TTT4250 - Acoustical Measurement Techniques

Laboratory Exercise 5

Hearing

performed by

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Summary

This report examines the hearing level of 9 different people. The hearing level is tested using two different methods, the pure tone audiometry (PTA) and the New Early Warning Test (NEWT). NEWT is a quick and automated test to determine hearing level and this report will compare it to PTA which is the standard for measuring hearing level today. With NEWT it is also possible to test the hearing level with hearing protection devices (HPD), such as foam earplugs or earmuffs, and determine the attenuation of the HPDs. The attenuation is how much the HPD dampens different frequencies and this is calculated using the hearing level without HPDs and comparing it to the hearing level with HPDs. This makes it possible to check whether the HPD fullfill the requirements in the standards they follow and also to look at the frequency response of the HPDs, which affects how the dampened sound is perceived.

The NEWT is found to be a good indication of potential hearing loss when both ears are affected, but gives results that are different from the PTA, which could be due to many reasons, e.g. a dribbling noise in the room where NEWT was conducted or that the PTA was performed by unqualified persons. However, if NEWT is conducted often it may work well as an indicator for when a PTA is neccesary. One weakness of NEWT is that it is unable to test the two ear separately. The consequence of this is that it could hide hearing loss in one ear, as the other is able to compensate. This is very unfortunate and if one should use NEWT as a preventive measure to avoid hearing damage it must be supplied with an initial PTA and maybe PTAs regularly. It is therefore debatable if NEWT is suitable for this use.

The attenuation for the different HPDs was not linear in the frequency range, and had the largest attenuation for higher frequencies, whcih is where the hearing is most sensitive. The sum of the average attenuation for the foam earplugs are 44.1 dB and the sum of the average attenuation for the earmuffs are 46.3 dB. The expanded uncertainty was calculated for the attenuation of the HPDs and found to be 8.4 dB for earplugs and 9.1 dB for earmuffs. A possible source of error for the measurement of the attenuation is that the foam earplugs may not have been correctly inserted in the ear. It seems that for most frequencies the earmuffs give the highest attenuation.

Contents

1 Introduction

This report examines the hearing level of 9 different people using both Pure Tone Audiometry (PTA) and New Early Warning Test (NEWT). This will be compared in an attempt to see if NEWT is a viable alternative to PTA, as NEWT is quicker and easier to conduct and could potentially make it possible for the general population to get their hearing tested more often to uncover starting hearing loss early. The hearing threshold changes naturally as we age and different frequencies are very differently affected. Testing regularly with NEWT would be more relevant for people who are exposed to high sound pressure levels often and are in risk for hearing damage, as opposed to a way to discover natural changes, but it could also be used for this.

Over 5% of the world's population require rehabilitation for disabling hearing loss and it is estimated that by 2050 over 700 million people will have disabling hearing loss, which is approximately 10 % of the population [1]. Hearing damage is irreversible and can also be accompanied by tinnitus, which manifests as a constant, often high frequency, beeping noise. There is no treatment available that can cure tinnitus. There are a few things that is possible to do to relieve symptoms, e.g. habituating, which means learning to live with the condition and learn to block it out of the concious part of the brain, or masking devices that sit inside the ear and produce constant low level white noise that can mask some of the tinnitus symptoms, [2].

The attenuation of two heaing protection devices (HPD), foam earplugs and earmuffs, will also be calculated, using the NEWT method. This is useful in order to check that the HPDs fulfill the requirements of the standard they are made after. HPDs are also the easiest way to prevent hearing damage if a person is exposed to high sound pressure levels. The higher the sound pressure level, the less exposure time is needed before hearing damage occurs. Situations that can cause hearing loss is e.g. night clubs, concerts, riding motorcycles, construction sites, etc..

This report will discuss the necessary theory of hearing and give some numbers on what qualifies as hearing damage, theory and method of the PTA and NEWT, as well as the results from the tests and the uncertainty of the results, and also a discussion of these results before concluding with whether NEWT is a good alternative to PTA.

2 Theory

2.1 Hearing system and hearing damage

The human hearing is a very efficient transducer that changes air pressure variations into a neural-electrical signal which the brain translates as music, speech, noise, etc. [3]. The ear tramsits three basic physical properties of the sound waves, which is the frequency, time duraction and sound level. These are considered the fundamental proterties of a sound wave, and it is possible to reconstruct the sound from these properties.

The ear has three different part, as shown in Figure 2.1, the external ear, the middle ear and the inner ear.

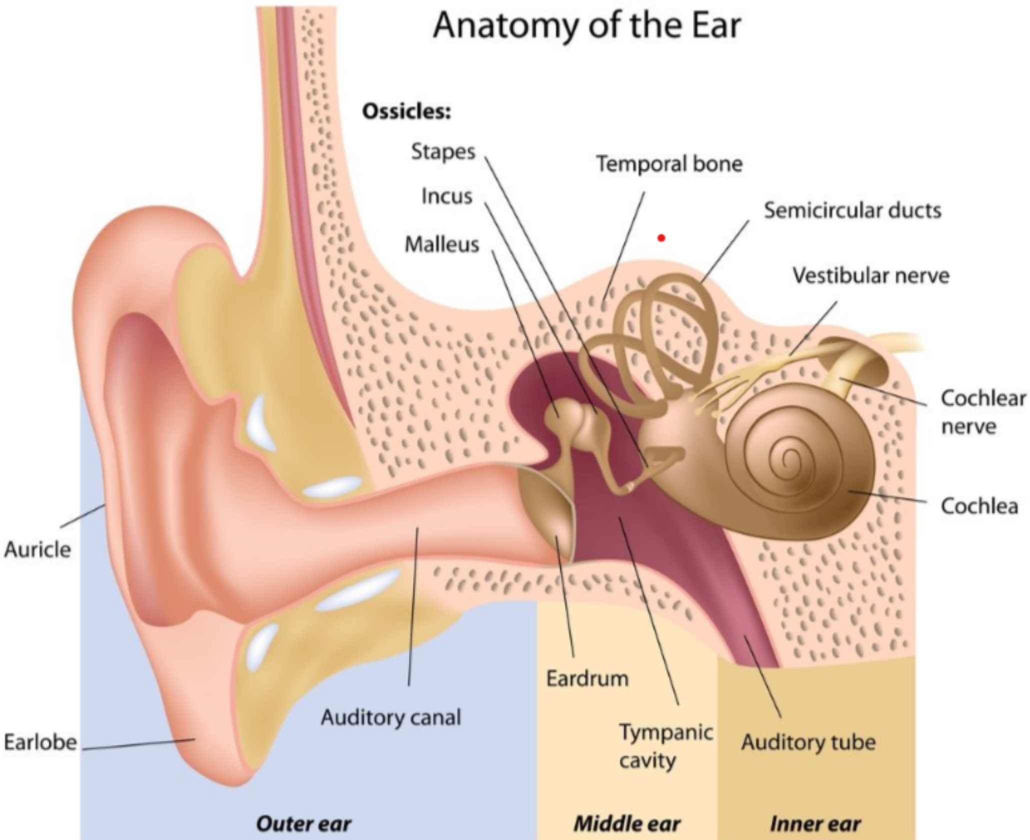


Figure 2.1: Illustration of the anatomy of the ear, [3]

The external ear consist of theauricle, which helps capture sound in the environment and the ear, or auditory, canal, which channels the sound to the eardrum. The eardrum separates the outer and middle ear. The middle ear consists of three bones, the malleus, incus and stapes. The inner ear consists of the auditory tube, also called the eustachian tube, which is connected to balance, the cochlea, which is a complex structure and containt important sensory receptors, the hair cells.

There are two types of hair cells, the inner hair cells and the outer hair cells. The inner hear cells translates the sound vibration into electric charges. When these hairs are bent by the variations in the air pressure it induces a neural-electronical potential that activates a neural response in the auditory nerve that connect the hair cells to the brainstem. The outer hair cells serve a different purpose. When the hairs are bent, the size of the outer hair cells change, especially the length of the hairs. This helps amplify the low-level sounds that enter the cochlea. The cochlea reacts differently to different frequencies. High frequencies cause a movement in the base of the cochlear and lower frequencies work at the apex. This frequency tuning is related to the motility of the outer hair cells.

