Bio-Inspired Information Processing

Master Thesis

Psychophysical Measurements of Temporal Integration Effects in Cochlear Implant Users

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Abstract

In this study, the effect of high stimulation rates on temporal integration in cochlear implant hearing was investigated. We measured threshold amplitudes, maximal acceptable levels and a line of equal loudness in 11 cochlear implant users (all with implants from MED-EL). The measurements were done (a) with a clinically used single channel stimulation rate of 1500 pulses per second (pps) and (b) at a high stimulation rate of 18000 pps, both for an apical electrode and a basal electrode. The duration of the stimulation pulse trains varied from 1 pulse to 5400 pulses. Additionally, we collected data on the perception of the different stimulation rates and stimulation electrodes using a questionnaire. A power-law like function was used to fit the threshold amplitudes of individual subjects with a high accuracy ($R^2 = 0.96 \pm 0.05$). The change of the stimulation electrode did not cause any systematic effects regarding threshold amplitudes or the slope of the temporal integration (TI) curve. We found lower thresholds for the high rate and slopes of −3.48 dB and −5.55 dB per tenfold increase in duration for the low and high rate, respectively. The DR was increased with the high rate by 6.58 ± 3.79 dB. Since the increased DRs at the high rate were accompanied by higher variability of the given answers, the same number of audible loudness steps in the given DR is expected for both rates. Some of the subjects perceived the change in stimulation rate with a change in pitch, whereas most participants were only sensitive to a variation of the stimulation electrode. It is noteworthy, that besides pitch, the perception of other characteristics like sharpness are affected by changes in stimulation rate and stimulation electrode.

Acknowledgements

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This work would not have been possible without the help of the test participants. Many thanks for your time, effort and patience!

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Thank you.

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Introduction

1.1 Motivation

Most people take hearing for granted. Ears cannot be closed like the eyes. What it means to people not to hear, can therefore only be understood when hearing does not work properly anymore (Zeh, 2018). According to the WHO classification, in Germany, about 16% of people show hearing impairment. A higher prevalence rate is observed in men than in women, which might be due to noisier working conditions (Von Gablenz and Holube, 2015).

A cochlear implant (CI) allows most people with severe to profound deafness, but a functional auditory nerve to hear, sometimes even after living without hearing for many years. This is possible as the electrode array of a CI resides in the scala tympani of the cochlea, where electrode contacts directly stimulate type I spiral ganglion neurons (SGNs). Stimulation is delivered via short electrical pulses, bypassing the middle ear structures and hair cells in the inner ear.

Since the first cochlear implant has been placed about half a century ago, considerable improvements in electrical hearing have been made. However, regarding the benefits of modifications in coding strategies like high stimulation rates, opposing opinions are held.

Further investigations on parameters that induce changes in the CI users hearing experience, are needed. One goal is to enhance speech understanding, which in many cases needs to be supported by lip-reading. Other targets are for instance the improvement of music perception or the facilitation of communication in noisy environments.

1.2 Objective

Signal processing in cochlear implants assumes a close relation of stimulation amplitude and perceived loudness. Understanding the exact mechanisms and influences of different parameters could help to find a superior approach to loudness coding. The aim of this study is to investigate in which way temporal integration in CIs is affected by different stimulation rates, and how changes in stimulation position and rate are perceived by CI users.

As reviewed by Heil et al. (2017), acoustic hearing thresholds (THRs) in quiet follow the same trend in all of the various species studied: Thresholds decrease with a slope of about 7 dB per tenfold increase in duration. We are interested to which extent this regularity is found in electric hearing. To this end, we measured thresholds, maximal acceptable levels (MAL) and a line of equal loudness between THRs and MALs, as a function of stimulus duration. Besides the effects described by Heil et al. (2017), we expect to find similar relations for MAL and the loudness-balanced curve (BAL).

It is disputed whether high single-channel stimulation rates are beneficial for speech intelligibility with CIs or not. Continuous interleaved sampling (CIS) is a coding strategy in which single electrodes are sequentially stimulated. Thus, at no point in time more than one electrode is active. Even with this method, nerve cells close to one electrode contact might also register pulses sent out by other electrodes (particularly of those in immediate vicinity). This finding has been supported by studies that show a broad current spread throughout the whole cochlea (e.g. Ifukube and White, 1987). Therefore, the actual stimulation rate of a single neuron might be the repetition frequency of a single electrode multiplied by the number of stimulation contacts in use. The stimulation frequency for a single electrode is usually set to approximately 1500 pps in MED-EL implants, in which 12 electrodes are available. This leads to a maximal global stimulation rate of about 18000 pps, given that a stimulation of any electrode contact is observable at all locations in the cochlea.

For all investigations with CI users, a large variability between the individual participants' performance is observed. This can partly be explained by different progression of diseases (including degeneration of the distal parts of SGNs), different levels of training with the CI due to differing time spans since implantation or residual hearing of the non-implanted side, etc. For this reason, most analyses in this thesis are done on an individual level first. Nonetheless, we expect effects of stimulation rate and stimulation duration that are common to all participants even when showing up in different absolute numbers. We do not hypothesize systematic effects of stimulation position on the outcomes of THR, MAL and BAL.

Comparable measurements were already conducted and analysed in a previous study by our research group (unpublished). Despite some changes in the methods, these former results will be compared to those of the study at hand. Besides the subjects' THRs, MALs and the balancing task for stimuli of different duration and varying stimulation rate that have been done before, we are also interested in how the above mentioned parameters change the perception of stimuli and investigate this accordingly.

2

Fundamentals

2.1 Basics of Hearing

In normal hearing, sound waves travel through the ear canal to the tympanum, where sound pressure changes lead to a back and forth movement of the membrane. Malleus, incus and stapes, the smallest bones in the human body, transfer this movement to the fluid in the cochlea (perilymph) via the oval window. In the cochlea, motion of the perilymph through scala vestibuli and scala tympani causes movement of vestibular and basilar membrane. With this, a deflection of hair cells in the organ of Corti is initiated. Potassium channels in the membrane of inner hair cells open, causing the membrane potential to depolarise. This depolarisation leads to neurotransmitter release at the synapses linking hair cells and spiral ganglion neurons (SGNs). As a consequence, action potentials (APs) are elicited in the SGNs and forwarded via auditory nerve fibres to higher neuronal levels. For more information on the anatomy of the inner ear see e.g. Patestas and Gartner (2016, p. 306 – 308).

The last step of forwarding information from SGNs to the brain, is the only one that is shared between acoustic hearing and electric hearing with cochlear implants. For CI users, most of the explained pathway is replaced by external and internal parts of the implant (see Figure 2.1). SGNs are stimulated directly by an electrode array, without any mechanical components involved.

With a CI, sounds of the environment are recorded by the microphone. The speech processor then filters and compresses this audio signal according to the programmed speech processing strategy before it is sent through an inductive connection from the transmitter (external coil) to the receiver (internal coil). Here, stimulation pulses are generated and directed by thin wires to electrode contacts that are placed through the round window into the scala tympani. Activation of these electrodes elicits APs in the SGNs, which relay information from the auditory periphery via the auditory nerve to the brain.

It is known that the dynamic range is smaller, the SGN firing rate is less variable and phase locking is stronger with electrical than with acoustic stimulation (Boulet et al.,

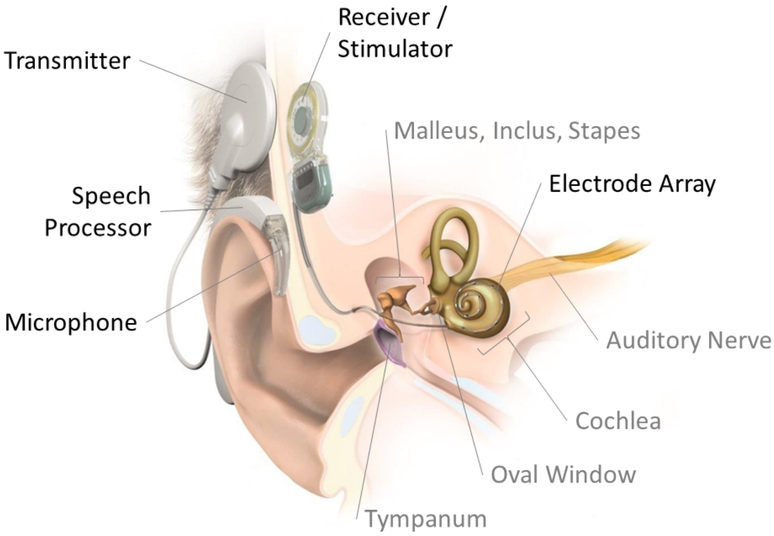


Figure 2.1: Cochlear Implant System (Maestro) from MED-EL. Text in black describes all parts of a cochlear implant. Components of the auditory periphery are labelled in grey. Modified from www.medel.com/de/image-gallery.

2016). However, there are many open questions in CI hearing for which there is still a need for research.

2.2 Related Work

2.2.1 Temporal Integration

Temporal integration (TI) describes the effect that detection thresholds decrease with an increase in stimulus duration.

Early studies already investigated this duration-intensity reciprocity in acoustic hearing. According to Stevens and Hall (1966), when keeping the stimulation level constant, loudness grows, following a power function of duration. The perceived loudness increases only up to a critical duration of about 150 ms for supra-threshold and 230 ms for threshold measurements. From there, loudness is independent of duration (see Figure 2.2, left). Fastl and Zwicker (2006, p. 217) found that already from about 100 ms on, loudness does not change with increasing duration. McFadden (1975) did measurements on the loudness of stimuli that differed in sound pressure level and duration. He found, to maintain equal loudness, intensity must decrease by between 3 and 15 dB for each doubling of duration, depending upon the subject (see an example of one subject in Figure 2.2, right). Differences to the results of other studies (e.g. −4 dB per doubling of duration in Stevens and Hall, 1966) were discussed and attributed to differences in the experimental procedure.

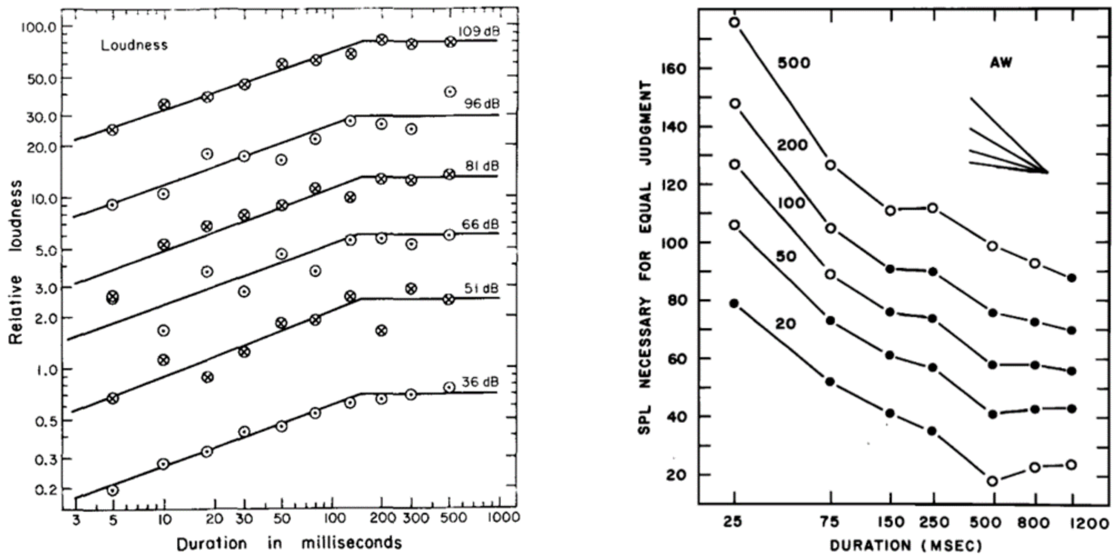


Figure 2.2: Illustrations of the relation of loudness and stimulus duration. **Left:** Loudness growth as a function of stimulus duration at six levels of stimulus magnitude (in dB peak SPL). From Stevens and Hall (1966). **Right:** Acoustic-integration curves for a 1000-Hz tone at different levels of judged loudness. The set of straight lines shown have slopes of -10, -20, -40, and -66 dB/decade. From McFadden (1975).

By now, this kind of measurement has been done with many species, including humans, primates, carnivores, aves and even fish (see in Figure 2.3 the blue, red, green and black lines, respectively). The measurement revealed besides inter-individual differences, striking similarities in the overall shape of these curves. An almost linear function describes the relationship of amplitude (in dB) and time (on a logarithmic scale). This power-law relationship has a slope of of about -2 dB per doubling of duration or approximately -7 dB per tenfold increase of duration (decade).

The term temporal integration might be misleading, as it is not clear if some quality of the stimulus is really integrated, as this would require some kind of computation (Viemeister and Wakefield, 1991). Also, the slope of the above mentioned functions would have to be steeper (-10 dB per decade) in case of perfect integration of intensity. Consequently, many different equations describing the amplitude vs. duration relationship have been suggested. In addition to duration, other factors like the shape of the temporal amplitude envelope or the duration of the silent gaps between trains of stimulation have been found to influence integration (e.g. Heil et al., 2017).

With long stimulation duration, adaption comes into play. Adaption might be an opposing factor to temporal integration. Litvak et al. (2001) found adaption over the course of 100–200 ms after pulse train onset. With deafened cats, Zhang et al. (2007) investigated the adaption of auditory nerve fibre firing by direct electrical stimulation of the

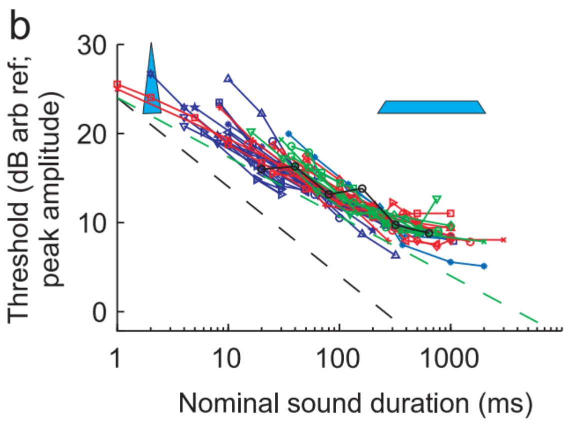


Figure 2.3: Threshold amplitudes as a function of duration obtained in different studies. The curves show the thresholds of various species (blue: humans and primates, red: carnivores, green: aves, black: fish) after vertically shifting each curve to obtain close overlap. The dashed black and green lines have slopes of -20/2 dB and -20/3 dB per tenfold increase in duration, respectively. From Heil et al. (2017).

fibres. They described the decrement in firing rate with decaying exponential models, comparable to those used for acoustic stimulation. For different stimulation rates, they found differences in the rate decrements. With the high stimulation rate (5000 pps) they observed a higher amount of rate decrement than with the lower rates of 1000 pps and 250 pps. These differences might not only be attributed to adaption but also to more asynchronous firing after some period of high-rate stimulation. Therefore, when investigating TI, one must always keep these effects in mind.

2.2.2 Models of Amplitude-Duration Relationship

Various models describing TI have been proposed. An overview of the most important contributions can be found in Heil et al. (2017). It is assumed that centrally the same processing takes place in acoustic and electric hearing, with modified neural input from electrical stimulation.

One of the easiest functions to describe the effect of TI is of the form

$$I(t) = k/t \tag{2.1}$$

where the threshold amplitude $I(t)$ is determined by a constant k divided by the duration t. With larger duration, the amplitude decreases. $I(t)$ originally represented acoustic intensity. With the advent of CIs, also the electrical stimulation amplitude was referred to as $I(t)$. This simple model has been extended by a threshold intensity, the minimal stimulation amplitude I_∞ that is necessary to reach threshold, even for very long stimulus duration (Hughes, 1946; Garner and Miller, 1947).

$$I(t) = I_\infty \cdot (1 + \tau/t) \tag{2.2}$$

The parameter τ represents a time constant, similar to k in Eq. 2.1. This function also models the flattening of the amplitude-duration curve for very large t.

Proposed e.g. by Green et al. (1957) was a function for the integration of intensity in a power-law like relationship of duration and amplitude:

$$I(t) = I_1 \cdot t^b \tag{2.3}$$

with I_1 representing the function value $t = 1$, and b for the slope of the decreasing values for increasing duration. Perfect integration of acoustic intensity would be obtained with a slope of -10 dB per decade. Even if individual participants' slopes sometimes are that steep, the average usually shows shallower slopes (see Figure 2.3). Models for acoustic hearing were mostly based on integration of the input itself, whereas models like the one for electric stimulation by McKay et al. (2013) claim an integration of the linearly smoothed auditory nerve response.

Plomp and Bouman (1959) proposed a model that represents leaky integration of intensity of the form

$$I(t) = I_\infty/(1 - e^{-(t/\tau)}) \tag{2.4}$$

with an exponential decay of amplitude with a time constant τ. This function was also sometimes extended with a scaling constant.

In different studies, a large variability of time constants was found. There are several attempts to explain these differing results. One explanation might be, that there are two systems with different time constants active for different tasks. A slow system is assumed when integration of information over a long period is beneficial for detecting a weak signal in noise. In contrast, the system might be fast to avoid masking effects, if needed (Eddins and Green, 1995, p. 207). Another way to explain the large differences could be a distinction between peripheral processing with sharp temporal resolution and a more central processing stage for TI. For instance, Zwislocki (1960) claims that auditory temporal summation takes place in nuclei of higher order with a time constant of about 200 ms, whereas at lower levels, shorter time constants are observed.

Opposing to the classical integration theories, new models for TI came up. The so-called multiple-looks model by Viemeister and Wakefield (1991) assumes that over a longer time, more independent looks at the stimulus are possible, thereby lowering the amplitude that is necessary to detect the stimulus. Instead of summing up intensities in any way over a certain period, one could also think of the auditory system scanning the incoming auditory information for detection events (Heil and Neubauer, 2003). With longer time, the probability of reaching detection threshold increases.

Each of the models named here accounts well for a certain part of the experimental data, but still new attempts to model the relation of amplitude and duration are made.

