Temporary Changes in Hearing of Pop-rock Musicians

- Before and After Rehearsal -

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Department of Electronic Systems
Section of Acoustics
Fredriks Bajers Vej 7
http://es.aau.dk/sections/acoustics/

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Participants:

Javier Galdón Romero

Supervisor:

Karen Reuter

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Abstract:

This report concerns the hearing assessment performed for musicians involved in a pop-rock band who often attending to a rehearsal place twice per week. Hearing threshold determination as well as otoacoustic emissions are obtained before and after rehearsal. The purpose is to document the temporary changes in hearing encountered for each group member to convince them about the necessity of protecting their hearing.
To realise about the effects of being exposed to intense loud sounds, musicians are compared in terms of their hearing with a non-exposed population composed of twelve subjects who reported normal hearing function.
Eventually, the noise exposure level monitored at both rehearsal and an eventual concert are to be contrasted observing moderate hearing losses of the potentially visitors.

Preface

This report is written by project group 10gr1062 at the Section of Acoustics, Department of Electronic Systems at Aalborg University during the 4th semester of the master programme in the period spanning from February 1st, 2009 to June 3rd, 2009. The project concerns an analysis of the temporary changes in hearing of pop-rock musicians before and after rehearsal
The reader should pay attention to the following on perusal of this report:

- The report is divided into two major parts:
  - The main report which is divided into numbered chapters.
  - The appendices which are arranged alphabetically.
- Figures, tables and equations are enumerated consecutively according to the chapter number. Hence, the first figure in chapter one is named figure 1.1, the second figure figure 1.2 and so on.
- The Harvard method is used for citation. The bibliography can be found after the main report.
- The CD contains data sheets used in this project.

Aalborg University, June 3rd 2009.

Javier Galdón Romero
<galdon@es.aau.dk>

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List of Abbreviations

ATS	Asymptotic Threshold Shift
BM	Basilar Membrane
CF	Characteristic Frequency
CHABA	Comitte of Hearing, Bioacoustics and Biomechanics of the National Academic of Sciences
DP	Distortion Product
DPOAEs	Distortion Product Otoacoustic Emissions
DRC	Damage-Risk Criteria
FFT	Fast Fourier transform
HT	Hearing Threshold
HTLAN	Hearing Threshold Level associated with Age and Noise
IHCs	Inner Hair Cells
LAeq	Equivalent Continuous A-weighted Sound Pressure Level
NIHL	Noise-Induced Hearing Loss
NIPTS	Noise-Induced Permanent Threshold Shifts
OAEs	Otoacoustic Emissions
OHCs	Outer Hair Cells
OSHA	Occupational Safety and Health Administration
PTS	Permanent Threshold Shift
SLM	Sound Level Meter
SNR	Signal Noise Ratio
SPL	Sound Pressure Level
STFT	Short-Time Fourier Transform
TEOAEs	Transient Evoked Otoacoustic Emissions
TS	Threshold Shift
TTS	Temporary Threshold Shift
TTS2	Temporary Threshold Shift 2 min after the cessation of the exposure

Chapter 1

Introduction

Many researches over time have been focused on the potentially risk of hearing damage of occupational noise exposure [Ward, 1970] [F.P.Marques and Costa, 2006]. In an industrial situation, recovery periods around 16 hours were required for exposure levels above 100 dB to restore completely the initial sensitivity. Some workers exposed to such a noise may indeed develop a chronic hearing disorder. Likewise, the estimate risk of hearing damage was found to be around twelve fold higher for groups exposed to intense noise than for non-occupational exposure workers.

Aside, some investigations have been oriented to determine the effect of being exposed to intense loud sounds from leisure activities [W.Clark, 1991] [Airo et al., 1996] [Maassen et al., 2001] [Maassen et al., 2001]. Live or amplified music, attending frequently to discos, exposure from personal listening devices or being exposed to fireworks are to be potentially dangerous in terms of hearing whether the exposure time is exceeded. For instance, some of the mentioned investigations [Maassen et al., 2001] [Maassen et al., 2001] reported that 2/3 of disco visitors experienced hearing problems such a tinnitus. Furthermore, one weekly visit to a disco over a period of 10 years could develop a moderate hearing loss around 6 dB, being more raised for assiduous visitors up to around 20 dB at 4000 Hz. Hence, high levels of noise detected from leisure activities are indeed a significant cause of developing hearing losses.

However, while standardised rules are in charge of regulating the maximum allowed sound pressure levels in occupational places [ISO 1999, 1990], there is a lack of control of the noise from leisure activities, and in mostly cases the exposed population are the own responsible of being aware of the risk of developing a hearing disease caused by the noise.

Music bands are a population considered potentially exposed to intense loud sounds during either concerts or at rehearsal places. In fact, the incidence of developing hearing losses among musicians is exceptionally high [Brashears, 2001]. Several studies reported hearing losses from 30 to 50% of symphony orchestra musicians [Axelsson and Lindgren, 1978] [Royster et al., 1991]).

The necessity of an acute sense of hearing for the career of a musician entails a great deal of hearing conservation responsibility of this population. A hearing assessment must be addressed them to be educated in protecting their hearing. Nevertheless, musicians are not often reciprocal in maintaining their audiological health by wearing ear plugs when playing in a concert or during their rehearsal days since they cite that their music can not be heard in a natural manner.

The most effective demonstration of the risk of hearing damage is to personalise the effect of the noise by testing the hearing levels as well as the musician's Otoacoustic Emissions(OAEs) before and after the exposure [Brashears, 2001]. The latest allow to detect temporary losses of the normal function of the musician'cochlea caused by the effect of the noise. In fact, one of the most characteristic reactions of the human auditory system to an intense sound is reflected in an amplitude reduction in both hearing levels and OAEs denoted as a shift.

The underlying purpose is to convince the musicians about their own temporary loss of Outer Hair Cells (OHCs) function, which are the sensory cells in charge of the active process within the cochlea. Without the presence of those cells, approximately around 55-60 dB of hearing loss will be present [Berlin et al., 1996].

There are two main methods to evaluate the human hearing status, determining the subject's hearing levels and analysing the low level sounds produced by the hearing system denoted as OAEs. The former consists on a test of hearing whereas the latest evaluates the status of the human cochlea. Both are recommended to determine a normal hearing function. Furthermore, many people exposed to noise over years showed noticeable hearing levels but an absent or reduced OAE amplitude. Frequently, moderate exposure levels that are not intense enough to elicit a shift by performing an audiometry are present when recording an OAE tracing [Brashears, 2001].

To summarise, people exposed to intense loud sounds from leisure activities, as the case of musicians involved in a band, must be aware of the recommended average safe hours per day depending on the level of the exposure, for instance the guidelines provided by the Occupational Safety and Health Administration (OSHA). Aside from their responsibility, hearing assessment is to be an appropriate tool for testing the health status of their hearing and convincing them of the potential risk of hearing damage caused by the affects of noise.

Chapter 2

Project Description

This chapter contains the research process to be followed in this project. It defines the scope, the procedure and the formulation of the problem to be solved.

2.1 Project Scope

The scope of this project is to document the changes in hearing encountered before and after the exposure for each member belongs a pop-rock band who often attend to play in a rehearsal twice per week. It also concerns a hearing assessment performed for a population of twelve normal hearing subjects considered non-exposed to intense loud sounds. Thereby, two populations which differ significantly in their music leisure habits can be compared. Likewise, the sound pressure level obtained during the rehearsal period is to be compared with other prevalent leisure activities, such as concert events.

2.2 Project Procedure

This section gives an overview of the research process followed in this project. Each step is briefly described to help the reader to obtain a quick understanding of the whole procedure.

Study of the different hearing assessment methods In order to detect the temporary changes in hearing after an exposure in an efficient manner, the prevalent methods regarding hearing assessment are to be studied in terms of efficiency and average used time. Both populations will be tested with the same methods for the comparison afterwards.

Temporary hearing changes in musicians detected before and after rehearsals Each member belongs the musician band is to be tested in terms of hearing before and after a rehearsal day in order to detect temporary hearing changes caused by the exposure to noise.

Hearing assessment for control population The non-exposed population are subjected to a hearing assessment with a view to collect an average of their hearing status and the normal function of their cochlea. Those results will be employed as a reference for comparison with musicians'hearing initial status.

Comparison An analysis between both populations is performed to find out the risk of being exposed to intense loud sounds over many years.

2.3 Problem Formulation

The temporary loss of the normal function of the human hearing system when being exposed to noise is to be tested among three musicians involved in a music band with the aim to convince them about the necessity of protecting their hearing. The main questions to be solved throughout this project are,

- Is there a substantial difference in the normal function of a musician's cochlea as well as the obtained hearing levels before and after a rehearsal?Is it appreciated a general pattern among musicians?
- Which are the differences encountered between the non-exposed and potentially exposed populations to intense loud sounds?

Chapter 3

Physiology of Hearing System Anatomy

This chapter is to be a theoretical review of the basic structure and function of the human hearing system anatomy. Due to the purpose of this project is to make an assessment of the risk of hearing impairment for a population being exposed to intense loud sounds in different situations, a background of the physiology of the auditory system results indispensable to understand the sound process along the human ear and the main causes of hearing loss.

3.1 Structure and Functionality

The human ear consists of three main parts, the outer, the middle and the inner ear. Its basic structure is shown in figure 3.1. The main parts involved in the sound process have been marked.

The main function of the outer and middle ear is to conduct the incoming sound to the cochlea, which is located in the inner ear. When the incoming sound is modified and localized by means of the visible part of our ear (*pinna*), it travels along the auditory canal and causes the *eardrum* or tympanic membrane to vibrate. This vibration of the eardrum is transmitted through the middle ear by three small bones known as *ossicles*, to the cochlea. A movement of the ossicles cause the oval window to move, and a pressure difference is applied across one membrane located in the cochlea, known as *Basilar Membrane* (BM). The stimulus displacement of the BM varies depending on the frequency of the stimulus, creating different band pass filters. Eventually, a non-linear mechanism takes place by means of the hair cells assisting the filtering process as well as the mechanical into electrical transduction in the auditory nerve.

Every part involved in the function of the auditory system is explained in the following sections.

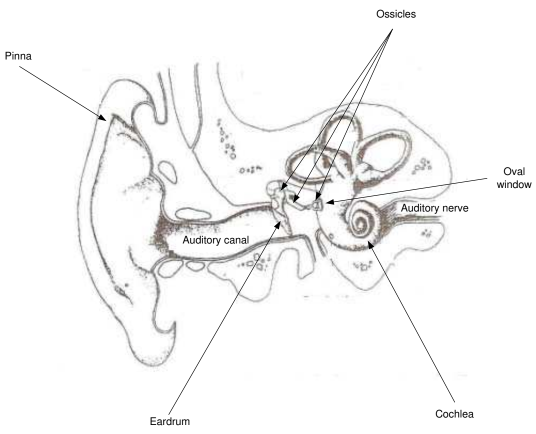


Figure 3.1: Basic structure of the human auditory system showing the outer, middle and inner ear [Moore, 1997].

3.2 Outer Ear

The outer ear consists of two main parts, the pinna and the auditory canal. The pinna modifies the incoming sound, particularly at high frequencies. This results to be important in the human ability to localize sounds [Moore, 1997]. The auditory canal length is around 2.5 cm and the diameter is around 0.6 cm [Møller, 2000]. The sound travels across the auditory canal causing a vibration which is transmitted to the middle ear by the tympanic membrane and the ossicles.

3.3 Middle Ear

The middle ear is comprised of the tympanic membrane and the three small bones called ossicles. The tympanic membrane, also known as eardrum, terminates the ear canal. Its main function is to convert sound into vibration which is transmitted by the ossicles. These bones are the *malleus*, the *incus* and the *stapes*, coupling the eardrum with the oval window. They have minute muscles attached to them which contract upon exposure to intense sounds . This contraction or reflex allows to reduce the transmission of sound through the middle ear but only at low frequencies [Moore, 1997]. However, the activation of the reflex results to slow to protect against impulsive sounds.

There are two main functions of the middle ear according to [Moore, 1997],

- Provide an efficient transfer of sound from the air to the fluids in cochlea. This results particularly effective at middle frequencies, between 500 to 4000 Hz.
- Reduce the transmission of bone-conducted sound to the cochlea, which can be undesirable whether the transmission is loud enough to mask other external sounds.

3.4 Inner Ear

The vibrations are transmitted through the middle ear to the cochlea by means of the oval window, which is an opening located in the bony wall of the cochlea, as it can be seen in figure 3.1.

In the inner ear the response of the BM within the cochlea to a certain stimulus as well as the functionality of the sensory cells of hearing result to be the most important processes to understand the physiology of the cochlea and thereby, the psychology of hearing.

3.4.1 Cochlea

As it was stated before, the cochlea is a snail-shaped bony structure which contains the sensory organ of hearing. Normally it is studied like if it has been unwound, and its length is approximately 3.5 cm [Møller, 2000]. The cochlea has three different fluid-filled tubes that are separated by two membranes. The *Reissner's membrane* provides isolation between two of those tubes, the *scala media* and the *scala vestibuly.* Likewise, the latest is separated by the BM from the *scala tympani.* This membrane plays an important role in the frequency selectivity process that takes place in the inner ear.

Basilar Membrane

When the vibrations are transmitted to the cochlea by the ossicles, particularly the stapes, the oval window is set in motion and a pressure difference is applied across the BM [Moore, 1997]. Then, the BM experiments a movement which varies along its length.

The start of the BM is called *base* and its width is around 150 μm, and the end is called *apex* with a width around 450 μm. This is shown in figure 3.2. The BM is stiffer in the basal than at the apex , what it is believed to be the reason of that the ear creates a sound wave on the BM that travels from the base to the apex when an incoming sound appears [Møller, 2000].

The response of the BM depends on the type of stimulus generated. It can be a sinusoidal stimulation or a short impulse (click), and the response is very different depending on each case. When a short impulse is generated, the response occurs all along the BM since this stimulus contains a wide range of frequencies [Moore, 1997]. Nevertheless, when a sinusoidal stimulus reaches the ear, the response of the BM is a travelling wave whose envelope increases in amplitude at the beginning until a certain peak and decreases abruptly afterwards. The frequency that provides the maximum displacement of a particular region of the BM is known as the *characteristic frequency* (CF) for that region [Moore, 1997]. These displacements depend on the frequency of the incoming stimulus. High frequency sounds produce maximum displacement near the base and the rest of the BM remains almost quiet. On the other hand, when a low frequency sinusoid reaches

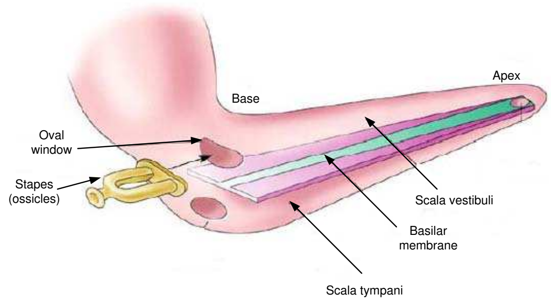


Figure 3.2: Unwound cochlea showing the base and the apex part of the BM. The start of the BM (base) is narrower than the end part (apex). The two fluid-filled tubes which are separated by the BM are also shown, the scala vestibuli and the scala tympani. This picture has been extracted from a course given by [Pedersen].

the ear, the vibrations are extended along the BM but the maximum displacement is achieved near the apex [Moore, 1997]. This excitation of the BM is illustrated in figure 3.3.

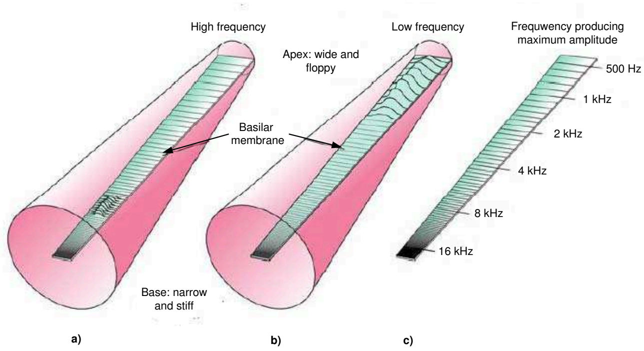


Figure 3.3: The excitation of the BM differs according to the frequency of stimulation. High frequency sounds produce maximum displacement near the base and the rest of the BM remains almost quiet (a)). Low frequency sounds produce the maximum near the apex but the vibrations are extended along the BM (b)). Therefore, the response of the BM varies along its length where the high frequency sounds are located at the base part and as long as the travelling wave moves toward the apex part, only the low frequency sounds are present (c)). This picture has been extracted from a course given by [Pedersen].

Some parts of the BM vibrate with a greater amplitude than others and they differ in the phase of vibration at different points, but the CF is the same for each region. Therefore, each region can be considered as a band pass filter with a certain CF [Moore, 1997]. The amplitude of the response of the BM does not grow proportionally with the amplitude of the stimulus and thereby, the vibration of the BM is considered as a non-linear process.

Whether two different tones reach the ear and the separation between them is large enough, the BM provides two patterns of vibration, but when they are closely spaced in frequency, those vibrations can interact caused by both tones [Moore, 1997].

Organ of Corti

Once the frequency separation process has been carried out at the BM, the sensory cells located in the Organ of Corti, which is placed along the BM, are activated to compress the vibration of the BM and to transform the mechanical displacements into neural code in the auditory nerve. There are two main sensory cells within the Organ of Corti, the OHCs and the IHCs.

- **OHCs** They are the main responsible for the active process which is carried out within the cochlea. There are around 30000 OHCs in humans [Møller, 2000]. This active process known as *Cochlear Amplifier* presents two main functions:

    1. OHCs assist the filtering process at the BM in such a way that for low sound intensities, they reduce the influence of friction of the BM motion and compensate the energy losses. This action provides an increase of the vibration amplitude of the BM around 50 dB near the apex part[Møller, 2000]. If the *Cochlear Amplifier* process is not active, a hearing loss occurs.
    2. OHCs compress the vibration of the BM over most of the input amplitude range [Moore, 1995]. This compression occurs before the sound is transformed into electrical displacements.

- **IHCs** They are in charge of the mechanical into electrical transduction in the auditory nerve. There are around 10000 IHCs in the human cochlea [Møller, 2000]. This function together with the OHCs compression allows the auditory system to process sounds over a range around 100 dB.

It is important to notice that a person exposed to intense loud sound for a long time period will experiment the normal instantaneous fatigue by the response of the sensory cells plus the mechanical fatigue due to the over-exposure. This over-exposure can produce losses of either OHCs or IHCs, causing *Noise-Induced Hearing Loss* (NIHL). The effect of the sensory cells on the auditory system is different. Loss of IHCs has a direct consequence on permanent hearing damage while loss of OHCs represents a less severe risk, affecting mainly the sensitivity and the frequency selectivity of weak sounds [Ordoñez, 2005].

Chapter 4

Hearing Assessment

This chapter is to be a theoretical review about the most prevalent techniques employed for hearing assessment, such as audiometries and Otoacoustic Emissions (OAEs). Firstly, it describes the main standardized audiometric methods and makes the selection of the most effective in terms of precision and speed. Eventually, the sorts of OAEs used to assure the risk of hearing impairment will be described.

4.1 Audiometry

The audiometry is a technique to measure the human hearing ability. Normally, the device used for this purpose is an audiometer, which generates some stimuli of known levels for each frequency. The subject who participates in the test is normally asked to give a response by pressing a button when he perceives an stimulus. The underlying technique is based on varying the level intensity of several stimuli in order to find out the limit between audible and inaudible sound [M.Lydolf, 1999]. The lowest level which a subject recognizes the stimuli on repeated trials is called the absolute threshold of hearing.

4.1.1 Hearing Threshold

In terms of psychophysics, a particular stimulus intensity which is detected by the subject in a detection experiment during 50 % of repetitive trials is denoted as threshold [M.Lydolf, 1999]. This is frequently used for clinical purposes. Applying this term for hearing, the degree of a patient's hearing loss can be quantified in terms of the magnitude of the stimulus needed for him to respond to it. The smallest intensity of such stimulus that a person needs to detect its presence is called *Hearing Threshold* [Gelfand, 1997].

In audiometric tests, a threshold of normal hearing subjects, often young people who are considered healthy listeners, is required as a reference. This means that the HTs of the subjects will be obtained relative to the average threshold at each frequency for those people. Based on [ISO 389-7, 2005], the reference threshold of hearing at a certain frequency is defined as the sound pressure level of a pure tone or a one-third-octave band of noise corresponding to the median value of the binaural thresholds of hearing of otologically normal persons within the age limits from 18 years to 25 years inclusive. In figure 4.1, two reference threshold curves are depicted for pure tones under binaural free-field conditions and for one-third octave bands of noise under binaural diffuse-field listening conditions, with black line and dashed blue line respectively.

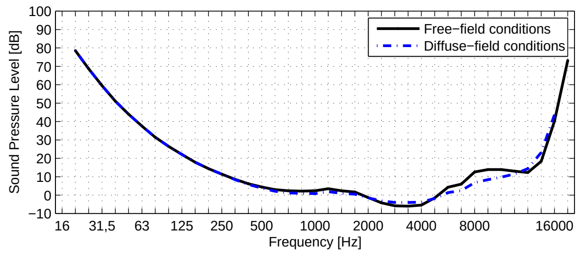


Figure 4.1: Reference thresholds of hearing for pure tones under binaural free-field listening conditions and for one-third-octave bands of noise under binaural diffuse-field listening conditions. The data are obtained from [ISO 389-7, 2005].

The reference thresholds for the free-field conditions curve † correspond to 0 dB HL (Hearing Level) and is represented as a horizontal line at the top of the audiogram ‡, and the degree of hearing loss (positive threshold) or the sensitiveness (negative threshold) with respect to the average is depicted by how much the threshold falls below or above this line respectively [Moore, 1997], following the equation 4.1:

$$HL = 20log\frac{dBSPL}{dBSPL0}[dBHL] \tag{4.1}$$

where *dBSPL* is the sound pressure level obtained by the subject at a certain frequency and *dBSPL0* is the sound pressure level of the reference threshold for pure tones under binaural free-field listening conditions at this frequency.

4.1.2 Standardized Audiometric Methods

There are many methods to measure the HTs for a certain population, depending mostly on the detection task as well as the type of stimuli. Since for the purpose of this project, the selected audiometric method is required to be as fast and reliable as it ever will, only two methods are considered of interest based on the researches made by [M.Lydolf, 1999], the Ascending and the Békésy method. This section describes theoretically those methods with a view to select the most reliable in terms of efficiency and time consuming.

They are included in the denominated air conduction (AC) measurements, which consist on a sound transmission through the outer and middle ear to the inner ear §.

†The HTs determined under free-field conditions are used to calibrate the audiometers.

‡An audiogram is a plot which represents the hearing levels versus frequency.

§Other methods can also be used, such us the bone conduction (BC) measurements or free-field threshold measurements, but they are not reported in this project.

Ascending Method

This method is considered the most reliable and fast within the manually methods of limits †. It consists on approaching the HT of the subject by a series of small changes in the level of the stimulus until the threshold is reached. For every frequency in the desired range (normally between 250 Hz and 8 kHz), an stimulus of duration around 1-2 s is presented to the subject by means of headphones.

According to [ISO 8253-1, 1989],

- The order of the presentations of the test tones must be from 1 kHz upwards, followed by the lowest octave band until a repeated test is carried out at 1 kHz. The difference between the tested level at this frequency must not be higher than 5 dB to consider the test as valid.
- The most sensitive ear of the subject is measured at the first time and when all octave bands have been tested, the procedure is repeated for the remaining ear. Whether the sensitive ear is unknown, the right ear is firstly tested.
- The initial stimulus level is to be typically 40 dB (audible level) and then, the intensity is decreased in 10 dB stepwise until the subject is not able to hear the tone. This is used for the familiarization session of the test.
- After each failure, the level of the test tone is increased in steps of 5 dB until the subject makes a detection.
- After the response, the level is decreased in steps of 10 dB until no detection occurs and then, another ascent begins.
- The test can be concluded either after three reversals at the same level out five ascents for the extended version or after two reversals out of three ascents for the shortened version.

An example of the determination of the HT when using the Ascending method is depicted in figure 4.2.

Békésy Method

This method is considered as an automatic version of the methods of limits, where the subject directly controls the changes in the stimulus intensity, resulting in a fast procedure often used for clinical audiometry.

† The methods of limits include the Ascending, Descending and Bracketing method. The HT of the subject is determined by a series of small changes of the levels of the stimulus until the threshold is reached.

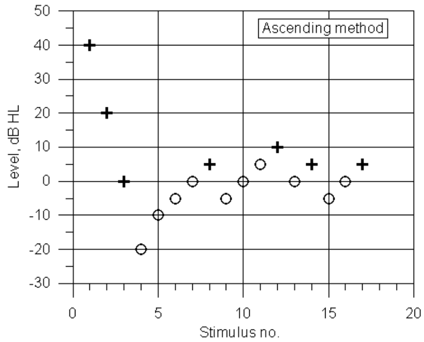


Figure 4.2: Determination of the HT when using the Ascending method [Poulsen, 2007]. The '+' symbolizes a response whereas 'o' means that no response occurs. In this example the HT is 5 dB after three reversals.

Firstly, a continuous tone or a sequence of pulse tones is presented to the subject. According to [ISO 8253-1, 1989], pulse tones are preferably used for threshold determination †.

As long as the subject hears a tone, he will press the button. Then, the stimulus intensity is decreased continuously with a stepwise around 2 dB/s [Poulsen, 2007]. When the signal is no longer audible, the subject releases the button and the stimulus intensity increases with the same stepwise than before. The levels where the button is either pressed or released are recorded as peaks or valleys respectively, which will be used to calculate the hearing threshold afterwards. The method finishes when a specific number of reversals has been carried out.

For instance, an example of the Békésy recording can be seen in figure 4.3.

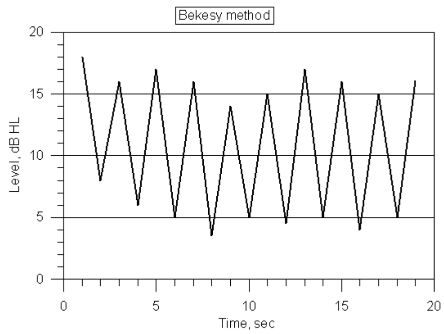


Figure 4.3: An example of the Békésy recording [Poulsen, 2007]. After a specific number of reversals, the HT of the subject is calculated by averaging the peaks and the valleys, and calculating the mean of both averages.

† The standard [ISO 8253-1, 1989] states that the continuous tone are used only for some specialized audiological purposes.

Based on [ISO 8253-1, 1989], the procedure to determine the HT of a subject for the Békésy method is as follows,

- A familiarization session is required in order to guarantee that the subject understands the task. The attenuation of the intensity level of the stimulus must start at the first test frequency (1 kHz).
- Once the test starts, it should be continued until both ears have been tested.
- The first reversal following a change of frequency must be ignored.
- The test can be concluded when six reversals have been obtained after the first one and the peaks or valleys do not deviate by more than 10 dB among themselves.
- The HT is determined by averaging three peaks and three valleys for a given frequency and ear, and calculating the mean of both averages.

Selection of the Method

For the purpose of this project, the chosen audiometric method is to be as efficient as it ever will in such a way that any change in the auditory system of a subject can be detected in a short period of time.

Based on the researches made by [M.Lydolf, 1999],

The two standardized audiometric methods explained before seems to be faster than others after an evaluation of eight different methods for determination of HT in terms of accuracy, reproducibility and efficiency. This comparison is to be used as a benchmark to determine the audiometric method which will be used throughout this project. 24 subjects with 3 repetitions were evaluated at 500, 1000 and 2000 Hz in that investigation. The main results obtained are described as follows,

- **Determination of HT** Békésy method showed thresholds about 1.5 dB higher than the Ascending method . Other studies reported that the HT for this method were more sensitive than those obtained in this investigation. The reason might be related with the procedure used had some variabilities with respect to the rules in [ISO 8253-1, 1989]†. The standard deviation within subjects was around 1.6 - 2.0 dB for both Békésy and Ascending methods.
- **Averaged Used Time** Ascending and Békésy methods resulted to be faster than the others involved in this investigation. The time employed was around 1 - 1.5 min.

†According to [ISO 8253-1, 1989], an average difference exists between HT levels determined by manual audiometry (Ascending method) and those recorded by automatic audiometers (Békésy method). In fact, this standard assumes that the HT levels when using the Békésy method are 3 dB lower, meaning thresholds more sensitive, than those obtained by the Ascending method when using a 5 dB stepwise.

- **Efficiency** This term is defined here as the relation between the used time and the achieved standard deviation within subjects at the given time. After the comparison, the tendency was a decreasing of the standard deviation within subjects as a function of time to a level below 2 dB within around 1 min of measurement time. Ascending showed to be the most efficient of the methods of limits, but Békésy method was the most efficient of the eight methods tested. The initial standard deviation within subjects was smaller that any of the other methods. After eight pair of reversals, the standard deviation reached a level of 1.64 dB which resulted to be the minimum found.

Therefore, Békésy test is the most appropriate method for the determination of the HT of a subject. However, some technical problems reported in appendix C prevented this method to be used during the HT measurements. The Ascending method was selected instead.

4.2 Otoacoustic Emissions (OAEs)

Apart from the audiometric methods, there are other techniques used to measure the normal function of the cochlea. OAEs can be used to predict earlier hearing losses in newborn and young adults but they are also a particular useful technique to evaluate the cochlear status in older adults. The main advantage compared with the audiometric methods is that they are an objective indicator of the activity originated by the motion of the outer hair cells. Hence, they are not subjectively dependent of the subjects.

OAEs can emerge spontaneously due to the nature compressions and refractions of the air in the ear canal, but are commonly measured when eliciting an stimulus. Depending on the level of the stimulation and type of technique used, OAEs can detect hearing losses of between 20 and 30 dB [Otodynamics, 1997].

They can be detected only when the middle ear system is operating properly and are often used to confirm the normal function of the BM, the structure of the organ of Corti and the health of the outer hair cell system.

Although they can detect a hearing loss in a specific frequency region, there are not strong arguments to relate the OAEs levels of a person with the audiometric thresholds with accuracy.

4.2.1 Classification of OAEs

There are two general categories of OAEs, the *Spontaneous* and the *Evoked*. The latest includes a classification depending on whether the presented stimulus is a click or two pure tones are generated. All OAEs reflect cochlear processes.

Spontaneous Otoacoustic Emissions (SOAEs)

SOAEs are very narrow bands of frequencies (less than 30 Hz) recorded in the external ear canal in the absence of a stimulus [Hall, 2000]. They are usually inaudible for the subjects who participate in a test for measuring them. The cochlea, specially the outer hair cells, is emitting energy at one or more frequencies which is recorded by means of a very sensitive microphone. Thereby, the nature of the active cochlear process can be measured.

The presence of SOAEs suggests that the cochlear hearing sensitivity is close to the frequency where an SOAE is detected [Robinette et al., 1997].

In figure 4.4, a typical SOAE from a young, normal hearing female is depicted. It can be noticed that the likelihood of SOAEs increases in the most sensitive human hearing region, e.g. between 1000 - 2000 Hz, with an amplitude which can vary between -5 to 15 dB(SPL). The SOAEs appears as peaks arising at least 3 dB above the noise floor presents in the ear canal [Robinette et al., 1997].

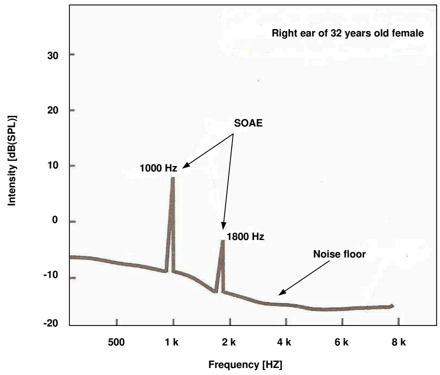


Figure 4.4: An SOAE recorded in the external ear canal for the right ear of a 32 years old woman in the absence of a stimulus [Hall, 2000]. Two peaks at 1000 Hz and at 1800 Hz arise sharply above the noise floor. The amplitude of the SOAEs often varies from -5 to 15 dB(SPL), and they increase in the most sentitive human hearing region, e.g. between 1000 - 2000 Hz.

However, SOAEs are not applied clinically since there are no arguments to conclude a dysfunction of the cochlea when they are not present. Furthermore, no more than 60% of normal hearing people present them [Hall, 2000]. The occurrence of SOAEs depends on many factors, such us gender, the selected ear or the age [†], meaning a great variability for each individual and their study does not result precise. Therefore, SOAEs are not further studied in this project.

[†] The SOAEs result more common in females than in males and are more often found in the right ear [Hall, 2000].

Transient Evoked Otoacoustic Emissions (TEOAEs)

They belong the *Evoked* group of OAEs. The stimulus is presented generally as a click of around 0.1 ms and with an intensity near of 80 dB(SPL). A broadband of frequencies up to around 6 kHz composes the spectrum of the stimulus. During the process, the cochlea is activated simultaneously from basal to apical regions of the basilar membrane (BM), and the response is recorded within the external ear canal.

The main characteristic of TEOAEs is that a general impression of the spectrum from the outer hair cells response can be obtained in a short period of time. Whether a healthy ear is being evaluated, this spectrum mirrors directly the spectral characteristics of the stimulus used. The shorter the stimulus, the broader the frequency range of the stimulus [Hall, 2000].

In figure 4.5, an example of TEOAEs obtained up to almost 6 kHz above the noise floor is depicted. Normally in adults, TEOAEs arise amplitudes from 10 to 15 dB(SPL). To analyse the behaviour of these emissions, different TEOAEs are often measured to assure that the data obtained are reliable in terms of reproducibility. Likewise, the difference between the amplitude of the stimulus and the noise are calculated at each band of frequency.