The normal hearing range is a frequency range of 20 Hz-20 kHz with a dynamic range of up to 120 dB re 20 μPa, where the hearing threshold of 20 μPa is considered 0 dB. As mentioned the ear responds differently for different frequencies and this is shown in Figure 2.2 , which depicts normal hearing. From this it is clear that the sound pressure level must be much higher for lower frequencies, in order for a person with normal hearing to be able to hear it.

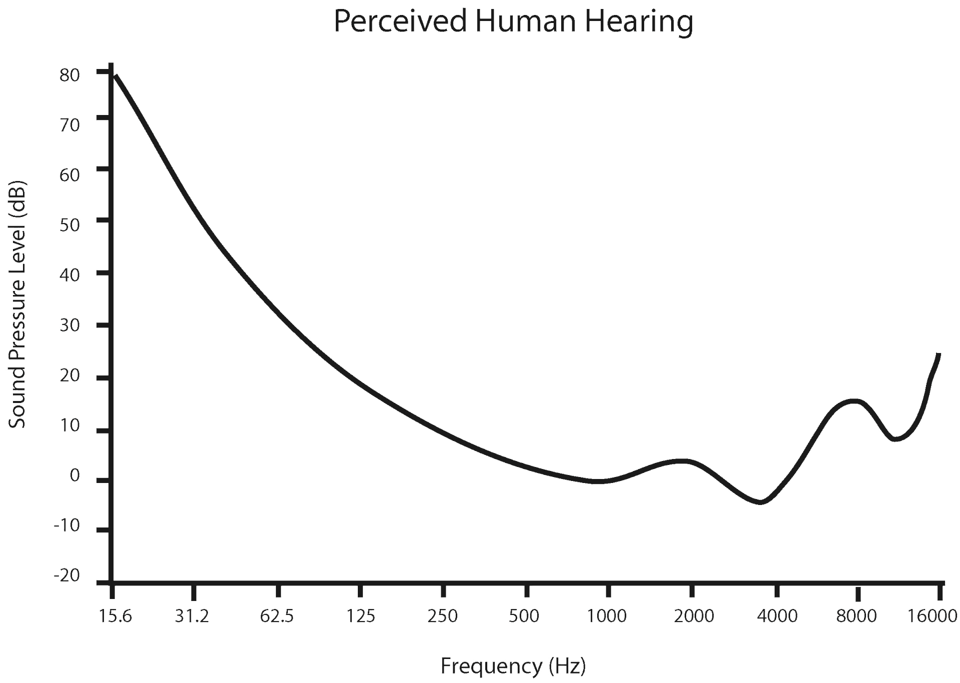


Figure 2.2: Perceived human hearing for different frequencies, [3].

Hearing can be described by hearing level. The threshold for the frequencies will be moved according to when an individual can detect different frequencies. So if a sound at 500 Hz is detected at 50 dB, the hearing loss will be 40 dB, as the normal threshold for this is 10 dB, as shown in Figure .

The World Health Organization defines normal hearing between 0 and +20 dB in hearing threshold [1]. ANSA defines hearing loss from this scale, shown in Table 2.1.

Degree of hearing loss	Hearing loss [dB]
Normal	-10 to 15
Slight	16 to 25
Mild	26 to 40
Moderate	41 to 55
Moderately severe	56 to 70
Severe	71 to 90
Profound	91+

Table 2.1: Degrees of hearing loss, [4]

Another way of describing hearing is by the equal loudness curves, as shown in Figure 2.3.

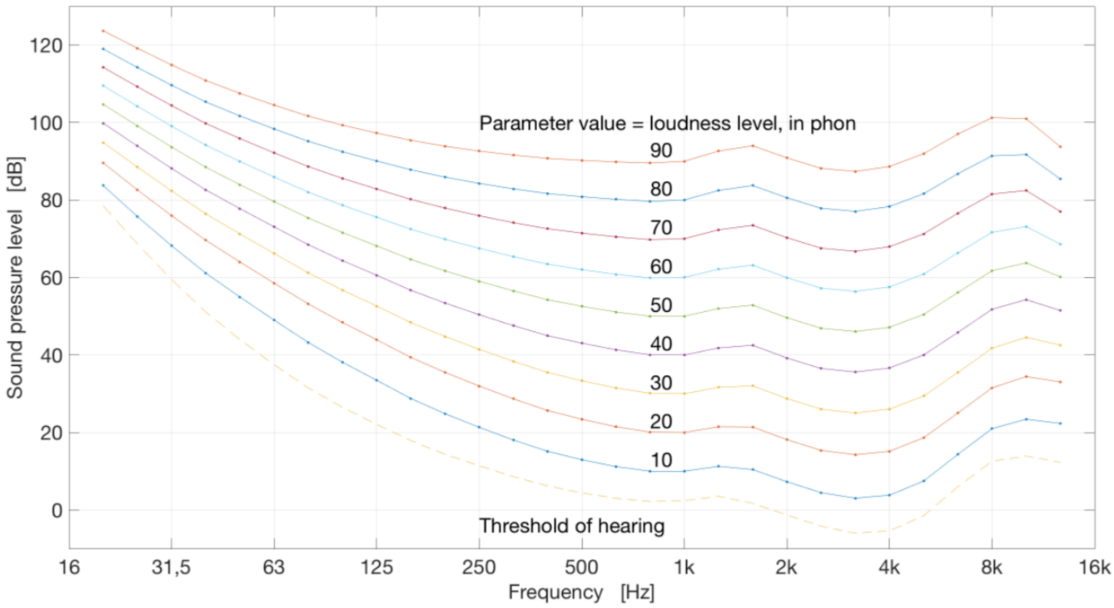


Figure 2.3: Equal loudness plots showing the necessary sound pressure level to achieve a certain loudness of a pure tone, which is Phon, [3].

These curves attempts to shown what sound pressure levels that are necessary for different frequencies for them to sound equally loud to the listener. The reference frequency is chosen to be 1 kHz. The unit of loudness for pure tones are Phon and corresponds to the sound pressure level at 1 kHz. This means that 60 dB at 125 Hz is perceived as equally loud as 40 dB at 1 kHz. This curve is similar in shape to the hearing level curve, as the ear is less sensitive to lower frequencies and therefore a larger sound pressure level is needed before it appears equally loud to a lower sound pressure level at a higher frequency. Also worth noting is that the hearing threshold corresponds to the curve for 0 Phon.

From both the hearing level curve and the equal loudness it is clear that the human ear is most sensitive for frequencies around 3-4 kHz, and this is because the ear canal has a resonance frequency in this frequency range. In the range 500 - 4000 Hz listeners are able to discriminate between 1 dB in sound level (50 dB and 51 dB) and about half a percentage in tonal frequency (2000 Hz and 2010 Hz) [3].

2.2 Pure Tone Audiometry (PTA)

This technique is considered the best way of determining of hearing sensitivity. The stimulus is a pure tone that has a duration of 500 ms, followed by 4-6 s of silence. Then the sound pressure level is increased from below the first point until a response is given from the listener. The the strength of the stimulus is reduced until there is no response from the listener. The ascent and descent is repeated three or more times. The hearing threshold for the relevant frequency is considered the sound pressure level that is detected 2 out of 3 times, or minimum 2 times if it is repeated more. The ears are tested separately and the frequency range is 500 - 8000 Hz, which corresponds to the frequency range of speech. When the audiometry is finished the resulting graph is called an audiogram. The frequencies are tested at octave intervals, meaning the frequencies are doubled for the next frequency.

The psychometric function is the probablity that the signal is detected given certain stimulus levels, and is shown in Figure 2.4.

