Computer aided measurement of tinnitus spectra, residual inhibition and loudness growth

Master's Thesis

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Abstract

In this study, computer software was developed for measuring several aspects of tinnitus ('ringing in the ear'). Being able to measure these aspects can help future research in getting a better understanding of tinnitus. The software can measure tinnitus spectra, to get an idea of the frequencies present in the tinnitus. The software can also measure the depth and duration of the residual inhibition effect and measure loudness functions, that describe a subject's loudness growth. The loudness functions are measured with a modified version of the Oldenburg-ACALOS procedure. The software is equipped with capabilities to analyze and visualize the measured data, and a profile-based storage system. Experiments have been performed with this software on both normal hearing people and tinnitus patients. With the results of these experiments, the software is evaluated.

Preface

As a student in Artificial Intelligence I was always looking for an opportunity to apply the skills and knowledge that I learnt to solve problems in the ‘real world’. With this project I have found my first real challenge in doing so and I hope many more are to come.

I am thankful towards Harald Haalboom, Rick Schoffelen, Emile de Kleine, Wiebe Horst, Jan Tinbergen, Hero Wit and Dave Langers for their reflection on the research and sharing their opinion during the project.

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Contents

1. Introduction

1.1 What is tinnitus?

Tinnitus, or ‘ringing in the ears’ in common language, is a so called ‘phantom perception’ of sound. This means that only the affected subject can hear the sounds ‘in his or her head’. The type of sound that is perceived usually resembles one or several tones or noises (i.e. no voices). Doing scientific research on tinnitus is really difficult, because there’s almost nothing on the ‘outside’ that can be measured objectively. A lot of research depends on the subjective measures of the subject. Nonetheless, tinnitus can have an enormous influence on a person’s life. Common issues caused by tinnitus, are problems with sleeping, problems with concentration and stress (Alster et al., 1993; Folmer & Griest, 2000; Dobie, 2003). A lot of everyday activities can suffer from these issues and tinnitus can even result in not being able to work or have a normal relationship and social life. In the past, tinnitus used to be not taken seriously and was in many cases put aside as a psychological issue. The common advice to patients with tinnitus used to be: ‘just learn to live with it’. The more we learn about tinnitus, the more it becomes clear that it is not a psychological issue. However, as with any perception, psychology plays a role in the interpretation of the perception. Experimental remedies on the psychological field may offer relief of tinnitus, but will never cure tinnitus.

1.2 Goal of this study

Many theories about the mechanism of tinnitus exist, but none of them is proven. Finding proof is one of the major difficulties in tinnitus research, because the subjective nature of tinnitus makes it hard to measure objectively. The goal of this study is to develop and evaluate a single computer program that contains methods for measuring several aspects of tinnitus: tinnitus spectra and global properties (i.e. which ear and what type of sound), residual inhibition and loudness growth. The advantage of having these tests together in one computer program is that information can be combined and interchanged more easily. Eventually, this can help future research on tinnitus to a higher level.

1.3 Artificial intelligence in tinnitus research

In many areas of tinnitus research, knowledge of Artificial Intelligence proves to be useful. Tinnitus has a lot to do with perception and especially understanding of perception at the level of the brain. Understanding of perception is also very important for development of solid psychophysical test procedures. Knowledge about human-machine interaction will help to improve the test procedures for better user friendliness and this improves the reliability of the test data. Finally, good programming skills and understanding of measurement equipment will help to realize the intended design. All of the knowledge and skills described above are part of the discipline of Artificial Intelligence.

2. Theoretical background

2.1 Introduction

An estimated 13% of all people in the US suffer from tinnitus, making tinnitus an extremely prevalent disorder (McFadden, 1982). Only one quarter of them seeks medical help for their disorder (McFadden, 1982). The number one cause for tinnitus is exposure to loud sounds, but there are many other causes, like an ear infection, concussion of the brain, tumor or side-effect of medication. A good treatment for tinnitus is still not available, but more research is being done on tinnitus to find out the mechanism behind it. This study being one of them.

2.2 The ear and the auditory pathway

Figure 2.1 shows the inner ear. When sound from outside the body enters the ear canal it is mechanically conducted through the middle ear by the eardrum, the hammer, the anvil and the stirrup. Finally the vibrations are conducted to the cochlea. Inside the cochlea the basilar membrane is situated. The stiffness of it is variable along the basilar membrane, resulting in a different resonance frequency for each part of the membrane. When a sound is conducted to the basilar membrane, only the parts of the membrane of which the resonance frequency corresponds to the frequencies in the sound start to vibrate. In other words, the frequencies in the spectrum of the presented sound are now spread over the basilar membrane. The membrane contains many hair cells that can be divided in two categories: the inner hair cells and the outer hair cells. The inner hair cells respond to the vibration of 'their' part of the basilar membrane by generating neural potentials that are sent through the auditory nerve to the brain. Different theories exist about the function of the outer hair cells, but none of them has been proven yet. One thing in general that can be said about the outer hair cells is that they have the ability to start vibrating themselves. It is also confirmed that the outer hair cells receive efferent information from the brain. Their specific function however is still unknown. A hypothesis about the function of the outer hair cells will be discussed in the chapter 'Discussion'.

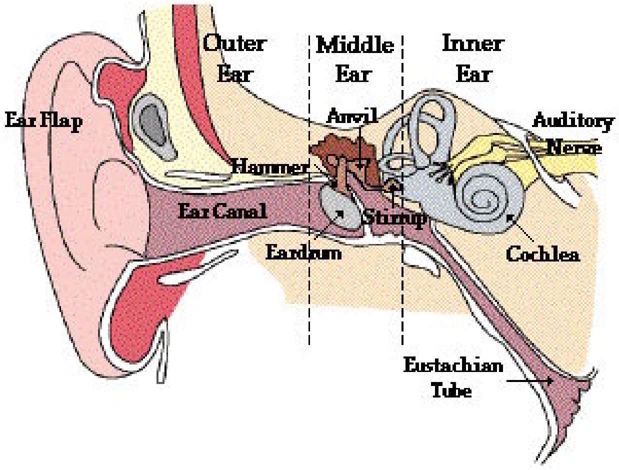


Figure 2.1   The inner ear (image courtesy of http://www.nasa.gov).

The neural potentials that are generated by the inner hair cells, travel through the auditory nerve to the brainstem, where the signal is first processed by the cochlear nucleus (Figure 2.2), which plays an important role in tonotopic organization. The next step in the auditory pathway is the superior olivary nucleus. The olivary nucleus is thought to play a role in the detection of phase and loudness differences between ears, which is very important for localization. Then the signal reaches the inferior colliculus, which is thought to play an important role in integration of perceptual signals (i.e. startle reflex and ocular reflex). From the inferior colliculus the signal flows to the thalamus. In the thalamus, the medial geniculate nucleus relays the auditory signal to the auditory receiving area (Figure 2.2). The auditory receiving area can be divided into three stages: the primary, secondary and tertiary auditory cortex. Each stage represents another level of processing of the auditory information (Kalat, 2001).

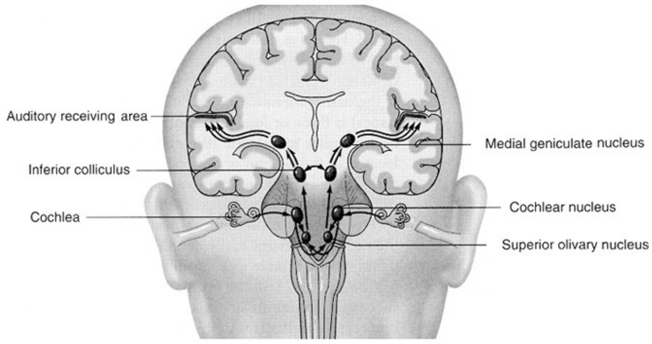


Figure 2.2 The auditory pathway (image courtesy of http://www.bvu.edu).

2.3 The mechanism of tinnitus

It is important to understand that tinnitus is a symptom and not a disease. As already mentioned, tinnitus can have many causes and it is highly unlikely that all these forms of tinnitus will have the exact same underlying mechanism. Therefore, it is unlikely as well, that there will be one remedy that cures all forms of tinnitus. Many theories exist about the mechanism that causes tinnitus, but none of them is proven yet. Some theories propose that the subjects might be directly perceiving their own spontaneous otoacoustic emissions, originating in vibration of the outer hair cells, or other somatosounds, like blood flowing through veins. A study by Penner (1990) shows that in only 4% of all cases an objective correlate can be found with spontaneous otoacoustic emissions. The same percentage was found for an objective correlate with somatosounds (McFadden, 1982).

One issue that many other theories on the mechanism of tinnitus seem to share, is that tinnitus originates in an abnormal amount of gain somewhere in the auditory system (Jastreboff & Hazell, 1993; Eggermont & Roberts, 2004). This abnormal amount of gain could be explained as the auditory system trying to compensate a lack of input from damaged inner hair cells. In this case the tinnitus should go side by side with damaged inner hair cells and hearing loss on the same frequency as the sound of the tinnitus. Another indication of an abnormal amount of gain is that tinnitus often coexists with, or is preceded by hypersensitivity of the auditory system for certain sounds (Jastreboff & Hazell, 1993). This hypersensitivity is called hyperacusis and it is also an indication of increased gain in the auditory system.

In some theories, tinnitus is explained as caused by damage to the outer hair cells (Jastreboff & Hazell, 1993). Subjects with this type of damage usually have normal audiograms, but nonetheless experience tinnitus. These theories are supported by pathological findings of damaged outer hair cells in subjects with this type of tinnitus and normal audiograms.

Another interesting finding is that tinnitus often persists if the auditory nerve is cut. This is strong evidence for the idea that tinnitus is caused in the brain by a mechanism that tries to compensate the lack of input on the auditory nerve. This could be compared to phantom pain that is experience by people who have lost a limb (Jastreboff & Hazell, 1993). Even normal hearing people seem to have the mechanism that compensates for a lack of input. Most people start to experience some sort of tinnitus after a while, when they are placed in an anechoic chamber.

2.4 Remedies for tinnitus

A remedy that proves to be working in some cases, is the use of a hearing aid or white noise masker (Jastreboff & Hazell, 1993). Both devices present more sound to the ear than under normal circumstances, which results in more input to the auditory system. This helps in preventing the hypersensitivity of the auditory system due to a lack of input. However, it does not cure the tinnitus in any way.

A problem that may cause many remedies to initially fail, is the strong imprinting of the tinnitus in the brain (Jastreboff & Hazell, 1993). The neural pathways that recognize the sound of the tinnitus have been stimulated so much, because the tinnitus is always present, that even a very soft version of the tinnitus is enough to activate them and initiate the full experience of tinnitus. ‘Unlearning’ the pattern of the tinnitus is difficult and this strongly influences the effect of any possible remedy. Differences might become noticeable after months (Jastreboff & Hazell, 1993).

2.5 Measuring tinnitus spectra

To be able to confirm or reject theories about the mechanism of tinnitus, a lot more information is needed about how the tinnitus behaves, what it sounds like and if it can be manipulated somehow (Norena et al., 2002). A simple test to get an idea about what a subject is hearing, is through interaction with the subject and the use of an audiometer. With the audiometer tones, noise and warbles can be presented to imitate different kinds of tinnitus. The researcher raises or lowers the pitch until the subject says that the sound matches the tinnitus (more or less). A more precise way of testing could be achieved with a computer program that helps the researcher in presenting all kinds of sounds and helps the subject in matching them. This has been done in a study of Roberts, Moffat & Bosnyak (2005). The results of this study show that in many cases there is a correlation between the audiogram and the spectrum of the tinnitus. The frequency of the tinnitus is usually around the frequency where with the hearing loss is the most severe.

2.6 Measuring residual inhibition

Another aspect of tinnitus that can be measured, is the so called ‘residual inhibition’ effect. This means that the tinnitus can be influenced with the presentation of sounds to the subject. After such a sound is presented, the subject experiences that the tinnitus is (partially) suppressed for a while. Unfortunately, the effect usually does not last long. According to the online tinnitus archive (www.tinnitusarchive.org, gathered by the Oregon Tinnitus Clinic between 1981 – 1994) , approximately 88 percent of the tinnitus subjects experience some form of residual inhibition. The duration of this effect typically lies between 30 seconds and 2 minutes, for approximately 80% of the subjects.

Studying the residual inhibition effect might help to evaluate existing theories on the mechanism of tinnitus or bring up new theories. It can be studied while performing an fMRI scan simultaneously, to see if any activity or inactivity in the brain is noticeable during the inhibition. A risk, however, is that conclusions about the generation of tinnitus are made, based on the correlation between residual inhibition and the fMRI scans. The generation of tinnitus and the suppression of it during residual inhibition can be totally different mechanisms.

The computer program of Roberts, Moffat & Bosnyak (2005) also contains a test for residual inhibition. The results of this test show correlation with both the audiogram and the tinnitus spectrum, meaning that residual inhibition is best evoked with frequencies that resemble the tinnitus.

2.7 Measuring loudness growth

The term loudness growth is used to describe the relation between the subjective loudness of a sound, as perceived by a subject, and the objective level of this sound in decibels. The mathematical description of this relation is called the loudness function. Loudness functions are not uniform across all frequencies that the human auditory system can perceive, it may vary depending on the frequency.

Loudness functions can tell a lot about the auditory system. Any hearing loss (i.e. raised thresholds on an audiogram) will be visible in the loudness functions, but it will also be visible how this hearing loss affects sounds at different levels. In the last decades several procedures have been developed to measure loudness functions. The most difficult problem in developing these procedures is to measure a subjective loudness scale objectively. A recently developed and well performing procedure to measure loudness functions is the Oldenburg-ACALOS method (Brand & Hohmann, 2002; Brand & Hohmann, 2001). This is an adaptive method in the sense that it adjusts to the responses of the subject. This adaptation plays a crucial role in objectifying the subjective loudness perception, because it assures that the entire dynamic range of the subject is covered and that the levels of the stimuli are distributed equidistantly over this range.

