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Measuring Hearing Protection Performance Results in a MIRE-Compliant Reverberatory Chamber Versus a non-MIRE Compliant Room

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ABSTRACT

Measuring Hearing Protection Performance Results in a MIRE-Compliant Reverberatory Chamber Versus a non-MIRE Compliant Room

Mahela Sanguinetti

Noise Reduction Rating (NRR) is a method developed by the Environmental Protection Agency (EPA) to determine the effectiveness of hearing protection devices (HPD). The limitations of NRR values have led to use of other methods, including fit-testing hearing protectors on the individuals who will use them. The fit-testing method used in this study is the Microphone in Real Ear (MIRE) method, which describes how to test earmuffs in a reverberatory chamber. A reverberatory chamber is extremely costly and not likely to be available at work-sites. If fit-testing could be completed in any room instead of in a reverberatory chamber, work-sites could save on the cost of the chamber and may be more likely to fit-test hearing protectors.

In this study, the MIRE method was used. Both Noise Reduction (NR) and Insertion Loss (IL) were determined for nine subjects, both in an ordinary room and in a reverberatory chamber. Subjects were tested while wearing earmuffs and earplugs at different times. Results showed minor deviations in values between the reverberatory chamber and ordinary room when averaged from 125 Hz to 8000 Hz for each given subject and condition. The orientation of subjects affected observed NR and IL by less than 5 dB.

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INTRODUCTION

Chronic noise exposure is a common workplace hazard throughout the United States. Exposures to high noise levels can cause noise- induce~~d~~ hearing loss (NIHL), especially when routine exposures exceed 90 dBA when averaged over an 8 hour period. NIHL can be limited in two ways: engineering controls and personal protective equipment (PPE). Hearing protection devices (HPD) are the focus of this study.

NIHL can be reduced if exposed individuals wear HPDs properly. Properly worn HPDs may provide individuals with an average of 20 – 40 dB of attenuation (Rabinowitz, 2000). Some HPD's have much greater ability to block noise than others. To help in selecting an HPD that has sufficient effectiveness for a given noise exposure, the Environmental Protection Agency (EPA) developed the Noise Reduction Rating (NRR). The Occupational Safety and Health Administration (OSHA) currently uses the NRR to determine whether the HPDs used by workers are properly selected.

The NRR is intended to be a conservative estimate of the protection factor of the HPD. It is based on the lowest 5% of observed laboratory results (29 CFR 1910.95). However, many critics, such as Burks and Michael (2003) express concern that the testing protocol has a lack of realism that leads to inflated estimates of NR. For example, Burks and Michael state that the protection of HPDs has two basic flaws: 1) the unpredictability of field performance, and 2) the lab data only represent a point measurement taken in an ideal environment.

Other concerns about the NRR include (Berger, 2000c, Burks and Michael, 2003, Neitzel, et al, 2006) that actual protection and attenuation during use may be lower than by NRR values as evidenced by the continuing high incidence rate of hearing loss across all occupations. Mining, for example, has a 50% incident rate of compensable hearing loss (Bureau of Labour Statistics, 2005).

For the above reasons, investigators have been trying to accurately determine the protection factor of the hearing protectors using individual "fit-tests." There are two protocols most commonly used for such studies: 1) the Microphone In Real Ear (MIRE) standard, and 2) the Real-Ear Attenuation at Threshold (REAT) test (Berger, 2005). Both require substantial expertise and relatively expensive test rooms. The former must be completed in a reverberation chamber that meets MIRE standards, and the second must be completed in an audiometric test booth or room that meets American National Standards Institute (ANSI) standards.

It would be helpful, both for field studies and for use by practitioners if fit-tests could be done in ordinary rooms instead of expensive test chambers. To determine if fit-tests can be done in an ordinary room with little or no loss of accuracy, this study experimentally determined and compared "insertion loss" (IL) and "noise reduction" (NR) values in an ordinary room and results for the same subjects and HPD's in a reverberatory chamber.

Standard Protocols for Fit-Testing

REAT is the "gold standard" protocol for Fit-Testing. The REAT method must be conducted in an extremely quiet environment since it basically is an audiometric test done with and without the subject wearing hearing protection. The subject responds when he or she first hears the test sound, thus allowing determination of their threshold. The audiometric test is done once with ear protection and again without. The difference between the threshold without hearing protection and with hearing protection is the threshold shift, which is due to the hearing protectors.

The MIRE method does not involve audiometric testing. Therefore, a quiet environment is not necessary for this method. Instead, a tiny microphone is placed inside an earplug or earmuff to record the amount of sound that passes through to the ear canal. Another microphone is placed on the person's shoulder. The frequencies between 125 and 8000 Hz are measured at both microphones and the difference in their reading is the attenuation. Both the IL and the NR can be obtained this way. A reverberatory chamber is necessary to avoid the effects of orientation.

LITERATURE REVIEW

There are currently two categories of HPDs: earplugs and earmuffs. Although both types of HPD's offer intra-aural and sub-aural protection, some sound reaches the ear drum due to bone conduction, air leaks, vibration, and transmission through the HPD (Berger, 2000c). With bone conduction, noise can bypass all pathways into the ear canal by vibrating the skull. That vibration can be transmitted all the way to the inner ear as noise. Air leaks are due to the HPD not having the appropriate seal with the tissue inside the ear (see Figure 1). For maximum attenuation of HPD's an air tight seal is necessary.

Sound energy causes the ear protector to vibrate so that it becomes a secondary source of sound that reaches the ear canal. Vibration of HPD's is due to the flexibility of the tissue in the ear canal. This vibration limits the amount of low frequency noise that can be attenuated. The vibration of the HPD causes a sound to be heard inside the HPD between the protector and the ear drum as seen in Figure 1.

Finally there is transmission loss. Transmission loss is caused by sound waves penetrating the HPD. Transmission loss can cause an attenuation deficiency in frequencies above 1 kHz (Berger, 2000c).

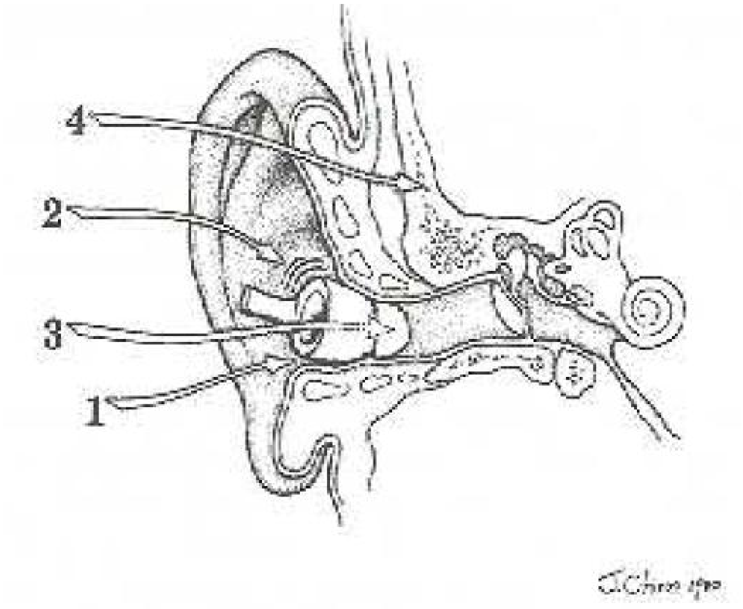

Figure 1: Earplug in Ear

It is important to quantify the performance of hearing protectors. The EPA rates all hearing protectors and labels the HPDs with the NRR. OSHA inspectors use NRR (29 CFR 1910.95) to determine if an employer is providing HPDs that are sufficiently protecting. A NRR is intended to represent the level of protection a hearing protector can provide reliably. The higher the NRR, the greater the expected noise reduction during use. The NRR is based on a C-Scale noise level. To apply it when only the A-Scale values are known, we can conservatively estimate the A-Scale NRR value by subtracting 7dB from the C-scale value. OSHA also recommends a 50% “safety factor” after that correction. Therefore the appropriate attenuation for an HPD when using A-Scale values is determined by using the NRR reduced by 7 and divided by 2. Presumably this additional “correction” by OSHA provides an appropriately conservative predicted attenuation for that particular protector. However, many believe this practice is not representative of all protectors (Berger, 2000c). Some HPDs should perhaps be discounted by more than 50% and others by much less.

In addition, some researchers (Behar, 1981) say that NRR is simplified and not a good way to determine noise reduction because the method in which the NRR is determined (ANSI 1974) requires 1) ideal conditions for testing, and 2) that the experimenter supervises the fitting. It is plausible the observed NRR often would be much lower without such supervision. In many, perhaps most cases, workers wearing the HPD have had little training or supervision during fittings. In the workplace, many people are novices and simply use the manufacturer's instructions to don their hearing protectors. In other cases they may have no instructions at all. Because of the alleged bias of the ANSI 1974 method, Berger (1998) proposed ANSI 1997. This method requires that researchers should use a group of naïve subjects and obtain noise attenuation based on self-application of the hearing protectors without instructions. Berger's proposed ANSI 1997 demonstrated that naïve workers were able to obtain the same noise attenuation in the workplace as in the lab.

There are additional issues with the NRR. ANSI 1974 is a method used to predict the average noise attenuation amongst a population of a randomly selected group of workers. Berger's method of ANSI 1997 is an individual-based assessment. Other researchers who disagree state that it is nearly impossible to obtain the same noise attenuation of a HPD in individuals and in the real world as in the lab (Neitzel, et al, 2006); (Burks and Michael, 2003).

If the NRR is not the best method for determining noise reduction of HPD in the workplace, other ways of determining their noise attenuation should be considered. The REAT method may not be easily employed in the workplace because it requires a very quiet environment to test the subject.