2.2.3 Rate Effects

It has been found, similar to normal hearing listeners, also for CI users the detection of pulse trains is facilitated with increasing duration at a fixed stimulation rate. When keep-

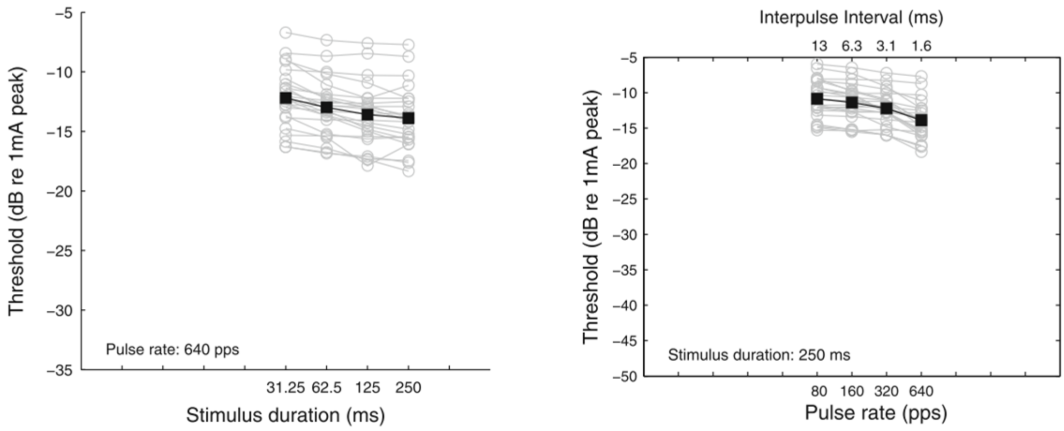


Figure 2.4: Threshold amplitudes as a function of duration (temporal integration) and as a function of pulse rate (multi-pulse integration). Thresholds are shown for two individual stimulation sites measured in 12 ears in grey open circles and for group mean in black filled squares. **Left:** Temporal integration; **Right:** Multi-pulse integration. From Zhou et al. (2015).

ing the duration fixed, an increase in stimulation rate does reduce detection thresholds (multi-pulse integration, MPI) (see Figure 2.4). Zhou et al. (2015) showed that with a higher stimulation rate, and therefore more pulses in a fixed period of time, amplitude reduction is necessary to hold the perceived loudness of the stimulus constant. This effect of rate is seen in threshold and at comfortable loudness, but is stronger for threshold measurements than for comfortable loud stimuli (McKay and McDermott, 1998). McKay et al. (2013) noted that especially for short durations, threshold amplitudes might be determined by the number of pulses that have been integrated (MPI) rather than by the time that has passed since stimulus onset (TI).

2.2.4 Forward Masking

When two signals are presented successively, the first can mask the second one. This means that depending on the first signal (masker), the detection threshold of the second signal (probe) can increase. Nelson and Donaldson (2002) found no effect of the masker level on the time constant τ of the recovery process of forward masking, but they reported large inter-individual variability for the time constant. Considerable variation for different participants was also found by Adel et al. (2017). They tested the effects of masker pulse rate on masking of a probe stimulus. When presented at the same loudness, more and longer-lasting masking is induced by low-rate pulse train maskers (250 pps) when compared to high-rate pulse train maskers (5000 pps).

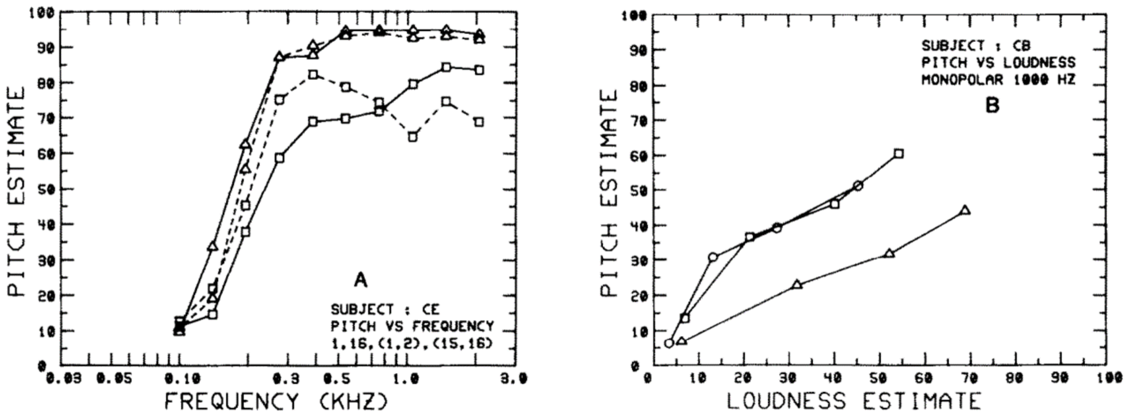


Figure 2.5: Pitch estimates as a function of stimulus frequency and as a function of loudness. **Left:** Pitch as a function of frequency for one subject. Squares: apical; triangles: basal. Loudness was balanced at a medium level (50% of dynamic range). **Right:** Pitch as a function of level for one subject. Pitch and loudness estimates were obtained from the same stimulus set. The stimulus was a 300 ms burst of 1000 Hz. From Shannon (1983).

2.2.5 Perception of Stimulation Rates

Using high single channel stimulation rates in CI coding strategies is not assumed to have any effect on the percepts of single electrodes. However, recent studies on pitch perception lead to the conclusion that this assumption might not be true (Landsberger and McKay, 2005).

It is widely known that stimulation of different electrodes in a cochlea implant leads to the perception of characteristic pitch (Shannon, 1983). Besides varying pitch with the place of stimulation, pitch differences can also be induced by varying the stimulation rate. This has been reported by Shannon (1983), along with the notion that interactions of pitch perception with loudness perception are present (see Figure 2.5).

Recent studies by Karg et al. (2018) showed that changes in pitch perception can also be realised with increasing stimulation rates above 300 Hz, which has been known as the critical rate for a long time (see Figure 2.6, left). Landsberger and McKay (2005) found that there are rarely changes in pitch perception observed between 200 Hz and 1500 Hz, but for some subjects, depending on electrode, changes in perception were elicited for varying the stimulation rate between 1500 Hz and 12000 Hz. Nevertheless, for rates higher than the critical rate, only inconsistent pitch discrimination was observed. Landsberger and McKay (2005) remarked also, that rate discrimination might not only be enabled by differences in pitch itself or changes in loudness, but is obtained by other features as well. This was confirmed by Karg et al. (2018). Changes in stimulation rate were also perceived in changes of categories like rough–smooth or strong–weak (see Figure 2.6, right).

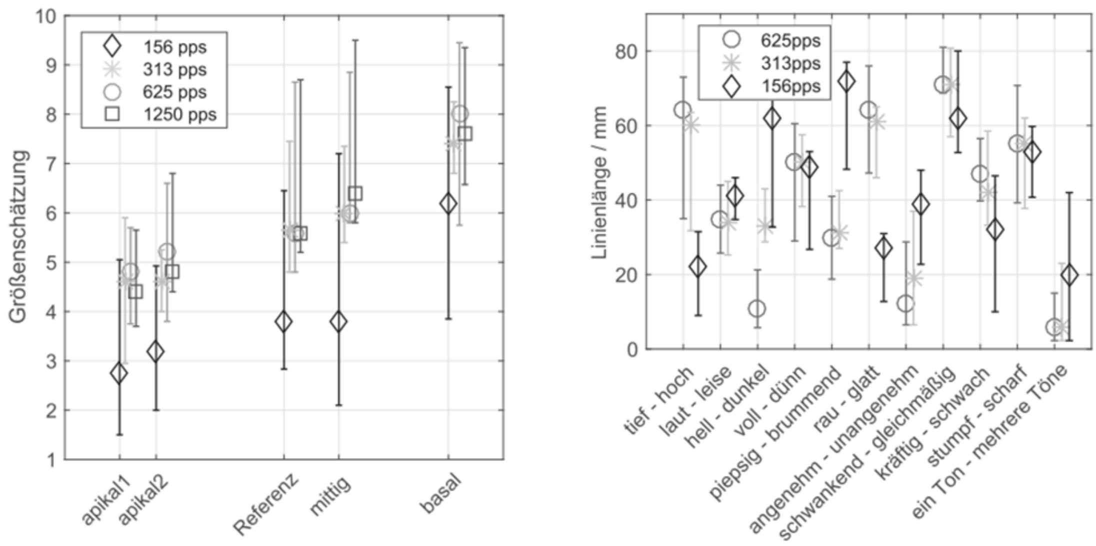


Figure 2.6: Pitch estimation of different stimulation rates as a function of electrode position and for different categories. **Left:** Medians and interquartile ranges of the individual estimations of pitch (given as 'Größenschätzung'). Each electrode was judged five times by each of the nine subjects. **Right:** Medians and interquartile ranges of the individual estimations of the semantic difference (given as 'Linienlänge') of several categories depending on different pulse rates. From Karg et al. (2018).

2.3 Preceding Study

The experiments in this Master's Thesis are based on the investigations of a prior student in the lab.[1] She investigated the effects of different stimulation duration (ranging from 0.3 to 1000 ms) and stimulation rate (1200 pps vs. 25000 pps) on threshold, maximal acceptable levels and a curve of equal loudness. One of the main findings was that threshold curves are best described with a function of the form

$$I(t) = I_\infty + (I_0 - I_\infty) \cdot e^{(-t/\tau)} \qquad (2.5)$$

This function models the flat portions of the threshold vs. duration curve for very small durations (contained only 1 or 2 pulses) with I_0 and the long durations (above approximately 200 ms) with I_∞. Between those flat parts, there is an exponential decay of amplitudes. It was found that the saturation for long durations is reached earlier with the higher stimulation rate. Further, for an increase of the stimulation rate, the dynamic increase was on average increased by 8.33 ± 0.93 dB. The explanatory power of these findings is restricted due to a limited number of participants and some methodological inconsistencies.

[1]Bachelor Thesis: Schwanda, D. (2017). Hörwahrnehmung von CI-Trägern : Einfluss von hohen Stimulationsraten und Integration von Pulsfolgen in Abhängigkeit von der Stimulationsdauer.

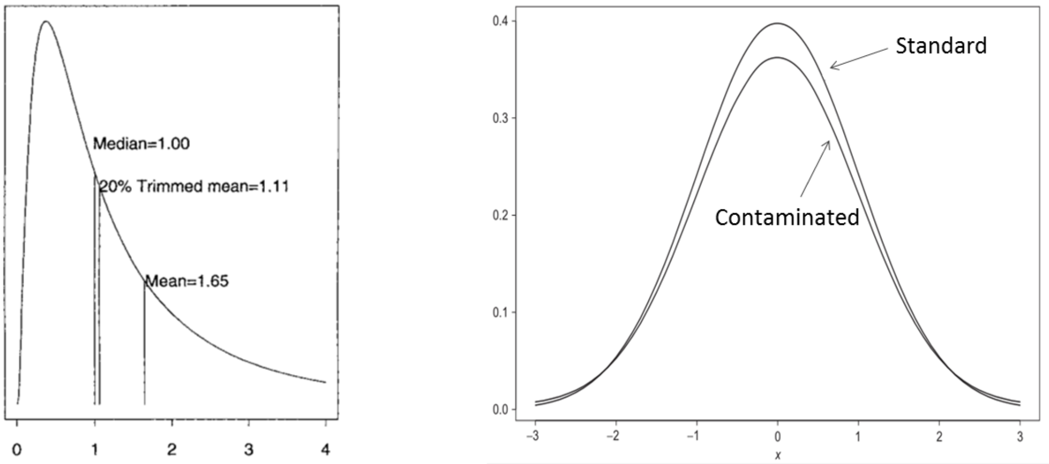


Figure 2.7: Left: Location of the population mean, median, and 20% trimmed mean for a log-normal distribution. **Right:** Normal and contaminated normal distribution. The normal distribution has variance 1, and the contaminated normal distribution has variance 10.9, illustrating that variance is highly sensitive to the tails of a distribution. Modified from Wilcox (2011).

2.4 Robust Statistics

In an ideal world, researchers would always have enough participants to represent a whole population and with this, variables with normal distribution. Unfortunately, it is not that simple. “To begin, distributions are never normal” (Wilcox, 2011, p. 1). This quote reflects the main reason for the usage of robust statistics instead of the classical methods. Standard methods, like t-tests or the widely used Analysis of Variance (ANOVA), rely on normally distributed and homoscedastic data sets. But, as in this study, distributions do not always fulfil these requirements.[2]

Deviation from standard normal distribution can arise from heavy tails, outliers or skewed distributions. The first two mentioned factors influence the standard deviation of the sample mean, which leads to low power (probability of correctly rejecting a null hypothesis) for statistical testing.

For the comparison of multiple groups, usually two values are used to describe the obtained data. The first typically taken value is a measure of location and the second one a measure of scatter or scale. If these measures are only slightly effected by small changes of the underlying distribution, they are called robust.

[2] A brief article reflecting the need for robust statistics can be found here: https://theconversation.com/new-statistical-methods-would-let-researchers-deal-with-data-in-better-more-robust-ways-67981.

2.4.1 Measures of Location

With this measure, one tries to represent a typical participant or object of the data set at hand. The most popular measures for this aim are mean and median (Wilcox, 2011).

Figure 2.7, left panel, demonstrates how the mean in many cases does not represent the most typical value to obtain from a distribution. With skewed distributions, the mean is too much influenced by heavy tails. In cases where outliers (values that are a lot smaller or larger than the rest of the distribution) exist, the mean is torn towards these values. Median or trimmed means give a better estimate of a typical value.

For calculations of the trimmed mean, the tails of the distribution (that might be heavy or include outliers), are ignored to a certain extent. A γ-trimmed mean is the mean of a distribution that has been truncated at the γ and 1-γ quantiles. According to Wilcox (2011) it is empirically shown that the optimal amount of trimming is around 20%, even for very small sample sizes, like the one with 12 samples in this thesis.

2.4.2 Measures of Scale

Wilcox and Keselman (2003) illustrate the need for robust estimations of scale by contaminating a normal distribution with samples of another distribution. A contaminated distribution is a mixed distribution that is in one part obtained by sampling from a standard normal distribution and the other part comes from a normal distribution with a larger standard deviation. Like this, the so-called contaminated normal distribution looks very similar to the standard normal distribution, but its variance differs enormously due to some additional values at the ends of the distribution. These heavy tails, which only represent a small proportion of the distribution, increase the calculated variance over-proportionally.

Contaminated distributions are what we might encounter in real life scenarios, when only a subset of the population deviates from the rest. In Figure 2.7, right panel, the tails of the contaminated normal distribution are only a bit higher, and the peak only little lower, but the variance is ten times higher. The variance is very sensitive to the tails of a distribution. This means, that a seemingly small subset of the samples can strongly influence a dataset. Robust statistics help to reduce these problems. (Wilcox, 2011) suggests using measures of scale that are less influenced by heavy-tailed distributions.

For instance, to determine the scatter of a distribution, the winsorized variance can be computed instead of regular variance. For this, a certain percentage (γ) of all very small/ very large values are replaced by the value of the smallest/largest value in range. From this so-called winsorized distribution, the regular variance is then computed.

3

Methods

3.1 Participants

11 subjects ($M = 56$ years, $SD = 14$ years; 8 female) with cochlear implants from MED-EL participated in our study. Two women (subjects S1 and S8) agreed to do the experiments with both ears, which leads to a total number of 13 measured ears. Details are shown in Table 3.1. Due to technical limitations, for S11 only low rate stimulation was done.[1] Therefore this participant is excluded from analyses on the effect of stimulation rate. The questionnaires were only answered completely in ten cases.

3.2 Equipment

The core of our experimental setup (see Figure 3.1) is a computer that is equipped with a parallel digital card (Model NI PCIe-6361, National Instruments, Austin, Texas, USA). Pulse trains were created by sending all information that describe their parameters (phase and gap duration, stimulation rate and duration of the pulse train, as well as the stimulation amplitude) to the Research Interface Box RIB II (Institute of Ion Physics and Applied Physics, University of Innsbruck). This box turns the given information into pulses that are then sent out to the implanted parts of a cochlear implant. This box was specifically built for cochlear implants from MED-EL. With this we had full control over the stimulation. In regular CI use, these pulses are delivered to the coil by a sound processor (placed behind the user's ear or above the coil) instead of the RIB. The subjects' sound processors were not used.

Communication with a cochlear implant requires to convey information in a special data stream to the RIB, which then sends it via the coil to the implant. Without this conversion by the RIB, a stimulation of the implant is not possible. From the RIB, two coils received the same information. One of them was placed above the implanted coil on

[1] It was not possible to adjust the threshold amplitudes for the high stimulation rate, because the subject perceived onset and offset artefacts of the stimulation pulses, even for amplitudes equal to zero CU.

Table 3.1: Biographical data and etiology of participants; (HL: Hearing loss).

ID	Age (years)	Gender	HL onset	Etiology	CI use (months)	CI Model
S1r	65	F	40	unknown	60	Sonata
S1l	65	F	40	unknown	54	Sonata
S2	23	M	1	Meningitis	120	Sonata
S3	53	F	30	hereditary	28	Synchrony
S4	78	M	58	acute HL	148	Pulsar
S5	42	F	1	Cholesteatoma	36	Synchrony
S6	55	M	5	Otitis	72	Concerto
S7	42	F	birth	Acute HL	60	Concerto
S8r	64	F	35	Meningitis	90	Concerto
S8l	64	F	27	Meningitis	30	Synchrony
S9	60	F	9	Otitis	72	Concerto
S10	59	F	30	unknown	132	Pulsar
S11	56	F	birth	unknown	144	Pulsar

the participants head to control the cochlear implant, whereas the other coil was used to monitor the delivered stimulation during the experiment. For this aim, the second coil was placed on a RIB detector box (Institute of Ion Physics and Applied Physics, University of Innsbruck). This box simulates the internal part of the implant. It receives all information sent by the coil and turns it into a voltage at the different electrode contacts. With an oscilloscope (Model TBS1104, Tektronix, Beaverton, Oregon, USA), these currents were made visible to the experimenter.

Participants responded to the stimuli either by using a computer mouse to click response buttons of a graphical user interface on the computer screen or by pressing the respective buttons on a computer keyboard.