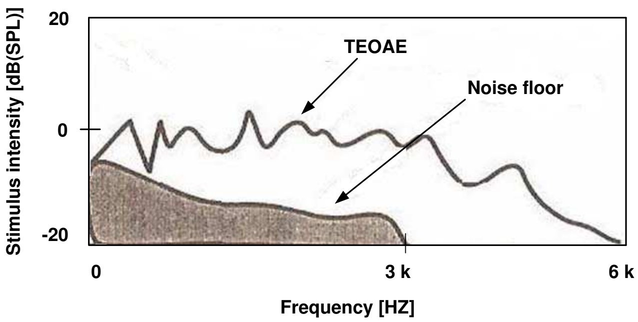


Figure 4.5: An spectrum of TEOAEs and the noise floor measured within the external ear canal up to almost 6 kHz [Hall, 2000]. TEOAEs normally arise amplitudes from 10 to 15 dB(SPL).

A cochlear dysfunction in the subject at a certain frequency band can be derived from an analysis of TEOAEs when either no response is found or there is a reduction in the SNR after a sound exposure. They provide frequency information of the cochlear status of the subjects between 500 to 6000 Hz, being considered as an objective indicator of hearing losses between 20 and 30 dB.

Distortion Product Otoacoustic Emissions (DPOAEs)

DPOAEs are the most prevalent *Evoked* OAEs measurements used for clinical purposes. They consists on eliciting a vibration in a specific region of the BM by means of two pure tones stimuli closely spaced in frequency, known as *primaries* and denoted with f1 and f2. The higher frequency is normally f2 and the lower is f1, and the separation between them is the ratio f2/f1. Once the stimuli is generated, the outer hair cells response is recorded in the external ear canal.

Whether the *primaries* tones are not too far or too close together in terms of frequency [†], a DPOAE will be generated as the intermodulation distortion product between those pure tones at a different frequency. The response is being *distorted* since it appears at a certain frequency that is not present in the stimuli. The prominent and largest distortion product in humans is 2f1 - f2, even though other frequencies can also be observed, such as f2 - f1, 2f2 - f1 or 3f1 - 2f2 [Robinette et al., 1997].

The main advantage of the DPOAE measurements is that a narrowband spectral analysis is carried out and thereby, specific regions of the BM can be analysed. A hearing impairment may be observed when a reduction of DPOAE amplitude is found, meaning a decrease in the SNR, either if the subject is being compared with a normal hearing population or the behaviour in the cochlear response is to be analysed after a sound exposure. DPOAEs measurements result particularly useful to test the higher frequency region of the cochlea but are less sensitive than TEOAEs to small cochlear dysfunctions leading to only 10 up to 20 dB [Otodynamics, 1997].

The typical values used clinically are a ratio f2/f1 equals 1.22 and the levels for the *primary* tones between 55 to 65 dB (SPL). In figure 4.6, an example of DPOAE measurements is shown. The primaries tones intensities are L1 = 65 dB (SPL) and L2 = 55 dB (SPL), corresponding to the frequencies f1 = 2000 Hz and f2 = 2400 Hz respectively. The largest distortion product is found at the frequency 2f1 - f2 = 1600 Hz with an intensity around 10 dB (SPL) above the noise floor. According to the studies reported in [Hall, 2000] and [Robinette et al., 1997], a DPOAE can be considered as valid when its level is at least 3 dB(SPL) above the noise generated by the environment as well as the subject's body motion.

According to [Robinette et al., 1997], the selected ear and the gender do not cause significant differences in DPOAE measurements. Nevertheless, the age seems to affect the results since DPOAE amplitudes decrease when increasing the age at most frequencies. This must be taken into account when evaluating a certain population.

[†] The *primaries* tones must be within one-third octave of each other [Robinette et al., 1997].

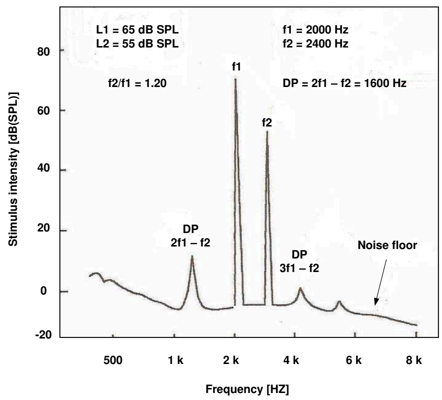


Figure 4.6: An example of DPOAE measurements [Hall, 2000]. The primaries tones show intensities of L1 = 65 dB (SPL) and L2 = 55 dB (SPL), corresponding to the frequencies f1 = 2000 Hz and f2 = 2400 Hz respectively. The major distortion product is found at the frequency 2f1 - f2 = 1600 Hz, and with an intensity higher than 3 dB(SPL) with respect to the noise floor. Therefore, the DPOAE obtained can be considered valid.

Chapter 5

Assessment of Changes in Hearing

This chapter describes the changes in hearing originated after a sound exposure. They are often analysed in terms of the shift produced when comparing the data obtained for the hearing assessment before and after the exposure. To be detected, the post exposure measurements must be recorded in a short period of time immediately after the cessation of the exposure. Temporary Threshold Shift (TTS) as well as OAEs Shift characteristics will be explained.

5.1 Temporary Threshold Shift (TTS)

When the auditory system is exposed to an intense sound level during either short or prolonged time periods, a loss of sensitivity occurs. This over-simulation implies a change in the response of the inner ear, meaning a fatigue of the system. The degree of damage will depend on the severity of the exposure and the sensitivity of each subject [Ordoñez, 2005]. A direct consequence of this change in response can be observed temporally by measuring the HT of a subject before and after the exposure. In fact, the difference between the absolute threshold before and after the exposure is known as *Temporary Threshold Shift*.

There are many factors that can influence the magnitude of the TTS during and after a sound exposure, but according to [Ordoñez, 2005] the most relevant are,

- The frequency region where the noise presents greatest concentration of energy
- The duration of the noise exposure
- The intensity of the noise exposure
- The frequency of the stimuli which are used during the hearing assessment

In light of these factors, TTS will diminish after the cessation of the noise whether the duration and the intensity of the exposure have not been severe enough and then, the normal HTs of the subject will be recovered completely. But a partial deafness or a great degree of hearing loss can occur when, even though the ear has recovered as much as it ever will, the remaining threshold shift is permanent [Miller, 1974]. This threshold shift is known as *Permanent Threshold Shift*(PTS), and it persists continuously.

TTS experiments consists of three main parts:

Pre-exposure The initial conditions of the subjects are measured within this phase. They are often used as a reference of the HTs of the subject to be compared with the post-exposure data afterwards. Normally, several repetitions of the test must be carried out to assure the accuracy of the responses since the determination of the threshold depends significantly on the susceptibility of the subject.

Exposure It is referred to the time that the subject is to be exposed to the noise. When the purpose of the experiment is to monitor the growth of TTS during the fatiguing stimulus, the HTs are measured after each predetermined cessation of the exposure [Ordoñez, 2005].

Post-exposure In this period the HTs are determined at different times after the complete cessation of the noise to assure that the subject's auditory system recovers the initial conditions. HTs are compared as the existing difference between the current values at this phase and the initial conditions. Thus, the TTS of each subject are obtained and to assure reliability of the results, they have to be measured at the same frequencies and with the same audiometric method.

Normally, TTS are studied in terms of both time and frequency characteristics.

5.1.1 Time Characteristics of TTS - Growth and Recovery

A general impression of the increase of the magnitude of TTS in time for different exposure cases is depicted in figure 5.1. The time in noise is plotted along the horizontal axis and the magnitude of TTS measured in [dB] is plotted on the vertical axis. These predictions are made at 2 min after the cessation of the exposure[†], which can be either a band noise between 2400 and 4800 Hz or a pure tone at 4000 Hz [Miller, 1974]. It is noticed that the more intensity of the exposure noise, the TTS growth increases more rapidly. For instance, when the intensity of the noise is 110 dB, a normal hearing person exposed only a bit more than 15 min reaches a TTS level around 40 dB, which may result in a hearing loss or a PTS. However, whether this person is exposed to 70 dB of noise, more than 4 hours are need to experiment any significant TTS. It is important to take into account that these predictions are made for the most susceptible frequency region, and therefore, the risk of hearing damage is greater than for other exposure cases.

After several days of being exposed to the same noise at a specific level, the TTS is believe to remain stable [Ordoñez, 2005]. This value is known as *Asymptotic Threshold Shift*(ATS).

[†]TTS 2 min after the cessation of the exposure is denoted as TTS_2

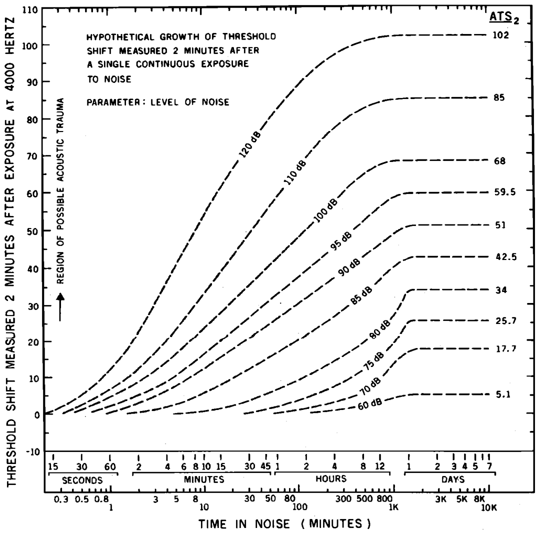


Figure 5.1: Hypothetical growth of TTS after various single and continuous exposures to noise. These curves are obtained for an average of normal hearing young adult exposed to a band of noise or pure tone centered near 4000 Hz [Miller, 1974]. Due to the human hearing system is more susceptible at this frequency region, it can be considered as the region of greatest risk of hearing damage.

Once the stimulus has been completely ceased, a recovery process takes place in the middle ear. This recovery depends basically on the duration of the exposure, the intensity and the specific frequency region of the noise. In addition, there are differences in the recovery process depends on whether the hearing system is exposed to the point of an ATS is induced or only a TTS can be observed. The recovery is longer for the ATS case. When the TTS is less than 40 dB, and the duration of the exposure is less than 8 hours, the recovery can be considered rapid [Miller, 1974]. However, if the duration is longer, as can be seen in the dashed lines in figure 5.2, the decline of the TTS requires several days to be completely recovered. Furthermore, whether the intensity of the level is above 100 dB, and the duration of the exposure persists many days, PTS are normally induced.

5.1.2 Frequency Characteristics of TTS

The occurrence of TTS is highly dependent on the frequency range of the noise exposure. If the hearing system is stimulated by means of pure tones, the maximum shift is often observed at frequencies about 1/2 octave above the centre frequency of the octave band of the stimulus [Melnick, 1991]. But according to [Ordoñez, 2005], some studies reported that for frequencies below 500 Hz, this criterion is not fulfilled since at those frequencies, high stimulus levels are required to find both the audibility thresholds and the TTS.

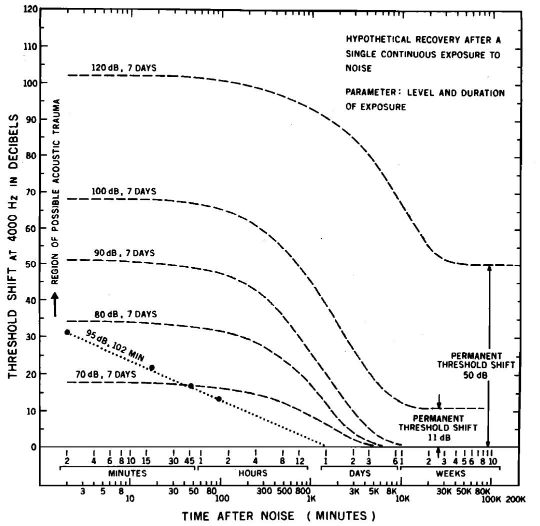


Figure 5.2: Hypothetical recovery of TTS after various single and continuous exposures to noise. These curves are obtained for an average of normal hearing young adult exposed to a band of noise or pure tone centered near 4000 Hz [Miller, 1974]. Due to the human hearing system is more susceptible at this frequency region, it can be considered as the region of greatest risk of hearing damage.

On the other hand, when the auditory system is exposed to a broadband noise, the maximum shift is generally located in the most sensitive frequency area, e.g. the lowest HT of the subject. In humans, this sensitive area is between 3 and 5 kHz [Melnick, 1991].

5.2 OAEs Shift

OAEs are also a useful technique to measure the changes in hearing before and after a sound exposure. The OAEs measurements normally show different frequency patterns that are highly dependent on the subjects, whereas the HT determination seems to follow a similar behaviour between subjects and its average results more representative [Ordoñez, 2005]. Hence, there is not a common recovery pattern for OAEs shift. Furthermore, large standard deviations across subjects are often found for pre-exposure values.

However, a common feature is that the frequency regions where the subject's hearing anatomy results more affected by the exposure can be found and thereby, the similarities between TTS and OAEs Shift can be derived.

Chapter 6

Sound Exposure Level and NIPTS

This chapter pursues the goal of giving a general overview of the determination of occupational noise exposure as well as the estimation of the risk of hearing impairment of the population exposed to intense noise levels. This estimation is based on the maximum occupational noise level allowed by the Danish Legislation and the calculation of the Noise-Induced Permanent Threshold Shift (NIPTS) in accordance to [ISO 1999, 1990]. However, it is important to notice that there are not plausible noise level rules behind leisure activities. In fact,people who often attend to leisure places where the exposure to noise can cause a serious hearing impairment are the own responsible of protecting against hearing disorders.

6.1 Occupational Noise Exposure

In order to determine the occupational noise exposure, different methods can be employed, directly with a miniature microphone close to the human ear, or indirectly by using a sound level meter. Due to the purpose of this measurement in this project is to be used as a population representative value to make a comparison of the noise exposure levels between different leisure activities, the second method using the sound level meter will be carried out.

Generally, the instantaneous sound pressure recorded by a microphone in a sound level meter is frequency weighted according to different filtering process given by [IEC 61672-1, 2002]. These filters are mainly the zero weighting Z, the A or C. Among them, the most widely used is the A-weighting, whose curve tries to be approximated to the response of the human hearing system giving more importance to the frequency bands with greater sensitivity [Ordoñez, 2005]. Therefore, each weight has a value for each frequency band which is representative of the sensitivity of the human ear at this particular frequency. The A-weighting curve is illustrated in figure 6.1. The curve values have been extracted from [IEC 61672-1, 2002].

This implies that equal loudness of sound will produce the same risk of hearing damage for all exposed individuals.

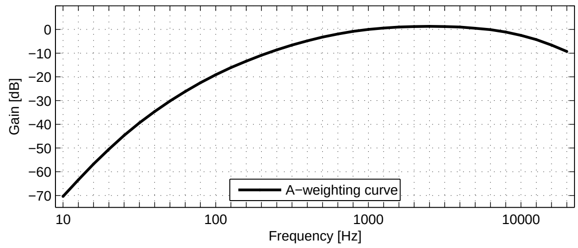


Figure 6.1: A-weighting curve employed by the sound level meters for filtering sound pressure levels. The values are given by [IEC 61672-1, 2002].

6.1.1 Equivalent Continuous A-weighted Sound Pressure Level

A standardised measurement of a sound exposure whose levels are fluctuating over time is the Equivalent Continuous A-weighted Sound Pressure Level (LAeq), and it is defined as: *the value of the A-weighted sound pressure level of a continuous, steady sound that, within a specified time interval, has the same mean-square sound pressure as a sound under consideration whose level varies with time.* This is stated in the equation 6.1 given by [ISO 1999, 1990],

$$L_{Aeq,T} = 10log[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \frac{P_A^2(t)}{P_0^2} dt] \qquad [\text{dB}] \qquad (6.1)$$

where $t2 - t1$ is the period T over which the average is taken starting at $t1$ and ending at $t2$, $PA(t)$ is the instantaneous A-weighted sound pressure of the sound signal and $P0$ is the reference sound pressure of 20 μPa.

When using a Sound Level Meter(SLM) for recording the sound exposure, the equation 6.1 can be directly transformed into 6.2 according to [ISO 1999, 1990],

$$L_{Aeq,T_{meas}} = 10log[\frac{1}{n} \sum_{i=1}^{n} (10^{0.1L_{pAi}})] \qquad [\text{dB}] \qquad (6.2)$$

where n is the total number of samples collected with the sound level meter within the measurement duration $Tmeas$, and $LpAi$ is the A-weighted sound pressure level, in decibels, for the sample i.

6.1.2 Noise Exposure level

To obtain the exposure to noise for a population at risk the $LAeq$ is calculated over an average working day, normally assumed to be of 8 hours of duration, by the equation 6.3 according to [ISO 1999, 1990],

$$L_{EX,T0} = L_{Aeq,Te} + 10log(\frac{Te}{T0}) \qquad [dB] \tag{6.3}$$

where Te is the effective duration of the exposure during the working day and $T0$ is the reference duration, normally 8 hours.

In addition, whether the exposure averaged over n days is desired, the equation 6.4 is employed,

$$L_{\bar{EX},T0} = 10log[\frac{1}{k}\sum_{i=1}^{n} 10^{0.1(L_{EX,T0})i}] \qquad [dB] \tag{6.4}$$

where k factor can be either fixed to a nominal number of days when the exposure is to be normalized or equal to n whether an average value is desired. $(L_{EX,T0})i$ is the noise exposure value for each day.

6.2 Assessment of Hearing Impairment

Once the exposure level over an average working day has been calculated, one can be guided by the noise legislation of the country in question or calculating the risk of hearing impairment by the estimation of NIPTS.

6.2.1 Maximum Exposure Level at Working Places

In accordance with the Danish Legislation [Legislation, 2002],

- Sustained noise of 75-80 dB(A) carries the risk of hearing damage.
- Sustained noise of 85 dB(A) carries the risk of serious hearing damage.
- Sustained noise of 90 dB(A) implies that the risk of serious hearing damage is almost three times as high as when a noise of 85 dB(A).

Therefore, a noise exposure level exceeding 85 dB(A) can cause a serious risk of hearing damage for a 8 hours working day.

6.2.2 Noise-Induced Permanent Threshold Shift(NIPTS)

When a population is exposed to an intense sound level during certain period of time, a fatigue of the hearing system occurs and a change in the response of the inner ear can be observed after the exposure. This implies a Threshold Shift (TS) of the person's hearing level, which can be considered temporary † or permanent depends on the duration of the exposure. Whether the purpose is to obtain the risk of hearing damage for exposure times of years, the *Noise-Induced Permanent Threshold Shift* (NIPTS) must be calculated.

NIPTS is a function of the level and the duration of the exposure as well as the frequency at which the risk of hearing impairment is to be assessed [Ordoñez, 2005]. This value is only valid for statistical distributions of groups of people, but it is not to be applied to individuals. The median NIPTS ‡ can be calculated directly from the $L_{EX,T0}$ by the equation 6.5 [ISO 1999, 1990],

$$N_{0,50} = [u + vlog(T/T_1)](L_{EX,T0} - L_0)^2 \qquad \text{[dB]} \tag{6.5}$$

where u and v are frequency dependent constants, T is the exposure time, in years, T_1 is one year of exposure, and L_0 is the cut-off sound pressure level defined as a function of frequency (it is assumed that levels below L_0 means no risk of hearing damage). This expression can only be used for exposure times between 10 and 40 years.

The u, v and L_0 values used to determine the NIPTS for the median value of the population ($N_{0,50}$) for the most sensitive frequencies between 500 and 6000 Hz are extracted from [ISO 1999, 1990], and they are presented in table 6.1.

Frequency [Hz]	u	v	L_0 [dB]
500	-0.033	0.110	93
1000	-0.020	0.070	89
2000	-0.045	0.066	80
3000	+0.012	0.037	77
4000	+0.025	0.025	75
6000	+0.019	0.024	77

Table 6.1: Values of u,v and L_0 used to determine the NIPTS for the median value of the population ($N_{0,50}$).

When the $L_{EX,T0}$ is less than L_0, it must be deemed to be equal to L_0 and thereby, the NIPTS is zero [ISO 1999, 1990].

†It is described in deep in section 5.1.

‡The median potential NIPTS corresponds to the 0, 50 fractile value. This value represents the 50% percentage of individuals at risk of obtaining NIPTS due to the effects of the noise exposure. The 0, 1 and 0, 9 fractile can also be calculated but they are not reported in this project. Further information can be found in [ISO 1999, 1990].

6.2.3 HT Level Associated with Age and Noise (HTLAN)

NIPTS must be compared with the hearing levels obtained for a population of normal hearing non-exposed to the intense loud sound in question to obtain the *Hearing Threshold Level associated with Age and Noise*(HTLAN). Thereby, the compensation due to the age is also taken into account.

HTLAN of a population exposed to noise is calculated by the equation 6.6 according to [ISO 1999, 1990],

$$H' = H + N - \frac{HN}{120} \qquad [\text{dB(HL)}] \tag{6.6}$$

where H is the HT level of the non-exposed population for a certain frequency, N is the NIPTS of the exposed population and the term $\frac{HN}{120}$ is the compensation due to the age and noise. This latest term starts to modify the result significantly when $H + N$ is more than approximately 40 dB. Those HT levels can be calculated for the same sensitive frequencies that are employed for the calculation of NIPTS in table 6.1.

Therefore, a comparison between the HT levels between the exposed and non-exposed population can be carried out to find out the magnitude of the TS for each frequency.

The risk of hearing impairment due to the noise exposure and the age is calculated comparing the HT levels for each frequency with a certain limit of tolerable hearing loss know as *fence*. This term is defined in [ISO 1999, 1990] as *a hearing threshold level above which degrees of hearing handicap (or disability) are deemed to exist.* For instance, the *Comitte of Hearing, Bioacoustics and Biomechanics of the National Academic of Sciences* (CHABA) proposed in 1965 a *Damage-Risk Criteria* (DRC) for both continuous and intermittent exposures to steady noise based on two assumptions [Ward, 1970],

- A lifetime of daily exposure must produce no more than 10 dB of NIPTS at 1000 Hz or below, 15 dB at 2000 Hz, or 20 dB at 3000 Hz or above.
- NIPTS will not exceed the TTS produced by the daily exposure. It is assumed that the average of TTS_2 is equal to the average of NIPTS.

6.2.4 Uncertainty of the Hearing Risk from Leisure Activities

Although the determination of the occupational noise exposure can be employed for the estimation of the risk of hearing impairment from leisure time activities, there is a huge lack of rules to limit the maximum allowed noise levels. In fact, people who are exposed to intense sound levels during leisure activities, mostly young, can be alarmingly at risk of developing hearing disorders when being exposed during either short or prolonged time periods. Therefore, those potential visitors must be aware of the great deal of responsibility that entails being exposed to intense sound levels and therefore, taking precautionary measures against possible hearing disorders.

Chapter 7

TTS and OAE Shift for Musicians after Rehearsals

This chapter reports the changes in hearing of pop-rock musicians detected before and after rehearsal. Both TTS and OAE Shifts are stated for individual musicians and across musicians.

7.1 Scope of the Analysis

This study entails an analysis of the risk of hearing damage for musicians that are exposed to intense sounds during their rehearsals. The most effective demonstration of this risk is to personalize the effect of noise by testing the HT and the OAEs before and after a rehearsal. Thereby, their own temporary reduction of HT and temporary loss of OHC function are analysed. The eventual purpose is to prevent the musicians about the consequences of being exposed to loud music over many years and convincing them of the necessity of protecting their hearing.

7.2 Scenario

The measurements have been carried out in a quite room located in *Huset*, Aalborg, Denmark. It is nearest the facilities where the musicians often attend to play in order to start the measurements after rehearsals as early as possible. This room is not provided of the ideal acoustic conditions required for hearing assessment. Therefore, noise floor is expected to be present during the recordings of the musicians's cochlear response. Nevertheless, isolated acoustic chambers were not found close to the rehearsal place, but the selected room was considered quite enough to perform such analysis.

7.3 Musicians

The band involves a total of four musicians, three males and one female. They are formed by a singer, who also employs an electric guitar, a lead electric guitarist, one bassist and one drummer. The age of the musicians is 24 years old. Only the last three are evaluated due to time limitations.

7.4 Experiment Method

Each musician's hearing is tested per rehearsal day. The experiment consists of three main parts ordered as follows,

Questionnaire + Instructions A questionnaire is provided by the tester to check the hearing diagnosis and the music leisure habits of the musicians. Instructions are also given for them for understanding the experiment tasks. This first part takes around 5 min.

Pre-exposure measurements Before starting the exposure period, a hearing assessment including both HT and OAEs is performed for each musician. This period takes around 1 hour.

Post-exposure measurements After the exposure period, the musician is subjected to short and fast HT and OAEs measurements for a duration around 1 hour.

7.4.1 Procedure

HT determination, TEOAEs and DPOAEs measurements are performed for both pre-exposure and post-exposure periods.

Pre-exposure Procedure

The measurement order is stated as follows. The right ear is firstly measured for every test.

1. HT determination. The ascending method is used to test both musician's ears [†]. HT levels are determined from 250 to 8000 Hz. The measurement procedure is stated in appendix C. The starting hearing level is set at 40 dB(HL) (reasonable audible level), and both ears are tested before a refitting of the headphones occurs. Four repetitions are carried out to minimise the effect of the location of the headphones in the musician's head, and to ensure the reliability of the obtained results. A break between 5-10 min is set between repetitions to avoid a lack of concentration of the tested musician.

[†] Further information about the ascending method used can be found in section 4.1.2.

2. OAEs. TEOAEs are measured for a frequency range between 500 and 5000 Hz, whereas DPOAEs are presented up to 4000 Hz. A total of 8 recordings (4 TEOAEs and 4 DPOAEs) are performed for each ear refitting the probe every time a measurement is ended. Thereby, the noise caused by the movement of the probe is minimised when it does not fit correctly into the musician's ear canal.

Post-exposure Procedure

The same measurements are carried out after the exposure, but considerations regarding the stimuli levels and the selected frequency range of the recordings are specified. In order to obtain reliable TS for both HT and OAEs, measurements after the exposure are to be recorded as early as possible.

- OAEs. One TEOAE and one DPOAE are recorded before refitting the probe. A total of eight recordings per each sort of measurement (four per ear) are performed in several times scheduled in section 7.4.2.
  - TEOAE recording. The stimulus level is reduced from the initial pre-exposure set of around 84 to nearest 75 dB(SPL) to avoid that the TEOAE response is being affected by an over-exposure. Otherwise, this measurement could represent a prolongation of the exposure and the result would not be valid. The frequency range for each recording is the same than during the pre-exposure period.
  - DPOAE recording. To reduce the measurement time, only the most sensitive frequencies are considered, obtaining *2f1-f2* DP from a range between 635 to 2796 Hz [†].
- HT determination. Only the most sensitive frequencies are tested, obtaining the musician's HT for 1000, 2000 and 4000 Hz. The starting hearing level is set at 30 dB(HL).

7.4.2 Time Schedule for The Experiment

The time schedule for the whole experiment is depicted in figure 7.1.

All measurements start testing the musician's right ear and there is no balance for the measurement order since only three musicians are tested. The whole experiment took around 4 hours.

Regarding post-exposure measurements, it is important to state that the recordings starting times are a bit different depending mainly on the facility to place correctly the probe

[†] This range is obtained from the ILO software when computing the DPOAE recording with a resolution of 8 points/octave and ending the measurement manually.

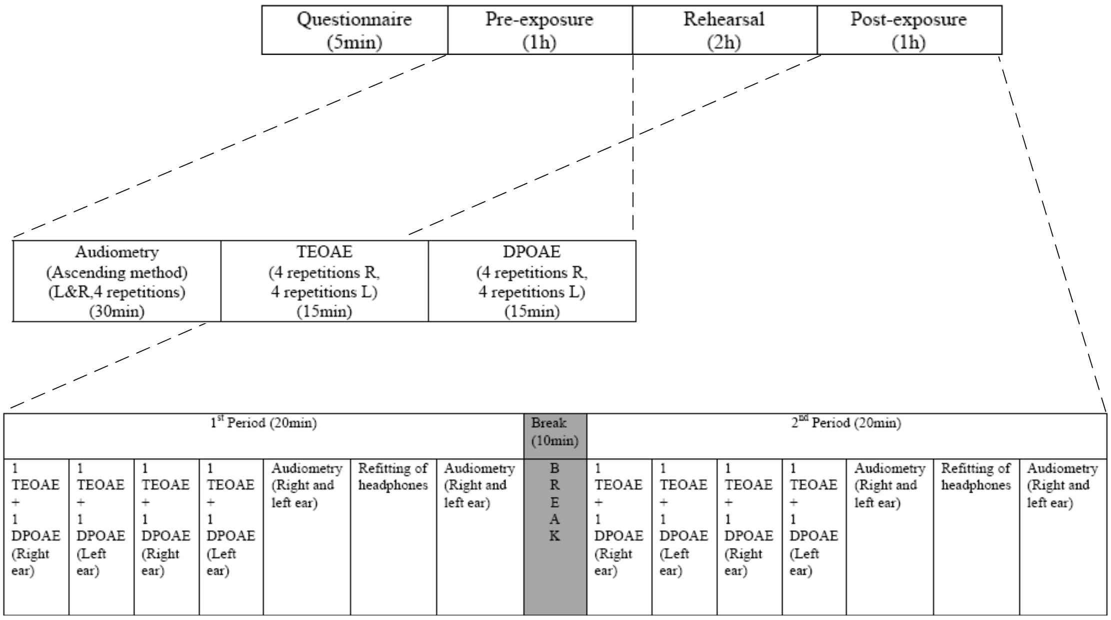


Figure 7.1: Time schedule for the experiment. The measurement order before and after the rehearsal is the same for the three tested musicians.

on the musician's ear canal. In table 7.1, the recording times after the exposure are stated for each recording and for every musician. The bassist reported some problems to fit the probe into his ear canal and the measurements were delayed. The remaining times across musicians are considered similar and they are used to establish the post-exposure intervals when comparing shifts across musicians.

The results for the questionnaire can be found in appendix A. Although the bassist reported a moderate tinnitus, he was included in the experiment since the eventual purpose is to study the hearing status of the musician populations.

The musicians are instructed about their tasks previous to the beginning of the experiment. Those instructions can be found in appendix B.

The measurement reports regarding HT determination and OAEs can be found in appendix C and E respectively.

The results presented in the following sections have been ordered with respect to the time schedule, starting with the OAEs results and ending with HT determination. But hearing levels are firstly obtained during the pre-exposure period to check the hearing status of the musicians.

Period	Musician	1st TEOAE right ear [min]	1st DPOAE right ear [min]	1st TEOAE left ear[min]	1st DPOAE left ear [min]
1	Lead electric guitarist	10	10	11	15
1	Bassist	10	11	12	14
1	Drummer	10	11	13	15
2	Lead electric guitarist	40	42	43	45
2	Bassist	41	43	49	50
2	Drummer	40	41	42	45
Period	Musician	2nd TEOAE right ear [min]	2nd DPOAE right ear [min]	2nd TEOAE left ear[min]	2nd DPOAE left ear [min]
1	Lead electric guitarist	16	18	20	22
1	Bassist	15	16	19	22
1	Drummer	16	17	18	20
2	Lead electric guitarist	46	47	50	52
2	Bassist	52	54	70	70
2	Drummer	46	48	49	51
Period	Musician	1st HT right ear [min]	1st HT right ear [min]	2nd HT left ear[min]	2nd HT left ear [min]
1	Lead electric guitarist	25	27	29	31
1	Bassist	24	26	28	30
1	Drummer	22	23	25	27
2	Lead electric guitarist	55	57	59	61
2	Bassist	72	73	75	76
2	Drummer	52	53	55	57

Table 7.1: Post-exposure starting times for each recording and for each musician.

7.5 TEOAE Results

The most appropriate analysis of a TEOAE response entails a time-frequency analysis since TEOAE is, in fact, a measure of the ear response *transiently* evoked by an stimulus, and thereby, both domains required to be analysed simultaneously. For a better understanding of such results, the analysis in the time domain and in the frequency domain is previously explained.

7.5.1 TEOAE Response

The non-linear method † used by ILO88 software to calculate the TEOAEs provides two different waveforms corresponding to the even and odd sweep ‡ obtained during the recording. As it is stated in appendix D, the correlation between both responses must be greater than 65% to validate a TEOAE. Then, the average of the responses is calculated and the obtained data are normalised to obtain dB(SPL) afterwards.

All musicians' cochlea TEOAE responses can be found in appendix E. As an example, the averaged TEOAE response obtained for the lead electric guitarist is depicted on the right side of figure 7.2. Each recording obtained after refitting the probe is presented on the left side. The similarity between them shows that the effect of the probe fitting into the ear canal is minimised.

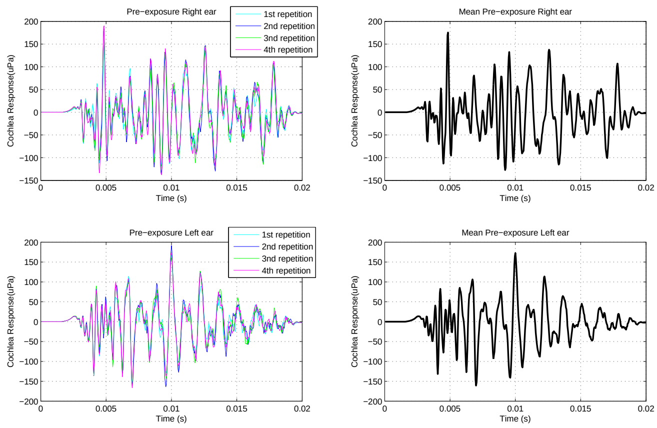


Figure 7.2: TEOAE response obtained as the average of the even and odd sweeps provided by ILO88 software corresponding to the pre-exposure measurements of the lead electric guitarist. The right ear is presented on the top and the left ear at the bottom. Each recording obtained after refitting the probe is presented for both ears on the left side. A high similarity between them is observed, minimising the effect of the probe fitting into the ear canal.

