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# ESTIMATING FREQUENCY AND SPECTRAL RIPPLE DISCRIMINATION THRESHOLDS WITH THE AUDITORY CHANGE COMPLEX IN NORMAL HEARING SUBJECTS AND COCHLEAR IMPLANT USERS

## A COMPARISON WITH ESTIMATED BEHAVIOURAL DISCRIMINATION THRESHOLDS

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# Content

# Abstract

Objective

The goal of this study was to investigate the relationship between estimated behavioural and electrophysiological frequency and spectral ripple discrimination thresholds in normal hearing subjects and cochlear implants (CI) users. The Auditory Change Complex (ACC; a neural response as a reaction to a within-stimulus change (Kim, 2015)) was investigated as a possible objective measure of auditory discrimination. In addition, the relationship between speech perception and discrimination thresholds (both behavioural and electrophysiological) was investigated in CI users.

Method

Stimuli consisted of spectral ripples with different densities (ripples per octave) and a phase inversion at midpoint, and pure tones with a base frequency of 1000 Hz and a frequency increase at midpoint. Total duration of a stimulus was 1240 msec, meaning that change occurred at 620 msec. Behavioural discrimination thresholds were estimated using a single-interval yes/no test. Electrophysiological thresholds were estimated with the ACC in a 2-channel EEG-recording. Twenty-one normal hearing subjects and ten CI users (nine MED-EL, one Advanced Bionics) participated in this study. A within-subject comparison of thresholds found in both tests was made to determine the relationship between the thresholds.

Results

*Frequency*: Normal hearing subjects and CI users did not differ in behavioural thresholds, but CI users showed worse electrophysiological thresholds. Behavioural thresholds were a more sensitive measure of auditory discrimination than electrophysiological thresholds. No significant correlation was found between behavioural and electrophysiological thresholds for normal hearing subjects (N = 12). A significant strong and positive correlation was found for CI users (N = 8), indicating higher (i.e., worse) behavioural thresholds with higher electrophysiological thresholds. Variation in offset between behavioural and electrophysiological threshold was large between subjects. No correlation was found between speech perception and behavioural and electrophysiological thresholds in CI users.

*Spectral ripples*: CI users showed worse behavioural and electrophysiological thresholds than normal hearing subjects. Behavioural thresholds were more sensitive than electrophysiological thresholds. No significant correlation was found between behavioural and electrophysiological thresholds for normal hearing listeners (N = 12) nor CI users (N = 5). Offset between behavioural and electrophysiological threshold varied considerably between subjects. Once again, no correlation was found between speech perception and behavioural and electrophysiological thresholds in CI users.

Discussion and Conclusion

Based on the results from this study, the applicability of the ACC as an objective measure of auditory discrimination appears limited. It was found to be possible to estimate an electrophysiological auditory discrimination threshold using the ACC in normal hearing listeners and CI users. However, a significant relation between behavioural and electrophysiological thresholds was only found for frequency discrimination in CI users. Offset between both thresholds was found to vary considerably between subjects, which limits possible clinical value. Additionally, frequency and spectral ripple thresholds did not correlate with speech perception scores in CI users, which further reduces possible clinical value.



*Keywords*: cochlear implant, auditory discrimination, auditory change complex, spectral ripples, frequency

# 1. Introduction

Being able to discriminate sounds, and thus differences in frequency, intensity, etc., is essential for understanding speech (e.g., Harris, Mills, He, & Dubno, 2008). For example, strong correlations have been found between frequency discrimination and speech perception in noise (Parbery-Clark, Skoe, Lam, & Kraus, 2009). This discriminatory capacity is, however, not a given for everyone. People with hearing loss or people who are deaf are not (always) able to discriminate sounds (to the same extent as normal hearing listeners), even when they have a conventional hearing aid or a cochlear implant (CI). This negatively impacts their speech perception (e.g., Zhang et al., 2019). It is therefore important that besides auditory detection also auditory discrimination can be measured in CI users. Though subjective behavioural measures of auditory discrimination are available, they are not always a viable option, especially when investigating auditory discrimination in difficult-to-test populations such as paediatric, non-compliant, or non-verbal patients. Objective measures are thus required.

In recent years, the Auditory Change Complex (ACC) has gained attention as a possible objective measure of auditory discrimination. Especially discrimination thresholds determined using the electrically-evoked ACC have been shown to correlate well with speech perception measures in CI users (e.g., He et al., 2013). The thresholds based on ACC recordings will be central to this thesis. Specifically, spectral ripple and frequency discrimination thresholds will be investigated, as spectral ripple discrimination has been shown to correlate well with speech and music perception in CI users (e.g., Won, Drennan, & Rubinstein, 2007; Won, Drennan, Kang, & Rubinstein, 2010) and frequency discrimination has been shown to correlate well with speech perception in noise (e.g., McGuire, Firestone, Zhang, & Zhang, 2021; Zhang et al., 2019). First, a brief introduction will be given on the anatomy and physiology of the ear, cochlear implants, and auditory evoked potentials. After this, the ACC will be discussed in detail and the research questions and goals of the current study will be described.

## 1.1 Anatomy and physiology of the ear

The human ear can be divided into three parts: the outer, middle, and inner ear (McFarland, 2014).

### 1.1.1 Outer ear

The outer ear consists of the auricle and the ear canal. The function of the auricle is to capture and transmit sound waves towards the ear canal. In addition, it supports sound localisation (Seikel, Drumright, & King, 2015). The ear canal has the function of amplifying the sounds of some frequencies, while at the same time suppressing sounds of other frequencies (Emanuel, Maroonroge, & Letowski, 2000). The tympanic membrane can be found at the end of the ear canal. Due to acoustic energy the tympanic membrane vibrates (McFarland, 2014).

### 1.1.2 Middle ear

The tympanic cavity and the ossicles (the malleus, incus, and stapes) together are referred to as the middle ear (Seikel et al, 2015). The ossicles function as a lever, an amplifier of the vibrations of the tympanic membrane, and transfer these vibrations to the oval window.

An important feature of the middle ear is the transfer of sound waves that travelled through air (in the outer ear) to periodic pressure variation in liquid (perilymph in the inner ear). The impedance of a fluid is higher than the impedance of air. This difference of impedance causes a loss of sound (Lamoré, 2008). The ossicles serve as an amplifier to compensate for this loss.

### 1.1.3 Inner ear

The inner ear can be found in the osseus labyrinth (Maroonroge, Emanuel, & Letowski, 2000). The two major components of the inner ear are the cochlea and the vestibular system.

The cochlea is divided into three parts: the scala vestibuli, scala tympani, and scala media. At

the onset of the basilar membrane, the beginning of the cochlea, the scala media is rigid. Towards the apex, the end of the basilar membrane, the scala media grows more flexible. The onset of the basilar membrane is stimulated by high frequencies, while the end of the basilar membrane is stimulated by low frequencies: the basilar membrane is tonotopically organised (Maroonroge et al., 2000).

The organ of Corti is the sensory end organ of the scala media. It consists of sensory hair cells that transmit signals to the auditory nerve. The neural impulses travel through the auditory nerve and the auditory brainstem to the auditory cortex (Maroonroge et al., 2000).

## 1.2 Cochlear implants

Cochlear implants are used to help individuals with profound sensorineural hearing loss or deafness. Sensorineural hearing loss is caused by problems located in the cochlea, the auditory nerve, or further up the auditory pathway (Isaacson & Vora, 2003). There are many causes for sensorineural hearing loss, including normal aging, exposure to loud noise, diseases and head trauma, or it can be genetically determined (Morton & Nance, 2006).

When there are problems with the functioning of the cochlea, acoustic stimulation is not available to provide a sense of hearing. This makes it necessary to resort to other options to communicate. To be able to provide a sensation of hearing, electrical stimulation through implantation of electrodes in the cochlea is used (Clark, 2004).

A cochlear implant (CI) consists of an external section (the microphone and speech processor), an internal section (the electrode array that is inserted into the cochlea), and the receiver-stimulator forming the bridge between these two sections (Clark, 2004). The electrodes in the cochlea are activated based on the input they receive from the external section of the device. Extraction of information about sounds is limited in multiple domains (frequency, temporal, amplitude) in CI users (Macherey & Carlyon, 2014). One of the main restrictions of cochlear implants is that the number of electrodes inserted into the cochlea is relatively limited. Consequently, the dynamic range of effective stimulation is also limited (Lenarz, 2017).

After receiving a CI at a young age, the majority of congenitally or prelingually deafened children are able to perceive speech to a high accuracy and develop close to normal language skills (Peterson, Pisoni, & Miyamoto, 2010) that are comparable to those of age-matched normal-hearing children (Dowell, Dettman, Blamey, Barker, & Clark, 2002). Postlingually deafened CI users are often able to perceive and produce speech without major difficulties and without the need of visual aid after receiving an implant. There is, however, a substantial amount of variation between CI users. Some CI users achieve word recognition scores of 95% or higher, whilst other CI users may struggle to obtain word recognition scores of 20% (e.g., Helms et al., 1997; Wilson & Dorman, 2007). The underlying causes of this individual variation are not completely understood as of yet (Peterson et al., 2010).

Even though CI users might be able to achieve close to normal speech perception, this is often only the case in an otherwise quiet environment. CI users frequently experience problems with understanding speech in noise (Fu, Shannon, & Wang, 1998).

## 1.3 Objective measures of auditory discrimination

Behavioural measures of auditory discrimination are readily available and are often used in clinical settings. A major disadvantage of behavioural measures of auditory discrimination, however, is that they are subjective and that there might be factors present (either linguistic, cognitive or behavioural) that can have an effect on and are difficult to disentangle from auditory discrimination (He, Grose, & Buchman, 2012). Objective measures, such as electrophysiological methods, may make it possible to investigate auditory discrimination without effects of non-auditory factors. For this reason, electrophysiological methods may be suitable for objectively measuring auditory discrimination in difficult-to-test populations, such as young children or people with cognitive impairments, for whom behavioural measures are not a feasible option (Boothroyd, 1991; Ostroff, Martin, & Boothroyd, 1998).

In the following, an electrophysiological method, electroencephalography (EEG), and its relation to auditory evoked potentials (AEPs), which can be used for objectively measuring auditory capacity, will be described.

### 1.3.1 Measuring auditory evoked potentials using electroencephalography

The central nervous system generates spontaneous neuroelectric activity (Jacobson, 1994). EEG, a non-invasive method, is an often used method for measuring this activity. Using electrodes that are placed on the scalp, the neuroelectric activity of firing neurons can be measured (Light et al., 2010). An advantage of EEG is that the temporal resolution is good. The spatial resolution, however, is relatively poor (Lakshmi, Prasad, & Prakash, 2014).

Evoked potentials (EPs) are measured using EEG. EPs are electrical changes occurring in the central nervous system. The EP is named after the sensory system that is being stimulated. An EP caused after stimulation of the auditory system is thus named an auditory evoked potential (AEP) (McPherson, 1996).

### 1.3.2 Classification of auditory evoked potentials

AEPs can be classified into three types based on latency (Møller, 1994) (see Figure 1 (Khuwaja, Haghighi, & Hatzinakos, 2015, p. 2) for a visualisation):

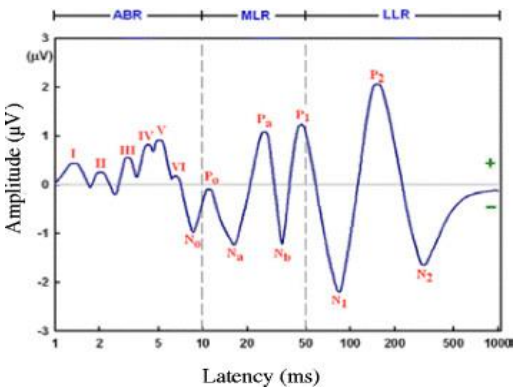



*Figure 1 – Classification of auditory evoked potentials by latency into auditory brainstem responses, middle-latency responses, and long-latency responses, including common nomenclature of different (positive and negative) peaks. Reprinted from "40-Hz ASSR fusion classification system for observing sleep patterns" by G.A. Khuwaja, S.J. Haghighi and D. Hatzinakos, 2015, EURASIP Journal on Bioinformatics and Systems Biology, p. 2.*

1. Short-latency auditory evoked potentials (SLAEP): SLAEPs occur within 10 msec after presentation of a stimulus. Electrocochleographic potentials and auditory brainstem responses fall into this category (Møller, 1994).
2. Middle-latency auditory evoked potentials (MLAEP): MLAEPs occur 10-50 msec after presentation of a stimulus (Møller, 1994). MLAEPs are affected by attention, wakefulness, and age (Pratt, 2011).
3. Long-latency auditory evoked potentials (LLAEP): LLAEPs occur 50-500 msec after presentation of the stimulus (Møller, 1994). LLAEPs can be endogenous (or cognitive) or exogenous (or obligatory) (Näätänen, 1992). Exogenous potentials are elicited by an external change that is related to the dimensions of the stimulus, such as timing or sequencing. Endogenous potentials occur in response to internal changes related to perception or cognition. LLAEPs occurring at a latency between 200-600 msec are considered to be endogenous. Responses with a latency shorter than 200 msec are considered to be exogenous (McPherson, 1996).

In this thesis, there will be a focus on LLAEPs, also known as cortical auditory evoked potentials (CAEP) (Kim, 2015). Cortical responses are important when looking at hearing capabilities of CI users because when a CAEP is present in the signal, this is indicative of activation of the higher levels of the auditory pathway through electrical stimulation (Cullington, 2002). In addition, there is evidence that cortical function and CI outcomes have a stronger relation than CI outcomes and neural responses derived from lower levels of the auditory system (Anderson, Lazard, & Hartley, 2017).

### 1.3.3 Slow Vertex Potential

The Slow Vertex Potential (SVP), also known as the (P1-)N1-P2 complex or onset response, is an exogenous CAEP that is usually measured from the vertex. It consists of negative and positive peaks that are elicited by an abrupt change in auditory environment (Hyde, 1994a, 1994b). It reflects auditory detection (e.g., Martin, Tremblay, & Korczak, 2008). The SVP can be elicited by different types of stimuli (e.g., tonal stimuli, speech, and noise). The N1 can be found around 100 msec after stimulus onset. The P2 is visible at around 175 msec after stimulus onset. The latency and amplitude of the SVP are slightly variable between normal hearing listeners (Hyde, 1994a, 1994b). The amplitude of the SVP is generally larger when the listener attends to the stimulus than when no attention is given to the sound (Liang, Houston, Samy, Abedelrehim, & Zhang, 2018).

Postlingually deafened CI users have (P1-)N1-P2 responses that are comparable to neural responses of normal hearing listeners (Ponton & Eggermont, 2001), but latencies may be increased whilst amplitudes may be decreased (Kelly, Purdy, & Thorne, 2005; Ponton, Don, Eggermont, Waring, & Masuda, 1996). Prelingually deafened CI users may show immature or atypical waveforms (Gordon, Tanaka, Wong, & Papsin, 2008).

## 1.4 The Auditory Change Complex

The Auditory Change Complex (ACC) is an exogenous CAEP that is visible in response to changes in an ongoing stimulus (e.g., changes in frequency or intensity). The ACC is thought to reflect neural detection of auditory changes in the auditory cortex (Kim, 2015; Martin, Tremblay, & Stapells, 2007), which might make it suitable to be used as an objective measure of auditory discrimination. This would be valuable for examining auditory discrimination in difficult-to-test populations. While some studies have found that the ACC is less sensitive than behavioural measures of auditory discrimination (e.g., Brown et al., 2017; Won et al., 2011), other studies claim that the ACC might provide evidence over behavioural auditory discrimination (i.e., the ACC was visible in the absence of correct behavioural auditory discrimination; Mathew et al., 2017, 2018). The latter claim is, however, not supported by much evidence and may therefore be questioned. More research on this topic is warranted.

The ACC generally has a smaller P-P amplitude than the SVP. It does have similar morphologic characteristics, both in normal hearing listeners and CI users (e.g., Brown et al., 2008; Martin & Boothroyd, 1999). While some studies find prolonged latencies for the ACC compared to the SVP (e.g., Martin & Boothroyd, 1999), others do not (e.g., Brown et al., 2008). Shetty and Manjula (2012) showed that different transducers (headphones or loudspeakers) did not lead to significant differences in amplitude or latency of the ACC. They did find an effect of gender, with women generally having shorter latencies than men, possibly due to smaller head circumference.

### 1.4.1 Brief overview of research on the ACC

Ostroff et al. (1998) investigated the ACC in normal hearing subjects using syllables changing from consonant to vowel. They found that it was possible to detect a response to the change in the middle of the syllable that was similar in morphology to the SVP. According to Ostroff et al. this response indicated whether auditory discrimination capacity was present and they saw possible clinical value. After this, Martin and Boothroyd (1999, 2000) investigated the ACC in tonal stimuli, to ascertain that changes in spectrum, amplitude and periodicity all elicited the ACC separately. In addition, it turned out to be possible to elicit the ACC in subjects with (sensorineural) hearing loss, both in subjects with and without hearing aids (e.g., Kumar, Singh, Sanju, & Kaverappa, 2020; Martinez, Eisenberg, & Boothroyd, 2013; Tremblay, Billings, Friesen, & Souza, 2006).

Since then, multiple studies have been executed on the ACC where different aspects of the response were investigated. Examples include looking at stimulus presentation strategies for increasing efficiency of the measurements and obtaining the clearest responses (Martin, Boothroyd,

Ali, & Leach-Berth, 2010; Vonck, Lammers, van der Waals, van Zanten, & Versnel, 2019), effect of pre-transition duration on the ACC (Ganapathy, Narne, Kalaiah, & Manjula, 2013), and the relationship between the ACC and behavioural measures of auditory discrimination (e.g., He, Grose, & Buchman, 2012) and speech perception (Vonck et al., 2021). Although most studies have investigated (pure tone) frequency changes or speech stimuli, spectral ripple changes have received more interest in the last few years (e.g., Horn, Won, Rubinstein, & Werner, 2017; Lopez Valdes et al., 2014, 2015).

Research on the ACC in children is relatively scarce. Martinez and colleagues (2013) investigated the ACC as a response to speech stimuli in normal hearing adults and children, and children with hearing aids. They found that it was possible to record the ACC in children, but only included children that were older than two. Chen and Small (2015) showed that the ACC could be elicited in normal hearing four-month old infants in response to speech stimuli. They do note that stimuli duration should be longer when investigating infants because of a longer refractory period. Research in children using stimuli other than speech is lacking and more research is needed.

### 1.4.2 Advantages and disadvantages of the ACC

Compared to the Mismatch Negativity (MMN) and P300, that are traditionally used to investigate auditory discrimination, there are multiple advantages to be named for the ACC (Kim, 2015). A major advantage is that fewer trials are needed to evoke the ACC response. In addition, all stimuli that are presented can be used for investigating auditory discrimination, not only the deviant stimuli. This leads to a smaller number of responses needed to obtain a relatively good signal-to-noise ratio (Kim, 2015). Moreover, it has been shown that the ACC, in general, has larger amplitudes than the MMN (around 2.5 times larger; Martin & Boothroyd, 1999), which makes the ACC easier to detect than the MMN. Another advantage of the ACC is that it can be measured in the absence of attention and does not require active participation, in contrast to the P300 (Kim, 2015). These aspects argue well for clinical application of the ACC in difficult-to-test populations, for whom (prolonged) attention to a task or active participation may not be possible. Lastly, good test-retest reliability of the ACC has been found both in normal hearing subjects (Tremblay, Friesen, Martin, & Wright, 2003) and CI users (Friesen & Tremblay, 2006).

The major advantage of the ACC as a measure of auditory discrimination over behavioural measures is that it is not affected by non-auditory factors such as linguistic and cognitive capabilities (He et al., 2012). However, compared to behavioural measures, a disadvantage of electrophysiological measures such as the ACC is that an EEG set-up is needed to collect the data. In addition, because of the noise that is inevitably present in the signal, it might be difficult to disentangle the actual signal from noise. The ACC is therefore expected to be less sensitive than behavioural measures of auditory discrimination.

### 1.4.3 The ACC in CI users

When investigating the ACC in CI users there is a distinction between direct (often named the Electrical ACC) and indirect stimulation of the implant when eliciting the ACC: see Figure 2 (Beynon, Luijten, & Mylanus. 2021, p. 693). Indirect stimulation consists of presenting stimuli in the free field. When using direct stimulation, the speech processor is bypassed and a stimulus is presented directly to the electrodes of the implant. An advantage of direct stimulation is that it allows for more control of the output of the electrode array. In addition, settings of the speech processor may differ between CI users and this might make it difficult to compare results from different CI users. This is avoided by using direct stimulation (Brown et al., 2008). However, direct stimulation is less ecologically valid than indirect stimulation, since what CI users hear after direct stimulation is different from what they hear

in daily life (e.g., Brint, 2017; Martin, 2007). For this reason, indirect stimulation will be used in the current study.

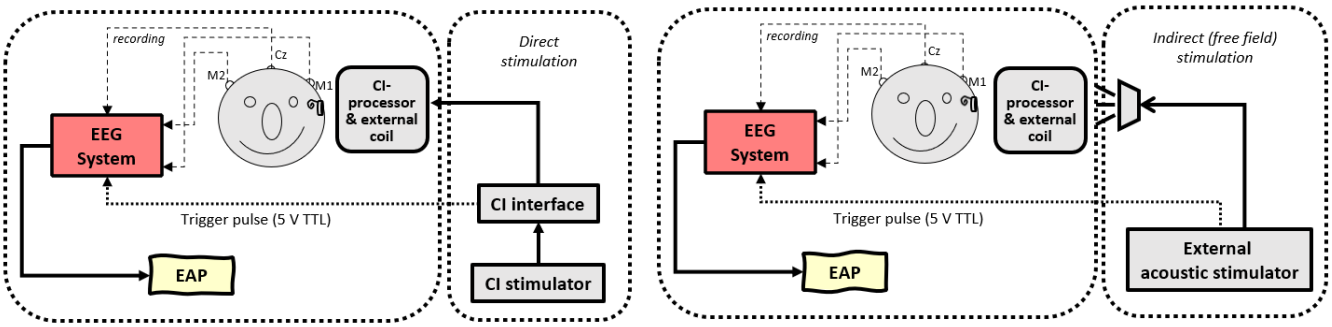



*Figure 2 – Schematic overview of conventional extracorporeal EEG setups with (a) direct stimulation: electrical pulses are generated by clinical CI software, directly streamed through the speech processor and presented to the intracochlear electrodes vs. (b) indirect stimulation: sounds are presented to the CI processor via a soundfield loudspeaker by an external stimulator. In both setups, an external EEG device is triggered by a stimulator to record time-locked electrically evoked auditory potentials (EAP). Reprinted from "Intracorporeal cortical telemetry as a step to automatic closed-loop EEG-based CI fitting: A proof of concept" by A.J. Beynon, B.M. Luijten, and E.A.M. Mylanus, 2021, Audiology Research, 11, p. 693.*

The first study that investigated the use of the ACC in CI users was by Friesen and Tremblay (2006) who showed that the ACC could be evoked reliably in CI users using speech stimuli. Different response patterns were found for good and poor CI users. After this, studies have been executed on the ACC in CI users focusing on, among others, removing CI artefact (e.g., Martin, 2007), use of different types of stimuli such as pure tones (e.g., Liang et al., 2018), speech (Martinez et al., 2013), and spectral ripples (Won et al., 2011), and changes of different aspects of the signal such as frequency (Liang, 2017), amplitude (Han & Dimitrijevic, 2020), and gap detection (He, Grose, Teagle, & Buchman, 2014), direct stimulation of the implant and electrode discrimination (e.g., Mathew et al., 2017), estimating thresholds (e.g., Liang et al., 2018), and relation of these ACC-based thresholds with behavioural discrimination (e.g., Mathew et al., 2017).

### 1.4.4 The ACC and frequency discrimination

#### 1.4.4.1 Normal hearing subjects

The first stimulus type that will be investigated in this study is pure tones containing frequency changes. Compared to research on effects of stimulus parameters on the ACC and possible relationships of amplitudes and latencies of the ACC with behavioural measures of frequency discrimination, research on estimating discrimination thresholds using the ACC is relatively scarce. However, recently it has become clear that the ACC-based electrophysiological discrimination threshold appears to be a more robust measure of auditory discrimination than ACC amplitude, as there is a lot of inter-subject variability in ACC amplitudes in response to frequency changes in normal hearing subjects (e.g., Harris et al., 2008; Martin & Boothroyd, 2000; Vonck et al., 2019). For this reason thresholds are thought to be better suited for potential clinical use (Vonck et al., 2021). Hence, this thesis will focus on ACC-based electrophysiological thresholds for frequency discrimination.

Only few studies have investigated frequency discrimination thresholds using the ACC, namely Harris and colleagues (2008), He and colleagues (2012), Brown and colleagues (2017), and Vonck and colleagues (2021). The thresholds that were found in these studies are shown in Table 1.

*Table 1 - Overview of frequency discrimination thresholds (obtained using the ACC) in normal hearing listeners*

| Publication | Behavioural threshold | Electrophysiological threshold |
|---|---|---|
| *Harris et al. (2008)* | Not investigated | Young: *M* = 1.2% (0.5 kHz)/1.6% (3 kHz), range = 0.8 – 1.8% of base frequency (N = 10); Old: *M* = 2.4 (0.5 kHz)/2.1% (3 kHz), range = 1.2 – 3.4% of base frequency (N = 10) |
| *He et al. (2012)* | *M* = 3.6 Hz (0.72% of base frequency of 0.5 kHz), range = 1.9 – 5.7 Hz (i.e., 0.4 – 1.1%) (N = 12) | *M* = 5.8 Hz (1.2% of base frequency of 0.5 kHz), range = 5 – 10 Hz (i.e., 1 – 2%) (N = 12) |
| *Brown et al. (2017)*[1] | *M* = ±1.1% range = 0.3 – 2.1% (standard tone: C4) (N = 10) | *M* = ±1.2%, range = 0.3 – 1.5 cents (standard tone: C4) (N = 10) |
| *Vonck et al. (2021)*[2] | range = 0.2 – 3% (base frequencies of 0.5, 1, 2, 4 kHz) (N = 12) | range = 0.3 – 5% (base frequencies of 0.5, 1, 2, 4 kHz) (N = 12) |

*[1]: Brown and colleagues provided values in cents. These values were converted to percentage of base frequency of the standard tone for comparison with results from other studies.*
*[2]: Vonck and colleagues did not provide average values, only range.*

A three-alternative forced-choice task (3AFC) was used for estimating behavioural threshold. Significant correlations between electrophysiological and behavioural thresholds were found by Brown and colleagues (2017), He and colleagues (2012), and Vonck and colleagues (2021). Though Brown et al. did investigate speech perception in noise, they did not perform a statistical analysis to investigate whether speech perception and frequency discrimination thresholds were related. Harris and colleagues did not investigate behavioural frequency discrimination thresholds nor speech perception. They only investigated what the average frequency discrimination threshold was in normal-hearing listeners using the ACC and looked at differences between young and old adults. Vonck and colleagues (2021) investigated frequency discrimination thresholds using the ACC in normal hearing and hearing-impaired participants. Significant correlations between electrophysiological thresholds and speech perception thresholds were found, as well as a significant correlation between electrophysiological and behavioural thresholds. Vonck and colleagues conclude that the ACC has potential clinical value, but only for difficult-to-test populations, since estimating ACC-based thresholds is a time-consuming job that does not provide better results than behavioural measures. This conclusion is corroborated by the results of Brown et al. (2017), that show that ACC-based thresholds are less sensitive than behavioural thresholds, which argues for a preference to obtain behavioural thresholds.

Although there seems to be evidence for relationships between electrophysiological frequency discrimination thresholds and both behavioural frequency discrimination thresholds and speech perception in normal hearing subjects at first glance, further inspection of the literature provides a more nuanced picture. There are differences in how ACC thresholds were estimated in the four mentioned studies, with some deciding to have experts visually identify the ACC and obtaining a visual discrimination threshold (Brown et al., 2017; Harris et al., 2008; He et al., 2012), which can be seen as subjective, and one study choosing to use a fixed cut-off amplitude for all participants (Vonck et al., 2021), which fails to take into account individual differences in the amplitude of evoked potentials. Moreover, sample sizes were relatively small. This makes it difficult to draw firm conclusions regarding the relationship between electrophysiological frequency discrimination threshold, behavioural frequency discrimination threshold, and speech perception. For this reason, more research is needed.

#### 1.4.4.2 CI users

Only few studies have looked at estimating frequency discrimination thresholds using the ACC in CI users. Early data on frequency discrimination thresholds in CI users comes from a case study by Martin

(2007). In this study, Martin looked at auditory discrimination of synthetic vowels in a single MED-EL (Innsbruck, Austria) CI user. There were two conditions: one in which the participant was instructed to ignore the stimuli and one in which the participant was asked to attend to the stimuli and to press a button when a change was heard. This behavioural measure was compared to the electrophysiological data that was collected at the same time. However, very few is said about these thresholds in the paper. Additionally, the use of synthetic vowels has the downside of possible effects of amplitude and periodicity change, next to the frequency change that is being investigated, and it is difficult to disentangle effects of the different acoustic dimensions. In addition, it is not mentioned how presence of the ACC was determined. According to Martin, there is reasonable agreement between ACC-based thresholds and behavioural thresholds. This agreement is better when comparing ACC threshold to the condition where the participant paid attention to the stimuli. However, no statistical analysis is provided, which strongly diminishes the value of these results and subsequent conclusions.

More recently, Liang and colleagues (2018) investigated behavioural and electrophysiological frequency discrimination thresholds in twelve postlingually deafened CI users (who wore devices from Cochlear (Sydney, Australia)) using the ACC and a stimuli with a base frequency of 160 Hz. Average behavioural frequency discrimination threshold was 3.79%, but there was a large amount of variability between the CI users included in the study (range = 0.67 – 9.66%). The ACC was investigated using only three magnitudes of frequency change (0, 5, and 50%), whereas a two-alternative forced-choice (2AFC) procedure was used to estimate (much more precise) behavioural thresholds. No average electrophysiological threshold was provided. A significant correlation was found between the behavioural and electrophysiological thresholds. Moreover, the ACC amplitude was smaller for poor and moderate performers (based on the behavioural test) than good performers. Additionally, a significant correlation was found between ACC n1 latency and speech perception.

Zhang et al. (2019) only investigated frequency discrimination thresholds in twenty CI users (who wore devices from Cochlear) behaviourally using a three-alternative forced-choice (3AFC) task, but did use stimuli that contained within-stimulus changes. Thresholds found by Zhang and colleagues (*M* = 5.48, 3.94, and 7.78% for the base frequencies 0.25, 1, and 4 kHz, respectively) were in the same range as found by Liang and colleagues (2018). In addition, Zhang and colleagues found strong correlations between frequency discrimination thresholds and several measures of speech perception.

In a companion study to the 2019 publication by Zhang and colleagues (2018), McGuire and colleagues (2021) describe a study in which behavioural frequency discrimination and speech perception scores are investigated in relation to electrophysiological outcomes (i.e., the ACC) in 21 CI users (who wore devices from Cochlear). The same base frequencies as used by Zhang et al. (2019) were used. A 3AFC task was used to estimate behavioural discrimination thresholds. Average thresholds were 8.68, 4.43, and 7.69% for the base frequencies 0.5, 1. And 4 kHz, respectively. For the ACC, three magnitudes of frequency change were tested for each base frequency (0, 10, and 70%). This gives a very rough estimate of the electrophysiological discrimination threshold. Behavioural results and multiple speech perception scores were compared to latency and amplitude of the ACC. The ACC n1 was shown to be related to speech perception scores. The relationship between behavioural and electrophysiological thresholds was not investigated in this study.