To create the stimulation pulses and to adapt them in real time corresponding to the participants responses, Python (Version 2.7, 32-bit) was used. The scripts were written by members of the research group. For data analysis MATLAB with the Curve Fitting Toolbox (Version 9.5.0.944444 (R2018b), The MathWorks Inc., Natick, Massachusetts) and R (Version 1.2.747 (2018), R Foundation for Statistical Computing, Vienna, Austria) with various packages, including WRS (Version 0.35 (2018), Wilcox & Schönbrodt) for robust statistics were used.

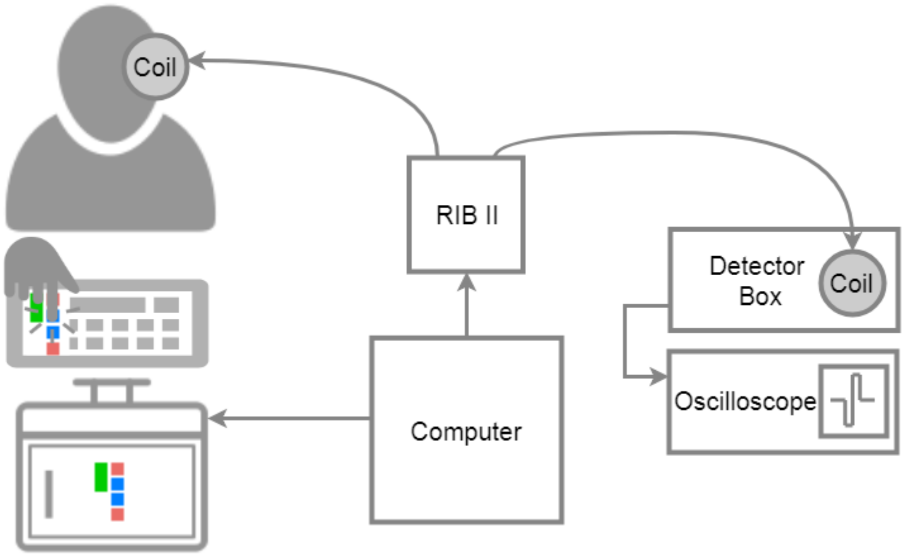


Figure 3.1: Experimental setup. The experimenter started the different parts of the study and handed instructions to the participants. During the subparts of the experiment, subjects operated the computer by themselves.

3.3 Stimuli

For all of measurements, monopolar stimulation was applied. Biphasic, charge-balanced pulses were used with the cathodic (negative) phase leading. To allow very high stimulation rates, phase duration was chosen to be 23.33 µs only, with a minimal gap (inter-phase gap) of 2.1 µs between negative and positive components of the pulse. A stimulation amplitude of 1200 CU (62 dB re 1 CU) is set as an upper limit for stimulation by RIB II software and hardware. 1 CU is approximately 1 µA.

Stimuli differed in stimulation electrode, stimulation rate and the number of pulses (see Table 3.2 and for number of applied pulses converted into the respective duration Table 3.3).

All stimuli of one measurement were presented in randomised order. This does not apply to any of the preliminary measurements. Randomisation was also limited to a certain amount in the loudness balancing task.

3.3.1 Electrodes

The same measurements were done with stimulation of two different electrodes on the array. If not hindered by any reason, electrodes 3 (apical) and 10 (basal) were selected. Otherwise, neighbouring electrodes were chosen.

Table 3.2: All stimuli defined by the number of pulses in a pulse train.

Rate (pps)	Number of Pulses								Electrodes	Reps.
1500			1	4	15	45	150	450	apical, basal	max. 4
18000	1	5	18	54	180	450	1800	5400	apical, basal	max. 4

Table 3.3: All stimuli defined by duration of the pulse trains.

Rate (pps)	Duration (ms)								Electrodes	Reps.
1500			0.67	2.67	10	30	100	300	apical, basal	max. 4
18000	0.06	0.28	1	3	10	30	100	300	apical, basal	max. 4

3.3.2 Stimulation Rates

Two stimulation rates (the inverse of the distance between the starting points of following pulses in a pulse train) were used. The lower stimulation rate (1500 pps) represents a typical stimulation rate present at a single contact of the electrode array in normal CI settings, whereas the higher rate (18000 pps) was chosen to investigate the effect of the overall stimulation rate, which is up to 12 times a single channel stimulation rate.

3.3.3 Number of Pulses

At the higher rate, stimuli with the number of pulses ranging from 5 to 5400 were presented. For the lower rate, the stimuli consited of 4 to 450 pulses. In total seven different durations for 18000 pps and five durations for 1500 pps were used. In addition one pulse was used as stimulus. This one pulse can be assigned to both stimulation rates.

In all experiments, the presented pulse trains were separated by a silent gap of 500 ms. With a fixed pause, the rhythm of the stimulation varied due to pulse train duration. Since the longest duration used was 300 ms, the effect of forward masking was presumably reduced to a minimum after the pause. Nelson and Donaldson (2002) found average time constants of 54 ms for the exponential decay of masking after a 320 ms long masker with a frequency of 500 Hz. Even at the largest time constant they found (163ms), less than 5% threshold shift would be observed for a 10 or 30 ms probe pulse train after a pause of 500 ms. Nevertheless, these results might not be applicable to our situation with the high stimulation rate. Regarding the effect of stimulation rate on forward masking time constants, no studies investigated rates as high as the ones we use in this study. However, Adel et al. (2017) showed, when presented at the same loudness, masking by pulse trains of high stimulation rate was even less than masking induced by low-rate pulse train maskers. For CI hearing it has been found that the time constant is largely

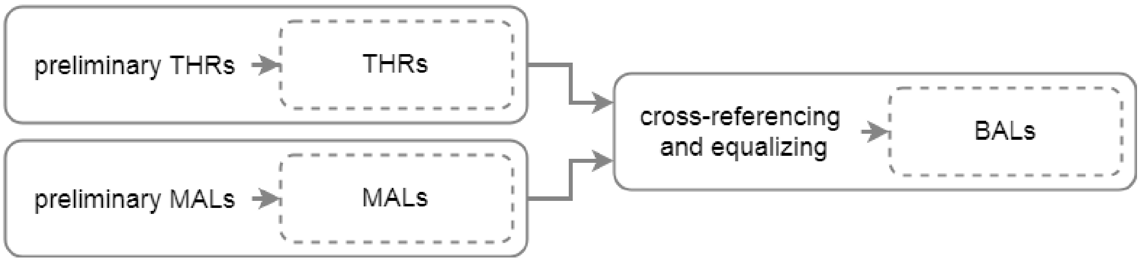


Figure 3.2: Three main parts of the experiment followed by the questionnaire.

independent of masker level (Nelson and Donaldson, 2002). This allows to have the same pause length in-between pulse trains even for MAL and balancing measurements, where larger current amplitudes are present.

3.4 Experimental Procedure

The experiment consisted of three parts (see Figure 3.2) plus a questionnaire in the end.

In the first part, current amplitudes corresponding to threshold (THR) for all combinations of electrode, stimulation rate and duration were determined four times each. In cases where the result was out of range (above 1200 CU) for two times, the other two trials of this condition were skipped. A method of adjustment was used, where participants increase and decrease the stimulation amplitude themselves to the desired value (for more information on this method see Gelfand, 2017). The method of adjustment is supposed to be faster than an new adaptive alternative forced choice paradigm proposed by Rader et al. (2018), but might be less accurate in terms of test/retest reliability (Rader et al., 2018). On the other hand, participants were very motivated to adjust their thresholds themselves and reported that they "always wanted to do this".

The second part was very similar, only this time they adjusted the stimulus levels to the maximal acceptable amplitude, defined as MAL.

The third part consisted of a loudness balancing procedure (BAL). Participant matched the perceived loudness of a reference stimulus of 300 ms duration to stimuli of shorter durations in all of the four electrode × stimulation rate combinations.

In none of the main blocks visual feedback regarding the chosen current amplitude was given. Only in the training phase of THR and MAL, a representation of chosen amplitudes was visible. Throughout the experiment pauses were automatically initiated every 20 minutes if participants did not ask for a pause before.

Afterwards, with a questionnaire, subjects reported their perception of the balanced stimuli, first in a open question format and afterwards with standardised questions.

3.4.1 Thresholds

Prior to threshold measurements, a training phase made sure that the participants understood the task and became familiarised with the setup. After two pure training trials that were not used for the experiment, preliminary threshold estimates were acquired. In this phase, three (four at the higher rate) points in the duration-threshold curve (in each electrode × stimulation rate combination) were determined. From these, a first estimation of the threshold was obtained by a linear interpolation in the log-log representation of these duration-threshold pairs.

Each point of the definite threshold was measured four times. The starting points, from which subjects then adjusted to the threshold amplitudes, varied randomly in a range from 80% to 90% or 110% to 120% of the previously mentioned preliminary threshold estimates. Care was taken to ensure that two of the starting points were above and two below the preliminary threshold estimate. These variations are unknown to the subject and reduce biases of the threshold amplitude induced by the starting point or the direction from which the threshold is reached (Gelfand, 2017, p. 149).

In the training phase, the starting current amplitude was always zero, whereas it was adapted by the above mentioned method in the following measurements with the aim to reduce biases and to save time. From the starting points, participants adjusted the perceived loudness by increasing and decreasing the current amplitudes until the stimulus was just audible but still very quiet. They were encouraged to use the larger step buttons first to reach the threshold fast and then use the smaller step changes for fine adjustments. Further, they were asked to bracket their thresholds (reach it from above and below) before saving the response, which reduces biases as well (Gelfand, 2017, p. 149).

3.4.2 Maximal Acceptable Levels

Again, a short training phase made sure that each participant understood the task and became familiarised with the setup. Similar to the THRs, previously gained knowledge about the threshold current amplitudes was used for the starting points. Here, 120% of the THR amplitude was used as the stimuli's starting level for preliminary MAL measurements, which were done for the longest pulse train duration (300 ms). By subtracting THR from MAL, the dynamic range (DR) was computed. From just below 50% of the estimated DR as starting point, the participants adjusted the perceived loudness by increasing first and decreasing (if needed) the current amplitude until the stimulus was very loud, but still acceptable over a longer time. They were encouraged to use the larger steps first to reach the amplitude fast and then use the smaller step changes for fine adjustments to the MAL.

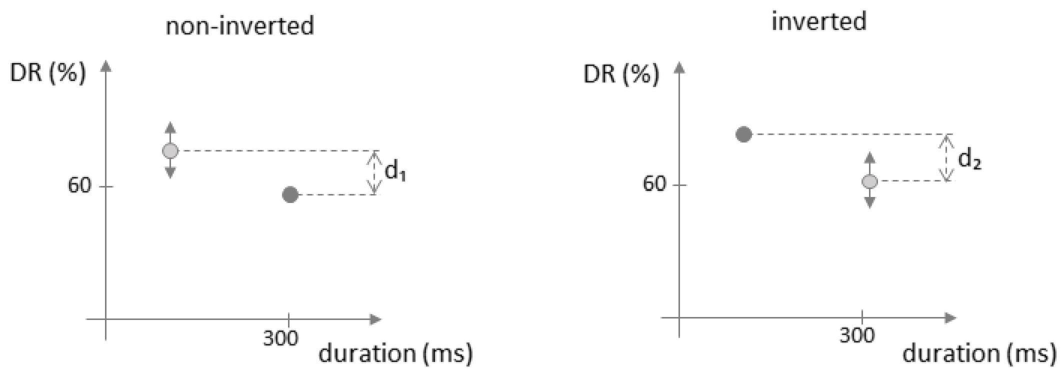


Figure 3.3: Scheme of the balancing procedure proposed by Adel et al. (2017), d_1 and d_2 correspond to the amplitude difference of long (300 ms) and shorter stimuli that were loudness-balanced by the participants. In both figures the darker dot represents the fix stimulus (reference), the light grey one with the arrows represents the variable stimulus. **Left:** Non-inverted trials. **Right:** Inverted trials.

3.4.3 Curve of Equal Loudness

In this part of the experiment, we aimed for a curve of equal loudness for each of the four electrode × rate conditions. All points on this curve should be perceived as being equally loud. When determining the amplitudes at which a probe stimulus has the same perceived loudness as a reference stimulus, the participants were offered a slightly modified graphical user interface. For this experimental part it was extended by two visual displays that flashed in grey and yellow at the time the fixed stimulus (grey display) and the variable stimulus (yellow display) was presented. This is done to give some indication on which of the two stimuli is fixed (grey) and for which the amplitude can be adjusted by the participant (yellow). Colours were chosen such that they are perceived on the computer screen with approximately the same luminance.

The subjects were instructed to adjust the amplitude of the stimulus (the one that was presented simultaneously with the yellow flashing display) until its loudness matched the loudness of the other stimulus (the one that was presented simultaneously with the grey flashing display).

Before the comparisons within one frequency × electrode condition were started, a reference stimulus (300 ms) of each condition was adjusted to the loudness of the 1500 pps stimulus at the apical electrode, which was fixed to 60% of its DR. This so-called cross-balancing will later on allow for comparisons across different conditions. Right after the cross-balancing, subjects were presented with all of the four balanced stimuli in a row. As they had been balanced before, all of them should appear at the same loudness. In case this was not true, subjects were able to change the amplitude of individual signals (making them either louder or softer in small step sizes) to equalise them in terms of loudness.

After the cross-balancing and equalizing, the experiment continued with adjusting loudness of two signals of different durations but with the same electrodes and pulse rates. In each condition, the perceived loudness of the shorter duration stimuli had to be matched to the cross-balanced 300 ms stimulus. All comparison pairs (stimulus with duration smaller than 300 ms vs. stimulus with duration equal to 300 ms) were compared four times each. In two of the four trials, the reference (the stimulus that is fixed in amplitude) was the 300 ms signal at the previously obtained amplitude. These trials are called non-inverted. In the other two trials, this 300 ms served as probe (the stimulus that has to be adjusted) which was compared to the fixed amplitude of the shorter stimuli. These are the so-called inverted trials. This procedure allows a more accurate balancing and has already been done by Adel et al. (2017) with

$$L_{short,bal} = L_{long,ref} + \frac{L_{short} - L_{long,ref} + L_{short} - L_{long}}{2} \tag{3.1}$$

where $L_{short,bal}$ is the loudness-balanced level of the short stimulus, $L_{long,ref}$ is the level of the long stimulus at loudness balanced to 60% DR (= main reference). L_{short} is the level of the short stimulus balanced to match the long stimulus loudness and L_{long} is the level of the long stimulus balanced to match the short stimulus loudness. Simplified, the formula describes the average of the differences between amplitudes of short and long stimuli by the two methods (non-inverted: d_1 and inverted: d_2) added to the amplitude of the long reference stimulus $L_{long,ref}$.

$$L_{short,bal} = L_{long,ref} + \frac{d_1 + d_2}{2}. \tag{3.2}$$

For a visualisation see Figure 3.3. In both cases (non-inverted and inverted) the probe stimulus had a starting value which randomly varied around the estimated value of the probe stimulus either above (between +5% to +10%) or below (between −10% to −5%) the estimated dynamic range level. In case of the first trial of non-inverted measurements, the best estimation of the probe was to take the same level of the DR that was used for the reference stimulus. In the inverted trials, this same level of the DR was used. In the second trial of the inverted measurements, the value that was obtained in the first trial was used as an estimation of the starting level and then varied by the ±5% to ±10% DR.

In those cases where no MAL was obtained, the initial starting value was set to 60% of the range between threshold and the maximal stimulation amplitude of 1200 CU, which is always below the actual 60% DR and might therefore be below the iso-loudness value. For the second comparison, a starting value was chosen by adding variability in the range of +5 to +10% to the previously obtained value which then reaches the estimation from above. Like this, also those values are reached once from below and once from above. This minimised the bias induced by reaching a value from a higher or from a lower amplitude and still allowed for balancing values for those durations where no MAL has been obtained before.

Table 3.4: Signals to be compared with the questionnaire.

Comparison	Signal 1	Signal 2
1	apical, **1500** pps, 300 ms	apical, **18000** pps, 300 ms
2	basal, **1500** pps, 300 ms	basal, **18000** pps, 300 ms
3	**apical**, 1500 pps, 300 ms	**basal**, 1500 pps, 300 ms
4	**apical**, 18000 pps, 300 ms	**basal**, 1500 pps, 300 ms
5	apical, 1500 pps, **300** ms	apical, 1500 pps, **30** ms
6	apical, 18000 pps, **300** ms	apical, 18000 pps, **30** ms

3.4.4 Questionnaire

Following the loudness balancing, signal pairs of either (a) same electrode, but different stimulation rate, (b) same stimulation rate, but different electrode, or (c) same electrode (apical), same stimulation rate, but different duration (30 ms vs. 300 ms) were presented. In total, six comparisons were made (see Table 3.4). For each of the comparison pairs, subjects were asked if they can distinguish between the two signals and if yes, how (see Appendix B for the instructions). Simultaneously to signal 1, the left display panel flashed in blue, with the second signal the right panel flashed red. This coding of blue and red stimulus was used to identify the two signals. By pressing a repeat button, the two stimuli were presented again. This could be done as often as desired. After the open questions were answered for all comparisons, the signals of each comparison pair had to be described in terms of eleven word pairs. These pairs describe the ends of a continuum, like *tief* - *hoch* ["low - high"] or *rau* - *glatt* ["rough - smooth"]. The participants' task was to determine the relative position of the two signals on this continuum. For examples see the instructions in Appendix B. Here again, the participants repeated the signals as often as desired.

3.5 User Interface

A special graphical user interface (GUI) created with PyGObject (Version 3.24.1) and Glade (Version 3.14.2) was displayed to the participants of our study.

Buttons to increase or reduce the stimulation amplitude in large and small steps were visible, as well as a button to save the amplitudes. In addition, one button to pause the session and another one to quit the experiment plus, for loudness balancing, a button to state that a stimulus was not possible to be balanced, were present. Except the latter three options, all responses could also be entered via a computer keyboard. The corresponding keys were colour-matched to those on the screen. The GUIs can be seen in the instructions in Appendix B.

Changing the amplitude in large or small steps caused an increase or decrease of the

Table 3.5: Step sizes for different quantisation stages.