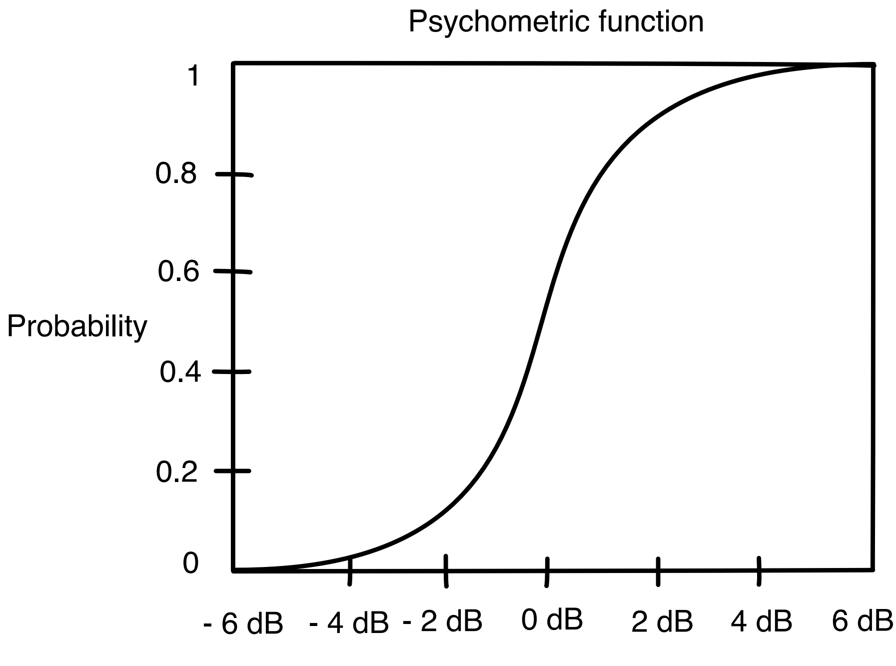


Figure 2.4: Psychometric function, describing the realtionship between probability of detection and stimulus level.

The physchometric function is the error function with a standard deviation of 1.4 over a range of ± 6 dB. The expected hearing threshold is 0 dB and this is where there is a 50 % chance of positive response of the listener.

There are many factors that can affect a person and their response to the test, such as if they listened to loud music earlier that day, is they are tired or sick, if they had a stressful day, etc. All of this could influence their response, and therefore it is a stochastic process and related to a probability of a person answering yes or no. The techinal term for this possible increased hearing threshold is that the hearing threshold has a Temporary Threshold Shift (TSS). This will resolve it self, and is as the name suggests only temporary. It is also possible to get a Permanent Threshold Shift (PTS) which is hearing loss, resulting in higher hearing thresholds, which could be for certain frequencies or only one ear.

The levels in audiometry are expressed as Hearing level, HL, in dB. It is defined so that a hearing level of 0 dB is the sound pressure which is considered the normal hearing threshold, that is the average of just audible pure tones, which corresponds to the 50 % point on the psychometric function, which is valid for large populations between 18 and 25 year olds.

2.3 New Early Warning Test (NEWT)

The New Early Warning Test (NEWT) is an automated method delevoped by SINTEF and NTNU in 2014. It also uses pure tones, but the duration of each signal is 150 ms and 2 signal are used for each instance. It is with raised cosine fade in and out of 10 ms each, with a 150 ms time gap in between [3]. This is done because a simple pure tone has an effect on the tested person and with this type of stimulus the listener seems to give more stable response. The different levels are presented in a randomized order, always approaching the expected hearing threshold using the prior sound pressure level and the psychometric function. The hearing threshold is determined by a maximum likelihood estimation using the psychometric function. The NEWT method is based on using four loud speaker arranged around the listener, and can therefore not test the two ears individually.

The choosing of the first level is shown in Figure 2.5.

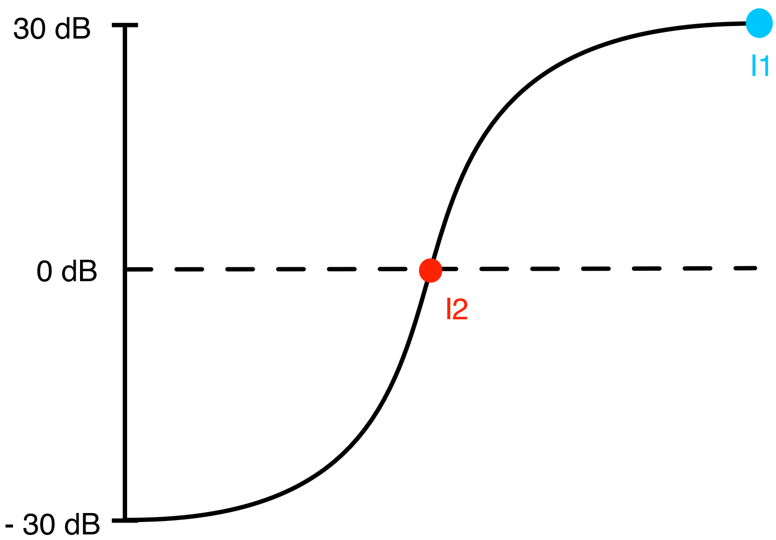
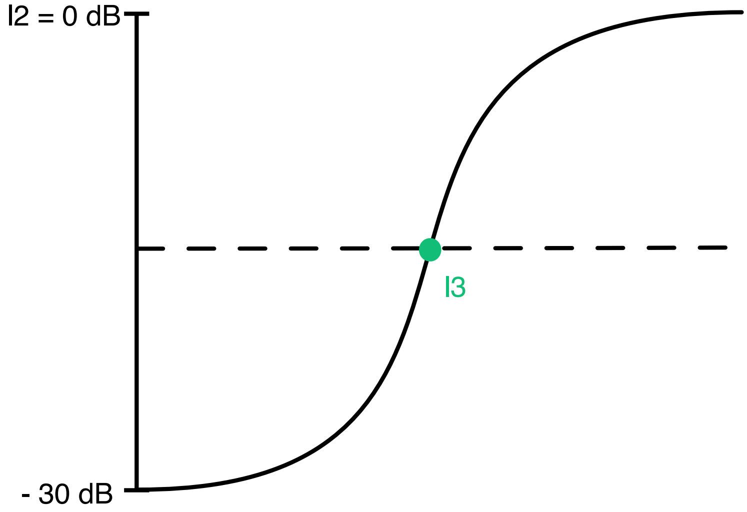
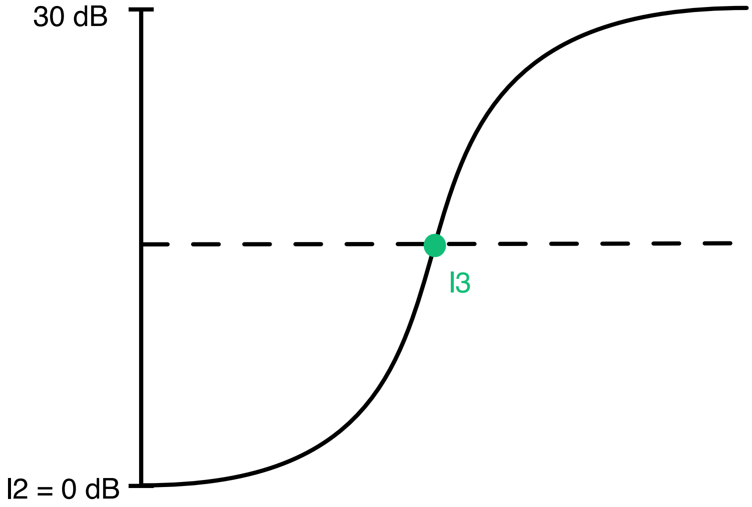


Figure 2.5: This illustrateds how the first level of the NEWT method is chosen. The upper limit is 30 dB and the lower limit is 30 dB, and the first level is chosen to be at 50 % probability on the psychometric function with these upper and lower limitsm, which is 0 dB.

The upper limit is 30 dB and the lower limit is - 30 dB. The first level is 0 dB, which corresponds to 50 % probability of detection, and this is 0 dB. When the test continues it uses the last level to determine the next level. This is shown in Figure 2.6.



(a) If the previous level was heard, the previous level is used as the upper limit for the psychometric function and the lower limit is the same as for the previous test.