According to Berger's (1986) study, the MIRE approach is one of the most promising field fit-testing methods for research. The MIRE approach is applied to research with ear muffs. It requires a reverberatory chamber. A mannequin or acoustical test fixture is recommended. According to Neitzel et al (2006), the MIRE test produced a lower within-day variability than the Real Ear Attenuation (REAT). The MIRE method tends to be much faster than REAT. Since it does not necessarily require a quiet environment, it can be done in the workplace in a quiet office.

Several studies have been done using MIRE. For example, a study by Berger (Earlog 13, 1984) was conducted to see if plugs and muffs worn at the same time will protect hearing more than just one type of protector. This was done by using 3 types of plugs and 4 different types of muffs. First testing was on subjects who had no assistance in donning the protectors, then with some assistance, and finally with total assistance. The results showed that there was a limit to total attenuation due to bone conduction pathways and that wearing both hearing protectors attenuated at least 5 dB more than wearing either protector alone. They also showed that subjects who were assisted in inserting the ear plug properly had a higher attenuation of sound. Berger recommended that plugs or muffs alone are not enough in a 105 dBA time-weighted noise exposure with low frequencies and that it might be helpful to wear both protectors. Berger also stated that real world attenuation is different than the attenuation found in a lab.

Burks and Michael (2003) also agreed that it is impossible to predict attenuation of a hearing protector in the real world with lab measurements. Toivonen et al (2002) showed that noise attenuation with ear plugs is better on subjects that are trained to properly insert them. They sampled 54 randomly selected subjects, with 25 of the subjects untrained and 29 trained. The results from the MIRE method showed that “the averaged A-weighted noise attenuation was 21 dB for the untrained subjects and 31 dB for the trained subjects.” With a difference of 10 dB, this study showed that ear plug insertion training greatly improved poor attenuations.

Based on the above finding, for this study an experimenter-supervised fitting method was used to assist subjects in proper ear plug insertion. The experimenter made sure that all fits followed the example written by Berger (Earlog 19, 1998). Here Berger states that one of the methods is to pull the ear outward and upward while inserting the plug into the ear. This is the most effective method they found to be easily trainable. Toiven et al (2002) was one of many to state the importance of experimenter-assisted testing.

The Berger et al (1998) study of the validity of using subject-fit data, showed that a real-world estimation of field attenuation more closely matched subject-fit test results than did experimenter-fit research. However, since the point of this study was to investigate the necessity of a reverberation chamber, this study employed subject-fit experimenter assisted research to minimize variability.

Murphy et al (2004) developed a new standard and lab protocol that estimated the field attenuation of HPDs. They found the sample sizes necessary to provide the acceptable reproducibility based on the desired level of precision. For example, according to their calculations, for a precision of 6 dB attenuation 4 subjects are sufficient for sampling with the Bilsom UF-1 ear muffs and 10 subjects were necessary for EAR classic ear plugs. The sample size for this study was 9 subjects.

Cui et al (2003), described determination of IL in a chamber using the MIRE method. They stated that: "The main advantage of the MIRE technique is minimizing the subjectivity of the test, for the subject just 'lends' his head during the test. However, the involvement of human subjects increases the cost of testing and also limits the test conditions to avoid any potential hazard to the subjects."

Cui et al states that IL can be measured in 3 different ways:

$$\text{Passive IL} = SPL_{\text{open Ear}} - SPL_{\text{Passive Protected Ear}} \quad \ldots\ldots\ldots\ldots \quad (1)$$

$$\text{Total IL} = SPL_{\text{open Ear}} - SPL_{\text{Total Protected Ear}} \quad \ldots\ldots\ldots\ldots \quad (2)$$

$$\text{Active IL} = SPL_{\text{Passive Protected Ear}} - SPL_{\text{Total Protected Ear}} \quad \ldots\ldots \quad (3)$$

Where: IL = Insertion Loss, dB

$SPL_{\text{open ear}}$ = Measurement with sound on and no headset

$SPL_{\text{Passive Protected Ear}}$ = Measurment with sound on and headset on

$SPL_{\text{Total Protected Ear}}$ = same conditions as in passive but with Active Noise Reduction (ANR)

No active noise control HPDs were tested for this study

IL for this study was determined from measured Open Ear and the Passive Protected Ear values using Equation 1, where the sound signal is not changed and no other conditions are added. Schroeter and Poesselt (1986) showed that artificial flesh influences the IL of earmuffs near the frequency of resonance (between 100 and 250 Hz) and that the external ear affects IL above 1kHz. Due to the possibility of artifacts from using artificial subjects, this study chose to use live subjects to achieve real-world results.

IL is the amount of sound lost in using a HPD (IL = Noise exposure measured with HPD - Noise exposure measured without HPD). NR is the amount of sound reduced at the time of use of a HPD (NR = Noise exposure measured outside of the HPD – Noise exposure measured inside the HPD).

Casali et al (1995) compared results using the MIRE technique to two psychophysical procedures that employed REAT. Their 10 subjects were each fitted with 3 earmuffs and 3 cap mounted muffs. Their MIRE results were significantly different from their REAT results. The results could have been affected by the lack of threshold-level sound stimuli needed for the MIRE tests. This lack of threshold-level sound stimuli is also the reason that the MIRE tests do not need a very quiet test room to get reproducible results.

Using the standard REAT protocol (ANSI S3.19-1974), Robinson et al, (1992) compared the attenuation of earmuffs in a reverberatory chamber to the attenuation of earmuffs in a semi-reverberatory chamber similar to a common office. Three earmuffs, Peltor H7A (large volume), Peltor H9A (small volume), and Cabot Safety Model 1720, were tested. The semi-reverberatory chamber acoustical environment was obtained in the reverberatory chamber by hanging one sheet of 5.1 cm thick Sonex acoustical foam on each of the reverberatory chamber's four walls. There were 3 three speakers in the reverberatory chamber. They turned off two speakers and moved the third speaker so that it was directed at the center of the subject's head (front incidence). Their results indicated that there was significant difference at most frequencies between these two environments. The biggest deviation was 2.7 dB among all center frequencies of one-third octave band, a deviation of little significance when selecting hearing protection. Robinson et al, (1992) concluded that a reasonable estimate of the protection level provided by an earmuff can be determined in a common office by the REAT method.

In a normal room, Durkt, (1993) and Giardino et al, (1996) used MIRE to evaluate the noise reduction obtained by miner's earmuffs while working. They put one microphone under the earmuff and another microphone on the outside of the earmuff cup. The authors did not determine whether the noise reduction of the earmuff measured in the miners workplace was equal or comparable to the noise reduction of an earmuff measured in a reverberatory chamber. It was not clear if there was a difference for the noise reduction.

Toivonen et al, (2002) measured the noise attenuation of earplugs using the MIRE method to determine if teaching the proper insertion of earplug by users improved HPD effectiveness. The measurements were performed in a normal office room. A miniature Sennheizer KE4-211-2 microphone was fixed to the end of the earplug and inserted into the ear canal. The microphone was situated between the eardrum and the earplug. Sound Pressure Level (SPL) was measured in the ear canal with and without and earplug in the ear. SPL was also later measured with the same microphone at distance of 5 cm to the side of the subject's head. Also, the subject was checked with the REAT method, but only at 1000 Hz. This study showed that with proper instruction, the MIRE method was 4 dB higher than REAT at 1000 Hz. The author did not compare MIRE with REAT at other frequencies.

More recently, Neitzel et al, (2006) conducted a study at construction worksites to measure the variability in attenuation of HPDs and the difference between attenuation test systems. In a common office they compared attenuation measurements made with two systems, “Fit-Check” TM (Neitzel, 2006) (which is essentially REAT) and a so-called “FlashTest Microphone-in-Real-Ear” (Neitzel, 2006). All 1/3 octave center frequencies were measured for 20 workers using two earplugs (foam and custom-molded). Both of the earplugs tested required a vent that passed through the earplug to allow for MIRE attenuation measurements. This vent allowed a microphone to be inserted into the earplug to measure SPL inside the ear canal while the earplug was worn. Another microphone was placed on the shoulder of each subject. NR was obtained by subtracting the results from the two microphones. The estimated free-field “transfer function of open ear” (TFOE) factors (ISO, 2002) were applied to the group mean frequency-specific FlashTest attenuations to obtain noise IL. TFOE is used when comparing NR to IL; it is the sound amplification of the ear. The TFOE IL was compared to the IL of the group mean frequency-specific attenuation determined from the Fit-Check TM method. Their results indicated that for both earplugs the attenuation measured using the MIRE method was lower than the attenuation measured using the REAT method. Moreover, the difference between the two test systems was highly variable. The authors also stated that the effect of background noises on the Fit-Check test, plus the variability of subjects due to re-fitting their earplugs, could have produced the large differences between the MIRE and REAT measurements. Finally, the authors speculated that there was an over-prediction of the attenuation from the REAT measurements at low frequencies due to physiological masking.

Researchers in the past have used the MIRE method either only in a reverberatory chamber or only in an office environment but have not done both with the same subjects. The objective of this study was to determine if there is a difference in attenuation when testing in a reverberatory chamber as compared to testing in an ordinary office environment (i.e., regular room or reverberatory chamber). The independent variables of this study were location, subject, orientation to the source, and type of protector. The dependant variables were NR and IL.

APPARATUS

Noise was measured using a OROS OR38 Analyzer (Oros, Inc., Dulles, VA), which includes NVGate software (software version #nvgate 4.22). The OR38 is a multi-analyzer and recorder for acoustics and vibration and is used to capture the information needed for frequency analysis. The NVGate software includes the calibration suite and plug-in analyzers for multiple FFTs, order analysis, and simultaneous recording of time domain signal.