Quantisation Stage	Fine Steps	Large Steps
0 – 150 CU	1.18 CU	18.90 or 28, 35 CU
150 – 300 CU	2.36 CU	18.90 or 28, 35 CU
300 – 600 CU	4.72 CU	18.90 or 28, 35 CU
600 – 1200 CU	9.45 CU	18.90 or 28, 35 CU

current level depending on the amplitude according to Table 3.5. For trials starting at zero amplitude, before the first reversal (changing from increasing to decreasing the amplitude or vice versa) large steps changed the current amplitude by 28.35 CU. After the first reversal and for all trials that did not start at zero amplitude, large steps changed the level by ±18.90 CU.

3.6 Analyses

It was not possible to only use robust methods throughout this thesis. Therefore, fitting of data is not done with any of the robust methods (even if there are robust methods available, see Wilcox, 2011, p. 471-629). Instead, conventional non-linear least squares estimation was used. In addition, standard deviation was calculated to show variability within or between subjects.

Having said this, for all averages and the statistical analyses of effects on a measure, robust methods were chosen. The average of one participants answers was calculated by the median. For averaging over different subjects, trimmed means with 20% trimming were calculated. A robust version (based on 20% trimmed means) of a factorial repeated measures ANOVA was applied when calculating the effects of several factors on the results.[2] Mainly the functions *wwtrim* and *wwwtrim* from the WRS package (Wilcox and Schnbrodt, 2018) were used. These functions allow for two- and three-factorial repeated measures analyses (two or three within-subject factors). The outcome of these methods are the test statistic Q and its corresponding p-value.

To analyse the questionnaires, cross-correlation matrices were computed. With these, it is possible to find in which categories the stimuli that are compared differ in a similar or opposite way. However, with this method only those correlations present in a majority of the participants are obtained. Analyses on an individual level are not done.

[2]This amount of trimming is suggested by Rand Wilcox in his book (Wilcox, 2011). Additionally, in private correspondence, he confirmed that it is the right choice for the data set at hand.

3.7 Side project: Building an amplifier

To be able to listen to the stimuli, we decided to build an amplifier. Listening to stimuli was necessary many times to check the experiment for mistakes and to make sure that timing of auditory and visual stimuli happens in parallel. For listening to the signals acoustically, the signal had to be changed to four different audible frequencies instead of the four frequency × electrode combinations in the real experiment.

In figure 3.4 the electronic circuit of the amplifier is shown. With this device, it is possible to amplify the signal up to a factor of ten in a range of 15 Hz to 150 Hz. This range is desirable, as we aimed to build a device which can also be used otherwise than just amplification of the output signal of the detector box for headphones.

When using the amplifier, we connected the detector box to the input (instead of the oscilloscope, that was usually connected to monitor the pulses produced by the RIB). Headphones were connected to the output of the amplifier to listen to the signals.

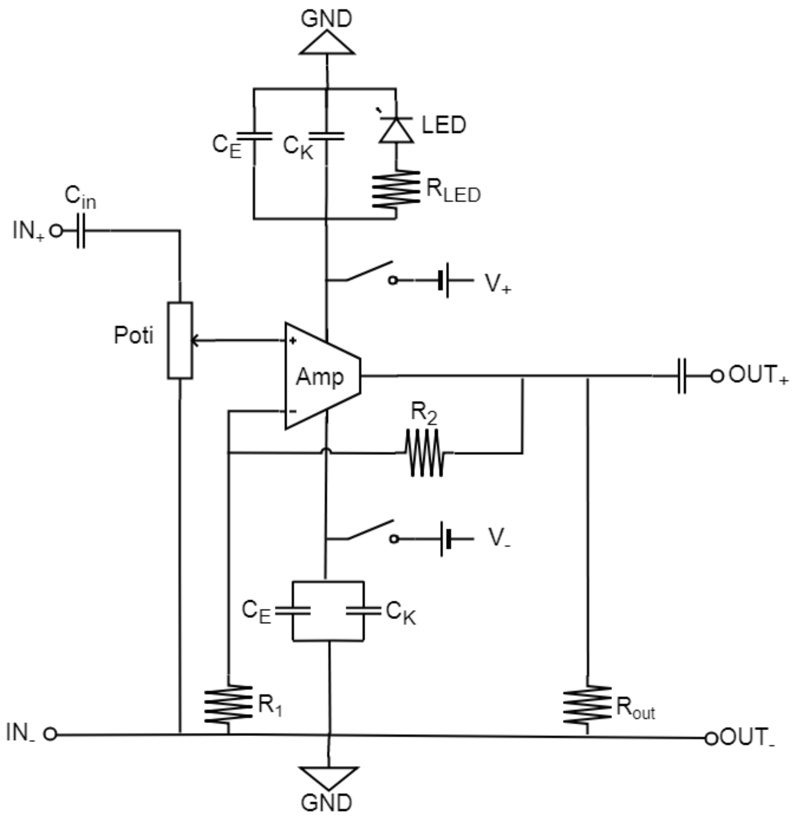


Figure 3.4: Electronic circuit of the amplifier. With $C_{in} = C_{out} = C_E = 1\mu\text{F}$, $C_K = 220\,\text{nF}$, $R_1 = 1\,\text{k}\Omega$, $R_2 = 10\,\text{k}\Omega$, $R_{LED} = 330\,\Omega$, $R_{out} = 9\,\text{k}\Omega$, Operational Amplifier (Model LM675, Texas Instruments) and a Potentiometer of $10\,\text{k}\Omega$.

4

Results

Throughout this chapter, the majority of the results is given in dB re 1 CU. Nevertheless, most calculations were done with CU levels and only transformed into the decibel scale afterwards.

Unless otherwise indicated, for the calculation of averages, trimmed means with 20% trimming were used. Additionally the standard deviations are given. For all statistical tests, an alpha-level of 0.05 was used.

Results of the balancing task are presented by the level difference of the long (= 300 ms) and the short (≤ 300 ms) stimulus in one comparison pair. This difference is added to the amplitude level of the long stimulus. Originally, the level of the long stimulus varied, due to non-inverted and inverted trials. However, as we assume linearity in a small range around the obtained points, this conversion is appropriate.

4.1 Effects of Duration, Rate and Electrode

With the method of only skipping an experimental condition if MAL has not been reached twice, we obtained many data points, even for short durations. Additionally, setting the MAL to the maximal level of 1200 CU in case it was not reached, allowed us to do the balancing even for very short durations. As a consequence, we obtained almost complete data sets for all participants.

Figure 4.1 shows an overview of all participants' amplitudes. The median of each participant's data points for each measurement is shown as a circle. The solid circles and lines represent the trimmed means of all participants' data points. The axes in the middle show the duration of the stimuli, whereas the axes above and below the graphs display the number of pulses of the stimuli. This representation was chosen, as the duration of the one-pulse stimuli is ambiguous. For the two rates different durations are assumed for the one-pulse stimulus. In contrast, the number of pulses is clear.

Data points of subject S5 are partly outside the axis limits, but have still been included for calculating the means.

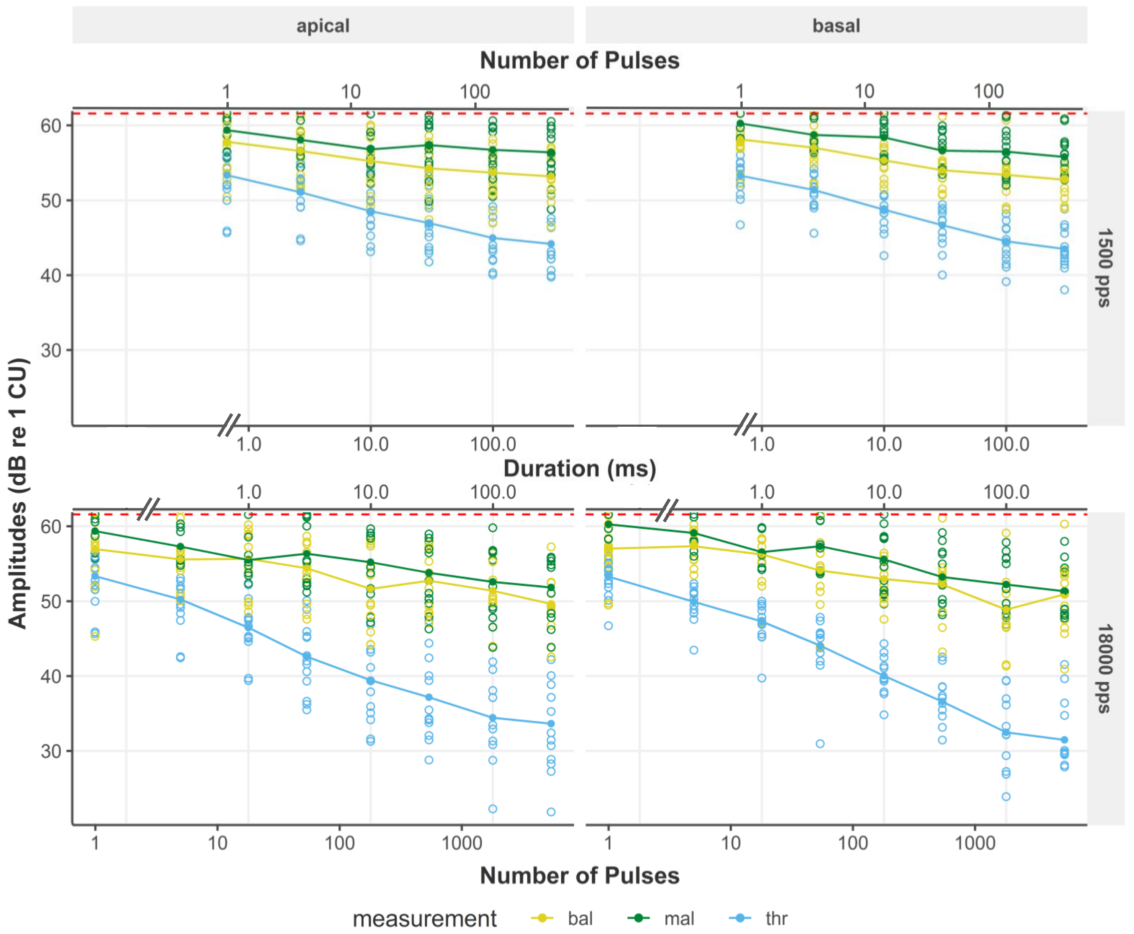


Figure 4.1: Amplitudes as a function of duration (middle axes) and number of pulses (axes above and below the graphs) for thresholds (blue), maximal acceptable levels (green) and loudness balancing (yellow) of all subjects. Circles show the median of each participant's data points. Solid points and lines represent the trimmed mean of the data. Dashed red line represents the maximal possible stimulation amplitude of 1200 CU. **Top:** 1500 pps. **Bottom:** 18000 pps. **Left:** Apical electrode. **Right:** Basal electrode.

Having a look at Figure 4.1 leads to the assumption that all measurements are influenced by several factors. Statistical testing of the effect of Electrode, Rate and Measurement for the duration of 300 ms confirms this. There is no significant effect of Electrode ($Q = 2.43$, $p = 0.119$), but lower amplitudes for the higher Rate ($Q = 12.32$, $p < 0.001$), as well as a significant effect of Measurement ($Q = 21.03$, $p < 0.001$), with significantly smaller amplitudes for THR compared to MAL and BAL. These effects are shown in Figure 4.2. None of the interaction terms reached significance level.

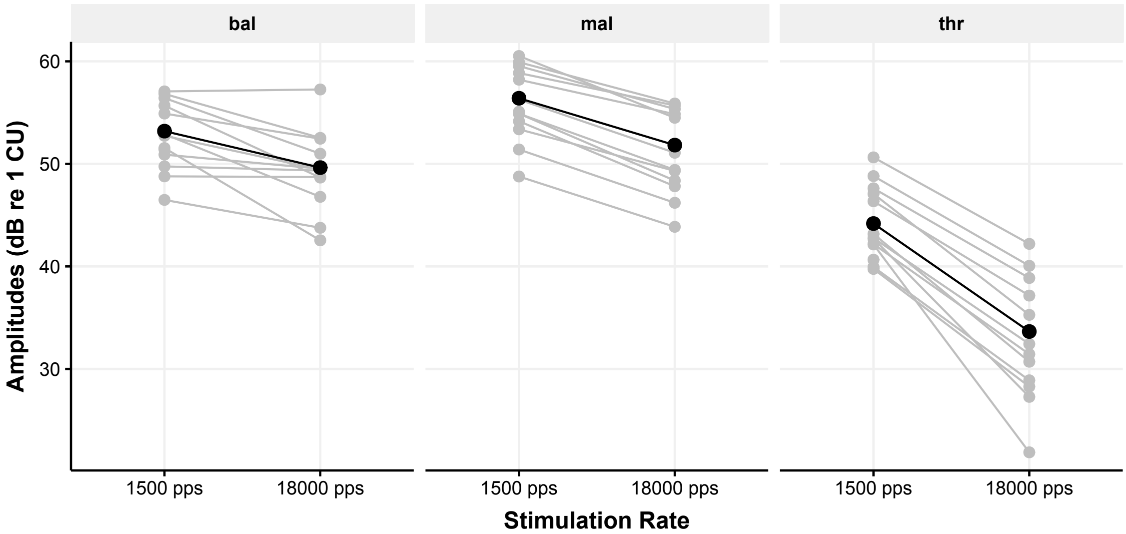


Figure 4.2: Amplitudes of the 300 ms stimulus at the apical electrode for balancing (bal), maximal acceptable loudness (mal) and thresholds (thr). Grey lines represent individual subjects, in black the trimmed mean of all participants is depicted.

4.2 Loudness Integration

In Chapter 2, several functions have been introduced. Of those, Eq. 2.2 to Eq. 2.5 were fitted to the threshold amplitudes as a functin of the number of pulses for each individual subject (except for S11). Table 4.1 shows the trimmed means of all participants' determination coefficients (R^2) for the four conditions of electrode × rate.

Exemplary fitting of the four different functions can be seen in Figure 4.3. In this figure, the data points of subject S7 are shown together with four lines corresponding to different functions.

Table 4.1: Values for the goodness of fit (R^2) for fitting data points of all participants to the functions suggested by Hughes, 1946 (Eq. 2.2), and Plomp and Bouman, 1959 (Eq. 2.4), the power function (Eq. 2.3), and the function used by the former student D. Schwanda (Eq. 2.5).

		R^2			
Rate (pps)	Electrode	Hughes	Plomp	Power	Schwanda
1500	apical	0.72 ± 0.12	0.57 ± 0.14	0.94 ± 0.08	0.92 ± 0.09
1500	basal	0.74 ± 0.07	0.59 ± 0.09	0.95 ± 0.03	0.95 ± 0.03
18000	apical	0.75 ± 0.05	0.66 ± 0.07	0.98 ± 0.02	0.94 ± 0.04
18000	basal	0.73 ± 0.04	0.65 ± 0.05	0.97 ± 0.02	0.94 ± 0.03

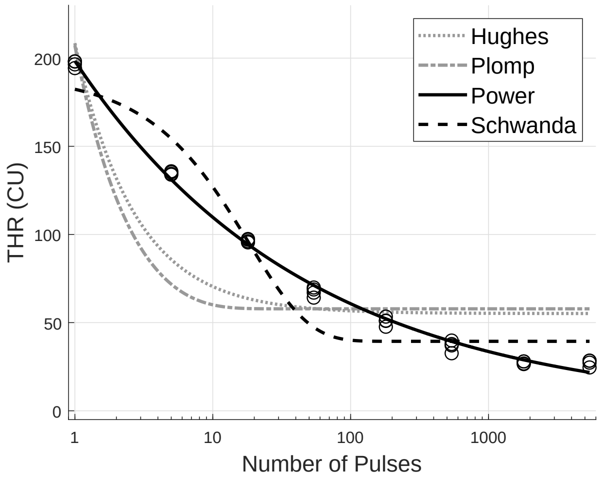


Figure 4.3: Exemplary fitting of data points for threshold amplitudes of subject S7, for 18000 pps, apical electrode. Grey dotted line: Model by Hughes, 1946 (Eq. 2.2); Grey dashed line: Model by Plomp and Bouman, 1959 (Eq. 2.4); Black solid line: Power function (Eq. 2.3); Black dashed line: Model by former student Daniela Schwanda with Eq. 2.5.

Based on the results in Table 4.1, we decided to only use the power function (Eq. 2.3) for fitting in all following figures and analyses. Fitting threshold data (in CU) of individual participants to a function of the number of pulses (N) of the form

$$I(t) = I_1 \cdot N^b$$

works quite well with an average of $R^2 = 0.95 \pm 0.06$ for the low rate and $R^2 = 0.97 \pm 0.02$ for the high stimulation rate. Detailed numbers and the goodness of fit obtained for fitting the amplitudes to a function of the duration instead of number of pulses are listed in Table A.2. Additionally, the fitting parameters I_1 and b are listed. Parameter I_1 is the function value when number of pulses/duration is set to one, and b represents the slope of the decreasing values for increasing number of pulses/duration.

Figure 4.4 shows exemplary threshold amplitudes and the power function fitted to them for subject S3. Data for low rate (left) and high rate (right) stimulation of the apical electrode are plotted. The function was fitted with CU values, but for better comparability of the slopes, amplitudes are displayed in dB re 1 CU. Fittings for each individual subject can be seen in Figures A.1 and A.2. There, data points of the threshold amplitudes and the power functions fitted to them for low and high rate at the apical electrode (left columns) and basal electrode (right columns) are shown. Again, the functions were fitted with CU values, but for better comparability of the slopes, amplitudes are given in dB re 1 CU.