(b) If the previous level was not heard, the previous level is used as the lower limit for the psychometric function and the upper limit is the same as for the previous test.

Figure 2.6: How the next level is chosen from the previous level in the NEWT method, [3].

If the last level was detected this will be used as the upper limit for the psychometric function, and the lower limit is the same as for the previous test. If the last level was not heard, it will be used as the lower limit for the psychometric function. The next level will then be the level for which the psychometric function is at 50 % probability.

2.4 Attenuation of hearing protectors (NS-EN 352-2:2002)

Hearing protectors come in many differnet forms, and the two most common are over-the-ear HPDs, often called earmuffs, or in-ear HPDs, earplugs. The earplugs are often made of a form of foam material and must be rolled into a cylindrical form to fit inside the ear canal, and then they expand to fit the ear canal. It is also possible to get molded earplugs, that are molded to fit the ear canal of an individual. The hearing protectors in this lab is made according to the standard NS-EN 352-2:2002 and this states that the minimum attenuation of HPD must be as shown in Table 2.2.

Frequency [Hz]	125	250	500	1k	2k	4k	8k
(M_s- s_f) [dB]	5	8	10	12	12	12	12

Table 2.2: Minimum attenuation according to NS-EN 352-2:2002, [5]. M_s is the mean attenuation data and s_f is the standard deviation measured according to EN 13819-2:2002.

A standardized form of measuring the attenuation of the HPDs are presented in ISO 4869-1:2018. The attenuation can be calulcated as

$$Attenuation = HL_{\text{with HPD}} - HL_{\text{without HPD}}, \tag{2.1}$$

where HL is the hearing level.

For this lab the NEWT method will be used to determine the attenuation, but Equation 2.1 is still valid.

2.5 Expanded uncertainty

For the attenuation of the HPDs the expanded unceratinty should be calculated. The measurements from all groups can be viewed as equivalent repitions that is the source of a type A uncertainty, which is a random unceratinty. The measurements are assumed to follow a normal distrbution [6].

The expanded uncertainty is calculated as follows, [7]. First the experimental standard deviation, $s(h_k)$, is calculated and is defined as

$$s(h_k) = \sqrt{\frac{1}{(n-1)} \sum_{k}^{n} = 1 \left(h_k - \bar{h}\right)^2} \tag{2.2}$$

This is then divided by the square root of the number of samples and multiplied by the coverage factor k. This gives the expanded uncertainty, U, as

$$U = k \cdot \frac{s(h_k)}{\sqrt{n}} \tag{2.3}$$

3 Method and Equipment

The measurements were perfomed at SINTEF's facilities at Strindvegen 4. The premises had permanent setups for both the PTA and NEWT. This lab was perfomed with two participants, and the PTA and NEWT was perfomed for both participants.

3.1 Pure Tone Audiometry (PTA)

An audiometer was used to conduct the PTA. It was calibrated according to ISO 389-1:2017 and was last calibrated 21-01-2020. The listener was turned away from the person conducting the test and the listener was wearing headphones. The setup of the PTA is shown in Figure 3.1.

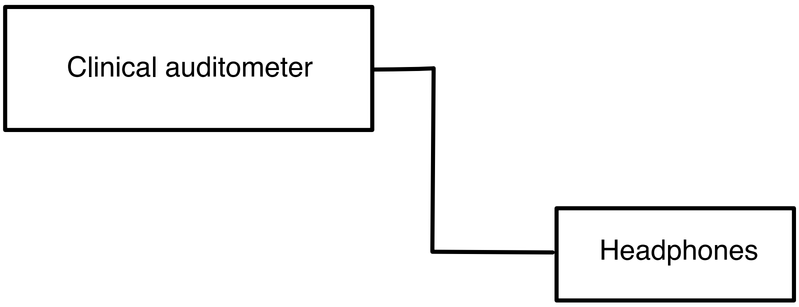


Figure 3.1: Sketch of the setup for the PTA. The headphones were used by the listener and the listener was turned away from the audiometer as to avoid them knowing when the noises were produced.

The first stimulus given was at 1 kHz and 40 dB. If the first sound pressure level was detected, the next sound pressure level was 15 or 20 dB weaker. If this level was not reported, i.e. not audible to the listener, the next level was 10 dB stronger. As the test continues it is conducted so that if the current level was reported as audible, the next level will be 5 dB lower and if it is not reported as audible the next level is 10 dB louder. This step is repeated until a sound pressure level is reached where it has been played at least three times and reported as audible at least two times. The lowest level that is reported as audible two times, out of three, is considered as the hearing threshold for that specific frequency. Furthermore the frequencies 2 kHz, 4kHz, 8 kHz and 500 Hz are tested in the same manner, in that specific order.

This is done for both ears and an audiogram, a curve of the thresholds per frequency, can be calculated.

3.2 New Early Warning Test (NEWT)

The listener is put inside a room with four loud speakers around them. The loud speakers are placed in such a manner that all of them has equal distance to the listener. A sketch of this is showed in Figure 3.2.

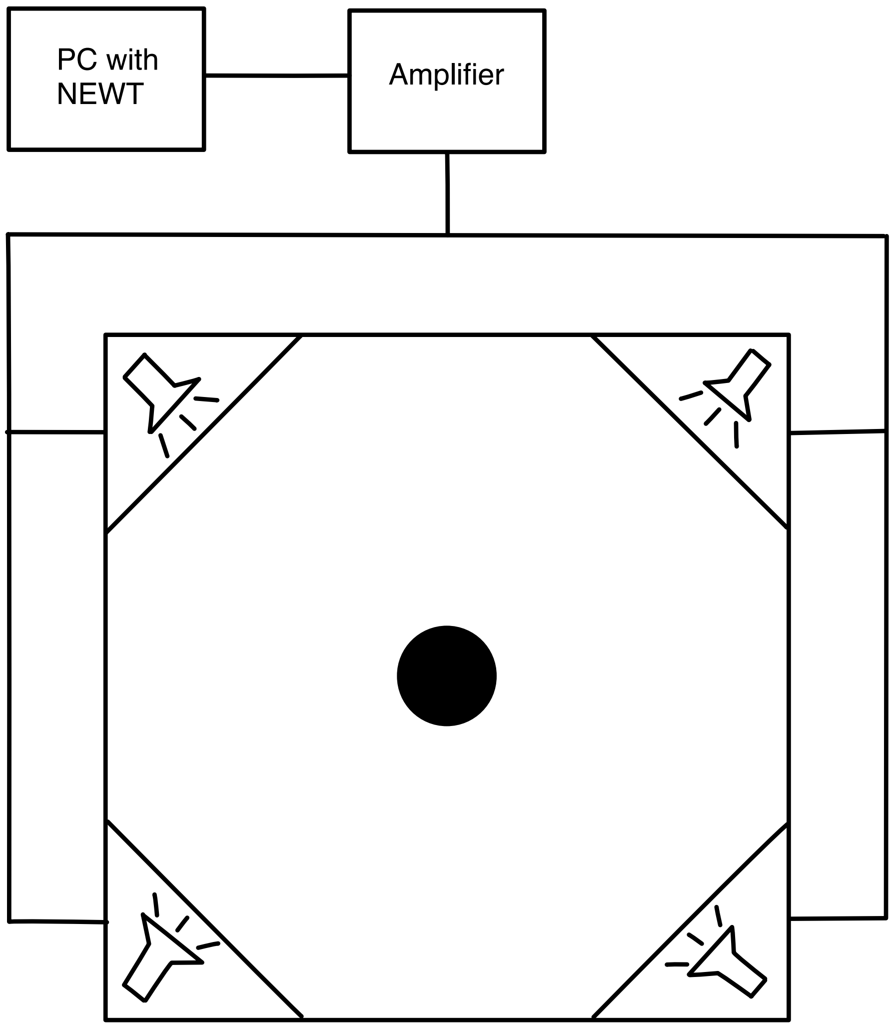


Figure 3.2: Setup of the NEWT. The listener was placed in the middle of four loud speakers, marked by a black circle, which were connected to an amplifier which was connected to the PC running NEWT.

