) und 10,2 dB (48 Hz), in CI-Trägern 11,8 dB (24 Hz und 8,6 dB (48 Hz). Die Signale wurden per Kopfhörer (NH) bzw. Audiokabel (CI-Träger) dargeboten (siehe Kapitel 6.1.1).

Die gleiche Testbedingung im Freifeld führte insbesondere bei CI-Trägern zu einem geringeren CMR (N=8, siehe Kapitel 6.1.2). Die Begründung für diese Reduktion wird vor allem dem in der Freifeldbedingung normierten Schalldruckpegel des Störgeräusches von 65 dB SPL in 1m Abstand gesehen. Vielen CI-Trägern war dieser Pegel zu leise. Die Kalibrierung der Signale bei Darbietung per Audiokabel wurde dagegen individuell nach Vorbild des Oldenburger Hörfeldes vorgenommen und zielte auf einen subjektiv angenehm lauten Pegel des jeweiligen Probanden ab. Die optimale Lautheit scheint also einen großen Einfluss auf den CMR bei CI-Trägern zu haben.

Der zweite Parameter, der in der anschließenden Testkondition variiert wurde, war die ii) spektrale Anordnung der Rauschbänder und des Signals (siehe Kapitel 5.3.2). Die Bandbreite der Rauschbänder wurde in dieser Kondition konstant gehalten (24 Hz). Die Mittenfrequenzen wurden dagegen von den Kanalmitten des CI-Systems zwischen die Kanalmitten transponiert (siehe Abbildungen 20 und 25). Der Präsentationspegel wurde auf 70 dB SPL normiert (Darbietung per Kopfhörer für NH und CI-Träger). Die Ergebnisse weisen auf einen geringen Einfluss der Signal- und Verdeckermittenfrequenzen (OFM und FB) sowohl bei NH (12,7 dB in der OFM+FB Testkondition und 12,8 dB in der Transpositionsbedingung, N=7), als auch bei CI-Trägern (9,2 dB in der OFM+FB Testkondition und 8,5 dB in der Transpositionsbedingung, N=11) hin. Es wird angenommen, dass zum einen die Bandpassfilter-Bank deren Filterfunktionen überlappen und zum anderen die Kompressionsfunktion Maplaw im MED-EL CI-System zu einer spektral breiten nervösen Aktivierung des Spiralganglions führen. Darüber hinaus führt auch die Superposition von elektrischen Feldern von benachbarten intracochleären Elektroden zu einer, gerade bei hohen Stimulationsamplituden, überlappenden Anregung von Hörnervfaserpopulationen. Dies macht eine klare Korrelation des CMR mit der Anordnung der schmalbandigen Verdecker in einem akustischen Experiment bei normalem Hörprogramm unmöglich.

Diese Annahme wird unterstützt von der darauf folgenden Testbedingung (siehe Kapitel 5.3.3): die Korrelation des CMR mit der Fähigkeit der CI-Träger (N=13) benachbarte Elektroden anhand der subjektiven Tonhöhe zu unterscheiden. Dies soll ein Maß für die Unterschiedlichkeit der Hörnervfaserpopulation sein, die mit der entsprechenden Elektrode bei angenehm lautem Pegel erregt wird. In der dritten Testbedingung konnte allerdings keine signifikante Korrelation (Pearson-Korrelationsfaktor $r=-0,21$) nachgewiesen werden. Es wird angenommen, dass die spektral breite Aktivierung von Hörnervfasern Rückschlüsse von der Tonhöhenunterscheidungsfähigkeit auf den CMR verhindert.