The speakers for this study were Infiniti Primus Model #160. The amplifiers used in this study to drive the speakers were Behringer Model # EP1500. An equalizer, DDX model #131, was also used.

For this study the doseBusters dual microphone harness was used (doseBuster, Inc. Pennsylvania). This harness was developed by Dr. Kevin Michael and Dr. Alton Burks (Pittsburgh, PA). Depending on the frequency, the noise floor for the microphone is roughly 35 dB.

The earplugs used in this study were disposable PVC Foam Earlink 3L regular size earplugs (E-A-R, Indianapolis, IN). They have a 2 mm in diameter tube that passes through the center of the earplug to allow for a microphone to be screwed to record noise between the plug and the ear drum. The earmuff used in this study was the North Gun Muffler Hearing Protector with foam filled cushion (Brea, California).

To calibrate the system, the Norsonic AS Norway Sound Calibrator type 1251 was used. The system was calibrated daily at 1000 Hz and 114.0 dB.

Photo 1: A photograph of the Reverberatory Chamber found in Room 242 of the Mineral Resource Building at West Virginia University.

The reverberatory chamber is a custom-built structure located at West Virginia University in the Mineral Resource Building within a lab (See Photo 1). The chamber is constructed out of a “2x4” pine stud framing with 3 ½ inch R-19 Fiberglass insulation placed between all studs. The inside walls are faced with 5/8 inch plywood covered in turn by ½ inch drywall and sealed with glossy enamel paint. The exterior walls and ceiling are faced with another layer of ½ inch drywall. The whole structure rests on 1” foam “gym mats” which in turn lay on 3/8” laminate floor tiles on concrete floor. The chamber is compliant with the MIRE standard requirements. The chamber meets the uniformity requirements of ANSI 12.42-1995 in regards to the diffuse sound field. The differences between all locations in the chamber are all within 2 dB. The directionality of the chamber at every 1/3 octave band frequency from 630 Hz to 8000 Hz also meets the ANSI 12.42-1995 requirements, except at 500 Hz. The maximum SPL for the directional microphone that was used for measurement should not be more than 3 dB and at 500 Hz it was 4 dB.

The other room used in this study, Room 246, is a standard lab with tables, chairs, lab hoods, lab counters and supplies.

Subjects for this study were IMSE graduate students who were paid volunteers. There were eight males and one female. Eight subjects were Caucasian and one was Asian. Their weights ranged from approximately 140 lbs to 250lbs and their heights ranged from 5’2” – 6’2”.

METHODS

The methodology used for sampling was as follows for all 9 subjects:

- Prepare OR38 noise analyzer
    - Make sure system is on and all wires are properly plugged in
    - Using NVGate software, set up program for white noise, octave band analysis and dB linear signal(which is a signal without any weight/change)
- Prepare the sound source amplifiers
    - Make sure sound is preset to a level no louder than 90 dB
- Prepare microphones
    - Set up 2 microphones for subject noise sampling
    - Set up 1 microphone to measure constant, non-directional ambient and background noise
    - Set up another microphone to measure sound that is transferred inside the HPD
    - Calibrate both EAR microphones using the Norsonic AS type 1251
- Prepare reverberatory chamber for sampling by MIRE standards
    - Place chair for subject in the center of the reverberatory chamber
    - Place 3 speakers in 3 corners of the room and equidistance from subject
- Prepare ordinary room for sampling
    - Place chair for subject in center of the room
    - Place 1 speaker on a table approximately 18” from the head of the subject
- Prepare subject with instructions on what he or she will be doing.

- Begin with Insertion Loss (IL) sampling in the reverberatory chamber
    - First, sample white noise with only a microphone in the subject's ear
    - Next, fit earplug with microphone in the subjects ear and sample again
- Keeping the ear plug in the subject's ear, begin Noise Reduction (NR) sampling
    - For NR sampling, make sure the ear plug with microphone is still in the ear and the second microphone is still attached to the subject's shoulder
    - With the ear plug still in the subject's ear, move to an ordinary room
- Begin sampling in ordinary room
    - To test with the same earplug fit, begin sampling for NR first (both ambient and in ear sampling)
    - With earplug still in ear, begin IL sampling
    - Remove earplug and complete IL sampling without earplug
- Repeat all methods of ear plug sampling with ear muffs

The standard that was followed for measurement of insertion loss (IL) for this study was the MIRE and acoustical test fixture methods for the measurement of IL of circumaural hearing protective devices. It is an American National Standard (ANSI S12.42-1995) that specifies aspects of noise research with ear muffs. It states that IL "shall be summarized as means and standard deviations for at least the third-octave bands centered at 125, 250, 500, 1000, 2000, 4000, and 8000 Hz."

RESULTS

The nine subjects were tested both with ear plugs and with ear muffs in both the ordinary room and the reverberation chamber. In both rooms they faced at 0°, 90°, and 270° to the sound source. Each test was replicated twice for each subject.

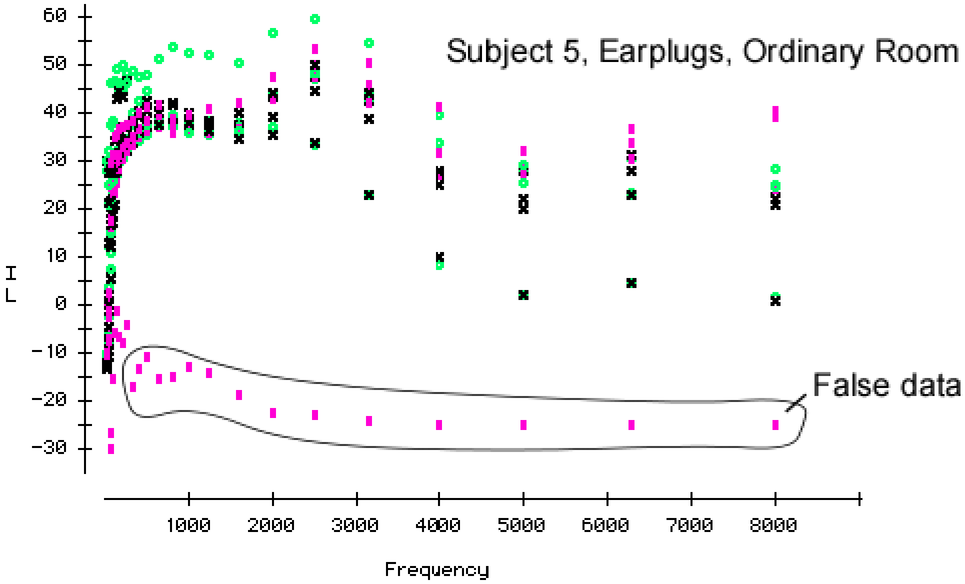

Figure 3 : Shows all the data in replication 2 for earplugs

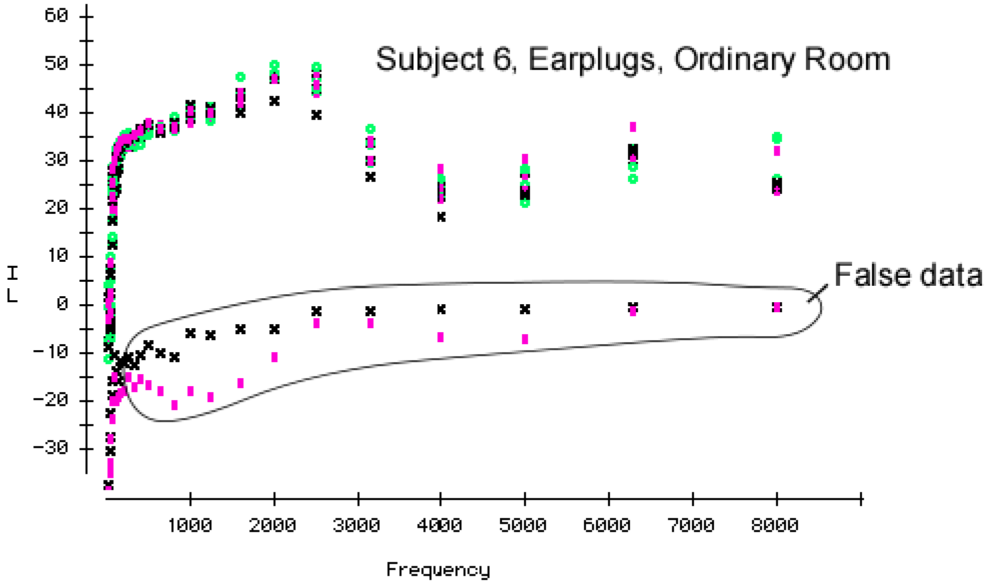

Figure 4: Shows all the data in replication 1 for Subject 6

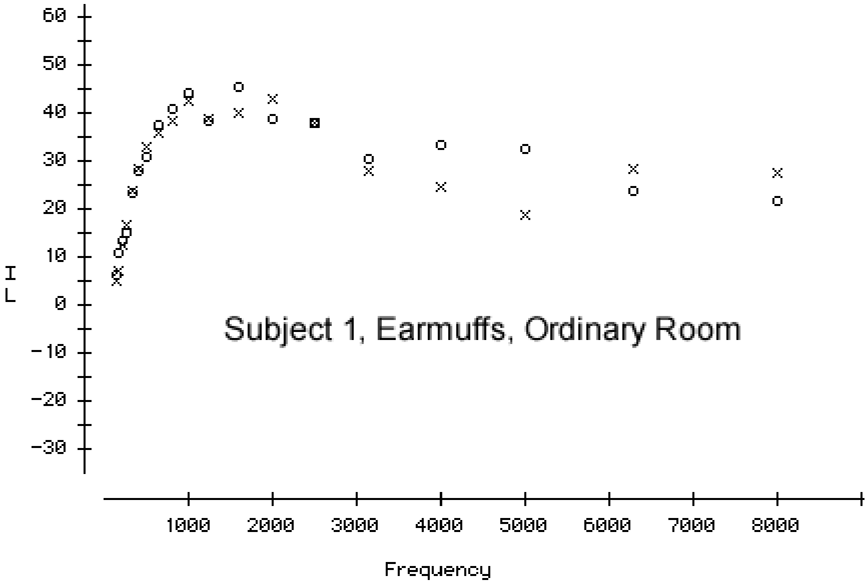

Figure 5: One set of replications for Subject 1

Consistency of replications

As can be seen in Figures 3 and 4, some of the results for Subject 5 and 6 are obviously incorrect. The string of negative IL values at around -20 dB would, if real, suggest that the ear plugs acted as strong amplifiers (e.g., a hearing aid), which cannot be so. Instead, they are the result of an erratically recurring instrument error. This problem affected about 10% of the data collected from Subjects 5 and 6. As shown in Figure 4, the instrument errors for Subject 6 are not as negative as subject 5. Both sets of erroneous data were removed for analysis. In both cases, the subjects were wearing earplugs in the ordinary room when the instruments failed during one of the two replications. The “good” replication fit well with other data in each case.