Measuring loudness growth is very important for evaluation of theories on tinnitus mechanisms, since abnormal gain in the auditory system is thought to play a role in tinnitus (Jastreboff & Hazell, 1993). Therefore, effects of abnormal gain should show up in the loudness functions. The original article of Brand & Hohmann (2002) focuses primarily on evaluation of the ACALOS method, but it also confirms that in the measured loudness functions of hearing impaired people a phenomenon called ‘loudness recruitment’ can be seen. Loudness recruitment is a change in the slope of the loudness function that occurs with shifted hearing thresholds. The upper threshold of the auditory system remains unaffected by hearing loss. It is only in the lower parts of the function (i.e. lower levels) that differences appear.

3. Design and implementation

3.1 Design constraints

When developing software that is used in experiments with human subjects, there's virtually no room for error. In the development of software that is simply used for something like writing an article, an error may be frustrating but not harmful. In experiments with subjects, an error can have a much bigger impact. In the case of this project, the subject hears sounds through a pair of headphones. The sounds are computer controlled. An error in the software might therefore result in the presentation of harmful sounds. Damaging a person's hearing is unacceptable, especially when it is a patient who already has a hearing impairment. Any damage with hearing impaired people can mean the difference between leading a normal life and not being able to interact with the outside world anymore. Knowledge of safe hearing levels is required as well as understanding of calibration and different decibel scales. Programming skills are also very important to make sure that the program really does what it is expected to do. No time should be spared if it is spent on checking the code and testing the program. Finding errors on trial-and-error basis is not a good idea when working with human subjects. The developer should also think about the program being used by other researchers and making it as 'fool-proof' as possible. This way the developer takes as much responsibility for the safety of the subject as possible.

Another important constraint is that the testing methods should be reliable and efficient, since these kind of tests are often uncomfortable for a subject. Tinnitus subjects have less tolerance for a long test than normal hearing subjects, since focusing on the tinnitus itself is often considered very fatiguing (Brand & Hohmann, 2002; Jastreboff & Hazell, 1993). This fatigue can result in a temporarily more severe tinnitus and less reliable results from the tests, because tired subjects can respond less accurately. Hence, the goal is to develop testing methods with high reliability and as little discomfort as possible.

The software should also be user friendly for both the subject and the researcher. There is however a trade-off between user friendliness and flexibility. The program should allow for many different experiments to be performed, with different stimuli, durations, etc. Within these flexibility options the program should then be as easy as possible to use.

3.2 Implemented features

3.2.1 Loudness and safety

For development of the software, Matlab (version 2006b) was chosen as the programming language. Matlab handles complex mathematics easily and the GUIDE component of Matlab is a great tool for developing a graphical user interface. Another advantage is the easy interaction with the ActiveX control element for the Tucker Davis hardware.

A couple of features were implemented in this software to prevent the subject from listening to harmful sounds. The first feature is that the entire software package is calibrated to an absolute maximum of 90 dB HL. When the calibration is done correctly no louder sounds are possible. 90 dB HL is safe for normal hearing people when it is not presented for too long. For patients, for instance a subject with hyperacusis, 90 dB HL is not guaranteed to be safe. Therefore, a global setting in the software can be used to limit all sounds to a maximum set by the researcher.

The last feature that has to do with the level of the stimuli can be found in the testing methods. None of the tests present loud stimuli 'out of the blue'. In all cases, the levels of the stimuli presented to the subjects are adjusted either by the subjects themselves or by the ACALOS method that carefully tries to find the dynamic range of a subject's auditory system and stops when the subject indicates a sound as too loud. The only stimulus in the entire program that is presented with a level not depending on the subject's responses, is the first stimulus of the ACALOS test. The first stimulus has a moderate level of 50 dB HL.

3.2.2 Interface, instructions and controls

The software is designed to run on a computer with a dual screen setup. This separates the graphical user interfaces for the researcher and the subject over two screens. The language for the researcher's interface is English. The language for the subject's interface is initially Dutch. All text lines in the subject's part of the interface are loaded from a set of text files on the hard drive. These text files can be modified easily by non-programmers to translate them or formulate the phrases differently.

On the screen of the subject a progress bar appears during the tests. This keeps the subject informed on the progress of the test that is currently running.

The subjects can interact with the interface on their screen with a response knob. This knob is actually a rotary knob and pushbutton at the same time. It is connected through USB and the driver software converts the knob's activities into keyboard commands. Rotation generates a *left* or *right arrow* command and pushing generates a *space bar* command. An advantage of this configuration is that it is easy to switch to another input device. The USB connection is very common and many input devices can be configured to generate key commands. The reason for this design was a request to prepare the software for future use in an fMRI scanner, where metal objects cannot be used because of the strong magnetic field of the scanner. A non-metal input device can easily be connected to the software.

3.2.3 Settings

The program contains a settings window (Figure 3.1) that allows the researcher to do many experiments with basically the same test routines. In the settings window the following parameters can be adjusted.

- Maximum level (dB HL) – as described under 'Loudness and safety', this parameter can be used to limit every stimulus in the software to a maximum output level.

- Stimulus mode – This parameter indicates on which ear the stimuli are presented and about what ear the questions are formulated. The stimuli can be presented to the left, the right or both ears. The questions can be formulated about the ear(s) the stimuli are presented to, or the opposite ear . This is called contra-lateral testing and it allows to study the effect of stimuli to the tinnitus perception on the opposite ear.
- ACALOS parameters – Currently, only one parameter is available here. This parameter controls the number of iterations in the last phase of the ACALOS test (see section 4.6.1, step 4).
- Residual Inhibition parameters – These parameters control the way the residual inhibition test is performed. More about these parameters is explained in the chapter 'Methods' and in the help-file that is included with the software.
- Stimuli selection – This selection window controls which stimuli are used during the ACALOS and residual inhibition tests.

3.2.4 Storage of results

For each subject, a profile can be created that contains general information about the subject (name, date of birth, gender, registration number and short description). The results of each test performed with this subject will be stored to this profile. With the results of each test, the date it is was performed on is stored, as well as the settings that were used to configure the test.

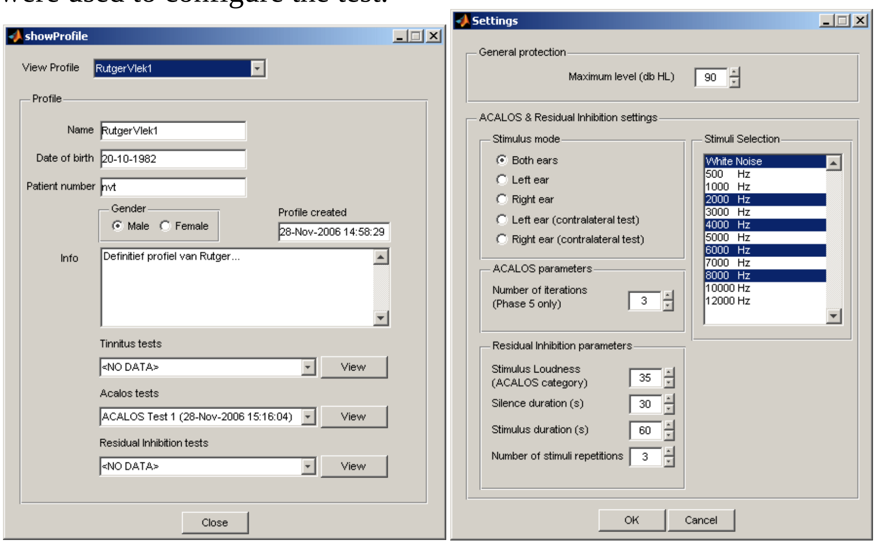


Figure 3.1 The analysis module (left) and the settings window (right)

3.2.5 Data analysis

To analyze and view the data, an analysis module was implemented (Figure 3.1). This module shows the most important results for each test and includes a function to print the results. The profile data can also be exported to Microsoft Excel format.

3.2.6 Help function

To help a researcher in working with this program, a Windows CHM-conform help file was created. It contains full documentation on all program features.

3.3 Stimulus generation and hardware

The software is meant to cooperate with Tucker Davis hardware (more on this in the chapter ‘Methods’) and it utilizes a real-time processor (RP2) to produce the stimuli. A virtual circuit was designed for this real-time processor. On startup of the software this circuit is loaded into the real-time processor. The software then interacts with it through ‘tags’. These ‘tags’ allow the software to modify the circuit in order to change parameters like gain and frequency, and control gates to start and stop certain signals. The circuit and a list of the available tags can be found in Appendix B.

In the circuit there are two sound generators. One produces Gaussian noise and one produces sine waves. The Gaussian noise is controlled by several gates that can result in three different signal paths. The first path is a direct path that leaves the Gaussian noise untouched, which makes it the white noise stimulus. The second path is through a Butterworth band pass filter. This filter can be set to a certain center frequency and bandwidth. This setup is used for producing the NBN10 stimuli. The third path is actually at first the same as the second path, but in series with the first Butterworth filter it is routed through another Butterworth filter with the exact same specifications (frequency and bandwidth). This setup is used for the NBN3 stimuli. The three signal paths of the Gaussian noise and the one of the sine wave finally are summed together. The summed signal is fed into a modulator that can be switched on or off. If the modulator is turned on it modulates the amplitude of the signal with a sine wave at a frequency of 2 Hz and a depth of 40%. This way the sound can be made ‘pulsating’. In the last step the signal is split into two signals (for stereo outputs) and fed into the gates that control whether the left and right channels are open or closed.

4. Methods

4.1 Equipment

In preparation of the experiments the software was installed on a computer with two TFT screens. The computer itself and the first screen are placed in the room where the researcher sits during the experiments. This screen displays the research environment of the software. The second screen is placed inside a sound isolated booth and displays the subject’s environment of the software. A connection to the computer outside the booth was made through a wall mounted patch panel. To register the responses of the subject, a USB control knob (of the type Powermate by Griffin Technology) was placed inside the isolated booth and connected through the patch panel to the computer outside the booth.

For generating the stimuli, the software controlled a rack of hardware (Figure 4.1). This hardware was manufactured by Tucker Davis Technologies and consisted of the following modules:

- 1 x Real-Time Processor (RP2)
- 1 x Headphones Buffer (HB7)
- 2 x Programmable Attenuators (PA5)

The stimuli were presented using Telephonics TDH-49 headphones with MX-41/AR ear cushions. The Tucker Davis equipment was placed outside the isolated booth and the headphones inside the booth were connected through the wall mounted patch panel.

Figure 4.1 The Tucker Davis hardware and how it is connected.

4.2 Stimuli

The combination of the software and the hardware described above allowed for many different stimuli to be produced. Currently the setup is able to produce the following stimuli.

- White noise (Gaussian)
- Sine waves at 11 frequencies
- Narrow band noise (NBN10) filtered at 11 different center frequencies
- Very narrow band noise (NBN3) filtered at 11 different center frequencies

The 11 frequencies described above (for the sine waves and both types of narrow band noise) are 500Hz, 1kHz, 2kHz, 3kHz, 4kHz, 5kHz, 6kHz, 7kHz, 8kHz, 10kHz and 12kHz. The NBN10 narrow band noise is produced by filtering the Gaussian noise with a second order Butterworth band pass filter set to a bandwidth of 10% of the centre frequency at the -3 dB roll off point. The NBN3 very narrow band noise is produced by filtering the Gaussian noise with two second order Butterworth band pass filters in series. Both filters are set to a bandwidth of 3% of the centre frequency at the -3 dB roll off point.

4.3 Calibration

4.3.1 Calibrating to Sound Pressure Level

All stimuli (34) were calibrated to an output level of 90 dB SPL (Sound Pressure Level). This calibration was performed with the following equipment:

- Bruel & Kjaer 2636 measuring amplifier
- Bruel & Kjaer 2660 preamplifier (set to linear +20 dB)
- Bruel & Kjaer 4134 microphone head
- Kemar artificial head with a DB100/175 coupler built in

The attenuators (PA5) were set to 0 dB attenuation and the headphones buffer (HB7) was set to -18 dB gain for an AC signal. The differential switch on the headphones buffer was switched off, since it is meant for mono signals only. The Telephonics headphones were placed on the Kemar artificial head and the calibration was performed on the right earphone only.

4.3.2 Calibrating to Hearing Level

The levels of the stimuli in the software are all expressed in the dB HL (Hearing Level) scaling. This scaling is commonly used in audiometrics and represents the amount of decibels above the average hearing threshold (for normal hearing people) for a sound. For sinusoidal sounds these average thresholds are well known and registered in an ISO-norm. However, for the types of stimuli used in this project there is no HL-scaling available. This problem lead to the first experiment in this project: to measure the average hearing thresholds for each stimulus with normal hearing subjects.

With the SPL calibration completed, stimuli could be presented with a known level to a subject to measure the hearing threshold in dB SPL for each stimulus. For each stimulus the following procedure was used to estimate a subject's hearing threshold.

- A stimulus is presented for 1 second followed by 1 second of silence.
- The subject is asked to press a button every time he/she hears a sound.
- Starting at 50 dB SPL the stimulus level drops with 10 dB each time the subject presses the button.
- If the subject no longer presses the button (because the level is inaudible) the stimulus is presented again. If, after a total of 4 seconds (in which the stimulus is presented twice) no response is given, the stimulus level is increased with a step of 10 dB. This procedure of time-out and increase in level is repeated until the stimulus becomes audible again and the subject presses the button.

- Now the stimulus level is decreased again every time the subject presses, but the step size is now 3 dB. The decreasing sequence ends when the subject doesn't answer for 4 seconds (and the stimulus has become inaudible again).
- The hearing threshold is then calculated from the last audible level.