This test was done three times for each participant, with earmuffs, foam earplugs and without HPD. The order of the tests differed for the different participants, in order to reduce the learning effect for the NEWT metod [6], so that, e.g., one participant was tested without HPDs first, and the other was tested with earplugs first. In addition both of the participants tested some special HPD, but these measurements are outside the scope of this report, and will not be presented or discussed.

3.3 Equipment

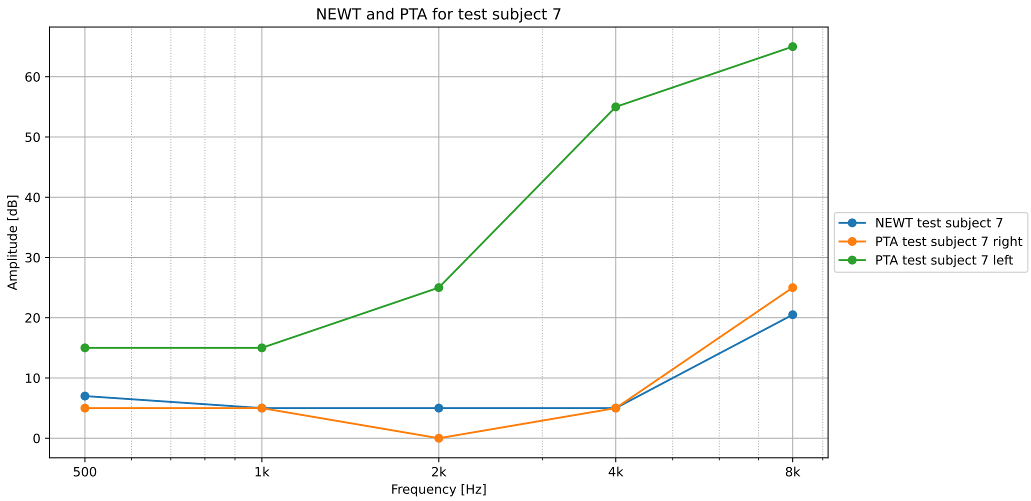
The equipment used this report is shown in Table 3.1.

Table 3.1: Equipment list.

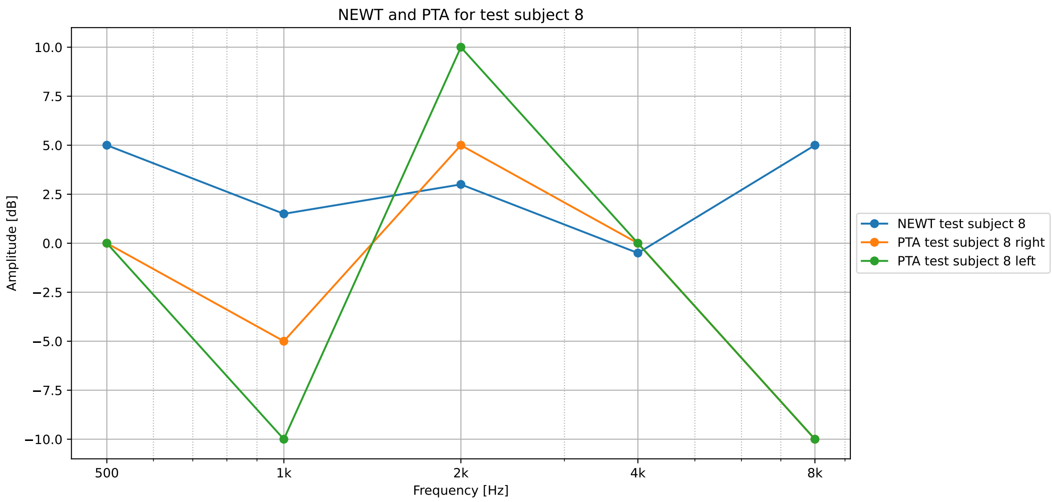
Equipment	Model number/type
Clinical Audiometer	Orbiter 922 Version 2
Headphones	Sennheiser HDA 200
Loud speakers	
Computer with NEWT	
Amplifier for NEWT	
Earmuffs	
Foam ear plugs	
Molded ear plugs	

4 Results

The Pure Tone Audiometry and NEWT was performed on both participants of the group. The results for person 7 and 8 is shown in Figure 4.1, respectively (a) and (b).



(a) Results for PTA and NEWT for person 7.



(b) Results for PTA and NEWT for person 8.

Figure 4.1: Results for the hearing level of person 7 and 8 using both PTA and NEWT.

The attenuation of the two different HPDs were calculated using Equation 2.1. The attenuation for each HPD was then averaged for each frequency. Figure 4.2 shows the average attenuation for earplugs and earmuffs using the results from all 9 people, where 7 were tested with earplugs and 5 were tested with earmuffs. Some were tested for both, but there was 7 test results for earplugs and 5 test results for earmuffs. As a side note it is important to be careful when averaging the results, as desibel is a logarithmic scale, and this must be considered when doing the calculations.

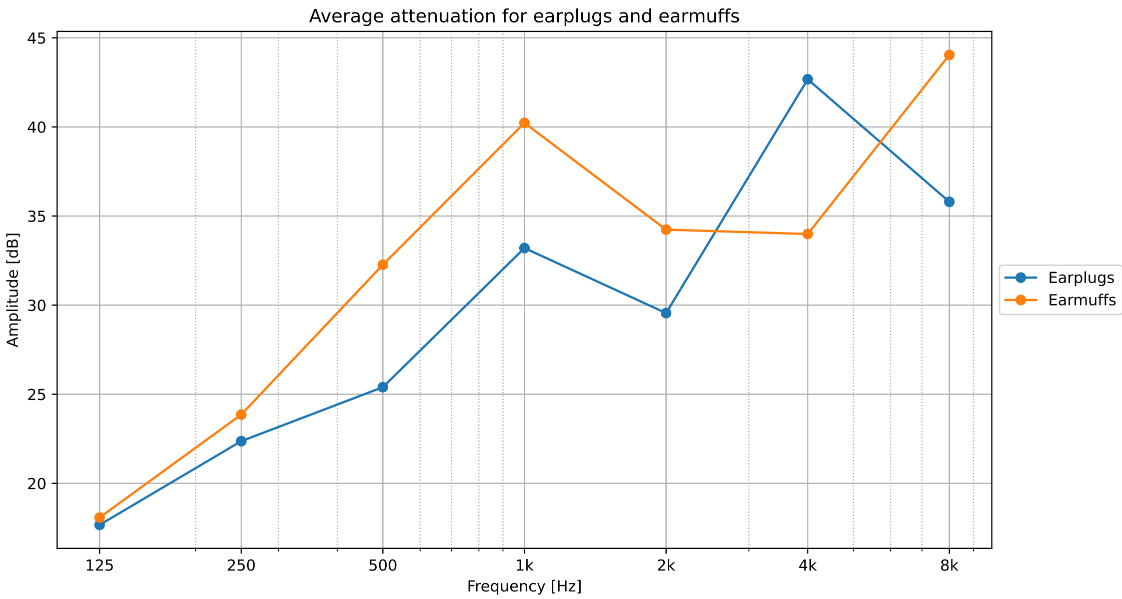
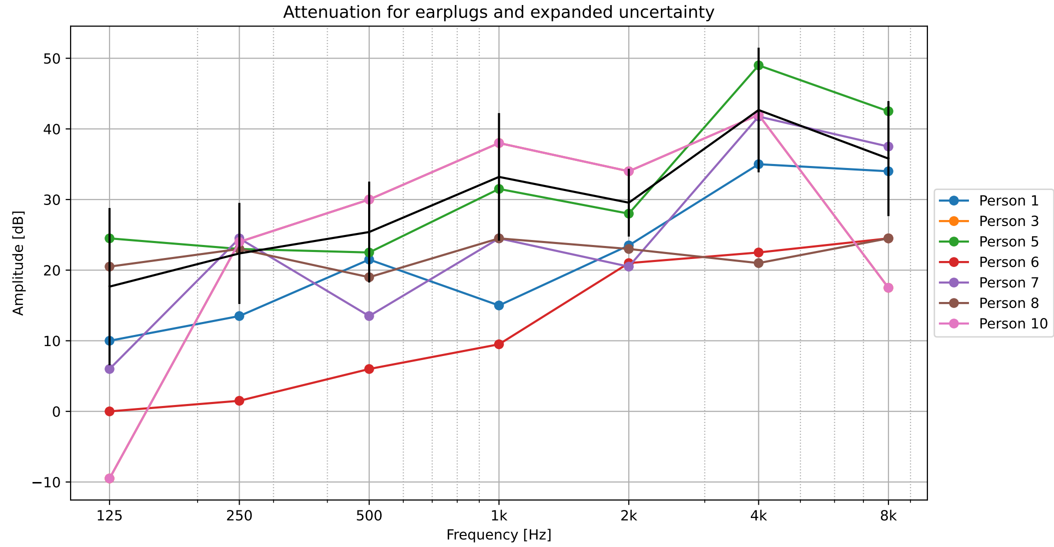