Electrophysiologically estimated frequency discrimination thresholds (using the ACC) have not been investigated extensively in CI users. Therefore, not much is known about the correlation between behavioural and electrophysiological frequency discrimination thresholds in CI users. Additionally, frequency discrimination thresholds have not been investigated systematically using the ACC in MED-EL CI users (only the one participant in the study by Martin (2007)). An advantage of cochlear implants manufactured by MED-EL over implants manufactured by other companies is that the CI artefact visible in the EEG-recording appears to be smaller for MED-EL implants (e.g., Mathew et al., 2017). This is a

major advantage when investigating thresholds. Further research on frequency discrimination thresholds in general and in CI users of implants manufactured by MED-EL is needed.

### 1.4.5 The ACC and spectral ripple discrimination

#### 1.4.5.1 Normal hearing listeners

Spectral ripple discrimination has shown a good correlation with speech and music perception in CI users (e.g., Won et al., 2007; 2010), which argues well for the use of these stimuli for investigating auditory discrimination in this group of subjects. Therefore, besides frequency discrimination, spectral ripple discrimination will be central to this thesis.

Spectral ripples are stimuli consisting of periodically alternating peaks and valleys in the spectral domain. The stimuli are created by summating multiple pure tone frequency components. Two parameters of spectral ripples can be changed: density and depth. Density can be manipulated by increasing or decreasing the number of ripples per octave (RPO; Supin, Popov, Milekhina, & Tarakanov, 1994). Depth manipulation consists of changing the peak-to-valley ratio of the stimulus (Supin, Popov, Milekhina, & Tarakanov, 1999). Spectral ripple discrimination can be investigated by presenting a stimulus with an inversed phase compared to the standard stimulus (Supin et al., 1994). Detection of this phase inversion increases in difficulty as density of the signal increases. A higher threshold thus indicates a better discrimination capability. Spectral ripple discrimination thresholds have been investigated behaviourally in a few studies. A brief overview of a few of these studies is provided here.

Henry, Turner, and Behrens (2005) investigated the differences in spectral ripple discrimination thresholds between normal hearing, hearing-impaired, and cochlear implant listeners using ripples with a 30 dB depth. In addition, the relationship between spectral ripple discrimination and speech perception was investigated. Thresholds were estimated using a 3AFC task. Generally speaking, normal hearing listeners (N = 12) had the best thresholds (*M* = 4.8 RPO, range = 2.03 – 7.55). In addition, the results showed that spectral ripple discrimination and speech recognition were correlated.

Horn and colleagues (2017) investigated spectral ripple discrimination in 36 normal hearing adults and 58 infants at different depths using a single-interval test (modelled after the test designed by Won et al., 2011, which will be explained further in the section on spectral ripple discrimination in CI users). Horn and colleagues found that thresholds increased with an increasing depth and that there was a difference between discriminatory capacity of adults and infants at lower depths. This difference was not visible at the highest depth that they investigated (20 dB). For adults, the average threshold appeared to be around 14.5 RPO (range = 7 – 22) when using stimuli with a 20 dB depth.

To the best of our knowledge, only one study has investigated spectral ripple discrimination thresholds using the ACC in normal hearing participants: Brown and colleagues (2017). Won and colleagues (2011) also investigated spectral ripple discrimination in normal hearing participants, but used vocoder processing, which approximates what CI users hear, and results will therefore be discussed in the next section on spectral ripple discrimination in CI users.

Brown and colleagues (2017) investigated behavioural and electrophysiological spectral ripple discrimination thresholds in ten musicians and ten non-musicians using ripples with a 30 dB depth. A strong correlation was found between both discrimination thresholds, but the electrophysiological test was less sensitive than the behavioural test. Non-musicians showed an average threshold around 5.5 RPO (range = 2 – 8 RPO) on both the behavioural and electrophysiological test.

#### 1.4.5.2 CI users

Spectral ripple discrimination has been shown to correlate well with speech and music perception in CI users (e.g., Davies-Venn, Nelson, & Souza, 2015; Litvak, Spahr, Saoji, & Fridman, 2007; Won et al., 2007; Won et al., 2010). Additionally, it could be argued that the discrimination of change in a pure tone does not reflect whether CI users can discriminate speech, which is a much more complex signal.

Spectral ripples are also complex signals and discrimination of spectral ripples is therefore expected to correlate better with speech perception. This argues for using spectral ripples as stimuli to investigate auditory discrimination in CI users.

Henry et al. (2005) investigated behavioural spectral ripple discrimination in normal hearing, hearing impaired, and CI listeners using a 3AFC task. For the 23 CI users (wearing Cochlear devices), an average discrimination threshold of 0.62 RPO (range = 0.13 – 1.66) was found. In addition, a significant relation between spectral ripple discrimination threshold and speech perception was found.

Won and colleagues (2011) developed a 'single-interval' yes/no test to estimate behavioural spectral ripple discrimination thresholds. In this test, a single stimulus is presented (containing either a within-stimulus change or no change) and listeners are instructed to click on either 'yes' (a change was heard) or 'no' (no change was heard). In fourteen postlingually deafened CI users (who wore devices from Cochlear, Advanced Bionics (Santa Clarita, USA), and MED-EL), this single-interval test was used to estimate behavioural spectral ripple discrimination threshold. Electrophysiological thresholds were only estimated for three normal hearing participants (using vocoder processing). Using the single-interval test, CI users showed an average behavioural spectral ripple discrimination threshold of 6.16 ripples per octave (RPO) (range: 2.37 – 13.69). These thresholds are higher than thresholds found in other studies that investigated behavioural spectral ripple discrimination in CI users (e.g., Henry et al., 2005; Lopez Valdes et al., 2014, 2015). Won and colleagues found a significant correlation between discrimination threshold and speech perception measures. Data from the three normal hearing listeners showed that electrophysiological thresholds obtained using the ACC approximated the thresholds that were found in the single-interval behavioural test, but that behavioural thresholds were always higher (i.e., better).

To the best of our knowledge, only one study investigated the ACC as an electrophysiological measure to estimate spectral ripple discrimination threshold. Lopez Valdes et al. (2015) used a single-interval test and EEG-recording to investigate spectral ripple discrimination in thirteen CI users (who wore devices from Cochlear or Advanced Bionics). In addition, they compared ACC-based electrophysiological thresholds with thresholds estimated using mismatch negativity (MMN; which they also investigated in an earlier study (Lopez Valdes et al., 2014)) to investigate which method was more robust. A 3AFC task was used for comparison with the electrophysiological thresholds estimated using MMN. Behavioural thresholds obtained from the single-interval test ranged from 0.35 – 5.22 RPO (*M* = 1.74). This is considerably lower than the thresholds found by Won and colleagues (2011), even though the same single-interval procedure was used. Thresholds obtained by using the 3AFC task were slightly lower than the thresholds found using the single-interval paradigm (*M* = 1.05, range = 0.24 – 2.60). The electrophysiological test using the ACC revealed a mean threshold of 1.01 RPO (range = ±0.20 – 2). Using the MMN, a mean threshold of 1.21 RPO was found. The correlation between the single-interval threshold and the ACC-based threshold did not reach statistical significance, but did show a trend in that direction. The correlation between the 3AFC task and the MMN-based threshold was significant. The authors conclude that the MMN is a more robust objective measure of spectral ripple discrimination, but that the ACC may be used as an additional measure, with the advantage of having a shorter acquisition time than the MMN.

Since only Lopez Valdes and colleagues (2015) investigated spectral ripple discrimination using the ACC in CI users, it is clear that more research is needed. For this reason, the current study employs a similar research design to Lopez Valdes to further investigate spectral ripple discrimination in CI users, using a single-interval test for estimating behavioural discrimination threshold and using the ACC for estimating electrophysiological discrimination threshold.

## 1.5 Current study

### 1.5.1 Research design

The first part of this thesis aims to (1) investigate the ACC as an objective measure for estimating frequency discrimination threshold, and (2) investigate the relationship between the electrophysiological (ACC-based) threshold and behavioural discrimination threshold (based on a single-interval test) in normal hearing subjects and CI users. The second part of this thesis aims to (1) investigate the ACC for objectively estimating spectral ripple discrimination threshold, and (2) investigate the relationship between the electrophysiological (ACC-based) threshold and behavioural discrimination threshold (based on a single-interval test) in normal hearing subjects and CI users.

In addition, the relationship between speech perception of the CI users included in this study, based on scores obtained one year post-operation, and behavioural and electrophysiological discrimination thresholds will be investigated. This all is to investigate the potential value the ACC might have as an objective measure of auditory discrimination for use in clinical practice.

To this end, two experiments are conducted in this study:

1. Estimating behavioural and electrophysiological frequency discrimination thresholds in normal hearing subjects and CI users.
2. Estimating behavioural and electrophysiological spectral ripple discrimination thresholds in normal hearing subjects and CI users.

These experiments aim to answer the following research questions:

**Experiment 1**

1.1 Can the ACC be used as an objective measure to estimate frequency discrimination thresholds in normal hearing subjects?
1.2 What is the relationship between behavioural frequency discrimination thresholds (based on a single-interval test) and electrophysiological frequency discrimination thresholds (based on presence of the ACC) in normal hearing subjects?
1.3 Can the ACC (evoked via indirect stimulation of the cochlear implant) be used as an objective measure to estimate frequency discrimination thresholds in subjects with cochlear implants?
1.4 What is the relationship between behavioural frequency discrimination thresholds (based on a single-interval test) and electrophysiological frequency discrimination thresholds (based on presence of the ACC) in subjects with cochlear implants?

**Experiment 2**

2.1 Can the ACC be used as an objective measure to estimate spectral ripple discrimination thresholds in normal hearing subjects?
2.2 What is the relationship between behavioural spectral ripple discrimination thresholds (based on a single-interval test) and electrophysiological spectral ripple discrimination thresholds (based on presence of the ACC) in normal hearing subjects?
2.3 Can the ACC (evoked via indirect stimulation of the cochlear implant) be used as an objective measure to estimate spectral ripple discrimination thresholds in subjects with cochlear implants?
2.4 What is the relationship between behavioural spectral ripple discrimination thresholds (based on a single-interval test) and electrophysiological spectral ripple discrimination thresholds (based on presence of the ACC) in subjects with cochlear implants?

### 1.5.2 Relevance of the current study

More research on the relationship between behavioural and electrophysiological auditory discrimination thresholds is necessary to investigate whether this relation is strong enough for electrophysiological measures of auditory discrimination to be reliably used in clinical practice. Should the ACC prove to be a suitable objective measure of auditory discrimination, a possible future application lies in the use of the ACC in assessing auditory discrimination in paediatric CI (and possibly also hearing aid) users, or patients that have cognitive disabilities that prevent them from participating in behavioural tests of auditory discrimination. Relevance of the current study lies in further clarifying the relationship between behavioural and electrophysiological (ACC-based) auditory discrimination thresholds in both normal hearing adults and adult CI users, and the relationship between these discrimination thresholds and speech perception in adult CI users.

### 1.5.3 Hypotheses

A correlation between behavioural and electrophysiological thresholds is expected (negative for frequency discrimination, positive for spectral ripple discrimination). It is expected that there will be an offset of x rpo/% frequency change between behavioural and electrophysiological thresholds, with the behavioural discrimination threshold being more sensitive than the electrophysiological discrimination threshold. It is hypothesized that this offset will be similar for all participants (i.e., even though different thresholds are expected for different subjects, the offset between thresholds within a participant is expected to be in the same range for all participants). The P-P amplitude of the ACC is expected to become smaller as discrimination becomes more difficult. Latency of the ACC n1 may be increased with increasing difficulty.

Results for normal hearing subjects and CI users are expected to be similar, with a similar offset between behavioural and electrophysiological thresholds, albeit that the thresholds for CI users in general are expected to be worse than for normal hearing subjects because of the limited information about sounds that is available when using a CI (Macherey & Carlyon, 2014). In addition, a relationship between behavioural and electrophysiological thresholds and speech perception scores (negative for frequency discrimination, positive for spectral ripple discrimination) is expected in CI users.

# 2. Method

## 2.1 Participants

Twenty-one normal hearing adults (21-57 years, *M* = 24.5, *SD* = 8.1; five men, sixteen women) participated in this study. Thirteen participants completed testing for frequency discrimination, fourteen for spectral ripple discrimination. Six participants took part in both tests. Seven participants only completed testing for frequency discrimination and eight participants only participated in testing for spectral ripple discrimination. All participants had normal hearing thresholds (≤25 dB) as defined by pure tone audiometry at all octave frequencies from 250 to 4000 Hz. None of the participants reported a history of neurological, cognitive, or hearing problems. All participants signed informed consent forms. See Table A1 in Appendix A for an overview of demographic details of the normal hearing subjects.

Ten CI users (nine MED-EL, one Advanced Bionics) were included as participants in this study (59-79 years, *M* = 69.4, *SD* = 6.9; five men, five women). All participants were unilaterally implanted. Nine were postlingually deafened and one was prelingually deafened. Participants were recruited through the Radboud University Medical Centre. All participants were more than six months post-switch on of the implant. Informed consent forms were signed by all participants. For an overview of participant characteristics: see Table A2 in Appendix A. In this overview, speech perception scores are also available. These scores (obtained from the NVA test (Bosman, 1989), a Dutch open speech perception

test that consists of monosyllabic words) were obtained approximately one year post-implantation.

The CI users all took part in both experiments (spectral ripples and frequency) in one session. Behavioural and electrophysiological testing for one experiment were performed for one type of stimulus first, and then for the other stimulus type. Order of presentation of the two stimulus types was randomized over the participants.

## 2.2 Experiment 1

### 2.2.1 Stimuli

The stimuli used to estimate frequency discrimination thresholds consisted of pure tones. A 1000 Hz tone was chosen as base frequency (corresponding to intracochlear frequency allocation of the medial electrode stimulation site). Total duration of a stimulus was 1240 msec, with a rise and fall time of 20 msec each, a reference tone (the base frequency) of 600 msec (a pre-transition duration of 100 msec has been shown to be sufficient to evoke an ACC using tonal stimuli (Ganapathy et al., 2013)), and a target tone (containing an upward frequency change) of 600 msec. Change (which took place at 620 msec) occurred at zero crossing ($0^o$ phase) to ensure that audible clicks were not present in the signal (Dimitrijevic, Michalewski, Zeng, Pratt, & Starr, 2008). Stimuli were created in Praat (Boersma & Weenink, 2021) by concatenating the reference tone and a target tone. Twelve stimuli containing different magnitudes of change between 0.1 and 50% were created (0.1, 0.2, 0.3, 0.5, 1, 1.5, 2, 5, 7.5, 10, 20, and 50%). In addition, a no-change stimulus was created by concatenating two 1000 Hz tones. See Figure 3 for an example of a stimulus. The stimuli used for the behavioural and electrophysiological tests were identical.

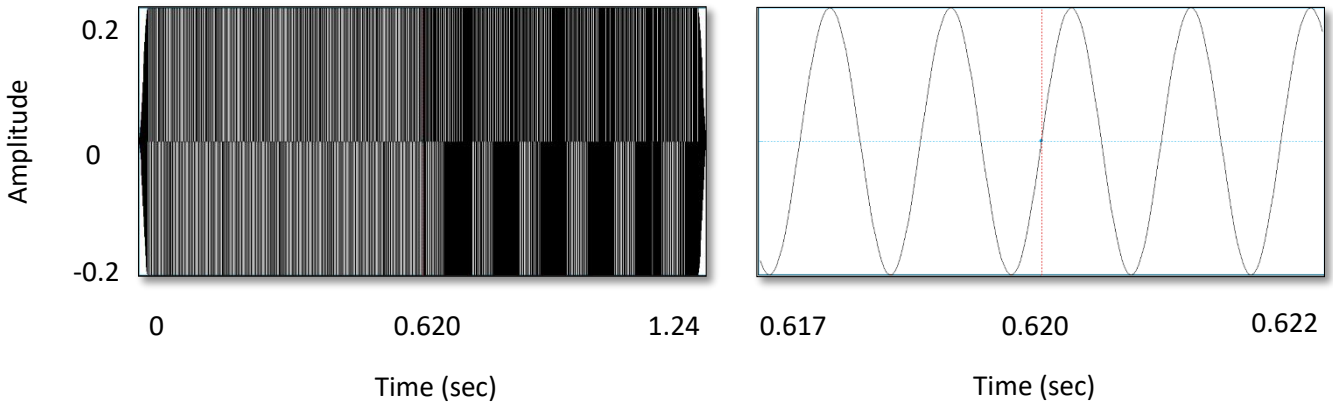



*Figure 3 – Left: Waveform of a stimulus containing a 1% frequency change (i.e. the first half of the stimulus is 1000 Hz, the second half is 1010 Hz). Right: Waveform of the same stimulus showing the point of concatenation. The red dotted line shows the exact point of concatenation. No temporal discontinuity is visible.*

### 2.2.2 Behavioural test

Stimuli were presented in the free field at 65 dB through a loudspeaker at a 1-metre distance from the participant placed at $0^o$ azimuth for normal hearing subjects. Loudness was calibrated using a Brüel-Kjær Investigator 2260. For the CI users, stimuli were presented at most comfortable loudness (MCL) for each participant, determined using a 10-point loudness scale, where a 6 was defined to be MCL by the CI subject (for an overview of the loudness settings per participant: see Table A2 in Appendix A).

Stimuli were presented to the speaker through an audio amplifier (Ecler MPA4-80R). To mimic the listening conditions of a unilateral CI user, one ear was plugged in normal hearing participants. In addition, a noise-cancelling headphone was placed over the same ear to provide extra noise cancellation. The better ear (that was used for testing) was chosen based on pure tone audiometry. If a CI user used a hearing aid in the contralateral ear, this was turned off. If substantial residual hearing

was present in the contralateral ear, this ear was plugged. This was done for four CI users.

Before the behavioural frequency discrimination test, participants had to perform a loudness balancing task. In this task, participants heard a stimulus pair, the first part always being the control stimulus of a 1000 Hz, presented at 65 dB/MCL (reference tone), and the second part being one of the other stimuli (containing a change of x%; target tone). The participant was asked to increase or decrease the loudness of the target stimulus (in steps of 2 dB) until it sounded equally loud as the reference stimulus. Each stimulus pair (twelve in total) was presented twice, with the target tone always objectively louder than the reference tone in the first trial and less loud in the second trial. Duration of the loudness balancing test was approximately ten minutes.

In the behavioural test, participants were instructed to indicate on a laptop whether they heard a within-stimulus change by clicking on either 'yes' (a change was heard) or 'no' (no change was heard). Figure 4 shows the interface of the behavioural test. Participants could see on the screen how far along they were in the test. No feedback was provided about correctness of the response.


*Figure 4 - Interface behavioural test (Translation: Did you hear a change halfway through this sound? Your reaction time will be recorded).*

For frequency discrimination, eleven frequency changes (0.1, 0.2, 0.3, 0.5, 1, 1.5, 2, 5, 10, 20, and 50%) were tested in the behavioural test. 110 stimuli pairs with a change (ten per change) and twenty stimuli pairs without a change were presented randomly (130 in total). A psychometric curve was fitted in RStudio (RStudio Team, 2020) to determine the point of 70% correct. The magnitude of frequency change corresponding to this point was defined as the behavioural discrimination threshold. In addition to percentage correct, average reaction time was calculated for each magnitude of frequency change. Before the actual test participants, were given a practice test with five stimuli. Total duration of the behavioural test was approximately ten minutes.

### 2.2.3 Electrophysiological test

#### 2.2.3.1 Recording procedure

Participants were seated in a comfortable chair and were asked to relax and limit movements. They were instructed to keep their eyes open. Participants were asked to attend to the stimuli they heard. Total duration of the EEG recording was approximately one hour and twenty minutes. Breaks were provided every 15-20 minutes (or as needed).

The changes that were presented in the electrophysiological test depended on the threshold found in the single-interval test for a specific participant. Based on the threshold, very small changes that were not discriminated correctly behaviourally, or the large changes that were very easy to discriminate behaviourally were not included in the electrophysiological test. This quasi-adaptive method was used to shorten the time that was needed for the EEG-recording. One or two stimuli that were at or below behavioural discrimination threshold were presented, to ascertain that no ACC was visible there. The procedure for determining presence of the ACC is described in section 2.2.3.2 on data analyses.

The same stimulus presentation as used in the behavioural test was used in the electrophysiological test. The same ear was tested as in the behavioural test. For every stimulus, a trigger pulse (+5V TTL sync pulse) was sent from the stimulation PC (stimuli were presented through a LabVIEW interface; Bitter, Mohiuddin, & Nawrocki, 2006) to the EEG recording system (Medelec Synergy system; Oxford Instruments, UK), to ensure exact time-locking between stimulus and

response. A recording window of 2000 msec was used, including a pre-stimulus time of 200 msec to avoid any misinterpretation of the subsequent peaks. Interstimulus interval was 1000 msec (with a 10% latency jitter). See Figure 5 for an overview of the set-up used in this experiment.

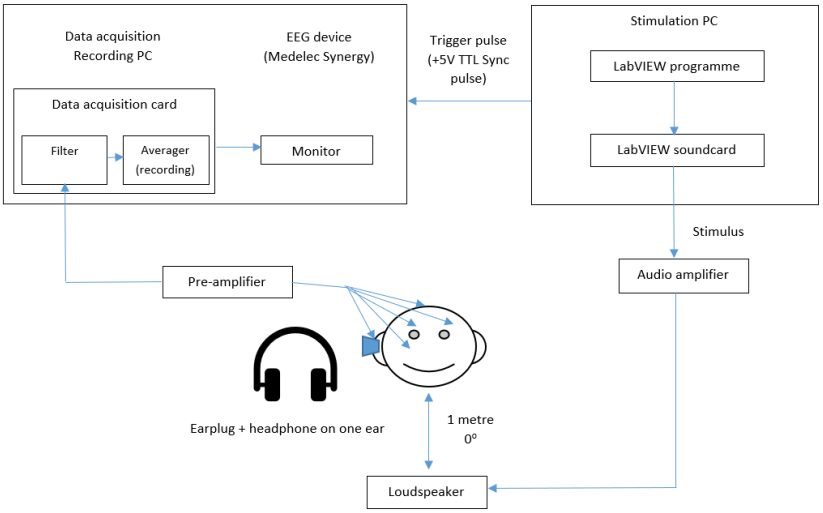



*Figure 5 – Recording set-up for the electrophysiological test. Electrodes are placed at Cz (non-inverting), contralateral mastoid (inverting), off-centre on the forehead (ground), and below and above one eye. Stimuli are presented in the free field, one ear is plugged and covered by a noise-cancelling headphone for normal hearing participants and CI users with substantial hearing in the contralateral ear.*

A 2-channel set-up was used. Electrodes for the first channel were placed at the vertex (Cz; non-inverting, active), the contralateral mastoid (inverting, reference) and off centre on the high forehead (ground). Electrodes for the second channel were placed above and under one eye to monitor eye movements. Impedance of all electrodes was kept below 7 kΩ and was monitored during recording. Data was acquired with a sampling rate of 25 kHz, an amplifier gain of 50.000, a notch filter of 50 Hz, and a high and low pass filter of 0.1-30 Hz. The filter used for monitoring eye movement was set between 10 and 100 Hz.

Artefact rejection was set between 50 and 70 µV for the first channel and 100 µV for the second channel to reject noise (mainly EMG). For each frequency change, between twenty-five and fifty responses were obtained in one block and averaged online. Large changes (i.e., where the ACC was clearly visible and approximate threshold was not near) were only presented in one block to reduce measurement times. Changes estimated to be close to threshold were presented in multiple blocks (two-four times). In addition, a no-change stimulus was presented in one block.

#### 2.2.3.2 Data analysis

The P1 is typically rather small in adults (Martin, 2007) and was therefore not analysed. P-P amplitude of the N1-P2 (onset SVP) and n1-p2 (ACC) complexes as well as latency of the peaks were analysed. P-P amplitude of the ACC was normalised by dividing the n1-p2 P-P amplitude by N1-P2 P-P amplitude of the SVP onset response. When a clear SVP was lacking, the response was not included in the analysis.

The presence of the ACC was determined visually. One researcher and one experienced audiologist identified the SVPs and ACCs. For the SVP, N1 was defined as the largest negativity between 80 and 150 msec post-stimulus onset, and P2 as the largest positivity between 160 and 250 msec post-stimulus onset. For the ACC, the n1 was defined as the largest negativity between 690 and 790 msec, and the p2 as the largest positivity between 770 and 880 msec. The range of latencies between which peaks and troughs had to be present in order for them to be identified as part of the SVP or ACC was expanded for CI users, to account for possible prolonged latencies (Budd, Barry, Gordon, Rennie, &

Michie, 1998; Liang et al., 2018). For the SVP, N1 was defined as the largest negativity between 90 and 200 msec post-stimulus onset. P2 was defined as the largest positivity between 150 and 300 msec post-stimulus onset. For the ACC, n1 was defined as the largest negativity between 720 and 820 msec. The p2 was defined as the largest positivity between 770 and 900 msec. Discrimination threshold was defined as the smallest frequency change that evoked the ACC.

### 2.2.4 Statistical analyses

A paired samples t-test, Pearson correlation coefficient, and linear regression were used to investigate the relationship between behavioural and electrophysiological thresholds. A p-value ≤ 0.05 was considered significant. A Pearson correlation coefficient was used to investigate the correlation between inter-peak interval (IPI; difference between latency of the N1 and n1), and magnitude of frequency change. A one-sample t-test was used to determine whether the IPI differed significantly from the expected 620 msec (based on time of stimulus change). Furthermore, a one-way ANOVA was used to determine the effect of magnitude of frequency change on IPI. A Pearson correlation coefficient and a one-way ANOVA were used to investigate magnitude of frequency change and its relation with or effect on normalised P-P amplitude of the ACC.

In addition, a Pearson correlation was used to investigate the relationship between the behavioural and electrophysiological thresholds, and speech perception scores in CI users. Furthermore, a comparison between the normal hearing subjects and the CI users was made. To investigate the age differences between the two groups, an independent samples t-test was used. An independent samples t-test was also used to investigate whether normal hearing subjects and CI users differ in discrimination thresholds. Furthermore, d'-values were calculated for all participants and an independent samples t-test was used to investigate the possible difference in d'-values between normal hearing listeners and CI users.

## 2.3 Experiment 2

### 2.3.1 Stimuli

The spectral ripples consisted of a summation of 4000 pure tone frequency components, logarithmically spaced between 100 and 8000 Hz, with a depth of 20 dB. Most studies investigating spectral ripple discrimination have used a depth of 30 dB (i.e., all studies that were discussed in the introduction of this thesis, for both normal hearing subjects and CI users, with the exception of Horn et al., 2017). In this study, however, it was decided to use a depth of 20 dB. Discrimination of phase inversion is more difficult at lower depths (Horn et al., 2017), which was confirmed in a pilot study. Research has shown that a density higher than 2.1 RPO leads to a distorted signal (caused by the speech processor) in CI users (Winn & O'Brien, 2019), which might make interpretation of discrimination of stimuli with a density higher than 2.1 RPO unreliable in CI users. Since the stimuli created for the current study are intended to be used for both normal hearing subjects and CI users, it is important to consider the effect of higher depths, at which discrimination is easier. Ideally, the discrimination threshold for CI users should lie below 2.1 RPO to avoid distortion of the signal. Earlier studies have found behavioural thresholds ranging from 0.13-1.66 RPO (Henry et al., 2005) to 2.37-13.69 (Won et al., 2011). These studies used stimuli with a depth of 30 dB. To try and keep threshold below 2.1 RPO for the CI users it was decided to create stimuli with a depth of 20 dB instead of 30 dB.

Total duration of a stimulus was 1240 msec, with a rise/fall time of 20 msec and a phase inversion ($\pi/2$) at midpoint. To ensure no audible clicks were present in the signal, a 6-msec ramp was created at the changing point (i.e., between 617 and 623 msec). Stimuli were created using MATLAB (2020). Stimuli with 22 different densities were created (0.125, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6.5, 8, 9.5, 11, 12.5, 14, 15.5, 21.5 RPO). See Figure 6 for examples of change and no-change stimuli.

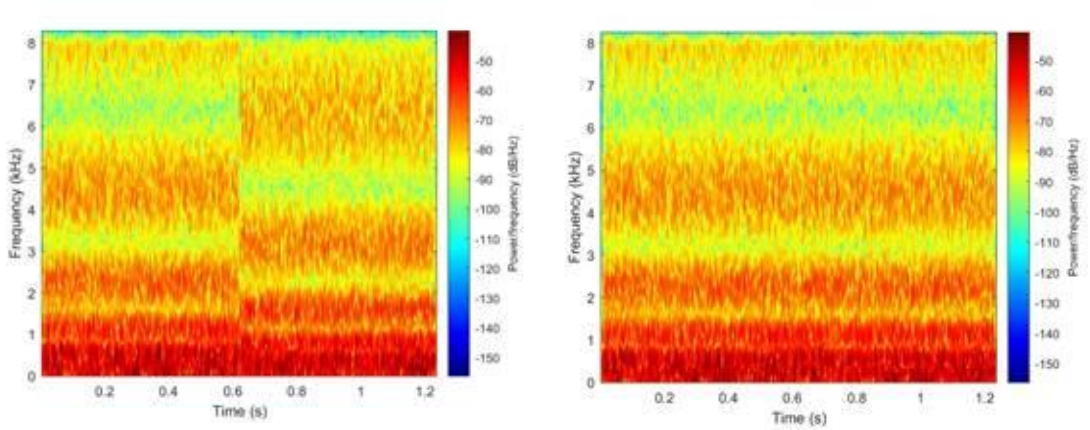



*Figure 6 - Left: Spectrogram of a spectral ripple with a density of 1 RPO and phase inversion visible at the midpoint. Right: Spectrogram of a no-change ripple with a density of 1 RPO.*

### 2.3.2 Behavioural test

Behavioural spectral ripple discrimination thresholds were estimated by presenting stimuli at 65dB for normal hearing subjects/MCL for CI users through a loudspeaker at a 1-metre distance placed at 0° azimuth. One ear was plugged in normal hearing subjects and four CI users with substantial residual hearing. The stimuli were presented to the speaker through an audio amplifier (Ecler MPA4-80R). Using the same interface (see Figure 4) as in Experiment 1, participants had to indicate whether they heard a change in a stimulus. For spectral ripples, twelve densities were tested (0.5, 2, 3.5, 5, 6.5, 8, 9.5, 11, 12.5, 14, 15.5, 21.5 RPO), i.e., 120 stimuli pairs with a change (ten per density) and 24 stimuli pairs (two per density) without a change were presented randomly (144 in total).

Prior to the spectral ripple discrimination test, each CI user was presented with a ripple with a density of 0.5 RPO (easiest stimulus tested) to ascertain that they were able to hear the phase inversion in this stimulus. Before the actual behavioural test, participants were given a practice test with five stimuli. Total duration of the behavioural test was approximately ten minutes. Psychometric curves were fitted in RStudio (RStudio Team, 2020) after the test to estimate the behavioural discrimination threshold. Threshold was defined as the density corresponding to the point of 70% correct in the psychometric curve.

### 2.3.3 Electrophysiological test

#### 2.3.3.1 Recording procedure

The procedure in Experiment 2 was the same as the procedure employed in the first experiment. Stimuli were presented in the sound field at 65 dB/MCL through a loudspeaker set at 0° azimuth, connected to an audio amplifier (Ecler MPA4-80R). The same quasi-adaptive method as used in Experiment 1 was used to determine which stimuli were presented in the EEG-recording session. Recording set-up was the same as in Experiment 1.