After performing this experiment on a group of normal hearing subjects, an average hearing threshold in dB SPL was calculated for each stimulus. These hearing thresholds were used in the final calibration routine to adjust all stimuli to the maximum allowed output of 90 dB HL.

4.4 Training procedure

To help the subject in understanding how to work with the program, a training routine was developed. This routine trains the subject in handling the response knob and prepares the subject for the type of questions and response scales that can be expected in the tests. Subjects are asked to try how the scales on the screen respond to the movement of the response knob. Subjects are also given control over the loudness and pitch of a stimulus to let them find out what is meant with the terms *pitch* and *loudness*.

4.5 Tinnitus test procedure

The purpose of the tinnitus test is to get an idea of what the subject's tinnitus sounds like. The test is inspired by a similar test by Roberts, Moffat & Bosnyak (2005). The test consists of 7 steps:

1. The subject is asked on which ear the tinnitus is predominantly perceived (left, right or both ears) – all following stimuli will now be presented to this ear only (or both in case of tinnitus on both ears)
2. The subject is asked to set the level of a 1kHz sine wave to a comfortable level
3. The subject is asked what type of tinnitus is perceived (tonal, ringing or hissing, corresponding with a sine wave, an NBN3 or an NBN10 stimulus). There is an audio example for each type of sound. The example is played at the level indicated in step 2.
4. The subject is asked if the tinnitus is pulsating or steady in nature. Example sounds are played and the example depends on the type of sound selected in step 3.
5. The subject is asked to indicate the general severity of the tinnitus on a linear scale from -50 to 50 with five labels: 'very soft', 'soft', 'moderate', 'loud', 'very loud' (originally in Dutch this was 'zeer zacht', 'zacht', 'matig', 'hard', 'zeer hard') evenly distributed over it.
6. The subject is asked to match the loudness of each stimulus from a set of stimuli to the loudness of the tinnitus. The type of sound that is used for these stimuli is the type that was selected in step 3. With this type of sound 11 frequencies are presented twice in random order. By rotating the response knob, the level of the stimulus can be changed until it matches the loudness of the tinnitus (in steps of 1 dB). Pressing the button submits this answer and proceeds to the next stimulus.

7. An average matching loudness is calculated for each of the 11 stimuli from the previous step. The stimuli are presented again at this matched loudness three times in random order. The subject is asked to give each stimulus a ‘likeness rating’. This indicates how much the stimulus is part of the tinnitus that is perceived. The exact question was: ‘Is this sound part of your tinnitus?’ (in Dutch: ‘Komt dit geluid voor in uw Tinnitus?’). A linear scale from 0 to 100 was used with five labels: ‘no’, ‘a little bit’, ‘moderate’, ‘clearly’, ‘identical’ (originally in Dutch this was ’niet’, ‘klein beetje’, ‘matig’, ‘duidelijk’, ‘identiek’) evenly distributed over it (Figure 4.2).

For answering the ‘multiple choice’ questions in step 1, 3 and 4, so called ‘radio buttons’ were used (Figure 4.2). By rotating the knob, the correct answer could be selected and by pressing it the answer was submitted.

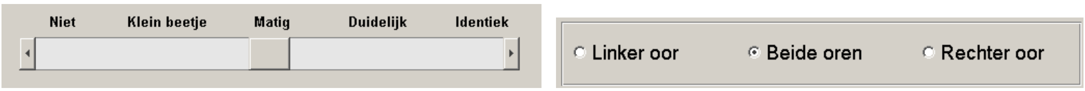


Figure 4.2 Response scales for the tinnitus test.

4.6 ACALOS test procedure

4.6.1 The adaptive procedure and the response scale

The purpose of the ACALOS test (Brand & Hohmann, 2002) is to estimate loudness functions. These functions show how the subject perceives the loudness of sounds at different levels. The following procedure is used to measure a loudness function.

1. The procedure starts with a level of 50 dB HL. If the subject rates this level as too loud or inaudible, the level is changed with 15 dB until the subject gives a rating between ‘very soft’ and ‘very loud’.
2. Starting at the level where the previous step ended two alternating sequences are started. One sequence is ascending while the other is descending. The software alternates between both sequences every other presentation of a level. For the ascending sequence a step size of 10 dB is used below 60 dB HL and above it a step size of 5 dB is used. The ascending sequence ends when either the maximum allowed level is reached or the subject has answered ‘too loud’. For the descending sequence a step size of 15 dB is used until the sound becomes inaudible. If this happens, the descending sequence turns into an ascending one with a step size of 5 dB until the sound becomes audible again. The descending sequence ends when either the direction is changed into an ascending sequence and the sound has become audible again or the sound was never inaudible and the minimum of -30 dB HL was reached. This minimum is determined by the maximum amount of attenuation the hardware is capable of.
3. A linear interpolation is made between the levels where the ascending and descending sequence ended (in other words the subject’s maximum and minimum). With this linear interpolation five new levels are calculated and presented, based on five of the eleven available loudness categories that are

internally connected to the response scale as seen in Figure 2.1. Categories 5, 15, 25, 35, and 45 are used for this interpolation.

4. The model (see section 4.6.2) is fitted to all previously measured data points. From this fitted function 5 new levels are calculated and presented (again at categories 5, 15, 25, 35, and 45). This step is iterated 2 times (and every time a new fit is made). After the final repetition a third and final model fit is made to all previously measured data points. This final fit is the actual measured loudness function.

All stimuli were presented twice for two seconds with a silence of one second in between. The response scale (Figure 4.3) is permanently visible to the subject. This response scale contains 11 response alternatives, some of which are labeled and some unlabeled. The labeled ones are ‘very soft’, ‘soft’, medium’, ‘loud’, ‘very loud’, ‘TOO LOUD’ (originally in Dutch these were ‘zeer zacht’, ‘zacht’, ‘middel’, ‘luid’, ‘TE LUID’). The response alternatives correspond with an internal loudness category ranging from 0 to 50 in steps of 5. These loudness category numbers are used in the calculation of the ACALOS function, but are not visible to the subject.

During the presentation of a sound, the bar that highlights the currently selected loudness category on the response scale is colored red. The selection bar can be changed to another category, but submitting the answer can only be done when the entire stimulus of 5 seconds in duration has ended. This is indicated by the color of the selection bar changing from red to green when the sound has ended. The response alternative ‘TOO LOUD’ is always available and always shown in green when the selection bar is moved over it. Pressing the ‘TOO LOUD’ alternative stops the stimulus immediately. Such a response is remembered as an absolute maximum and the program never exceeds a level that is once rated as ‘TOO LOUD’.

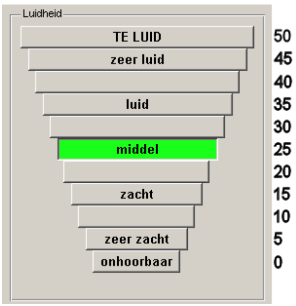


Figure 4.3 The ACALOS response scale. The numbers on the right side indicate the loudness category as used in calculations, but they are not visible to the subject.

4.6.2 The modified ACALOS model

The model that was used in this study to fit the data is shown in Equation 1. It consists of two linear parts, one below category 15 (Equation 1a) and one above category 35 (Equation 1b), and a Bezier function (Equation 1c) in between (category 15 to 35), to smooth the intersection between the linear parts. A special situation occurs when the two linear parts have the same slope and thus form a single straight line. In this situation the

Bezier function is not able to smooth the intersection, since it is already smooth. Calculating the Bezier function anyway would result in a division by zero and therefore no solution of the equation. To avoid this exception an extra condition was added to the selection conditions of the linear parts (this is different compared to the formula of Brand & Hohmann (2002)). Now the linear functions are used to calculate the model output between the categories 15 and 35 in case both slopes are identical.

$$M(C) = \begin{cases} \left(\dfrac{C-25}{m_{lo}}\right) + L_{cut} & for \quad C \le 15 \vee (C \le 25 \wedge m_{lo} = m_{hi}) \quad \textbf{Equation 1a} \\ \left(\dfrac{C-25}{m_{hi}}\right) + L_{cut} & for \quad C \ge 35 \vee (C \ge 25 \wedge m_{lo} = m_{hi}) \quad \textbf{Equation 1b} \\ x_3\left(\left(t(C) + \dfrac{x_2}{2x_3}\right)^2 - \dfrac{x_2^2}{4x_3^2}\right) + x_1 & for \quad (15 < C < 35) \wedge m_{lo} \ne m_{hi} \quad \textbf{Equation 1c} \end{cases}$$

Where:

$$t(C) = \frac{C}{y_2} - \frac{y_1}{y_2}$$

$$x_1 = \frac{15-25}{m_{lo}} + \mathrm{L}_{\mathrm{cut}} \qquad y_1 = 15$$

$$x_2 = (2 \cdot L_{cut}) - 2\left(\frac{15-25}{m_{lo}} + \mathrm{L}_{\mathrm{cut}}\right) \qquad y_2 = (2 \cdot 25) - (2 \cdot 15)$$

$$x_3 = \left(\frac{15-25}{m_{lo}} + \mathrm{L}_{\mathrm{cut}}\right) + \left(\frac{35-25}{m_{hi}} + \mathrm{L}_{\mathrm{cut}}\right) - (2 \cdot L_{cut}) \qquad y_3 = 15 - (2 \cdot 25) + 35$$

M	**: The model output in decibels**
C	**: The model input in a certain loudness category (0 to 50)**
m_{lo}	**: Slope of the lower linear part of the model**
m_{hi}	**: Slope of the upper linear part of the model**
L_{cut}	**: The point in decibels where both linear parts would intersect if no smoothing was applied**

Fitting of the model to the measured data points was done using a least-squares method. Equation 2 describes this calculation of the squared error. The model parameters that are adjusted to get the best fit, i.e. the least squared error, are m_{lo}, m_{hi} and L_{cut}.

$$\varepsilon = \sum_i (E_i - M(C_i))^2 \qquad \textbf{Equation 2}$$

M	**: The sound pressure in dB HL**
C_i	**: The subjective loudness (between 0-50) as rated by the subject at presentation of level E_i**
E_i	**: The level of the stimulus in dB HL**
ε	**: The squared error between the model and the subject's responses.**

4.6.3 Differences between the modified ACALOS and original model

There are several differences between the method used in this study and the ACALOS method as originally proposed by Brand & Hohmann (2002):

- The starting level of the test is lowered from 85 to 50 dB HL. The step size turning points are lowered equally. The reason for this was a suspected offset (approximately 10 dB) in our calibration which made 85 dB HL too loud. In our opinion, even with a correct calibration, 85 dB seems quite loud to start with. These arguments lead to the fair amount of level reduction.
- A level once indicated as 'TOO LOUD' will never be exceeded. In the original method a maximum of 5 dB above the last level rated as 'TOO LOUD' was allowed. To ensure that no harmful sounds are presented to the subject this constraint has been changed. Unfortunately it increases the chance that the ACALOS method does not cover the subject's entire loudness range, but safety had a higher priority in this study.
- The testing range is extended below 0 dB HL to -30 dB HL. Brand & Hohmann themselves already indicated that it would be better to extend the range. Fortunately, the equipment used in this study had the capabilities to do so.
- The linear interpolation step is used to generate 5 new categories instead of 4. The generated levels are now based on the same 5 categories as the next step and the first model fitting procedure has more data to work with.
- After the linear interpolation in the step above, the model is used for further data fitting. In the original ACALOS method the data are always fitted to a linear function and the model is used for the final fit only. With the new fitting procedure, the adaptation during the test results in equidistant dispersal of the stimuli over the subjective loudness scale instead of the scale in decibels.
- The model that is used to fit the data is the inverse of the one used by Brand & Hohmann. This makes much more sense, since the category is now the parameter and the level in dB is the result on which the error to the data is calculated.
- The Bezier smoothing was explicitly omitted when the slopes of the linear parts are identical. Calculating a Bezier function in this case would have resulted in a division by zero and therefore no solution of the equation.
- The model formula (the inverse of Brand & Hohmann's) was corrected. An essential pair of round brackets was missing in the function description in the appendix of the original article. It is assumed that the erroneous formula is only a misprint in the article and has not been used to generate the published results with. An error of this type would result in a fatal error in the software that cannot go unnoticed.

4.7 Residual inhibition test procedure

The purpose of the residual inhibition test is to quantify the residual inhibition effect in terms of depth and duration. The test is inspired by the works of Roberts, Mofat & Bosnyak (2005). NBN10 type stimuli are used to evoke the residual inhibition. These stimuli are presented at a level corresponding to the loudness category 35 of the previously estimated ACALOS functions. Therefore, every stimulus in the residual inhibition test requires a premeasured ACALOS function to estimate this level from.

During the residual inhibition test the selected stimuli are presented three times in random order with the following procedure:

1. The subject is asked to listen to his/her tinnitus for 30 seconds
2. The stimulus is presented for 60 seconds
3. Directly after the stimulus ends, the subject is asked how the tinnitus has changed in comparison to the situation before the presentation of the stimulus (step 1).
4. The subject is asked to indicate when the tinnitus is back to its normal loudness again

The response scale that is used for answering the question in step 3 is shown in Figure 4.4. The slider responds to the rotation of the knob and the answer is submitted when the knob is pressed. The scale is a linear one between -50 and 50. In step 4 the subject simply presses the knob when the tinnitus has returned to its normal loudness.

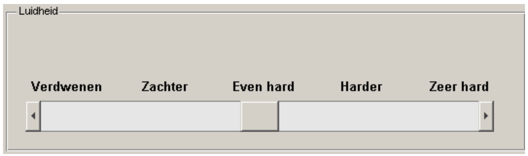


Figure 4.4 Response scale for indication of the residual effect depth

4.8 Subjects and measurement program

During the project several experiments were performed. The first experiment was to measure the average hearing threshold of normal hearing subjects for the stimuli in the software (see section 4.2). This experiment was performed with 10 normal hearing subjects (5 male, 5 female, all thresholds ≤ 20 dB HL). The experiment took about 15 minutes for each subject in which the thresholds for 34 stimuli were measured. Subjects were recruited on voluntary basis (no payment).