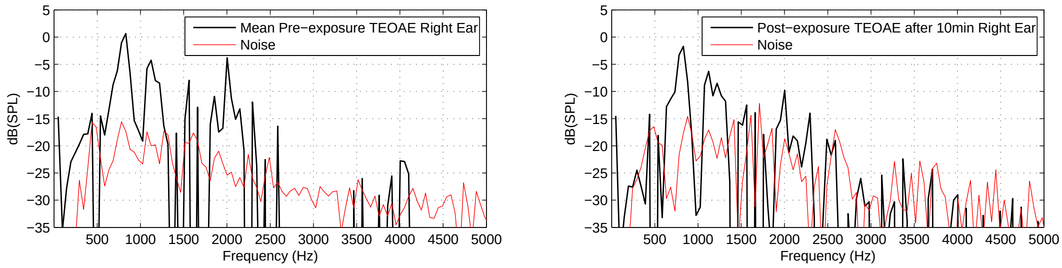
On the other hand, a frequency response analysis provides energy information about the most remarkable TEOAEs of the musicians. ILO88 software provides the TEOAE spectrum data with a resolution of 128 samples.

SNR must be greater than 3 dB(SPL) to validate a measurement of a TEOAE §. Each recording must be analysed in terms of its SNR to find out the frequency range where a TEOAE can be considered reliable and therefore, not affected by the noise floor. This ratio has been calculated for all recordings obtained for the musicians as the most sensitive frequency bands in terms of hearing, meaning 1000,2000,3000 and 4000 Hz. The results

†It is briefly explained in appendix D.

‡Those waveforms are called A and B respectively by ILO88 software.

§This is explained in details in appendix D.



(a) Pre-exposure **(b)** Post-exposure after 10min

Figure 7.3: Comparison between the averaged pre-exposure TEOAE spectrum of the bassist's right ear and the corresponding TEOAE 10 min after the exposure. A smooth reduction of the energy is appreciated after the exposure.

are stated in table E.1 in appendix E, together with the averaged pre-exposure and post-exposure TEAOE spectra for each musician. The majority of the TEOAE responses showed high SNR at both 1000 and 2000 Hz, but the recordings are affected by the noise from 3000 Hz upwards [†]. Only the lead electric guitarist reported high SNR at 3000 Hz.

To exemplify the amplitude differences caused by the noise exposure, the bassist's TEOAE spectrum for the right ear before (left side) and 10 min after the exposure (right side) are presented in figure 7.3. An energy reduction can be appreciated during the post-exposure recording. This is not necessarily an indicative or a precursor to a hearing impairment, but it pretends to be an indicative from the OHCs that they need to be protected from the exposure noise [Brashears, 2001].

7.5.2 TEOAE Shift

Time-frequency analysis of the musicians' TEOAE response is carried out to show the TEOAE shift. This allows to make a comparison in terms of amplitude reduction as well as to evaluate the predominance of the frequency components along the BM.

Since a TEOAE is relatively short (20 ms) and contains changes in time, meaning a non-stationary signal, the conventional FFT analysis is not recommended [Konopka et al., 2002]. A Short-Time Fourier transform (STFT) is applied instead. The spectrogram[‡] is obtained by windowing the duration of the TEOAE waveform (20 ms) in segments of approximately 2 ms[§]. Other studies [Zhang et al., 1998] employed a 5 ms window instead,

[†] High levels of noise are usually found in the latter portions (greater than 12 ms) of TEOAE recordings [Hatzopoulos et al., 2000].

[‡] The time-frequency plot is known as spectrogram.

[§] ILO88 provides a TEOAE waveform with a resolution of 512 samples. The STFT is calculated for every selected Hamming window of 50 samples obtaining the spectrogram by means of a Matlab's function. For a better resolution, an overlapping of 49 samples and an interpolation to obtain a FFT length of 1024 points are performed.

but a shorter window width is deemed to provide better resolution.

Time-frequency analysis offers a direct and clear method to analyse the complicity of a TEOAE basically for two reasons according to [Zhang et al., 1998],

- Time-frequency analysis is effective in the research of the individual differences and rule of TEOAE and its relations with hearing loss.
- By the research of the short-time spectrum, time-frequency relations and latencies of TEOAE, new approaches of revealing the mechanism of TEOAE can be reached.

Regarding the location of the frequency components along the BM, whether a high frequency stimulus reaches the ear, the base part results excited and the rest of the BM remains almost quiet. However, when a low frequency stimulus, the vibrations are extended along the BM but the maximum displacement is achieved near the apex. This is reported in details in section 3.4.1. Therefore, whether a broadband signal elicits a BM vibration, as the case of musicians playing in a rehearsal place, both high and low frequency components are expected to be present. When a time-frequency analysis is carried out for a health ear, an ideal decrease from the base to the apex of the BM should become evident, meaning greater amplitudes of high frequency components at the base part and as long as the recoding time increases, only low frequencies should be detected (near the apex part).

For instance, a non-exposed normal hearing subject [†] reported a TEOAE time-frequency analysis closed to the commented ideal case. It is shown in figure 7.4. This subject reported high levels of SNR when measuring TEOAEs from 1000 to 3000 Hz, reaching up to 21.3 dB(SPL) at 1000 Hz. The greater amplitudes at those frequencies are found from 6 to 8 ms, and a decay suggesting the ideal decrease from the base to the apex of the BM is observed as long as the latencies of TEOAEs increase. It is important to state that the amplitude colour bar range has been changed with respect to the following time-frequency analysis belong the musicians, since this subject reported raised amplitudes up to 20 dB(SPL). The presence of low frequencies at the early times is due to the fact that when low frequencies stimuli reach the ear, the whole BM can be excited, even though the maxima are found at the apex part.

A comparison between pre-exposure and post-exposure TEOAE spectrograms for each musician's ear is performed. In addition, an study across musicians is stated.

TEOAE Shifts for Individual Musicians

Each musician's ear has been analysed separately, showing the time-frequency analysis for the mean pre-exposure and the four recordings that took place during the post-exposure measurement period.

[†] 12 normal hearing subjects non-exposed to intense loud sounds have been measured for a comparison with the musicians.

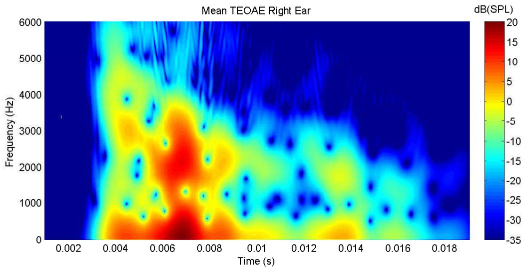


Figure 7.4: Time-frequency analysis for a normal hearing subject non-exposed to intense loud sounds. This subject reported high levels of SNR when measuring TEOAEs from 1000 to 3000 Hz, reaching up to 21.3 dB(SPL) at 1000 Hz. The greater amplitudes at those frequencies are found from 6 to 8 ms, and a decay suggesting an ideal decrease from the base to the apex part of the BM should be noticed as long as the latencies of TEOAEs increase. The amplitude colour bar range is from 20 to -35 dB(SPL).

As a general comment, variations with time are not found. But TEOAEs reach amplitude maxima in specific time windows, depending on the frequency components. The majority of the subjects reported noticeable TEOAEs from 1000 to 2000 Hz. Also, a high variability between both ears is found for every musician.

Lead electric guitarist TEOAE Shifts for the lead electric guitarist's right and left ears are shown in figures 7.5 and 7.6 respectively.

Regarding the right ear, pre-exposure amplitudes around -5 dB(SPL) are found near 5 ms at 3000 Hz together with unexpected higher levels near 0 dB(SPL) from low frequencies up to 1000 Hz. However, when low frequency sounds reach the ear, the whole BM is expected to vibrate rather than only the apex part. From the middle to the apex part of the BM, amplitudes from -10 dB(SPL) up to 5 dB(SPL) are observed mainly at low frequencies. In light of the post-exposure results, there is no a notable amplitude reduction, but differences around 5 dB(SPL) are observed mostly from 8 to 15 ms, affecting the frequency range between 1000 and 3000 Hz. The lead electric guitarist showed greater SNR levels at those frequencies. After 46 ms of exposure, the recovery of the ear is not completely reached.

On the other hand, the left ear presents the commented ideal decrease, being more emphasized than for the right ear. Noticeable amplitudes are found from 5 to 14 ms, reaching TEOAE levels up to almost 5 dB(SPL). In contrast with the right ear, a greater amplitude reduction is observed for the post-exposure recordings, achieving TEOAE shifts up to 10 dB(SPL) for high frequencies. The lower frequencies do not show a considerable reduction. A slow recovery is observed after 50 min of exposure.

Bassist TEOAE Shifts for the bassist's right and left ears are shown in figures 7.7 and 7.8 respectively.

With respect to the right ear, pre-exposure amplitudes approximately from 0 to -10 dB(SPL) are observed for the lower frequencies up to 2000 Hz, in the time period from 6 to 12 ms. This vibration occurs in the centre of the BM. There are no remarkable amplitudes from 3000 Hz upwards since the obtained SNR showed that those amplitude levels are affected by the background noise (SNR below 3 dB(SPL)). In light of the post-exposure results, the TEOAE shifts show a great amplitude reduction, reaching maxima near 10 dB(SPL) at the higher frequencies 41 min after the exposure. No explanation has been found about the reason that post-exposure recordings obtained before 41 min show less TEOAE shifts. However, as an hypothesis for a further work, this musician reported tinnitus in the questionnaire, and the measurements could be affected by this hearing disease. A notable recovery process is observed at the latest post-exposure recording after 52 min of exposure.

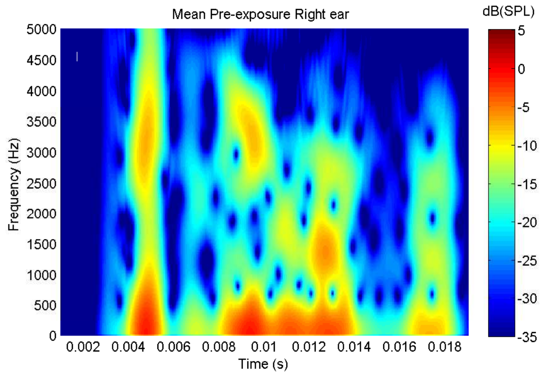
Focusing on the left ear, a lack of TEOAE response is found at the apex part of the BM for the mean pre-exposure time-frequency analysis. It suggests that there is almost no presence of the low frequency components, but the greatest amplitudes at those frequencies encountered at the early times within 6 ms after the stimulation are in contrast with this hypothesis. But some remaining low frequency components are expected near the base part of the BM. Therefore, no remarkable conclusions can be extracted from the pre-exposure time-frequency analysis. When comparing pre-exposure and post-exposure recordings, it can be observed that most TEOAES are attenuated. However, some problems found were fitting the probe for the latest measurement doubt the reliability of the comparison.

Drummer TEOAE Shifts for the drummer's right and left ears are shown in figures 7.9 and 7.10 respectively.

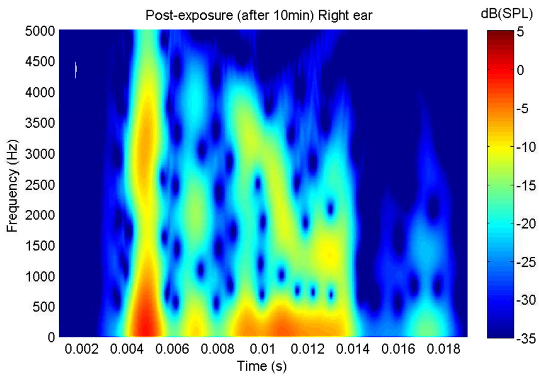
When analysing the TEOAE shifts on both drummer's ears, weak TEOAE responses are found in comparison with those obtained by the other musicians. There are no remarkable differences found between pre-exposure and post-exposure measurements. The greater amplitudes appear at low frequencies, and the vibrations are extended along the BM from the early times until 15 ms. In fact, the TEOAE responses from the left ear show an unexpected low frequency component TEOAE near the base part (around 4 ms). A hypothesis proposed by [Zhang et al., 1998]† suggests that those amplitudes might not belong the TEOAE response,

Early TEOAE might be produced before 3 ms, even as early as 1 ms.This implies that the olivo-cochlear bundle was not involved in the initiation control of TEOAE.

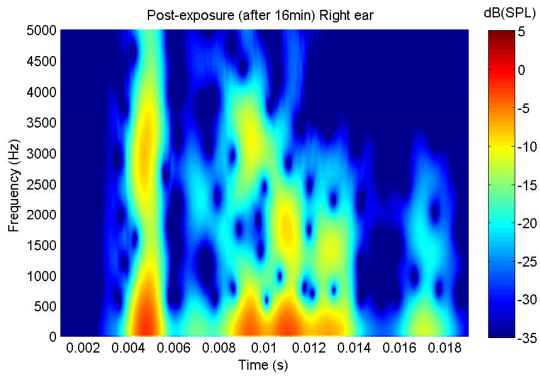
†They recorded and analysed by means of 3D time-frequency TEOAE results, 30 normal hearing and 25 hearing impaired human subjects.



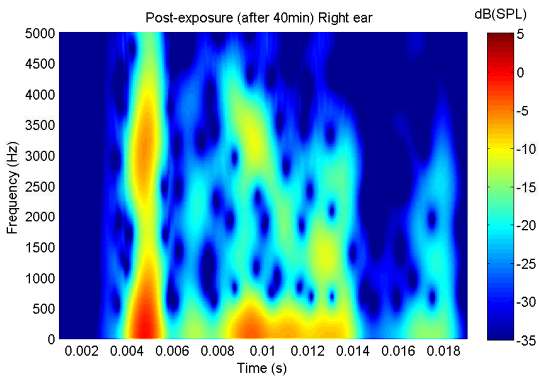
(a) Pre-exposure



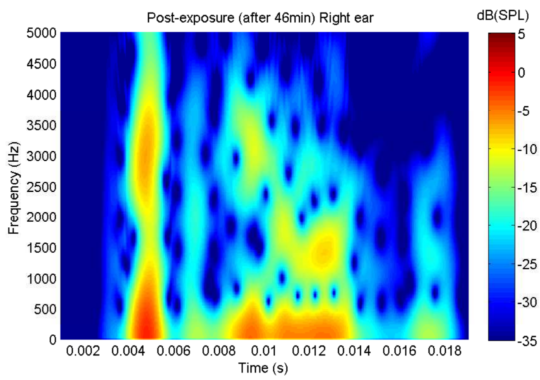
(b) Post-exposure after 10min



(c) Post-exposure after 16min

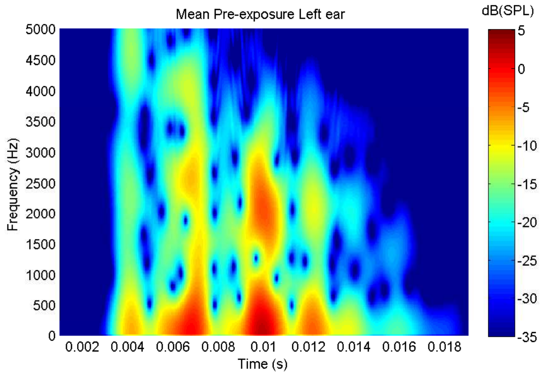


(d) Post-exposure after 40min

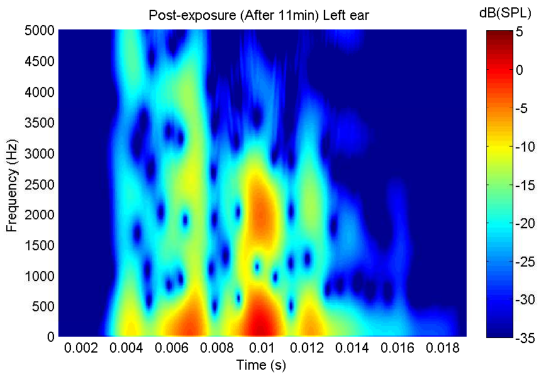


(e) Post-exposure after 46min

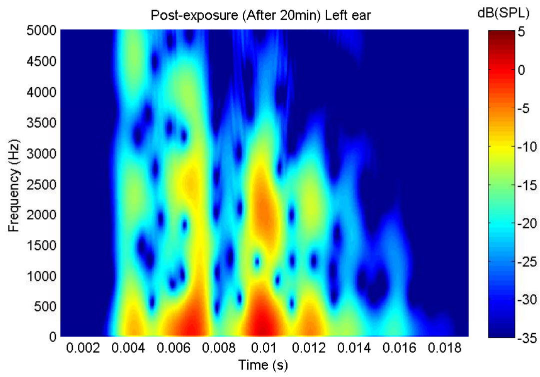
Figure 7.5: TEOAE time-frequency analysis when measuring the lead electric guitarist's right ear. The mean-pre-exposure and post-exposures measurements after 10,16,40 and 46 min are depicted for visual TEOAE shift comparison.



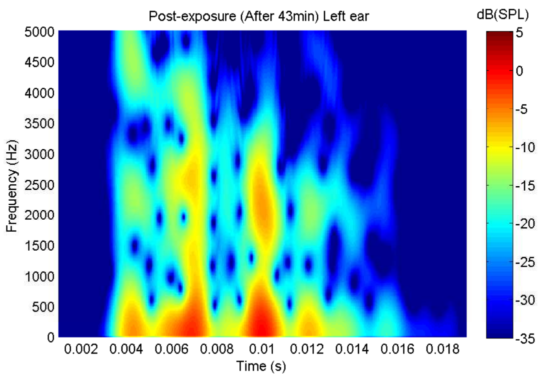
(a) Pre-exposure



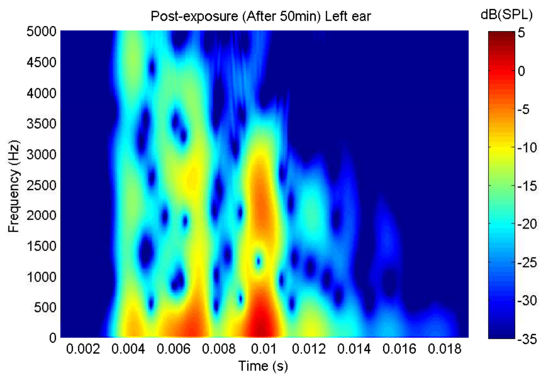
(b) Post-exposure after 11min



(c) Post-exposure after 20min

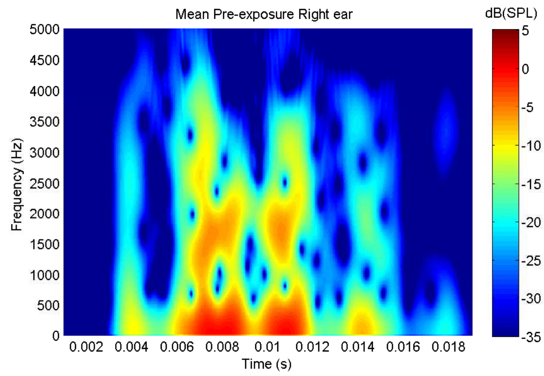


(d) Post-exposure after 43min

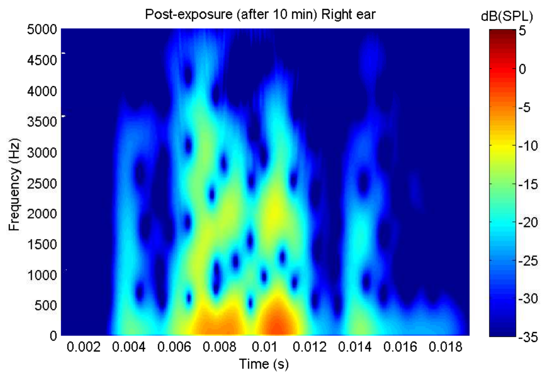


(e) Post-exposure after 50min

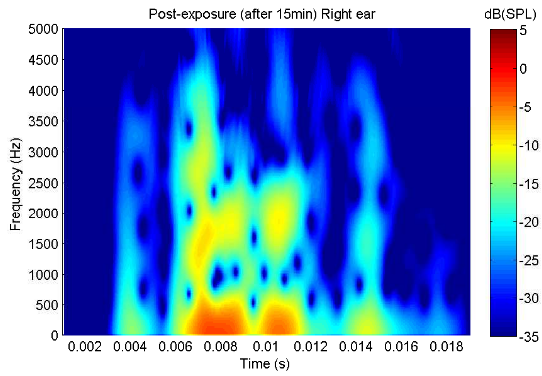
Figure 7.6: TEOAE time-frequency analysis when measuring the lead electric guitarist's left ear. The mean-pre-exposure and post-exposures measurements after 11,20,43 and 50 min are depicted for visual TEOAE shift comparison.



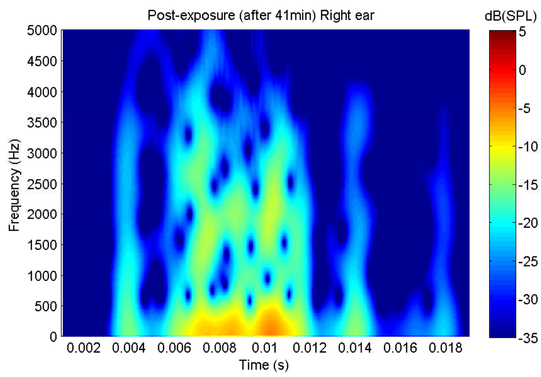
(a) Pre-exposure



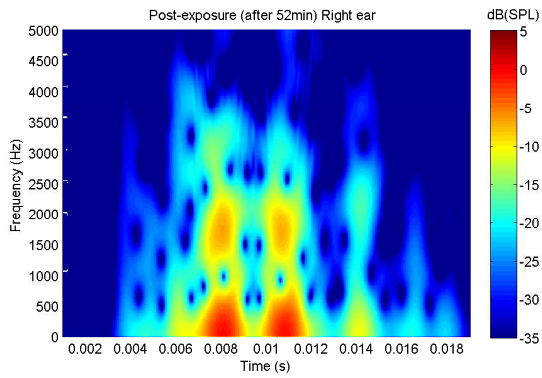
(b) Post-exposure after 10min



(c) Post-exposure after 15min

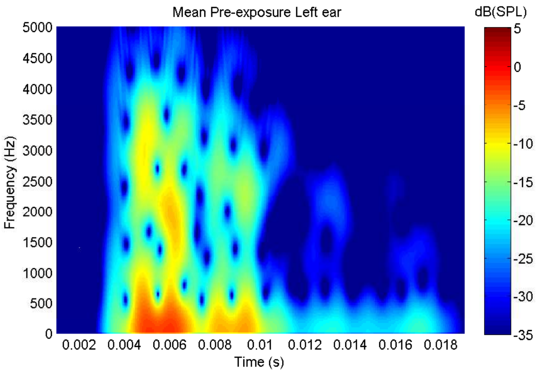


(d) Post-exposure after 41min

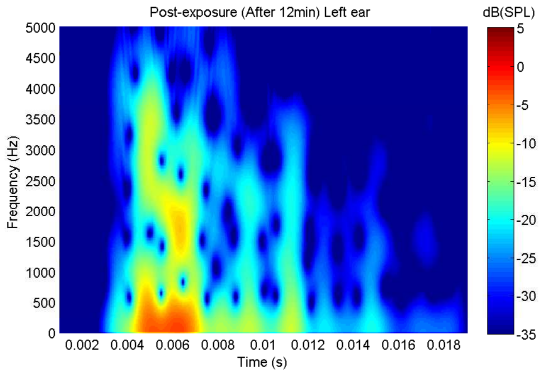


(e) Post-exposure after 52min

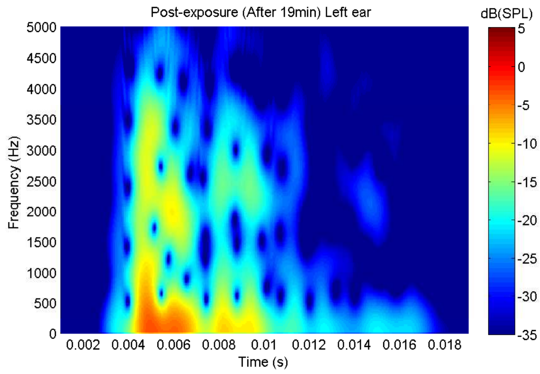
Figure 7.7: TEOAE time-frequency analysis when measuring the bassist's right ear. The mean-pre-exposure and post-exposures measurements after 10,15,41 and 52 min are depicted for visual TEOAE shift comparison.



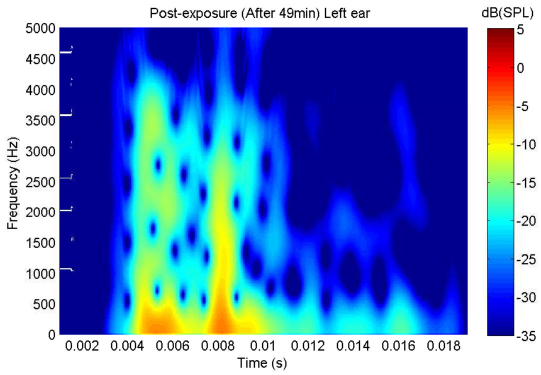
(a) Pre-exposure



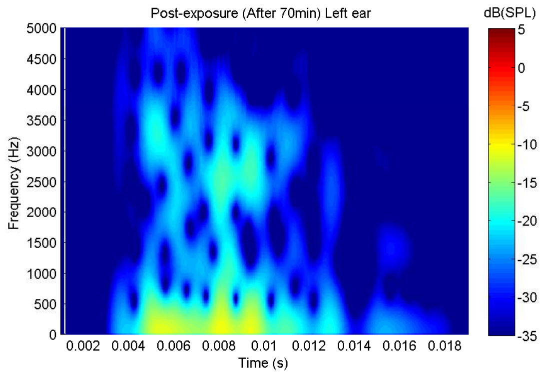
(b) Post-exposure after 12min



(c) Post-exposure after 19min

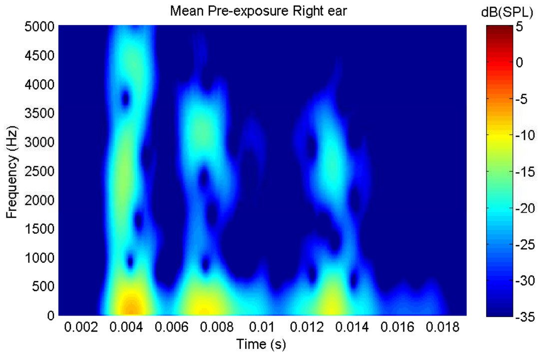


(d) Post-exposure after 49min

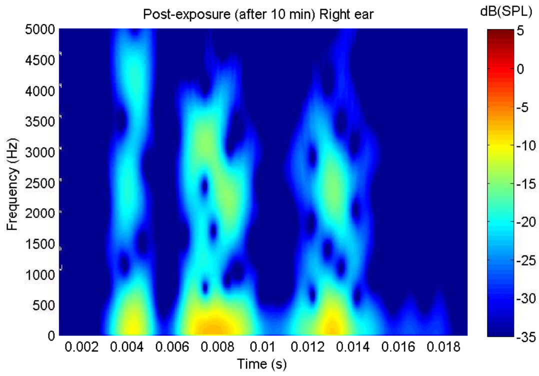


(e) Post-exposure after 70min

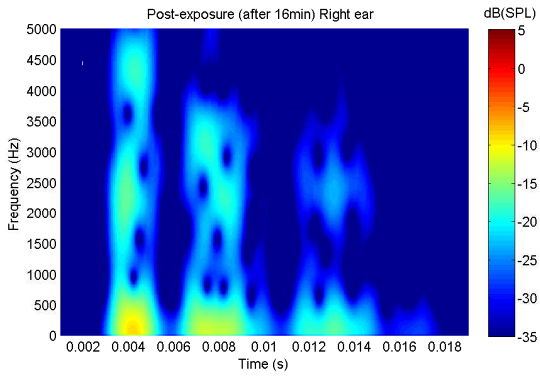
Figure 7.8: TEOAE time-frequency analysis when measuring the bassist's left ear. The mean-pre-exposure and post-exposures measurements after 12,19,49 and 70 min are depicted for visual TEOAE shift comparison.



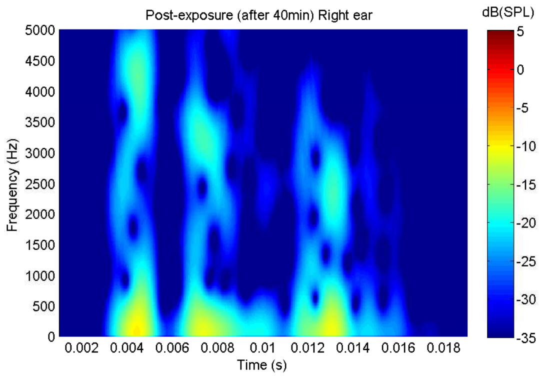
(a) Pre-exposure



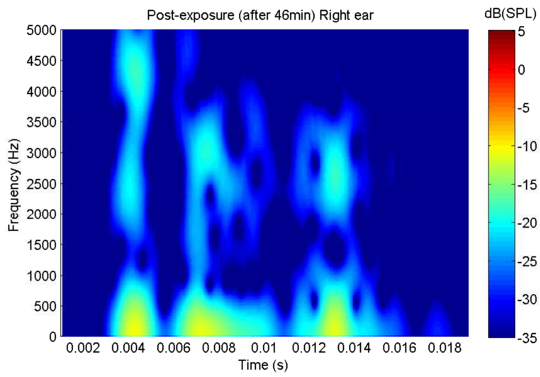
(b) Post-exposure after 10min



(c) Post-exposure after 16min

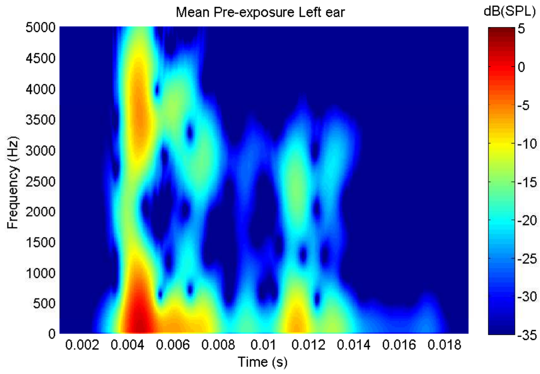


(d) Post-exposure after 40min

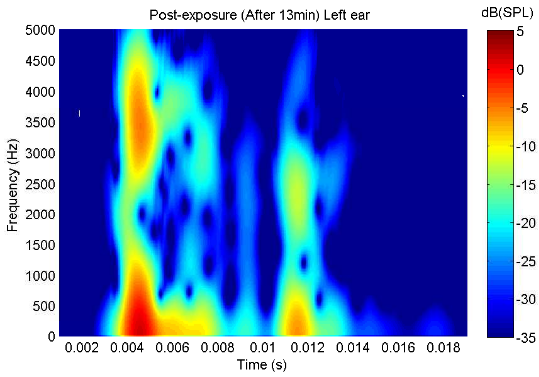


(e) Post-exposure after 46min

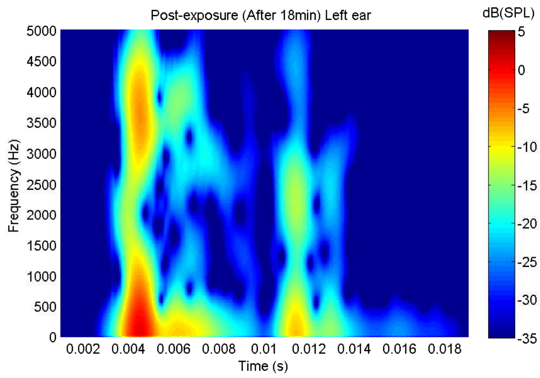
Figure 7.9: TEOAE time-frequency analysis when measuring the drummer's right ear. The mean-pre-exposure and post-exposures measurements after 10,16,40 and 46 min are depicted for visual TEOAE shift comparison.



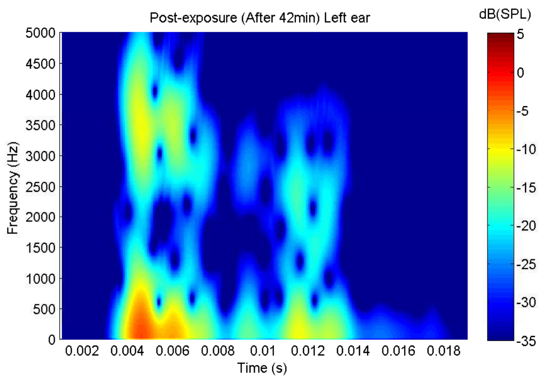
(a) Pre-exposure



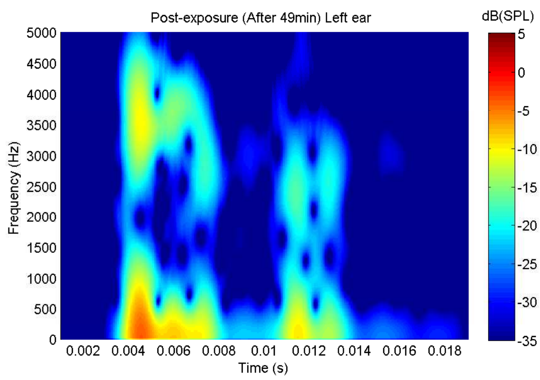
(b) Post-exposure after 13min



(c) Post-exposure after 18min



(d) Post-exposure after 42min



(e) Post-exposure after 49min

Figure 7.10: TEOAE time-frequency analysis when measuring the drummer's left ear. The mean-pre-exposure and post-exposures measurements after 13,18,42 and 49 min are depicted for visual TEOAE shift comparison.

