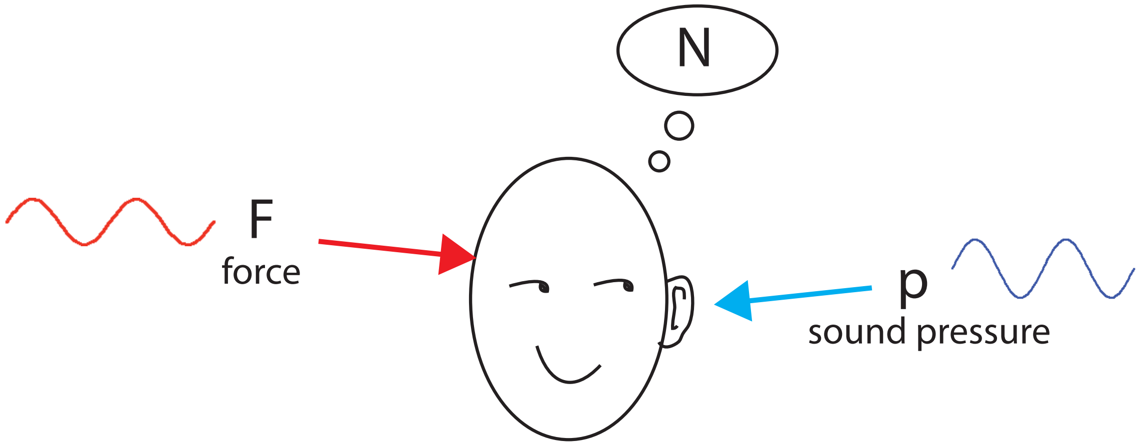

Growth of Loudness for Bone Conduction

Master of Science Thesis in the Master's Programme in Sound and Vibration

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Master's Thesis 2012:123

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Abstract

During the twentieth century the relation between loudness and sound pressure level has been investigated to some extent, but a similar investigation for bone conduction is still missing.

The aim of this master's thesis is to investigate the relation between loudness and excitation level for bone conduction. A listening test has been designed in which the method of magnitude estimation was used - both with and without an anchor sound. A pure tone at 1 kHz and noise with bandwidth 1 bark band, centered around frequency 1 kHz, was used as stimuli. The excitation levels was 20 to 75 dB HL with a step size of 5 dB and the number of participants was 34.

The listening test resulted in a loudness function that could be approximated to a power function of intensity with an exponent of 0.2.

Contents

Acknowledgements

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1. Introduction

In humans sound waves can be transmitted to the cochlea via two different ways: **air conduction (AC)** and **bone conduction (BC)**. Sound waves in air are typically transmitted via air conduction, while our own voice is transmitted both by air conduction and bone conduction. The transmission path for AC goes through the ear-canal, the tympanic membrane and the middle ear ossicles into the cochlea[Rei 09]. The transmission path for BC goes through the skull bone into the cochlea. Sound waves in air do excite the skull bone to some extent, but this excitation is very small and for a normal hearing person it is negligible compared to the AC path. An exception is when we hear our own speech. There sound waves are transmitted via AC, but also from the oral cavity to the cochlea directly via the skull bone. In this case what we hear is a combination of both paths. This explains why our own voices sound different when heard through recordings.

An important finding in bone conduction physiology research was when von Békésy in 1932 reported the cancellation of the perception of a bone conduced tone by an air conduced tone[Stn 06]. A conclusion that von Békésy made was that, although the transmission to the inner ear is different, the final process for AC and BC stimulation are the same.

For persons with single-sided deafness or certain types of conductive or mixed hearing loss, a bone conduction hearing solutions can be helpful. A **BAHA** is such a device and it consists of a microphone, a sound processor and an actuator. The microphone picks up sound waves in the air (i.e. pressure fluctuations) and the actuator forwards the sound with an oscillating force applied to the head. The actuator is usually connected directly to an osseointegrated[1] implant[Car 97] and this type of bone conduction is called **direct bone conduction (DBC)**. The actuator might also be attached to the head using a **softband** and the force is then applied to the head outside the skin. A softband is an elastic band that is attached around the head. The vibrator is then snapped onto an adaptor (a plastic piece) that is a part of the softband. The softband is attached around the head so that the adaptor is positioned on the hard bone just behind the ear - the mastoid. Vibration force transferred through the adaptor to the cochlea will - from now - be what is meant when **bone conduction (BC)** is mentioned in this thesis

[1] Osseointegration is the formation of a direct interface between an implant and bone, without intervening soft tissue.

1.1. Background

Force Hearing Level

In hearing by BC the excitation force is usually expressed in terms of **force hearing level** (FL_{HL}) and in units **decibel hearing level, dB HL**. The force hearing level is given by the logarithm of the excitation force relative to the hearing threshold for BC:

$$FL_{HL} = 20 \log_{10} \left(\frac{F}{F_{th}} \right) \quad \text{dB HL.} \tag{1.1}$$

At 1kH the hearing threshold for BC is 42.5 dB relative to 1 μN[ISO 94]. This gives the force at the hearing threshold:

$$F_{th} = 1\mu N \cdot 10^{42.5/20} = 133.35 \quad \mu\text{N.} \tag{1.2}$$

Loudness

Loudness, N, is the sensation that corresponds most closely to sound intensity[Fas 90]. The relation between sensation and physical stimulus can be measured by answering the question how much louder (or softer) a sound is heard relative to a standard sound. The unit is *sone*; a doubling in sones corresponds to a doubling of loudness. The scale is defined so that silence approaches 0 sones . And a 1 kHz tone at 40 dB SPL - presented as a frontal plane wave in a free field - has a loudness of 1 sone.

In psychoacoustics there is another quantity called *loudness level* and it is important to distinguish this from loudness. The loudness level, L_N, of a sound is defined as the sound pressure level of a 1-kHz tone (in a plane wave and frontal incident) that is as loud as the sound[Fas 90]. Its unit is *phon*. By comparing sounds of different frequencies with a standard sound of 1 kHz, *equal loudness contours* can be measured.

The relation between loudness in sones and loudness level in phons has been determined by a variety of methods in several laboratories[Ste 56]. The median values of the results obtained can be represented by the equation[Ste 55]:

$$10 \cdot \log_{10}(N) = 0.3 \cdot (L_N - 40). \tag{1.3}$$

This equation was later used in ISO 131-1979 - *Expression of Physical and Subjective Magnitudes of Sound or Noise in Air*[Iso 79]. However, this standard is now withdrawn.

The work in this thesis focuses on *loudness*.

Steven's Power Law

In 1955 Stevens publishes a paper[Ste 55] that summarizes data from a number of attempts - that were made between 1930 and 1954 - to measure the loudness function for AC. He suggests that for the typical listener the loudness N of a 1 kHz tone can be approximated by a power function of intensity I, of which the exponent is $\log_{10}(2)$. The equation is: $N \propto I^{0.30}$. Sound intensity is proportional to the pressure squared and for AC the law can also be expressed as $N \propto p^{0.60}$, where p is sound pressure. The law hold for levels above about 40 dB SPL. Between 30 and 40 dB SPL a vertex can be seen in the loudness function, and for lower excitation levels the slope of the function is steeper.

The law is later extended (*On the Psychophysical Law*, 1957) to hold also for other intensity sensations. The equation is then written as

$$S = aI^k, \tag{1.4}$$

where S is the magnitude of the sensation, a and k are constants - that are different for different type of sensations - and I is the intensity of the stimuli. The equation is denoted *Steven's power law*.

The approach is that Stevens power law can be applied to BC. In this case the fact that intensity is proportional to force squared[2] can be used. The listening test that is described in this work measures loudness as a function of excitation force and the results gives a number on the constant k for BC .

1.2. Scope

The aim of this work is to investigate loudness sensation as a function of excitation level for bone conduction, BC. In hearing by BC the skull bone is excited by a force, F, while loudness, N, is a subjective quantity. A listening test is designed and implemented to measure the relation between the two quantities, i.e. the loudness function for BC.

It is of interest to see if the loudness function can be approximated by a power function of intensity, as suggested by S.S. Stevens (see Section 1.1):

$$N = a \cdot I^k, \tag{1.5}$$

where I is sound intensity and a and k are a constants that are specific for the type of stimuli. The intensity is proportional to the excitation force squared:

$$I = b \cdot F^2 \tag{1.6}$$

Inserting Equation 1.6 in Equation 1.5, and then taking the logarithm, gives the following relation between loudness and excitation force:

$$10 \cdot \log(N) = m + k \cdot 10 \cdot \log(F^2), \tag{1.7}$$

where m is some constant.

The listening test in this study aims to measure k and can not be used to measure m.