The second experiment was about the measurement of the ACALOS functions for normal hearing subjects (see section 4.6). While the implemented ACALOS test is capable of testing 12 different stimuli, only a selection of stimuli was used for this experiment. This selection consisted of White Noise and 4 frequencies of the NBN10 noise (2kHz, 4kHz, 6kHz, 8kHz). Initially 15 subjects were recruited on voluntary basis to take part in the experiment. Preceding to the experiment, an audiogram was made. From the results of the audiogram, three subjects were excluded from the group of normal hearing subjects because their thresholds exceeded the constraints for the normal hearing group (thresholds ≤ 20 dB HL). The remaining normal hearing group consisted of 3 female and 9 male subjects with an average age of 26.5 ± SD=7.8 years. As mentioned, the experiment started with making an audiogram, followed by a brief explanation, the training program and finally the ACALOS test. The whole experiment took about 30 to 45 minutes for each subject. Three of the normal hearing subjects have performed the ACALOS test three times within a period of two months.

The third experiment was performed with tinnitus patients. The goal in this experiment was to evaluate the other implemented tests (see section 4.5 and 4.7), since the tinnitus and residual inhibition test do not work with normal hearing people. 6 subjects participated in the experiment on voluntary basis (3 male, 3 female) with an average age of 51.7 ± SD=16.3 years. The procedure for this experiment started with an in-take conversation, asking the subject to describe the tinnitus in detail and the researcher explaining the experiment. The training program was performed and, depending on the time available, we decided which tests would be performed.

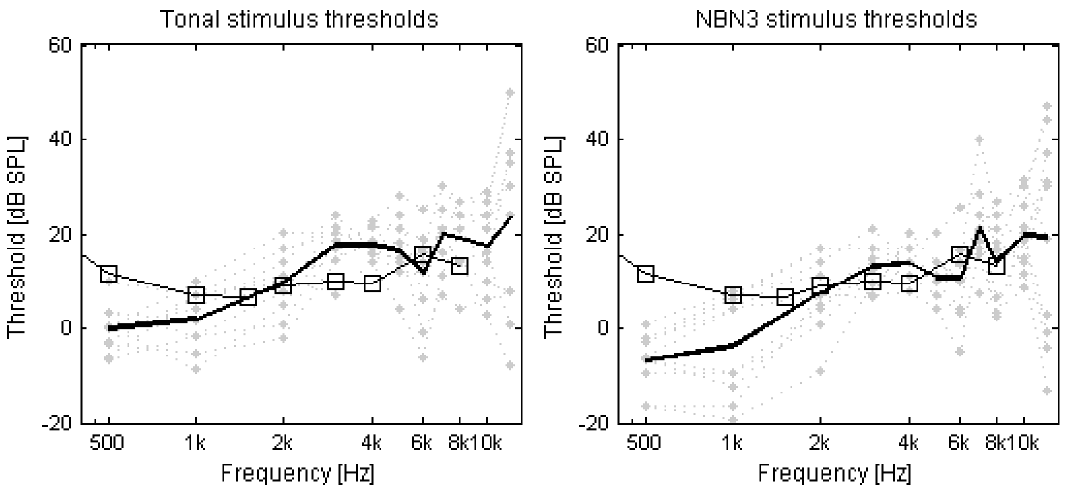
- 2 subjects performed only the ACALOS test (total duration including in-take and training: about 30 minutes)
- 2 subjects performed the tinnitus test and then the ACALOS test (total duration including in-take and training: about 45 minutes)
- 2 subjects performed the ACALOS test and then the residual inhibition test (total duration including in-take and training: about 60 minutes)

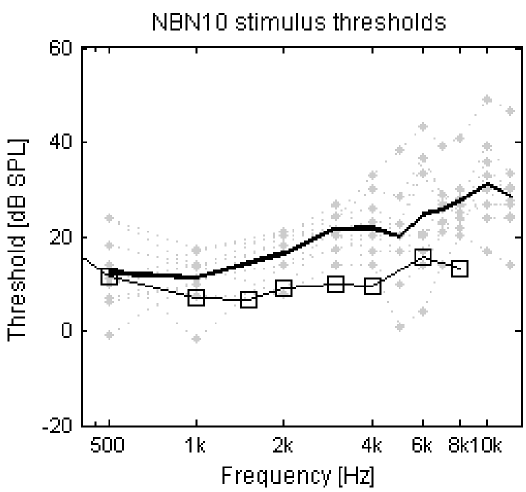
The selected stimuli for the ACALOS and residual inhibition test were White Noise and 4 frequencies of the NBN10 noise (2kHz, 4kHz, 6kHz, 8kHz). These are the same 5 stimuli as in the previous experiment.

5. Results

5.1 Hearing Level Calibration

The results of the HL Calibration experiment can be found in Figure 5.1. These results show a plot of the thresholds against the frequency of the stimulus for each type of stimulus (sine, NBN10, NBN3). The average of 10 measurements was calculated and is shown in the figures too. The measurement with white noise resulted in an average threshold of 21.5 dB SPL. All standard deviations can be found in Table 5.1. In each figure a plot is included of the ISO-standard conversion table (NEN-ISO 389-2 (1996)). This ISO standard describes the average thresholds for tonal stimuli. A valid comparison can be made between this ISO standard and the average thresholds for the tonal stimuli. The measurements in this study seem to underestimate the thresholds for low frequency sounds and overestimate the thresholds for high frequency sounds. The ISO-standard is also displayed in the other figures, to help showing that there’s quite a difference in the thresholds between the NBN10 and NBN3 stimuli. The thresholds of the NBN3 stimuli are much lower and more like the tonal stimuli thresholds. This is not surprising since the NBN3 is filtered with a very narrow bandwidth, making it sound almost like a sine wave.





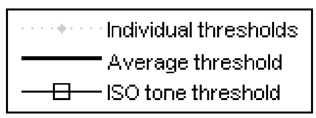


Figure 5.1 Results of the HL calibration. The plots show the measured hearing thresholds for 10 subjects, the average thresholds and the ISO tone thresholds. Each type of stimulus was presented at 11 frequencies.

Table 5.1 Standard deviations of the average thresholds of the HL calibration experiment.

Stimulus type	Standard deviation
White noise	3.6 dB
Tonal (sine)	8.5 dB (average over all frequencies)
Hissing (NBN10)	7.3 dB (average over all frequencies)
Ringing (NBN3)	9.1 dB (average over all frequencies)

Thresholds were tested up to 12 kHz, but both the TDH-49 headphones and the calibration equipment are only certified up to 8 kHz. The stimuli beyond 8 kHz have been calibrated and measured in this experiment, but the reliability of this data is not guaranteed. Therefore the HL-scaling for the stimuli above 8 kHz is never used in the ACALOS and residual inhibition test. Only in the tinnitus test the stimuli beyond 8 kHz are used, but the reliability of this test doesn't depend on the HL-scaling.

5.2 Results of the ACALOS test

5.2.1 The ACALOS test with normal hearing subjects

Figure 5.2 shows typical results of an ACALOS test performed with a normal hearing male subject at the age of 46. Each of the five stimuli has its own loudness function.

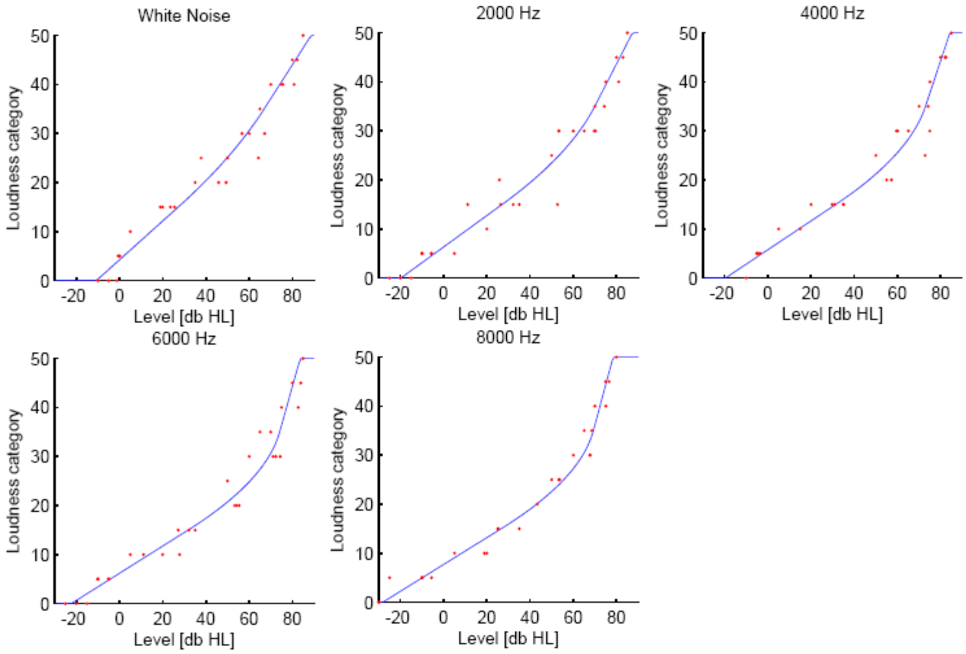


Figure 5.2 The loudness functions of a normal hearing subject tested with 5 stimuli: White Noise and NBN10 filtered at 4 different center frequencies

From the group of 12 normal hearing subjects an average loudness function was calculated (Figure 5.3) with a 95% confidence interval around it. For this confidence interval a normal distribution of the data is assumed. The figure shows that the measurements among normal hearing subjects are quite consistent, so to a certain degree there seems to be consensus about the subjective scale of loudness between subjects.

A trend can be seen in the loudness functions of normal hearing people (Figure 5.3), showing that the upper part of the curve gets a little steeper for higher pitched sounds, while the lower part remains roughly the same. It is important to notice that most curves intersect the x-axis at a negative level, meaning that the subject would have negative hearing threshold. This is not very likely and a possible explanation for this is an offset in the calibration of approximately 10 dB.

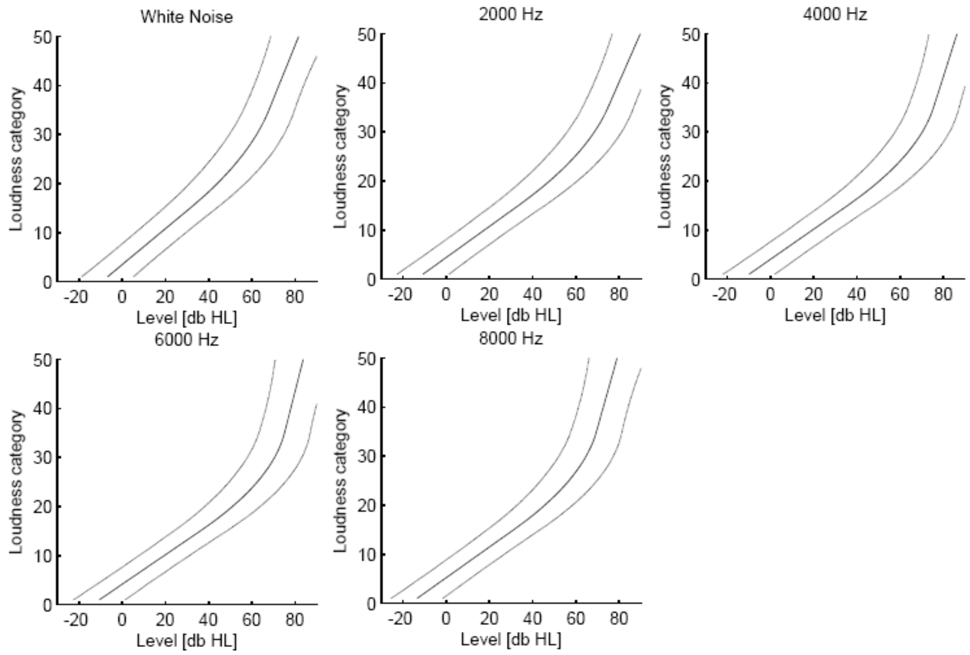


Figure 5.3 Average loudness functions of 12 normal hearing subjects with 95% confidence intervals around it. The 5 stimuli are: White Noise and NBN10 filtered at 4 different center frequencies

Another way to evaluate the ACALOS method is to study how well the fitting procedure was performed. The (root-mean-square) error that remains between the data points and the best fitted function was calculated. Table 5.2 shows the average intra-individual error for each subject. Averages over all subjects were calculated to give an idea of the error that remains when fitting the data for each of the five stimuli in general. These averages show that fits on the 8 kHz NBN10 were generally the best and fits on the 2 kHz NBN10 were the worst.

Table 5.2 The average intra-individual error in dB between data and fitted loudness function for each subject. Differences between the averaged values for each type of sound are not significant.

	White noise	2 kHz NBN10	4 kHz NBN10	6 kHz NBN10	8 kHz NBN10
NHsubject 1	6.7	8.7	6.6	4.9	5.8
NHsubject 2	8.4	7.0	5.2	5.6	8.2
NHsubject 3	4.4	5.8	5.4	7.2	4.6
NHsubject 4	6.8	6.1	6.3	5.8	3.9
NHsubject 5	5.4	4.9	5.5	4.4	4.5
NHsubject 6	6.8	9.3	8.0	7.0	5.3
NHsubject 7	6.2	4.8	8.6	6.1	5.1
NHsubject 8	7.5	5.7	4.0	7.0	5.2
NHsubject 9	5.7	9.6	5.3	7.2	6.0
NHsubject 10	6.8	5.4	5.5	7.3	6.4
NHsubject 11	6.5	9.1	5.8	6.9	6.4
NHsubject 12	7.0	8.9	5.9	7.0	6.4
Average	6.5	7.1	6.0	6.4	5.7

5.2.2 The ACALOS test re-test reliability and response distribution

Three of the 12 normal hearing subjects performed the ACALOS test three times within a period of two months. With the data from this experiment something can be said about the test-retest reliability of the ACALOS test. Figure 5.4 shows an example of three repeated ACALOS functions with one subject. Table 5.3 shows the standard deviation between the three ACALOS functions within each subject for each of the 5 stimuli. With the relatively small standard deviations the test re-test reliability is very good, with an overall average deviation of 2.4 dB.