#### 2.3.3.2 Data analyses

SVPs and ACC were identified visually by five researchers and one experienced audiologist for normal hearing subjects, and by one researcher and one experienced audiologist for CI users. The same ranges of latencies for the SVP and ACC that were used in the first experiment were also used in this second experiment.

### 2.3.4 Statistical analyses

The same statistical analyses as performed in Experiment 1 were performed for the results from the second experiment.

# 3. Results

## 3.1 Experiment 1

### 3.1.1 Loudness balancing

Eight out of thirteen normal hearing subjects indicated they needed a loudness difference larger than 5 dB (based on mean between loudness chosen in the two trials per stimulus pair) for at least one stimulus pair in order for the two parts to sound equally loud: see Figure 7 and Table B1 in Appendix B.

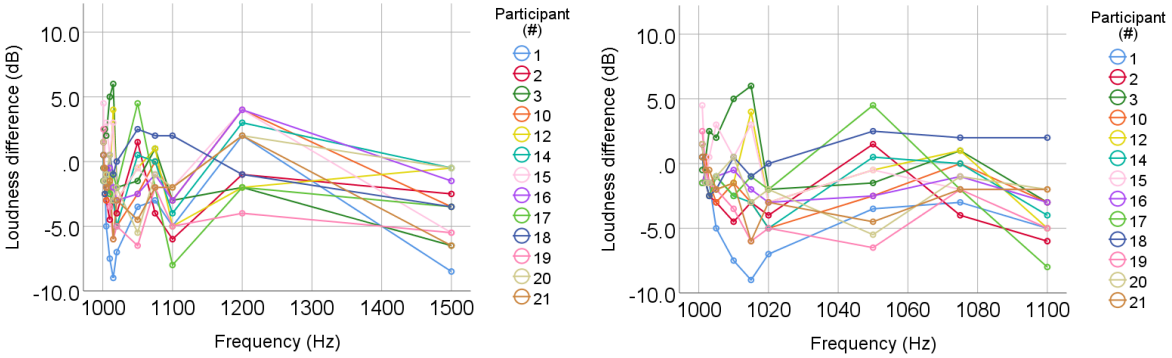



*Figure 7 – Left: Scatter plot frequency vs. loudness difference needed between reference tone (1000 Hz, 65 dB) and target tone (frequency change of x Hz) in order for the two parts of a stimulus pair to sound equally loud (based on mean between loudness chosen in the two trials per stimulus pair) for normal hearing participants (N = 13). Right: Zoomed-in version of the same scatterplot.*

One CI user (#1) was unable to complete the loudness balancing task. Eight out of nine CI users indicated they needed a loudness difference larger than 5 dB (based on mean between the two trials per stimulus pair) for at least one stimulus pair: see Figure 8 and Table B2 in Appendix B. A large range in responses was visible in the loudness balancing task, with some CI users indicating that a stimulus needed to be up to 7 dB softer, and others indicating that a stimulus needed to be 20 dB louder than the reference stimulus in order for them to sound equally loud.

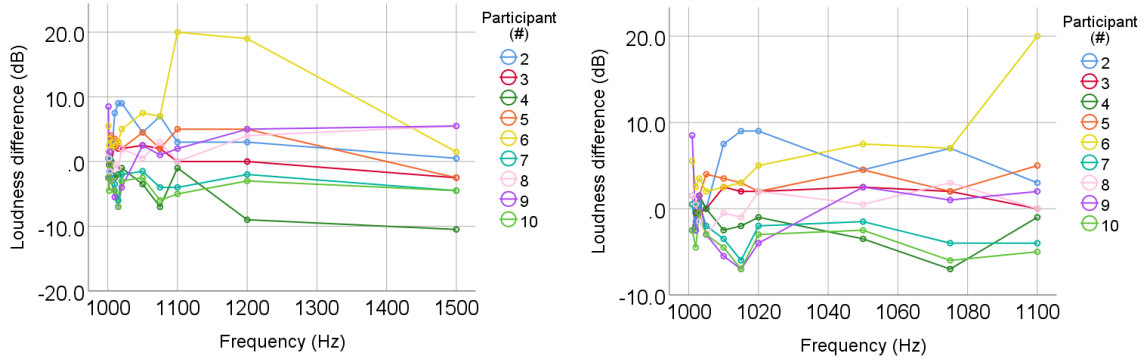



*Figure 8 - Left: Scatter plot frequency vs. loudness difference needed between reference tone (1000 Hz, 65 dB) and target tone (frequency change of x Hz) in order for the two parts of a stimulus pair to sound equally loud (based on mean between loudness chosen in the two trials per stimulus pair) for CI users (N = 9). Right: Zoomed-in version of the same scatterplot.*

All participants showed a mixed pattern in their results. That is, they sometimes indicated they needed a larger loudness difference for small frequency changes than for larger frequency changes, but they did not always do this (e.g., results from normal hearing subject #12 showed small differences for stimuli 1001-1010, 1050, 1075 and 1500 Hz, and larger differences for 1015, 1020, 1100 and 1200 Hz). Additionally, ten out of thirteen normal hearing subjects and all CI users showed relatively large (> 5

dB) differences between the loudness they chose in the first and second presentation of a stimulus pair (e.g., CI user #5 chose a loudness of 80 dB in the first presentation of a pair and 51 dB in the second presentation), for at least one stimulus pair: see Table B1 and B2 in Appendix B. It was decided not to adjust the loudness of any stimulus pairs.

### 3.1.2 Behavioural results

#### 3.1.2.1 Normal hearing subjects

The behavioural frequency discrimination results were interpolated and threshold was defined as the 70% correct ratio in the psychometric curve plotted for each participant. The average behavioural discrimination threshold for normal hearing subjects was 1004.5 Hz (0.45% of base frequency, *SD* = 2.7, range = 1001.1 – 1011.6, N = 13): see Figure 9 for a typical example of a psychometric curve fitted for the results of one participant (for all psychometric curves: see Table C1 in Appendix C).

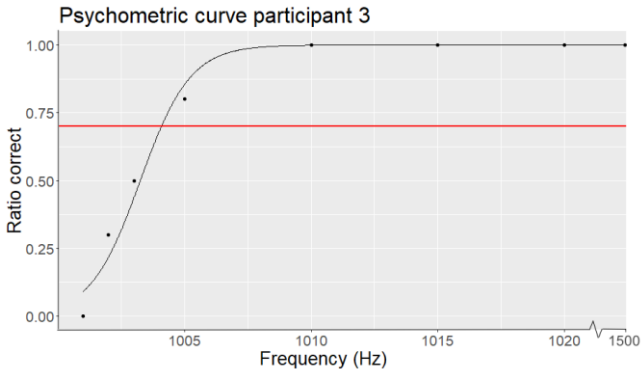



*Figure 9 – Typical psychometric curve fitted for the results of the behavioural discrimination test of a normal hearing listener (#3). Threshold, defined as the 70% correct ratio (red line), for this subject is 1004.1 Hz.*

The number of false positives per participant are visible in Figure 10. Participant #18 showed six false positives (out of a possible 20). When a participant showed >3 false positives, the participant was excluded from further analyses. Without the outlier, average behavioural frequency discrimination threshold was 1004.4 Hz (0.44% of base frequency, *SD* = 2.9; range = 1001.1 – 1011.6, N = 12): see Figure 10.

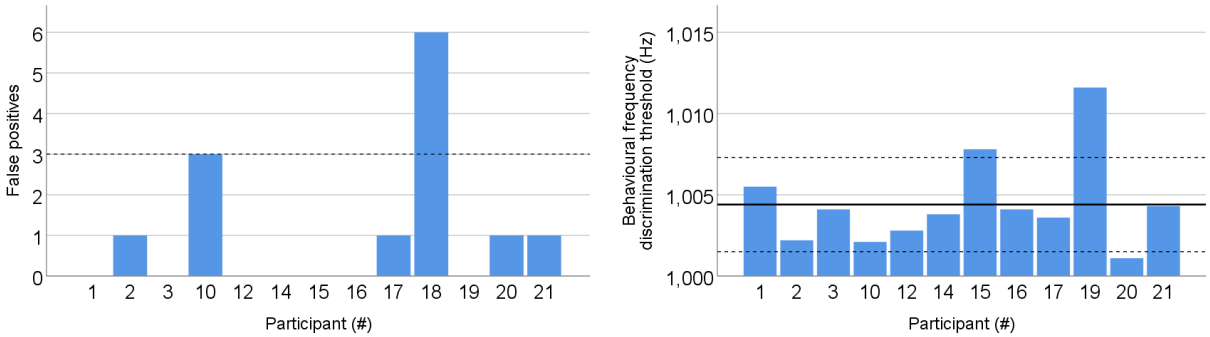



*Figure 10 - Left: Number of false positives per normal hearing subject (N = 13). Right: Behavioural frequency discrimination threshold per normal hearing subject (N = 12). Black line indicates mean threshold, black dotted lines indicate +/- 1 SD.*

#### 3.1.2.2 CI users

For one participant (#1) the discrimination threshold was above 1500 Hz (easiest stimulus tested) and was therefore not determined. The average behavioural discrimination threshold for CI users was 1021.1 Hz (2.1% of base frequency, *SD* = 20.6, range = 1004.0 – 1067.0, N = 9): see Figure 11 for a

typical example of a psychometric curve fitted for the results of one CI user (for all psychometric curves: see Table C2 in Appendix C).

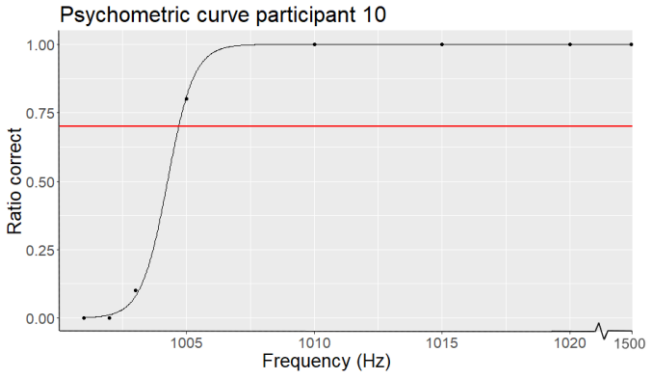



*Figure 11 - Typical psychometric curve fitted for the results of the behavioural discrimination of a CI user (#10). Threshold, defined as the 70% correct ratio (red line), for this subject is 1004.7 Hz.*

The number of false positives per participant are visible in Figure 12. When a participant showed >3 false positives, the participant was excluded from further analyses. Participant #5 (6/20 incorrect) was therefore excluded from the dataset and further analyses were performed with eight participants. Without the outlier, average behavioural frequency discrimination threshold was 1018.8 Hz (1.9% of base frequency, *SD* = 20.8; range = 1004.0 – 1067.0, N = 8): see Figure 12.

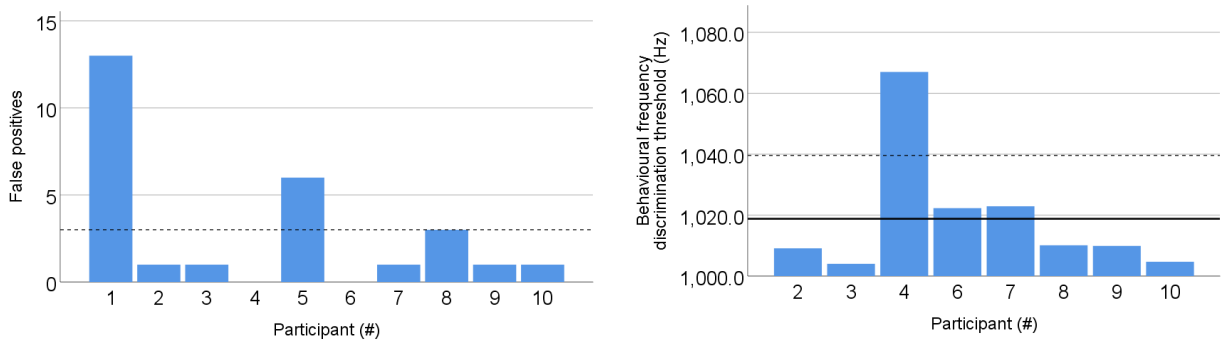



*Figure 12 - Left: Number of false positives per CI user (N = 10). Right: Behavioural frequency discrimination threshold per CI user (N = 8). Black line indicates mean threshold, black dotted line indicates + 1 SD.*

### 3.1.3 Electrophysiological results

Any negative disturbance of time-locked eye movements that could have influenced auditory responses was absent because 2-channel recordings were performed. No major disturbances in the SVP and/or ACC were caused by the acquired eye movements.

In some traces, the p2 could not be identified, but a clear n1 appeared to be present at a similar latency as earlier traces where a p2 could be identified. It was decided to still identify the n1 (and thus the ACC) and to not identify a p2. A P-P amplitude was therefore not calculated, but the trace was used for estimating the discrimination threshold.

#### 3.1.3.1 Normal hearing subjects

The mean electrophysiological frequency discrimination threshold for normal hearing subjects was 1011.3 Hz (1.13% of base frequency; *SD* = 6.1, range = 1005 – 1020, N = 12): see Figure 13.

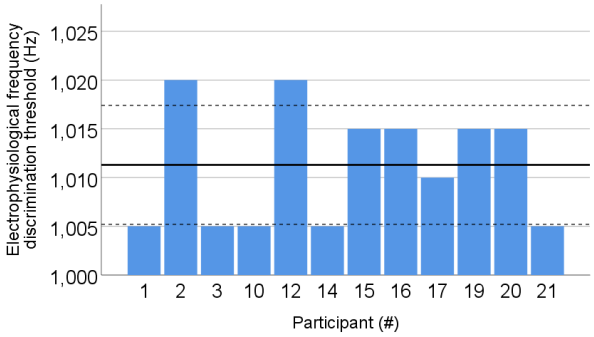



*Figure 13 - Electrophysiological frequency discrimination threshold per normal hearing subject (N = 12). Black line indicates mean threshold, black dotted lines indicate +/- 1 SD.*

In Figure 14, typical examples are shown of neural responses to a stimulus with a large frequency change (left) and a small frequency change (right), the latter showing an absent ACC. See Table D1 in Appendix D for the P-P amplitudes and latencies of the SVP and ACC per frequency change, per normal hearing subject.

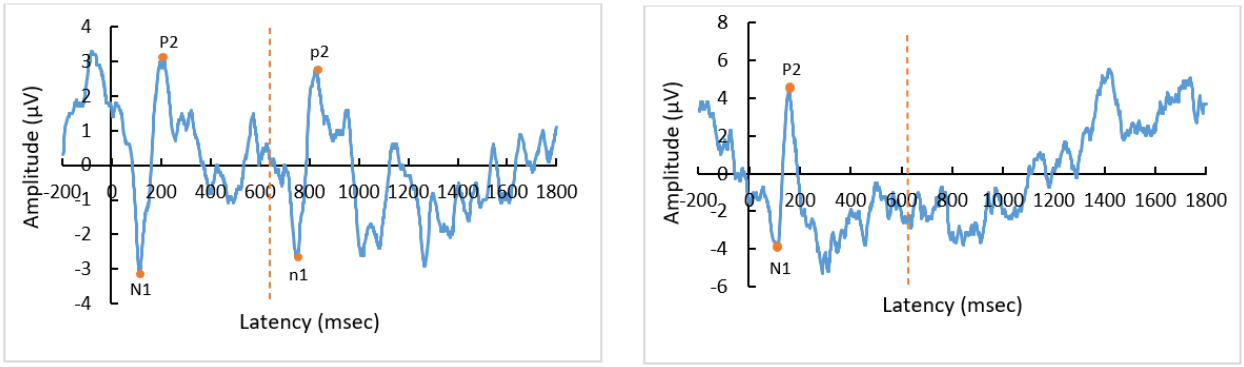



*Figure 14 – Left: Typical example of a neural response of a normal hearing subject to a stimulus with a frequency change from 1000 to 1050 Hz (large change; easy to discriminate; #3). Right: Typical example of a neural response of a normal hearing subject to a stimulus with a frequency change from 1000 to 1005 Hz (small change; more difficult to discriminate; #2). Frequency change occurred at midpoint (620 msec, indicated by the orange dotted line) Both the SVP (N1-P2) and ACC (n1-p2) are indicated by orange dots.*

### 3.1.3.2 CI users

The mean electrophysiological frequency discrimination threshold for CI users was 1082.5 Hz (8.2% of base frequency; *SD* = 77.2, range = 1020 – 1200, N = 8): see Figure 15.

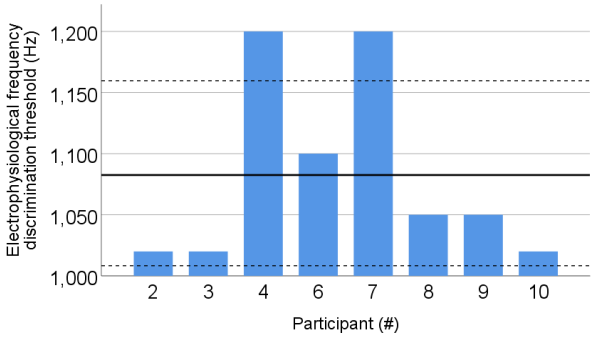
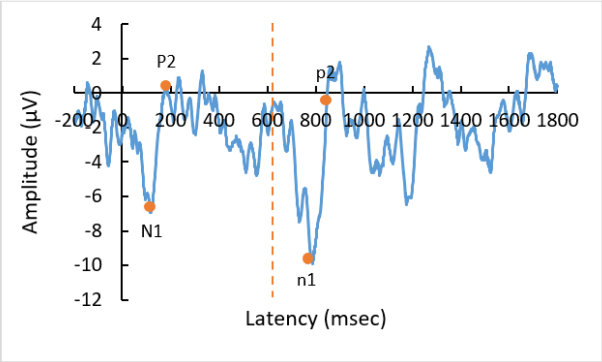



*Figure 15 - Electrophysiological frequency discrimination threshold per CI user (N = 8). Black line indicates mean threshold, black dotted lines indicate +/- 1 SD.*

In Figure 16, typical examples are shown of neural responses to a stimulus with a large frequency change (left) and a small frequency change (right), the latter showing an absent ACC. See Table D2 in Appendix D for the P-P amplitudes and latencies of the SVP and ACC per frequency change, per CI user.



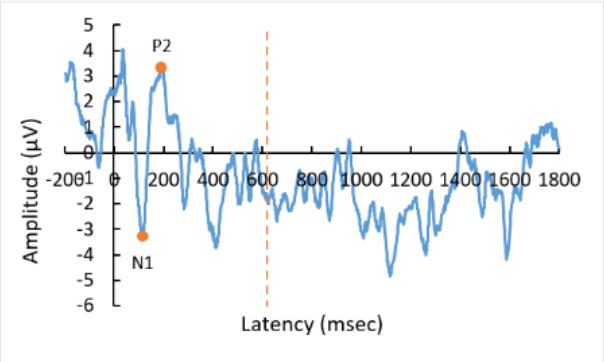




*Figure 16 – Left: Typical example of a neural response (of a CI user, #4) to a stimulus with a frequency change from 1000 to 1500 Hz (large change; easy to discriminate). Right: Typical example of a neural response (of a CI user, #4) to a stimulus with a frequency change from 1000 to 1100 Hz (smaller change; more difficult to discriminate). Frequency change occurred at midpoint (620 msec, indicated by the orange dotted line). Both the SVP (N1-P2) and ACC (n1-p2) are indicated by orange dots.*

### 3.1.3.3 Relationship magnitude of frequency change (Hz) and latency n1

Expected inter-peak interval (IPI) between N1 and n1 was 620 msec (based on time of stimulus change). Mean IPIs per magnitude of frequency change for normal hearing subjects and CI users are visible in Table 2.

*Table 2 – Mean IPI per frequency change normal hearing subjects (left) and CI users (right)*

| Frequency change (Hz) | Mean IPI (msec) |
|---|---|
| *1100* | 622.9 (N = 9) |
| *1050* | 634.8 (N = 12) |
| *1020* | 626.4 (N = 10) |
| *1015* | 642.2 (N = 10) |
| *1010* | 660.7 (N = 6) |
| *1005* | 668.0 (N = 5) |
| *Mean* | 638.7 |

| Frequency change (Hz) | Mean IPI (msec) |
|---|---|
| *1500* | 636.9 (N = 7) |
| *1200* | 640.3 (N = 7) |
| *1100* | 630.5 (N = 4) |
| *1050* | 633.2 (N = 5) |
| *1020* | 633.3 (N = 3) |
| *Mean* | 635.7 |

For normal hearing subjects, a two-tailed Pearson correlation showed a statistically significant moderate, negative correlation between magnitude of frequency change and IPI ($r(52) = -.404$, $p = .003$), indicating longer response latencies with decreasing magnitude of frequency change: see Figure 17.

A one-sample t-test showed a significant difference between expected IPI of 620 msec and actual IPI ($M = 638.7$, N = 12): $t(51) = 5.544$, $p < .001$. IPI significantly differed for the different frequencies (one-way ANOVA: $F(5,46) = 5.443$, $p = .001$). A Tukey post hoc test revealed significant differences between 1005 and 1020 Hz ($p = .006$), 1005 and 1050 Hz ($p = .040$), 1005 and 1100 Hz ($p = .003$), 1010 and 1020 Hz ($p = .024$), and 1010 and 1100 Hz ($p = .012$), with the smaller magnitudes of frequency change showing higher average IPIs than the larger frequency differences: see Figure 17.

For CI users, a two-tailed Pearson correlation showed no statistically significant correlation between magnitude of frequency change and IPI ($r(24) = .067$, $p = .745$): see Figure 17.

A one-sample t-test showed a significant difference between the expected IPI of 620 msec and the actual IPI ($M = 635.7$): $t(25) = 3.264$, $p = .003$). IPI did not significantly differ for the different frequencies (one-way ANOVA: $F(4,21) = .112$, $p = .977$).

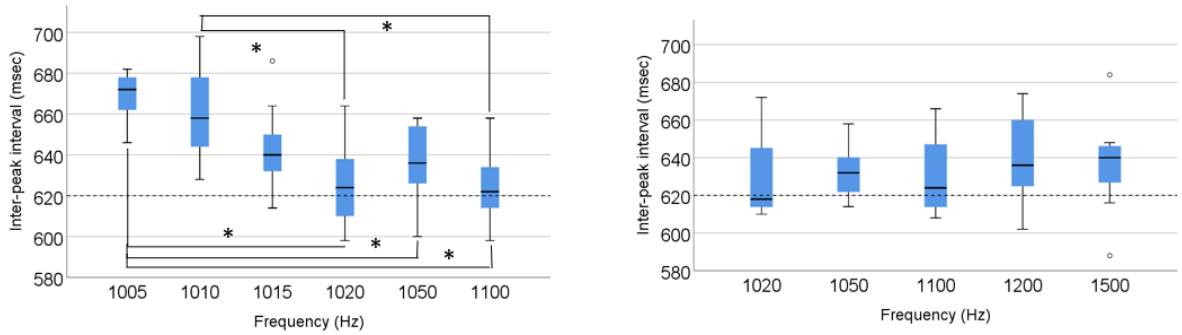



*Figure 17 – Boxplots showing IPI as a function of frequency change (Hz) for normal hearing subjects (left) and CI users (right). Black dotted line indicates expected IPI of 620 msec. Asterisks indicate p < .05.*

### 3.1.3.4 Effect of magnitude of frequency change (Hz) on P-P amplitude of the ACC

For normal hearing subjects, mean normalised P-P amplitude of the ACC was 0.7 ($SD = 0.4$, range = 0.2 – 2.1): see Figure 18. A Pearson correlation showed no significant relation between magnitude of frequency change and ACC P-P amplitude ($r(44) = .250$, $p = .093$). No significant differences were found between ACC P-P amplitudes of different magnitudes of frequency change (one-way ANOVA: $F(5,40) = 1.085$, $p = .383$).

For CI users, mean normalised P-P amplitude of the ACC was 0.9 ($SD = 0.5$, range = 0.5 – 2.0): see Figure 18. A Pearson correlation showed no significant relation between magnitude of frequency change and ACC P-P amplitude ($r(19) = .168$, $p = .468$). ACC P-P amplitudes of different magnitudes of frequency change did not differ significantly (one-way ANOVA: $F(4,16) = .416$, $p = .795$).

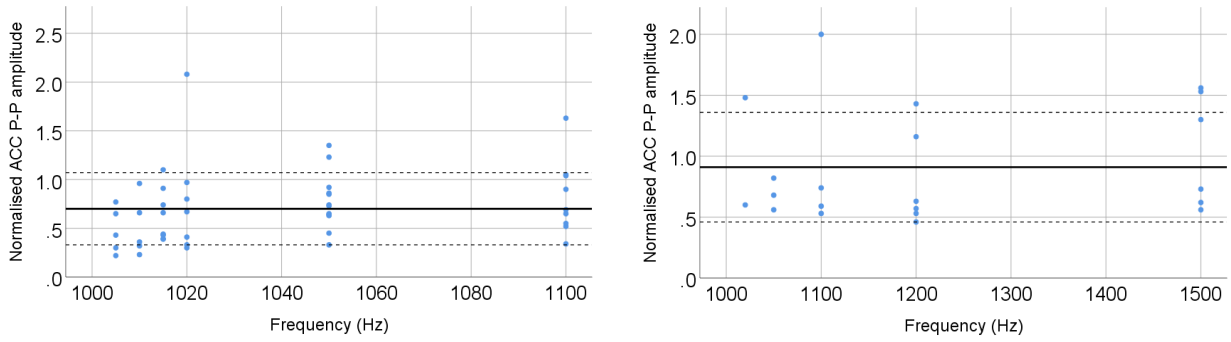



*Figure 18 - ACC P-P amplitude as a function of frequency change (Hz) for normal hearing subjects (left) and CI users (right). Black line indicates mean ACC P-P amplitude, black dotted lines indicate +/- 1 SD.*

## 3.1.4 Relationship between behavioural and electrophysiological results

For normal hearing subjects, in all cases except one (#1), the behavioural frequency discrimination threshold was lower (i.e., better) than the electrophysiological threshold that was found: see Figure 19. For one participant (#1), the electrophysiological threshold was 0.5 Hz lower than the behavioural threshold. The mean offset between both thresholds was 7.8 Hz ($SD = 6.3$ Hz, range = 0.5 – 17.8). A

paired-samples t-test showed a significant difference between behavioural (*M* = 1004.4 Hz) and electrophysiological (*M* = 1011.3 Hz) thresholds (*t*(11) = 3.583, *p* = .004).

For CI users, in all cases the behavioural frequency discrimination threshold was lower (i.e., better) than the electrophysiological threshold: see Figure 19. The mean offset between both thresholds was 63.8 Hz (*SD* = 63.4 Hz, range = 10.9 – 177.1). A paired-samples t-test showed a significant difference between behavioural (*M* = 1018.8 Hz) and electrophysiological (*M* = 1082.5 Hz) thresholds (*t*(7) = -2.937, *p* = .022).

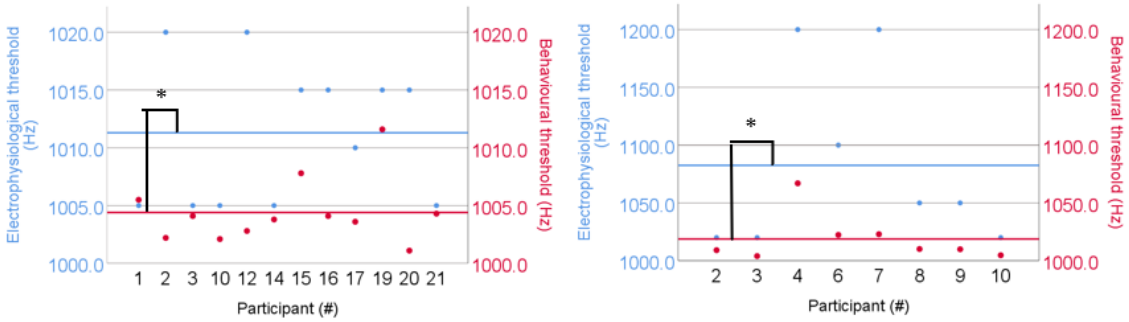



*Figure 19 - Behavioural (pink) and electrophysiological (blue) frequency discrimination thresholds per participant for normal hearing subjects (left, N = 12) and CI users (right, N = 8). The blue and pink lines indicate the mean thresholds (*p < .05).*

For normal hearing subjects, a two-tailed Pearson correlation showed no statistically significant relationship between behavioural and electrophysiological frequency discrimination thresholds (*r*(10) = .041 *p* = .900). A linear regression with electrophysiological threshold as the independent variable and behavioural threshold as the dependent variable showed that electrophysiological threshold did not significantly predict behavioural threshold (*β* = .041, *t*(10) = .129, *p* = .900): see Figure 20.

For CI users, a two-tailed Pearson correlation showed a statistically significant strong positive relationship between behavioural and electrophysiological frequency discrimination thresholds (*r*(6) = .819, *p* = .013). A linear regression with electrophysiological threshold as the independent variable and behavioural threshold as the dependent variable showed that electrophysiological threshold significantly predicted behavioural threshold (*β* = .819, *t*(6) = 3.49, *p* = .013). Electrophysiological threshold significantly explained the variance in behavioural threshold ($R^2$ = .670; *F*(1,6) = 12.192, *p* = .013): see Figure 20.

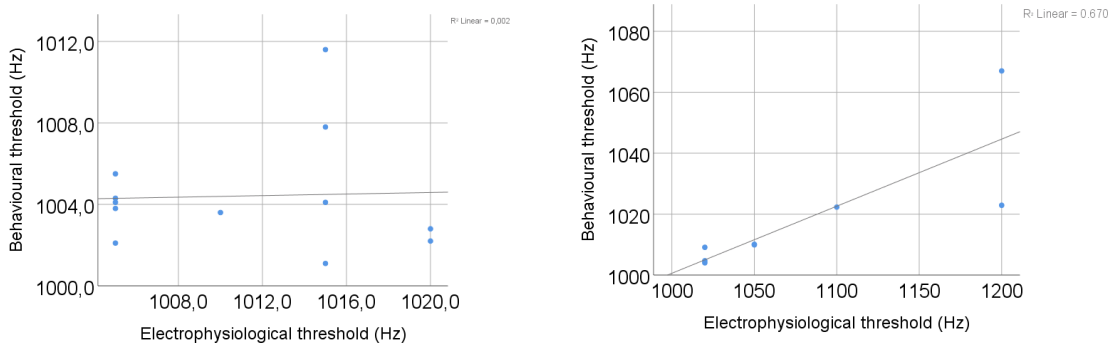



*Figure 20 - Scatter plot electrophysiological vs. behavioural frequency discrimination thresholds for normal hearing subjects (left, N = 12) and CI users (right, N = 8).*

### 3.1.5 Relationship between frequency discrimination thresholds and speech perception in CI users

For an overview of the speech perception scores obtained one year after implantation: see Table A2 in Appendix A.

No statistically significant correlation was found between behavioural frequency discrimination threshold and speech perception score ($r(6) = -.395$, $p = .333$) nor between electrophysiological frequency discrimination threshold and speech perception score ($r(6) = -.053$, $p = .900$): see Figure 21.