When taking all measurements (THR, BAL, and MAL) into account, testing the effects of Measurement, Rate, and Electrode on the slopes reveals significant disparity in the slopes for the different Measurements ($Q = 12.71$, $p<0.001$). The curves are steeper

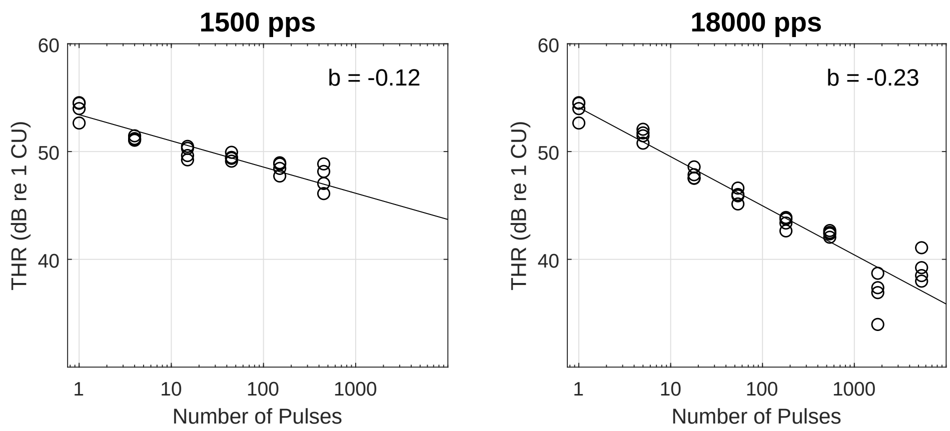


Figure 4.4: Exemplary threshold amplitudes of subject S3 (black circles) for stimulation at the apical electrode. Black Lines: Power function of the form $I(t) = I_1 \cdot N^b$. **Left:** Low stimulation rate. **Right:** High stimulation rate.

for the higher RATE ($Q = 428.69, p < 0.001$). The effect of ELECTRODE is not significant ($Q = 3.79, p = 0.052$). Further, the interaction terms of MEASUREMENT and RATE ($Q = 4.16, p = 0.016$) reached the significance level of 0.05 as well as the interaction of RATE and ELECTRODE: $Q = 5.68, p = 0.017$. Post hoc testing revealed no difference of the slopes for MAL and BAL ($p = 0.373$), but significantly steeper slopes for THR than for the other two measurements (both $p < 0.001$ with $p_{crit.} = 0.03$ and $p_{crit.} = 0.02$). The significant interaction term shows that the difference of the slopes in THR and the two other measurements is even stronger for the higher stimulation rate than for the low rate.

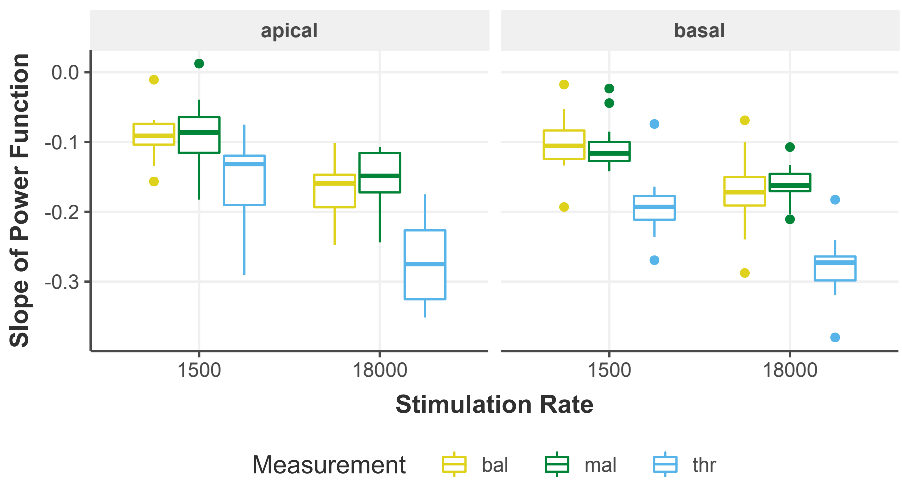


Figure 4.5: Slopes (b) of the power function fitted to data of BAL (yellow), MAL (green) and THR (blue) for low and high stimulation rate. **Left:** Apical Electrode. **Right:** Basal Electrode.

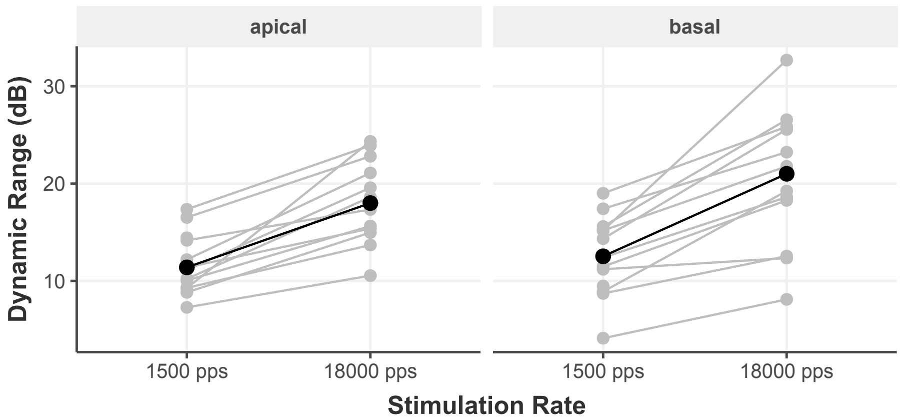


Figure 4.6: Dynamic Ranges of the 300 ms stimuli for different stimulation electrodes and rates. Individual participants' DRs in grey, trimmed mean of all subjects in black. **Left:** Apical electrode. **Right:** Basal electrode.

4.3 Dynamic Range

An increase in dynamic range can be seen in Figure 4.1 for increasing duration and for a comparison of low rate (upper panels) to high rate (lower panels). When only looking at the duration of 300 ms (see Figure 4.6), for increasing the rate, a increase in DR of 6.44 ± 3.00 dB for the apical electrode, and at the basal electrode an increase of 7.42 ± 4.30 dB is present (trimmed geometric means were calculated here). The duration of 300 ms was chosen, as this is approximately the length of one phoneme and commonly used as pulse train duration in clinical fitting, too.

Statistical testing with the factors Rate and Electrode confirms that the the DR is significantly larger for the higher Rate ($Q = 68.09, p < 0.001$). Neither the factor Electrode ($Q = 0.15, p = 0.698$), nor the interaction of the two factors is significant.

4.4 Variability of the Data

Dividing the standard deviation (SD) of each participant's data points by the respective DR gives the percentage of DR that is varied at the four repetitions of the exact same stimulus (see Figure 4.7). One can see that the normalized standard deviation incrases drastically when increasing the rate for the balancing task, wheras the difference between the two rates is smaller for THR and MAL.

Statistical testing with the effect of the three factors Measurement, Rate, and Electrode on these normalised SDs of the 300 ms stimuli was done. The normalised standard deviations vary significantly with Measurement ($Q = 10.59, p < 0.001$) and are larger with the high Rate ($Q = 28.30, p < 0.001$), but are not dependent on the Electrode

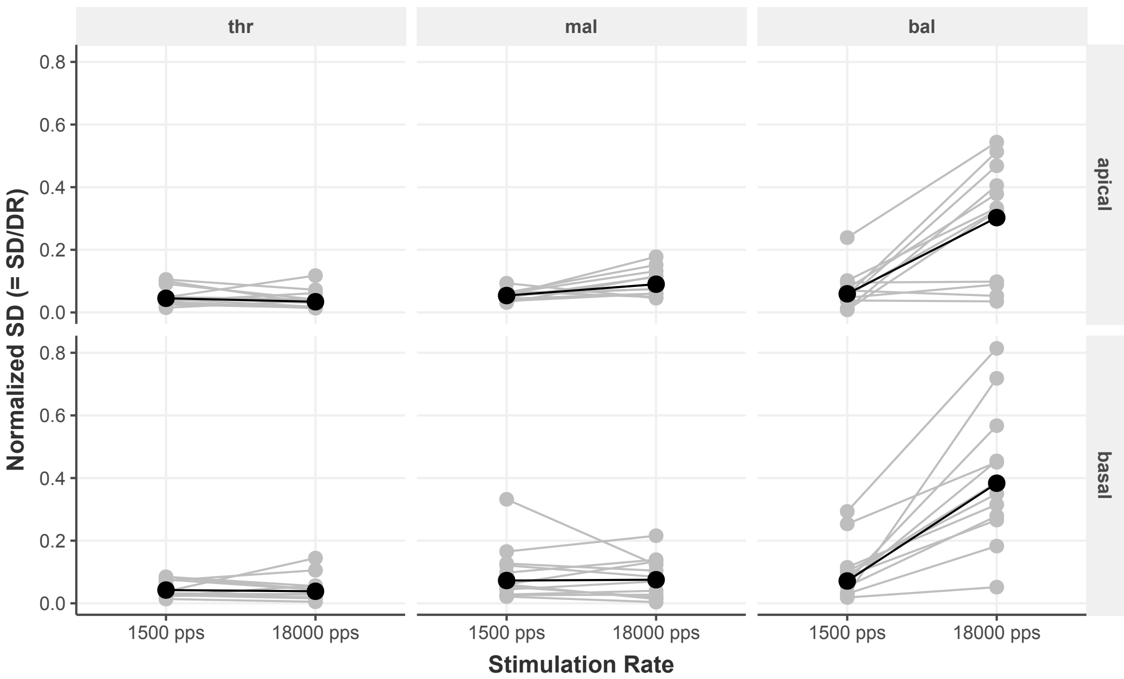


Figure 4.7: Standard deviations of each participants four data points for the three measurements at 300 ms duration divided by the respective dynamic range. **Left:** Thresholds. **Middle:** Maximal acceptable levels. **Right:** Balancing. **Top:** Apical Electrode. **Bottom:** Basal electrode.

($Q = 1.04, p = 0.308$). In addition, the interaction term of MEASURE x RATE shows significance with $Q = 6.77, p = 0.001$. Multiple comparisons reveal differences between all of the types of measurement with average values of 3.93%, 6.96%, and 16.47% for THR, MAL, and BAL, respectively. The interaction term shows that the rate effect is only present for BAL, but not for the other two measurements. The average values are listed in Table A.3.

4.5 Estimation of Loudness Growth Functions

Assuming that the loudness of all conditions' 300 ms stimuli was successfully adjusted to one level by the cross-balancing, Figure 4.8 gives an estimation on which percentage of the DR is needed for a stimulus to be perceived equally loud with different stimulation rates.

For the analyses, data of subject S2 was removed, because for him the loudness above a certain amplitude did not change anymore.[1] Other participants also adjusted BAL am-

[1]Compliance level may have been reached for this participant. Even with increasing the amplitude, this

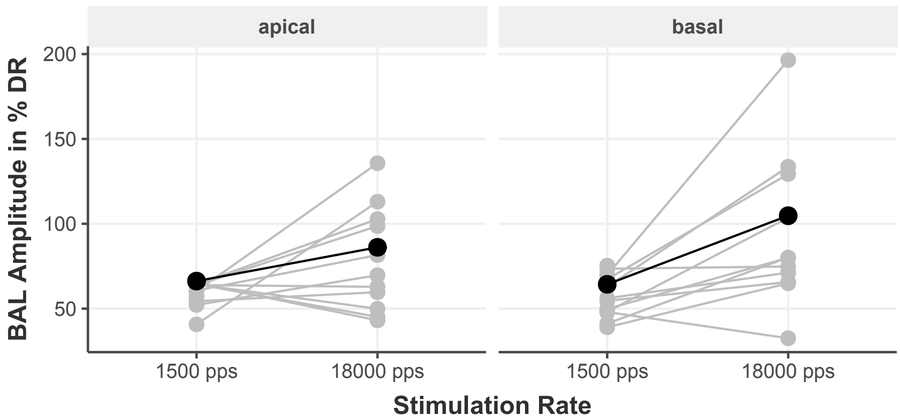


Figure 4.8: Loudness-balanced amplitudes of the 300 ms stimuli of different conditions expressed in percent of the dynamic range. Data of individual participants in grey, trimmed mean over all subjects in black. **Left:** Apical electrode. **Right:** Basal electrode.

plitudes above the limits they set with the MAL before, but for those it was not reported that loudness does not increase above a certain amplitude.

Statistical testing of the influence of the factors Electrode and Rate on the amplitude value of balanced stimuli revealed that there is no significant effect of Electrode ($Q = 0.11, p = 0.740$), but an effect of Rate ($Q = 5.71, p = 0.017$) with significantly smaller amplitudes (expressed in %DR) for the low rate (58.88 ± 10.02%) than for the high rate (80.63 ± 38.26%). The interaction of the two factors did not reach significance level.

From the questionnaire results (Figure A.4 top and bottom, second column: category *laut - leise*) it becomes evident that the loudness was not successfully equalized by all subjects. The second column represents the category of loudness. In the upper panel it can be seen that at least for subject S1r and S11 the stimuli of different stimulation rates presented at the apical electrode were not equally loud. The other subjects' responses are clustered around zero (no difference in loudness perceived) in a symmetrical manner. Apart from the two outliers, it can therefore be assumed that the two stimuli were about equally loud.

4.6 Perception of the Stimuli

From the questionnaire, we obtained the quality of both stimuli in a comparison pair on a continuous scale between two words (for translations of the word pairs see Table A.1). The absolute positions of our participants' answers are not of interest, as no reference was given. In the following, only the difference of the two stimuli is shown.

subject reported not to perceive any differences above a certain amplitude.

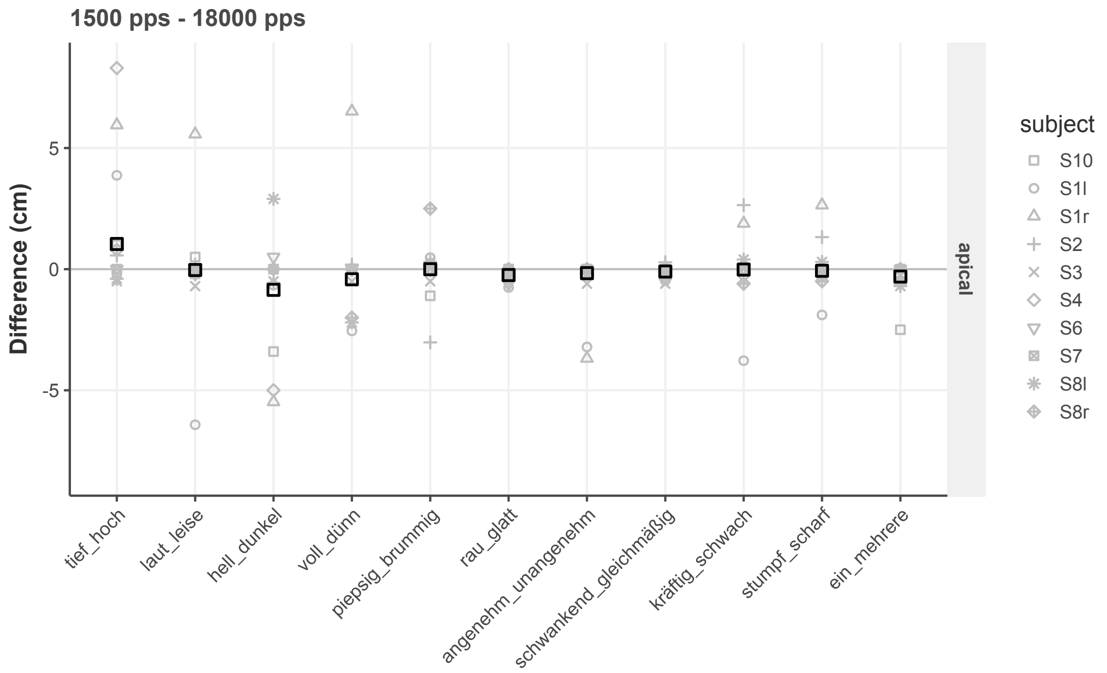


Figure 4.9: Differences of the signals for different categories. Comparison of rates, apical electrode. The answer for the signal with the high rate was subtracted from the answer to the signal of the low rate. Grey markers of different shapes represents the differences perceived by individual subjects. The black squares are trimmed means of all participants' differences in the respective categories.

In the first block, stimuli of different rates have been compared by the subjects. The second block consisted of electrode comparisons and in the third one, participants judged their perceptions of signals of different duration. Since it became evident, that the categories offered in the questionnaire can not describe signals of different durations, data from the third block are not analysed here.

A look at Table 3.4 shows, that the first signal was presented with the lower rate (for comparisons 1 and 2) or at the apical electrode (for comparisons 3 and 4). The difference shown in the figures is calculated by subtracting the position of the marker for the second signal from the position of the marker made for the first signal. Therefore, positive differences are obtained, when the first signal (low rate or apical electrode) was judged closer to the second word in the word pair. A value equal to zero means that the participant did not perceive any difference between the two signals.

Figures 4.9 and 4.10 show the average answers of rate and electrode comparisons in addition to the individual answers of each subject. The Figures provide only an overview. An analysis of individual participants' answers can be obtained from Figure A.4. Each of the figures only contains differences obtained from one of the comparisons in each block,

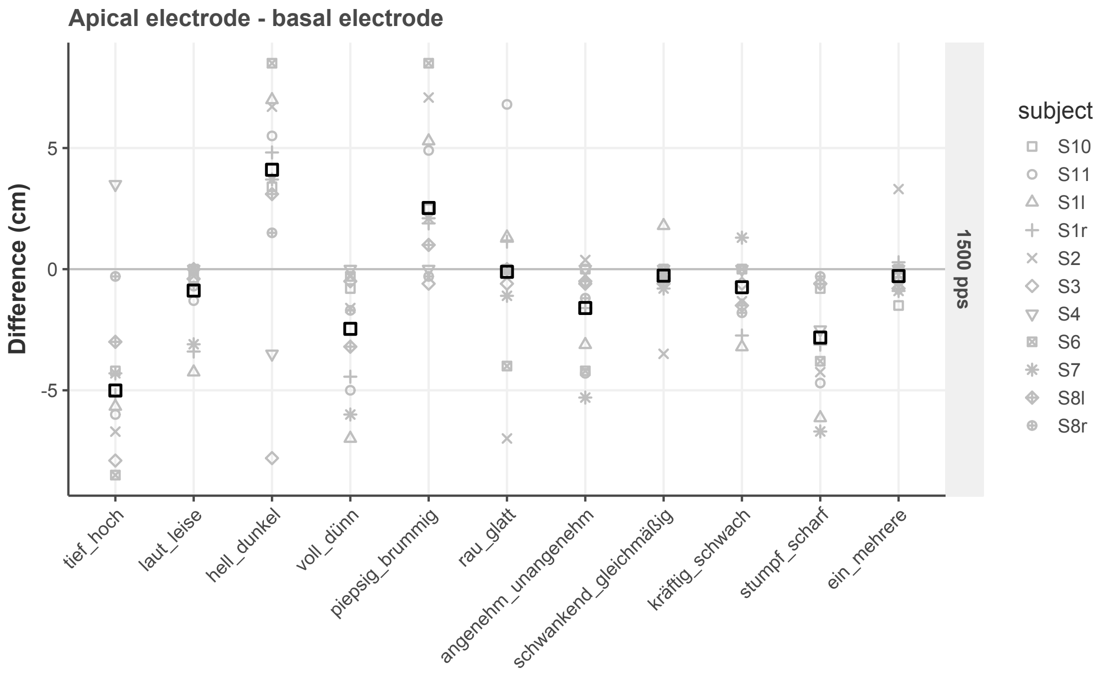


Figure 4.10: Differences of the signals for different categories. Comparison of electrodes, 1500 pps. The answer to the signal at the basal electrode was subtracted from the answer to the signal at the apical electrode. Grey markers of different shapes represents the differences perceived by individual subjects. The black squares are trimmed means of all participants' differences in the respective categories.

as no considerable disagreement between comparison 1 and 2 and between comparison 3 and 4 were found (see Figure A.4).