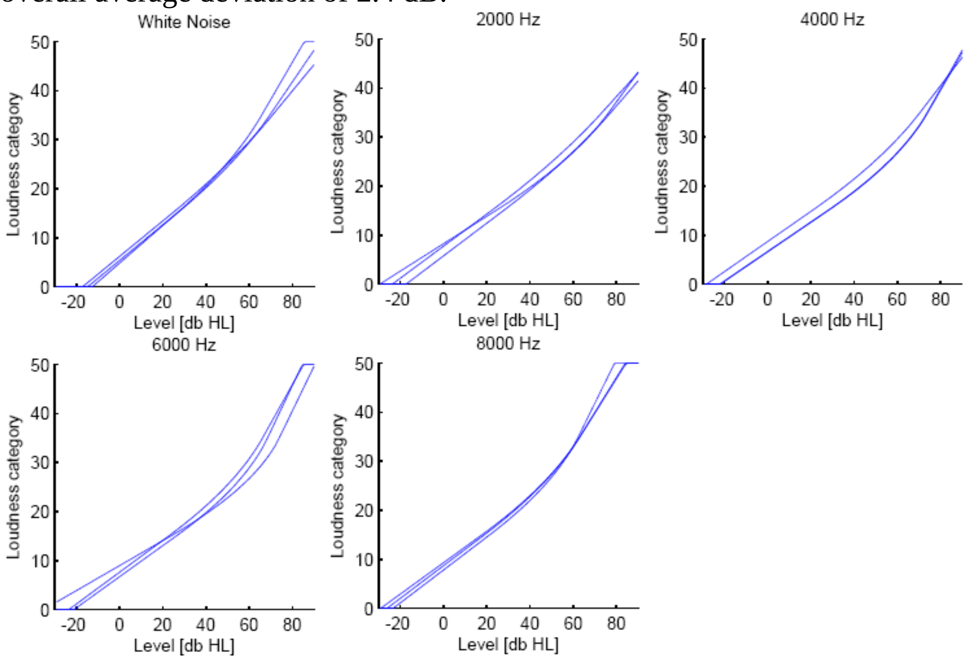


Figure 5.4 The results of three repeated ACALOS tests within a period two months for one subject. The stimuli are: White Noise and NBN10 filtered at 4 different center frequencies

Table 5.3 Standard deviation (dB) between the three repeated ACALOS tests within each subject.

	White noise	2 kHz NBN10	4 kHz NBN10	6 kHz NBN10	8 kHz NBN10	Average
NHsubject 1	2.8	3.1	2.9	2.1	3.8	2.9
NHsubject 7	1.9	2.3	1.9	3.2	1.1	2.1
NHsubject 9	1.9	2.6	2.8	1.6	2.4	2.2
Average	2.2	2.6	2.5	2.3	2.4	2.4

Another way to evaluate the ACALOS test is to study how the responses are distributed over the response scale. In the best case the distribution would be uniform, but the results show that it is a bit different (Figure 5.5). Figure 5.5 also shows the trend that the unnamed categories are chosen less frequently than the named ones. It can also be seen that the lower categories get slightly more responses then the higher categories. This is most likely caused by the first part of the ACALOS test (the part before the model is used for fitting). During the first part, stimuli are not yet distributed equidistantly over the subject's loudness domain. This causes more stimuli to be categorized under the lower categories, since the subject is more sensitive to differences in the lower range. The categories 'inaudible' and 'TOO LOUD' get fewer hits, because these are not part of the categories that are repeatedly estimated and presented to the subject (i.e. only categories 5, 15, 25, 35 and 45 are repeatedly presented).

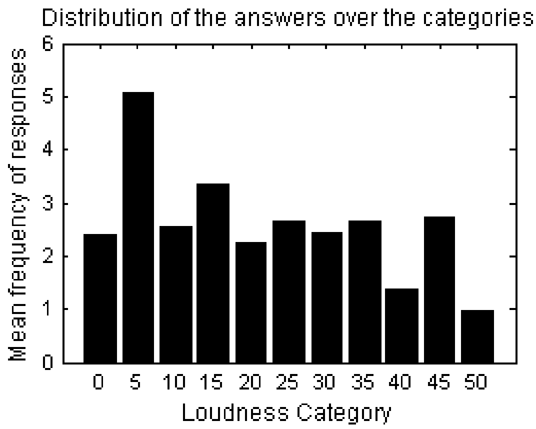


Figure 5.5 Mean frequency of responses per category for the ACALOS tests performed on 12 normal hearing subjects. Categories 10, 20, 30 and 40 are unlabeled, the other ones labeled.

5.2.3 The ACALOS test with tinnitus patients

A typical ACALOS test result from a tinnitus patient can be seen in Figure 5.6. An audiogram (Figure 5.7) was made of the subject's right ear to give an idea of the amount of hearing loss. The subject described his tinnitus sound as a tone. With an audiometer an approximate match with this tone was made at a frequency of 6 kHz. The subject described the tinnitus to be steady (and not pulsing) in nature. The ACALOS test was performed on the right ear only, since this was the ear that the subject experienced tinnitus from. The results show a raised hearing threshold. The lower parts of the loudness functions are steeper compared to the functions of normal hearing subjects, but the upper parts are very similar to the functions normal hearing subjects. This could be called a mild version of loudness recruitment. Although the audiogram (Figure 5.7) shows shifted hearing thresholds at 6 kHz and 8kHz, the ACALOS test does not show shifted thresholds for these frequencies. This could possibly be explained by the differences in stimuli between the audiogram (tones) and the ACALOS test (NBN10). A tone has only one specific frequency, but the NBN10 has a wider spectrum of frequencies. The NBN10 might contain frequencies that the subject is more sensitive to and thus, result in a lower hearing threshold for the NBN10 compared to the tone at the same frequency as the center frequency of the NBN10 sound. The five other results of the ACALOS test with tinnitus patients can be found in Appendix C.

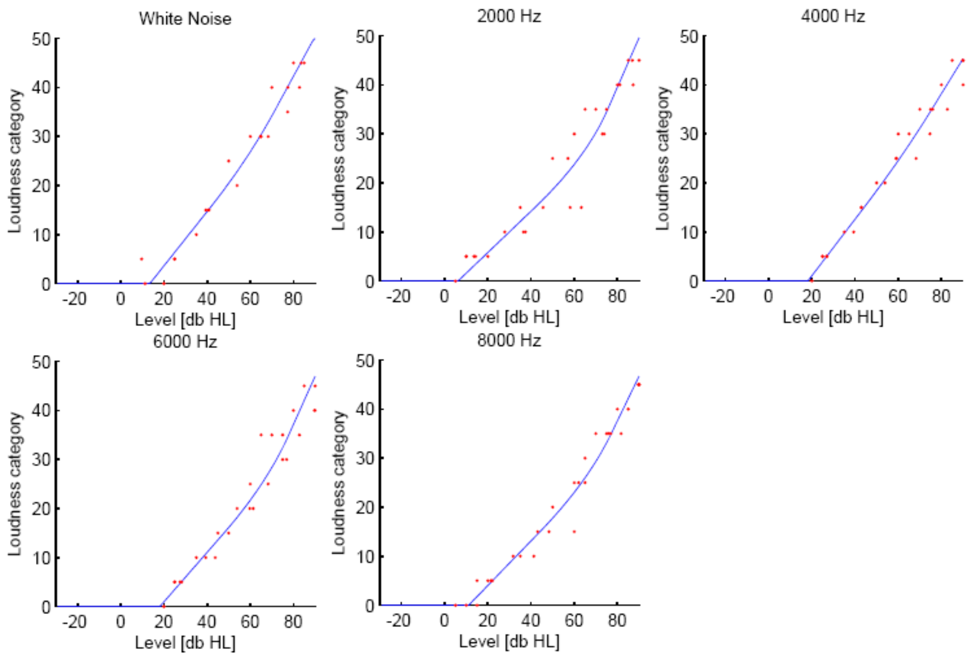


Figure 5.6 Typical loudness functions from a subject with tinnitus. The 5 stimuli are: White Noise and NBN10 filtered at 4 different center frequencies

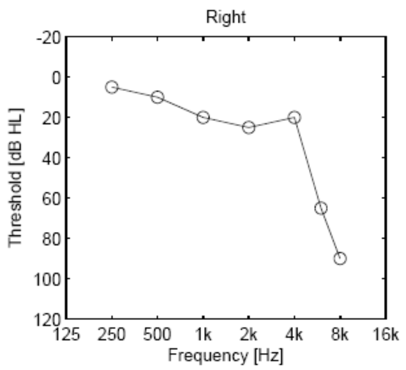


Figure 5.7 Pure tone audiogram measured at the right ear of the same tinnitus subject.

5.3 Tinnitus test

Figure 5.8 shows the results of one single tinnitus test. The subject (58 years old, female) had done a ‘classical tinnitus test’ in the past. In this test the subject reported that her tinnitus resembled most a 4 to 6 kHz warble tone. In the tinnitus test developed for this project she categorized her tinnitus as ‘ringing pulsing tinnitus on both ears’ with general severity 0 (corresponding with ‘moderate’ or ‘matig’, in Dutch) on a scale from -50 to 50. Before the subject’s participation in the tinnitus test an audiogram was made (Figure 5.9). This audiogram shows hearing loss in especially the higher frequency regions. It is interesting to notice that both the results of the loudness matching and the likeness rating test show that the sound of the tinnitus is in the higher frequency regions. This is consistent with the results of Roberts, Moffat & Bosnyak (2005), who showed that the shape of the tinnitus spectrum is in most cases related to the shape of the audiogram.

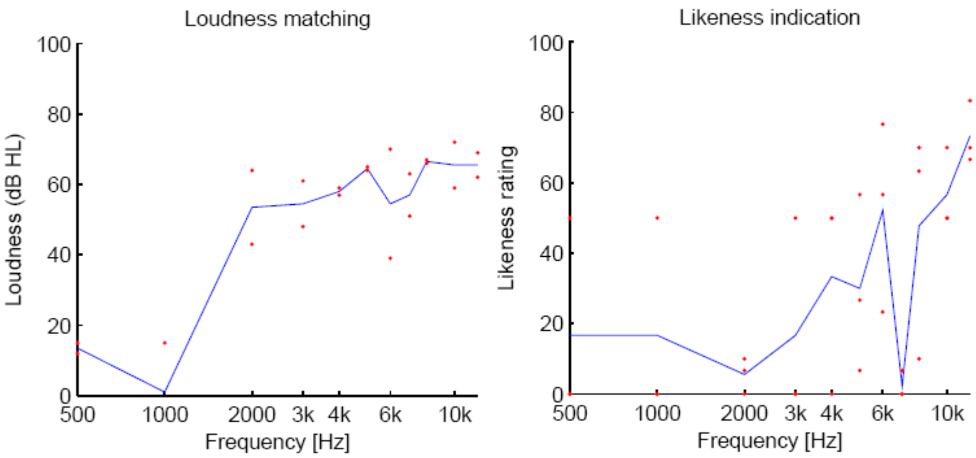


Figure 5.8 The result of the loudness matching task (left) and the result of the likeness rating task (right) of subject 1. The measured data points are shown in red. The average of these points is shown with the blue graph. Stimuli were presented to both ears simultaneously.

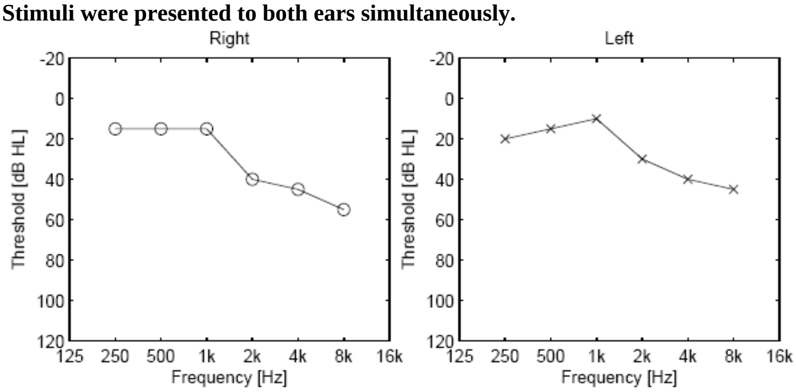


Figure 5.9 Pure tone audiograms of the left and right ear of subject 1.

Figure 5.10 shows the results of the second tinnitus test. With the help of the tinnitus test, the subject (65 years old, male) rated his tinnitus as ‘ringing pulsing tinnitus’ with general severity 0 (between -50 and 50). The tinnitus test was performed on the left ear only, since the subject suffered from a severe hearing loss (Figure 5.11) and the equipment range was not sufficient to exceed the thresholds of the right ear. The subject reported that even on the left ear, not all stimuli were audible, due to hearing loss. This makes the final outcome of the tinnitus test (Figure 5.10) very unreliable.