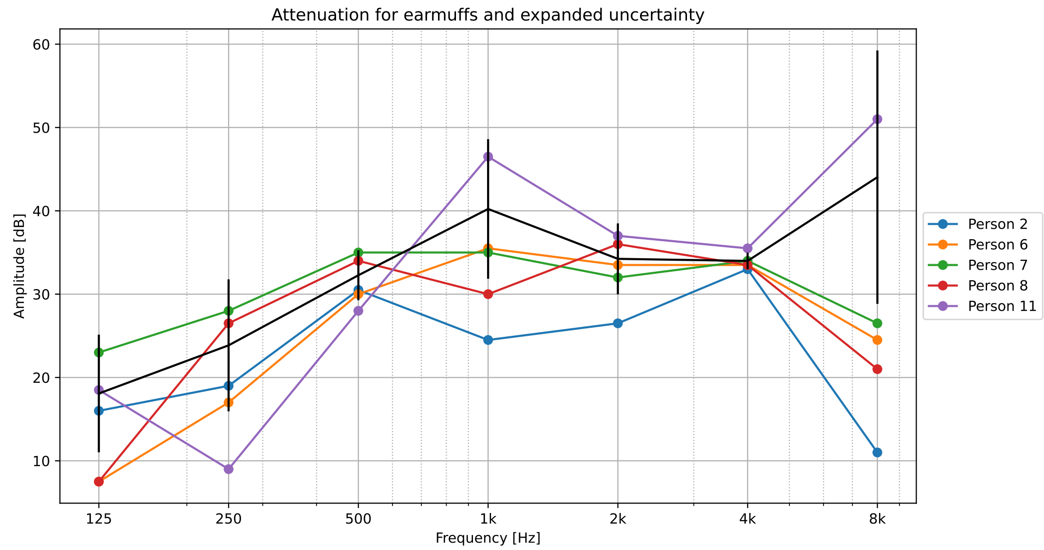
Figure 4.2: Average attenuation for earmuffs and earplugs, calculated using Equation 2.1 and averaging the results.

The sum of the average attenuation for earplugs were calculated to be 44.1 dB and 46.3 dB for earmuffs.

The expanded uncertainty was calculated as described in chapter 2. This is shown in Figure 4.3, where all the attenuations are plotted, together with the average attenuation and the expanded unceratinty for both HPDs. For earplugs the coverage factor was $k = 2.365$ and for earmuffs the coverage factor was $k = 2.571$, corresponding to a two tailed t-distribution with a 95 % confidence interval and respectively 7 and 5 degrees of freedom.



(a) The attenuation for each person for each frequency is plotted, for earplugs. The black line is the average attenuation and the vertical black lines shows the expanded unceratinty.



(b) The attenuation for each person for each frequency is plotted, for earmuffs. The black line is the average attenuation and the vertical black lines shows the expanded unceratinty

Figure 4.3: Expanded uncertainty for earplugs, (a), and earmuffs, (b), plotted together with the attenuations of the individual measurements.

The average expanded uncertainty for earplugs are 8.4 dB and for earmuffs it is 9.1 dB.

5 Discussion

From Figure 4.1(a) it is clear that person 7 has a substantial hearing loss on the right ear. This has been confirmed by PTA performed by trained audiologists, although the hearing threshold was even higher here than before, which could be an error due to the fact the person conducting the PTA was not a trained and qualified audiologist. This is therefore a PTS, as opposed to a TTS, which can have different causes, but will go away over time. A TSS could be due to being exposed to loud sounds prior to the test, etc. as discussed in chapter 2. A PTA is a permanent shift of the hearing threshold, and is caused by damage to the hearing, and this damage could be caused by many things. The NEWT and the PTA for the left ear are similar, and this shows that NEWT is not suitable to detect hearing loss in only one ear, as the ear with normal hearing is able to hear the sounds and hides this shifted hearing threshold for the other ear. This is a consequence of NEWTs inability to test the ears separately.

For person 8 the results of the NEWT and PTA of both ears have similar levels, and it seem that NEWT gives a good indication of hearing levels when both ears have realtively equal hearing thresholds. However, it is a bit too high for some frequencies and a bit too low for other frequencies, when compared to the PTA. It is not possible to conlude which of the methods that is the most accurate representation of the true hearing level.

What should be noted here is that the room in which the NEWT measurements were conducted has a faint dribbling noise, potentially from plumbing, as it sounded like water running. This is unfortunate, as silence is paramount, when testing the hearing threshold. It may contribute to too high levels. Another thing that could contribute to too low thresholds is the fact that the listener presses a button when they hear a sound. This is the case for both PTA and NEWT. For both methods, the listener knows they will be exposed to a quiet noise, and will listen for it. It is possible that the listener presses the button when no sound is played, or maybe when a very quiet noise is played and it is a coincidence that the button is pressed at the right time and that the listener has not actually heard the sound, but only imagines the sound. Especially for PTA, there is a potential for a learning effect. The same frequency is played multiple times in a row, to determine the hearing threshold for that frequency and because of this the listener knows what sound to expect. Something the group experienced when conducting the PTA was that the listener sometimes pressed when there was no sound played. The author experienced, when being the person whos hearing was being tested using PTA, that for lower sound pressure levels, that the sound was audible in the ear that was not tested, after the noise ended. This is crosstalk, and could be avoided using white noise in the opposite ear. TSS could also possibly affect any of the participants, and this is not easy to uncover, by looking at the results, without testing over several days.

The expanded uncertainty seems reasonable, and there is, for many frequencies, a lot of coinciding results with a few outliers. The average expanded unceratinty is a bit larger for earmuffs, and it is also visible from the plots that the results are more scattered, especially for 8 kHz. Some of the results are suspiciously low for the earplugs, especially for person 6. This also opens up for the uncertainty of how well the earplugs were fitted inside the ear. The foam earplugs are meant to be rolled up into a cylindrical shape and placed inside the ear. Then it is important to wait and hold them in place while they expand so that they fit snuggly inside the ear canal. This is a possible source of error for these attenuation measurements. It seems that the earmuffs have higher attenuation that the earplugs for all frequencies, except for 4 kHz. The earmuffs give less room to wear them incorrectly, but wearing the earplugs incorrectly is assumed to give lower values for the attenuation. It seems that for just this frequency the earmuffs have lower attenuation than the earplugs. The fact that there may be PTS and TTS should not affect the attenuation, as it is calculated using the measured hearing thresholds of each individual, using Equation 2.1.

6 Conclusions

NEWT seems like a quick and sufficiently accurate indicator for when a PTA is needed, but only if the hearing thresholds for both ears are similar. This is difficult to know without a PTA, and therefore NEWT might hide hearing damage to one ear, and will give a false sense of security. Given that an inital PTA is conducted, NEWT could be a good tool to regularly check to uncover begining hearing damage, as long as one is particularly attentive to the potential worsening of hearing on each individual ear. It may be more suitable to get regular PTAs as a supplement to NEWT, and it is therefore debatable if there is any point in using NEWT instead of regularly getting PTAs, although NEWT is quicker. This is especially relevant for people that are often exposed to high sound levels over long time. The sum of the average attenuation of earplugs were found to be 44.1 dB and 46.3 dB for earmuffs. The values for each frequency also satisfies the requirement in [5]. The expanded unceratinty seems reasonable, and it is assumed that the attenuations for the HPDs are relatively close to the true attenuation.