TEOAE Shifts Across Musicians

By inspection of the time-frequency analysis, the lead electric guitarist shows the greater TEOAE amplitude regarding pre-exposure measurements, being close to the ideal commented decrease. Only time-frequency analysis has been performed for the individual musicians, since an analysis of the spectrum differences for the closest measured intervals across musicians in time is expected to be unstable according to [Zhang et al., 1998].

7.6 DPOAE Results

Aside the transient characteristics reflected when evaluating TEOAE responses, an static analysis of the recordings is also performed, meaning the study of the OAE response for specific frequency points (DP) when eliciting different dual frequencies (f1,f2) [Zhang et al., 1998].

7.6.1 DPOAE Shift for Individual Musicians

Each musician's ear has been analysed separately, showing the pre-exposure (including the standard deviation between repetitions) and post-exposure DP found for the selected frequency range between 635-2796 Hz †. In light of the obtained standard deviation between pre-exposure measurements, consistent results and no influence of the measurement procedure can be concluded.

As a general conclusion, no noticeable DPOAE shifts are found due to the exposure, and special attention must be focused on making a difference between a real shift and a shift induced by the noise floor. In contrast with TEOAEs, those measurements result more vulnerable to the noise presence.

Lead electric guitarist Figure 7.11 represents a collection of the mean pre-exposure and post-exposure DPOAE measurements for both lead electric guitarist's ears. The corresponding DPOAE shifts for both ears are also depicted at the end of each collection with a grey colour scale.

Regarding the right ear, the pre-exposure and post-exposure measurements tend to be similar up to 1500 Hz, achieving DPOAE levels up to 10 dB(SPL). Only remarkable shifts around 10 dB(SPL) are appreciated from 1800 Hz upwards. No attention must be focused on the first sharp shifts since they are believed to be affected by the noise floor at some post-exposure measurements such, as 42 and 47 min after the exposure. The

† This range is obtained when calculating the DP 2f1-f2 for the different dual frequencies provided by ILO88 software. The latest frequency is set by ending the measurement manually in order to get a fast DPOAE response in the most sensitive human range in a short period of time for post-exposure measurements.

recovery process is observed as long as the measure time after the exposure increases, as it was expected.

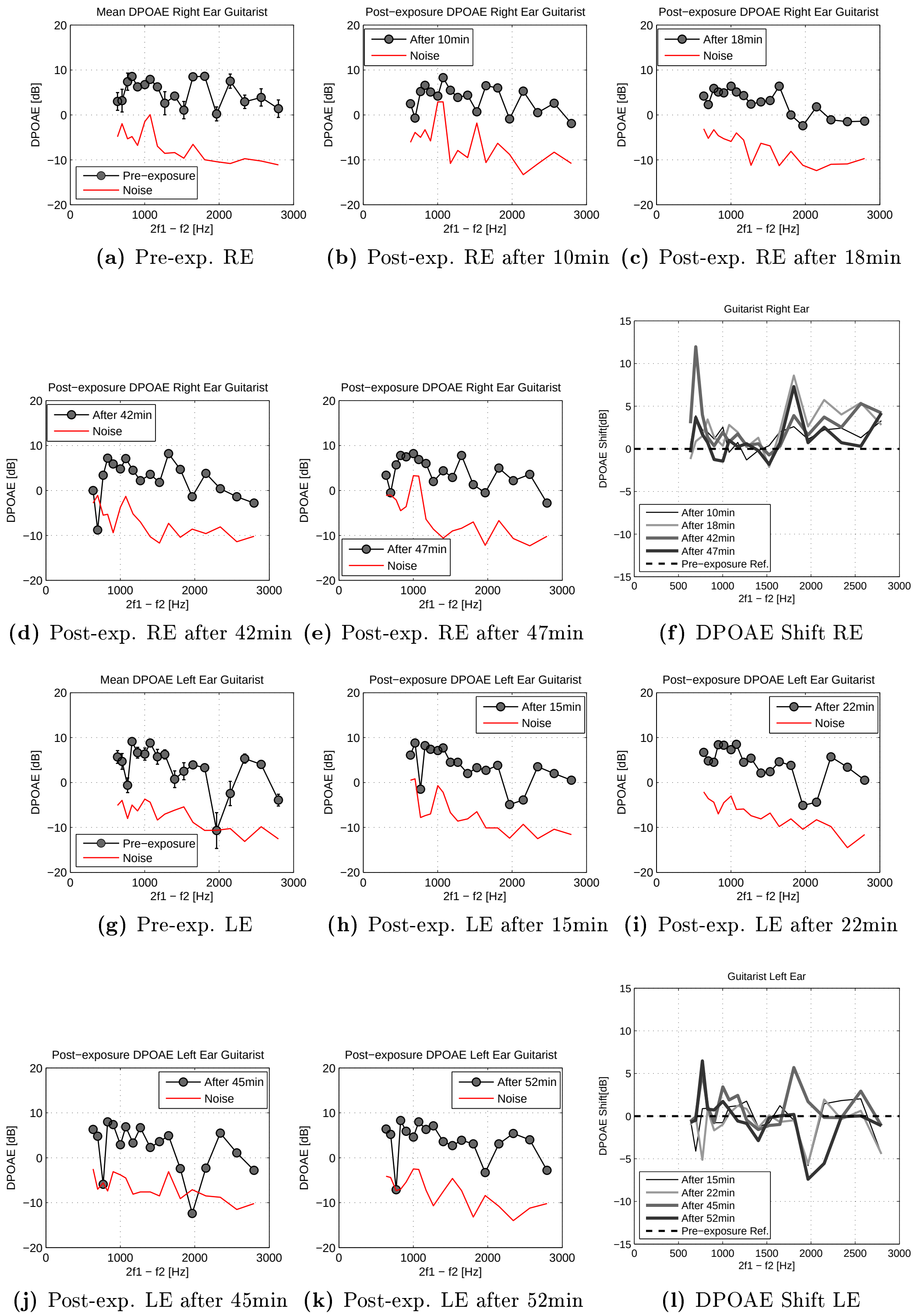
On the other hand, the left ear shows a great similarity between pre-exposure and post-exposure measurements, and thereby, no noticeable shifts are expected. The sharp peaks observed at the starting DP frequencies as well as those found around 2000 Hz are expected to be due to the noise effect.

Bassist Figure 7.12 represents a collection of the mean pre-exposure and post-exposure DPOAE measurements for both bassist's ears. The corresponding DPOAE shifts for both ears are also depicted at the end of each collection with a grey colour scale.

Mostly post-exposure recordings at the right ear are affected by the noise floor, resulting in a great variability of the DPOAE shifts. Only the DPOAE shift corresponding to 11 min after the exposure is analysed. Shifts less than 5 dB are found, but they are deemed negligible.

For the left ear, noticeable DPOAE shifts can only be observed from 2000 Hz upwards, reaching levels up to 8 dB(SPL). The recovery of the different measure times is appreciated.

Drummer Figure 7.13 represents a collection of the mean pre-exposure and post-exposure DPOAE measurements for both ears of the drummer. The corresponding DPOAE shifts for both ears are also depicted at the end of each collection with a grey colour scale. Regarding the drummer's right ear, the noise artefacts are clearly affecting the DPOAE shifts, for instance at around 1400 Hz, and they must not be confused with the real shifts. By visual inspection of each recording, no remarkable shifts are found. The conclusions extracted from the results of the remaining ear are the same.



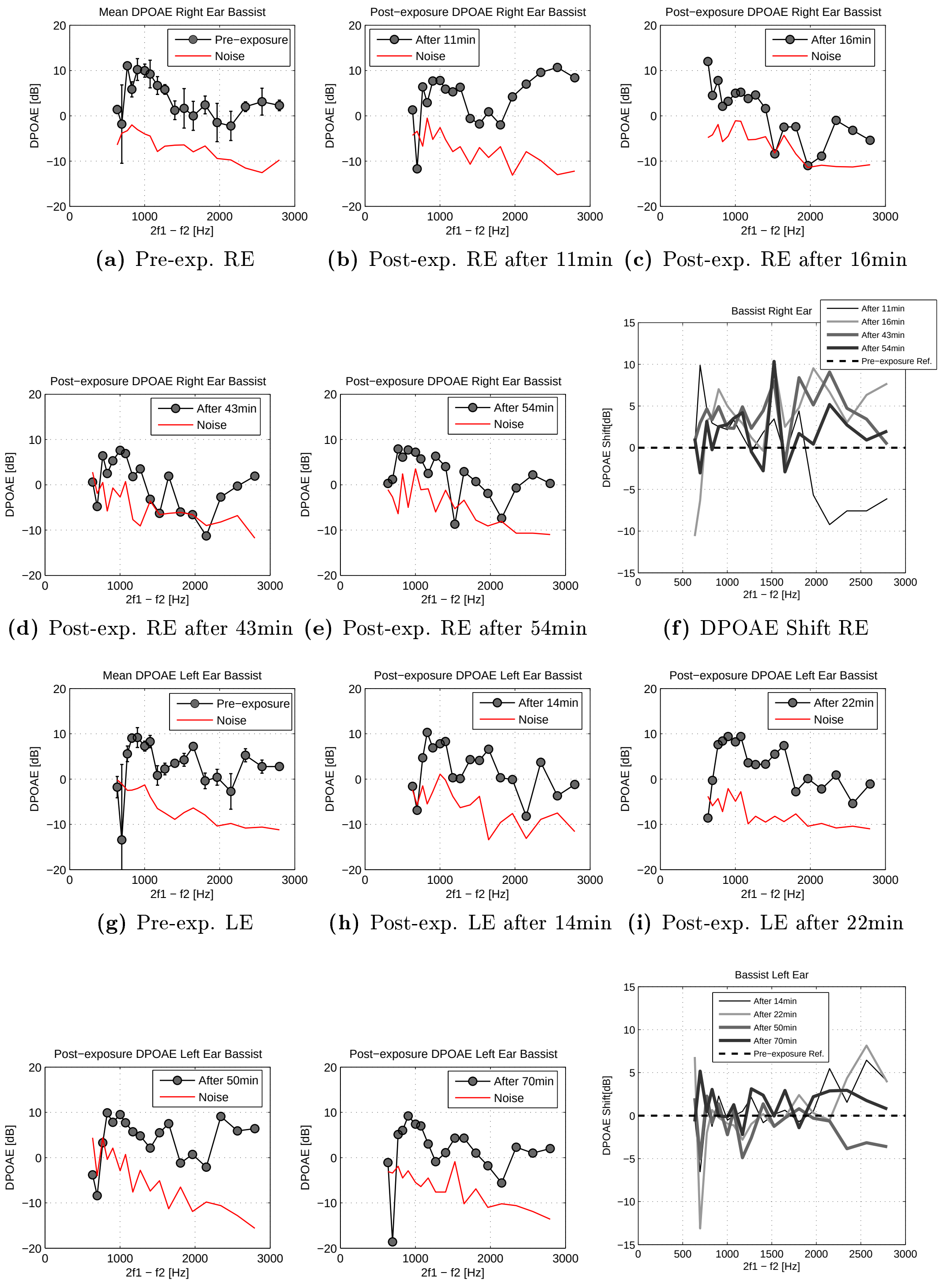
(a) Pre-exp. RE (b) Post-exp. RE after 10min (c) Post-exp. RE after 18min

(d) Post-exp. RE after 42min (e) Post-exp. RE after 47min (f) DPOAE Shift RE

(g) Pre-exp. LE (h) Post-exp. LE after 15min (i) Post-exp. LE after 22min

(j) Post-exp. LE after 45min (k) Post-exp. LE after 52min (l) DPOAE Shift LE

Figure 7.11: DPOAE Shifts observed for the lead electric guitarist's ears during the times scheduled for the experiment.



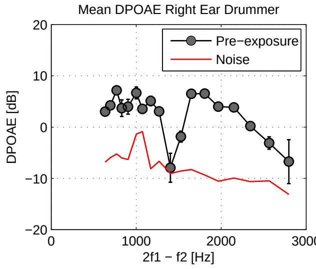
(a) Pre-exp. RE (b) Post-exp. RE after 11min (c) Post-exp. RE after 16min

(d) Post-exp. RE after 43min (e) Post-exp. RE after 54min (f) DPOAE Shift RE

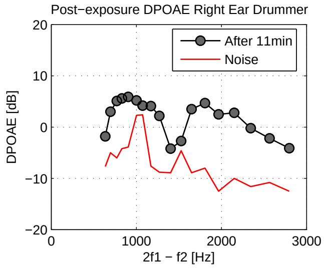
(g) Pre-exp. LE (h) Post-exp. LE after 14min (i) Post-exp. LE after 22min

(j) Post-exp. LE after 50min (k) Post-exp. LE after 70min (l) DPOAE Shift LE

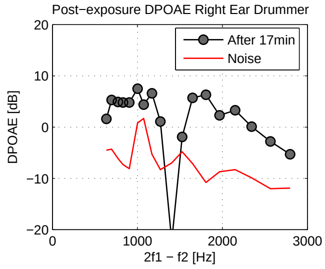
Figure 7.12: DPOAE Shifts observed for the bassist's ears during the times scheduled for the experiment.



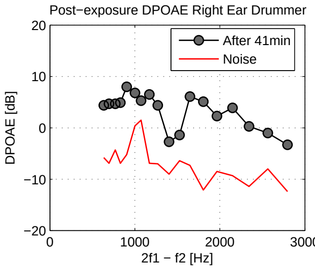
(a) Pre-exp. RE



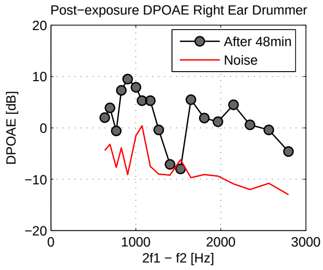
(b) Post-exp. RE after 11min



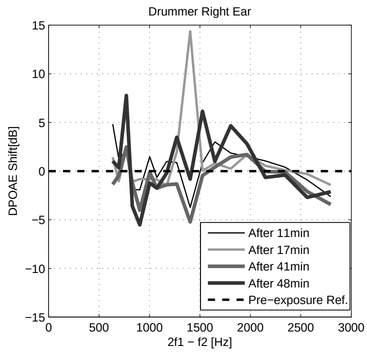
(c) Post-exp. RE after 17min



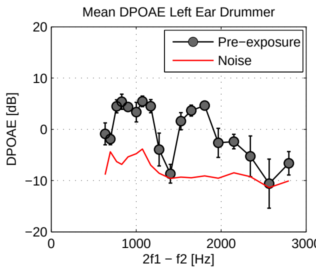
(d) Post-exp. RE after 41min



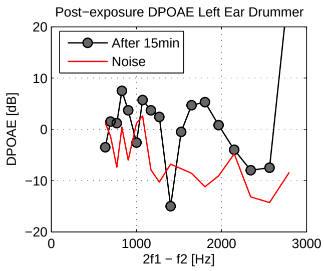
(e) Post-exp. RE after 48min



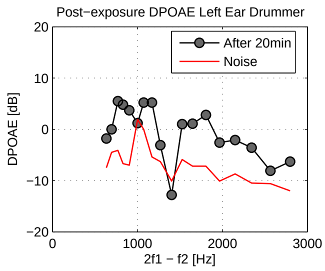
(f) DPOAE Shift RE



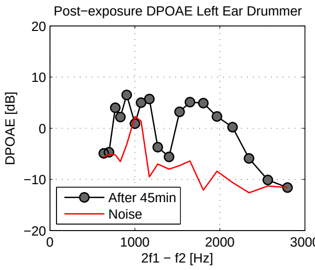
(g) Pre-exp. LE



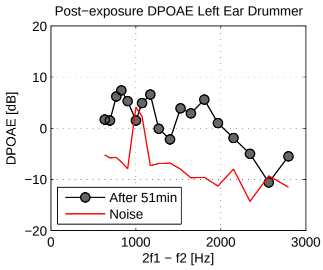
(h) Post-exp. LE after 15min



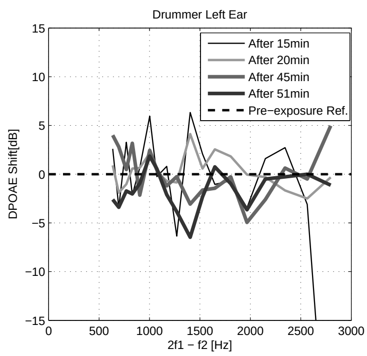
(i) Post-exp. LE after 20min



(j) Post-exp. LE after 45min



(k) Post-exp. LE after 51min



(l) DPOAE Shift LE

Figure 7.13: DPOAE Shifts observed for the drummer's ears during the times scheduled for the experiment.

7.6.2 DPOAE Shift Across Musicians

Two different intervals for both musician's ears are selected with a view to cover all DPOAE shifts across musicians. Regarding the right ear, the former interval is between 10 and 18 min after the exposure and the latest is between 41 and 54 min after the exposure. However, for the left ear, the intervals are between 14 and 22 min and between 45 and 52 min. It is important to notice that for the latest left ear interval, the bassist has been rejected since the last DPOAE measurement was made 70 min after the exposure, and the measure times for the remaining musicians did not match with this time. DPOAE shifts with the corresponding standard deviation among musicians are depicted in figure 7.14, for a mean pre-exposure reference, meaning the average between the mean pre-exposure DPOAE levels found for each musician.

Due to the great variability between individual musicians denoted with the great error bars shown in figure 7.14 for both ears, a group average is not considered representative at all. A solution could be to collect a large number of musicians obtaining meaningful results.

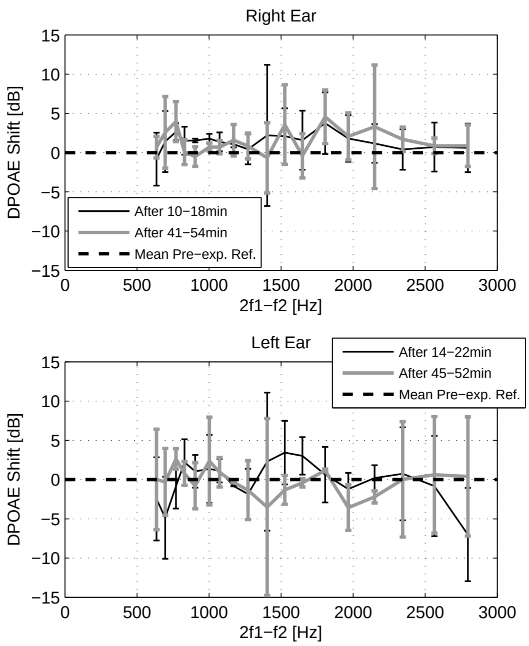


Figure 7.14: Mean DPOAE shift across musicians. Two intervals after the exposure are selected for each ear. The mean pre-exposure DPOAEs obtained across the musicians are stated as a reference for calculating the shifts.

7.7 HT Results

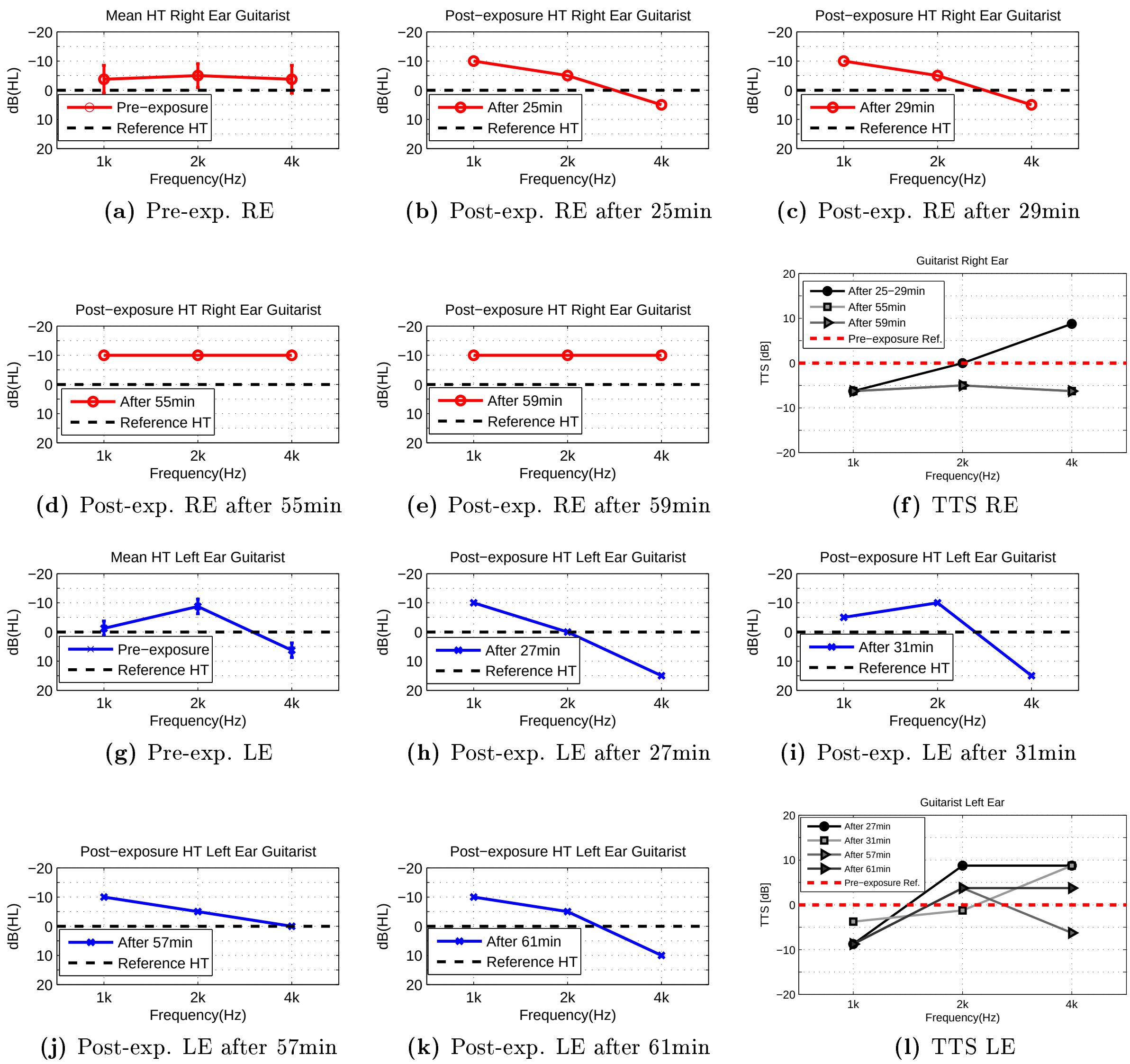
A comparison between the pre-exposure and post-exposure HT of every musician determined at the most sensitive octave band frequencies of hearing is performed in this section. The octave band frequencies analysed are 1000, 2000 and 4000 Hz. The standard deviation between repetitions during pre-exposure HT determination is also calculated, showing consistent results and no lack of concentration for the musicians. In addition, a comparison across musicians at different intervals is also stated.

7.7.1 TTS for Individual Musicians

Lead electric guitarist Figure 7.15 depicts the TTS found for both lead electric guitarist's ears. The pre-exposure and post-exposure HT determination are also shown at the times scheduled for the experiment. After 25 and 29 min of exposure the musician obtained the same HT for each octave band frequency. Likewise, after 55 and 59 min of exposure the same situation occurs. This suggests either a lack of concentration for the musician or a learning of the method during post-exposure HT determinations. Therefore, no conclusions can be extracted for TTS on the lead electric guitarist's right ear. In spite of this situation, TTS are only present at 4000 Hz. On the other hand, the left ear shows a recovery at 2000 and 4000 Hz, with TTS up to almost 10 dB after 27 min of exposure. No TTS is found at 1000 Hz, the musician reported even better HT levels. Since the measurement start at this frequency, a lack of concentration of the musician could influence such results.

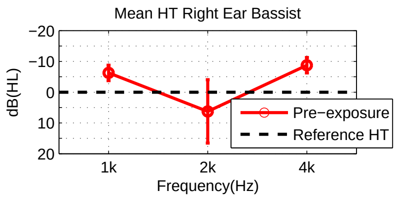
Bassist Figure 7.16 depicts the TTS found for both bassist's ears at the times scheduled for the experiment. A great TTS variability is observed at 2000 Hz for the bassist's right ear. The musician also reported a considerable standard deviation at this frequency, suggesting that the obtained results are no consistent at all. Regarding the left ear, TTS are observed at 2000 and 4000 Hz, and the recovery after 76 min is complete at 2000 Hz, but only slightly at 4000 Hz where the TTS reaches almost 20 dB after 26 min of exposure. There are no differences between the post-exposure measurements obtained 73 and 76 min after the exposure.

Drummer Figure 7.17 depicts the TTS found for both drummer's ears at the times scheduled for the experiment. With respect to the right ear, a complete recovery is observed at 2000 Hz and slightly at 4000 Hz, where the TTS are above 15 dB. No explanation is found about the TTS results at 1000 Hz. On the other hand, the left ear shows a complete recovery at 1000 Hz, but the TTS at 4000 Hz does not vary when increasing the post-exposure time. A great inconsistency is found at 2000 Hz, and no conclusions are extracted.

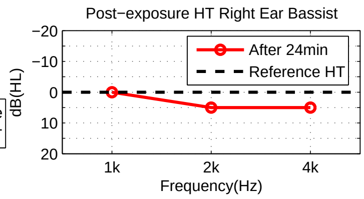


(a) Pre-exp. RE
(b) Post-exp. RE after 25min
(c) Post-exp. RE after 29min
(d) Post-exp. RE after 55min
(e) Post-exp. RE after 59min
(f) TTS RE
(g) Pre-exp. LE
(h) Post-exp. LE after 27min
(i) Post-exp. LE after 31min
(j) Post-exp. LE after 57min
(k) Post-exp. LE after 61min
(l) TTS LE

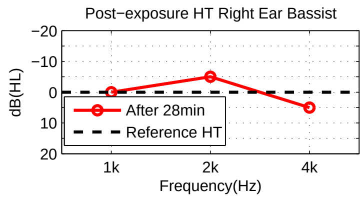
Figure 7.15: TTS for both lead electric guitarist's ears. The pre-exposure and post-exposure HT determinations at the times scheduled after the exposure are also depicted. Only the most sensitive octave band frequencies in terms of hearing are tested (1000-4000 Hz).



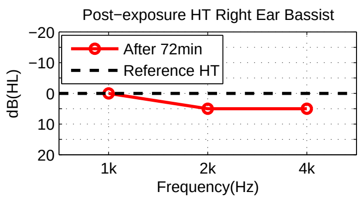
(a) Pre-exp. RE



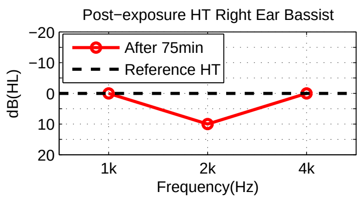
(b) Post-exp. RE after 24min



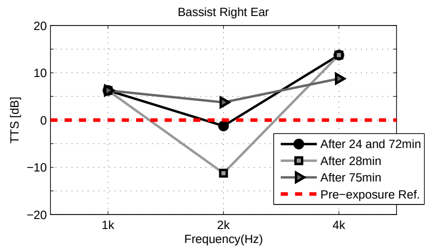
(c) Post-exp. RE after 28min



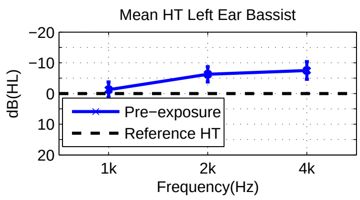
(d) Post-exp. RE after 72min



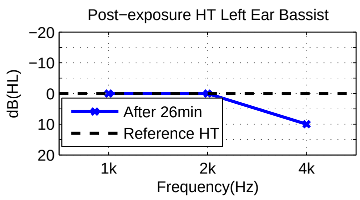
(e) Post-exp. RE after 75min



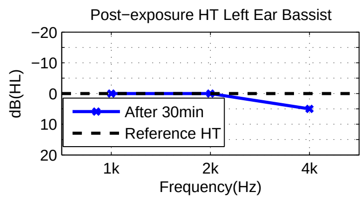
(f) TTS RE



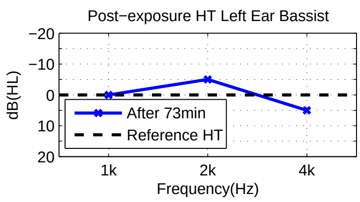
(g) Pre-exp. LE



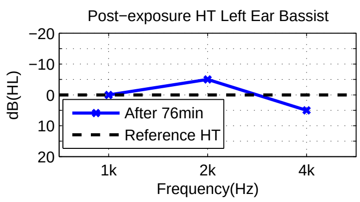
(h) Post-exp. LE after 26min



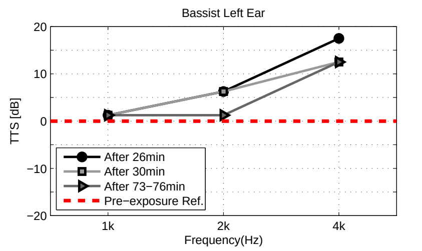
(i) Post-exp. LE after 30min



(j) Post-exp. LE after 73min

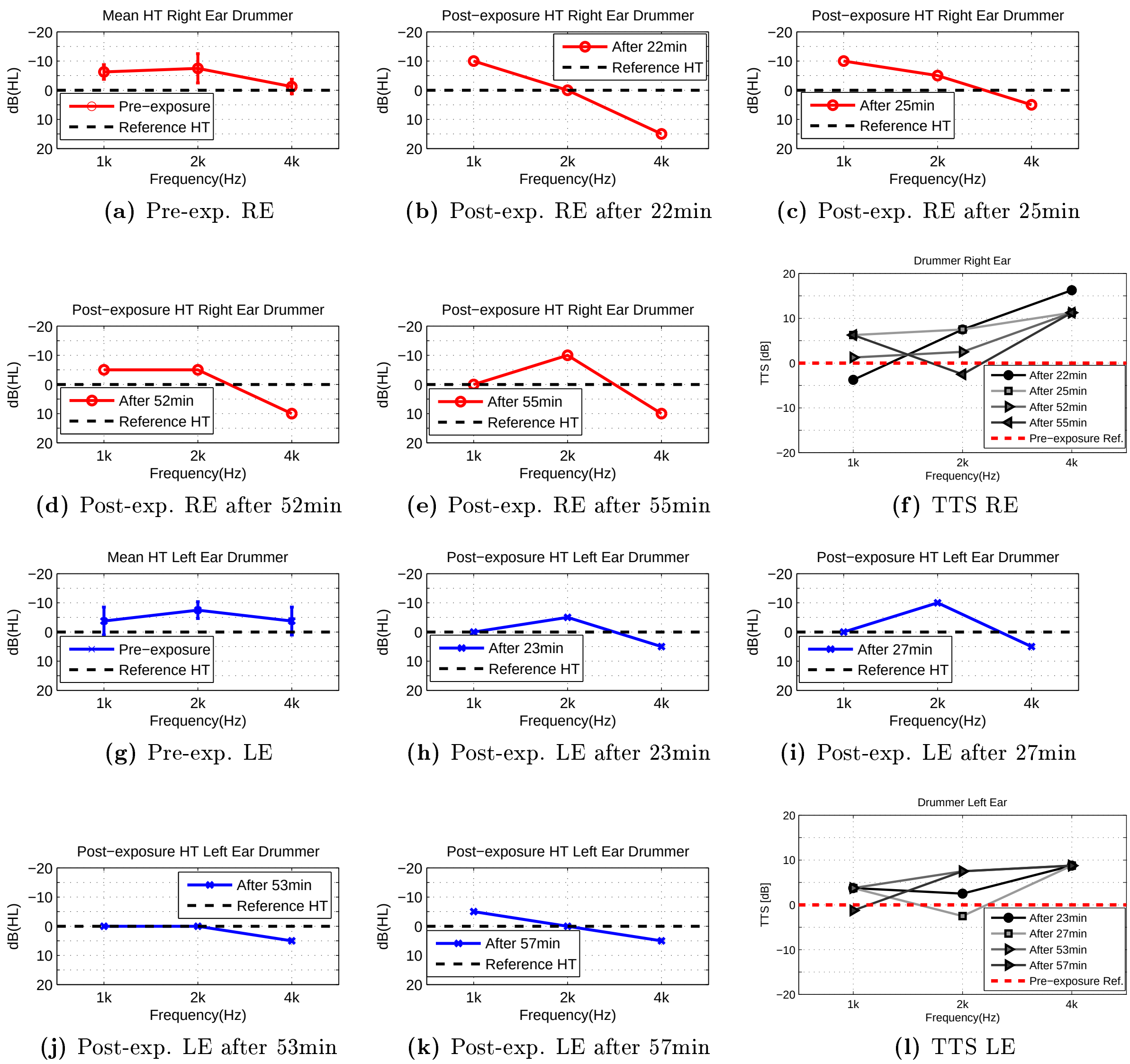


(k) Post-exp. LE after 76min



(l) TTS LE

Figure 7.16: TTS for both bassist's ears. The pre-exposure and post-exposure HT determinations at the times scheduled after the exposure are also depicted. Only the most sensitive octave band frequencies in terms of hearing are tested (1000-4000 Hz).