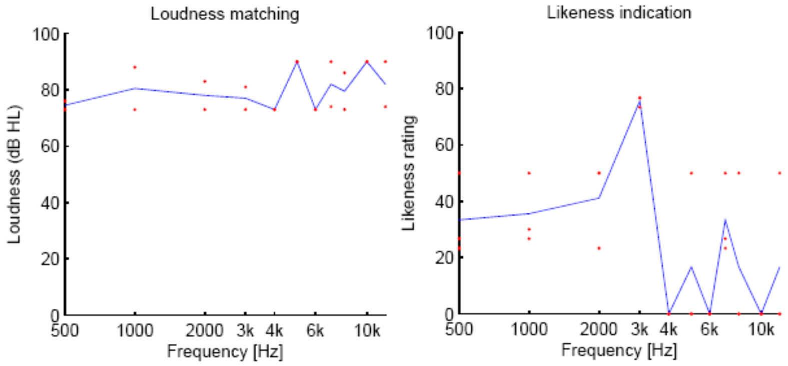


Figure 5.10 The result of the loudness matching task (left) and the result of the likeness rating task (right) of subject 2. The measured data points are shown in red. The average of these points is shown with the blue graph.

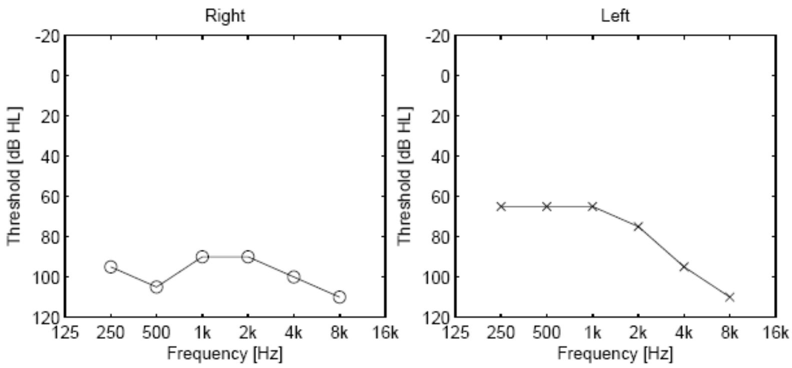


Figure 5.11 Pure tone audiograms of the left and right ear of subject 2.

5.4 Residual inhibition test

Figure 5.12 shows the result of a residual inhibition test. The subject (49 year old, male) performed an ACALOS test (previously described in Figure 5.6) first and afterwards an audiogram was made (previously described in Figure 5.7). Due to the available time and the fatigue of the subject a tinnitus test was not performed, but in a simple matching procedure with an audiometer the subject described that the sound of the tinnitus resembled best to a steady tone at 6 kHz. The results of the residual inhibition test (Figure 5.12) suggest that this is the frequency were the residual inhibition effect could be evoked the best. This is consistent with the hypothesis that the best stimulus to evoke residual inhibition with, is a sound that is near the tinnitus frequency.

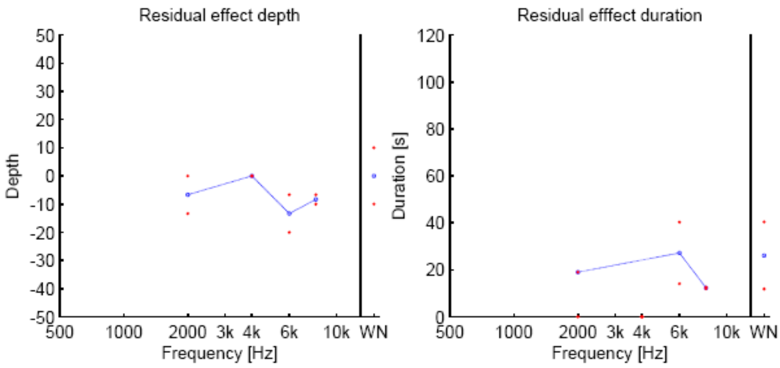


Figure 5.12 Result of a residual inhibition test with subject 5. Shown on the left is the depth of the effect (negative is inhibition, positive is excitation) after presentation of the NBN10 stimuli with center frequencies of 2, 4, 6, and 8 kHz and White Noise (WN). Shown on the right is the duration of the effect. The measured data points are shown in red. The average of these points is shown with the blue graph. In the duration plot, data points with 0 effect depth are excluded from this average.

Table 5.4 Raw data from the residual inhibition test as described in Figure 5.12. Stimulus numbers are presented in chronological order.

Stimulus Nr.	NBN10 Freq. (Hz)	Depth [-50/50]	Duration [sec.]
1	WN	-10.0	40.4
2	6000	-20.0	40.3
3	2000	-13.3	19.0
4	8000	-6.7	12.6
5	4000	0	0
6	6000	-6.7	14.1
7	2000	0	0
8	WN	10.0	11.9
9	8000	-10.0	12.0
10	4000	0	0

Figure 5.13 shows the results of subject 3. With this subject (47 year old, female), an audiogram measurement (Figure 5.14) and ACALOS test were performed in advance. The subject described her tinnitus as several high pitched noise-like sounds on both ears. It is also worth mentioning that the tinnitus appeared together with symptoms of Menière's Disease and the subject had experienced periods of hyperacusis in the past, but not at the moment of measurement. From the results of the residual inhibition test (Figure 5.13) it can be seen that only with the white noise stimulus residual inhibition could be evoked consistently. The other stimuli had a variable effect or even evoked what could be called residual excitation. This excitation effect lasted longest with the 6 kHz stimulus. After the experiment the subject described that she had experienced an increase in symptoms of Menière's Disease (nausea) and tinnitus during the experiment, probably due to fatigue. Table 5.5 shows the raw data of the residual inhibition test. In this data it can be seen that during the experiment the residual effect depth decreased (which means more inhibition) to the end of the experiment.

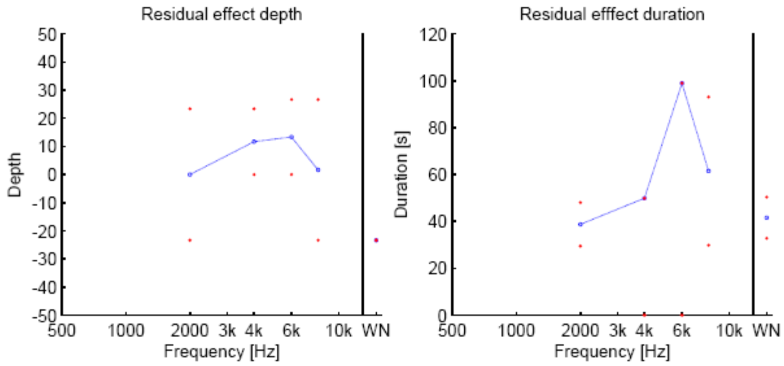


Figure 5.13 Result of a residual inhibition test with subject 3. Shown on the left is the depth of the effect (negative is inhibition, positive is excitation). Shown on the right is the duration of the effect. The measured data points are shown in red. The average of these points is shown with the blue graph. In the duration plot, data points with 0 effect depth are excluded from this average. On the right side of both figures the data for the White Noise stimulus is shown.

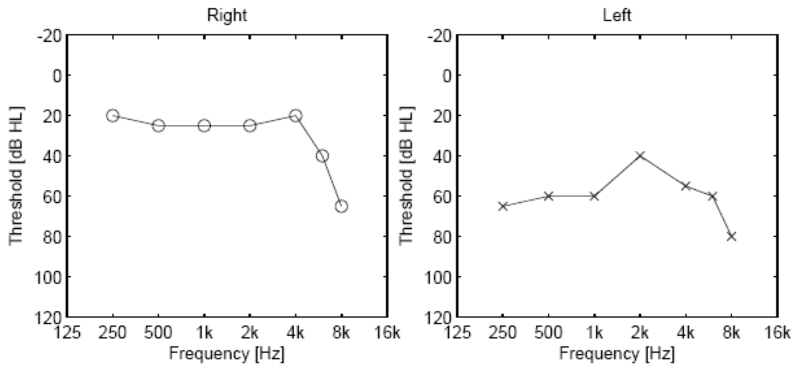


Figure 5.14 Pure tone audiogram of the left and right ear of the same subject with tinnitus.

Table 5.5 Raw from the residual inhibition test as described in Figure 5.13. Stimulus numbers are presented in chronological order.

Stimulus Nr.	NBN10 Freq. (Hz)	Depth [-50/50]	Duration [sec.]
1	6000	26.7	98.9
2	8000	26.7	93.1
3	4000	23.3	49.9
4	2000	23.3	48.0
5	WN	-23.3	50.4
6	WN	-23.3	32.8
7	6000	0	0
8	8000	-23.3	29.9
9	2000	-23.3	29.5
10	4000	0	0

6. Discussion

6.1 Design

An evaluation can be made of the design of the program itself. During the experiments that have been performed, there was some hassle with the USB control knob. Under some scarce circumstances the push contact in the knob generated two signals instead of one. This was interpreted by the software as if the knob was pushed twice. Trying to solve this problem in the software was not successful. The interaction between multiple threads in Matlab wasn't fast enough to register the first click and block the second one. The only place to filter out the double click properly is in the driver that comes with the knob, but source-code of this driver was not available. The interface in general meets the constraints as described under 'Design and implementation' and proved to be easy in use during the experiments. During the experiments one case occurred in which the subject was not at all familiar with computers and how to operate them. The concept of a knob that controls what's happening on a screen, was confusing for this subject and this lead to a longer but finally successful experiment.

6.2 The ACALOS test

6.2.1 General evaluation of the ACALOS test

In general, all changes to the original design of Brand & Hohmann (2002) seem to perform well. The ACALOS interface worked nicely and most subjects had no problem in understanding what they were supposed to do with it. One disadvantage of the indication bar changing from red to green when the sound stops, is that a visual cue is given just after the presentation of the sound. Audiovisual integration might therefore result in a subject 'hearing' the offset of a sound that is normally inaudible. This might introduce false positives to the measurement. Another disadvantage of the red and green indication bar is that it will be perceived differently by people with color blindness. The difference in intensity of the colors however, will be large enough to see the bar changing from red to green (i.e. dark to light).

Furthermore, it is worth mentioning that the order in which five stimulus types were tested in the ACALOS test was not randomized. The order was always white noise followed by NBN10 at 2kHz, 4kHz, 6kHz and 8kHz. A few subjects mentioned that it took some time to get used to the way of testing and the kind of stimuli they could expect. This might have resulted in a learning effect during the ACALOS test and therefore possibly less reliable results for the white noise and more reliable results for the last NBN10 noises. This effect however, cannot be found in the dispersal of the data points around the fitted function. The intra-individual error of the data points to the fitted function (Table 5.2) shows no significant decrease in error during the ACALOS test (i.e. between stimuli going from White Noise to NBN10 at 8 kHz).

6.2.2 The shape of the ACALOS functions

A very interesting finding of this project was the consistency of the shape of the ACALOS functions. This shape is of course forced into the possible solutions of the model, but the distribution of the data points around it seem to confirm that the model is quite accurate. That raises the question why the ACALOS functions are shaped the way they are.

A possible explanation for the consistency of the shape over different subjects has a cultural basis. We often check our lingual description of a certain loudness with other people ('do you find that loud too?' or 'that sound is really soft!'). In doing so, we have learnt what to call 'loud' and what to call 'soft'. This is however no guarantee that we really perceive it the same way, since we only learnt to call it the same.

Apart from this cultural explanation, there are also mechanisms in the auditory system that could contribute to the way we perceive loudness. From the ACALOS results it is obvious that the relation between the acoustic sound pressure in the cochlea and the loudness, as perceived by the subject, is not linear. The first place that such a non-linearity could occur is at the level of the inner hair cells. Initially, one would think that the an inner hair cell would simply encode the acoustic sound pressure in the cochlea to a certain neural firing frequency and send this through an auditory nerve fibre to the brain. However, studies have shown that the neurons in a an auditory nerve fibre do not have the capability to encode the entire human auditory range (Viemeister, 1988). Therefore, a theory was developed, proposing that loudness encoding is spread over several fibres, each with a different loudness range. Together, these fibres are able to encode the entire dynamic range (approximately 120 dB). With the loudness perception distributed over several fibres, non-linearity could easily occur, especially at the point where one fibre reaches the upper threshold of its loudness encoding range and another fibre takes over. How the different fibres are connected to the inner hair cells is not know, but it is proposed that each inner hair cell connects to three types of fibres (Preyer & Gummer, 1996).

After the acoustic sound pressure in the cochlea is converted to neural potentials, the signal travels through the auditory nerve to the brain. At this point, another mechanism is thought to play a role in the perception of loudness. Inspired by the work of Yates (1990), an article by Preyer & Gummer (1996) describes that the auditory nerve also carries efferent information from the brain back to the ear. This efferent information is sent to the outer hair cells. The outer hair cells are known to be able to vibrate and thus generate acoustic sound pressure in the cochlea. The theory describes that at low sound pressure the auditory system plays an active role in boosting the level, by creating a positive feedback loop back to the outer hair cells. The outer hair cells start to vibrate, which adds acoustic energy to the original sound and this is perceived by the inner hair cells as a 'louder' sound. This outer hair cell feedback loop is thought to be functioning for sounds at low levels only, up to a certain threshold. The theory describes a fixed amount of gain for sounds under a certain threshold. However, since we do not know if any interpretation is done in the brain before the signal is fed back to the outer hair cells, the amount of gain could very well be depending on the input level. In both cases, the perception of loudness gets more complex, and certainly not linear.

Finally the encoded loudness, that is sent as neural potentials through the auditory nerve, is interpreted by our central nervous system. This introduces another level of possible non-linearity in our loudness perception.

If we now take a look at tinnitus and the theory that tinnitus is caused by compensation to a lack of input by the auditory system, it is not surprising that tinnitus has so many different occurrences. As explained previously, there are many mechanisms that could influence the perception of loudness and the gain applied to sounds at different levels. A malfunction in any of these mechanisms could result in an abnormal amount of gain that the central nervous system will try to compensate. Under some circumstances this could lead to the experience of tinnitus.