[2]Intensity is work over unit area and work can also be expressed as force times velocity: $I = W/A = Fv/A$. In terms of impedance this gives $I = F^2/ZA$. If we assume that the area is constant we get $I \propto F^2$.

1.3. Related work

The first article by R. P. Hellman, on *Growth of Loundess at 1000 and 3000 kHz*, described in this chapter is an investigation of the loudness function for AC. The listening test described Section 3 takes a lot of inspiration of one of the methods used in this article, namely the method of magnitude estimation. This method is described further in Section 2.2.

The second article, by S. Stenfelt and B. Håkansson, is *Air versus Bone Conduction: an Equal Loudness Investigation*. If the results from this study are combined with results from investigations of the loudness function for AC, an estimation of the loudness function for BC can be made.

Growth of Loudness at 1000 and 3000 Hz

Method: Magnitude estimation and magnitude production.
Transfer path: AC.
Subjects: Students and staff at the university, 9-11 subject in each test design.
Test signal: Pure tone.
Frequencies: 1000 and 3000 Hz.
Amplitudes: 11 different levels between 10 and 100 dB SPL.

Loudness as a function of sound pressure level was measured by magnitude estimation and by magnitude production[Hel 76]. In the same study growth of loudness was also measured indirectly by loudness matches and by interfrequency matching. No systematic difference in shape of the loudness functions between 1000 and 3000 was found. The results obtained from magnitude estimation and magnitude production can be seen in Figure 1.1. Above about 30 dB SPL the results shows that the loudness functions are power function of the sound pressure level. This is consistent with Stevens power law, see Section 1.1. The slopes of the curves are slightly different for the two methods. By combining the results of the two methods the exponent (previously referred to as k) was found to be 0.30 (relative to sound intensity). This holds for levels larger than about 30 dB SPL. Below 30 dB SPL the loudness function is steeper.

Air Conduction versus Bone Conduction: an Equal Loudness Investigation

Method: Loudness balance
Transfer path: AC and BC.
Subjects: 23 normal hearing and 8 with an hearing impairment.
Test signal: Narrow band noise.
Center frequencies: 250, 500, 750, 1000, 2000, 4000 Hz.
Amplitudes of the AC sound: 30, 40, 50, 60, 70 dB HL.

This artice from 2001, by Stefan Stenfelt and Bo Håkansson, describes a study were loudness balance testing was conducted between AC and BC. The participants heard

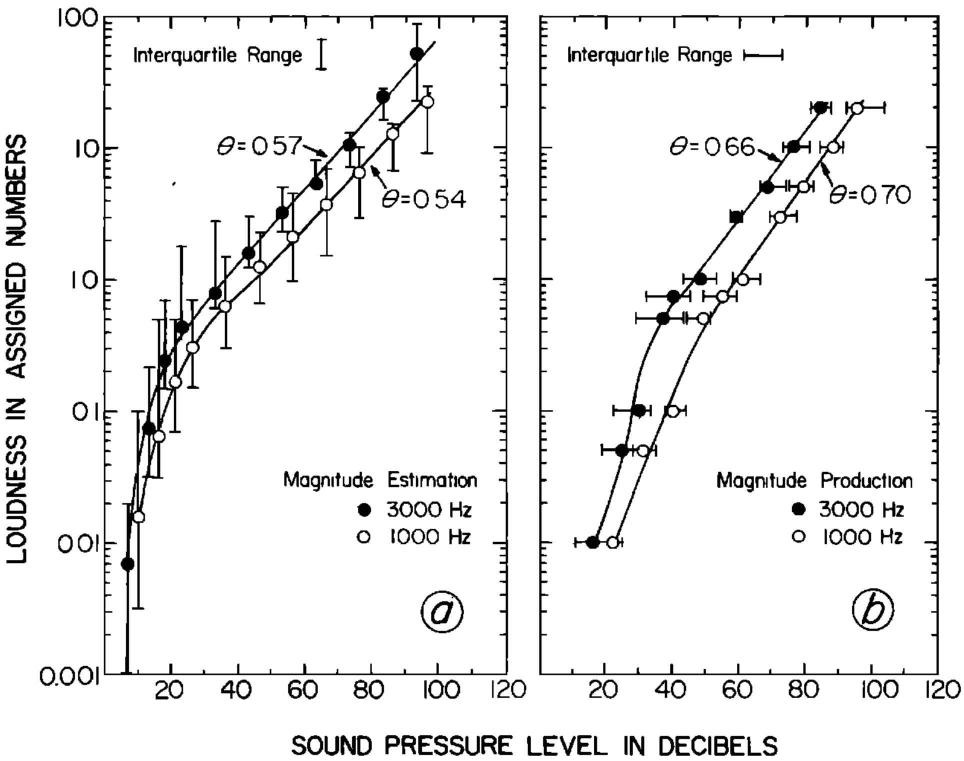

Figure 1.1.: The results from magnitude estimation and from magnitude production that was performed for AC[Hel 76]. The vertical and the horizontal bars show the interquartile ranges. The slope of about 0.6 is relative sound pressure. This corresponds to 0.3 relative sound intensity.

one sound through earphones and the task was to adjust another sound, heard through a bone transducer fitted to the subject, for equally loudness by bracketing the standard.

The results for the normal hearing group can be seen in Figure 1.2. The levels for the AC sound is in units dB HL, while the units for the levels of the BC sound is calibrated in such a way that the levels, for AC and for BC, coincide at 30 dB HL. In the article, possible explanations for the difference in growth of loudness between AC and BC are discussed[3]. The contraction of the stapedius muscle in the middle ear is mentioned as one part of the explanation. Another part that is mentioned, is distortion from the bone transducer and tactile stimulations. This especially happens for higher amplitudes at the lowest frequencies.

It seems possible to utilize data presented in the article to calculate a coefficient for the loudness function for BC. Together with Stevens power law, and the accepted exponent of 0.30 for AC, such a derivation is made. The result is seen in Figure 1.3 and

[3]The article does not directly discuss the concept of loudness, but qualitatively this is the discussion.

the procedure is explained further in Appendix B. The function in Figure 1.3 is again calibrated so that the levels coincide at 30 dB HL. The derivation gives the exponent 0.33 for the loudness function of BC at 1 kHz.

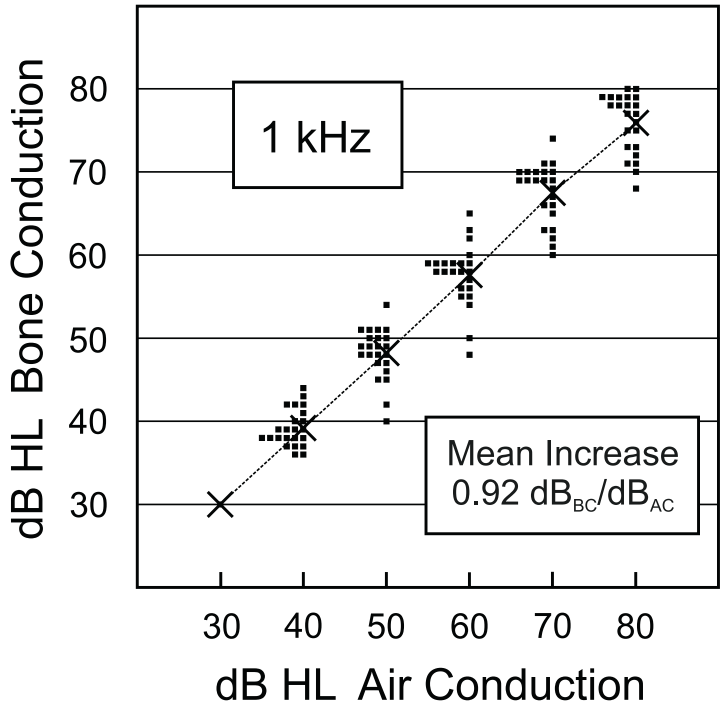

Figure 1.2.: Results that were obtained from the loudness balance test between AC and BC for the normal hearing group[StHå 01]. Individual results are represented by dots. The BC mean for each level is given by the crosses along the dotted lines.