(a) Pre-exp. RE
(b) Post-exp. RE after 22min
(c) Post-exp. RE after 25min
(d) Post-exp. RE after 52min
(e) Post-exp. RE after 55min
(f) TTS RE
(g) Pre-exp. LE
(h) Post-exp. LE after 23min
(i) Post-exp. LE after 27min
(j) Post-exp. LE after 53min
(k) Post-exp. LE after 57min
(l) TTS LE

Figure 7.17: TTS for both drummer's ears. The pre-exposure and post-exposure HT determinations at the times scheduled after the exposure are also depicted. Only the most sensitive octave band frequencies in terms of hearing are tested (1000-4000 Hz).

7.7.2 TTS Across Musicians

Figure 7.18 depicts the mean TTS across musicians with respect to the mean pre-exposure values obtained for all of them. Two different intervals are selected for each ear, 22-29 min and 52-59 min after the exposure for the right ear whereas 23-31 min and 53-61 min for the left ear. The bassist has been rejected for the second interval in both ears since the HT determination run late compared with the remaining musicians.

As a general conclusion, there are no considerable TTS at 1000 and 2000 Hz, and the standard deviation among musicians indicates that a similar pattern between them is found in contrast with OAEs shifts which reported high variability between individuals. Considerable shifts around 10 dB are appreciated at 4000 Hz for both ears during the first interval. Apparently, no TTS are found for the second interval at the same frequency, but a great variability is observed between musicians for the right ear. It is important to emphasize that only three musicians have been tested, and even one has been rejected for the second interval. Thereby, no general conclusions can be extracted. This outlines the need of more musicians to be tested to obtain more precise results.

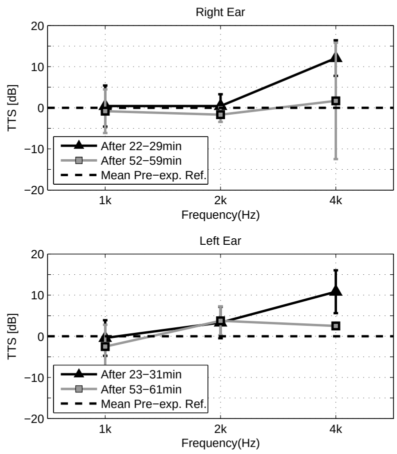


Figure 7.18: Mean TTS across musicians with respect to the mean pre-exposure values obtained for all of them. Two different intervals are selected for each ear.

Chapter 8

Hearing Assessment for Control Population

This chapter is to present the average hearing assessment results of a population non-exposed to intense loud sounds composed of twelve normal hearing subjects. The age is from 23 to 28 years old, and there is no gender considerations. HT and OAEs results are performed for all of them.

8.1 Scope of the Analysis

The underlying purpose of measuring a population non-exposed to loud music as the musicians are when playing in a rehearsal place is to obtain a measure reference to compare both groups. Thereby, some conclusions will be extracted about their hearing status and eventually, an analysis of the hearing damage for the population at risk, in this case the musicians, can be extrapolated.

8.2 Results

An overall result of the obtained average for the HT and OAEs of the control population is presented here. The same measurement method than when tested the musicians during the pre-exposure period has been performed.

Whether an individual inspection is desired, further information is reported in appendices C and D, corresponding to HT determination and OAEs measurements respectively.

The subjects are required to fill out the same questionnaire than the musicians, and the same instructions for a better understanding of their tasks during the measurements were provided for them. They can be found in appendices A and B.

The results are presented with the same order followed during pre-exposure measurements carried out for the musicians.

8.2.1 HT Results

The average HT determination obtained for both ears including the standard deviation between the twelve tested subjects is depicted in figure 8.1. Mostly HT are found above the pre-exposure reference, showing remarkable hearing levels. The small standard deviation for every octave band frequency indicates that there is a high similarity across subjects, except at 2000 and 4000 Hz, where the variability is more raised. Both ears provided highly close results.

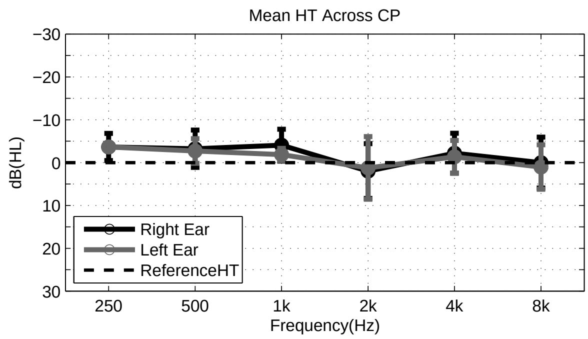


Figure 8.1: Mean HT determination for both ears including the standard deviation for twelve non-exposed normal hearing subjects. The black line represents the right ear, whilst the grey line represents the left ear. The dashed line is to indicate the reference hearing threshold given by [ISO 389-7, 2005].

8.2.2 TEOAE Results

Both TEOAE waveform and its spectrum are presented by averaging the results obtained for every individual subject.

Twelve tested subjects showed satisfactory results when measuring TEAOEs. The average TEOAE waveform obtained for this population is depicted for both ears in figure 8.2.

The greater amplitudes of the TEOAE response are found during the 5-10 ms after the stimulus is elicited. For longer latencies of TEOAEs the amplitude is considerable decreased, meaning that almost no vibration is encountered at the apex part of the cochlea for mostly subjects. Aside, a remarkable similarity is found between both ears.

From figure 8.3,it can be extracted that the energy concentration of the average TEAOE spectrum is located near the range between 700 and 1500 Hz for both right (left side) and left (right side) ears. In fact, as it is stated in [Hatzopoulos et al., 2000], the majority of normal hearing subjects produce sharp TEOAE peaks up to -10 dB(SPL) near the frequency range 1000-2000 Hz.

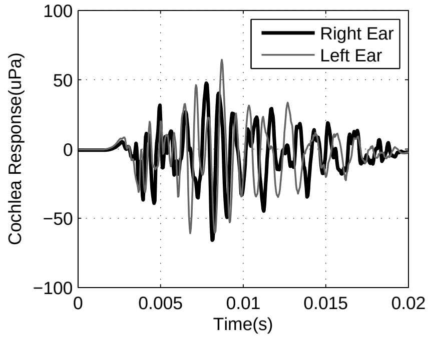
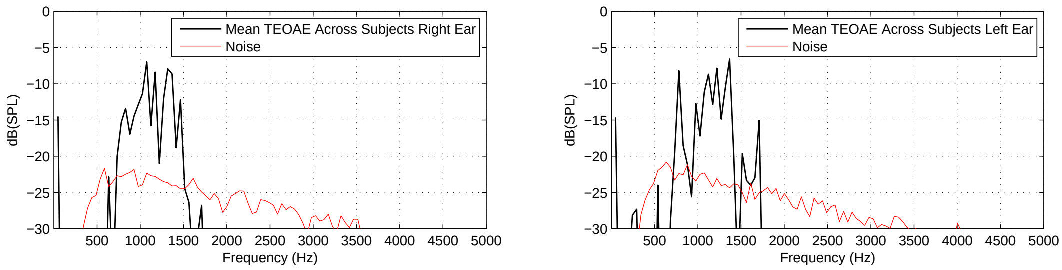


Figure 8.2: TEOAE waveform obtained by averaging the individuals results for twelve non-exposed normal hearing subjects. The thick black colour represents the right ear, whilst the thin grey colour is used for the left ear.



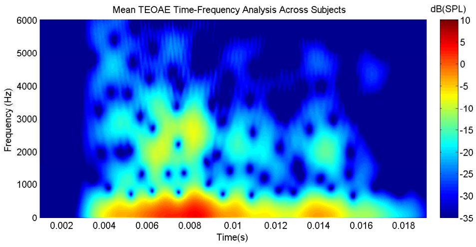
(a) Right Ear **(b)** Left Ear

Figure 8.3: TEOAE frequency response obtained by averaging the individuals results for twelve non-exposed normal hearing subjects. The black line represents the TEOAEs found across subjects and the red line is the noise floor recorded during the measurements.

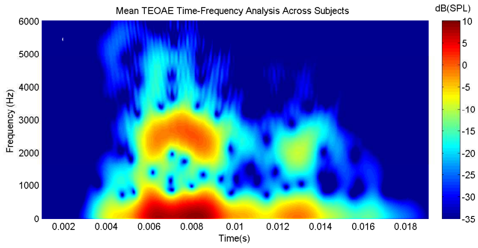
Time-frequency Analysis Across Subjects

Figure 8.4 represents the average TEOAE time-frequency analysis representative of the control population. The right ear is depicted in the left side and the left ear on the right side. The procedure followed when performing this analysis has been detailed in section 7.5.2.

In light of the results, weak TEOAE responses are found from 4000 Hz upwards in both ears. The most remarkable amplitudes appears at low frequency ranges with values near 10 dB(SPL), more emphasized from 5 to 10 ms. This suggests that low frequency components of the stimulus cause a vibration along the BM, but the apex part does not present remarkable TEOAEs as it was expected from the theory. In contrast with the latest two analysis based on an unique domain, either time or frequency, this analysis allows to visualise some differences among both ears. The left ear presents more strongly TEAOEs near 0 dB(SPL) for higher frequency components up to 3000 Hz.



(a) Right Ear

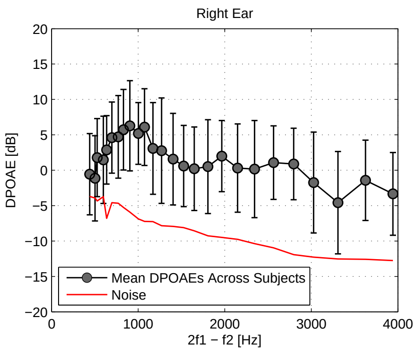


(b) Left Ear

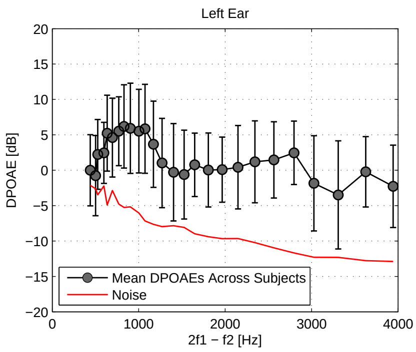
Figure 8.4: TEOAE time-frequency analysis for both ears by averaging the individual results for twelve non-exposed normal hearing subjects.

8.2.3 DPOAEs Results

Figure 8.5 shows the measured DPOAEs obtained when averaging the individual scores of 12 non-exposed normal hearing subjects. This allows to make an inspection of the static characteristics of the subjects' hearing system instead of the transient ones. Amplitude levels from 0 to 5 dB (SPL) are found from the lower frequencies up to 3000 Hz. No remarkable differences are found between the ears.



(a) Right Ear



(b) Left Ear

Figure 8.5: Mean DPOAEs for both ears including the standard deviation by averaging the individual results for 12 non-exposed normal hearing subjects.

A group average does not result representative of an individual's DPOAEs. The standard deviation presented as error bars reflects a hihgh variability between subjects. Further information can be found in appendix D, where all individual DPOAE data are shown.

Chapter 9

Comparison

This chapter pretends to give an overview about the differences encountered between populations which differ significantly in their music leisure habits, as it is the case of both the tested musicians and the control population. Comparison regarding HT determination and OAEs are performed taken into account all data collated for the subjects who participated in the experiment. Only pre-exposure recordings are employed for the musicians. Aside, a comparison in terms of the exposure level monitored in the facilities of the musicians and in a concert is to be performed. Likewise, the risk of hearing impairment is determined by the estimation of the NIPTS.

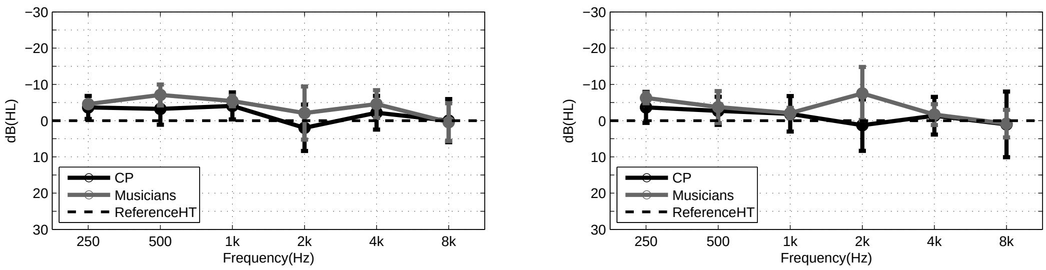
9.1 Between Exposed and Non-exposed population

Comparison regarding HT determination and OAEs is carried out between the non-exposed normal hearing twelve subjects belong the control population and the three members involved in the tested musician band who often attend to play to their rehearsal place twice per week. The weaker hearing levels and OAEs expected for the musicians will be highly dependent on the number of years exposed to intense loud sounds. It is important to state that the mentioned band is formed one and a half year ago and no concerts are registered so far. Therefore, the expected difference among both populations is not to be raised. For a feasible comparison, a greater number of musicians should be tested in order to obtain a representative pattern of this population.

9.1.1 Questionnaire Results

The main results obtained for the questionnaire can be found in appendix A.

Neither the control population subjects nor musicians were suffering from a cold when the measurements were recorded. Otherwise, it could influence the hearing results. However, one of the musicians suffered from tinnitus diagnosed clinically, and near 50% of the control population had either an infection or acumulative wax at least once. Surprisingly, all musicians have ever worked in a noisy environment, but more than 50% of the control population did not report to work in such environment. Even when mostly members for both populations were exposed to either firearms, shootings or fireworks at least once, the audiometries did not reported damage caused by those noises.



(a) Comparison Mean HT Right Ear   **(b)** Comparison Mean HT Left Ear

Figure 9.1: Comparison of the average HT with the corresponding standard deviation between 12 non-exposed normal hearing subjects and three musicians for both right and left ears. The black line represents the control population whereas the grey line represents the musicians.

Regarding music leisure habits, the requirements for the control population were that none could be involved in a musician band or playing an instrument frequently. Only three subjects showed to play an instrument for a period of maximum 6 hours but yearly, and therefore they were not rejected for the analysis. Mostly subjects reported to use either their computers or music players using headphones frequently. Aside, since the majority of the tested subjects were young people, they attend either to concerts or discotheques for a maximum period of 4 hours per week.

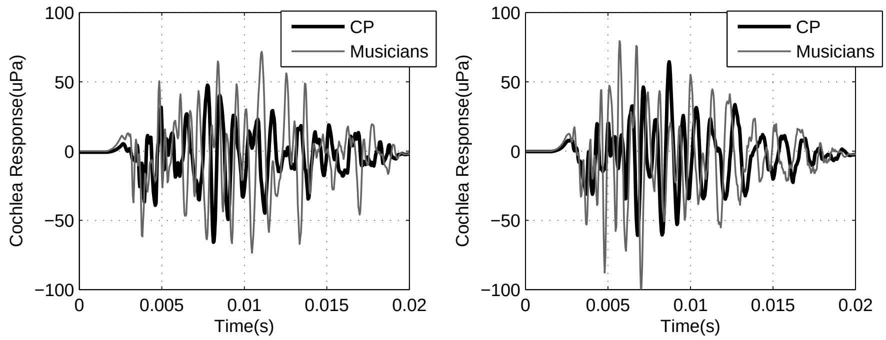
9.1.2 HT Determination

Figure 9.1 shows the mean hearing levels obtained for both groups, the musicians (before the rehearsal) and the control population. The comparison for the right ear is depicted on the left side and the left ear on the right side. The standard deviation across subjects is also presented for every octave band frequency. Hearing levels of the musicians are slightly raised for both ears, mainly at 2000 Hz where they achieved remarkable levels around -5 dB(HL) for the right ear and -10 dB(HL) for the left ear. Both ears reported a similarity pattern between populations.

9.1.3 TEOAEs

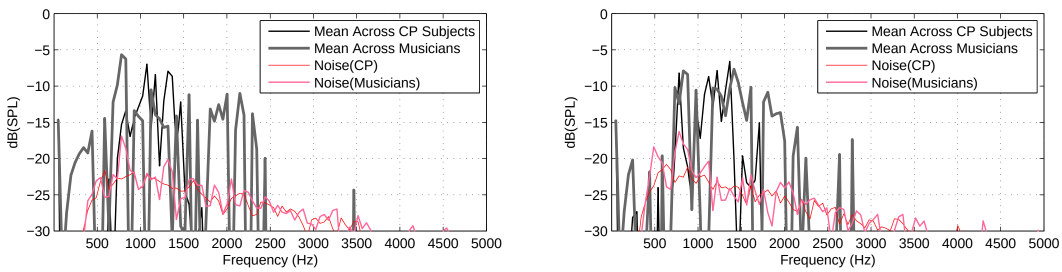
The TEOAE responses obtained in both time and frequency domains are compared between both populations for better understanding of the eventual time-frequency analysis.

Figure 9.2 shows the average TEOAE waveform obtained for both tested groups. The comparison for the right ear is depicted on the left side and the left ear on the right side. Apparently, the musicians present greater amplitudes along the BM for both ears. Those amplitudes are mainly encountered from the early times (around 5 ms) to 12 ms for both populations.



(a) Comparison Right Ear **(b)** Comparison Left Ear

Figure 9.2: Comparison of the average TEOAE waveform between 12 non-exposed normal hearing subjects and three musicians for both right and left ears. The thick black line represents the CP whereas the thin grey line represents the musicians.



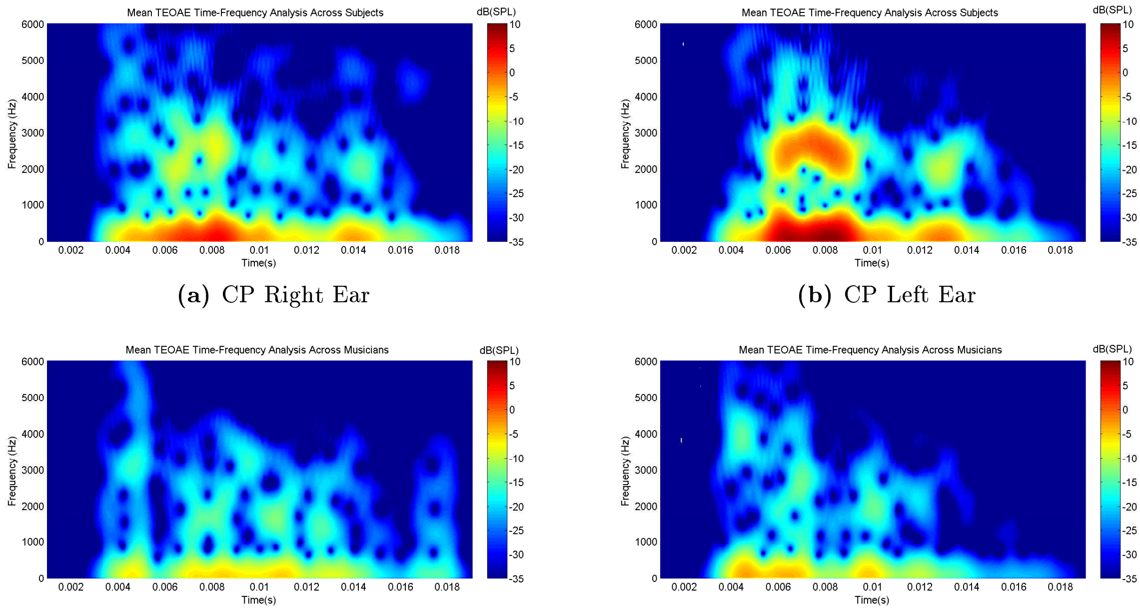
(a) Comparison Right Ear **(b)** Comparison Left Ear

Figure 9.3: Comparison of the average TEOAE frequency response between 12 non-exposed normal hearing subjects and three musicians for both right and left ears.

For a more significant analysis, both TEOAE responses are depicted in frequency domain in figure 9.3. The black line represents the average frequency response obtained for the control population whereas the grey line is to be representative of the musicians. The average noise floor is also depicted in both cases. Energy concentration of the control population is located from 800 to 1800 Hz in both ears. However, musicians showed a wider frequency response. It can be noticed that sharp dips are observed in the musicians' TEOAE response where no detection is found. But control population shows a smoother response. This is believe to be due to the lack of a great number of musicians tested. In addition, when the spectrum of a non-stationary signal is desired, as it is the cases of the human TEOAE waveform, a STFT results more appropriate than the conventional FFT to figure out about the changes in time †.

Eventually, the time-frequency analysis is shown in figure 9.4. The amplitude colour

†This has been explained in details in section 7.5.2



(a) CP Right Ear (b) CP Left Ear

(c) Musicians Right Ear (d) Musicians Left Ear

Figure 9.4: Comparison of the average time-frequency analysis for the TEOAEs between 12 non-exposed normal hearing subjects and three musicians for both right and left ears. The thin black line represents the average TEOAE across control population subjects, whilst the thick grey line represents those corresponding with the musicians. The average of the noise floor is also depicted for both cases.

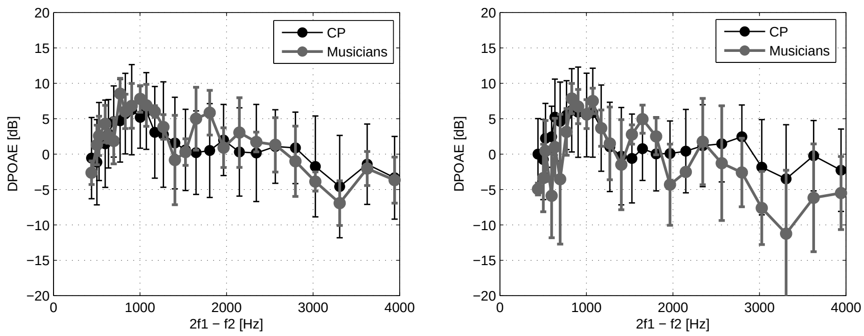
range is presented from 10 to -35 dB(SPL). A significant amplitude difference is observed between both populations, but the appearance of the most noticeable TEOAE responses are similar for both groups, being located approximately from the early times around 4 ms until 14 ms. As a general observation, the presence of TEOAEs are normally found around this period and for frequencies lower than 3000 Hz.

TEOAE responses of a maximum of 9 dB(SPL) are found at the lowest frequencies from 6 to 8 ms for the control population's left ear , whilst musicians TEOAE responses are below -2 dB(SPL). Regarding the right ear, the maxima encountered are 5 dB(SPL) and -5 dB(SPL) for the control population and the musicians respectively.

The believed reason to the significant amplitude difference between both populations is related with the lack of members tested for the musician group rather than an amplitude fall encountered for them.

9.1.4 DPOAEs

Regarding DPOAEs, the analysis carried out for both groups is depicted in figure 9.5. The thin black line represents the mean DP for the control population. The thick grey line is to show the mean DP results for the musicians. The standard deviation across



(a) Comparison Right Ear **(b)** Comparison Left Ear

Figure 9.5: Comparison of the mean DPOAEs including the standard deviation between 12 non-exposed normal hearing subjects and three musicians for both right and left ears. The thin black line represents the mean DP for the control population whereas the thick grey line is to show the mean DP results for the musicians.

subjects is also depicted. No noticeable differences are found until 1500 Hz for both ears. For higher frequencies, musicians reveal weaker DP, being more notable for the left ear. No global conclusions can be extracted in terms of comparison since a great variability across subjects is found in both cases.

9.2 Between Noise Exposure Levels from Different Leisure Activities

In order to establish a comparison between the average exposure level monitored during the rehearsals and in other music leisure activities, an indoor concert of 1 hour of duration has been continuously recorded. Thereby, a calculation of the exposure level per day for both activities is carried out. The measurement procedure is stated in appendix F.

L_{Aeq} and $L_{EX,8h}$

The SPL of a music band concert was recorded and lasted around 1 hour, and the average L_{Aeq} obtained was L_{Aeq} = **101.3 dB(A)**. This value is obtained automatically by the SLM. The instantaneous L_{Aeq} recorded during the exposure is illustrated in figure 9.6.

Mostly instantaneous L_{Aeq} values are in the range between 90 to 110 dB(A), being the maximum reached at 111.1 dB(A), and the minimum at 66.5 dB(A). This minimum corresponds to a break during the concert.

On the other hand, the average L_{Aeq} in the musicians' rehearsal place is also calculated. The rehearsal duration is to be around 2 hours. Only two days could be eventually

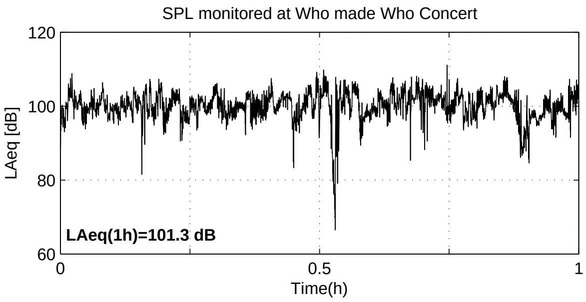


Figure 9.6: Instantaneous L_{Aeq} monitored during the *Who made Who* concert. The concert lasted around 1hour.

monitored since the batteries of the SLM were ended during one of the recordings. They are depicted in figure 9.7. The average L_{Aeq} obtained was 101.2 and 101.3 dB(A), for the second and third day respectively. Maximum recorded levels were up to 125 dB(A) and the minimum around 60 dB(A). The reason for those minima are due to breaks between songs.

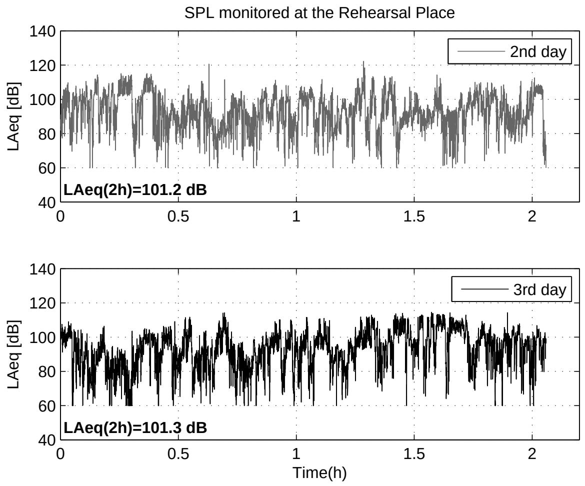


Figure 9.7: Instantaneous L_{Aeq} monitored during two rehearsal days of the *Ottocovariance* band. The duration of the rehearsal is around 2 hours. The average L_{Aeq} per day is presented.

Focusing on the recommendations stated by Occupational Safety and Health Administration (OSHA) given in table 9.1, no more than 2 hours will be allowed for the musicians to be playing without protecting their hearing.

Whether the noise exposure level over 8 hours is desired, the equation 6.3 given in section 6.1.2 is employed. The obtained results for both events are presented in table 9.2. Likewise, the noise exposure level averaged over 2 days of rehearsal for the musicians is obtained according to equation 6.4, and the result is 95.2 dB(A).

	Average Safe Hours per Day	
Noise Level [dB(A)]	No Protection	15dB Protection
90	8	No limitation
95	4	No limitation
100	2	8
105	1	4
110	1/2	2
115	0	1
120	0	0
125	0	0

Table 9.1: Average safe hours per day recommended by OSHA without and with 15 dB hearing protection.

		Average LAeq[dB(A)]	Te[h]	LEX,8h[dB(A)]
Rehearsals	2nd day	101.2	2	95.1
	3rd day	101.3	2	95.2
Concerts	–	101.3	1	92.3

Table 9.2: Noise exposure levels over 8 hours calculated for both rehearsal and concert events. The effective duration of the exposure (Te) is 2 and 1 hour for the rehearsal and the concert respectively.

Based on [Legislation, 2002], the noise exposure level over 8 hours would suppose a serious hearing damage without wearing ear plugs in both events. The maximum allowed sound pressure level per day is 85 dB(A).

NIPTS

In order to obtain the risk of hearing damage of being exposed over 10 years for both cases, the median potential NIPTS are calculated and presented in table 9.3.

Frequency [Hz]	Rehearsal(NIPTS)	Concert(NIPTS)
500	0	0
1000	6	3
2000	5	3
3000	16	11
4000	20	15
6000	14	10

Table 9.3: Median potential NIPTS ($N_{0,50}$) values that the population could develop over 10 years of exposure for both events.

Based on the DRC proposed by CHABA, as it is stated in section 6.2.3, musicians attending to their rehearsal place frequently during 10 years of exposure could suffer moderate hearing losses, mainly at 4000 Hz. No severe NIPTS are found for the concert event. Nevertheless, when the exposure noise are considered quite long (10 min or more), the CHABA limits can be exceeded [Ward, 1970]. On the other hand, the average L_{Aeq} obtained at the concert can not be considered representative at all for those events since only one concert has been recorded. Likewise, the duration of this sort of events is often longer, between 2 and 3 hours. Therefore, SPL monitored at different concert places is deemed to be a more realistic value of this exposure.

Chapter 10

Conclusions

HT and OAEs are not considered directly related to determine the hearing status of a subject. The former also depends on the subject's cognitive detection whereas the latest reflects a more objective hearing assessment. The present analysis in this project reveals that both methods does not detect remarkable TS for the lower frequency components analysed. Some similarities are found for higher frequencies, where moderate shifts appears mainly for TEOAEs and TTS. Nevertheless, the recovery obtained by TTS is more noticeable than for OAEs shifts. The believed reason might be that the recovery of the OHC function reflected by OAEs shift requires a longer period to be completed. An OAE shift obtained one day after the exposure may be more representative of the recovery process.

Regarding TS observed across musicians, HT determination reveals a similar pattern whilst OAEs, mainly DPOAEs, show a great variability between them. Therefore, a group average can not be considered representative at all of the individual's DPOAEs. This outlines the necessity of a greater number of musicians for more precise results.

Differences between the two sort of OAEs tested are found. DPOAEs represents the static characteristics of the hearing system whereas TEOAEs reflects the transient ones. As a general observation in light of the results, TEOAEs are more tolerable to high noise level environments. Mostly DPOAEs results are affected by the noise floor at specific frequency points. However, TEOAE frequency responses show high SNR at 1000 and 2000 Hz.

TEOAE time-frequency analysis reports to be more efficient in the research of the individual differences encountered for the musicians before and after the exposure, allowing to detect the predominance of the frequency components along the BM. Since TEOAE response is a non-stationary signal, a STFT showed more consistent results than the conventional FFT analysis. TEOAE shifts are mainly encountered for higher frequencies.

The non-exposed normal hearing subjects reported remarkable hearing levels with a high similarity across them, and no significant differences are observed between ears. The TEOAE time-frequency analysis reveals the presence of low frequency components along the BM, but maxima TEOAEs are not found at the apex part as it was expected.

For the comparison performed between musicians and the non-exposed population, a similar pattern in terms of hearing level is found for both groups, being slightly raised for the musicians. In contrast, weaker TEOAEs are observed for the latest group, but the potential reason derives from the lack of greater number of subjects rather than being affected by the exposure noise. No global conclusions are extracted from the DPOAE comparison due to the high variability between subjects.

Eventually, the risk of hearing damage of being exposed to loud music over 10 years is expected to cause moderate hearing losses for high frequencies, either for musicians in the rehearsal place or for potential visitors at concerts.

Chapter 11

Future Work

For further improvements of the present work, some considerations are presented as follows,

- For a more efficient determination of the HT in terms of the average used time, the Békésy test should be performed instead the ascending method. It reported less standard deviation within subjects and faster hearing level detection.
- In order to obtain more representative results of the temporary changes in hearing of musicians involved in pop-rock bands, a greater number of subjects must be tested. A high variability across musicians is observed in the results since only three musicians could be tested.
- To figure out about whether the differences encountered before and after the exposure are significantly different, an statistical analysis should be performed. This can also be applied for the comparison between the musicians and the control population.

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Appendices

Appendix A

Questionnaire and Results

This appendix presents the questionnaire to be filled out for the subjects and the obtained results encountered for both populations expressed in terms of percentage.

Template

This a questionnaire carried out for the master thesis project performed by the group 1062 of the Acoustic Department of Aalborg University. It must be filled in the form below prior to perform the listening test. If you want to participate in this experiment, please read the instructions carefully and complete this questionnaire. Your data will be treated confidentially.

Personal Data

- Name: ....
- Surname: ....
- Age: ....
- Gender:
  ◯ Man
  ◯ Woman
- Telephone number: ....
- E-mail address: ....

Hearing Diagnosis

1. Have you ever tested your hearing before?
   ◯ Yes
   ◯ No
   If your answer was *Yes*, please specify when, where an how it was realized?.................................

2. Do you have a known history of hearing disorder diagnosed by a medical doctor?

   ◯ Yes

   ◯ No

   If your answer was *Yes*, please specify which and when it was diagnosed?...................................

3. Have you ever experimented any hearing problem, such as infections, buzzing noises in the ear, excess of accumulative wax...?

   ◯ Yes

   ◯ No

   ◯ I don't know

   If your answer was *Yes*, please specify which and how often?..

4. Are you suffering from tinnitus?

   ◯ Yes

   ◯ No

   ◯ I don't know

   If your answer was *Yes*, please specify how long did you have it?...

5. Have you ever taken any medicine or another kind of drugs which could affect your hearing in a certain extent?

   ◯ Yes

   ◯ No

   ◯ I don't know

6. Do you know if anyone in your family have ever suffered form a diagnosed hearing disorder?

   ◯ Yes

   ◯ No

   ◯ I don't know

   If your answer was *Yes*, please explain what kind of hearing disorder?.......................
   ....

7. Are you suffering form a cold at present?

   ◯ Yes

   ◯ No

8. Have you ever worked in a very noisy environment?

   ◯ Yes

◯ No

If your answer was *Yes*, please specify which kind of noise environment and how long and how often were you exposed to? Did you use hearing protectors?...