6.3 Tinnitus test

The tinnitus test is performed on two subjects only. This is not enough to base a solid discussion on, however some things can be said about it. It is very nice to have a test that helps normal hearing people, or a researcher in this case, understand what a person with tinnitus is actually hearing. Performing such a test with a very strict procedure on a computer however, might give a false confidence in what a subject is hearing. During the test, the subject is forced to make a choice between a limited set of answers regarding the tinnitus, for instance the type of tinnitus (tonal, ringing, hissing) and the pulsing or steady nature. The subject might have been able to give much more precise details about the sound of the tinnitus in a conversation, but with the computer program only a limited set of answers can come out. In my opinion the outcome of the test has to be interpreted very wisely and must not be overrated. The second part of the tinnitus test, where the loudness matching and likeness rating is performed, doesn’t suffer from this problem. The results of these tests show however, that the likeness rating test is quite a difficult task. The dispersal of the data is quite large, which makes it not really reliable. A possible reason for this large dispersal is the fact that many people find it quite hard to understand the conceptual difference between *loudness* and *pitch*. They might be matching the wrong concept in this test.

In my opinion, the best idea about what a tinnitus patient hears can be acquired by a combination of the tinnitus test and a face-to-face conversation with the patient. More research might provide some insight in how well subjects are able to perform tasks like the loudness matching or likeness rating task. With ‘fake’ tinnitus sounds this might even be done with normal hearing subjects.

6.4 Residual inhibition test

Just like the tinnitus test, the residual inhibition is performed on two subjects only and thus does not provide material for a solid discussion. One thing that came up, during the tests, was the problem of what exactly is being measured with the residual inhibition test. The subject is asked explicitly to compare the loudness of the tinnitus just before the stimulus with the loudness just after the stimulus. However, remembering a loudness that was perceived a little more than a minute ago might be difficult and comparing a new perceived loudness to it might be even more difficult. What, for example, would be measured when a person experiences a slowly increasing tinnitus loudness during the experiment due to fatigue? This is something that was described by a subject after finishing the residual inhibition test. The test might therefore measure the long-term effect of the test itself as well as the relatively short-term effect of the residual inhibition. Some research on this effect should probably be done to find out what exactly is measured in this test. Another issue worth investigating is the optimal loudness for evoking residual inhibition. Perhaps the subjective loudness category 35 was not loud enough and a stronger effect might have occurred with louder stimuli or a longer duration of the stimulus. In the original study of Roberts, Moffat & Bosnyak (2005) a method was used in which the stimuli that were used to evoke residual inhibition with, were matched in loudness by the subject with a 1 kHz tone at 65 dB SL (above the subject's threshold).

One thing about this test that seems to work really well in practice is the use of the ACALOS functions to predict 'equal loudness' for all stimuli in the residual inhibition test. Given the results and the reliability of the ACALOS test, the loudness of the stimuli in the residual inhibition test is now much more reliable compared to the original procedure of Roberts, Moffat & Bosnyak (2005). This is also very useful for a reliable research on the effect of loudness on the residual inhibition.

7. Conclusion

The intended design of the software has been successfully realized and is performing well. During the experiments, the software proved to be easy in use for both the researcher and the subject. Data analysis and visualizing results was especially easy. The power of combining different tests has been exploited by using of the ACALOS test results for estimating ‘equal loudness’ of the stimuli in the residual inhibition test. This has improved the reliability of the residual inhibition, since there is more confidence about the loudness of the presented stimuli.

The modified ACALOS test for measuring loudness growth proved to be working very well. It has a high test-retest reliability (2.4 dB average deviation) and a reasonably small error between the data and the fitted function (average intra-individual error of 5.7 dB). The results of the modified ACALOS test show consistency in the shape of the loudness functions for normal hearing people, which corresponds with the findings of Brand & Hohmann (2002). However, it is suspected that the functions have been shifted (approximately 10 dB), due to imperfections in the calibration.

The tinnitus test works well. However, the dispersal of the data of the likeness rating task seems to indicate that this part of the test is possibly too difficult or not specific enough in questioning the subject. Improvement is possible on this part of the test. Results from this test correspond with the findings of Robert, Moffat & Bosnyak (2005), in the sense that correlation was seen between the audiogram and the measured tinnitus spectrum.

The residual inhibition test performed well, but the question can be raised what exactly is measured. The formulation of the questions and the way of testing might result in a mixed measurement of residual inhibition and long term effects (i.e. fatigue and attention). Improvement might be possible, but residual inhibition will always remain hard to measure. The results measured in this study suggest that there could be a correlation between the audiogram, the measured tinnitus spectrum and the residual inhibition effect. This is in correspondence with the findings of Robert, Moffat & Bosnyak (2005), however, not only residual inhibition was found, but also residual excitation.

Although improvement is still possible, it can be concluded that the successful development of this software has opened the door for further tinnitus research and possibly the evaluation of several hypothesized mechanisms of tinnitus.

8. References

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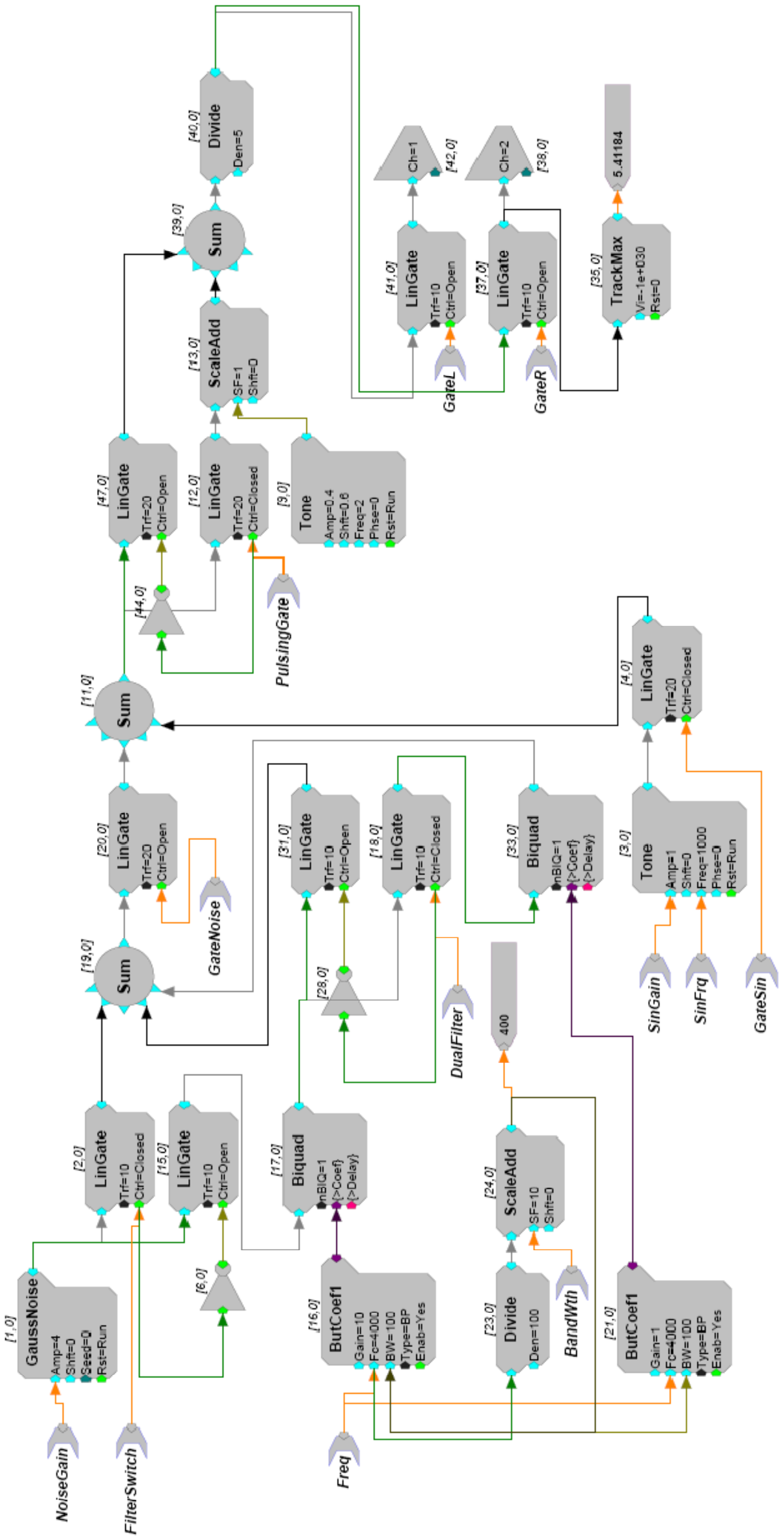
Appendix A: Abbreviations and definitions

ACALOS	:	Adaptive Categorical Loudness Scaling.
Audiogram	:	A measurement of a subject's hearing thresholds for tones at different frequencies.
Butterworth filter	:	A type of electronic filter.
CHM-file	:	Compressed Html Help; a Microsoft file standard for creating help files for software.
dB	:	Decibel.
dB HL	:	Decibel Hearing Level; the amount of decibels above the average hearing threshold of normal hearing people (specific for each sound).
dB SL	:	Decibel Sensation Level; the amount of decibels above a subject's hearing threshold (specific for each sound and each subject).
dB SPL	:	Decibel Sound Pressure Level; proportional loudness as defined in physics, not related to the subject's threshold or type of sound but relational to the sound pressure in Pascal.
Gaussian noise	:	A type of noise in which the frequencies that are present in it occur with a Gaussian distribution.
Hyperacusis	:	Over-sensitivity to certain frequency ranges of sound.
Menière's disease	:	A disorder in the inner ear that can affect hearing and balance and is characterized by episodes of dizziness and tinnitus.
NBN3	:	Narrow Band Noise; it is specifically created for this application and consists of Gaussian noise that is filtered by two Butterworth band pass filters in series. The 3 (percent) indicates the bandwidth of both filters in a percentage of the center frequency (that is the same for both filters) to the point of 3 dB roll off. This stimulus type is used to imitate the sound of ringing tinnitus.
NBN10	:	Narrow Band Noise; it is specifically created for this application and consists of Gaussian noise that is filtered with a Butterworth band pass filter. The 10 (percent) indicates the bandwidth of the filter in a percentage of the center frequency to the point of 3 dB roll off. This stimulus type is used to imitate the sound of hissing tinnitus.
Recruitment	:	A hearing impairment where sounds at low levels are inaudible or perceived to soft but sounds at high levels are perceived as having the same loudness as they would for an unimpaired listener.
SD	:	Standard deviation.
USB	:	Universal Serial Bus; a way of connecting peripherals to a computer.