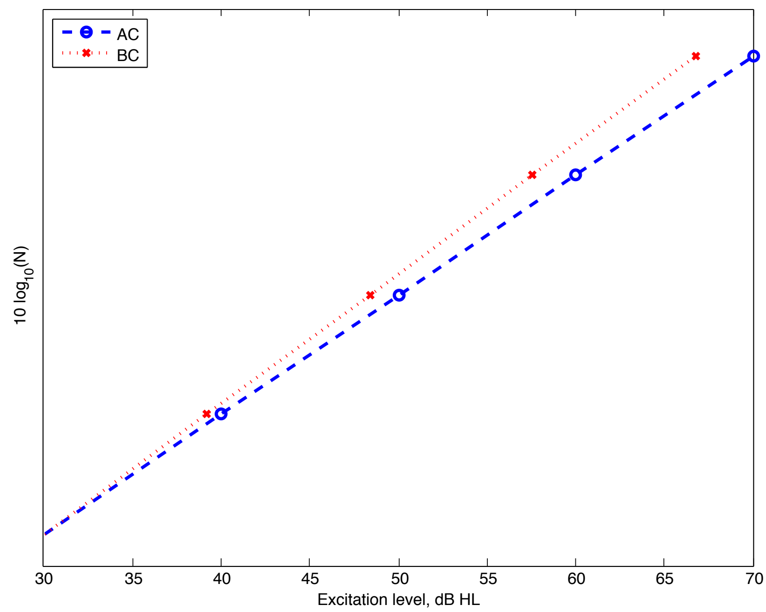

Figure 1.3.: The graphs show loudness functions for AC and for BC. The rightmost curve shows how the loudness function for AC, as described by Stevens power law and the exponent 0.30 (i.e. $N \propto I^{0.30}$), looks like. By using the results in Figure 1.2, in combination with this loudness function for AC, the loudness function for BC is derived. The leftmost curve shows this function and its slope corresponds to an exponent of 0.33.

1.4. What is new?

During the twentieth century the relation between loudness and sound pressure level has been investigated to some extent, but a similar investigation for bone conduction has not been made before to that extend. A methodology, that has previously been used to measure growth of loudness for AC is here applied to BC. A listening test is designed and implemented for BC. The test is designed in such a way that it could also be used for analyzing DBC.

The article *Air Conduction versus Bone Conduction: an Equal Loudness Investigation* relates the loudness of a sound heard trough AC with the loudness of a sound heard trough BC. The outcome of the study suggests that the loudness function might be somewhat steeper for BC than it is for AC. It is of interest to see if an investigation of the loudness function, that is performed for BC only, could corroborate this suggestion.

For AC the loudness function on a logarithmic scale, has a slope that can be approximated to a power function of intensity. The power function is often referred to as Steven's power law. Above about 40 dB SPL the value of the exponent in this power law is accepted as 0.3. Between 30 and 40 dB SPL a vertex can be seen in the loudness function, and for lower excitation levels the slope of the function is steeper. This vertex coincides with the reference point for the sone scale (1 sone) as suggested by Zwicker & Fastl[Fas 90]. If found in this study, such a vertex point could possibly relate the BC loudness function to the AC loudness funciton.

2. Method

In this section some different methods, that can be used to measure growth of loudness, are discussed. The chosen method and the motives behind is presented.

2.1. Direct Method versus Indirect Method

The perception of a psychophysiological stimuli can be measured either directly or indirectly. The method used in this thesis is a **direct measurement method**. That means that the ratio of loudness is measured directly by comparing sounds at different intensity levels. All sounds are heard through BC and the listener is asked to rate the loudness of the sounds.

An alternative could be to use an **indirect measurement method**. Using this method, the listener would hear sounds both trough AC and trough BC sound. The listener is then asked to rate the loudness of the BC sound relative to the AC sound. This method was used in [StHå 01], were the listener was asked to adjust the BC sound until it was perceived equally loud as the AC sound.

Both methods have their pros and cons. An advantage with the indirect method is that the results would be calibrated to the sone scale; Let us assume that the listener hears a tone that has a sound pressure level corresponding to 2 sones. The listener adjusts a BC sound until it is perceived equally loud as the AC sound. Then it could be assumed that the loudness of the BC sound is 2 sones. However here is a danger. The results from measurements of the loudness function for AC differs a lot between different investigations. If this function is just adopted to BC, then the errors will also be adopted to the loudness function of BC. Furthermore, new errors will be introduce because of uncertainties in the loudness matching between AC and BC. Let us now assume that a second listening test is performed in order to relate DBC to BC. Hearing through DBC requires an implant. A person who has an implant has it because he/she has an hearing impairment and can either not hear at all through AC, or can only hear poorly through AC. Therefore DBC can not be compared directly to AC. If the loudness function is measured for DBC by using an indirect method, DBC would be compared to BC. This extra step would introduce additional errors to the loudness function.

An advantage with the direct method is that no errors are adopted from previous investigation of the loudness function for AC. This method is also easier to implement than the indirect method, since the setup is more simple and it does not require calibration of headphones. Another advantages is that the same method and setup[1] can be

[1] For safety reasons a recommended adjustment of the setup if it should be used for DBC is that a galvanic isolation is used between the power amplifier and the actuator.

used for an investigation of the loudness function for DBC.

2.2. Magnitude Estimation versus Magnitude Production

The direct method can basically be divided into two submethods; **magnitude estimation** and **magnitude production**. In magnitude estimation the listener hears sounds with different amplitudes and the task is to rate the loudness of the sound. This can for example be done by asking the subject to assign a number to each sound, corresponding to the loudness of the sound.

In magnitude production the task for the listener is to adjust the stimuli. For example the listener is asked to adjust the level of a sound so that it corresponds to a certain number. Another approach could be to compare an adjustable sound to a reference sound. The listener could then be asked to adjust the adjustable sound until it is perceived, for example, twice as loud as the reference sound. It has sometimes been noticed that some intervals are easier to determine than other. For example the intervals 'twice as loud' and 'half as loud' are known to be easier to determine than other intervals.

In the study described in Section 1.3, both magnitude production and magnitude estimation was used. Figure 1.1 shows the results of this investigation. The two methods gave rise to loudness functions with similar shape but with slightly different slopes. An interpretation could be that, in magnitude estimation, the subject tends to underestimate the loudness of the loudest sounds and overestimate the loudness of the softer sound.

In the listening test in this work the method of magnitude estimation is used. The method is well known and frequently used, which is an advantage. Magnitude estimation is also the fastest method, meaning that many estimates can be made for each force level and also that more levels can be tested.

2.3. Absolute versus Relative Method

It might be helpful to present a reference sound, a so called **anchor sound**, to the listener. The loudness of one variable sound could then be rated relative to the loudness of the anchor. This is what is meant with a **relative method**. In the **absolute method** no anchor sound is used.

Although the listener might experience that the task to rate a sound is easier with an anchor, it does not necessarily results in better data; the anchor is also a contributing bias. The ear adapts to sounds with different levels, and after hearing a loud sound it is harder to hear a soft sound. This could possible lead to that the loudness of a sound, that is much softer than the anchor, is underestimated. Similarly, the loudness of a sound that is much louder than the anchor, might be overestimated.

In the listening test in this work magnitude estimations are made both with and without an anchor. To avoid training effects on the loudness estimates, the experiment part without an anchor was always done first and the anchor sound is first presented in the last part of the listening test.

3. Listening Test

Method: Magnitude estimation - with and without an anchor sound.
Transfer path: BC.
Subjects: 33 normal hearing.
Test signal: Pure tone and noise within one critical band.
Frequency/center frequency: 1000 Hz.
Amplitudes: 20 to 75 dB HL with a step size of 5 dB.

The listening test is divided into two main parts and a training part in the beginning, see Figure 3.2. Each part starts with pure tones, Stimulus 1, and ends with noise, Stimulus 2. In the beginning is a short trial part where no anchor is used. Part 1 is a repetition of the trial part but this time more estimates are done and Part 1 also consists of more different amplitudes than the trial part. In the last part, Part 2, an anchor sound is introduced. The anchor sound, denoted as Sound 1, has a constant amplitude throughout the test and is given the value 100 that represents the loudness of the sound. The other sound, denoted as Sound 2, has a new amplitude for each estimate. The task for the listener is to estimate the loudness of Sound 2 relative to Sound 1. In Part 1 and Part 2 each amplitude and stimulus are repeated twice.

3.1. Participants

Participants were collected through invitations by email to students and staff on Technical Acoustics at Chalmers University, staff at Cochlear BAS and acquaintances in the Gothenburg region. Initially 34 people took part of the study. After checking the form that all participants had to fill in, the data of one participant, who stated him/herself as sensorineural hearing impaired, was excluded. The remaining test group consists of participants who are between 22 and 46 years old, with a mean of 32 years and a standard deviation of 6 years. All of the participants listed their own hearing as either 'quite good', 'good', or 'very good'.