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[7] Acoustic Measurements - TTT4250, Measurement uncertainty, ISO/IEC Guide 98-3 Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (ISO GUM), Dong, H., 11-02-2022.

A Appendix: Python script for the post-processing and calculations.

```
import matplotlib.pyplot as plt
import numpy as np
import scipy.stats as stat

# import numpy.random.standard_t as t
x_axis_pta = [500, 1000, 2000, 4000, 8000]
x_axis_newt = [125, 250, 500, 1000, 2000, 4000, 8000]
x_ticks_pta = ["500", "1k", "2k", "4k", "8k"]
x_ticks_newt = ["125", "250", "500", "1k", "2k", "4k", "8k"]

molded_earplugs_person8 = [13, 24, 33, 33, 41, 31.5, 39]

filename_pta = "pta.csv"
filename_newt = "newt.csv"


def read_csv(filename):
    return np.genfromtxt(filename, skip_header=1, delimiter=';')


def pl tt_simple_short(array, title, name_of_file):
    fig, ax = plt.subplots()
    ax.semilogx(x_axis_pta, array)
    ax.grid(which="major")
    ax.grid(which="minor", linestyle=":")
    ax.set_xlabel("Frequency [Hz]")
    ax.set_ylabel("Amplitude [dB]")
    ax.set_title(title)
    ax.set_xticks(x_axis_pta)
    ax.set_xticklabels(x_ticks_pta)
    plt.savefig(name_of_file)
    plt.show()


def pl tt_simple_long_unc(array, title, name_of_file, exp_unc):
    fig, ax = plt.subplots()
    ax.semilogx(x_axis_newt, array, marker="o")
    ax.grid(which="major")
    ax.grid(which="minor", linestyle=":")
    ax.set_xlabel("Frequency [Hz]")
    ax.set_ylabel("Amplitude [dB]")
    ax.set_title(title)
    ax.set_xticks(x_axis_newt)
```

```
    ax.set_xticklabels(x_ticks_newt)
    plt.errorbar(x_axis_newt, array, yerr=exp_unc)
    plt.savefig(name_of_file)
    plt.show()


def pl tt_simple_long(array, title, name_of_file):
    fig, ax = plt.subplots()
    ax.semilogx(x_axis_newt, array, marker="o")
    ax.grid(which="major")
    ax.grid(which="minor", linestyle=":")
    ax.set_xlabel("Frequency [Hz]")
    ax.set_ylabel("Amplitude [dB]")
    ax.set_title(title)
    ax.set_xticks(x_axis_newt)
    ax.set_xticklabels(x_ticks_newt)
    plt.savefig(name_of_file)
    plt.show()


def pl tt_multi_short(n_m_array, title, name_of_file, lengend_array):
    assert len(n_m_array.shape) == 2  # hvis denne failer har du en funky array
    fig, ax = plt.subplots()

    for i in range(n_m_array.shape[0]):
        ax.semilogx(x_axis_pta, n_m_array[i],
                    label=f"{lengend_array[i]}", marker="o")

    ax.grid(which="major")
    ax.grid(which="minor", linestyle=":")
    ax.set_xlabel("Frequency [Hz]")
    ax.set_ylabel("Amplitude [dB]")
    ax.set_title(title)
    ax.set_xticks(x_axis_pta)
    ax.set_xticklabels(x_ticks_pta)
    plt.legend(bbox_to_anchor=(1, 0.5), loc="center left")
    plt.savefig(name_of_file)
    plt.show()


def pl tt_multi_long(n_m_array, title, name_of_file, lengend_array):
    assert len(n_m_array.shape) == 2  # hvis denne failer har du en funky array
    fig, ax = plt.subplots()

    for i in range(n_m_array.shape[0]):
        ax.semilogx(x_axis_newt, n_m_array[i],
                    label=f"{lengend_array[i]}", marker="o")

    ax.grid(which="major")
```

```
    ax.grid(which="minor", linestyle=":")
    ax.set_xlabel("Frequency [Hz]")
    ax.set_ylabel("Amplitude [dB]")
    ax.set_title(title)
    ax.set_xticks(x_axis_newt)
    ax.set_xticklabels(x_ticks_newt)
    plt.legend(bbox_to_anchor=(1, 0.5), loc="center left")
    plt.savefig(name_of_file)
    plt.show()


def pl tt_multi_long_unc(n_m_array, title, name_of_file, lengend_array, exp_unc, average):
    assert len(n_m_array.shape) == 2  # hvis denne failer har du en funky array
    fig, ax = plt.subplots()

    for i in range(n_m_array.shape[0]):
        ax.semilogx(x_axis_newt, n_m_array[i],
                    label=f"{lengend_array[i]}", marker="o")

    ax.grid(which="major")
    ax.grid(which="minor", linestyle=":")
    ax.set_xlabel("Frequency [Hz]")
    ax.set_ylabel("Amplitude [dB]")
    ax.set_title(title)
    ax.set_xticks(x_axis_newt)
    ax.set_xticklabels(x_ticks_newt)
    plt.legend(bbox_to_anchor=(1, 0.5), loc="center left")
    plt.errorbar(x_axis_newt, average, yerr=exp_unc, color='0')
    plt.savefig(name_of_file)
    plt.show()


def pl tt_multi_short_unc(n_m_array, title, name_of_file, lengend_array, exp_unc, average):
    assert len(n_m_array.shape) == 2  # hvis denne failer har du en funky array
    fig, ax = plt.subplots()

    for i in range(n_m_array.shape[0]):
        ax.semilogx(x_axis_pta, n_m_array[i],
                    label=f"{lengend_array[i]}", marker="o")

    ax.grid(which="major")
    ax.grid(which="minor", linestyle=":")
    ax.set_xlabel("Frequency [Hz]")
    ax.set_ylabel("Amplitude [dB]")
    ax.set_title(title)
    ax.set_xticks(x_axis_pta)
    ax.set_xticklabels(x_ticks_pta)
    plt.legend(bbox_to_anchor=(1, 0.5), loc="center left")
    plt.errorbar(x_axis_pta, average, yerr=exp_unc)
```

```
    plt.savefig(name_of_file)
    plt.show()


def attenuation(data_with, data_without):
    return data_with - data_without


def db_to_pressure(measurements):
    return 10 ** (measurements / 10)


def pressure_to_db(measurements):
    return 10 * np.log10(measurements)


def average_spl(stacked_vec):
    pressure_vec = db_to_pressure(stacked_vec)
    avg_vec = np.average(pressure_vec, axis=0)
    db_vec = pressure_to_db(avg_vec)
    return db_vec


###########################
# Reading the files
###########################

data_newt_raw = read_csv(filename_newt)
data_newt = data_newt_raw[:, 2:]

data_pta_raw = read_csv(filename_pta)
data_pta = data_pta_raw[:, 1:]

#######################
# Group results
#######################

############################################
# Comparison of NEWT without HPD and PTA
############################################
NEWT_without_person7 = data_newt[11, :]
NEWT_without_person8 = data_newt[14, :]

NEWT_without_person7_short = data_newt[11, 2:]
NEWT_without_person8_short = data_newt[14, 2:]

PTA_person7_right = data_pta[4, :5]
PTA_person7_left = data_pta[4, 5:]

PTA_person8_right = data_pta[5, :5]
PTA_person8_left = data_pta[5, 5:]