A closer look at Figure 4.9 reveals that the different stimulation rates are not perceived as being different in any of the categories for the majority of the participants (mean is always close to the zero line). Only a few subjects (e.g. S1r, S11 and S4) seem to perceive a difference between the two signals. They describe the signal with the lower rate as being *higher* and more *light*.

In Figure 4.10 the perceived differences for stimulation of different electrodes are displayed. In contrast to the rate differences, most people perceive the two signals as being different in many of the listed categories. Almost all participants judged the signal at the apical electrode to be *lower* and *darker* than the other signal. The differences perceived in the categories *voll - dünn*, *piepsig - brummig*, and *stumpf - scharf* are almost as strong as the difference for pure pitch (*tief - hoch* and *hell - dunkel*). The signal at the apical electrode appears more *full*, *humming* and *dull* than the signal at the basal electrode. Additionally, most people found stimulation of the apical electrode more *comfortable*.

Cross-correlations were calculated to display how the differences in the categories

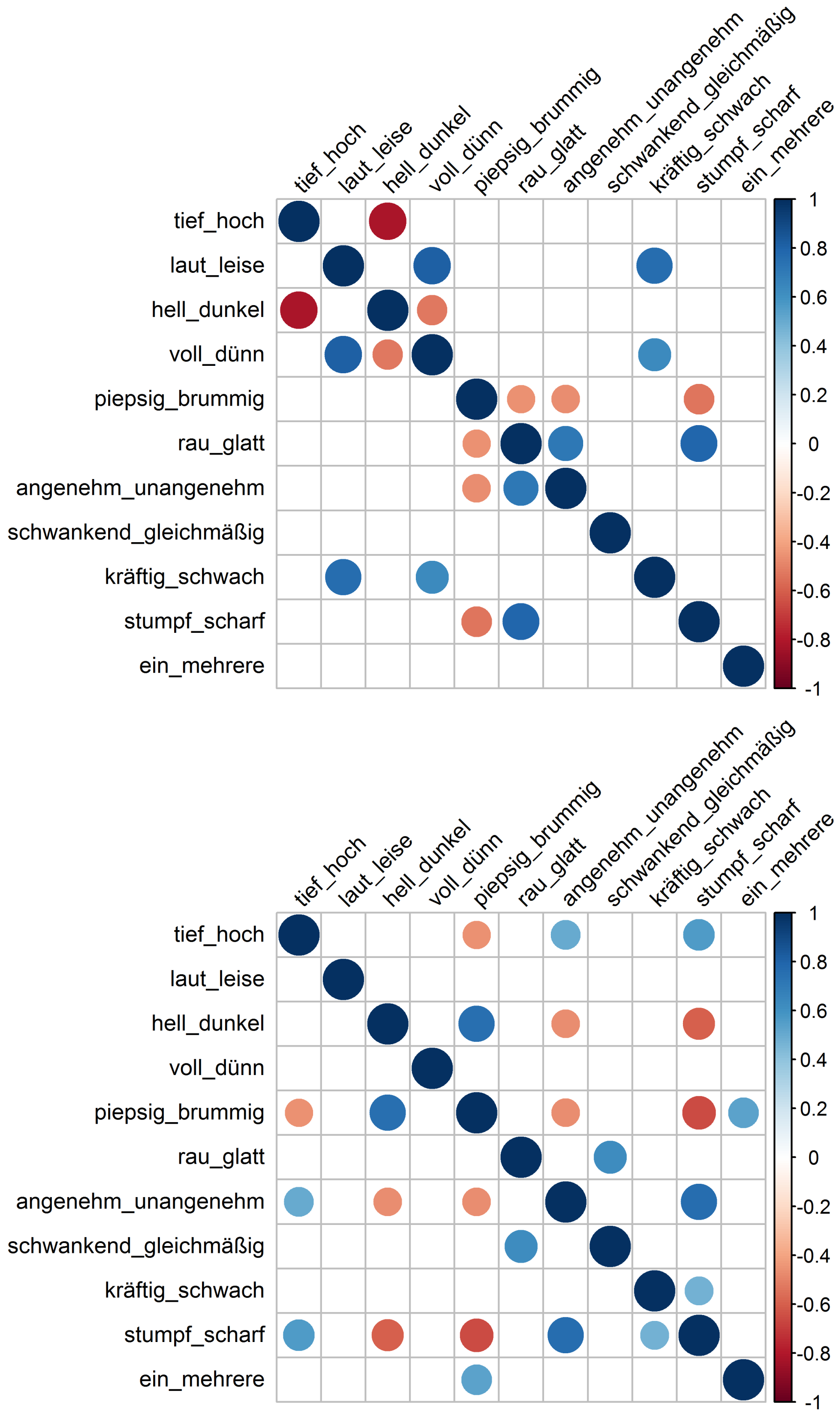


Figure 4.11: Cross-correlation matrix for answers on the comparison of different electrodes. Positive (blue) and negative (red) correlation coefficients are shown for those correlations exceeding an alpha level of 0.05. The strength of the correlations is given by colour intensity and size of the circle. **Top:** Comparison of rates. **Bottom:** Comparison of electrodes.

correlate with each other. A strong positive correlation means, that for both categories a strong difference of the same sign is observed. It can be seen that the correlations reveal different patterns depending on the kind of comparison (comparison of rates or electrodes) that is made.

For the comparison of rates (see Figure 4.11, top), the largest positive correlation with $r = 0.81$ is found for *laut - leise* and *voll - dünn*, negative correlated are *hell - dunkel* and *tief - hoch* ($r = -0.82$).

For the comparison of electrodes (see Figure 4.11, bottom) many correlations with *stumpf - scharf* occurred. The largest positive correlations are those between *stumpf - scharf* and *angenehm - unangenehm* as well as between *piepsig - brummig* and *hell - dunkel*. The strongest negatively correlated categories are *stumpf - scharf* and *piepsig - brummig* with a r-value of -0.65.

5

Discussion

5.1 Effects of Duration, Rate and Electrode

Overall, MAL and BAL curves look very similar, only shifted vertically, whereas the threshold curve differs in its shape from the other two. Differences in the shape of threshold and supra-threshold curves have already been described by Stevens and Hall (1966). They reported that the critical duration from which loudness is perceived independent of duration is shifted towards shorter durations for supra-threshold measurements. For electrical hearing, differences between threshold and supra-threshold curves have been observed by McKay and McDermott (1998). The shift of the critical duration to shorter durations has also been observed in the previous study in this lab by Daniela Schwanda. In our data, large inter-individual differences regarding the critical duration are found (see Figures A.1 and A.2). Some subjects seem to reach saturation for threshold amplitudes in some conditions already at a duration of 10 ms (e.g. S3, 18000 pps, basal or S8, 18000 pps, apical), whereas others did not reach the critical duration until the longest duration of 300 ms (e.g. S1r or S7). However, the critical durations were not examined in the course of this work.

The main effect of stimulation rate (lower thresholds for the higher rate) is in line with previously published results (e.g. McKay and McDermott, 1998; Zhou et al., 2015) and matches those results obtained in a former study by our group. For pulse trains of 300 ms duration, we found approximately 11 dB lower threshold amplitudes when stimulating with 18000 pps instead of 1500 pps (rate increased by factor 12). This is similar to a decrease of 3.08 dB for a doubling of the rate. Comparable values were found by Carlyon et al. (2015), with a decrease of 7.7 dB for 400 ms pulse trains after increasing the rate from 500 pps to 3500 pps (rate increased by factor 7), which is similar to a threshold decrease of 2.74 dB per doubling of the rate. Lower amplitudes caused by higher rates might be attributed to the effects of facilitation. With small inter-pulse intervals, several sub-threshold pulses can enable an action potential (Boulet et al., 2016).

As hypothesized, there was no systematic effect of stimulation electrode found for threshold amplitudes. Nevertheless, some subjects showed lower thresholds for any of the electrodes. An extreme case can be seen in Figure 4.1 with really low amplitudes for one subject only at the basal electrode.

When looking at the MAL and BAL curves of Figures 4.1, one needs to be aware of the ceiling effect at short durations. Especially for durations below 10 ms, participants often reached the maximal possible stimulation level of 1200 CU. With this, the curve seems to bend down, as only those data points are include in the calculation of the trimmed means, that were inside the measurable range. It seems like THRs are not effected by this.

5.2 Loudness Integration

In contrast to the results of Green et al. (1957), who also used a power-law like function for fitting, we do not have to vary the exponent with duration. At least for threshold amplitudes, fitting is satisfying with an overall mean of $R^2 = 0.96 \pm 0.05$.

The fitting to the function proposed by a former student of the group (Eq. 2.5), also yields high determination coefficients with an overall mean of $R^2 = 0.94 \pm 0.06$. Our choice for the power function was based on the better fitting as well as on the benefit of having one free parameter less. This third parameter was necessary for the dataset of the former study, as many very short as well as very long stimuli were used. This led to pronounced saturation at long durations as well as to a flattening of the curve for very short durations, were only one or two pulses were presented to the participants. Both of the flat parts in the curve are missing in the data set at hand.

Just like reported in other studies, our measurements show large inter-individual variability. Regarding the steepness of the fitted threshold function, results vary from $b = -0.07$ (basal, 1500 pps) for subject S7 to $b = -0.38$ (basal, 18000 pps) in subject S5. The mean of $b = -0.17 \pm 0.06$ for the low rate and $b = -0.28 \pm 0.05$ for the high stimulation rate can be translated to −3.48 dB and −5.55 dB decrease in threshold per decade, respectively. The slope for the high stimulation rate closer to the amplitude decrease of −20/3 dB per decade reported by Heil et al. (2017) for acoustic hearing (see Figure 2.3), whereas the curve for the lower rate stimulation is much more shallow. Already Donaldson et al. (1997) reported much shallower slopes for CI users when compared to normal hearing listeners. Their slopes are at about 2 or 3 dB per doubling of duration (Shannon, 1983). It seems like only with very high stimulation rates slopes of normal hearing participants and CI users become more similar.

According to (Zhou et al., 2015), the slope of the TI curve might be associated with nerve survival. This has already been suggested by Shannon (1983) for normal hearing. Steeper curves were in both investigations associated with neural health. Since we do not have any information of our subjects' neural health, this hypothesis cannot be tested on an individual level. No speech intelligibility scores or other data on the performance of individual participants was collected, either. Following the reasoning of Zhou et al. (2015), the steeper slopes at the basal electrode that we found are associated with healthier neurons at the basal part of the cochlea. This is contradicting to the commonly observed start of hearing loss at high frequencies. It can be assumed that the health of SGNs near the base is worse than close to the apex.

5.3 Dynamic Range

The dynamic range was increased with increasing stimulation rate for all durations, but even more for longer than for shorter stimulus duration. For the 300 ms pulse trains, an increase of the DR of 6.58 ± 3.79 dB was observed. The general increase can be explained by the fact that especially threshold amplitudes are lowered by increasing the rate, but not so much the amplitudes of measurements at comfortable loudness, and even less the MAL amplitudes. The same has been reported by McKay and McDermott (1998).

Bonnet et al. (2012) report an increase in DR of 1.3 dB for a doubling of the stimulation rate. Our values suggest 1.84 dB for a doubling of the rate. Since the rates we compared (1500 pps and 18000 pps) are much higher then theirs (774 pps and 3868 pps), there must be an additional influence on the effect of rate on THRs and MALs for rates higher than 3868 pps. The increase of DR in our data is also much stronger than the one found by Zhou et al. (2012). They found an increase in DR of 1.19 dB for a doubling of the stimulation rate, for increasing the rate up to 5000 pps.

The fact that the dynamic range increased even more for long durations, is explained by the differences in slopes for the two rates. The threshold curve for the higher stimulation rate showed a steeper slope, leading to a more pronounced DR increase for long durations.

For CI fitting in the clinics, only single electrode DRs are set. Since we assume that many neurons throughout the cochlea are stimulated by single electrode contacts, the actually possible DR might be larger.

5.4 Variability of the Data

Investigations on the benefit of large dynamic ranges on speech understanding have been conducted by several researchers, as it is assumed that there might be a positive effect of larger dynamic ranges. Significant effects were found by Fu and Shannon (2000); Cosendai and Pelizzone (2001), with larger dynamic ranges leading to better vowel recognition. However, the results are mixed. Bento et al. (2005) found no difference in the size of the psychophysical dynamic range between two groups that have been divided depending on their speech perception scores for open-set sentences in quiet.

In addition to increased dynamic ranges by higher rates as we observed it in our data, Azadpour et al. (2018) found that the just noticeable differences (JNDs) are also increased by increasing the stimulation rate from 500 pps to 3000 pps. With an increase in JNDs, the loudness steps in a given range become fewer. The increase in JNDs can be explained by increased stochasticity in ANF firing in response to higher-rate stimulation (Zhang et al., 2007), which leads to more noise in the sensory and neural representations of the sounds.

Standard deviations are not the same as JNDs, but we assume that the variability of the participants data points is related to JNDs. In those cases when a subject noticed a difference, the amplitude would have been adjusted to the THR, BAL or MAL amplitude. With this, larger SDs might relate to larger JNDs.

Statistical testing revealed only a significant effect of stimulation rate on the normalised SDs for the balancing task, but almost unchanged normalised SDs for THR and MALs. This finding suggests that the number of loudness steps is equal for the two stimulation rates, even if the absolute SDs (as well as the dynamic ranges) are larger for the higher stimulation rate.

Several participants had difficulties in adjusting the loudness of different stimuli. Apparently this task was even harder for the high rate stimuli which led to large variability of data points in this condition. It seems like for the apical electrode two groups are present: One that keeps approximately the same normalised SDs, and the other group that shows a large increase in normalised SDs with the high rate (see Figure 4.7).

Larger dynamic ranges are only beneficial if the number of loudness steps is also increased. That might not be the case for the increase of stimulation rates from 1500 pps to 18000 pps that we investigated in this study. This is supported by the notion of Galvin and Fu (2009) that high stimulation rate generally do not provide any advantage in intensity resolution.

The mean variability of BAL amplitudes 16.47% larger than the maximal variation of starting points for the balancing task. This leads to the conclusion, that the BAL amplitudes are not reliable. THR and MAL are not affected. In some cases, the quantisation steps (listed in Table 3.5) are larger than the standard deviation of a participant's data points. One example is subject S4 with a MAL of 365 ± 1.30CU for 300 ms. Around this amplitude, the fine step sizes are 4.72 CU. This shows that some participants judgements are even finer than the smallest step size possible.

5.5 Estimation of Loudness Growth Functions

A look at Figure 4.8 reveals again very high variability between different subjects. In addition, for BALs large intra-individual variability is present (Figure 4.7). For some participants, the BAL amplitude for the high-rate stimulation is at a higher, for others at a lower level (in %DR) than for the low stimulation rate. However, even with this variability, the means shown in Figure A.3 point to the conclusion of shallower loudness growth for the high stimulation rate.

Shallower loudness growth functions for higher stimulation rate were already observed by Galvin and Fu (2009). They connected shallower loudness growth with larger JNDs for intensity discrimination. With this, the variability of our data (section above) is directly linked to the slope of loudness growth functions. The results are in line: Higher rates lead to shallower loudness growth, which causes larger variability.

5.6 Perception of the Stimuli

The results of the questionnaire in Figures 4.9 and 4.10 make clear that most participants have a much stronger change in pitch perception through varying the electrode than by changing the stimulation rate from 1500 pps to 18000 pps. However, for some participants changing the rate induces an equally strong change in pitch perception as varying the stimulated electrode from apical to basal. Landsberger and McKay (2005) reported the same: Only for some participants and at some electrodes, pitch percept can be elicited with a change of stimulation rates higher than 1500 pps. As a possible explanation, they claim that the pitch percept might be related to the periodicity of the amplitudes of the evoked potentials. They assume that higher-rate stimuli can produce a much lower periodicity, which enables pitch perception.

The difference in the category *rau - glatt*, that has been observed for signals of different stimulation rate by Karg et al. (2018) is not found here, but for some people, signals of different stimulation rate are perceived as a difference in the category *kräftig - schwach*, which was found by the mentioned study as well. It seems like those participants that perceived the rate difference are not amongst those that perceive the electrode difference very strongly.

Interestingly, only at the low rate, all participants judged the signals at the apical electrode louder than the signal at the basal electrode (see Figure 4.10). This cannot be explained by the relation of pitch and loudness described e.g. by Shannon (1983), as this effect is of the opposite direction. Usually a positive correlation of pitch and loudness is observed. This pattern is not visible for the comparison of electrodes at the high rate (see Figure A.4, bottom).

Overall, in addition to pitch perception, other categories are also affected by changing stimulation rate or stimulation electrode. These effects are in some cases not systematic, whereas other correlations show up in the majority of participants.