3.2. Force levels

It is desirable that the range of amplitudes is as big as possible, but there are some limitations. The lowest possible amplitude that might be of interest to test is the hearing threshold and the highest amplitude to be tested must be lower than any amplitude that might cause damage to the test persons hearing. Further limitations are given by the characteristics of the actuator and of the electrical components in the setup. For high amplitudes distortion occurs due to nonlinearities in the apparatus and for very low amplitudes the signal to noise ratio is low, since the signal is then closer to the noise floor. Figure 3.1 shows total harmonic distortion, THD, of the actuator as the function of the voltage in to the actuator, U_{act}. The lowest level in the listening test (20 dB HL) is achieved for $U_{act} \approx -40$ dB rel. 1 V. The THD is then about 2%. The highest amplitude (75 dB HL) is achieved for $U_{act} \approx 15$ dB rel. 1 V, corresponding to a THD of about 11%. For details about the calibration of the force levels, see Appendix A.

3.3. Signal type and frequency

Two different types of signals are used in the listening test; a pure tone at 1 kHz and noise with a bandwidth of one bark band centered around frequency 1 kHz. The frequency of 1 kHz is chosen since it is a commonly used test frequency. It is also unusual to have a hearing loss around this frequency. A pure tone might however result in modal shapes into the human head. The vibration amplitude of a pure tone may for some subjects be greatly affected by a resonance or mode, whilst for others not. To mitigate undesired effects from resonances, noise - which is less prone to cause inter-subject differences - is utilized. Noise consisting of frequencies within one bark band mainly excites hair cells, in the cochlear, within one critical band. Theoretically the noise signal and the pure tone should give rise to similar loudness functions if the energy in both signals is the same.

A butterworth digital filter, with a lower frequency of 920 Hz and an upper frequency of 1080 Hz, is used in Matlab to create the noise. A vector with uniformly distributed pseudorandom numbers[1] was filtered through this filter. To avoid clipping the signal is ramped up, respectively ramped down, during 125 ms. A hanning window split into two pieces was used for this purpose. The total length of the signal was 1 second.

3.4. Background noise

Part of the listening test was performed at at Applied Acoustics, Chalmers University, and part of it was performed at Cochlear BAS. In both cases the test was performed in a room with good sound isolation and with short reverberation time. The background noise was roughly the same in both rooms. In one of the rooms it was measured as $L_{Aeq} = 24$ dB SPL at listeners position by using a sound level meter[2]. The actuator was enveloped by a plastic housing to avoid sound radiation, but at high force levels it was still possible to hear sound radiation from the actuator. At the lower amplitudes the strongest noise source was the sound of the clicking of the computer mouse. The SPL from this click, inside the test room, was measured as $L_{Apeak} = 68$ dB SPL at listeners position.

[1] The command `rand` was used in Matlab.

[2] Hand-held Analyzer 2250 Light from Brüel & Kjær.

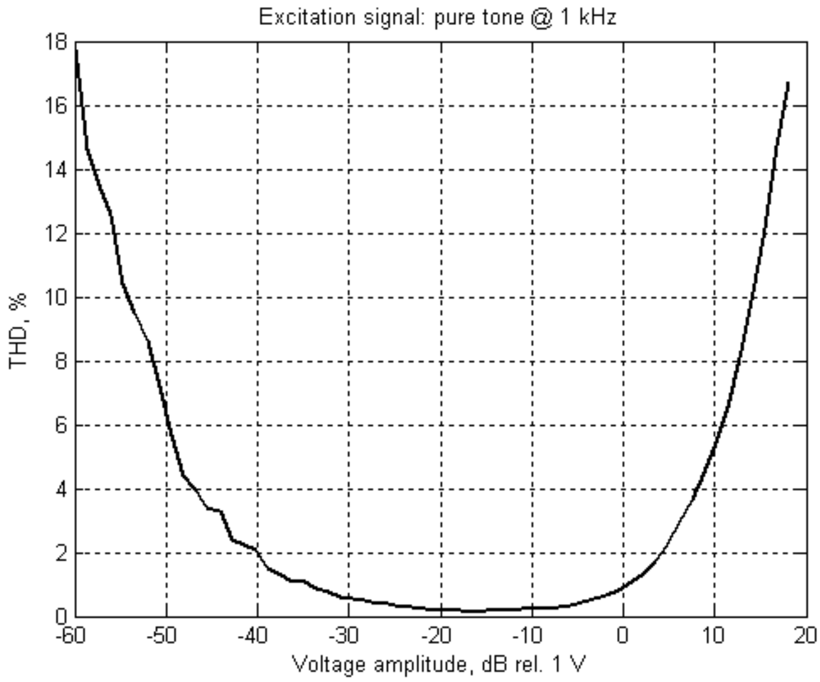

Figure 3.1.: Total harmonic distortion of the actuator as a function of the voltage to the actuator, U_{act}.

3.5. Test Flow

Figure 3.2 shows the overall algorithm of the listening test. Each part (Part 1 and Part 2) consists of 12 different levels that are repeated 4 times. In the two first repetitions a pure tone is heard and in the two latter repetitions narrow band noise is heard. The order of the twelve levels are random for each repetition. The only limitation of the randomization is that the first stimuli in the first repetition is not allowed to have the maximum level of 75 dB HL. The training session in the beginning consists of five levels and two repetitions. In the first repetition the stimulus is a tone and in the second repetition it is narrow band noise. Figure 3.3 shows the algorithm that is repeated for each new stimuli, i.e. for each new level of the sound.

3.6. Graphical User Interface

The GUI for Part 1 of the listening test is seen in Figure 3.4 and 3.5. When the button 'Listen' is pressed the stimulus is heard during one second. A number that represents the loudness of the stimulus is filled into the grey box. When 'Enter' is pressed, on the keyboard of the computer, the button 'Next' appears. For each new level the listener can press 'Listen' as many times as desirable but as soon as the button 'Next' is pressed

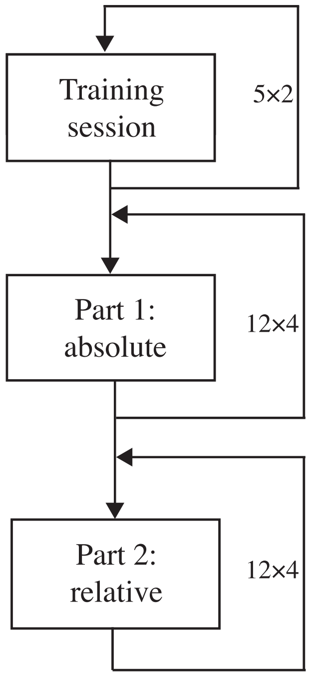

Figure 3.2.: The overall algorithm for the listening test.

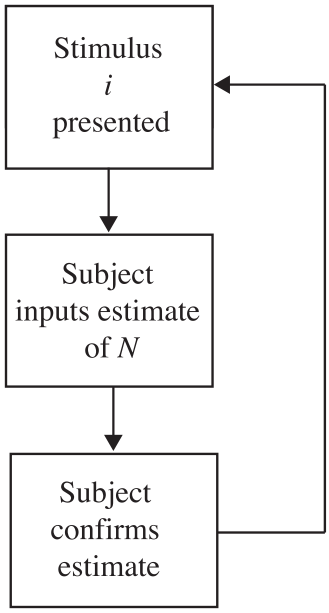

Figure 3.3.: Algorithm that is repeated for each new stimulus.

it is not possible to go back to the previous estimate.

In Part 2 the design is slightly different, see Figure 3.6 and 3.7. This time an anchor sound, that has constant amplitude throughout the whole listening test, is presented. The anchor sound is called 'Sound 1' and the variable sound is called 'Sound 2'. The anchor sound is assigned the value 100 that represents its loudness. The listener is asked to rate the loudness of Sound 2 relative to Sound 1.

Two versions of the GUI exist; one Swedish version and one English version. The english version is shown in Figure 3.4 - 3.7. The visual design of the Swedish version is the same as for the English version, but the text is replaced with text in Swedish, see Table 3.1. Three participants used the English version of the listening test and all other participants used the Swedish version.

Table 3.1.: The written text in the English and the Swedish version of the listening test. Figure 3.4 - 3.7 show the text in its context.