For the rest of the data, replications were highly consistent. Figure 5 shows typical results for a subject.

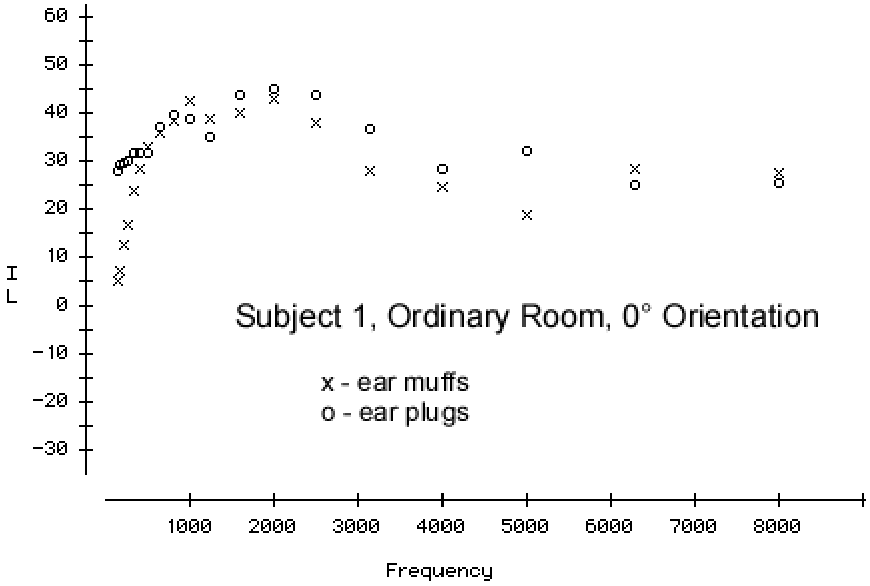

Figure 6: Comparison of earplugs and earmuffs for one subject for one set of conditions

Table 1: Mean IL & NR Across All Subjects

		IL		NR	
		Muffs	**Plugs**	**Muffs**	**Plugs**
Reverberatory Chamber	0	25.4	31.9	24.6	29.7
	90	25.3	32.2	25.2	30.3
	270	25.1	32.1	24.7	29.7
	AVG	**25.3**	**32.1**	**24.8**	**29.9**
Ordinary Room	0	26.2	33.2	29.4	34.9
	90	24.3	32.7	26.5	32.9
	270	26.7	34.6	26.9	32.8
	AVG	**25.7**	**33.5**	**27.6**	**33.5**

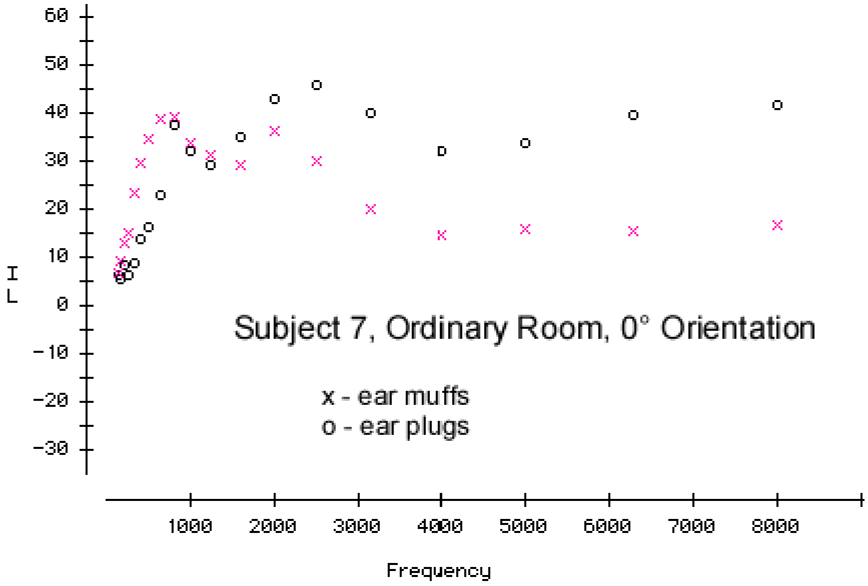

Figure 7: Comparison of Earmuff to Earplug

Earmuffs vs. Earplugs

A comparison of earmuffs to earplugs (see Figures 3 - 6 and Table 1) consistently showed that earplugs attenuated more noise at frequencies lower than 500 Hz but performed roughly the same as earmuffs at higher frequencies. Mostly because of the superior low frequency performance, IL values for earplugs averaged 1.4 dB higher for earplugs and NR values average 3.6 dB higher for earplugs than earmuffs.

Subject 7 was an exception whose IL and NR values were roughly 25 dB higher for the earplugs than the earmuffs (see Figure 7). In addition, for this subject the earplugs showed relatively poor performance at the lowest frequencies. A possible reason for this exceptionality could be the fit of the earplug. Subject 7 was inexperienced at fitting earplugs and also had a smaller body frame and a small face width. The small face width lessens the clamp force of the earmuffs on the head, thereby lessening IL and NR.

Effect of Orientation in Each Test Room

The effect of orientation to the sound source was slight in the reverberation chamber, as expected. As shown on Table 1, the greatest difference between average values of IL and NR between any two orientations in the reverberation chamber was less than 1.4 dB, considering both the earplug and the earmuff.

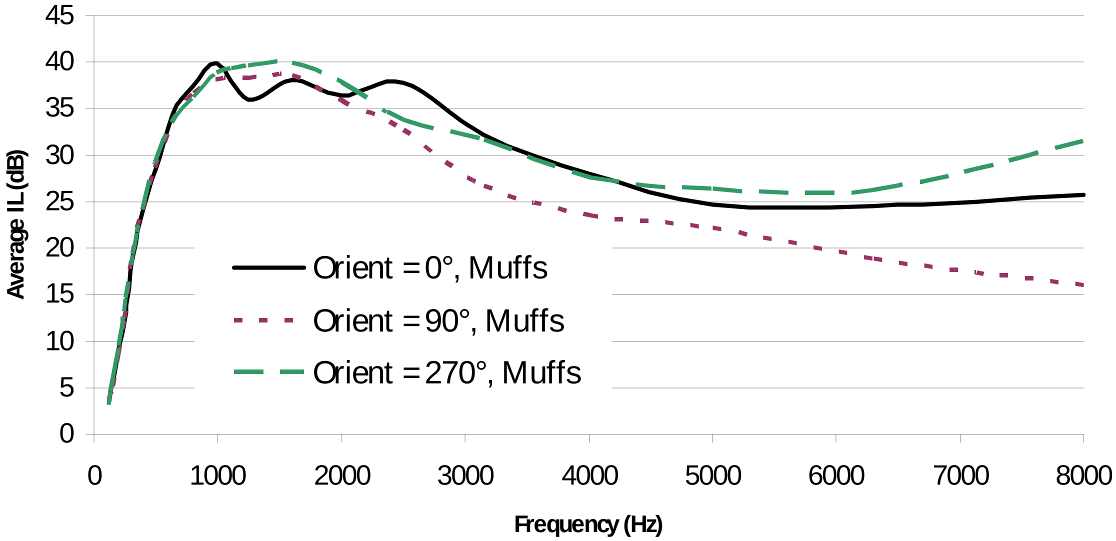

Figure 8: Effect of Orientation to Source on Mean IL Values for Earmuffs in the Ordinary Room Averaged over all subjects

There was somewhat more deviation due to orientation in the ordinary room. As shown in Figure 8, there was virtually zero deviation at frequencies below 500 Hz, as expected. However, at frequencies above 2000 Hz, the 90° orientation was at least 5 dB lower than the results at 0° and 270°. Averaged over all frequencies, the 90° orientation produced the lowest IL and NR values, as was expected since in that orientation the head would act as a barrier for the tested ear.

As shown in Table 1, for IL the greatest mean difference due to orientation was 2.4 dB for the earmuff and 1.9 dB for the earplug. The differences were greater for values for NR. For earmuffs the greatest difference in average NR values was 2.8 dB and the greatest difference was 3.6 dB when wearing the earplugs.