9. Have you ever been exposed to intense loud sounds, such as firearms, shootings, fireworks...?

   ◯ Yes

   ◯ No

Music Leisure Habits

1. Do you often attend to concerts and/or discotheques?

   ◯ Yes

   ◯ No

   If your answer was *Yes*, please specify:

   - How often?
     ◯ Daily
     ◯ Weekly
     ◯ Monthly
     ◯ Yearly
   - Exposure time (in hours)?
     ◯ 1 or less
     ◯ 1-2
     ◯ 2-4
     ◯ 4-6
     ◯ 6-8
     ◯ 8-10
     ◯ More than 10

2. Are you involved in a music band?

   ◯ Yes

   ◯ No

   If your answer was *Yes*, please specify:

   - Which kind of music do you normally play?..............................

- How often do you play in a rehearsal place?
  ◯ Daily
  ◯ Weekly
  ◯ Monthly
  ◯ Yearly
- Exposure time (in hours)?
  ◯ 1 or less
  ◯ 1-2
  ◯ 2-4
  ◯ 4-6
  ◯ 6-8
  ◯ 8-10
  ◯ More than 10

3. Do you often play an instrument?

   ◯ Yes

   ◯ No

   If your answer was *Yes*, please specify:

   - Which kind of instrument do you play?.....................
   - How often do you play?
     ◯ Daily
     ◯ Weekly
     ◯ Monthly
     ◯ Yearly
   - How many hours (in hours)?
     ◯ 1 or less
     ◯ 1-2
     ◯ 2-4
     ◯ 4-6
     ◯ 6-8
     ◯ 8-10
     ◯ More than 10

4. Do you normally use your computer or a portable music player with headphones?

   ◯ Yes

   ◯ No

   If your answer was *Yes*, please specify:

- How often?
  - ◯ Daily
  - ◯ Weekly
  - ◯ Monthly
  - ◯ Yearly
- Exposure time (in hours)?
  - ◯ 1 or less
  - ◯ 1-2
  - ◯ 2-4
  - ◯ 4-6
  - ◯ 6-8
  - ◯ 8-10
  - ◯ More than 10

5. Have you been in a noisy environment the last 24 hours?

   ◯ Yes

   ◯ No

Results

The most interesting results are presented in terms of percentage in tables A.1 and A.2.

	Musicians		Control population	
	Yes	No	Yes	No
Hearing tested before	100%	–	58%	42%
Tinnitus/Infections(Wax)	33%	67%	42%	58%
Suffering from a cold at present	–	100%	–	100%
Worked in a noisy environment	100%	–	33%	67%
Exposed to firearms/fireworks	67%	33%	50%	50%

Table A.1: Hearing diagnosis encountered for both populations as results of the questionnaire. The answers are presented in percentage for each population.

		Musicians				Control population			
		Occurrence frequency of the activity							
Activity	Exp. Time(h)	Daily	Weekly	Monthly	Yearly	Daily	Weekly	Monthly	Yearly
Concerts/Discos	1 or less	–	–	–	–	–	–	–	–
	1-2	–	33%	–	–	–	8%	8%	–
	2-4	–	67%	–	–	–	25%	17%	–
	4-6	–	–	–	–	–	–	8%	–
	More than 10	–	–	–	–	–	–	8%	–
Computer/MPs with headphones	1 or less	–	–	–	–	8%	–	8%	–
	1-2	–	–	–	–	17%	8%	–	–
	2-4	33%	–	–	–	8%	8%	–	–
	4-6	–	–	–	–	8%	–	–	–
	6-8	33%	–	–	–	8%	8%	–	–
Play an instrument frequently	1 or less	–	–	–	–	–	–	–	8%
	1-2	–	–	–	–	–	–	–	8%
	2-4	–	67%	–	–	–	–	–	–
	4-6	–	33%	–	–	–	–	–	8%

Table A.2: Music leisure habits encountered for both populations as results of the questionnaire. The occurrence frequency of the activity for each population is presented in terms of percentage.

Appendix B

Instructions for Subjects

This appendix contains the instructions given for the subjects during the measurements for both tested populations, the musicians and the control population subjects. The musicians were also instructed during post-exposure measurements and about the duration of this interval, but due to the procedure to be followed for them remains the same conditions that those stated in the following sections, they are not included in the report.

Instructions Template

Welcome to the experiment!

This listening test is carried out for the master thesis project performed by group 1062 of the Acoustic Department of Aalborg University. This test is part of an experiment that studies the risk of hearing damage from music leisure activities. The test consists of three different parts:

1. A questionnaire to find out your hearing diagnosis as well as your music listening habits.
2. An audiometry for detecting your hearing threshold levels.
3. Two evoked sorts of otoacoustic emissions for testing the normal functionality of your hearing system anatomy.

The total duration of the test is around one hour.

Each part of the test is described in details in the following sections. You should read them thoroughly and whether you have any doubt, do not hesitate to ask to the test experimenter. The methods employed during the test are often used clinically and they do not involve any risk for your ears. You are free to leave the test wherever you want if you feel any annoyance.

Personal Questionnaire

The first part consists of a questionnaire with a view to discover the status of your hearing and your main music listening habits. This part of the test takes around 5 minutes.

Pure Tone Audiometry

The second part consists of testing your hearing by means of an audiometry. This is to be performed using an audiometer and you are required of wearing a pair of headphones. When you place them, be sure that they fit your ears correctly. Each ear will be tested separately, starting with the right ear.

You will hear different elicited pure tones for each ear. When you hear a tone, you have to press the corresponding button for the tested ear. The red button corresponds to the right ear and the blue button for the left one. Once the test starts, it will be continued until both ears have been tested. The audiometry will be repeated four times to ensure the reliability of the results.

In order to guarantee that you understand perfectly the task, a familiarization session will be performed at the beginning.

The duration of this task is around 30 minutes. A break between 5-10 minutes is made before starting with the next task.

Otoacoustic Emission Measurements

These measurements are carried out to test the normal function of your cochlea. To perform this part of the test, a probe will be inserted in your ear. Both ears will be tested separately.

Different evoked stimuli are presented to the ear and the response of your cochlea is analysed. During this process, you do not have to do any task, the only requirement is to be relaxed and quiet due to those measurements are very sensitive to the movements of the probe as well as your body motion.

Two sorts of otoacoustic emissions will be carried out for both ears with a break of 5 minutes between them. Four repetitions per ear are required to ensure the reliability of the results. A total of 8 recordings are to be performed for each type of otoacoustic emissions.

In order to guarantee that you understand perfectly the task, a familiarization session will be performed at the beginning of each measurement.

The duration of this task is around 30 minutes.

Appendix C

HT Measurements

This measurement report describes the procedure followed to obtain the HT of a certain population using the ascending method.

Room Overview

Regarding the measurements for the control population, the listening cabin B at Aalborg University, Fredrik Bajers Vej 7 B5-108, 9220 Aalborg, Denmark is employed. This room is often used for listening experiments. It is double-door construction and has sound isolating walls, floor and ceiling [†]. It consists of a steel box resting on springs for anti-vibrating purposes.

HT determination of the musicians are performed in a quite room near the rehearsal place. It has been described in section 7.2.

Limitations

Békésy method was selected to be used during the measurements. Nevertheless, due to technical problems regarding the communication between the audiometer and the available software, the numerical data for the Békésy tracing could not be stored and the method was rejected. It is important to notice that this method is more efficient and faster than the selected ascending method according to the comparison made by [M.Lydolf, 1999], even though the latest shows reliable results.

Equipment

The equipment used is listed in table C.1.

[†]The acoustic isolation of the room is necessary to assure that experiments and recordings are not disturbed by noise from the outside.

Item	Type	AAU LBNR
Clinical Audiometer	Madsen ORBITER 922	33968
Headphones	Sennheiser HDA 200	52735

Table C.1: Measurement equipment used during HT measurements.

Measurement Method

Stimuli

Pure tones of duration around 1-2 s are presented to the subject by means of headphones, from 250 to 8000 Hz.

Measurement System

The *Orbiten 922* audiometer provided by Madsen Electronics is used for the Ascending method. The *HDA 200* headphones provided by Sennheiser are employed during the measurement. This audiometer provides user-friendly audiological instrumentation of high quality [Electronics, 1994].

Measurement Procedure

Equipment Setup

The signal flow diagram employed when measuring the HTs of the subjects is shown in figure C.1.

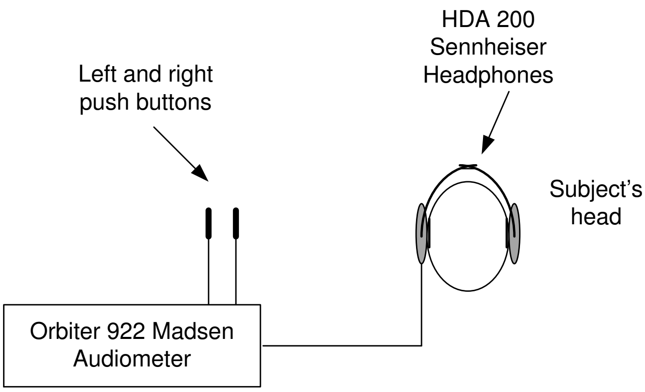


Figure C.1: Signal flow diagram among equipment when measuring HTs.

Procedure

The procedure has been performed following the steps stated in [ISO 8253-1, 1989], as it is described in section 4.1.2. Four repetitions have been carried out for the reliability of the results. Both ears are tested before ending each repetition, starting at the right ear. A break of around 5-10 min is performed between repetitions. Eventually, a refitting of the headphones is carried out for each repetition to minimise the influence of the position of the headphones on the subject's head.

Results

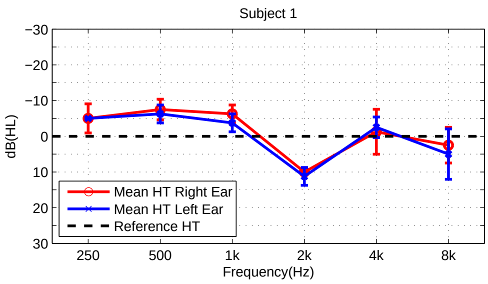
HT Determination for Individual Normal Hearing Subjects

The obtained HTs for each subject as well as the standard deviation per octave band frequency between repetitions are depicted in figures C.2 and C.3 from the subjects 1 to 8 and from 9 to 12 respectively. Hearing levels are obtained from 250 to 8000 Hz. The red colour represents the right ear whereas the blue shows the left ear. The dashed line corresponds to the reference hearing levels according to [ISO 389-7, 2005]. All subjects reported normal hearing levels above 20dB(HL), except the subject 12 who suffers a moderate hearing loss at 8000 Hz. But he has not been rejected for the experiment since such octave frequency band is not considered of interest for the analysis.

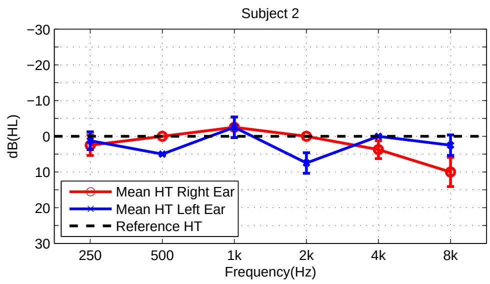
No similarities between ears are found for mostly subjects.

HT Determination for Individual Musicians

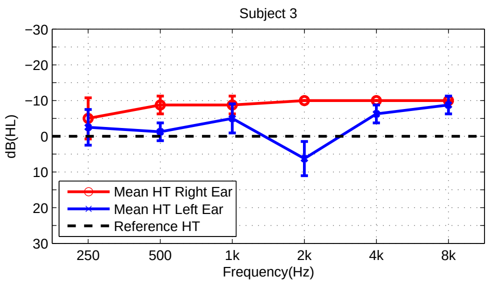
Figure C.4 shows the mean pre-exposure hearing levels obtained for the tested musicians. The standard deviation between repetitions is also presented. It can be observed that the variability among repetitions is greater than for the control population subjects. The believed reason is that the room near the rehearsal place presents higher levels of noise floor since it is not acoustic isolated. In spite of this, musicians reported substantial hearing levels.



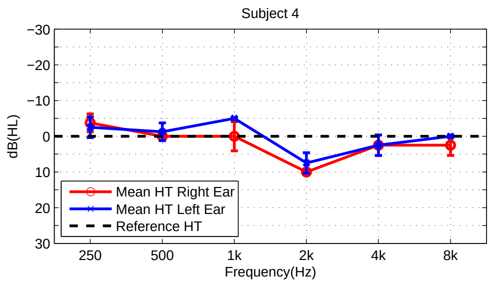
(a) Subject 1



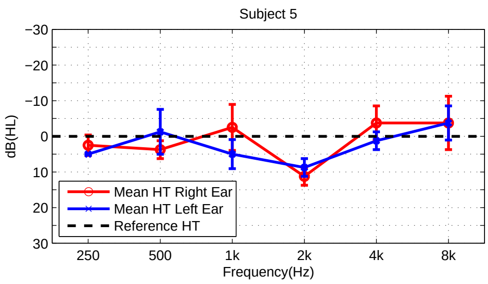
(b) Subject 2



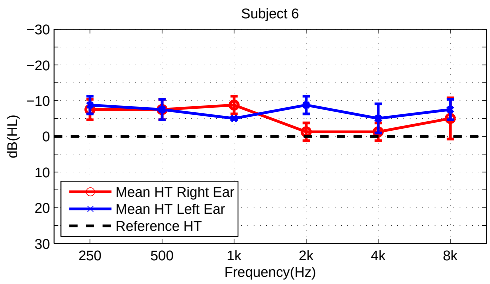
(c) Subject 3



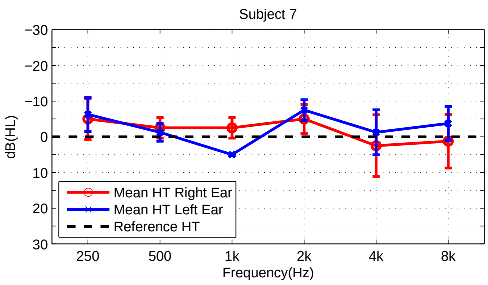
(d) Subject 4



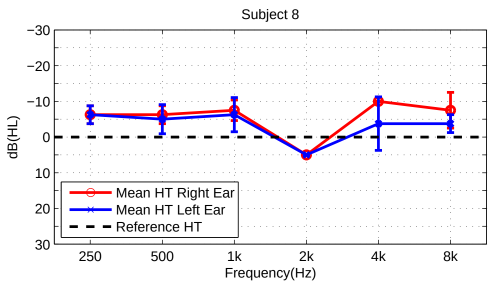
(e) Subject 5



(f) Subject 6

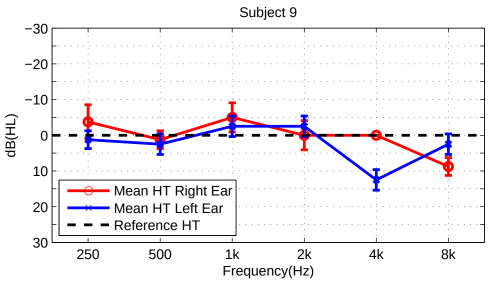


(g) Subject 7

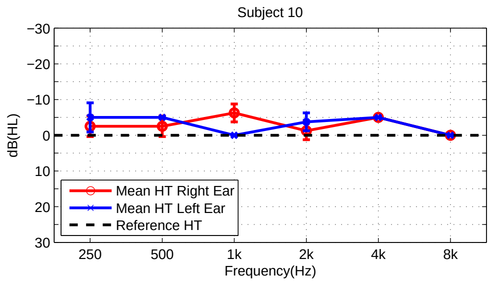


(h) Subject 8

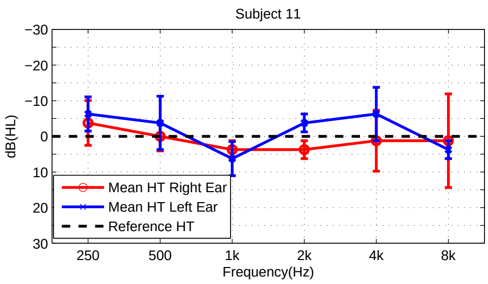
Figure C.2: HT determination obtained from the subjects 1 to 8 of the control population. Hearing levels are obtained from 250 to 8000 Hz. The red colour represents the right ear, whereas the blue depicts the results from the left ear. The dashed line corresponds to the reference hearing levels according to [ISO 389-7, 2005]. Standard deviation between repetitions can also be observed.



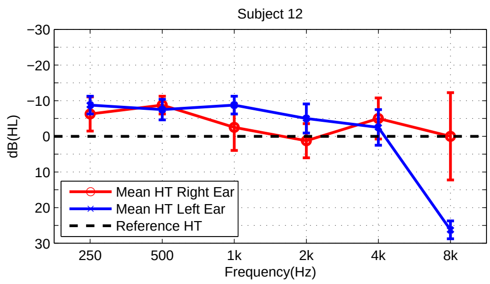
(a) Subject 9



(b) Subject 10

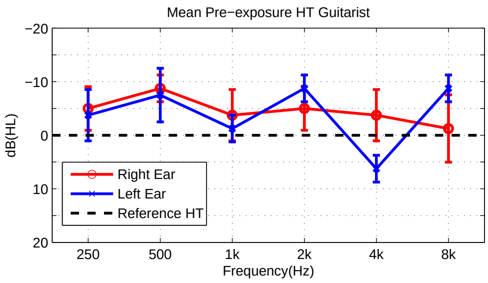


(c) Subject 11

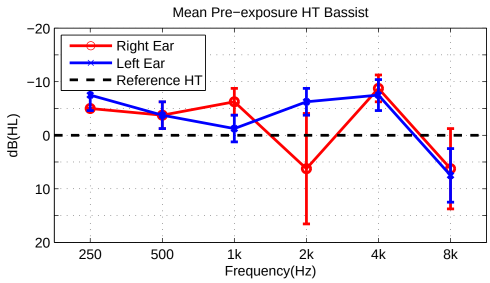


(d) Subject 12

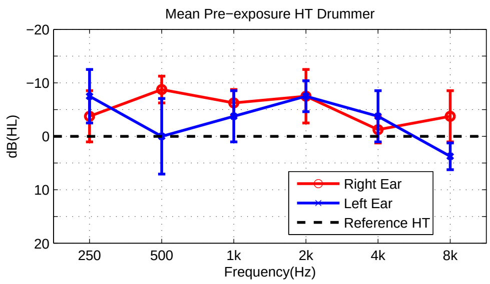
Figure C.3: HT determination obtained from the subjects 9 to 12 of the control population. Hearing levels are obtained from 250 to 8000 Hz. The red colour represents the right ear, whereas the blue depicts the results from the left ear. The dashed line corresponds to the reference hearing levels according to [ISO 389-7, 2005]. Standard deviation between repetitions can also be observed.



(a) Mean Pre-exposure HT Guitarist



(b) Mean Pre-exposure HT Bassist



(c) Mean Pre-exposure HT Drummer

Figure C.4: HT determination obtained from the three tested musicians. Hearing levels are obtained from 250 to 8000 Hz. The red colour represents the right ear, whereas the blue depicts the results from the left ear. The dashed line corresponds to the reference hearing levels according to [ISO 389-7, 2005]. Standard deviation between repetitions can also be observed.

Appendix D

OAEs Measurements for Control Population

Purpose

This measurement report describes the procedure followed to obtain the TEOAEs and DPOAEs measurements for the control population in this project, obtaining a complete overview of the cochlear status not being highly dependent of the technique employed. They have been performed according to the *ILO88 User Manual* provided by Otodynamics [Otodynamics, 1997].

The eventual purpose is to analyse the normal functionality of the auditory system of the subjects who participate in this test to be compared with the data obtained for people exposed to sound in rehearsal places afterwards.

Room Overview

The measurements took place in the listening cabin B at Aalborg University, Fredrik Bajers Vej 7 B5-108, 9220 Aalborg, Denmark. This room is often used for listening experiments. It is double-door construction and has sound isolating walls, floor and ceiling [†]. It consists of a steel box resting on springs for anti-vibrating purposes.

Equipment

The equipment used is listed in table D.1.

[†] The acoustic isolation of the room is necessary to assure that experiments and recordings are not disturbed by noise from the outside.

Item	Type	AAU LBNR
Measurement system	ILO96 Otodynamics	52661
Measurement analyser	ILO88 Otodynamics	47389
Probe	Otodynamics	52661
Stand for fixing the cord	Soundking	1340-03

Table D.1: Measurement equipment used when recording TEOAEs and DPOAEs.

Measurement Method

Stimuli

- **TEOAE Stimuli**

  The default stimulus employed by the measurement system consists on a click which has a broad frequency spectrum useful for evoking responses from the cochlea between 500 to 6000 Hz [Otodynamics, 1997]. Thereby, all frequency regions of the cochlear response can be tested simultaneously. The intensity of the sharp peak is around 84 dB (SPL) and it is repeated at intervals of 20 ms.

- **DPOAE Stimuli**

  Two stimuli $f1$ and $f2$ are automatically swept across the frequency range from 1000 to 6000 Hz. They can also be fixed for a full analysis of a particular frequency region. It depends of the selected test †. The interval between steps chosen by the tester determines the resolution of the measurements. Although a higher resolution provides higher quality of the results, longer time is required. A 3 points/octave interval is recommended by [Otodynamics, 1997].

  The values selected for the level of the pure tones are $L1 = 65$ dB (SPL) and $L2 = 55$ dB (SPL) for $f1$ and $f2$ respectively, and the ratio $f2/f1$ equals 1.22. ‡

Measurement System

The ILO96 Otodynamics consists of four stimulus channels and two inputs channels for OAE measurements. It can run all existing *ILO88*, *ILO95* and *ILO V-5* softwares from Otodynamics, providing mainly TEOAE and DPOAE measurements. Further information can be found in [Otodynamics, 2001].

† The main DPOAE test provided by Otodynamics is the known as *DP-Gram*, which allows to measure a series of DPOAEs at the main distortion product frequency $2f1 - f2$ in the range 1000 - 6000 Hz. However, when DPOAEs are in the presence of excessive noise or they are small, the *DP Spectrum* technique is often used. It consists on fixing both pure tones providing a full analysis of the response in a specific frequency region. This enhances the efficiency [Otodynamics, 1997].

‡ As it is stated in section 4.2.1, the typical values used clinically are a ratio $f2/f1$ equals 1.22 and the levels for the *primary* tones between 55 to 65 dB (SPL).

Measurement Analyser

The ILO88 Otodynamics is a measurement analyzer of the OAEs, providing an objective testing of the cochlea normal function. To elicit an stimulus and recording the response of the cochlea, a probe is used as a transducer during the measurements. It contains two loudspeakers and a microphone. A band pass filter is used to analyse the response in the specified frequency range.

Once the name and the selected ear of the subject has been identified, the software firstly performs an acoustic probe fit and then, an OAE recording is carried out when the stimulus presents no excessive background noise. This procedure is explained in the following section.

Measurement Procedure

Equipment Setup

The signal flow diagram employed for both TEOAEs and DPOAEs measurements is shown in figure D.1.

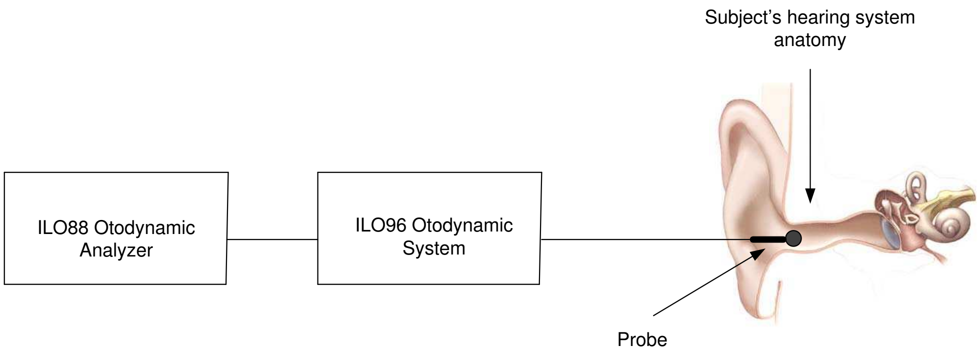


Figure D.1: Signal flow diagram among equipment during TEOAE and DPOAE measurements.

When recording OAEs, some recommendations must be followed to assure that the variations in the response are due to the normal cochlear function and reduce the unavoidable background noise presents during the measurements. The noise can be generated either by the environment or by the subject's motion.

Ambient environmental noise

- The measurements must be recorded in a quiet room.

- The probe closes perfectly the external ear canal avoiding the air noise entering inside. To achieve this, a probe tip is used.
- The cord from the equipment to the probe is stabilized by means of an stand to minimize the rubbing with the subject or the chair.

Noise by the subject's motion The tester must instruct the subjects to be quiet and remaining limit movements during measurements. Generally, the noise is generated by the breathing or blood flow, and it is greater for the low frequency region (less than 1000 Hz). Some instructions are filled by the subjects to assure that they understand the tasks.

TEOAE Procedure

The procedure for the TEOAEs measurements consists of two main parts, the known as *Checkfit Stage* and the TEOAEs recording. The first part monitors the stimulus and the background noise level before starting the measurements for an appropriate stimulus level adjustment and fixing system. The recording session shows both time and frequency analysis of the response of the cochlea in real time as well as the spectrum and eventually it stores the data after a predetermined period.

There are several recommendations to be followed during both parts for considering the test as valid. They are based on [Otodynamics, 1997].

Checkfit Stage

Before starting the TEOAEs measurements, the probe must be fitted correctly in the external ear of the subject. At this stage, the stimulus and background noise characteristics are monitored in real time to be adjusted by the tester. This assures a proper quality for the measurements.

- Stimulus Characteristics

  Since the stimulus used during TEOAEs measurements has been denoted as a click, the stimulus waveform must be as short as possible and less than 1 ms [Otodynamics, 1997]. Thereby, an oscillatory stimulus waveform is considered inappropriate for recording TEOAES measurements in adults. This oscillation is often due to either the noise environment presents in the room or the noise produced by the subject.

  Therefore, whether a click stimulus is presented, its frequency spectrum must be as flat as possible in the frequency range from 500 to 6000 Hz [†].

[†]It must be noticed that a decrease in the response is observed towards 6 kHz due to the eardrum reflection [Otodynamics, 1997] and the band pass filter provided by the measurement analyser.

- Background Noise Characteristics

  A suitable level of noise for TEOAEs measurements is around 45 to 52 dB (SPL), when eliciting a stimulus click around 84 dB (SPL) [Otodynamics, 1997].

To achieve this, the listening room must be quiet and the subjects must be instructed by the tester to remain as quiet as possible. In addition, the selection of the probe plays an important role to be well fitted to the ear.

TEOAE Recording

Once the probe has been fitted properly and the stimulus level is set, the TEOAEs are recorded. The ILO88 software provides two different cochlea waveforms called A and B, corresponding to the even and odd sweep respectively. The recordings are obtained by using a non-linear method, consisting on evoking three clicks of positive polarity and a fourth click of an inverse polarity which has a relative magnitude of 10 dB higher than the positive polarity [Hatzopoulos et al., 2000]. This is commonly used since it cancels the stimulus artefact which could be misinterpreted a TEOAE response.

The duration of the test is to be around 50 s and 4 repetitions with refitting of the probe for each subject are performed to obtain feasible results.

To consider a TEOAE test as valid, at least two significant sharp peaks must be located in the response of the cochlea throughout the frequency range between 500 to 6000 Hz. A sharp peak is considered normally significant in any frequency band when the following requirements are fulfilled,

- The SNR is greater than 3 dB.
- The reproducibility, meaning the correlation (in percentage) between the even and odd sweep recorded simultaneously, is greater than 65%.

DPOAE Procedure

The DPOAE procedure is also divided into a fixing probe part and a measurements recording part.

Checkfit Stage

This stage is similar than that of the TEOAEs procedure, but some details needs to be clarified. A click stimulus is also elicited but two probe loudspeakers are required for the pure tones $f1$ and $f2$. The responses obtained from those transducers must be similar for a correct recording of TEOAEs. In addition, whether strong peaks and valleys are observed in the stimulus waveform, the background noise level may be excessive and then, the frequency spectrum is no longer flat.

DPOAE Recording

Once the probe has been fitted properly and the levels of the stimuli are set, DPOAEs are recorded. The duration of the test is to be around 30 s and 4 repetitions with refitting of the probe for each subject are performed to obtain feasible results.

To consider a DPOAE test as valid, some requirements must be fulfilled,

- The test must be performed until the distortion product values of the response of the cochlea are sufficiently above the background noise [†].
- Healthy ears normally present DPOAE levels around 10 dB (SPL), being highlighted up to 20 dB (SPL) for young and infants ears. DPOAEs less than -10dB (SPL) cannot be considered as valid [Otodynamics, 1997].

Results

All individual results for the control population has been included for a visual inspection of the reader. No individual comments are presented since the objective is to compare the average obtained with the musicians results.

TEOAE Results

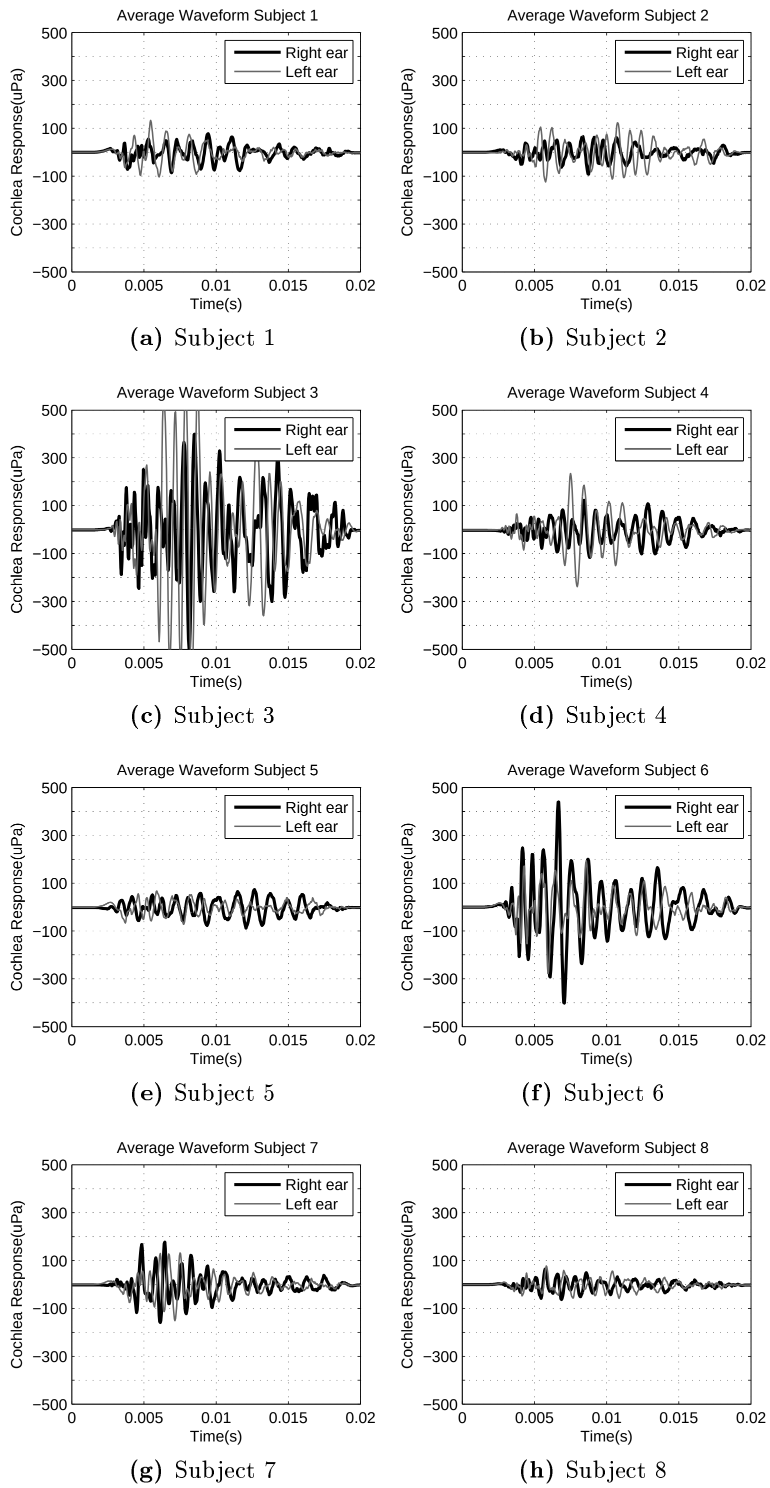
TEOAE Waveform for Individual Subjects

TEOAE waveforms are presented in figures D.2 and D.3, from the subjects 1 to 8 and from 9 to 12 respectively. The thick black line represents the right ear and the thin grey line represents the grey line. Remarkable amplitude differences are found among subjects.

TEOAE Frequency Response for Individual Subjects

TEOAE frequency responses for both ears of the control population can be found in figures D.4, D.5 and D.6 for the subjects 1 to 4, 5 to 8 and 9 to 12 respectively. Subjects 3 and 6 reported higher TEOAE peaks than the remaining subjects.

[†] The background noise levels have been obtained with two standard deviations representing the limits of the 95% of confidence region. The DPOAEs should be above this limit.