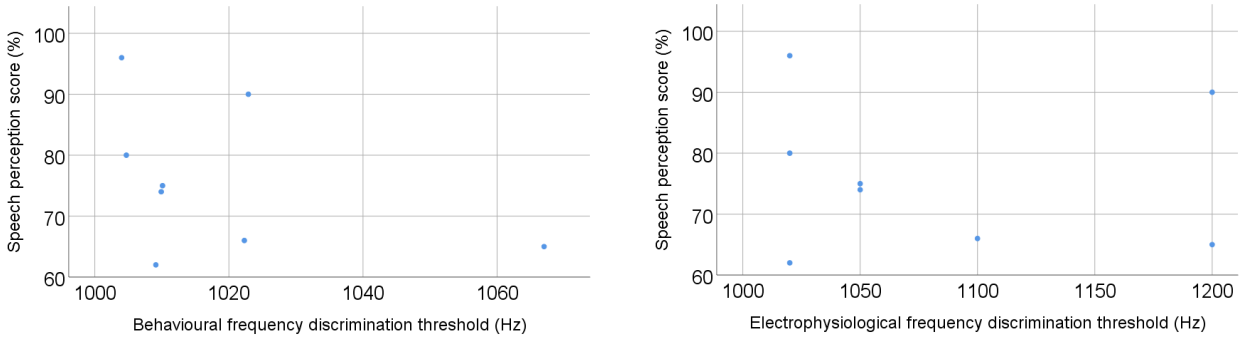



*Figure 21 - Left: Scatter plot behavioural frequency discrimination threshold vs. speech perception score (N = 8). Right: Scatter plot electrophysiological frequency discrimination threshold vs. speech perception score (N = 8).*

### 3.1.6 Comparison between normal hearing subjects and CI users

An independent samples t-test showed a significant difference in age for participants of the frequency experiment (*M* normal hearing = 22.8 (N = 12), *M* CI users = 69.0 (N = 8); $t(9.3) = -16.223$, $p < .001$). Only ages of those who successfully completed behavioural and electrophysiological testing were included.

Normal hearing participants ($M = 1004.4$) and CI users ($M = 1018.8$) did not differ significantly in their behavioural frequency discrimination thresholds (independent samples t-test: $t(7.2) = -1.940$, $p = .093$), but did differ significantly in their electrophysiological thresholds (*M* normal hearing = 1011.3, *M* CI users = 1082.5; independent samples t-test: $t(7.1) = -2.604$, $p = .035$). An independent samples t-test showed that the offset between behavioural and electrophysiological frequency discrimination thresholds differed significantly between normal hearing subjects ($M = 7.8$) and CI users ($M = 63.8$): $t(7.1) = -2.571$, $p = .037$.

In Table 3, d'-values ((calculated by subtracting the z-value of the false alarm rate from the z-value of the hit rate) are visible for all participants (including outliers who were removed from earlier analyses due to their high amount of false positives). The outliers show lower d'-values than the other participants. An independent samples t-test showed a significant difference between d'-values of normal hearing participants ($M = -2.55$, $SD = .38$, range = -2.93 – -1.44) and CI users ($M = -1.60$, $SD = .79$, range = -2.42 – .11): $t(21) = -3.816$, $p = .001$.

*Table 3 - d'-values per participant for the behavioural frequency discrimination task. An asterisk indicates the outliers that were not included in analyses of the behavioural and electrophysiological thresholds.*

| Participant number NH | d' value | Participant number CI | d' value |
|---|---|---|---|
| *1* | -2.67 | *1** | .11 |
| *2* | -2.82 | *2* | -1.86 |
| *3* | -2.73 | *3* | -2.09 |
| *10* | -2.32 | *4* | -1.83 |
| *12* | -2.91 | *5** | -.50 |
| *14* | -2.70 | *6* | -1.86 |
| *15* | -2.43 | *7* | -1.77 |
| *16* | -2.63 | *8* | -1.50 |
| *17* | -2.60 | *9* | -2.42 |
| *18** | -1.44 | *10* | -2.23 |
| *19* | -2.35 | | |
| *20* | -2.93 | | |
| *21* | -2.63 | | |
| *Mean* | -2.55 | | -1.60 |

## 3.2 Experiment 2

### 3.2.1 Behavioural results

#### 3.2.1.1 Normal hearing subjects

The behavioural spectral ripple discrimination results were interpolated and threshold was defined as the 70% correct ratio in the psychometric curve plotted for each participant. The average behavioural discrimination threshold for normal hearing subjects (N = 14) was 13.8 RPO (*SD* = 4.4, range = 8.8 – 21.5): see Figure 22 for a typical example of a psychometric curve (for all psychometric curves: see Table C3 in Appendix C).

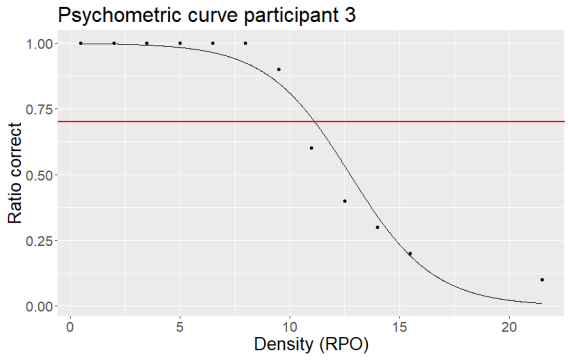



*Figure 22 – Typical psychometric curve fitted for the results of the behavioural discrimination test of a normal hearing listener (#3). Threshold, defined as the 70% correct ratio (red line), for this subject is 11.1 RPO.*

Three participants (#5,#7, and #13) showed much higher (i.e., better) behavioural thresholds than the other participants (21.5, 21.2, and 20.7 RPO, respectively). Two participants (#5, #6) showed a relatively high amount (7/24 and 6/24 respectively) of false positives: see Figure 23. It was decided to exclude data from all participants who had a number of false positives larger than three from the dataset. Further analyses were performed with twelve participants. Without the two outliers, the average behavioural discrimination threshold was 13.2 RPO (*SD* = 4.2, range = 8.8 – 21.2, N = 12): see Figure 23.

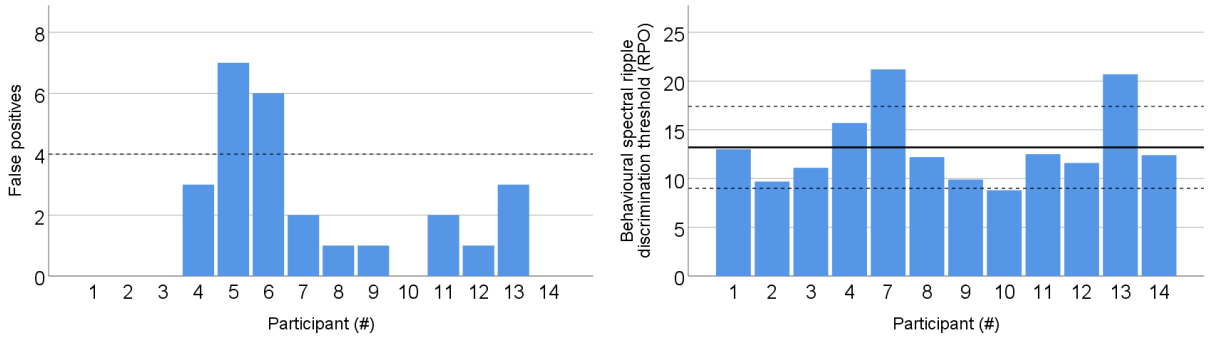



*Figure 23 - Left: Number of false positives per normal hearing subject (N = 14). Right: Behavioural spectral ripple discrimination thresholds per normal hearing subject (N = 12). Black line indicates mean threshold, black dotted lines indicate +/- 1 SD.*

### 3.2.1.2 CI users

For five participants (#1, #3, #5, #7, #8), the response pattern of the behavioural test was unreliable (i.e., they had low scores for low and high(er) scores for high RPO stimuli) and it was therefore not possible to estimate a behavioural discrimination threshold for these CI users. Threshold was therefore estimated for five CI users: see Figure 24 for a typical example of a psychometric curve (for all psychometric curves: see Table C4 in Appendix C). In addition, all participants with an unreliable response pattern showed a high amount of false positives: see Figure 25. It was decided to exclude all participants with a number of false positives > 3, from the dataset. Further analyses were performed with five participants. Average behavioural discrimination threshold (N = 5) was 1.2 RPO (*SD* = 0.4, range = 0.8 – 1.8; see Figure 25).

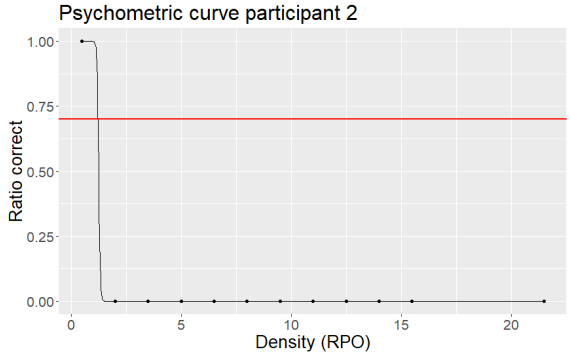



*Figure 24 - Typical psychometric curve fitted for the results of the behavioural discrimination test of a CI user (#2). Threshold, defined as 70% correct (red line) for this subject is 1.2 RPO*

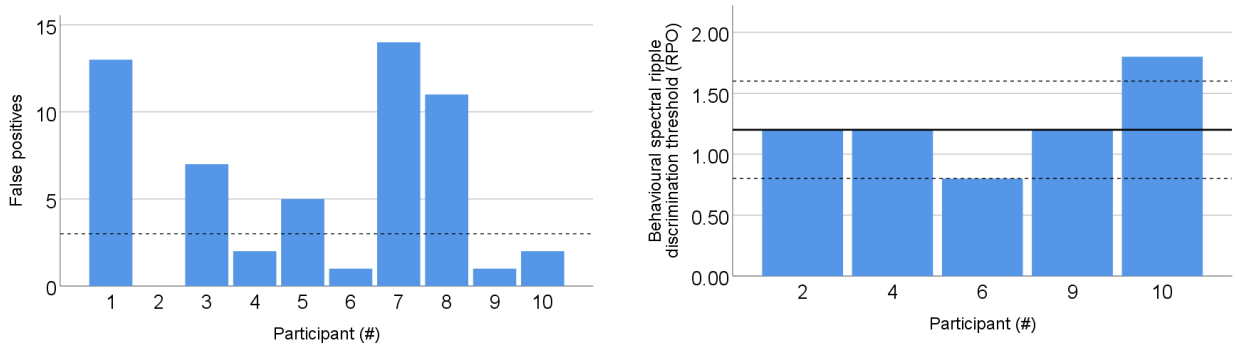



*Figure 25 – Left: Number of false positives per CI user (N = 10). Right: Behavioural spectral ripple discrimination threshold per CI user (N = 5). Black line indicates mean threshold, black dotted lines indicate +/- 1 SD.*

### 3.2.2 Electrophysiological results

Since 2-channel recordings were performed, any negative disturbance of time-locked eye movements that influence auditory response was absent. All acquired eye movements did not cause any disturbance in the SVP and/or ACC responses.

As was the case in Experiment 1, a p2 could not always be identified. Only the n1 was then identified. A P-P amplitude was not calculated, but the trace was used for threshold estimation.

#### 3.2.2.1 Normal hearing subjects

The mean electrophysiological threshold for normal hearing subjects was 5.9 RPO (*SD* = 1.35, range 3.5 – 8.0, N = 12): see Figure 26.

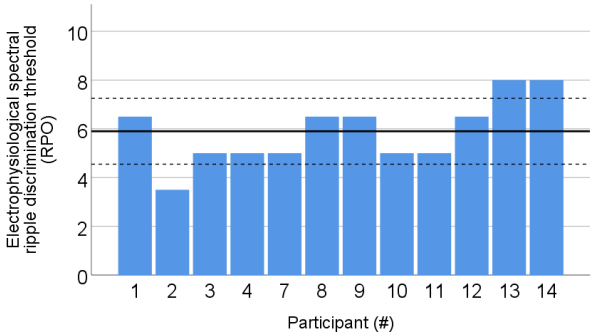



*Figure 26 - Electrophysiological spectral ripple discrimination threshold per normal hearing subject (N = 12). Black line indicates mean threshold, black dotted lines indicate +/- 1 SD.*

In Figure 27, typical examples are shown of neural responses to a stimulus with a low (left) and high (right) density, the latter showing an absent ACC. See Table D3 in Appendix D for the P-P amplitudes and latencies of the SVP and ACC per density, per participant.

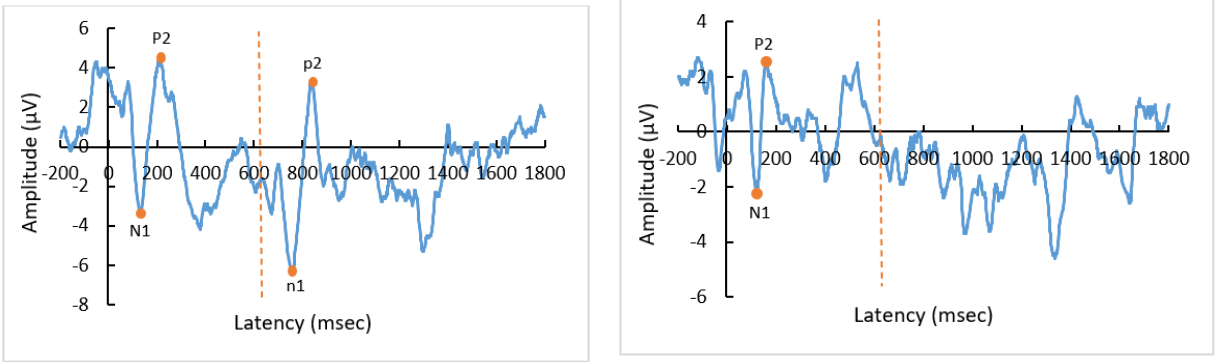



*Figure 27 – Typical example of a neural response (of a normal hearing subject, #3) to a stimulus with a density of 1 RPO (low density; easy to discriminate: left) and 8 RPO (high density; more difficult to discriminate: right). Phase inversion occurred at midpoint (620 msec, indicated by the orange dotted line). Both the SVP (N1-P2) and ACC (n1-p2) are indicated by orange dots. Both graphs show an offset response around 1330 msec.*

#### 3.2.2.2 CI users

The mean electrophysiological threshold for CI users was 0.8 RPO (*SD* = .2, range = 0.5 – 1, N = 5): see Figure 28.

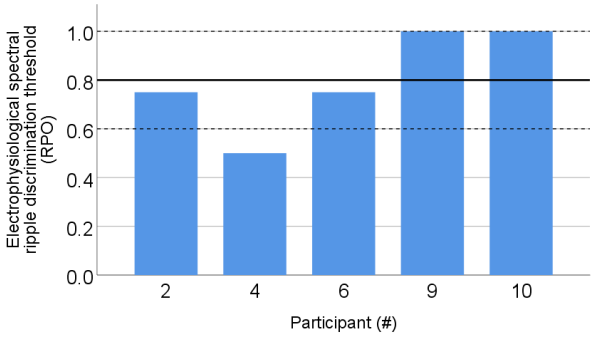



*Figure 28 - Electrophysiological spectral ripple discrimination threshold per CI user (N = 5). Black line indicates mean threshold, black dotted lines indicate +/- 1 SD.*

In Figure 29, typical examples are shown of neural responses to a stimulus with a low (left) and high (right) density, the latter showing an absent ACC. See Table D4 in Appendix D for the P-P amplitudes and latencies of the SVP and ACC per density, per participant.

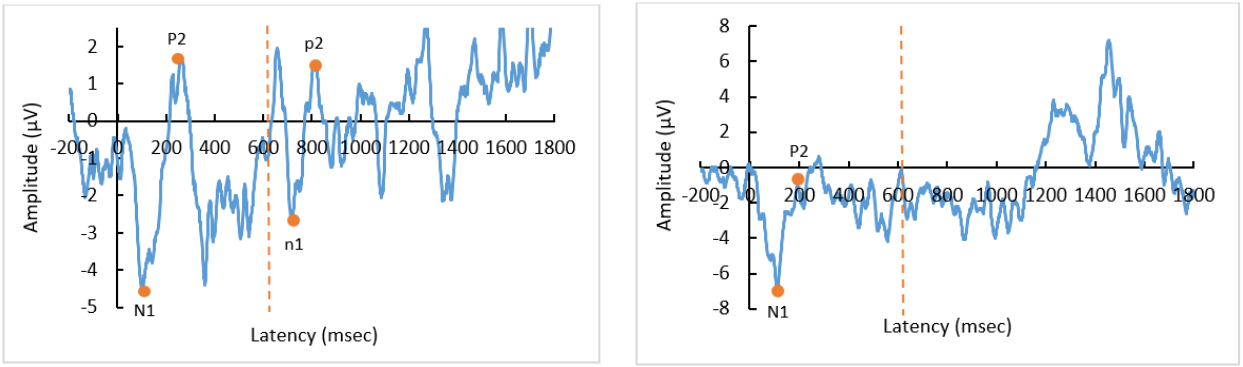



*Figure 29 – Typical example of a neural response (of a CI user, #10) to a stimulus with a density of 0.25 RPO (low density; easy to discriminate: left) and 1.25 RPO (higher density; more difficult to discriminate: right). Phase inversion occurred at midpoint (620 msec, indicated by the orange dotted line). Both the SVP (N1-P2) and ACC (n1-p2) are indicated by orange dots. Both graphs show an offset response around 1330 msec.*

### 3.2.2.3 Relationship density (RPO) and latency n1

Expected inter-peak interval (IPI) between N1 and n1 was 620 msec (based on time of stimulus change). For mean IPIs per frequency change for normal hearing subjects and CI users: see Table 4.

*Table 4 – Mean IPI per density for normal hearing subjects (left) and CI users (right). Mean IPI could not be calculated for densities 0.5 and 2.5 RPO for normal hearing subjects and 1 RPO for CI users because only one data point was available for these densities.*

| Density (RPO) | Mean IPI (msec) |
|---|---|
| *0.125* | 649.3 (N = 8) |
| *0.25* | 616.0 (N = 2) |
| *0.5* | - |
| *1* | 617.2 (N = 12) |
| *2* | 615.0 (N = 2) |
| *2.5* | - |
| *3* | 628.4 (N = 5) |
| *3.5* | 630.0 (N = 2) |
| *4* | 621.8 (N = 10) |
| *4.5* | 630.7 (N = 3) |
| *5* | 634.4 (N = 10) |
| *6.5* | 656.7 (N = 6) |
| *8* | 653.0 (N = 2) |
| *Mean* | 631.0 |

| Density (RPO) | Mean IPI (msec) |
|---|---|
| *0.125* | 642.5 (N = 4) |
| *0.25* | 626.5 (N = 4) |
| *0.5* | 646.8 (N = 5) |
| *0.75* | 646.5 (N = 4) |
| *1* | - |
| *Mean* | 643.4 |

For normal hearing subjects, a two-tailed Pearson correlation showed a weak, but statistically significant positive correlation between RPO and IPI ($r(62) = .293$, $p = .019$), indicating longer response latencies with increasing density (i.e., difficulty): see Figure 30. When stimuli with a density lower than 1 RPO were not included in the analysis, a two-tailed Pearson correlation showed a statistically significant moderate positive correlation between RPO and IPI ($r(51) = .624$, $p < .001$).

A one-sample t-test (with RPO under 1 included) showed a significant difference between the expected mean IPI of 620 msec and the actual mean IPI ($M = 631.0$): $t(62) = 4.438$, $p < .001$. IPI was shown to significantly differ for the different densities (one-way ANOVA: $F(12,51) = 5.560$, $p < .001$). Post hoc analyses could not be performed due to the small number of data points.

For CI users, a two-tailed Pearson correlation showed no statistically significant correlation between RPO and IPI ($r(16) = .259$, $p = .299$): see Figure 30.

A one-sample t-test showed a significant difference between the expected mean IPI of 620 msec and the actual IPI ($M = 643.4$): $t(17) = 4.116$, $p < .001$. IPI did not significantly differ for the different densities (one-way ANOVA: $F(4,13) = 1.446$, $p = .274$).

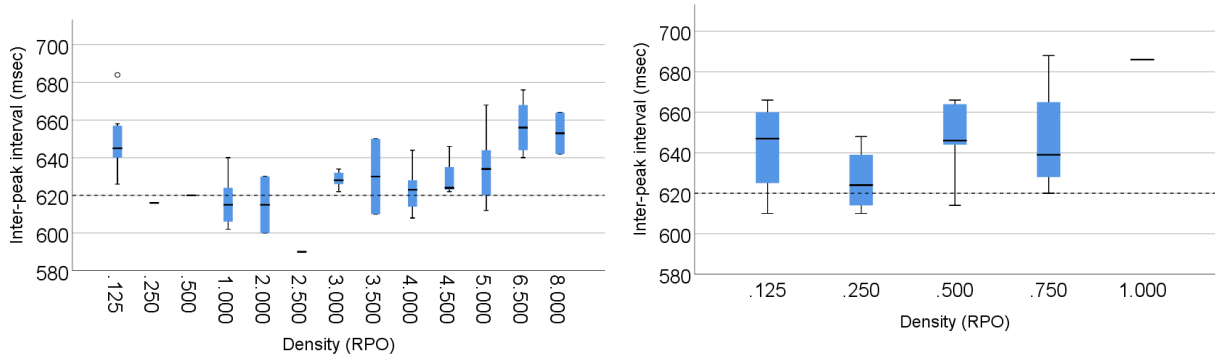



*Figure 30 - Inter-peak interval as a function of density (RPO) for normal hearing subjects (left) and CI users (right). Black dotted line indicates expected IPI of 620 msec.*

### 3.2.2.4 Effect of density (RPO) on P-P amplitude of the ACC

For normal hearing subjects, mean normalised P-P amplitude of the ACC was 0.7 ($SD = 0.3$, range = 0.2 – 1.6): see Figure 31. A two-tailed Pearson correlation showed a marginally significant weak negative relation between density and ACC P-P amplitude ($r(58) = -.248$, $p = .056$), indicating smaller P-P amplitudes with higher densities (i.e., increased difficulty). No significant differences were found between ACC P-P amplitudes of different densities (one-way ANOVA: $F(10,49) = 1.433$, $p = .194$).

When stimuli with densities under 1 RPO were not included in the analysis, a Pearson correlation showed a significant negative weak relation between density and P-P amplitude of the ACC ($r(48) = -.316$, $p = .025$). No significant difference between ACC P-P amplitudes of different densities was found (one-way ANOVA: $F(8,41) = 1.693$, $p = .129$).

For CI users, mean normalised P-P amplitude of the ACC was 0.8 ($SD = 0.4$, range = 0.2 – 1.4): see Figure 31. A two-tailed Pearson correlation showed no significant relation between density and ACC P-P amplitude ($r(12) = .330$, $p = .250$). No significant differences were found between ACC P-P amplitudes of different densities (one-way ANOVA: $F(3,10) = .431$, $p = .735$).

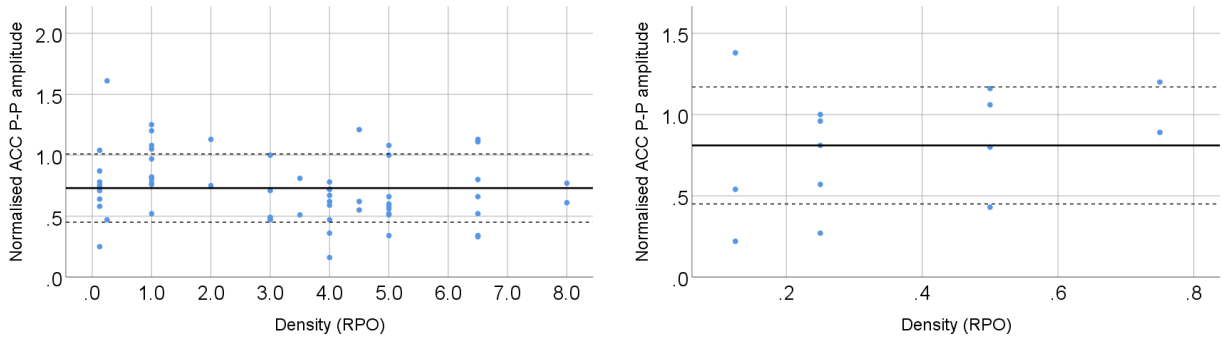



*Figure 31 - ACC P-P amplitude as a function of density (RPO) for normal hearing subjects (left) and CI users (right). Black line indicates mean ACC P-P amplitude, black dotted lines indicate +/- 1 SD.*

### 3.2.3 Relationship between behavioural and electrophysiological results

For normal hearing subjects, in all cases, the behavioural spectral ripple discrimination threshold was higher (i.e., better) than the electrophysiological threshold: see Figure 32. The mean offset between both thresholds was 7.3 RPO (*SD* = 4.0, range = 2.6 – 16.2). A paired-samples t-test showed a significant difference between behavioural (*M* = 13.2 RPO) and electrophysiological (*M* = 5.9 RPO) thresholds (*t*(11) = 6.552, *p* < .001).

For CI users, in all cases, the behavioural spectral ripple discrimination threshold was higher (i.e., better) than the electrophysiological threshold: see Figure 32. The mean offset between both thresholds was 0.4 RPO (*SD* = 0.3, range = 0.05 – 0.8). A paired-samples t-test showed a significant difference between behavioural (*M* = 1.2 RPO) and electrophysiological (*M* = 0.8 RPO) thresholds (*t*(4) = 3.084, *p* = .037).

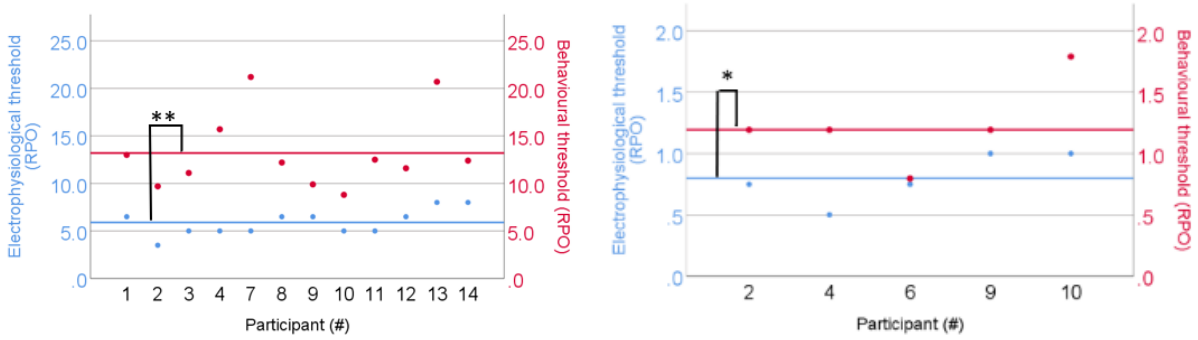



*Figure 32 – Behavioural (pink) and electrophysiological (blue) spectral ripple discrimination thresholds per participant for normal hearing subjects (left; N = 12) and CI users (right; N = 5). The blue and pink lines indicate the mean thresholds (*p < .05; **p < .001).*

For normal hearing subjects, a two-tailed Pearson correlation showed no statistically significant relationship between behavioural and electrophysiological spectral ripple discrimination thresholds (*r*(10) = .265, *p* = .405). A linear regression with electrophysiological threshold as the independent variable and behavioural threshold as the dependent variable showed that electrophysiological threshold did not significantly predict behavioural threshold (*β* = .265, *t*(10) = .870, *p* = .405): see Figure 33.

For CI users, a two-tailed Pearson correlation showed no statistically significant relationship between behavioural and electrophysiological spectral ripple discrimination thresholds ($r(3) = .468$, $p = .427$). A linear regression with electrophysiological threshold as the independent variable and behavioural threshold as the dependent variable showed that electrophysiological threshold did not significantly predict behavioural threshold ($\beta = .468$, $t(3) = .917$, $p = .427$): see Figure 33.

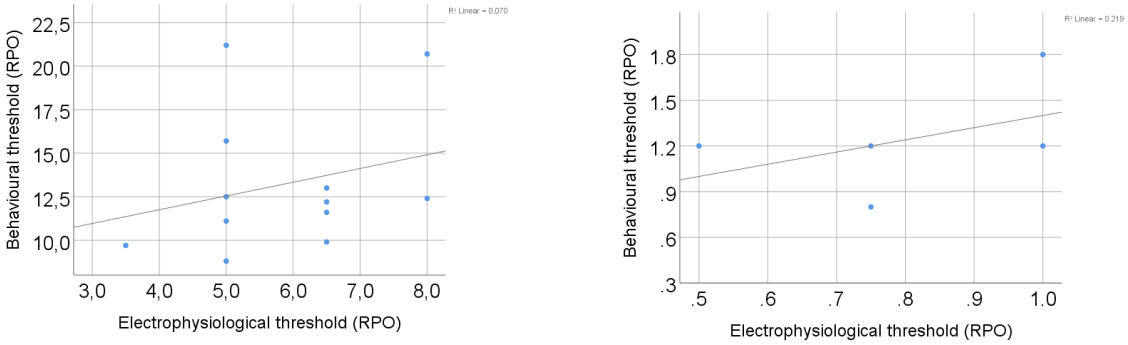



*Figure 33 - Scatter plot electrophysiological vs. behavioural spectral ripple discrimination thresholds for normal hearing subjects (left; N = 12) and CI users (right; N = 5).*

### 3.2.4 Relationship between spectral ripple discrimination thresholds and speech perception in CI users

For an overview of the speech perception scores obtained one year after implantation: see Table A2 in Appendix A.

No statistically significant correlation was found between behavioural spectral ripple discrimination threshold and speech perception score ($r(3) = .729$, $p = .163$) nor between electrophysiological spectral discrimination threshold and speech perception score ($r(3) = .791$, $p = .111$): see Figure 34.

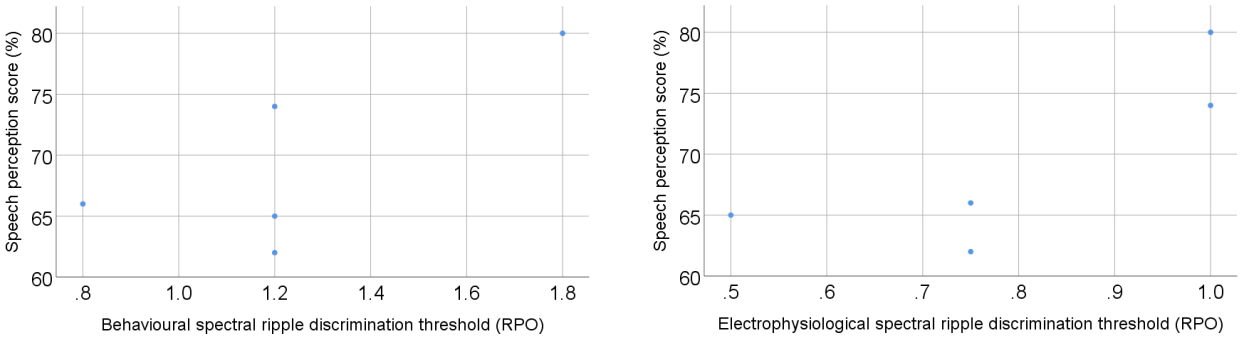



*Figure 34 – Left: Scatter plot behavioural spectral ripple discrimination threshold vs. speech perception score (N = 5). Right: Scatter plot electrophysiological spectral ripple discrimination threshold vs. speech perception score (N = 5).*

### 3.2.5 Comparison between normal hearing subjects and CI users

An independent samples t-test showed a significant difference in age for participants of the spectral ripple experiment ($M$ normal hearing = 21.8 (N = 12), $M$ CI users = 67.6 (N = 5): $t(4.1) = -12.882$, $p <$ .001). Only participants who successfully completed behavioural and electrophysiological testing were included.