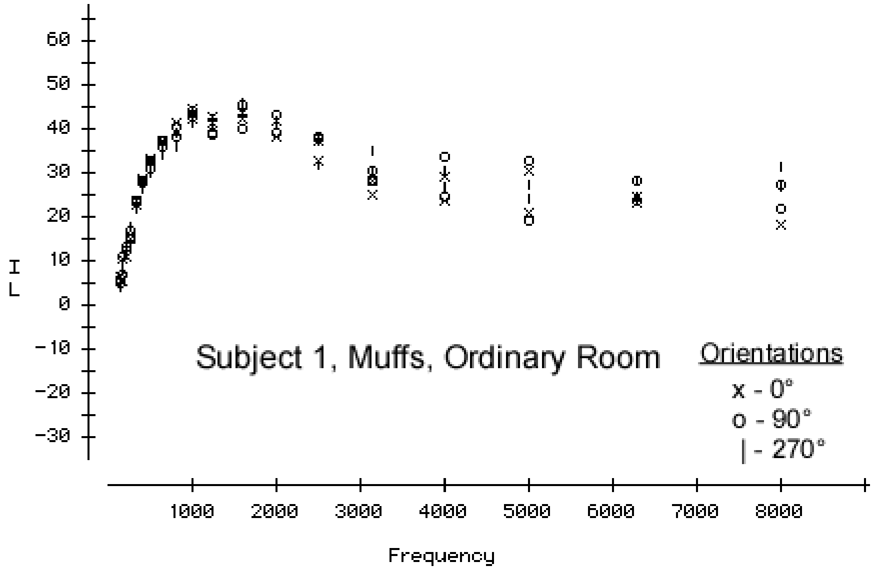

Figure 9: IL for subject wearing earmuffs comparing 3 orientations to sound source

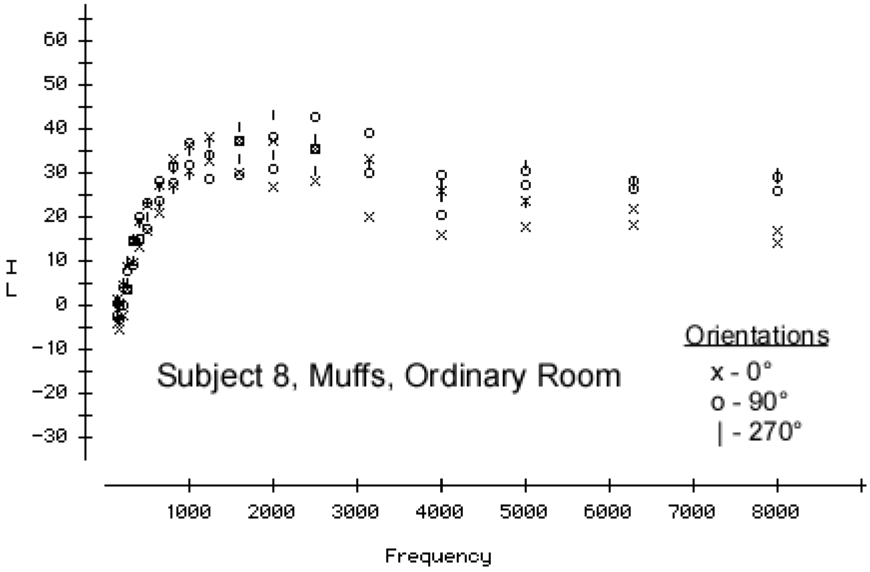

Figure 10: Shows little difference between orientations

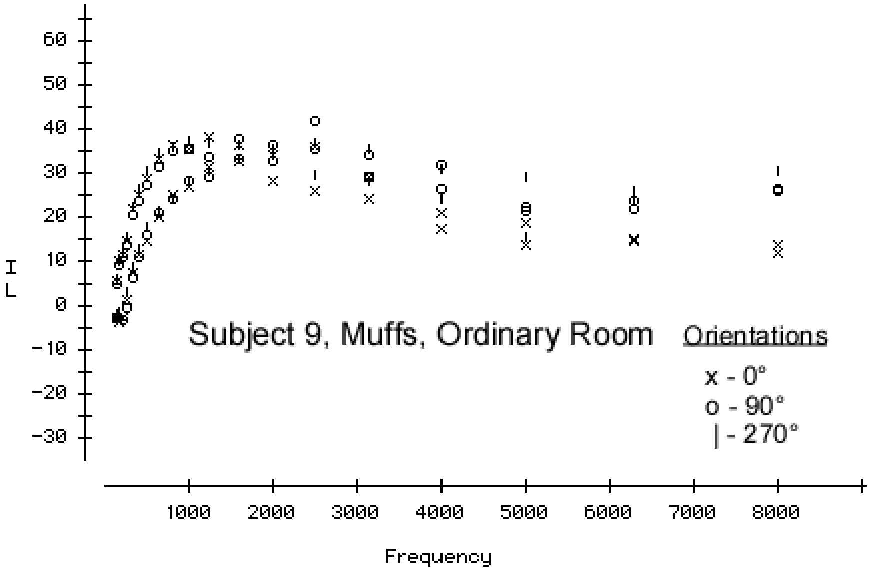

Figure 11: Shows a parallel path of orientation

Although the average deviations due to orientation were modest when averaged over all subjects, they were substantial for Subject 8 who had deviations as high as 10 dB at 3000 Hz (See Figure 10). Subject 9 also had more differences than most subjects (see Figure 11). With Subject 9 the difference was mostly between replications, possibly due to a different fit of the earmuffs between replications.

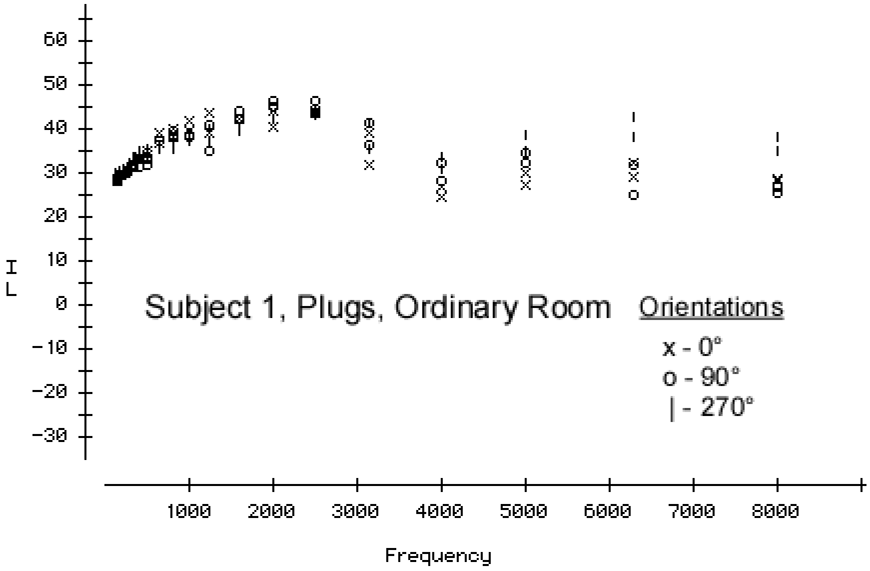

Figure 12: Shows the closeness among orientations for the use of earplugs in an ordinary room