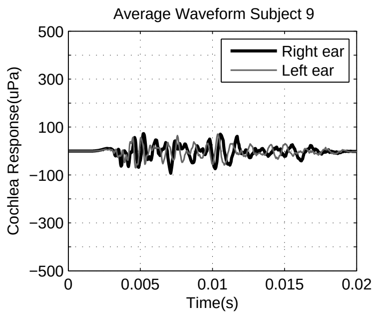
(a) Subject 1 (b) Subject 2

(c) Subject 3 (d) Subject 4

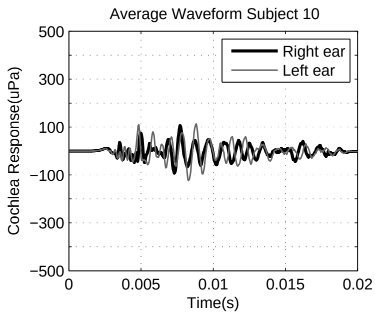
(e) Subject 5 (f) Subject 6

(g) Subject 7 (h) Subject 8

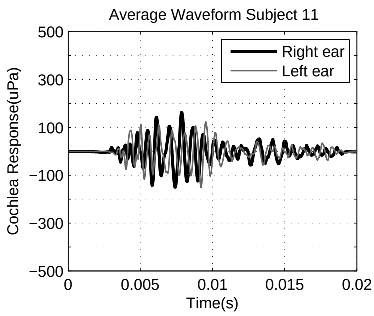
Figure D.2: TEOAE waveforms from the subjects 1 to 8 of the control population. The thick black line represents the right ear whereas the thin grey line symbolises the left ear.



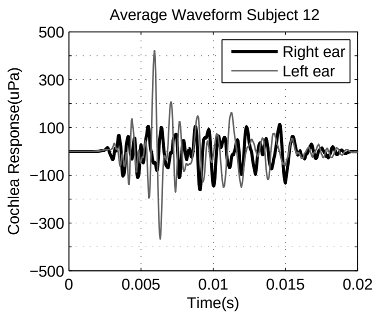
(a) Subject 9



(b) Subject 10

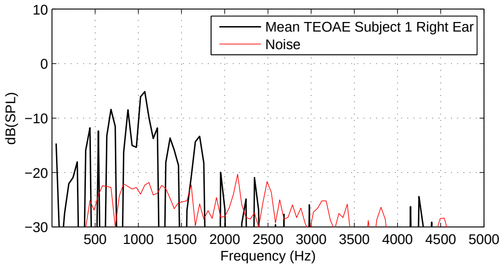


(c) Subject 11

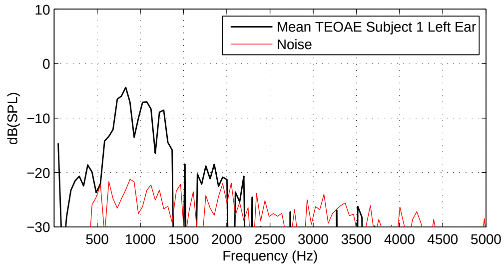


(d) Subject 12

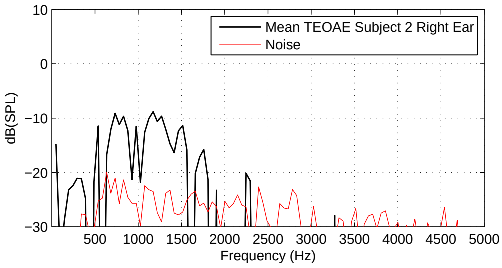
Figure D.3: TEOAE waveforms from the subjects 9 to 12 of the control population. The thick black line represents the right ear whereas the thin grey line symbolises the left ear.



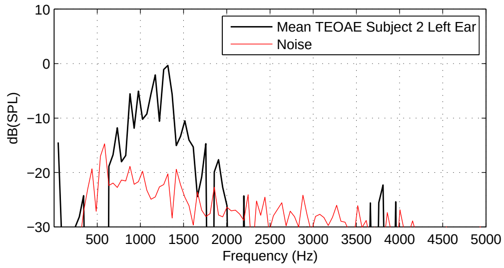
(a) Subject 1 Right Ear



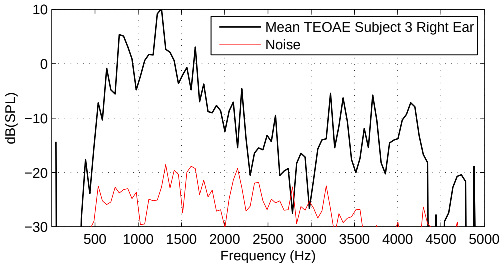
(b) Subject 1 Left Ear



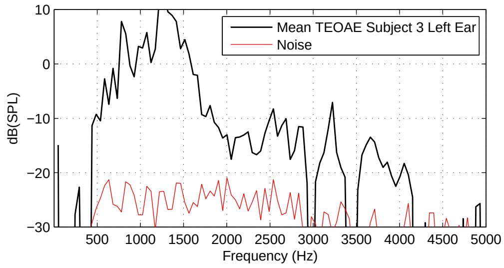
(c) Subject 2 Right Ear



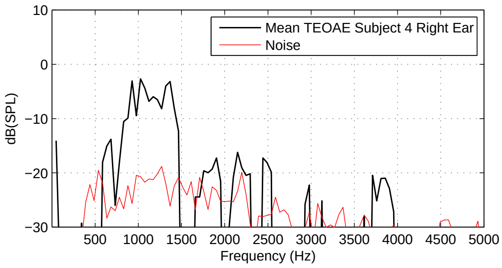
(d) Subject 2 Left Ear



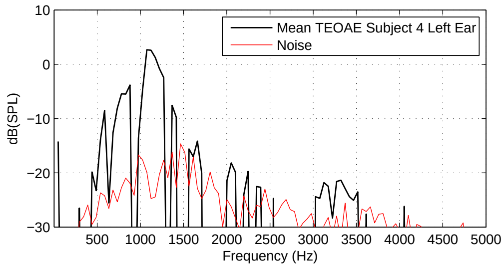
(e) Subject 3 Right Ear



(f) Subject 3 Left Ear

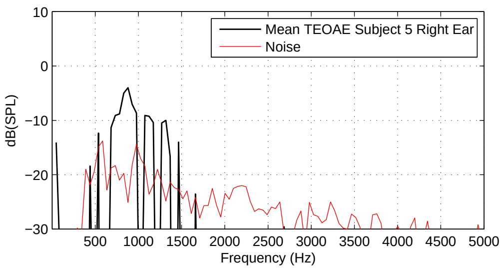


(g) Subject 4 Right Ear

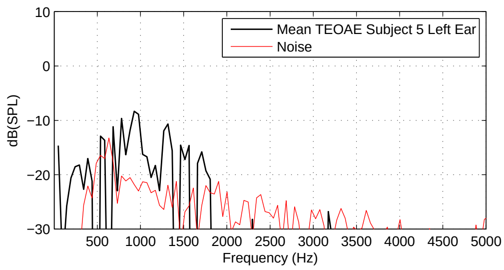


(h) Subject 4 Left Ear

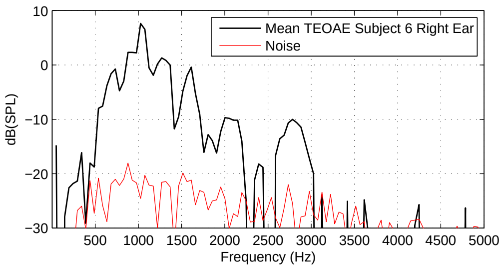
Figure D.4: TEOAE frequency responses for both ears from subjects 1 to 4 of the control population. The right ear is presented on the left side and the left ear on the right side. The black line represents the average TEOAEs and the red line the noise floor during the recording.



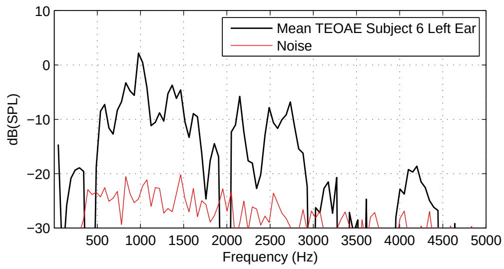
(a) Subject 5 Right Ear



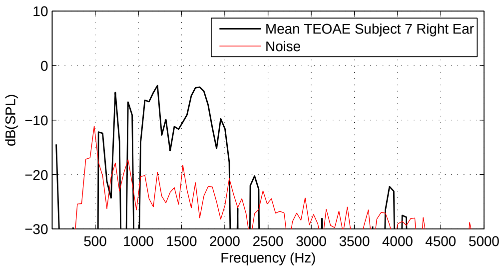
(b) Subject 5 Left Ear



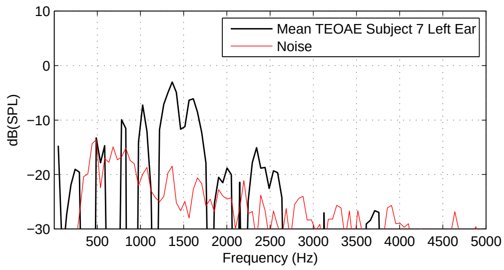
(c) Subject 6 Right Ear



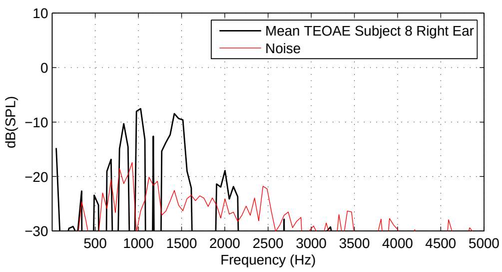
(d) Subject 6 Left Ear



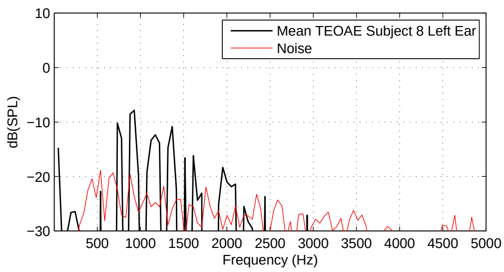
(e) Subject 7 Right Ear



(f) Subject 7 Left Ear

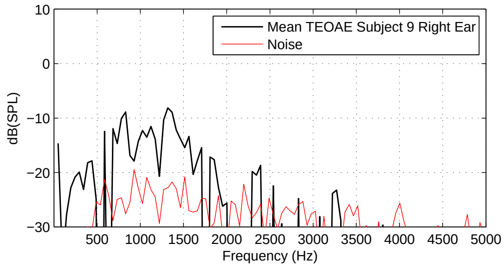


(g) Subject 8 Right Ear

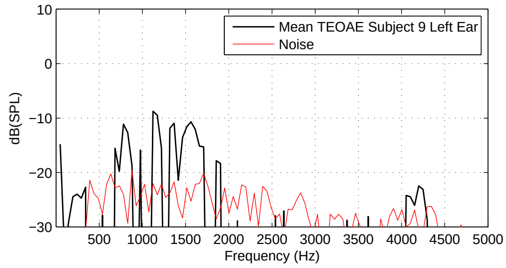


(h) Subject 8 Left Ear

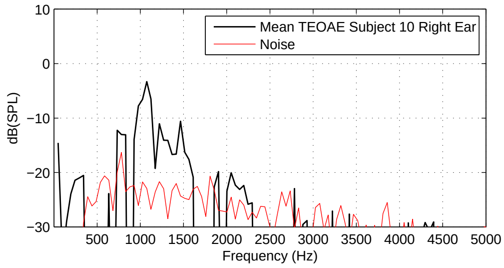
Figure D.5: TEOAE frequency responses for both ears from subjects 4 to 8 of the control population. The right ear is presented on the left side and the left ear on the right side. The black line represents the average TEOAEs and the red line the noise floor during the recording.



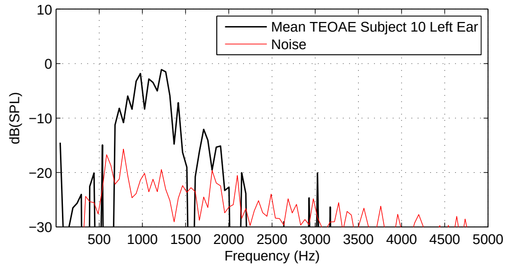
(a) Subject 9 Right Ear



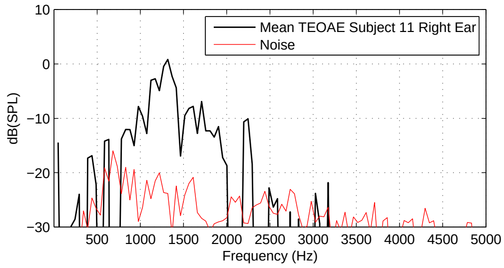
(b) Subject 9 Left Ear



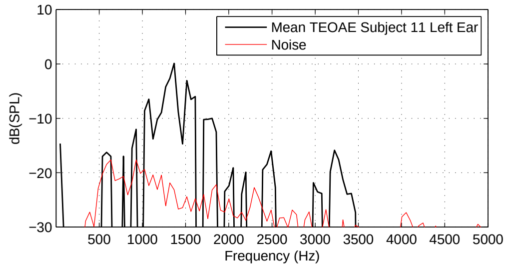
(c) Subject 10 Right Ear



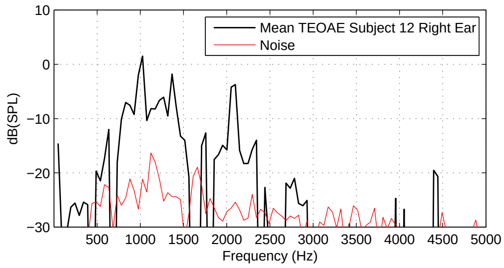
(d) Subject 10 Left Ear



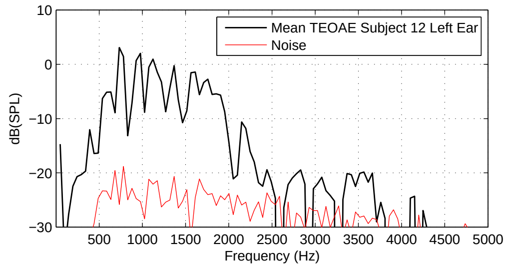
(e) Subject 11 Right Ear



(f) Subject 11 Left Ear



(g) Subject 12 Right Ear



(h) Subject 12 Left Ear

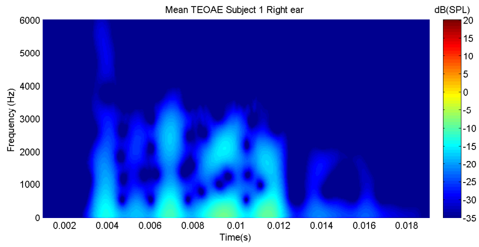
Figure D.6: TEOAE frequency responses for both ears from subjects 9 to 12 of the control population. The right ear is presented on the left side and the left ear on the right side. The black line represents the average TEOAEs and the red line the noise floor during the recording.

Time-frequency Analysis for Individual Subjects

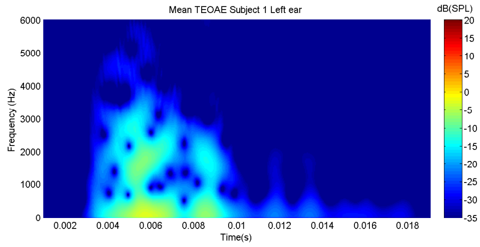
TEOAE time-frequency analysis obtained from the control population subjects are shown in figures D.7, D.8 and D.9 corresponding with the subjects 1 to 4, 5 to 8 and 9 to 12 respectively. The colour bar range is stated from 20 to -35 dB(SPL). Subjects 3 reported TEOAE amplitudes up to almost 20 dB(SPL) from the early times until the apex part of the BM. The remaining subjects showed weaker TEOAE responses. Remarkable differences are encountered among subjects.

DPOAE Results

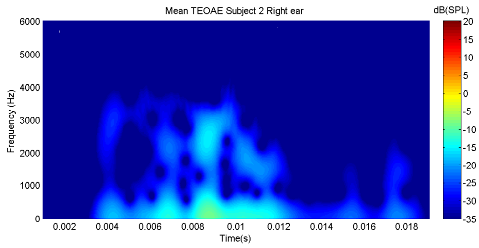
DPOAEs found for the control population are depicted in figures D.10, D.11 and D.12 from the subjects 1 to 4, 5 to 8 and 9 to 12 respectively. Subject 5 reported no consistent DPOAEs but mostly remaining subjects showed DP above 0 dB.



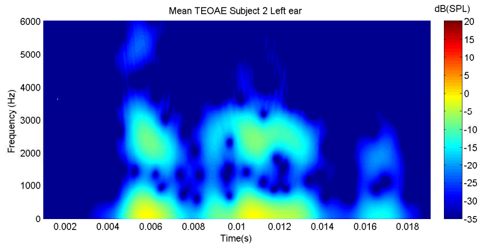
(a) Subject 1 Right Ear



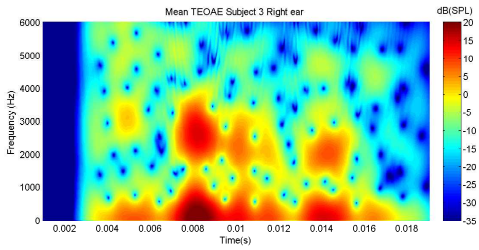
(b) Subject 1 Left Ear



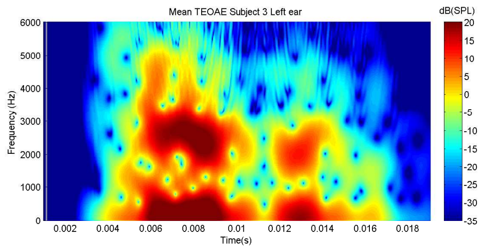
(c) Subject 2 Right Ear



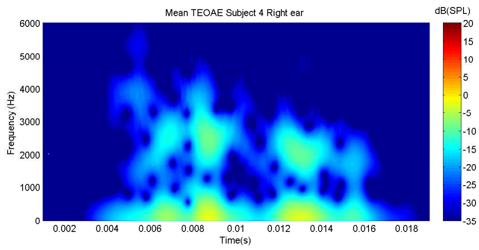
(d) Subject 2 Left Ear



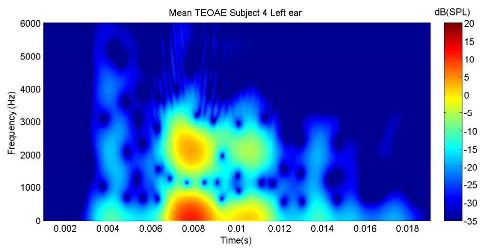
(e) Subject 3 Right Ear



(f) Subject 3 Left Ear

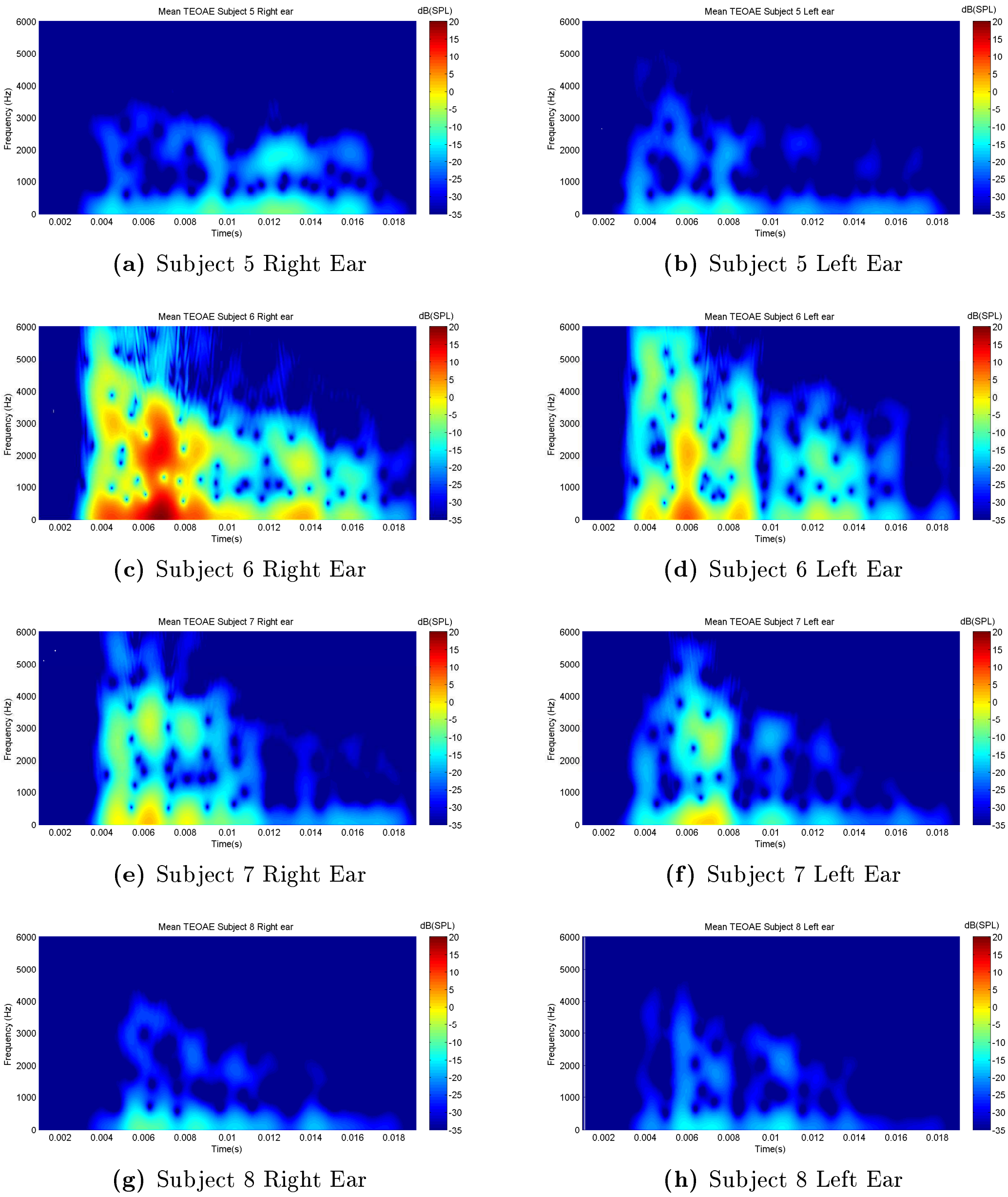


(g) Subject 4 Right Ear



(h) Subject 4 Left Ear

Figure D.7: TEOAE time-frequency analysis for both ears from subjects 1 to 4 of the control population. The right ear is presented on the right side and the left ear on the left side.



(a) Subject 5 Right Ear

(b) Subject 5 Left Ear

(c) Subject 6 Right Ear

(d) Subject 6 Left Ear

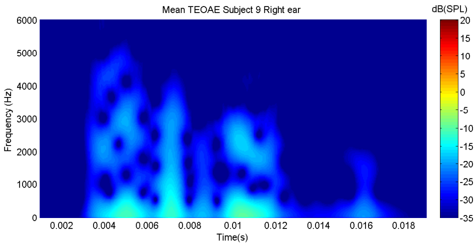
(e) Subject 7 Right Ear

(f) Subject 7 Left Ear

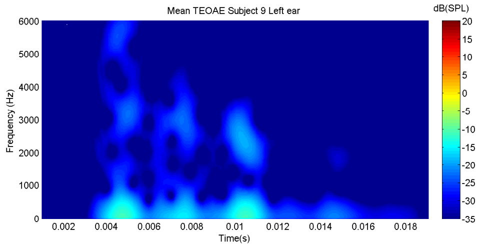
(g) Subject 8 Right Ear

(h) Subject 8 Left Ear

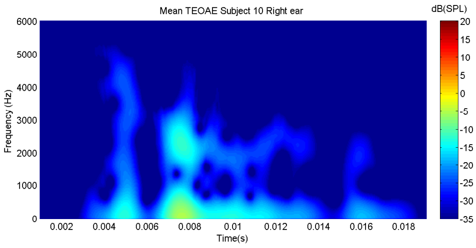
Figure D.8: TEOAE time-frequency analysis for both ears from subjects 4 to 8 of the control population. The right ear is presented on the right side and the left ear on the left side.



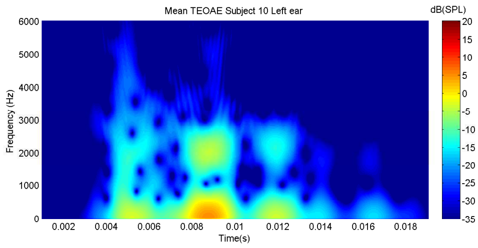
(a) Subject 9 Right Ear



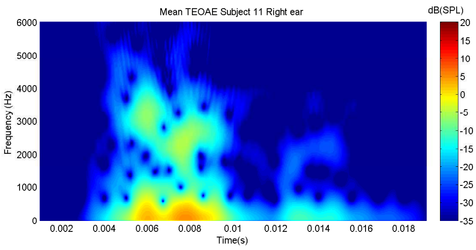
(b) Subject 9 Left Ear



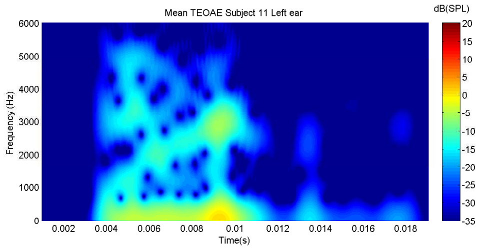
(c) Subject 10 Right Ear



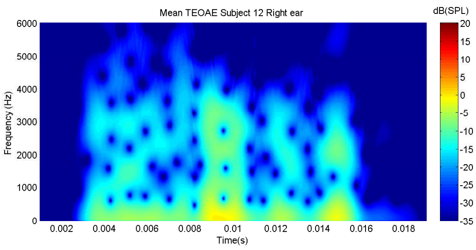
(d) Subject 10 Left Ear



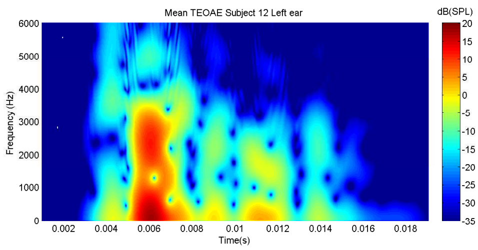
(e) Subject 11 Right Ear



(f) Subject 11 Left Ear

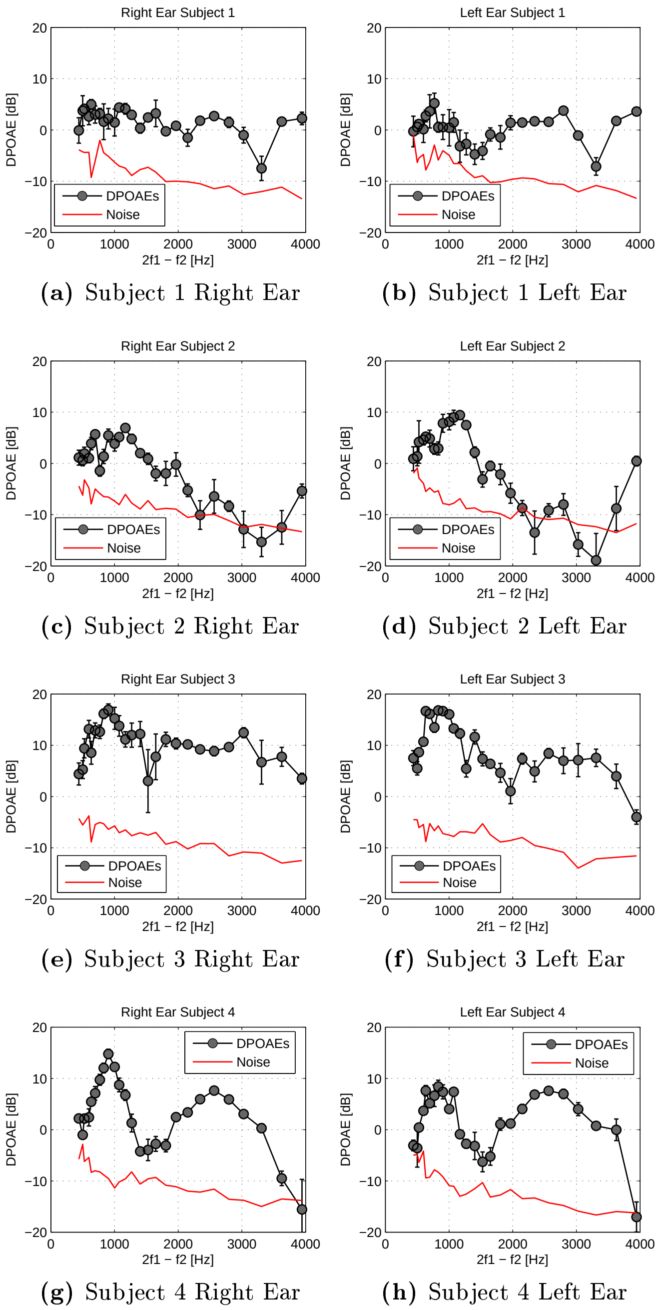


(g) Subject 12 Right Ear



(h) Subject 12 Left Ear

Figure D.9: TEOAE time-frequency analysis for both ears from subjects 8 to 12 of the control population. The right ear is presented on the right side and the left ear on the left side.



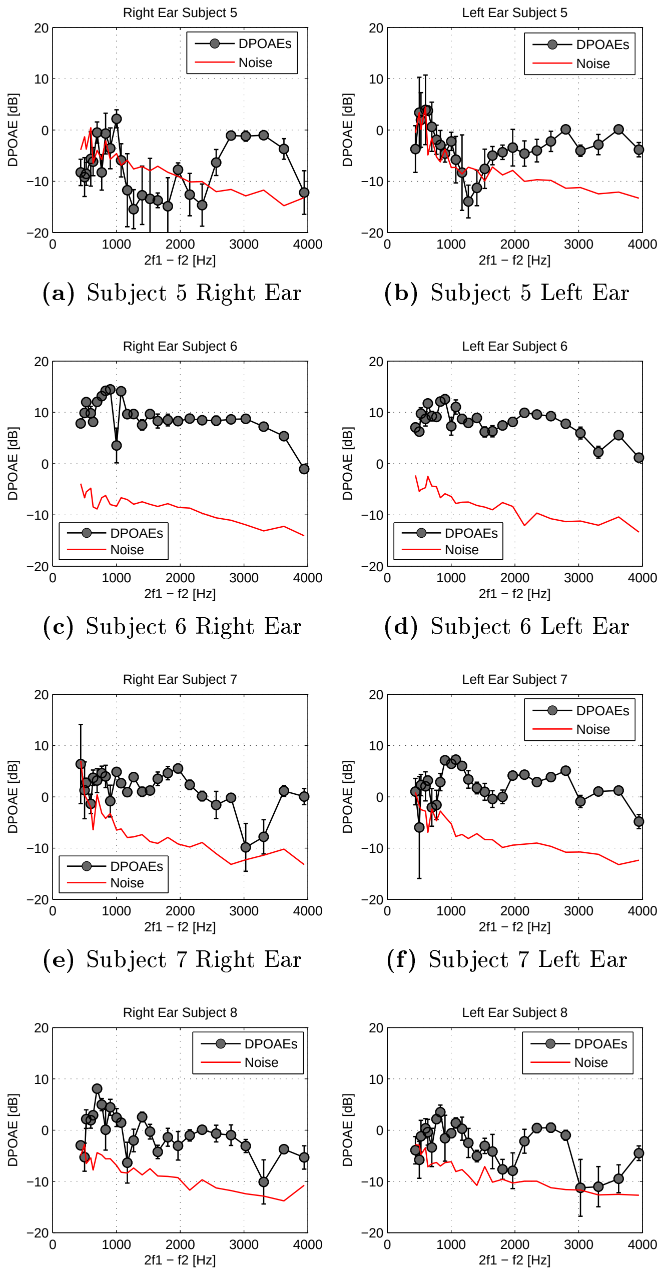
(a) Subject 1 Right Ear (b) Subject 1 Left Ear

(c) Subject 2 Right Ear (d) Subject 2 Left Ear

(e) Subject 3 Right Ear (f) Subject 3 Left Ear

(g) Subject 4 Right Ear (h) Subject 4 Left Ear

Figure D.10: Mean DPOAEs for both ears from subjects 1 to 4 of the control population. The noise floor is also depicted.



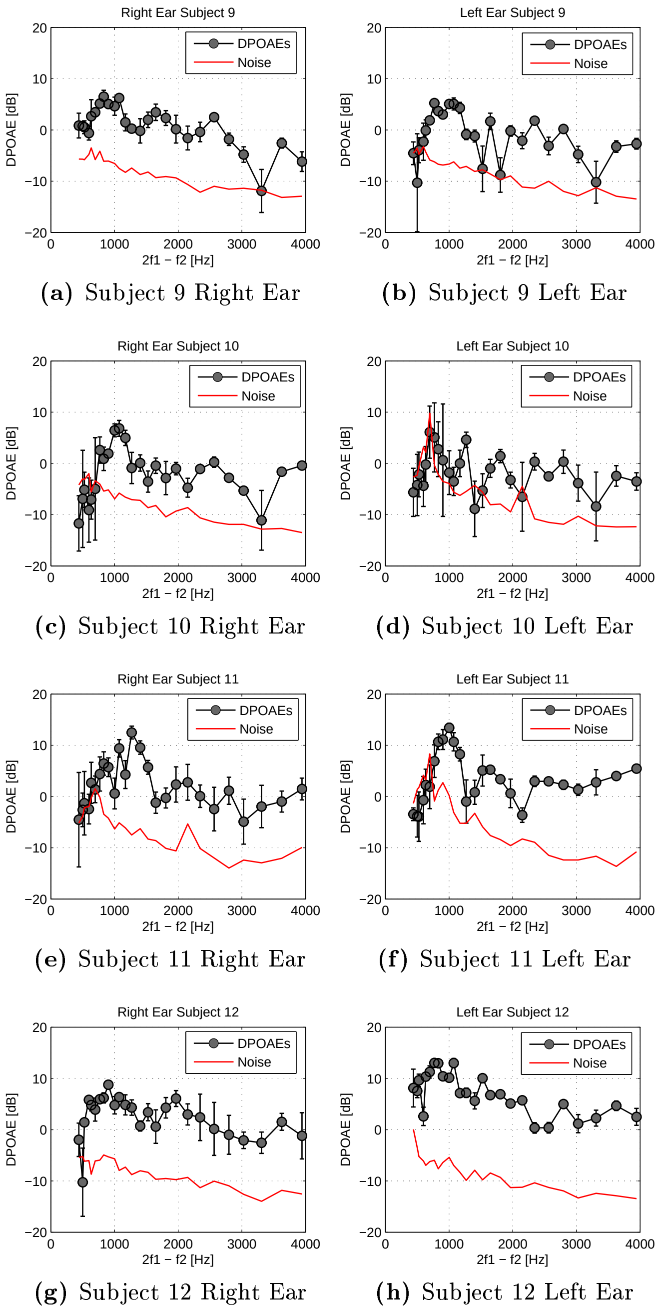
(a) Subject 5 Right Ear (b) Subject 5 Left Ear

(c) Subject 6 Right Ear (d) Subject 6 Left Ear

(e) Subject 7 Right Ear (f) Subject 7 Left Ear

(g) Subject 8 Right Ear (h) Subject 8 Left Ear

Figure D.11: Mean DPOAEs for both ears from subjects 4 to 8 of the control population. The noise floor is also depicted.