English version	**Swedish version**
Listen	Lyssna
Next	Nästa
Sound 1	Ljud 1
Sound 2	Ljud 2
Assume that Sound 1 has a loudness of 100 . What loudness does Sound 2 have? Type in the fitting number, then press Enter.	Anta att ljudvolymen för Ljud 1 är 100. Mata in den ljudvolym som du anser gäller för Ljud 2 i rutan nedan. Tryck sedan på Enter på tangentbordet för att uppdatera värdet.
You perceived the loudness of Sound 2 as xxx . If this number fits your perception press Next. If it does not fit, please change the number and press Enter.	Du anser att ljudvolymen för Ljud 2 är xxx . Stämmer det? Tryck i så fall på Nästa. Om det inte stämmer, vänligen mata ni ett nytt värde och tryck sedan på Enter.
Type in a number that represents the loudness of the sound you heard. Press Enter on the keyboard to proceed.	Mata in en siffra som du anser motsvarar ljudvolymen på det ljud du hörde. Tryck sedan på Enter på tangentbordet för att uppdatera värdet.
You perceived the loudness of the sound as xxx. If this number fits your perception press Next. If it does not fit, please change the number and press Enter.	Du anser att ljudvolymen på det ljud du hörde motsvaras av siffran xxx. Stämmer det? Tryck i så fall på Nästa. Om det inte stämmer, vänligen mata ni ett nytt värde och tryck sedan på Enter.

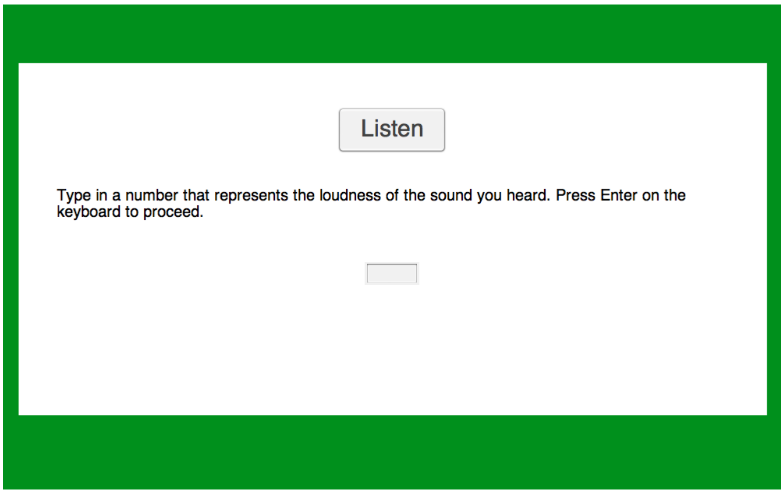

Figure 3.4.: This is how the GUI looks like in Part 1 - and also during the training part - each time a new stimulus is presented to the listener.

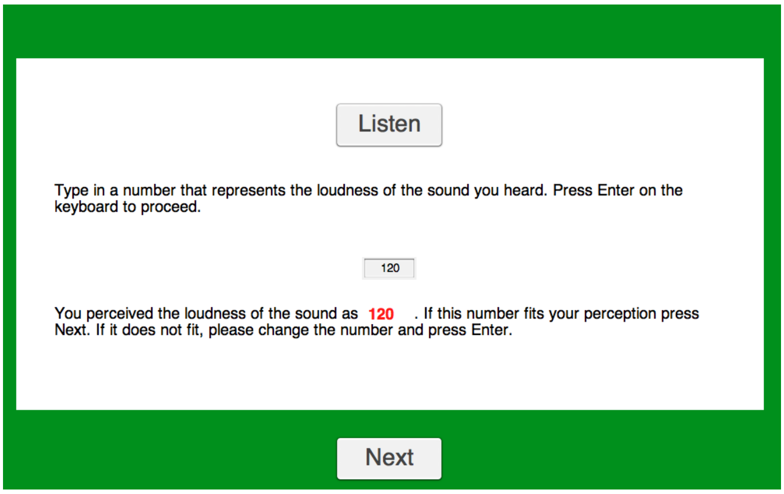

Figure 3.5.: When a number is filled into the grey box, and 'Enter' is pressed on the keyboard on the computer, the GUI is updated. Note that the number '120' is just an example of a number that the listener might fill into the box.

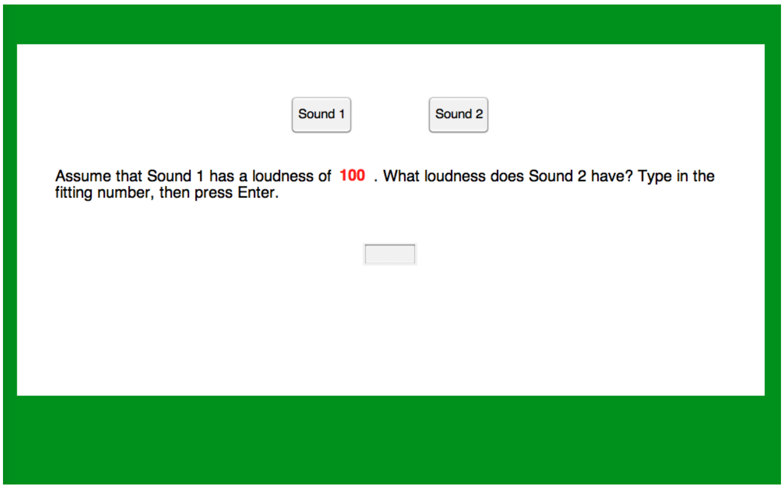

Figure 3.6.: This is how the GUI looks like in Part 2 each time a new stimulus is presented to the listener.

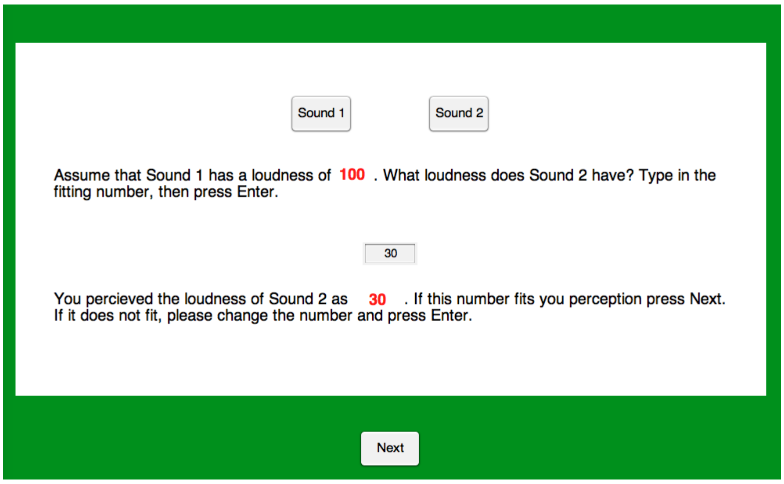

Figure 3.7.: When a number is filled into the grey box, and 'Enter' is pressed on the keyboard on the computer, the GUI is updated. Note that the number '30' is just an example of a number that the listener might fill into the box.

3.7. Test Setup

The subjects sit on a chair, in front of a computer on a table, in a quiet room. The actuator is attached to the mastoid (hard bone) behind one of the subjects ear, using a softband. The softband is tightened so that it is not too loose but not so tight that it is uncomfortable for the listener. The static force of the plastic piece (on the softband) on the mastoid was about 2 - 3 N. The subject hears all sounds through the actuator and uses mouse and keyboard to navigate through the test on the computer. Figure 3.8 shows the setup. The following equipment was used:

- Computer, mac book pro with Matlab
- Sound card, Edirol FA-66
- N4L Laboratory power amplifier LPA01
- Actuator, Baha Cordelle II Headworn, serial no: 0801597
- Softband
- Cables

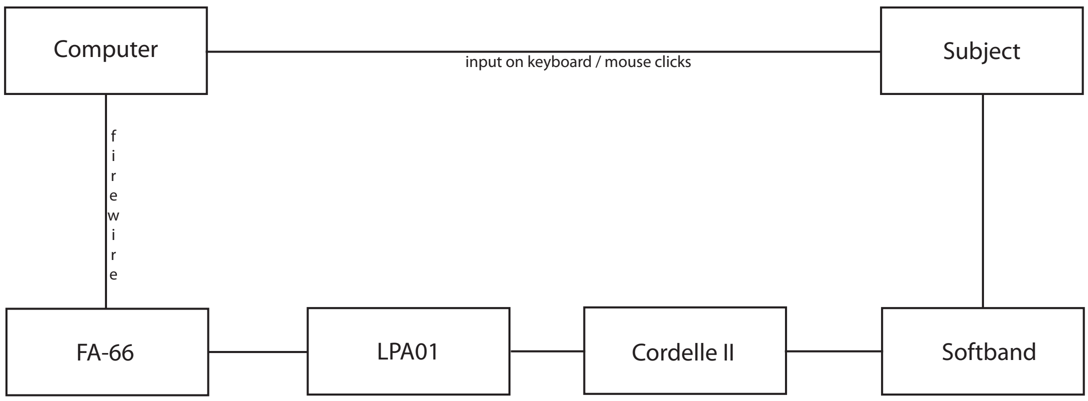

Figure 3.8.: Setup during the listening test.