```

```python
group_results_stack = np.vstack((NEWT_without_person7_short, NEWT_without_person8_short, PTA_person7_right,
                                PTA_person7_left,
                                  PTA_person8_right,
                                  PTA_person8_left))

# pl tt_multi_short(group_results_stack,title="Results for test subject 7 and 8", name_of_file="group_results.pdf", lengend_array=["NEWT test subject 8", "NEWT test subject 7", "PTA test subject 7 right","PTA test subject 7 left","PTA test subject 8 right","PTA test subject 8 left"])


person7 = np.vstack((NEWT_without_person7_short, PTA_person7_right, PTA_person7_left))
person8 = np.vstack((NEWT_without_person8_short, PTA_person8_right, PTA_person8_left))

pl tt_multi_short(person8, title= "NEWT and PTA for test subject 8", name_of_file="results_person8.pdf", lengend_array=["NEWT test subject 8", "PTA test subject 8 right", "PTA test subject 8 left"])
pl tt_multi_short(person7, title= "NEWT and PTA for test subject 7", name_of_file="results_person7.pdf", lengend_array=["NEWT test subject 7", "PTA test subject 7 right", "PTA test subject 7 left"])


########################################
# Attenuation of HPD
########################################

# Making av vector with all the NEWT results without HPD
NEWT_without_HPD = data_newt[[0, 2, 4, 6, 8, 11, 14, 17, 19], :]
NEWT_without_earplugs = data_newt[[0, 4, 6, 8, 11, 14, 17], :]
NEWT_without_earmuffs = data_newt[[2, 8, 11, 14, 19], :]

# Making a vector with all the NEWT results with earmuffs
NEWT_with_earmuffs = data_newt[[3, 9, 12, 15, 20], :]

# Making av vector with all the NEWT results with earplugs
NEWT_with_earplugs = data_newt[[1, 5, 7, 10, 13, 16, 18], :]

# Person 7
NEWT_with_earmuffs_person7 = data_newt[12, :]
NEWT_with_earplugs_person7 = data_newt[13, :]

attenuation_earmuffs_person7 = attenuation(NEWT_with_earmuffs_person7, NEWT_without_person7)
attenuation_earplugs_person7 = attenuation(NEWT_with_earplugs_person7, NEWT_without_person7)

# Person 8
```

```
NEWT_with_earmuffs_person8 = data_newt[15, :]
NEWT_with_earplugs_person8 = data_newt[16, :]

attenuation_earmuffs_person8 = attenuation(NEWT_with_earmuffs_person8, NEWT_without_person8)
attenuation_earplugs_person8 = attenuation(NEWT_with_earplugs_person8, NEWT_without_person8)

att_earmuffs_7_8 = np.vstack((attenuation_earmuffs_person7, attenuation_earmuffs_person8))
att_earplugs_7_8 = np.vstack((attenuation_earplugs_person7, attenuation_earplugs_person8))

# Molded earplugs
attenuation_molded_earplugs_person8 = attenuation(molded_earplugs_person8, NEWT_without_person8)
pl tt_simple_long(attenuation_molded_earplugs_person8,title="Attenuation for molded earplugs person 8", name_of_file="att_molded_person8.pdf")
# pl tt_simple_long(PTA_person8_right, title="Hearing treshold person 8", name_of_file="hearing_tresh_pers8.pdf")

# pl tt_multi_long(att_earmuffs_7_8, title="Attenuation for earmuffs for person 7 and 8",name_of_file="att_earmuffs_group.pdf", lengend_array=["Person 7", "Person 8"])
# pl tt_multi_long(att_earplugs_7_8, title="Attenuation for earplugs for person 7 and 8",name_of_file="att_earplugs_group.pdf", lengend_array=["Person 7", "Person 8"])

##########################
# All results
##########################


attenuation_earplugs = attenuation(NEWT_with_earplugs, NEWT_without_earplugs)
attenuation_earmuffs = attenuation(NEWT_with_earmuffs, NEWT_without_earmuffs)
print("NEWT with earmuffs", NEWT_with_earmuffs)
print("Newt without hpd", NEWT_without_HPD)

# pl tt_multi_long(attenuation_earmuffs, title="Attenuation for earmuffs", name_of_file="att_earmuffs_all.pdf", lengend_array=["1", "2", "3", "4", "5", "6"])

# pl tt_multi_long(attenuation_earplugs, title="Attenuation for earplugs", name_of_file="att_earmuffs_all.pdf", lengend_array=["1", "2", "3", "4", "5", "6"])

avg_att_earmuffs = average_spl(attenuation_earmuffs)
avg_att_earplugs = average_spl(attenuation_earplugs)
att_plugs_muffs = np.vstack((avg_att_earplugs, avg_att_earmuffs))
```

```
# pl tt_simple_long(avg_att_earmuffs, title="Average attenuation for earmuffs", name_of_file="att_earmuffs_avgerage.pdf")
# pl tt_simple_long(avg_att_earplugs, title="Average attenuation for earplugs", name_of_file="att_earplugs_avgerage.pdf")
earplugs_earmuffs_molded = np.vstack((avg_att_earplugs, avg_att_earmuffs, attenuation_molded_earplugs_person8))
# pl tt_multi_long(earplugs_earmuffs_molded, title="Attenuation for earplugs, earmuffs and molded earplugs", name_of_file="att_earplug_earmuff_mlded.pdf", lengend_array=["1","2","3"])
pl tt_multi_long(att_plugs_muffs, title="Average attenuation for earplugs and earmuffs", name_of_file="avg_earplug_earmuffs.pdf", lengend_array=["Earplugs", "Earmuffs"])
#############################
# Expanded uncertainty
#############################

# Coverage factor k
#k = 2.447  # for a 95% confidence interval of the Students t-distribution for 6 samples
k_earplugs = 2.365 #for 7 samples
k_earmuffs = 2.571  # for 5 samples


# Standard deviation for a normal distribution
std_earplugs_pressure = np.std(attenuation_earplugs, axis=0)
std_earplugs_db = np.std(attenuation_earplugs, axis=0)
std_uncertainty_earplugs = std_earplugs_db / std_earplugs_pressure.shape[0]
std_earmuffs_pressure = np.std(db_to_pressure(attenuation_earmuffs), axis=0)
std_earmuffs_db = np.std(attenuation_earmuffs, axis=0)
std_uncertainty_earmuffs = std_earmuffs_db / std_earmuffs_pressure.shape[0]


uncertainty_earplugs = std_earplugs_db / np.sqrt(7)
expanded_uncertainty_earplugs_db = k_earplugs * uncertainty_earplugs


uncertainty_earmuffs = std_earmuffs_db / np.sqrt(5)
expanded_uncertainty_earmuffs_db = k_earmuffs * uncertainty_earmuffs

# pl tt_multi_long(np.vstack((avg_att_earmuffs, avg_att_earplugs)), title="Average attenuation for earplugs and earmuffs",
#                   name_of_file="avg_att_earplug_earmuff.pdf", lengend_array=["Earmuffs", "Earplugs"])


pl tt_multi_long_unc(attenuation_earmuffs, title="Attenuation for earmuffs and expanded uncertainty",
```

```
                            name_of_file="att_earmuffs_all_unc.pdf", lengend_array=["Person 2", "Person 6", "Person 7", "Person 8", "Person 11"],
                            exp_unc=expanded_uncertainty_earmuffs_db, average=avg_att_earmuffs)


pl tt_multi_long_unc(attenuation_earplugs, title="Attenuation for earplugs and expanded uncertainty",
                            name_of_file="att_earplugs_all_unc.pdf", lengend_array=["Person 1", "Person 3", "Person 5", "Person 6", "Person 7", "Person 8", "Person 10", "Average and expanded uncertainty"],
                            exp_unc=expanded_uncertainty_earplugs_db, average=avg_att_earplugs)


avg_expanded_earplugs = pressure_to_db(np.average(db_to_pressure(expanded_uncertainty_earplugs_db)))
print("avg exp earplugs", avg_expanded_earplugs)

avg_expanded_earmuffs = pressure_to_db(np.average(db_to_pressure(expanded_uncertainty_earmuffs_db)))
print("AVG exp earmuffs", avg_expanded_earmuffs)

avg_earplugs_sum = pressure_to_db(np.sum(db_to_pressure(avg_att_earplugs)))
print(avg_earplugs_sum)

avg_earmuffs_sum = pressure_to_db(np.sum(db_to_pressure(avg_att_earmuffs)))
print(avg_earmuffs_sum)
```