Normal hearing participants ($M = 13.2$) and CI users ($M = 1.2$) differed significantly in their behavioural spectral ripple discrimination thresholds (independent samples t-test: $t(11.4) = 9.842$, $p <$

.001) and their electrophysiological thresholds (*M* normal hearing = 5.9, *M* CI users = 0.8; independent samples t-test: $t(12.2) = 12.658$, $p < .001$). An independent samples t-test showed that offset between behavioural and electrophysiological spectral ripple discrimination thresholds differed significantly between normal hearing subjects (*M* = 7.3) and CI users (*M* = 0.4): $t(11.3) = 5.875$, $p < .001$.

In Table 5, d'-values (calculated by subtracting the z-value of the false alarm rate from the z-value of the hit rate) are visible for all participants (including outliers who were excluded from earlier analyses due to their high amount of false positives). It can be seen that, with the exception of normal hearing participant #5, the outliers show a lower d'-value than the other participants.

An independent samples t-test showed a significant difference between d'-values of normal hearing participants (*M* = -2.42, *SD* = .36, range = -3.05 – -1.59) and CI users (*M* = -.14, *SD* = .33, range = -.67 – .42): $t(22) = -15.925$, $p < .001$.

*Table 5 - d'-values per participant for the behavioural spectral ripple discrimination task. An asterisk indicates the outliers that were not included in analyses of the behavioural and electrophysiological thresholds.*

| Participant number NH | d' value | Participant number CI | d' value |
|---|---|---|---|
| *1* | -2.84 | *1** | -.05 |
| *2* | -2.34 | *2* | -.63 |
| *3* | -2.59 | *3** | .00 |
| *4* | -2.30 | *4* | -.06 |
| *5** | -2.61 | *5** | .42 |
| *6** | -1.59 | *6* | -.67 |
| *7* | -3.05 | *7** | .00 |
| *8* | -2.46 | *8** | .05 |
| *9* | -2.16 | *9* | -.35 |
| *10* | -2.16 | *10* | -.06 |
| *11* | -2.18 | | |
| *12* | -2.39 | | |
| *13* | -2.41 | | |
| *14* | -2.77 | | |
| *Mean* | -2.42 | | -.14 |

## 3.3 Comparison between frequency and spectral ripple discrimination thresholds

### 3.3.1 Normal hearing subjects

Frequency and spectral ripple threshold data of six normal hearing subjects who participated in both experiments are compared. An overview of their thresholds is provided in Table 6.

*Table 6 - Overview of the behavioural and electrophysiological thresholds for the normal hearing subjects who participated in both the spectral ripple and frequency experiments (N = 6).*

| Participant number | Spectral ripple threshold (RPO) | | Frequency threshold (Hz) | |
|---|---|---|---|---|
| | Behavioural | Electrophysiological | Behavioural | Electrophysiological |
| *1* | 13.0 | 6.5 | 1005.5 | 1005 |
| *2* | 9.7 | 3.5 | 1002.2 | 1020 |
| *3* | 11.1 | 5 | 1004.1 | 1005 |
| *10* | 8.8 | 5 | 1002.1 | 1005 |
| *12* | 11.6 | 6.5 | 1002.8 | 1020 |
| *14* | 12.4 | 8 | 1003.8 | 1005 |

A two-tailed Pearson correlation showed a statistically significant, strong, positive relationship between behavioural spectral ripple and frequency discrimination thresholds ($r(4) = .849$, $p = .033$), indicating higher (i.e., worse) frequency thresholds with higher (i.e., better) spectral ripple thresholds. With respect to the electrophysiological thresholds, no statistically significant correlation was found ($r(4) = -.369$, $p = .471$): see Figure 35.

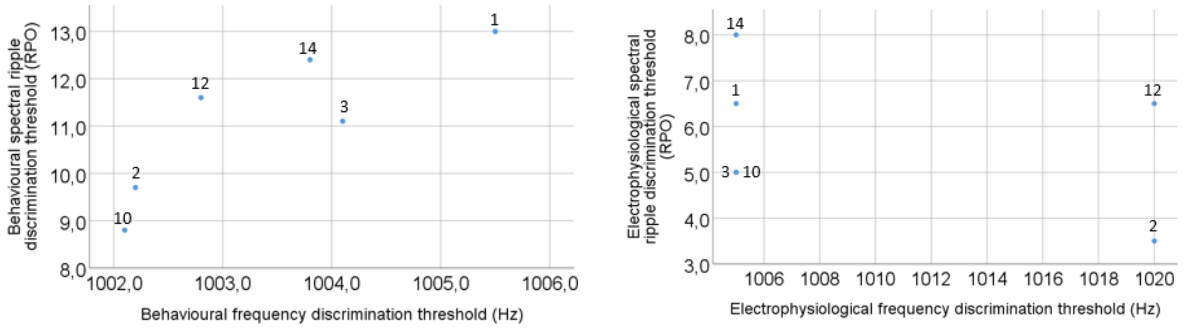



*Figure 35 - Behavioural spectral ripple vs. frequency discrimination thresholds (left; N = 6), and electrophysiological spectral ripple vs. frequency discrimination thresholds (right; N = 6).*

### 3.3.2 CI users

Spectral ripple and frequency threshold data of five CI users who successfully participated in both experiments are compared. An overview of their thresholds is provided in Table 7.

*Table 7 - Overview of the behavioural and electrophysiological thresholds for the participants who participated in both the spectral ripple and frequency experiments (N = 5).*

| **Participant number** | **Spectral ripple threshold (RPO)** | | **Frequency threshold (Hz)** | |
|---|---|---|---|---|
| | Behavioural | Electrophysiological | Behavioural | Electrophysiological |
| *2* | 1.2 | 0.75 | 1009.1 | 1020 |
| *4* | 1.2 | 0.5 | 1067 | 1200 |
| *6* | 0.8 | 0.75 | 1022.3 | 1100 |
| *9* | 1.2 | 0.75 | 1009.9 | 1050 |
| *10* | 1.8 | 1 | 1004.7 | 1020 |

A two-tailed Pearson correlation showed no statistically significant relationship between behavioural spectral ripple and frequency discrimination thresholds ($r(3) = -.671$, $p = .215$). With respect to the electrophysiological thresholds, no statistically significant correlation was found ($r(3) = -.649$, $p = .236$): see Figure 36.

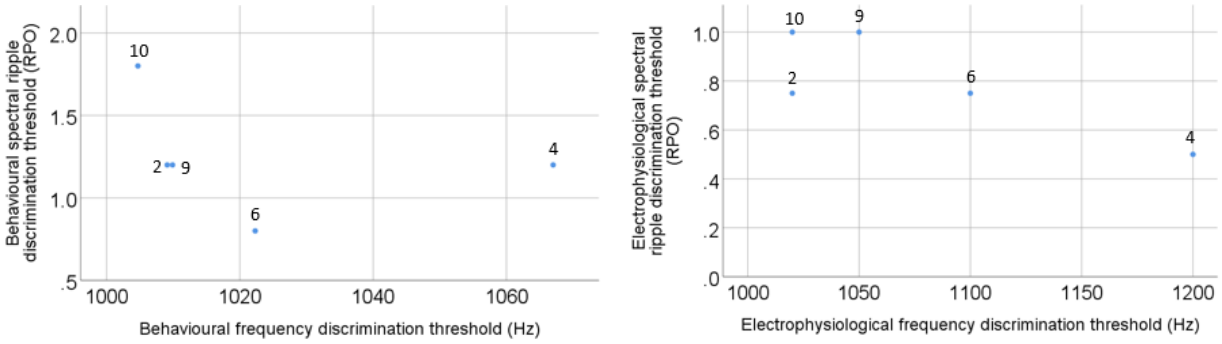



*Figure 36 - Behavioural spectral ripple and frequency discrimination thresholds (left; N = 5) and electrophysiological spectral ripple and frequency discrimination thresholds (right; N = 5).*

# 4. Discussion

In this study, the relationship between estimated behavioural and electrophysiological discrimination thresholds of frequency and spectral ripple stimuli was investigated in normal hearing subjects and CI users. The aim was to investigate the correlation between the estimated behavioural threshold that was based on a single-interval test, and the estimated electrophysiological threshold that was based on the presence of the ACC, to see if the ACC has potential clinical value as an objective measure of auditory discrimination. In addition, the relationship between the thresholds and speech perception in CI users was investigated. To this end, two experiments were conducted, one investigating pure tones containing frequency changes, and one investigating spectral ripples. The results of the two experiments will first be discussed separately. Subsequently, in a general discussion, limitations, clinical implications, and suggestions and recommendations for future research will be discussed.

## 4.1 Experiment 1

### 4.1.1 Loudness balancing

The pre-experimental loudness balancing task proved to be difficult for the majority of the normal hearing subjects and CI users. One CI user (#1) was unable to complete the task. Even after the researcher provided extra instructions the participant did not understand the task and got frustrated. It was decided to stop the loudness balancing task and to continue with the behavioural discrimination task for this CI user. Most other CI users mentioned that they did not hear a difference between reference and target part of the stimulus pair. Many participants (both normal hearing subjects and CI users) indicated that they needed differences larger than 5 dB between the first and second part of a stimulus pair in order for them to sound equally loud. Before the results were obtained, the intention was to adjust loudness of the second part of the stimulus pair based on the loudness balancing results for each participant when perceived difference was larger than 5 dB. This would help to minimize effects of perceived loudness on behavioural and electrophysiological thresholds. The expectation was that large loudness differences (> 5 dB) would only be present for large frequency changes (where an ACC would be present regardless of perceived loudness difference). However, the response pattern shown by the normal hearing subjects and the CI users was more variable than the expected pattern of larger perceived loudness differences for larger frequency changes (Suzuki & Takeshima, 2004).

It is possible that the reduced dynamic range of CI users has played a role in the results from the loudness balancing task. Whereas normal hearing listeners have a dynamic range of approximately 120 dB, with sixty to a hundred behaviourally discriminable steps between different intensities on this range (Moore, 2012), the dynamic range of CI users is much smaller. Due to compression by the implant, their range generally lies between six and thirty dB and their range has less behaviourally discriminable steps (Shannon, 1983). It is therefore likely that changing perceived loudness in steps of only 2 dB (as was done in this study) is too difficult for CI users and it is possible that, although large loudness differences were chosen between target and reference part of the stimulus pair, no loudness differences were actually perceived when the unchanged stimuli were used for further testing. However, this does not provide an explanation as to why normal hearing subjects showed variable results. It is possible that the loudness balancing task that was used for this study was too difficult, both for normal hearing listeners and CI users.

Based on the large variability in results from the participants, it was decided not to adjust loudness of the stimuli. When a few participants were asked if they heard a loudness difference during the EEG-recording (with stimuli that were not corrected for the perceived loudness differences), participants did not appear to hear differences. Nevertheless, loudness balancing between stimulus parts with different frequencies would be preferred to increase validity of the discrimination tasks, since a possible effect of perceived loudness on the discrimination thresholds cannot be excluded in

this study. If perceived loudness differences did have an effect on the thresholds found in this study, this would have led to an overestimation of the thresholds, since the perceived loudness difference may have led a listener to believe they perceived a change. It is very unlikely that perceived loudness differences have led to an underestimation of discrimination thresholds. When listeners were not able to discriminate between certain frequency differences, this result is most likely valid. Should any choices regarding, for example, rehabilitation be made based on these thresholds, these choices would be justified. A last important remark regarding loudness balancing is that none of the studies discussed in this thesis mentioned the use of a loudness balancing task in their publications.

### 4.1.2 Behavioural results

One normal hearing subject (#18) noted they heard a gap in the no-change stimuli. However, two 1000 Hz-sounds were concatenated at zero-crossing, with no gap present. The participant showed a high amount of false positives (six out of twenty). This was deemed too high for the test results to be reliable and the data from this participant was not included in further analyses. The average behavioural frequency discrimination threshold for normal hearing subjects was 1004.5 Hz (0.45% of base frequency, range = 1001.1 – 1011.6, 0.11-1.16% of base frequency). The results are in line with the results found by He and colleagues (2012) who found thresholds ranging from 0.38-1.14% of base frequency (which was 500 Hz; average threshold was 0.72%). Vonck and colleagues (2021) found thresholds ranging from 0.2-3% of base frequencies (using base frequencies of 500, 1000, 2000, and 4000 Hz), which is slightly worse (especially when looking at the upper end of the range) than thresholds found in the current study. Brown and colleagues found thresholds ranging from 0.3 – 2.1% (using a base frequency of 262 Hz), which is also slightly worse than the results from the current study. All three studies used a 3AFC task, as opposed to the single-interval task that was used in the current study. Although differences between results from different studies are small, the single-interval task used in the current study seems to have resulted in marginally lower (i.e., better) thresholds. It was expected that thresholds would be better when using the single-interval test (this will be explained in more detail in the General discussion). However, it should also be taken into account that the use of different base frequencies in the studies may also have led to differences in thresholds, albeit that large differences between thresholds at different base frequencies are only expected when comparing with stimuli that used a base frequency higher than 4000 Hz, where thresholds are expected to be worse (Lopez-Poveda, 2014). This was not the case for any of the studies discussed here. Still, the use of different base frequencies by the different studies complicates the comparison between the thresholds found in the current study and thresholds found in other studies.

Regarding the CI users, two of them (#1 and #5) showed a relatively high amount of false positives (thirteen and six out of twenty, respectively). These participants were therefore excluded from further analyses. The average behavioural frequency discrimination threshold for CI users was 1018.8 Hz (1.9% of base frequency, range = 1004.0 – 1067.0, 0.4 – 6.7% of base frequency). Liang et al. (2018) found an average threshold of 3.79% (range = 0.67 – 9.66%) using a 2AFC task with within-stimulus changes (base frequency of 160 Hz). Zhang and colleagues (2019) found average thresholds of 5.48, 3.94, and 7.78% in a 3AFC task (using base frequencies of 250, 1000 and 4000 Hz, respectively), and McGuire et al. (2021) found average thresholds of 8.68, 4.43 and 7.69% using a 3AFC task (and base frequencies of 250, 1000, and 4000 Hz, respectively). The average threshold found in the current study is lower (i.e., better) than thresholds found in earlier studies. It is possible that the task used for estimating thresholds had an effect on the results. The other studies used a 2/3AFC task, which may be more cognitively challenging than the single-interval task used in the current study. This will be discussed in more detail in the General discussion. Once again, the use of different base frequencies complicates the comparison with results from other studies. However, when only thresholds that were estimated

using a 1000 Hz base frequency are compared, it is still visible that average threshold found in the current study is better than thresholds found in other studies.

### 4.1.3 Electrophysiological results

The average electrophysiological frequency discrimination threshold for normal hearing subjects was 1011.3 Hz (1.13% of base frequency, range = 1005 – 1020, 0.5-2% of base frequency). These results are in line with the results found by Harris et al. (2008; thresholds ranging from 0.8-1% of base frequency), He et al. (2012; thresholds ranging from 5-10 Hz or 1-2% of base frequency), and Vonck et al. (2021; thresholds ranging from 0.3-5% of base frequency, albeit that the upper end of this range is higher than found in the current study). Despite differences in stimulus parameters (e.g., base frequency) and method used for estimating thresholds in these studies and the current study, frequency discrimination thresholds appear largely similar. This finding could suggest that discrimination thresholds estimated using an EEG-recording will always be in a similar range because of the limitations inherent to an EEG-recording (i.e., the noise that is present in the signal). This would entail that, with the techniques that are currently available for EEG analysis, more sensitive electrophysiological discrimination thresholds are not feasible yet.

The average electrophysiological frequency discrimination threshold for CI users was 1082.5 Hz (8.3%, range = 1020 – 1200, 2 – 20% of base frequency). To our knowledge, no earlier study has investigated electrophysiological frequency discrimination thresholds in CI users in a comparable manner to the one in this study. Liang et al. (2018) and McGuire et al. (2021) did look at the ACC for frequency stimuli, but both only investigated three magnitudes of change. This results in a very rough estimate of the electrophysiological threshold that cannot be compared to the more precise method used for estimating threshold in the current study. For this reason, results found in the current study cannot be compared to results from earlier studies.

When analysing the EEG-recordings, large inter-subject differences in EEG quality were found that could not be explained by poor impedance of the electrodes. For some participants it was therefore difficult to interpret the data. In some participants this caused a large offset between behavioural and electrophysiological thresholds. Given the relatively small number of participants that was included in this study, the correlation analysis was affected strongly by these large differences in offset.

Additionally, the CI artefact (that was expected to be small in MED-EL CI users: Mathew et al., 2017) that was visible for some CI users proved to be a problem when interpreting the EEG-recordings: see Figures E1 and E2 in Appendix E for examples of responses with and without CI artefact. Artefact at time of change was usually visible between 620 and 650 msec and was therefore not interpreted as being an ACC (that was expected at 720 msec). However, presence of the artefact interfered with n1 detection in some traces for five out of eight CI users. This interference may possibly have led to an underestimation of electrophysiological threshold in some CI users.

CI artefact was not visible for all CI users. For some, no artefact was visible at all, for others artefact was only visible at onset. Presence of the artefact may be explained by average MCL (most comfortable loudness) for each participant: see Figure E5 in Appendix E. CI users with a higher average MCL (and thus higher charge levels) showed a larger average artefact at onset of a stimulus than those with a lower average MCL. Normalised P-P amplitude of the CI artefact at frequency change in the middle of stimuli (seen around 620-650 msec) was not related to magnitude of frequency change (i.e., P-P amplitude was not larger for large frequency changes): see Appendix E.

In line with results from Vonck et al. (2019), a significant moderate negative correlation was found for normal hearing subjects between magnitude of frequency change and inter-peak interval (IPI) between N1 and n1, indicating a prolonged n1 with more difficult discrimination (smaller frequency changes). A significant difference between the expected IPI of 620 msec (based on time of within-stimulus change)

and the actual mean IPI was found in the current study, with the latter being longer than 620 msec. IPIs differed significantly between different magnitudes of change. Post hoc analyses revealed that smaller magnitudes of change differed significantly from larger magnitudes of change, with the latter having lower mean IPIs (thus indicating easier discrimination; Figure 17 shows which densities differed significantly). The only pair that deviated from these results is 1010-1050, where the IPIs did not differ significantly. Given the limited number of data points available per magnitude of change, it is possible that data points that deviated only slightly had a relatively large effect on the statistical analyses. For CI users, no correlation was found between magnitude of frequency change and IPI. IPI did differ from the expected IPI of 620 msec, but no significant differences were found between the average IPIs of different magnitudes of frequency change. The average IPIs per magnitude of change (visible in Table 2) also showed no trend in the direction of longer latencies with smaller magnitudes of change. However, average IPI of only five magnitudes of change was available for the CI users and the artefact that was visible for some participants complicated localisation of N1 and n1. Therefore, based on the current data, the relation between magnitude of frequency change and IPI for CI users remains unclear.

In contrast to the results found by Vonck et al. (2019) in normal hearing listeners, no effect of magnitude of change was found on the normalised P-P amplitude of the ACC for normal hearing subjects nor CI users. It was expected that as magnitude of change decreased (and difficulty increased), P-P of the ACC would decrease, but this was not found in the current study. This finding could possibly be explained by the relatively small number of participants and the relatively poor EEG-quality in some participants that may have led to over- or underestimation of P-P amplitudes, as well as CI artefact in some CI users.

### 4.1.4 Relationship between behavioural and electrophysiological thresholds

The behavioural frequency thresholds differed significantly from the electrophysiological thresholds. For eleven (out of twelve) normal hearing subjects and all CI users, the behavioural threshold was higher (i.e., better) than the electrophysiological threshold. For one normal hearing subject (#1), the electrophysiological threshold was marginally (0.5 Hz) better than the behavioural threshold. Better behavioural thresholds were expected, since studies have shown that behavioural tests are more sensitive methods for estimating discrimination thresholds (e.g., Brown et al., 2017; He et al., 2012).

For normal hearing subjects, the average offset between behavioural and electrophysiological threshold was 6.8 Hz, but the range (-0.5 – 17.8 Hz) and standard deviation (6.6 Hz) were large. Furthermore, a correlation analysis showed no relation between the estimated behavioural and electrophysiological frequency discrimination thresholds. A linear regression showed that the estimated electrophysiological threshold did not predict the estimated behavioural threshold.

In contrast, for CI users, a strong, positive relation was found between the thresholds, indicating a higher behavioural threshold with a higher electrophysiological threshold. 67% of the variance found in the behavioural thresholds could be explained by the variance in the electrophysiological thresholds. However, the average offset for CI users between behavioural and electrophysiological threshold was 63.8 Hz and the range (10.9 – 177.1 Hz) and standard deviation (63.4 Hz) were large, which leads to question the value of the significant correlation between the behavioural and electrophysiological thresholds.

The results of the current study for the normal hearing subjects are not in line with the literature (Brown et al., 2017; He et al., 2012; Vonck et al., 2021). Unfortunately, to our knowledge, no other study has investigated the relationship between behavioural and electrophysiological frequency discrimination thresholds using the ACC in CI users. The only comparison that can be made is to studies that investigated the relation between these thresholds in normal hearing participants. Brown and colleagues, He and colleagues, and Vonck and colleagues all found a significant correlation between behavioural and electrophysiological frequency discrimination thresholds. These three studies all used

a 3AFC task to estimate behavioural discrimination thresholds, whereas the current study used a single-interval test. It was expected that the single-interval test would be more closely related to the electrophysiological ACC-recording because the stimuli used for both types of threshold estimation are the same (see the General discussion for a more detailed discussion). This does not appear to be the case for normal hearing subjects. Possible explanations for this result may include method used for estimating electrophysiological threshold (which was done visually in the current study and differently for some of the other studies), stimulus parameters (e.g., duration, loudness), or EEG-setup. It is, however, unclear why these possible explanations may have had an effect in normal hearing subjects, but not in CI users.

### 4.1.5 Relationship with speech perception in CI users

No correlation was found between speech perception score and behavioural nor electrophysiological discrimination thresholds in CI users. A negative correlation was expected, with lower (i.e., better) discrimination thresholds related to higher (better) speech perception scores. Instead, some participants with a high threshold had a high speech perception score or a low threshold with a low speech perception score.

Results from this study are not in line with earlier studies that investigated the relation between speech perception and frequency discrimination. Liang and colleagues (2018) and McGuire and colleagues (2021) found a relation between ACC n1 latency and speech perception. They did, however, not investigate electrophysiological thresholds. Zhang et al. (2019), and McGuire et al. (2021) both found significant relations between behavioural frequency discrimination thresholds (using a 3AFC task) and several measures of speech perception (in quiet and in noise). It is possible that the method used for estimating behavioural threshold (3AFC versus single-interval) has played a role in the results found. Another explanation may be that the speech perception scores obtained by Zhang et al. and McGuire et al. were obtained around the same time as the thresholds. In the current study, speech perception scores that were obtained one year post-implantation were used. For some CI users, this was around ten years ago, whereas for others, it was only four months since this score was obtained (range = 17 – 144 months). Although Lenarz, Sönmez, Joseph, Büchner, and Lenarz (2012) found no more improvement in speech perception six months post-implantation in postlingually deafened CI users, it is still possible that speech perception scores would have been different had speech perception tests been performed at the same time as threshold estimation. For future research, it would be preferred to obtain speech perception measures in the same period as threshold estimation.

### 4.1.6 Comparison between normal hearing subjects and CI users

The two participant groups in this study were shown to significantly differ in age, with the CI users being older than the normal hearing subjects. For frequency discrimination, a significant difference was only found for electrophysiological discrimination thresholds, but not for behavioural thresholds. The expectation was that CI users would have worse thresholds. The information they receive via their implant is much more limited than what listeners with a normal hearing perceive (Macherey & Carlyon, 2014), which was assumed to complicate auditory discrimination. It was therefore surprising that, as a group, normal hearing subjects and CI users did not differ in behavioural frequency discrimination threshold. However, the range of thresholds found for the CI users was much larger than the range for normal hearing listeners, indicating that there are CI users with frequency discrimination capabilities similar to those of normal hearing listeners, whereas there are also CI users that experience more difficulty discriminating between different frequencies. This is in line with observations of large variation in CI outcomes between users (e.g., Helms et al., 1997; Wilson & Dorman, 2007).

Regarding the correlation between behavioural and electrophysiological thresholds, it stood out that only the correlation between frequency thresholds in CI users reached statistical significance.

Frequency thresholds in normal hearing subjects were not correlated. Concerning offset between behavioural and electrophysiological thresholds, it was found that this offset differed significantly between normal hearing subjects and CI users. The offset was larger for CI users. Since the range of behavioural results was also larger for frequency in CI users, it makes sense that this also transfers to the offset between behavioural and electrophysiological thresholds.

Lastly, a comparison between normal hearing subjects and CI users was made for d'-values. The d'-value is calculated using the hit rate and false positive rate, thereby taking both sensitivity and specificity into account. The d'-values differed between normal hearing subjects and CI users. Absolute values were higher for normal hearing subjects, indicating a better response to the signal (Stanislaw & Todorov, 1999). Better values for normal hearing subjects were expected, since it was hypothesized that CI users would have worse thresholds (and thus a lower sensitivity) than normal hearing subjects. Additionally, a difference could be seen between those participants that were identified as outliers and those that were not, with the latter having higher (better) d'-values. This is logical, given the fact that the participants identified as outliers showed a high amount of false positives, thereby increasing their false positive rate, which in turn reduces the d'-value.

### 4.1.7 Conclusion frequency discrimination

In this study, it has been shown that although it is possible to use the ACC to estimate an electrophysiological frequency discrimination threshold in normal hearing subjects and CI users, there appears to be no relationship between estimated behavioural and electrophysiological frequency discrimination in normal hearing subjects. A significant correlation was found for the CI users. Nonetheless, the offset between behavioural and electrophysiological threshold varied considerably between participants. Additionally, discrimination thresholds did not correlate with speech perception scores in CI users. This limits possible clinical value. The relatively small number of participants that was included in this study may have had an effect on the statistical analyses. Nevertheless, given the considerable amount of variation that was visible between participants in this study (that is also expected to be visible when a larger group of participants is included), the ACC does not appear to be suitable to be used as an objective measure to investigate auditory discrimination capability in normal hearing subjects. In CI users, more research is necessary, perhaps including more participants and further investigation of speech perception measures and their relation with frequency discrimination.

## 4.2 Experiment 2

### 4.2.1 Behavioural results

Two normal hearing subjects showed a relatively high number of false positives in the behavioural test. It is not clear what caused this. Due to their high number of false positives (>3), these participants (#5 and #6) were excluded from further analyses, since their results were deemed unreliable. Furthermore, three participants (#5, #7 (excluded due to high number of false positives), and #13) showed high behavioural thresholds (in comparison to the other participants). For participants #7 and #13 it is unclear why they showed much higher thresholds. All participants received the same instructions and the two participants with high thresholds did not have extensive musical experience (which could have a small effect on discrimination capacity, as has been shown by Brown et al., 2017).

The average behavioural spectral ripple discrimination threshold, estimated using a single-interval test, for the normal hearing subjects was 13.2 RPO (range = 8.8 – 21.2). Horn et al. (2017) also used a single-interval test to estimate spectral ripple discrimination thresholds in normal hearing subjects and using a stimulus with a 20 dB depth (other parameters, such as duration and range of summated pure tones, did differ). Their results showed thresholds between 7 – 22 RPO. This range is similar to the range of thresholds found in this study. Other studies that have investigated behavioural spectral ripple discrimination thresholds in normal hearing subjects are Henry et al. (2005) and Brown

et al. (2017). These studies used a 3AFC task and stimuli with a depth of 30 dB. Thresholds found in these studies ranged from 2.03 – 7.55 and 4 – 7.5 RPO, respectively, which is markedly lower than the thresholds found in this study. This was unexpected, given the fact that a higher peak-to-valley ratio was thought to make discrimination easier (Horn et al., 2017). It is possible that the different method used for of estimating threshold (single-interval versus 3AFC) has led to this difference in thresholds (this will be discussed further in the General discussion).

Regarding the reliability of the behavioural responses in CI users, fifty percent of the participants showed a high amount (>3) of false positives ( #1, #3, #5, #7, #8). This was unexpected since they heard a ripple with a density of 0.5 RPO before testing. This was done to ascertain they could discriminate the easiest density that was being tested, which was the case for all participants, but also entails that all CI users knew what a change in a ripple sounded like. Implant type or CI settings cannot provide an explanation for the high false positive rate in some CI users. However, it is unclear whether there were confounding cues that some participants used when deciding whether they heard a change. Possible confounds that are present in spectral ripples are mentioned in multiple publications (e.g., Aronoff & Landsberger, 2013; Lopez Valdes, 2017) and it is thus possible that some CI users were more sensitive to these confounds than others. Additionally, since two normal hearing listeners already showed a relatively high amount of false positives, it was expected that there would also be some CI users that would show the same results. Furthermore, the fact that CI users subjectively perceive less differences in the stimuli that were tested in the behavioural test than normal hearing listeners may provide an explanation as to why they are more likely to show false positives than normal hearing listeners.

The average behavioural spectral ripple discrimination threshold for the CI users was 1.2 RPO (range = 0.8 – 1.8). The thresholds found in this study are lower (i.e., worse) than the thresholds found by Won et al. (2011), who found thresholds ranging from 2.37 – 13.69 RPO (*M* = 6.16) using a single-interval test. Lopez Valdes et al. (2015) found an average of 1.74 RPO, which is similar to the average threshold of the current study, but the range of the current study is smaller than the range found by Lopez Valdes and colleagues (0.4 – 5.2), who also used a single-interval test. Lower thresholds in the current study were expected, given the fact that a lower depth was used (20 dB) compared to Won et al. and Lopez Valdes et al. (who used 30 dB), and a lower depth was thought to make discrimination more difficult. The average threshold found in the current study is higher (i.e., better) than the average threshold found by Henry et al. (2005), which was 0.62 RPO (range = 0.13 – 1.66). Henry and colleagues used a 3AFC task, which is thought to be more difficult than the single-interval task (which will be discussed in more detail in the General discussion), which may explain the lower thresholds found by Henry and colleagues.

### 4.2.2 Electrophysiological results

The average electrophysiological spectral ripple discrimination threshold, estimated by presence of the ACC, for normal hearing subjects was 5.9 RPO (range = 3.5 – 8.0). To the best of our knowledge, only one other study investigated spectral ripple discrimination in normal hearing subjects using the ACC. Brown et al. (2017) found thresholds ranging from 4 – 8 RPO. These results are in the same range as the results found in the current study. However, as mentioned before, Brown and colleagues used stimuli with a 30 dB depth and it was hypothesized that discrimination is easier at higher depths. It was therefore expected that the thresholds in the current study would be lower (i.e., worse) than the thresholds found by Brown and colleagues. This did not turn out to be the case, but there are possible explanations for this result. For example, method used for determining presence of the ACC may have impacted the estimated thresholds in this study (where thresholds were identified visually) and in the study by Brown and colleagues (where thresholds were identified both visually and using an automatic peak-identifying algorithm). Additionally, stimulus parameters (e.g., duration of stimuli or loudness) or EEG-recording settings (placement of electrodes, filter settings, etc.) may have played a role. However,

as mentioned earlier, this may also indicate that discrimination thresholds based on presence of the ACC will always be similar, regardless of stimuli parameters or method for estimating threshold, due to the limitations of EEG-recordings. The noise that is inevitably present in EEG-recordings may always mask the ACC when investigating difficult-to-discriminate changes.