Zusammenfassend lässt sich sagen, dass der entwickelte akustische Hörtest für die Bestimmung des CMR bei CI-Trägern geeignet ist. Darüber hinaus konnte gezeigt werden, dass CI-Träger von kohärenten Pegelschwankungen in unterschiedlichen Frequenzkomponenten profitieren können (t-Test der Mithörschwellen bei gepaarten Stichproben, $\text{uncorrelated}_{\text{OFM+FB}}$-$\text{comodulated}_{\text{OFM+FB}}$, $p<0,01$). Die gewonnenen Testergebnisse sind überraschend, da die wenigen bisher experimentell gewonnen Literaturdaten (Wagner, 2002) einen nur gering ausgeprägten CMR bei CI-Trägern in einem Flankenbandexperiment vorhersagten. Diese Arbeit konnte jedoch zeigen, dass unter den beschriebenen Testbedingungen und mit dem eingesetzten Testsetup, ein signifikanter CMR bei CI-Trägern messbar ist. Übereinstimmend mit Literaturdaten aus Sprachtests sind vermutlich eine relativ breitbandige spektrale Stimulation über mehrere CI-Kanäle (Nelson and Jin, 2004) und ein individuell angenehmer Präsentationspegel wichtige Voraussetzungen für den Nachweis eines CMR bei CI-Trägern zu sein.

Um frequenzübergreifende Prozesse (Chatterjee and Oba, 2004; Verhey, 2008) bei CI-Trägern in einem CMR Experiment nachzuweisen, stellte sich allerdings ein akustischer Test mit den gegebenen Einschränkungen durch den Sprachprozessor (Bandpass-Filterbank mit überlappenden Filterfunktionen und Kompressionsfunktion Maplaw) als nur eingeschränkt aussagekräftig heraus. Um dieser Frage weiter nachzugehen sind zusätzliche Tests mit kanalspezifischer Stimulation unter exakter Kontrolle der Stimulationspulse erforderlich.

9. Literature

Battmer RD, Dillier N, Lai WK, Begall K, Leypon EE, Gonzalez JC, Manrique M, Morera C, Muller-Deile J, Wesarg T, Zarowski A, Killian MJ, von Wallenberg E, Smoorenburg GF (2010) Speech perception performance as a function of stimulus pulse rate and processing strategy preference for the Cochlear Nucleus CI24RE device: relation to perceptual threshold and loudness comfort profiles. Int J Audiol 49:657-666.

Baumann U, Seeber B (2001) Bimodale Versorgung mit Cochlea-Implantat und Hörgerät: Verbesserung von Sprachverständnis und Lokalisation. Z Audiol:36–39.

Blamey P, Arndt P, Bergeron F, Bredberg G, Brimacombe J, Facer G, Larky J, Lindstrom B, Nedzelski J, Peterson A, Shipp D, Staller S, Whitford L (1996) Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants. Audiol Neurootol 1:293-306.

Brungart D, Iyer N, Simpson B (2006) Monaural speech segregation using synthetic speech signals. J Acoust Soc Am 119:2327-2333.

Buechner A, Brendel M, Saalfeld H, Litvak L, Frohne-Buechner C, Lenarz T (2010) Results of a pilot study with a signal enhancement algorithm for HiRes 120 cochlear implant users. Otol Neurotol 31:1386-1390.

Buus S (1985) Release from masking caused by envelope fluctuations. J Acoust Soc Am 78:1958-1965.

Chatterjee M, Oba S (2004) Across- and within-channel envelope interactions in cochlear implant listeners. J Assoc Res Otolaryngol 5:360-375.

Clark G (2003) Cochlear Implants. Fundamentals and Applications. New York, Berlin Heidelberg.

Cohen LT, Richardson LM, Saunders E, Cowan RS (2003) Spatial spread of neural excitation in cochlear implant recipients: comparison of improved ECAP method and psychophysical forward masking. Hear Res 179:72-87.

Cullington HE, Zeng FG (2011) Comparison of bimodal and bilateral cochlear implant users on speech recognition with competing talker, music perception, affective prosody discrimination, and talker identification. Ear Hear 32:16-30.

Drennan W, Rubinstein J (2008) Music perception in cochlear implant users and its relationship with psychophysical capabilities. J Rehabil Res Dev 45:779-789.

Durlach N (1963) Equalization and cancellation theory of binaural masking-level differences. J Acoust Soc Am 35:1206–1218.

Epp B, Verhey JL (2009) Superposition of masking releases. Journal of Computational Neuroscience 26:393-407.