4. Results

4.1. Raw Data

The raw data of the listening test is shown in Figure 4.1. The data consists of the numbers that were assigned to the stimuli by the listeners.

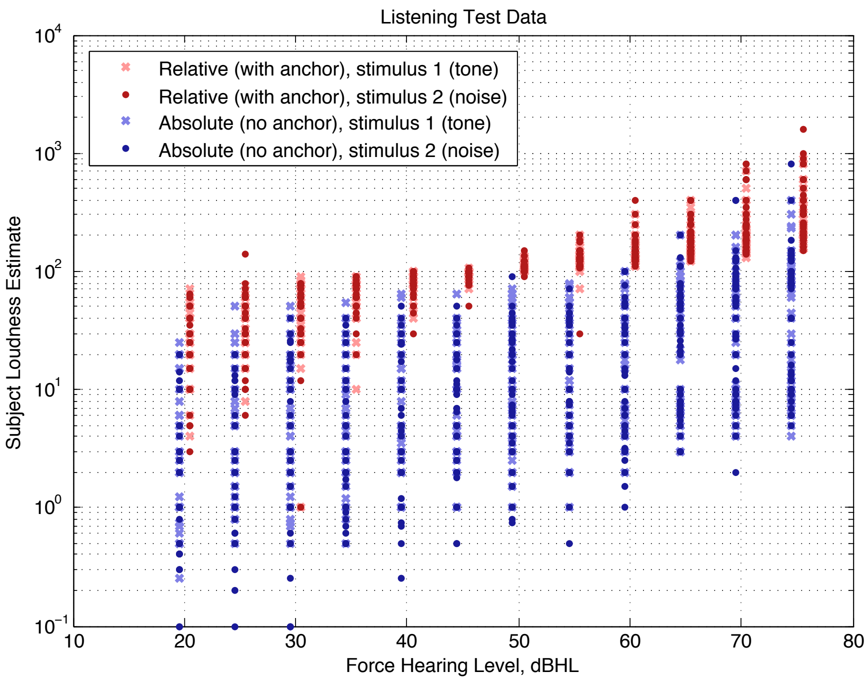

Figure 4.1.: Raw data of the listening test. Each mark (dot or cross) represents one single estimate.

4.2. Statistical Analysis

Data from 33 participants is analyzed. For a few estimates the listener has answered with the number zero, meaning that the listener could not hear the sound. If the sound can not be heard, its loudness can not be rated and these estimates have therefore been excluded from the analysis.

Figure 4.2 shows the **geometric means** of the data from the listening test. The geometric mean of a vector with n elements is given by the n-th root of the product of all elements in the vector. In the same figure vertical bars indicates **inter quartile ranges**, that is the difference between the upper and the lower quartiles.

Regression analysis is used to fit straight lines to the geometric means of the data, see Figure 4.3. Logarithmic scales were used, so that the x-axis represents $10 \cdot \log_{10}(F^2/F_{th}^2)$ and the y-axis represents $10 \cdot \log_{10}(N)$. In this plot the slope of the lines corresponds to the exponent in Stevens power law. The data was also analyzed using the statistical software Minitab. Values obtained for the exponent k are seen in Table 4.1.

To calculate the **confidence intervals** t-distribution was assumed. The degree of freedom, df, i.e. the number of estimates per signal type and test design, is $df \gg 120$ which gives $k_\alpha = 1.96$. The analysis in Minitab gives values on the standard error, SE. The confidence interval is then given by the formula

$$CI = \pm k_\alpha \cdot SE, \tag{4.1}$$

where SE is specific for the degree of uncertainty that is required. The values of CI for a 95% confidence interval can be seen in Table 4.1.

The same procedure is repeated, but this time straight lines are fitted to smaller intervals of the data; one line is fitted for the data between 20 - 35 dB HL, another between 40 - 55 dB HL and a third between 60 - 75 dB HL. The exponent of the loudness function is derived for each of these intervals and can be seen in Table 4.2.

The exponent obtained from the analysis over the total range (20-75 dB HL) is close to 0.2 for both stimuli and for both test designs. But when the data is analyzed in intervals different exponents are obtained for different intervals. This is especially clear for the relative test design, where an anchor at 47.5 dB HL was used; in this case the loudness function is much more flat around the anchor point and steeper far away from the anchor.

The **squared correlation coefficient**, R^2, answers, in short, the question 'how good is the line in fitting the data point?'. It measures the variation in the samples relative to the total spread. The squared correlation coefficient is defined as[Arv]

$$R^2 = 1 - \frac{SSE}{SS_{yy}} = \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y}_i)^2}. \tag{4.2}$$

In this equation SSE is the sum of the squared differencees of the actual value, y, and the value predicted by the regression line, $\hat{y}$. SS_{yy} is the sum of the squared differences of the actual value, y, and the average value $\bar{y}$.

Analysis of variance (ANOVA) was used on the the absolute estimation test data, including both force level and subject in the model, which resulted in values of $R^2 =$ 91.21% for Stimulus 1 and $R^2 = 92.31\%$ for Stimulus 2. This implies that the seemingly low R^2 values in Table 2 for the absolute estimation data is due to individual offset in loudness scale, not a poor linear fit with respect to slope of the loudness function.

All analyzes, and both test designs, gives a somewhat higher value on the coefficient k for the stimuli 2 (noise) than for stimuli 1 (tone). The difference is especially clear

Table 4.1.: Regression analysis on the hole range of 20-75 dB HL.

	k, **mtab**	CI, **mtab**	R^2,**mtab**
tone, abs	0.191	± 0.0204	29.9 %
noise, abs	0.225	± 0.0213	35,3 %
tone, rel	0.177	± 0.0067	77,2 %
noise, rel	0.197	±0.0077	76,1 %

Table 4.2.: Regression analysis on separate parts of the range of force hearing levels.

Range [dB HL]	**20-35**	**40-55**	**60-75**
k **(tone, abs)**	0.17	0.19	0.23
k **(noise, abs)**	0.23	0.21	0.29
k **(tone, rel)**	0.25	0.13	0.18
k **(noise, rel)**	0.29	0.13	0.20

when the four lowest, and the four highest, levels of the relative test design are analyzed separately. According to the confidence intervals the difference between the slope for the tone and the noise is significant for the relative test design but not for the absolute test design.

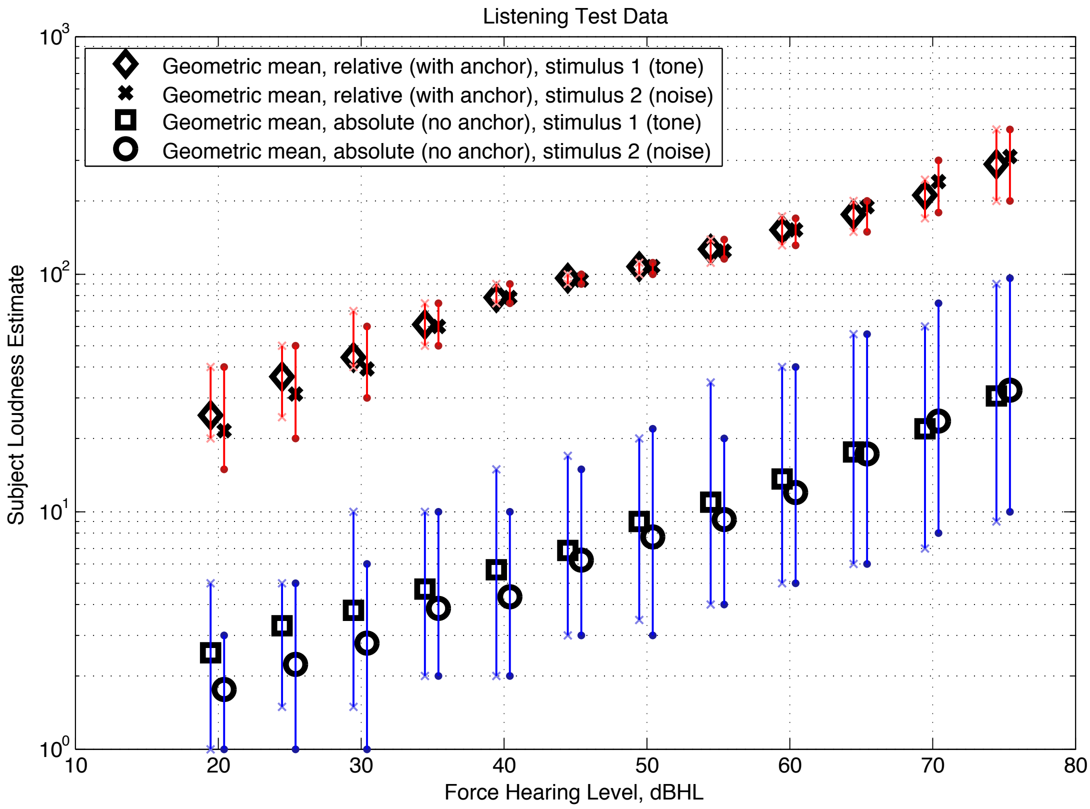

Figure 4.2.: Data from the listening test. The bold symbols (square, circle, diamond and cross) shows the geometric mean of the data. The vertical bars indicates inter quartile ranges. Stimulus 1 is a pure tone at 1 kHz and Stimulus 2 is noise with bandwidth 1 bark band around center frequency 1 kHz.