The average electrophysiological spectral ripple discrimination threshold for the CI users was 0.8 RPO (range = 0.5 – 1). This is slightly lower (i.e., worse) than the average threshold found by Lopez Valdes et al. (2015), who found an average threshold of 1.01 RPO, with the range of thresholds in the current study being smaller than the range found by Lopez Valdes and colleagues (0.2 – 2). Lower (i.e., worse) thresholds were expected for the current study, since a lower depth was used for the ripples. What may have also influenced the results is the method used for determining presence of the ACC: visually (subjectively) in the current study versus objectively by Lopez Valdes and colleagues. In addition, Lopez Valdes and colleagues used an artefact attenuation strategy to reduce the effects of CI artefact on interpretation of the EEG-recordings, which may have led to more sensitive threshold estimation.

The large inter-subject differences in EEG quality made it difficult to analyse the data and consequently made it difficult to identify the ACC. This sometimes led to a low (i.e., bad) electrophysiological threshold in combination with a high (i.e., good) behavioural threshold. The possible relationship between the two thresholds is affected strongly by this, especially given the relatively small number of participants in this study. The inter-subject variability in EEG quality may complicate the use of EEG-recordings for estimating discrimination thresholds in clinical practice. Additionally, although CI artefact was expected to be small in MED-EL CI users (e.g., Mathew et al., 2017), artefacts caused by the CI still proved to be a problem for the interpretation of some traces in multiple CI users in the current study (see Figures E3 and E4 in Appendix E for examples of responses with and without CI artefact). The artefact at time of phase inversion (when visible) was seen around 620-650 msec and was not interpreted as an ACC, but did complicate the interpretation of a possible n1. For three of the five CI users, CI artefact interfered with n1 detection in some, but not all, traces. This may have led to an underestimation of electrophysiological threshold.

Not all participants showed an artefact caused by their CI and for some participants it was only visible at on- or offset of the stimulus. When looking at the average MCL of the different participants (see Figure E5 in Appendix E), it can be seen that there are large differences in average MCL between participants. Further inspection of the EEG-data showed that CI artefact was larger in CI users with higher average MCLs (and thus higher charge levels). Normalised P-P amplitude of the CI artefact at time of phase inversion was not related to density: see Appendix E.

During the EEG-recording sessions it was noticed that a clear ACC appeared to be lacking or was rather small for most normal hearing subjects when presenting stimuli with a density below 1 RPO. These stimuli are easy to discriminate behaviourally, but this was not reflected in the amplitude of the ACC. Inspection of the spectrograms of the spectral ripples showed a small amount of contrast between the two parts of the stimulus for the ripples with a density lower than 1 RPO (See Figure 37). Stimuli with a density of 1 RPO or higher showed a much clearer contrast, which may explain why the amplitude of the ACC was larger for stimuli with an RPO of 1 or higher. It was therefore decided to also perform the statistical analyses without the latencies and amplitudes that resulted from stimuli with a density lower than 1 RPO.

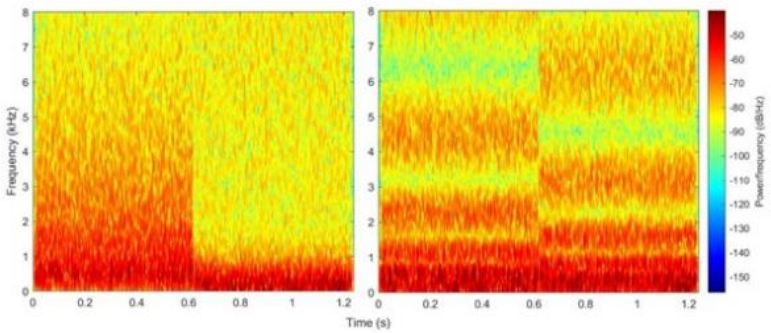



*Figure 37 - Spectrograms of spectral ripples with a density of 0.125 RPO (left) and 1 RPO (right) and phase inversion at the midpoint (620 msec).*

For normal hearing subjects, a weak to moderate positive correlation between inter-peak interval (IPI) between N1 and n1, and density was found, which indicates longer n1 latencies with increasing density (and thus difficulty). Furthermore, a difference was found between the expected mean IPI (of 620 msec) and actual mean IPI, with the latter being longer. In addition, IPIs found for different densities were different. Which densities differed significantly from each other could not be further investigated statistically because of the small number of data points that was available. Based on results from Vonck and colleagues (2019), the expectation was that lower RPO stimuli (easy to discriminate) would have shorter IPIs than higher RPO stimuli (more difficult to discriminate). This expected pattern, although not supported statistically, is visible when looking at the average IPIs per density (Table 4) where it can be seen that average IPI increases with increasing density (with the exception of 0.125 RPO, which may be explained by findings discussed in the previous paragraph).

In contrast, the results of the CI users showed no correlation between density and IPI. The IPIs that were found did differ significantly from the expected 620 msec (based on time of within-stimulus change), but there were no significant differences between the average IPIs of different densities. Average IPIs per density (Table 4) showed no trend in this direction either, with average IPI being similar for the different densities (with the exception of 0.25 RPO) and showing no trend in the direction of longer latencies with increasing density. However, average IPI of only four densities was available and CI artefact that was present for some participants made localisation of the peaks in the EEG-signal difficult. Therefore, no firm conclusions can be drawn regarding the relation between density and IPI for spectral ripple discrimination in CI users.

Regarding the effect of difficulty on P-P amplitude of the ACC, a (marginally) significant negative, but weak relation between density and P-P amplitude of the ACC was found for the normal hearing subjects, indicating smaller P-P amplitudes with higher densities (i.e., more difficult discrimination). This is in line with the literature, that has shown P-P amplitude becomes smaller with increasing difficulty (e.g., Brown et al., 2017; Vonck et al., 2019). Despite the negative correlation that was found in the current study, no significant differences in P-P amplitude were found between different densities. This may be explained by the fact that only two or three data points were available for some densities due to the quasi-adaptive method that was used in the electrophysiological test. Nevertheless, the general trend, which is in line with the literature, was that the P-P amplitude became smaller with increasing density (i.e., difficulty).

In contrast, for CI users, no correlation was found between density and P-P amplitude of the ACC nor did P-P amplitudes of different densities differ. It is possible that presence of a CI artefact in some participants may provide an explanation for this finding. When an artefact from the CI was visible, it was often difficult to determine amplitude of the ACC. It is therefore possible that in some cases amplitude of the SVP or ACC was over- or underestimated.

### 4.2.3 Relationship between behavioural and electrophysiological thresholds

The behavioural thresholds differed from the electrophysiological thresholds. For all normal hearing subjects and CI users, the behavioural threshold was higher (i.e., better) than the electrophysiological threshold. This was expected since literature has shown that, in general, a behavioural test is a more sensitive method for estimating discrimination thresholds (e.g., Brown et al., 2017; He et al., 2012). The average offset between behavioural and electrophysiological threshold for normal hearing subjects was 7.4 RPO and 0.44 RPO for CI users, but the range and standard deviation were large and the average therefore does not hold much value.

No significant relation was found between the estimated behavioural and electrophysiological thresholds for normal hearing subjects nor CI users. A linear regression showed that the electrophysiological threshold did not predict the behavioural threshold. However, for the CI users, it is important to consider that the results from only five participants were included in this analysis.

Results from the normal hearing subjects are not in line with the literature. Brown and colleagues (2017) did find a strong and significant correlation between behavioural and electrophysiological spectral ripple discrimination thresholds. However, Brown and colleagues used a 3AFC method to estimate behavioural discrimination threshold and used a different peak-to-valley ratio for their ripples than used in this study. These differences may have led to different estimated thresholds, which in turn may have led to a significant correlation for the thresholds found by Brown and colleagues, but not for the thresholds in the current study. The results of the current study for the CI users are in line with the results from Lopez Valdes et al. (2015), who also used a single-interval test to estimate behavioural spectral ripple discrimination threshold, but a different peak-to-valley ratio. They did not find a significant correlation between behavioural and electrophysiological discrimination thresholds either. They did, however, find a trend in this direction.

### 4.2.4 Relationship with speech perception in CI users

No relation was found between speech perception scores one year post-implantation and behavioural or electrophysiological spectral ripple discrimination thresholds. This is in contrast with multiple studies (e.g., He et al., 2013; Henry et al., 2005; Won et al., 2007; Won et al., 2010) who found a relation between spectral ripple discrimination and speech perception in CI users (with Henry et al. looking specifically at discrimination thresholds). Possible explanations of this difference in results may be the different depths of the stimuli and time of obtainment of speech perception scores.

In the current study, spectral ripples with a depth of 20 dB were used, whereas most studies used a depth of 30 dB. Litvak and colleagues (2007) used a different depth in their study and still found a correlation between spectral ripple discrimination and speech perception. For this reason it was expected that spectral ripple discrimination and speech perception would be correlated, regardless of the depth that was used. This does always appear to be the case, at least not in the current study. It is also possible that time of obtainment of speech perception scores has played a role. In the current study, thresholds were correlated with speech perception scores that were obtained approximately one year after implantation, whereas most other studies carried out speech perception tests at the same time as spectral ripple testing. In the current study, time since implantation varied between participants (ranging from 17-115 months). It is possible that in the meantime speech perception has changed for some CI users, which had an effect on the correlation analysis performed in this study. Lastly, it is important to mention that only data from five CI users was used for this analysis. Data from more CI users would have been preferred to give the statistical analysis more power.

### 4.2.5 Comparison between normal hearing subjects and CI users

The two participant groups in this study were shown to significantly differ in age, with the CI users being older than the normal hearing subjects. Spectral ripple discrimination thresholds (both behavioural and electrophysiological) were shown to be worse for CI users. This was expected, given

the fact that CI users receive limited information in multiple domains (frequency, temporal, amplitude; Macherey & Carlyon, 2014) via their implant. As a consequence, the perception of complex signals (i.e., spectral ripples) is more difficult than for listeners with normal hearing.

No relation was found between behavioural and electrophysiological thresholds for normal hearing subjects nor CI users. Concerning offset between behavioural and electrophysiological thresholds, it was found that this offset differed significantly between normal hearing subjects and CI users. The offset was smaller for CI users. This was expected, since the range of behavioural thresholds was also smaller in CI users.

Furthermore, the d'-values (calculated using the hit rate and false alarm rate) differed between normal hearing subjects and CI users for the spectral ripples. Higher absolute values, indicating a better response to the signal (Stanislaw & Todorov, 1999) were found for normal hearing subjects. This was expected, since CI users were hypothesized to have worse thresholds (and thus a lower sensitivity) than normal hearing subjects. Furthermore, participants who were identified as outliers showed lower d'-values than other participants.

### 4.2.6 Conclusion spectral ripple discrimination

Whilst it is possible to estimate an electrophysiological spectral ripple discrimination threshold using the ACC in normal hearing subjects and CI users, there appears to be no relationship between the electrophysiologically estimated spectral ripple discrimination threshold and estimated behavioural threshold. The average offset between behavioural and electrophysiological thresholds was 7.4 RPO for normal hearing subjects and 0.44 RPO for CI users, but the range was large. Moreover, no correlations between speech perception and behavioural and electrophysiological thresholds were found in CI users. It is important to consider that only a relatively small group of participants was included (especially for the CI users), which makes it difficult to draw firm conclusions. Nevertheless, a considerable amount of variation was visible between participants (especially for the normal hearing subjects) and it is expected that this will also be the case when a larger group of participants is included. Based on the results of this study, the ACC does not appear to be a suitable measure for estimating spectral ripple discrimination threshold in an objective manner in normal hearing subjects nor CI users.

## 4.3 The relationship between frequency and spectral ripple discrimination thresholds

### 4.3.1 Normal hearing subjects

Based on the results from Brown and colleagues (2017), it was expected that better frequency discrimination would correlate with better spectral ripple discrimination in normal hearing subjects. They found a significant, strong linear regression between spectral ripple and frequency discrimination (both for behavioural and electrophysiological thresholds). According to Brown et al. this may suggest that the discrimination of both types of stimuli may make use of the same auditory skill. However, there was no significant relationship between the electrophysiological thresholds of spectral ripple and frequency discrimination for normal hearing subjects in the current study. A significant positive correlation was even found between the behavioural thresholds of both tests, showing worse (higher) frequency discrimination thresholds with better (higher) spectral ripple discrimination thresholds. This may be the result of the small number of participants. Additionally, Brown et al. used a 3AFC task for estimating behavioural thresholds whereas the current study used a single-interval task. It is possible that the different methods used for estimating behavioural discrimination thresholds played a role in the results found in the current study.

Results from the spectral ripple and frequency tests largely matched (e.g., no significant correlation between behavioural and electrophysiological thresholds, significant correlation between IPI and difficulty), but differed for one analysis: the effect of difficulty (density/magnitude of frequency change) on P-P amplitude of the ACC. Based on the literature, a significant effect of difficulty was

expected, with the P-P amplitude becoming smaller with increasing difficulty. This was found for the spectral ripples, but not for frequency. It is unclear why this difference exists, but it could possibly be explained by the difference in number of observations.

### 4.3.2 CI users

No relations were found between either the estimated behavioural spectral ripple and frequency thresholds nor the electrophysiological thresholds for the CI users. Brown and colleagues (2017) found that spectral ripple and frequency discrimination were correlated in normal hearing subjects. It was therefore expected to find a relation between the two stimulus types for the CI users in the current study. This was not the case, which may be explained by the fact that only five CI users were included in this analysis. Additionally, it is possible that (some of) the CI users used confounding cues for spectral ripple discrimination instead of the phase inversion, which may rely on another skill than the one used for frequency discrimination. However, more research would be needed to support this claim.

What stood out when comparing the results from the behavioural spectral ripple and frequency discrimination tasks, is that much fewer participants had a high amount of false positives in the frequency test. This can probably be explained by the fact that no (or less) confounding factors are present in pure tones than in spectral ripples. Additionally, most listeners are more familiar with pure tones (that are, e.g., also used for pure tone audiometry), whereas spectral ripples proved to be strange-sounding stimuli that took some time getting used to. Still, before testing began, all CI users were presented with a 0.5 RPO stimulus (easiest stimulus in behavioural test) to ascertain that they all could discriminate the easiest stimulus. All CI users were able to do this. The result that 50% of the CI users had a high amount of false positives was therefore a surprise. Results from the electrophysiological testing for frequency and spectral ripples matched in CI users (e.g., no significant correlation between IPI and difficulty) for all but one analysis: the relation between behavioural and electrophysiological thresholds, which was significant for frequency, but not for spectral ripples. It is unclear why this difference exists. A possible explanation could be the number of participants included in both analyses.

## 4.4 General discussion

In this general discussion, one observation that was seen in all experiments is discussed briefly. In addition, remarks regarding methodology and possible effects on results that were applicable to both types of stimuli and/or both participant groups, are considered, as well as possible limitations of the current study. Moreover, suggestions and recommendations for future research are discussed.

### 4.4.1 General results

The morphology of the ACC was largely similar to the morphology of the onset SVP. However, in some cases, the p2 was not visible, but there did appear to be a clear n1. This was seen both in normal hearing subjects and CI users, for spectral ripples and frequency stimuli. In these cases, it was decided to still mark the trace as having an ACC, but a P-P amplitude could not be calculated. Other studies have not mentioned this observation.

### 4.4.2 Methodology and its possible effects on results

#### 4.4.2.1 Subjective method for determining presence of the ACC

The presence of the ACC was determined visually in this study, which is subjective. It could be argued that it would have been better to use a more objective method to determine presence of the ACC. At first, it was attempted to find an objective method in this study, but the method that was tried (using mean and standard deviation of the 200 msec pre-stimulus signal that was recorded) was very sensitive to the quality of the signal, which made it impossible to identify the ACC in some participants. For this reason it was decided to use a subjective method. Still, a preference for an objective measure remains,

since this ensures the exact same criteria are used for threshold estimation in all subjects. It may be interesting to investigate thresholds found using objective and subjective methods in future studies, to see if differences exist between the two methods.

#### 4.4.2.2 Effect of attention

In this study, participants were asked to attend to stimuli (which leads to larger amplitudes, as has been shown by Martin (2007)). In other studies (e.g., Brown et al., 2017; Vonck et al., 2021) participants were allowed to watch a silent video or read, thereby shifting attention away from the auditory stimuli. Future studies could consider investigating the effect of attention on ACC threshold estimation and the subsequent effect on the relation between behavioural and electrophysiological thresholds. This is important because it is unlikely that difficult-to-test populations (such as infants), for whom the ACC is probably most valuable as an objective measure of auditory discrimination, can focus their attention on the task. When investigating the relationship between behavioural and electrophysiological thresholds it is expected that the correlation (if it exists) is better when a person is paying attention in the EEG-recording, since participants also have to pay attention in the behavioural task.

#### 4.4.2.3 Single-interval test for estimating behavioural discrimination threshold

The choice for a single-interval test to estimate behavioural threshold (instead of the more often used 3AFC task) was based on a study by Won and colleagues (2011). Multiple advantages are to be named for the single-interval task. Firstly, the single-interval task is thought to present less cognitive load than the 3AFC task and is thought to make less use of the working memory (Won et al., 2011). It is expected to be easier because it is a direct comparison without a silent interval between target and reference stimulus. Won and colleagues found better thresholds in CI users when using a single-interval test than when using a 3AFC task, which may indicate that the single-interval method is more sensitive than the 3AFC test. Listening may already be cognitively challenging for CI users, and the combination with the cognitive load of the 3AFC task may lead to underestimation of the actual discrimination threshold. This problem may possibly be avoided when using a single-interval test. Furthermore, the stimuli used in the single-interval test and ACC-recording are the same, whereas this is not the case when using a 3AFC task and an ACC-recording for threshold estimation. Lastly, the single-interval test may be more comparable to real-life listening situations since dynamic differences are present within the stimuli and it is thus less static than the 3AFC task where one stimulus deviates from the other two.

For normal hearing subjects in the spectral ripple test it was indeed the case that the thresholds found in the current study appeared to be either similar (Horn et al., 2017) or better (Brown et al., 2017; Henry et al., 2005) than the thresholds that were found by studies that had used the 3AFC task (even though most studies used higher depths, which was though to make discrimination easier). The same thing can also be said for the frequency experiment in normal hearing subjects (He et al., 2012; Vonck et al., 2021), although the differences were very small and the use of different base frequencies may also have played a role in the thresholds that were found.

For CI users, frequency thresholds in this study were better than in other studies (that used a 2/3AFC task; Liang et al., 2018; McGuire et al., 2021; Zhang et al., 2019), indicating that the single-interval task may be more sensitive. Thresholds found for spectral ripple discrimination were worse than for other studies that used a single-interval task (Lopez Valdes et al., 2015; Won et al, 2011). However, these studies used a peak-to-valley ratio of 30 dB (as compared to 20 dB in this study), which was thought to make discrimination easier. This does indeed appear to be the case in CI users. When comparing results to Henry et al. (2005), who used a 3AFC task (and a peak-to-valley ratio of 30 dB), thresholds found in the current study are better.

Based on these findings, the use of a single-interval test may be preferred over the 2/3AFC task. This preference appears to be strongest for spectral ripples in normal hearing subjects (where thresholds using the single-interval task were considerably better compared to thresholds found using

a 2/3AFC task), whereas benefit of the single-interval task is small for frequency testing in normal hearing subjects. For CI users, use of a single-interval task appears to provide more sensitive thresholds for both spectral ripple and frequency testing.

#### 4.4.2.4 Free field presentation of stimuli for CI users

For this study, it was decided to present the stimuli in the free field. This was deemed to be the most ecologically valid method, as it is closest to daily listening situations for CI users (e.g., Martin, 2007). However, it also assumes that fitting is optimal for all CI users, which may not be the case. It is therefore unclear whether differences in settings/suboptimal settings have caused inter-subject differences. This may be avoided when using direct stimulation of the implant, but this is a less ecologically valid method, since it corresponds less well to daily life listening situations. There are advantages and disadvantages to be named for both methods and as of yet no clear preference of one over the other exists for estimating auditory discrimination thresholds.

#### 4.4.2.5 Loudness balancing

Whilst a loudness balancing test was used prior to the behavioural frequency test, this test was not employed prior to the spectral ripple test. It is possible that perceived loudness differences had an effect on the behavioural and electrophysiological thresholds that were found for the spectral ripples. Although perceived loudness differences were not used for adjusting frequency stimuli, the results do provide an insight in perceived loudness differences between different frequencies. This information is not available for spectral ripples. Future research could consider implementing a loudness balancing task for spectral ripple stimuli, to gain information on perceived loudness difference between the original and phase-inverted part of a ripple. Results could then be used for adjusting loudness, should that turn out to be necessary.

However, based on the results seen for both normal hearing subjects and CI users in the current study, adjusting stimuli based on perceived differences in loudness may be challenging. Many listeners showed no clear pattern in their results (i.e., going up and down in perceived loudness difference needed in order for the two parts of the stimulus to sound equally loud over the range of frequencies that was presented). Additionally, adjusting stimuli for each individual would be a time-consuming job. This would probably not be feasible, especially in clinical practice, and would reduce the usefulness of the ACC in clinical practice.

#### 4.4.2.6 Ramps in spectral ripple stimuli

A factor that may have possibly contributed to the relatively high behavioural spectral ripple thresholds for normal hearing subjects that were found in this study, is the fact that the ripples contained a 6-msec ramp placed in the middle of the stimulus. This ramp was used to avoid an audible click at the phase inversion. This ramp may, however, have caused the sensation of a gap. The perception of a gap was confirmed by two normal hearing subjects. Studies have shown that the average gap detection threshold lies between four and five msec for normal hearing subjects (e.g., Giannela Samelli & Schochat, 2008; He et al., 2012; Michalewski, Starr, Nguyen, Kong, & Zeng, 2005;). It is therefore possible that (some of) the normal hearing subjects perceived gaps, which caused them to think they perceived a change in the stimulus and thereby possibly affecting their discrimination thresholds. It is less likely that this has played a role in CI users. Research by Blankenship, Zhang, and Keith (2016) has shown that average gap detection thresholds in CI users lie around 24 msec (ranging from 5 – 100 msec). Nevertheless, this is a methodological problem that would need to be avoided in future studies.

#### 4.4.2.7 Age differences

A large difference was seen between the average age of the normal hearing subjects and the CI users. Since the main goal of this study was a within-subject comparison of behavioural and electrophysiological discrimination thresholds, the large age difference is thought to be less relevant

for this study. An effect of age can, however, not be excluded when looking at the differences between the normal hearing subjects and the CI users. Since cognitive function declines with age (Deary et al., 2009), this may have led to differences in thresholds in the behavioural test (which depends partially on cognitive function) between the young normal hearing subjects and the older CI users in this study. Recent studies have found no difference between cognitive functions of older CI users and age-matched normal hearing subjects (e.g., Sorrentino, Donati, Nassif, Pasini, & Redaelli de Zinis, 2020), which means that possible differences between these two groups would probably not be caused by differences in cognitive function and comparison with an age-matched group on behavioural thresholds would be recommended. Additionally, decreased EEG power (i.e., decreased amplitude) has been found with increasing age (e.g., Polich, 1997). Although this effect was found to be small for the N1 and P2, it is still possible that age had an effect on the thresholds found in the electrophysiological recordings. This provides another reason as to why age-matched participant groups are recommended in future research.

### 4.4.3 Future research

Some suggestions for future research were already discussed in the previous section. Next to additional suggestions for future research, recommendations regarding stimulus choice and test design will be discussed in this section. Lastly, clinical implications will be considered.

#### 4.4.3.1 Electrophysiological discrimination threshold and speech perception

Once the relation between behavioural and ACC-based electrophysiological discrimination thresholds is more clear, it could be considered to shift focus to the correlation between electrophysiological discrimination thresholds and speech perception (in quiet and in noise), specifically in CI users. Most studies that investigated the relationship between auditory discrimination thresholds and speech perception in CI users have looked at behavioural auditory discrimination (e.g., Liang et al., 2019). The relationship with electrophysiological discrimination has not been investigated by many studies, especially in CI users (e.g., McGuire et al., 2021, who did not look at thresholds, but at latencies and amplitudes of the ACC), and more insight into this relation would be valuable.

#### 4.4.3.2 ACC in noise

A few studies have investigated the relationship between behavioural discrimination thresholds (estimated using within-stimulus changes) and speech perception in noise in CI users (Zhang et al., 2019) and the aspects of the ACC (e.g., latency) and speech perception in noise (McGuire et al., 2021). This has value because speech perception in noise causes more problems in CI users than understanding speech in a quiet environment (Fu et al., 1998). Though significant correlations have been found between frequency/spectral ripple discrimination and speech perception in other studies (e.g., McGuire et al., 2021; Zhang et al., 2019), these studies all looked at behavioural discrimination thresholds or the ACC in quiet. Future research could consider investigating behavioural discrimination and the ACC in noise, to see whether a correlation is visible between speech perception in noise and discrimination thresholds in noise.

#### 4.4.3.3 ACC in children

Only few studies have investigated the ACC in children (e.g., Chen & Small, 2015; Martinez et al., 2013). Most studies have used speech stimuli (where multiple aspects of the signal, e.g., amplitude and frequency, change). Now that more and more is becoming clear in adults, it could be considered to investigate the feasibility of recording the ACC in children and infants. A start could perhaps be to investigate the ACC in older children (e.g., over five). A comparison could possibly be made between the single-interval behavioural procedure that was used in this study (and that is relatively easy) and the ACC. When investigating auditory evoked potentials in children, the fact that waveforms are not comparable to those of adults until adolescence should be taken into account (Pasman, Rotteveel,

Maassen, & Visco, 1999).

In addition to more research in infants and children, more research investigating prelingually deafened adults is necessary. Most studies only include postlingually deafened CI users or include only very few prelingually deafened CI users. Future research could consider investigating the ACC further in prelingually deafened CI users to see whether results from prelingually deafened CI users match the results previously obtained in postlingually deafened CI users.

#### 4.4.3.4 Recommendations for future research

It is unclear to what extent possible confounds in spectral ripples have played a role in spectral ripple discrimination in CI users in the current study. For future research the use of spectro-temporal ripples (Aronoff & Landsberger, 2013) could be considered to avoid possible factors that may confound the results from spectral ripple discrimination tasks. To our knowledge, there are no publications available that investigated the use of spectro-temporal ripples in ACC-recordings.

Regarding the decision between spectral ripples and frequency, the choice is complicated. Based on the results from the current study, there appears to be a preference for the use of pure tones with frequency changes, since a significant correlation was found between thresholds for CI users (although neither spectral ripples nor frequency thresholds correlated with speech perception). However, the rationale behind choosing spectral ripples appears to be better: ripples consisting of complex signals that are much closer to speech than pure tones.

Concerning the choice between a 2/3AFC task or a single-interval task for estimating behavioural discrimination thresholds, the results from the current study give reason to prefer the single-interval task. Thresholds found using this test were shown to be (marginally) more sensitive than thresholds found in earlier studies that used a 2/3AFC task.

#### 4.4.3.5 Clinical implications

As of yet, the use of the ACC as an objective measure of auditory discrimination is not feasible in clinical practice, partially because of the time needed to perform an EEG recording. More importantly, based on results from this study, one could question the usefulness. In order for the ACC to be helpful in clinical practice, recording time would need to be shorter and the relationship between behavioural and electrophysiological thresholds would need to be clearer. More research is needed for the ACC to be considered as a potential measure of auditory discrimination (in CI users) in clinical practice.

# 5. Conclusion

The current study has shown that whilst it is possible to estimate auditory discrimination thresholds with the ACC in normal hearing subjects and CI users, behavioural tests of auditory discrimination are always preferred since they are more sensitive than electrophysiological tests. Possible clinical value of the ACC appears limited. No relation was found between behavioural and electrophysiological frequency and spectral ripple discrimination thresholds in normal hearing subjects nor between both thresholds for spectral ripples in CI users. Potential clinical value may only exist for frequency discrimination and only for CI users since a significant relation was found for this group and this type of auditory change in the current study. However, offset between behavioural and electrophysiological thresholds varied considerably, which limits the applicability of the ACC as an objective measure of auditory discrimination. Furthermore, no relation between speech perception and frequency or spectral ripple discrimination was found in CI users. More research, in which more participants are included and without some of the methodological problems that were present in the current study, is necessary. For now, the ACC does not appear suitable for use as an objective measure of auditory discrimination.

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# Appendices

## Appendix A – Demographic characteristics of participants

*Table A1 - Demographic characteristics of the normal hearing participants (N = 21). Participant numbers followed by an asterisk indicate participants that are outliers and that were excluded from the statistical analyses.*

| Participant number | Gender | Age | Ear tested | Participated in which experiment? |
|---|---|---|---|---|
| *01* | M | 21 | R | Both |
| *02* | F | 22 | R | Both |
| *03* | M | 23 | L | Both |
| *04* | F | 21 | L | Spectral ripples |
| *05** | F | 29 | L | Spectral ripples |
| *06** | F | 21 | L | Spectral ripples |
| *07* | M | 23 | L | Spectral ripples |
| *08* | F | 22 | R | Spectral ripples |
| *09* | F | 21 | R | Spectral ripples |
| *10* | F | 21 | L | Both |
| *11* | F | 24 | R | Spectral ripples |
| *12* | F | 20 | L | Both |
| *13* | F | 22 | L | Spectral ripples |
| *14* | F | 21 | L | Both |
| *15* | F | 24 | L | Frequency |
| *16* | F | 22 | L | Frequency |
| *17* | M | 22 | L | Frequency |
| *18** | M | 57 | R | Frequency |
| *19* | F | 21 | L | Frequency |
| *20* | F | 23 | L | Frequency |
| *21* | F | 34 | L | Frequency |

*Table A2 - Demographic characteristics and implant details of the CI users (N = 10). Participant numbers followed by an asterisk indicate participants that are outliers and that were excluded from the statistical analyses (black indicates exclusion from spectral ripple testing, red indicates exclusion from frequency testing).*

| Participant number | Gender | Age | Aetiology/ Pre- or postlingual | Date of implantation | Side of implant | Implant type | Processor | Electrode array | Processing strategy | Disabled electrodes | Pure tone threshold at 1000 Hz (dB) | Speech perception score 1 year post-op (%)[1] | Loudness setting spectral ripples (dB) | Loudness setting frequency (dB) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *01*** | F | 67 | Unknown; prelingual | 10-10-2011 | L | MED-EL Mi10xx series (Concerto) | Sonnet | Flexsoft | FS4 | 11, 12 | 50 | 17 (Erber) | 73 | 70 |
| *02* | M | 69 | Slow progressive, possibly due to ototoxic medication; postlingual | 23-4-2018 | L | MED-EL Mi12xx series (Synchrony) | Sonnet | Flex20 | FS4 | | 30 | 62 (NVA) | 67 | 71 |
| *03** | M | 71 | Familiar, progressive; postlingual | 6-2-2012 | R | MED-EL Mi10xx series (Concerto) | Sonnet | Flexsoft | FS4-p | 12 | 35 | 96 (NVA) | 67 | 72 |
| *04* | F | 60 | Familiar, progressive; postlingual | 1-10-2012 | R | MED-EL Sonata | Sonnet | Medium | FS4 | | 40 | 65 (NVA) | 65 | 75 |
| *05*** | F | 75 | Familiar, progressive; postlingual | 21-2-2012 | R | MED-EL Sonata | Sonnet | Flexsoft | FS4 | 12 | 20 | 86 (NVA) | 68 | 76 |
| *06* | M | 73 | Familiar, noise, progressive; postlingual | 25-1-2013 | L | MED-EL Sonata | Sonnet | Medium | FS4 | 12 | 30 | 66 (NVA) | 70 | 74 |
| *07** | M | 79 | Unknown; postlingual | 26-11-2009 | R | MED-EL Sonata | Sonnet 2 | Flex24 | HDCIS | 11, 12 | 35 | 90 (NVA) | 72 | 76 |
| *08** | F | 64 | Progressive, discant; postlingual | 5-3-2012 | R | MED-EL Sonata | Sonnet | Flexsoft | FS4 | 12 | 30 | 75 (NVA) | 74 | 76 |
| *09* | M | 77 | Progressive; postlingual | 17-6-2020 | L | Advanced Bionics Naída Q90 | | | FS4 | | 25 | 74 (NVA) | 70 | 77 |
| *10* | F | 59 | Familiar, progressive; postlingual | 5-3-2012 | L | MED-EL Sonata | Sonnet | Flexsoft | FSP | 12 | 30 | 80 (NVA) | 70 | 78 |

[1]: Perception scores were obtained only from the CI ear.