Fletcher H (1940) Auditory patterns. Rev Mod Phys 12:47-61.

Florentine M, Buus S, Poulsen T (1996) Temporal integration of loudness as a function of level. J Acoust Soc Am 99:1633-1644.

Grose J, Hall J (1996) Cochlear hearing loss and the processing of modulation: Effects of temporal asynchrony. The Journal of the Acoustical Society of America 100:519-527.

Grose JH, Hall JW, 3rd (1992) Comodulation masking release for speech stimuli. J Acoust Soc Am 91:1042-1050.

Hall J, Haggard M (1983) Co-Modulation - A principle for auditory pattern analysis. J Acoust Soc Am 76:69-71.

Hall J, Haggard M, Fernandes M (1984) Detection in noise by spectrotemporal pattern analysis. J Acoust Soc Am 76:50-56.

Hall J, Davis A, Haggard M, Pillsbury H (1988) Spectro-temporal analysis in normal-hearing and cochlear-impaired listeners. J Acoust Soc Am 84:1325-1331.

Hansen M (2008) PsyLab. In. Institut fuer Hoertechnik und Audiologie Fachhochschule OOW Oldenburg, Germany.

Hilbert D (1912) Grundzüge einer allgemeinen Theorie der linearen Integralgleichungen: Cornell University Library.

HoerTech GmbH I (25. Juli 2000) Entwicklung und Evaluation eines Satztests in deutscher Sprache I: Design des Olden-burger Satztests. In.

http://www.hearcom.eu/prof/DiagnosingHearingLoss/AuditoryProfile/OMAModuleAcalos/05-kls-Kategoriale-Lautheitsskalierung-ger.pdf (2010) Kategoriale Lautheitsskalierung, Oldenburger Hörfeld. In.

Hussong A, Rau TS, Ortmaier T, Heimann B, Lenarz T, Majdani O (2010) An automated insertion tool for cochlear implants: another step towards atraumatic cochlear implant surgery. Int J Comput Assist Radiol Surg 5:163-171.

Kluenter H, Lang-Roth R, Beutner D, Hüttenbrink K, Guntinas-Lichius O (2010) Postural control before and after cochlear implantation: standard cochleostomy versus round window approach. Acta Otolaryngol 130:696-701.

Laszig R, Aschendorff A, Stecker M, Muller-Deile J, Maune S, Dillier N, Weber B, Hey M, Begall K, Lenarz T, Battmer RD, Bohm M, Steffens T, Strutz J, Linder T, Probst R, Allum J, Westhofen M, Doering W (2004) Benefits of bilateral electrical stimulation with the nucleus cochlear implant in adults: 6-month postoperative results. Otol Neurotol 25:958-968.

Levitt H (1971) Transformed Up-Down Methods in Psychoacoustics. Transformed Up-Down Methods in Psychoacoustics:467-477.

Li N, Loizou P (2010) Masking release and the contribution of obstruent consonants on speech recognition in noise by cochlear implant users. J Acoust Soc Am 128:1262-1271.

Loizou PC, Hu Y, Litovsky R, Yu G, Peters R, Lake J, Roland P (2009) Speech recognition by bilateral cochlear implant users in a cocktail-party setting. J Acoust Soc Am 125:372-383.

May F (2010) Charge Balanced Biphasic. In.

MED-EL (2007) Focus on Fine hearing Technology. In. Innsbruck: Company MED-EL.

MED-EL (2010) Maestro 4.0 Fitting Software. In.

Michelson RP, Merzenich MM, Pettit CR, Schindler RA (1973) A cochlear prosthesis: further clinical observations; preliminary results of physiological studies. Laryngoscope 83:1116-1122.

Nelken I, Rotman Y, Yosef O (1999) Responses of auditory-cortex neurons to structural features of natural sounds. NATURE 397:154-157.

Nelson D, Van Tasell D, Schroder A, Soli S, Levine S (1995) Electrode ranking of "place pitch" and speech recognition in electrical hearing. J Acoust Soc Am 98:1987-1999.