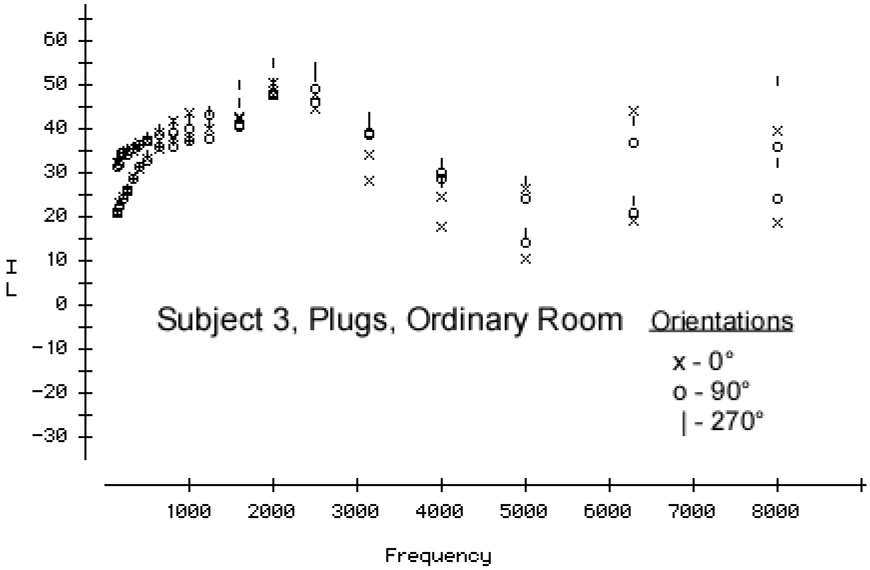

Figure 13: Erratic earplug fitting as seen by all three orientations

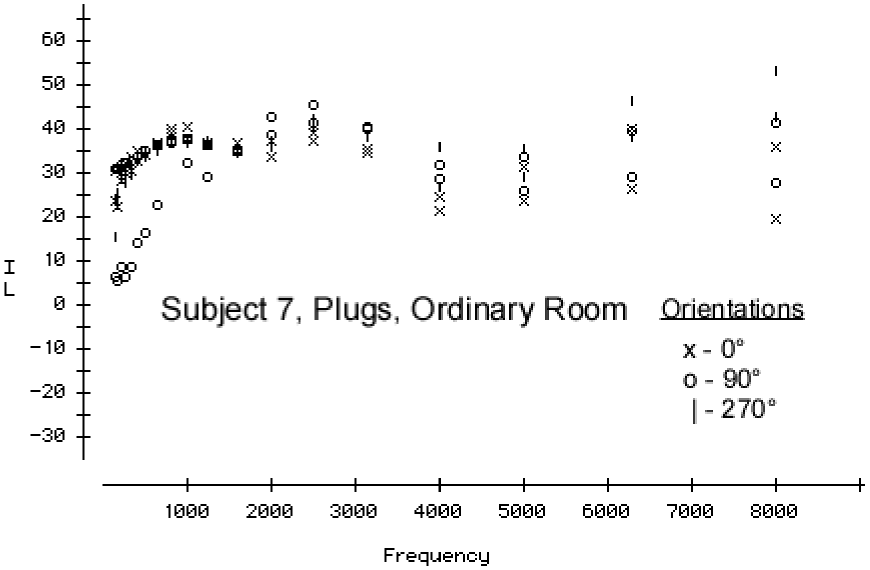

Figure 14: Shows closeness between orientations

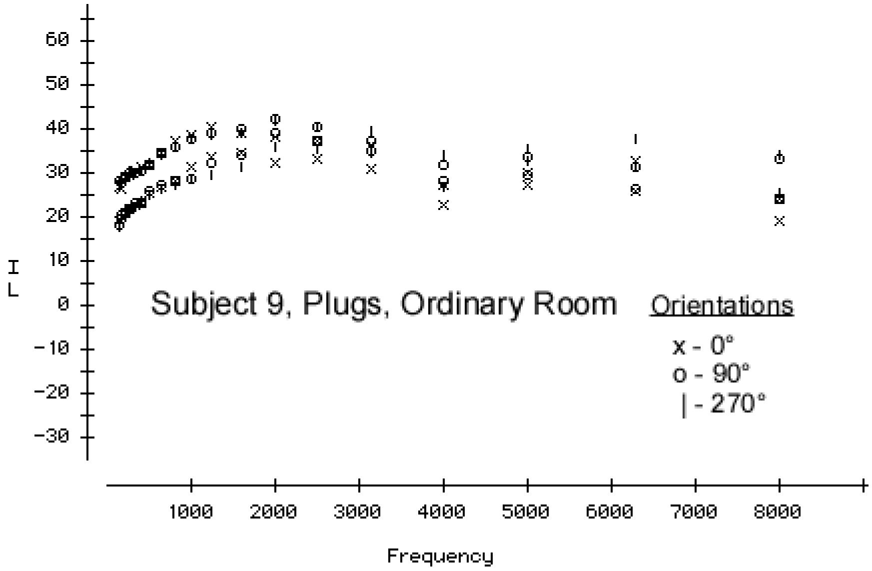

Figure 15: Shows offset profiles with frequency, possibly due to a difference in earplug fit between replications. Still shows a tight fit between all orientations.

For earplugs, Figure 12 (Subject 1) shows a close agreement for different orientations. However, as seen in Figure 9 (Subject 1) and Figure 11 (Subject 9), earmuffs showed a much closer agreement than earplugs. Earplugs for subjects 3 and 7 showed a much more erratic difference among all orientations (see Figures 13 & 14). Lastly, Subject 9 shows a similar pattern as seen with earmuffs. Replications seem to show a constant difference (See Figure 15), suggesting the difficulty of inserting earplugs the same way each time.