With the cross-correlation matrices the relation between the strength of perceived differences in all categories are computed. These correlations do not tell how a certain amount of increasing the rate or changing stimulation electrode affects the categories, but how the changes in categories are correlated to each other. Some correlations that were expected (e.g. *tief - hoch* and *laut - leise*), were only found in one of the comparisons. The only correlations that are observed in both of the comparisons were two negative correlations with *piepsig - brummig*. One with *angenehm - unangenehm* and another one with *stump - scharf*. Our participants often described certain stimuli of being comfortable or uncomfotable. Surprisingly, they never classified any signals as squeaky or humming, nor as sharp or dull before they worked on the questionnaire.

6

Summary

In this study, we investigated the effects of stimulation electrode and stimulation rate on the amplitudes of threshold (THR), loudness-balanced values at a comfortable level (BAL) and maximal acceptable levels (MALs) as a function of duration or number of pulses.

All of the three measurements revealed a lowering in amplitudes for increasing number of pulses, which was modelled by a function of the form $I(t) = I_1 \cdot N^b$. The function value when the number of pulses (N) is set to 1 is given with I_1, whereas b represents the slope of the decreasing values for increasing number of pulses. This function was successfully fitted to individual subjects' threshold amplitudes ($R^2 = 0.96 \pm 0.05$).

Electrode Effect:
Stimulating with an apical or a basal electrode

- Threshold amplitudes are not affected by the choice of the stimulation electrode.
- The slopes of the threshold curves are not different for apical and basal electrode.
- The dynamic range is not systematically altered by the choice of the stimulation electrode.
- No effect of stimulation electrode on the percentage of DR that is necessary to perceive stimuli equally loud was found.
- Changes in pitch perception elicited by different stimulation electrodes are accompanied by changes in other categories like *voll - dünn*, *piepsig - brummig*, and *stumpf - scharf*. The change in these categories is perceived almost as strong as *tief - hoch* and *hell - dunkel*.

Rate Effect:
Increasing the stimulation rate from 15000 pps to 18000 pps

- For pulse trains of 300 ms duration, threshold amplitudes were lowered by approximately 11 dB when stimulating with the high rate instead of the low rate.
- Steeper threshold curves are obtained for the high stimulation rate (−5.55 dB per decade) compared to the low rate (−3.48 dB per decade).
- THR curves have a steeper slope than MAL or BAL curves. The effect of steeper slopes for THR is enhanced at the higher stimulation rate.
- An increase of the stimulation rate led to an increase of the DR of 6.58 ± 3.79 dB for the 300 ms pulse trains.
- We assume that the number of audible loudness steps is equal for the two stimulation rates, even if the absolute SDs are larger for the higher stimulation rate.
- For the higher stimulation rate, a higher percentage of DR is needed to perceive stimuli equally loud as signals presented at the lower rate. This leads to the assumption of shallower loudness growth for the high rate.
- The rate increase was perceived by some participants as a change in pitch, as well as in changed perception of other characteristics.

Conclusion

From our results it becomes clear that an increase of the stimulus duration induces changes in almost all measures we analysed. These changes have been observed before, but never for stimulation rates as high as the one used in this study. It could be shown that above the previously assumed critical durations and critical rates, information (additional pulses) can be integrated and used by the auditory system. This concerns the amplitudes of THR, MAL and BAL, the slopes of the TI curve, the dynamic ranges, the steepness of loudness growth functions and also the perception of the stimuli.

Further studies are needed to clarify the effect of stimulation rate on the variability of the results obtained for the balancing task. In addition, the time course of forward masking for the high stimulation rate is unknown and requires further investigation.

All of the outcomes should also be linked to the perception of CI users, since improvements are only beneficial if they are perceived as such.

A

Appendix

A.1 Translations

Table A.1: Suggested translations for the word pairs in the questionnaire.

Original word pair	Translation
tief - hoch	low - high
laut - leise	loud - quiet
hell - dunkel	light - dark
voll - dünn	full - thin
piepsig - brummig	squeaky - humming
rau - glatt	rough - smooth
angenehm - unangenehm	comfortable - uncomfortable
schwankend - gleichmäßig	fluctuating - uniform
kräftig - schwach	strong - weak
ein Ton - mehrere Töne	one sound - several sounds

A.2 Fittings

A.3 Variability of the Data

A.4 Estimation of Loudness Growth

A.5 Questionnaire Answers

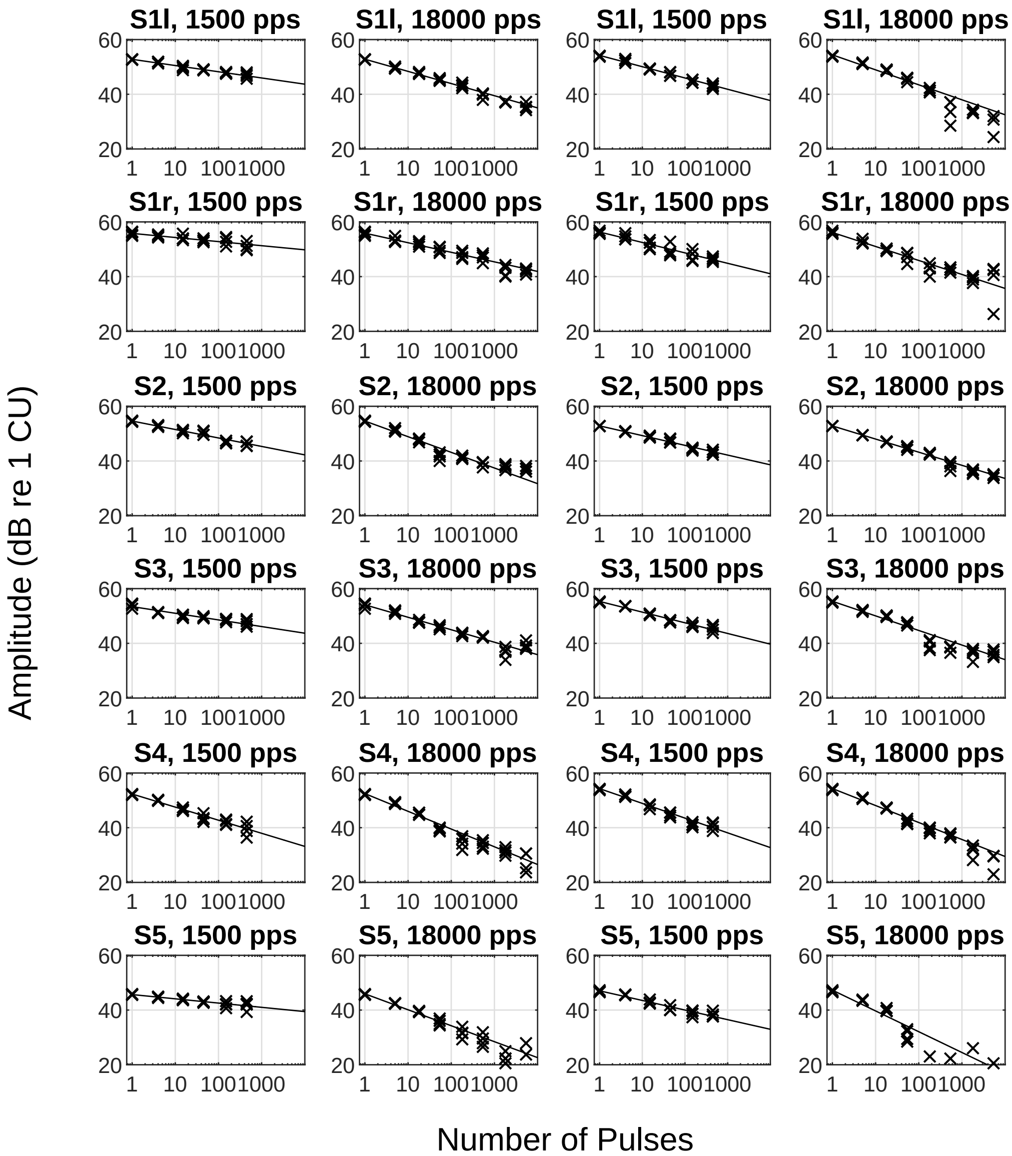


Figure A.1: Fitting (black lines) to threshold data points (crosses) for subject S1l to subject S5. Each with low and high rate. **Two columns on the left:** Apical electrode. **Two columns on the right:** Basal electrode.

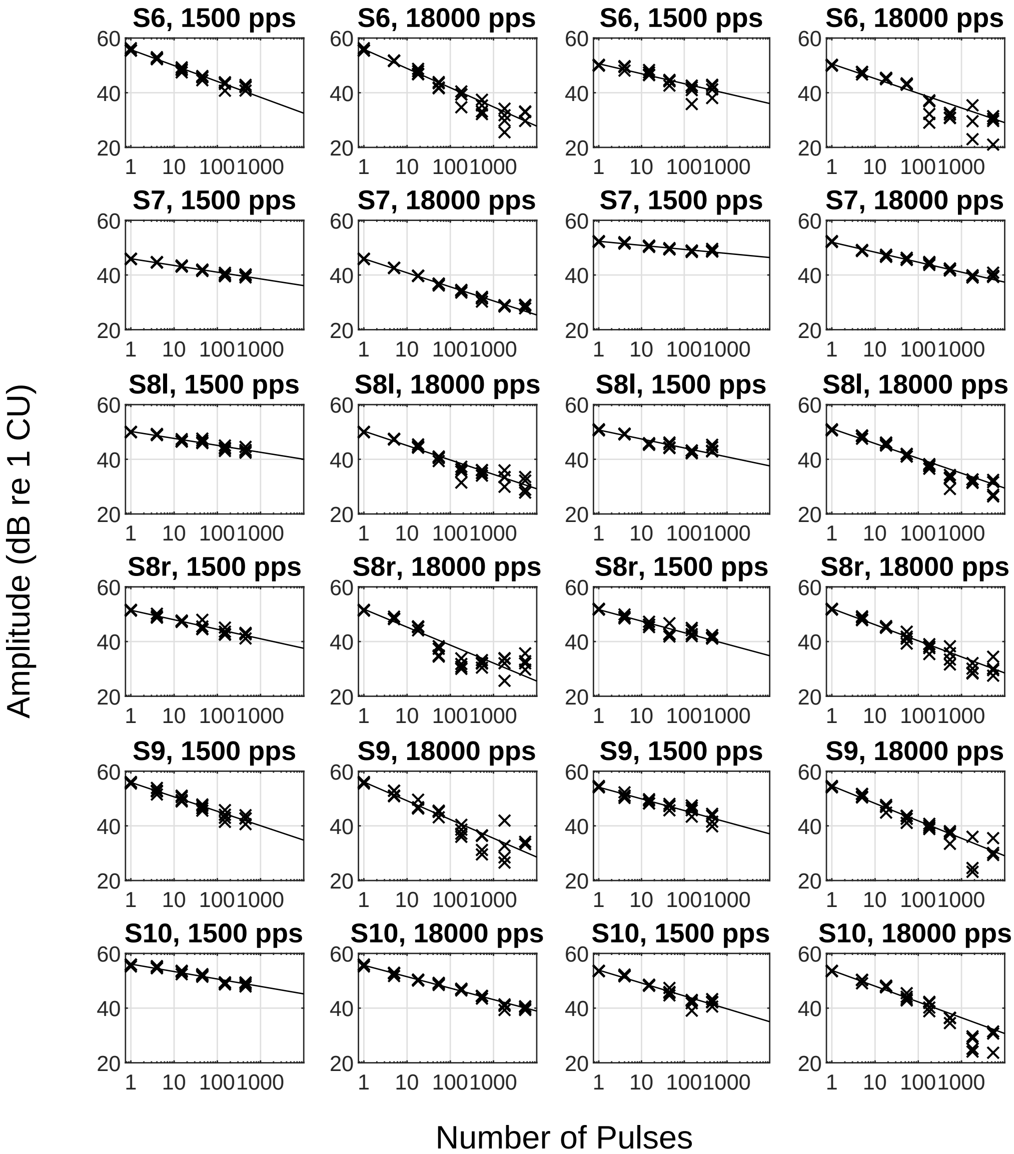


Figure A.2: Fitting (black lines) to threshold data points (crosses) for subject S6 to subject S10. Each with low and high rate. **Two columns on the left:** Apical electrode. **Two columns on the right:** Basal electrode.

Table A.2: Trimmed mean of fitting parameters I_1 ± standard deviation (SD), and the slopes (b) ± standard deviation (SD) across different subjects of fitting to Equation 2.3 calculated with duration and with number of pulses.

Meas.	Elec.	Rate	No. of Pulses on x-axis			Duration (ms) on x-axis		
		(pps)	R^2	I_1	b	R^2	I_1	b
THR	apical	1500	0.94 ± 0.08	472.56 ± 159.83	−0.15 ± 0.07	0.94 ± 0.08	437.59 ± 146.70	−0.15 ± 0.07
THR	apical	18000	0.98 ± 0.02	481.31 ± 158.10	−0.28 ± 0.06	0.98 ± 0.02	207.10 ± 87.68	−0.28 ± 0.06
THR	basal	1500	0.95 ± 0.03	451.68 ± 118.23	−0.19 ± 0.05	0.95 ± 0.03	416.90 ± 107.20	−0.19 ± 0.05
THR	basal	18000	0.97 ± 0.02	458.92 ± 116.11	−0.28 ± 0.05	0.97 ± 0.02	208.28 ± 59.20	−0.28 ± 0.05
MAL	apical	1500	0.75 ± 0.27	1049.61 ± 311.76	−0.09 ± 0.05	0.75 ± 0.27	1013.26 ± 303.97	−0.09 ± 0.05
MAL	apical	18000	0.87 ± 0.14	1286.35 ± 554.00	−0.15 ± 0.04	0.87 ± 0.14	842.66 ± 370.75	−0.15 ± 0.04
MAL	basal	1500	0.84 ± 0.20	1146.11 ± 262.63	−0.11 ± 0.04	0.84 ± 0.20	1101.61 ± 258.96	−0.11 ± 0.04
MAL	basal	18000	0.89 ± 0.09	1371.27 ± 597.05	−0.16 ± 0.03	0.89 ± 0.09	873.99 ± 368.27	−0.16 ± 0.03
BAL	apical	1500	0.88 ± 0.26	772.27 ± 304.56	−0.09 ± 0.04	0.88 ± 0.26	742.26 ± 291.58	−0.09 ± 0.04
BAL	apical	18000	0.93 ± 0.05	754.62 ± 305.87	−0.16 ± 0.04	0.93 ± 0.05	458.08 ± 210.34	−0.16 ± 0.04
BAL	basal	1500	0.79 ± 0.15	779.94 ± 226.69	−0.10 ± 0.04	0.79 ± 0.15	746.51 ± 219.40	−0.10 ± 0.04
BAL	basal	18000	0.91 ± 0.10	803.56 ± 266.84	−0.17 ± 0.06	0.91 ± 0.10	483.27 ± 217.09	−0.17 ± 0.06

Table A.3: Trimmed means of the intra-individual standard deviations (SD) divided by the corresponding dynamic ranges (DR).

Measurement	Electrode	Rate (pps)	SD (in %DR)
THR	apical	1500	4.50
THR	apical	18000	3.42
THR	basal	1500	4.28
THR	basal	18000	3.89
MAL	apical	1500	5.41
MAL	apical	18000	8.99
MAL	basal	1500	7.35
MAL	basal	18000	7.51
BAL	apical	1500	5.95
BAL	apical	18000	30.27
BAL	basal	1500	7.16
BAL	basal	18000	38.76

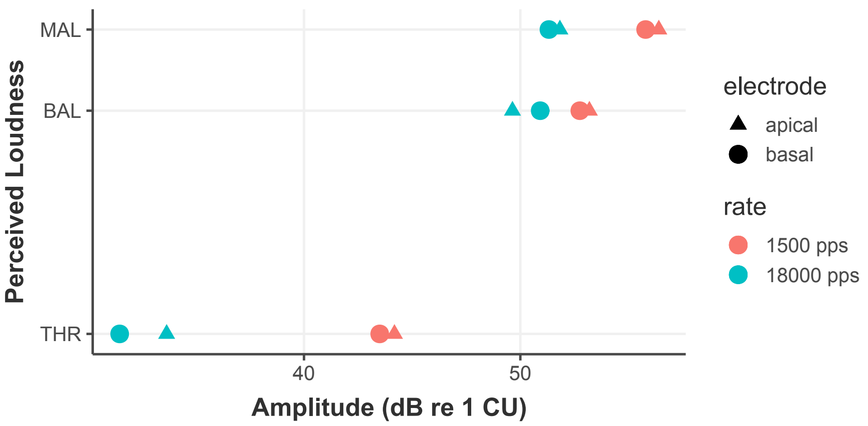


Figure A.3: Trimmed means of the amplitudes of the 300 ms stimuli for the apical (triangle) and basal (circle) electrode. Low stimulation rate in red, high stimulation rate in blue.