(a) Subject 9 Right Ear

(b) Subject 9 Left Ear

(c) Subject 10 Right Ear

(d) Subject 10 Left Ear

(e) Subject 11 Right Ear

(f) Subject 11 Left Ear

(g) Subject 12 Right Ear

(h) Subject 12 Left Ear

Figure D.12: Mean DPOAEs for both ears from subjects 9 to 12 of the control population. The noise floor is also depicted.

Appendix **E**

OAEs Measurements for Musicians

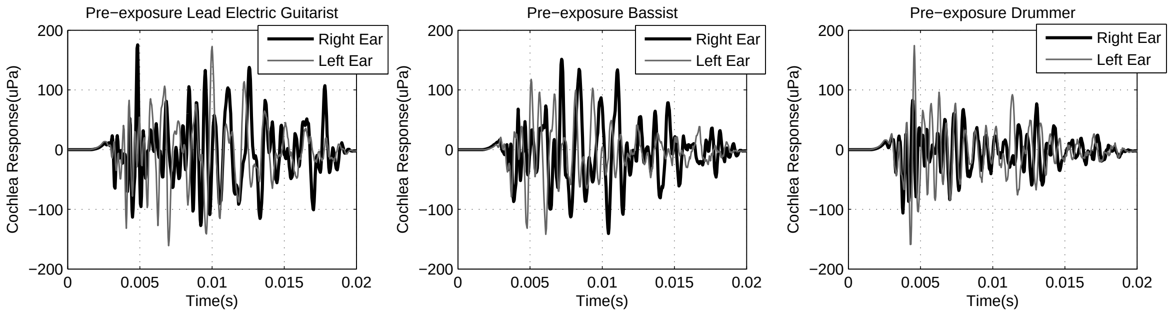
This appendix is to provide all TEOAEs and DPOAEs for the individual musicians. The procedure followed to perform the measurements is stated in appendix D. In consequence, only the results are presented.

TEOAEs for Individual Musicians

Only the pre-exposure results regarding TEOAE waveforms of the musicians are depicted in figure E.1 since the comparison between pre-exposure and post-exposure measurements is considered to be covered in chapter 9 with the time-frequency analysis. Nevertheless, the TEOAE waveforms are consider of interest to evaluate the individual differences.

In light of the results, noticeable differences are found for the individuals. The drummer reported considerable lower amplitudes than the remaining musicians. The lead electric guitarist's TEAOE waveform reflects a vibration along the whole BM, even at the apex part. Both ears present a similar TEOAE waveform pattern for every musician.

SNR Analysis Each TEAOE frequency response has been analysed in terms of its SNR in table E.1 to find out the frequency range where a TEOAE can be considered reliable and therefore, not affected by the noise floor. The most sensitive frequencies in terms of hearing has been analysed, meaning 1000, 2000, 3000 and 4000 Hz. The



(a) Lead electric guitarist **(b)** Bassist **(c)** Drummer

Figure E.1: TEOAE waveforms obtained for the three musicians. The thick black line represents the right ear, whilst the thin grey line symbolise the left ear.

reproducibility between the even and odd waveforms recorded is also presented for those frequency bands. The data marked with the symbol "xx" means that the SNR found is negative, and thereby, negligible. The majority of the responses showed high SNR at both 1000 and 2000 Hz, but the recordings are affected by the noise from 3000 Hz upwards. Only the lead electric guitarist reported high SNR at 3000 Hz.

			1000 [Hz]		2000 [Hz]		3000 [Hz]		4000 [Hz]	
			SNR[dB(SPL)]	Rep.[%]	SNR[dB(SPL)]	Rep.[%]	SNR[dB(SPL)]	Rep.[%]	SNR[dB(SPL)]	Rep.[%]
Musician	Meas.	Ear								
L.e. guitarist	Mean pre-exp.	R	13.3	94.7	14.5	96.2	5.4	77	0	52
		L	13.6	95.2	6.9	82	10.7	91	xx	27.25
	10min	R	12	94	10.6	92	3.6	69	xx	32
	16min	R	11.7	93	9.7	90	2.4	63	xx	0
	40min	R	11.1	92	12	94	2.1	62	xx	33
	46min	R	10.7	92	10.3	91	4.3	72	xx	41
	11min	L	13.4	95	4.2	72	9	88	xx	0
	20min	L	14.7	96	6.6	81	7.6	85	xx	0
	43min	L	14	96	6.9	83	10	90	xx	47
	50min	L	13.3	95	7.1	83	7.8	85	2.2	61
Bassist	Mean pre-exp.	R	11.4	92.7	8.5	87	xx	33	1.2	56
		L	6.3	80.5	10	90.2	0.7	53.2	xx	18.5
	10min	R	10	91	2.7	64	xx	40	xx	0
	15min	R	8.7	88	3.4	68	xx	36	xx	0
	41min	R	7.2	84	4.2	72	xx	0	xx	31
	52min	R	7.6	85	2.4	63	xx	0	xx	0
	12min	L	5.9	79	8.4	87	xx	38	xx	0
	19min	L	4.3	73	8.2	87	xx	0	xx	0
	49min	L	5.4	77	9.5	89	xx	34	xx	0
	70min	L	5.8	79	7.3	84	2.2	62	xx	40
Drummer	Mean pre-exp.	R	7	83	10.3	91	0.1	49.7	xx	39.5
		L	8	85.5	13.9	95.2	1.2	56	xx	32.7
	10min	R	9	88	9.7	90	2	61	xx	0
	16min	R	7.5	85	8	86	0.8	54	xx	0
	40min	R	6.7	82	8.4	87	0.5	52	xx	32
	46min	R	6	79	10.5	91	xx	0	xx	0
	13min	L	10.7	92	13	95	xx	46	xx	43
	18min	L	5.6	78	13.1	95	1.3	57	xx	0
	42min	L	4.6	74	12.7	95	xx	42	xx	0
	49min	L	5.4	77	14.8	96	xx	42	xx	0

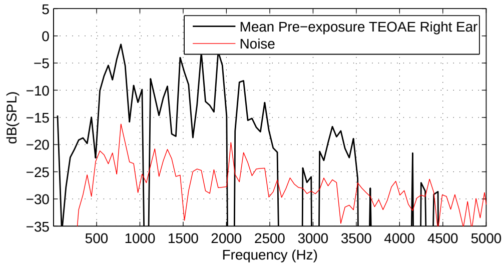
Table E.1: SNR and reproducibility between even and odd sweeps provided by ILO88 software of the musicians' TEOAE recordings before and after rehearsal. They are calculated at 1000, 2000, 3000 and 4000 Hz.

For a visual inspection of the individual TEOAE frequency responses obtained before and after the exposure, figures E.2, E.3, E.4, E.5, E.6 and E.7 have been included. But no individual analysis is reported since the TEOAE shifts for the musicians have been fully covered with the TEOAE time-frequency analysis.

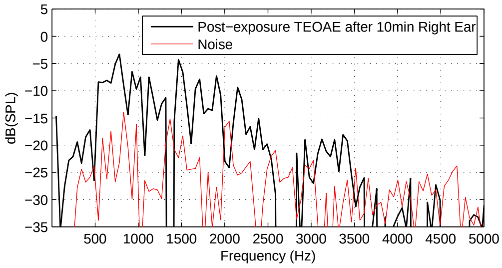
DPOAEs for Individual Musicians

Pre-exposure DPOAEs are presented in figure E.8 for every musician's ears. The standard deviation between teh 4 repetitions is also presented. The average noise floor is shown with red colour.

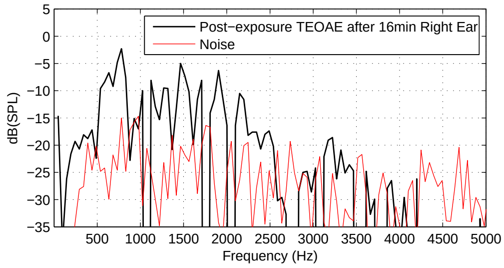
Moslty DPOAEs present amplitudes from 0 to 10 dB for the frequency range between 1000 and 2000 Hz for the three musician, but the drummer reported less amplitudes



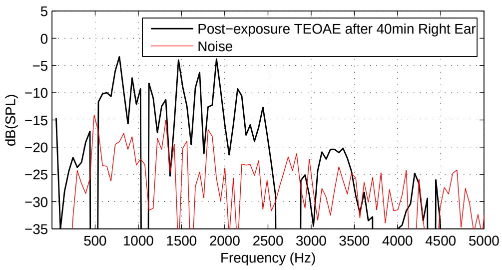
(a) Pre-exposure



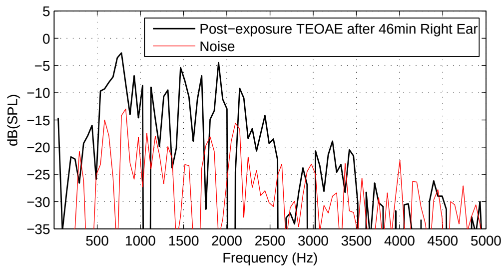
(b) Post-exposure after 10min



(c) Post-exposure after 16min

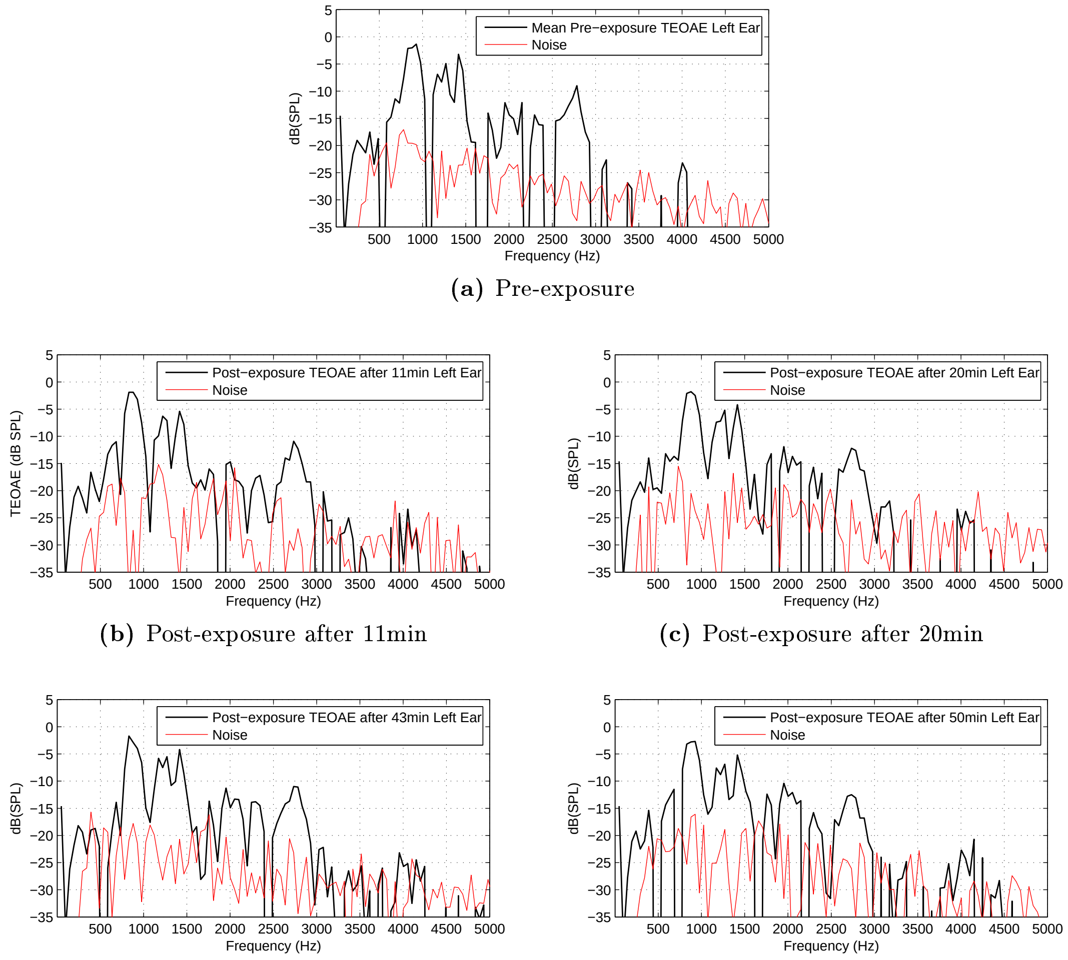


(d) Post-exposure after 40min



(e) Post-exposure after 46min

Figure E.2: TEOAE frequency responses for the lead electric guitarist's right ear before and after the exposure for the times scheduled in the experiment. The black line represents the TEOAEs whereas the red line symbolises the noise floor obtained during the recording.



(a) Pre-exposure

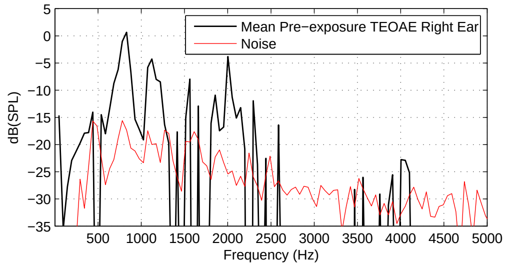
(b) Post-exposure after 11min

(c) Post-exposure after 20min

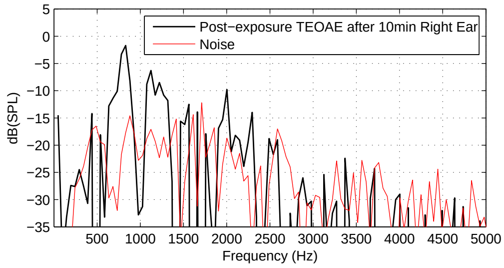
(d) Post-exposure after 43min

(e) Post-exposure after 50min

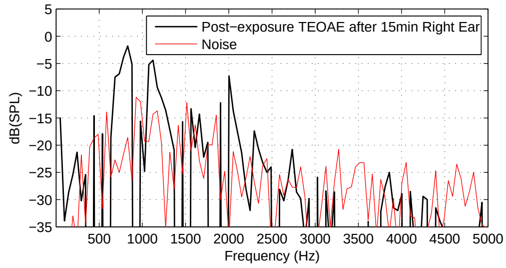
Figure E.3: TEOAE frequency responses for the lead electric guitarist's left ear before and after the exposure for the times scheduled in the experiment. The black line represents the TEOAEs whereas the red line symbolises the noise floor obtained during the recording.



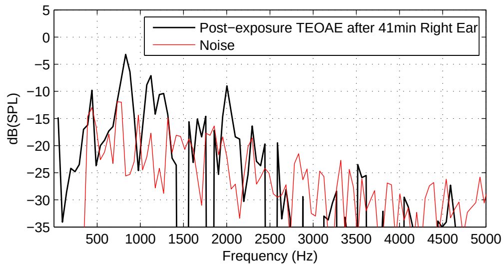
(a) Pre-exposure



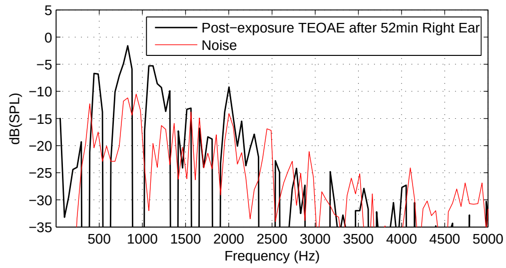
(b) Post-exposure after 10min



(c) Post-exposure after 15min

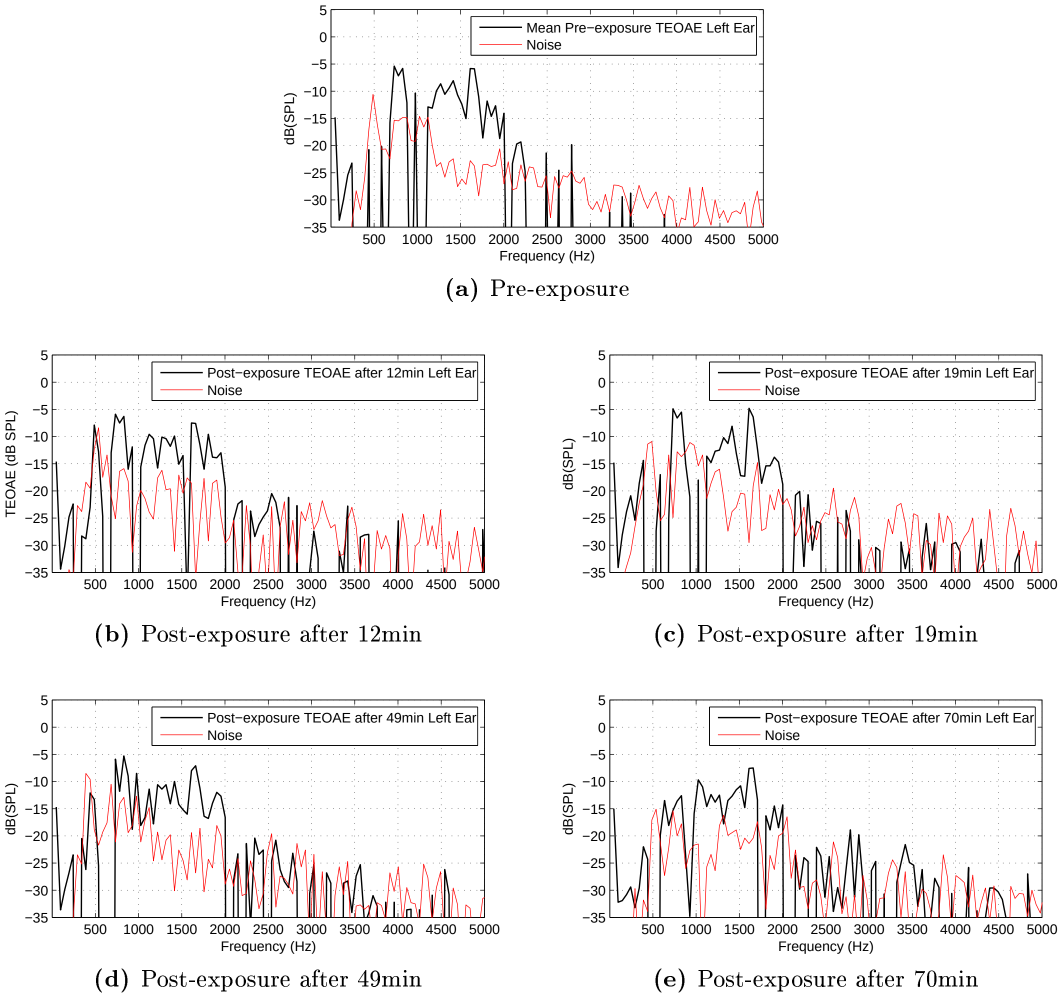


(d) Post-exposure after 41min



(e) Post-exposure after 52min

Figure E.4: TEOAE frequency responses for the bassist's right ear before and after the exposure for the times scheduled in the experiment. The black line represents the TEOAEs whereas the red line symbolises the noise floor obtained during the recording.



(a) Pre-exposure

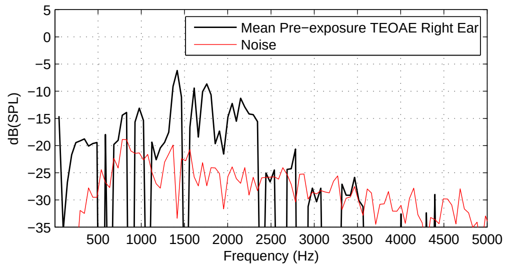
(b) Post-exposure after 12min

(c) Post-exposure after 19min

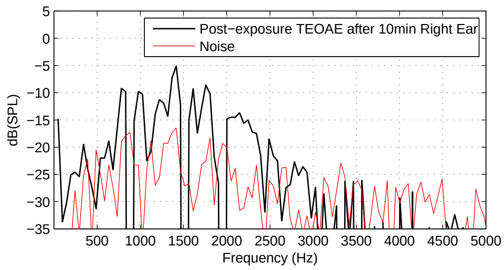
(d) Post-exposure after 49min

(e) Post-exposure after 70min

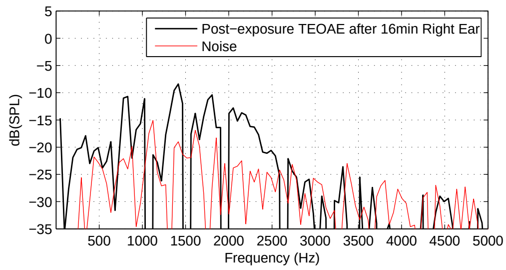
Figure E.5: TEOAE frequency responses for the bassist's left ear before and after the exposure for the times scheduled in the experiment. The black line represents the TEOAEs whereas the red line symbolises the noise floor obtained during the recording.



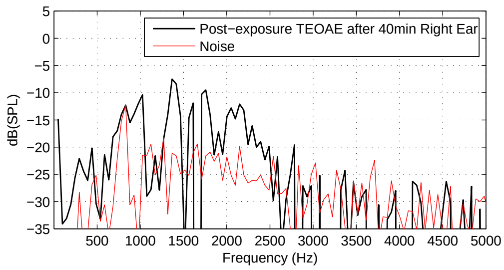
(a) Pre-exposure



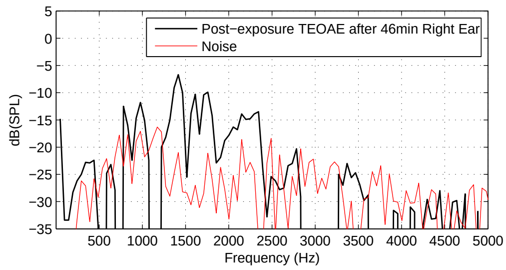
(b) Post-exposure after 10min



(c) Post-exposure after 16min

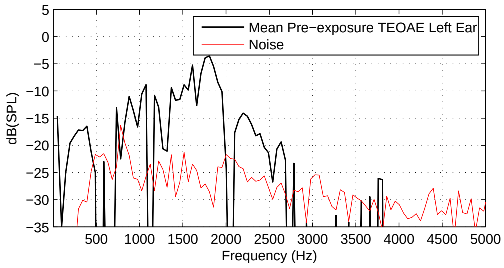


(d) Post-exposure after 40min

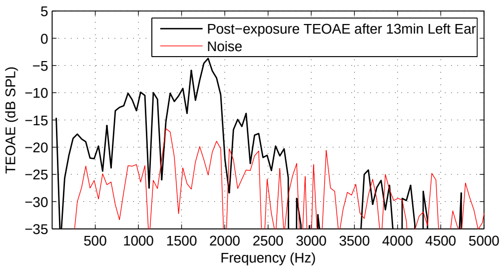


(e) Post-exposure after 46min

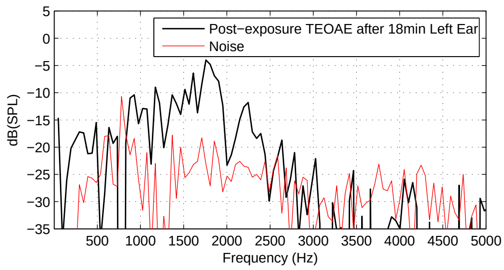
Figure E.6: TEOAE frequency responses for the drummer's right ear before and after the exposure for the times scheduled in the experiment. The black line represents the TEOAEs whereas the red line symbolises the noise floor obtained during the recording.



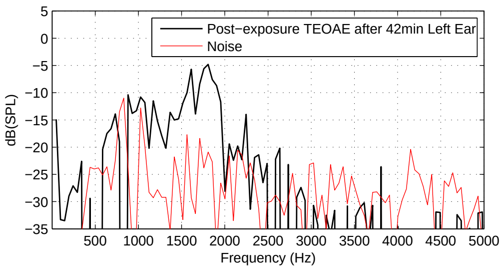
(a) Pre-exposure



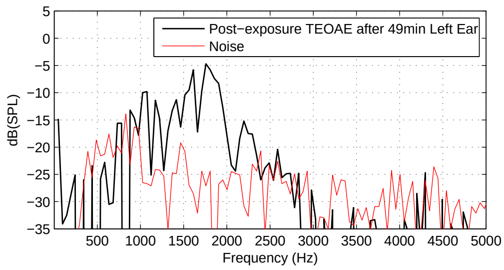
(b) Post-exposure after 13min



(c) Post-exposure after 18min

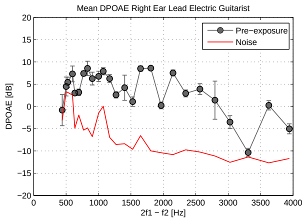


(d) Post-exposure after 42min

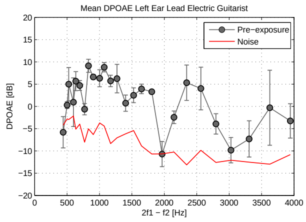


(e) Post-exposure after 49min

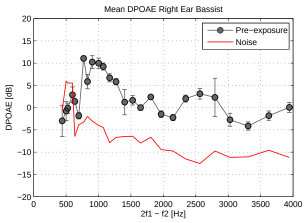
Figure E.7: TEOAE frequency responses for the drummer's left ear before and after the exposure for the times scheduled in the experiment. The black line represents the TEOAEs whereas the red line symbolises the noise floor obtained during the recording.



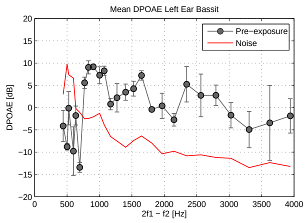
(a) Guitarist right ear



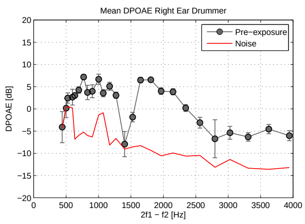
(b) Guitarist left ear



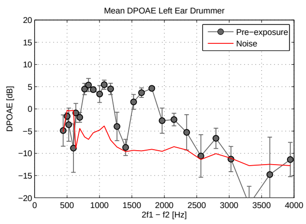
(c) Bassist right ear



(d) Bassist left ear



(e) Drummer right ear



(f) Drummer left ear

Figure E.8: Mean pre-exposure DPOAE with standard deviation between repetitions for every musician's ears. The average noise floor is also depicted with red colour.

and the measurements are affected by the noise floor. This matches with the results obtained for TEOAEs. The lead electric guitarist shows better DPOAEs on the right ear, whereas the bassist's left ear reported remarkable DPOAEs for frequencies above 2500 Hz. No similarity between ears can be concluded caused the noise floor disturbed the measurements at some DP frequencies.

Appendix F

Exposure Level Calculation

Purpose

This measurement report describes the procedure followed for recording the SPL at the concert and at the rehearsal place.. The purpose is to obtain the equivalent continuous A-weighted sound pressure level (LAeq) during the exposure time by means of a sound level meter to calculate the occupational noise exposure level according to [ISO 1999, 1990] afterwards.

Room Overview

The measurements took place in different rooms depending on the event:

- Concert event: in the *StudentHuset*, Gammel Torv 10, 9000 Aalborg, Denmark. The group band who was playing during the measurements is called *Who made who* from Denmark.
- Rehearsal place for musicians: both music rehearsal rooms in the *Huset Café*, Hasserisgade 10, 9000 Aalborg, Denmark. The musicians who were playing during the measurements belongs to the music group called *Ottocovariance* from Spain.

Equipment

The equipment used is listed in table F.1.

Item	Type	AAU LBNR
Sound Level Meter	B&K 2238 Mediator	33948-00
Measurement Analyzer	B&K Noise Explorer 7815	–
Calibrator	B&K 4231	33691
Stand	Trypod	33948

Table F.1: Measurement equipment for recording and analysing the SPL in both leisure activities.

Measurement Method

Measurement System

The sound level meter used during the measurements is the *2238 Mediator* provides by Brüel & Kjær, which complies with [IEC 61672-1, 2002] and [IEC 61672-2, 2003]. The Mediator is fit together with a pre-polarized free-field 1/2" condenser microphone type 4188.

It allows to measure a number of individual time periods (normally around 1 s) as well as an overall value of LAeq during the exposure time. Further details about this device can be found in the enclosure CD.

Measurement Analyser

After the measurements, the Mediator is connected to a PC for transferring the data which are analysed by means of the *Noise Explorer 7815* software provides by Brüel & Kjær.

Measurement Procedure

Equipment Setup

The location of the Mediator during the SPL recording for both events, at the concert and at the rehearsal place, are shown in figure F.1 and figure F.2 respectively.

Concert Event Setup

The Mediator is placed 5.25 m from the stage and the height is 1.68 m from the floor. The distance form the closest wall is 1.4 m to ensure that the recordings are not disturbed by the wall.

Rehearsal Place Setup

The Mediator is placed 1.55 m height. The distance form the closest wall is 1.1 m to ensure that the recordings are not disturbed by the wall.

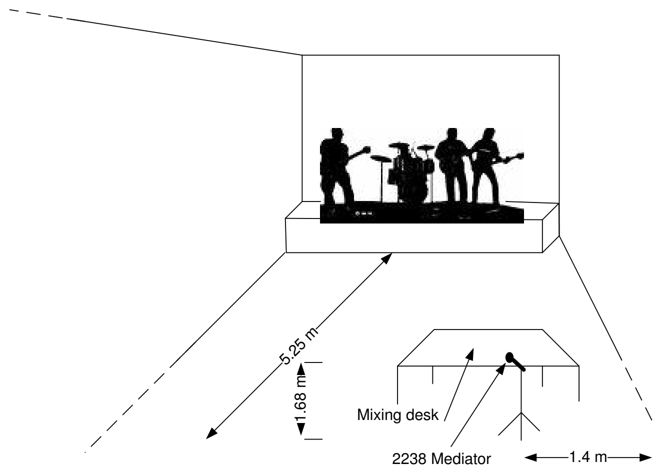


Figure F.1: Location of the Mediator during the *Who made Who* concert at the *StudentHuset* for recording the SPL. The Mediator is placed 5.25 m from the stage and the height is 1.68 m from the floor, being the microphone of the Mediator located at the position normally occupied by the head of a person, being absent.

Procedure

Before starting the measurements, the Mediator is calibrated to a free-field level of 93.8 dB using the B&K 4231 calibrator according to International Electrotechnical Commission standards.

The Mediator is recording continuously the LAeq during the exposure time using the main settings described in table F.2.

Setting	Characteristics
Amplitude	RMS
Bandwith	Broadband
Frequency weighting	A
Range	60 - 140 dB
Resolution	1 s
Sound incidence	Random (diffuse-field)

Table F.2: Mediator measurement setup used when recording measurements.

After recording the measurements, the data are transferred to a PC to be analysed.

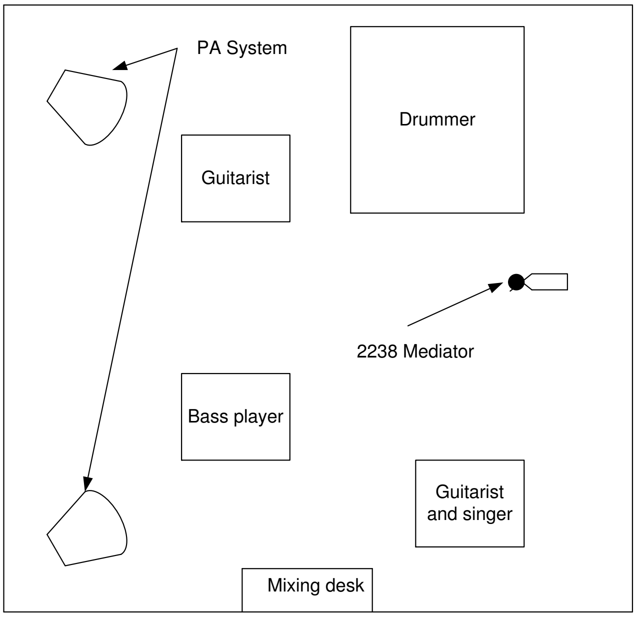


Figure F.2: Location of the Mediator during the measurements in the rehearsal place at the *Huset Café* for recording the SPL.

Enclosure: CD

A CD-ROM is attached as enclosure. This CD-ROM contains information to be studied if the reader desires additional insight into the different topics of the report.

Contents of the CD:

- Project Report (PDF format).
- Data sheets.
- OAEs data obtained by ILO96 Otodynamics.