## Appendix B – Loudness balancing results

*Table B1 - Loudness balancing results for the normal hearing subjects who participated in the frequency experiment (N = 13). The first number indicates the average loudness difference needed for a target stimulus to sound equally loud as the reference stimulus (always presented at 65 dB). Numbers between brackets indicate the two loudness settings chosen in the first and second trial of a target stimulus.*

| Participant number | 1001 | 1002 | 1003 | 1005 | 1010 | 1015 | 1020 | 1050 | 1075 | 1100 | 1200 | 1500 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | 1.5 (68-65) | -1.5 (66-61) | -1.5 (65-62) | -5 (61-59) | -7.5 (59-56) | -9 (58-54) | -7 (55-61) | -3.5 (62-61) | -3 (60-64) | -5 (60-60) | 2 (69-65) | -8.5 (57-56) |
| *2* | 1.5 (70-63) | -1.5 (64-63) | -2.5 (63-62) | -3 (63-61) | -4.5 (61-60) | -3 (64-60) | -4 (59-63) | 1.5 (68-65) | -4 (60-62) | -6 (54-64) | -1 (65-63) | -2.5 (67-58) |
| *3* | -0.5 (66-63) | 0.5 (66-65) | 2.5 (69-66) | 2 (63-61) | 4.5 (71-70) | 6 (72-70) | -2 (65-61) | -1.5 (64-63) | 1 (68-64) | -3 (64-60) | -2 (63-63) | -6.5 (61-56) |
| *10* | 0.5 (68-63) | 0.5 (66-65) | -1.5 (65-62) | -3 (63-61) | -1.5 (65-62) | -3 (64-60) | -5 (61-59) | -2.5 (64-61) | 0 (66-64) | -3 (64-60) | 4 (71-67) | -3.5 (65-58) |
| *12* | -1.5 (64-63) | -0.5 (66-63) | -1.5 (63-64) | -2 (65-61) | -1.5 (65-62) | 4 (68-70) | -3 (63-61) | -0.5 (66-63) | 1 (68-64) | -5 (62-58) | -2 (63-63) | -0.5 (65-64) |
| *14* | 0.5 (66-65) | -1.5 (64-63) | -1.5 (63-64) | -1 (65-63) | -2.5 (63-62) | -3 (62-62) | -5 (61-59) | 0.5 (66-65) | 0 (64-66) | -4 (62-60) | 3 (69-67) | -0.5 (65-64) |
| *15* | 4.5 (72-67) | -1.5 (66-61) | 0.5 (67-64) | 3 (71-65) | 0.5 (65-66) | 3 (68-68) | -3 (67-69) | -0.5 (68-61) | -2 (66-60) | -2 (64-62) | 4 (71-67) | -5.5 (65-54) |
| *16* | -1.5 (66-61) | -0.5 (66-63) | -1.5 (65-62) | -1 (65-63) | -0.5 (67-62) | -2 (64-62) | -3 (65-59) | -2.5 (66-59) | -1 (66-62) | -3 (62-62) | 4 (71-67) | -1.5 (65-62) |
| *17* | -1.5 (64-63) | -1.5 (64-63) | -2.5 (63-63) | -1 (65-63) | -2.5 (63-62) | -1 (66-62) | -2 (65-61) | 4.5 (72-67) | -2 (62-64) | -8 (56-58) | -2 (61-65) | -3.5 (65-58) |
| *18* | 0.5 (70-61) | -1.5 (66-61) | -2.5 (63-62) | -2 (65-61) | 0.5 (67-64) | -1 (66-62) | 0 (67-63) | 2.5 (68-67) | 2 (68-66) | 2 (68-66) | -1 (65-63) | -3.5 (65-68) |
| *19* | 2.5 (68-67) | -0.5 (66-63) | -1.5 (63-64) | -2 (63-63) | -3.5 (63-60) | -6 (60-58) | -5 (63-57) | -6.5 (60-57) | -2 (64-62) | -5 (62-58) | -4 (63-59) | -5.5 (59-61) |
| *20* | 1.5 (68-65) | -1.5 (64-63) | -1.5 (65-62) | -1 (65-63) | 0.5 (67-64) | -3 (62-62) | -2 (65-61) | -5.5 (60-59) | -1 (64-64) | -2 (64-62) | 2 (67-67) | -0.5 (65-64) |
| *21* | 0.5 (66-65) | -0.5 (66-63) | -0.5 (65-64) | -2 (63-63) | -1.5 (65-62) | -6 (58-60) | -3 (65-59) | -4.5 (62-59) | -2 (64-62) | -2 (62-64) | 2 (65-69) | -6.5 (59-58) |

*Table B2 - Loudness balancing results from the CI users (N = 10). The first number indicates the average loudness difference needed for a target stimulus to sound equally loud as the reference stimulus (always presented at 65 dB). Numbers between brackets indicate the two loudness settings chosen in the first and second trial of a target stimulus.*

| Participant number | 1001 | 1002 | 1003 | 1005 | 1010 | 1015 | 1020 | 1050 | 1075 | 1100 | 1200 | 1500 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | x | x | x | x | x | x | x | x | x | x | x | x |
| *2* | 1.5 (74-59) | -1.5 (71-57) | 1.5 (62-71) | 0 (71-59) | 7.5 (73-72) | 9 (74-74) | 9 (75-73) | 4.5 (70-69) | 7 (72-72) | 3 (68-68) | 3 (69-67) | 0.5 (67-64) |
| *3* | -2.5 (70-55) | -0.5 (68-61) | -0.5 (67-62) | 0 (67-63) | 2.5 (71-64) | 2 (72-62) | 2 (69-65) | 2.5 (70-65) | 2 (74-60) | 0 (68-62) | 0 (67-63) | -2.5 (67-58) |
| *4* | -2.5 (72-53) | -0.5 (70-59) | 1.5 (71-65) | 0 (71-59) | -2.5 (69-56) | -2 (70-56) | -1 (71-55) | -3.5 (68-55) | -7 (66-50) | -1 (68-60) | -9 (49-55) | -10.5 (55-54) |
| *5* | 0.5 (80-51) | 0.5 (70-61) | 1.5 (67-66) | 4 (69-69) | 3.5 (69-68) | 3 (70-66) | 2 (67-67) | 4.5 (70-69) | 2 (68-66) | 5 (70-70) | 5 (73-67) | -2.5 (63-62) |
| *6* | 5.5 (74-65) | 2.5 (70-65) | 3.5 (69-68) | 2 (67-67) | 2.5 (69-66) | 3 (70-66) | 5 (69-71) | 7.5 (74-71) | 7 (72-72) | 20 (88-80) | 19 (87-81) | 1.5 (69-64) |
| *7* | 0.5 (74-55) | -2.5 (68-57) | 0.5 (71-60) | -2 (71-55) | -3.5 (73-50) | -6 (68-50) | -2 (73-55) | -1.5 (72-55) | -4 (72-50) | -4 (72-50) | -2 (71-55) | -4.5 (73-50) |
| *8* | 1.5 (68-65) | 0.5 (64-67) | -1.5 (67-60) | -3 (63-61) | -0.5 (69-60) | -1 (66-62) | 2 (67-67) | 0.5 (68-63) | 3 (70-66) | 0 (64-66) | 4 (71-67) | 5.5 (71-70) |
| *9* | 8.5 (56-71) | -2.5 (70-55) | 1.5 (71-62) | -3 (67-57) | -5.5 (69-50) | -7 (64-52) | -4 (67-55) | 2.5 (70-65) | 1 (68-64) | 2 (74-60) | 5 (65-55) | 5.5 (73-68) |
| *10* | -2.5 (72-53) | -4.5 (68-53) | -0.5 (71-58) | -3 (69-55) | -4.5 (73-48) | -7 (68-48) | -3 (73-51) | -2.5 (72-53) | -6 (70-48) | -5 (72-48) | -3 (71-53) | -4.5 (73-48) |

## Appendix C – Psychometric curves

*Figure C1 - Psychometric curves for frequency discrimination in normal hearing subjects (N = 13). The threshold of 70% correct is indicated by the red line. Participant #18 is an outlier whose data was not included in the analyses.*

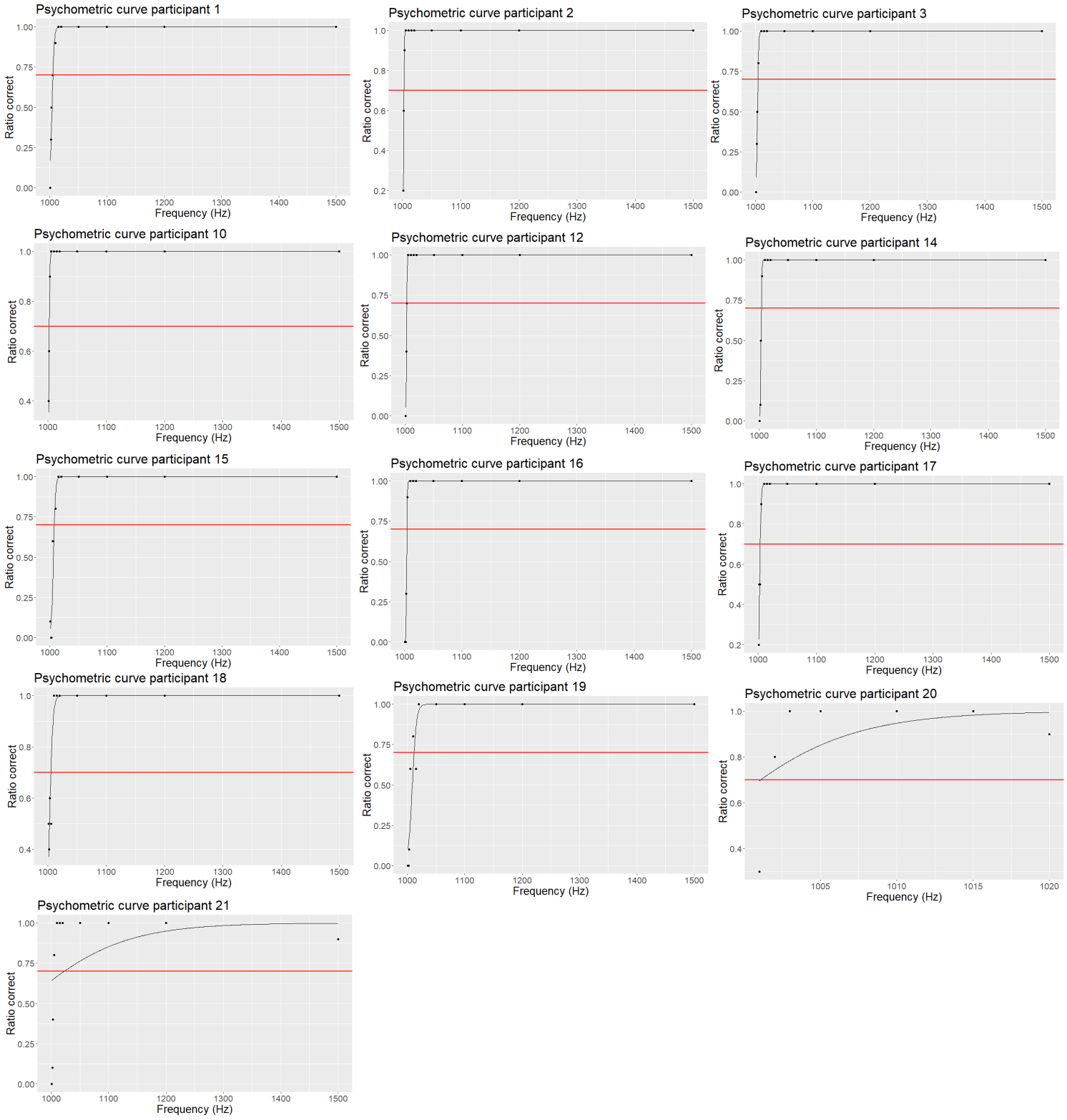


*Figure C2 - Psychometric curves for frequency discrimination in cochlear implant users (N = 10)). The threshold of 70% correct is indicated by the red line. Participants #1 and #5 were outliers whose data was not included in the analyses.*

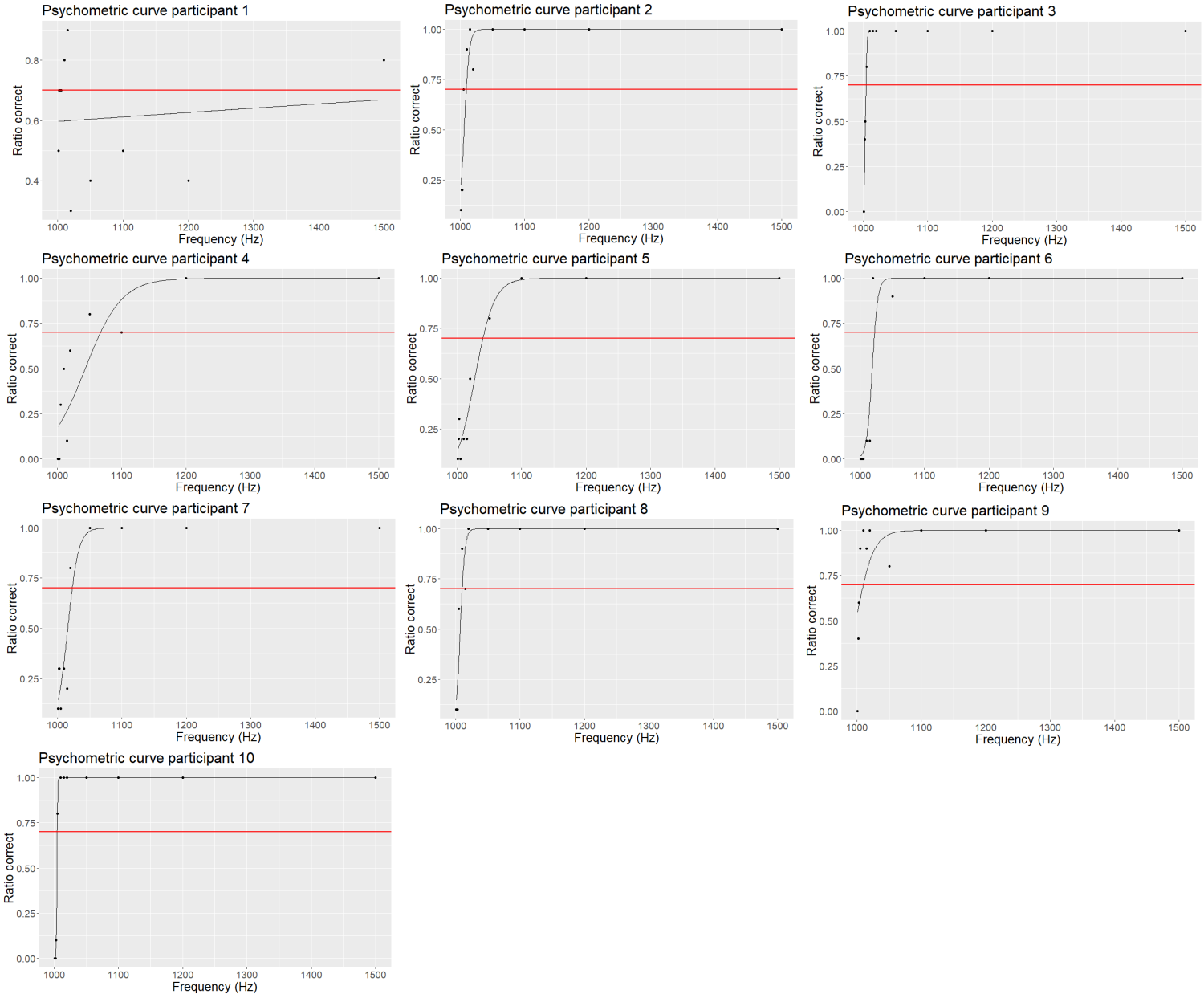


*Figure C3 - Psychometric curves for spectral ripple discrimination in normal hearing subjects (N = 14). The threshold of 70% correct is indicated by the red line. Participants #5 and #6 are outliers whose data was not included in the analysis..*

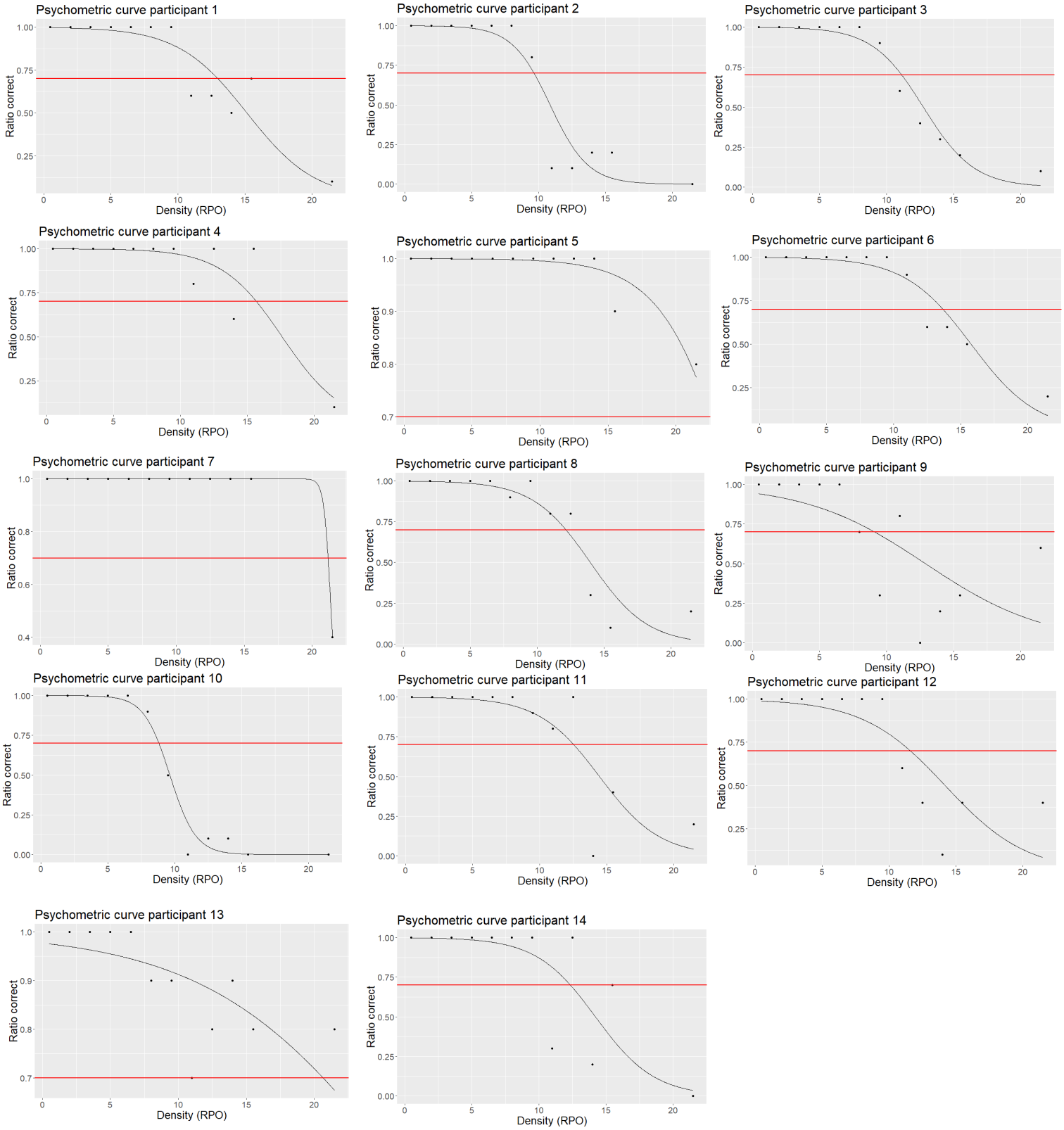
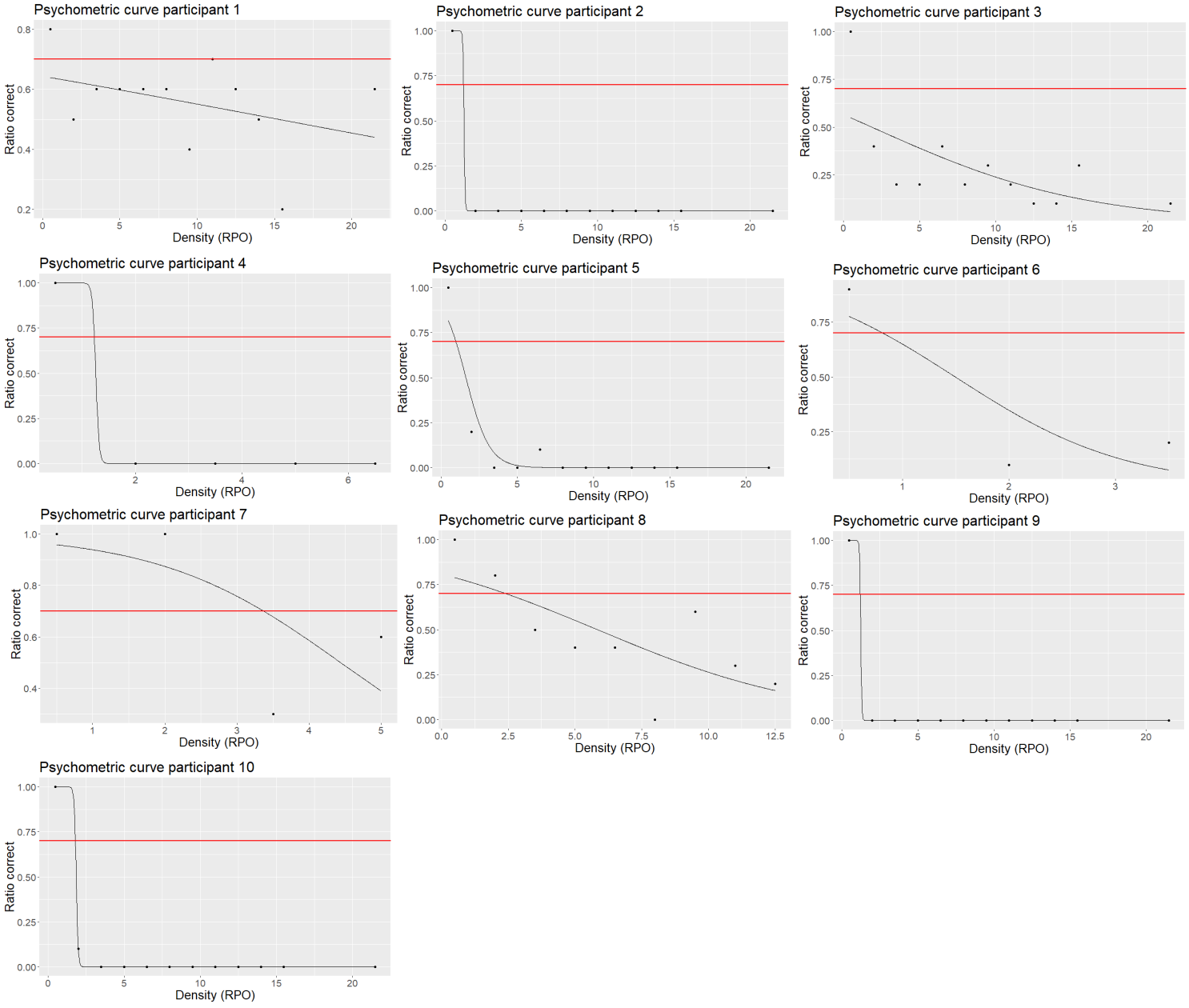


*Figure C4 - Psychometric curves for spectral ripple discrimination in cochlear implant users (N = 10). The threshold of 70% correct is indicated by the red line. Participants #1, #3, #5, #7 and# 8 were outliers whose data was not included in the analyses.*



## Appendix D – Amplitudes and latencies of SVP and ACC

*Table D1 - Amplitudes and latencies of the SVP and ACC for the frequency stimuli for the normal hearing subjects (N = 13). Amplitudes and latencies in bold were not used the statistical analyses. When a p2 was not identified, amplitude and latency of the n1 are provided.*

| **Participant number** | | **1** | **2** | **3** | **10** | **12** | **14** |
|---|---|---|---|---|---|---|---|
| *Behavioural threshold (Hz)* | | 1005.5 | 1002.2 | 1004.1 | 1002.1 | 1002.8 | 1003.8 |
| *Electrophysiological threshold (Hz)* | | 1005 | 1020 | 1005 | 1005 | 1020 | 1005 |
| *1100 Hz* | P-P SVP | 8.2 | 9.6 | 7.9 | 6.7 | 7.7 | **6.1** |
| | latency SVP | 112-176 | 114-168 | 108-188 | 96-170 | 112-182 | **80-172** |
| | P-P ACC | 8.5 | 5 | 2.7 | 4.6 | 5 | **5.5** |
| | latency ACC | 726-830 | 716-784 | 732-830 | 732-802 | 710-806 | **710-846** |
| *1050 Hz* | P-P SVP | 8.1 | 7.9 | 6.3 | 6.2 | 6.9 | 3.5 |
| | latency SVP | 116-204 | 92-160 | 114-206 | 104-180 | 104-172 | 95-170 |
| | P-P ACC | 5.1 | 5.1 | 5.4 | 4.6 | 2.3 | 4.3 |
| | latency ACC | 720-850 | 720-770 | 746-820 | 728-750 | 758-780 | 750-808 |
| *1020 Hz* | P-P SVP | 7.6 | 7.1 | 6.6 | 6.3 | 5.4 | 5.8 |
| | latency SVP | 110-190 | 90-160 | 108-176 | 108-168 | 114-166 | 76-166 |
| | P-P ACC | 6.1 | 2.1 | 2.7 | x | 1.8 | 3.9 |
| | latency ACC | 732-900 | 720-776 | 772-840 | x | 712-804 | 730-782 |
| *1015 Hz* | P-P SVP | 5.7 | **7.5** | 6.4 | 7.5 | **7** | 5.4 |
| | latency SVP | 120-196 | **106-160** | 112-182 | 124-182 | **112-164** | 92-154 |
| | P-P ACC | 4.2 | **x** | 2.8 | 2.9 | **x** | 2.1 |
| | latency ACC | 734-878 | **x** | 762-836 | 768-806 | **x** | 778-848 |
| *1010 Hz* | P-P SVP | 6.4 | **8.2** | 6 | 9.4 | **6.2** | 5.8 |
| | latency SVP | 116-198 | **102-158** | 108-180 | 126-180 | **110-184** | 74-160 |
| | P-P ACC | 4.2 | **1.8** | 1.4 | 3 | **1.3** | 2.1 |
| | latency ACC | 744-854 | **702-756** | 786-852 | 784-820 | **768-812** | 774-870 |
| *1005 Hz* | P-P SVP | 3.7 | **4.4** | 5 | 9.5 | **6.2** | 5.6 |
| | latency SVP | 114-172 | **108-158** | 110-182 | 116-182 | **108-174** | 80-160 |
| | P-P ACC | 2.4 | **1.7** | 1.5 | 2.1 | **2.6** | 4.3 |
| | latency ACC | 775-838 | **690-776** | 756-840 | 798-860 | **822-224** | 758-860 |
| *1003 Hz* | P-P SVP | | **4.8** | | **8.3** | | **7.7** |
| | latency SVP | | **104-160** | | **124-184** | | **80-182** |
| | P-P ACC | | **x** | | **2.6** | | **x** |
| | latency ACC | | **x** | | **814-880** | | **x** |
| *1002 Hz* | P-P SVP | | **5.8** | | | | |
| | latency SVP | | **110-150** | | | | |
| | P-P ACC | | **x** | | | | |
| | latency ACC | | **x** | | | | |
| *1001 Hz* | P-P SVP | | **6.3** | | | | |
| | latency SVP | | **114-158** | | | | |
| | P-P ACC | | **x** | | | | |
| | latency ACC | | x | | | | |
| *1000 Hz* | P-P SVP | 6.7 | 6.1 | 4.4 | 6.3 | 6.7 | 8.6 |
| | latency SVP | 110-196 | 114-162 | 118-182 | 126-174 | 108-158 | 80-166 |

| **Participant number** | | **15** | **16** | **17** | **19** | **20** | **21** |
|---|---|---|---|---|---|---|---|
| *Behavioural threshold (Hz)* | | 1007.8 | 1004.1 | 1003.6 | 1011.6 | 1001.1 | 1004.3 |
| *Electrophysiological threshold (Hz)* | | 1015 | 1015 | 1010 | 1015 | 1015 | 1005 |
| *1100 Hz* | P-P SVP | 8.8 | **5.9** | 6.1 | 4.2 | **6.1** | 3.2 |
| | latency SVP | 106-172 | **116-206** | 112-174 | 90-196 | **120-170** | 108-158 |
| | P-P ACC | 4.8 | **x** | 6.4 | 3.8 | **x** | 5.2 |
| | latency ACC | 728-800 | **x** | 770-820 | 724-846 | **x** | 726-820 |
| *1050 Hz* | P-P SVP | 4.6 | 2.7 | 6 | 6.3 | 3.9 | 8.7 |
| | latency SVP | 106-196 | 138-212 | 122-178 | 96-174 | 124-180 | 112-164 |
| | P-P ACC | 6.2 | 2.3 | 5.5 | 4.6 | 2.5 | 3.9 |
| | latency ACC | 762-824 | 738-818 | 780-840 | 732-852 | 760-860 | 748-812 |
| *1020 Hz* | P-P SVP | 3.8 | 3.7 | 3.3 | 4.9 | 4.8 | 6.8 |
| | latency SVP | 120-190 | 114-170 | 132-172 | 100-188 | 124-172 | 108-158 |
| | P-P ACC | 7.9 | n1 is -4,6 | 3.2 | n1 is 5,6 | n1 is 4,8 | x |
| | latency ACC | 742-840 | n1 is 728 | 730-846 | n1 is 738 | n1 is 750 | x |
| *1015 Hz* | P-P SVP | 5.4 | 6.1 | 5 | 6 | 3.5 | 7.8 |
| | latency SVP | 124-188 | 124-200 | 126-174 | 104-184 | 118-162 | 108-160 |
| | P-P ACC | 4.9 | 4 | 5.5 | 2.6 | n1 is -4,1 | n1 is -2,5 |
| | latency ACC | 740-850 | 760-828 | 790-922 | n1 is 748 | n1 is 750 | n1 is 744 |
| *1010 Hz* | P-P SVP | 4.3 | **3.9** | 5.6 | **4.4** | **5.5** | 5.6 |
| | latency SVP | **118-178** | **110-198** | 114-160 | **110-200** | **116-168** | 108-162 |
| | P-P ACC | **x** | **n1 is -6.1** | 5.4 | **2.6** | **3.6** | n1 is -3,2 |
| | latency ACC | **x** | **n1 is 766** | 772-850 | **754-846** | **778-916** | n1 is 752 |
| *1005 Hz* | P-P SVP | **4** | **7.8** | **5.2** | **6.9** | **3.7** | 6.3 |
| | latency SVP | **122-180** | **134-192** | **122-176** | **98-200** | **120-170** | 108-162 |
| | P-P ACC | **x** | **x** | **2.1** | **5** | **x** | 2.7 |
| | latency ACC | **x** | **x** | **750-788** | **792-830** | **x** | 780-864 |
| *1003 Hz* | P-P SVP | | | **4.2** | **6.6** | | **7.1** |
| | latency SVP | | | **110-154** | **96-200** | | **118-164** |
| | P-P ACC | | | **4.1** | **x** | | **x** |
| | latency ACC | | | **738-872** | **x** | | **x** |
| *1002 Hz* | P-P SVP | | | **3.4** | | | |
| | latency SVP | | | **126-156** | | | |
| | P-P ACC | | | **x** | | | |
| | latency ACC | | | **x** | | | |
| *1001 Hz* | P-P SVP | | | **5.4** | | | |
| | latency SVP | | | **124-178** | | | |
| | P-P ACC | | | **x** | | | |
| | latency ACC | | | **x** | | | |
| *1000 Hz* | P-P SVP | 11.8 | 4.1 | 5.2 | 4.6 | 5.3 | 6.5 |
| | latency SVP | 118-182 | 146-196 | 128-164 | 98-192 | 114-164 | 120-170 |