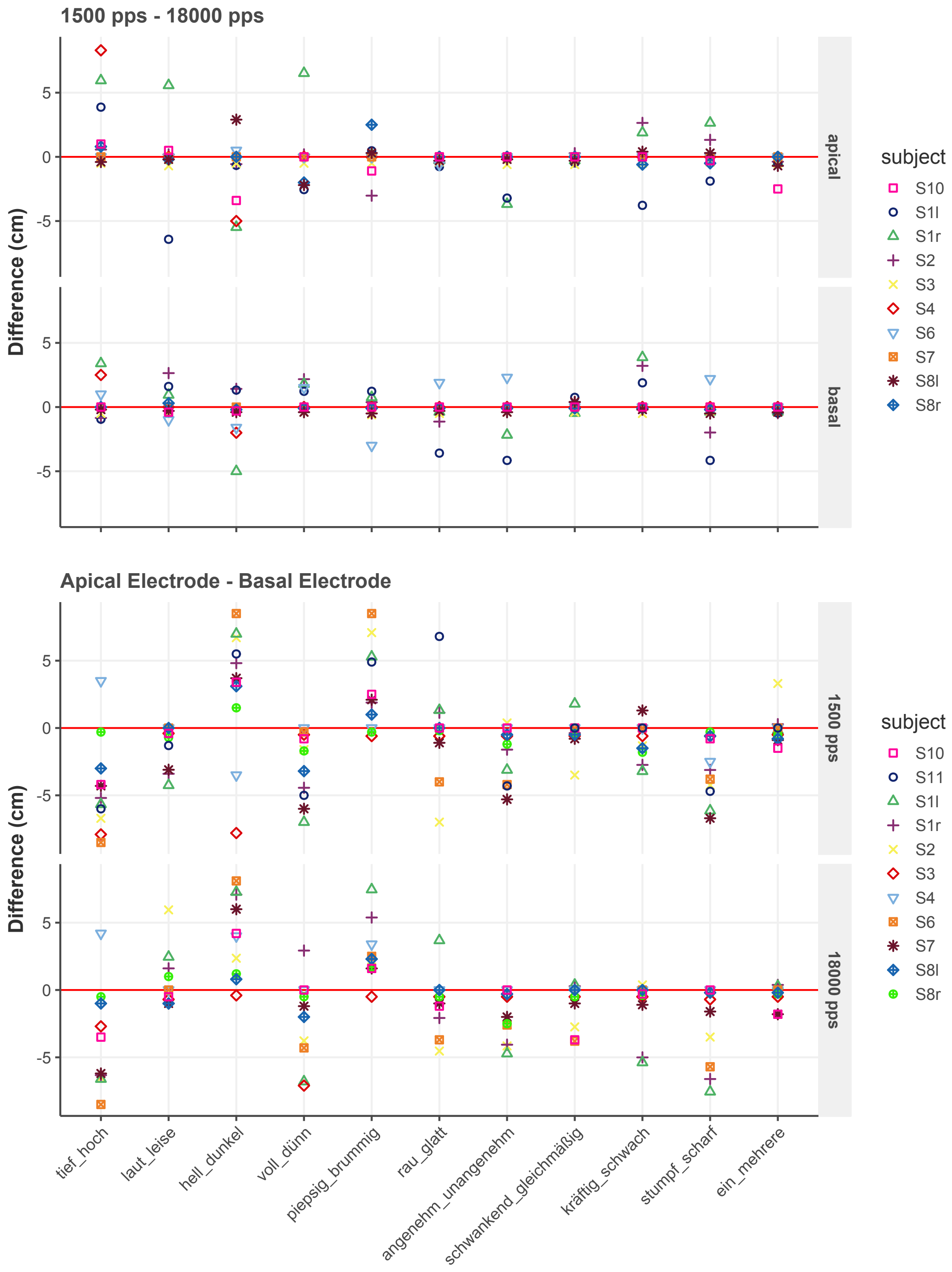


Figure A.4: Differences of the signals for different categories. Markers of different colours and shapes represents the differences perceived by individual subjects. **Top:** Comparison of rates, apical and basal electrode. Answer for the signal with the high rate was subtracted from the answer to the signal of the low rate. **Bottom:** Comparison of electrodes, 1500 pps and 1800 pps. Answer to the signal at the basal electrode was subtracted from the answer to the signal at the apical electrode.

B

Appendix

B.1 Information on the Experiment

B.2 Instructions

B.3 Questionnaire

Studie: Einfluss verschiedener Stimulationsparameter auf die Hörschwelle und die Hörwahrnehmung von CI-Trägern

Ablauf

Bei diesem Versuch soll getestet werden, wie sich verschiedene Stimulationsparameter auf die Hörschwelle und die Hörwahrnehmung von CI-Trägern auswirken. Dazu werden die Hörschwelle, die maximale Lautstärke, sowie Messwerte bei angenehmer und gut hörbarer Lautstärke für verschiedene Signale ermittelt.

Der Versuch beinhaltet im Wesentlichen zwei Teile. Zunächst werden Ihre Hörschwelle und die von Ihnen maximal tolerierbare Lautstärke ermittelt. Außerdem werden wir Ihnen Fragen zu Ihren Hörgewohnheiten, Ihren Erfahrungen und Ihrer Hörminderung stellen.
Im zweiten Teil werden Sie die Lautstärke von verschiedenen Signalen miteinander vergleichen und die Signalstärke ermitteln, die für jeweils zwei Signale die gleiche Lautheit hervorruft. Zudem werden sie die Hörwahrnehmung dieser Signale wiedergeben.

Insgesamt wird der Versuch etwa vier Stunden in Anspruch nehmen. Natürlich sind während dieser Zeit Pausen eingeplant.

Aufklärung

Bevor wir mit der Versuchsdurchführung beginnen, gehen wir die Probandenaufklärung gemeinsam durch und klären Ihre offenen Fragen. Wenn Sie mit der Versuchsdurchführung einverstanden sind, bitten wir Sie die Einverständniserklärung zu unterschreiben. Prinzipiell gilt, dass Ihre Teilnahme an dieser Studie freiwillig ist. Sie können jederzeit, auch ohne Angaben von Gründen, Ihre Teilnahme widerrufen, ohne dass Ihnen irgendwelche Nachteile entstehen.

Ihre personenbezogenen Daten werden während der wissenschaftlichen Untersuchung aufgezeichnet und gespeichert, jedoch nicht an Dritte weitergegeben. Auch bei Veröffentlichungen von Ergebnissen geht nicht hervor, wer an der Studie teilgenommen hat.

Vorbereitung

Um zu gewährleisten, dass wir Ihr Implantat während der Versuchsdurchführung ausschließlich in einem Bereich stimulieren, der für Sie angenehm ist, wird im ersten Teil der Durchführung Ihre Hörschwelle und die maximale Lautstärke, die für Sie gerade noch tolerierbar ist, ermittelt. Nach dieser ersten Einstellung wird der weitere Versuchsablauf ausschließlich mit kontrollierten Signalstärken, die Ihnen angenehm sind, durchgeführt.

Sollte wider erwartend ein Signal für Sie unangenehm laut sein, können Sie jederzeit die Spule entfernen und die Übertragung auf diese Weise unterbrechen. Aus diesem Grund haben Sie während der Versuchsdurchführung keinerlei Risiken zu erwarten.

Während der gesamten Versuchsdurchführung wird Ihr Implantat über ein eigens für MED-EL Implantate entwickeltes Interface mit gesicherten Protokollen (ohne Sprachprozessor) stimuliert. Entfernen Sie dazu bitte nach Aufforderung Ihren Sprachprozessor und schalten Sie ihn ab. Ihre persönlichen Einstellungen des Sprachprozessors werden auf diese Weise in keinem Fall verändert.

Durchführung der Messung

Bestimmung der **Hörschwelle** (untere Grenze):
In diesem Teil des Versuchs stellen sie das Signal/Geräusch so ein, dass Sie es gerade noch wahrnehmen können. Es soll sehr leise, gerade noch hörbar sein.

Bestimmung der **maximal tolerierbaren Lautstärke** (obere Grenze):
In diesem Teil des Versuchs stellen sie das Signal/Geräusch so ein, dass Sie es gerade noch tolerieren können. Es soll laut, allerdings weder unangenehm, noch schmerzhaft sein.

Angleichen der Lautstärke von verschiedenen Signalen:
Bei diesem Versuch sollen Sie zwei verschiedene Signale/Geräusche miteinander vergleichen und die Lautstärke des zweiten Signals so einstellen, dass es genauso laut ist, wie das erste. Dazu hören Sie die beiden Signale kurz hintereinander. Diese werden ständig wiederholt. Die Lautstärke des zweiten Signals verändert sich, wenn Sie die entsprechenden Tasten auf der Tastatur oder dem Bildschirm drücken.
Im Anschluss an den Versuch werden wir Sie über Ihre Hörwahrnehmung befragen.

HINWEIS: Sie erhalten unmittelbar vor den jeweiligen Versuchsteilen eine ausführliche Einweisung über die Vorgehensweise!

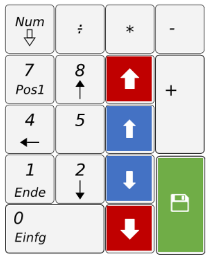
Ende

Nachdem wir die Durchführung der Versuche abgeschlossen haben und das spezielle Interface entfernt wurde, dürfen Sie Ihren eigenen Sprachprozessor wieder einschalten und aufsetzen.

Als kleines Dankeschön für Ihre Teilnahme an der Studie, mit der Sie einen wichtigen Beitrag zur Forschung und zur Verbesserung von Cochlea-Implantaten leisten, gibt es Kaffee und Kekse.

Bestimmung der Hörschwelle:

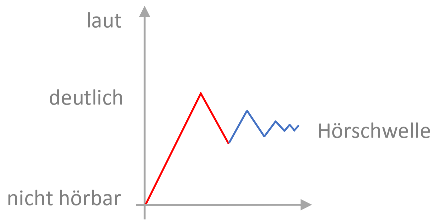
Mit der Hörschwelle ist die Lautstärke gemeint, bei der Sie ein Geräusch **gerade noch wahrnehmen** können.

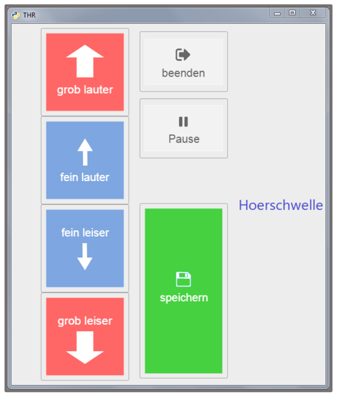


Bitte stellen Sie im ersten Schritt mit den Pfeiltasten die Lautstärke des Geräuschs so ein, dass Sie dieses deutlich hören können. Regeln Sie danach bitte die Lautstärke auf Ihre Hörschwelle ein.

Die **roten Pfeiltasten** verändern die Lautstärke in **großen Schritten**, während die **blauen Pfeiltasten** die Lautstärke in **kleineren Schritten** verändern.

Tipp: Am besten benutzen Sie zuerst die **roten Pfeiltasten**, um das Signal deutlich hörbar zu machen. Im Anschluss können Sie die Lautstärke mit den **blauen Pfeiltasten** genau auf Ihre Hörschwelle einstellen.





Wenn Sie mit ihrer Einstellung zufrieden sind, **speichern** Sie diese bitte. Dazu betätigen Sie die **grüne Taste**. Im Anschluss erfolgt das nächste Geräusch.

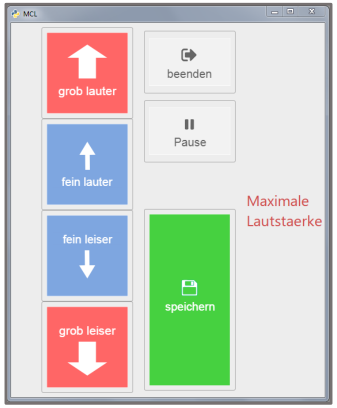
Ist Ihnen etwas unangenehm oder benötigen Sie eine Pause, **sagen Sie uns bitte ohne zu zögern Bescheid**. Ansonsten erfolgt nach ungefähr 20 Minuten automatisch eine kurze Pause.

Bevor der eigentliche Versuch startet, haben Sie die Möglichkeit das Verfahren an einigen Beispielen zu üben.

Bestimmung der maximalen Lautstärke:

Mit der maximalen Lautstärke ist die Lautstärke gemeint, die Ihnen beim Hören über einen längeren Zeitraum **gerade noch angenehm** ist.

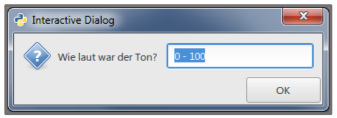
Tipp: Am besten benutzen Sie zuerst die **roten Pfeiltasten** (**große Schritte**), um nahe an die maximal angenehme Lautstärke zu gelangen. Im Anschluss können Sie die Feineinstellung mit den **blauen Pfeiltasten** (**kleine Schritte**) vornehmen.



Die Signale können deutlich lauter werden, als es mit Ihrer normalen CI-Einstellung der Fall ist!

Wenn möglich, stellen Sie die Lautstärke bitte so ein, dass sie für alle Geräusche ungefähr gleich laut ist.

Immer wieder öffnet sich ein Fenster und Sie werden gebeten der Lautstärke des Geräuschs eine Zahl zwischen **0 (nicht hörbar)** und **100 (maximale Lautstärke)** zuzuordnen. Der Zahlenwert soll dabei Ihre Wahrnehmung wiederspiegeln.



Wenn Sie mit ihrer Einstellung zufrieden sind, **speichern** Sie diese bitte. Dazu betätigen Sie die **grüne Taste**. Im Anschluss erfolgt das nächste Geräusch.

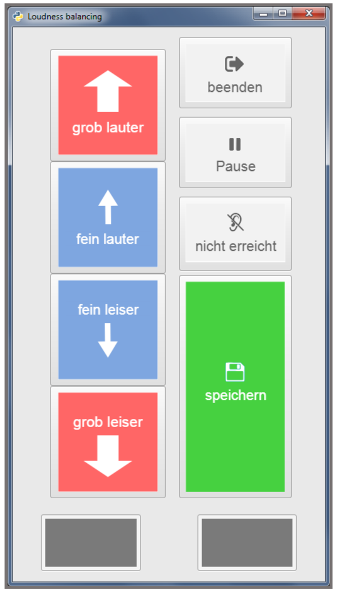
Ist Ihnen etwas unangenehm oder benötigen Sie eine Pause, **sagen Sie uns bitte ohne zu zögern Bescheid**. Ansonsten erfolgt nach ungefähr 20 Minuten automatisch eine kurze Pause.

Bevor der eigentliche Versuch startet, haben Sie die Möglichkeit das Verfahren an einigen Beispielen zu üben.

Abgleich der Lautstärke von zwei verschiedenen Geräuschen:

Bei diesem Versuch hören Sie zwei Geräusche, die kurz hintereinander ständig wiederholt werden. Die Geräusche unterscheiden sich in ihrer Lautheit und in anderen Merkmalen. Vergleichen Sie die Geräusche miteinander und stellen Sie die Lautstärke des zweiten Signals so ein, dass es **annähernd genauso laut** ist, wie das erste.

Auf dem Bildschirm sehen sie zwei graue Felder. Zeitgleich mit den beiden Geräuschen leuchten diese in hellgrau bzw. gelb auf. Die Lautstärke des Geräuschs, welches erklingt, wenn die linke Fläche **gelb leuchtet**, kann durch die Pfeiltasten **verändert** werden.



Tipp: Am besten benutzen Sie zuerst die **roten Pfeiltasten** (**große Schritte**), um die Lautstärke einmal lauter und einmal leiser als das andere Signal einzustellen. Im Anschluss können Sie die Feineinstellung mit den **blauen Pfeiltasten** (**kleine Schritte**) vornehmen.
Können Sie die gleiche Lautstärke gar nicht einstellen, klicken Sie auf die Schaltfläche **nicht erreicht**, bevor Sie **speichern**.

Wenn Sie der Meinung sind, dass beide Signale annähernd gleich laut sind, **speichern** Sie diese bitte. Dazu betätigen Sie die **grüne Taste**. Im Anschluss erfolgt das nächste Geräusch.

Ist Ihnen etwas unangenehm oder benötigen Sie eine Pause, **sagen Sie uns bitte ohne zu zögern Bescheid**. Ansonsten erfolgt nach ungefähr 20 Minuten automatisch eine kurze Pause.

Bevor der eigentliche Versuch startet, haben Sie die Möglichkeit das Verfahren an einigen Beispielen zu üben.

Abgleich der Lautstärke von vier verschiedenen Geräuschen:

Ihre Aufgabe besteht darin, **vier Signale nacheinander** zu hören und zu entscheiden, ob eines der Signale **lauter oder leiser ist als die anderen drei Signale**.

Falls die Lautstärke eines Signals von den anderen abweicht, klicken Sie entsprechend auf die **ist lauter-** oder **ist leiser-**Schaltfläche des jeweiligen (1., 2., 3., oder 4.) Signals. Daraufhin wird dieses Signal bei der nächsten Wiederholung lauter bzw. leiser abgespielt.

Wenn Sie die Signale noch einmal hören wollen, klicken Sie auf **Wiederholen**. Hören sich alle Signale gleich laut an, klicken sie auf die entsprechende Schaltfläche (**Gleich Laut**).

Damit ist dieses Teilexperiment beendet und Sie gelangen zurück vorherigen Experiment.

Bestimmung der Hörwahrnehmung:

Bei diesem Versuch hören Sie zwei Signale nacheinander. Auf dem Bildschirm sehen sie zwei graue Felder. Zeitgleich mit den beiden Geräuschen leuchten diese in **blau** bzw. **rot** auf.

Bitte beantworten Sie die Fragen auf dem Fragebogen.
Wenn Sie die Signale noch einmal hören wollen, klicken Sie auf **Wiederholen**.

Bestimmung der Hörwahrnehmung:

Bei diesem Versuch hören Sie wieder zwei Signale nacheinander. Auf dem Bildschirm sehen sie zwei graue Felder. Zeitgleich mit den beiden Geräuschen leuchten diese in **blau** bzw. **rot** auf.

Sie sollen angeben, **wie die Signale klingen.** Es werden Ihnen verschiedene Wortpaare wie „laut - leise" oder „tief - hoch" vorgegeben.
Bitte kreuzen Sie auf dem Pfeil die Eigenschaften von **Signal 1** (linkes Feld leuchtet blau) und **Signal 2** (rechtes Feld leuchtet rot) mit der entsprechenden Farbe an.

Wenn Sie die Signale noch einmal hören wollen, klicken Sie auf **Wiederholen**.

Beispiel 1:

„**Signal 1** hört sich leise an und **Signal 2** ist lauter, aber nicht sehr laut."

Beispiel 2:

„**Signal 1** hört sich genauso hoch an wie **Signal 2.**"

Hörwahrnehmung - Abfrage

Durchgang 1:

Können Sie die beiden Signale unterscheiden? ☐Ja ☐Nein

Woran?

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1

August 2018 - MO/AD – Fragebogen

BAI Bio-Inspired Information Processing — Hörwahrnehmung - Abfrage

Bitte kreuzen Sie auf dem Pfeil die Eigenschaften von **Signal 1** und **Signal 2** mit dem Stift der entsprechenden Farbe an.

Durchgang 1:

tief		*hoch*
laut		*leise*
hell		*dunkel*
voll		*dünn*
piepsig		*brummig*
rau		*glatt*
angenehm		*unangenehm*
schwankend		*gleichmäßig*
kräftig		*schwach*
stumpf		*scharf*
ein Ton		*mehrere Töne*

2
August 2018 - MO/AD – Fragebogen

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