Appendix B: Stimulus generation circuit for Tucker Davis RP2 hardware

Tag name	Description
NoiseGain	Controls the amplitude of the Gaussian noise
FilterSwitch	Controls whether the Butterworth filter(s) are bypassed (white noise) or not.
Freq	Controls the center frequency of both Butterworth filters
BandWth	Controls the bandwidth of both Butterworth filters and is expressed in a percentage of the center frequency.
DualFilter	Controls whether one or both Butterworth filters are used
GateNoise	Controls whether the noise signal paths are open or closed
GateSin	Controls whether the sine wave signal path is open or closed
SinGain	Controls the amplitude of the sine wave
SinFrq	Controls the frequency of the sine wave
PulsingGate	Controls whether the amplitude modulation is on or off
GateL	Controls whether the left channel is open or closed
GateR	Controls whether the right channel is open or closed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Seed=0
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NoiseGain
FilterSwitch
LinGate
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LinGate
Trf=10
Ctrl=Open
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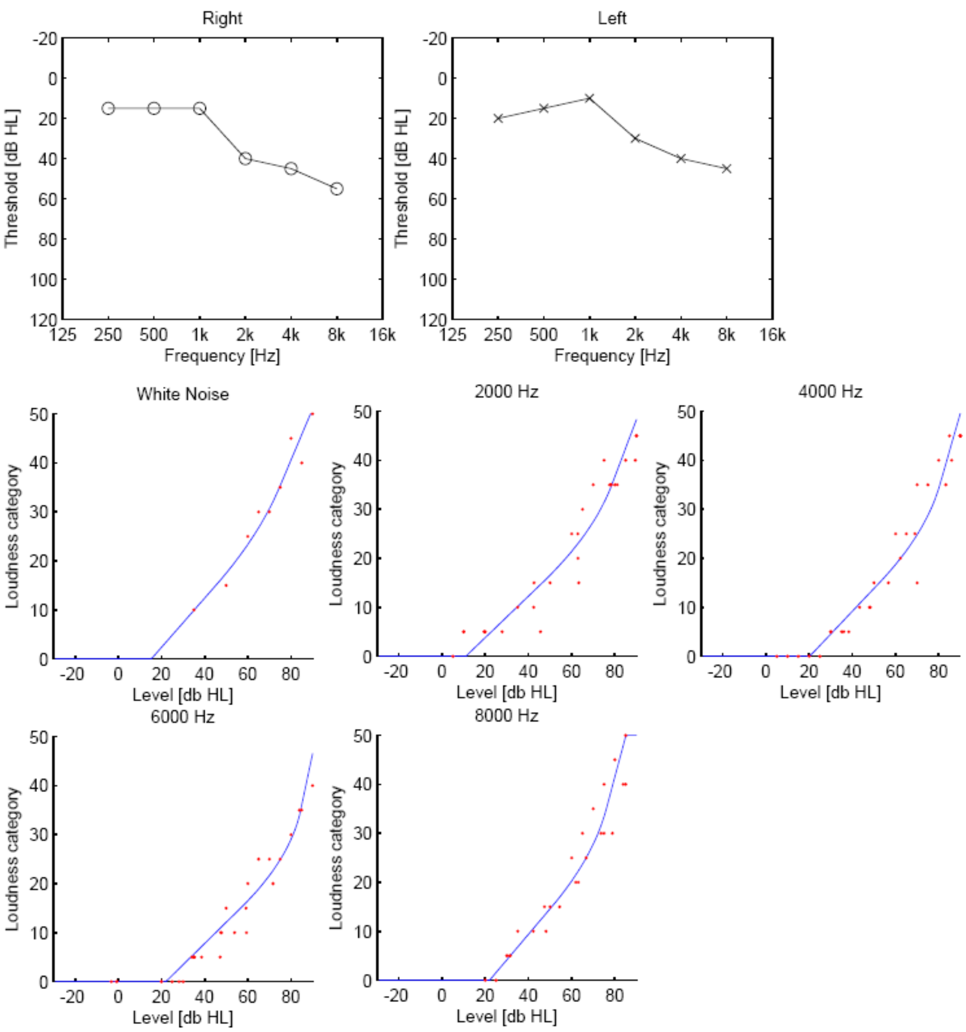
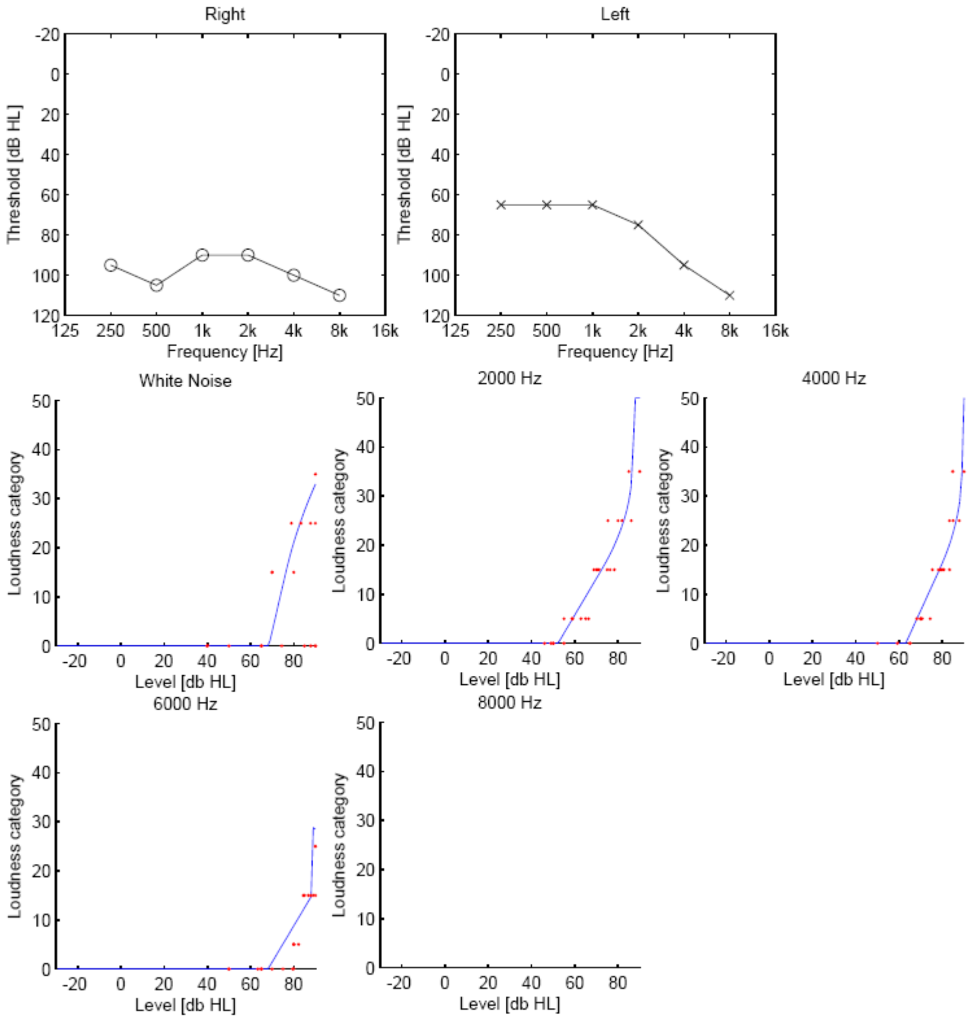
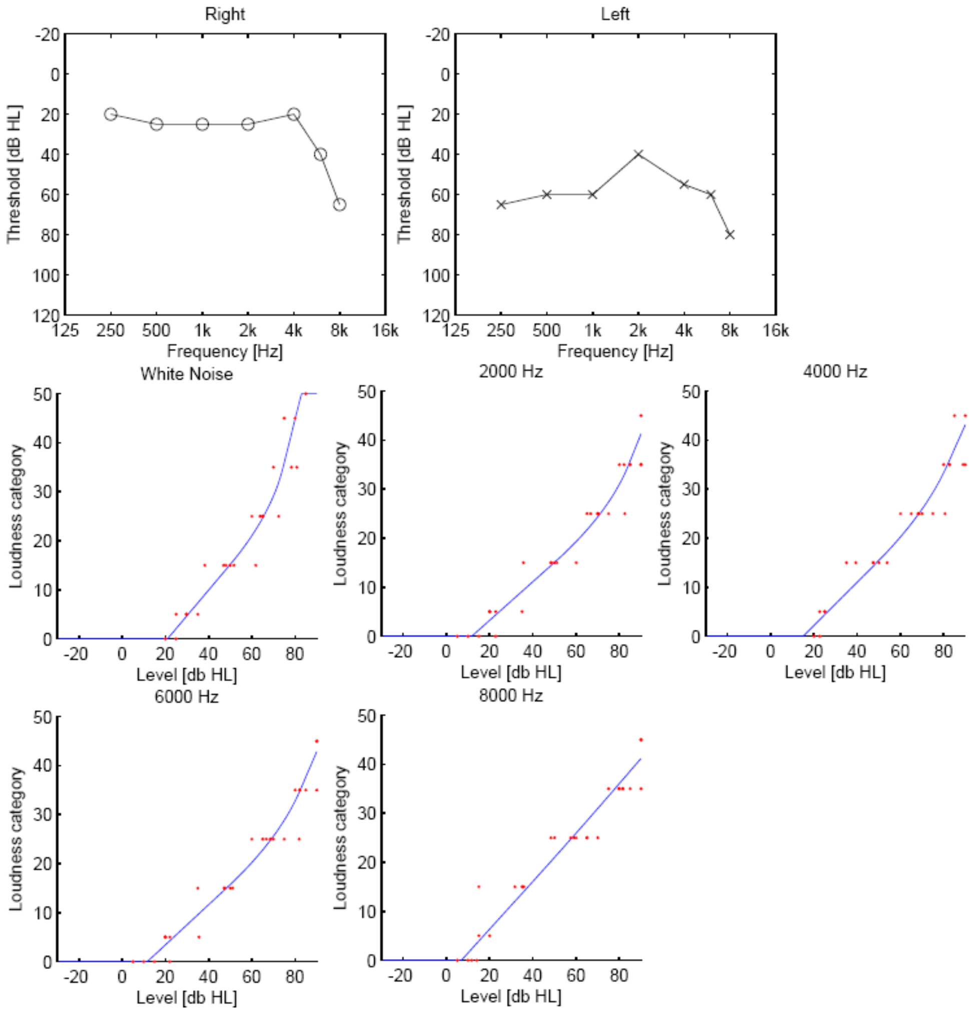
Appendix C: More results of the ACALOS test with tinnitus patients



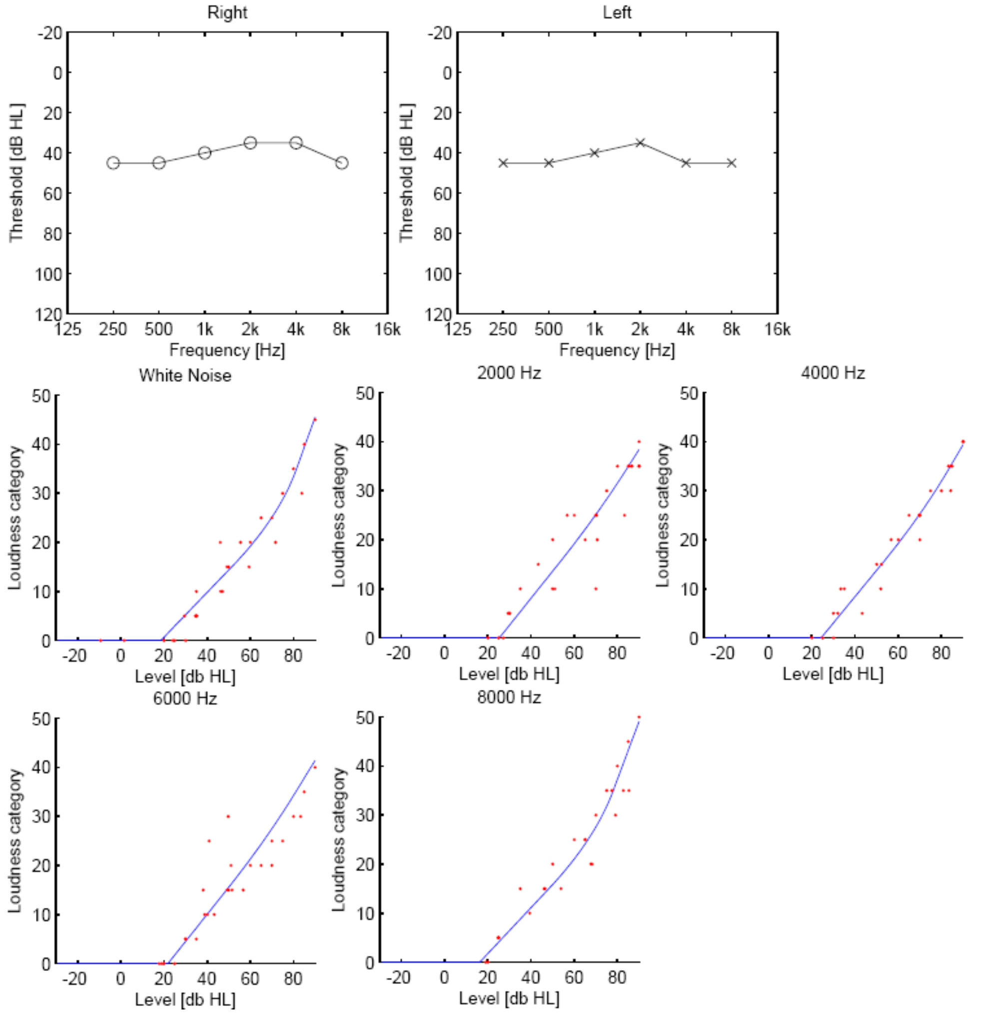
Subject 1 audiogram and ACALOS test results



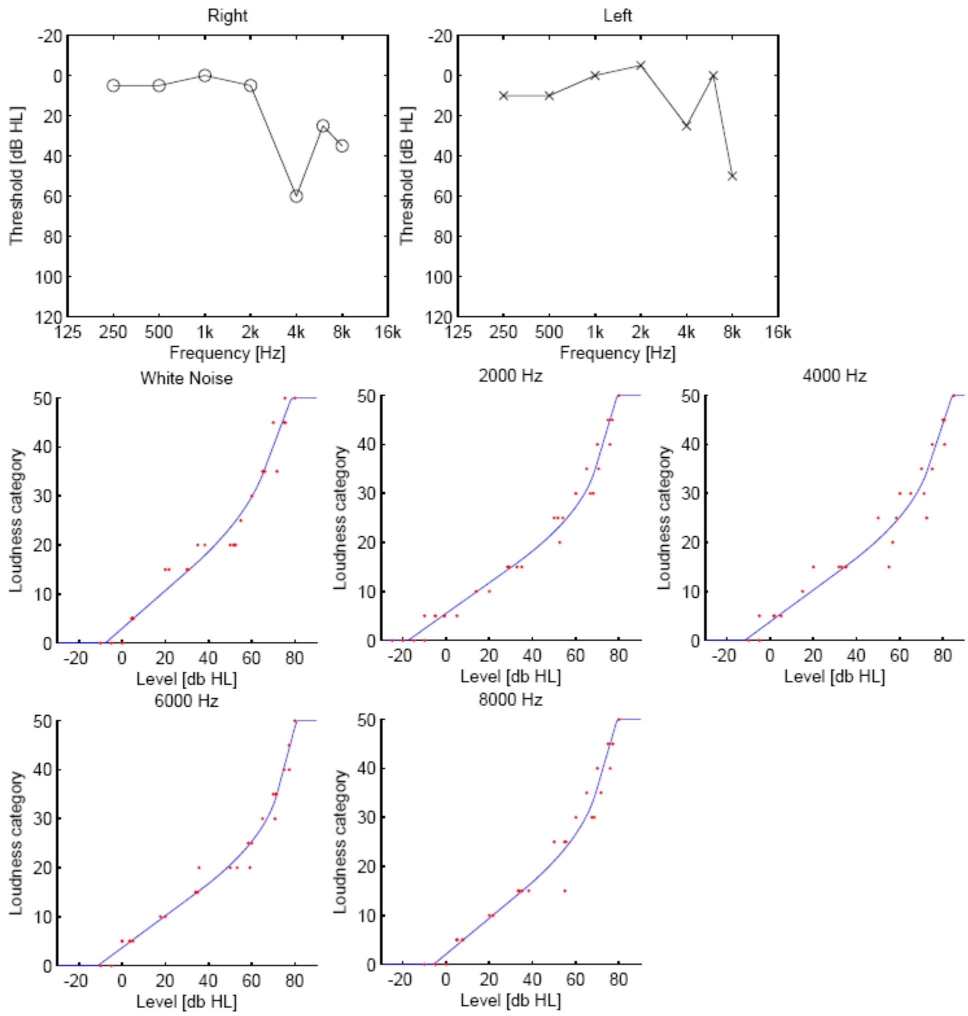
Subject 2 audiogram and ACALOS test results



Subject 3 audiogram and ACALOS test results



Subject 4 audiogram and ACALOS test results



Subject 6 audiogram and ACALOS test results