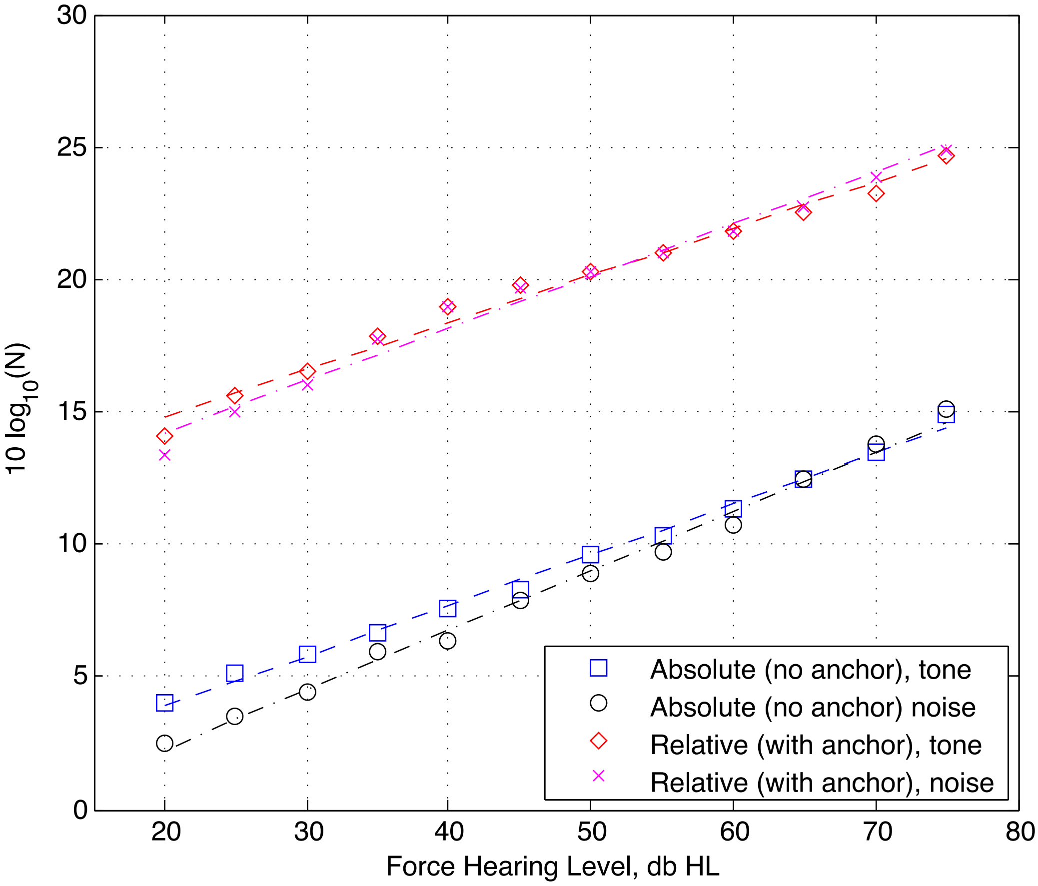

Figure 4.3.: Data from the listening test. The data point shows the geometric mean of the data and the dotted lines are curves fitted to these geometric means. The slope of the curves are: $k = 0.19$ for Stimulus 1 without anchor, $k = 0.23$ for Stimulus 2 without anchor, $k = 0.18$ for Stimulus 1 with anchor and $k = 0.20$ for Stimulus 2 with anchor.

5. Discussion and Conclusion

The exponent obtained from the regression analysis over the total range (20-75 dB HL) is close to 0.2 for both stimuli and for both test designs. Since both stimuli is within the same critical band it is expected that they should give rise to similar loudness functions, which is consistent with these results.

When the data is analyzed in intervals different exponents are obtained for different intervals. This is especially clear for the relative test design, where an anchor is used; in this case the loudness function is clearly more flat around the anchor point (47.5 dB HL) and steeper on the sides. The loudness function for AC shows a vertex so that the function is steeper below about 30 dB SPL. For the relative test design in this work the differences in slope between the different intervals show a similar behavior. However, this vertex is not seen in the absolute test design, indicating that the vertex occurs as an effect ofbias. The most obvious bias in this case is the anchor sound.

In the relative test design the squared correlation coefficients indicates that 77 % respectively 76 % of the data, for the tone respectively for the noise, can be explained by a linear relation between $10 \cdot \log_{10}(N)$ and force hearing level. For the absolute test design the corresponding portion is much lower. This is due to the fact that different listeners used different scales, resulting in a much bigger range of answers. If this fact is taken into account, which is made when the ANOVA is made, the squared correlation coefficients are instead much higher for the relative test design than they are for the absolute test design. In this case they indicates that 91 % respectively 92 % of the data, for the tone respectively for the noise, can be explained by a linear relation.

The accepted exponent of the loudness function for AC is 0.30. The results from the equal loudness investigation between AC and BC, that was made by B. Håkansson and S. Stenfeldt (see Section 1.3), indicates that the loudness function is steeper for BC than it is for AC. The calculations made in Appendix B estimates the exponent for BC as 0.33 while the results from the listening test implies that the exponent is about 0.2 for BC. How can this apparent contradiction be explained?

There tend to be a difference between the loudness functions that are measured with magnitude estimation and magnitude production respectively. In the measurement of the loudness function for AC at 1000 Hz and at 3000 Hz, see Section 1.3, the exponent obtained for 1 kHz by magnitude production was 0.35, while it was 0.27 when it was obtained by magnitude estimation. This could explain part of the discordant results, but is not enough as a single explanation.

If an essential difference could be found, between the method used in this investigation and the method that was used to measure the loudness function for AC, this could be a possible explanation of the discordant. The method, that is used in the listening test in the present study, appears to be very close to the method that is used in the measurement of the loudness function for AC at 1000 Hz and at 3000 Hz. In both measurements magnitude estimation is used, both measurements uses a relative method and in both cases the data from the first set of estimates is thrown away. A difference is however that in the present investigation the listener was clearly informed about that the first set of estimates is seen as a trial part, which does not seem to be the case in the previous investigation. Another difference is that in the AC measurement a bigger range of amplitudes is used than in the BC measurement. The range of amplitudes used in the AC measurement was 10 - 110 dB SPL with a step size of 10 dB, while the levels used in the present investigation is 20 dB HL - 75 dB HL with a step size of 5 dB. None of these differences in test design seem to give an evident explanation of why a steeper loudness function is obtained in the previous investigation than in the present investigation.

The next question is then if a meaningful disparity, between the listening test in this work and the listening test by Håkansson and Stenfeld, can be found? One thing to notice is that, in the equal loudness investigation between AC and BC, the signal was alternated so that the listener constantly heard a sound - either through AC or through BC. In the present investigation only sound heard through BC is used. If and how this could possible affect any results is left to the reader as a little exercise.

6. Further Work

To reproduce the listening test that is described in this work, but to do it for AC, would give important information. If it is found that the results give rise to an exponent k that is lower for AC than for BC - which would be consistent with the equal loudness investigation described in section 1.3 - it indicates that the methodology is the crucial point. If the results, on the other hand, shows that the loudness function is steeper for AC than for BC it gives a reason for further investigations.

Bibliography

[Ste 55] *The Measurement of Loudness*, S. S. Stevens (Psycho-Acoustic Laboratory, Harvard Univesity), *The Journal of the Acoustical Society of America*, Vol 27 Issue: 5 , pp 815-829, 1955.

[Ste 56] *Calculation of the Loudness of Complex Noise*, S. S. Stevens (Psycho-Acoustic Laboratory, Harvard Univesity), *The Journal of the Acoustical Society of America*, Vol 28 Issue: 5 , pp 807-832, 1956.

[Hel 76] *Growth of Loudness at 1000 and 3000 Hz*, Rhonoa P. Hellman, *Laboratory of Psychophysics, Harvard University, Massachusetts 02138*, 1976.