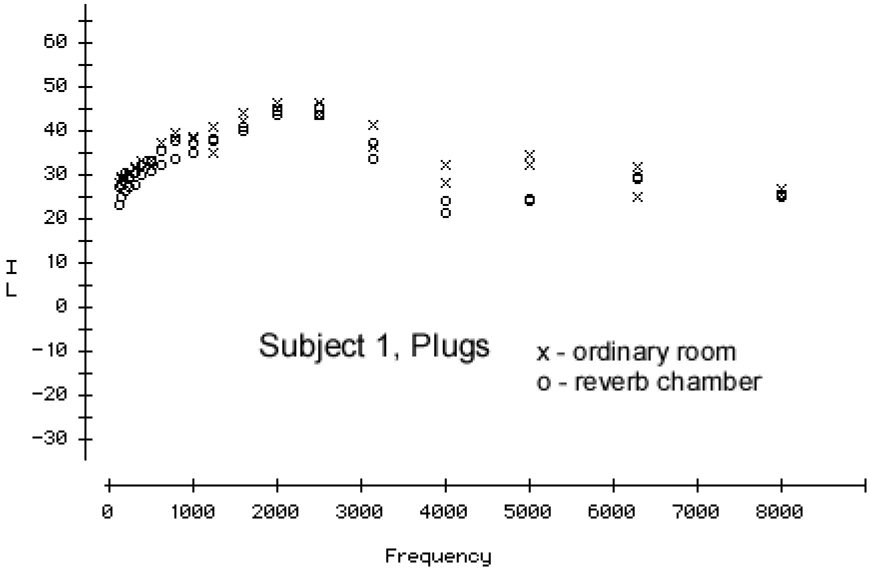

Figure 16: Shows closeness of IL between both rooms

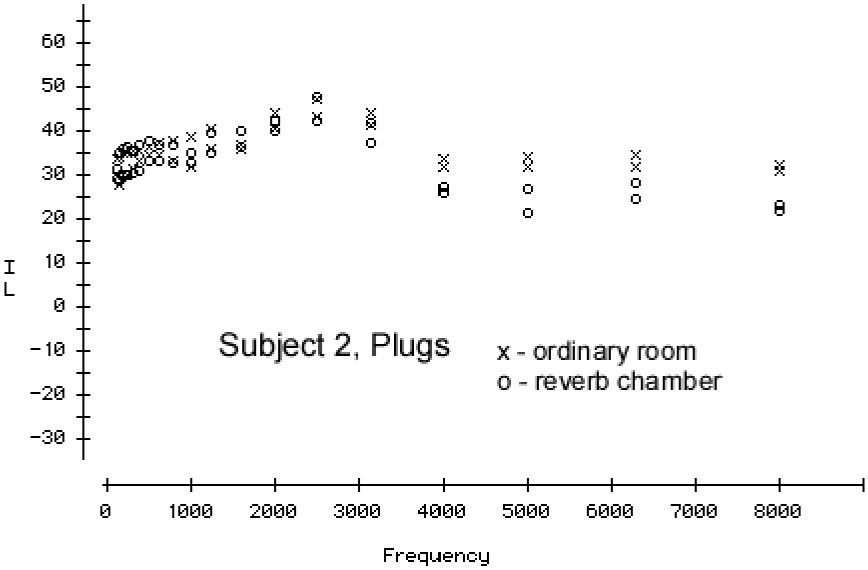

Figure 17: Shows closeness of IL between both rooms

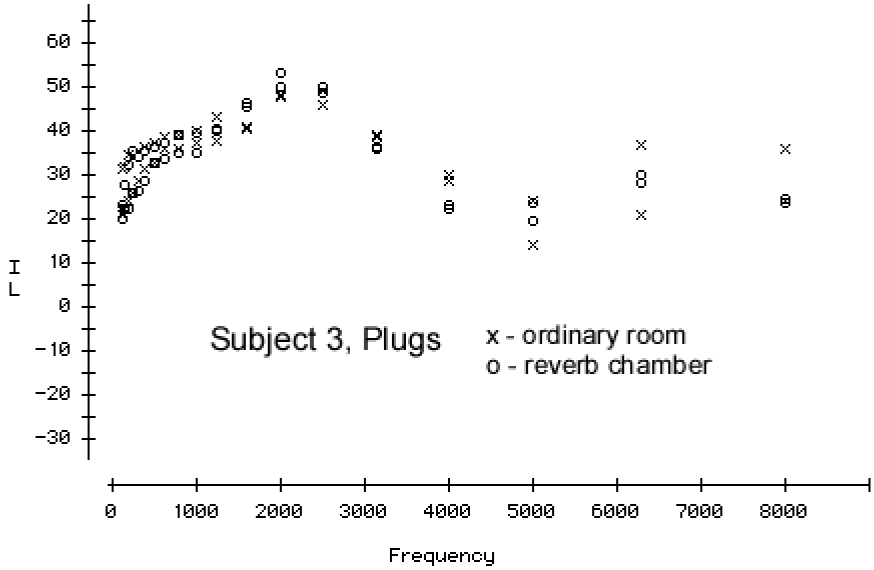

Figure 18: Shows closeness of IL between both rooms

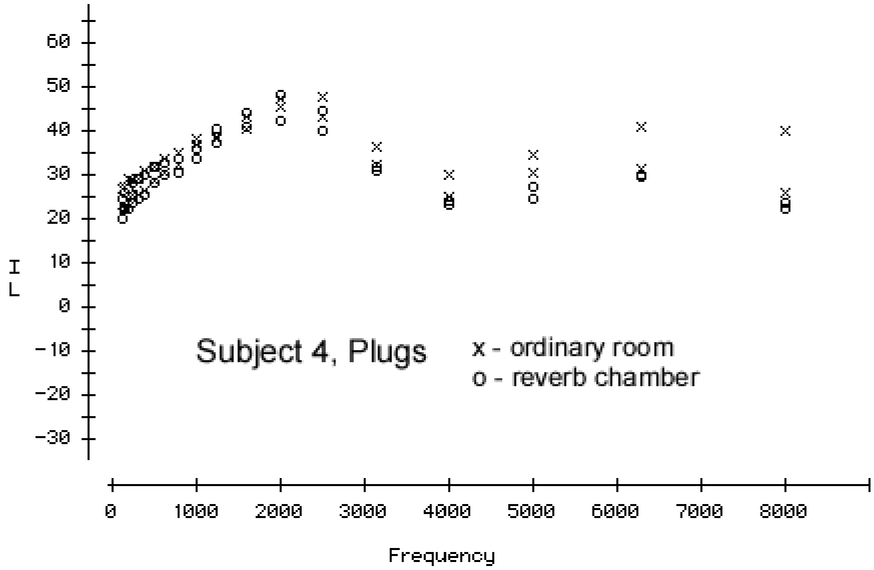

Figure 19: Shows closeness of IL between both rooms

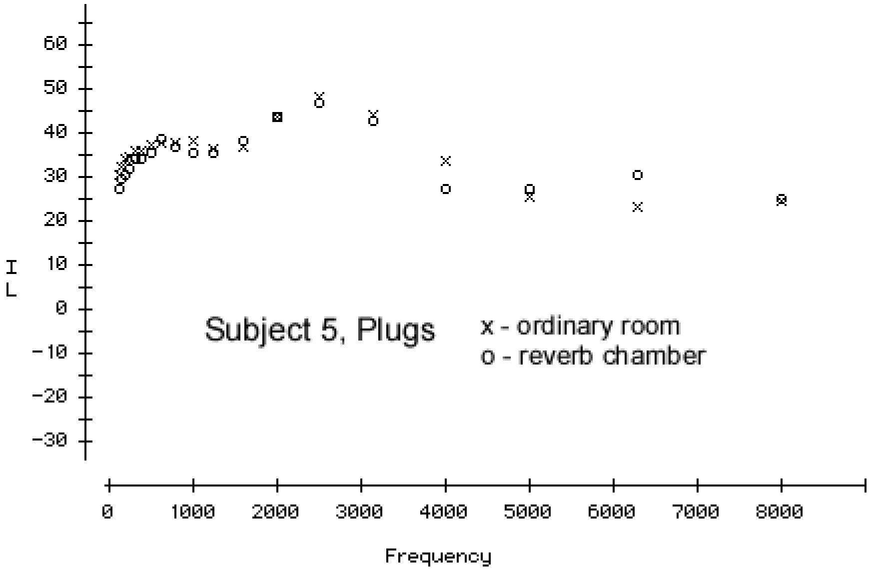

Figure 20: Shows closeness of IL between both rooms

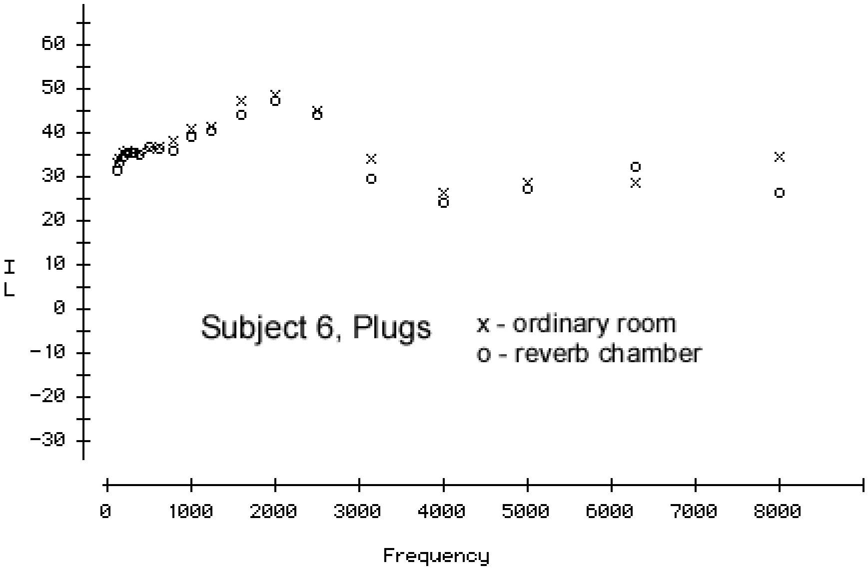

Figure 21: Shows closeness of IL between both rooms

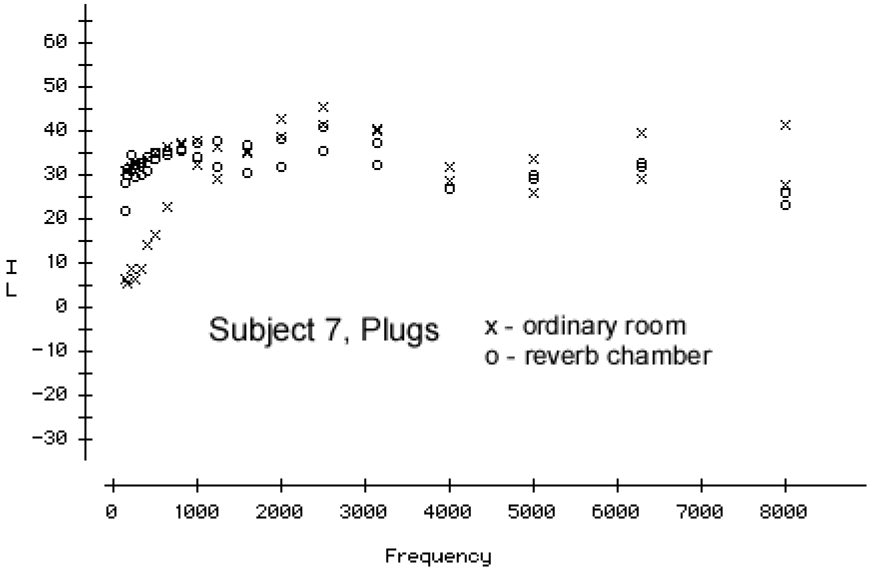

Figure 22: Shows closeness of IL between both rooms

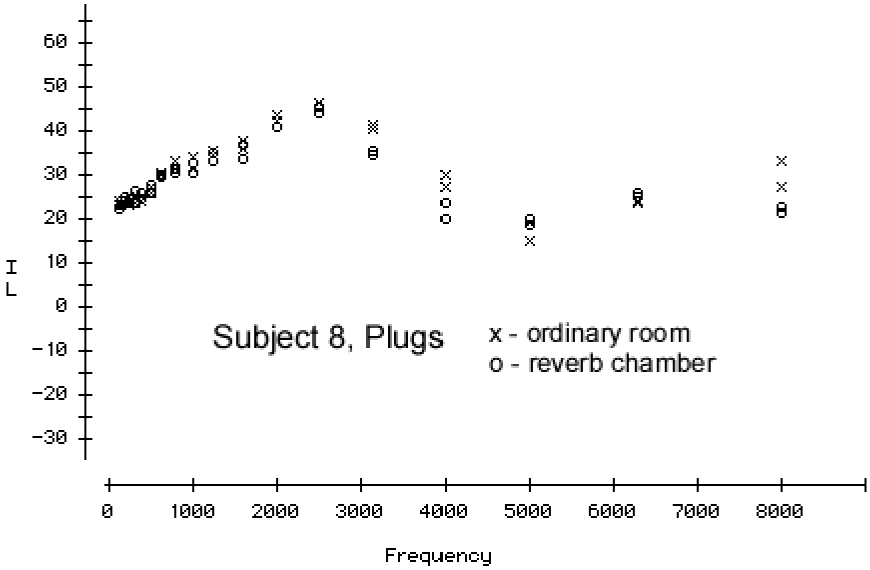

Figure 23: Shows closeness of IL between both rooms

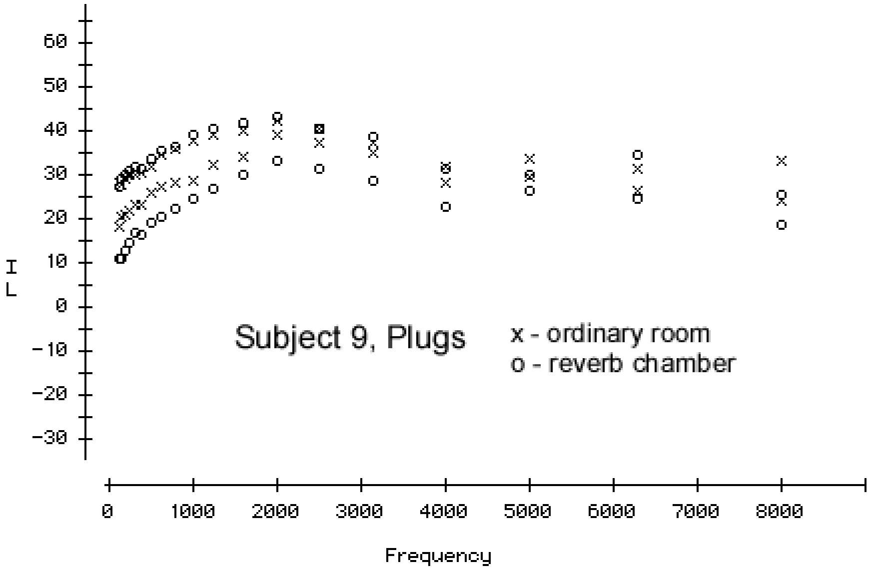

Figure 24: Shows closeness of IL between both rooms

Difference Between Rooms

Comparisons of results for NR and IL between both rooms show modest differences. For IL results for earplugs, the differences between the reverberatory chamber and ordinary room generally were within 5 dB, varying somewhat with frequency (see Figures 16 – 24).

For earmuffs, the differences between the reverberatory chamber and the ordinary room were generally within 3 dB. Summary values in Table 1 show a range of 3 dB with most values within 1 dB, a range of little practical importance when fitting or evaluating hearing protectors.