*Table D2 - Amplitudes and latencies of the SVP and ACC for the frequency stimuli for the CI users (N = 10). Amplitudes and latencies in bold were not included in the statistical analyses. When a p2 was not identified, amplitude and latency of the n1 are provided.*

| **Participant number** | | **2** | **3** | **4** | **6** |
|---|---|---|---|---|---|
| *Behavioural threshold (Hz)* | | 1009.1 | 1004 | 1067 | 1022.3 |
| *Electrophysiological threshold (Hz)* | | 1020 | 1020 | 1200 | 1050/1100 |
| *1500 Hz* | P-P SVP | 2.5 | | 7.3 | 5.2 |
| | latency SVP | 138-200 | | 116-182 | 104-188 |
| | P-P ACC | 3.9 | | 11.2 | 3.2 |
| | latency ACC | 726-782 | | 756-860 | 752-832 |
| *1200 Hz* | P-P SVP | 3.2 | 2.9 | 4.6 | 6 |
| | latency SVP | 124-172 | 142-210 | 118-200 | 108-178 |
| | P-P ACC | 2 | n1 is 0.5 | 6.6 | 3.4 |
| | latency ACC | 760-860 | n1 is 744 | 750-854 | 778-850 |
| *1100 Hz* | P-P SVP | 3.2 | 5 | **7.9** | 5.3 |
| | latency SVP | 130-194 | 122-208 | **116-188** | 110-176 |
| | P-P ACC | 6.4 | x | **x** | 3.9 |
| | latency ACC | 750-840 | x | **x** | 776-878 |
| *1050 Hz* | P-P SVP | 6.7 | 3.4 | **7.3** | **7.2** |
| | latency SVP | 148-247 | 158-222 | **116-180** | **116-190** |
| | P-P ACC | 5.5 | 1.9 | **x** | **x** |
| | latency ACC | 770-830 | 772-852 | **x** | **x** |
| *1020 Hz* | P-P SVP | 2.7 | 4.5 | **5.6** | **3.3** |
| | latency SVP | 146-222 | 150-222 | **120-174** | **128-170** |
| | P-P ACC | 4 | n1 is 4.9 | **x** | **x** |
| | latency ACC | 764-830 | n1 is 760 | **x** | **x** |
| *1015 Hz* | P-P SVP | **4.6** | **N1 is 15.3** | **10.8** | **6.2** |
| | latency SVP | **122-228** | **N1 is 152** | **116-176** | **124-188** |
| | P-P ACC | **x** | **x** | **x** | **x** |
| | latency ACC | **x** | **x** | **x** | **x** |
| *1010 Hz* | P-P SVP | **4.7** | **4.6** | **7.2** | **7.4** |
| | latency SVP | **134-196** | **150-218** | **118-172** | **114-188** |
| | P-P ACC | **x** | **x** | **x** | **x** |
| | latency ACC | **x** | **x** | **x** | **x** |
| *1005 Hz* | P-P SVP | **3.8** | **6.2** | **8.4** | **4.9** |
| | latency SVP | **150-238** | **142-216** | **118-184** | **120-184** |
| | P-P ACC | **x** | **x** | **x** | **x** |
| | latency ACC | **x** | **x** | **x** | **x** |
| *1003 Hz* | P-P SVP | **4** | **7.1** | | |
| | latency SVP | **106-180** | **152-222** | | |
| | P-P ACC | **x** | **x** | | |
| | latency ACC | **x** | **x** | | |
| *1002 Hz* | P-P SVP | **3.4** | **3.4** | | |

| | | | | | |
|---|---|---|---|---|---|
| | latency SVP | **126-176** | **154-210** | | |
| | P-P ACC | **x** | **x** | | |
| | latency ACC | **x** | **x** | | |
| *1000 Hz* | P-P SVP | 4.4 | 5.6 | 9.7 | 5.6 |
| | latency SVP | 126-180 | 140-218 | 120-194 | 124-190 |

| **Participant number** | | **7** | **8** | **9** | **10** |
|---|---|---|---|---|---|
| *Behavioural threshold (Hz)* | | 1022.9 | 1010.1 | 1009.9 | 1004.7 |
| *Electrophysiological threshold (Hz)* | | 1200 | 1050 | 1050 | 1020 |
| *1500 Hz* | P-P SVP | 3 | 8.9 | N1 is 3.1 | 5.6 |
| | latency SVP | 132-202 | 118-188 | N1 is 142 | 110-202 |
| | P-P ACC | 3.9 | 5 | n1 is 0.1 | 4.1 |
| | latency ACC | 776-848 | 734-798 | n1 is 780 | 726-794 |
| *1200 Hz* | P-P SVP | 3.7 | 6.6 | x | 7.2 |
| | latency SVP | 118-204 | 120-194 | x | 118-200 |
| | P-P ACC | 4.3 | 3.5 | x | 3.3 |
| | latency ACC | 768-850 | 794-860 | x | 736-810 |
| *1100 Hz* | P-P SVP | **5.5** | 5.3 | N1 is 2.9 | 6.4 |
| | latency SVP | **120-224** | 128-184 | N1 is 152 | 92-186 |
| | P-P ACC | **x** | 2.8 | n1 is 1.2 | 3.8 |
| | latency ACC | **x** | 840-900 | n1 is 760 | 720-782 |
| *1050 Hz* | P-P SVP | **4** | 3.8 | N1 is 4 | 4.8 |
| | latency SVP | **136-222** | 130-210 | N1 is 150 | 104-180 |
| | P-P ACC | **x** | 2.6 | n1 is 1 | n1 is -2.3 |
| | latency ACC | **x** | 762-838 | n1 is 790 | n1 is 762 |
| *1020 Hz* | P-P SVP | **4.9** | **8.5** | **4.3** | 5.7 |
| | latency SVP | **146-220** | **116-210** | **140-180** | 102-200 |
| | P-P ACC | **x** | **x** | **x** | 3.4 |
| | latency ACC | **x** | **x** | **x** | 774-820 |
| *1015 Hz* | P-P SVP | | **4.2** | **3.5** | **8** |
| | latency SVP | | **108-190** | **164-234** | **108-210** |
| | P-P ACC | | **x** | **x** | |
| | latency ACC | | **x** | **x** | |
| *1010 Hz* | P-P SVP | | **5.3** | **8** | **8.3** |
| | latency SVP | | **118-198** | **126-202** | **116-196** |
| | P-P ACC | | **x** | **x** | **x** |
| | latency ACC | | **x** | **x** | **x** |
| *1005 Hz* | P-P SVP | | **5.7** | **2.3** | **11.4** |
| | latency SVP | | **112-190** | **140-216** | **100-202** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | P-P ACC | | **x** | | **x** | | **x** |
| | latency ACC | | **x** | | **x** | | **x** |
| *1000 Hz* | P-P SVP | 5.3 | | 8.8 | | 2.3 | 8.8 |
| | latency SVP | 108-160 | | 130-202 | | 148-168 | 106-210 |

*Table D3 - Amplitudes and latencies of the SVP and ACC for the spectral ripple stimuli for the normal hearing subjects (N = 14). Amplitudes and latencies in bold were not taken into account in the statistical analyses.*

| **Participant number** | | **1** | **2** | **3** | **4** | **7** | **8** |
|---|---|---|---|---|---|---|---|
| *Behavioural threshold (RPO)* | | 13 | 9.7 | 11.1 | 15.7 | 21.2 | 12.2 |
| *Electrophysiological threshold (RPO)* | | 6.5 | 3.5 | 5 | 5 | 5 | 6.5 |
| *RPO 0.125* | P-P SVP | | 11.5 | 7.5 | 11.4 | 2.1 | 6.9 |
| | latency SVP | | 102-162 | 112-174 | 94-176 | 122-210 | 118-200 |
| | P-P ACC | | 2.9 | 5.6 | 6.6 | x | 6 |
| | latency ACC | | 742-780 | 758-812 | 738-828 | x | 758-870 |
| *RPO 0.250* | P-P SVP | 7.4 | | | | | |
| | latency SVP | 116-196 | | | | | |
| | P-P ACC | 3.5 | | | | | |
| | latency ACC | 732-818 | | | | | |
| *RPO 0.5* | P-P SVP | | | | | | |
| | latency SVP | | | | | | |
| | P-P ACC | | | | | | |
| | latency ACC | | | | | | |
| *RPO 1* | P-P SVP | 10.2 | 8.1 | 7.6 | 8.6 | 2.1 | 7.6 |
| | latency SVP | 120-220 | 100-170 | 128-204 | 110-184 | 118-196 | 132-228 |
| | P-P ACC | 7.8 | 6.2 | 9.5 | 9.3 | 1.1 | 7.4 |
| | latency ACC | 722-842 | 702-762 | 752-840 | 714-814 | 758-816 | 744-854 |
| *RPO 2* | P-P SVP | 9.7 | 8.1 | | | | |
| | latency SVP | 132-224 | 102-162 | | | | |
| | P-P ACC | 11 | 6.1 | | | | |
| | latency ACC | 732-866 | 732-802 | | | | |
| *RPO 2.5* | P-P SVP | | | | | 3.7 | |
| | latency SVP | | | | | 160-230 | |
| | P-P ACC | | | | | 3.5 | |
| | latency ACC | | | | | 750-806 | |
| *RPO 3* | P-P SVP | 11.1 | 8.2 | | | 3.3 | 4.9 |
| | latency SVP | 132-206 | 100-170 | | | 134-204 | 122-184 |
| | P-P ACC | 5.4 | 5.8 | | | 1.6 | 4.9 |
| | latency ACC | 760-838 | 732-820 | | | 756-798 | 748-828 |
| *RPO 3.5* | P-P SVP | | 5.9 | | 9.6 | x | |
| | latency SVP | | 104-164 | | 112-200 | x | |
| | P-P ACC | | 3 | | 7.8 | 3.2 | |
| | latency ACC | | 754-836 | | 722-832 | 774-848 | |
| *RPO 4* | P-P SVP | 7.8 | **9.1** | 7.8 | 8.9 | 4.3 | 4.7 |
| | latency SVP | 128-226 | **98-166** | 126-198 | 110-178 | 146-238 | 134-188 |
| | P-P ACC | 5.2 | **2.3** | 5.6 | 5.5 | 0.7 | 2.2 |
| | latency ACC | 742-870 | **744-850** | 750-824 | 732-840 | 754-812 | 758-836 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| *RPO 4.5* | P-P SVP | 7.4 | | | 6.6 | | |
| | latency SVP | 126-224 | | | 116-180 | | |
| | P-P ACC | 4.6 | | | 8 | | |
| | latency ACC | 772-896 | | | 738-832 | | |
| *RPO 5* | P-P SVP | 7.2 | | 8.1 | 7.9 | 3.2 | 4.4 |
| | latency SVP | 124-196 | | 122-192 | 108-180 | 146-234 | 128-178 |
| | P-P ACC | 4.2 | | 4.1 | 4.4 | 1.1 | 2.3 |
| | latency ACC | 752-844 | | 762-836 | 752-832 | 758-832 | 774-850 |
| *RPO 6.5* | P-P SVP | 4.4 | | **6.5** | | | 4.3 |
| | latency SVP | 126-218 | | **122-204** | | | 110-158 |
| | P-P ACC | 3.5 | | **2.2** | | | 1.4 |
| | latency ACC | 766-832 | | **798-914** | | | 786-862 |
| *RPO 8* | P-P SVP | **6.9** | | **4.7** | | | **4.1** |
| | latency SVP | **116-196** | | **120-156** | | | **118-184** |
| | P-P ACC | **x** | | **1.7** | | | **2.9** |
| | latency ACC | **x** | | **708-762** | | | **738-770** |
| *RPO 9.5* | P-P SVP | | | | | | |
| | latency SVP | | | | | | |
| | P-P ACC | | | | | | |
| | latency ACC | | | | | | |
| *No change* | | 6.5 RPO | 3.5 RPO | 5 RPO | 4 RPO | 2.5 RPO | 6.5 RPO |
| | P-P SVP | 4.5 | 5.5 | 9.2 | 4 | 1.9 | 4.9 |
| | latency SVP | 128-202 | 102-164 | 118-178 | 126-214 | 134-188 | 122-184 |

| **Participant number** | | **9** | **10** | **11** | **12** | **13** | **14** |
|---|---|---|---|---|---|---|---|
| *Behavioural threshold (RPO)* | | 9.9 | 8.8 | 12.5 | 11.6 | 20.7 | 12.4 |
| *Electrophysiological threshold (RPO)* | | 6.5 | 5 | 5 | 6.5 | 8 | 8 |
| *RPO 0.125* | P-P SVP | 3.3 | | | 5.6 | 6.9 | 4.7 |
| | latency SVP | 136-166 | | | 100-148 | 116-162 | 80-162 |
| | P-P ACC | 2.1 | | | 4 | 5.4 | 4.9 |
| | latency ACC | 792-864 | | | 758-824 | 742-852 | 764-884 |
| *RPO 0.250* | P-P SVP | | 4.1 | | | | |
| | latency SVP | | 130-184 | | | | |
| | P-P ACC | | 6.6 | | | | |
| | latency ACC | | 746-822 | | | | |
| *RPO 0.5* | P-P SVP | | | 3 | | | |
| | latency SVP | | | 120-202 | | | |
| | P-P ACC | | | 9.7 | | | |
| | latency ACC | | | 740-842 | | | |
| *RPO 1* | P-P SVP | 5.1 | 5.9 | 7.4 | 5.8 | 9.3 | 2.5 |
| | latency SVP | 130-216 | 132-194 | 132-206 | 110-176 | 112-176 | 110-204 |
| | P-P ACC | 4.2 | 7.1 | 6.1 | 6.1 | 7.4 | 5.5 |
| | latency ACC | 752-842 | 750-832 | 740-836 | 734-786 | 734-796 | 748-808 |
| *RPO 2* | P-P SVP | | | | | | |
| | latency SVP | | | | | | |
| | P-P ACC | | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | latency ACC | | | | | | |
| *RPO 2.5* | P-P SVP | | | | | | |
| | latency SVP | | | | | | |
| | P-P ACC | | | | | | |
| | latency ACC | | | | | | |
| *RPO 3* | P-P SVP | | 7.3 | | | | |
| | latency SVP | | 128-204 | | | | |
| | P-P ACC | | 3.4 | | | | |
| | latency ACC | | 762-830 | | | | |
| *RPO 3.5* | P-P SVP | | | | | | |
| | latency SVP | | | | | | |
| | P-P ACC | | | | | | |
| | latency ACC | | | | | | |
| *RPO 4* | P-P SVP | 6.6 | 7.5 | 3.7 | 2.2 | | 5.5 |
| | latency SVP | 132-198 | 120-184 | 124-192 | 132-174 | | 128-212 |
| | P-P ACC | 4.8 | 4.4 | 2.9 | 6.8 | | 2 |
| | latency ACC | 760-830 | 764-832 | 736-846 | 746-824 | | 756-812 |
| *RPO 4.5* | P-P SVP | | | | | 9.1 | |
| | latency SVP | | | | | 110-166 | |
| | P-P ACC | | | | | 5 | |
| | latency ACC | | | | | 734-814 | |
| *RPO 5* | P-P SVP | 6.2 | 6.1 | 5.8 | 5.2 | | 2.4 |
| | latency SVP | 130-212 | 112-168 | 120-218 | 126-172 | | 110-178 |
| | P-P ACC | 6.7 | 4 | 5.8 | 3.1 | | 5.7 |
| | latency ACC | 754-832 | 754-824 | 740-842 | 746-834 | | 778-844 |
| *RPO 6.5* | P-P SVP | 3.2 | **6.1** | **3.8** | 3.5 | 7.3 | 4.2 |
| | latency SVP | 126-182 | **126-176** | **114-182** | 112-174 | 102-158 | 122-180 |
| | P-P ACC | 3.6 | **1.9** | **0.7** | 3.9 | 4.8 | 2.2 |
| | latency ACC | 770-870 | **794-878** | **686-714** | 776-844 | 750-836 | 790-860 |
| *RPO 8* | P-P SVP | | **3.8** | **5.3** | **4.8** | 5.3 | 5.6 |
| | latency SVP | | **128-172** | **108-162** | **112-168** | 102-158 | 76-162 |
| | P-P ACC | | **x** | **x** | **2.2** | 4.1 | 3.4 |
| | latency ACC | | **x** | **x** | **680-732** | 744-830 | 740-820 |
| *RPO 9.5* | P-P SVP | | | | | **4.5** | |
| | latency SVP | | | | | **102-166** | |
| | P-P ACC | | | | | **2.3** | |
| | latency ACC | | | | | **722-774** | |
| *No change* | | 5 RPO | 5 RPO | 5 RPO | 6.5 RPO | 6.5 RPO | 6.5 RPO |
| | P-P SVP | 3 | 3.8 | 7.2 | 4 | 8.6 | 2.2 |
| | latency SVP | 128-222 | 128-180 | 132-208 | 110-176 | 110-160 | 72-198 |

*Table D4 - Amplitudes and latencies of the SVP and ACC for the spectral ripple stimuli for the CI users (N = 10). Amplitudes and latencies in bold were not used in the statistical analyses.*

| **Participant** | **2** | **4** | **6** | **9** | **10** |
|---|---|---|---|---|---|
| *Behavioural threshold (RPO)* | 1.2 | 1.2 | 0.8 | 1.2 | 1.8 |
| *Electrophysiological threshold (RPO)* | 0.75 | 0.5 | 0.75 | 0.75 | 1 |

| | | | | | | |
|---|---|---|---|---|---|---|
| *RPO 0.125* | P-P SVP | 3.4 | 6.3 | 6.2 | 0.9 | 4.8 |
| | latency SVP | 116-170 | 114-176 | 108-160 | 154-196 | 116-188 |
| | P-P ACC | 4.7 | 1.4 | x | n1 is 3.3 | 2.6 |
| | latency ACC | 756-864 | 780-850 | x | n1 is 764 | 770-846 |
| *RPO 0.25* | P-P SVP | 5.6 | 9.1 | 3.1 | 2.6 | 3.7 |
| | latency SVP | 122-192 | 124-182 | 128-198 | 188-232 | 130-192 |
| | P-P ACC | 3.2 | 2.5 | 3.1 | 2.5 | 3 |
| | latency ACC | 770-854 | 744-802 | 746-818 | 772-816 | 740-794 |
| *RPO 0.5* | P-P SVP | 2.5 | 4.4 | 4.4 | 1.7 | 5.4 |
| | latency SVP | 126-200 | 114-164 | 108-166 | 180-200 | 114-194 |
| | P-P ACC | 2.9 | 3.5 | 1.9 | 1.8 | n1 is -4 |
| | latency ACC | 770-850 | 780-850 | 772-830 | 794-850 | n1 is 760 |
| *RPO 0.75* | P-P SVP | 4.7 | **7.6** | 2.5 | N1 is 10.6 | 5.1 |
| | latency SVP | 128-218 | **122-184** | 116-164 | N1 is 170 | 120-192 |
| | P-P ACC | 4.2 | **5.1** | 3 | 1.7 | n1 is -0.8 |
| | latency ACC | 770-820 | **730-772** | 752-818 | 790-828 | n1 is 808 |
| *RPO 1* | P-P SVP | **3.6** | **7.5** | **7.2** | 2.1 | 3.5 |
| | latency SVP | **130-192** | **118-164** | **114-164** | 178-232 | 114-188 |
| | P-P ACC | **x** | **2.5** | **x** | 1.8 | n1 is -3.5 |
| | latency ACC | **x** | **790-860** | **x** | 770-824 | n1 is 800 |
| *RPO 1.25* | P-P SVP | **5.7** | **4.9** | **5.9** | | **6.1** |
| | latency SVP | **184-234** | **114-180** | **124-176** | | **110-190** |
| | P-P ACC | **x** | **5.2** | **x** | | **x** |
| | latency ACC | **x** | **740-808** | **x** | | **x** |
| *RPO 1.5* | P-P SVP | **5.2** | **5** | | **3.9** | **6.5** |
| | latency SVP | **126-200** | **112-164** | | **180-218** | **112-194** |
| | P-P ACC | **x** | **x** | | **x** | **x** |
| | latency ACC | **x** | **x** | | **x** | **x** |
| *RPO 2* | P-P SVP | | **7.1** | **6.9** | **x** | **8.1** |
| | latency SVP | | **114-182** | **120-160** | **x** | **114-194** |
| | P-P ACC | | **x** | **x** | **x** | **x** |
| | latency ACC | | **x** | **x** | **x** | **x** |
| *No change* | | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | P-P SVP | 3.7 | 11.2 | 4.6 | 1.7 | 5.1 |
| | latency SVP | 124-198 | 124--184 | 110-166 | 186-216 | 116-192 |

## Appendix E – Additional figures and analyses of EEG-recordings in CI users

In the figures below, artefacts visible in the EEG-recordings of some CI users are compared to EEG-recordings from other CI users without artefact for different stimuli (different magnitudes of frequency change (Figures E1 and E2) and different densities (Figures E3 and E4)).

Using a Spearman correlation, no significant correlation was found between normalised P-P amplitude of CI artefact at frequency change nor at spectral ripple phase inversion (CI artefact at change divided by artefact at onset of stimulus; normalisation was used because of large inter-subject differences in P-P amplitude of the CI artefact): $r_s$ = .444, $p$ = .112 and $r_s$ = .307, $p$ = .460, respectively.

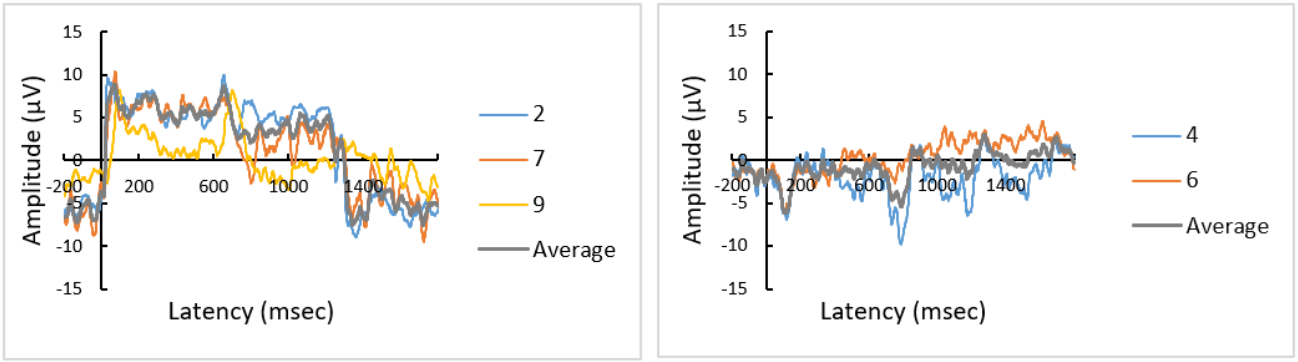



*Figure E1 - EEG recordings for stimulus 1000-1500 Hz with (left) and without (right) CI artefact.*

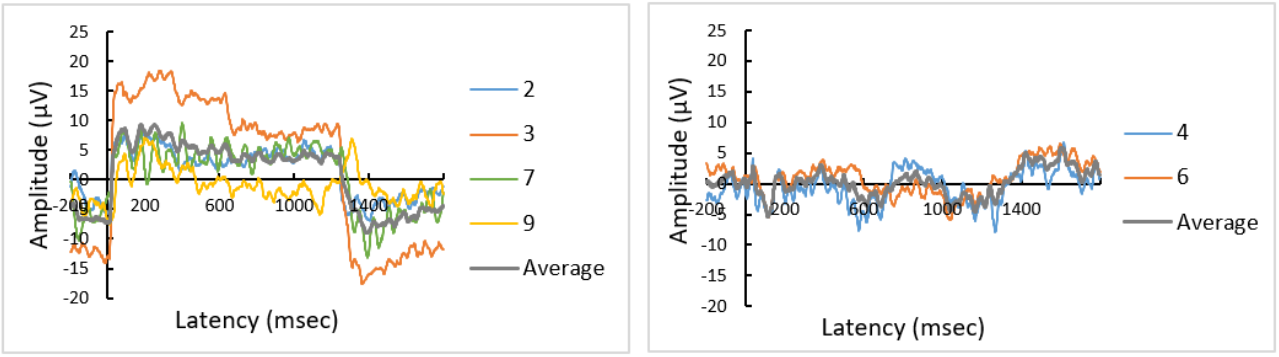



*Figure E2 – EEG recordings for stimulus 1000-1010 Hz with (left) and without (right) CI artefact.*

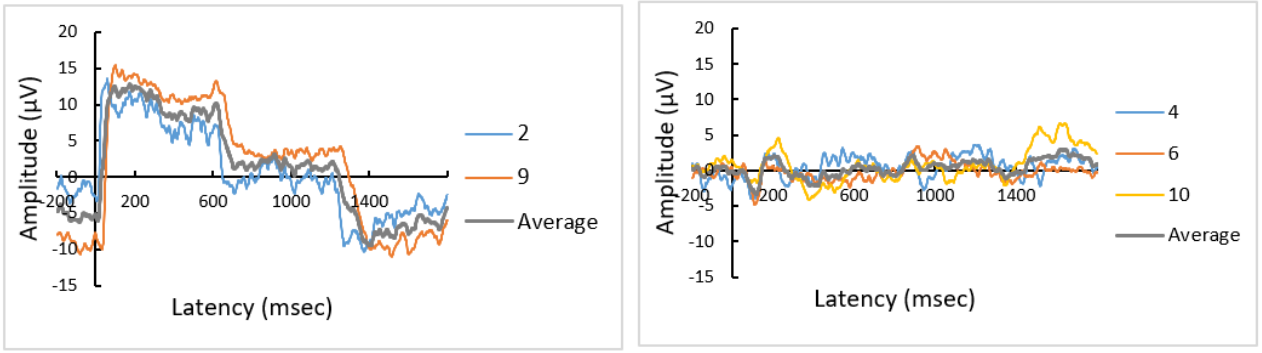



*Figure E3 – EEG recordings for stimulus with a density of 0.125 RPO with (left) and without (right) CI artefact*

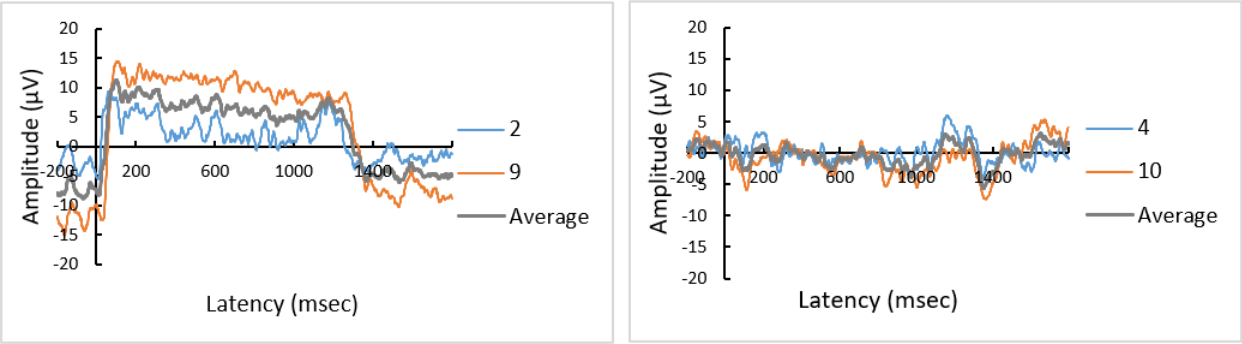



*Figure E4 - EEG recordings for stimulus with a density of 1.5 RPO with (left) and without (right) CI artefact*

For frequency, CI artefact was visible for participants #2, #3, #7, #8, #9 and #10. For spectral ripples, CI artefact was visible for participants #2, #9, and #10. For participants #8 and #10, CI artefact was only visible at the onset of a stimulus and was very small. For the other participants, CI artefact was larger and often also visible at time of stimulus change and offset. No artefact was visible for participants #4 and #6. Presence of artefact may explained by average MCL (see Figure E5). Participant #9 is not included in this analysis because this participant was the only CI user with an Advanced Bionics device. MCL cannot be compared between CI users with devices of different manufacturers without normalisation. For this reason, it was decided not to include participant #9 in this analysis, but only the seven MED-EL CI users that successfully completed testing. For the analysis average amplitude of CI artefact at onset (where possible from both frequency and spectral ripple data) was used to divide CI users in categories using a 5-point scale (where 1 indicates no/very small artefact (< 3 µV) and 5 a large artefact (> 20 µV)). This was then compared to average MCL per participant. A two-tailed Pearson correlation showed that average artefact size increased with increasing average MCL (and thus increasing charge levels): $r(5) = .941$, $p = .002$.

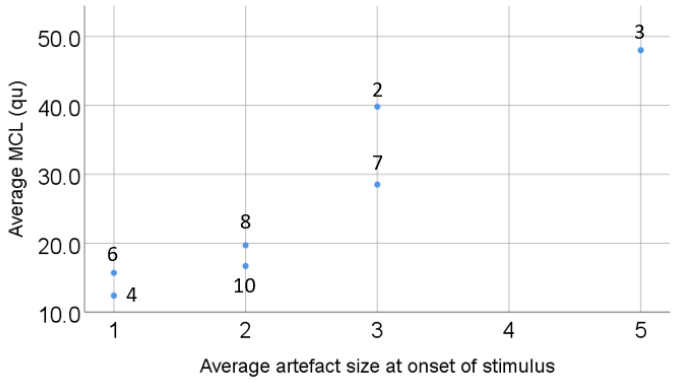



*Figure E5 – Scatter plot average artefact size at onset of stimuli (on a 5-point scale) vs. average MCL for the MED-EL CI users (N = 7).*