Nelson PB, Jin SH (2004) Factors affecting speech understanding in gated interference: cochlear implant users and normal-hearing listeners. J Acoust Soc Am 115:2286-2294.

O'Leary SJ, Richardson RR, McDermott HJ (2009) Principles of design and biological approaches for improving the selectivity of cochlear implant electrodes. J Neural Eng 6:055002.

Oxenham A (2008) Pitch Perception and Auditory Stream Segregation: Implications for Hearing Loss and Cochlear Implants. TRENDS AMPLIF 12.

Pierzycki RH, Seeber BU (2010) Indications for temporal fine structure contribution to co-modulation masking release. J Acoust Soc Am 128:3614-3624.

Qin M, Oxenham A (2003) Effects of simulated cochlear-implant processing on speech reception in fluctuating maskers. J Acoust Soc Am 114:446-454.

Richards VM (1987) Monaural envelope correlation perception. J Acoust Soc Am 82:1621-1630.

Schatzer R, Krenmayr A, Au DK, Kals M, Zierhofer C (2010) Temporal fine structure in cochlear implants: preliminary speech perception results in Cantonese-speaking implant users. Acta Otolaryngol 130:1031-1039.

Schooneveldt G, Moore B (1989) Comodulation masking release (CMR) as a function of masker bandwidth, modulator bandwidth, and signal duration. J Acoust Soc Am 85:273–281.

Shannon C (1949) Communication in the Presence of Noise. Proc IRE 37.

Shannon RV (1992) Temporal modulation transfer functions in patients with cochlear implants. J Acoust Soc Am 91:2156-2164.

Smith M, Delgutte B, Oxenham A (2002) Chimaeric sounds reveal dichotomies

in auditory perception. Nature 416:87-90.

Stickney GS, Zeng FG, Litovsky R, Assmann P (2004) Cochlear implant speech recognition with speech maskers. J Acoust Soc Am 116:1081-1091.

Stobich B, Zierhofer CM, Hochmair ES (1999) Influence of automatic gain control parameter settings on speech understanding of cochlear implant users employing the continuous interleaved sampling strategy. Ear Hear 20:104-116.

Verhey J (2008) Comodulation masking release: an example of across-frequency processing of coherent level fluctuations. Z Audiol 47:10-20.

Verhey JL, Dau T, Kollmeier B (1999) Within-channel cues in comodulation masking release (CMR): experiments and model predictions using a modulation-filterbank model. J Acoust Soc Am 106:2733-2745.

Verhey JL, Pressnitzer D, Winter IM (2003) The psychophysics and physiology of comodulation masking release. Exp Brain Res 153:405-417.

Wagner E-M (2002) Across-Channel Processing in Auditory Perception: A Study in Gerbils (Meriones unguiculatus) and Cochlear-Implant Subjects In: Dissertation Lehrstuhl für Zoologie: Technische Universität München.

Zeng F, Popper A, FAY R (2004) Cochlear implants: auditory prostheses and electric hearing. New York, Berlin: Springer.

Zeng FG (2002) Temporal pitch in electric hearing. Hear Res 174:101-106.

Zirn S, Karg S, Hemmert W, Kummer P (2010a) Comodulation Masking Release bei Cochlea Implantat-Trägern: Abhängigkeit von Stimulationsrate, Modulationsrate und Bandbreite des Maskierers. In: Jahrestagung der Deutschen Gesellschaft für Audiologie (DGA). Frankfurt.

Zirn S, Karg S, Hemmert W, Hempel J-M (2010b) Comodulation Masking Release bei Cochlea Implantat-Trägern: Abhängigkeit von der spektralen Zusammensetzung des akustischen Reizes In: Herbsttagung der ADANO. Zürich: German Medical Science GMS Publishing House.

Zwicker E (1961) Subdivision of the Audible Frequency Range into Critical Bands J Acoust Soc Am 33:248–248

Zwicker E, Fastl H (1999) Psychoacoustics - Facts and Models, 2. Edition.

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