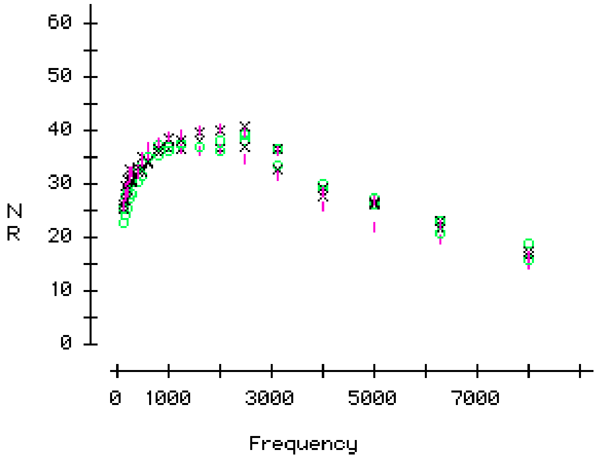

Figure 25: Shows Plugs in Reverberatory Chamber for Subject 1

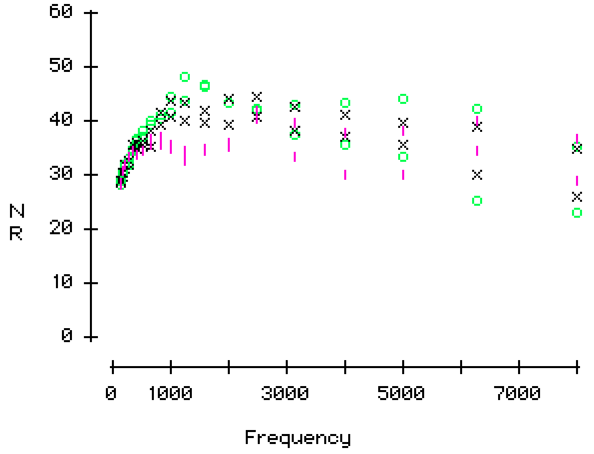

Figure 26: Shows Plugs in ordinary room for Subject 1

As seen in Figures 25 and 26, the reverberatory chamber and the ordinary room have a similar pattern of attenuation. The ordinary room has a slightly higher variance of approximately 10 dB which is of no practical importance.

DISCUSSION

Where they could be compared, results found in this study agreed with Berger (1998). For example, in a study conducted in a reverberation chamber following the MIRE standard, Berger (2000c) found that EAR foam earplugs provided 30 – 45 dB above 2000 Hz and below 2000 Hz the earplug can attenuate between 20 – 40 dB. Over the range of 125 to 8000 Hz, his average attenuation for a same earplug averaged to be 35 dB. Berger also found that the attenuation of the earplug can increase about 8 or 9 dB from 125 - 1000 Hz and will approach its attenuation limit of 40 dB at frequencies greater than or equal to 2000 Hz due to the limit imposed by bone conduction. This study agrees with the findings of Berger and also shows an approximate 40 dB attenuation limit with earplugs at 2000 Hz.

As seen in this study and as shown by Berger (2000c), earplugs tend to provide a higher attenuation than earmuffs at frequencies below 500 Hz and above 2000 Hz (see Figure 7). In this study, earmuffs exceeded earplugs in attenuation at frequencies around 1000 Hz by roughly 1 dB. Earmuffs also provided equivalent attenuation as earplugs in frequencies higher than 2000 Hz.

Table 2: Analysis of Variance of IL Results for All Subjects and Test Conditions

Source	df	Sums of Squares	Mean Square	F-ratio	Prob
Constant	1	3.242×10^6	3.242×10^6	114.98e3	< 0.0001
Subject	8	15191	1898.88	67.338	< 0.0001
Location	1	918.278	918.278	32.564	< 0.0001
HPD	1	51754.7	51754.7	1835.3	< 0.0001
Frequency	18	245687	13649.3	484.03	< 0.0001
Orientation	2	690.836	345.418	12.249	< 0.0001
Location*	2	873.215	436.608	15.483	< 0.0001
Location* HPD	1	235.257	235.257	8.3427	0.0039

Frequency*	36	2750.87	76.4131	2.7098	< 0.0001
Location* Frequency	18	4955.55	275.308	9.763	< 0.0001
Error	3788	106818	28.1991		
Total	3875	428891			

Table 3: Statistical Variance NR Results for All Subjects with Interactions

Source	Df	Sums of Squares	Mean Square	F-ratio	Prob
Constant	1	3.214×10^6	3.214×10^6	112.37e3	< 0.0001
Subject	8	31076.6	3884.57	135.77	< 0.0001
Location	1	10091.6	10091.6	352.72	< 0.0001
HPD	1	29566.9	29566.9	1033.4	< 0.0001
Frequency	18	224898	12494.3	436.7	< 0.0001
Orientation	2	945.425	472.713	16.522	< 0.0001
Location* Orientation	2	1605.2	802.6	28.053	< 0.0001
Location* HPD	1	217.913	217.913	7.6165	0.0058
Frequency* Orient.	36	3097.15	86.032	3.007	< 0.0001
Location* Frequency	18	16770.2	931.681	32.564	< 0.0001
Error	3788	108377	28.6106		
Total	3875	426201			

As seen in Tables 2 and 3 the analysis of variance shows that all variables are statistically significant, including all interactions. This suggests that the deviations found for different conditions are real and reasonably accurate because they are repeatable. However, as shown in Tables 2 and 3 and was discussed in the results, the deviations due to conditions were modest, however much confidence one might have in their repeatability.

For example, in Table 1 when the reverb chamber was compared to the normal room at the same orientations, the differences were almost all within 5 dB. Likewise in Table 1, when results for different orientations were compared in the same room, the deviations due to orientations were nearly all within 2 dB when integrated over the frequency range of interest. The fact that using a normal room or a different orientation could change fit-testing results by 0 to 5 dB would not normally significantly affect decisions as to whether a specific protector was adequate in a specific environment.

However, because of the high statistical significance, we can investigate the small deviations that did occur. For example, the effect orientation to the source would have on IL would seem clear. Since measurements are taken only in the ear and the ear is in the acoustic shadow of the head at 90°, one would expect the 90° IL results to be somewhat less than at 0° and 270°. Indeed, in the ordinary room, the 90° were typically 2 dB less than the other two orientations, which were almost identical. However, for the NR, the factors are more complicated. Measurements at the ear at 90° would still be lowest, but the SPL at the shoulder would presumeably be highest at 0°. Thus, NR at 0° or 90° should be largest, with 270° the lowest. Instead, we found that 0° had the highest NR, with 90° and 270° competing for second.

As expected, when facing 90° from the source, sound entering the hearing protector in the right ear is shadowed and lessened by the head. This is due to sound having to travel around the head and being absorbed by the head. High frequencies tend to be absorbed by the head whereas low frequencies can travel far. Higher frequencies are also easier to attenuate than lower frequencies. At 270° sound directly hits the tested ear and gives a higher attenuation than facing 0° and 90°. This is caused by more sound hitting the tested ear while facing 270° than when facing the other degrees.

The effect of Location with reverberatory chamber vs ordinary room was also modest. Robinson et al, (1992) compared the attenuation of earmuffs in a reverberatory chamber to the attenuation of earmuffs in a semi-reverberatory chamber similar to a common office using the REAT method. They also concluded that a reasonable estimate of the protection level provided by an earmuff can be determined in a common office by the REAT method. Our study used the MIRE method to determine attenuation. The two methods are comparable but slightly different in which one method could create more attenuation than the other. The REAT method gets less attenuation than the MIRE method at low frequencies.

The earmuffs were also different between our study and that of Robinson et al, (1992). They used three earmuffs, Peltor H7A (large volume), Peltor H9A (small volume), and Cabot Safety Model 1720. Our study used the North Gun Muffler Earmuffs with foam filled cushion (Brea, California). The difference in earmuffs could be an explanation to the difference in dB between Robinson’s study and this one. The biggest deviation in Robinsons study was 2.7 dB among all center frequencies of one-third octave band, a deviation of little significance when selecting hearing protection. The greatest deviation in our study was approximately 5 dB.

The semi-reverberatory chamber acoustical environment was obtained in the reverberatory chamber by hanging one sheet of 5.1 cm thick Sonex acoustical foam on each of the reverberatory chamber's four walls. Acoustics were different in the Semi-Reverberatory room than the Ordinary room used in this study. The ordinary room used in this study did not contain hanging one sheet of 5.1 cm thick Sonex acoustical foam on each of the reverberatory chamber's four walls, which could greatly affect the results between the two studies.

Nine subjects were tested in both a reverberatory chamber and an ordinary room. The results from this study show that due to such high statistical power, orientation does show to be statistically significant, but the differences are too small to be of practical importance. Slight effects were found and in the results of this study the reverberation showed slight effects of orientation, as expected.

The high- frequency attenuation measurements were lower than expected, possibly due to either insufficient high- frequency content of the noise stimulus or elevated high-frequency measurement system electrical noise. Either of these conditions will lead to erroneous measurements that underestimate the amount of attenuation afforded to the HPD wearer.

When looking at the results between both the reverberatory chamber and the ordinary room, in averaging frequencies between 125 Hz to 8000 Hz this study found few differences between the two rooms. The few differences found were a 5 dB gain or loss in NR and IL.

Even though the difference between IL and NR showed a mere 5 dB difference in the lab, the value in the field would be considered null. Also even though NR is faster than IL, IL showed a much smaller difference between both the reverberatory chamber and the ordinary room and should be considered for field sampling. Future research should consider sampling in both ears.

CONCLUSIONS

The results from this study support a number of conclusions:

1. The EAR 3L earplug was at least as effective as the North Gun Muffler earmuff.
2. The values were comparable to the values reported by Berger (1998).
3. As expected, the earmuff showed relatively poor performance for frequencies below 500 Hz, as expected.
4. The orientation in which the ear was in the shadow of the head produced an overall modestly (0.1-3 dB) higher IL and NR values than the 0° (facing source) orientation for both earplugs and earmuffs in the ordinary room.
5. The overall IL and NR values found in the ordinary room on the average deviated by less than 3 dB for earmuffs and 4 dB for earplugs from the reverberatory chamber.

The modest deviations for an ordinary room and the reverberatory chamber are unlikely to be of practical concern when fitting ear protectors to individuals.

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