[Iso 79] ISO 131-1979, *Physical and Subjective Magnitudes of Sound or Noise in Air*, 1979. Note: withdrawn.

[Håk 89] *Skull Simulator for Direct Bone Conduction Hearing Devices.* Håkansson, B. and Carlsson P (Department of Applied Electronics, Chalmers Unev-ersity of Technology, Göteborg, Sweeden). *Scand Audiol* 1989, 18 (91-98)

[Fas 90] *Psychoacoustics - Facts and Models*, 3rd Ed., Springer Verlag, H. Fastl and E. Zwicker,1990.

[ISO 94] ISO 389-3 *Acoustics - Reference zero for the calibration of audiometric equipment - Part 3: Reference equivalent threshold force levels for pure tones and bone vibratiors*, 1st ed., 1994.

[Car 97] *The Bone-Anchored Hearing Aid: Reference Quantities and Functional Gain*, Peder U. Carlsson and Bo Håkansson, *Ear & Hearing*, 1997;18;34-41.

[StHå 01] *Air versus Bone Conduction: an Equal Loudness Investigation*, Stefan Stenfelt *, Bo Håkansson (Department of Signals and Systems, Chalmers University of Technology), *Hearing Research* Volume: 167 Issue: 1-2 Pages: 1-12, 2001

[AFS 05] *Arbetsmiljöverkets Författningssamling - Buller (AFS 2005:16)*, Arbetsmiljöverket, Sweden, 2005.

[Stn 06] *Simultaneous cancellation of air and bone conduction tones at two frequencies: Extension of the famous experiment by von Békésy*, Stefan Stefelt, Department of Neuroscience and Locomotion, Division of Technical Audiology, Lindköping University, Sweden, 2006.

[Rei 09] *Bone Conduction Hearing in Human Communication - Sensitivity, Transmission, and Applications*, Sabine Reinfeldt, Division of Biomedical Engineering Department of Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden, 2009.

[Arv] *Regression Analysis*, lecture slides by Martin Arvidsson, Division of Quality Sciences, Department of Technology Management and Economics, Chalmers University of Technology.

A. Calibration of Force Levels

The force hearing level of the actuator on an artificial mastoid, F_{act}, as a function of numerical unit in Maltab, NU, is measured. An artificial mastoid is a mechanical system, with a built-in force transducer, that designed for measurements of the of the force of an actuator. The system is designed to simulate a situation where the actuator is attached outside the skin on the hard bone just behind the ear, i.e. the mastoid.

A.1. Equipment

The following equipment is used.

- Computer, Mac book pro
- Sound card, Edirol FA-66
- N4L laboratory power amplifier LPA01
- Baha Cordelle II Headworn, serial no: 0801597
- Softband
- Cable ties
- Artificial mastoid Type 4930, Bruel & Kjaer, serial no: 2733777, calibration due Oct. 2011
- Newton meter
- PC with Matlab
- Sound card DT9837A
- FLUKE 112 True RMS Multimeter

The artificial mastoid meets the requirements specified in IECR373, BS 4009 (1975), and ANSI S3.26-1981.

A.2. Procedure

The measurement setup can be seen in Figure A.1 . A pure tone at 1 kHz, and with numerical amplitude NU, is crated in Matlab on the mac. The spectrum of the electrical signal from the artificial mastoid, and also the electrical signal into the actuator, is measured using the sound card DT9837A and a Matlab program on the PC, written by Rasmus Elofsson (2012). A calibration of the artificial mastoid is imported into the program so that the signal to CH1 is monitored as force, $\tilde{F}_{act}$. The signal into CH2 is monitored as voltage, $\tilde{U}_{act}$. The spectrum of the signals are analyzed in narrow bands and by using a steady-state, linear spectrum with a frequency resolution of 10 Hz, Flattop window. To validate the measurement the signal into the actuator, $\tilde{U}_{act}$ was also measured using a voltage meter.

The data from the measurement is then used to calculate a calibration factor corresponding to the relation between numerical unit and force hearing level. The calibration factor is implemented in the listening test (Matlab program). The force of the actuator is then measured in a second measurement, using the numerical amplitudes in the listening test program that is expected to correspond to the hearing levels 20, 30, 40, 50, 60, 70, (75) dB HL. The same measurement is done both for a pure tone at 1 kHz and for noise within one bark band with center frequency 1 kHz. In the measurement of the noise signal the data is analyzed in 3rd octave bands.

A.3. Results

The results from the first measurement of F_{act} and U_{act} is seen in Table A.1. The results show a linear dependency over the hole range of amplitudes. The ratio between the rms value of the force, $\tilde{F}_{act}$, and numerical unit, NU, (top value) is calculated as

$$\frac{\tilde{F}_{act}}{NU} = 2.7558. \tag{A.1}$$

The voltages that are measured with the voltage meter agree with the voltage that is measured using the Matlab program. The deviation between the two measurement is $\leq$ 3% and can be explained by the limitations in digits of the voltage meter. For higher levels, where more digits were displayed, the accuracy is better.

The results of the measurement that is made to confirm that the calibration factor is implemented correctly in the listening test program are seen in Table A.2. The measurement show that for both tone and noise signal the error is ≤ 0.3 dB.

Table A.1.: Measured force and voltage for a pure tone at 1 kHz with numerical amplitude NU in the Matlab program.

NU	0.0005	0.001	0.01	0.02	0.05	0.1	0.2	0.3	[-]
U_{act}	10.30	20.6	206.1	412.2	1030	2061	4121	6180	[**mV**]
F_{act}	1.245	2.506	25.8	51.88	127.8	257.0	516.9	763.4	[**mN**]
FL_{HL}	19.40	25.48	45.72	51.80	59.63	65.7	71.77	75.16	[**dB HL**]

Table A.2.: Force hearing level measured for verification. In this table the force hearing levels are measured directly from the signal that is given by the listening test program and setup.

FL_{HL}**(expected)**	20.00	30.00	40.00	50.00	60.00	70.00	75.00	[**dB HL**]
FL_{HL} **(tone, measured)**	20.00	30.08	40.20	50.30	60.29	70.18	—	[**dB HL**]
FL_{HL} **(noise, measured)**	19.7	29.8	39.9	50.1	60.2	70.3	75.0	[**dB HL**]

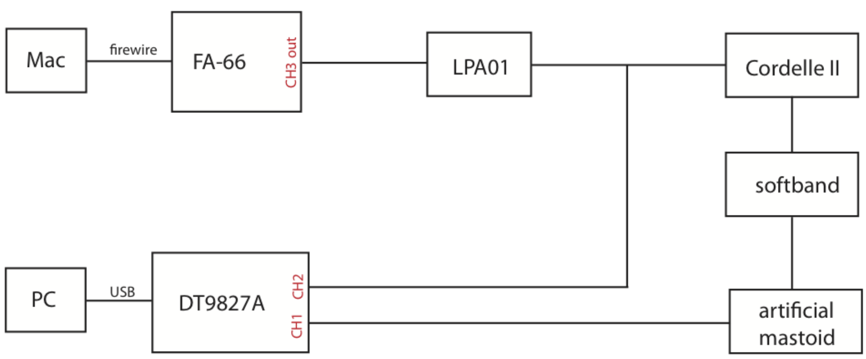

Figure A.1.: Setup during the measurement of F_{act} and U_{act}.

B. Derivation of Loudness Function for BC from Equal Loudness Investigation between AC and BC

The graph in figure 1.2 gives the following relation:

$$10 \cdot \log\left(\frac{F^2}{F_0^2}\right) = 0.92 \cdot 10 \cdot \log\left(\frac{p^2}{p_0^2}\right), \tag{B.1}$$

where F is the excitation force, p is sound pressure, p_0 is the sound pressure corresponding the the hearing threshold for a 1 kHz AC tone and F_0 is define in such a way that the two graphs coincide at SPL 30 dB HL.

Put now $F/F_0 = F_{temp}$ and $p/p_0 = p_{temp}$. This gives

$$\frac{1}{0.92} \cdot \log(F_{temp}^2) = \log(p_{temp}^2) \tag{B.2}$$

$$\Rightarrow F_{temp}^{2/0.92} = p_{temp}^2. \tag{B.3}$$

Stevens power law states that:

$$N = a \cdot (p^2)^{0.3} \qquad \Rightarrow \qquad N = b \cdot (p_{temp}^2)^{0.3}, \tag{B.4}$$

where a and b are constants. Inserting Equation B.3 in Equation B.4 gives

$$N = b \cdot (F_{temp}^2)^{0.3/0.92} = c \cdot (F^2)^{0.33}, \tag{B.5}$$

where c is a constant.

$$\therefore N \propto (F^2)^{0.33}. \tag{B.6}$$